CIS 3990

Mobile and IoT Computing

https://penn-waves-lab.github.io/cis3990-24spring

Lecture 7: Inertial Sensors & Inertial Sensing

Instructor: Mingmin Zhao (mingminz@cis.upenn.edu)

TA: Haowen Lai (hwlai@cis.upenn.edu)

Some material adapted from Gordon Wetzstein (Stanford), Sam Madden (MIT), Hari Balakrishnan (MIT), and Fadel Adib (MIT)

Sensing Modalities

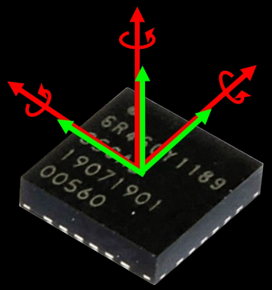
- Radio signals (EM waves): GPS, Cellular, Bluetooth, WiFi
- Ultrasound signals (mechanical waves): smart speakers
- Visual sensors: cameras, LIDAR
- Inertial sensors → **Focus of this lecture**

Radio

Acoustic

Visual

Inertial



Objectives of This Module

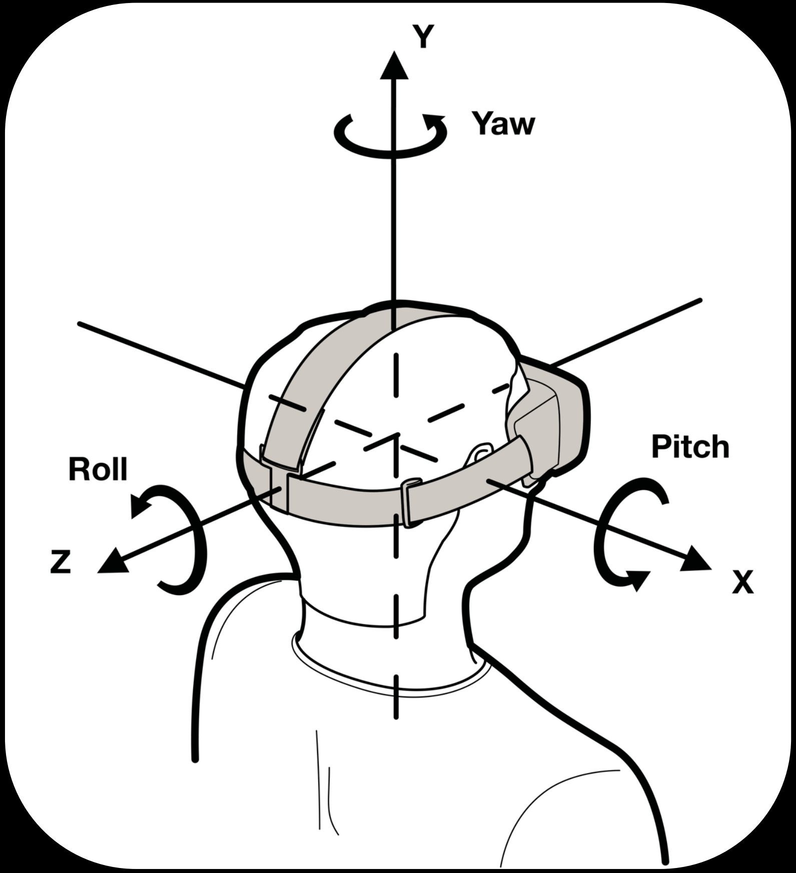
Learn how foundational sensing technologies can be used to extract diverse and meaningful insights

1. What are important application areas of Mobile and IoT sensing?
2. What are the foundational sensing mechanisms and how are they related to localization?
3. What processing algorithms can be used to transform raw sensor data?
4. Example sensing systems/solutions with real-world case studies.

Let’s understand inertial sensing in the context of VR

- **Goal:** track location and orientation of head or other device

- **Coordinates:** Six degrees of freedom:
  - Cartesian frame of reference (x, y, z)
  - Rotations represented by Euler angles (yaw, pitch roll)



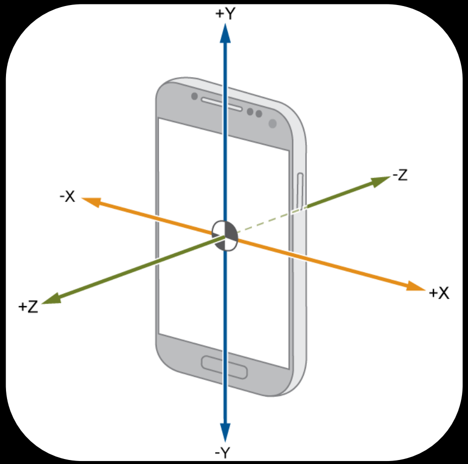
Source: Oculus

What are Inertial Sensors?

Inertial Sensors: Accelerometer

- **Newton's first law of motion (aka The Principle of Inertia):**
  + Every object perseveres in its state of rest, or of uniform motion in a right line, except insofar as it is compelled to change that state by forces impressed thereon.
  + Conservation of momentum in the absence of external forces.
- **Inertial sensors** capture the changes:

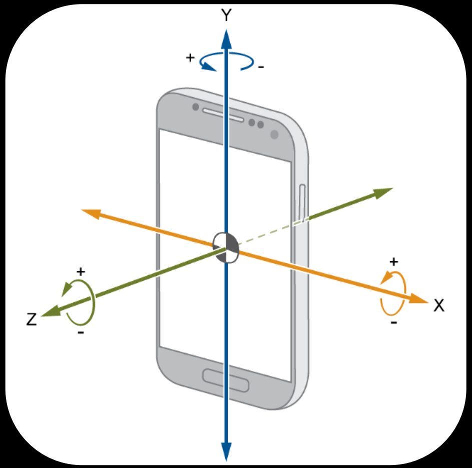
Accelerometer measures linear acceleration **a** in m/s^2



Inertial Sensors: Gyroscope

- **Newton's laws for rotation (analogous to laws for motion)**
  + A spinning object tends to spin with a constant angular velocity.
  + Conservation of angular momentum.
- **Inertial sensors** capture the changes:

Gyroscope measures angular velocity **ω** in degrees/s



Inertial Sensors: Magnetometer

- A magnetometer's operation is based on the interaction between magnetic fields and electric charges, which is described by Maxwell's equations – fundamental laws of electromagnetism.
- These sensors detect magnetic fields, including the Earth's geomagnetic field, allowing us to determine direction relative to the magnetic North Pole.

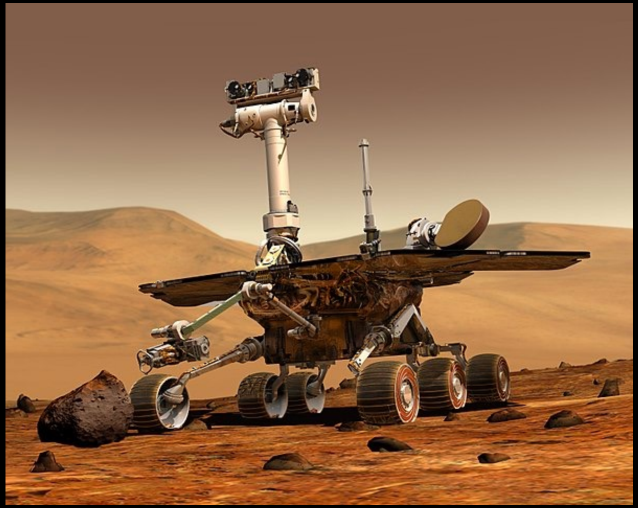
Magnetometer measures magnetic field strength **m** in μT (micro-Teslas).

IMU: Inertial Measurement Unit

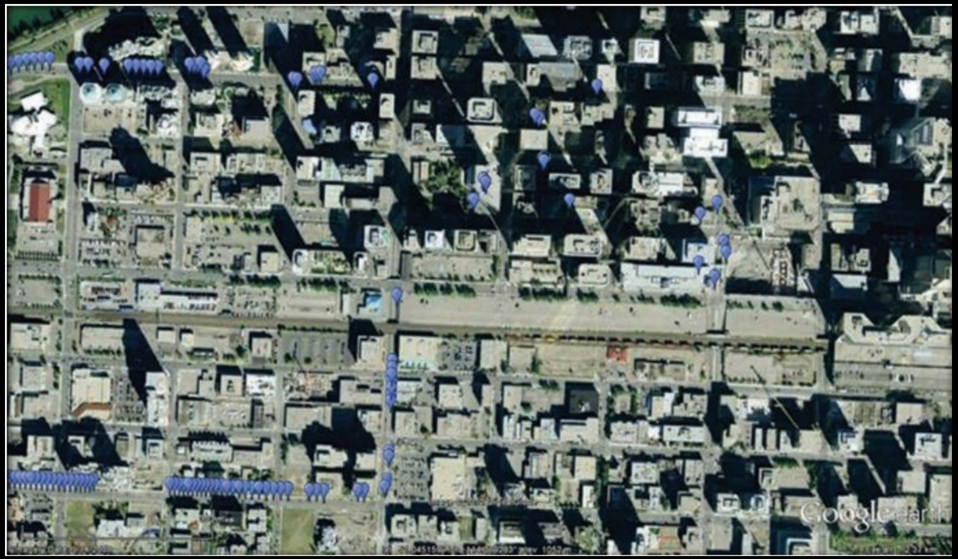
IMU consists of:

- **Gyroscope** measures angular velocity **ω** in degrees/s
- **Accelerometer** measures linear acceleration **a** in m/s^2
- **Magnetometer** measures magnetic field strength **m** in μT (micro-Teslas).

Where are IMUs used today?



Example Application: Inertial Navigation



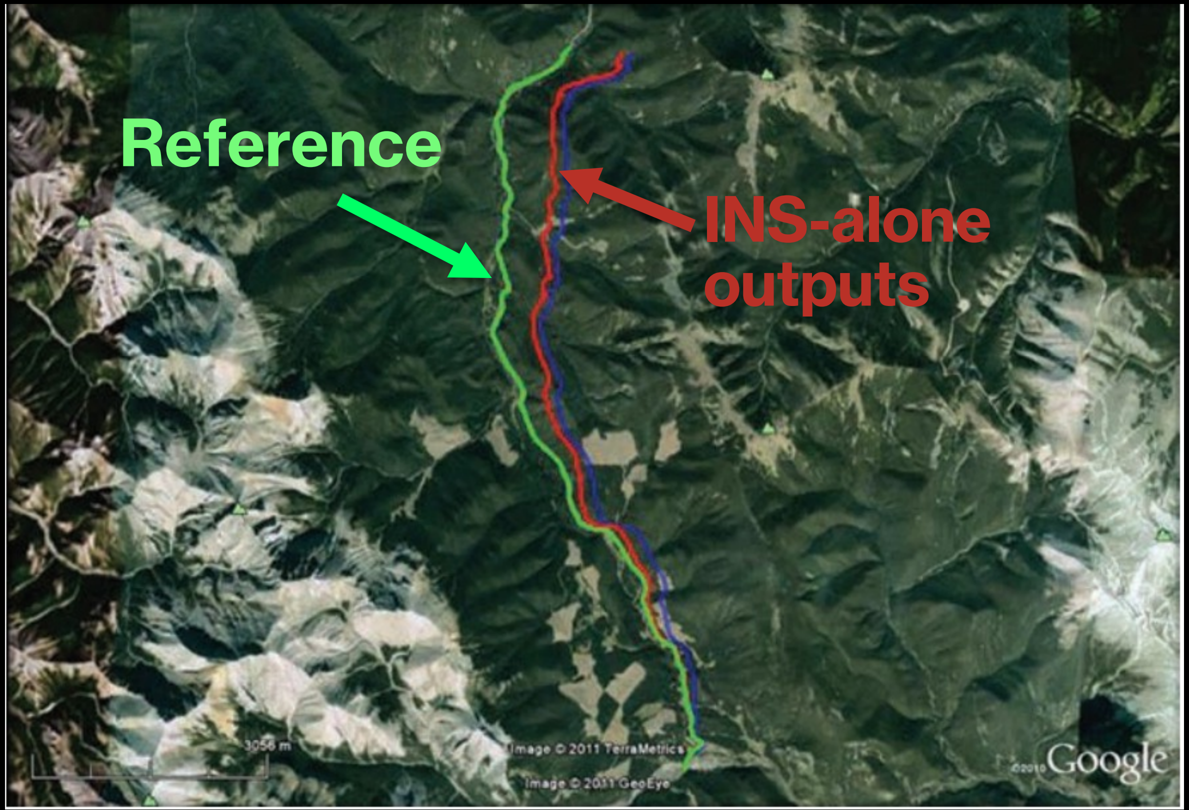
GPS only

GPS+INS

Key Idea: Integrate acceleration data over time to discover location (Inertial Sensing)

