ME336 Collaborative Robot Learning Spring 2019 Wednesday, March 22

Lecture 05
Images & Cameras

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Assistant Professor

Department of Mechanical and Energy Engineering

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of Science and Technology

A Dynamical System Approach for Softly Catching a Flying Object: Theory and Experiment

By Seyed Sina Mirrazavi Salehian; Mahdi Khoramshahi; Aude Billard (EPFL)

S. S. M. Salehian, M. Khoramshahi and A. Billard, "A Dynamical System Approach for Softly Catching a Flying Object: Theory and Experiment," in IEEE Transactions on Robotics, vol. 32, no. 2, pp. 462-471, April 2016. doi: 10.1109/TRO.2016.2536749

From Animals, to Computers, then Robots

The Concept of Vision

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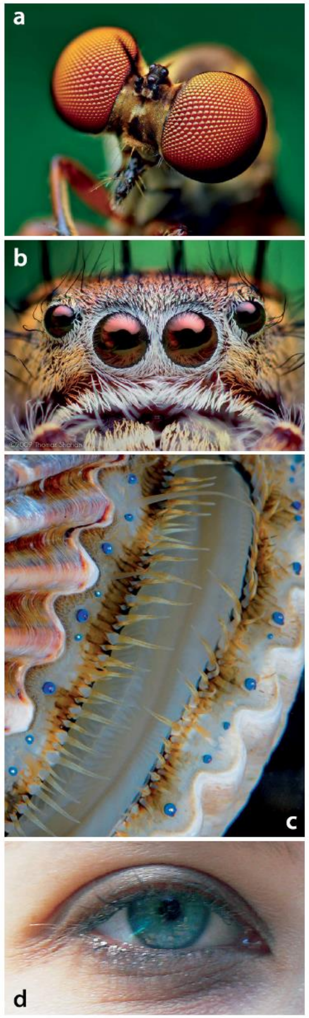
The Concept of Vision



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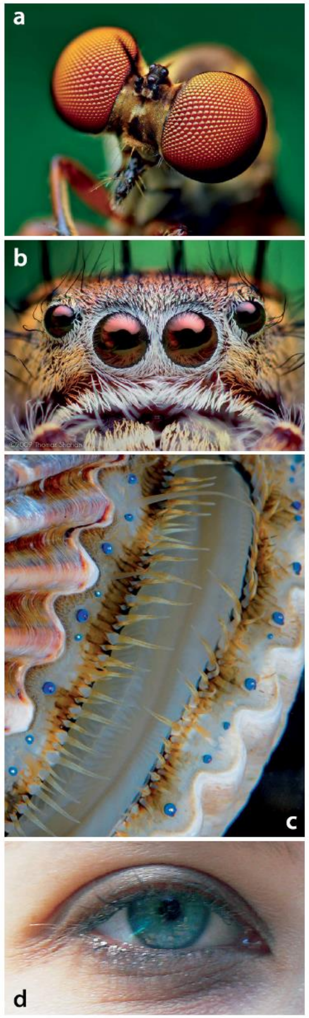

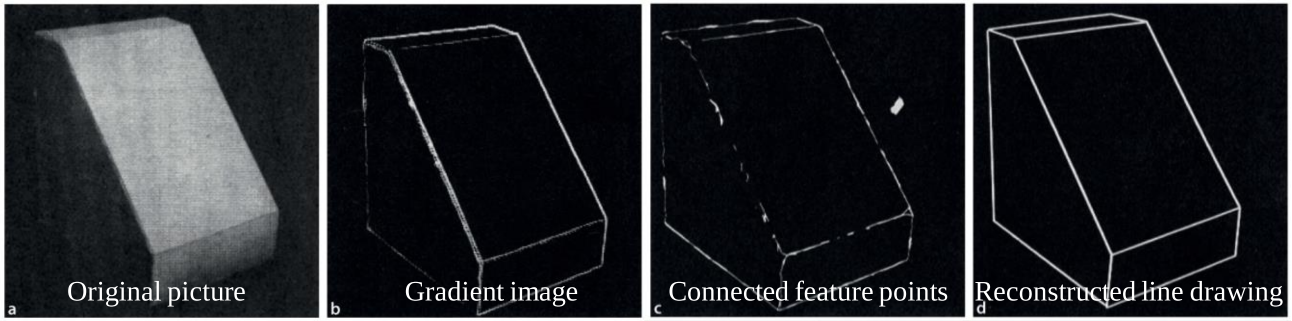

Early results in computer vision for estimating the shape and pose of objects,
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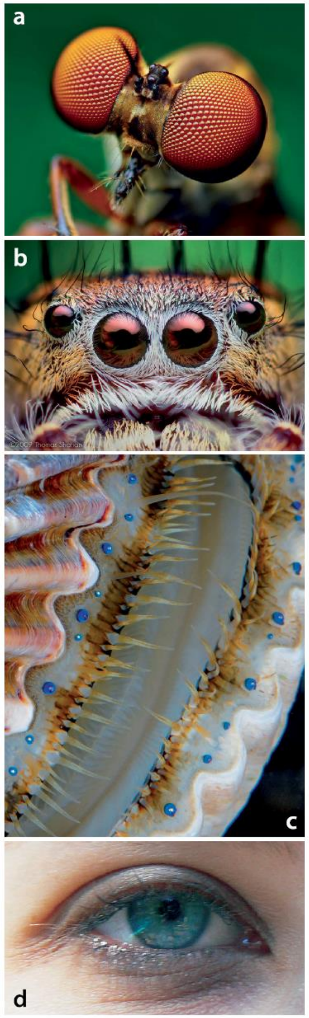

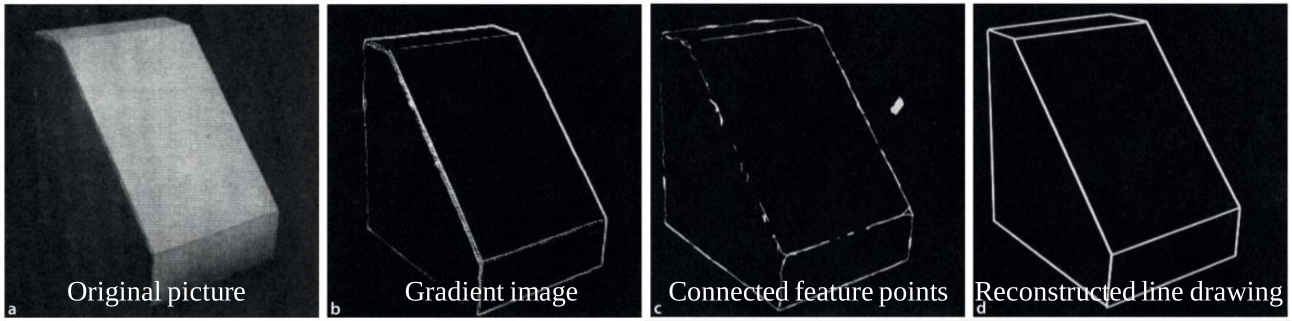

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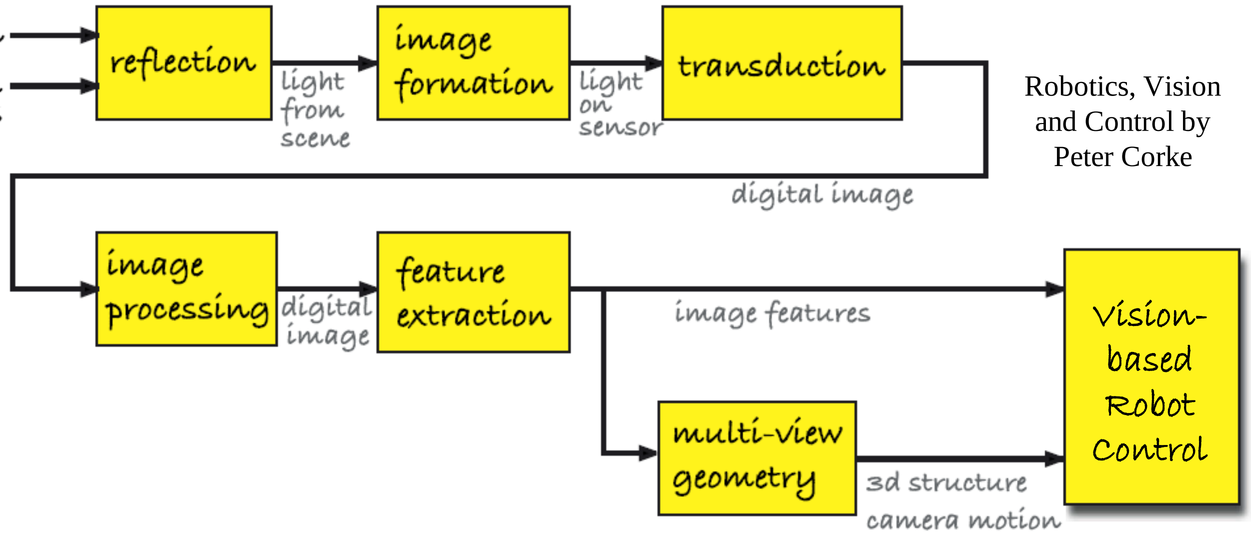

Robotics, Vision and Control by Peter Corke

What Does Vision Tell Us About the World?

Or the Robot as a Machine

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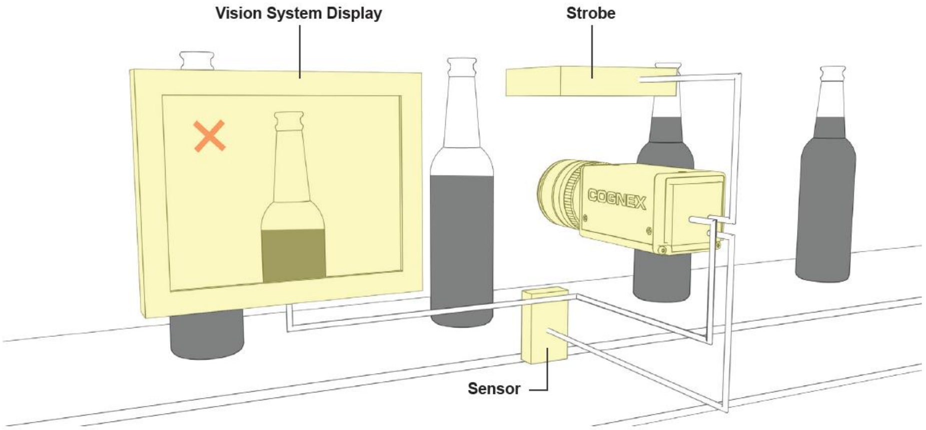
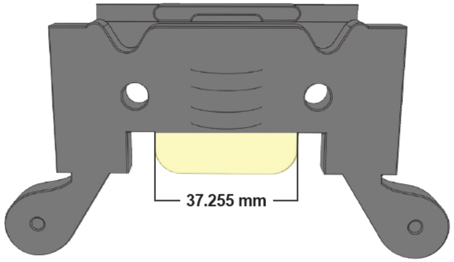
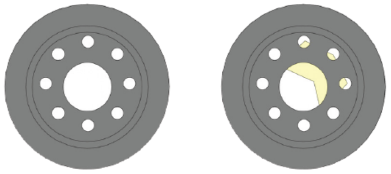
What Does Vision Tell Us About the World?

Or the Robot as a Machine

- Static features
  - Distance
  - Color
  - Shape
  - Texture
  - Environment
  - …







Good oil filter
(all holes are open)

Reject oil filter
(some holes are blocked)

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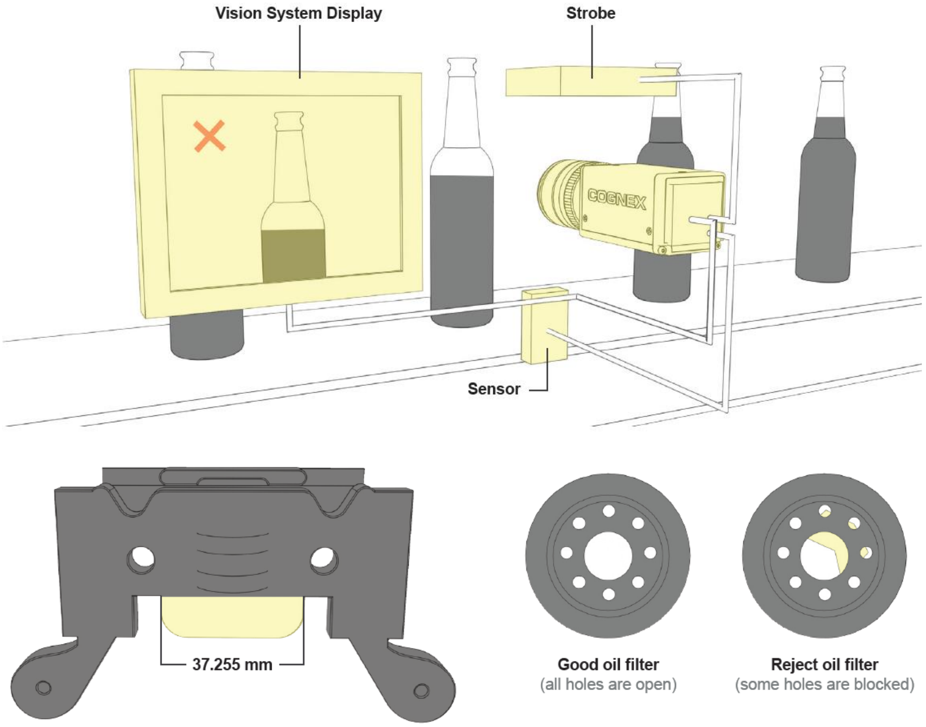

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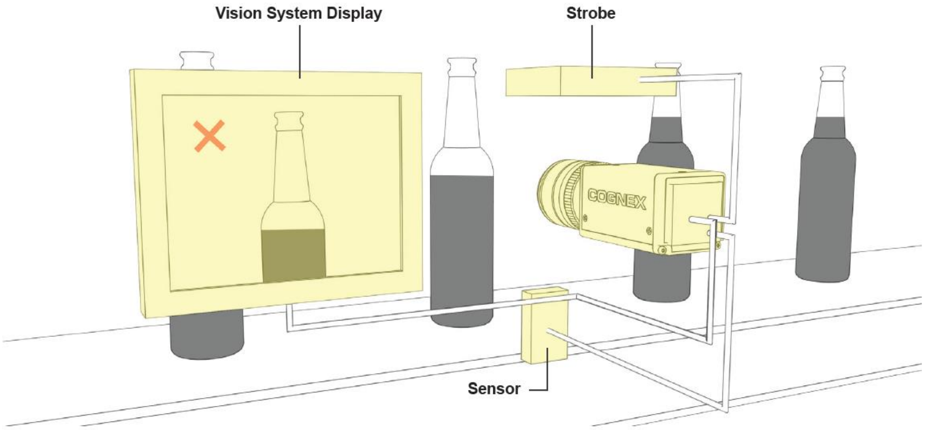

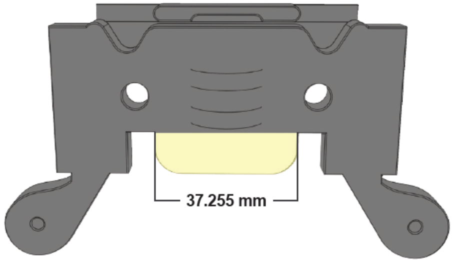

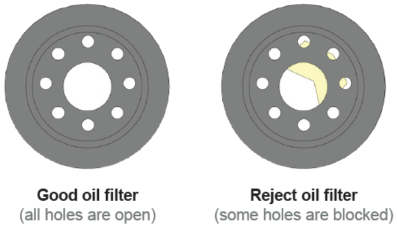

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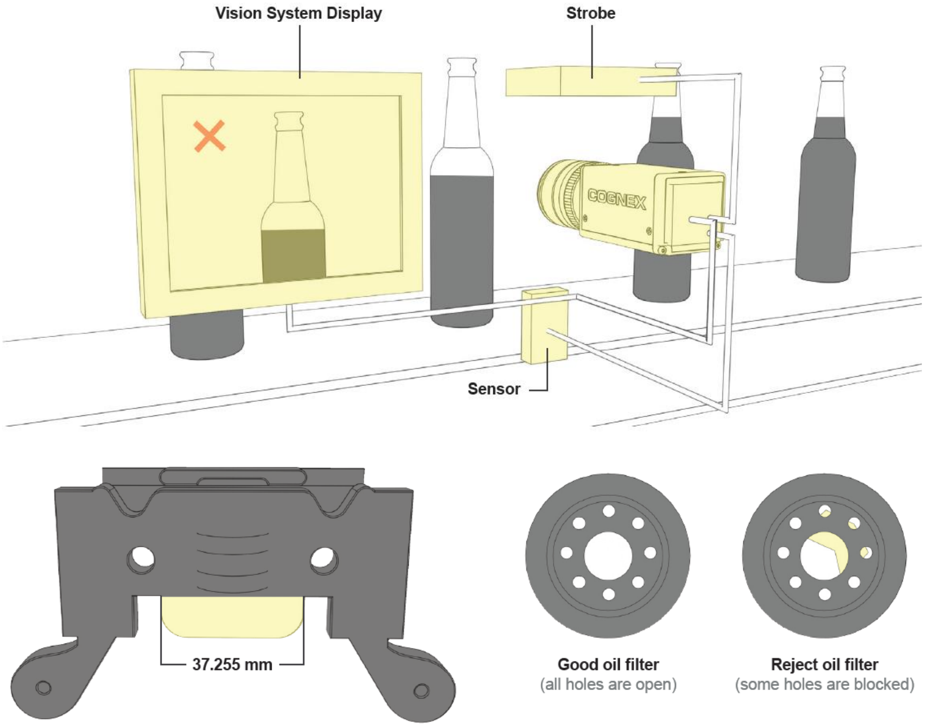
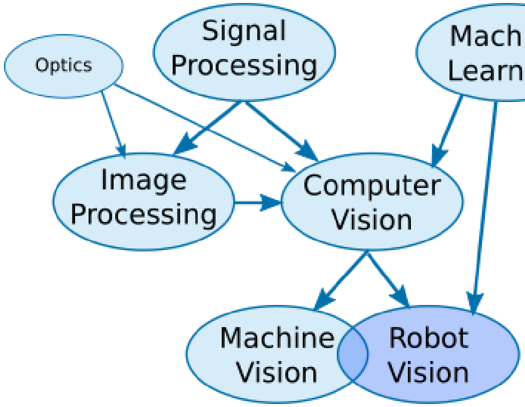
- Dynamic motions
- Understanding of the behavior
- *An important method to interact with the physical world*



