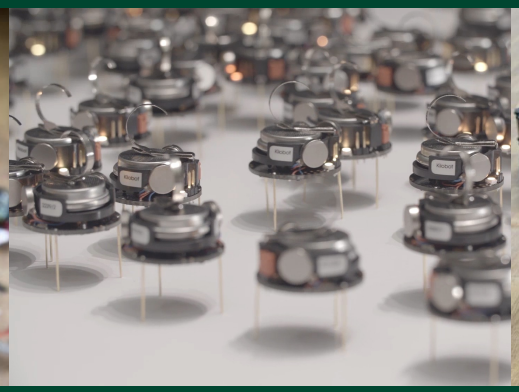
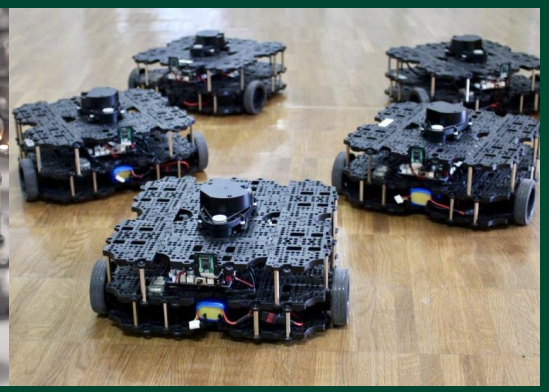
ECE693H, Spring 2025: Multi-robot System Design

“Perception 1”

Dr. Daniel Drew

College of Engineering
University of Hawai'i at Mānoa

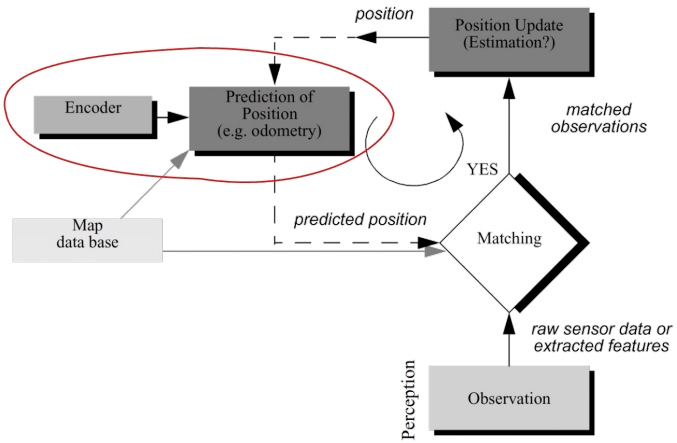
Action Recap

Action

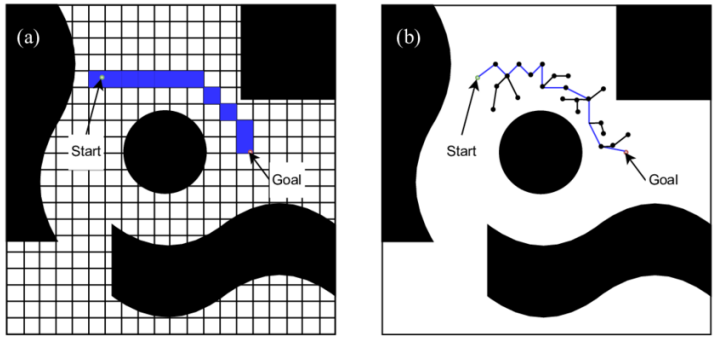
Ascending the stack from the motor

1. Electromagnetic motors
2. Motor gearing and mechanics
3. Motor driver electronics
4. Encoders

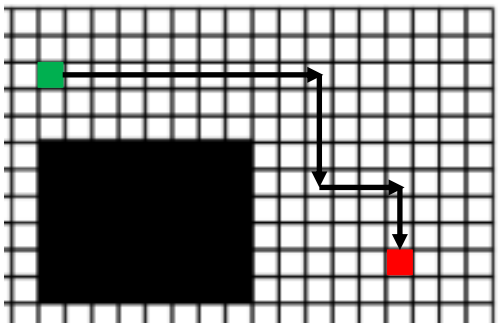
Localization / Odometry



Path and Motion Planning



Action: End-to-End Overview

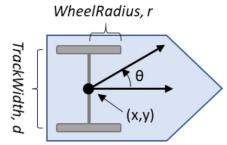


Path Planning

series of poses

$$[\,\boldsymbol{p}_{start}, \boldsymbol{p}_1, \boldsymbol{p}_2, \boldsymbol{p}_{\dots}, \boldsymbol{p}_{end}\,]$$

$$\boldsymbol{p}_i = [\boldsymbol{x}_i, \boldsymbol{y}_i, \boldsymbol{\theta}_i]$$



$$\begin{bmatrix} \dot{x} \\ \dot{y} \\ \dot{\theta} \end{bmatrix} = \begin{bmatrix} \frac{r}{2}\cos(\theta) & \frac{r}{2}\cos(\theta) \\ \frac{r}{2}\sin(\theta) & \frac{r}{2}\sin(\theta) \\ -r/d & r/d \end{bmatrix} \begin{bmatrix} \dot{\phi}_L \\ \dot{\phi}_R \end{bmatrix}$$

$$p' = f(x, y, \theta, \Delta s_r, \Delta s_l) = \underbrace{\begin{bmatrix} x \\ y \\ \theta \end{bmatrix}}_{\boldsymbol{p}_{i-1}} + \underbrace{\begin{bmatrix} \frac{\Delta s_r + \Delta s_l}{2}\cos\left(\theta + \frac{\Delta s_r - \Delta s_l}{2b}\right) \\ \frac{\Delta s_r + \Delta s_l}{2}\sin\left(\theta + \frac{\Delta s_r - \Delta s_l}{2b}\right) \\ \frac{\Delta s_r - \Delta s_l}{b} \end{bmatrix}}_{\boldsymbol{p}_i}$$

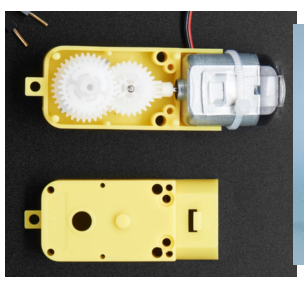
Kinematics

desired $\Delta s_r, \Delta s_l, \theta$

$$\Delta s = \frac{\Delta enc}{CPR * gr} * c_{wheel}$$

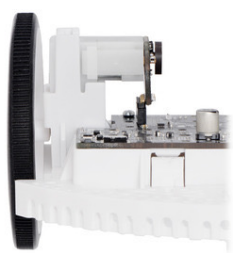
Odometry

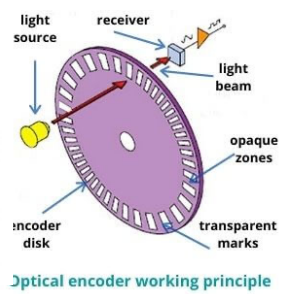
physical parameters



Motor

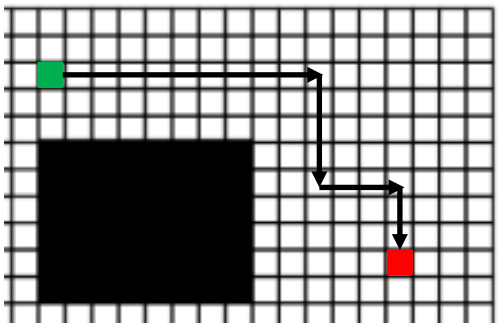
Wheel





Encoder

Action: End-to-End Overview



Path Planning

series of poses

$$[\,\boldsymbol{p_{start}}, \boldsymbol{p_1}, \boldsymbol{p_2}, \boldsymbol{p_{\ldots}}, \boldsymbol{p_{end}}\,]$$

$$\boldsymbol{p_i} = [\boldsymbol{x_i}, \boldsymbol{y_i}, \boldsymbol{\theta_i}]$$

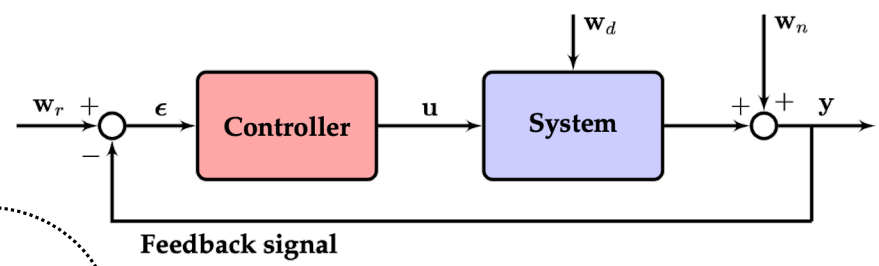
$$\begin{bmatrix} x \\ y \\ \theta \end{bmatrix} + \begin{bmatrix} \frac{\Delta s_r + \Delta s_l}{2} \cos\left(\theta + \frac{\Delta s_r - \Delta s_l}{2b}\right) \\ \frac{\Delta s_r + \Delta s_l}{2} \sin\left(\theta + \frac{\Delta s_r - \Delta s_l}{2b}\right) \\ \frac{\Delta s_r - \Delta s_l}{b} \end{bmatrix} \quad \Delta s = \frac{\Delta enc}{CPR * gr} * c_{wheel}$$

Kinematics / Odometry

What about speed?

$$\dot{\phi} = \frac{\Delta enc}{\tau \ * CPR * gr}$$

$$\begin{bmatrix} \dot{x} \\ \dot{y} \\ \dot{\theta} \end{bmatrix} = \begin{bmatrix} \frac{r}{2}\cos(\theta) & \frac{r}{2}\cos(\theta) \\ \frac{r}{2}\sin(\theta) & \frac{r}{2}\sin(\theta) \\ -r/d & r/d \end{bmatrix} \begin{bmatrix} \dot{\phi}_L \\ \dot{\phi}_R \end{bmatrix}$$



$$u = k_{\mathrm{p}} e + k_{\mathrm{i}} \int_0^t e(\tau)\, d\tau + k_{\mathrm{d}} \frac{de}{dt}$$

Easiest thing to do / assume: constant linear velocity

Questions?