Inertial Sensing alone is not enough for accurate positioning

Errors accumulate over time



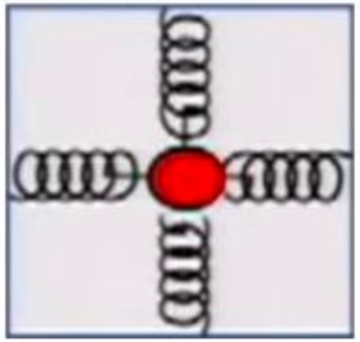
Key Idea: Fuse Data from Multiple Sensors
(Sensor Fusion)

Rest of this Lecture

- **Basic principles of operation of different IMU sensors**
- Understanding Sources of Errors
- Dead reckoning by fusing multiple sensors
- Example system: Pothole Patrol

Accelerometer

Mass on spring



Gravity

$1g = 9.8m/s^2$

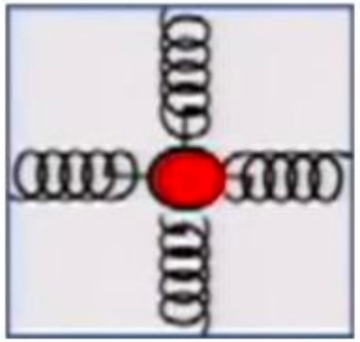
Free Fall

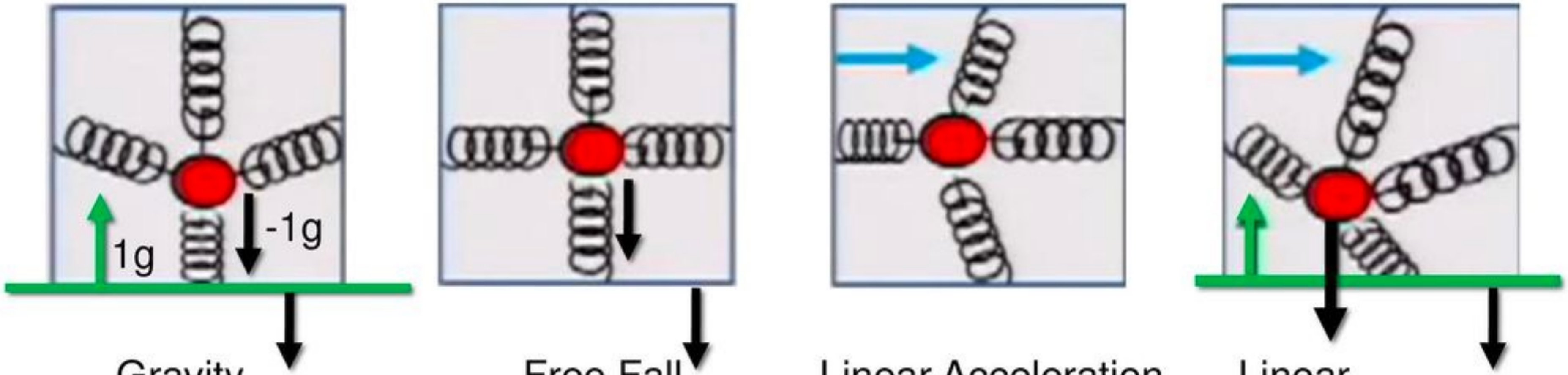
Linear Acceleration

Linear Acceleration plus gravity

Accelerometer

Mass on spring





Gravity

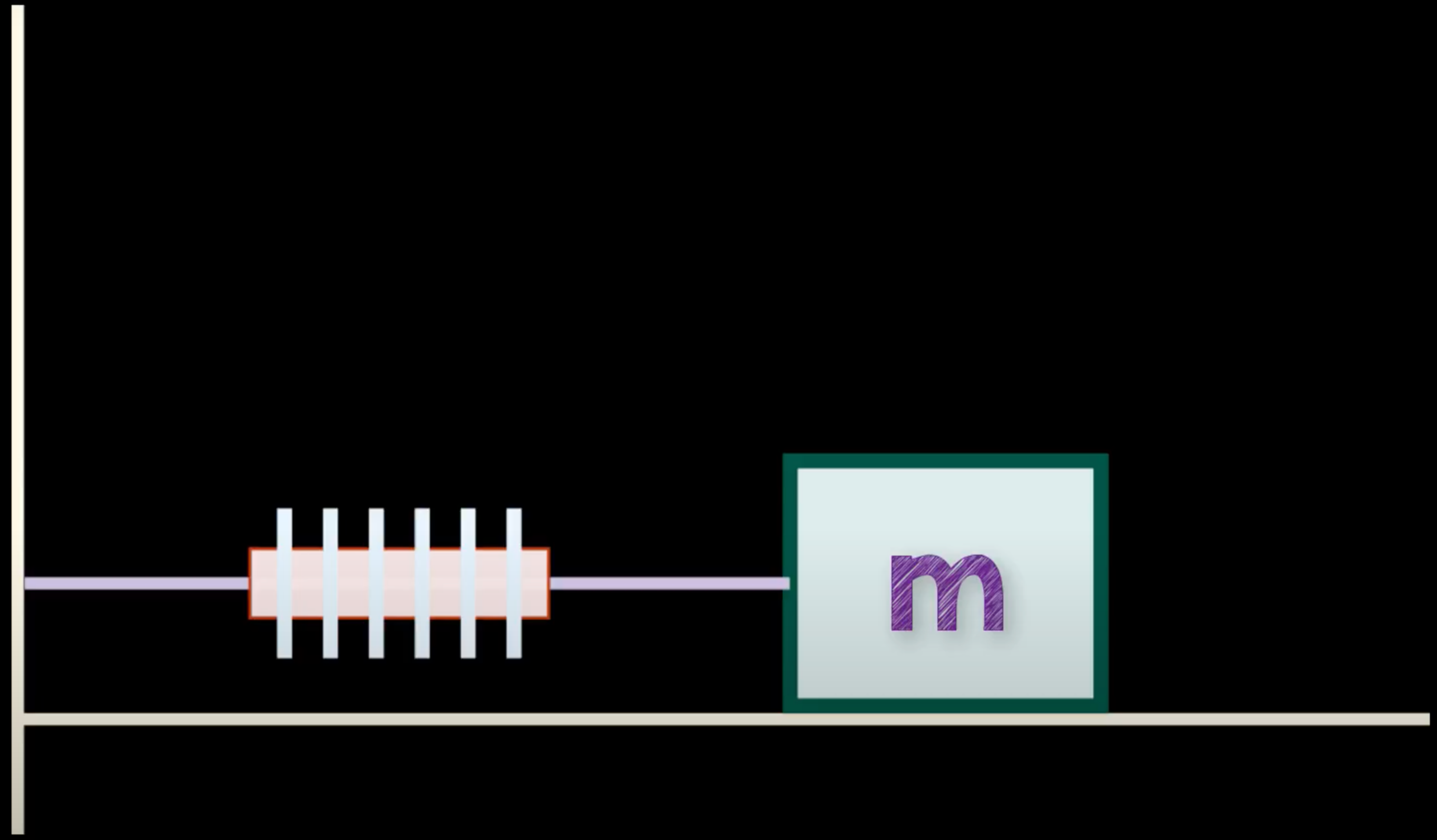
