# ELEC 3210
# Introduction to Mobile Robotics
# Lecture 4

**(Machine Learning and Infomation Processing for Robotics)**


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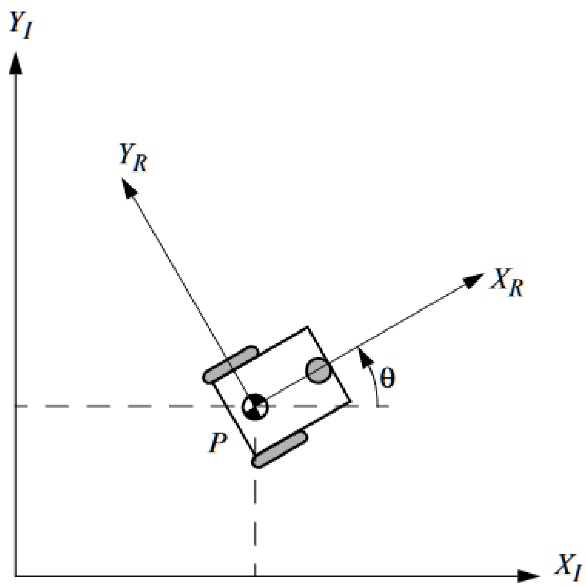
# Where am I?

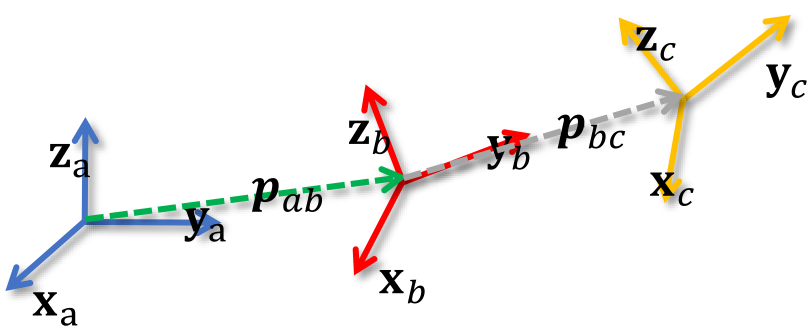
- A question with long history
- Solutions
  - Odometry and Dead Reckoning
  - Global Positioning System (GPS)
  - Map-based localization
  - Simultaneous localization and mapping (SLAM)
  - etc. (like wifi-based)

# L3 - Wheel Odometry

- Lecture 3
- From wheel spinning speed to odometry-based localization




$$
\begin{aligned}
\dot{\mathbf{X}}_I &= R(\theta)^{-1}\dot{\mathbf{X}}_R \\
&= R(\theta)^{-1}\begin{bmatrix} \frac{r\dot{\varphi}_1}{2} + \frac{r\dot{\varphi}_2}{2} \\ 0 \\ \frac{r\dot{\varphi}_1}{2l} + \frac{-r\dot{\varphi}_2}{2l} \end{bmatrix}
\end{aligned}
$$

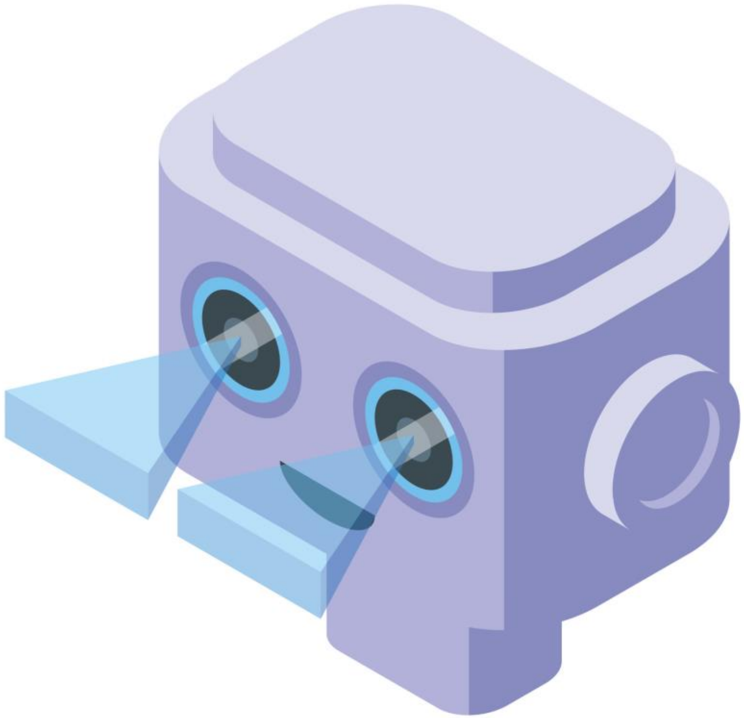


# Wheel Odometry Fails

- Drift occurs using wheel odometry
  - wheel slip etc.
  - uncertainties in the external world
  - we need robot perception and mapping

Courtesy:

# Sensors



# Sensors

# Sensors for Mobile Robots

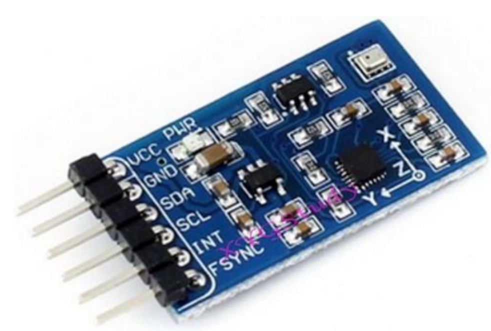
- **Interoceptive**: being stimuli arising within the body
  - accelerometer
  - gyroscope

- **Exteroceptive**: activated by stimuli received by an organism from outside
  - global positioning system (GPS)
  - camera
  - laser range finder

Courtesy: State Estimation for Robotics

# Interoceptive Sensors

- Accelerometer
  - measure translational accerlation
- Gyroscope
  - measure angular rate
- Inertial measurement unit (IMU)
  - Linear acceleration
  - Angular velocity

# IMU

- Pros
  - Almost always available and outlier-free
  - Very high-rate measurements
  - Very mature technology, widely available at very low cost
  - Remarkable performance improvement during aggressive motions
- Cons
  - Noisy sensor, cannot double integrate to obtain position
  - Synchronization and inter-sensor calibration requirements
  - Unable to operate when inertial and visual measurements are not in the same frame (e.g. on cars or trains)


Courtesy: Shaojie Shen

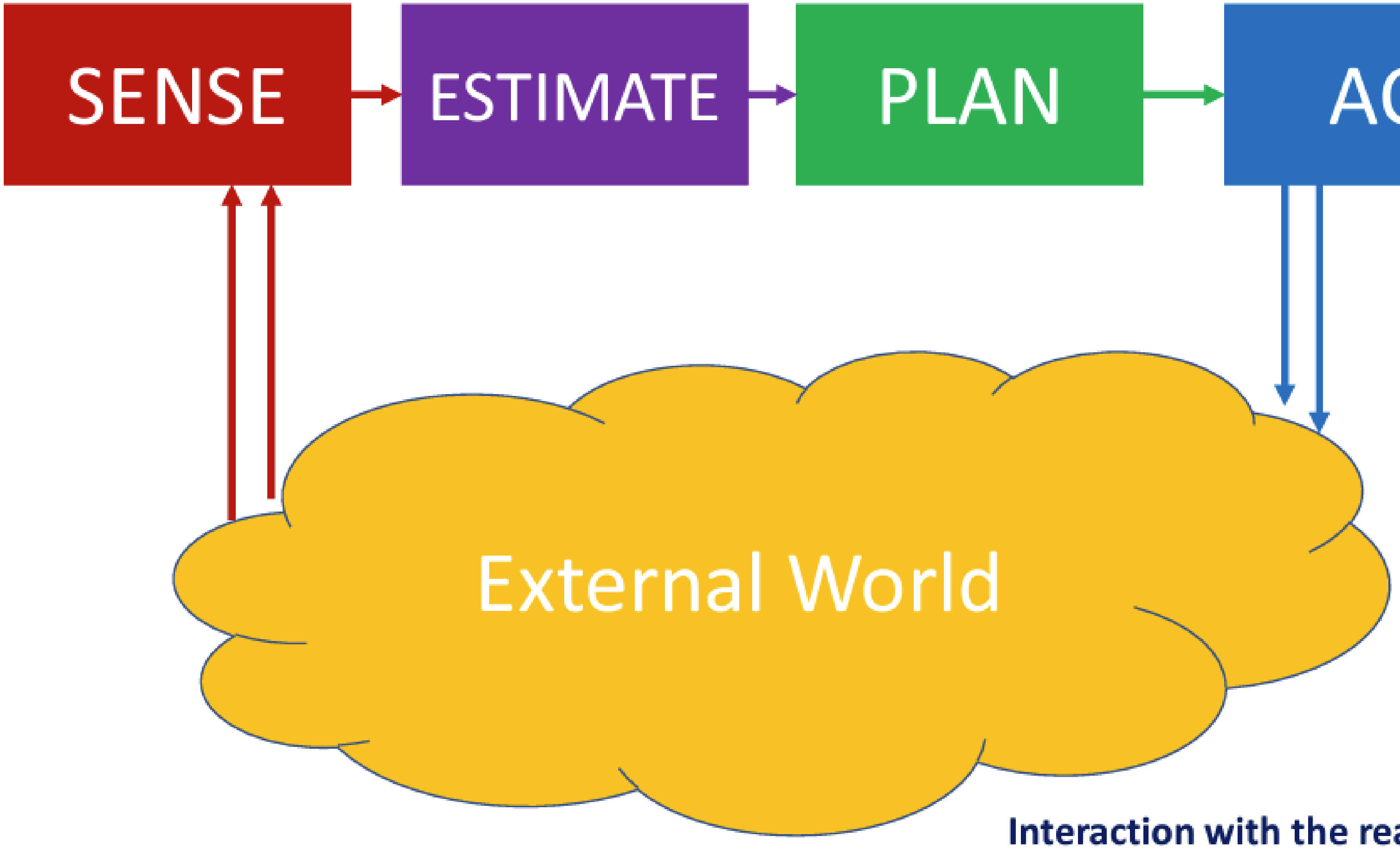
# IMU Demo

- 3D Tracking with IMU (Odometry-based)

Courtesy: SebMadgwickResearch on YouTube

# Back to Scheme

- Interaction with external world




**Interaction with the real world introduces uncertainty!**

Courtesy: Nikolay Atanasov

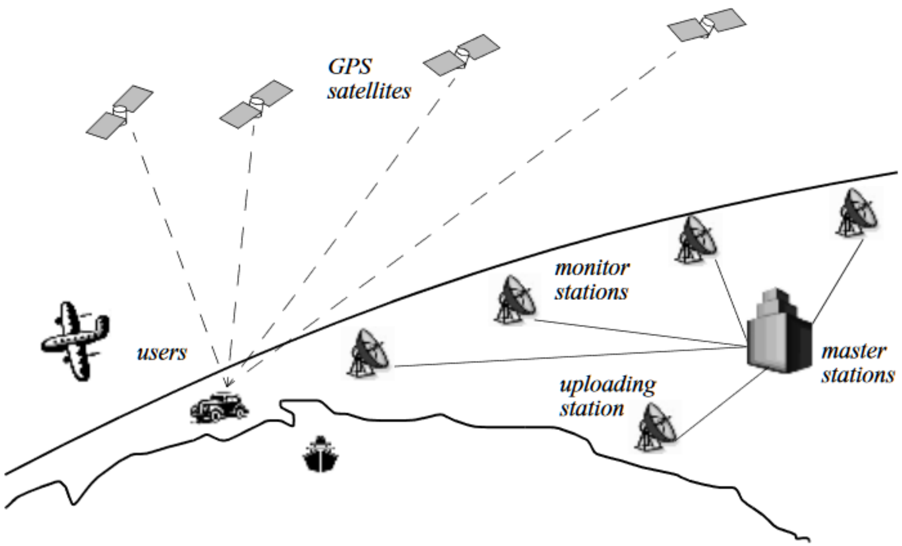
# Exteroceptive Sensors

# Exteroceptive Sensors

- GNSS
- Camera
  - Monocular
  - Stereo
- Range Sensors
  - 2D Laser
  - 3D LiDAR
  - Radar
- RGBD

# GNSS

- Global navigation satellite systems
- United States' Global Positioning System (GPS)
  - Commercial used error < 10m