Differentiating Concepts about Vision



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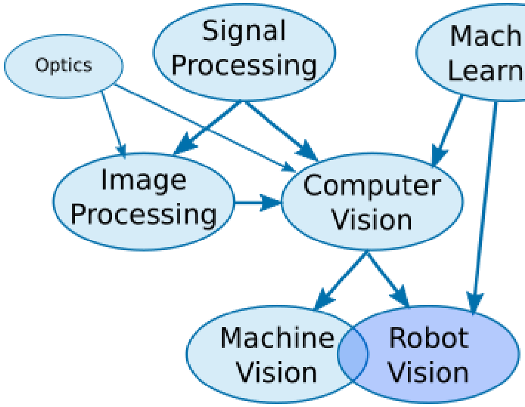

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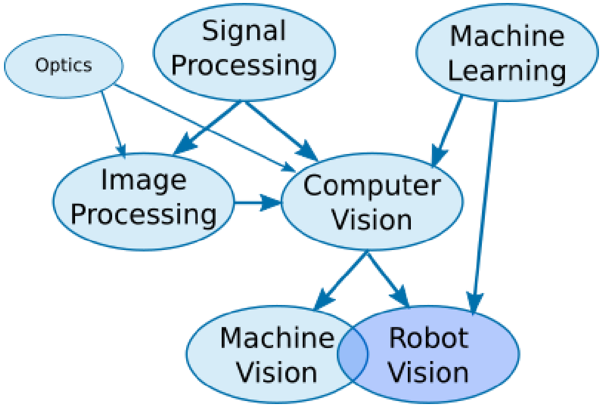

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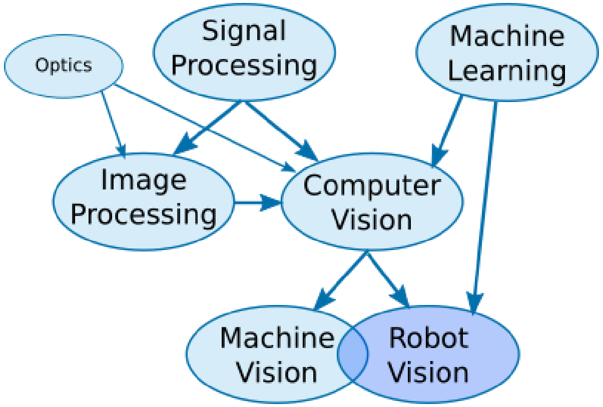

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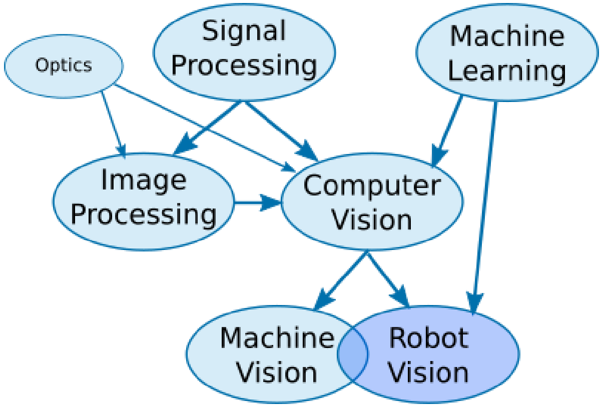

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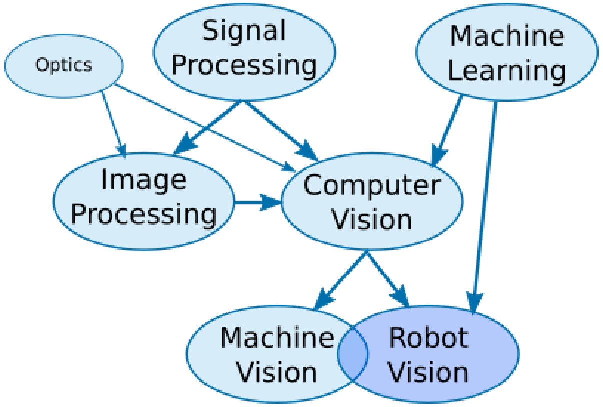

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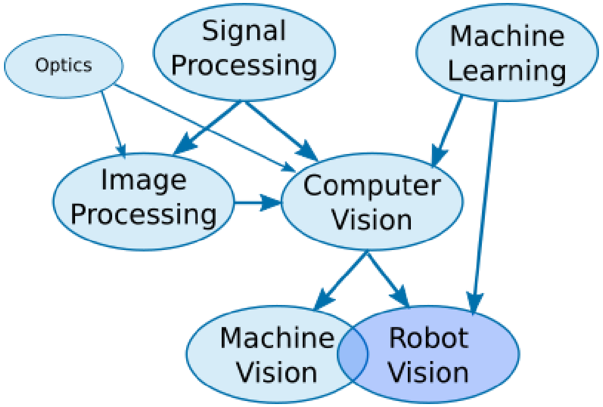

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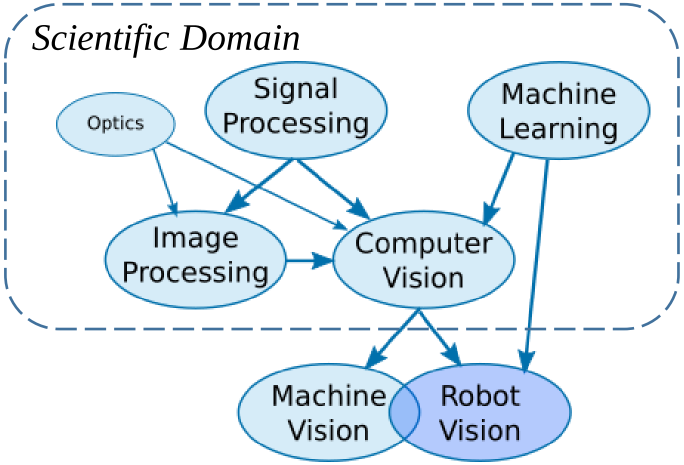

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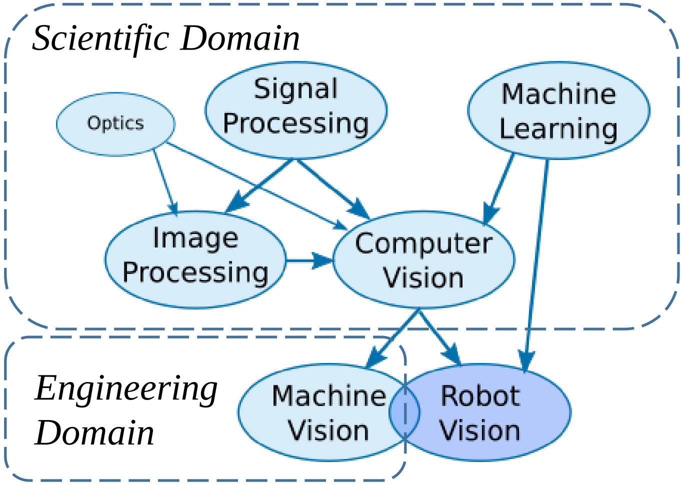

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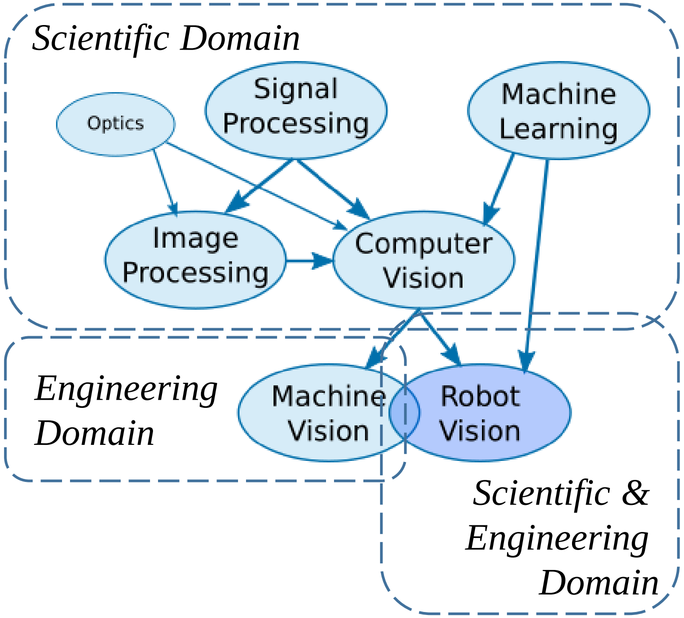

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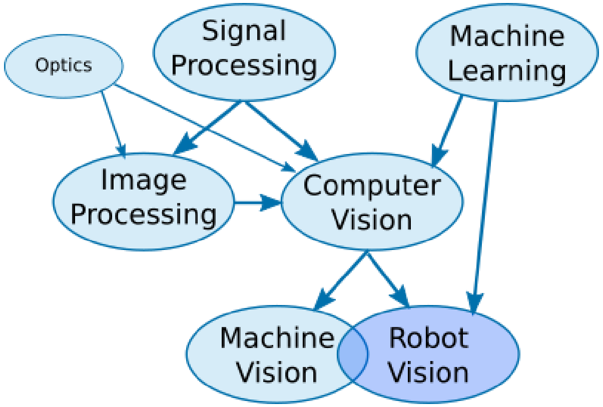
Differentiating Concepts about Vision

Technique	Input	Output
Signal Processing	Electrical signals	Electrical signals
Image Processing	Images	Images
Computer Vision	Images	Information/features
Pattern Recognition/Machine Learning	Information/features	Information
Machine Vision	Images	Information
Robot Vision	**Images**	**Physical Action**



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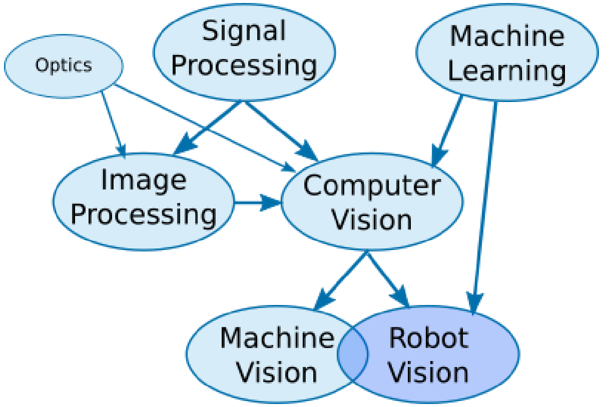

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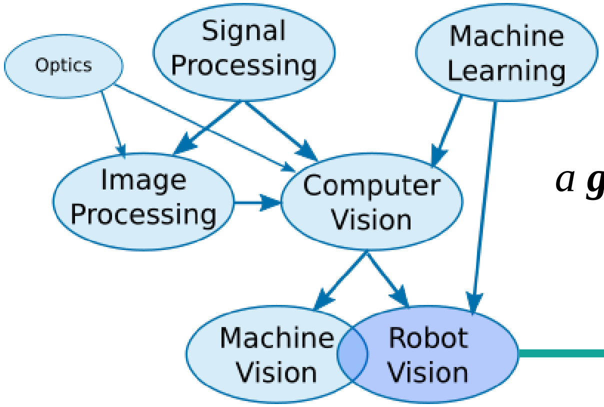

*a **goal** oriented **machine** that can **sense**, **plan** and **act***

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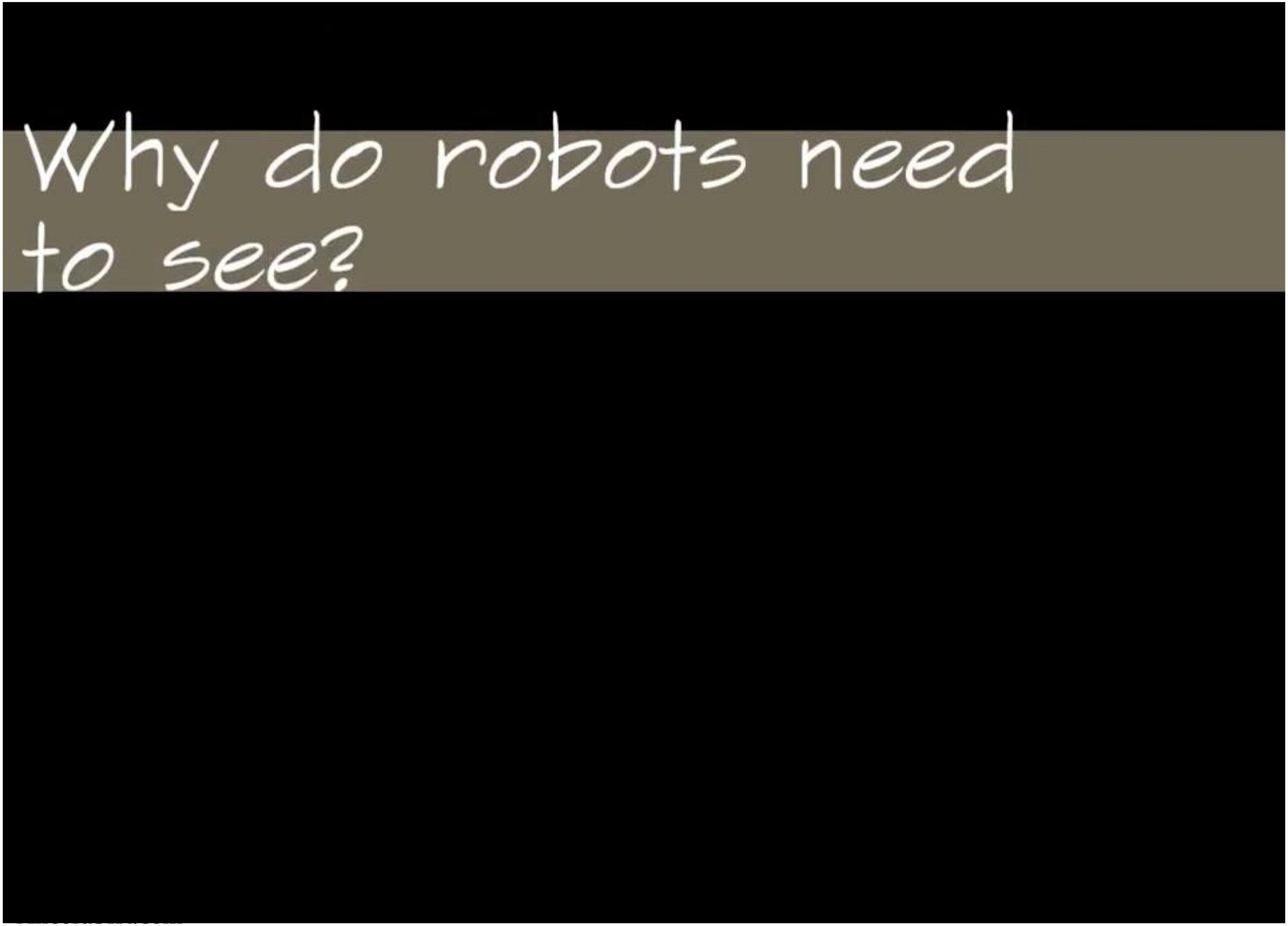

Why do robots need to see?

