# CMPE 185 Autonomous Mobile Robots

Perception, Sensors, and Sensor Uncertainty

Dr. Wencen Wu
Computer Engineering Department
San Jose State University

# What is Perception of Mobile Robots?

**Places / Situations**
*A specific room, a meeting situation, …*

***Servicing / Reasoning***

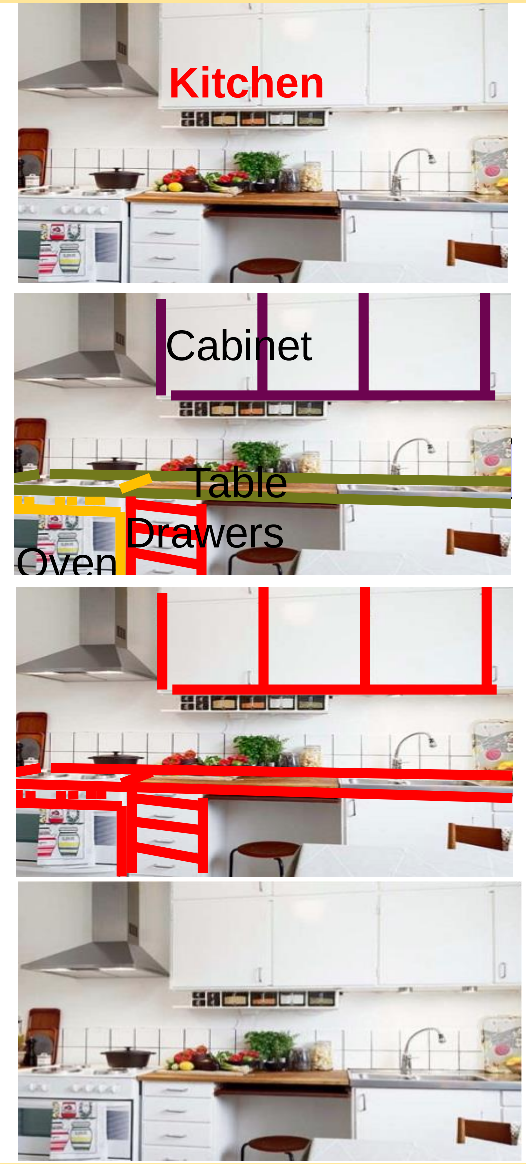
**Objects**
*Doors, Humans, Coke bottle, car , …*

***Interaction***

**Features**
*Corners, Lines, Colors, Phonemes, …*

***Navigation***

**Raw Data**
*Vision, Laser, Sound, Smell, …*



# Perception is Hard!

- **Understanding = raw data + (probabilistic) models + context**
  - Intelligent systems interpret raw data according to probabilistic models and using contextual information that gives meaning to the data.
- Dealing with real-world situations
- Reasoning about a situation

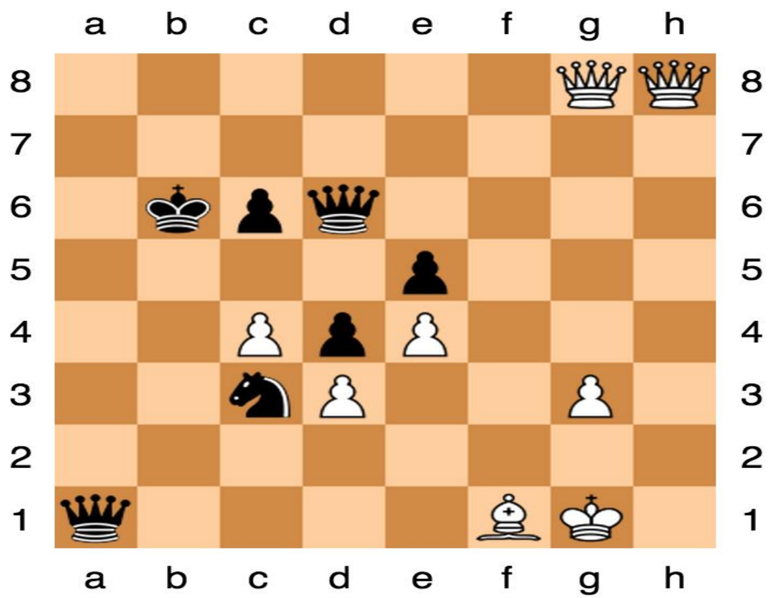
- Cognitive systems have to interpret situations based on uncertain and only partially available information

- They need ways to learn functional and contextual information (semantics / understanding)

# Perception is Hard!

- “In robotics, the easy problems are hard and the hard problems are easy”
  - S. Pinker. The Language Instinct. New York: Harper Perennial Modern Classics, 1994

beating the world’s chess master: EASY



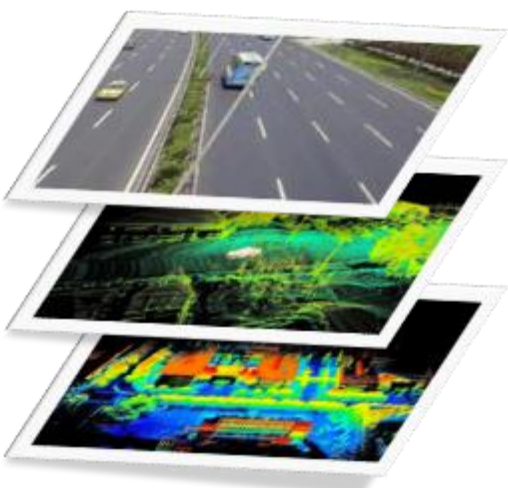

create a machine with some “common sense”: very HARD

# Example: Perception for a Self-driving Car

- Any information a self-driving car collects about itself or its environment requires sensing
- The self-driving cars that want to learn, map and/or navigate need to collect information about their surroundings
- All sensors have some degree of uncertainty
- Uncertainty can be reduced by multiple measurements.

