# Lecture 09
# Sensors

CE346 – Microprocessor System Design

Branden Ghena – Fall 2022

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

# Administrivia

- *Most* groups should have now received feedback from me on their proposals
  - I’ll get to the rest either today or tomorrow
  - For some of you, I gave action items, be sure to handle those soon

- Design presentations will be next week **Tuesday & Thursday**
  - Details are on Campuswire
  - Be sure to check the schedule for which day you are on

# 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 are common
    - As are sensors that produce a voltage/current

# Resistive sensors

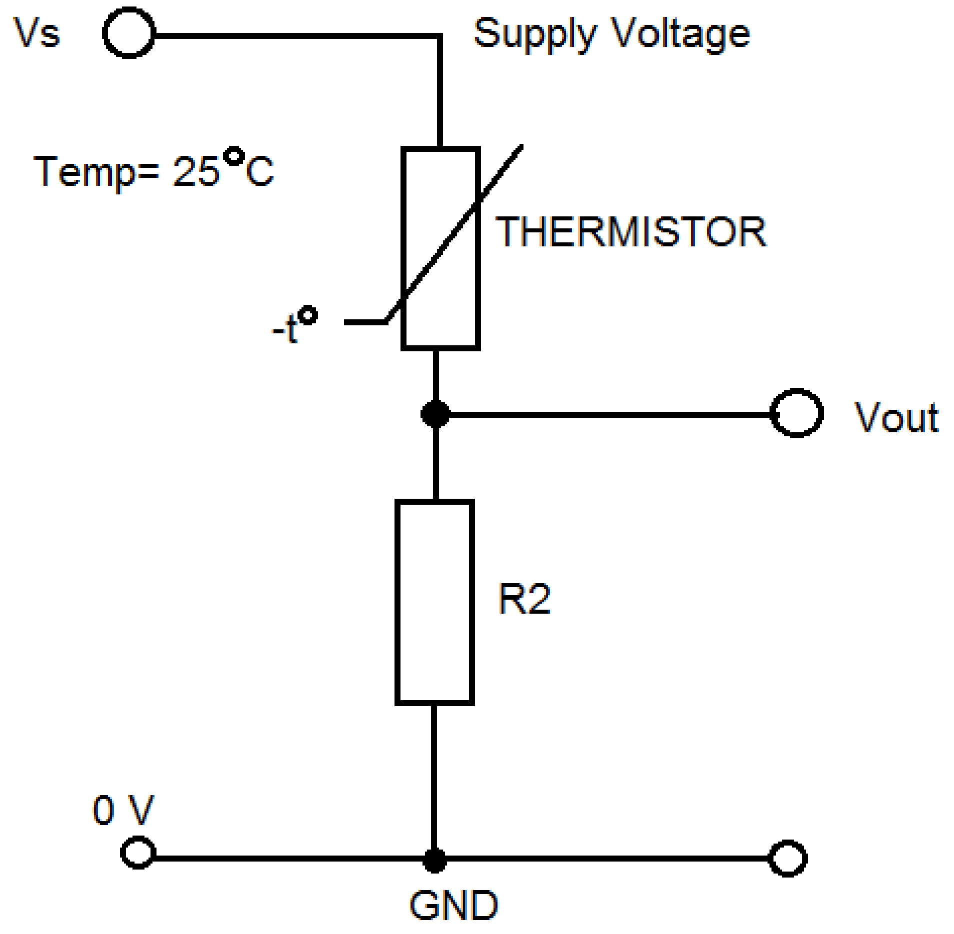
$$R = \frac{\rho L}{A}$$

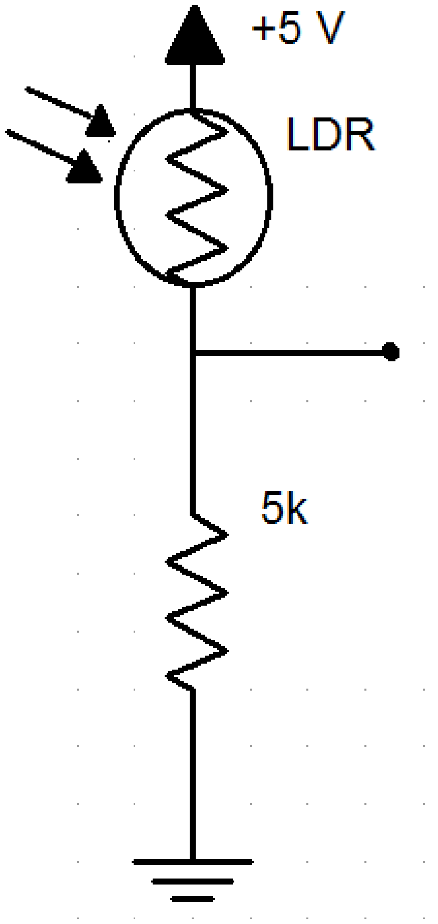
- L: length of the conductor
- A: area of the conductor
- ρ: resistivity of the conductor material

- 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

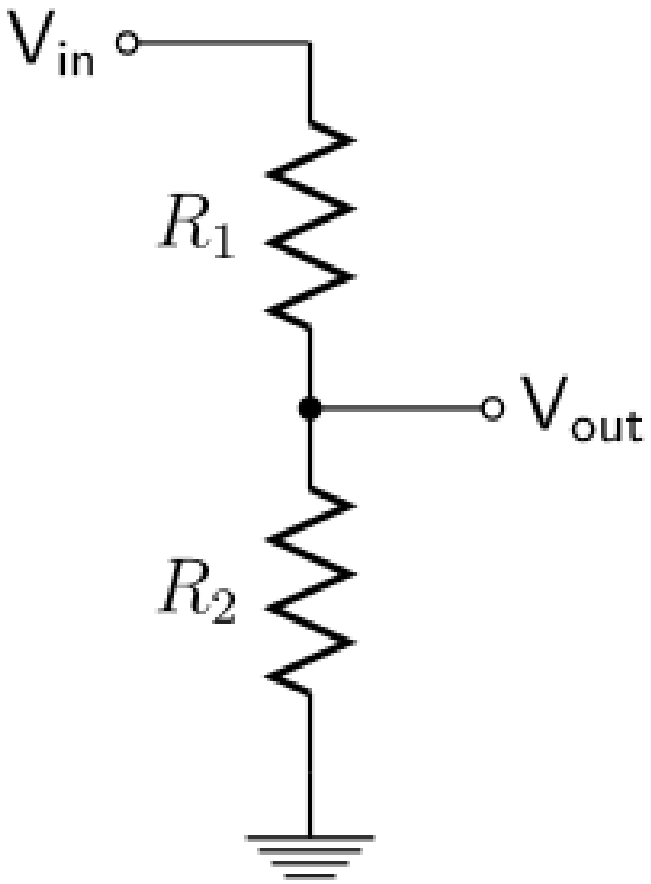
- $V_{out} = \frac{R_2}{R_1+R_2} * V_{in}$

Important! Learn this

  - $V_{in}$ is a voltage source
  - $R_1$ and $R_2$ are resistors

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

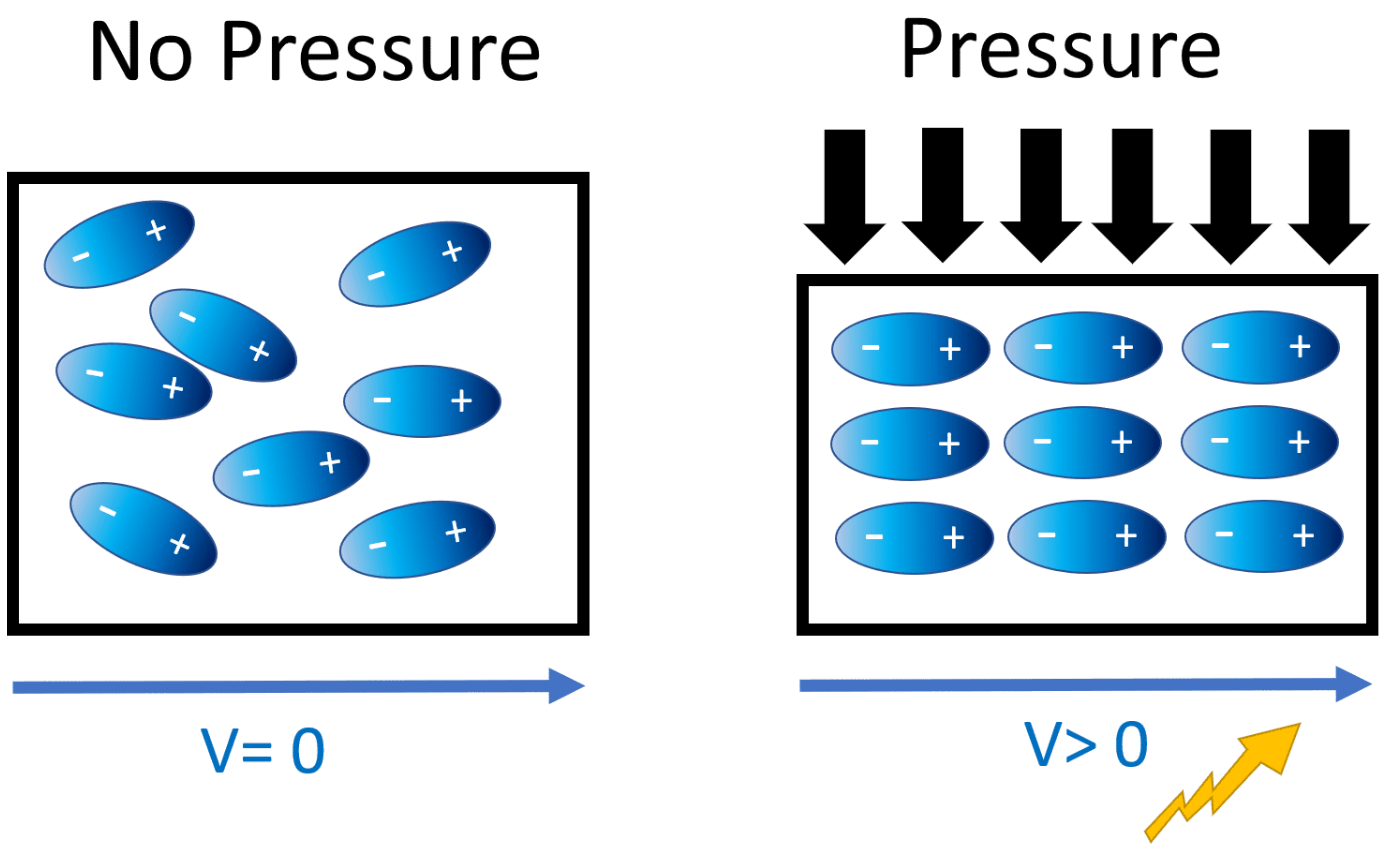
- Smaller $R_1$ means larger $V_{out}$
  - $V_{out}$ approaches $V_{in}$