$1g = 9.8 m/s^2$

Free Fall

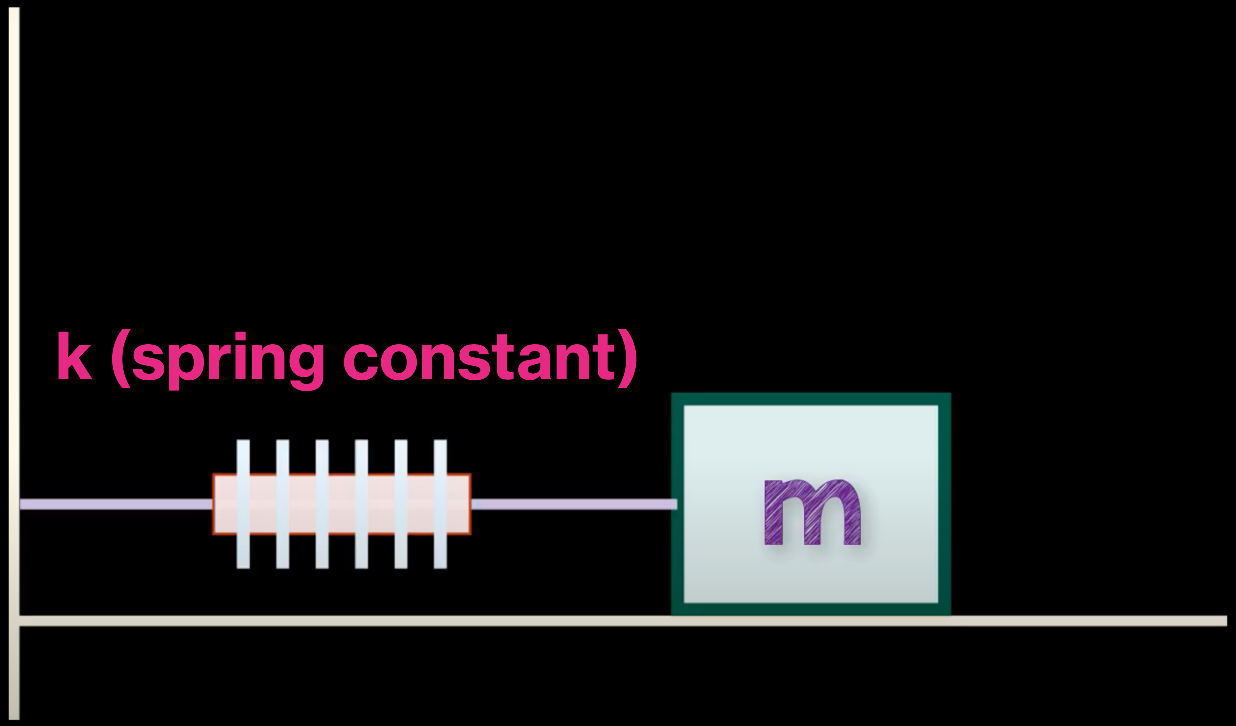
Linear Acceleration

Linear Acceleration plus gravity

How Accelerometers Work



What matters is the displacement



Hooke's Law

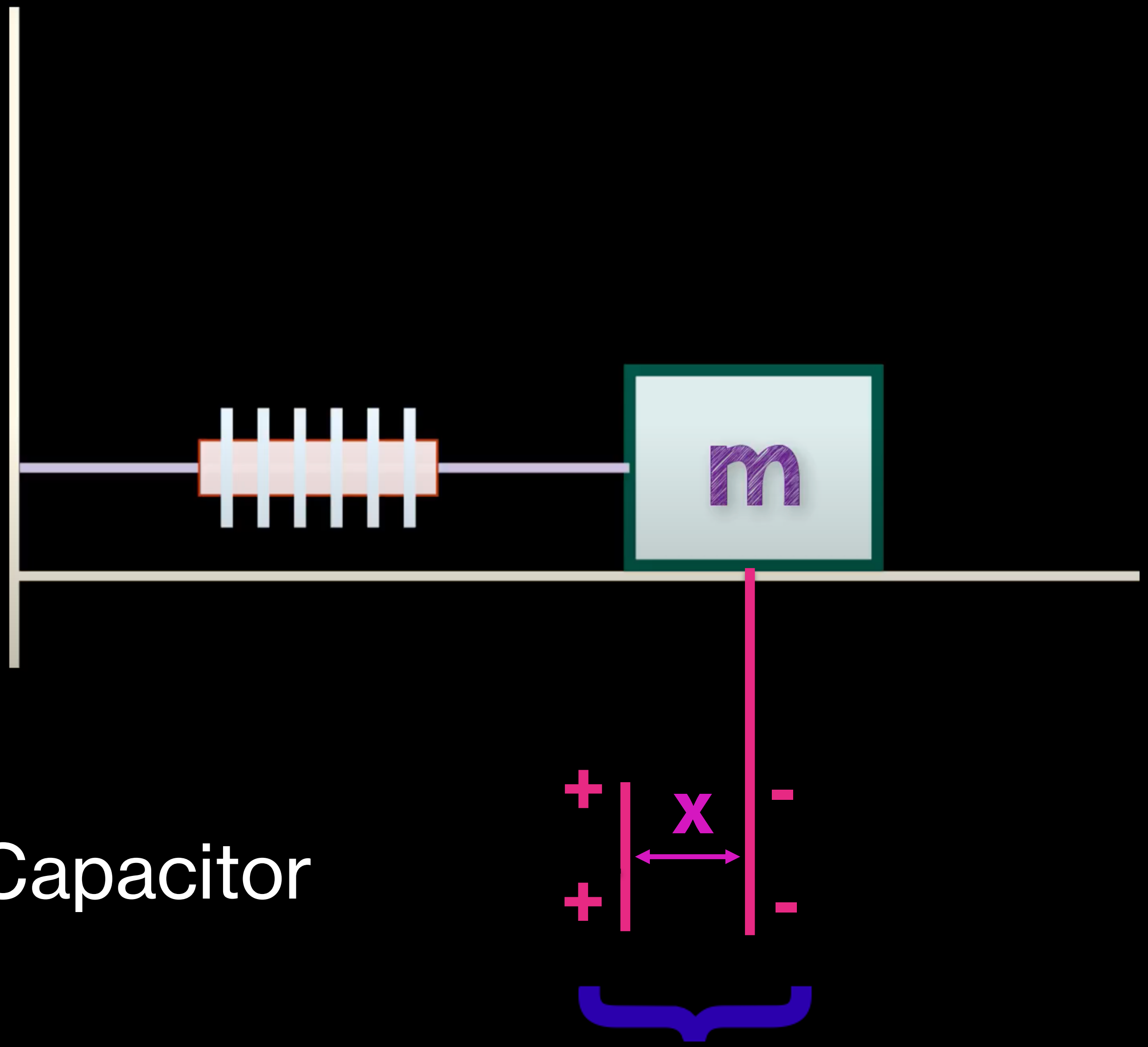
Newton's Law

$$F = kx$$

$$F = ma$$

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

Why not simply use displacement to measure displacement?

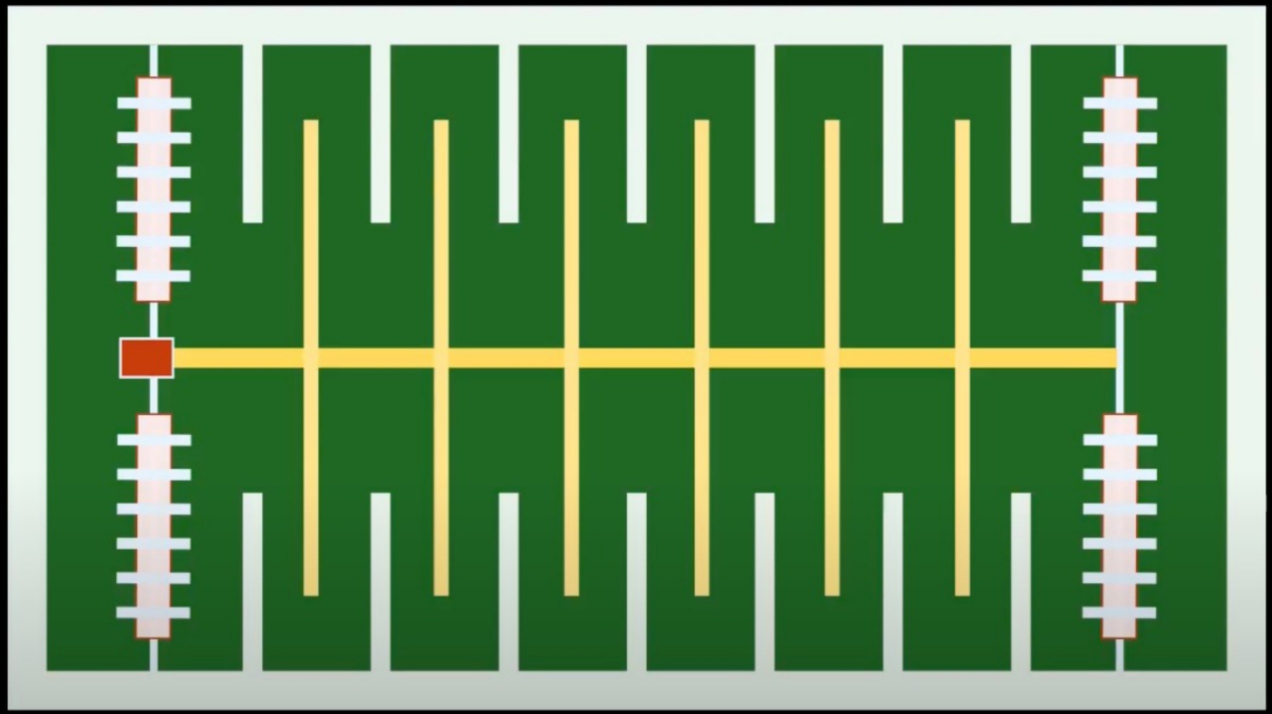


Capacitor

$$C = \epsilon \frac{Area}{x}$$

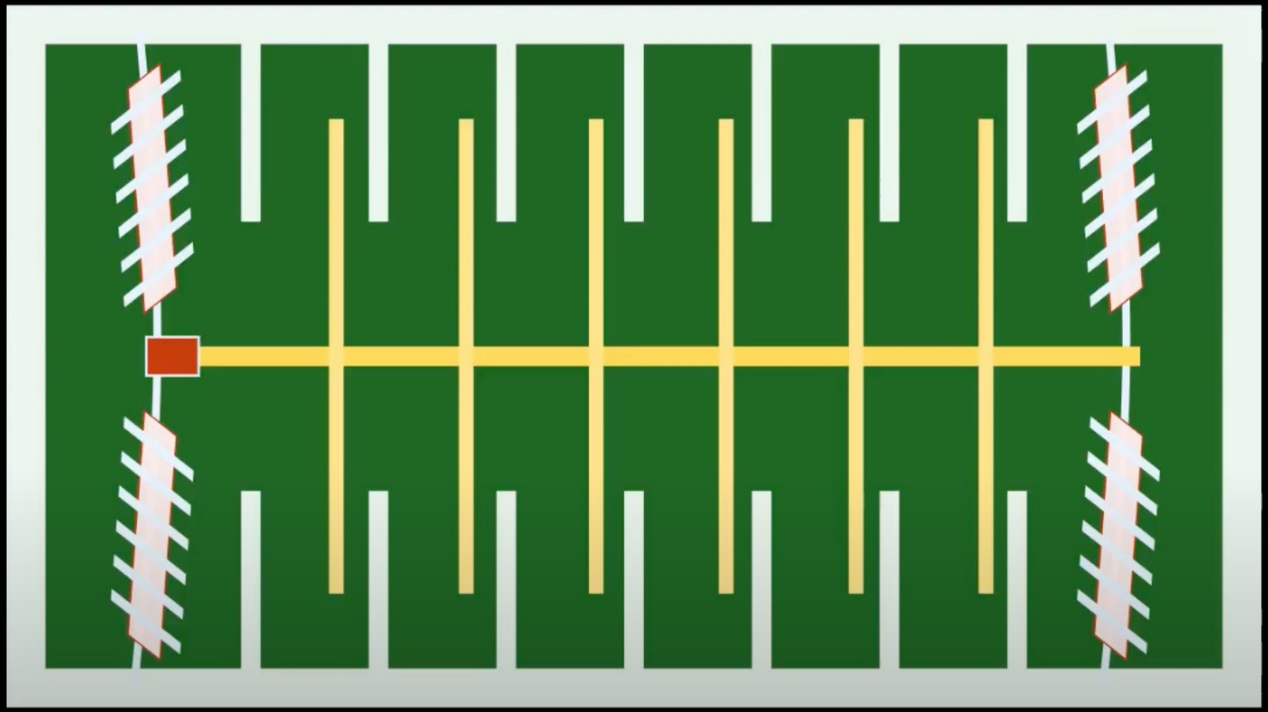
Measuring Displacement

- How do we measure displacement?
- Most common approach is to use capacitance and MEMS (Micro electro-mechanical systems)