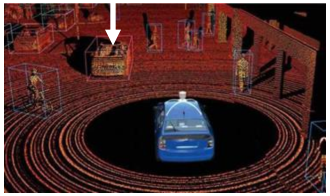
**Sensor HW**

**Sensor Fusion**



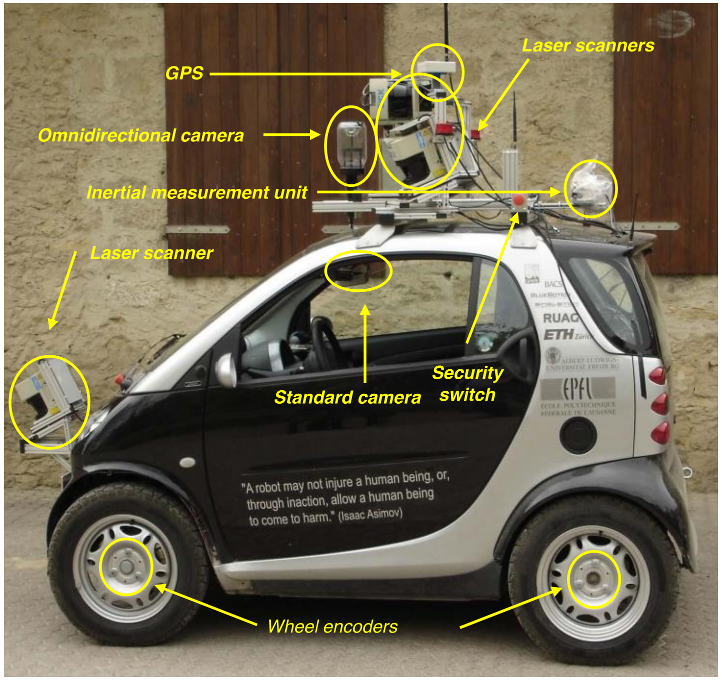
**Perception**

**Segmentation** **Classification** **Tracking**



# Common Sensors for Mobile Robots

- Wheel encoders
  - Local motion estimation (odometry)
- GPS
  - Global localization and navigation
- Inertial Measurement Unit (IMU)
  - Orientation and acceleration of the robot
- Laser scanners, Radar, Ultrasonic sensors
  - Obstacle avoidance, motion estimation, scene interpretation (road detection, pedestrians)
- Cameras
  - Texture information, motion estimation, scene interpretation
- Bumper
- …



# Classification of Sensors

- Robot = sensors + actuators
- Sensors are the key components for perceiving the environment

**What**:

- **Proprioceptive sensors**
  - measure values internally to the system (robot)
  - e.g. motor speed, wheel load, heading of the robot, battery status
- **Exteroceptive sensors**
  - information from the robots environment
  - distances to objects, intensity of the ambient light, unique features.

**How**:

- **Passive sensors**
  - Measure energy coming from the environment; very much influenced by the environment
- **Active sensors**
  - emit their proper energy and measure the reaction
  - better performance, but some influence on environment

# Classification of Sensors

| Sensor type | Sensor System | Proprioceptive (PC) or Exteroceptive (EC) | Active or Passive |
|---|---|---|---|
| Tacticle sensors | Bumbers | EC | P |
| Wheel/motor sensors | Brush encoders | PC | P |
| | Optical encoders | PC | A |
| Heading sensors | Compass | EC | P |
| | Gyroscope | PC | P |
| | Inclinometer | EC | A/P |
| Acceleration sensors | Accelerometer | PC | P |
| Beacons | GPS | EC | A |
| | Radio, ultrasonic, reflective beacons | EC | A |
| Motion/speed sensors | Doppler: radar or sound | EC | A |
| Range sensors | Ultrasound, laser rangefinder, structured light, time of flight | EC | A |
| Vision sensors | CCD/CMOS cameras | EC | P |

# Camera

- The images obtained from cameras are very useful for recognizing the environment around the robot
  - Object recognition, facial recognition
  - Depth information obtained from the difference between two images using two cameras (stereo camera)
  - Mono camera visual SLAM
  - Color recognition

# Camera

- Cheap
- Highest resolution
- Detect color and fonts

- Huge data → deep learning
- Bad at depth estimation
- Not good in extreme weather

# Range Sensors

- Measure relative distance (range) between sensor and objects in environment
- Range information is the key element for localization and environment modeling
- Most range sensors are active sensors
- Range sensor make use of propagation speed of sound or electromagnetic waves respectively

# Range Sensors

- Common types of range sensors
  - Sonar (ultrasonic sensor, SOund Navigation Ranging)
  - Radar (RAdio Detection And Ranging)
  - Lidar (Light Detection And Ranging , Laser range finder)
  - Infrared (IR)
  - Etc.

# Range Sensors

- Distance traveled by a wave is given by

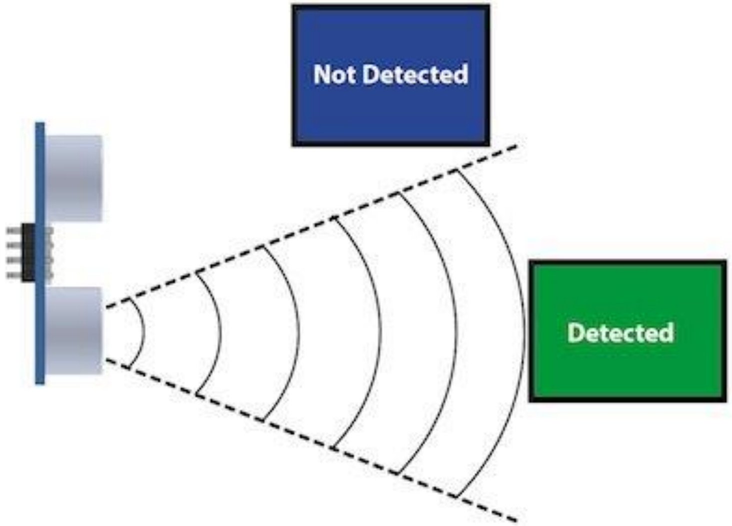
$$d = ct$$

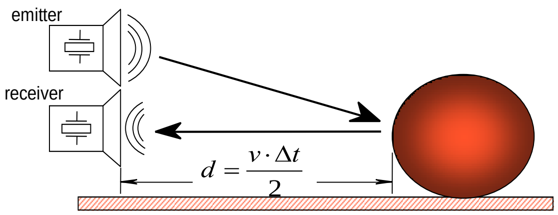
  - *d*: distance traveled (usually round-trip)
  - *c* = speed of wave propagation
  - *t* = time of flight

