CS283: **Robotics Fall 2019: Vision**

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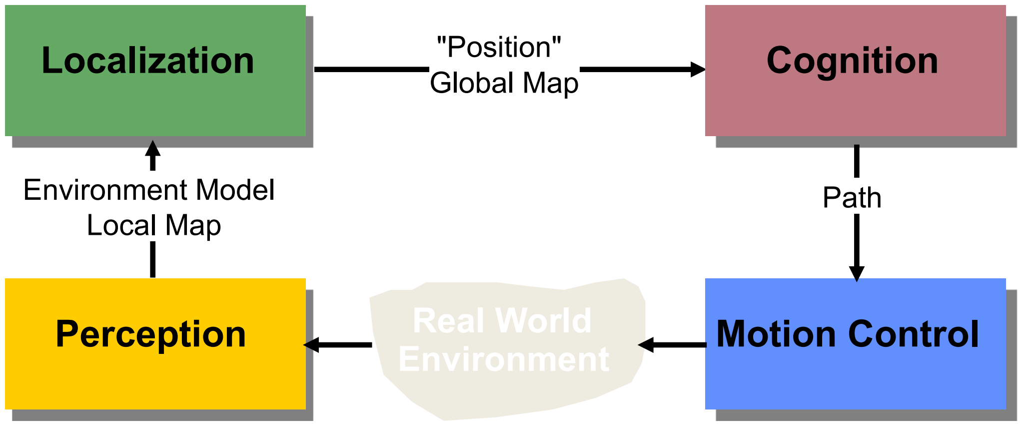
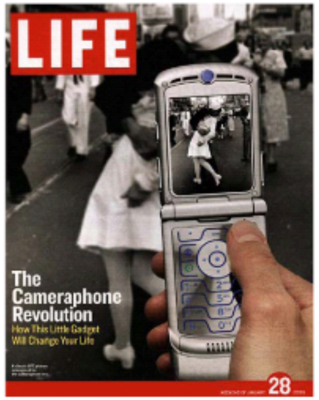
ShanghaiTech University

VISION

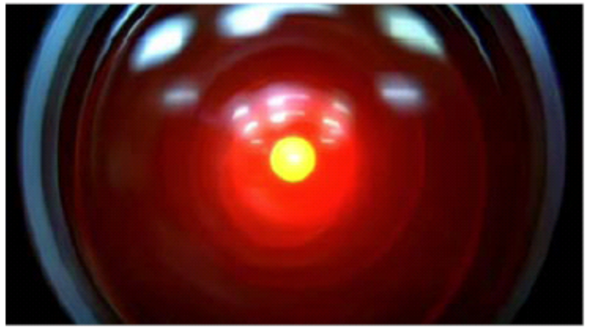


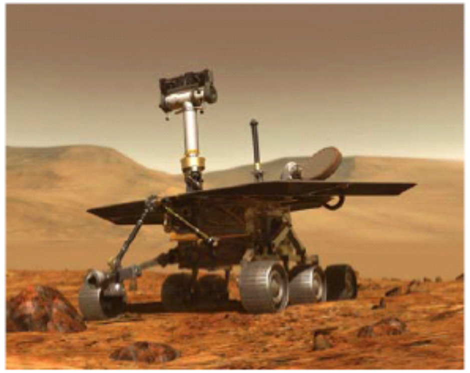
Introduction to Autonomous Mobile Robots pages 142ff

Computer Vision

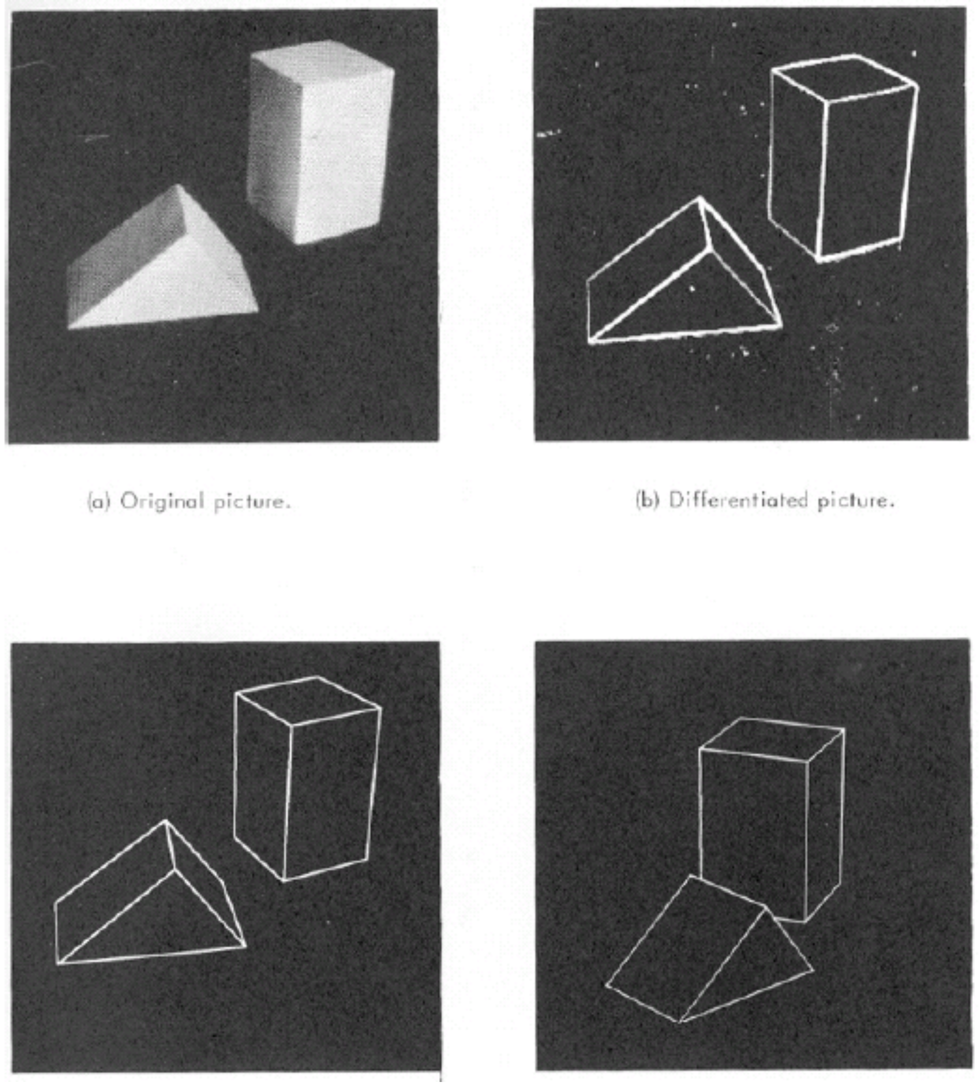





Origins of Computer Vision

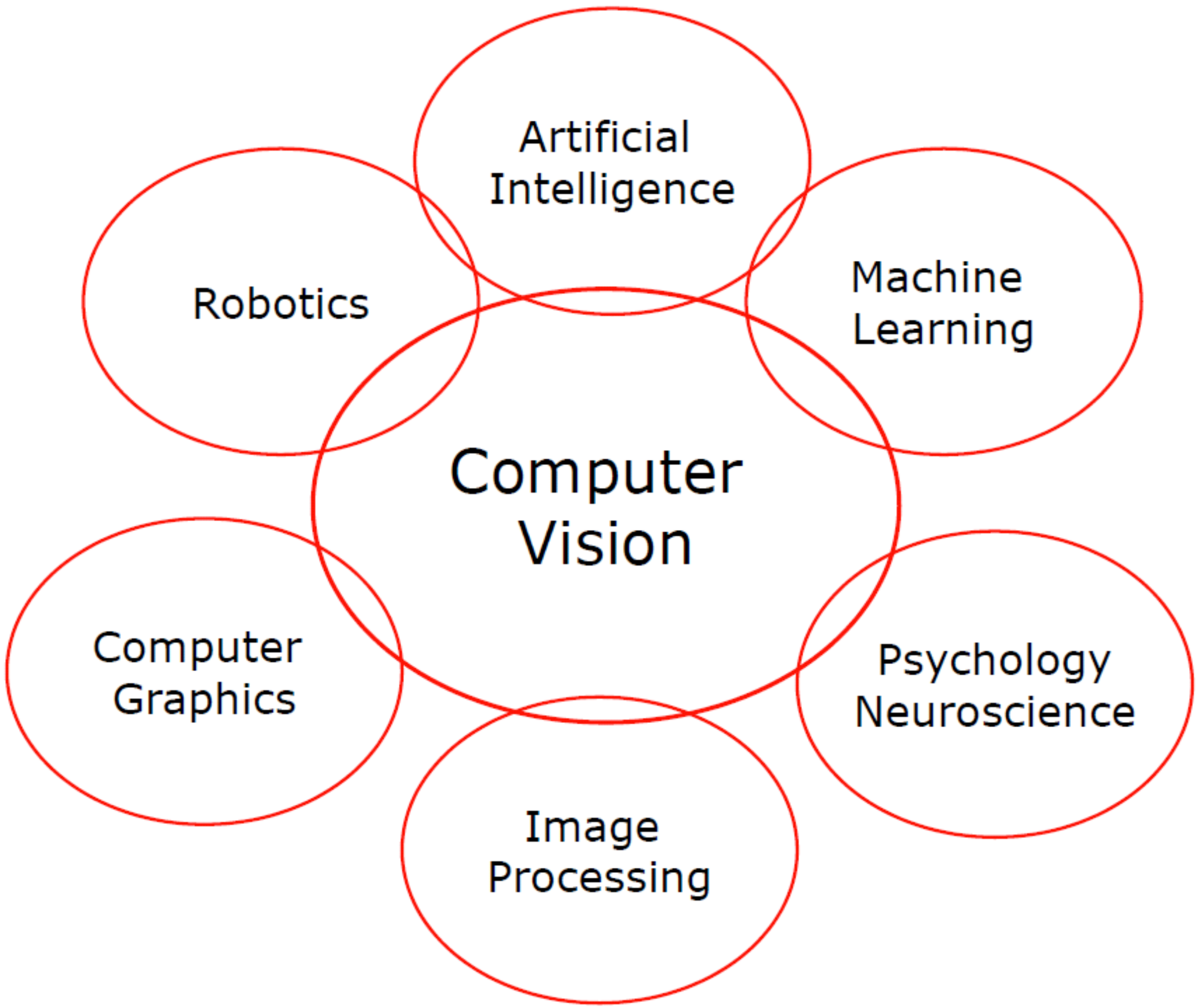


(a) Original picture.

(b) Differentiated picture.

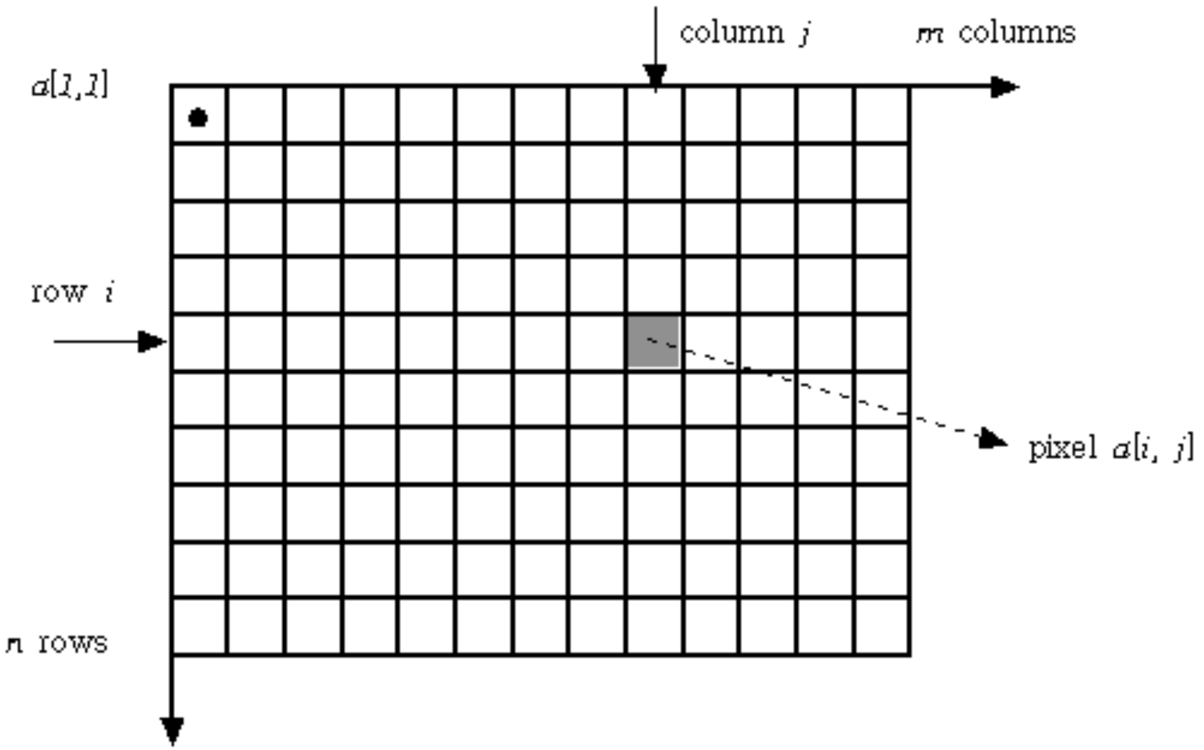
L. G. Roberts, *Machine Perception of Three Dimensional Solids,* Ph.D. thesis, MIT Department of Electrical Engineering, 1963.

Connection to other disciplines



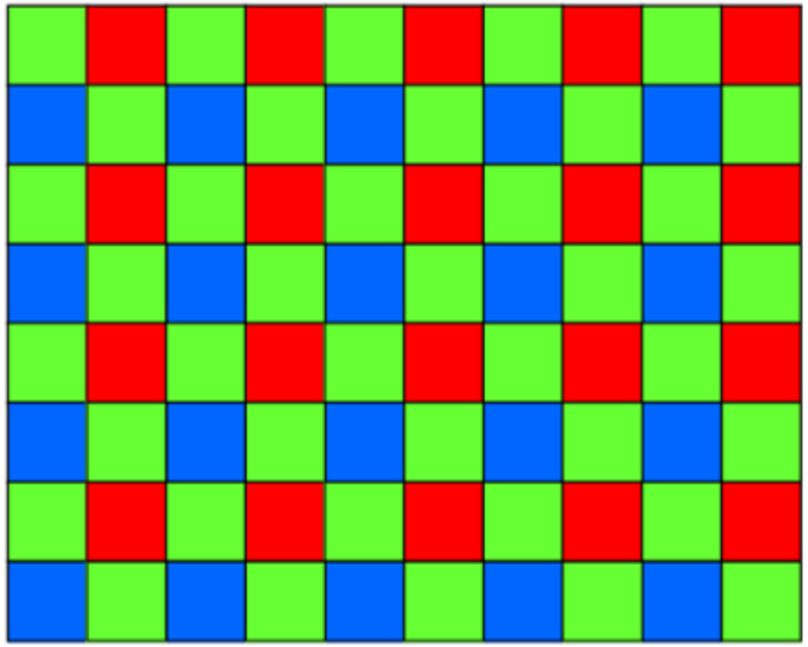
Image

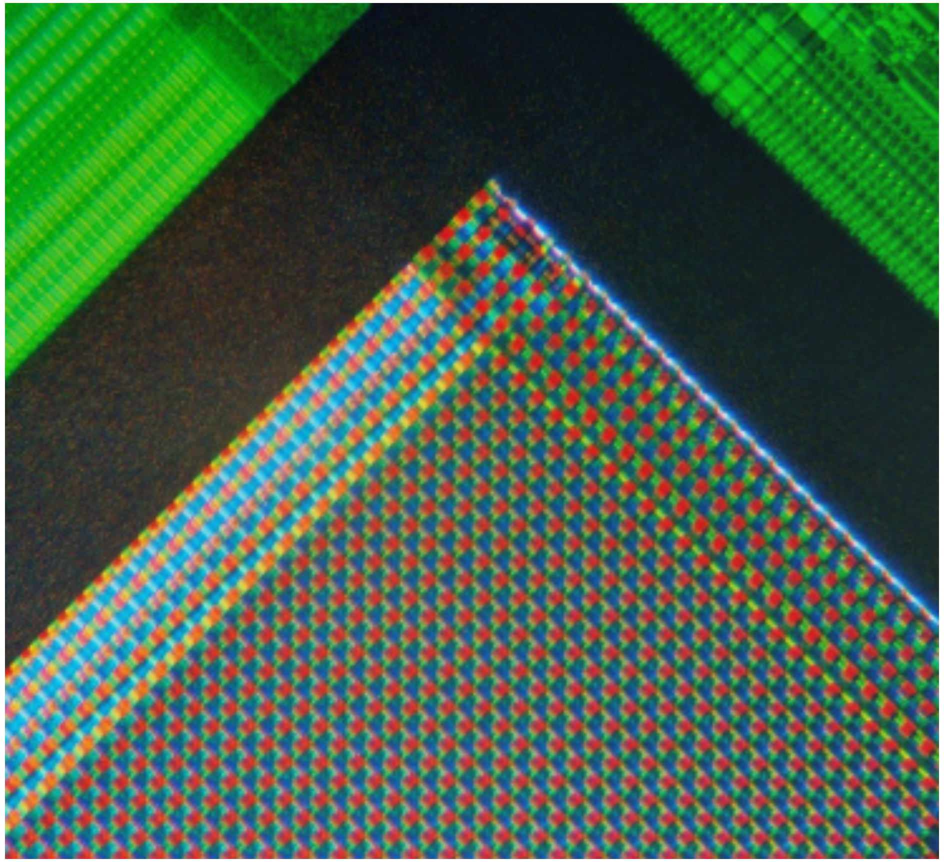
- Image : a two-dimensional array of pixels
- The indices [i, j] of pixels : integer values that specify the rows and columns in pixel values