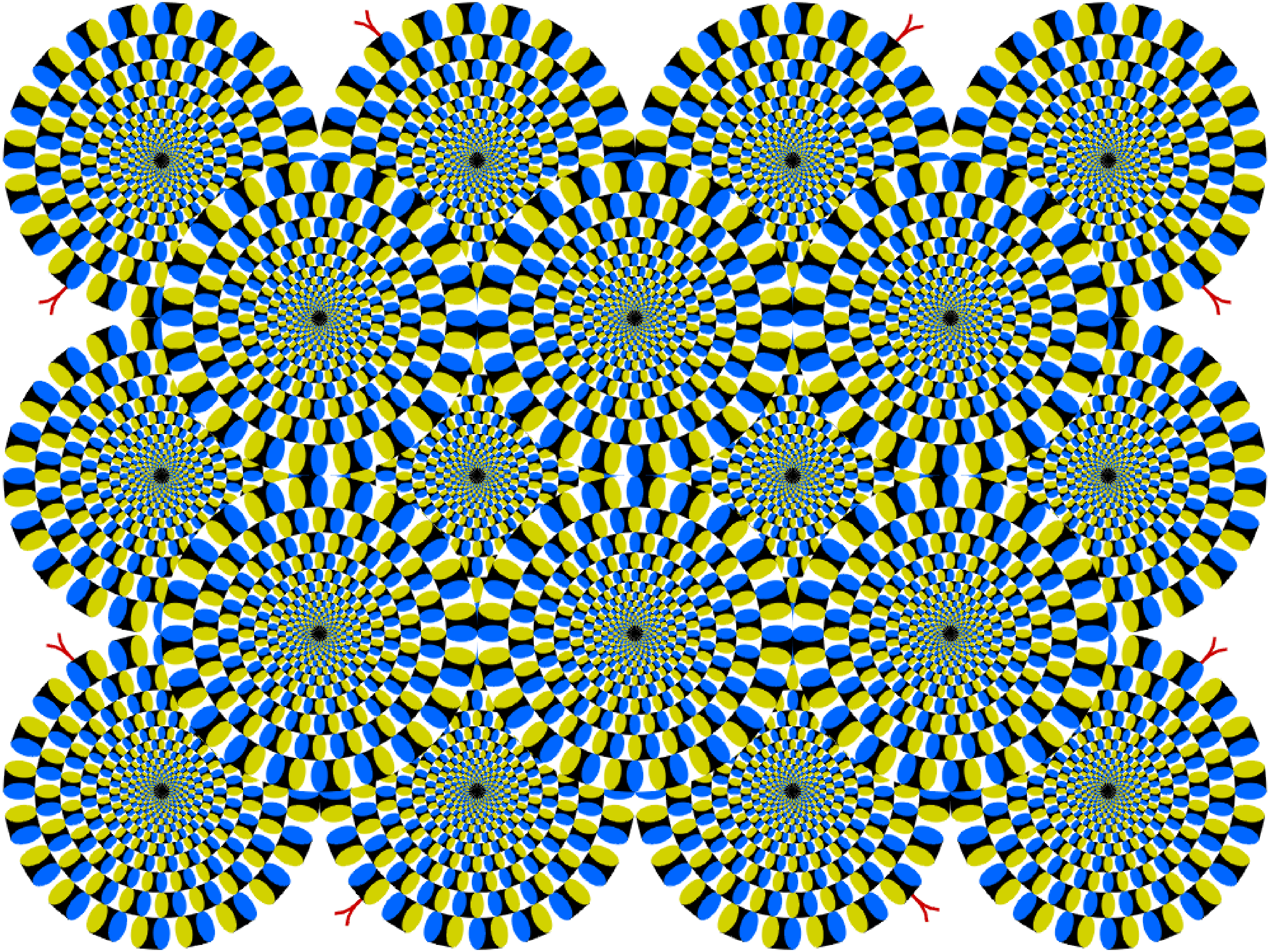

Image Representation

Example of a grayscale [0, 1] image within a planar area of size [*m*, *n*]

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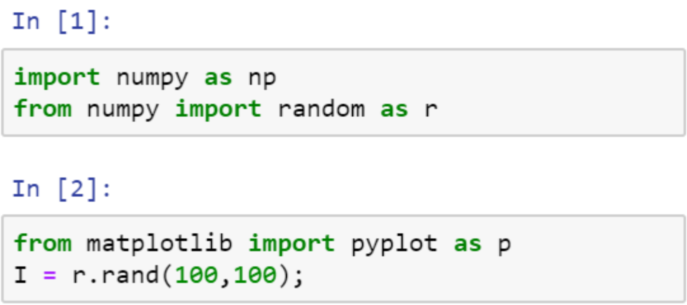

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import numpy as np
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In [2]:

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I = r.rand(100,100);
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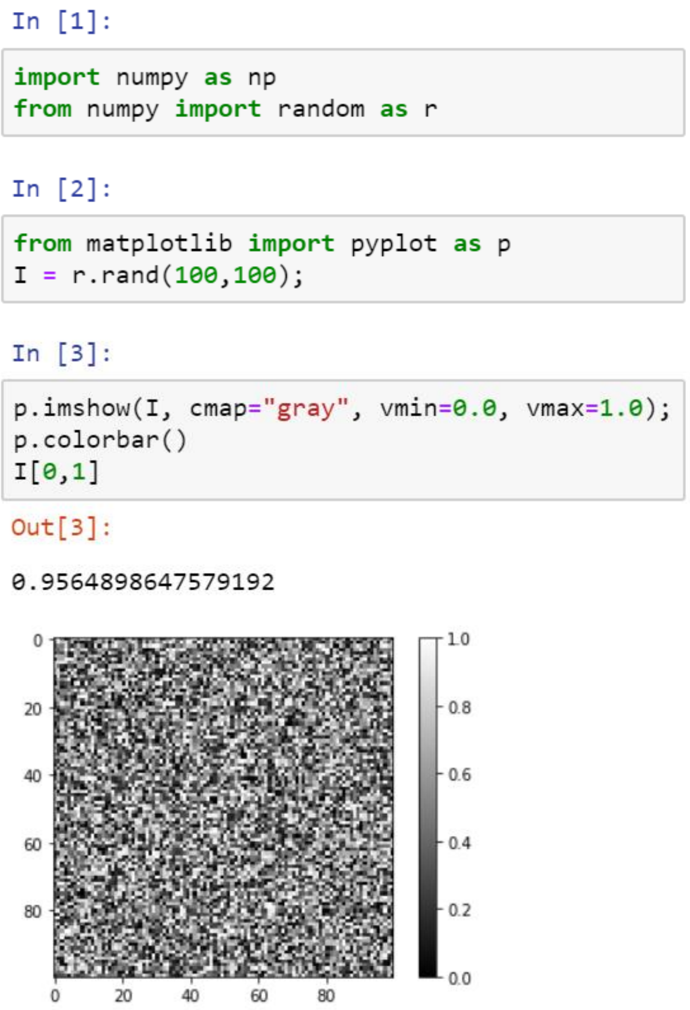

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Out[3]:

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0.9564898647579192
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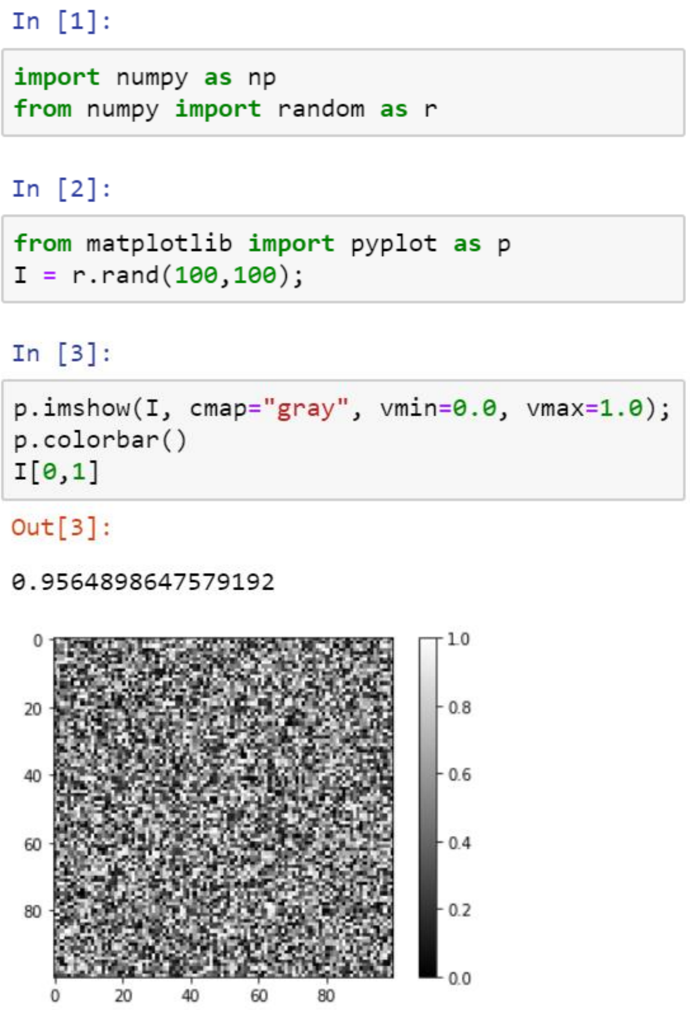

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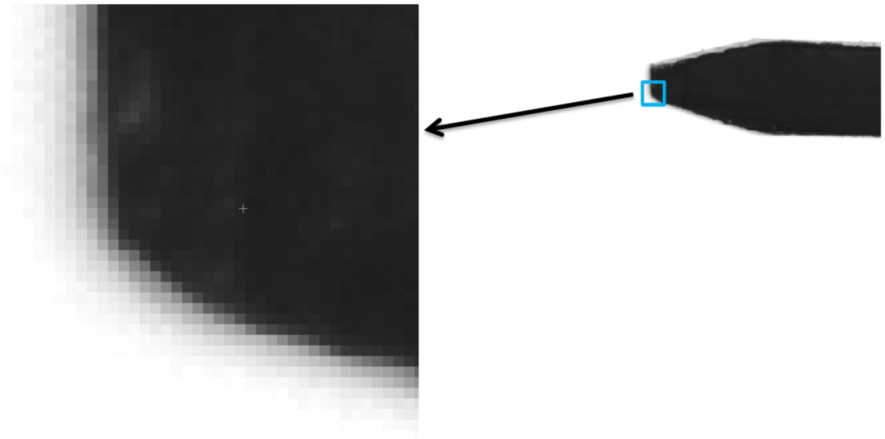

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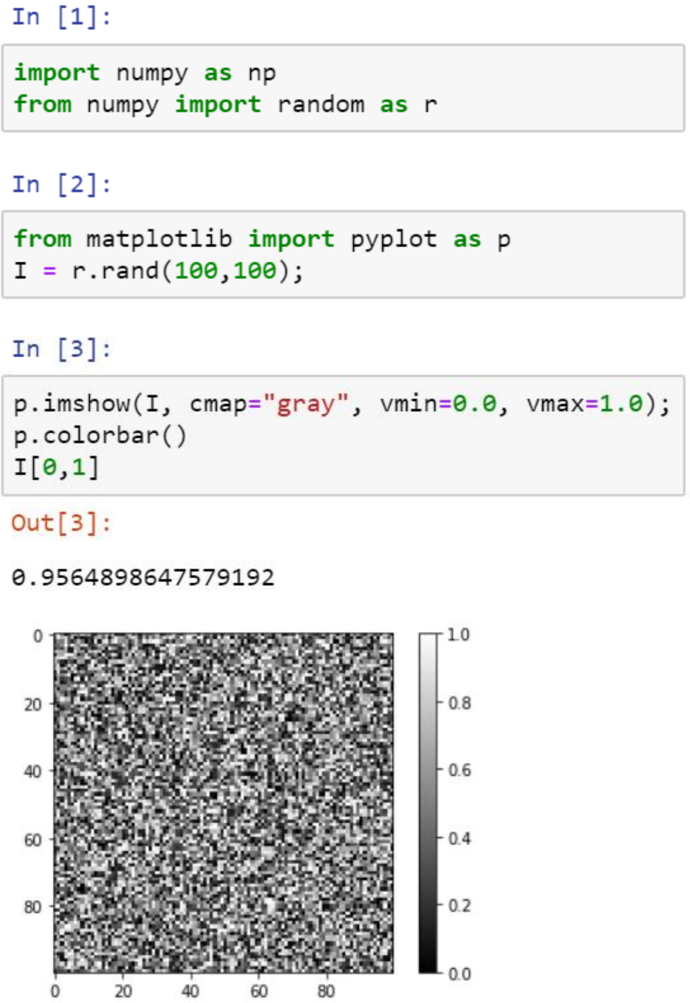

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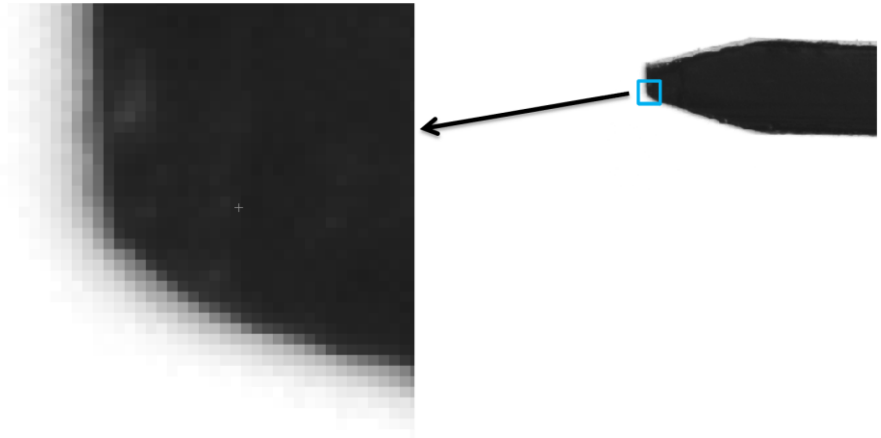

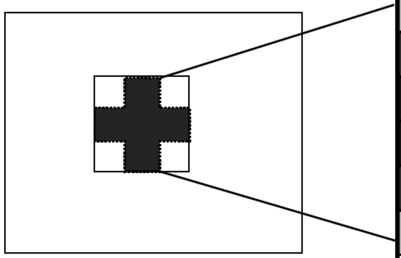

255	255	255	105	51	41	43	49	101	255	255	255
255	255	255	116	62	44	42	57	120	255	255	255
255	255	255	112	68	41	46	58	117	255	255	255
105	110	111	109	60	42	48	61	115	112	114	108
60	68	62	57	42	41	46	41	43	49	42	41
44	42	41	46	46	42	48	44	42	42	46	42
41	46	42	48	44	42	41	41	46	43	49	42
59	54	60	59	41	46	42	46	46	42	48	46
100	120	120	115	51	41	43	49	110	116	118	105
255	255	255	118	62	44	42	57	115	255	255	255
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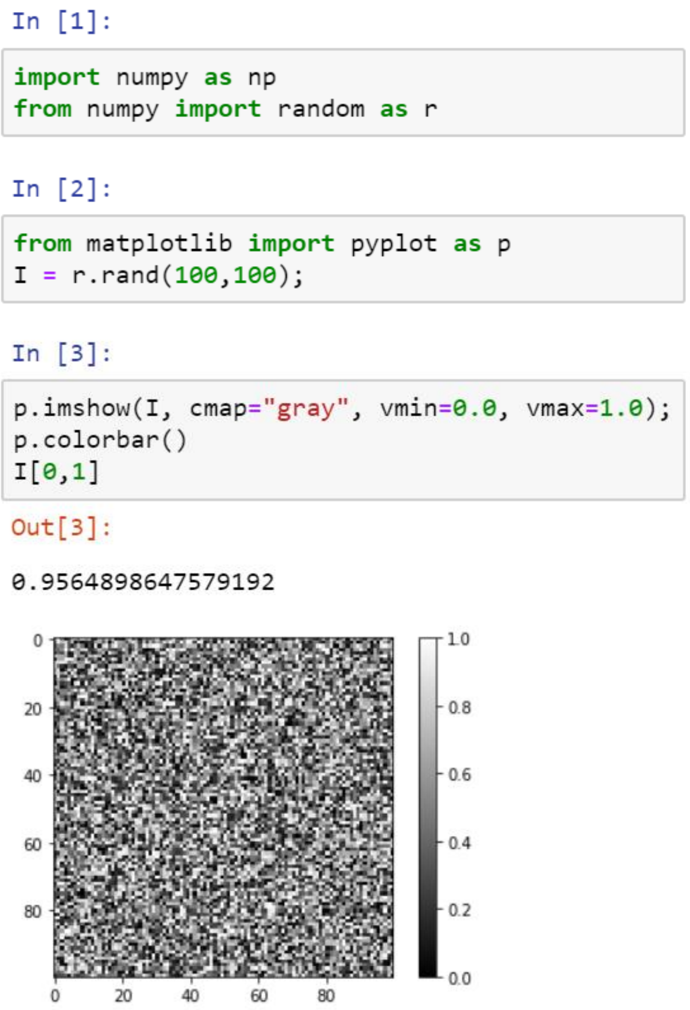

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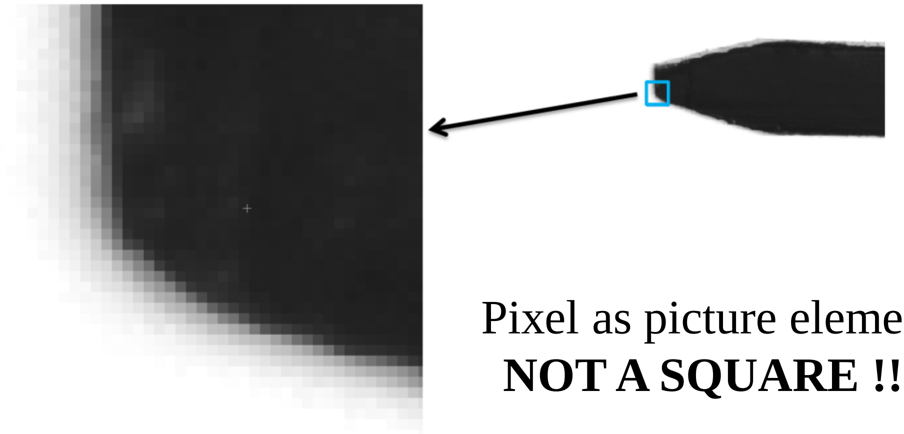
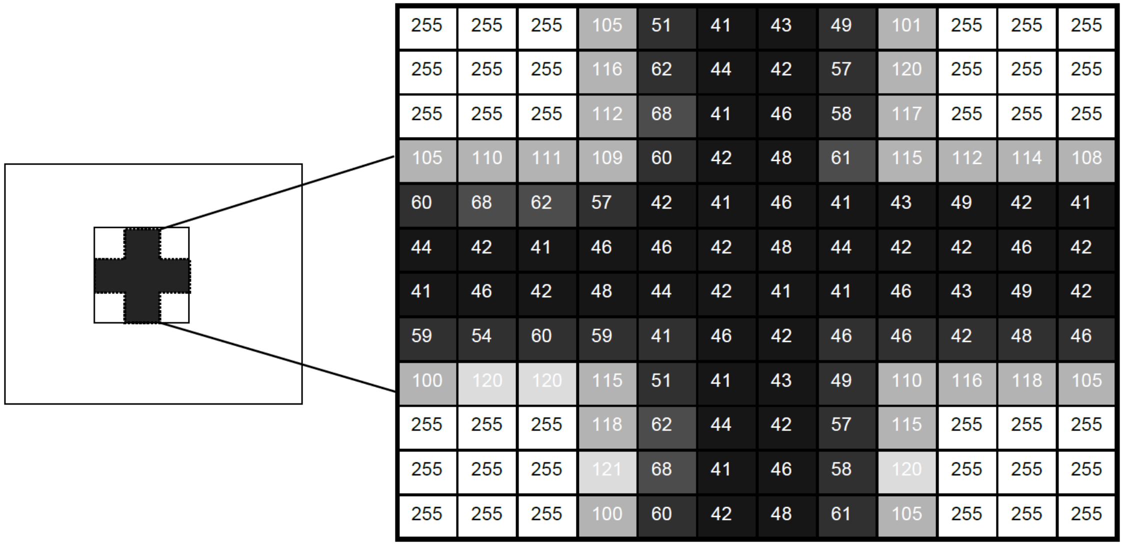


Pixel as picture element
NOT A SQUARE !!!