Class Overview

1. Lecture (~50 minutes)
2. Subsystem check-in (~15 minutes)

Perception: Lecture 1 of 2

Lecture 1: sensors → data acquisition
Lecture 2: signal processing → mapping

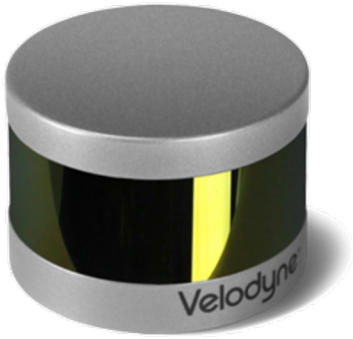
Lecture Overview: Ascending the Stack

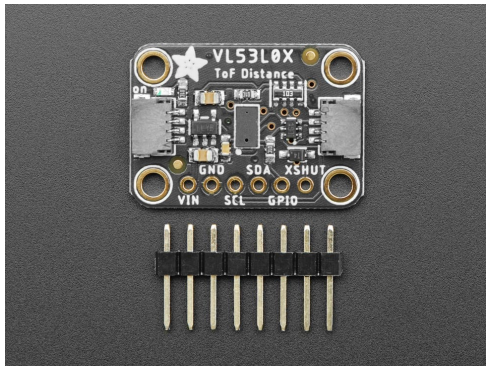
1. Overview / Taxonomy
2. Sensor physics
3. Data acquisition

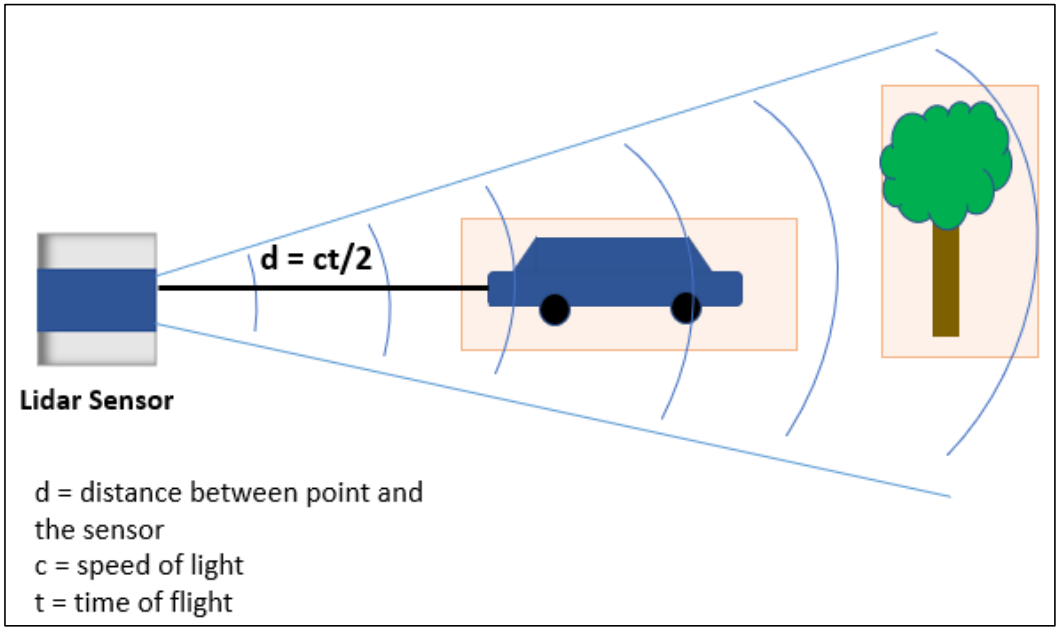
Sensors: Types and Examples

CLASS	QUANTITY	NAME
Active	**Distance** Time-of-flight, received angle/intensity	**LiDAR** **Ultrasonic** **Infrared**
Passive	**Intensity** Sound pressure Image Humidity	**IMU** **Altimeter / Barometer** **Microphone** **Camera**

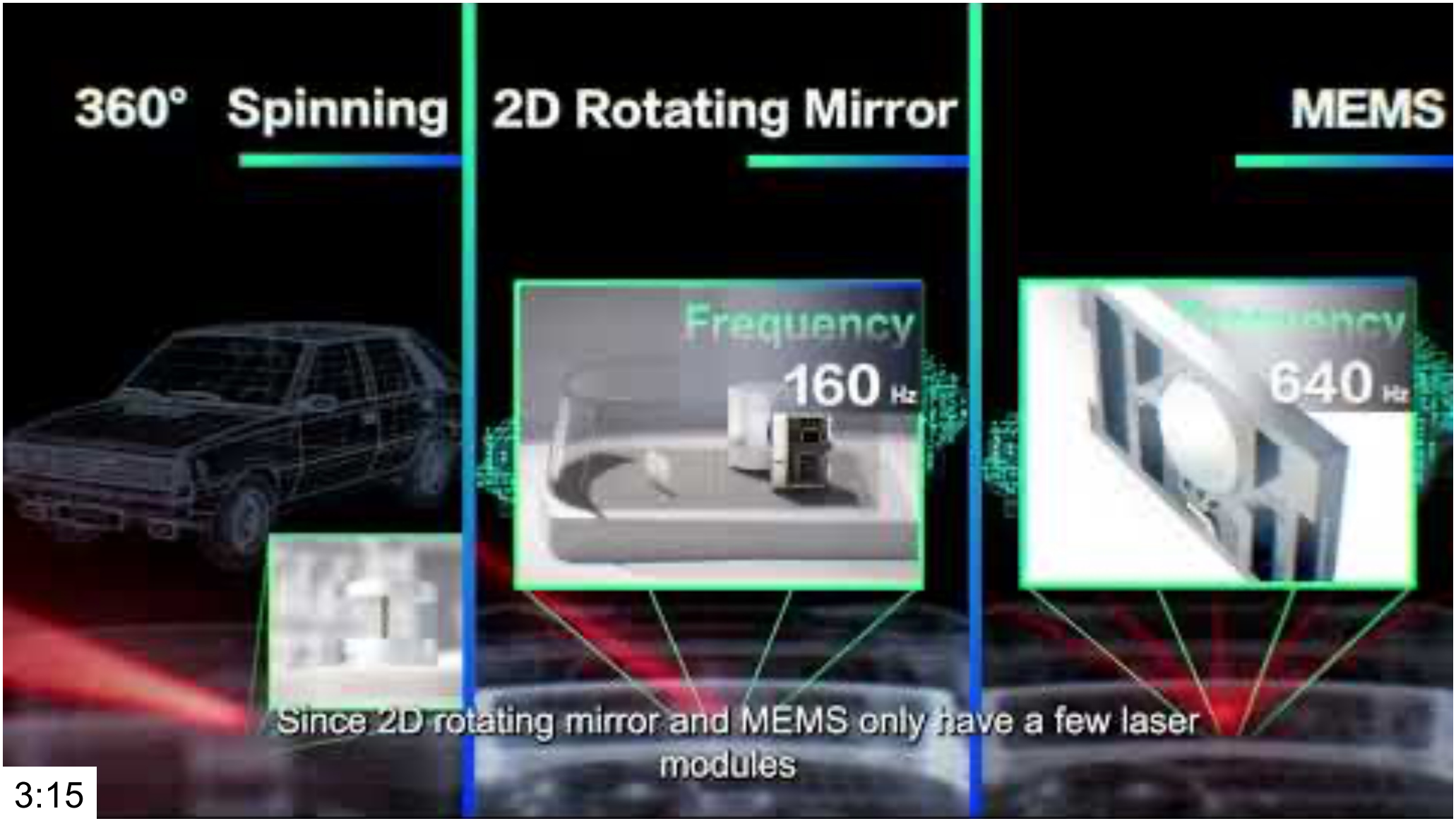
Sensors: Optical Time-of-Flight





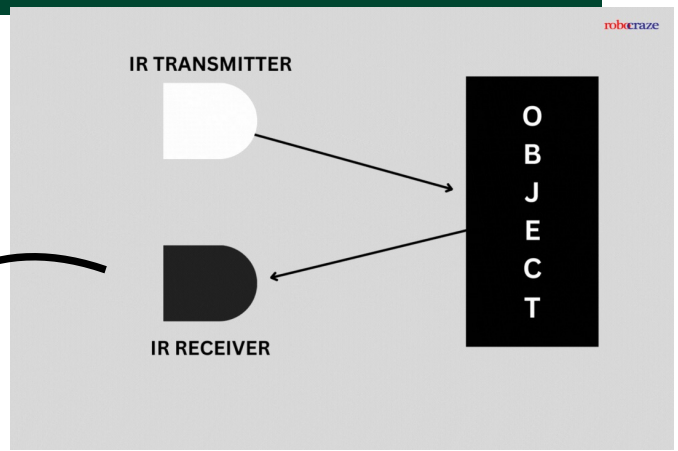


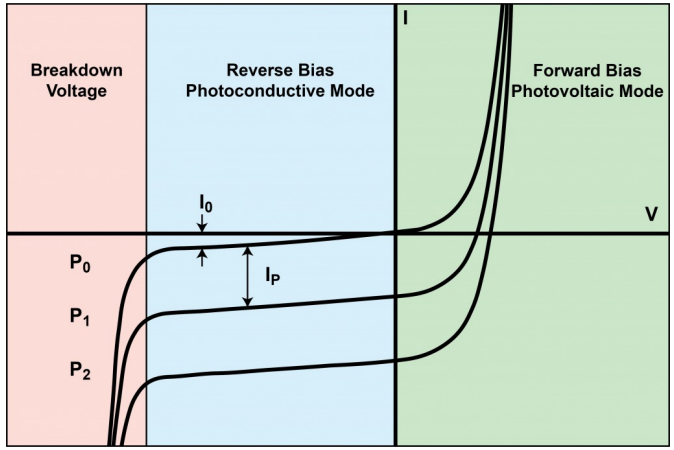
Light Detection and Ranging


360° Spinning
2D Rotating Mirror
MEMS
Frequency
160 Hz
640 Hz
Since 2D rotating mirror and MEMS only have a few laser modules