Digital Color Camera

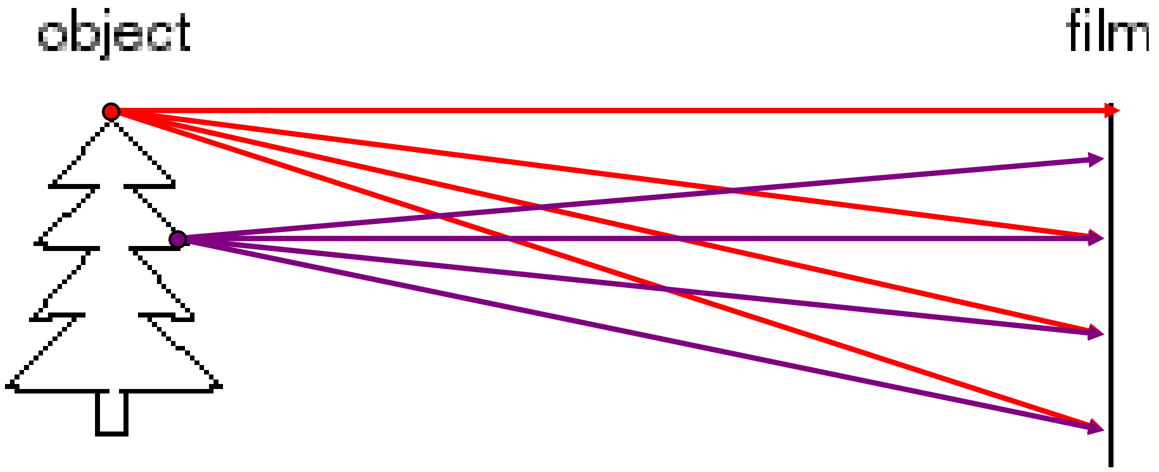
- Bayer Pattern:
  - 50% green, 25% red and 25% blue =>
  - RGBG or GRGB or RGGB.
  - 1 Byte per square
  - 4 squared per 1 pixel
  - More green: eyes are more sensitive to green (nature!)





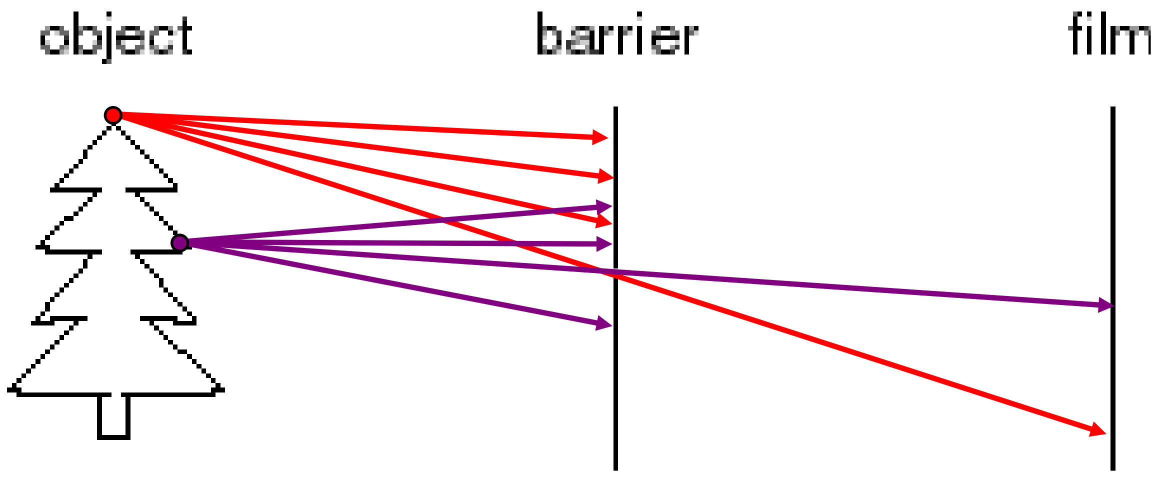
A micrograph of the corner of the photosensor array of a 'webcam' digital camera. (Wikimedia)

How do we see the world?



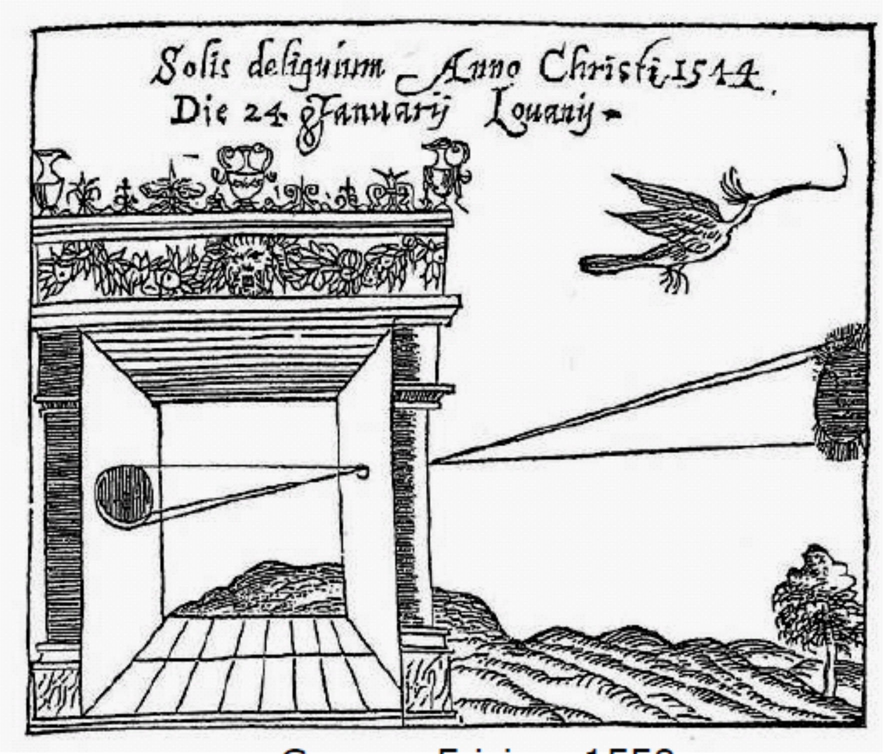
- Let's design a camera
  - Idea 1: put a piece of film in front of an object
  - Do we get a reasonable image?

Pinhole camera



- Add a barrier to block off most of the rays
  - This reduces blurring
  - The opening known as the **aperture**

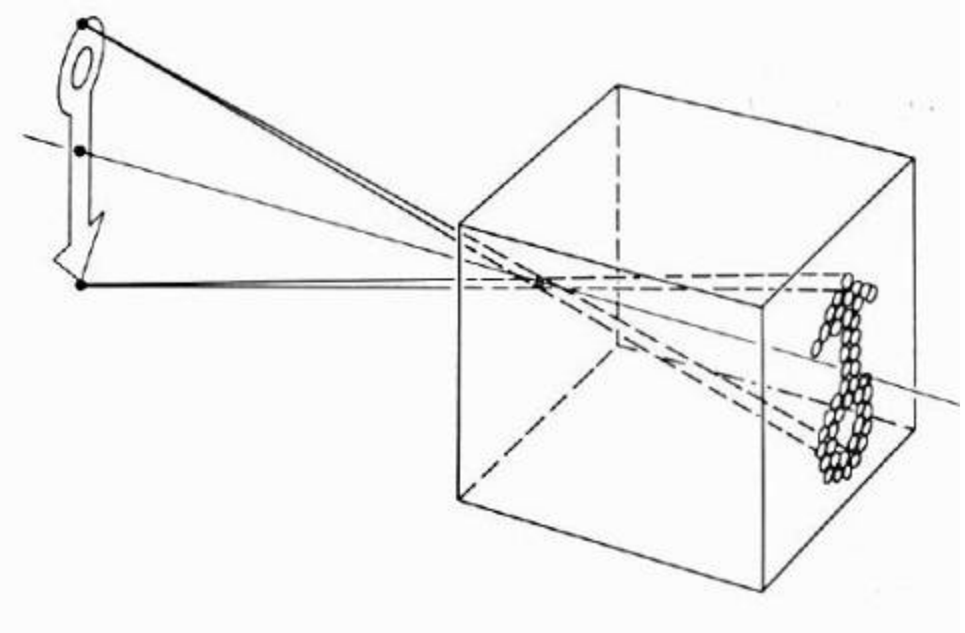
Camera obscura



Gemma Frisius, 1558

- Basic principle known to Mozi (470-390 BC), Aristotle (384-322 BC)
- Drawing aid for artists: described by Leonardo da Vinci (1452-1519)
- Depth of the room (box) is the effective focal length

Pinhole camera model



- Pinhole model:
  - Captures **pencil of rays** – all rays through a single point
  - The point is called **Center of Projection**
  - The image is formed on the **Image Plane**

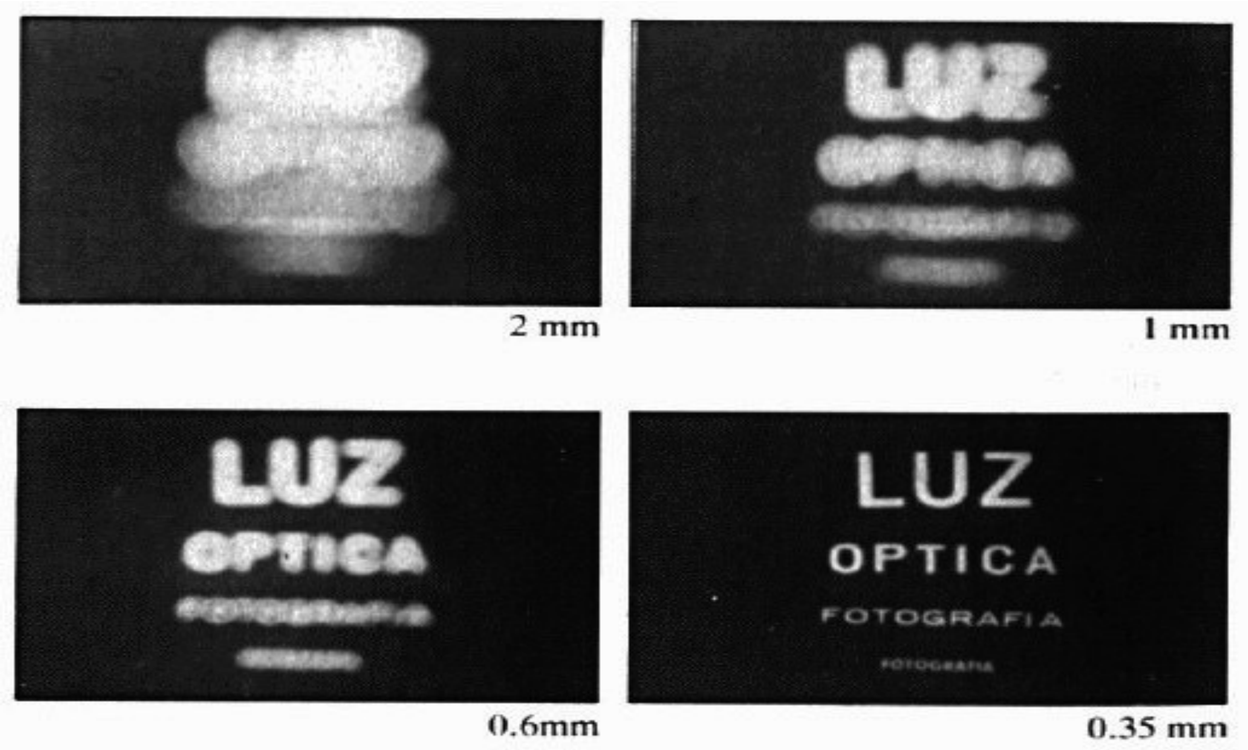
Slide by Steve Seitz

Home-made pinhole camera

Why so
blurry?

http://www.debevec.org/Pinhole/

Shrinking the aperture

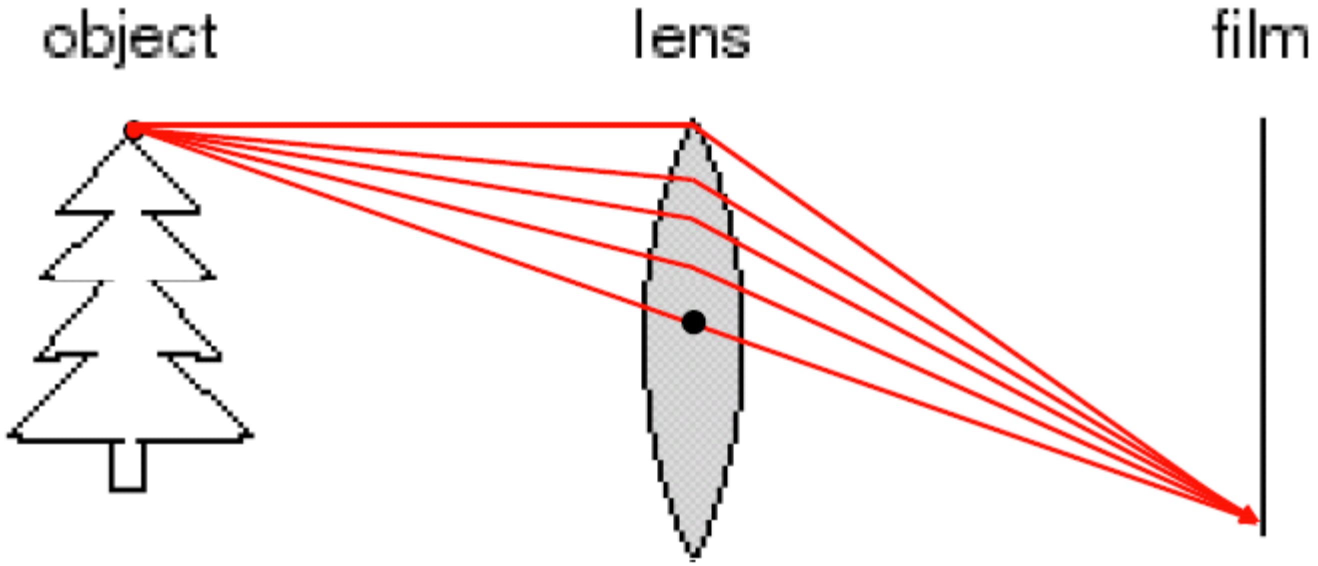


- Why not make the aperture as small as possible?
  - Less light gets through (must increase the exposure)
  - Diffraction effects…