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44	42	41	46	46	42	48	44	42	42	46	42
41	46	42	48	44	42	41	41	46	43	49	42
59	54	60	59	41	46	42	46	46	42	48	46
100	120	120	115	51	41	43	49	110	116	118	105
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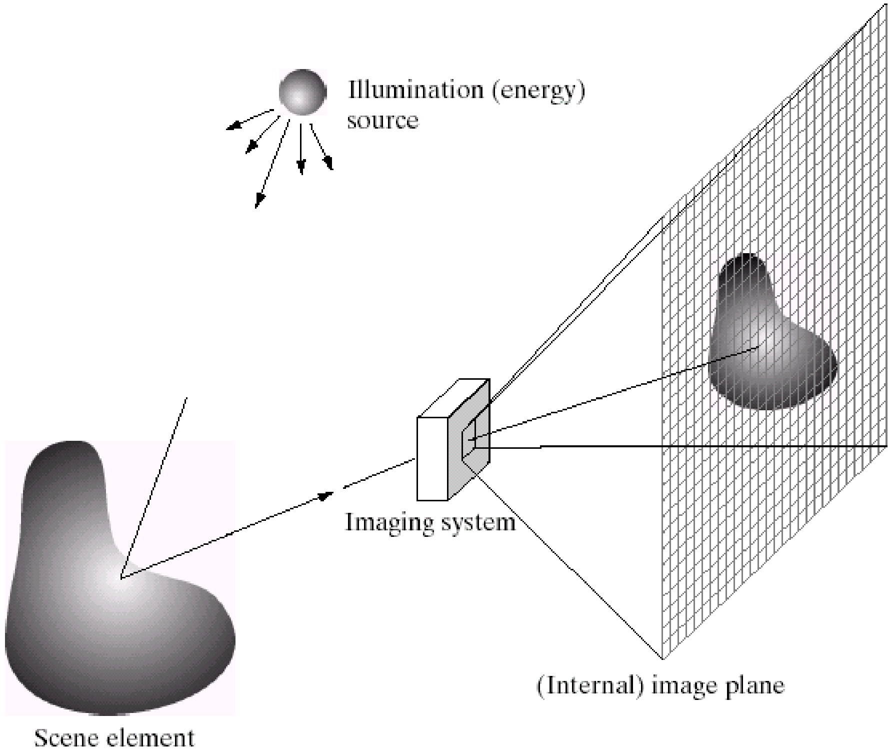
255	255	255	100	60	42	48	61	105	255	255	255

Formulation of An Image

As a 2D sampling of signal



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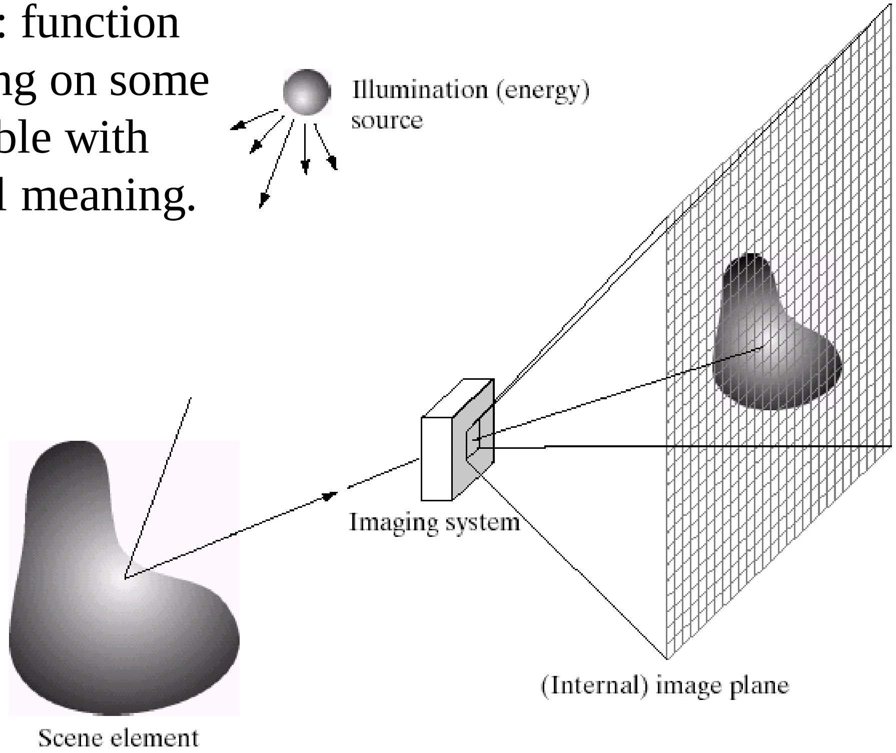
Formulation of An Image

As a 2D sampling of signal

Signal: function depending on some variable with physical meaning.



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As a 2D sampling of signal

Signal: function depending on some variable with physical meaning.

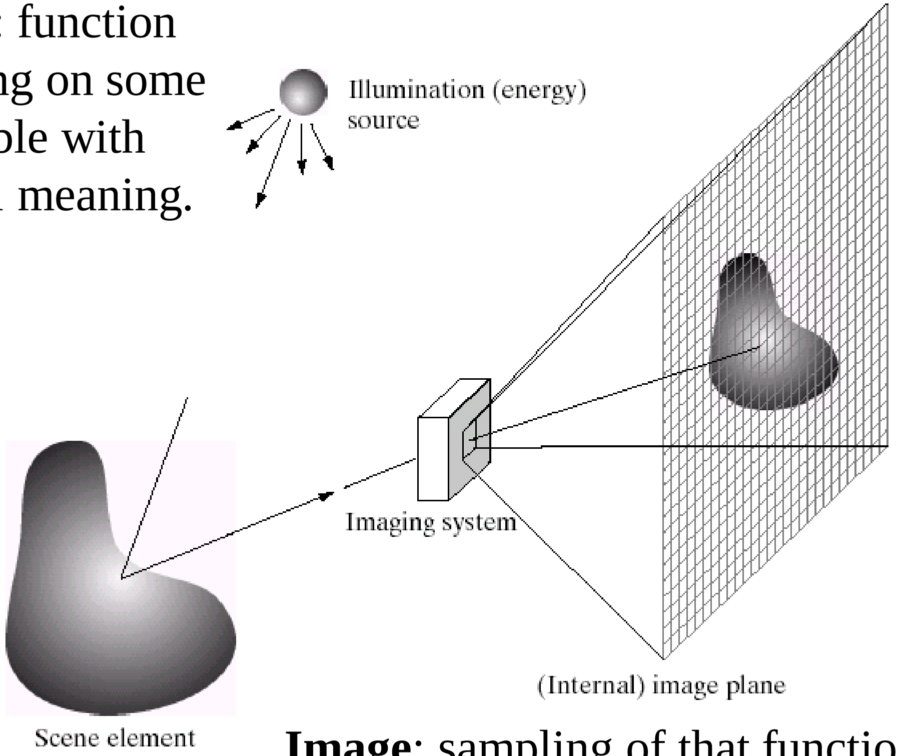

Image: sampling of that function.

- 2 variables: xy coordinates
- 3 variables: xy + time (video)
- ‘Brightness’ is the value of the function for visible light

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Formulation of An Image

As a 2D sampling of signal

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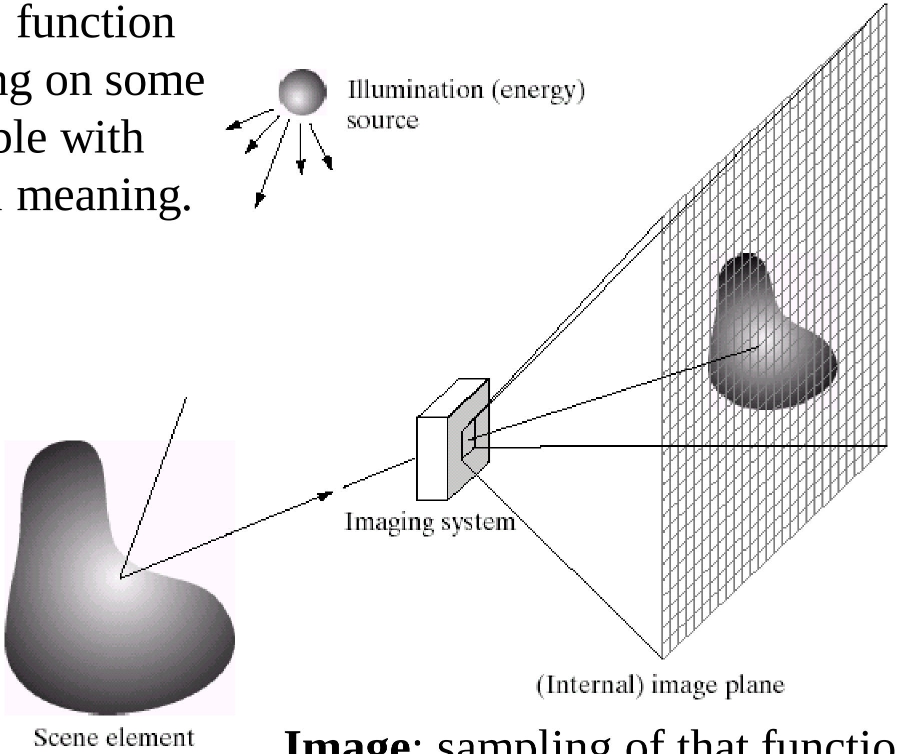

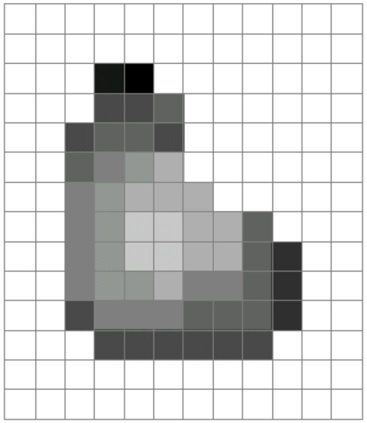

Can be other physical values too: *temperature*, *pressure*, *depth* …

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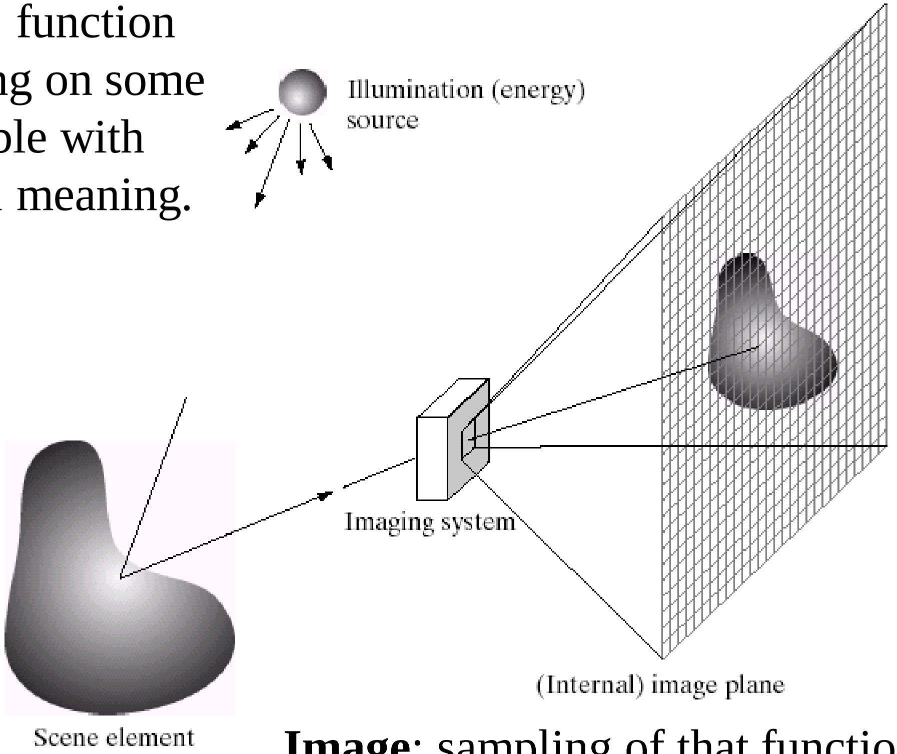

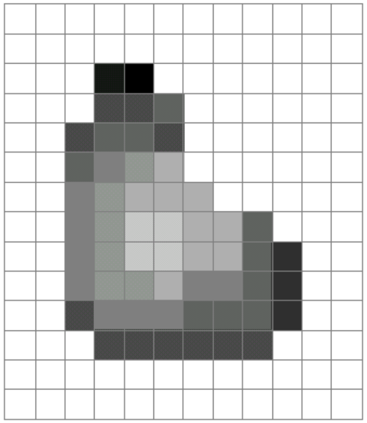

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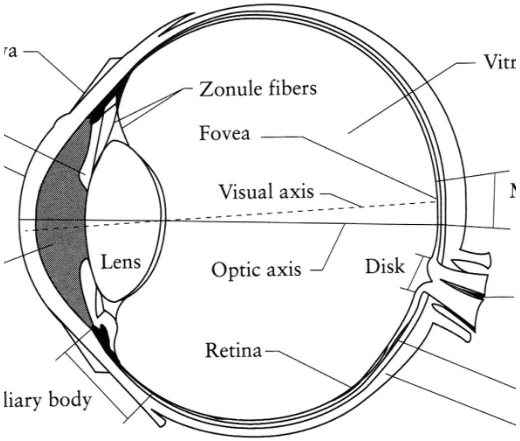

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Sampling Physical World Using Images

Physical Understanding of Images

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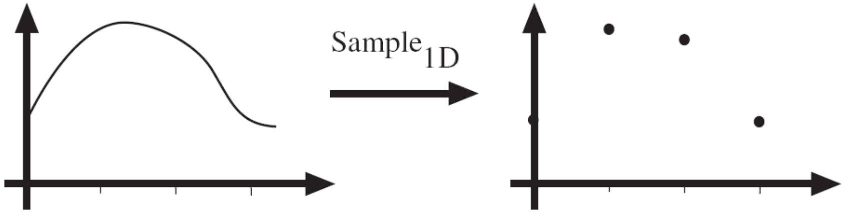

Sampling in 1D takes a function, and returns a vector whose elements are values of that function at the sample points.

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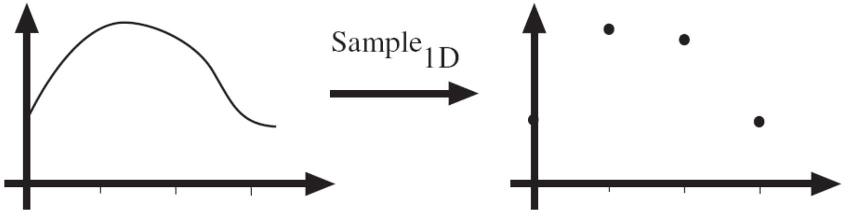

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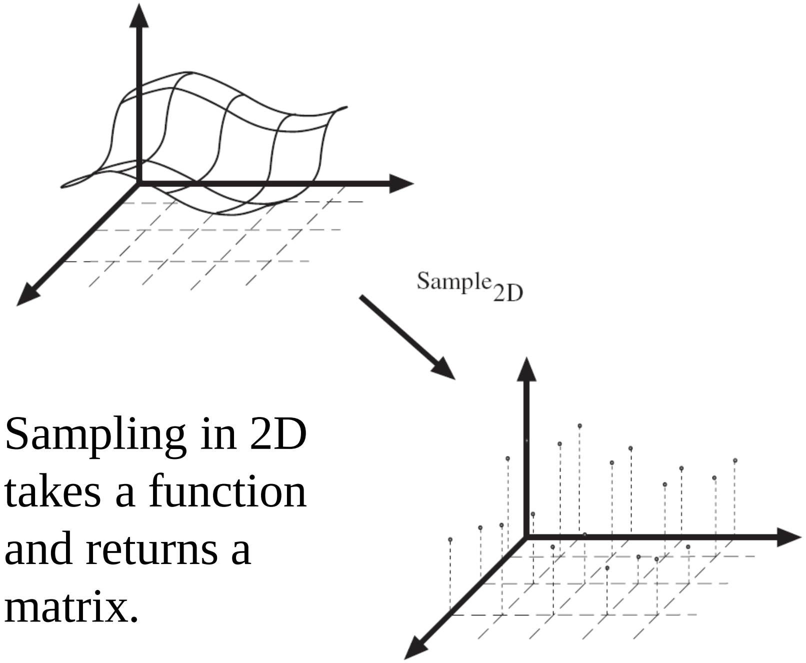

Sampling in 2D takes a function and returns a matrix.