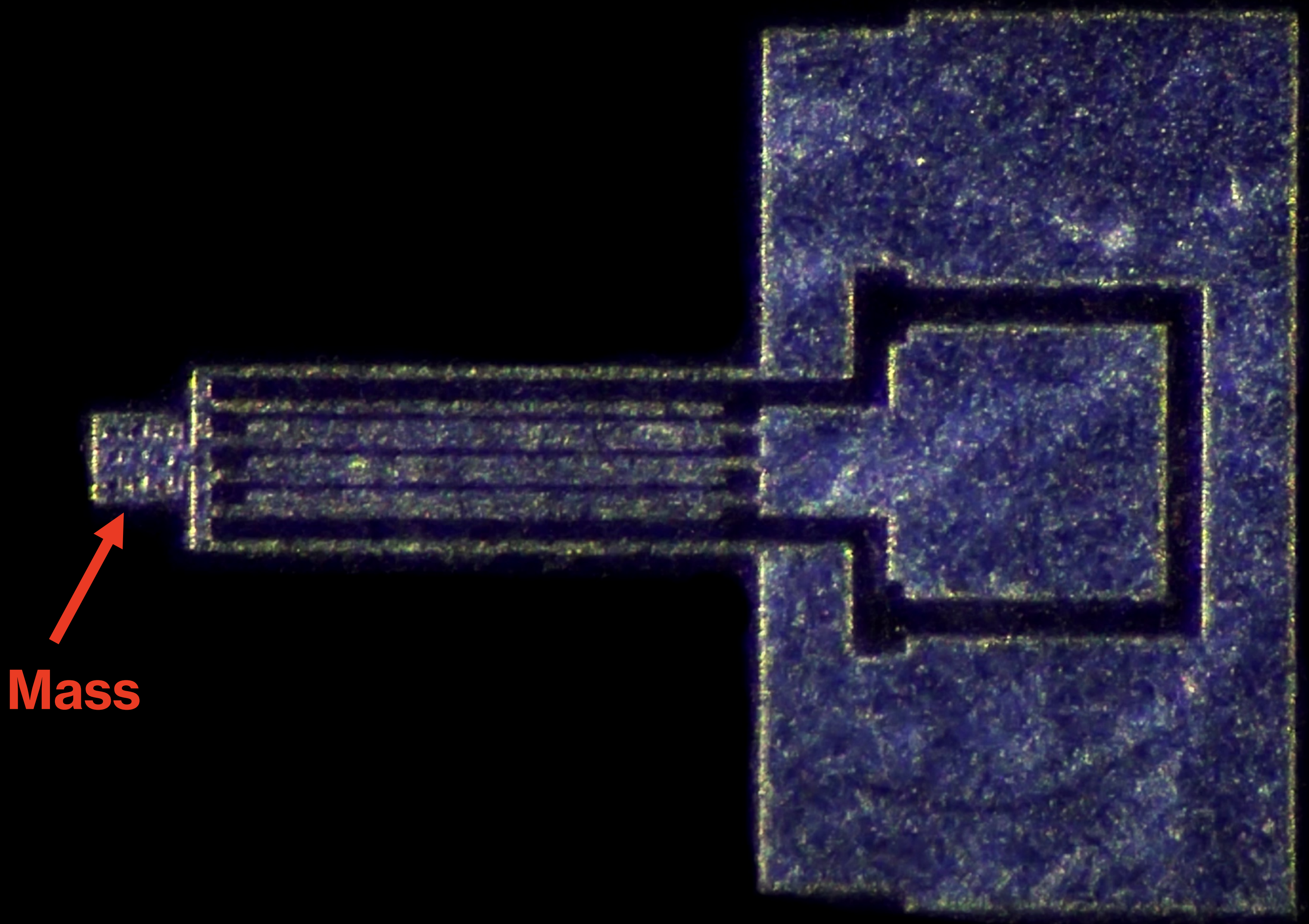


Measuring Displacement

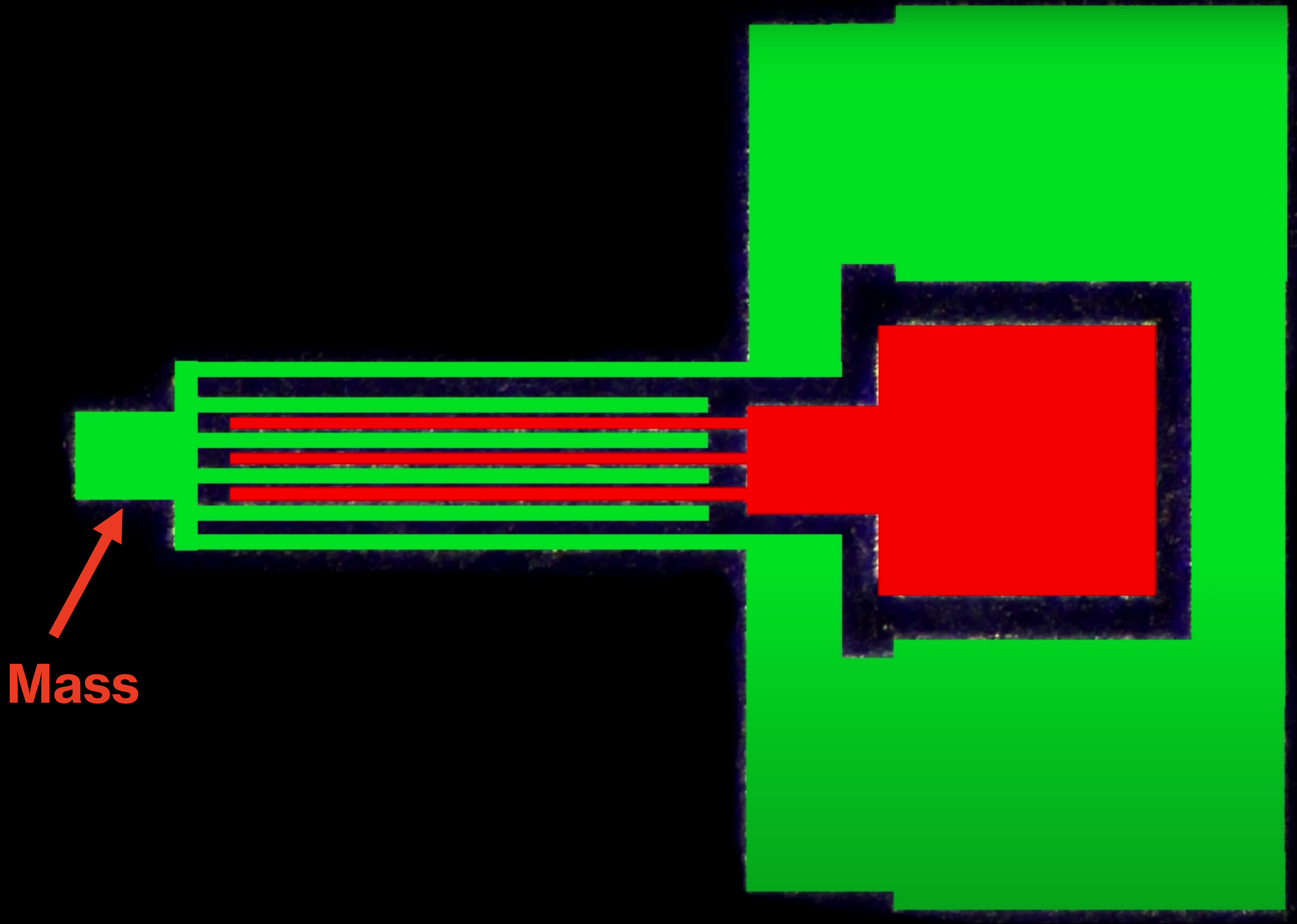
- How do we measure displacement?
- Most common approach is to use capacitance and MEMS (Micro electro-mechanical systems)



MEMS Accelerometer

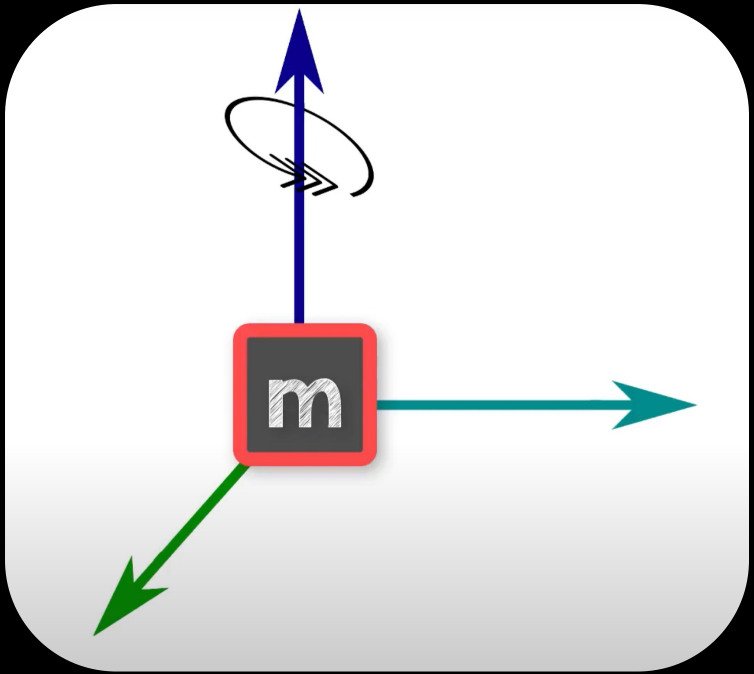


MEMS Accelerometer



How Gyroscopes Work?

The Coriolis Effect

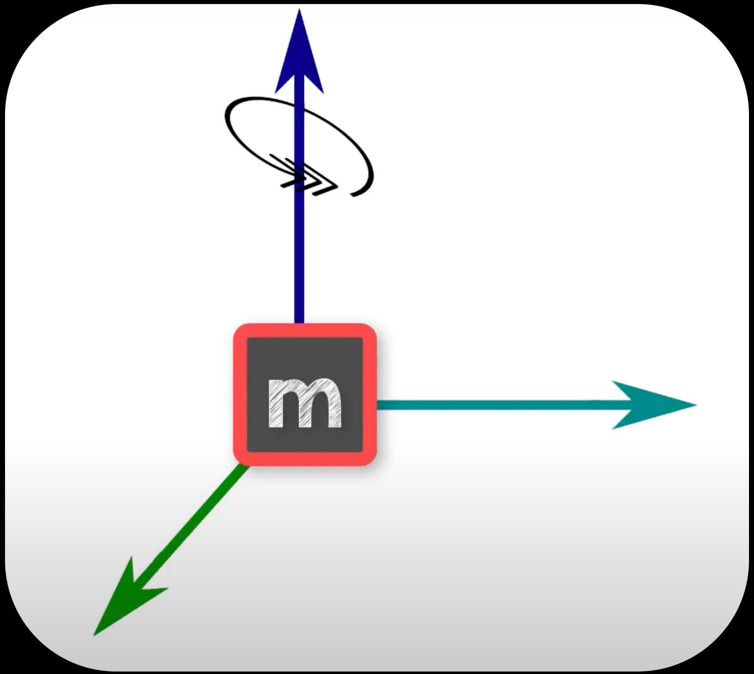


- Assume Vx
- Apply ω
- Experiences a fictitious force F(ω, Vx) following right hand rule

The Coriolis Effect

How Gyroscopes Work?

The Coriolis Effect

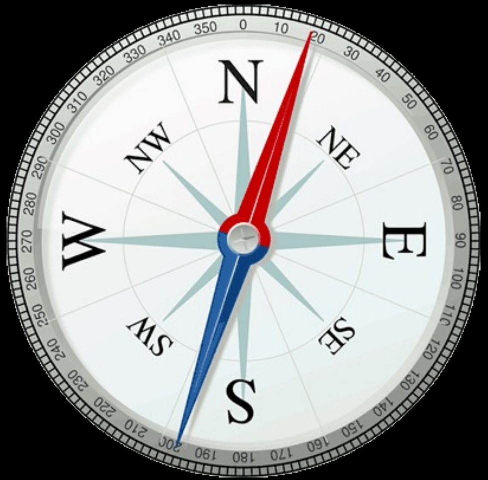


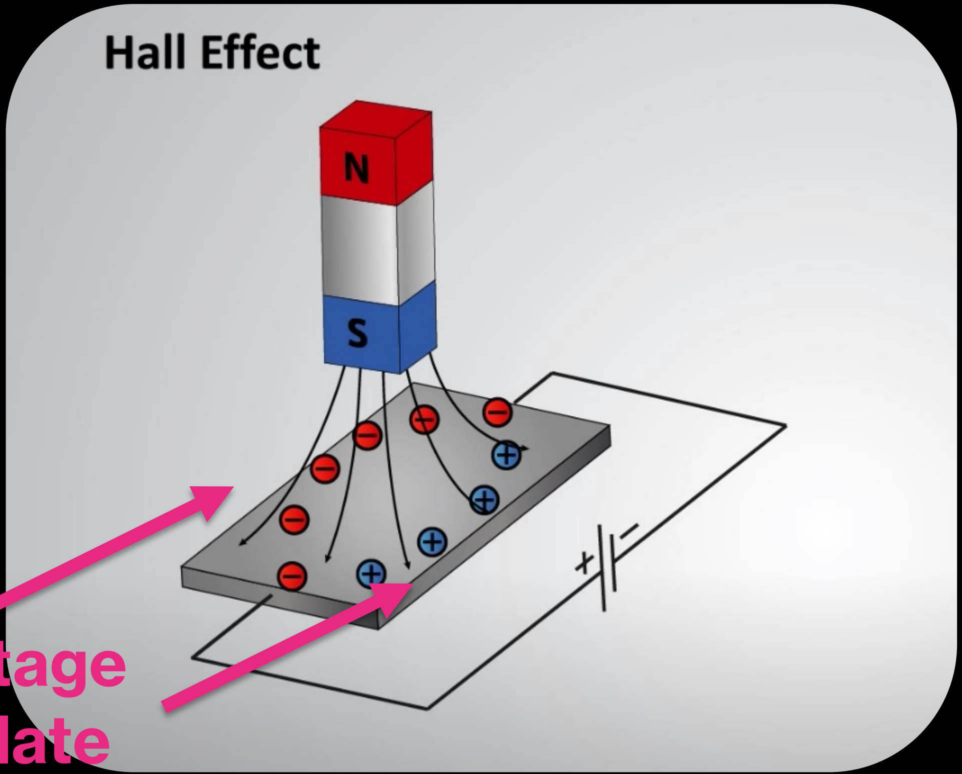
- Assume Vx
- Apply **ω**
- Experiences a fictitious force F(**ω**, Vx) following right hand rule

Can measure F in a similar fashion and use it to recover **ω**

How Magnetometers Work

- E.g., Compass
- Measure Earth’s magnetic field



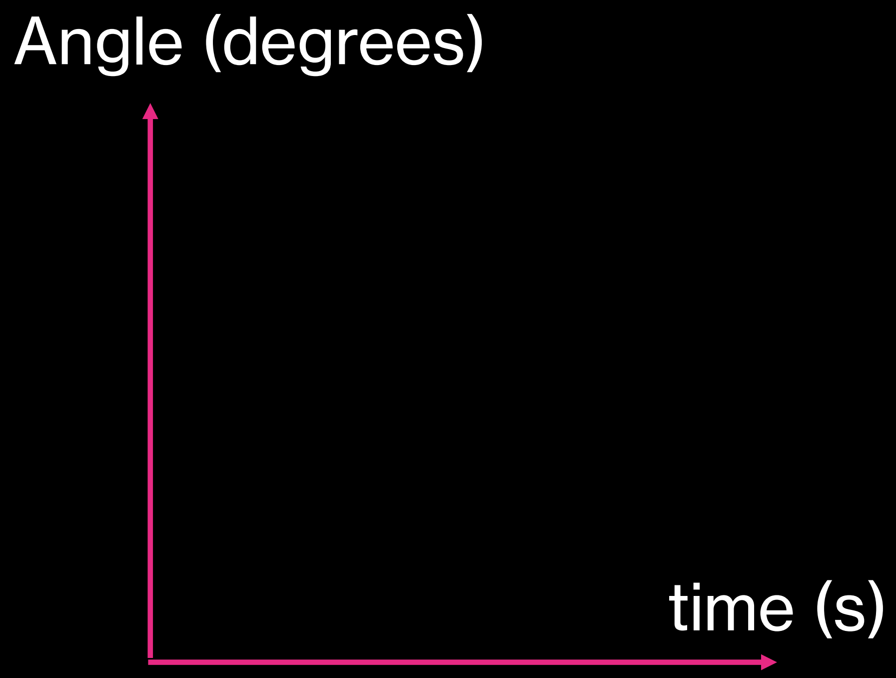


Measure voltage across the plate

Rest of this Lecture

- Basic principles of operation of different IMU sensors
- **Understanding Sources of Errors**
- Dead reckoning by fusing multiple sensors
- Example system: Pothole Patrol