- For sound, *v = 0.3 m/ms*
- For electromagnetic signals, *v = 0.3 m/ns* (one million times faster than sound)
- If distance = 3m:
  - $t_{ultrasonic}$= 10ms
  - $t_{laser}$ = 10 ns
  - $t_{laser}$ is difficult to measure, laser range sensors are expensive and difficult

# Range Sensors -- Sonar (Ultrasonic Sensor)

- Range between 12cm up to 5m
- Resolution of ~2cm
- Relative error 2%
- Sound beam propagates in a cone (approx.)
  - opening angles around 20 to 40 degrees




<http://www.robot-electronics.co.uk/shop/Ultrasonic_Rangers1999.htm>

# Range Sensors -- Sonar (Ultrasonic Sensor)

- Main characteristics
  - Precision influenced by angle to object
  - Useful in ranges from several cm to several meters
  - Typically relatively inexpensive

- Applications
  - Distance measurement (also for transparent surfaces)
  - Collision detection

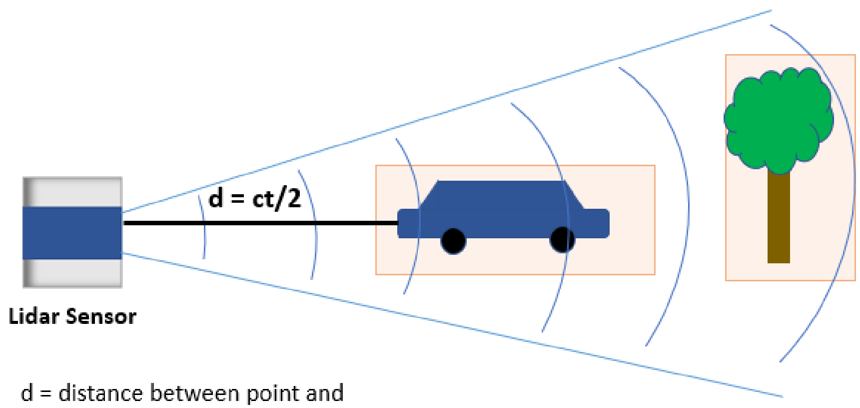
# Range Sensor: Infrared (IR)

- Active proximity sensor
- Emit near-infrared energy and measure amount of IR light returned
- Range: inches to several feet, depending on light frequency and receiver sensitivity
- Typical IR: constructed from LEDs, which have a range of 3-5 inches
- Challenges:
  - Light can be “washed out” by bright ambient lighting
  - Light can be absorbed by dark materials

# Range Sensors – LiDAR


## Lidar (Light Detection And Ranging , Laser range finder)

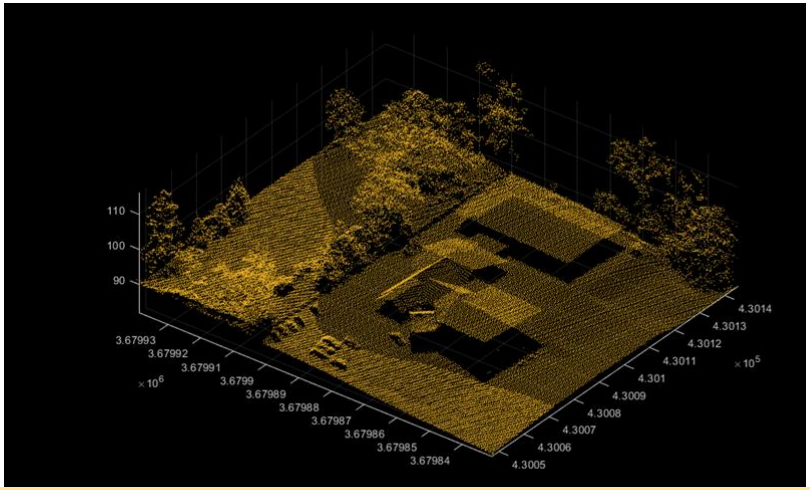
- Lidar is an active remote sensing system that uses laser light to measure the distance of the sensor from objects in a scene
  - Emits laser pulses
  - Time-of-flight principle




d = distance between point and the sensor
c = speed of light
t = time of flight

# Range Sensors – LiDAR

- A Lidar sensor stores the reflected laser pulses, or laser returns, as a collection of 3D points **– a point cloud**
- A Lidar sensor captures attributes to generate a 3D map of an environment
  - The location in xyz-coordinates
  - The intensity of the laser light
  - The surface normal at each point of a point cloud