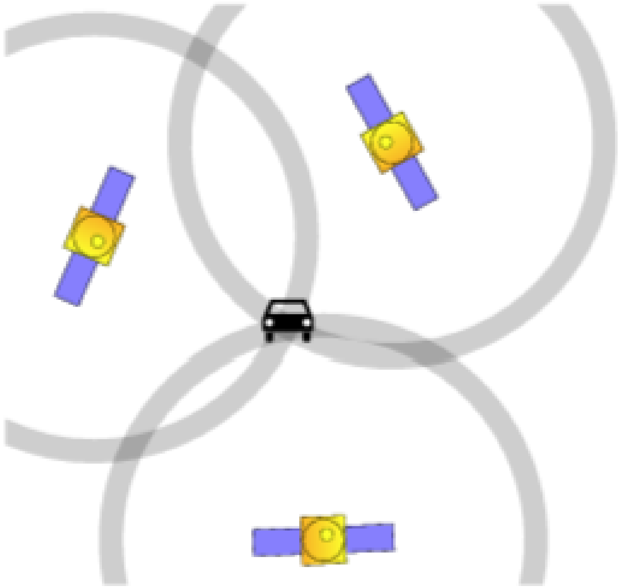


Courtesy: Introduction to Autonomous Mobile Robots

# GPS

- Non-direct range-based localization
- Satellite position is known by transmiting ephemeris parameters which describe its orbit
- c: speed of light

$$\mathbf{x} = (x, y, z)^\top \qquad \rho = c \cdot (t_{\text{recieve}} - t_{\text{transmit}})$$

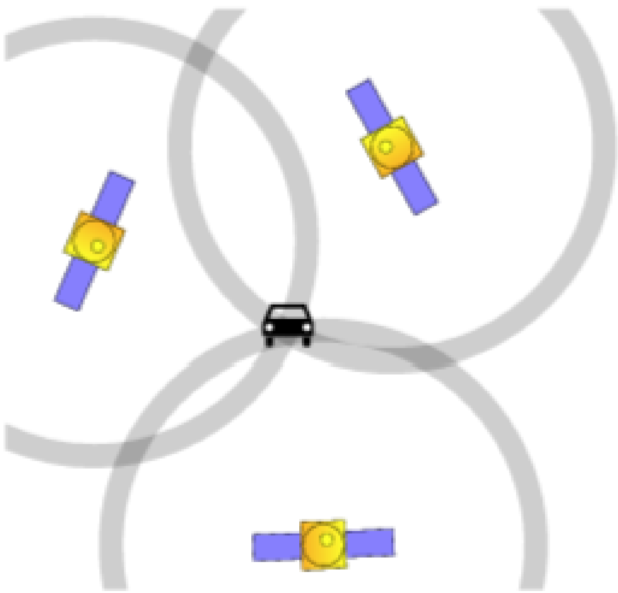


Courtesy: Niko Sünderhauf

# GPS

- Considering the receiver clock error
- Need at least four satellites to estimate the position

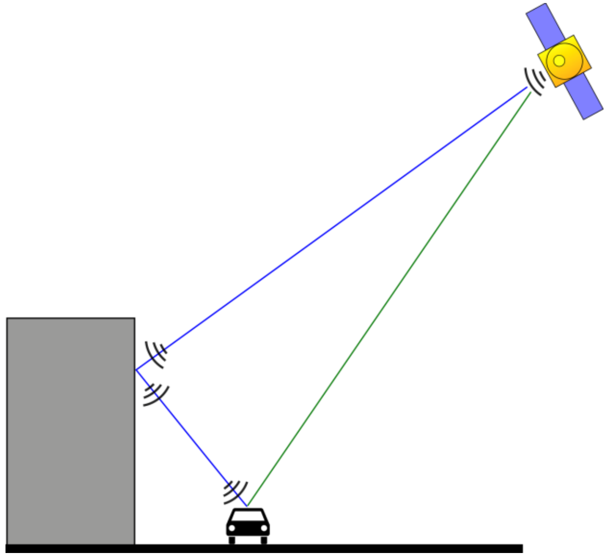
$$\mathbf{x} = (x, y, z, \delta_{\text{clock}})^\top$$



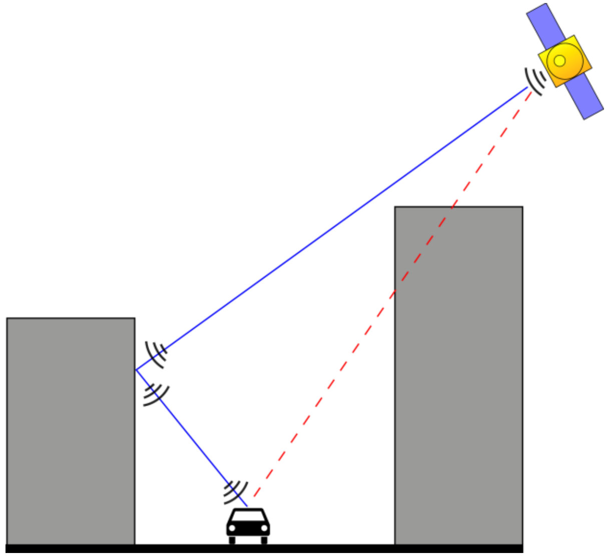
Courtesy: Niko Sünderhauf

# Multipath

- GPS-unfriendly/denied Areas
  - Urban, Forest, Park, Indoor, tunnel etc



**Received a second time**

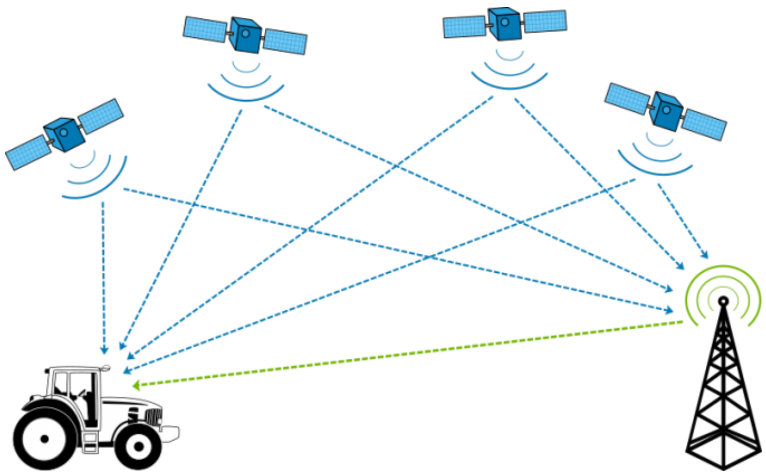


**Received a reflection**

Courtesy: Niko Sünderhauf

# Differential-GPS

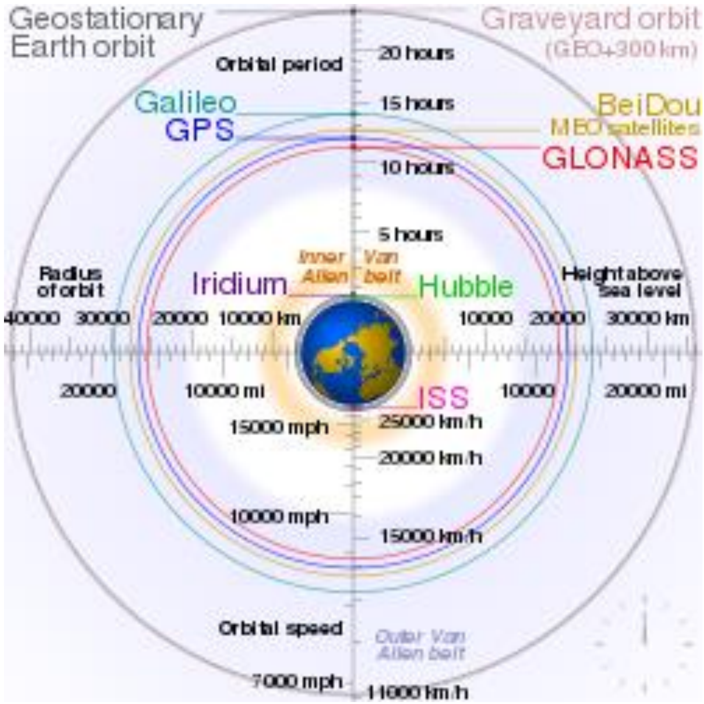
- Corrections sent by ground-based reference stations
- Accuracy: 1~3 meter



**Marine Department, HK**

# Other Countries and Regions

- Beidou (China)
- Galileo (Europe)
- GLONASS (Russia)
- NavIC (India)
- etc

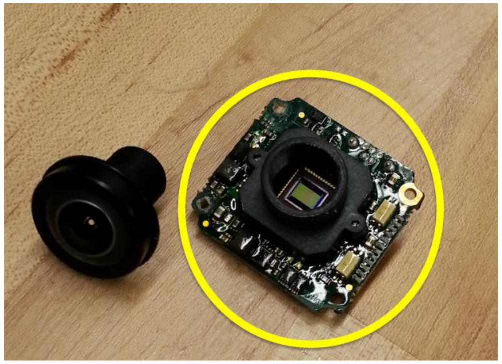


# Exteroceptive Sensors

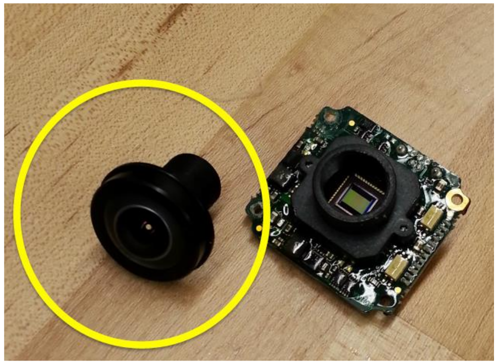
- GNSS ☑
- Camera
  - Monocular
  - Stereo
- Range Sensors
  - 2D Laser
  - 3D LiDAR
  - Radar
- RGB-D

# Camera - Monocular

- Simplest setup
- Depth unknown



**Sensor**

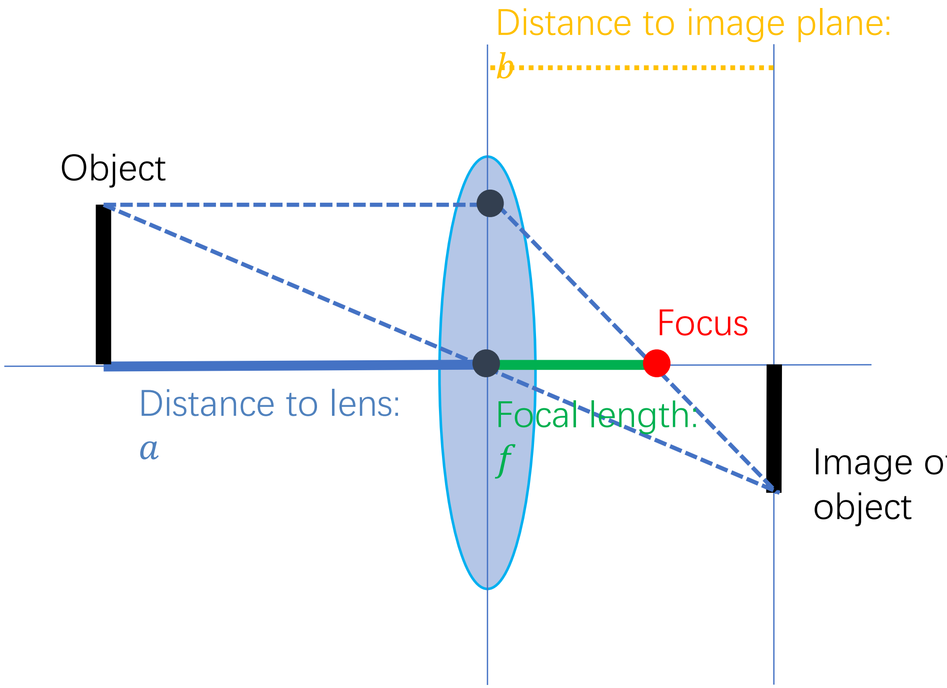


**Lens**

Courtesy: Shaojie Shen

# Lens

- Rays parallel to the optical axis meet focus after leaving the lens
- Rays through center of the lens do not change direction