Gyro Integration

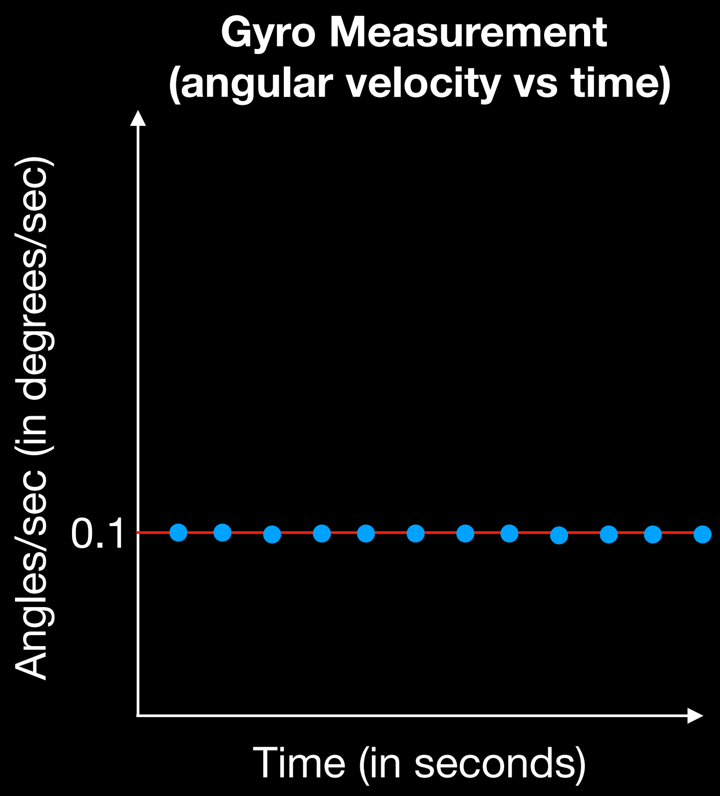


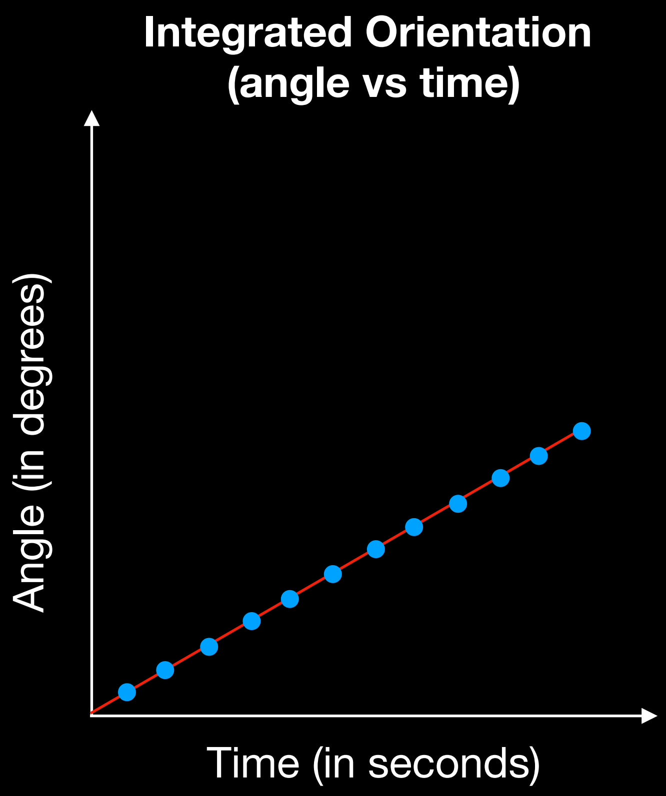
- Let’s plot this for gyro measurement and for orientation
- Let’s include ground truth and measured data for each

Consider:

- linear (angular) motion, no noise, no bias
- linear (angular) motion, with noise, no bias
- linear (angular) motion, no noise, bias
- nonlinear motion, no noise, no bias

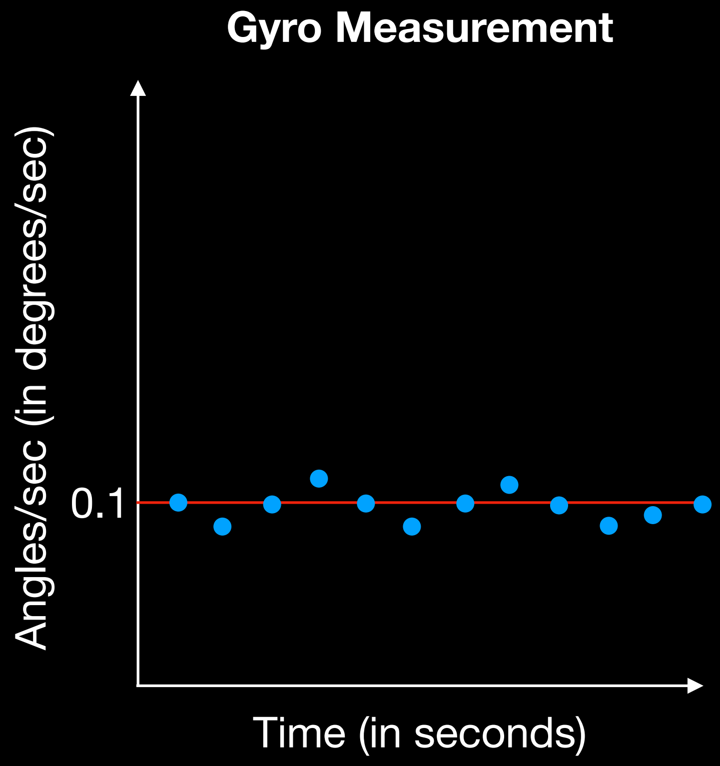
Gyro integration: linear motion, no noise, no bias

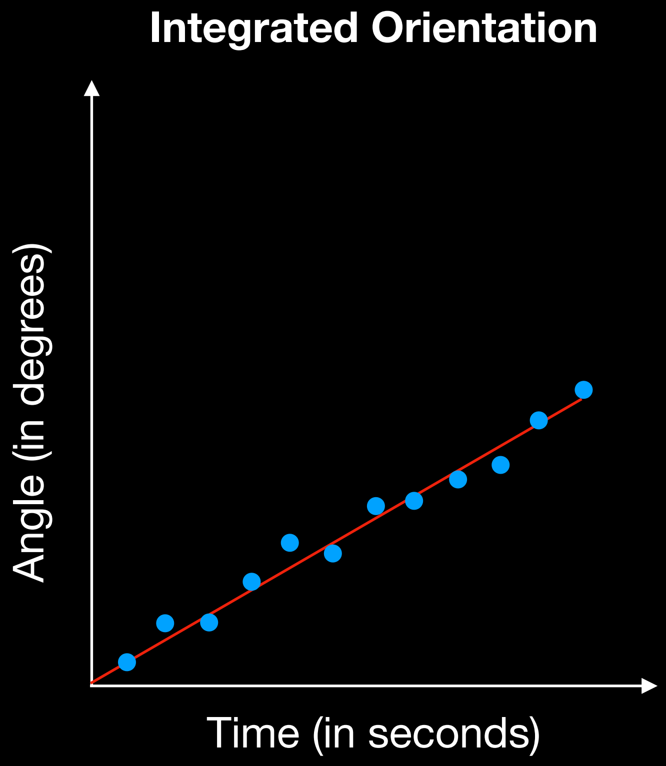




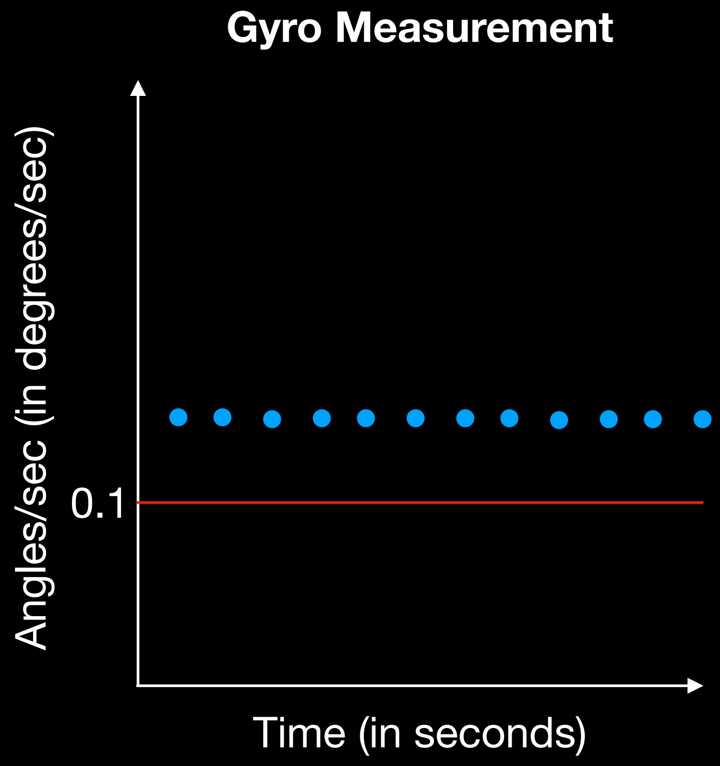
Ground truth
Measured/estimated angle

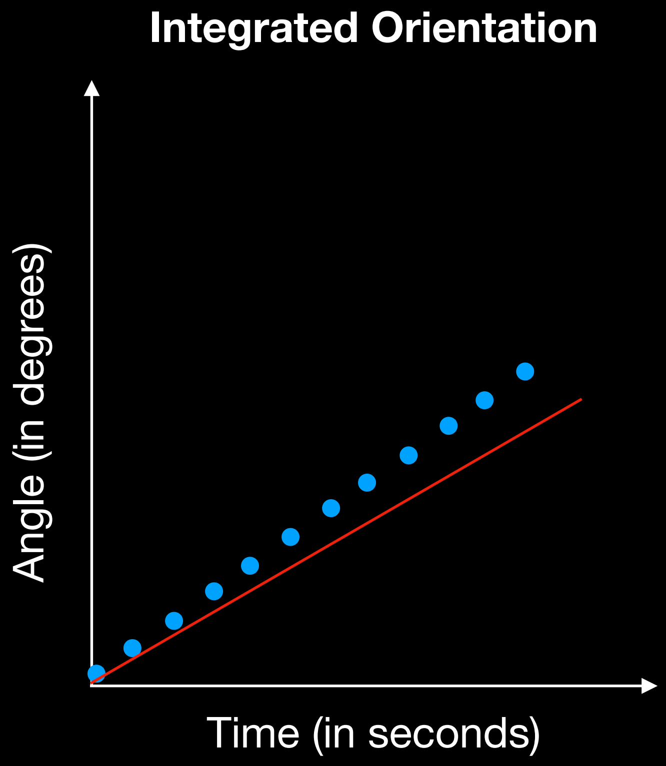
Gyro integration: linear motion, noise, no bias