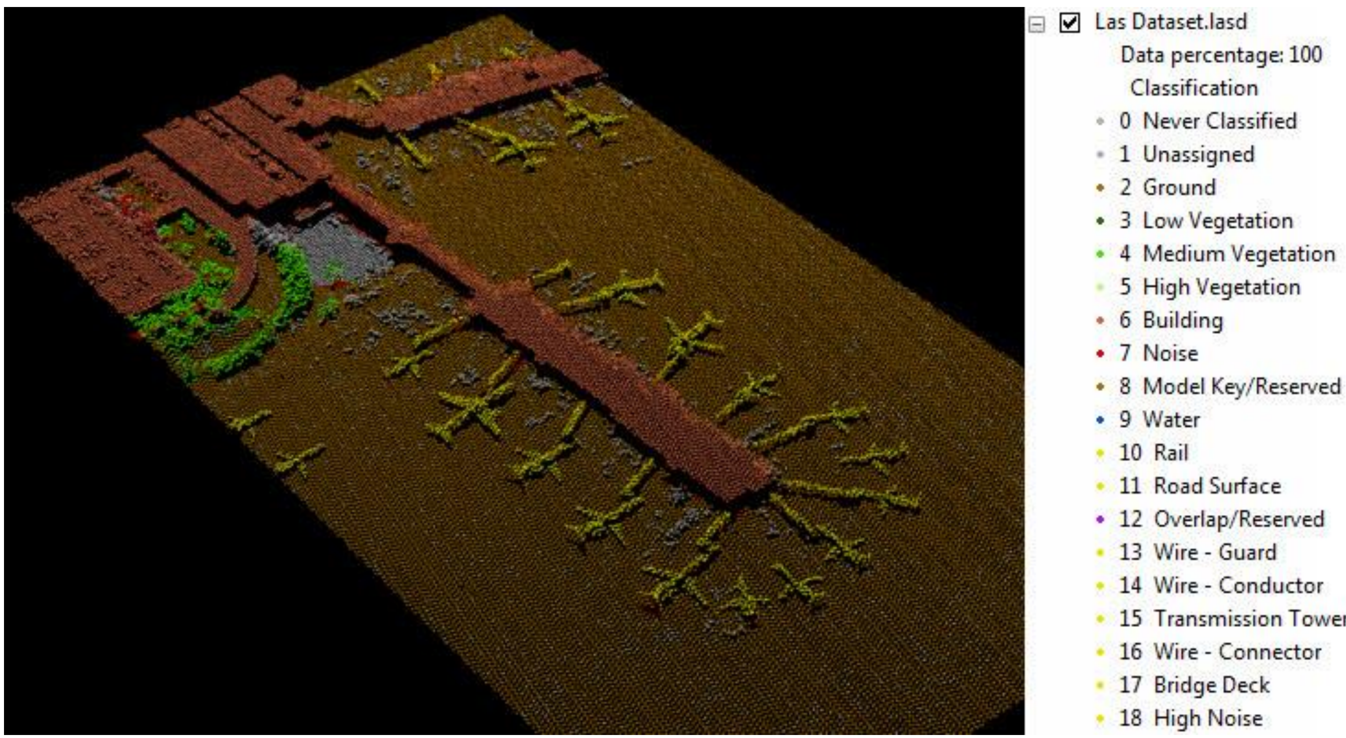
# Lidar Point Attributes

| Lidar attribute | Description |
|---|---|
| Intensity | The return strength of the laser pulse that generated the lidar point. |
| Return number | An emitted laser pulse can have up to five returns depending on the features it is reflected from and the capabilities of the laser scanner used to collect the data. The first return will be flagged as return number one, the second as return number two, and so on. |
| Number of returns | The number of returns is the total number of returns for a given pulse. For example, a laser data point may be return two (return number) within a total number of five returns. |
| Point classification | Every Lidar point that is post-processed can have a classification that defines the type of object that has reflected the laser pulse. Lidar points can be classified into a number of categories including bare earth or ground, top of canopy, and water. The different classes are defined using numeric integer codes in the **LAS files**. |
| Edge of flight line | The points will be symbolized based on a value of 0 or 1. Points flagged at the edge of the flight line will be given a value of 1, and all other points will be given a value of 0. |
| RGB | Lidar data can be attributed with RGB (red, green, and blue) bands. This attribution often comes from imagery collected at the same time as the Lidar survey. |
| GPS time | The GPS time stamp at which the laser point was emitted from the aircraft. The time is in GPS seconds of the week. |
| Scan angle | The scan angle is a value in degrees between -90 and +90. At 0 degrees, the laser pulse is directly below the aircraft at nadir. At -90 degrees, the laser pulse is to the left side of the aircraft, while at +90, the laser pulse is to the right side of the aircraft in the direction of flight. Most Lidar systems are currently less than ±30 degrees. |
| Scan direction | The scan direction is the direction the laser scanning mirror was traveling at the time of the output laser pulse. A value of 1 is a positive scan direction, and a value of 0 is a negative scan direction. A positive value indicates the scanner is moving from the left side to the right side of the in-track flight direction, and a negative value is the opposite. |

A LAS file is an industry-standard binary format for storing airborne lidar data.

# Lidar Point Classification

- Every Lidar point can have a classification assigned to it that defines the type of object that has reflected the laser pulse
- Classification codes were defined by the American Society for Photogrammetry and Remote Sensing (ASPRS) for LAS formats 1.1, 1.2, 1.3, and 1.4. ArcGIS supports all versions of LAS

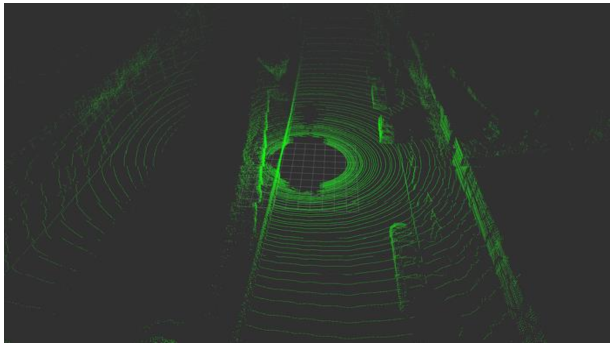



https://desktop.arcgis.com/en/arcmap/10.3/manage-data/las-dataset/lidar-point-classification.htm