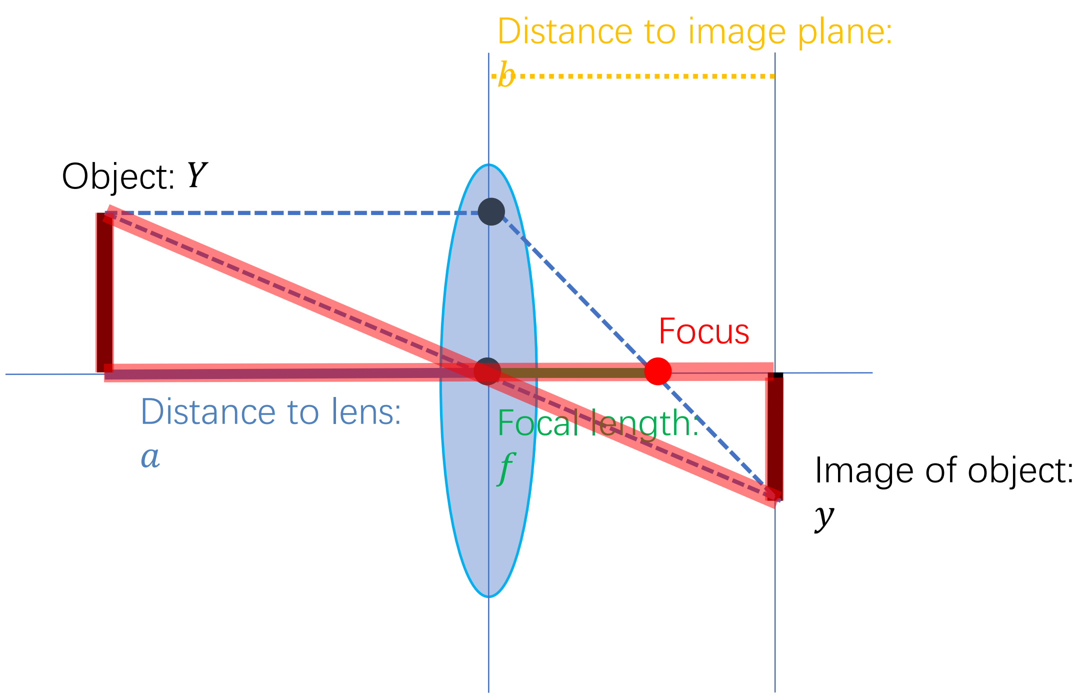



$$\frac{1}{f} = \frac{1}{a} + \frac{1}{b}$$

Courtesy: Shaojie Shen

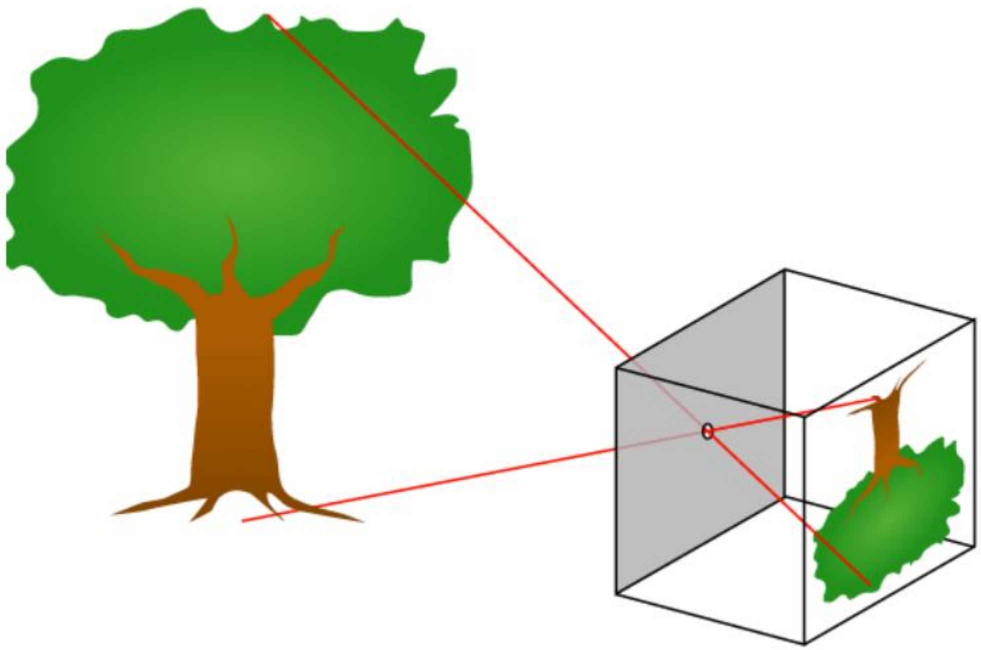
# Perspective Projection

- The object comes closer, the image becomes bigger
- A point moving on the same ray does not change its image
- If we only look at rays going through center of the lens:
- $\frac{Y}{a} = \frac{y}{b}$




Courtesy: Shaojie Shen

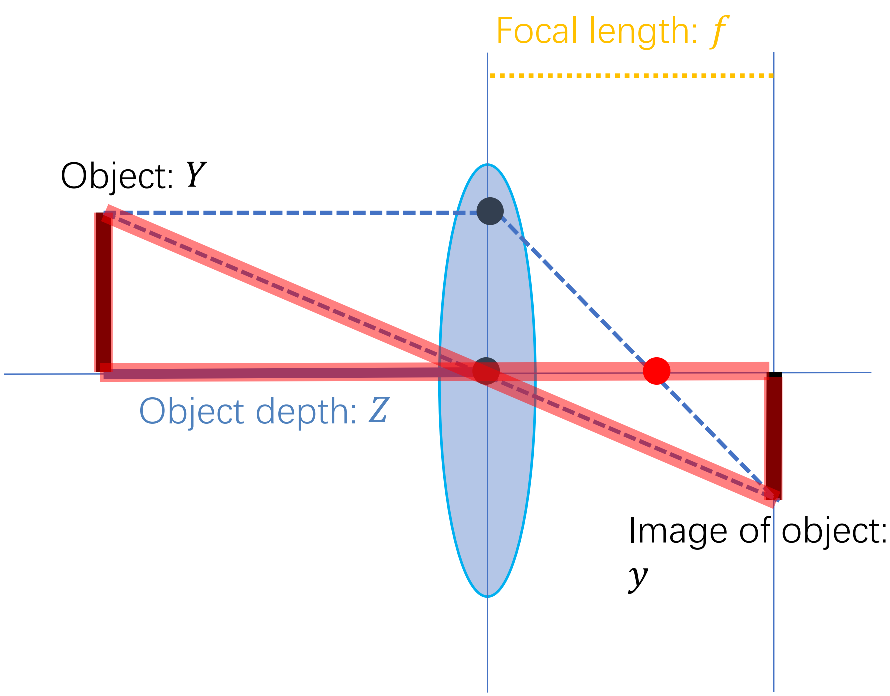
# Pin-hole Camera Model



Courtesy: Wikipedia

# Pin-hole Camera Model

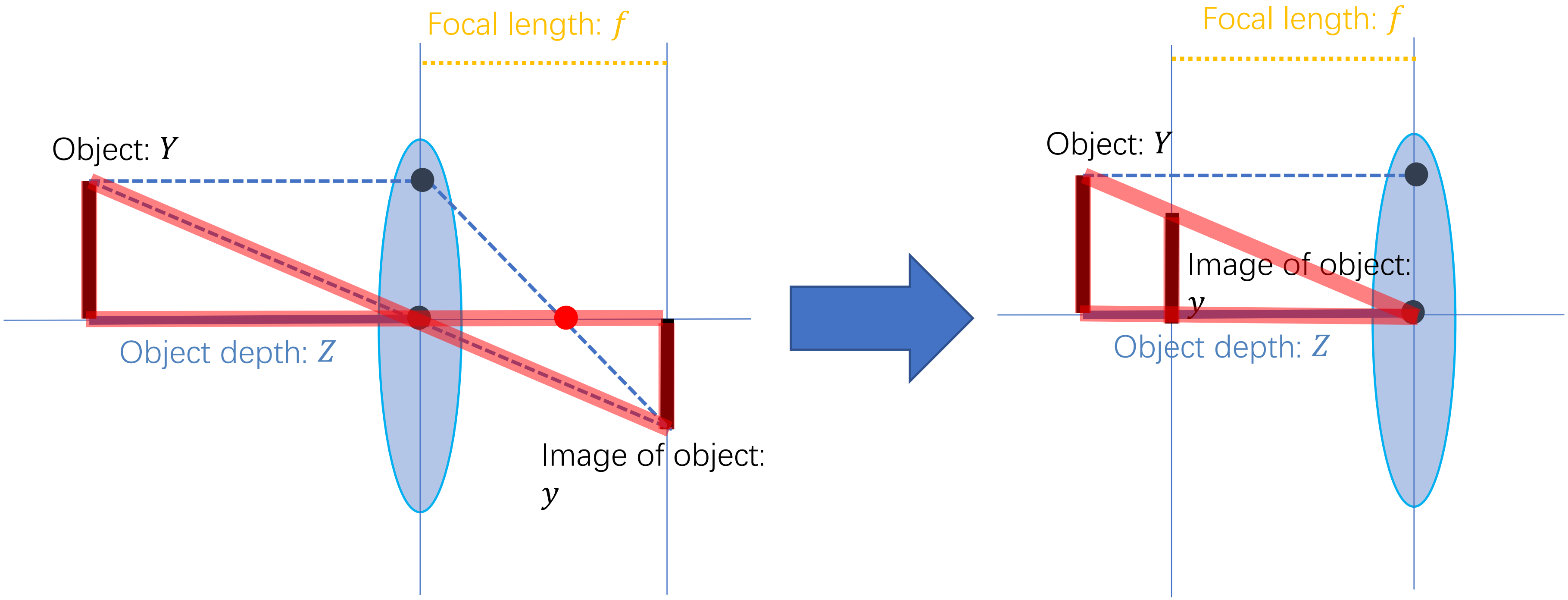
- If we replace $b$ with $f$ and include a minus because the object image is upside down $(Z = a, f = b)$
- $y = -f\frac{Y}{Z}$




Courtesy: Shaojie Shen

# Pin-hole Camera Model

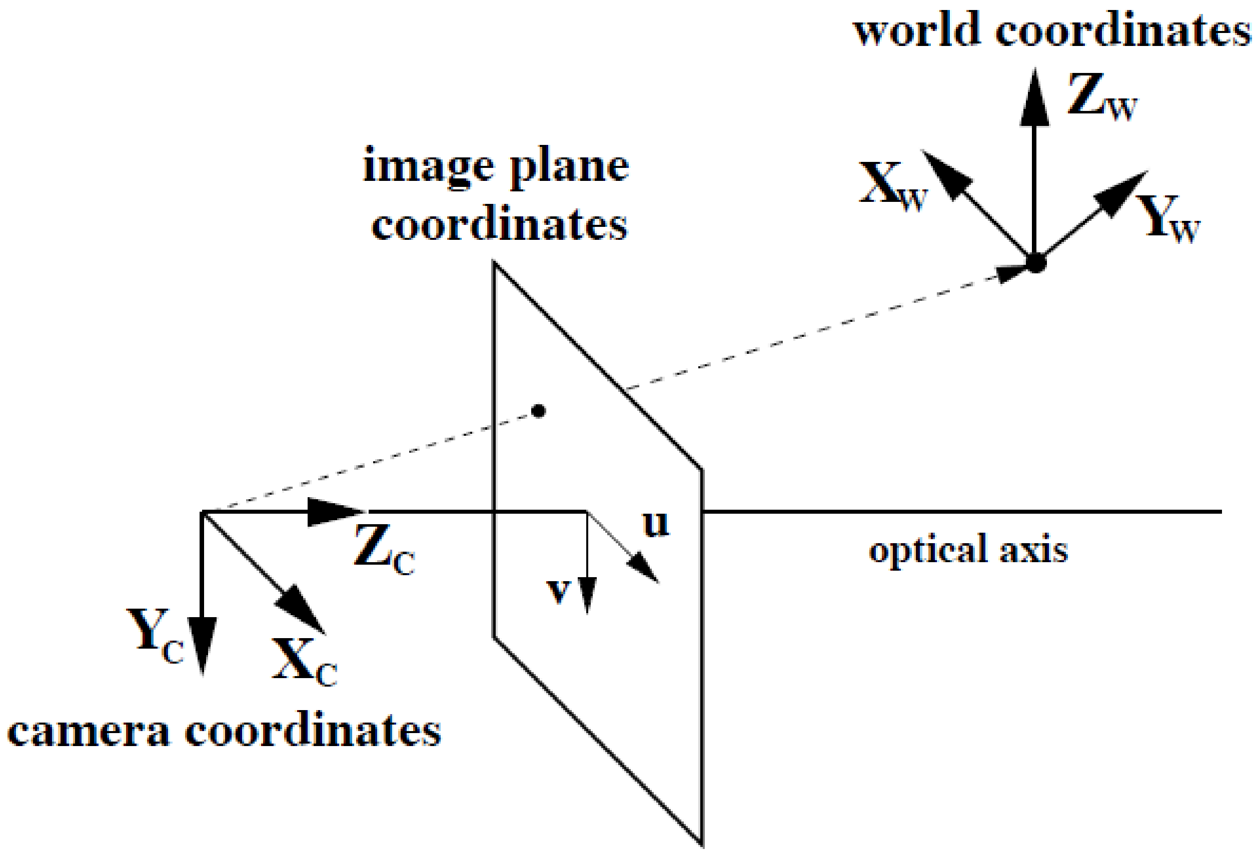
- Assume that the image plane is in front of the lens:
- $y = f\frac{Y}{Z}$