Slide by Steve Seitz

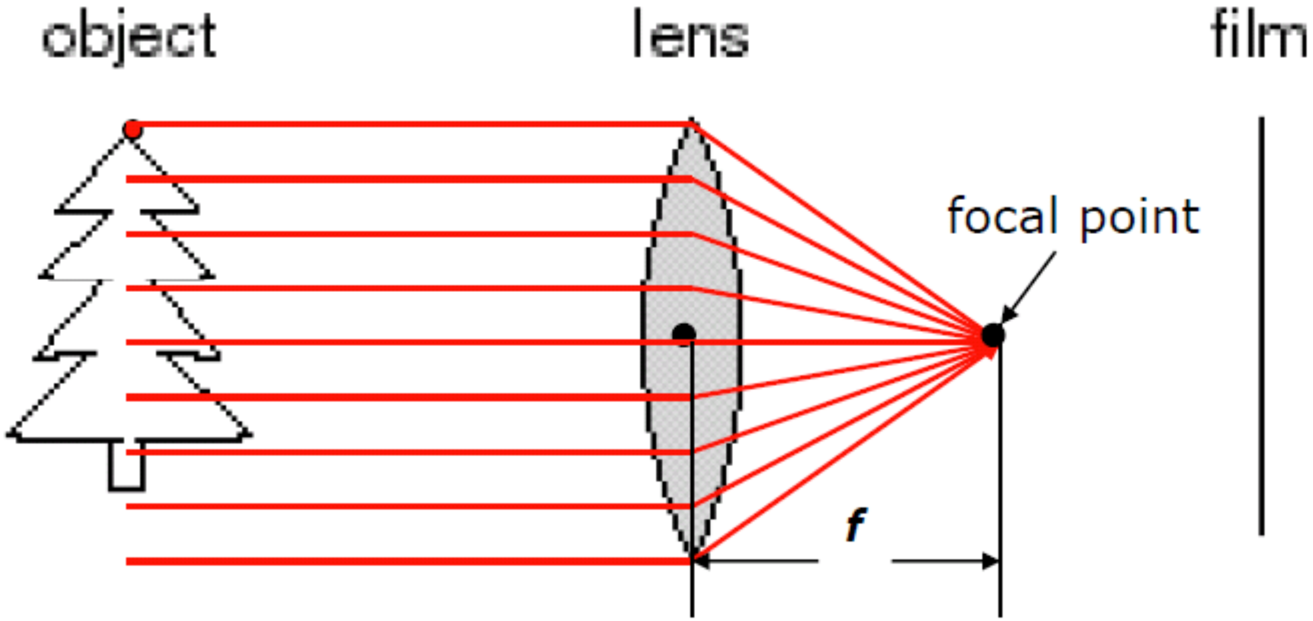
Shrinking the aperture

Solution: adding a lens



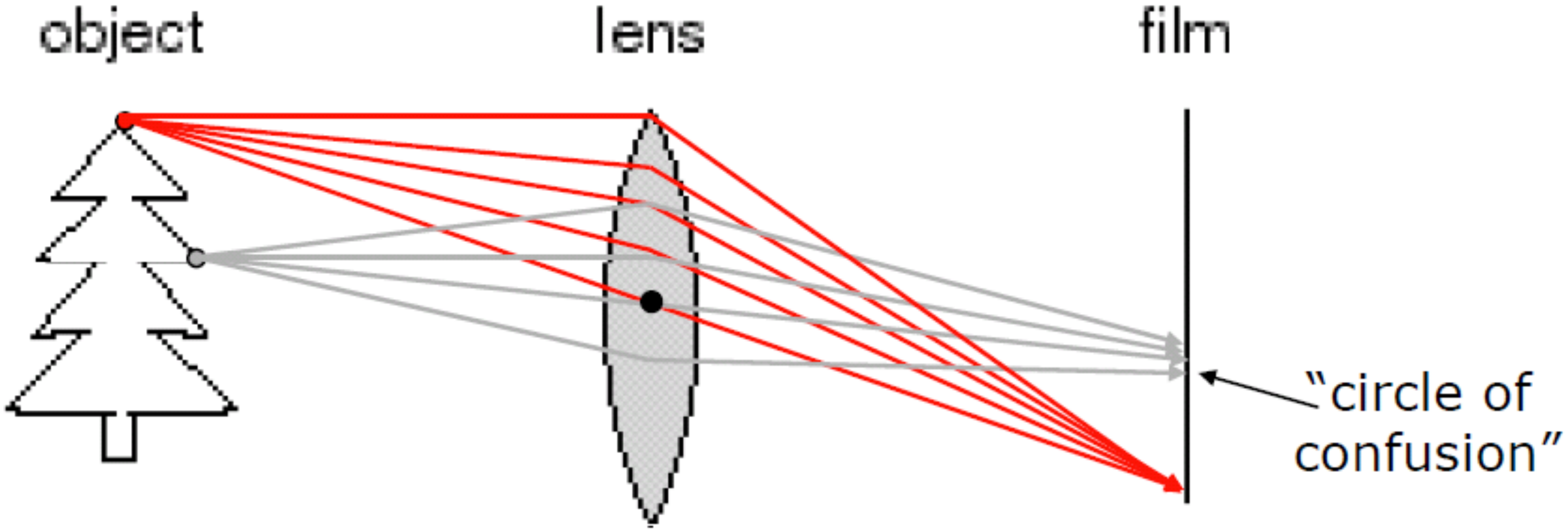
- A lens focuses light onto the film
  - Rays passing through the center are not deviated

Solution: adding a lens



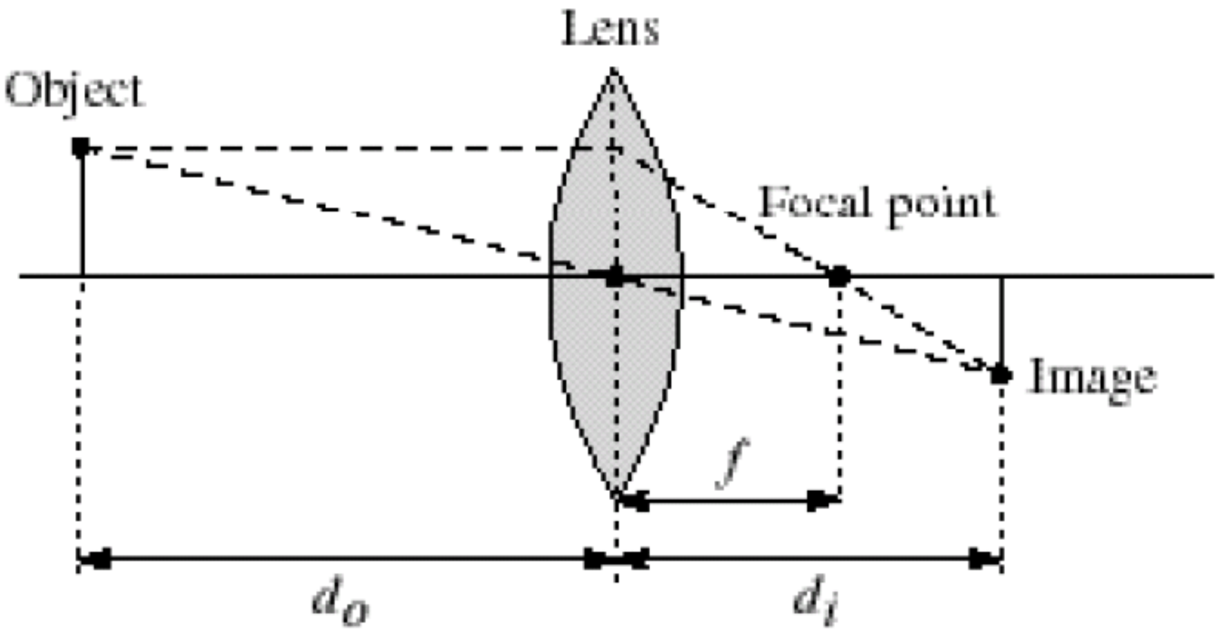
- A lens focuses light onto the film
  - Rays passing through the center are not deviated
  - All parallel rays converge to one point on a plane located at the *focal length f*

Solution: adding a lens



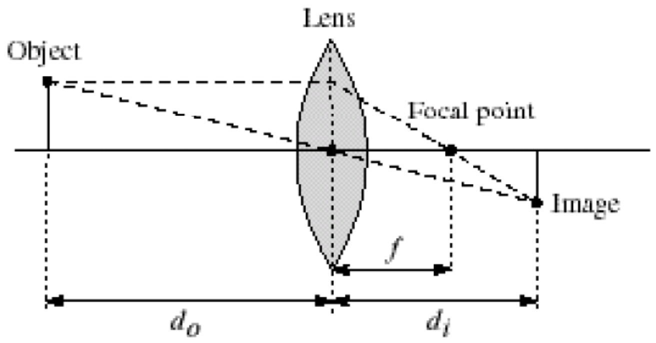
- A lens focuses light onto the film
  - There is a specific distance at which objects are "in focus"
    - other points project to a "circle of confusion" in the image

Thin lenses



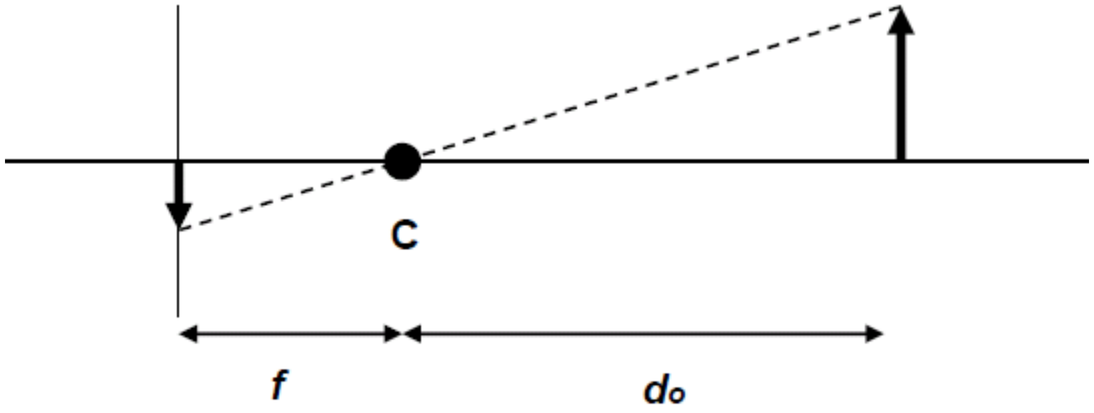
- Thin lens equation: $\frac{1}{d_0} + \frac{1}{d_i} = \frac{1}{f}$
  - Any object point satisfying this equation is in focus
  - This formula can also be used to estimate roughly the distance to the object ("Depth from Focus")

Pin-hole approximation



$$\frac{1}{d_0} + \frac{1}{d_i} = \frac{1}{f}$$

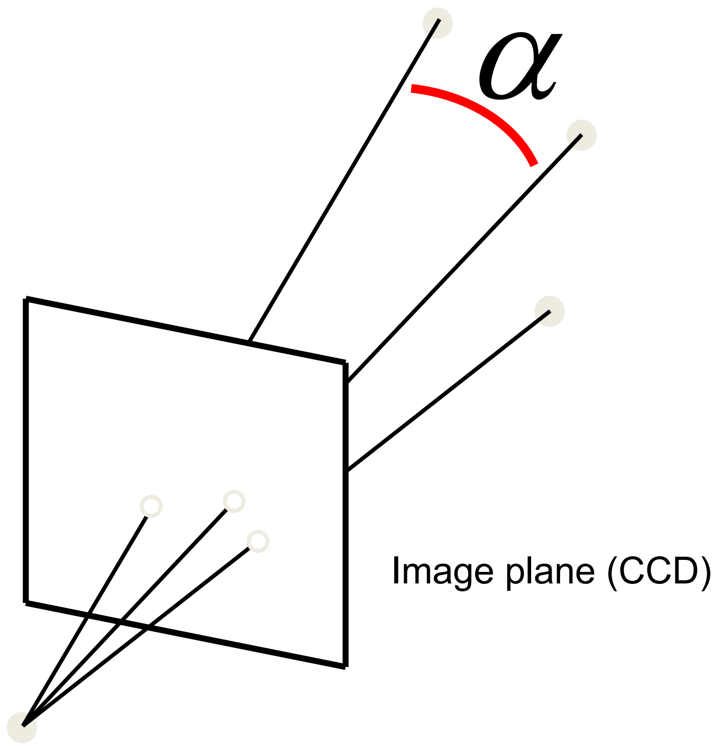
$$d_0 >> d_i \Rightarrow \frac{1}{d_i} \approx \frac{1}{f} \Rightarrow d_i \approx f$$



C = "optical center"

Pin-hole Model

Perspective camera



- For convenience, the image plane is usually represented in front so that the image preserves the same orientation (i.e. not flipped)
- **Notice: a camera does not measure distances but angles! Therefore it is a “bearing sensor”**

Perspective Projection onto the image plane

- To project a 3D scene point P = (x,y,z) [meters] onto the camera image plane p=(u,v) [pixels] we need to consider:
  - Pixelization: size of the pixel and position of the CCD with respect to the optical center
  - Rigid body transformation between camera and scene
- u = v = 0: where z-Axis passes trhough center of lens – z-Azis prependicular to lens (coincident with optical axis)

$$u = \frac{f}{z} \cdot x$$

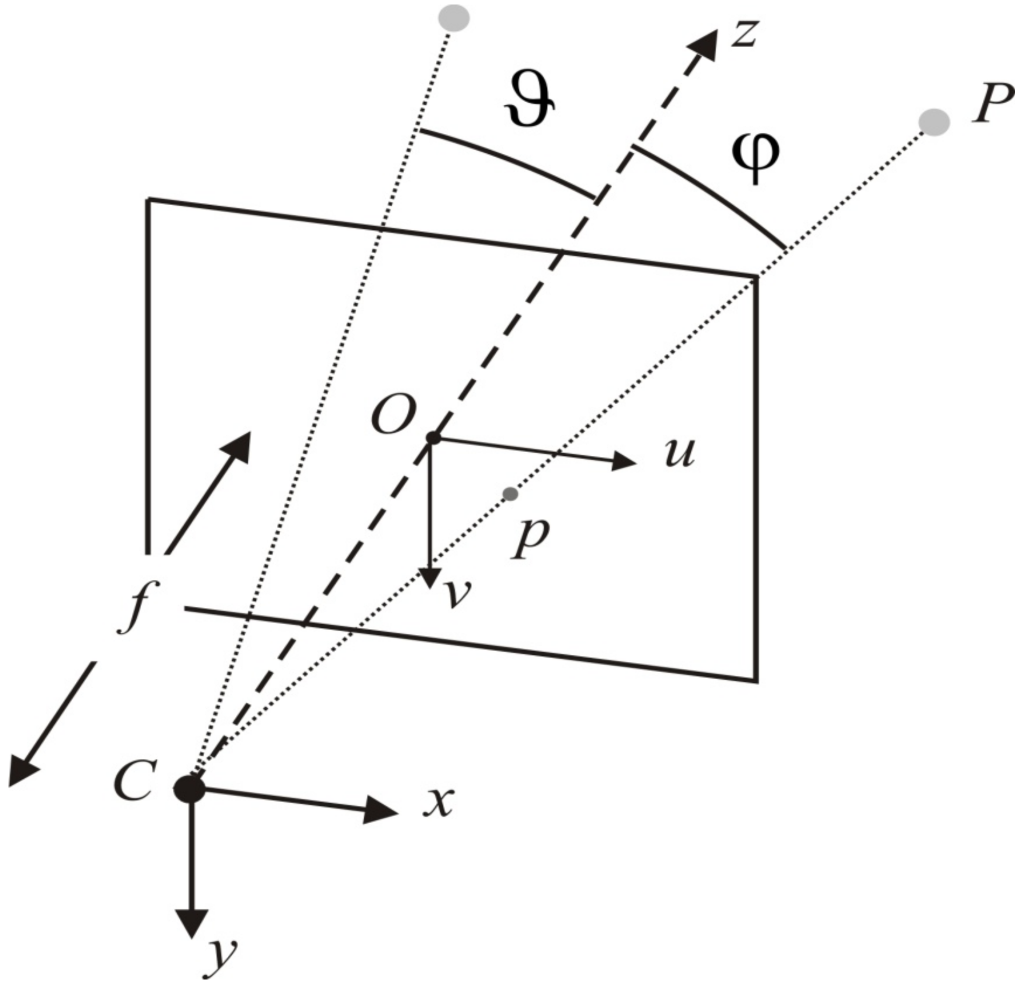
$$v = \frac{f}{z} \cdot y$$

Simple case
(without pixelization)

$$u = k_u \frac{f}{z} \cdot x + u_0$$

$$v = k_v \frac{f}{z} \cdot y + v_0$$

With pixelization
u_0, v_0 are the coordinates of the optical center
Ku and Kv are in [pxl/m]