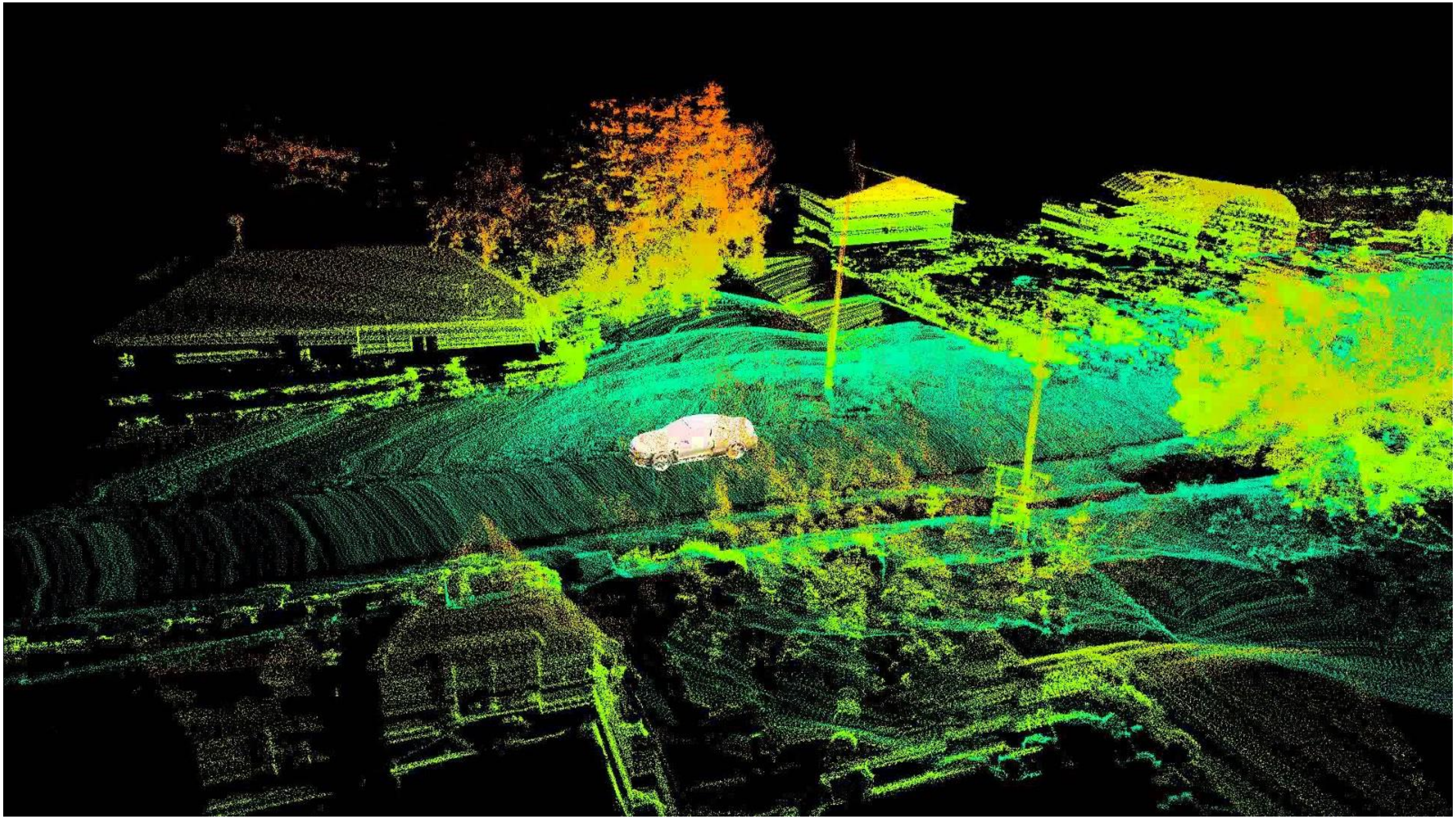
# Range Sensors – LiDAR

Lidar (Light Detection And Ranging , Laser range finder)

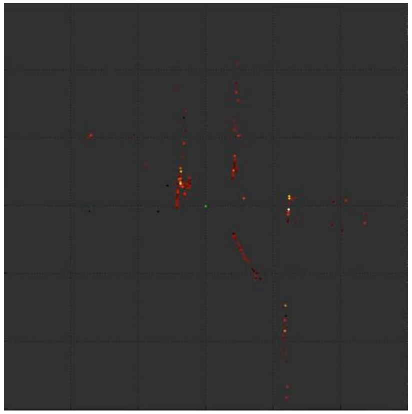
- The Velodyne HDL-64E uses 64 laser emitters.
  - turn-rate up to 15 Hz
  - The field of view is 360° in azimuth and 26.8° in elevation
  - Angular resolution is 0.09° and 0.4° respectively
  - Delivers over **1.3 million data points per second**
  - The distance accuracy is better than 2 cm and can measure **depth** up to 50 m
  - Expensive

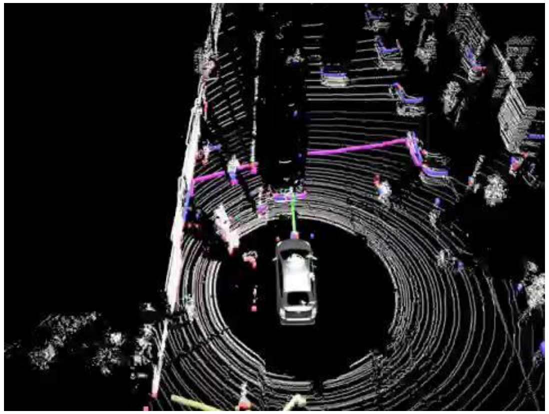
# How does the world look like in the eyes of an Autonomous Vehicle



# Range Sensors -- Radar v.s. LiDAR



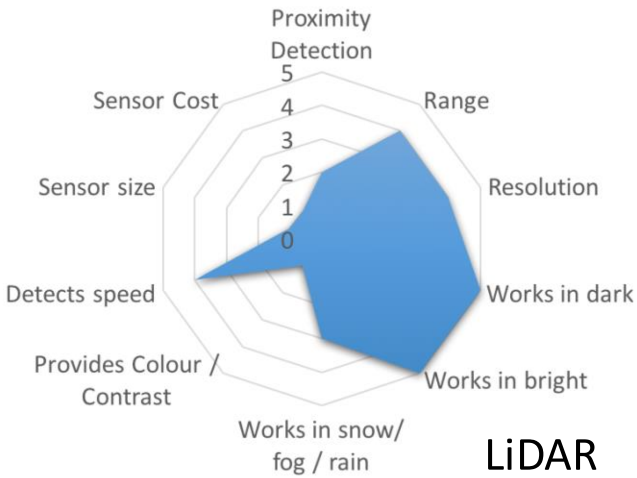
v.s



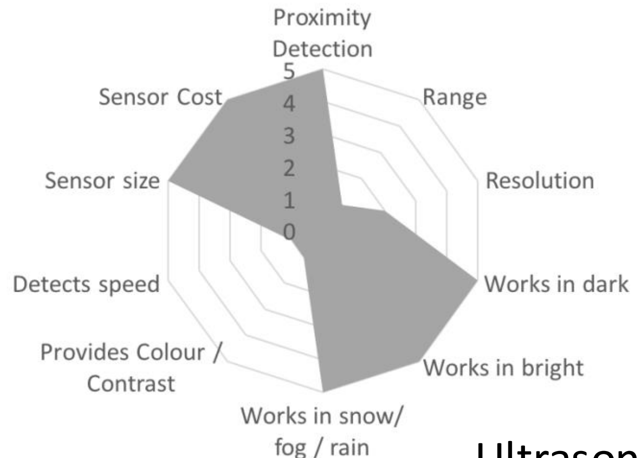
- Cheap
- Does well in extreme weather, i.e., rain, fog, snow
- Low resolution
- Most used automotive sensor for object detection and tracking