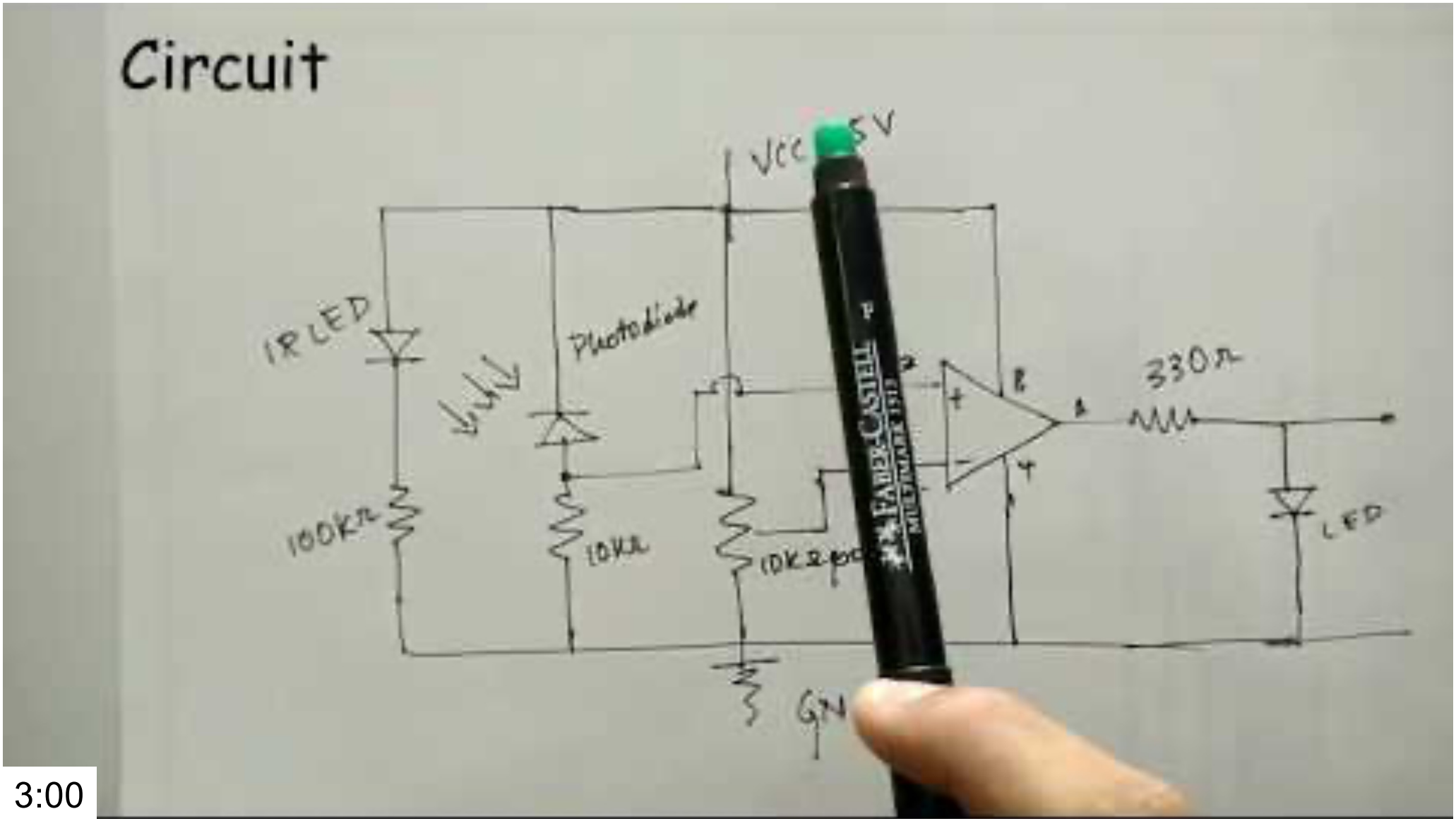
3:15

Sensors: Optical Non-ToF





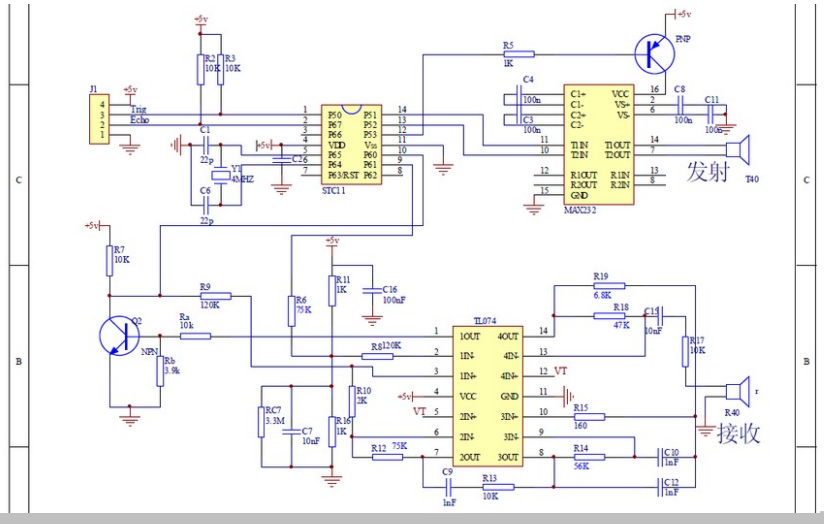
Photodiode

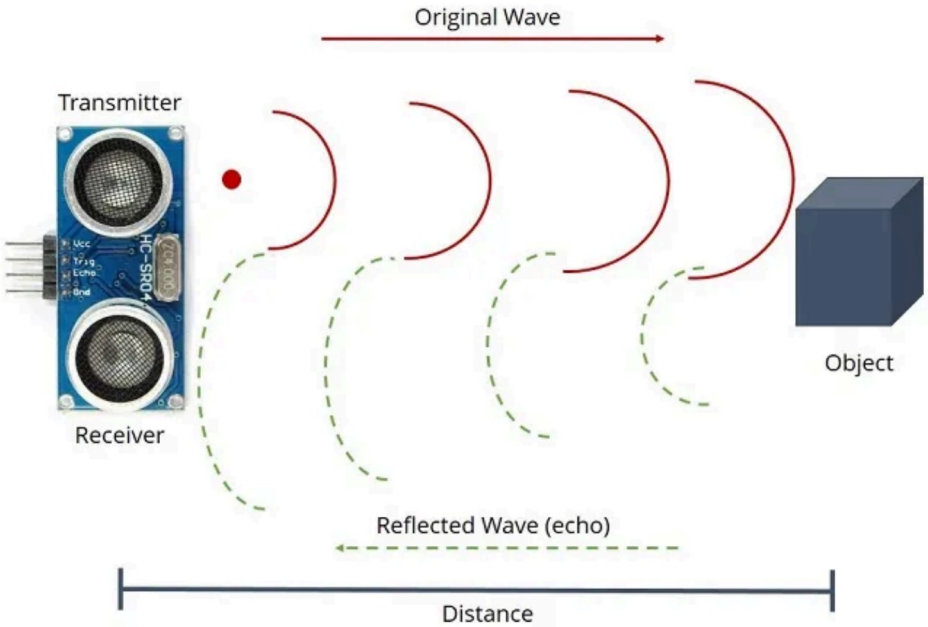

Circuit
VCC 5V
IR LED
Photodiode
100KΩ
10KΩ
10KΩ pot
330Ω
LED
GN

3:00

Sensors: Acoustic Time-of-Flight

HC-SR04 (common)

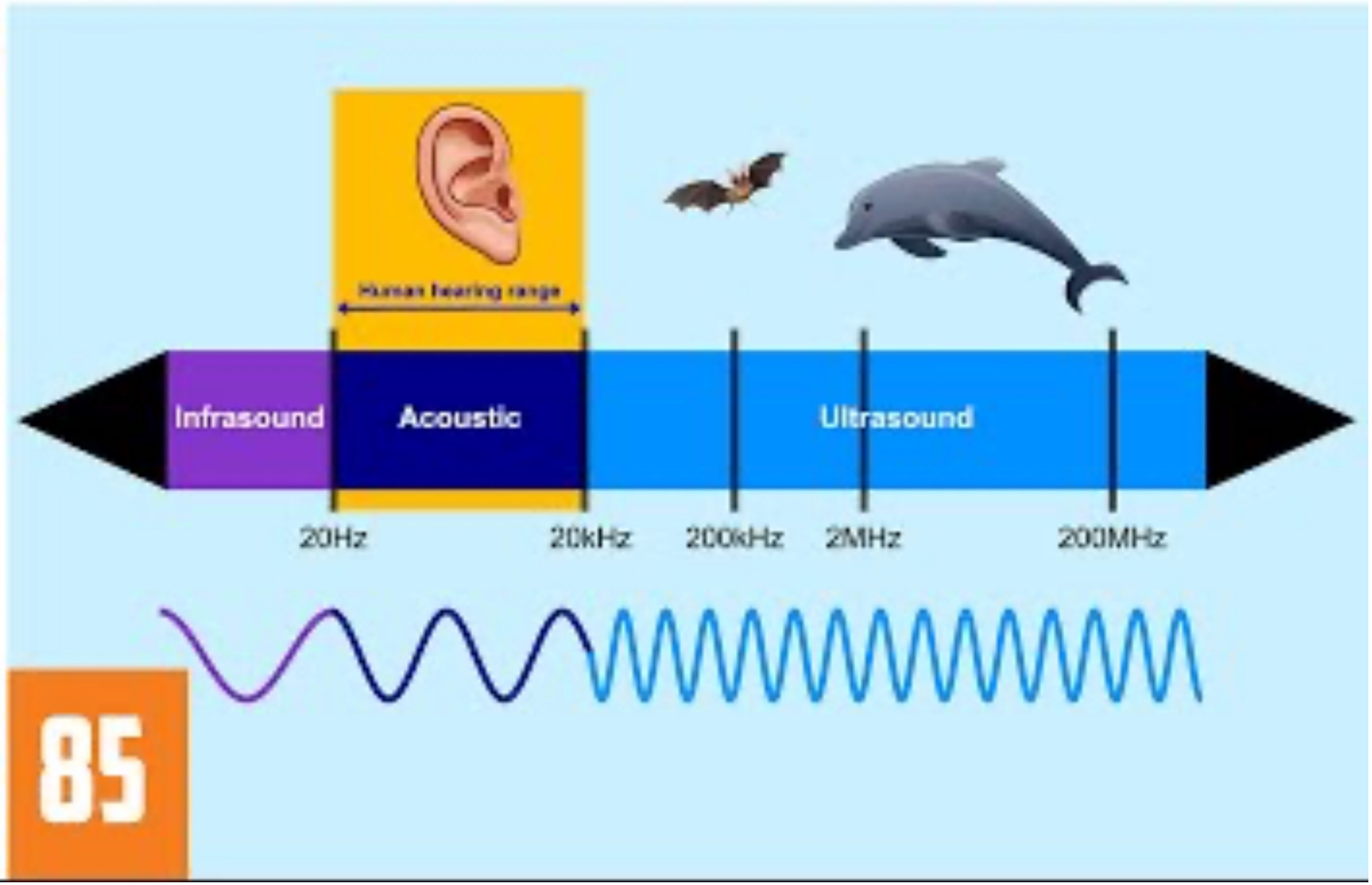




element14

presents

What Are Ultrasonic Distance Sensors?