Projection onto the image plane

- Observe that we can also rewrite this

$$u = k_u \frac{f}{z} \cdot x + u_0$$

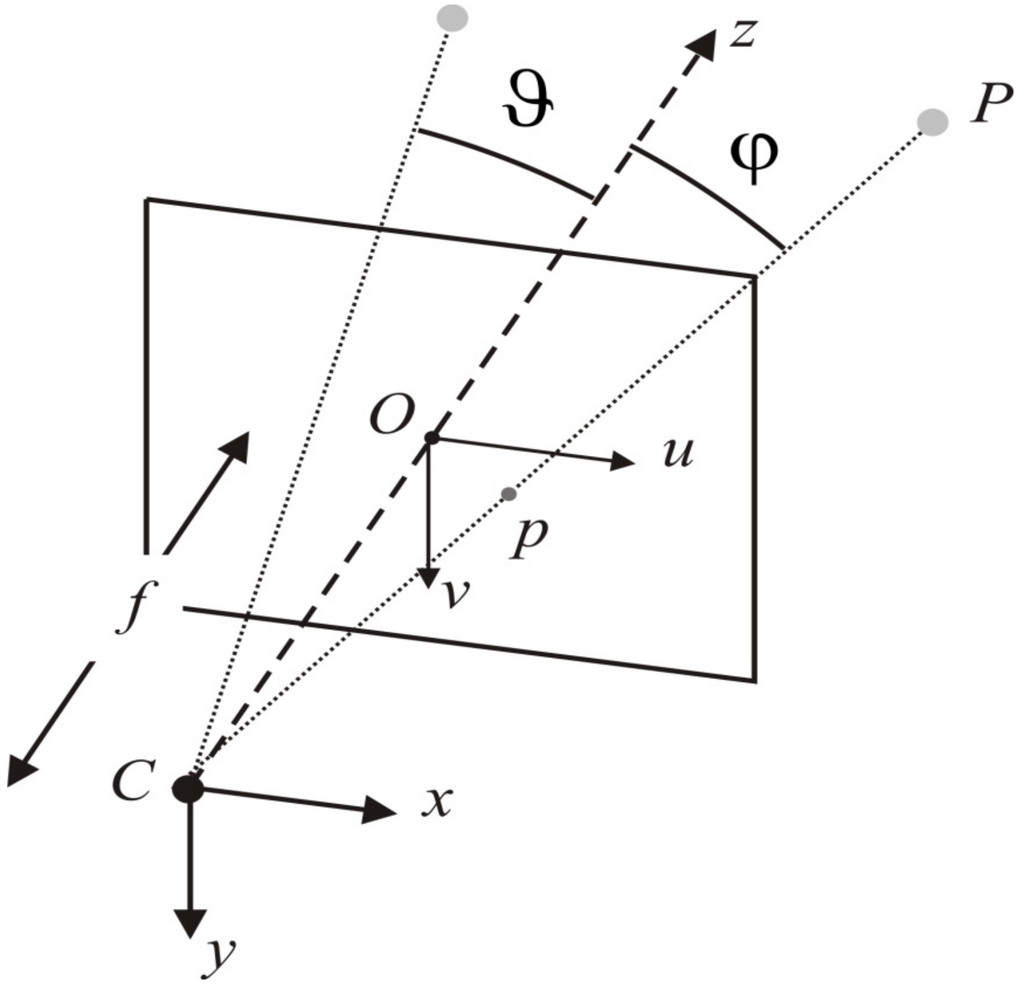
$$v = k_v \frac{f}{z} \cdot y + v_0$$

in matrix form (λ - homogeneous coordinates)

$$\lambda \begin{bmatrix} u \\ v \\ 1 \end{bmatrix} = \begin{bmatrix} k_u f & 0 & u_0 \\ 0 & k_v f & v_0 \\ 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} x \\ y \\ z \end{bmatrix}$$

Or alternatively

$$\lambda \begin{bmatrix} u \\ v \\ 1 \end{bmatrix} = \begin{bmatrix} \alpha_u & 0 & u_0 \\ 0 & \alpha_v & v_0 \\ 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} x \\ y \\ z \end{bmatrix}$$



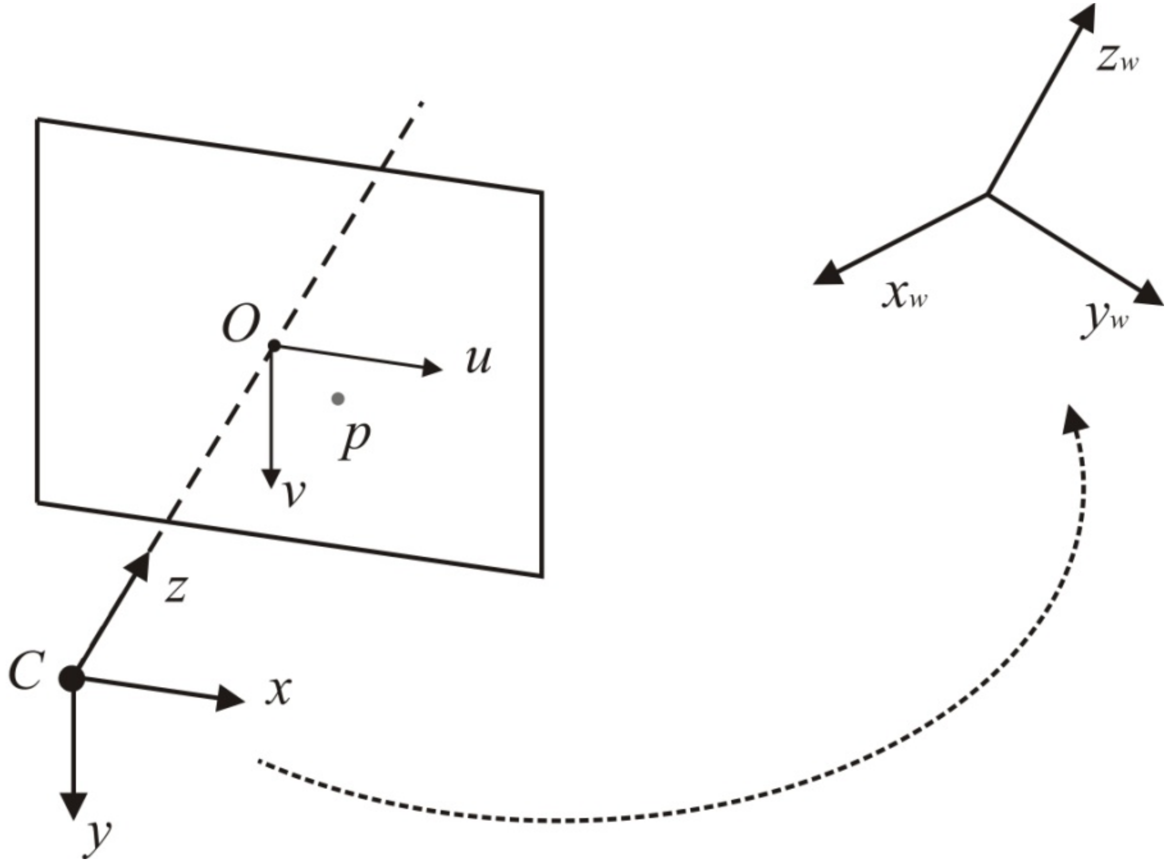
Projection onto the image plane

- Rigid body transformation from the World to the Camera reference frame

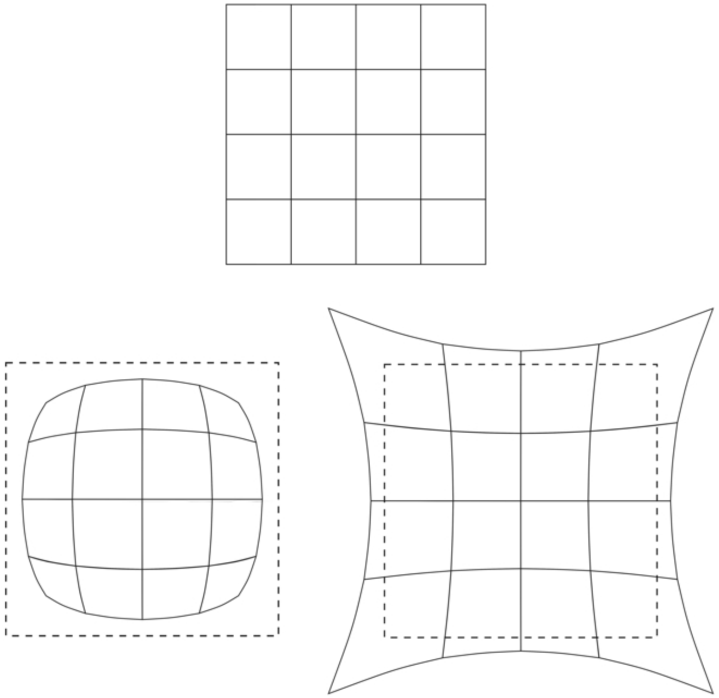
$$\lambda \begin{bmatrix} u \\ v \\ 1 \end{bmatrix} = \begin{bmatrix} \alpha_u & 0 & u_0 \\ 0 & \alpha_v & v_0 \\ 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} x \\ y \\ z \end{bmatrix} = A \begin{bmatrix} x \\ y \\ z \end{bmatrix}$$

$$\begin{bmatrix} x \\ y \\ z \end{bmatrix} = R \begin{bmatrix} x_w \\ y_w \\ z_w \end{bmatrix} + T$$

$$\lambda \begin{bmatrix} u \\ v \\ 1 \end{bmatrix} = A \cdot R \begin{bmatrix} x_w \\ y_w \\ z_w \end{bmatrix} + T$$



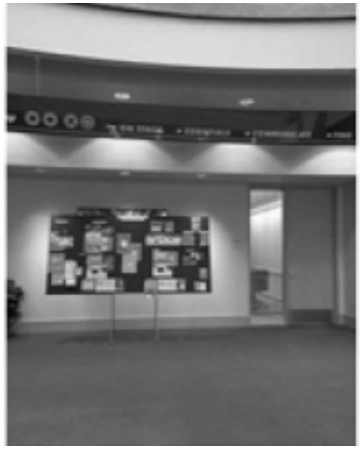
Radial distortion



$$\begin{bmatrix} u_d \\ v_d \end{bmatrix} = (1 + k_1 r^2) \begin{bmatrix} u - u_0 \\ v - v_0 \end{bmatrix} + \begin{bmatrix} u_0 \\ v_0 \end{bmatrix}$$

where

$$r^2 = (u - u_0)^2 + (v - v_0)^2 .$$



Barrel distortion Pincushion distortion

Camera Calibration

- How many parameters do we need to model a camera?

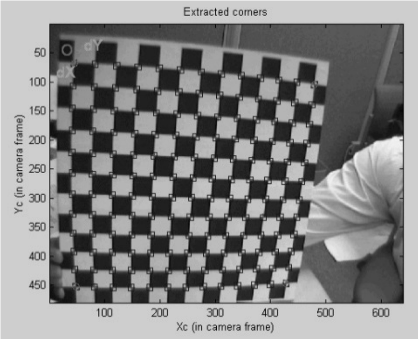
$$\lambda \begin{bmatrix} u \\ v \\ 1 \end{bmatrix} = \begin{bmatrix} \alpha_u & 0 & u_0 \\ 0 & \alpha_v & v_0 \\ 0 & 0 & 1 \end{bmatrix} \cdot R \begin{bmatrix} x_w \\ y_w \\ z_w \end{bmatrix} + T \qquad \begin{bmatrix} u_d \\ v_d \end{bmatrix} = (1 + k_1 \rho^2) \cdot \begin{bmatrix} u \\ v \end{bmatrix}$$

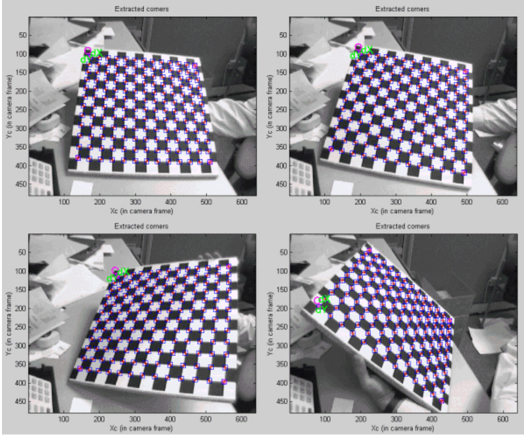
- 5 “intrinsic” parameters: α_u, α_v, u_0, v_0, k_1
- Camera pose?
- 6 “extrinsic” parameters (or 0 if the world and the camera frames coincide)

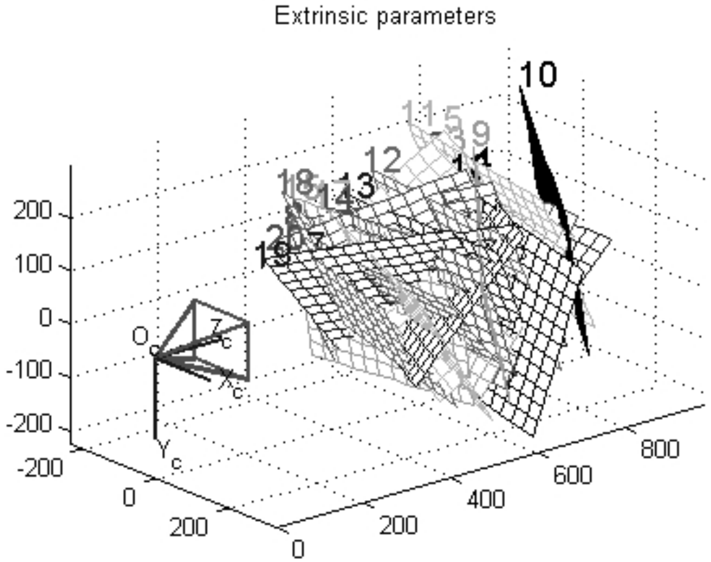
Camera Calibration: how does it work?

- Calibration: measuring accurately **intrinsic** + **extrinsic** parameters of the camera model.
- Parameters: govern mapping from scene points to image points
- Idea: known:
  - pixel coordinates of image points *p*
  - 3D coordinates of the corresponding scene points *P*
  - => compute the unknown parameters A, R, T by solving the perspective projection equation

$$\lambda \begin{bmatrix} u \\ v \\ 1 \end{bmatrix} = \begin{bmatrix} \alpha_u & 0 & u_0 \\ 0 & \alpha_v & v_0 \\ 0 & 0 & 1 \end{bmatrix} \cdot R \begin{bmatrix} x_w \\ y_w \\ z \end{bmatrix} + T$$







ADMIN

Admin

- HW 2 will be graded this week…
- HW 3 is published
  - Two weeks
  - Practical robotics knowledge: robot simulator gazebo and ROS navigation
  - Start early!
- Project:
  - Schedule a meeting with your TA advisor for this week! We will write down when you meet and who is absent. Part of your project score – meeting every week!
- Paper presentation selection thread is open – first come first serve

STEREO VISION

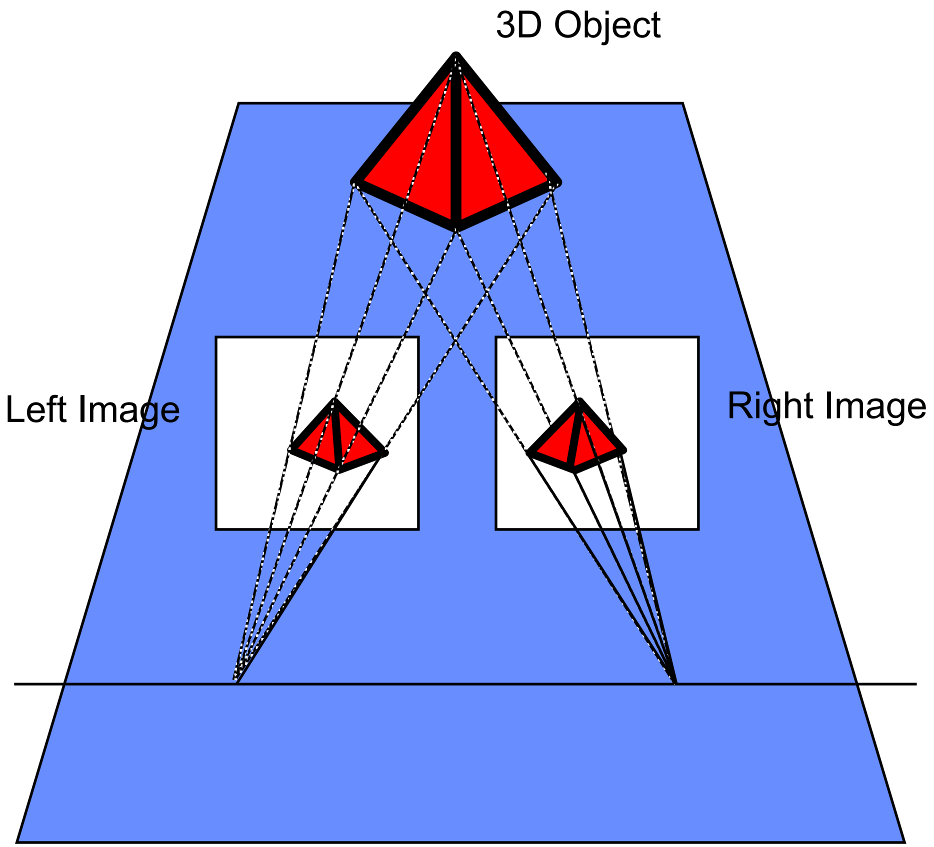
How do we measure distances with cameras?