# Generating voltage via piezoelectric effect

- Compression of the material generates a voltage

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



# 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)

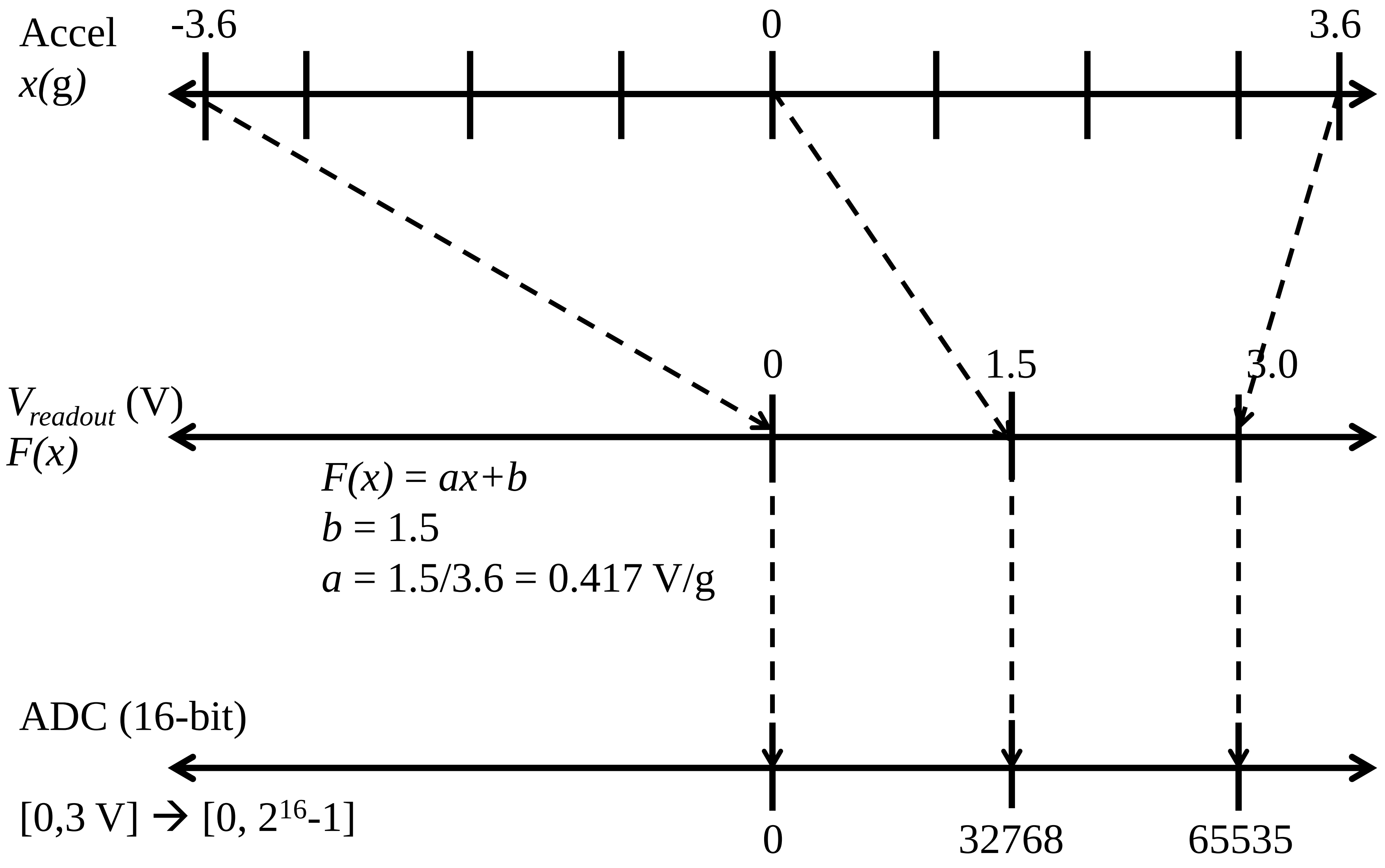
$$F(x) = ax + b$$

- 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



# Understanding transfer function: ADXL330 datasheet

- Ratiometric
  - Relative to sensor voltage
- Bandwidth
  - Data update speed of the sensor

## SPECIFICATIONS

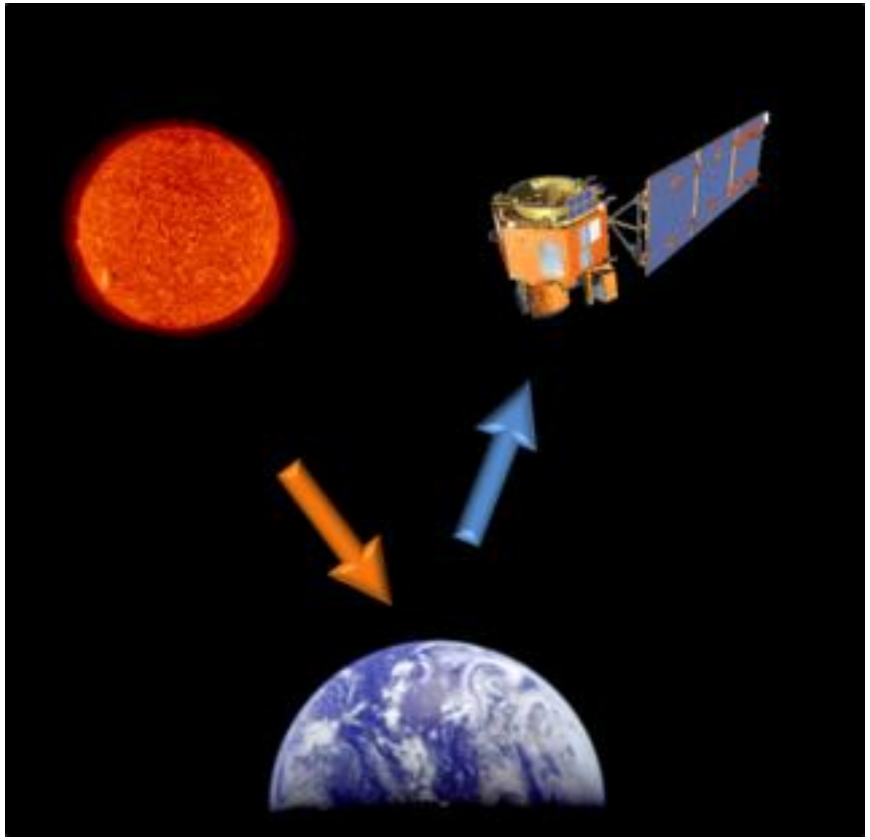
$T_A = 25°C$, $V_S = 3$ V, $C_X = C_Y = C_Z = 0.1$ μF, acceleration = 0 *g*, unless otherwise noted. All minimum and maximum specifications are guaranteed. Typical specifications are not guaranteed.