Sampling Physical World Using Images

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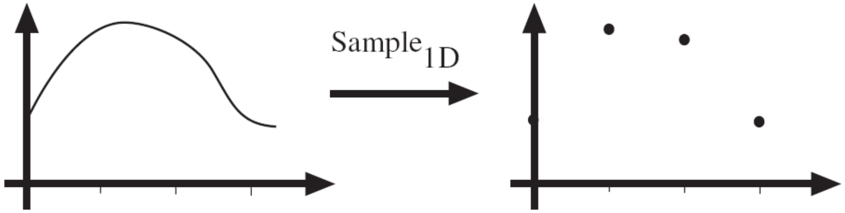

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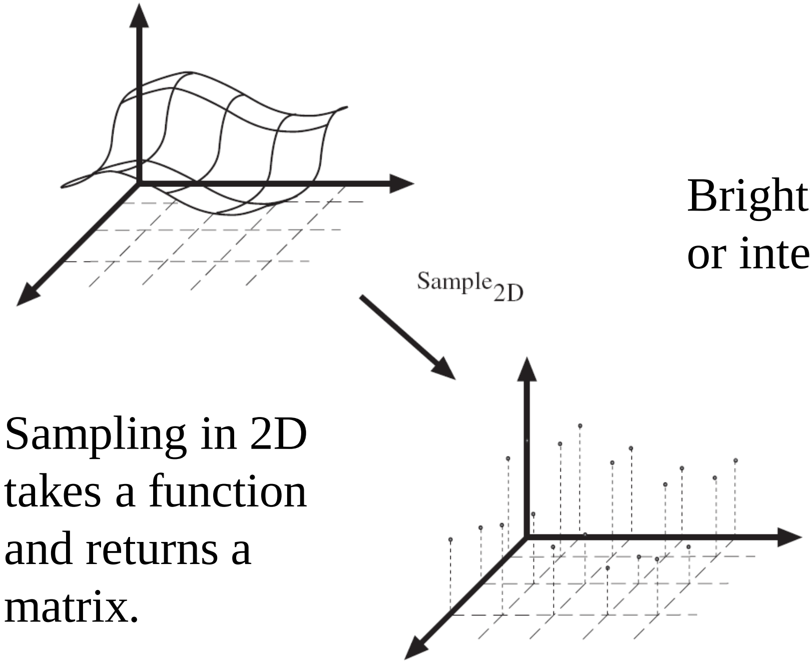
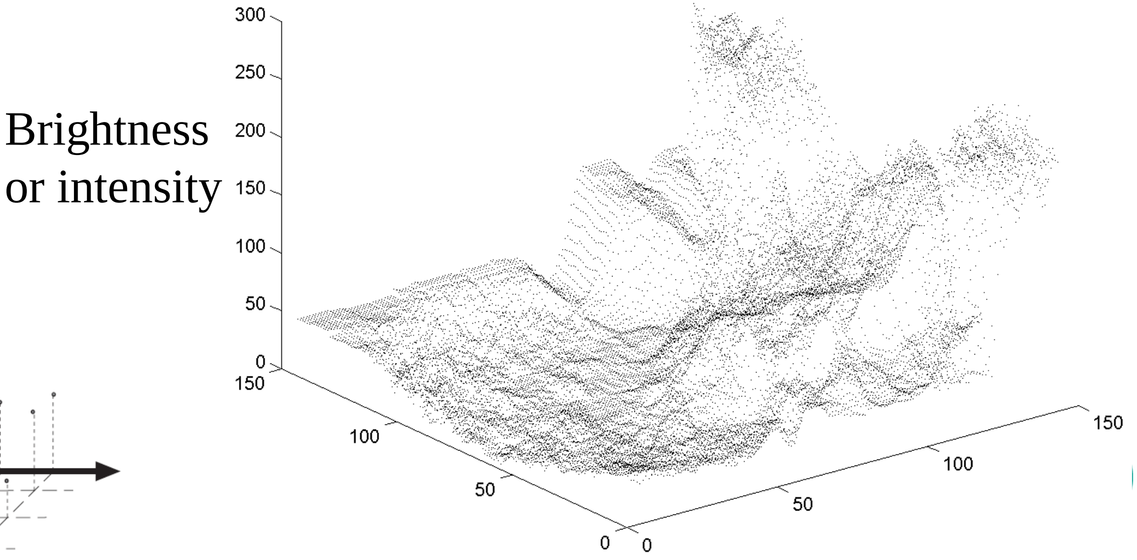
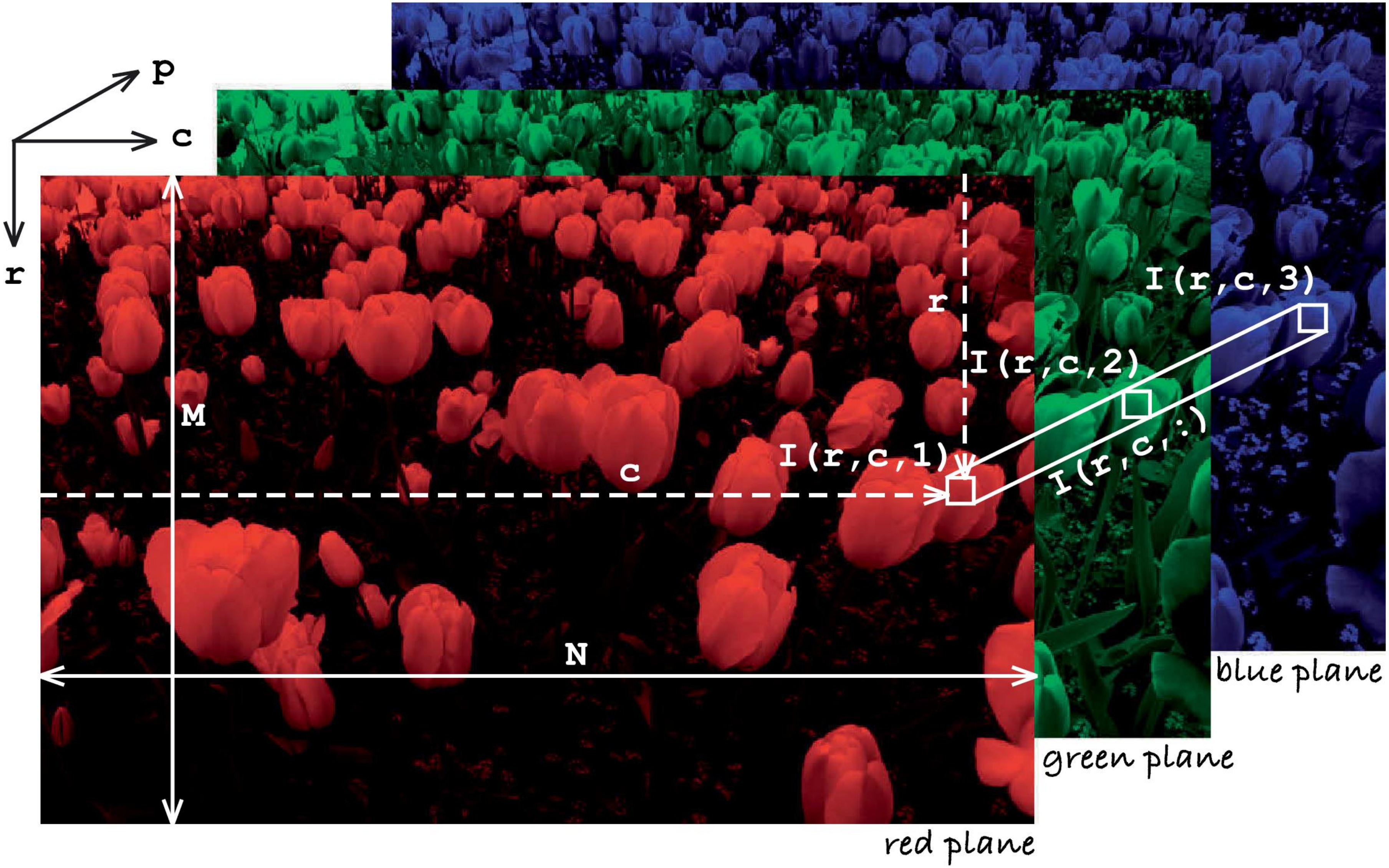


Sampling in 2D takes a function and returns a matrix.

Grayscale Digital Image



An RGB Image



A Robotic Way of Interpreting Images

An important method of sensing the environment

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An important method of sensing the environment

- Computer Vision
  - Digitization of physical world in multi-dimensional linear algebra
  - *Physical meaning is not a required way of interpretation or usage*

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Image Size: u, v

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Image Size: *u*, *v*

Color Space: **R**ed, **G**reen, **B**lue
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Image Size: *u*, *v*

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***[0, 1]** as normalized form, not an integer*
***[0, 255]** as a byte number of range 2^8=256 from 0 to 255,*
all in integer forms

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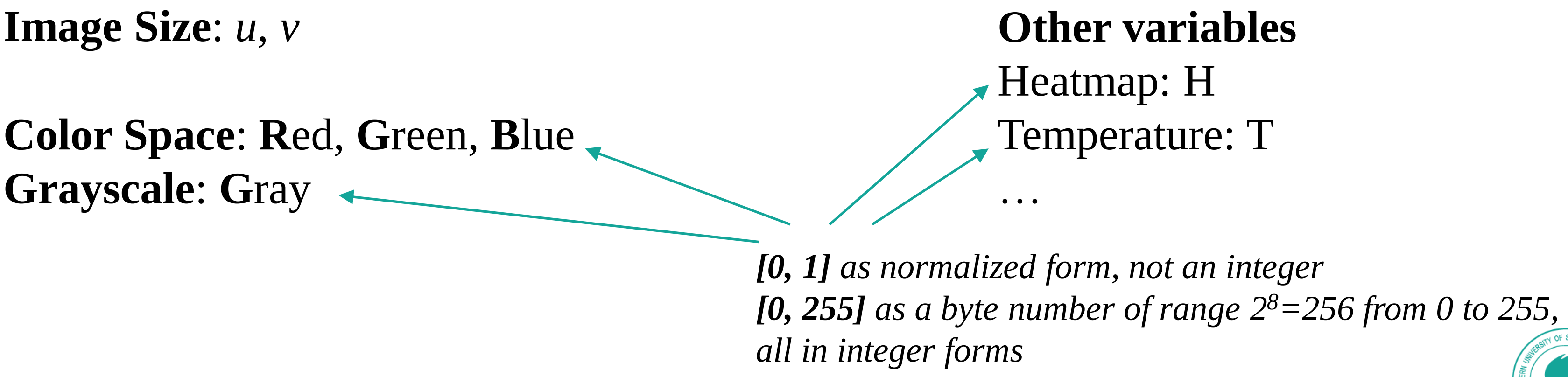

Image Size: *u*, *v*

Color Space: **R**ed, **G**reen, **B**lue
Grayscale: **G**ray

Other variables
Heatmap: H
Temperature: T
…

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Point Cloud: $x(u, v)$, $y(u, v)$, $z(u, v)$

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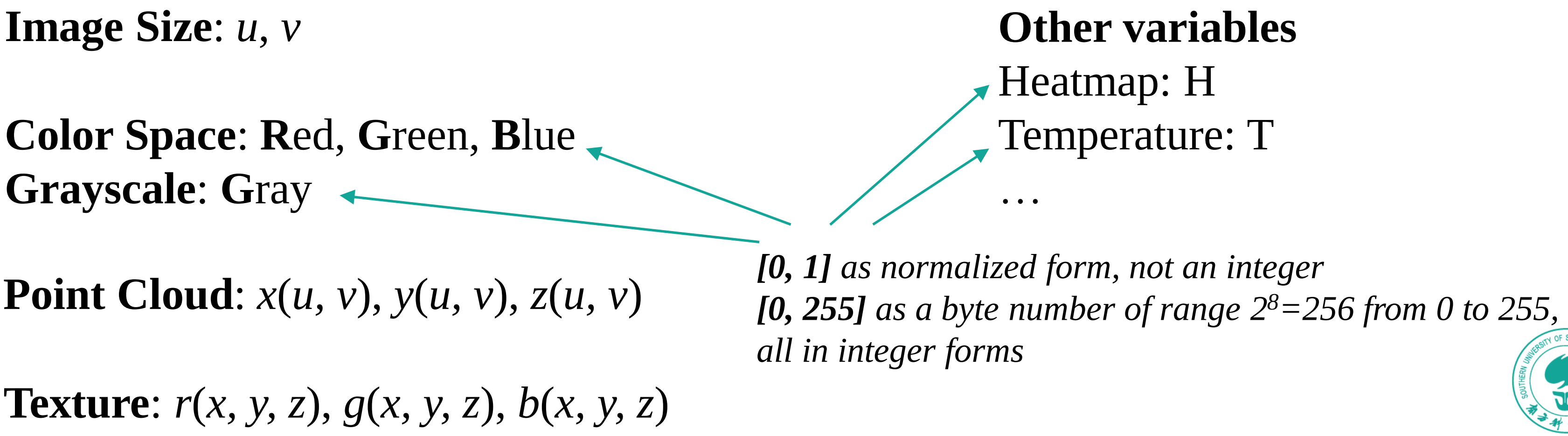

Image Size: *u*, *v*

Color Space: **R**ed, **G**reen, **B**lue
Grayscale: **Gray**

Point Cloud: $x(u, v)$, $y(u, v)$, $z(u, v)$

Texture: $r(x, y, z)$, $g(x, y, z)$, $b(x, y, z)$

Other variables
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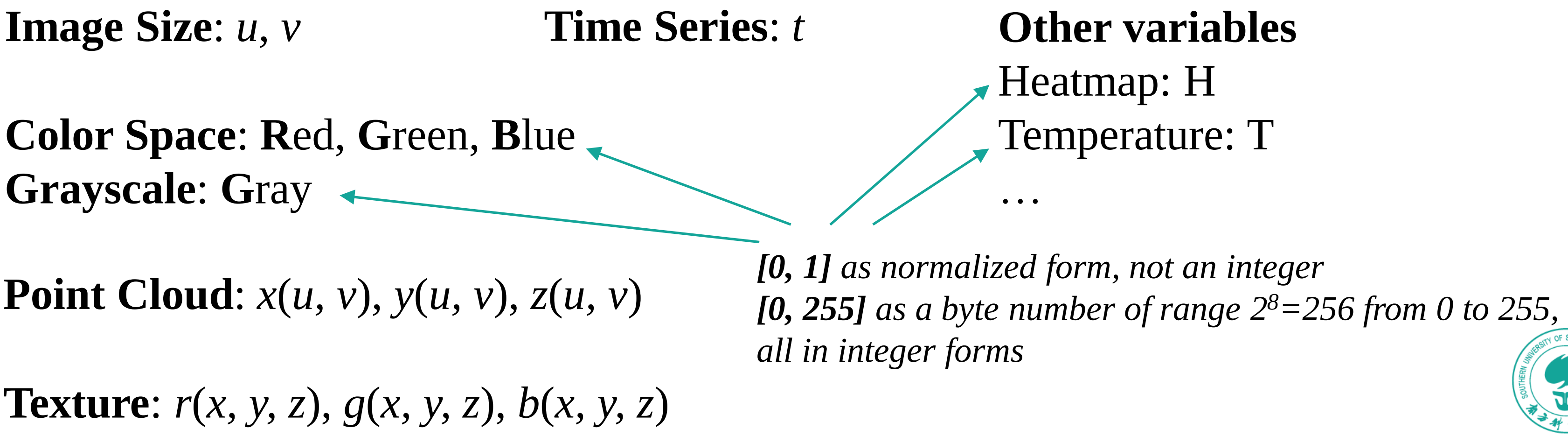

Image Size: *u*, *v*

Time Series: *t*

Other variables
Heatmap: H
Temperature: T
…

Color Space: **R**ed, **G**reen, **B**lue
Grayscale: **G**ray

Point Cloud: $x(u, v), y(u, v), z(u, v)$

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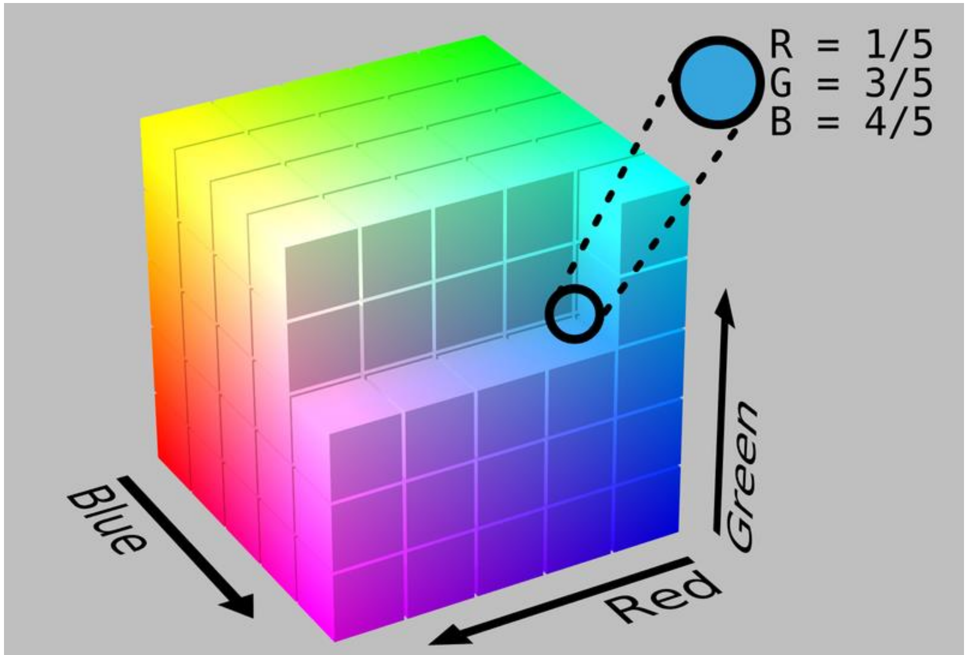

Color Space: **R**ed, **G**reen, **B**lue

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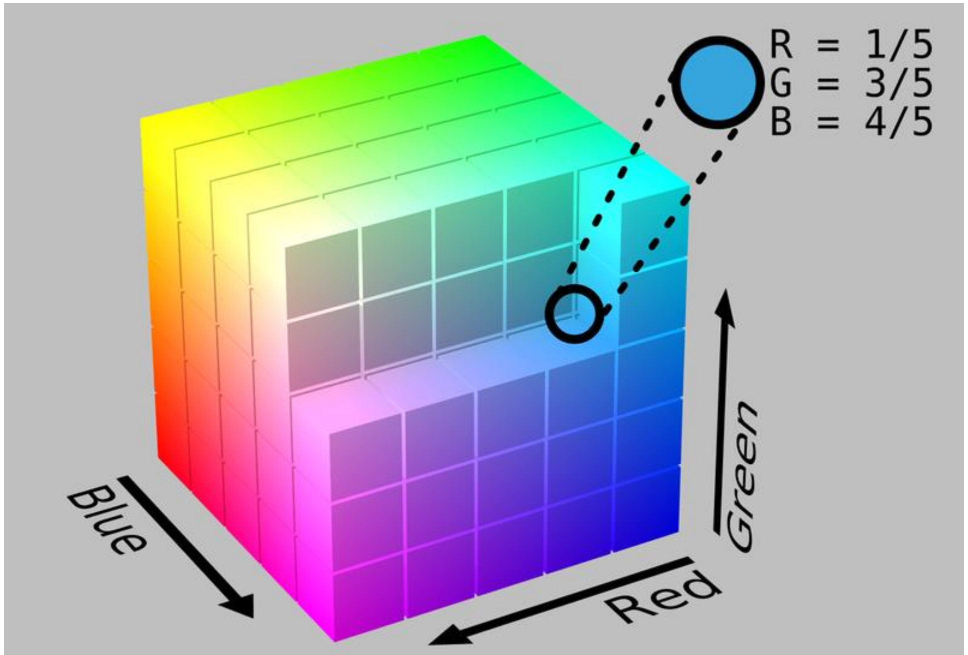