- Structure from stereo (Stereo-vision):
  - ➢use two cameras with known relative position and orientation

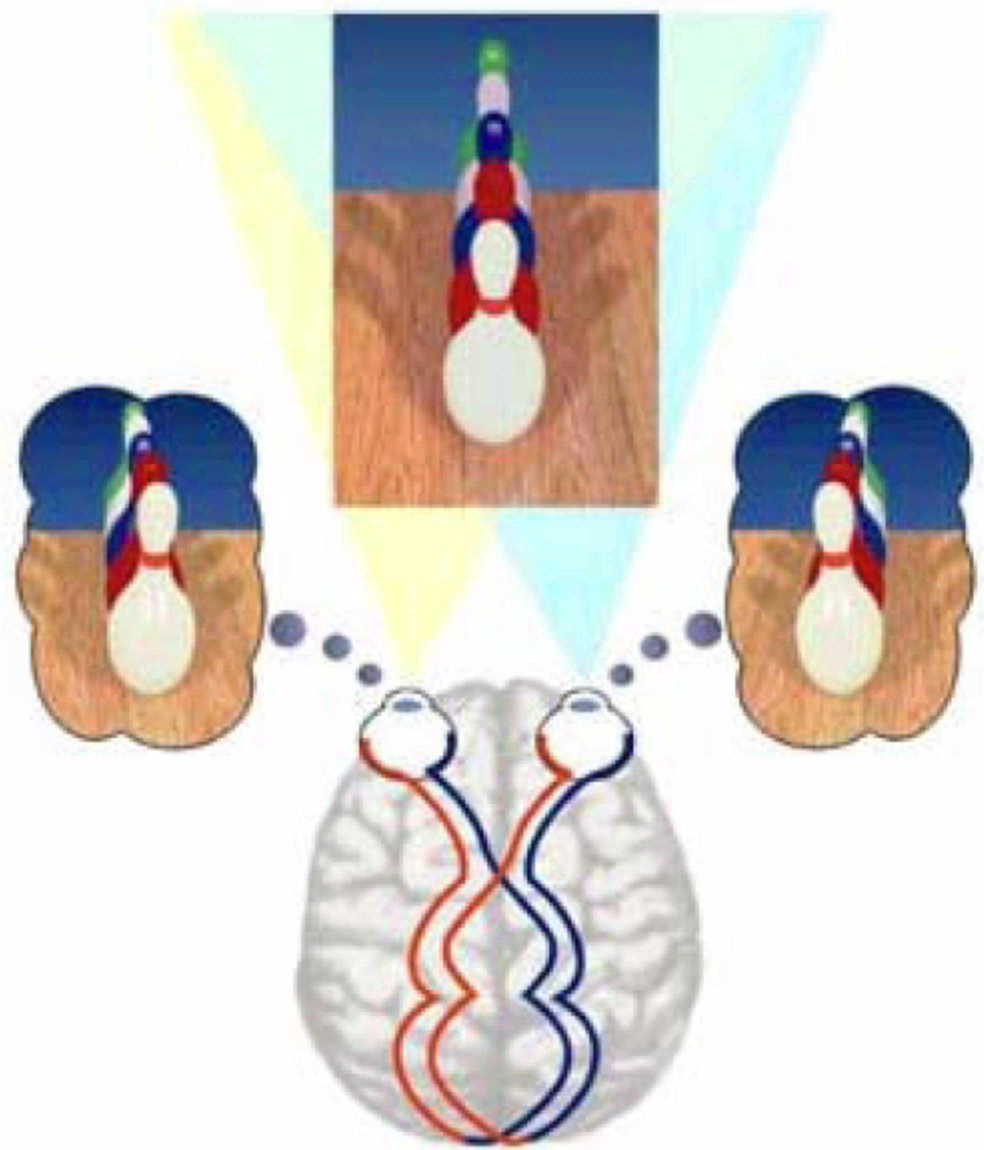

- Structure from motion:
  - ➢use a single moving camera: both 3D structure and camera motion can be estimated up to a scale

Stereo Vision

- Allows to reconstruct a 3D object from two images taken at different locations

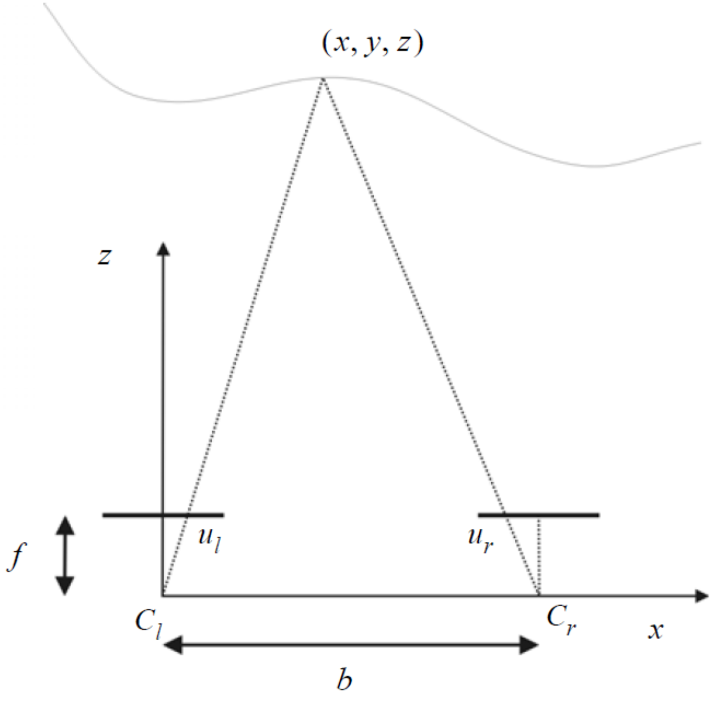


Disparity in the human retina



Stereo Vision - The simplified case

- The simplified case is an ideal case. It assumes that both cameras are identical and are aligned on a horizontal axis



$$\frac{f}{z} = \frac{u_l}{x},$$

$$\frac{f}{z} = \frac{u_r}{b - x}$$

$$z = b\frac{f}{u_l - u_r}$$

Distance

- b = baseline, distance between the optical centers of the two cameras
- f = focal length
- u_l-u_r = disparity

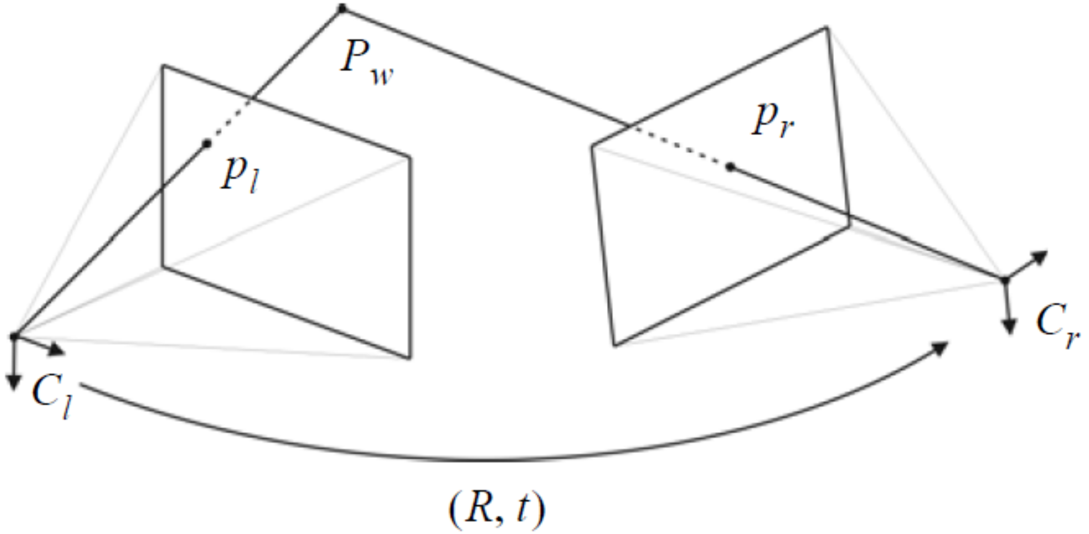
Stereo Vision: how to improve accuracy?

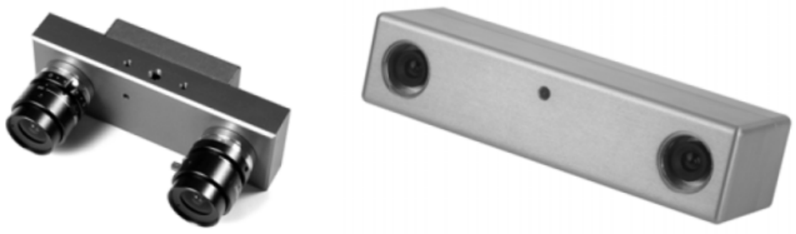
$$z = b\frac{f}{u_l - u_r}$$

1. Distance is inversely proportional to disparity (**u_l-u_r**)
   - closer objects can be measured more accurately
2. Disparity is proportional to ***b***
   - For a given disparity error, the accuracy of the depth estimate increases with increasing baseline ***b***.
   - However, as ***b*** is increased, some objects may appear in one camera, but not in the other.
3. Increasing image resolution improves accuracy

Stereo Vision – the general case

- Two identical cameras do not exist in nature!
- Aligning both cameras on a horizontal axis is very hard, also with the most expensive stereo cameras!

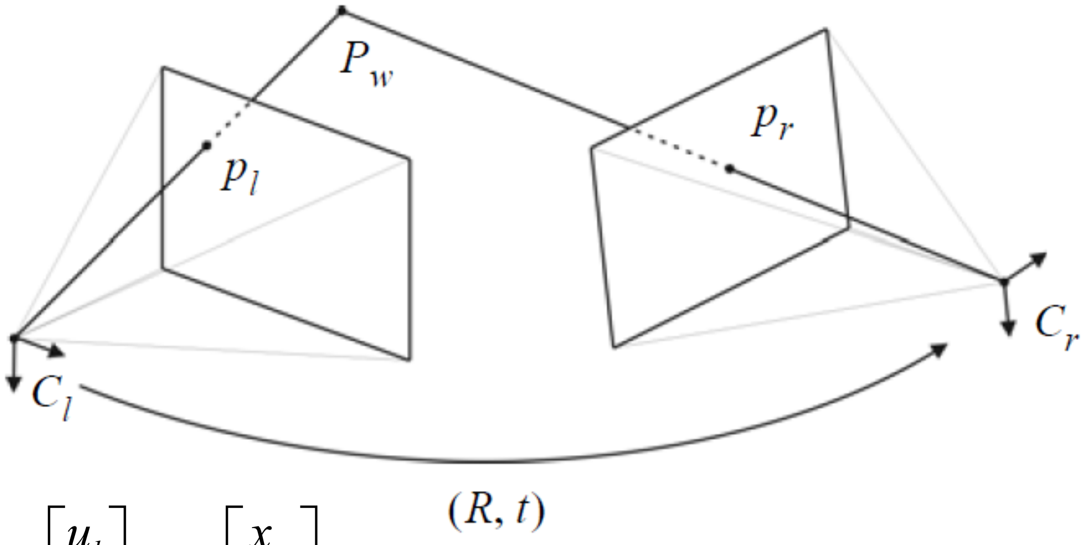




- In order to be able to use a stereo camera, we need first to estimate the relative pose between the cameras, that is, **Rotation** and **Translation**
- However, as the two cameras are not identical, we need to estimate:
  focal length, **image center**, **radial distortion**

Stereo Vision – the general case

- To estimate the 3D position we just construct the system of equations of the left and right camera



$$\lambda_l \begin{bmatrix} u_l \\ v_l \\ 1 \end{bmatrix} = A_l \begin{bmatrix} x_w \\ y_w \\ z_w \end{bmatrix}$$

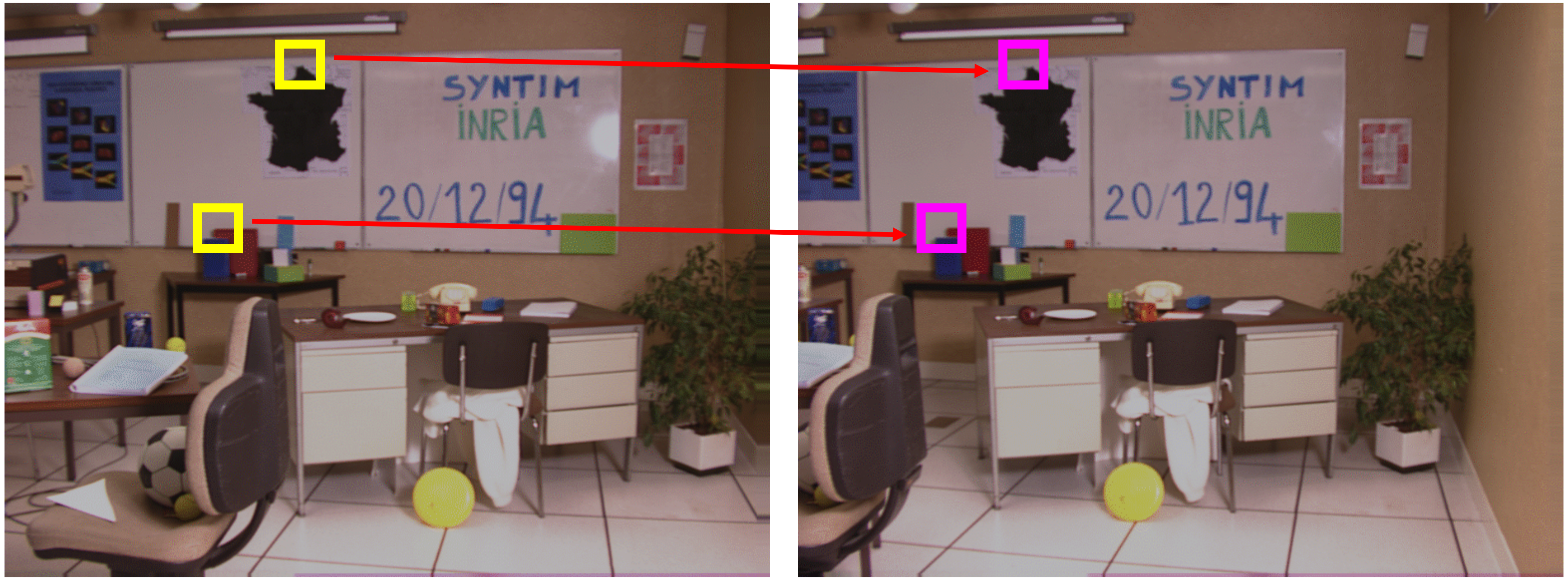
Left camera; world frame coincides with the left camera frame

$$\lambda_r \begin{bmatrix} u_r \\ v_r \\ 1 \end{bmatrix} = A_r \cdot R \begin{bmatrix} x_w \\ y_w \\ z_w \end{bmatrix} + T$$