**Table 1.**

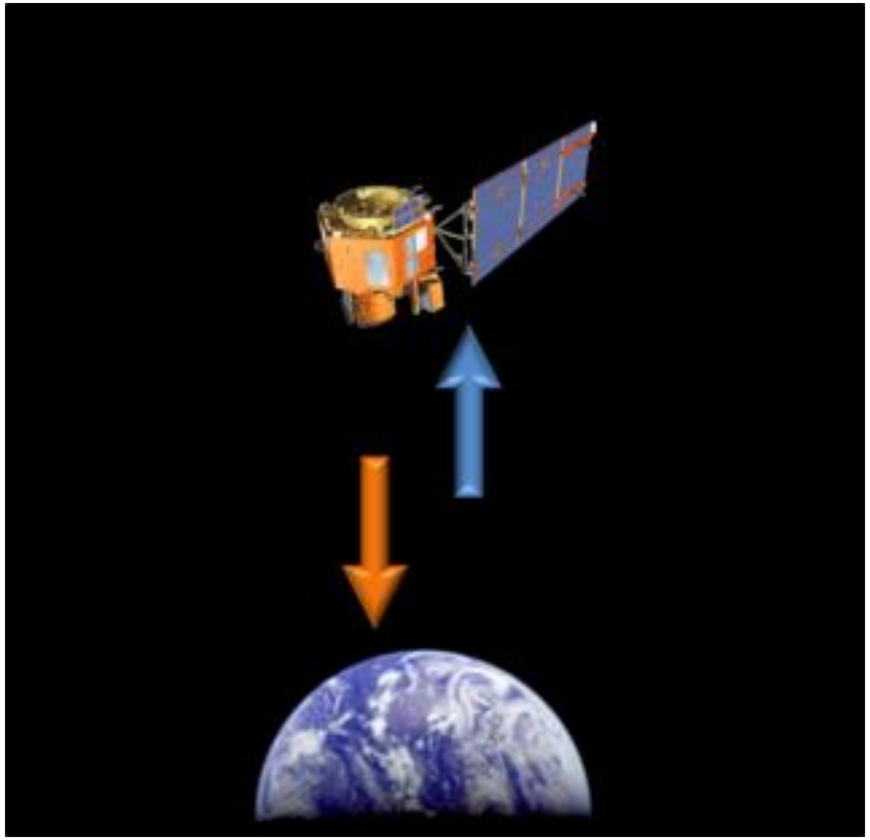
| Parameter | Conditions | Min | Typ | Max | Unit |
|---|---|---|---|---|---|
| SENSOR INPUT | Each axis | | | | |
| Measurement Range | | ±3 | ±3.6 | | *g* |
| Nonlinearity | % of full scale | | ±0.3 | | % |
| Package Alignment Error | | | ±1 | | Degrees |
| Inter-Axis Alignment Error | | | ±0.1 | | 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 | | m*g*/°C |
| NOISE PERFORMANCE | | | | | |
| Noise Density $X_{OUT}$, $Y_{OUT}$ | | | 280 | | μ*g*/√Hz rms |
| Noise Density $Z_{OUT}$ | | | 350 | | μ*g*/√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

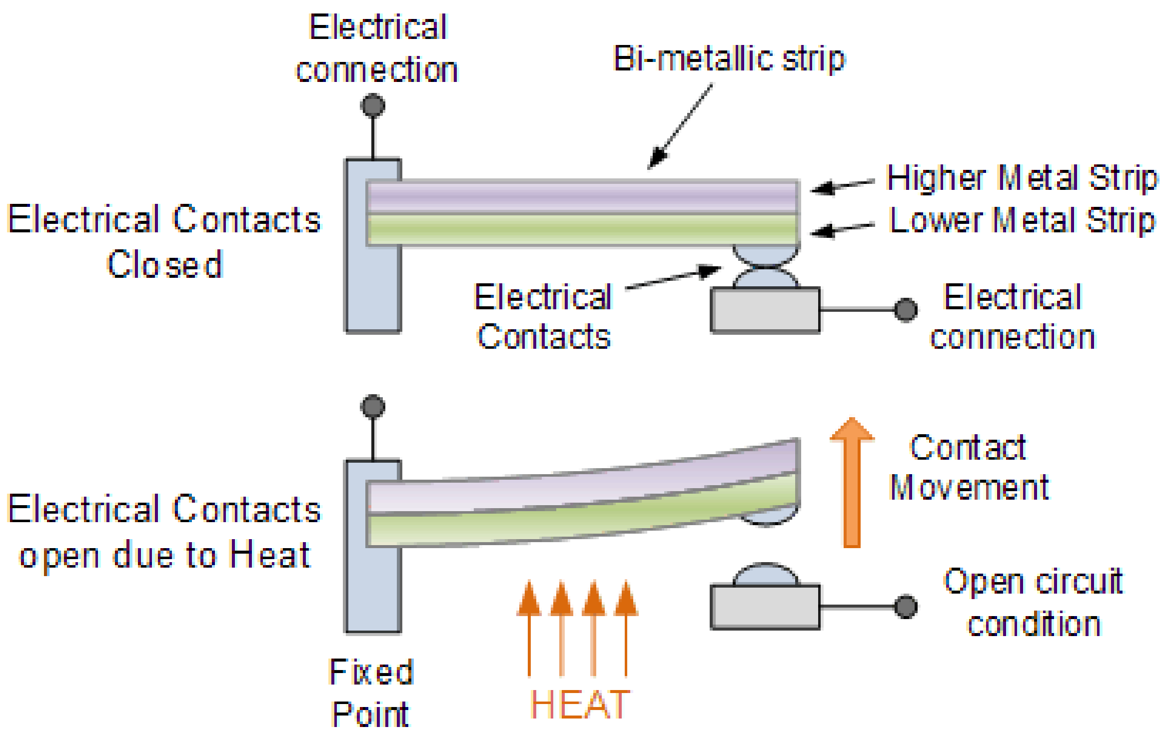
- What acceleration is the voltage reading 3.5 volts?
  - 3.5 v = 1v/g * x + 0v -> 3.5 g

# Outline

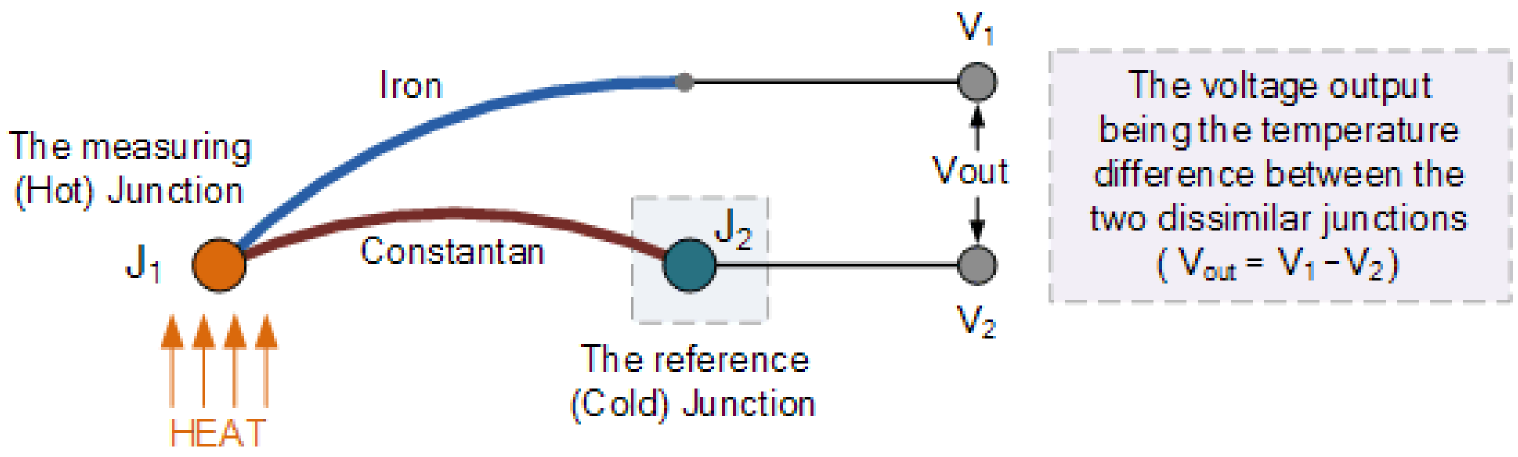
- Sensing Overview
- **Types of Sensors**
  - **Temperature**
  - Light
  - Inertial
  - Others
- Research case study

# 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



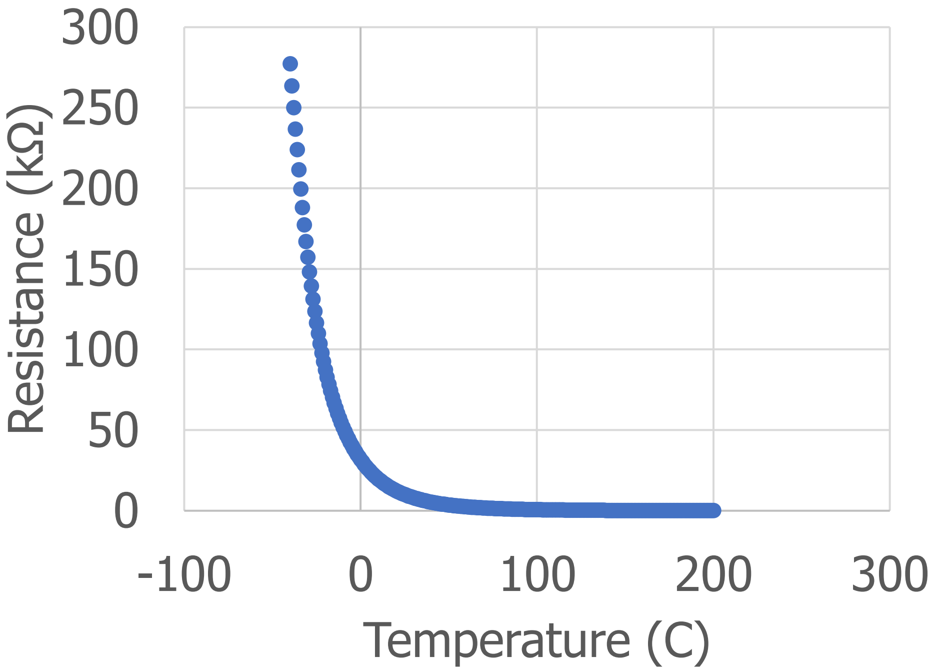
# Thermo-electric temperature sensing




- **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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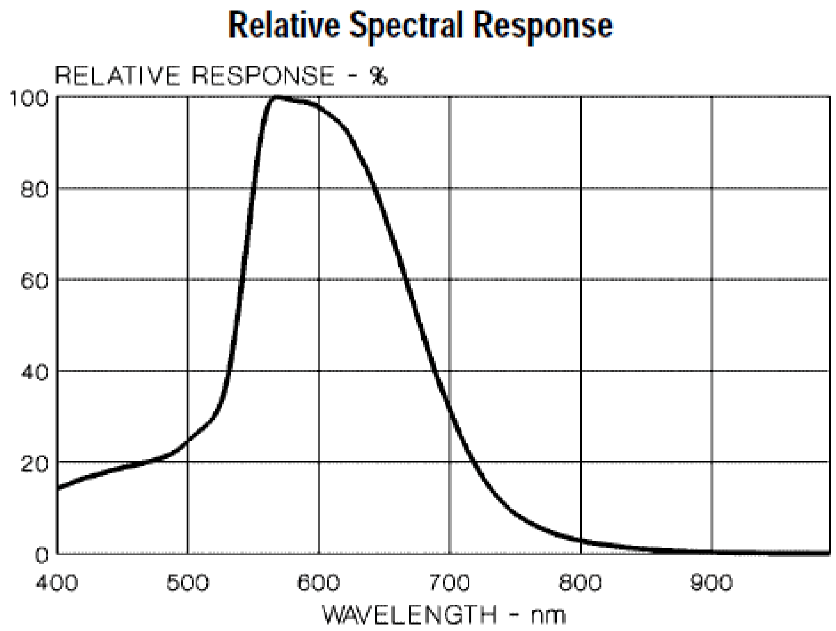
# Measuring light