- Expensive
- Extremely accurate depth information
- Resolution much higher than radar
- 360 degrees of visibility
- Does poorly in rain, fog, snow…

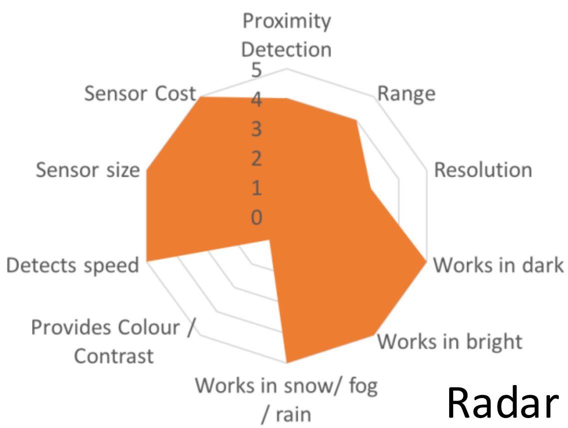
# Sensor Comparisons



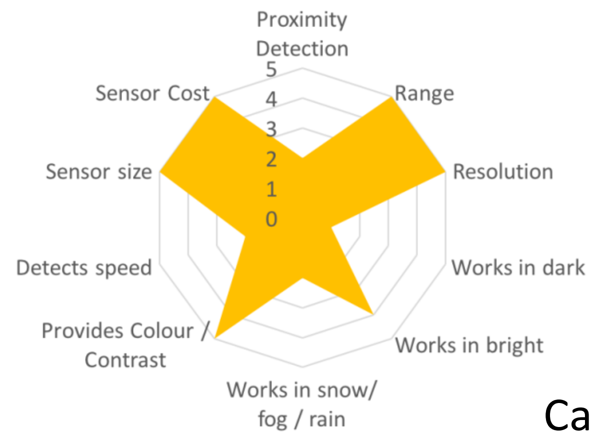

LiDAR




Ultrasonic



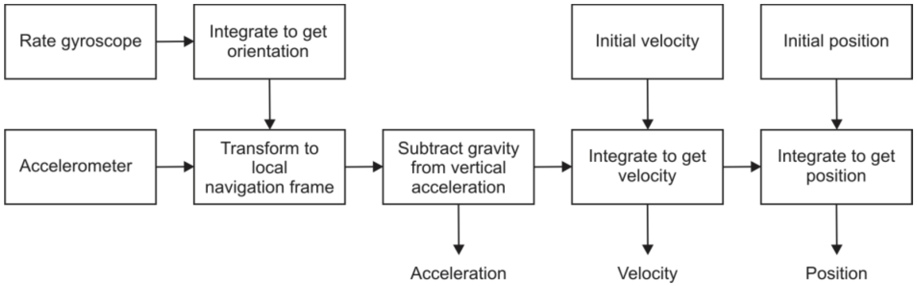

Radar

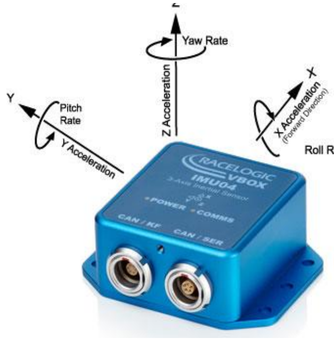



Camera

# Inertial Measurement Unit (IMU)

- An Inertial Measurement Unit (IMU) is a combination of sensors that uses **gyroscopes**, **accelerometers** and sometimes **magnetometers** to estimate the linear and angular motion of a moving vehicle with respect to an inertial frame, and the earth’s magnetic field.
- In order to estimate the motion, the gravity vector must be subtracted and the initial velocity has to be known
- After long periods of operation, drifts occurs: need external reference to cancel it

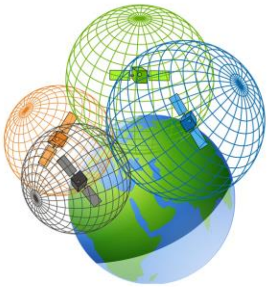


# Global Positioning System (GPS)

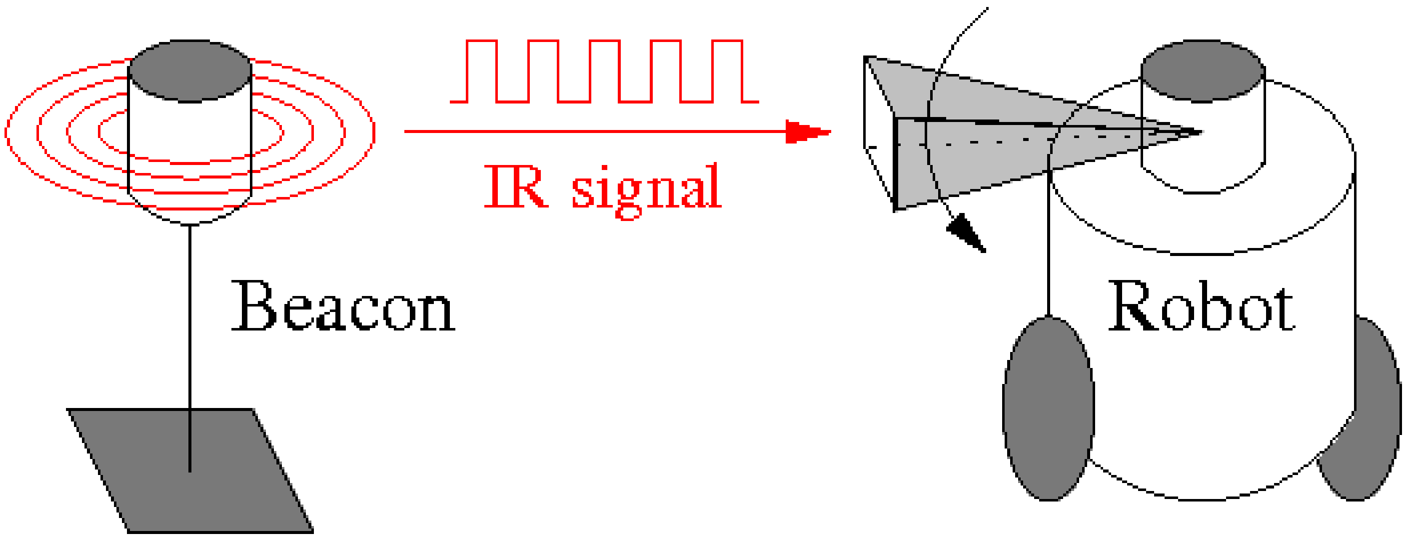
- Regular GPS, can get accuracy 10 – 15cm
- With a second receiver of known location, differential GPS (i.e.g, DGPS) can resolve down to 1 m.
- Carrier-phase can get resolution down to 1 cm.