Right camera

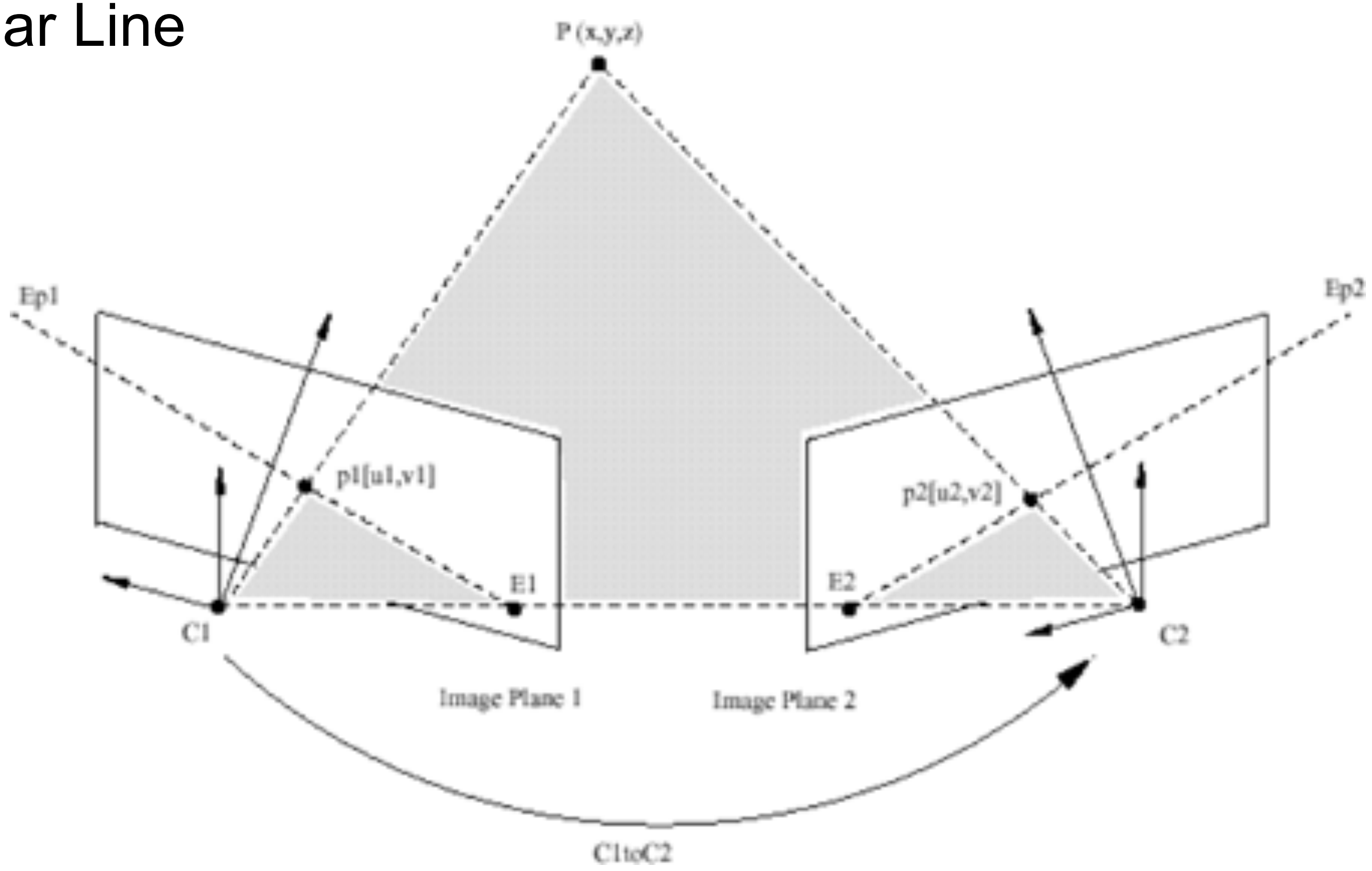
Stereo Vision: Correspondence Problem

- Matching between points in the two images which are projection of the same 3D real point
- Correspondence search could be done by comparing the observed points with all other points in the other image. Typical similarity measures are the Correlation and image Difference.
- This image search can be computationally very expensive! Is there a way to make the correspondence search 1 dimensional?



Correspondence Problem: Epipolar Constraint

- The correspondent of a point in an image must lie on a line in the other image, called Epipolar Line



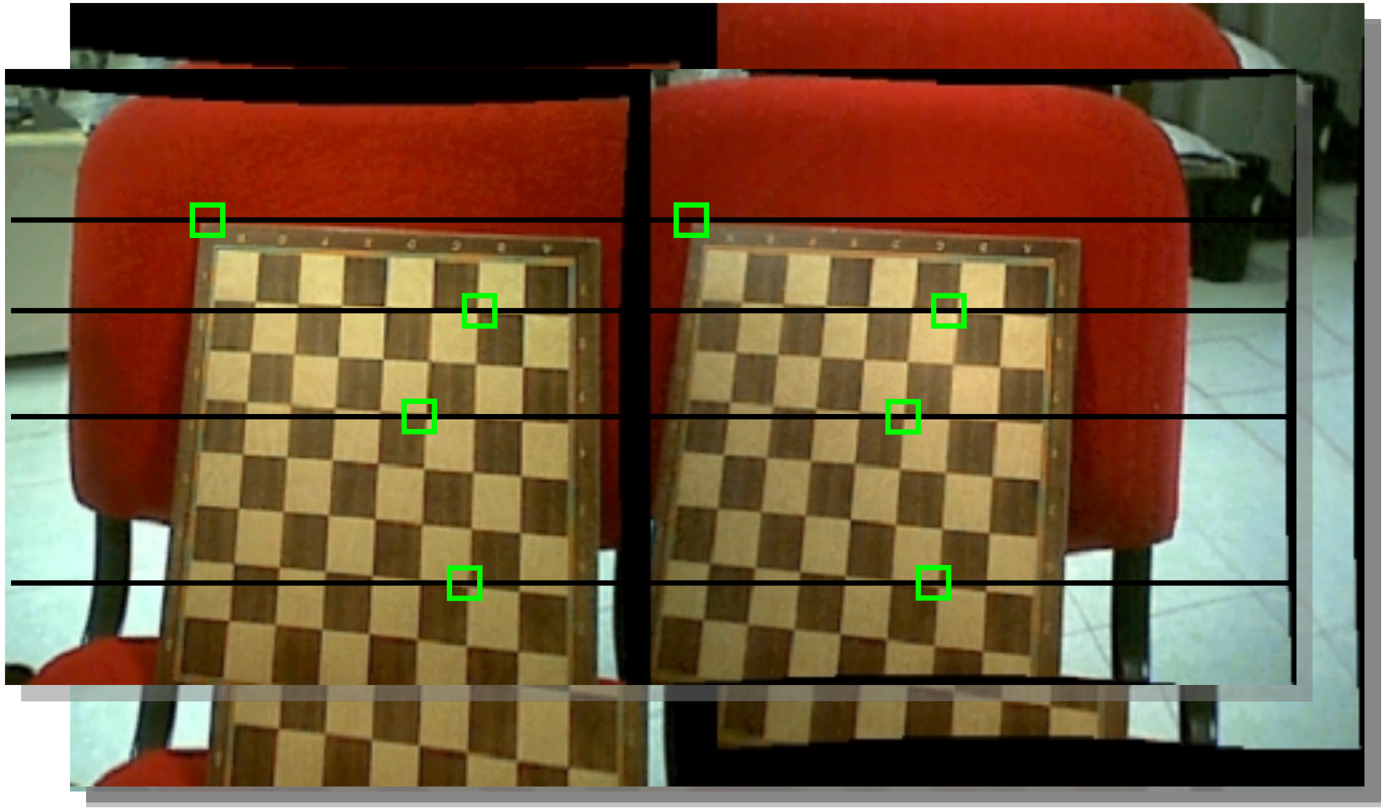
Correspondence Problem: Epipolar Constraint

- Thanks to the epipolar constraint, conjugate points can be searched along epipolar lines: this reduces the computational cost to 1 dimension!

Epipolar Rectification

- Determines a transformation of each image plane so that pairs of conjugate epipolar lines become collinear and parallel to one of the image axes (usually the horizontal one)

Rotation
⇩
Focal lengths
⇩
Lens Distortion
⇩
Translation



Stereo Vision Output 1 – Disparity map

- Find the correspondent points of all image pixels of the original images
- For each pair of conjugate points compute the disparity ***d* = *v-v'***
- ***d(x,y)*** is called Disparity map.

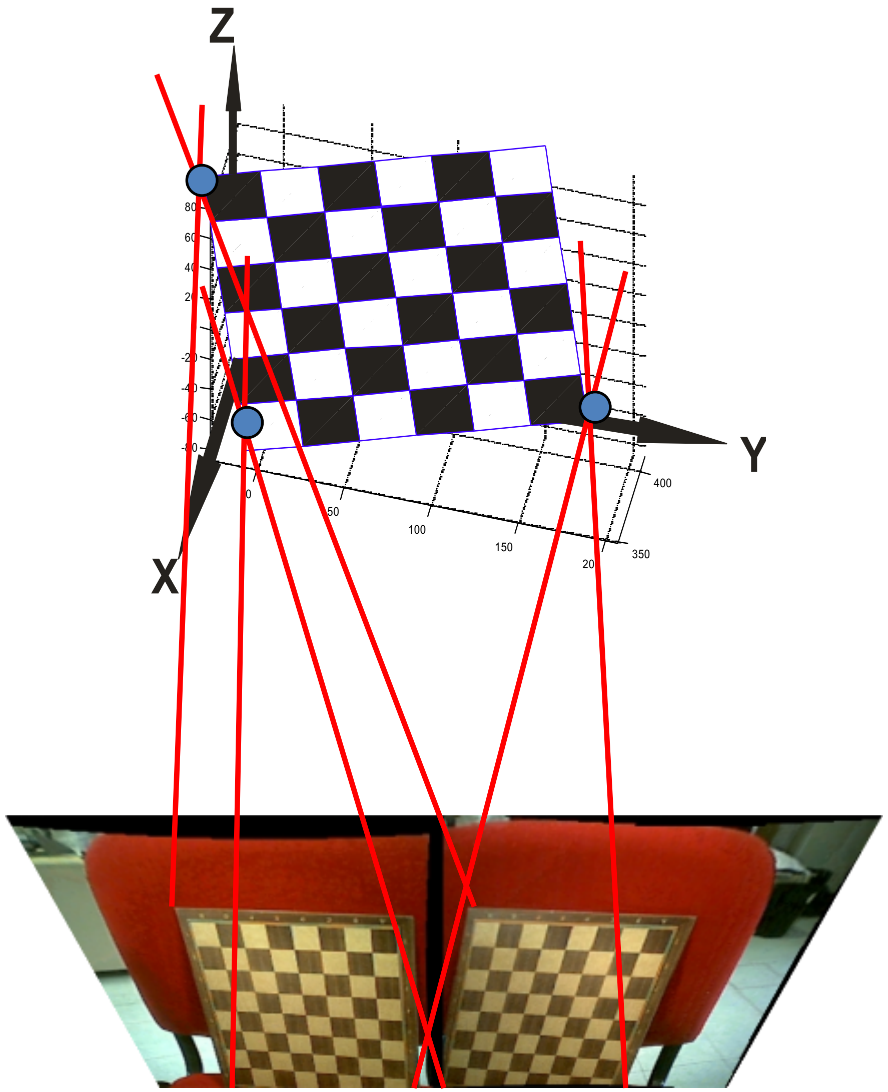
Left image

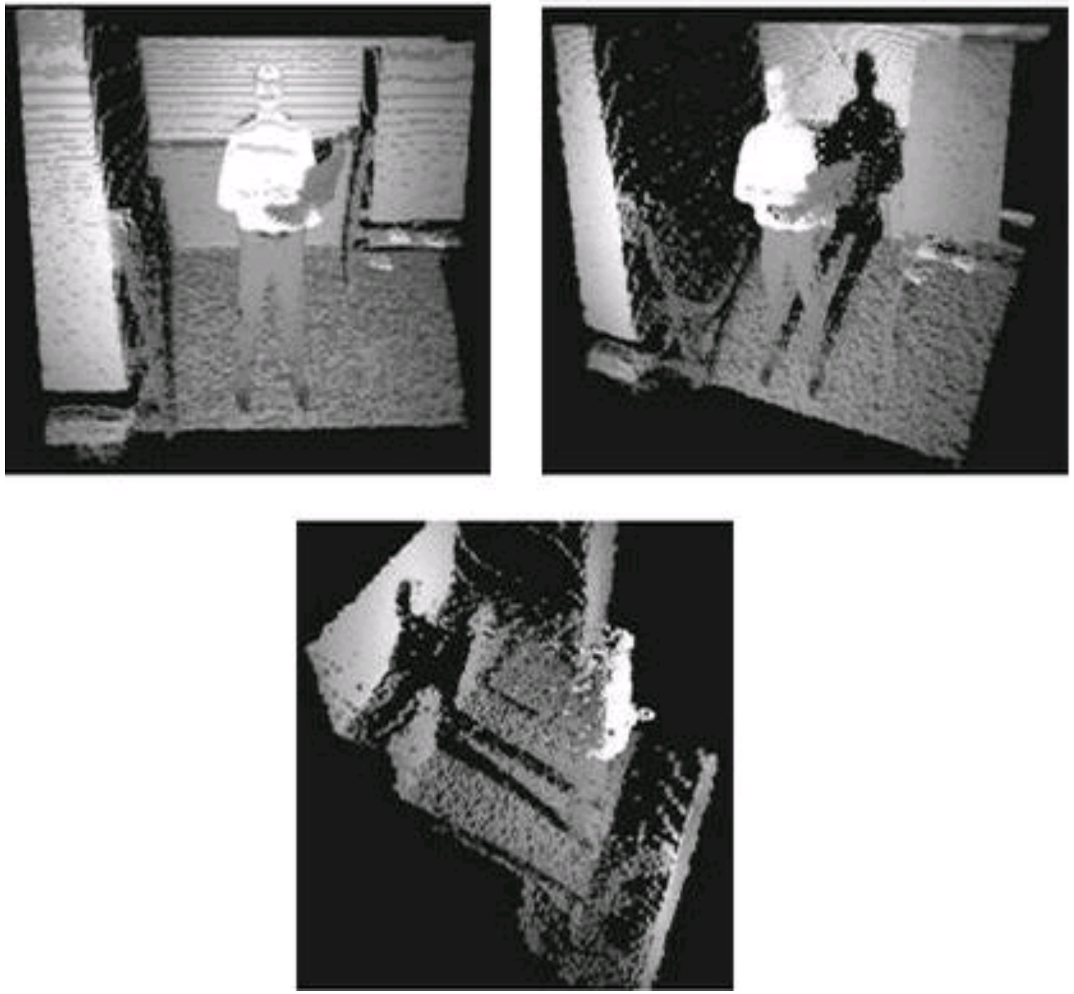
Right image

Disparity map

- Disparity maps are usually visualized as grey-scale images. Objects that are closer to the camera appear lighter, those who are further appear darker.