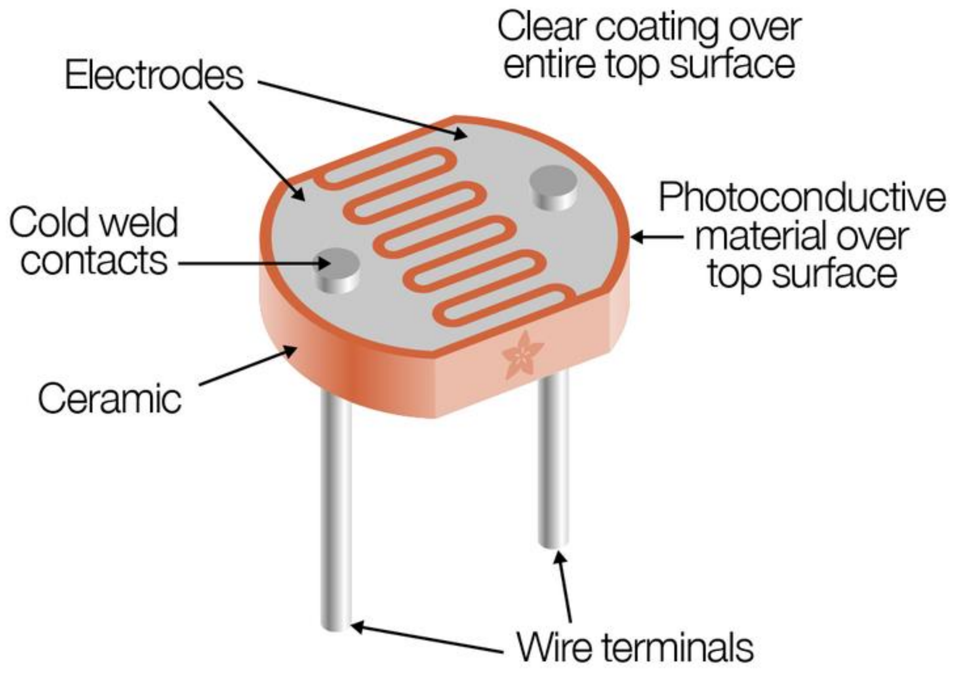
- Lux: unit of illuminance
- Beware spectrum sensitivity




| 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)




**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

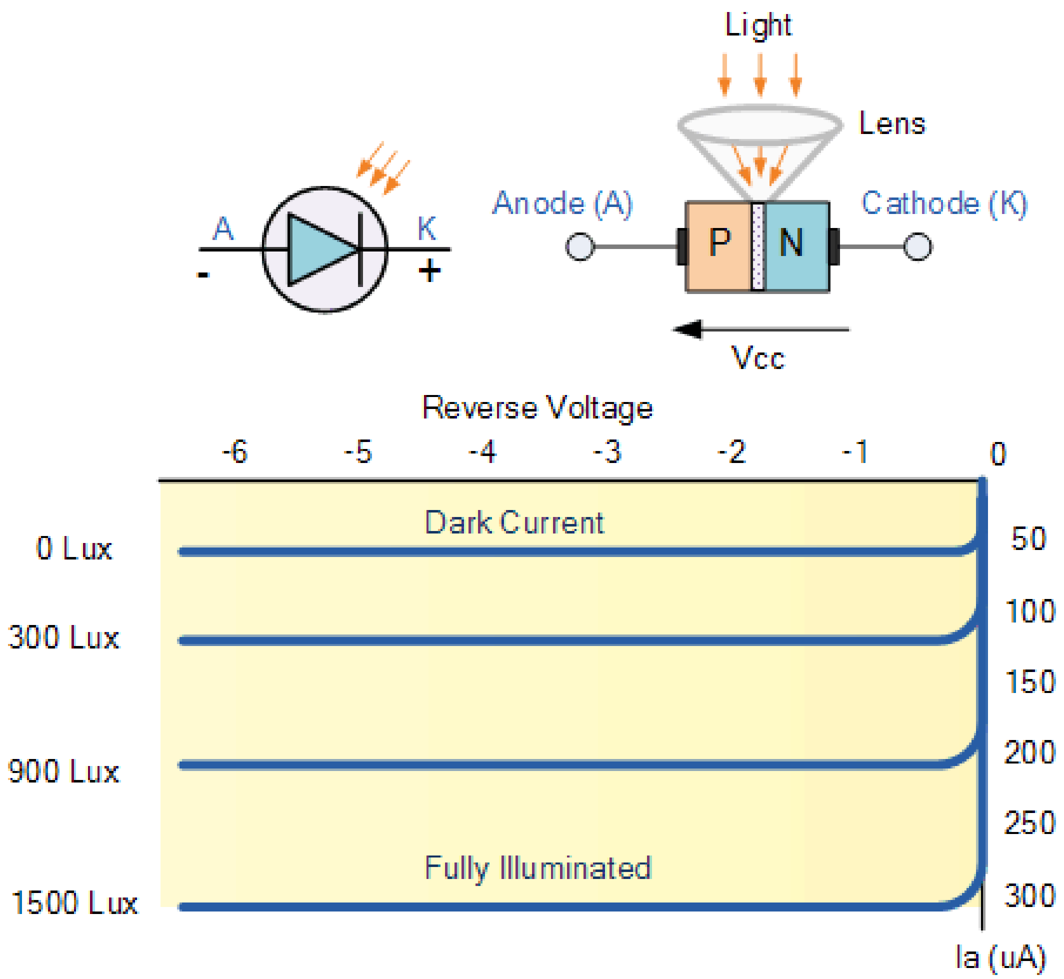
| SYMBOL | CHARACTERISTIC | TEST CONDITIONS | MIN | TYP | MAX | UNITS |
|---|---|---|---|---|---|---|
| $R_D$ | Dark Resistance | After 10 sec. @ 10 Lux @ 2856 °K | 0.2 | | | MΩ |
| $R_I$ | Illuminated Resistance | 10 Lux @ 2856 °K | 3 | | 11 | KΩ |
| S | Sensitivity | LOG(R100)-LOG(R10)** / LOG(E100)-LOG(E10)*** | | 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

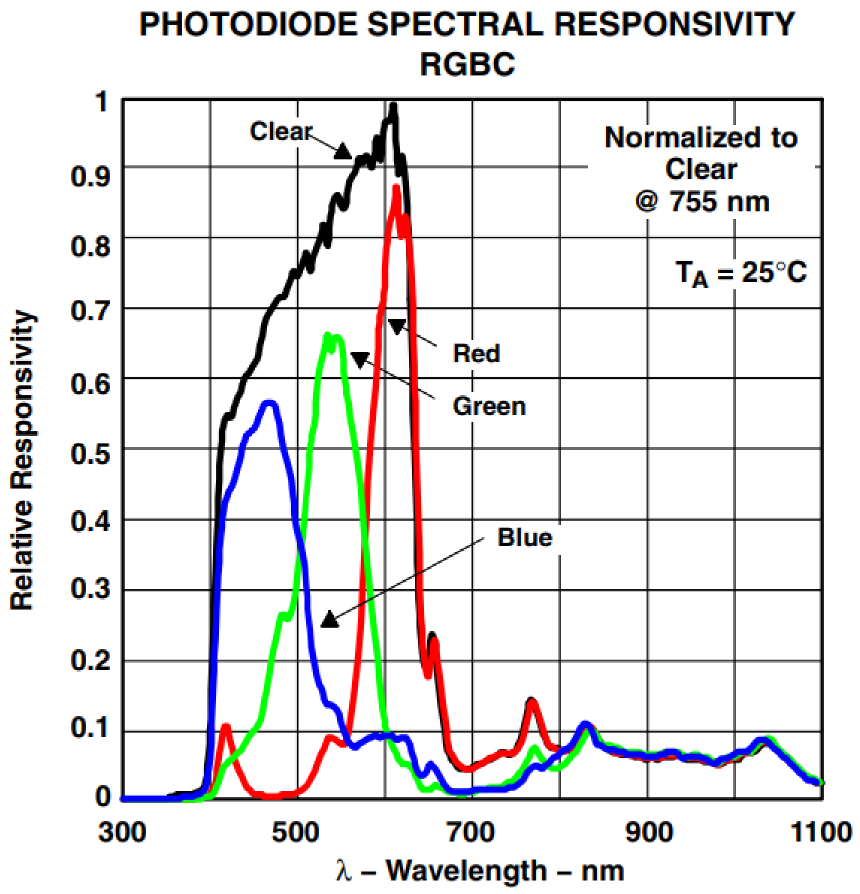
- When voltage is applied in reverse to an ideal diode, no current flows
- But some small amount of current leaks for real-world diodes
  - Proportional to light levels!
- LEDs can be used as (crappy) photodiodes as well!
  - Apply reverse voltage
  - Read in leak current as voltage across a resistor using ADC