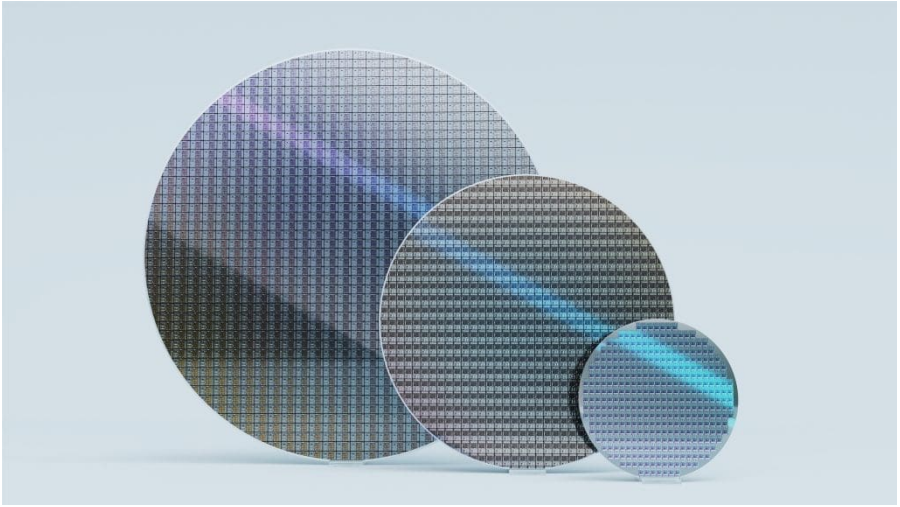


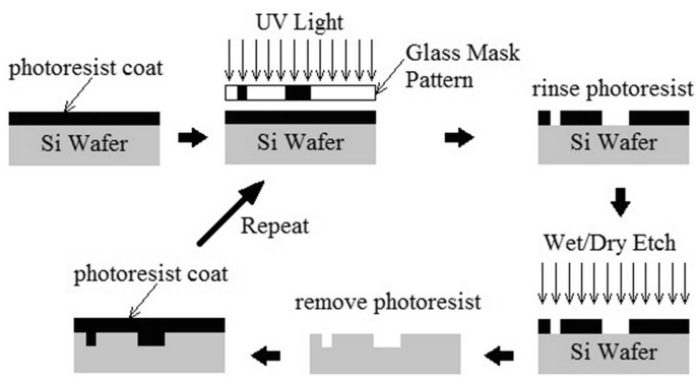
THE LEARNING CIRCUIT

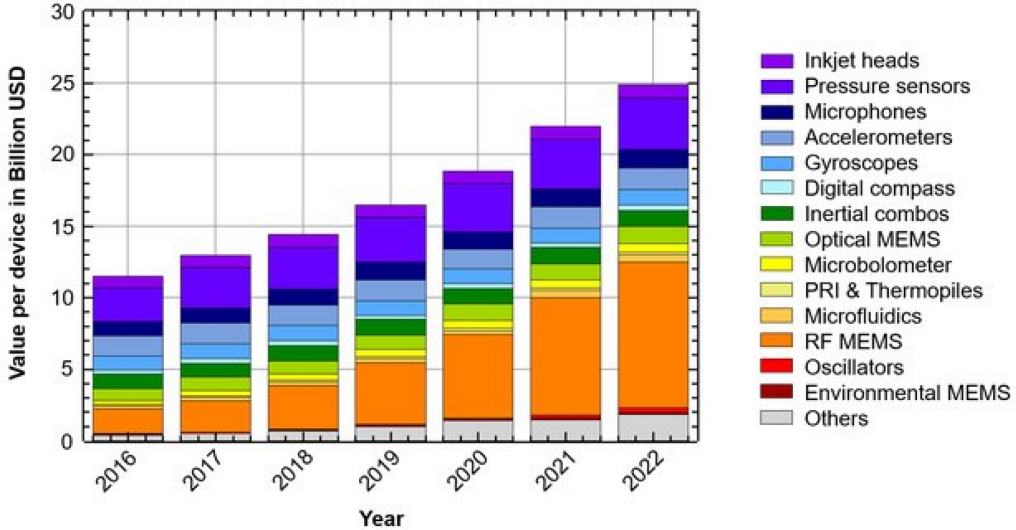
85

4:20

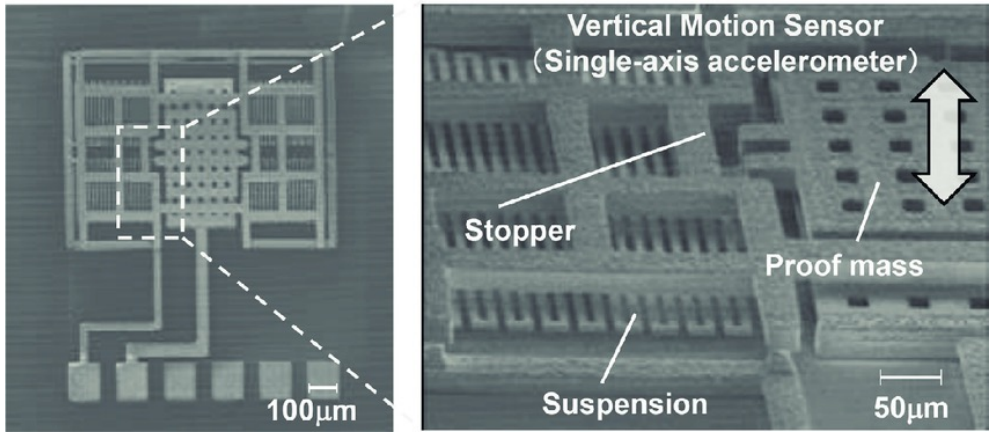
Interlude: Micro Electromechanical Systems (MEMS)

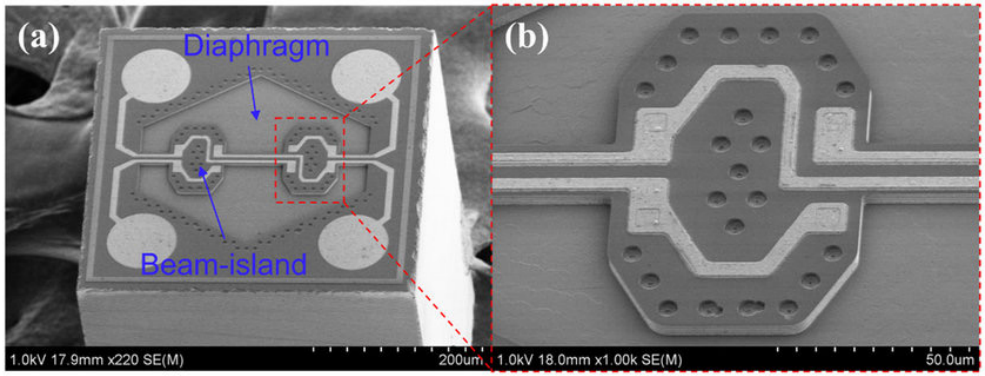


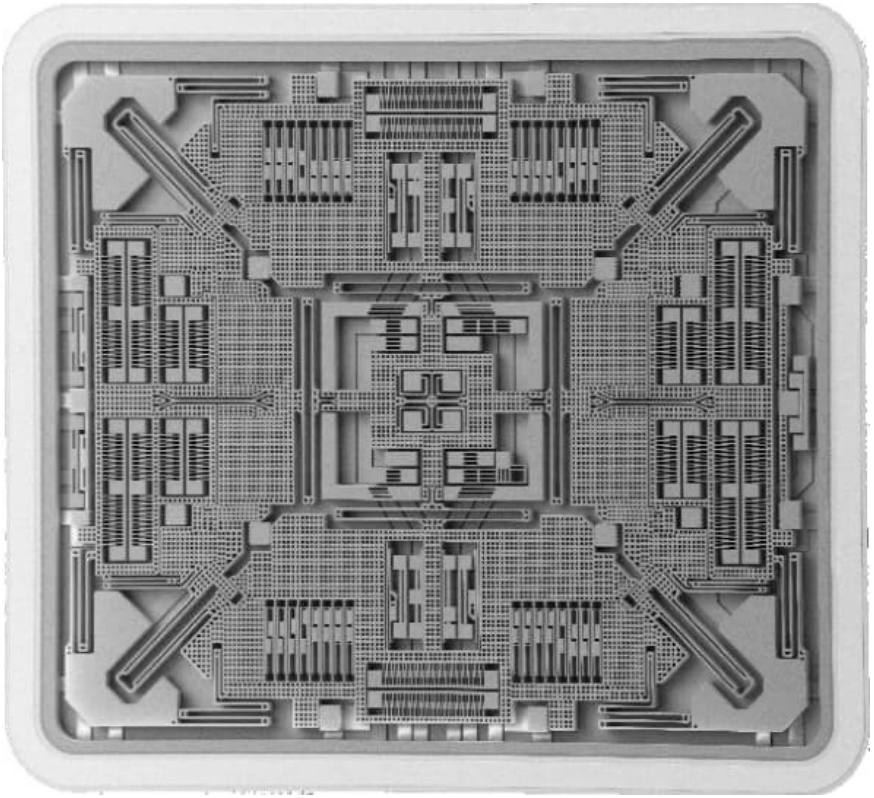




Interlude: Micro Electromechanical Systems (MEMS)

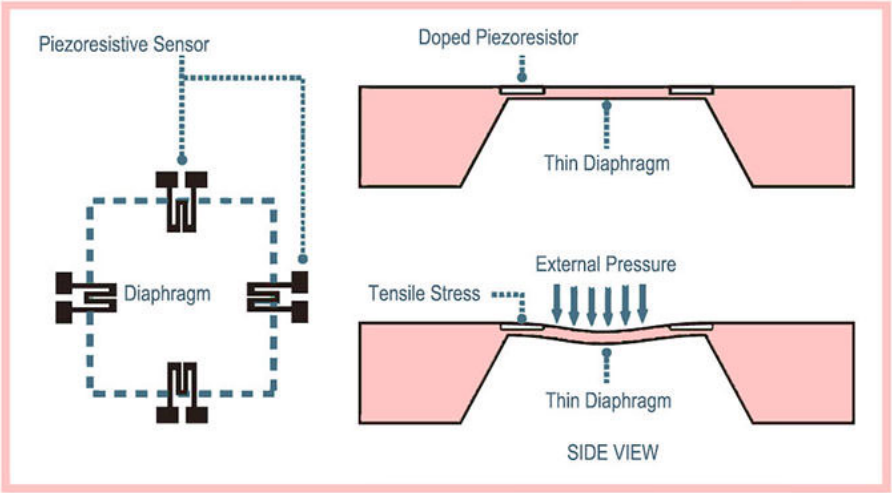




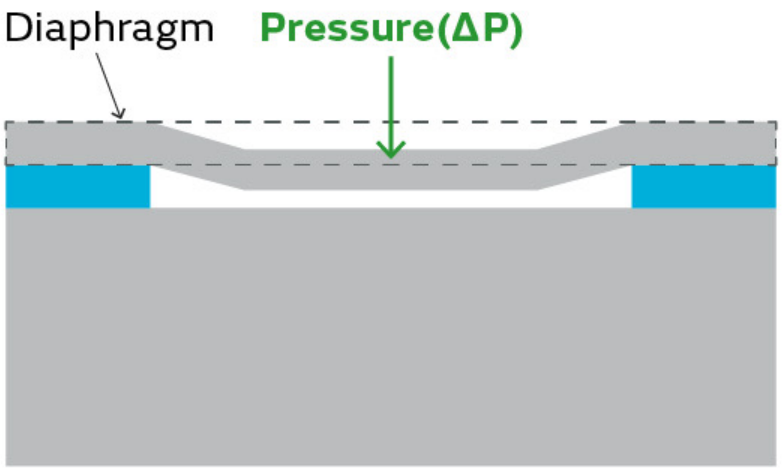


2:05

Sensors: Barometer / Altimeter



Piezoresistive Pressure Sensor

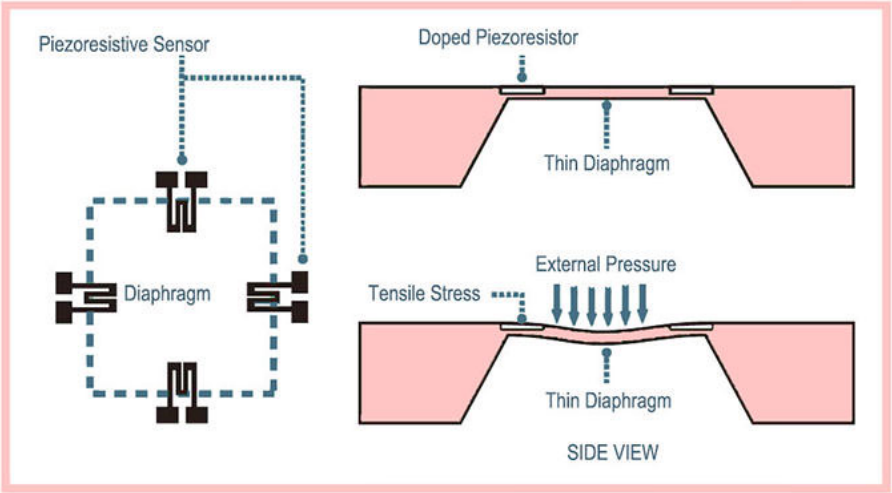


Displacement : $\Delta d \rightarrow$ Capacitance : ΔC

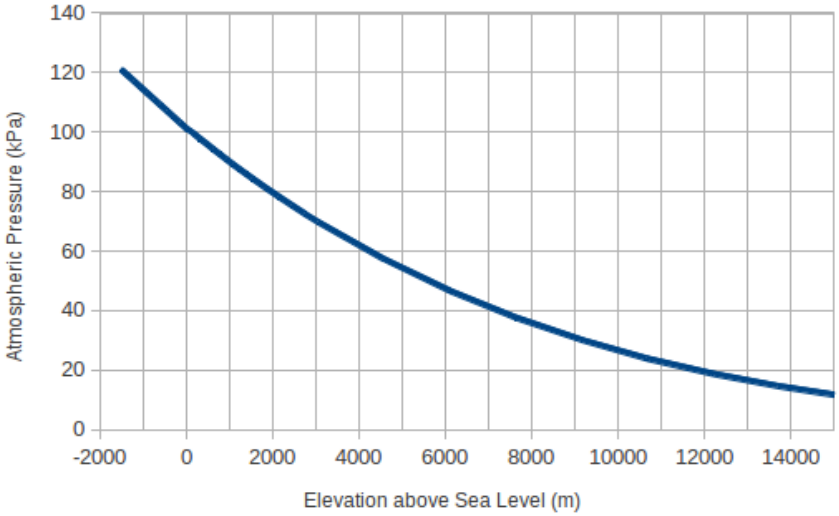
$\Delta P \propto \Delta d \propto {}^{1}/_{\Delta C}$