Color Space: **R**ed, **G**reen, **B**lue

Other variables

Heatmap: H

Temperature: T

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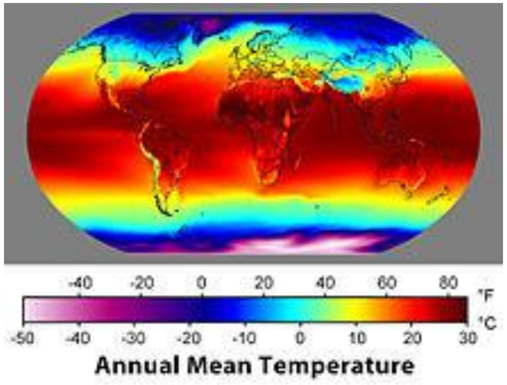

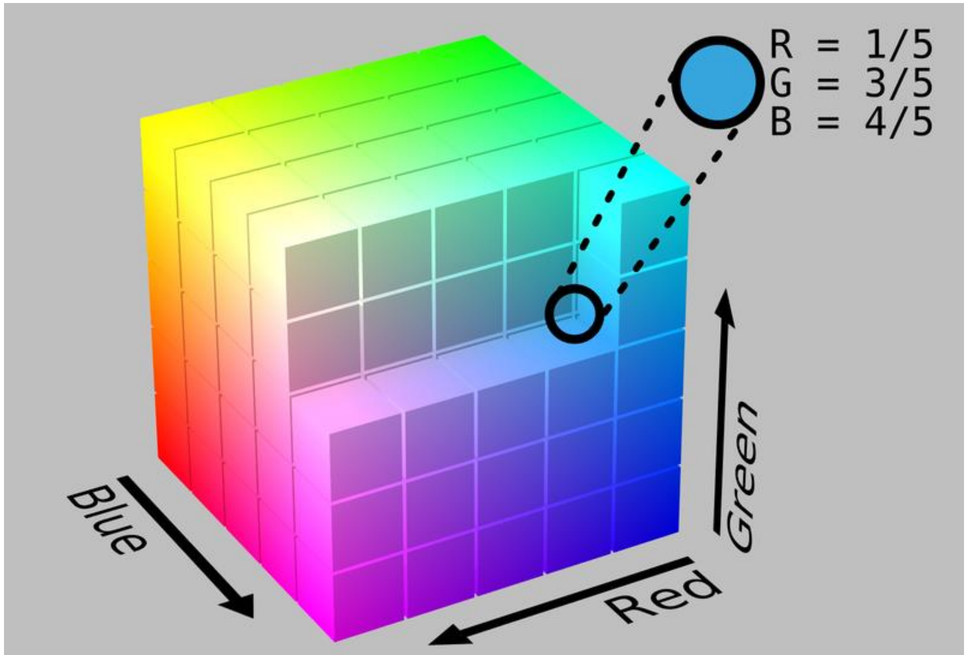

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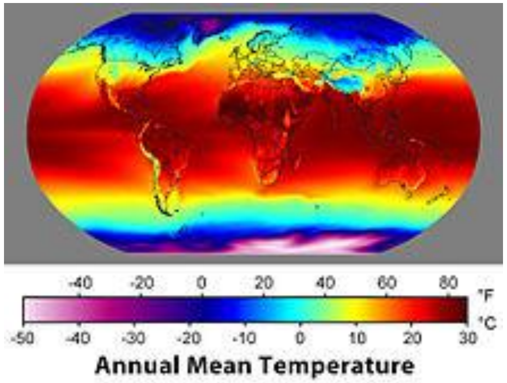

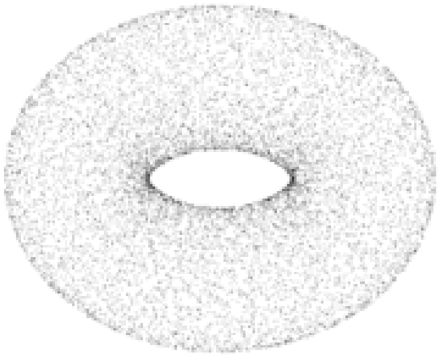

Point Cloud: $x(u, v)$, $y(u, v)$, $z(u, v)$

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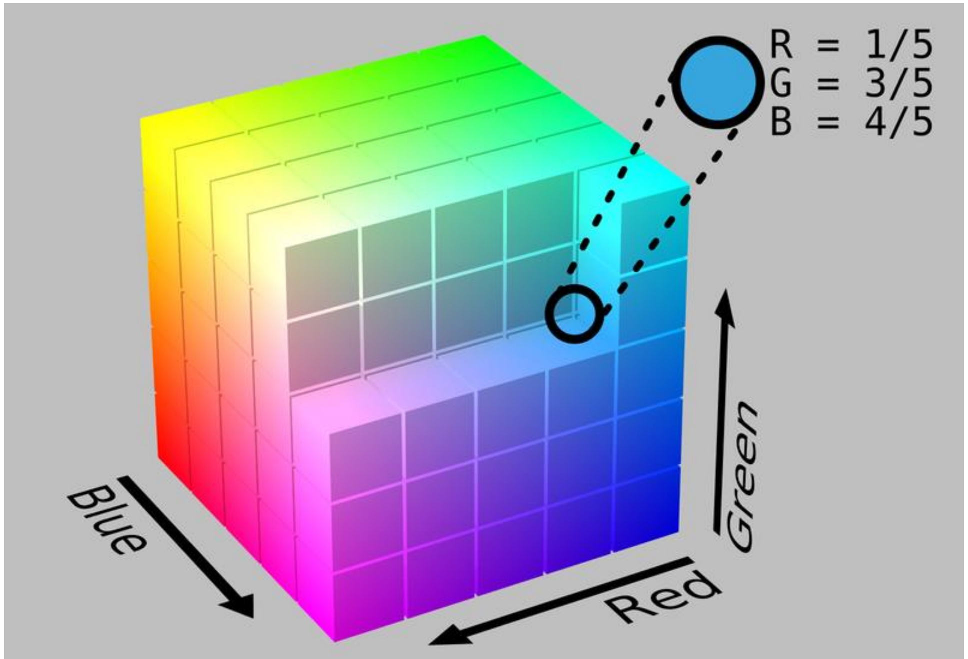


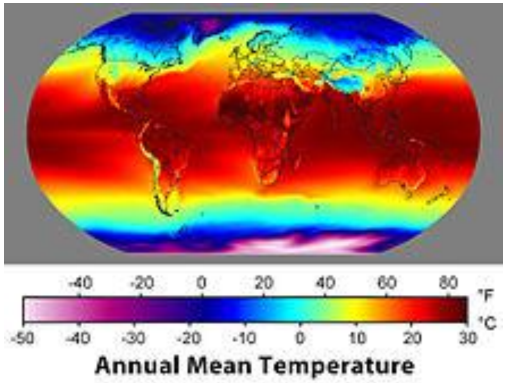
Color Space: **R**ed, **G**reen, **B**lue

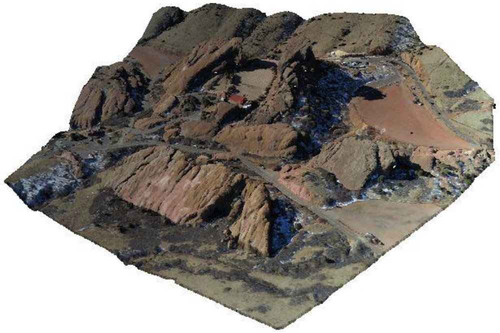
Other variables

Heatmap: H

Temperature: T

…



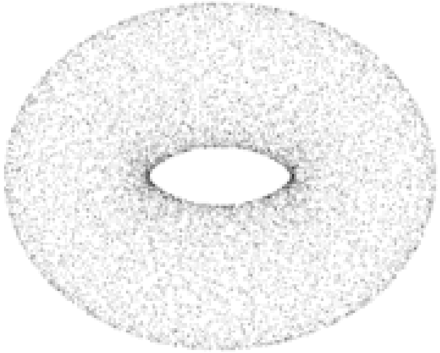


Texture:

$r(x, y, z)$,

$g(x, y, z)$,

$b(x, y, z)$



Point Cloud: $x(u, v)$, $y(u, v)$, $z(u, v)$

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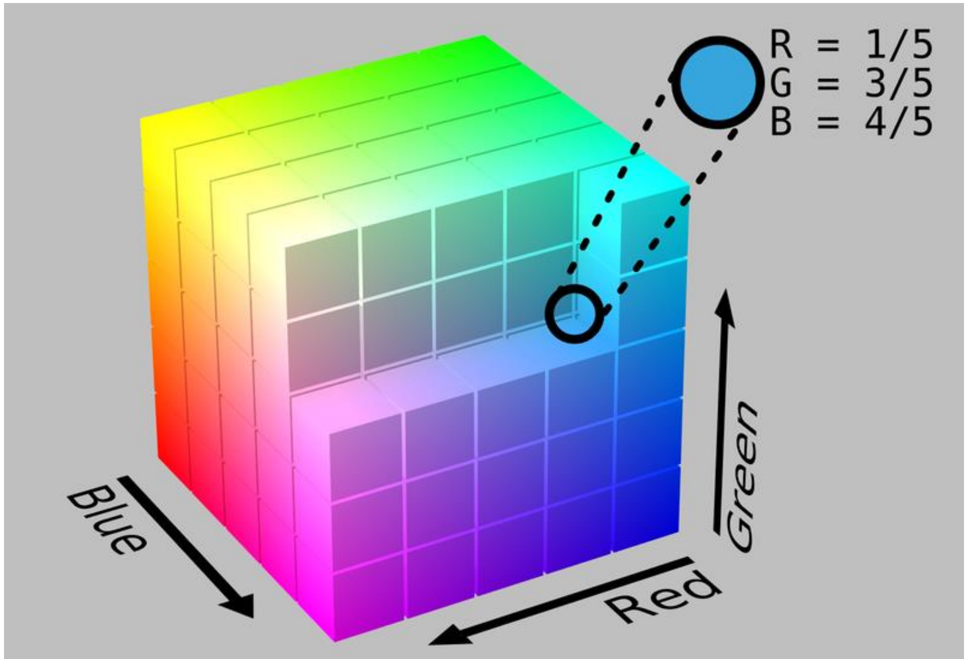

Color Space: **R**ed, **G**reen, **B**lue

Other variables

Heatmap: H

Temperature: T

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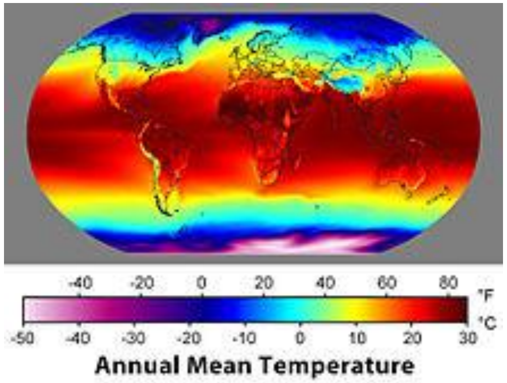
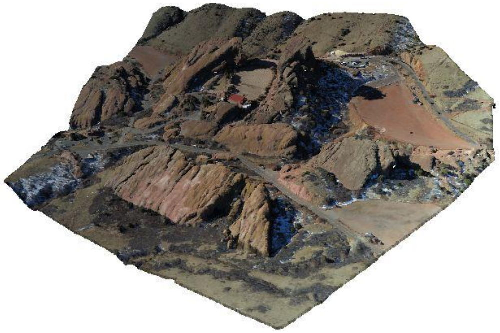


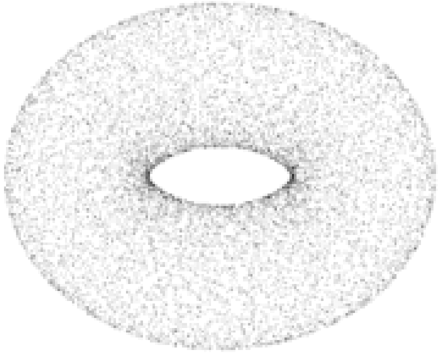


Texture:

r(*x*, *y*, *z*),

g(*x*, *y*, *z*),

b(*x*, *y*, *z*)



Point Cloud: $x(u, v), y(u, v), z(u, v)$

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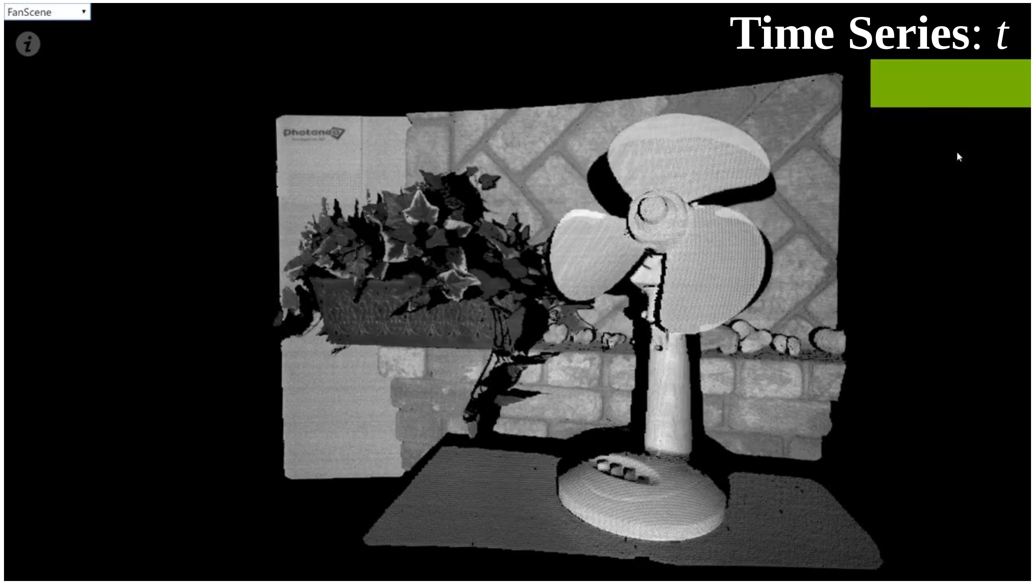
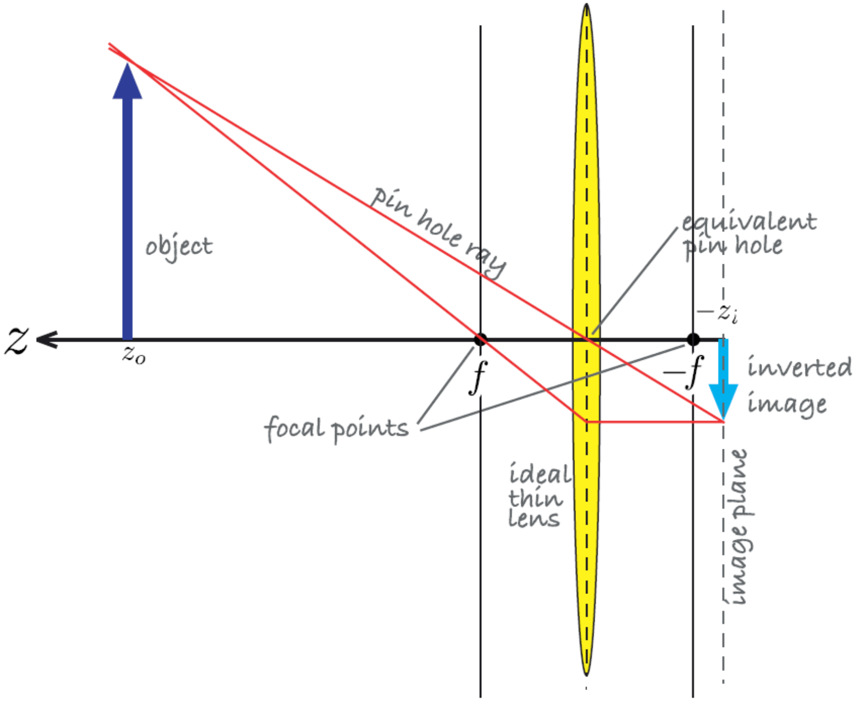