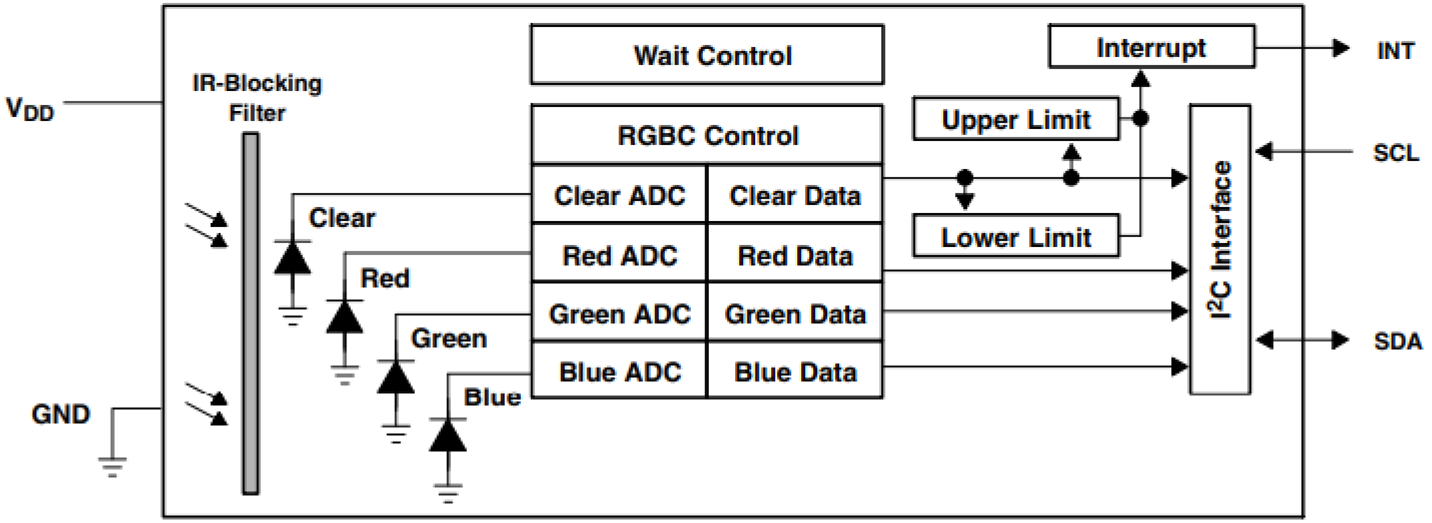

https://wiki.analog.com/university/courses/electronics/electronics-lab-led-sensor

# Light color sensing

- Respond to specific light colors separately



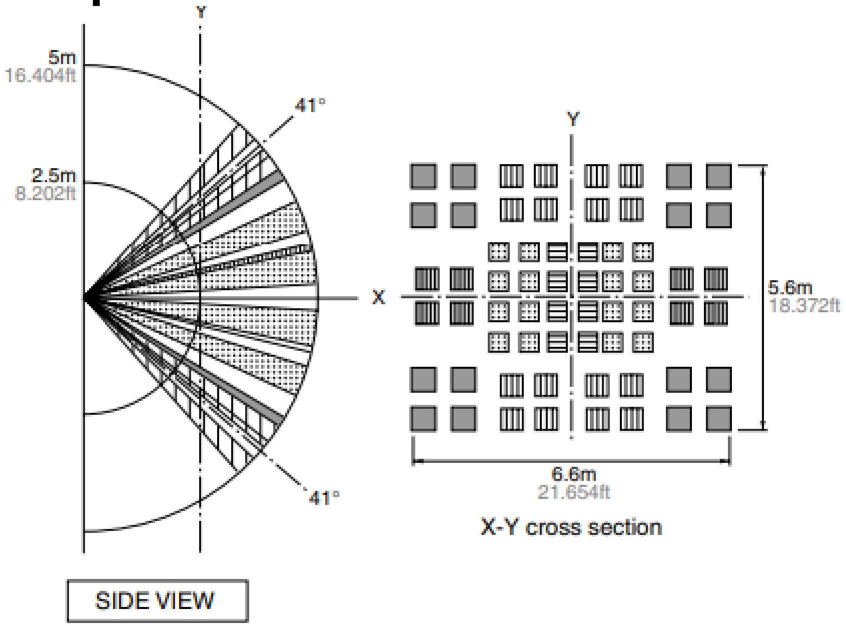

- Intelligent sensor: photodiodes combined with ADCs and a wired interface (I2C)
- Allows interrupting based on comparator too



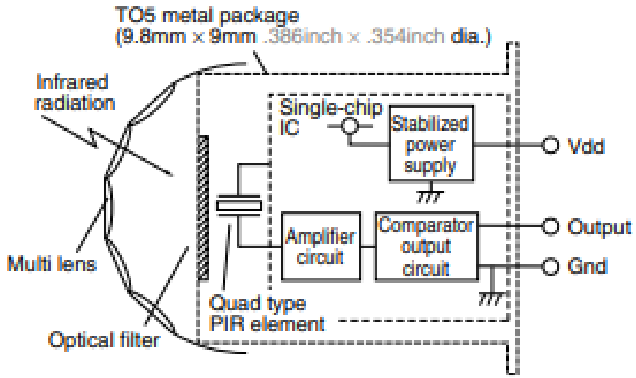
# Passive Infrared (PIR) sensor

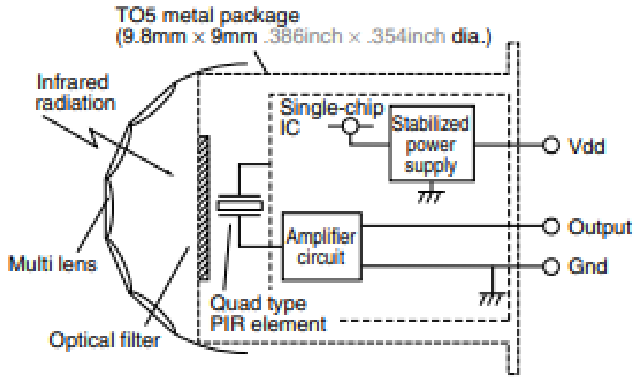
- Detect movement in the environment
  - By detecting change in IR levels

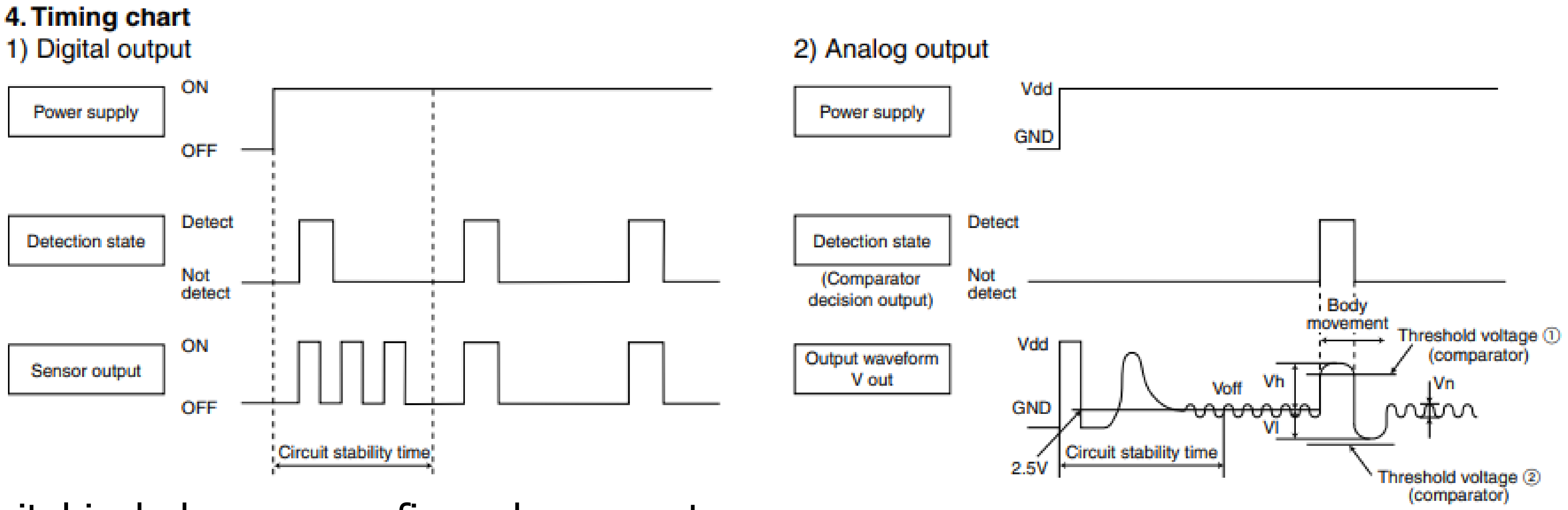
- Often come with plastic lens cover to improve field of view and range



# PIR sensors come in digital and analog forms




Digital includes a preconfigured comparator

# Outline

- Sensing Overview
- **Types of Sensors**
  - Temperature
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  - **Inertial**
  - Others
- Research case study