Capacitive Pressure Sensor

Sensors: Barometer / Altimeter

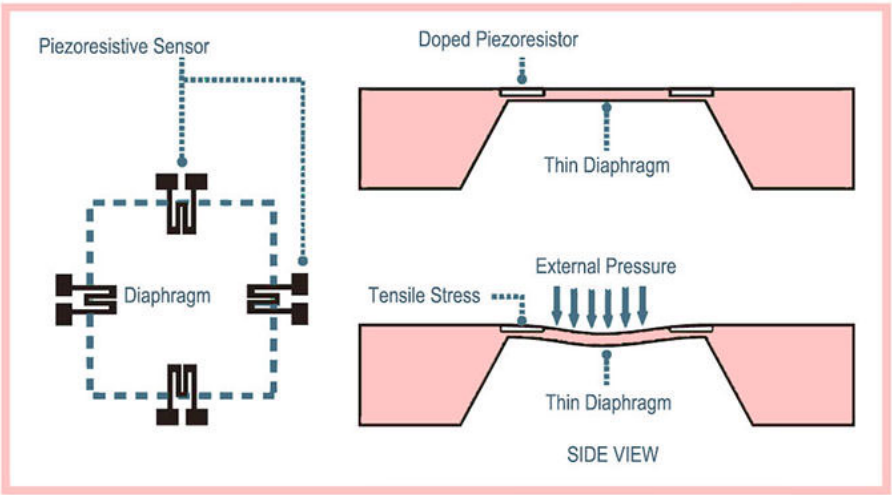


Piezoresistive Pressure Sensor

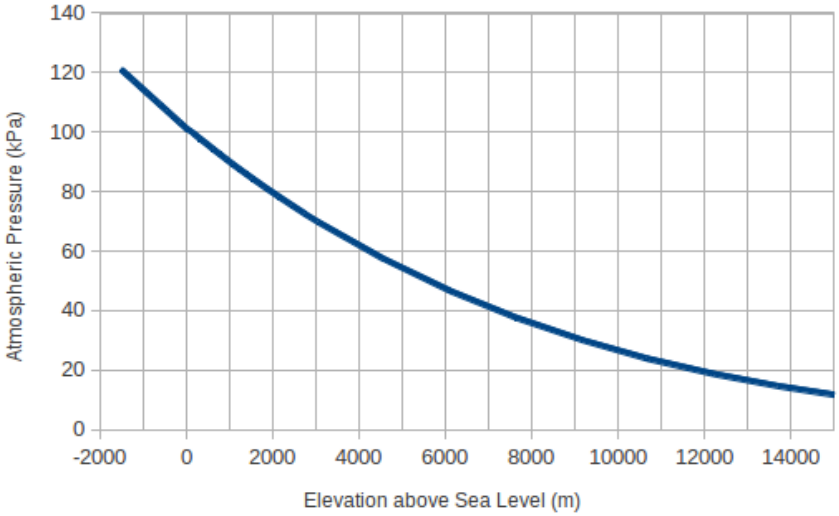


Barometer-based altimetry accurate to a few meters

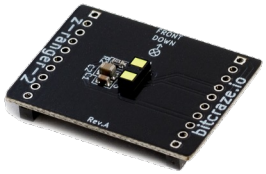
Sensors: Barometer / Altimeter



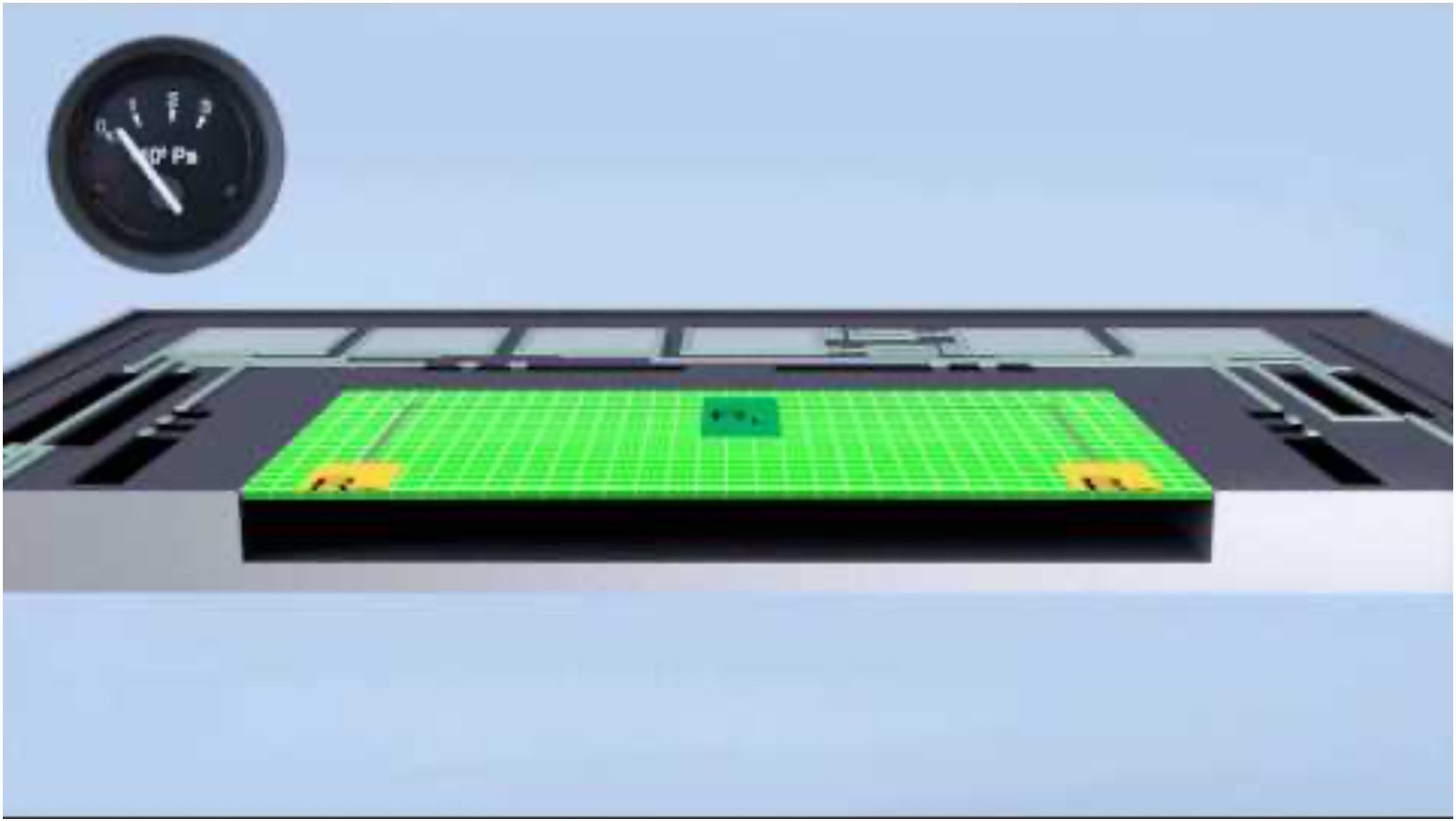
Piezoresistive Pressure Sensor



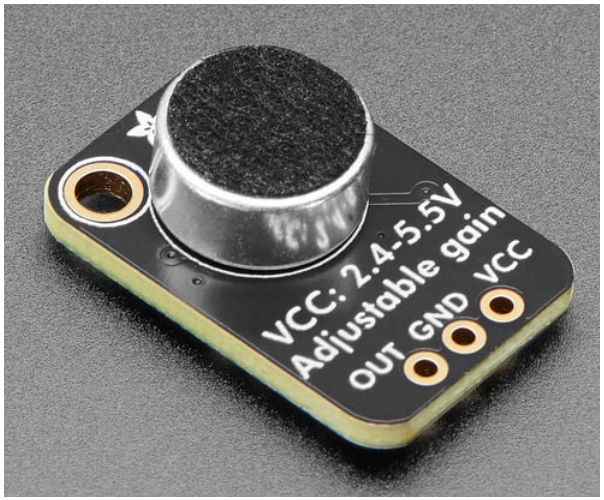
Barometer-based altimetry accurate to a few meters



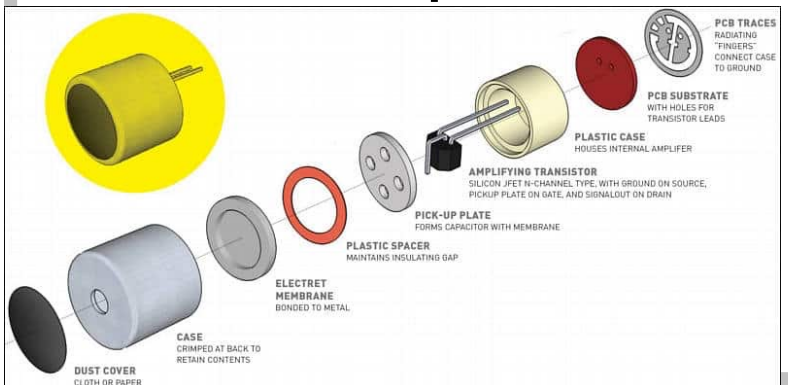
Note: small altimeters are usually optical tof, not pressure; they fly low enough to not need a barometer