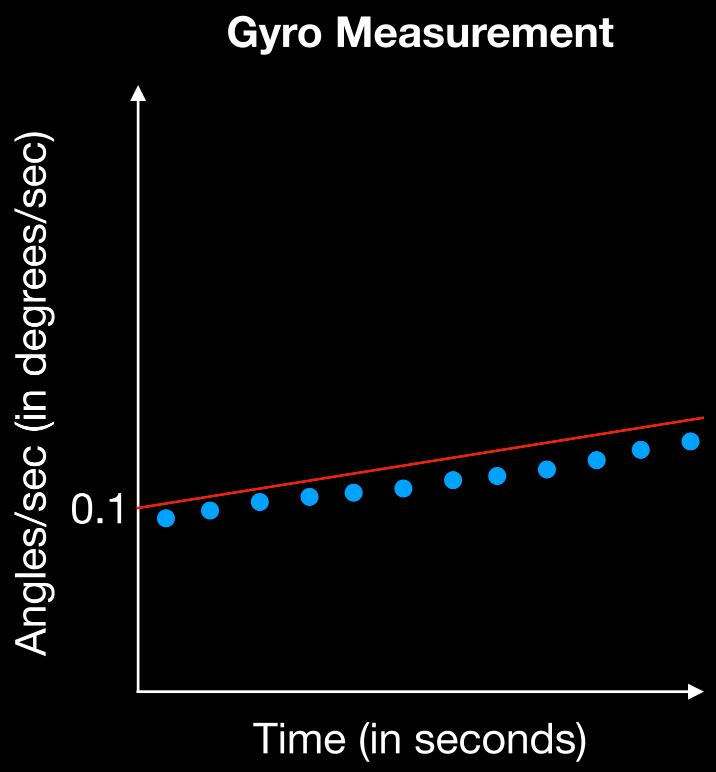


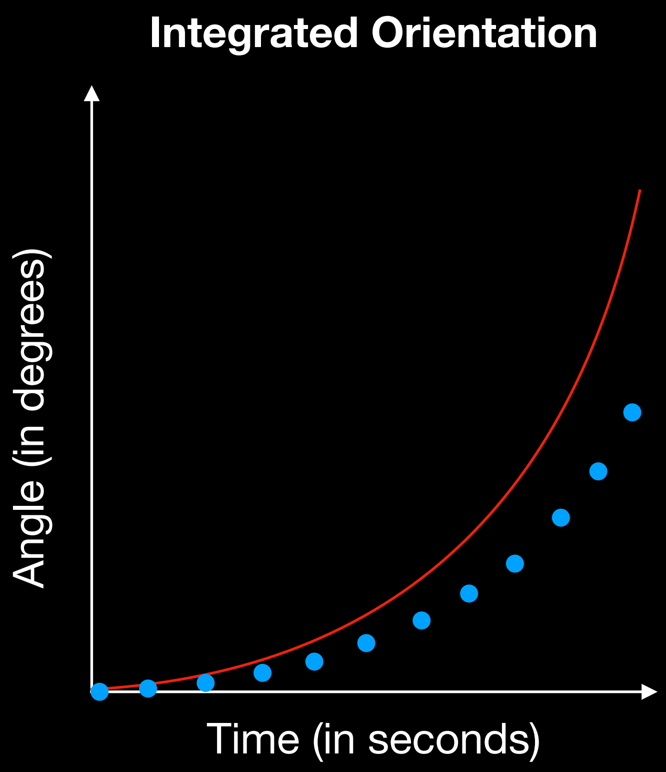
Gyro integration: linear motion, no noise, bias





Gyro integration: nonlinear motion, no noise, no bias





Gyro Integration aka *Dead Reckoning*

- Works well for linear motion, no noise, no bias = unrealistic
- If bias is unknown and noise is zero -> drift (from integration)
- Bias and noise variance can be estimated, other sensor measurements used to correct for drift (sensor fusion)
- Accurate in short term, but not reliable in long term due to drift

Rest of this Lecture

- Basic principles of operation of different IMU sensors
- Understanding Sources of Errors
- **Dead reckoning by fusing multiple sensors**
- Example system: Pothole Patrol

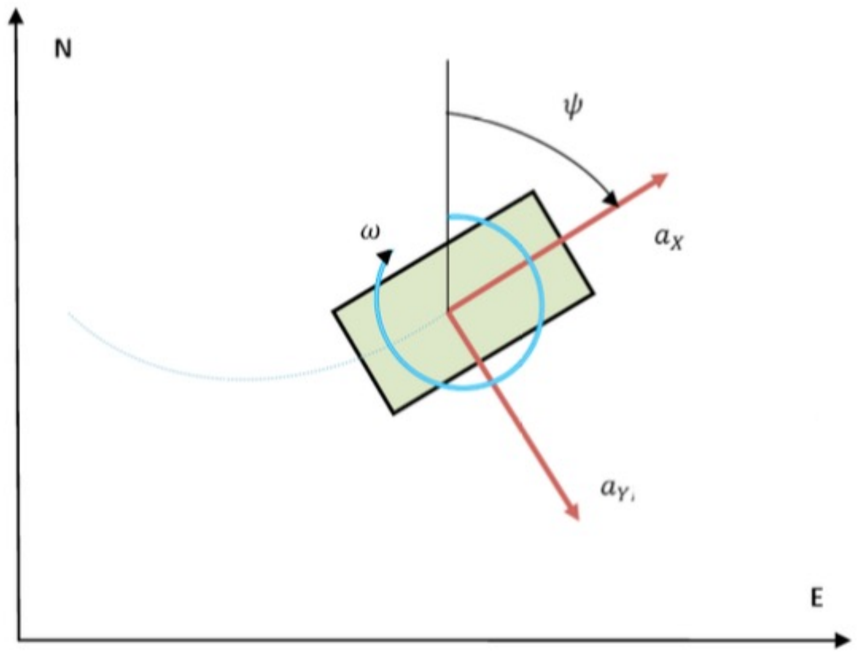

MISSION:IMPOSSIBLE
DEAD RECKONING

Dead Reckoning

- The process of calculating one's current position by using a previously determined position, and advancing that position based upon known or estimated speeds over elapsed time and course

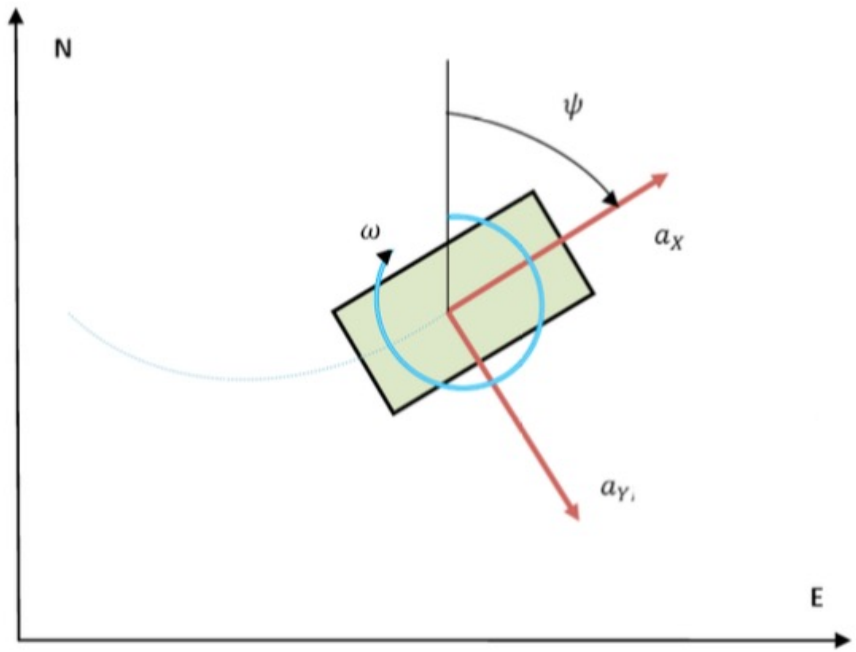
- Key things to keep in mind:
    - Frames of reference
    - Orientation change

2D Inertial Navigation in Strapdown System



Source: Basic Principles of Inertial Navigation
Seminar on inertial navigation systems
Tampere University of Technology

2D Inertial Navigation in Strapdown System



$$\begin{bmatrix} a_N \\ a_E \end{bmatrix} = \begin{bmatrix} \cos\psi & -\sin\psi \\ \sin\psi & \cos\psi \end{bmatrix} \begin{bmatrix} a_x \\ a_y \end{bmatrix}$$

$$a_N(t) = \cos\psi \cdot a_x(t) - \sin\psi \cdot a_y(t)$$
$$a_E(t) = \sin\psi \cdot a_x(t) + \cos\psi \cdot a_y(t)$$

2D Inertial Navigation in Strapdown System

Acceleration:

$$a_N(t) = \cos\psi \cdot a_x(t) - \sin\psi \cdot a_y(t)$$
$$a_E(t) = \sin\psi \cdot a_x(t) + \cos\psi \cdot a_y(t)$$

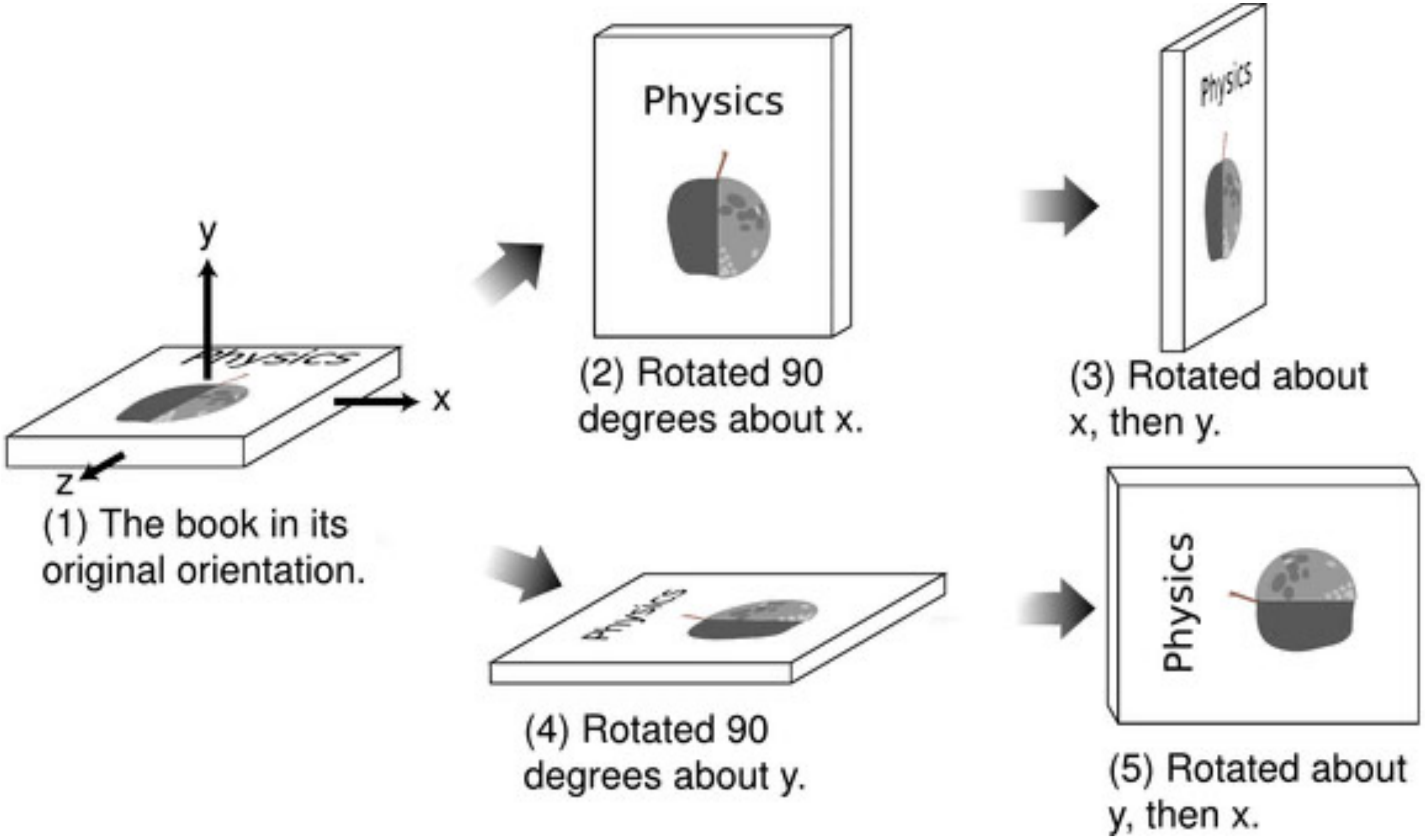
Velocity:

$$V_N(t) = V_N(t_0) + \int_{t_0}^{t} a_N(\tau)\, d\tau$$
$$V_E(t) = V_E(t_0) + \int_{t_0}^{t} a_E(\tau)\, d\tau$$