- Robot GPS receiver:
  - Triangulates relative to signals from 4 satellites
  - Outputs position in terms of latitude, longitude, altitude, and change in time



# Ground-Based Beacon Systems

- Used for localization
- Used by humans (e.g., stars, lighthouses)
- Beacons can be active or passive
- Known location of beacons allows localization
- Problem is that they are not flexible



# Other Types of Sensors

- Odor sensors
  - Detection of chemical compounds and their density in an area
  - A lot of applications, e.g., mine detection

- Touch sensors (tactile sensors)
  - Whiskers, bumpers etc.
  - mechanical contact leads to
    - closing/opening of a switch
    - change in resistance of some element
    - change in capacitance of some element
    - change in spring tension
    - Etc…

- Temperature sensor
- Light sensor
- …

# Sensors: Basic Characteristics

- Range
  - Lower and upper limits
  - E.g., IR range sensor measures distance between 10 and 80cm

- Resolution
  - Minimum difference between two measurements
  - For digital sensors, it is usually the A/D resolution

$$\text{e.g.}\ \frac{5V}{255(8\ bit)} = 0.02V$$

# Sensors: Basic Characteristics

- Dynamic range
  - Used to measure spread between lower and upper limits of sensor inputs
  - Formally, it is the ratio between the maximum and minimum measurable input, usually in decibels (dB)

$$Dynamic\ Range = 10\log[\frac{UpperLimit}{LowerLimit}]$$

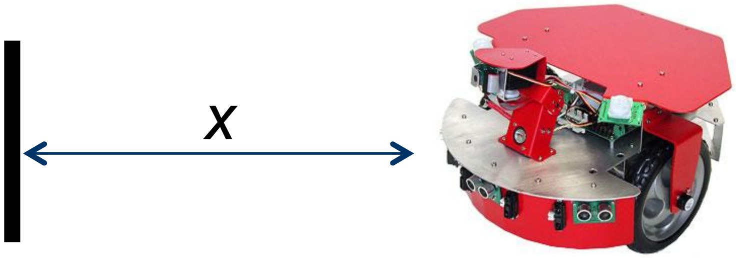
  - E.g., A sonar range sensor measures up to a max distance of 3m, with smallest measurement of 1cm

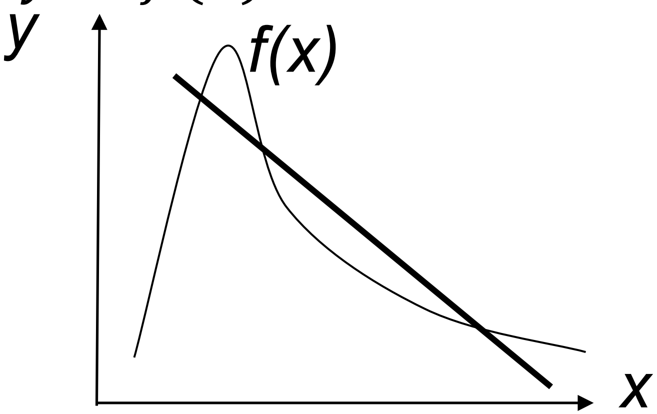
$$Dynamic\ Range = 10\log[\frac{3}{0.01}]$$

$$= 24.8dB$$

# Sensors: Basic Characteristics

- Linearity
  - A measure of how linear the relationship between the sensor's output signal and input signal
  - Linearity is less important when signal is treated after with a computer
- Linearity example
  - Consider the range measurement from an IR range sensor
  - Let x be the actual measurement in meters, let y be the output from the sensor in volts, and $y = f(x)$



# Sensors: Basic Characteristics

- Bandwidth or Frequency
  - The speed with when a sensor can provide a stream of readings
  - Usually there is an upper limit depending on the sensor and the sampling rate
    - e.g., sonar takes a long time to get a return signal
  - Higher frequencies are desired for autonomous control
    - e.g., if a GPS measurement occurs at 1 Hz and the autonomous vehicle uses this to avoid other vehicles that are 1 meter away
- Sensitivity
  - Ratio of output change to input change
    - E.g., range sensor will increase voltage output 0.1 V for every cm distance measured

# Sensors: Basic Characteristics

- Accuracy
  - The difference between the sensor’s output and the true value (i.e., $error = m - v$)

$$accuracy = 1 - \frac{|m - v|}{v}$$

m = measured value

v = true value

- Precision
  - The reproducibility of sensor results

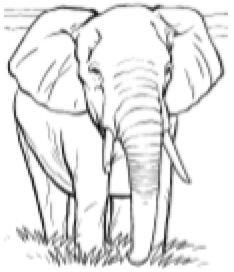
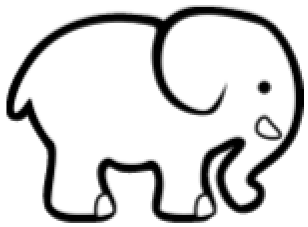
$$precision = \frac{range}{\sigma}$$

$\sigma$ = standard deviation

# Sensors: In Situ Characteristics

- Random Error
  - Non-deterministic
  - Not predictable
  - Usually described probabilistically


- Systematic Error
  - Deterministic
  - Caused by factors that can be modeled, e.g., optical distortion in camera