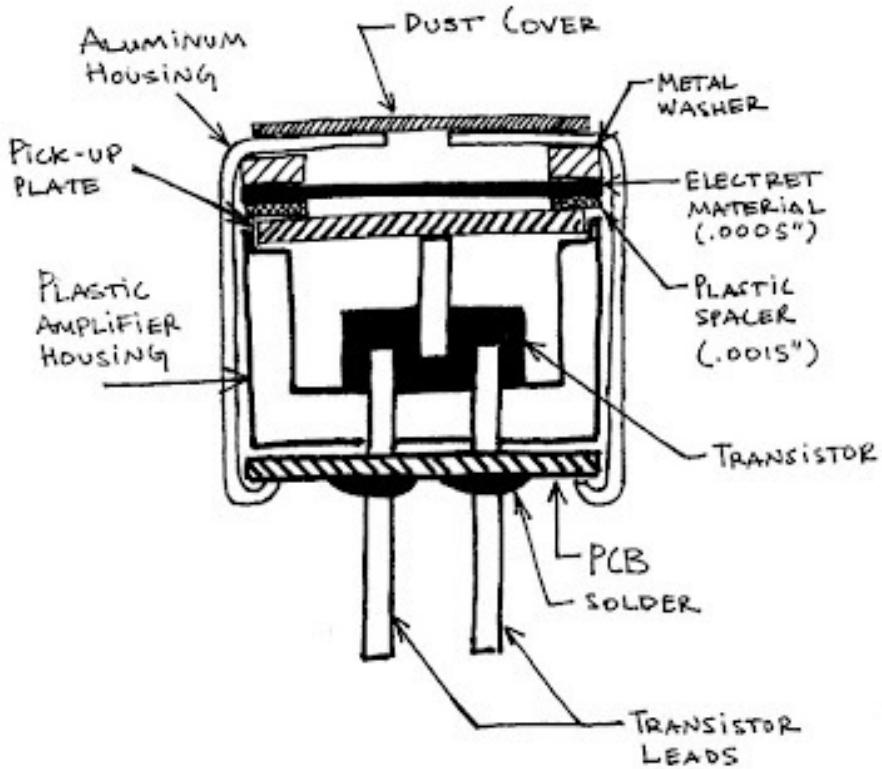


Sensors: Microphones



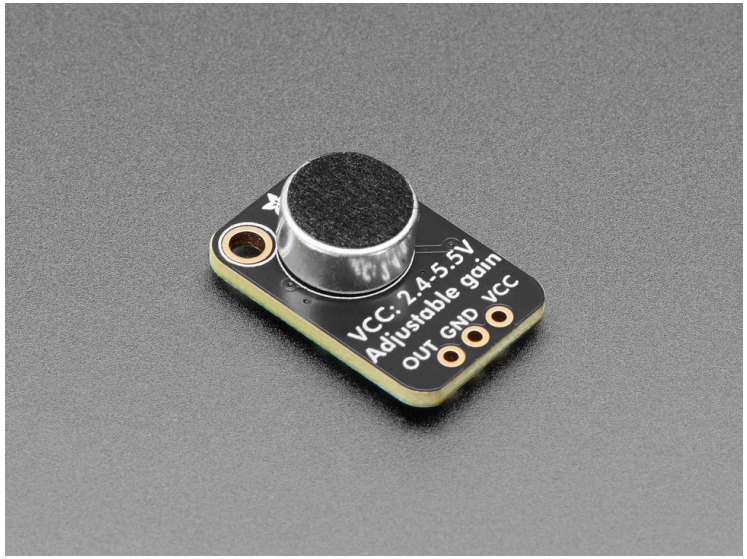
Electret microphone

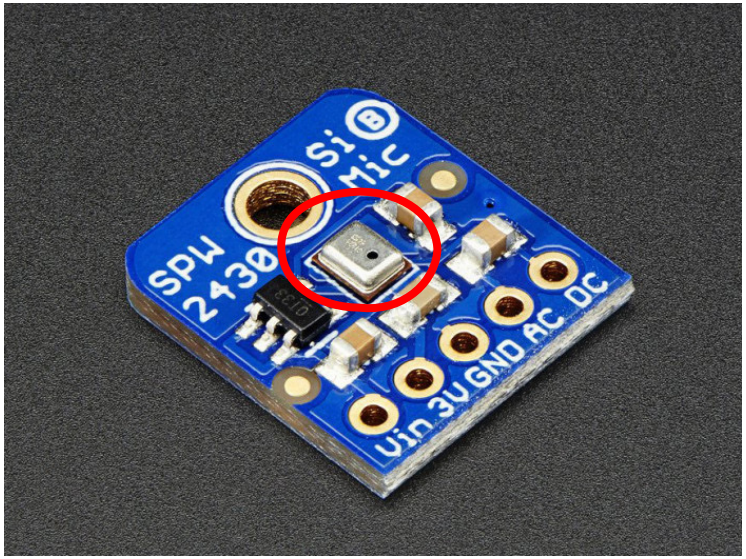




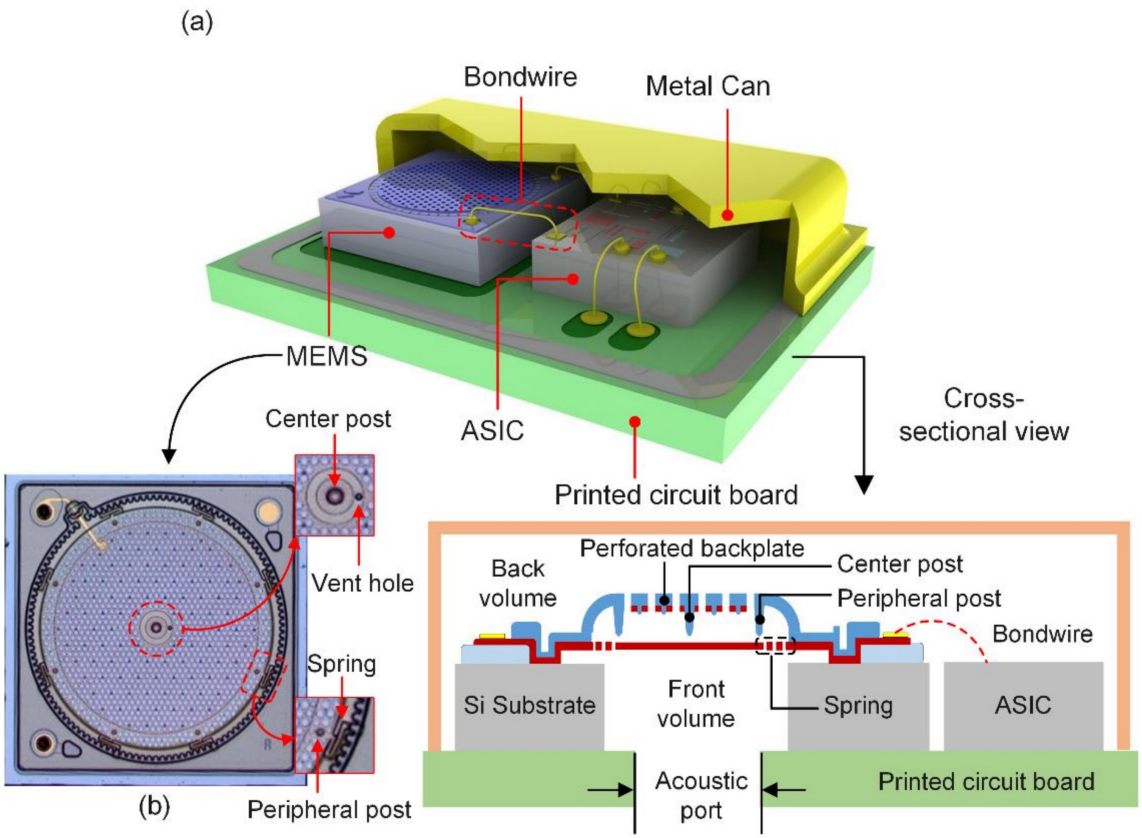
Electret materials have a permanent static charge, so capacitor doesn't need to be externally powered

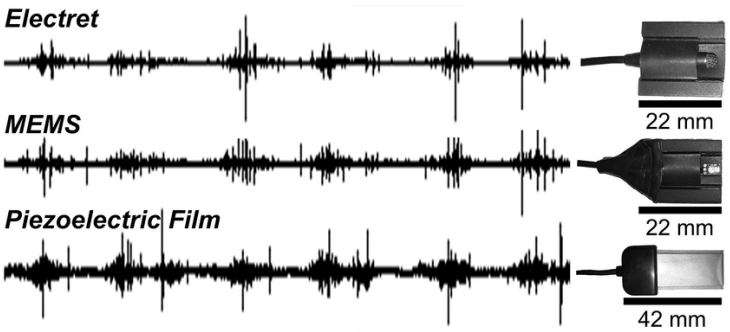
Sensors: Microphones





Sensors: Microphones





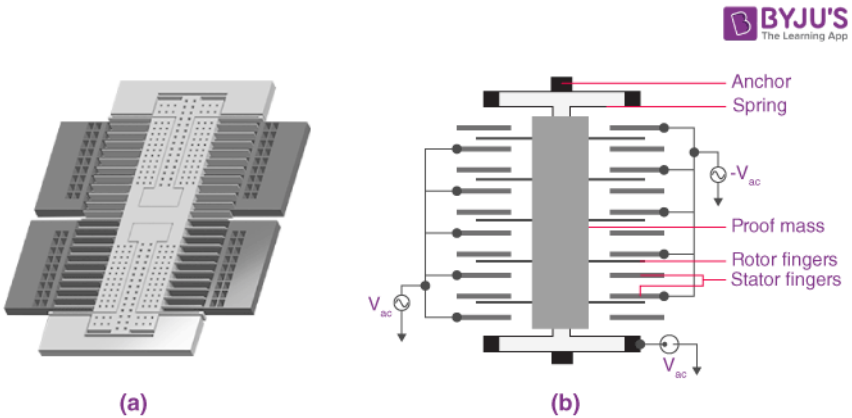
Inan et al., 2017

Common in mobile devices (e.g., smartphones)

Sensors: MEMS Inertial Measurement Unit

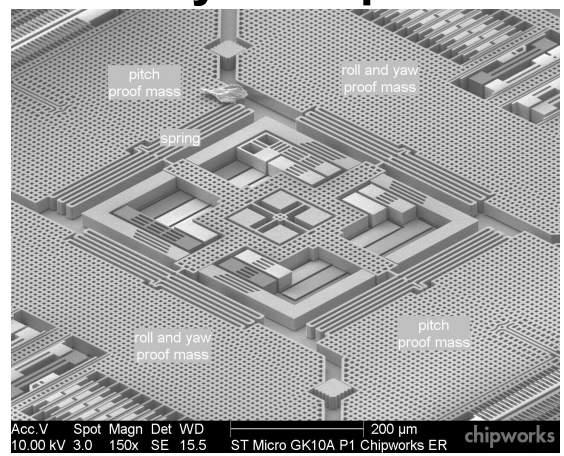
"6-axis IMU" = Accelerometer, gyroscope. "9-axis IMU" = Accel., gyro., magnetometer.