Courtesy: Shaojie Shen

# Camera Coordination System

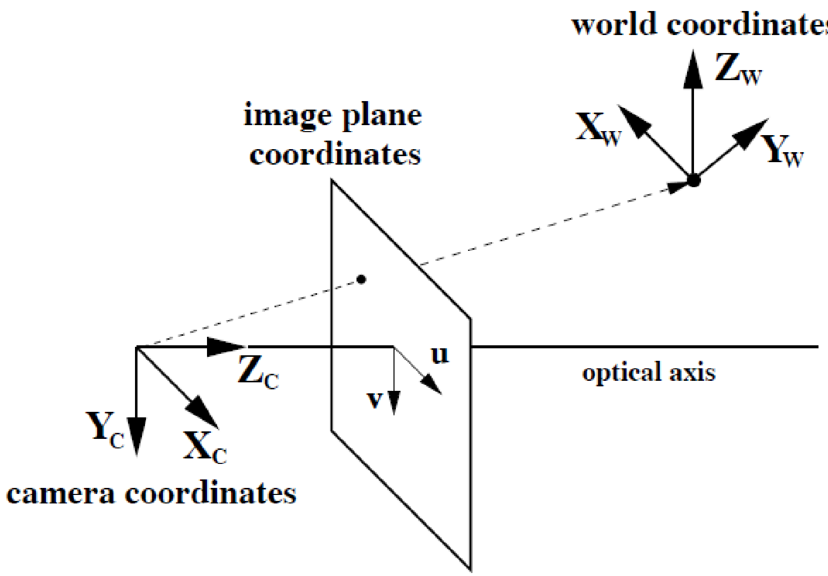
- How a point is shown in image plane?




Courtesy: Kostas Daniilidis

# Perspective Projection

- Optical axis is the z-axis
- The image plane $(u, v)$ is perpendicular to the optical axis
- **Translation of Origin:** Intersection of the image plane and the optical axis is the image center $(u_0, v_0)$
- **Rescale image plane:** $f$ is the distance of the image plane from the origin (in pixels)
- Formation:
  - $u = \frac{fX_c}{Z_c} + u_0$
  - $v = \frac{fY_c}{Z_c} + v_0$

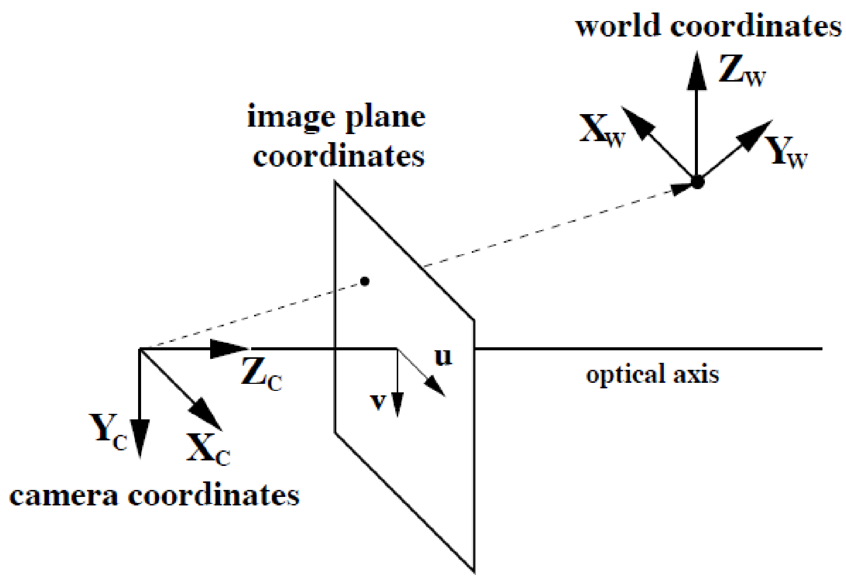



Courtesy: Shaojie Shen and Huan Yin

# Perspective Projection

- Matrix form:

$$\lambda \begin{pmatrix} u \\ v \\ 1 \end{pmatrix} = \begin{pmatrix} f & 0 & u_o \\ 0 & f & v_o \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \end{pmatrix} \begin{pmatrix} X_c \\ Y_c \\ Z_c \\ 1 \end{pmatrix}$$

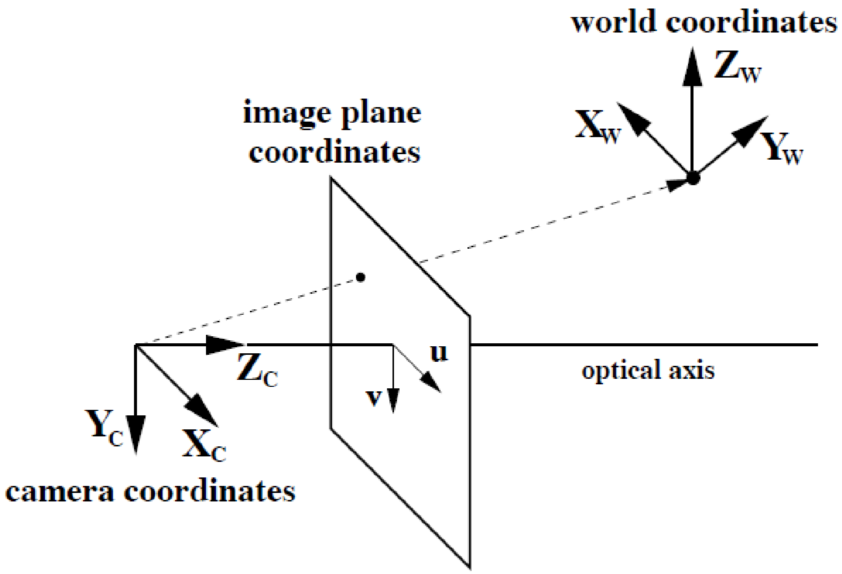



Courtesy: Shaojie Shen

# Perspective Projection

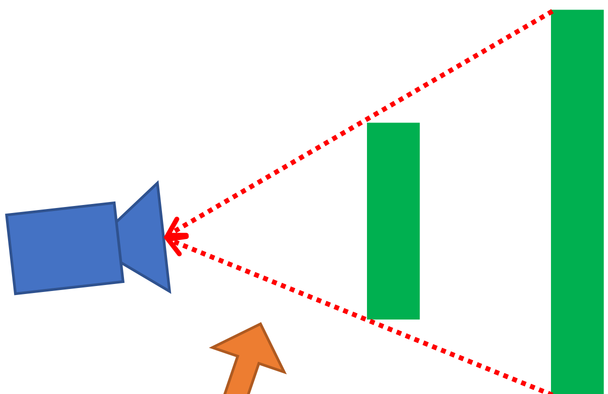
- From camera to world:

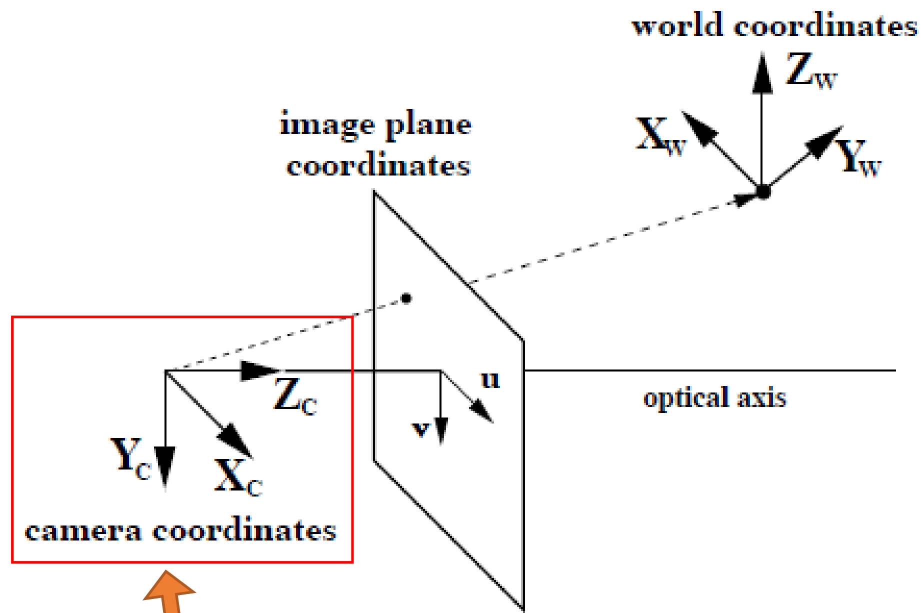
$$\begin{pmatrix} X_c \\ Y_c \\ Z_c \\ 1 \end{pmatrix} = \begin{pmatrix} R & t \\ 0 & 1 \end{pmatrix} \begin{pmatrix} X_w \\ Y_w \\ Z_w \\ 1 \end{pmatrix}$$




Courtesy:

# Pin-hole Camera Model






$$\boxed{\lambda}\boxed{\begin{pmatrix}u\\v\\1\end{pmatrix}} = \boxed{\begin{pmatrix} f & 0 & u_o\\ 0 & f & v_o\\ 0 & 0 & 1\end{pmatrix}}\boxed{\begin{pmatrix}R & t\end{pmatrix}}\boxed{\begin{pmatrix}X_w\\Y_w\\Z_w\\1\end{pmatrix}} = P\begin{pmatrix}X_w\\Y_w\\Z_w\\1\end{pmatrix}$$

Unknown Depth

Pixel Values

Intrinsic Calibration Matrix

Camera Pose

World Point

Courtesy: Shaojie Shen

# Resources

- Prof. Cyrill Stachniss's *Camera Basics and Propagation of Light*

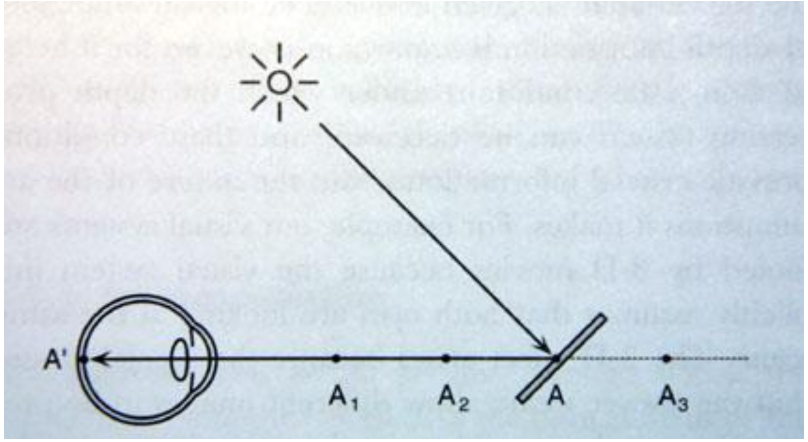

Courtesy: Cyrill Stachniss

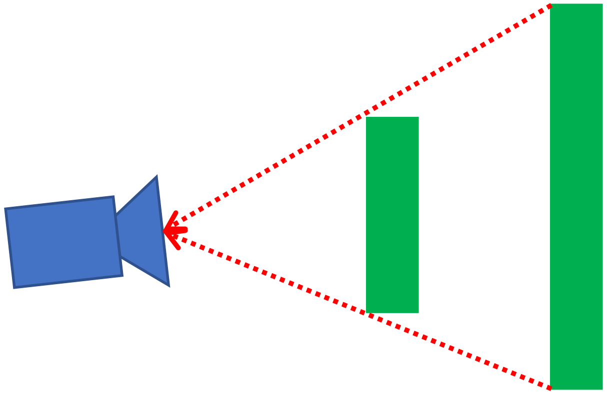
# Exteroceptive Sensors

- GNSS ☑
- Camera ☑
  - Monocular ☑
  - Stereo
- Range Sensors
  - 2D Laser
  - 3D LiDAR
  - Radar
- RGB-D