Time Series: *t*

Perspective Transform

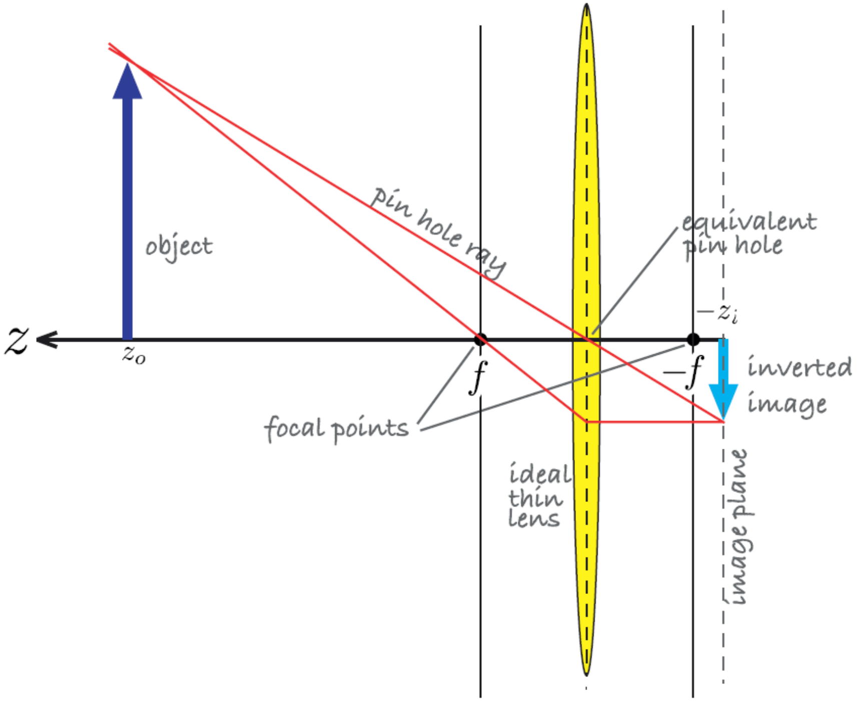
Camera Models



Perspective Transform

Camera Models

Lens Law $\frac{1}{z_o} + \frac{1}{z_i} = \frac{1}{f}$



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Camera Models

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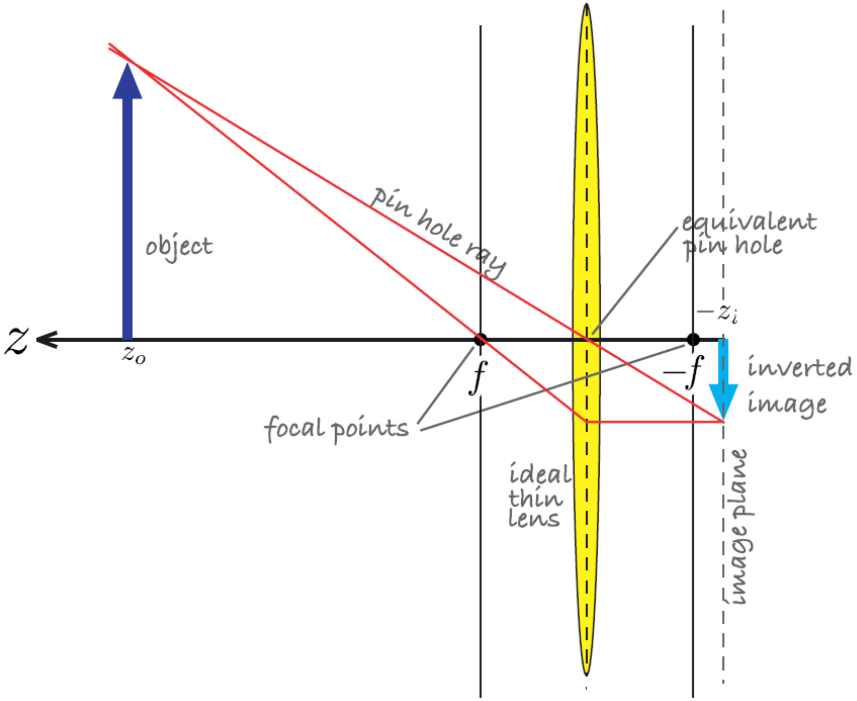
the distance
to the object



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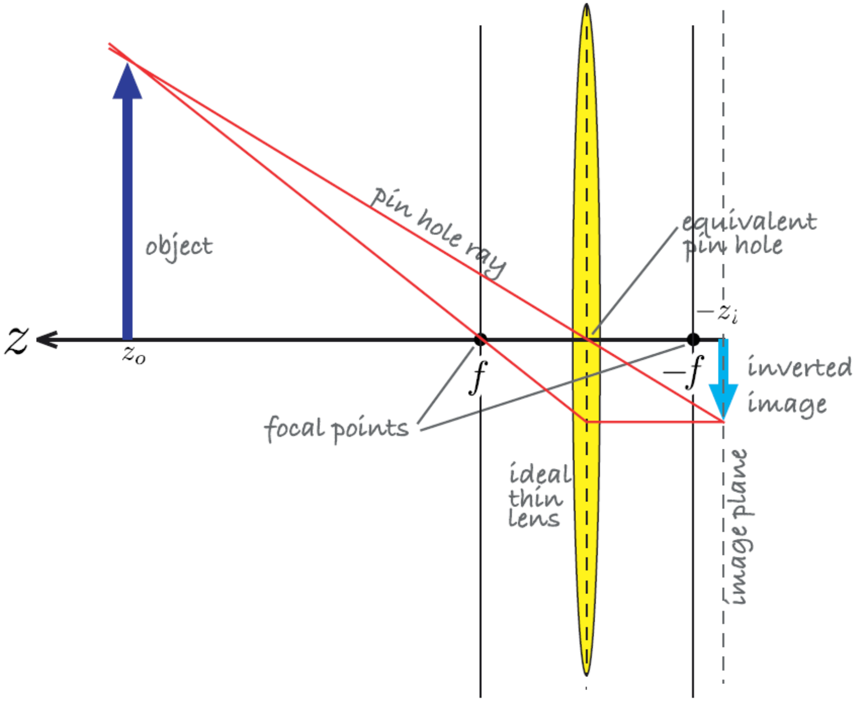
the distance to the object

the distance to the image



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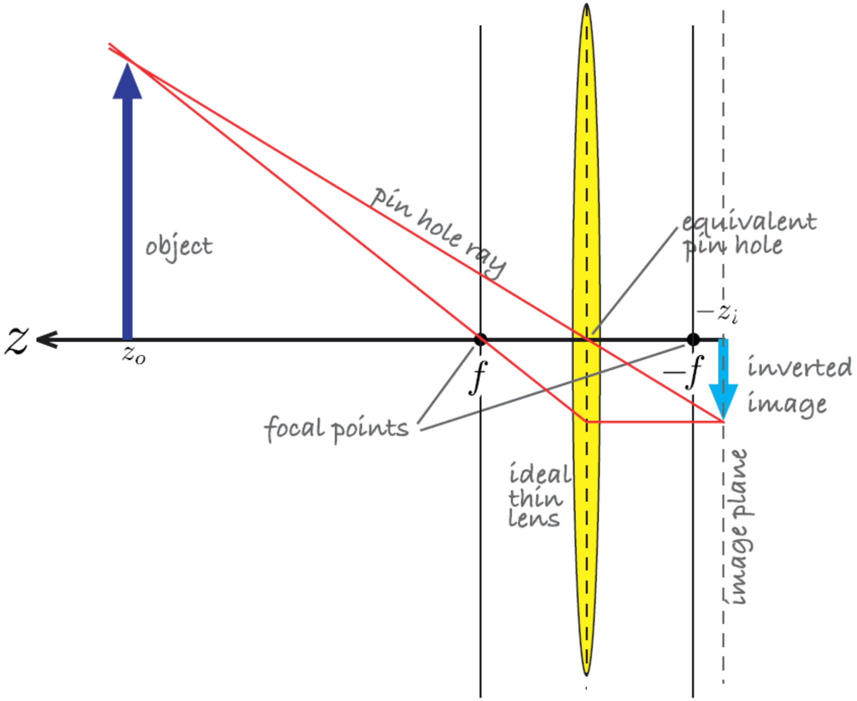
the focal length of the lens

the distance to the object

the distance to the image



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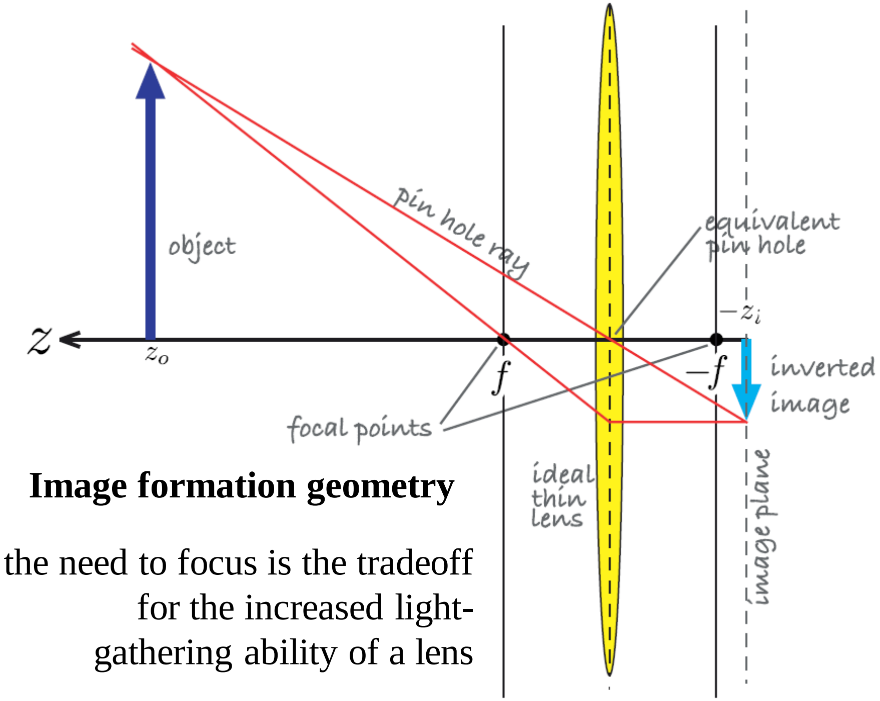

Image formation geometry

the need to focus is the tradeoff for the increased light-gathering ability of a lens

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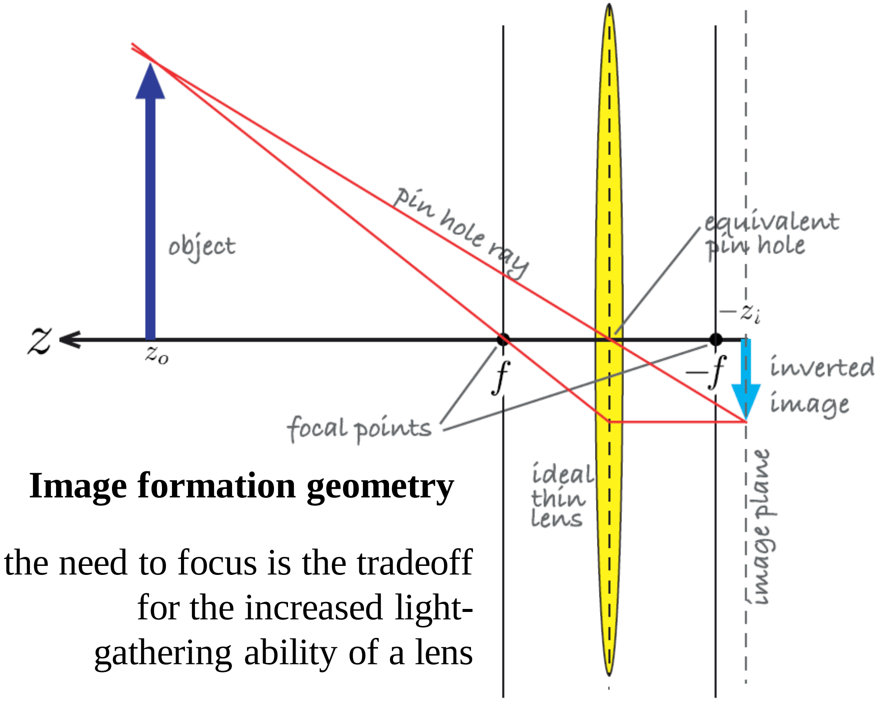

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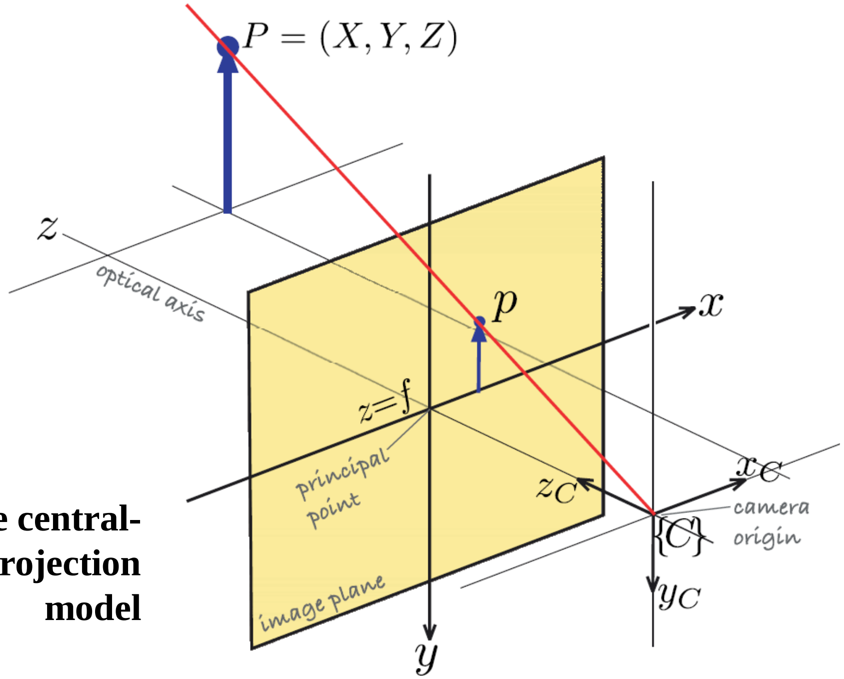

The central-projection model

Perspective Transform

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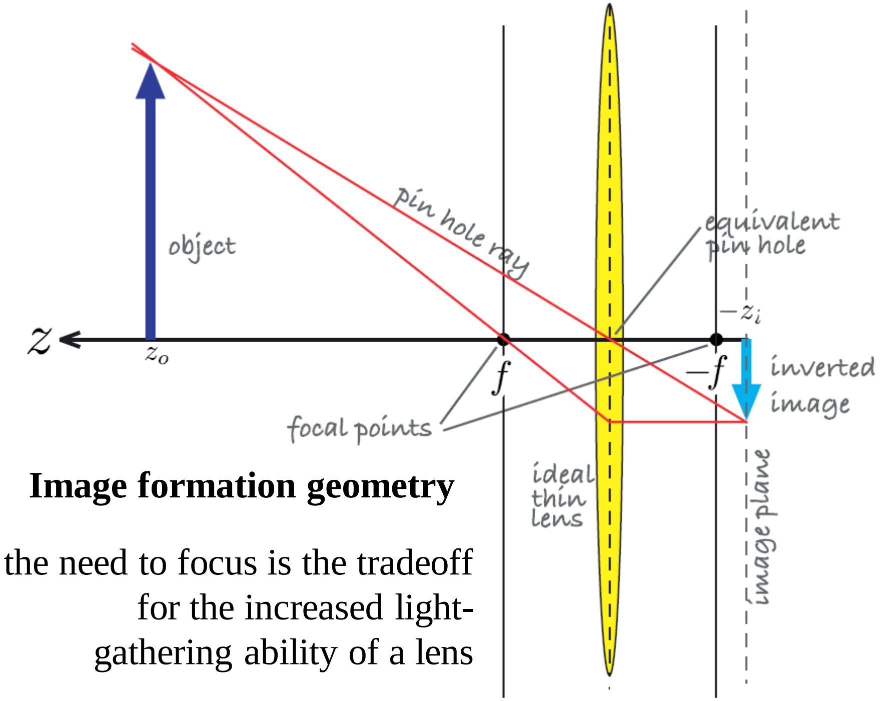
the focal length of the lens

the distance to the object

the distance to the image

perspective projection $x = f\frac{X}{Z},\ y = f\frac{Y}{Z}$



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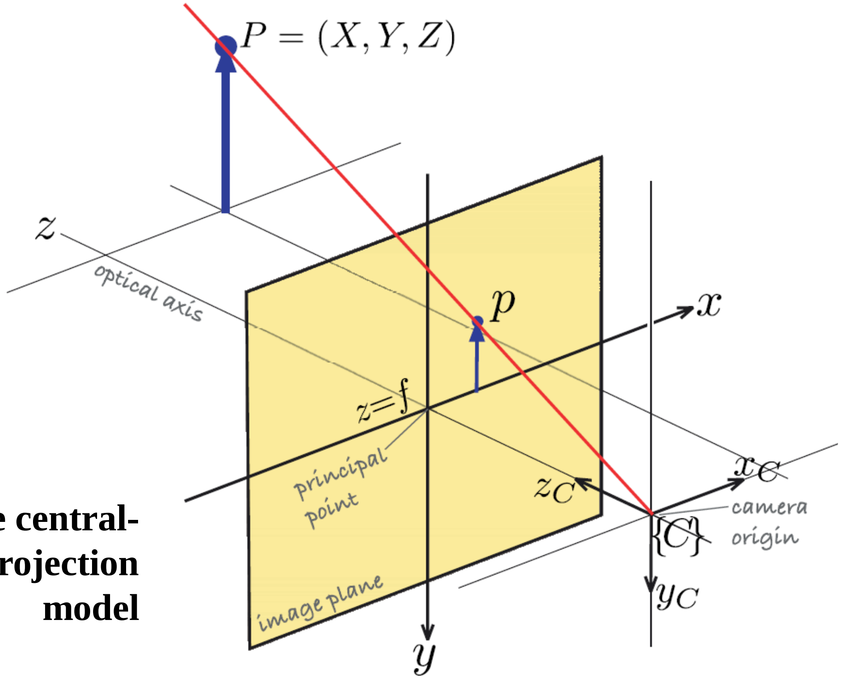

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the focal length of the lens

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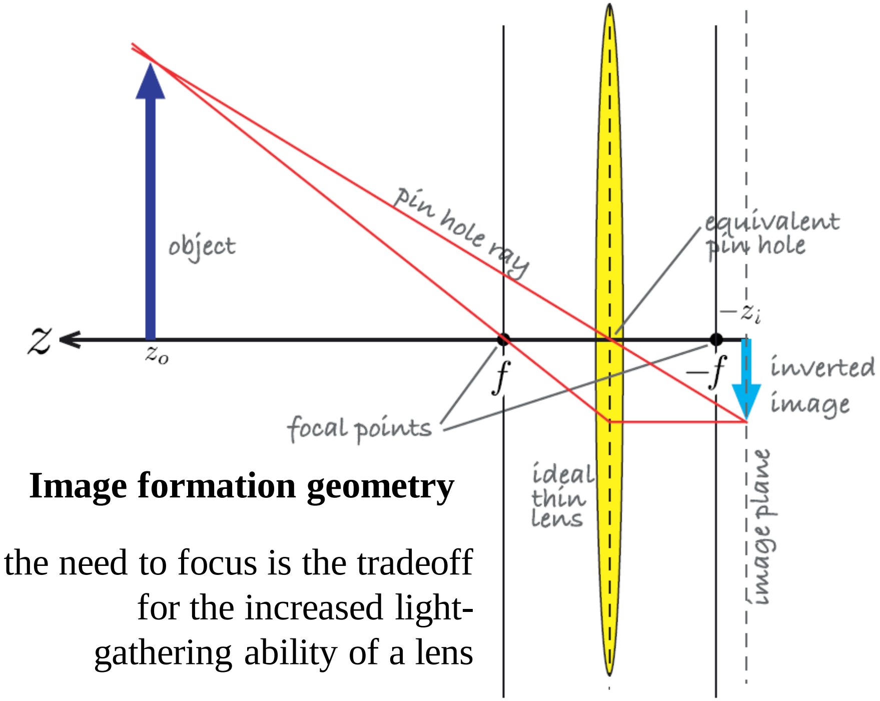
perspective projection $x = f\frac{X}{Z},\ y = f\frac{Y}{Z}$