Accelerometer

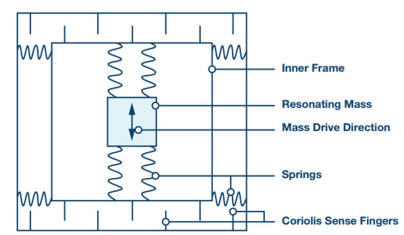


$$F = ma$$

Gyroscope



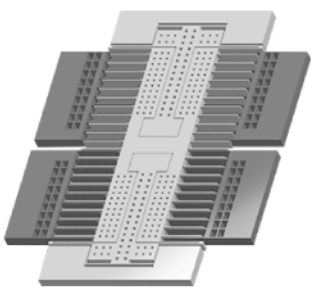
$$F_C = -2m(\Omega \times \boldsymbol{v})$$



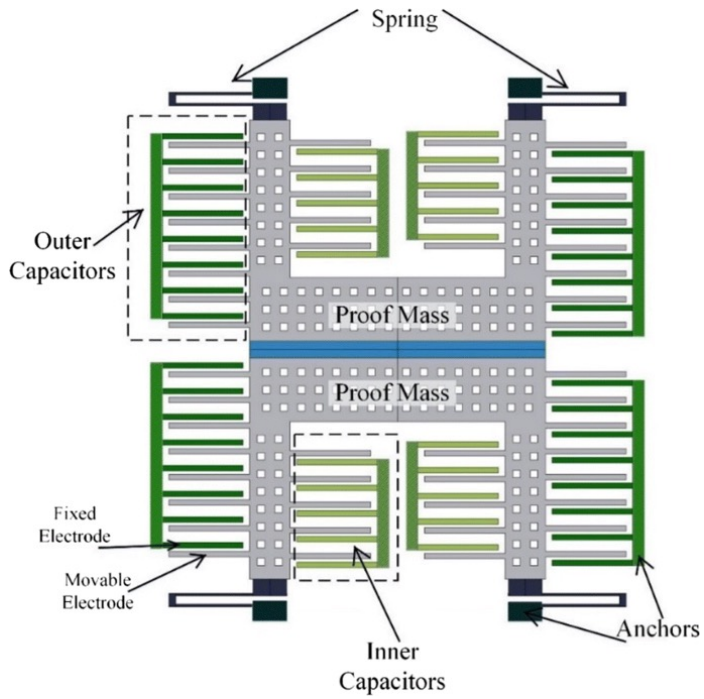
Sensors: MEMS Inertial Measurement Unit

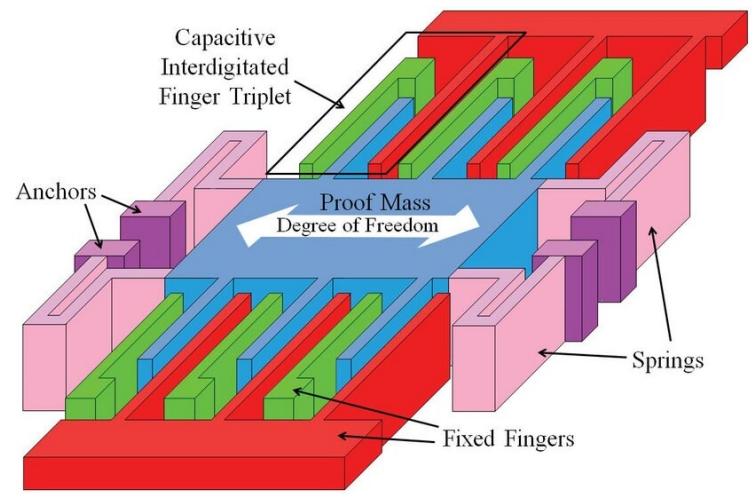
"6-axis IMU" = Accelerometer, gyroscope. "9-axis IMU" = Accel., gyro., magnetometer.

Accelerometer



$$F = ma$$





Sensors: MEMS Inertial Measurement Unit

$$\boxed{\boldsymbol{F = ma = kx}}$$

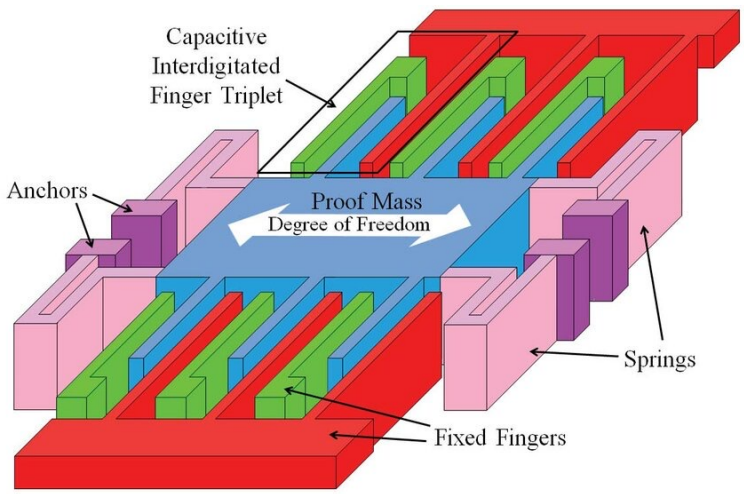
$$a = \frac{k}{m}\,x$$

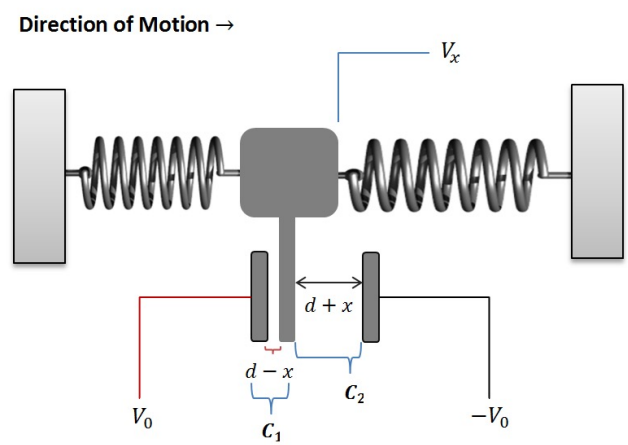
$$k_{beam} = \frac{12EI_b}{L^3} \qquad I_b = \frac{tw^3}{12}$$

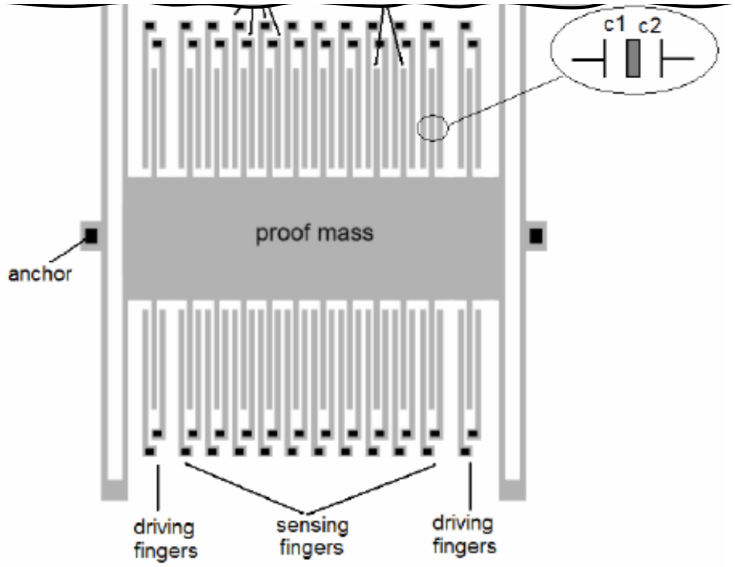
$$k_{tot} = k_{f1} + k_{f2} + k_{f2} + k_{f2}$$

$$x \propto \Delta C$$

$$C = \frac{\epsilon_0 A}{d}$$







Consider the MEMS accelerometer illustrated in the above figure. Acceleration causes displacement of the proof mass and a change in the capacitances C_1 and C_2. The displacement is approximately proportional to the capacitance difference:

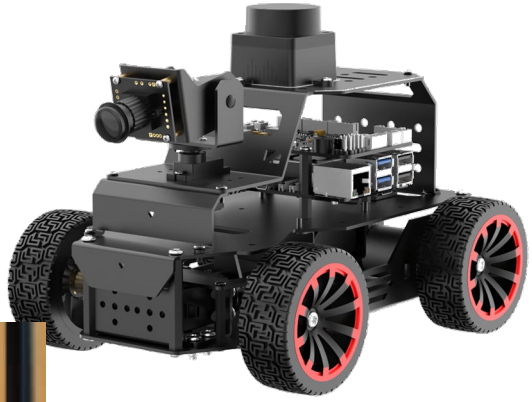
$\Delta C = C_2 - C_1$.

The accelerometer can be modeled by a spring-mass system. Assume the spring constant K = 200 N/m, the spacing between a driving and sensing fingers is

d = 5 μm, the total capacitance under zero acceleration is 20pF.

a) Determine the size of the proof mass such that the sensitivity of the displacement per unit g acceleration is larger than 100 nm/g and the resonant frequency is larger than 1 KHz.
b) Determine the sensitivity of the capacitance change per unit g acceleration.
c) If the smallest detectable capacitance change is 2fF, determine the resolution of the accelerometer.

Sensors: Cameras

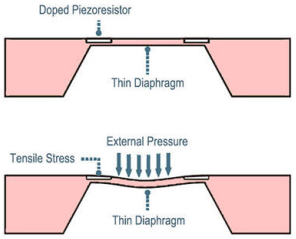


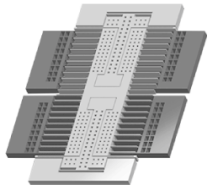
HOW DOES A CAMERA WORK
APERTURE
SHUTTER
SENSOR
2:05

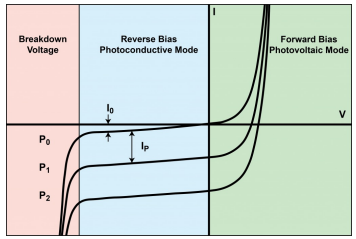
Lecture Overview: Ascending the Stack

1. Overview / Taxonomy
2. Sensor physics
3. Data acquisition

Many sensors involve a TRANSDUCTION from the physical quantity to a change in resistance, capacitance, or stored charge