# Depth Ambiguity

- Inverse Problem
  - multiple solution exists

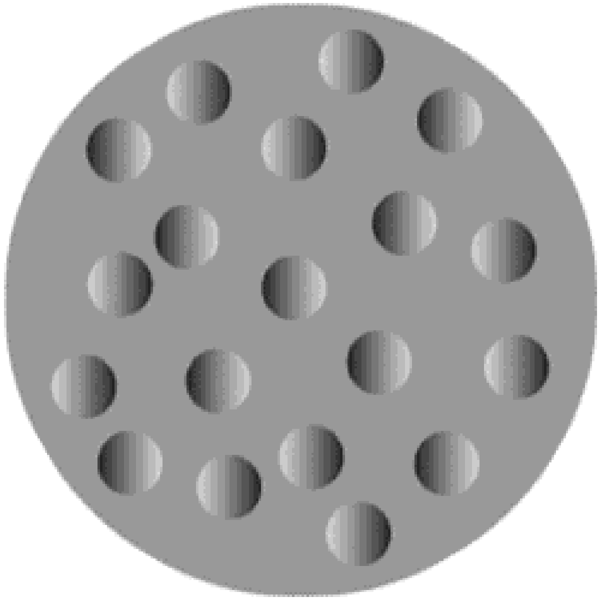


Courtesy: Shaojie Shen

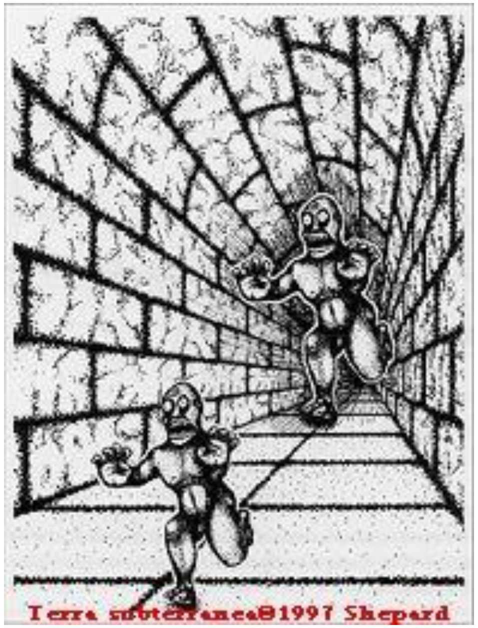
# Pictorial cues for 3D shape

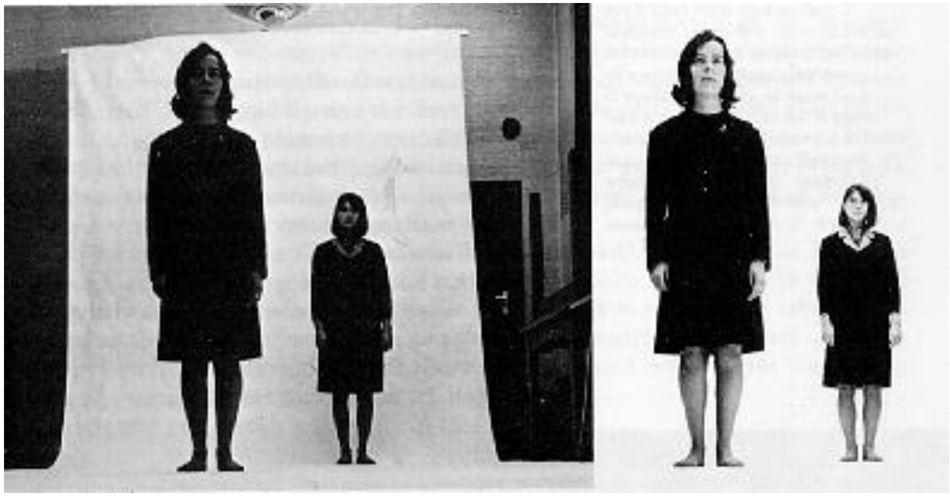
- Perspective projection gives us the relative position to horizon, therefore we can deduce its physical size
- Shading also reveal shape using illumination model



Courtesy: Shaojie Shen

# Pictorial cues for 3D shape



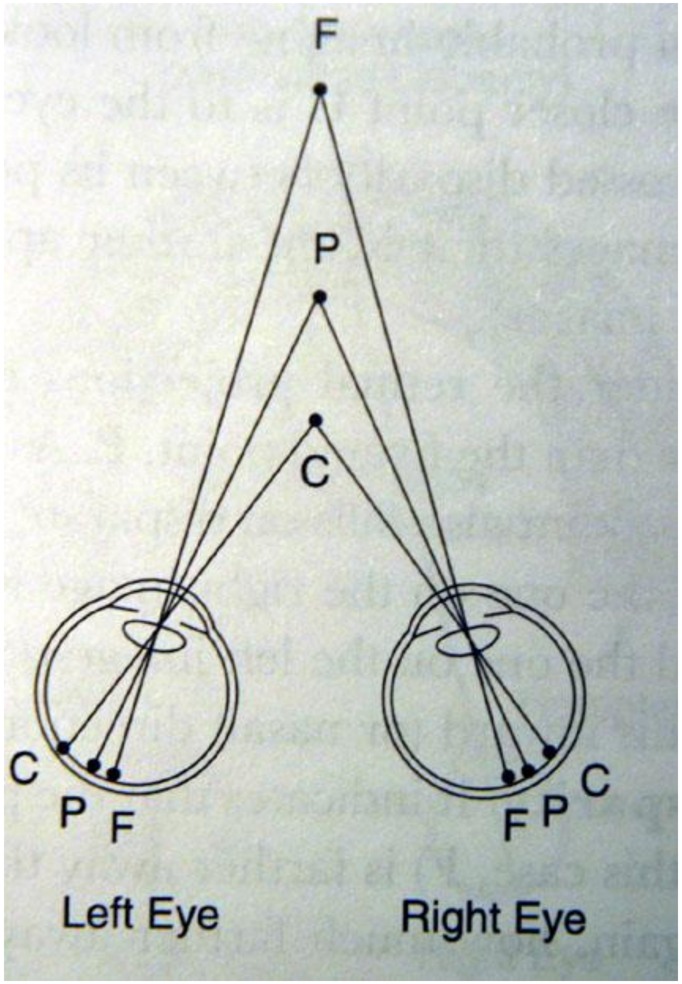
Courtesy: Shaojie Shen, Kostas Daniilidis

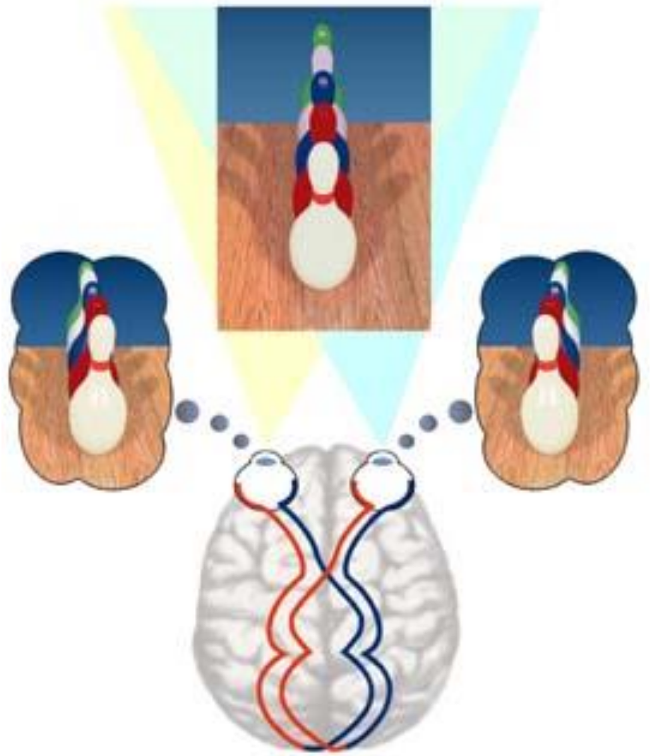
# Camera - Stereo

- Able to compute depth
- Depth accuracy affected by baseline, resolution, and calibration


Courtesy: Shaojie Shen

# Stereo Vision of Humans

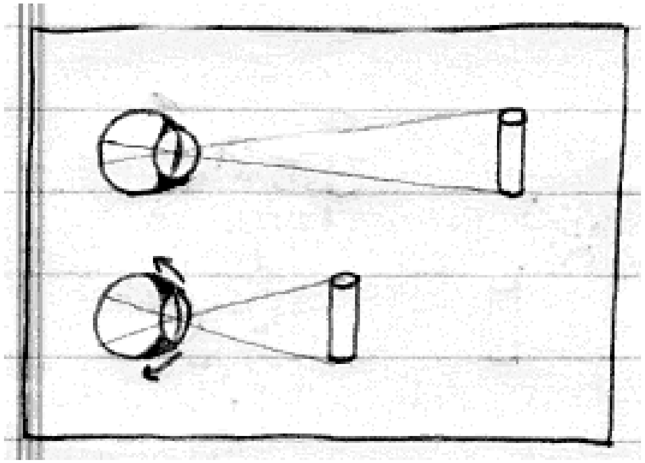


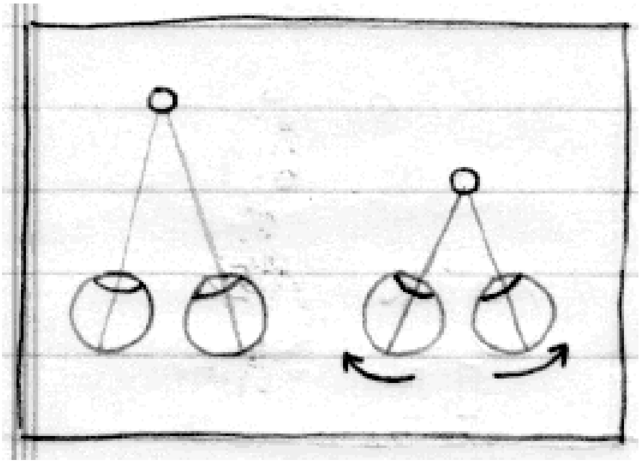
Courtesy: Shaojie Shen, Kostas Daniilidis

# Accommodation & Convergence

- **Accommodation** and **convergence** normally change in lock steps. For human, they are important sources of depth information at close distance.
- Human performance: up to a few meters



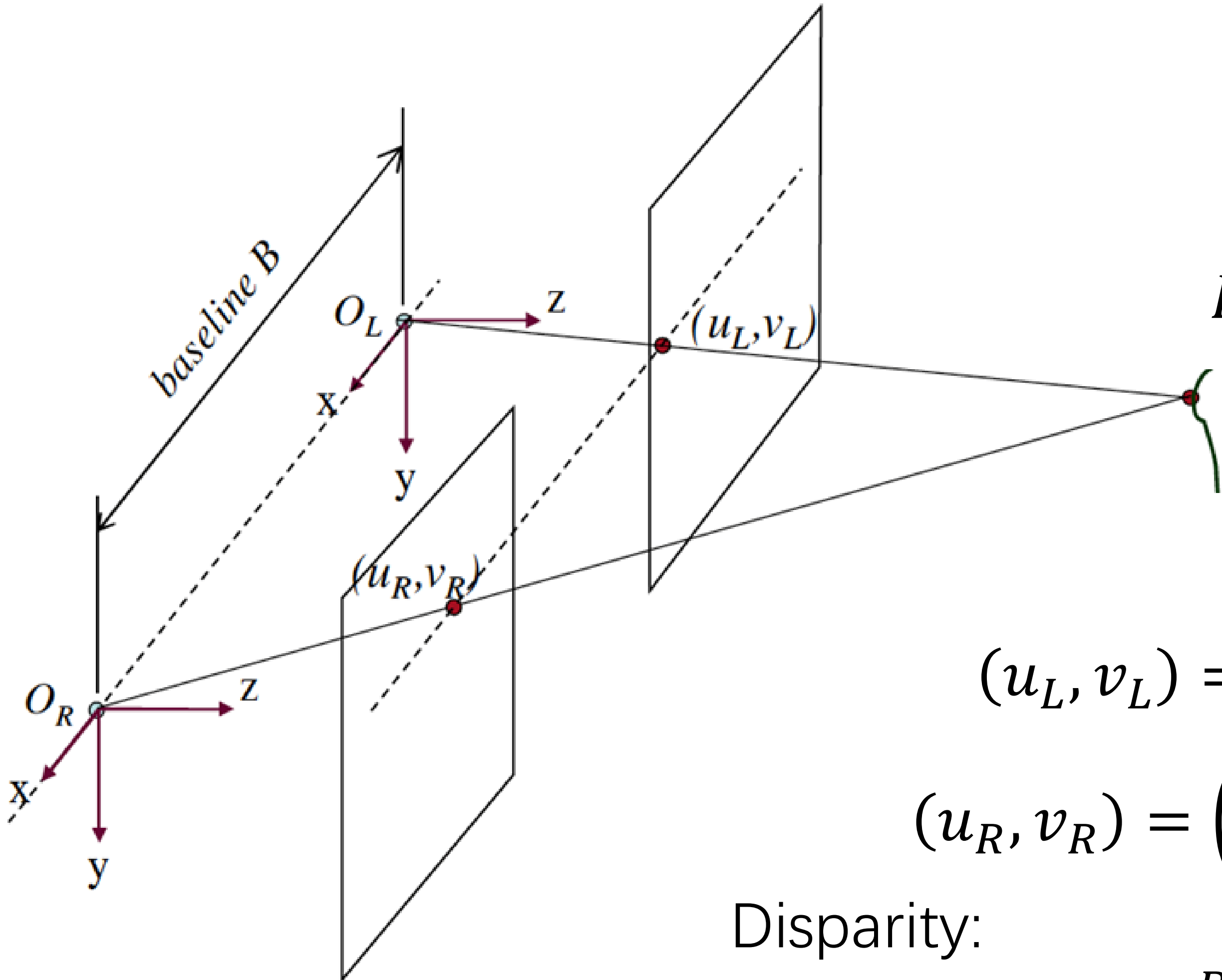
Accommodation



Convergence

Courtesy: Shaojie Shen

# Basic Stereo Derivations




$$P_L = (X, Y, Z)$$

$$(u_L, v_L) = \left(f\frac{X}{Z}, f\frac{Y}{Z}\right)$$

$$(u_R, v_R) = \left(f\frac{X - B}{Z}, f\frac{Y}{Z}\right)$$

Disparity:

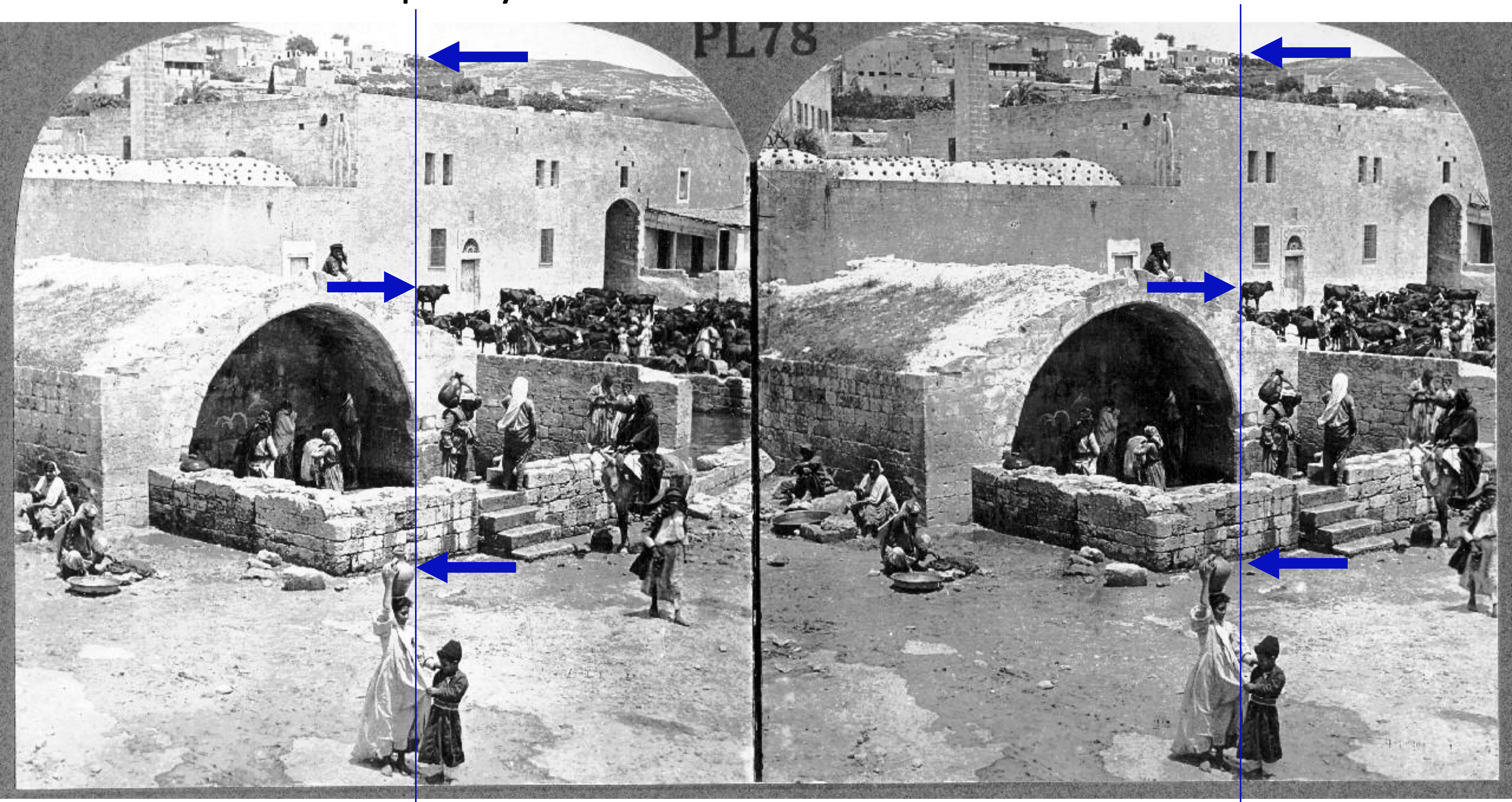
$$d = u_L - u_R = f\frac{B}{Z}$$

$$\boxed{Z = f\frac{B}{d}}$$

Courtesy: Shaojie Shen, Kostas Daniilidis

# Disparity

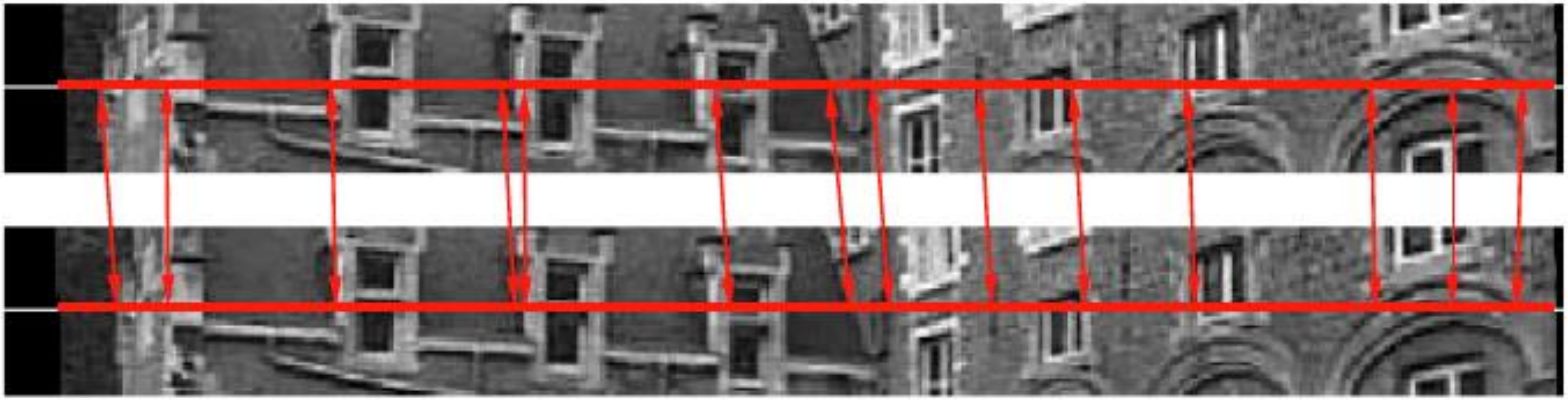
- Notice the disparity difference at different distances




Courtesy: Shaojie Shen, Kostas Daniilidis

# Depth by Stereo Vision

# Correpondence



Courtesy: Shaojie Shen, Kostas Daniilidis

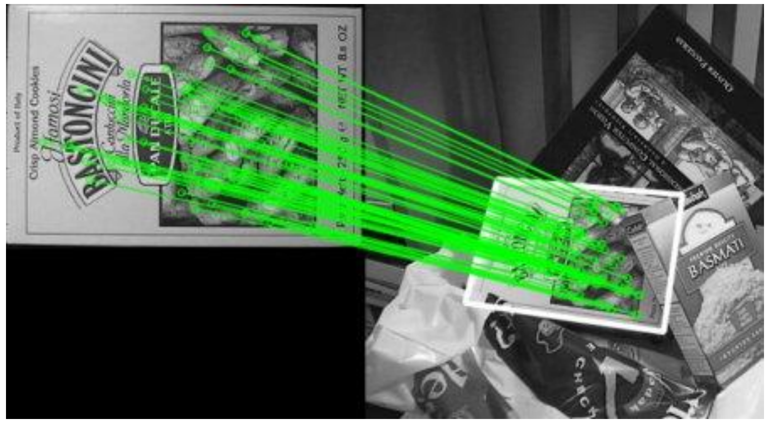
# Correpondence

- Student: "What are the three most important problems in computer vision?"
- Takeo Kanade: "Correspondence, correspondence, correspondence!"

**Prof. Takeo Kanade**

# Visual Perception/SLAM Topics

- one or two lectures in October/November




| | | | |
|---|---|---|---|
| L11 | 16/10 | Fast SLAM with Particle Filter | |
| L12 | 18/10 | Graph SLAM | |
| L13 | 25/10 | Place Recognition | |
| L14 | 30/10 | Advanced Topic – Visual SLAM 1 (TBD) | |
| L15 | 01/11 | Advanced Topic - Visual SLAM 2 | P2 Out |
| L16 | 06/11 | Path Planning 1 | P3 - Planning |
| L17 | 08/11 | Path Planning 2 | |

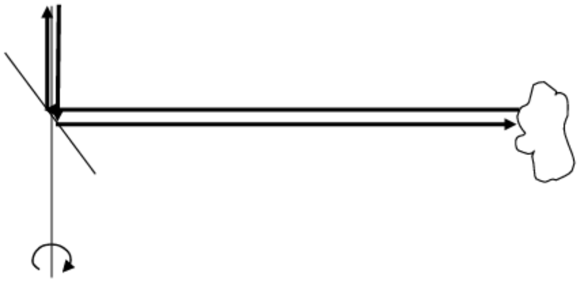
# Exteroceptive Sensors

- GNSS ☑
- Camera ☑
    - Monocular ☑
    - Stereo ☑
- Range Sensors
    - 2D Laser
    - 3D LiDAR
    - Radar
- RGB-D

# LiDARs vs Cameras

- Pros
  - wide field of view
  - precise depth
  - illumination free
- Cons
  - sparse points per raw scan
  - no RGB information
  - higher cost, generally