# 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)

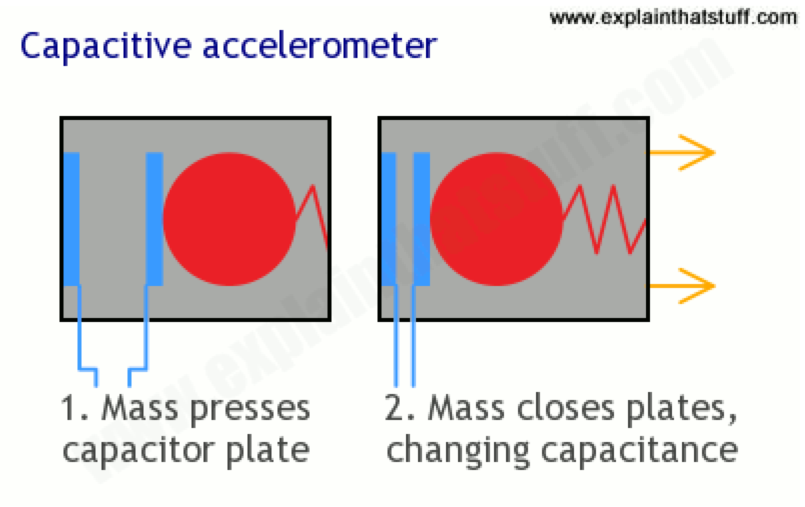
  - Sometimes 6DOF with Acceleration + one of the others

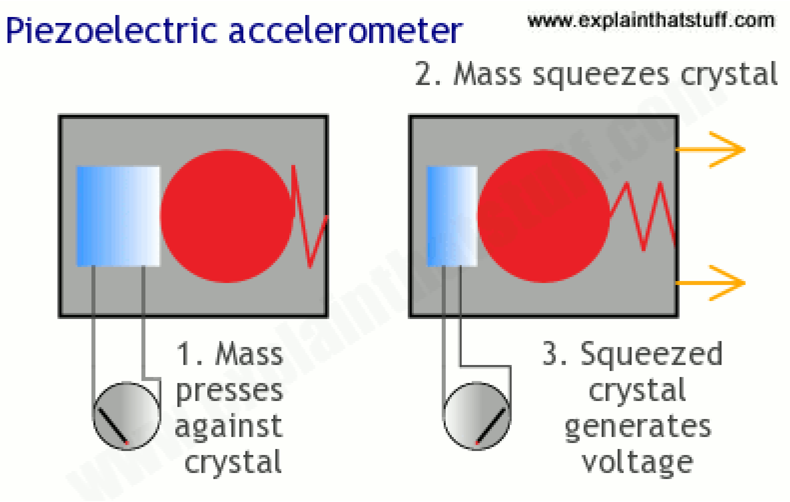
- Intelligent sensing: combines multiple sensors, ADCs, and computation with a wired interface
  - 9 analog inputs would otherwise be too many

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

# Sensing acceleration

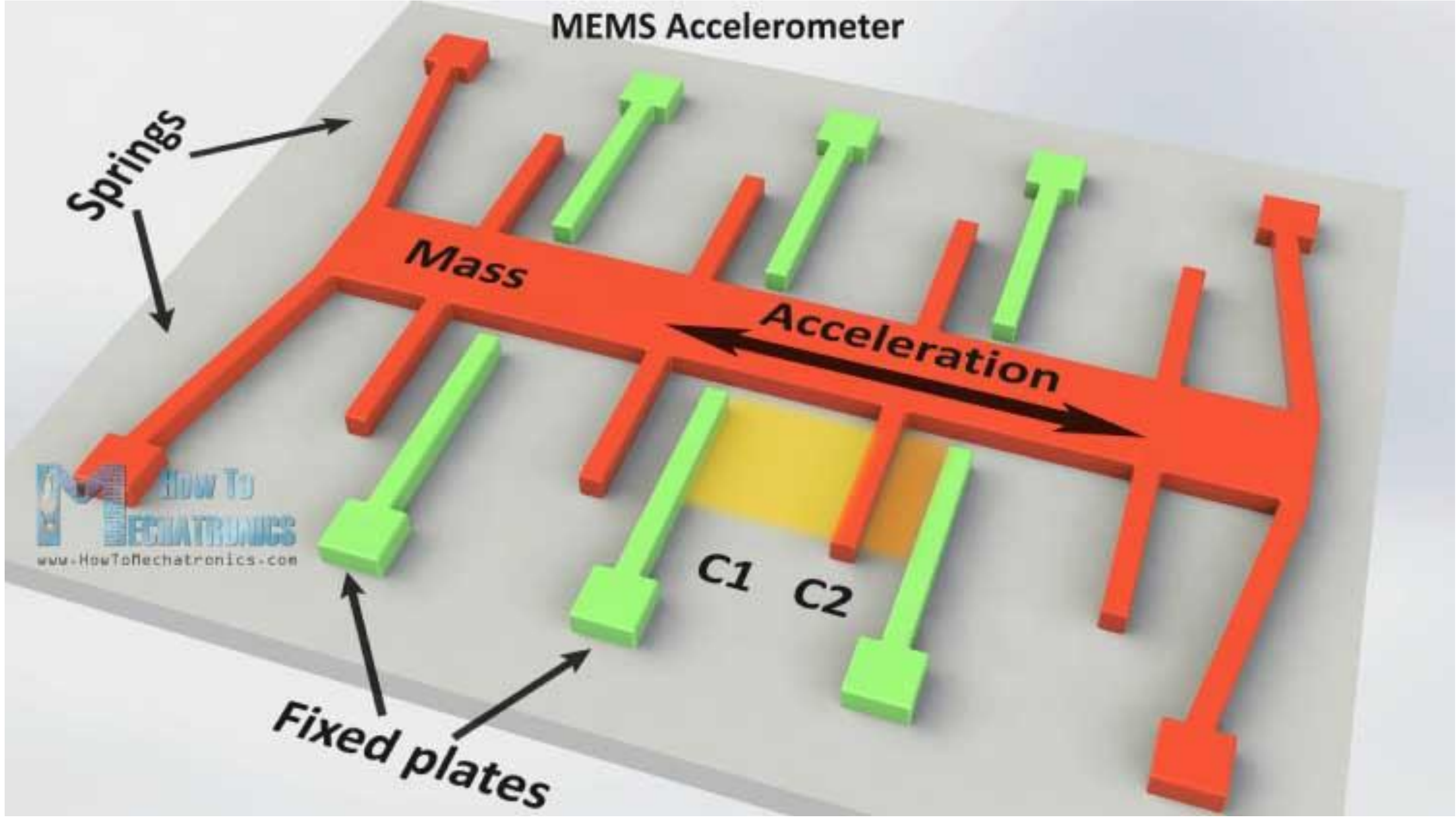
- Goal: create a voltage that changes based on force



# Microelectromechanical Systems (MEMS)

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

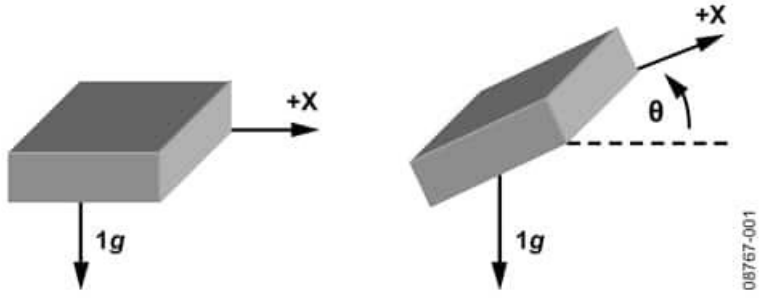


# Using accelerometers

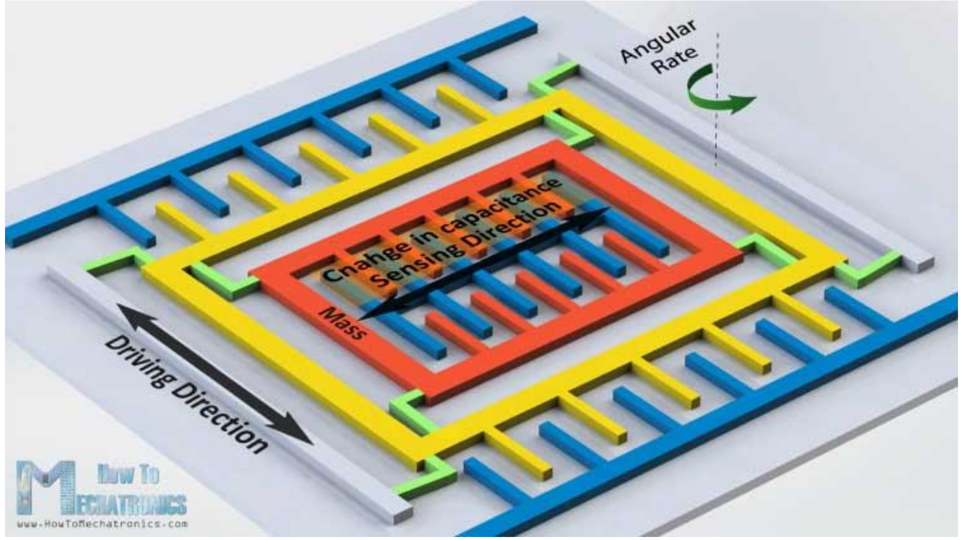
- Accelerometers usually measure in $g$'s
  - Where 1 g equals acceleration due to Earth gravity

- 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
  - $A[x] = 1\,g * \sin(\theta)$