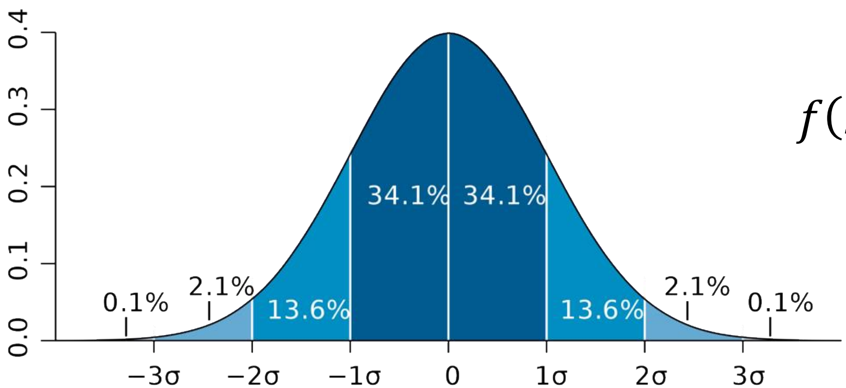
# Sensors: In Situ Characteristics

- Measurements in the real-world are dynamically changing and error-prone
  - Changing illuminations
  - Light or sound absorbing surfaces

- Systematic versus random errors are not well-defined for mobile robots
  - There is a cross-sensitivity of robot sensor to robot pose and environment dynamics
  - Difficult to model, appear to be random

# Sensor Uncertainty

- How can it be represented?
  - With probability distributions
- Representation
  - Describe measurement as a random variable *X*
  - Given a set of *n* measurements with values $\rho_l$
  - Characterize statistical properties of *X* with a probability density function *f(x)*




$$f(x) = \frac{1}{\sigma\sqrt{2\pi}} \exp\left[\frac{-(x-\mu)^2}{2\sigma^2}\right]$$

# Sensor Uncertainty

- Expected value of X is the mean $\mu$

$$\mu = E[X] = \int_{-\infty}^{\infty} xf(x)\,dx \Rightarrow \mu = E[X] = \frac{\sum^{n} x}{n}$$

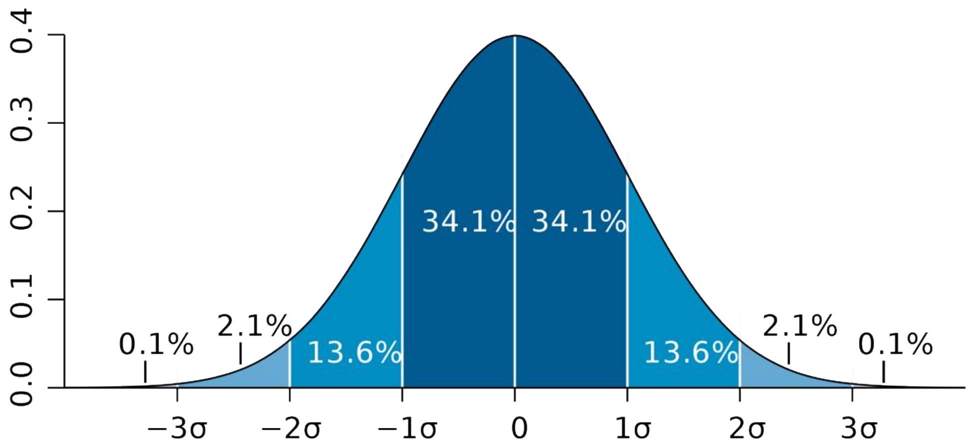
- The variance of $X$ is $\sigma^2$

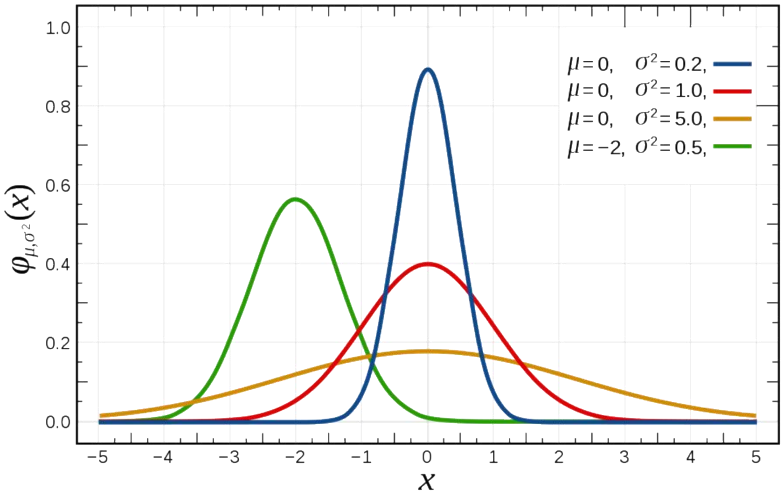
$$\sigma^2 = Var(X) = \int_{-\infty}^{\infty} (x-\mu)^2 f(x)\,dx \Rightarrow \sigma^2 = Var(X) = \frac{\sum^{n} (x-\mu)^2}{n}$$

# Sensor Uncertainty

- Use a Gaussian Distribution

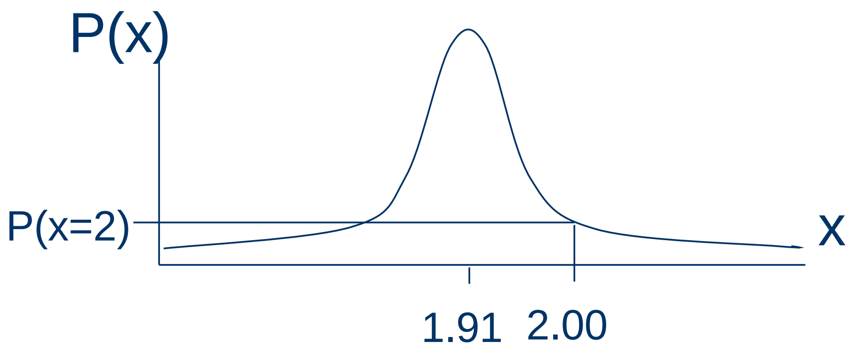
$$f(x) = \frac{1}{\sigma\sqrt{2\pi}} \exp[\frac{-(x-\mu)^2}{2\sigma^2}]$$



# Sensor Uncertainty

- How do we use the Gaussian?
  - Learn the variance of sensor measurements ahead of time
  - Assume mean measurement is equal to actual measurement
- Example:
  - If a robot is 1.91 meters from a wall, what is the probability of getting a measurement of 2 meters?
  - Answer: if the sensor error is modeled as a Gaussian, we can assume the sensor has the following probability distribution




  - Then, use the distribution to determine $\mathrm{P}(x = 2)$

- Thank you!