Stereo Vision Output 2 - 3D Reconstruction via triangulation





Stereo Camera Calibration

Totals:

Estimate the parameters for each camera in order the 3D-2D transformation

10 parameters for each camera need to be estimated

PLUS:

5 parameters for each camera in order to compensate lens distortion (radial & tangential distortion)

$$\begin{cases} \begin{bmatrix} u_{d,L} \\ v_{d,L} \end{bmatrix} = (1 + kc_{1,L}\rho^2 + kc_{2,L}\rho^4 + kc_{5,L}\rho^6) \cdot \begin{bmatrix} u \\ v \end{bmatrix} + \begin{bmatrix} 2kc_{3,L} \cdot u \cdot v + kc_{4,L}(\rho^2 + 2u^2) \\ kc_{3,L}(\rho^2 + 2v^2) + 2kc_{4,L} \cdot u \cdot v \end{bmatrix} \\ \begin{bmatrix} u_{d,R} \\ v_{d,R} \end{bmatrix} = (1 + kc_{1,R}\rho^2 + kc_{2,R}\rho^4 + kc_{5,R}\rho^6) \cdot \begin{bmatrix} u \\ v \end{bmatrix} + \begin{bmatrix} 2kc_{3,R} \cdot u \cdot v + kc_{4,R}(\rho^2 + 2u^2) \\ kc_{3,R}(\rho^2 + 2v^2) + 2kc_{4,R} \cdot u \cdot v \end{bmatrix} \end{cases}$$

$$\begin{cases} \begin{bmatrix} u_L \\ v_L \end{bmatrix} = f\left(\begin{bmatrix} X \\ Y \\ Z \end{bmatrix} \right) \end{cases}$$

$$\begin{cases} \begin{bmatrix} u_L \\ v_L \\ 1 \end{bmatrix} = \begin{bmatrix} f_{u,L} & 0 & u_{0,L} \\ 0 & f_{v,L} & v_{0,L} \\ 0 & 0 & 1 \end{bmatrix} \cdot \begin{bmatrix} r_{11} & r_{12} & r_{13} & t_x \\ r_{21} & r_{22} & r_{23} & t_y \\ r_{31} & r_{32} & r_{33} & t_z \end{bmatrix} \cdot \begin{bmatrix} X \\ Y \\ Z \\ 1 \end{bmatrix} \\ \begin{bmatrix} u_R \\ v_R \\ 1 \end{bmatrix} = \begin{bmatrix} f_{u,R} & 0 & u_{0,R} \\ 0 & f_{v,R} & v_{0,R} \\ 0 & 0 & 1 \end{bmatrix} \cdot \begin{bmatrix} r_{11} & r_{12} & r_{13} & t_x \\ r_{21} & r_{22} & r_{23} & t_y \\ r_{31} & r_{32} & r_{33} & t_z \end{bmatrix} \cdot \begin{bmatrix} X \\ Y \\ Z \\ 1 \end{bmatrix} \end{cases}$$

Stereo Camera Calibration

Estimates the parameters that manage the 3D – 2D transformation

$$\begin{cases} \begin{bmatrix} u_L \\ v_L \end{bmatrix} = f\begin{pmatrix} X \\ Y \\ Z \end{pmatrix} \\ \begin{bmatrix} u_R \\ v_R \end{bmatrix} = f\begin{pmatrix} X \\ Y \\ Z \end{pmatrix} \end{cases}$$

Stereo Camera Calibration

Totally:

Estimates the parameters that manage the 3D – 2D transformation

10 parameters for each camera need to be estimated

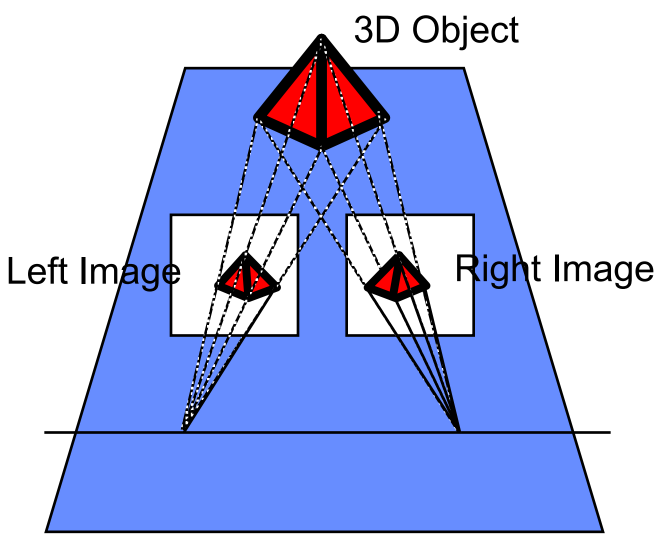
$$\begin{cases} \begin{bmatrix} u_L \\ v_L \\ 1 \end{bmatrix} = \begin{bmatrix} f_{u,L} & 0 & u_{0,L} \\ 0 & f_{v,L} & v_{0,L} \\ 0 & 0 & 1 \end{bmatrix} \cdot \begin{bmatrix} r_{11} & r_{12} & r_{13} & t_x \\ r_{21} & r_{22} & r_{23} & t_y \\ r_{31} & r_{32} & r_{33} & t_z \end{bmatrix} \cdot \begin{bmatrix} X \\ Y \\ Z \\ 1 \end{bmatrix} \\ \begin{bmatrix} u_R \\ v_R \\ 1 \end{bmatrix} = \begin{bmatrix} f_{u,R} & 0 & u_{0,R} \\ 0 & f_{v,R} & v_{0,R} \\ 0 & 0 & 1 \end{bmatrix} \cdot \begin{bmatrix} r_{11} & r_{12} & r_{13} & t_x \\ r_{21} & r_{22} & r_{23} & t_y \\ r_{31} & r_{32} & r_{33} & t_z \end{bmatrix} \cdot \begin{bmatrix} X \\ Y \\ Z \\ 1 \end{bmatrix} \end{cases}$$

Stereo Camera Calibration

PLUS
5 parameters for each camera in order to compensate for lens distortion (radial & tangential distortion)

$$\begin{cases} \begin{bmatrix} u_{d,L} \\ v_{d,L} \end{bmatrix} = (1 + kc_{1,L}\rho^2 + kc_{2,L}\rho^4 + kc_{5,L}\rho^6) \cdot \begin{bmatrix} u \\ v \end{bmatrix} + \begin{bmatrix} 2kc_{3,L} \cdot u \cdot v + kc_{4,L}(\rho^2 + 2u^2) \\ kc_{3,L}(\rho^2 + 2v^2) + 2kc_{4,L} \cdot u \cdot v \end{bmatrix} \\ \begin{bmatrix} u_{d,R} \\ v_{d,R} \end{bmatrix} = (1 + kc_{1,R}\rho^2 + kc_{2,R}\rho^4 + kc_{5,R}\rho^6) \cdot \begin{bmatrix} u \\ v \end{bmatrix} + \begin{bmatrix} 2kc_{3,R} \cdot u \cdot v + kc_{4,R}(\rho^2 + 2u^2) \\ kc_{3,R}(\rho^2 + 2v^2) + 2kc_{4,R} \cdot u \cdot v \end{bmatrix} \end{cases}$$

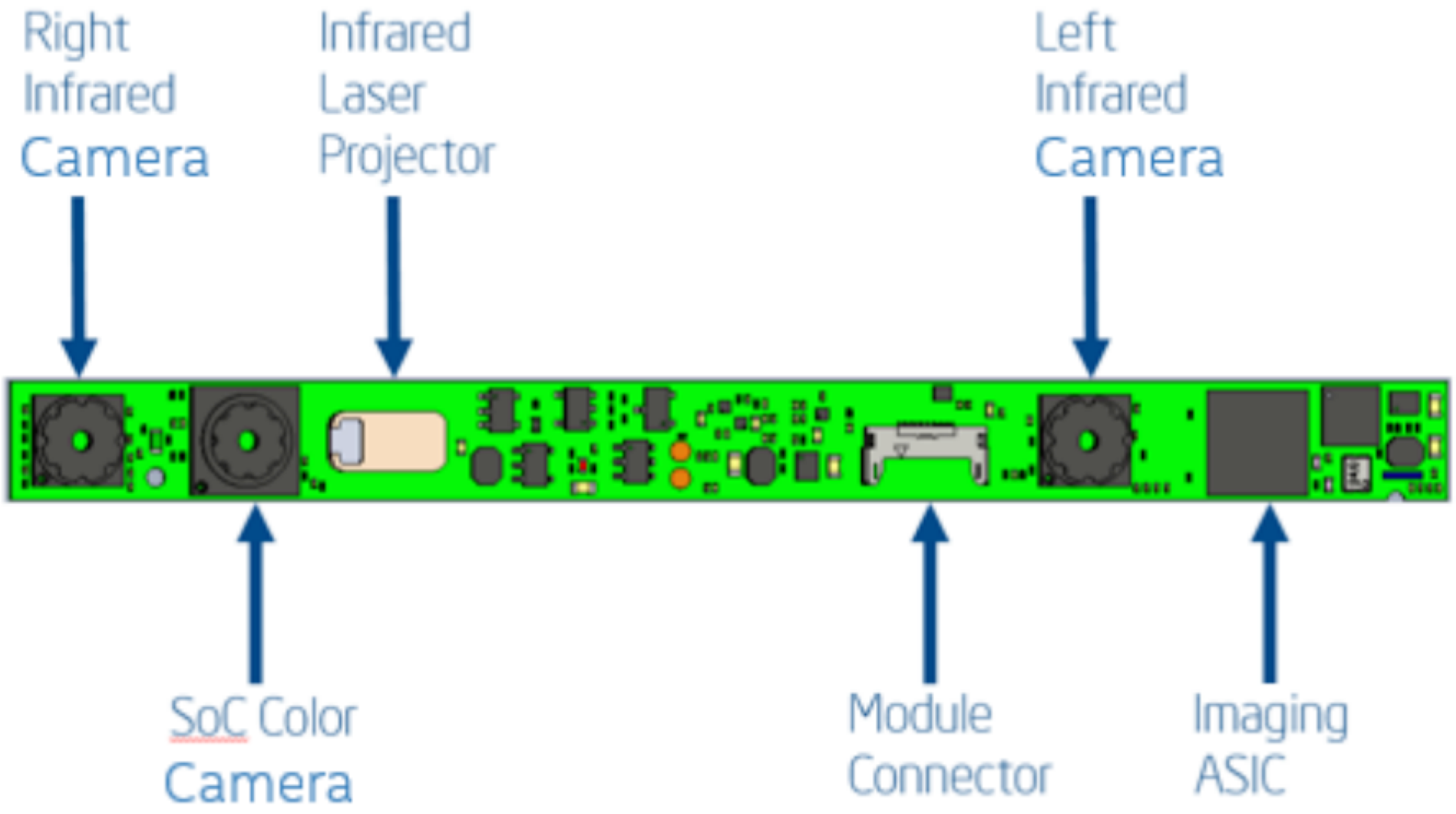
Stereo Vision - summary

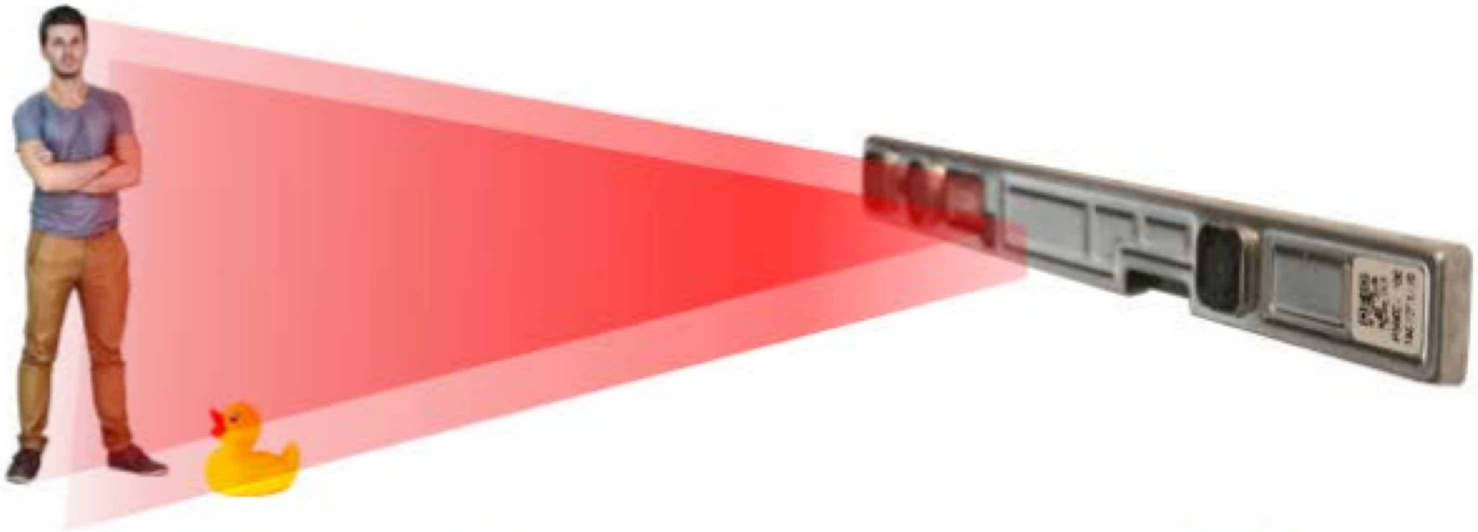


1. Stereo camera calibration -> compute camera relative pose
2. Epipolar rectification -> align images
3. Search correspondences
4. Output: compute stereo triangulation or disparity map
5. Consider baseline and image resolution to compute accuracy!

Device example:

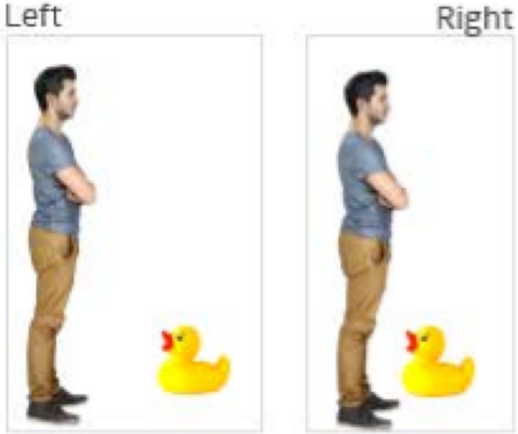
- 640x480 stereo infrared cameras
- 1920x1080 HD RGB camera
- Infrared Laser Projector
- Up to 60Hz





1 CAPTURE

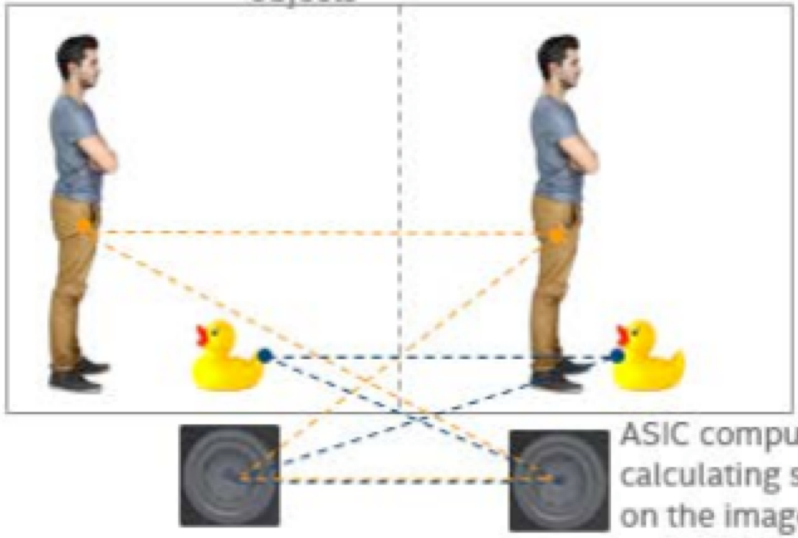
Project invisible light pattern on low texture surfaces like plain walls