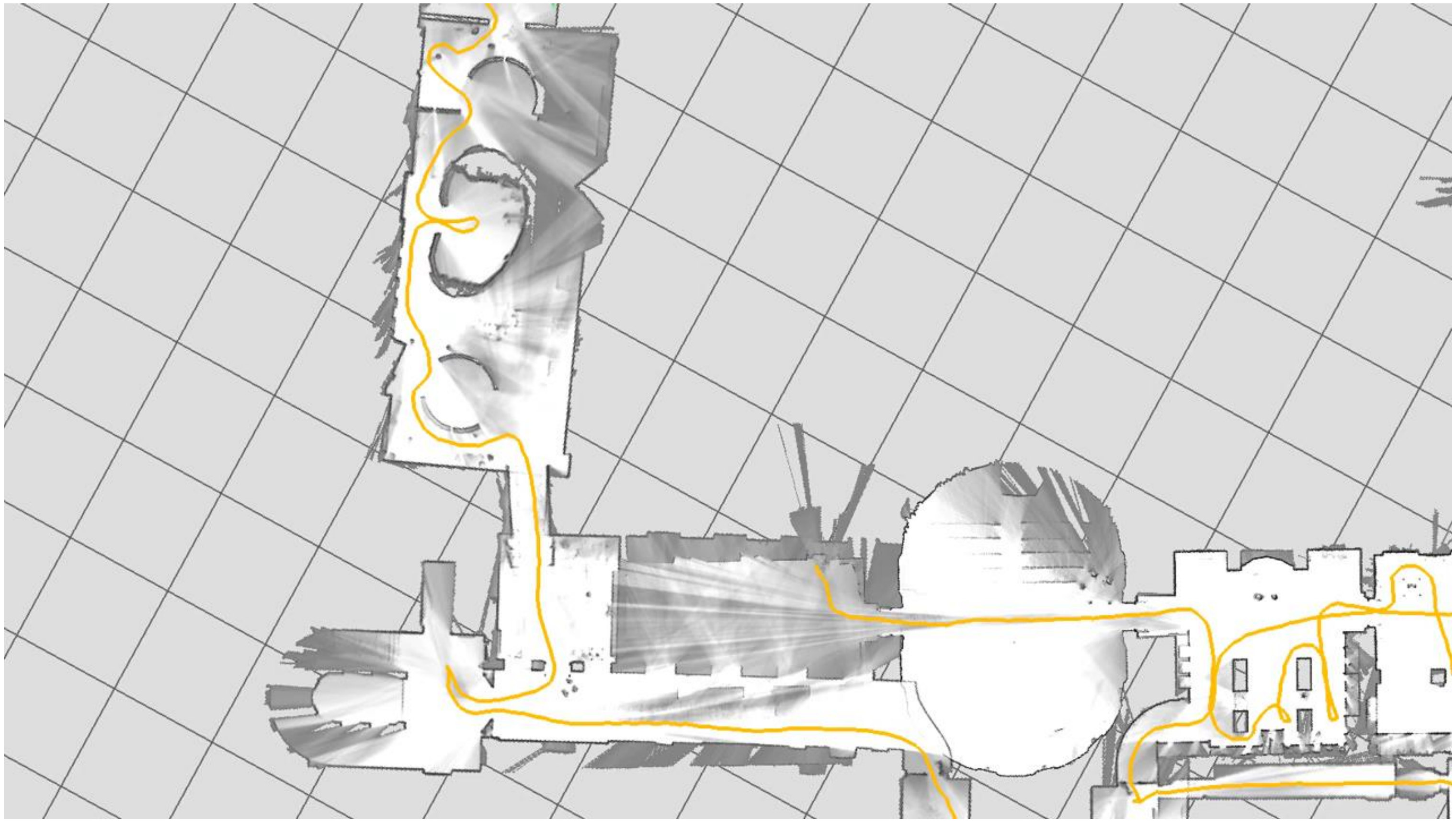

# 2D Laser Scanner

Courtesy: Wolfram Burgard

# 2D Laser SLAM

- Cartographer - 2D laser SLAM with loop closure



Courtesy: Cartographer

# 3D LiDAR Scanner

- LiDAR - Light Detection and Ranging
- Compared to 2D Laser Scanner
  - 3D Data
  - More expensive


**3 Years Ago**

# 3D LiDAR SLAM

- Kudan Lidar SLAM: Running on NVIDIA Isaac platform

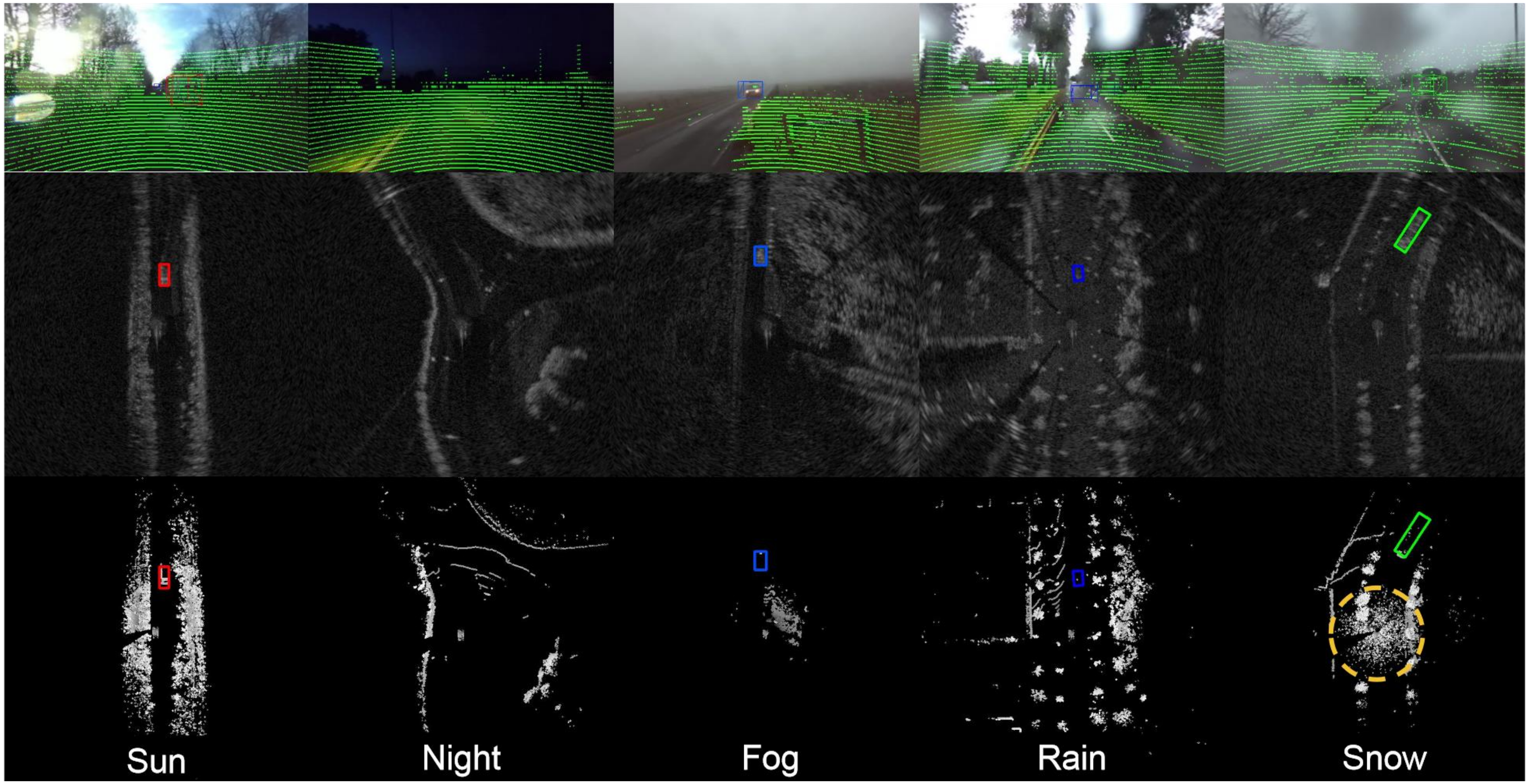
Courtesy: Kudan LiDAR SLAM

# Exteroceptive Sensors

- GNSS ☑
- Camera ☑
  - Monocular ☑
  - Stereo ☑
- Range Sensors ☑
  - 2D Laser ☑
  - 3D LiDAR ☑
  - Radar
- RGB-D

# Radar

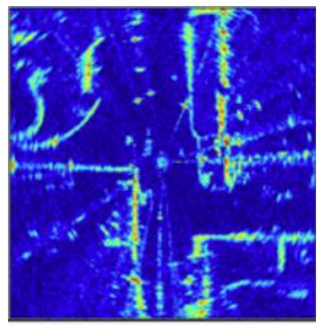
- Why Radar
  - All-weather robust

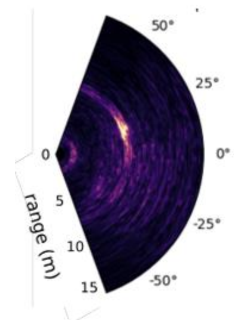



Courtesy: RADIATE Dataset

# Dense or Sparse Radar?

- Dense vs Sparse
  - Constant false alarm rate (CFAR)

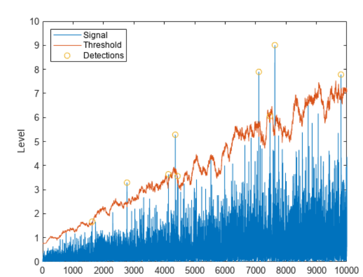





Raw Signal by TX/RX → Dense → Sparse

Electronic Processing

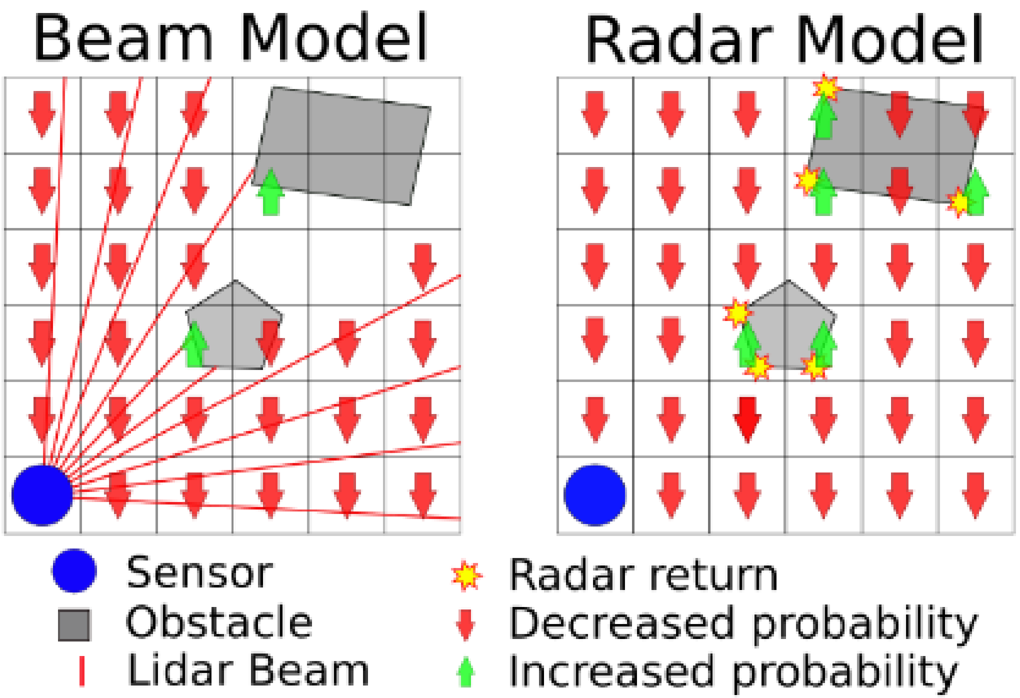
CFAR Filter




Courtesy: Papers

# LiDAR and Radar

- Range sensors with different sensings




Courtesy: A New Wave in Robotics: Survey on Recent mmWave Radar Applications in Robotics.

# Radar Sensor

- Imaging radar using multiple single-chip FMCW transceivers

Courtesy: Texas Instruments

# Pros & Cons of Radar

- Pros
  - All-weather robust
  - Speed of the detection (Doppler)
- Cons
  - Extremely noisy
  - Less support

# Exteroceptive Sensors

- GNSS ☑
- Camera ☑
  - Monocular ☑
  - Stereo ☑
- Range Sensors ☑
  - 2D Laser ☑
  - 3D LiDAR ☑
  - Radar ☑
- RGB-D