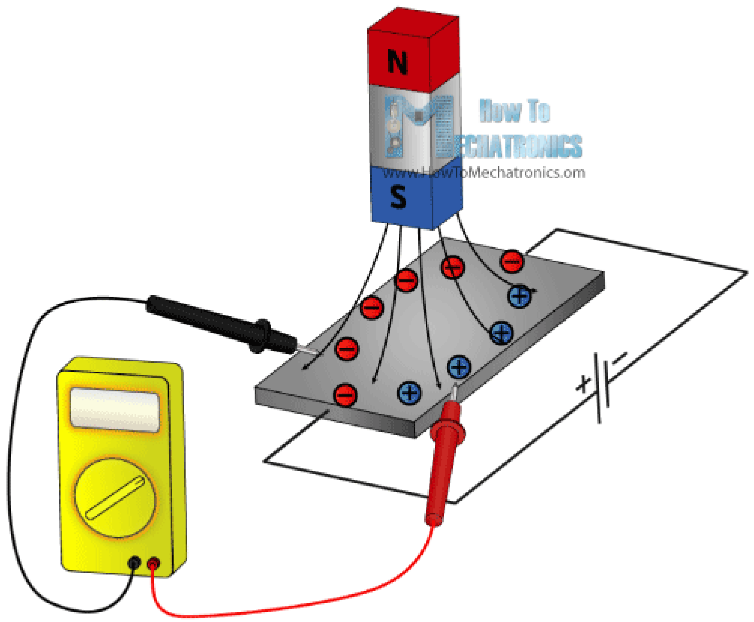
# Gyroscopes




- 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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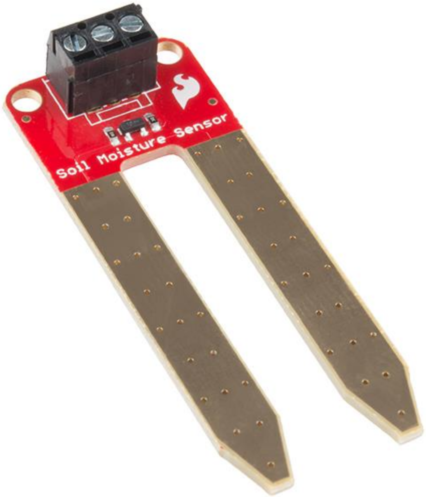
# Other sensors

- 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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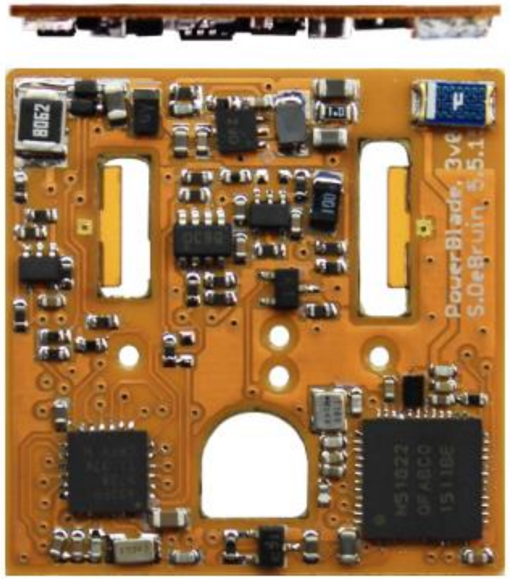
# PowerBlade current sensing

- 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

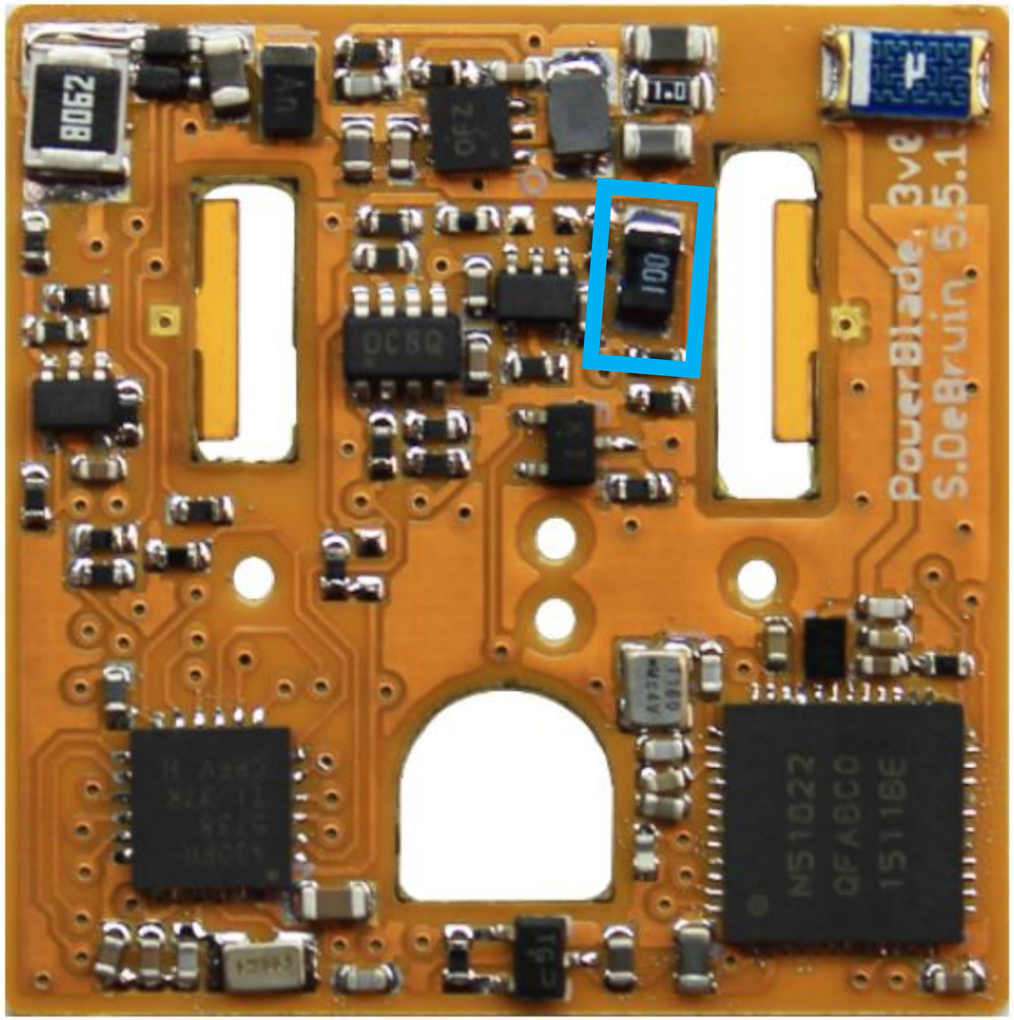


# Measuring current

- 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!