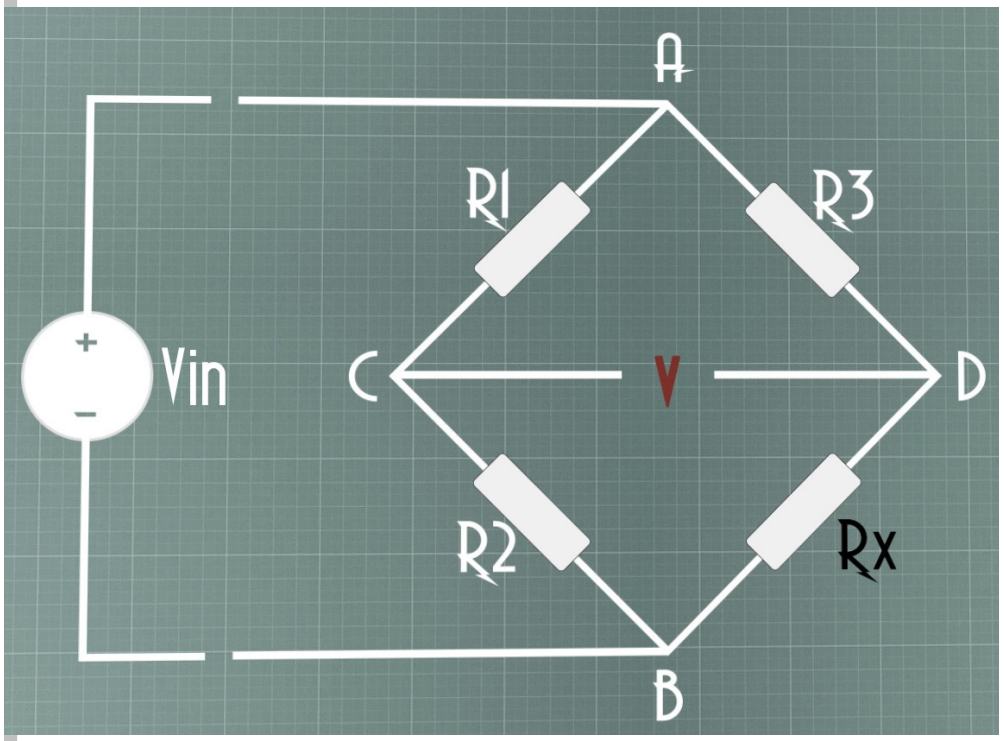






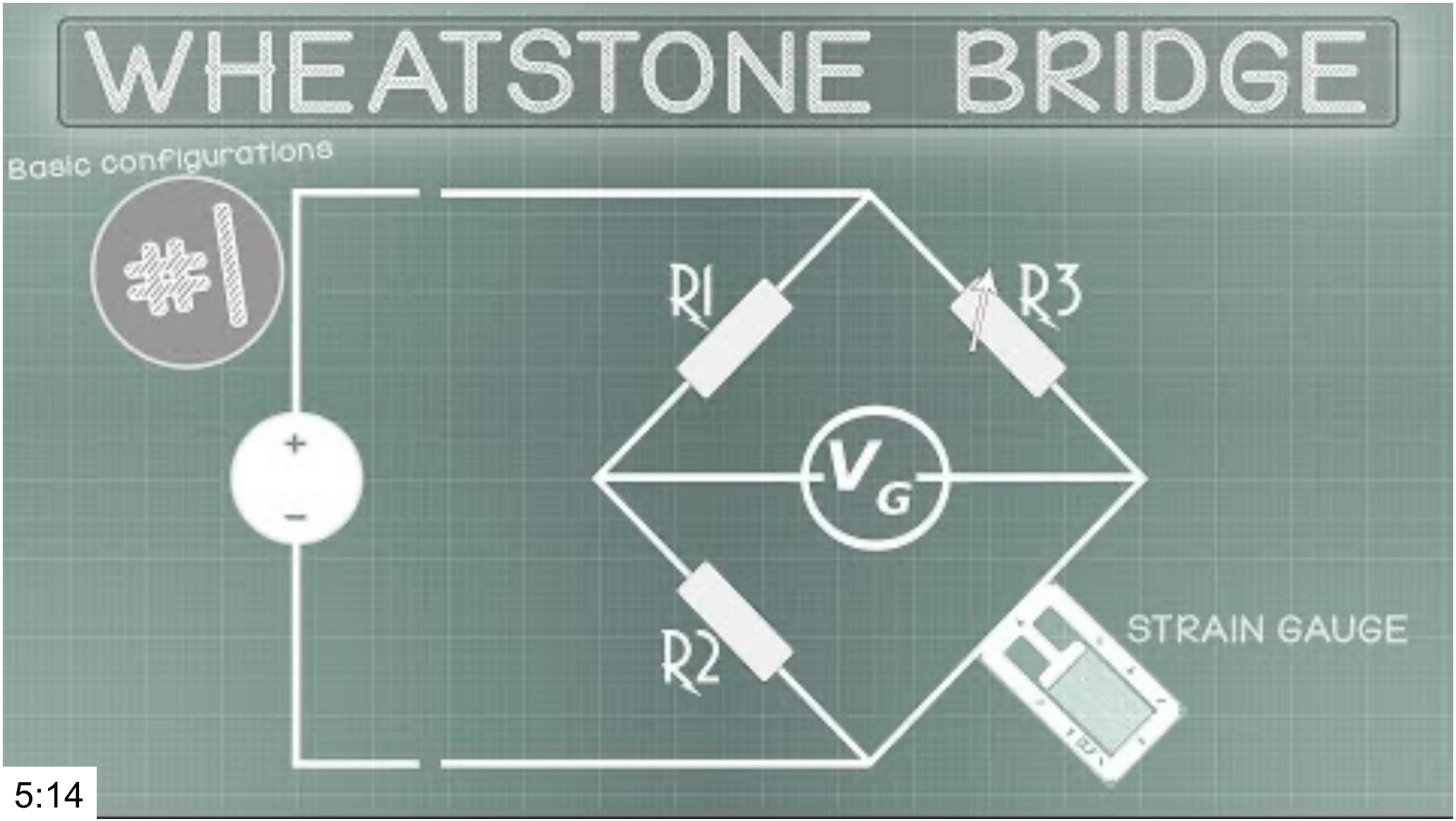
How do we turn this into data in our computer?

Readout Circuitry: Wheatstone Bridge



Many transducers output a change in resistance:
e.g., piezoresistive pressure sensors, strain gauges, load cells, thermocouples

Wheatstone bridges can:
-Increase sensitivity
-Compensate for environmental factors
-Allow for fully differential measurement


WHEATSTONE BRIDGE
Basic configurations
#1
R1
R3
+
−
V_G
R2
STRAIN GAUGE

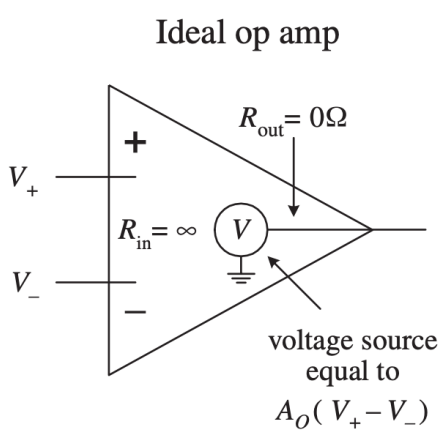
5:14

Readout Circuitry: Op. and Inst. Amplifiers

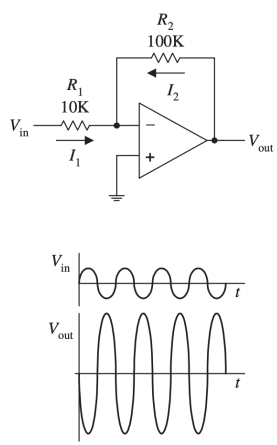
WHY USE AN AMPLIFIER?

- Typical voltage output of a strain sensor is mV
- Mainly interested in differential signals (e.g., Wheatstone bridge)
- Prevent loading of sensor circuit

e.g., piezoelectric sensors, microphones, strain gauges, thermocouples



Infinite open-loop gain, infinite input impedance, voltage difference between inputs is zero



op-amp in negative feedback

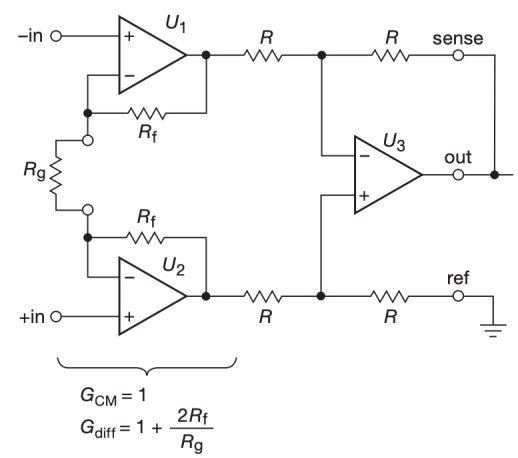
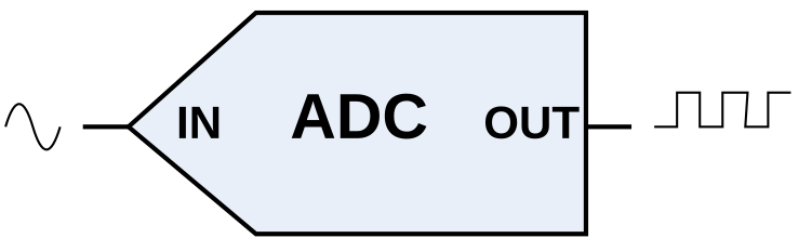


Figure 5.77. The classic three-op-amp instrumentation amplifier.

Analog-to-Digital Conversion: Basic Concept

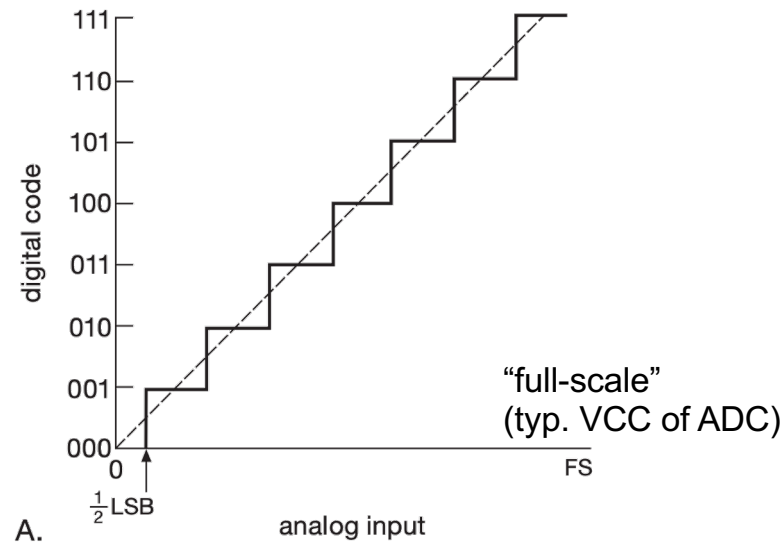
Output of sensor readout circuits is (almost always) an analog voltage

How do we convert this into something readable by a computer? (digital info)



Either built into your microcontroller (e.g., ESP32)
OR purchased as discrete IC (only when needed)

e.g., Successive Approximation Register (SAR)
Delta-Sigma, Flash



"3-bit" ADC:
000 to 111 in binary
0 to 7 in decimal

Resolution = $\frac{V_{ref}}{2^N}$

$$\frac{3.3V}{2^3} = 410mV \qquad \frac{3.3V}{2^{10}} = 3mV$$

Eletronic Basics #27:
ADC (Analog to Digital Converter)
fsample = 2 • fsignal = 20 kS/s
2

4:50

1. Lecture (~50 minutes)
2. Subsystem check-in (~15 minutes)

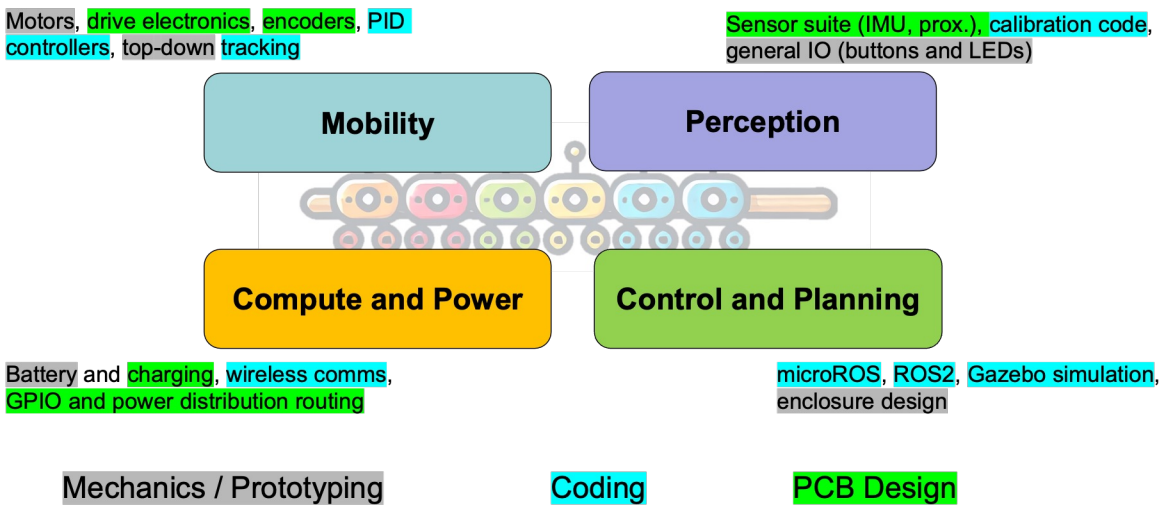
Questions?

Lecture 1: sensors → data acquisition
Lecture 2: signal processing → mapping

693H Robotic Subsystems

REMINDERS:

-PARTS ORDER DUE 2/3

-First Design Review Presentations are 2/10, 2/12

- -I will randomly select which two groups present which day. Be ready on 2/10.
- -Poll: DIY Powerpoints or Google Slides with (loose) templating?