Position:

$$X_N(t) = X_N(t_0) + \int_{t_0}^{t} V_N(\tau)\, d\tau$$
$$X_E(t) = X_E(t_0) + \int_{t_0}^{t} V_E(\tau)\, d\tau$$

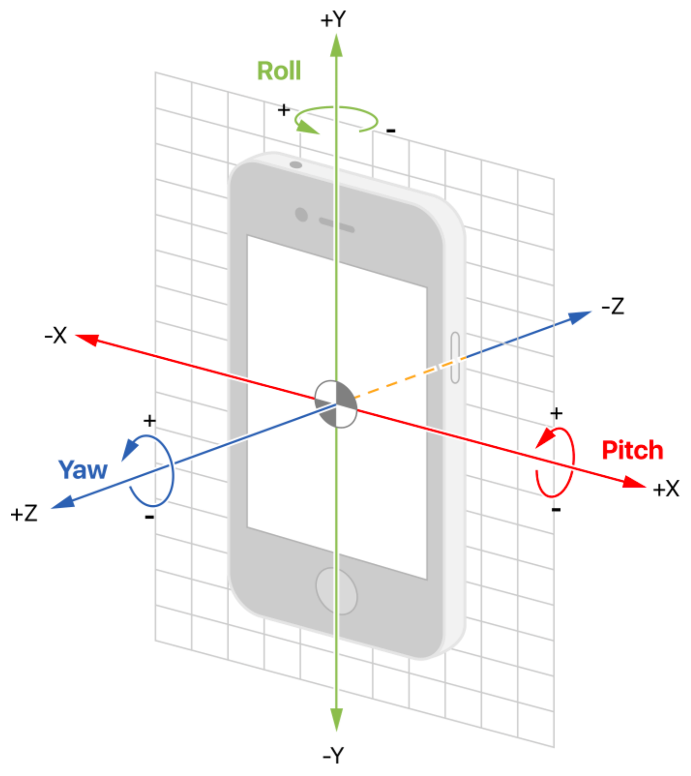
How about 3D Rotations?



Non-commutative = order matters!

3D Rotation Representations

- Rotation Matrix
  + 3 orthonormal vectors = 9 numbers
- Euler Angles (roll, pitch, yaw)
  + Symmetry problem, Gimbal lock
- Axis-angle
- Quaternions



Quaternions

- 4-dimensional number

Complex number	Quaternion
$3.14 + 1.59\,i$	$\underbrace{0.00}_{\text{Scalar part}} + \underbrace{8.46\,i + 2.64\,j + 3.38\,k}_{\text{"Vector" part}}$

$$i^2 = j^2 = k^2 = -1$$
$$ij = -ji = k$$
$$ki = -ik = j$$
$$jk = -kj = i$$

- *Unit* quaternions represent 3D rotations

$$q = \cos\left(\frac{\theta}{2}\right) + \sin\left(\frac{\theta}{2}\right)(u_x i + u_x j + u_x k)$$

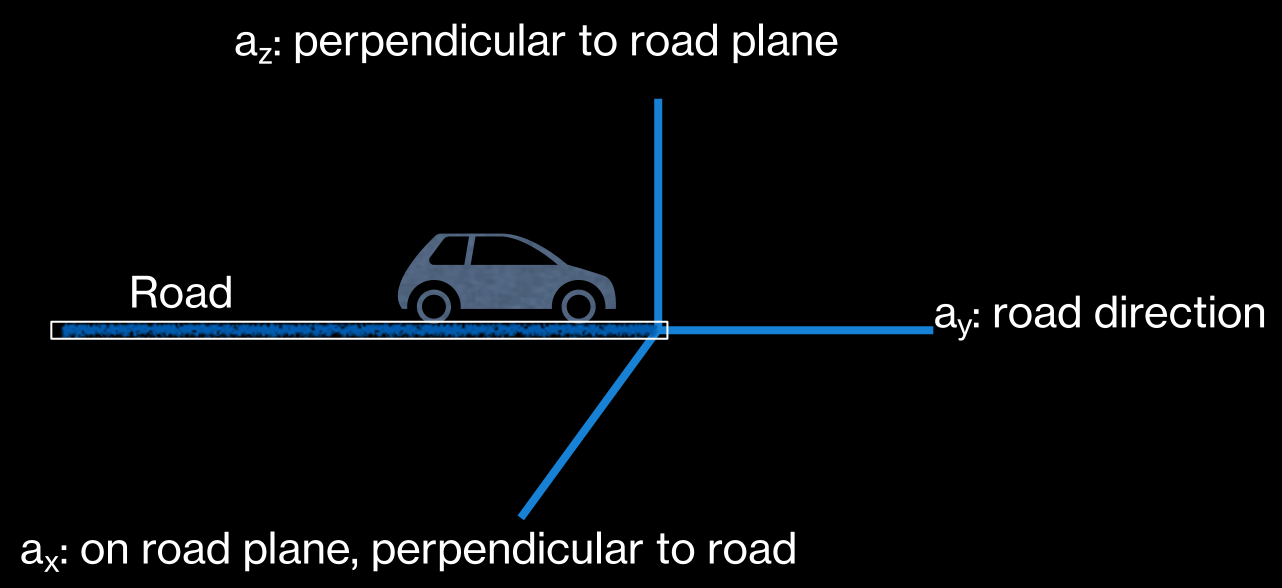
$$p \rightarrow q \cdot p \cdot q^{-1}$$

Rest of this Lecture

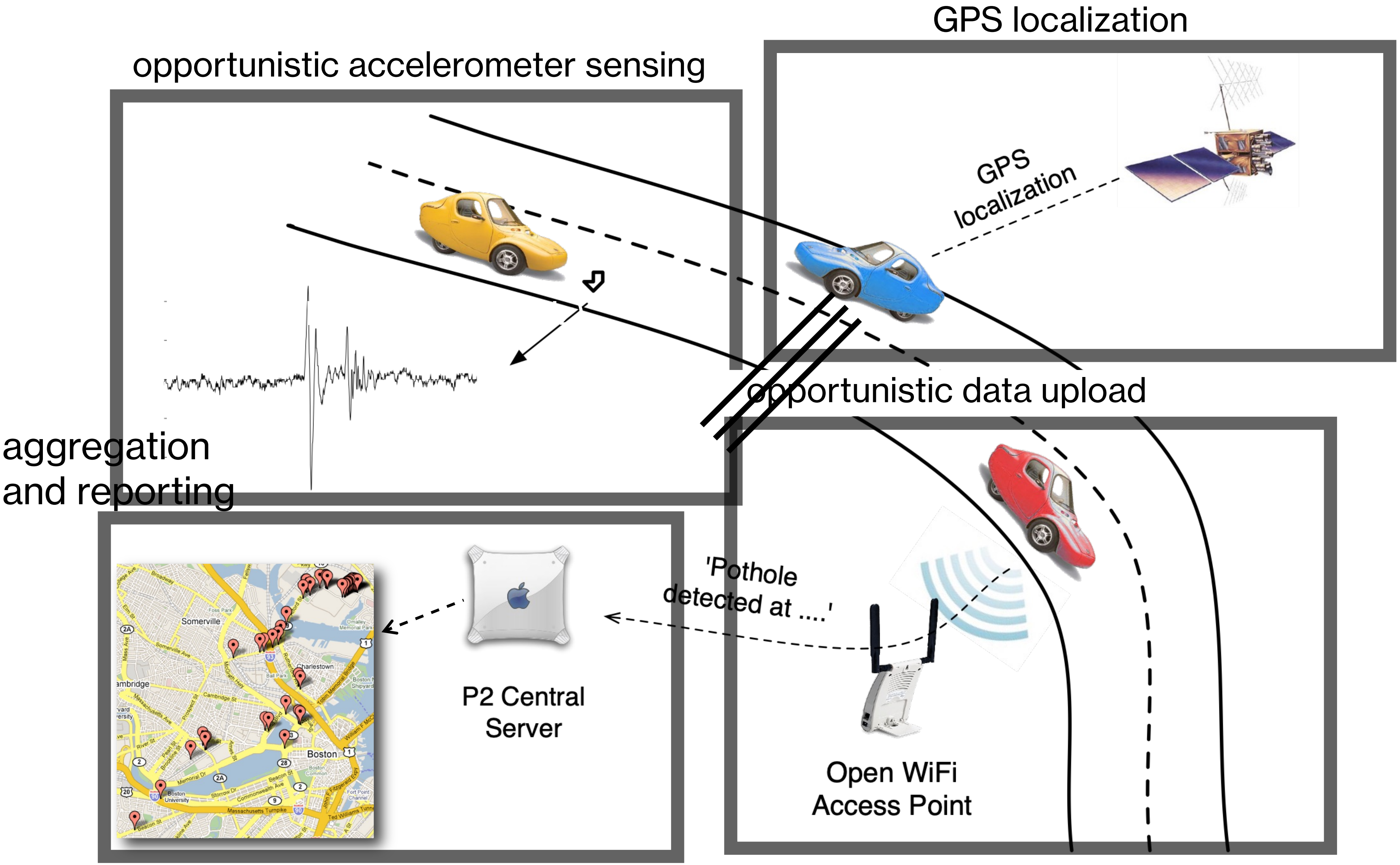
- Basic principles of operation of different IMU sensors
- Understanding Sources of Errors
- Dead reckoning by fusing multiple sensors
- **Example system: Pothole Patrol**

- road decay unavoidable, hard to predict
- current monitoring methods costly/ineffective

Acceleration vector

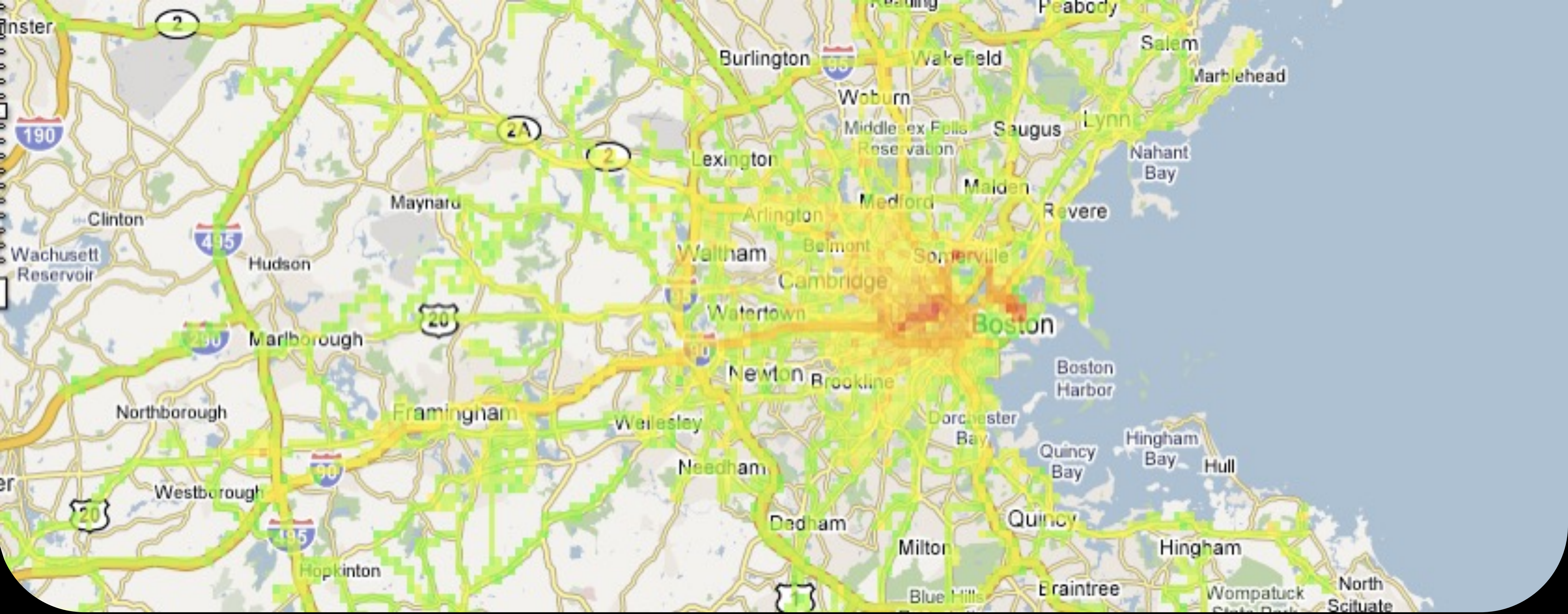


Pothole Patrol System Overview



Experimental Platform

- 7 Boston/Cambridge taxis
- small computer in glove box
- 380 Hz 3-axis accelerometer
- 802.11a/b/g wireless interface
- GPS receiver on roof
- <time,location,heading,speed,ax,ay,az>