Each camera sees a slightly different viewpoint

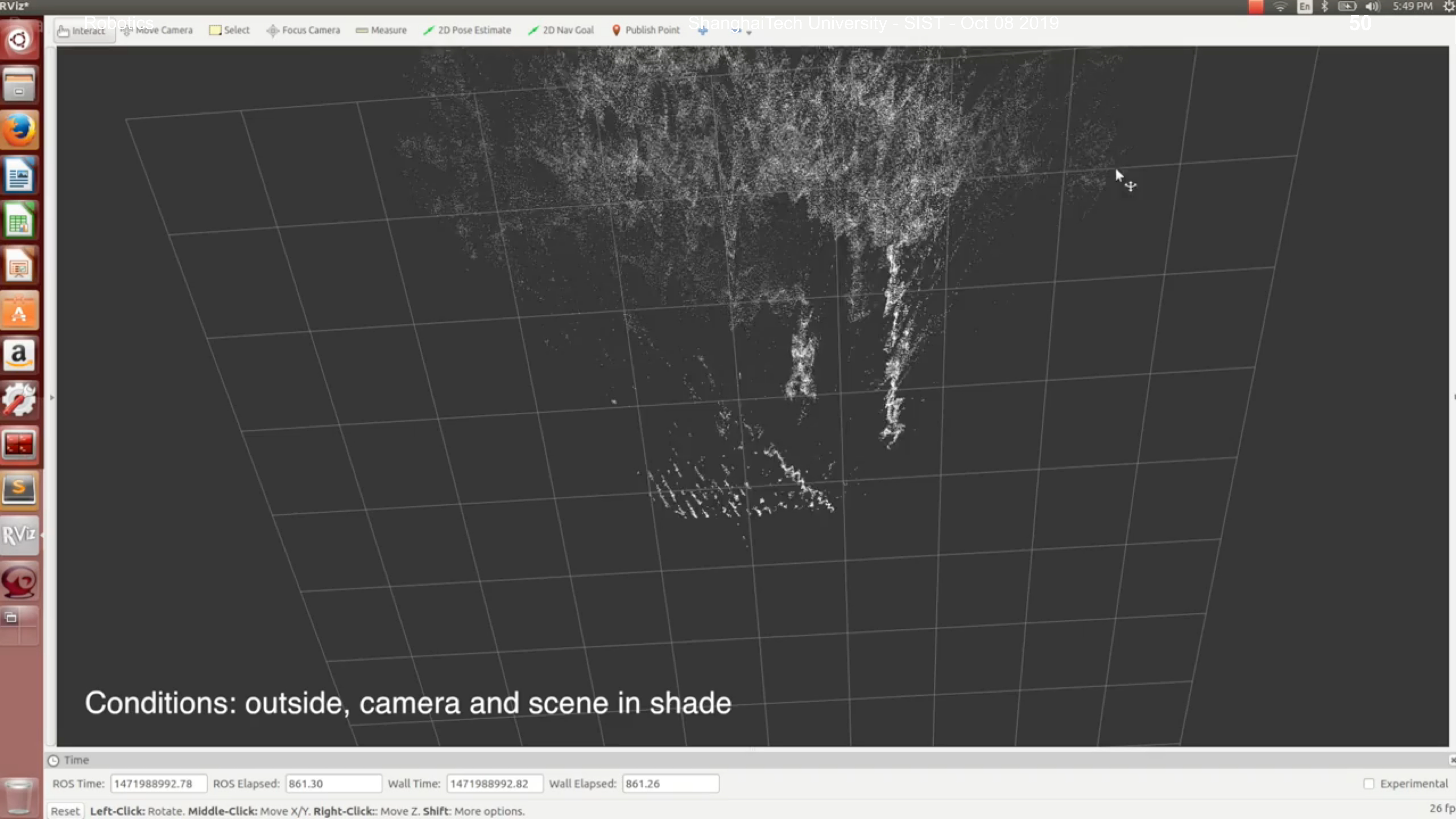
2 SEARCH

Closer objects shift more than further away objects



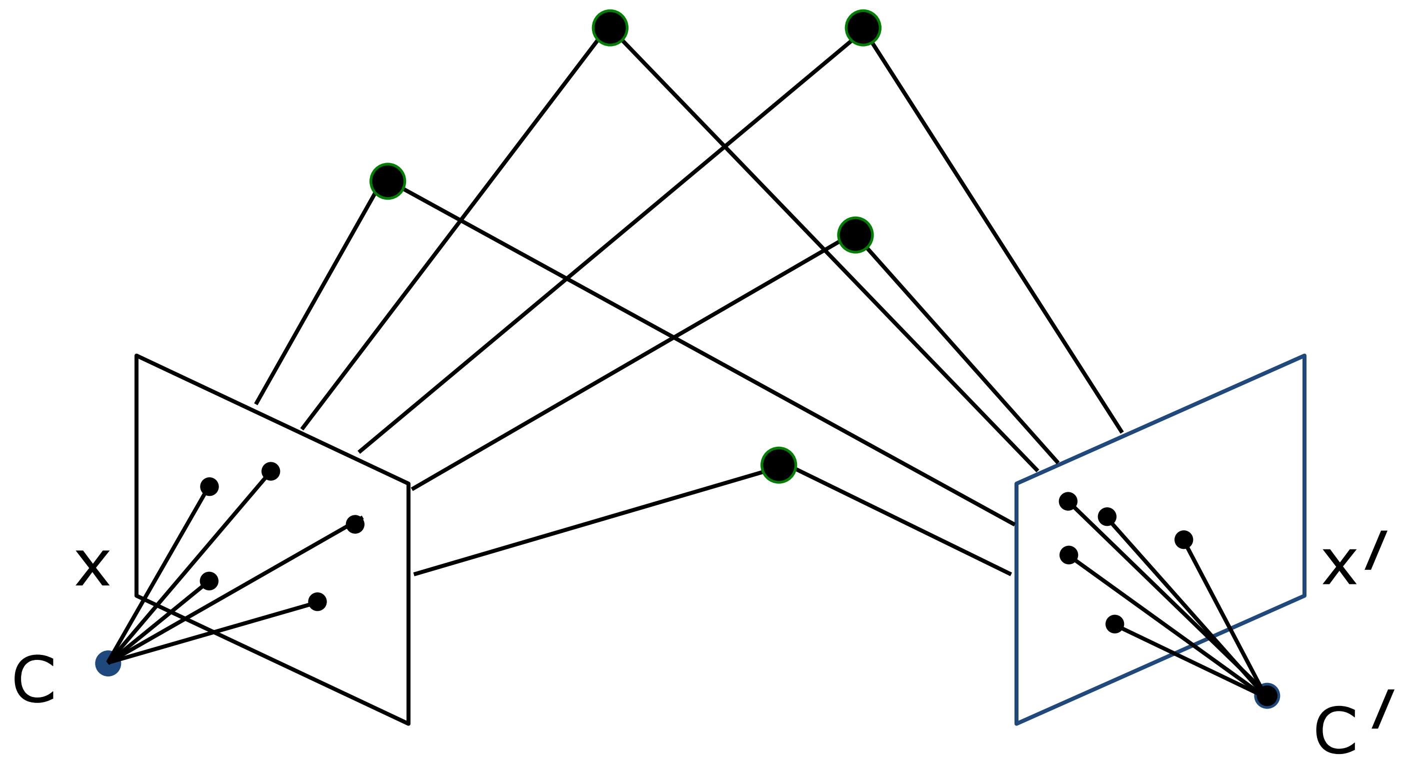
ASIC computes depth by calculating shift of every pixel on the image between the left and right images

3 DEPTH

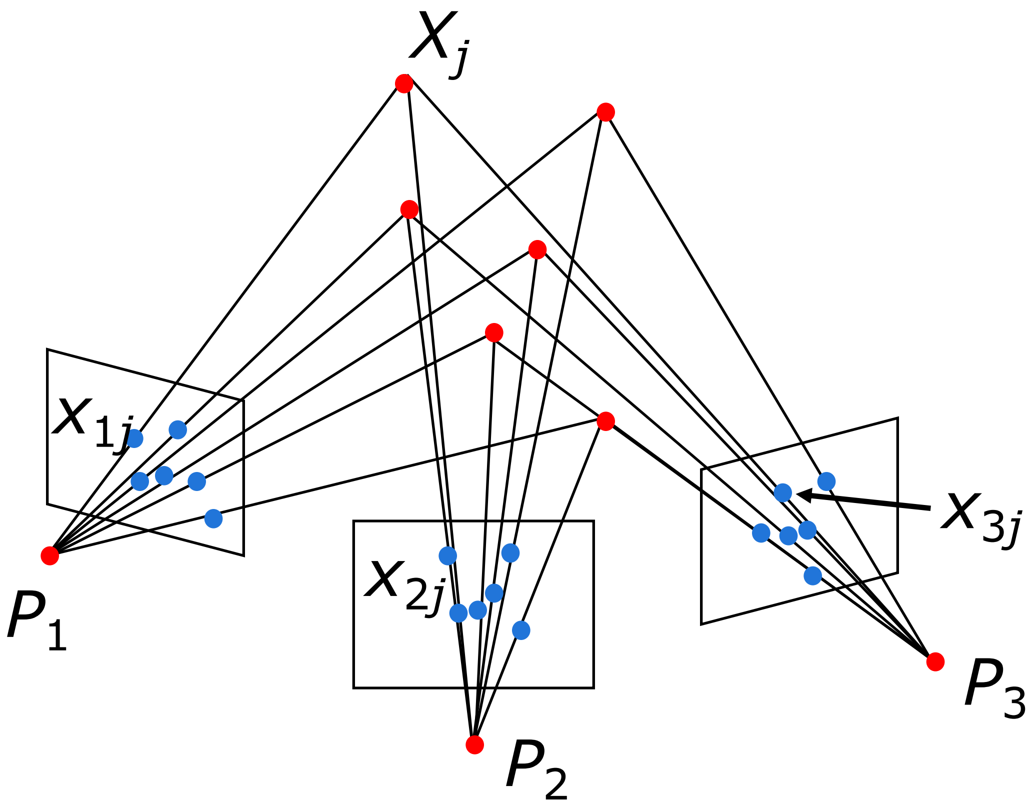

RViz*
Interact
Move Camera
Select
Focus Camera
Measure
2D Pose Estimate
2D Nav Goal
Publish Point
5:49 PM
Conditions: outside, camera and scene in shade
Time
ROS Time: 1471988992.78
ROS Elapsed: 861.30
Wall Time: 1471988992.82
Wall Elapsed: 861.26
Experimental
Reset
Left-Click: Rotate. Middle-Click: Move X/Y. Right-Click:: Move Z. Shift: More options.

Structure from motion

- Given image point correspondences, $\mathbf{x}_i \leftrightarrow \mathbf{x}_i'$,determine R and T
- Rotate and translate camera until stars of rays intersect
- At least 5 point correspondences are needed



Multiple-view structure from motion

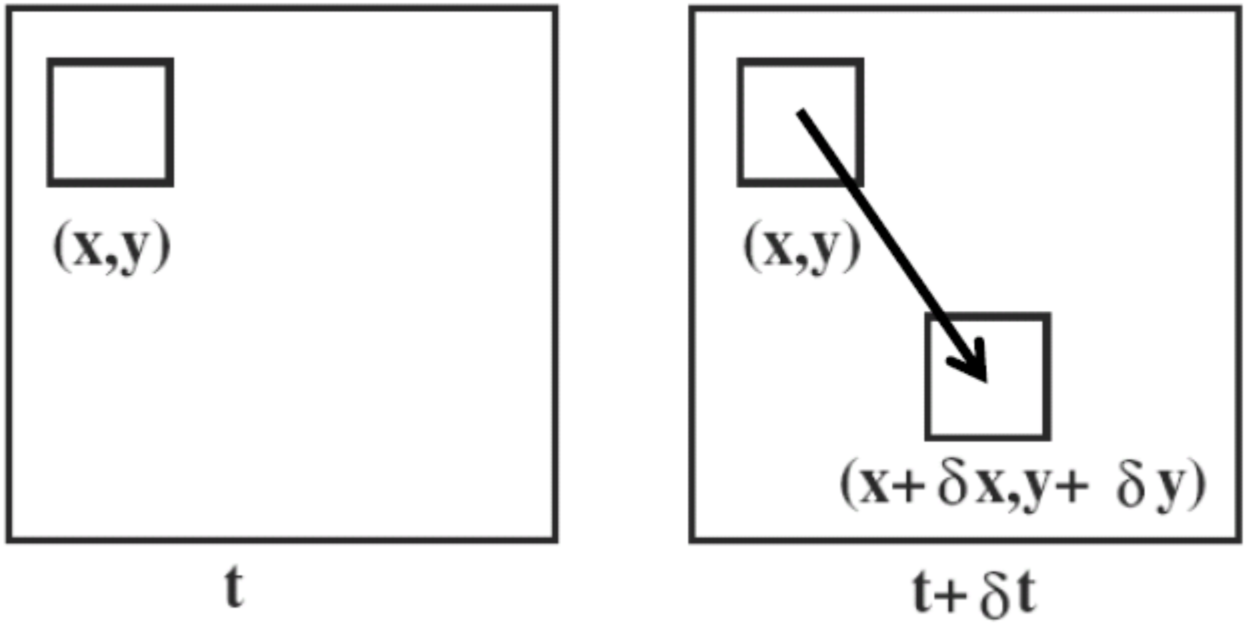


Multiple-view structure from motion

- Results of Structure from motion from 2 million user images from flickr.com - 2,106 images selected, 819,242 points

Optical Flow

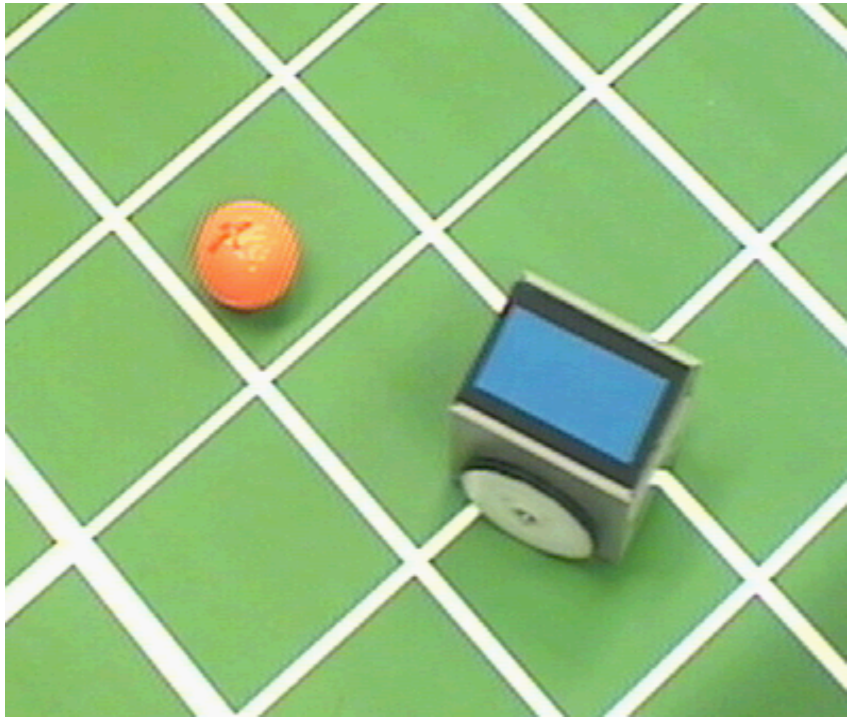
- It computes the motion vectors of all pixels in the image (or a subset of them to be faster)

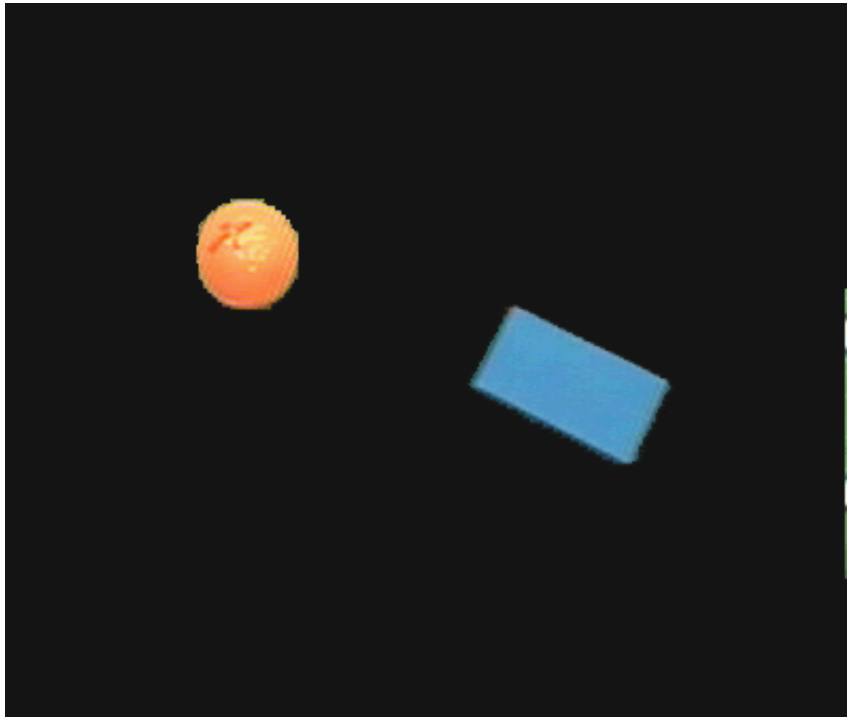


- Applications include collision avoidance

Color Tracking

- Motion estimation of ball and robot for soccer playing using color tracking





Color segmentation with fixed thesholds

- Simple: constant thresholding:
  - selection only **iff** RGB values (r,g,b) simultaneously in R, G, and B ranges:
  - six thresholds [Rmin,Rmax], [Gmin,Gmax], [Bmin,Bmax]:

$$R_{min} < r < R_{max} \ \ and \ \ G_{min} < g < G_{max} \ \ and \ \ B_{min} < b < B_{max}$$

- Alternative: YUV color space
  - RGB values encode intensity of each color
  - YUV:
  - U and V together color (or chrominance)
  - Y brightness (or luminosity)
  - bounding box in YUV space => greater stability wrt. changes in illumination