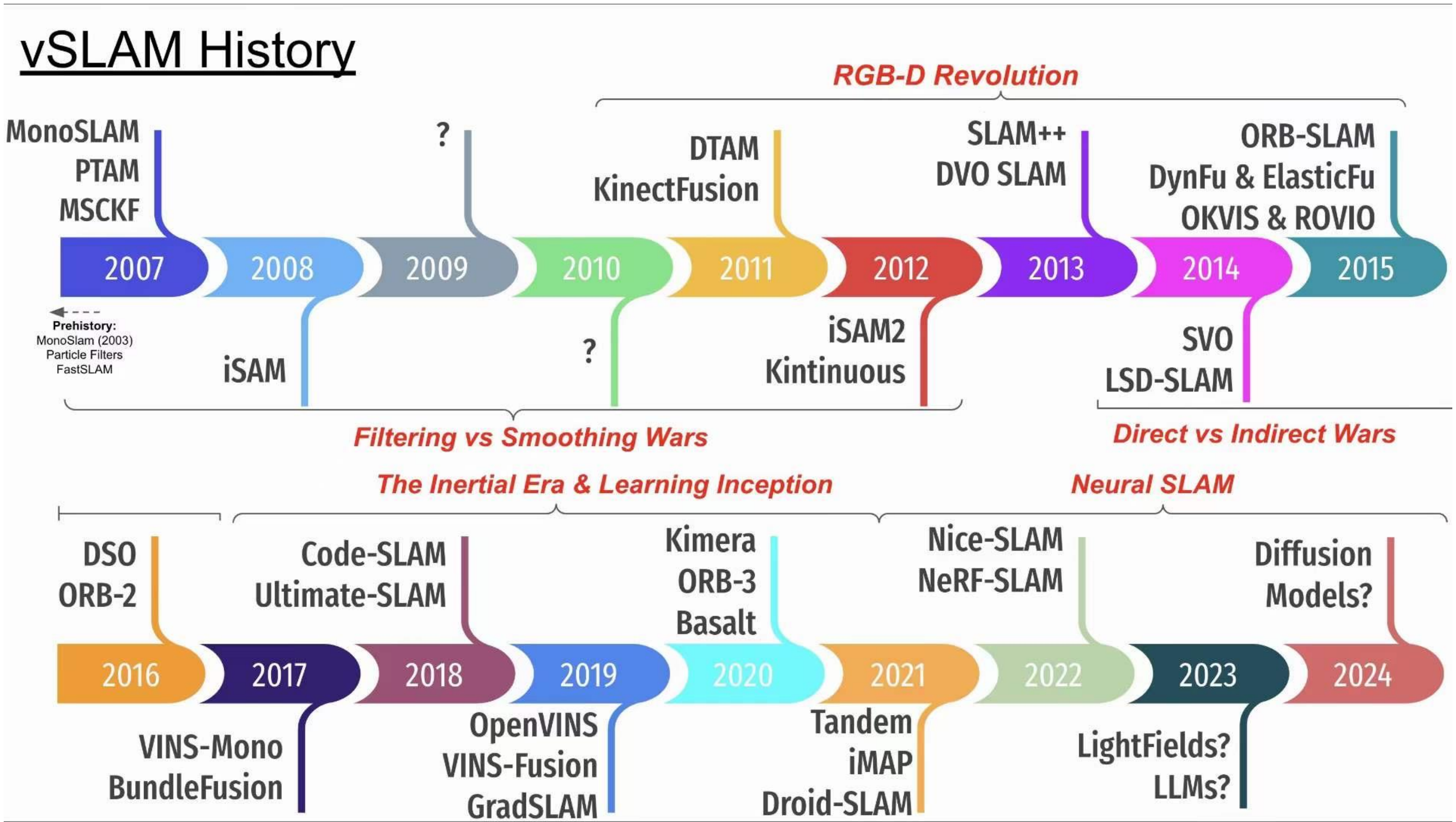
# RGB-D Sensor

- LiDAR depth (infrared) + Monocular
  - Intel Realsense
  - Microsoft Kinect
  - Intel L515


(a) (b) (c)

# RGB-D

- “RGB-D Revolution” from 2010 to 2015




Courtesy: Internet

# RGB-D Sensor

- Pros
  - fast speed for data capture
  - relatively good depth (compared to stereo vision)
- Cons
  - easily affected by illumination
  - **doe not work in outdoors!**

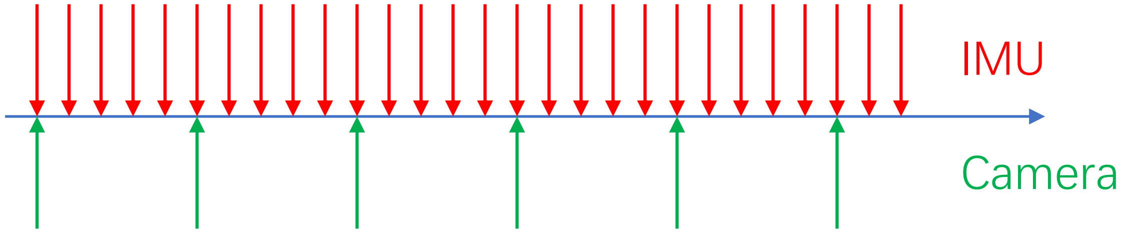
# Multi-Sensor Fusion

# Multi-sensor Fusion

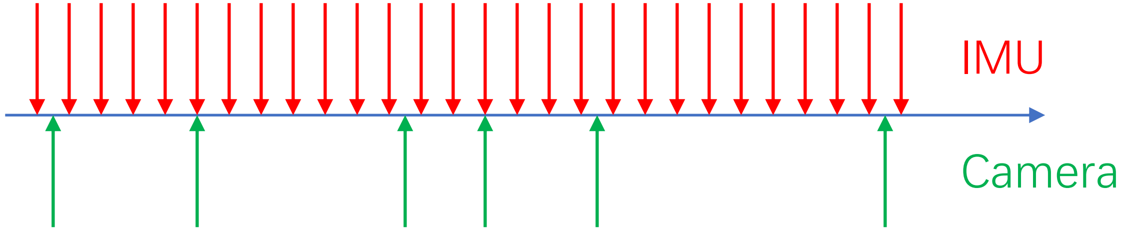
- Pros
  - more robust
  - higher precision
- Cons
  - high cost
  - time synchronization

# Time Synchronization

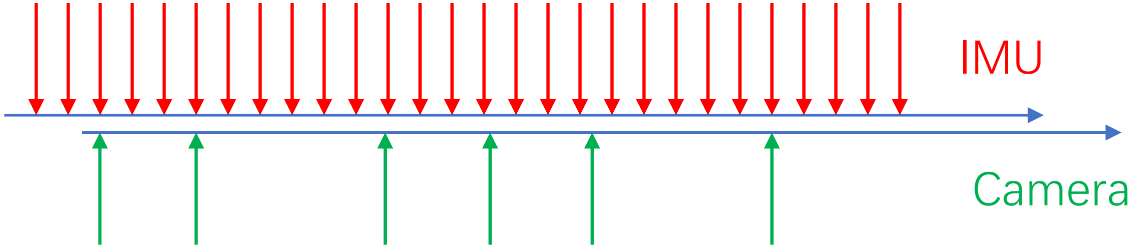
- Best: Sensors are hardware-triggered




- OK: Sensors have the same clock (e.g. running on the same system clock or have global clock correction) but capture data at different times




- Bad: Sensors have different clocks (e.g. each sensor has its own oscillator)




Courtesy: Shaojie Shen

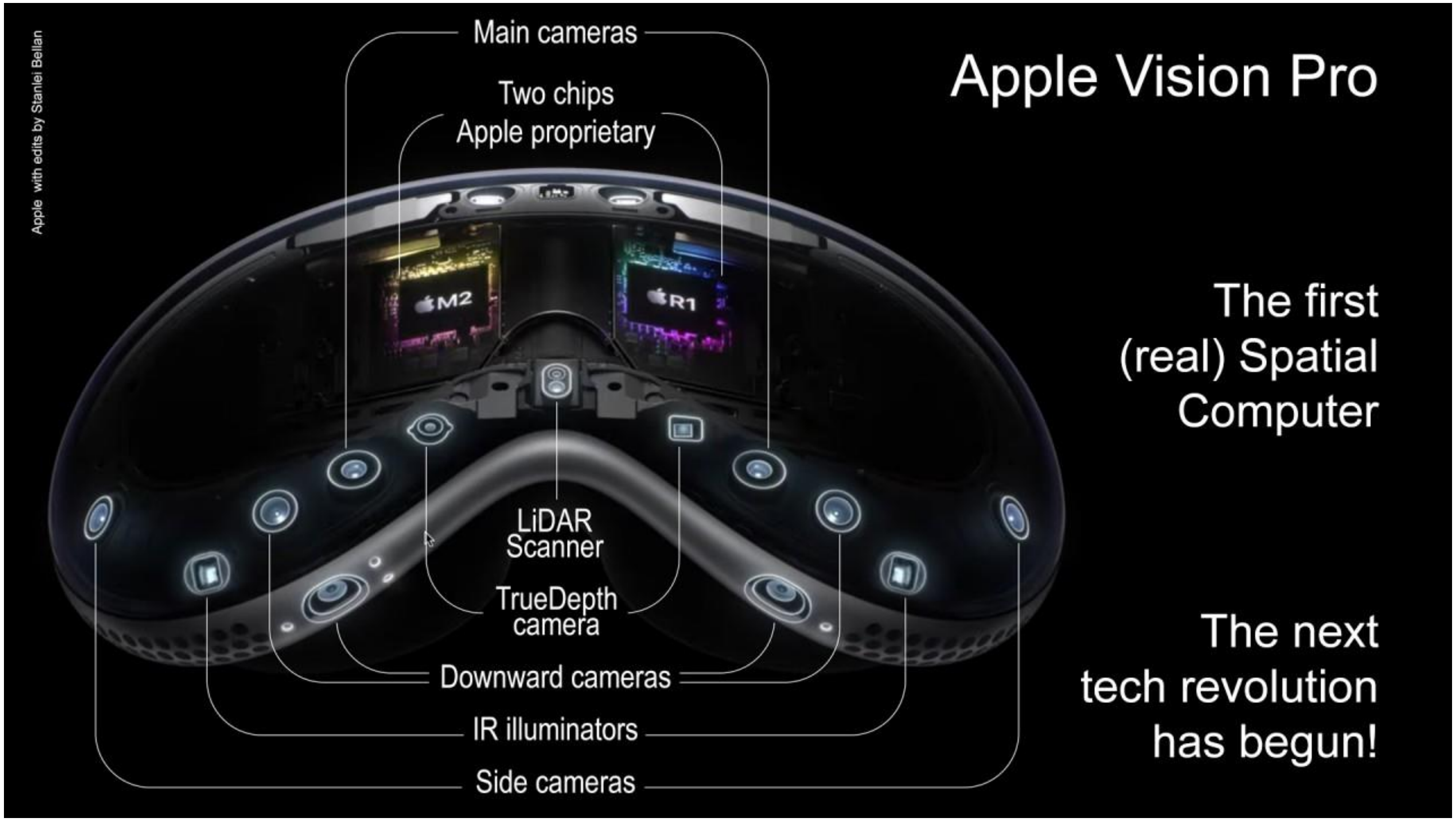
# Sensor-Fusion in Research

- R3Live


Courtesy: HKU Mars Lab

# Sensor-Fusion in Product

- Apple Vision Pro (AR/VR Product)
  - High-precision High-frequency Multi-sensor SLAM inside



# Summary

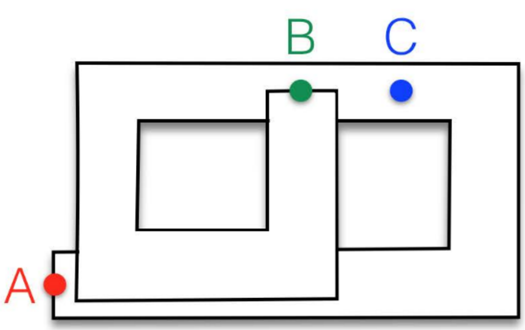
- Sensors
  - Interoceptive: IMU
  - Exteroceptive: GNSS, Camera, LiDAR, Radar, RGBD
    - Pros and Cons
  - Pros and Cons of each sensor

Conclusion

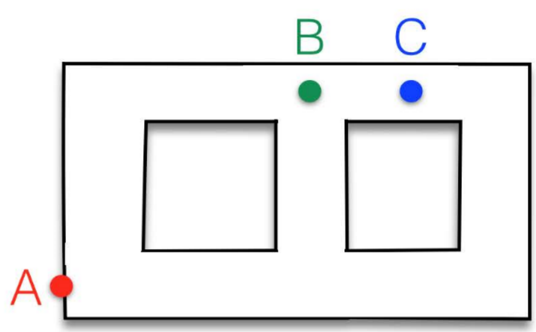
  - There is no perfect sensor
  - Multi-Sensor fusion is the trend for robotics

# L3 - Robot Localization

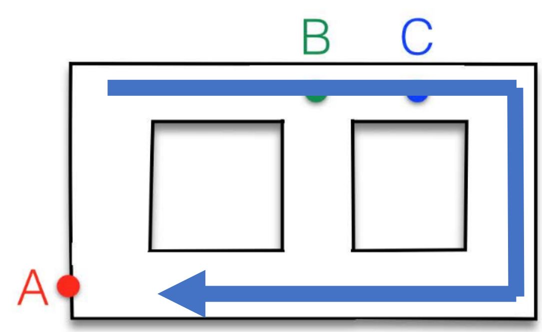
- **Odometry**
  - Wheel Odometry
  - Visual Odometry
  - LiDAR Odometry
  - etc




- **SLAM**
  - Simultaneous localization and mapping




- **Map-based Localization**
  - Localize on a given map



# Next Lecture

- Iterative Closest Points
  - LiDAR sensor-based Odometry
  - Project 1