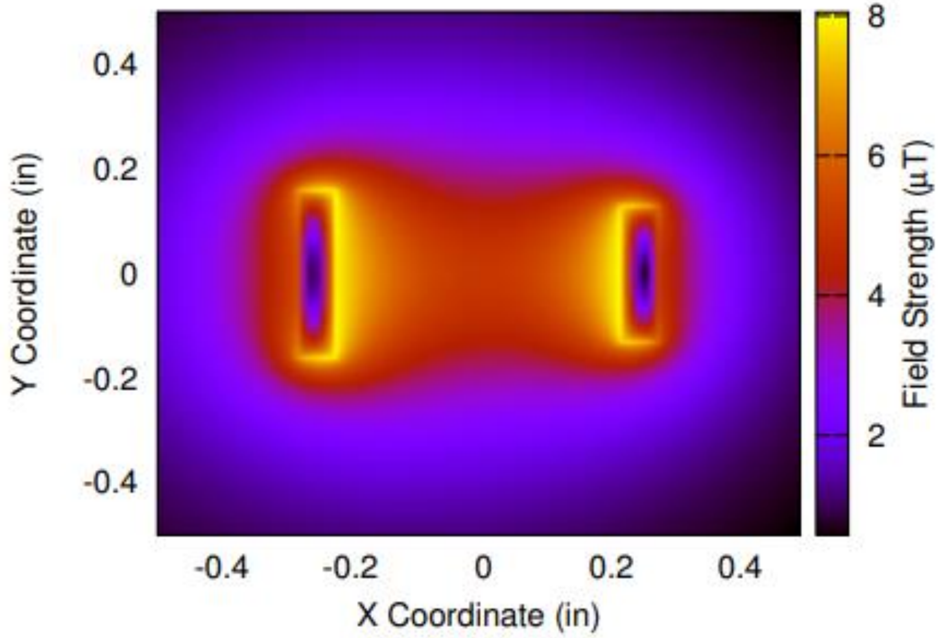


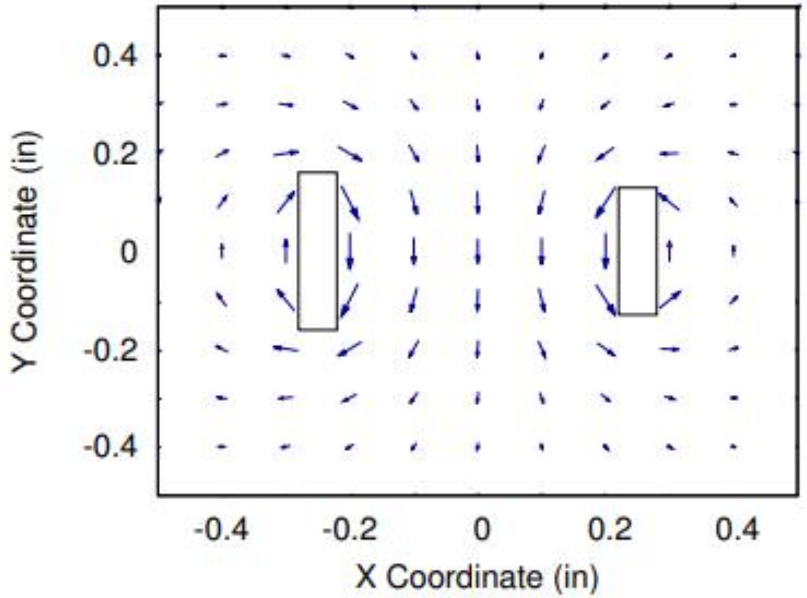
# Sensor placement

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

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

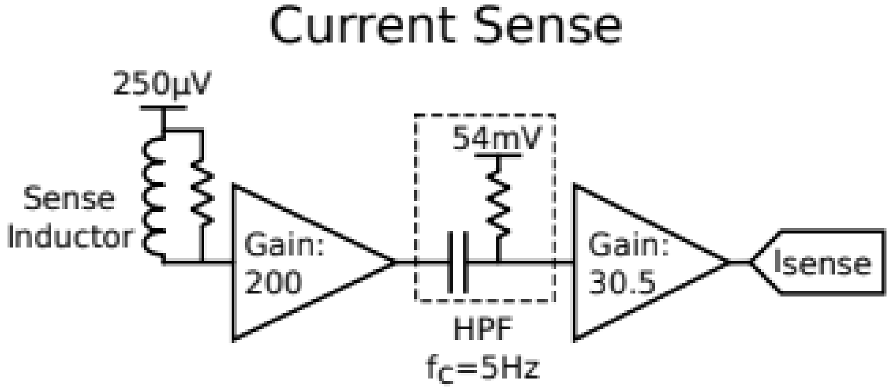
- Angled like the magnetic field is



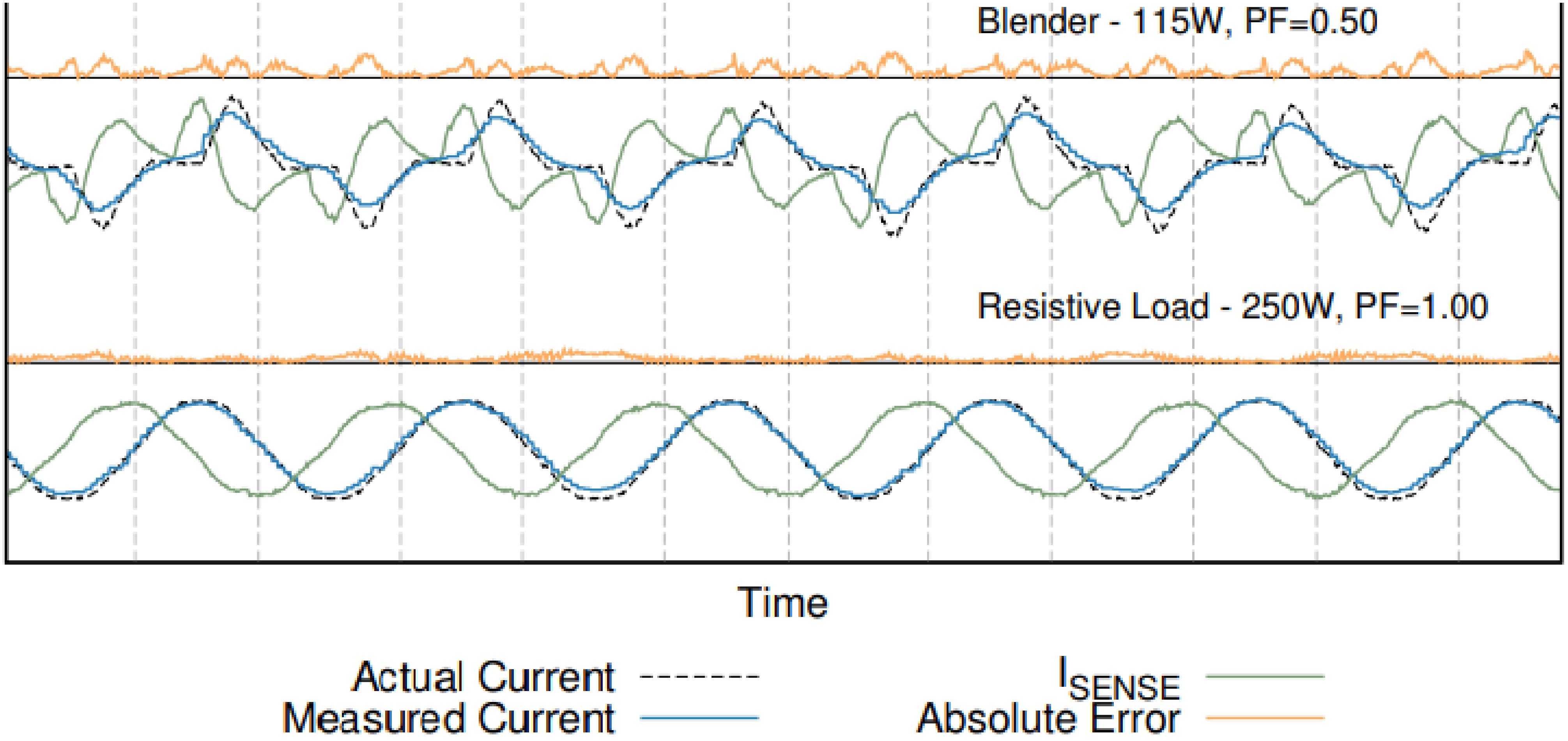



# Measuring sensor values

- 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



# At first, our output signal was this green line

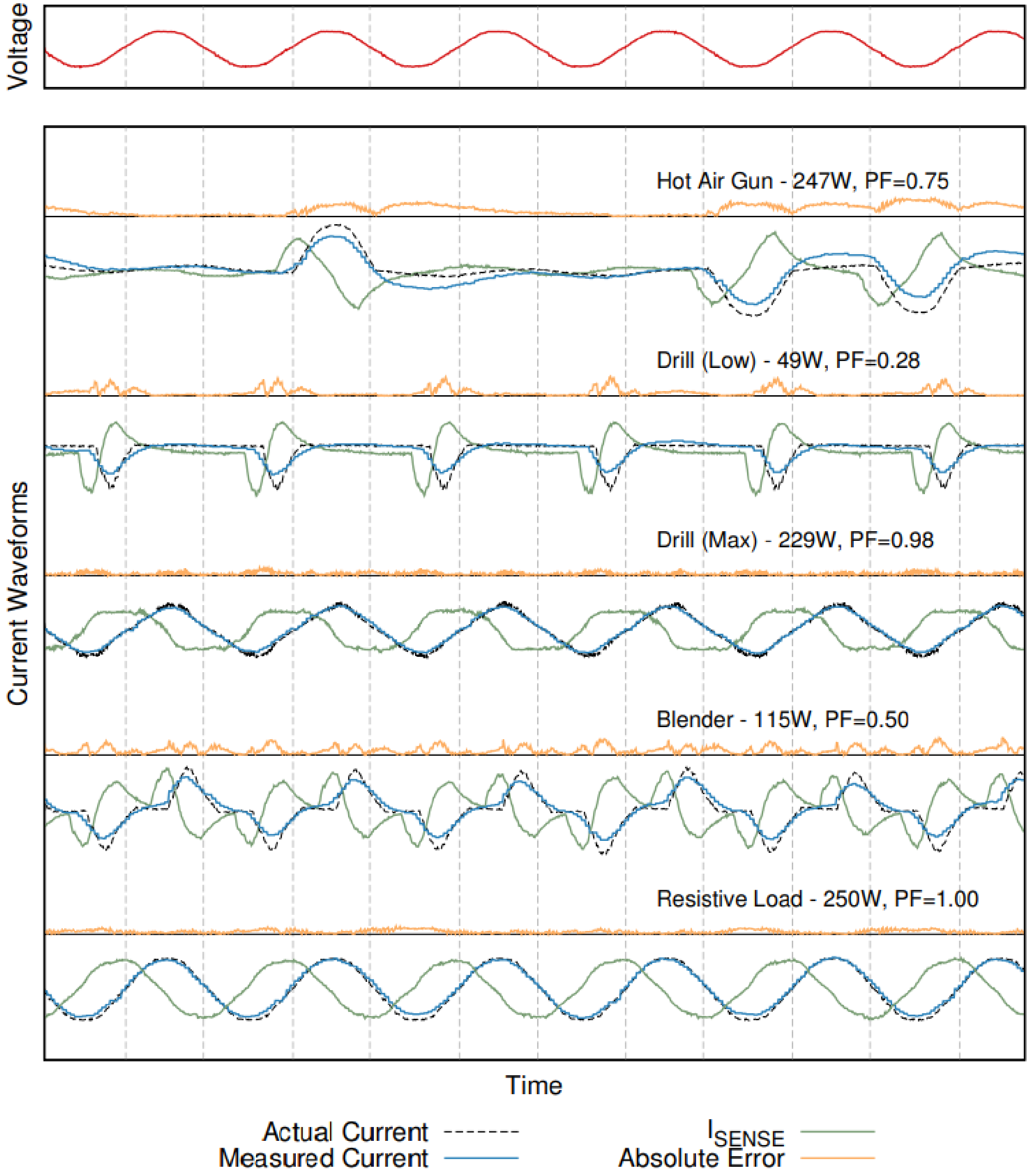


# Measurement into current

- 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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