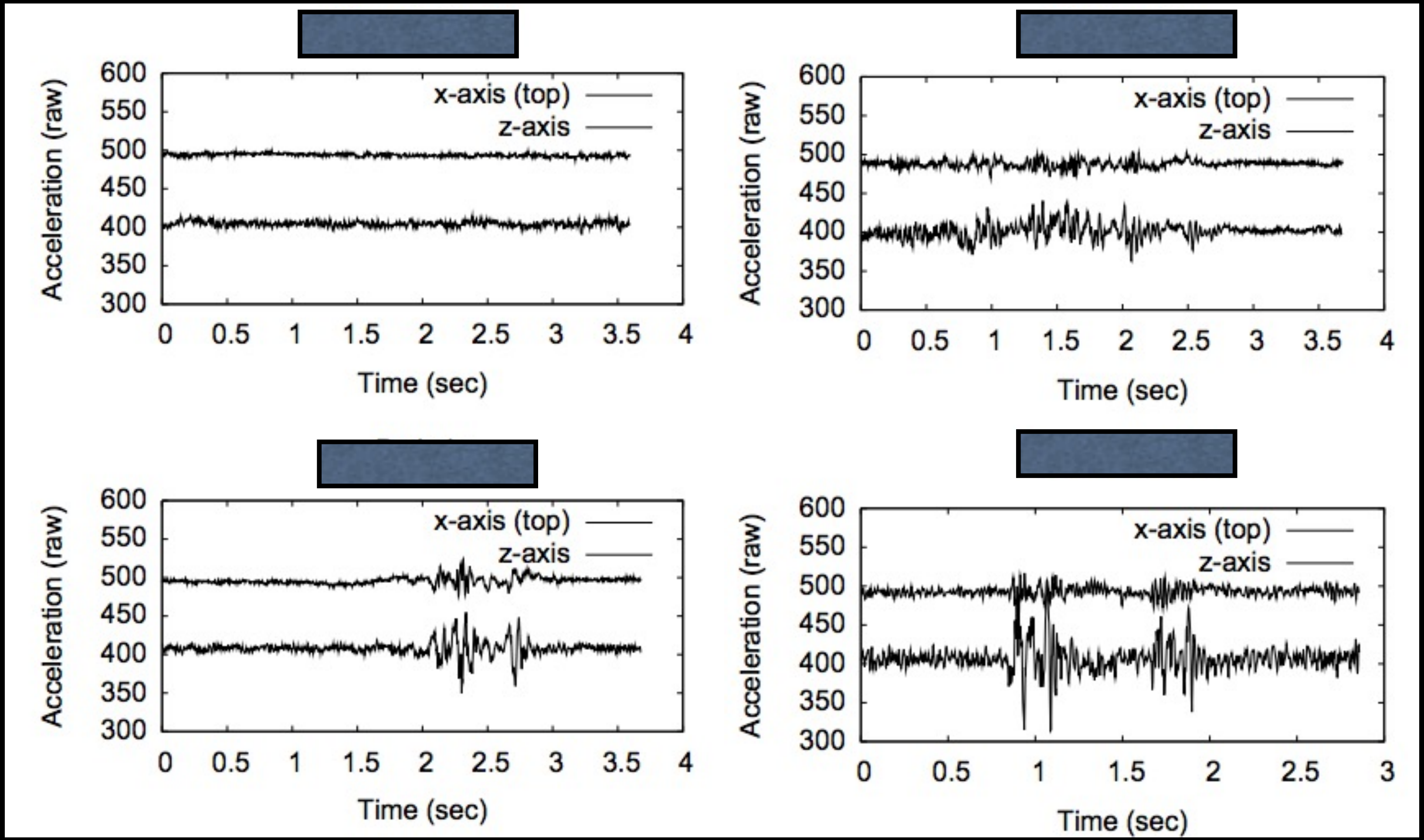
Wide-area Sensing & Crowdsensing

Sensor Placement

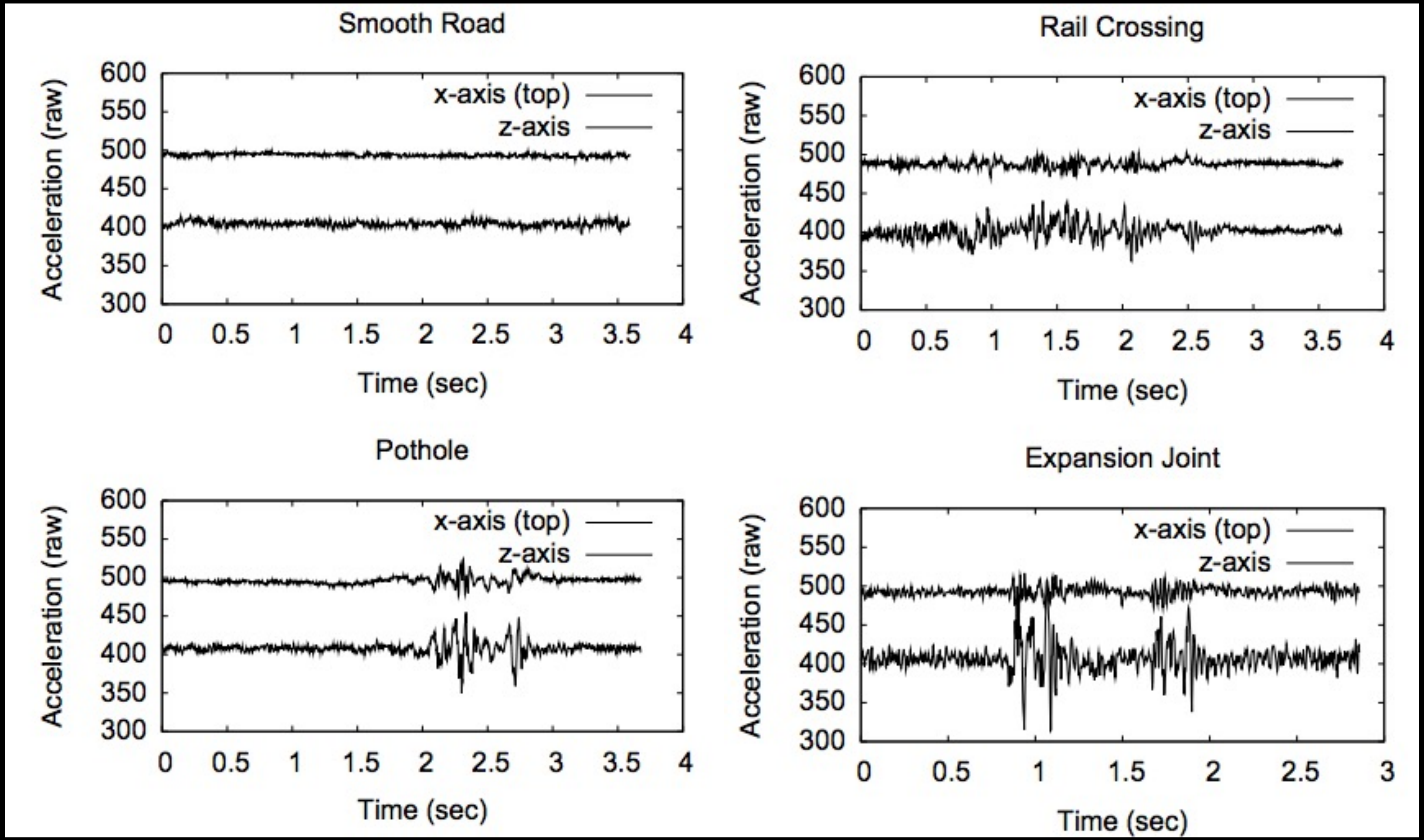
Pros? Cons?

Pothole & False Alarms

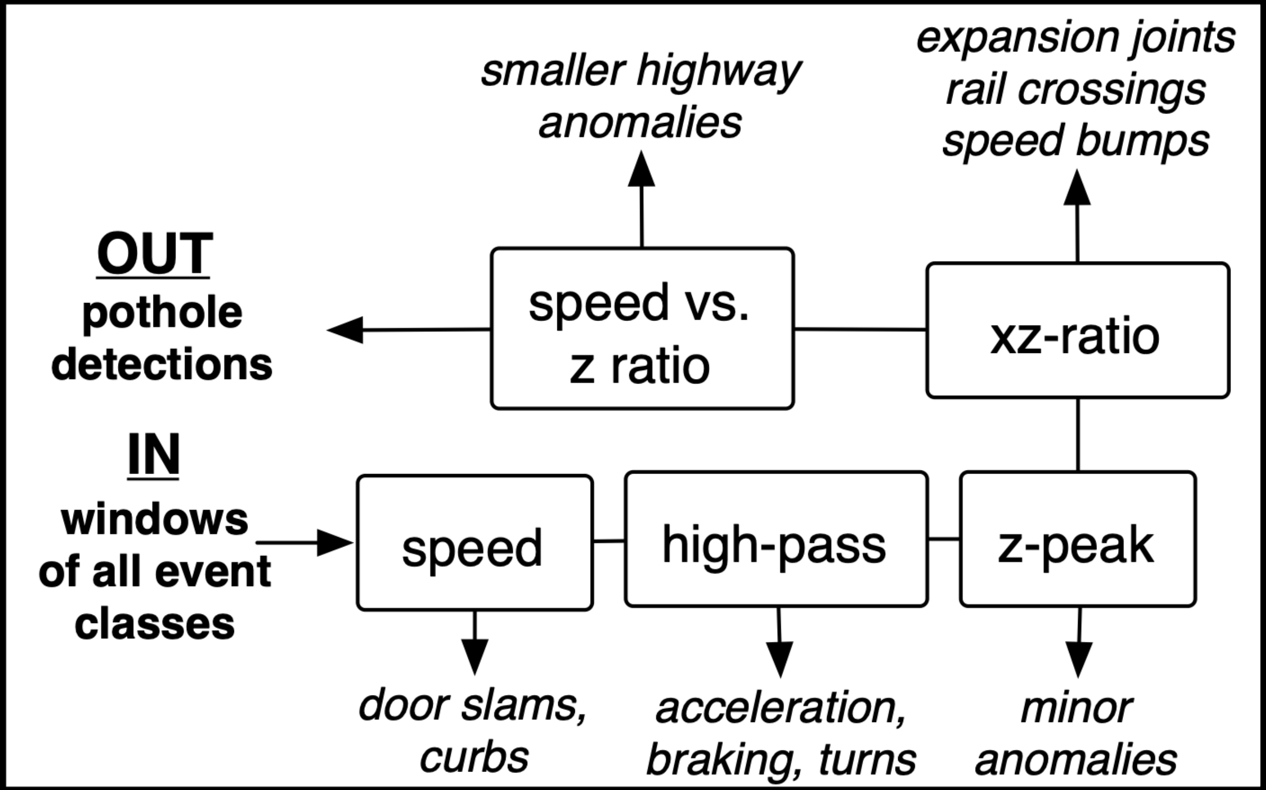
Challenge: Pothole vs “Not Pothole”



Challenge: Pothole vs “Not Pothole”



P^2 detector



Events usually of much shorter duration than 256 samples

Need to learn threshold parameters

iOS Lab 1 is out

- Topic: Develop a location app and explore the power drain vs accuracy trade-off
- Due: Mon Feb 19th, 11:59 pm

Next Lecture

- Time: Wed Feb 14th
- Topic: Applied ML for Mobile and IoT Sensing