$\boldsymbol{P} = (X, Y, Z)$



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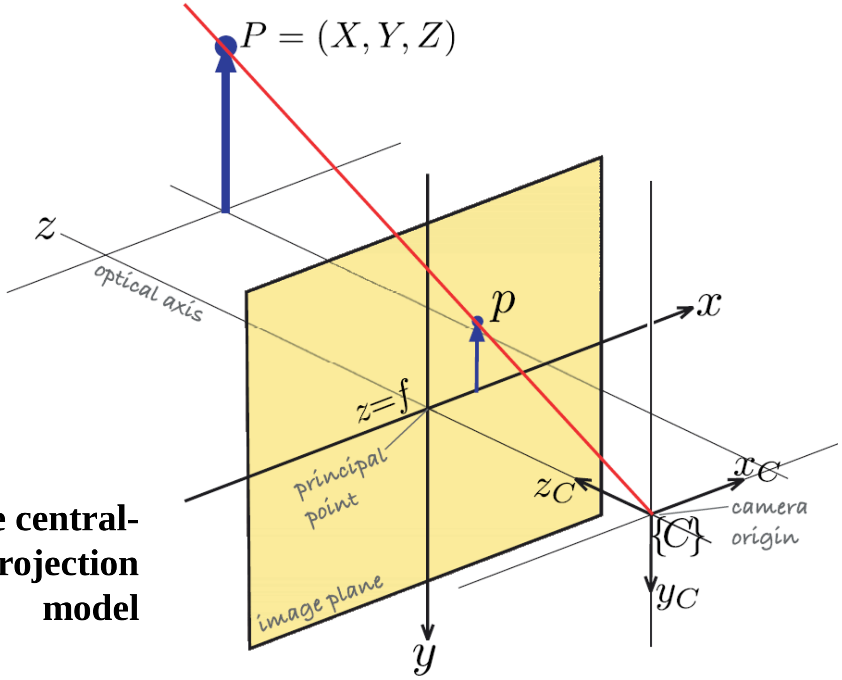

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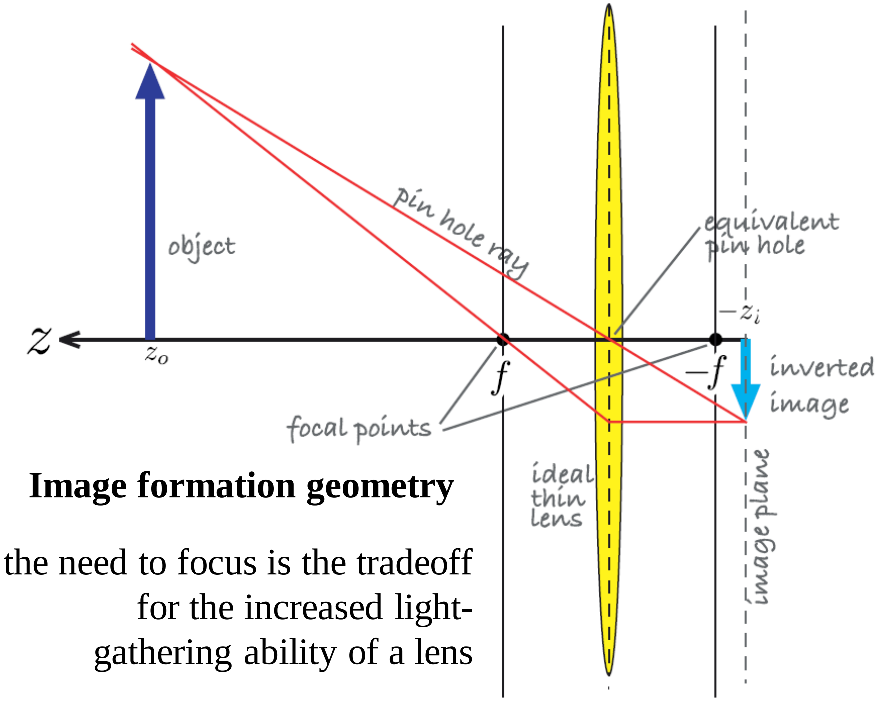
the distance to the image

perspective projection $x = f\frac{X}{Z},\ y = f\frac{Y}{Z}$

$$\boldsymbol{P} = (X, Y, Z) \xrightarrow{f} \boldsymbol{p} = (x, y)$$



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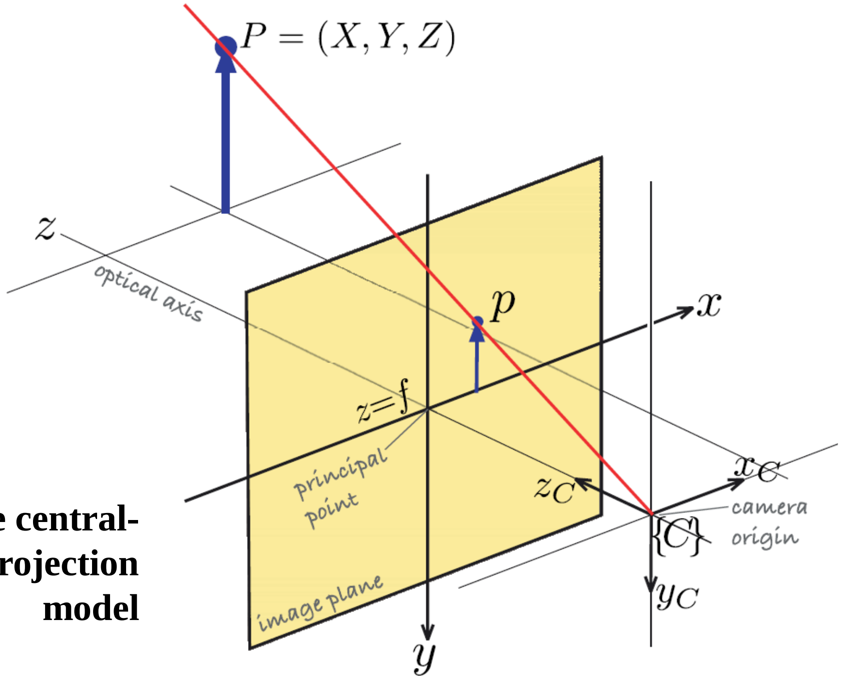


The central-projection model

Perspective Transform

Camera Models

Lens Law $\frac{1}{z_o} + \frac{1}{z_i} = \frac{1}{f}$

the focal length of the lens

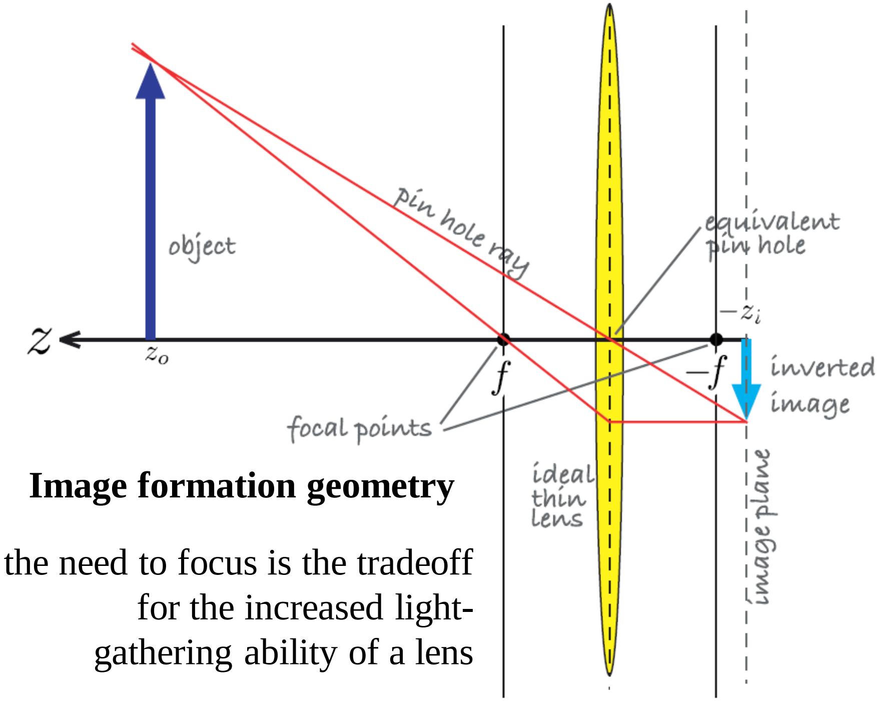
the distance to the object

the distance to the image

perspective projection $x = f\frac{X}{Z},\ y = f\frac{Y}{Z}$

$\boldsymbol{P} = (X, Y, Z) \xrightarrow{f} \boldsymbol{p} = (x, y)$

$\tilde{\boldsymbol{p}} = (x', y', z')$



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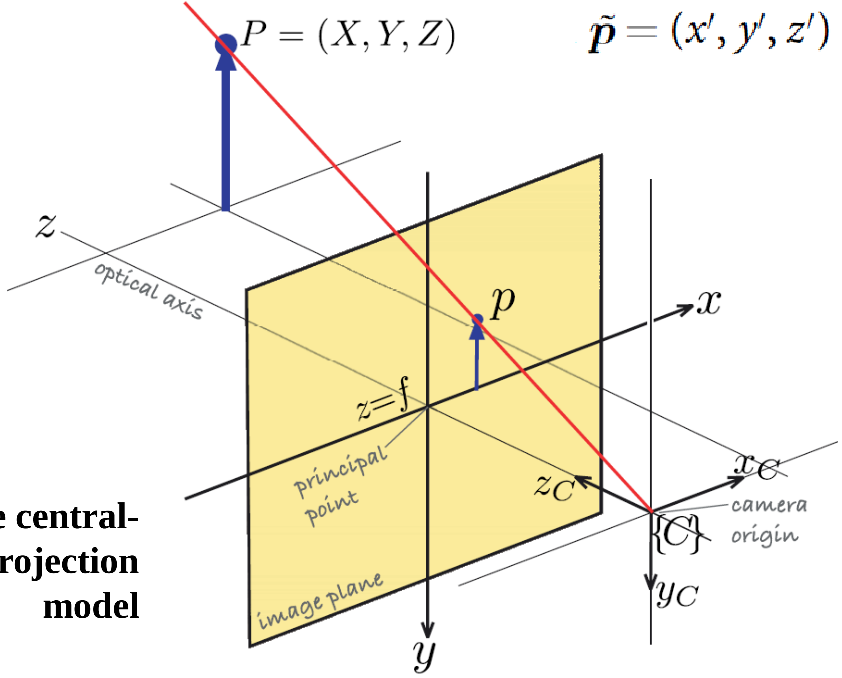

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homogeneous form

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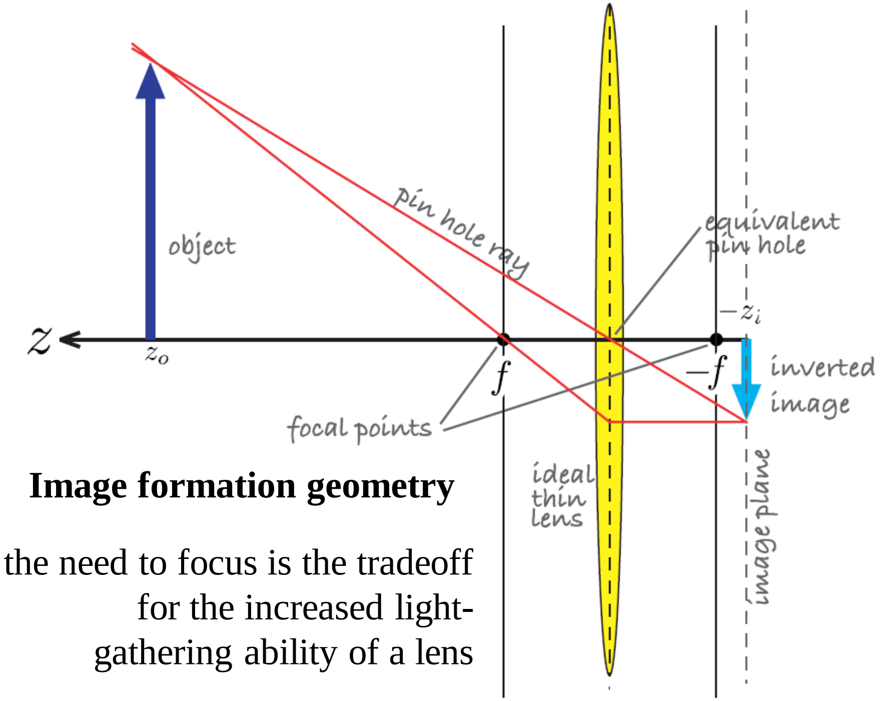
$x' = \frac{fX}{z'},\ y' = \frac{fY}{z'},\ z' = Z$



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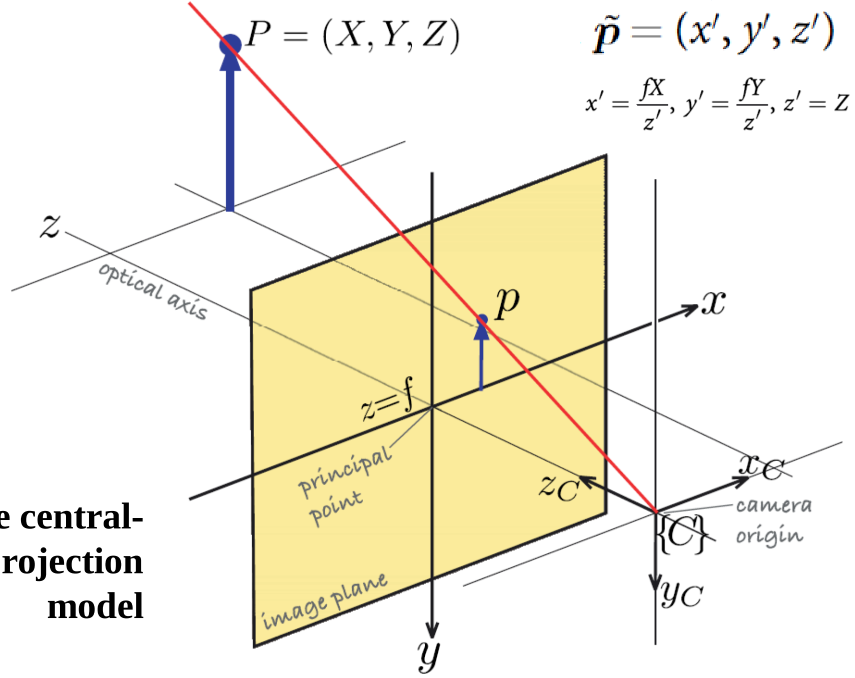

The central-projection model

Characteristics

Perspective Transform

- A mapping from 3D space to the 2D image plane $\mathbb{R}^3 \mapsto \mathbb{R}^2$.

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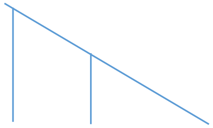
Characteristics

Perspective Transform

- A mapping from 3D space to the 2D image plane

$\mathbb{R}^3 \mapsto \mathbb{R}^2$.

- Straight lines in the world are projected to straight lines on the image plane.



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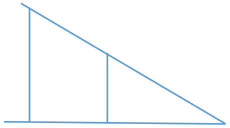
Characteristics

Perspective Transform

- A mapping from 3D space to the 2D image plane
- Straight lines in the world are projected to straight lines on the image plane.
- Parallel lines in the world are projected to lines that intersect at a vanishing point.
  - The exception are lines in the plane parallel to the image plane which do not converge.

$\mathbb{R}^3 \mapsto \mathbb{R}^2.$



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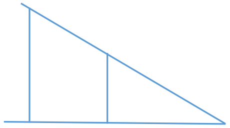

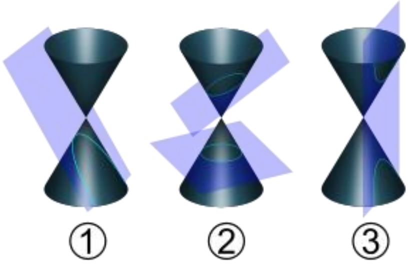

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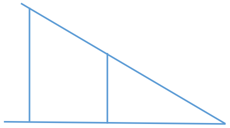

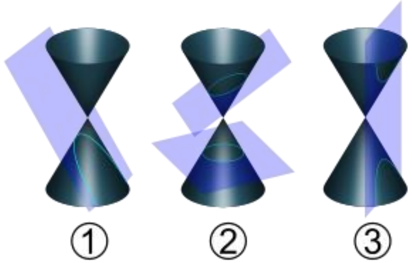

$$\boldsymbol{P} = (X, Y, Z) \xrightarrow{f} \boldsymbol{p} = (x, y)$$

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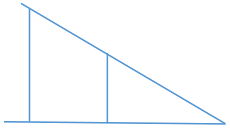
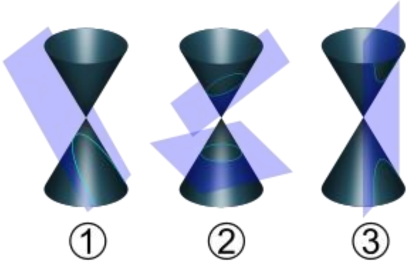
- **The mapping is not one-to-one and a unique inverse does not exist.**
- The transformation is not conformal
  - It does not preserve shape since internal angles are not preserved, different from translation, rotation and scaling.

$\mathbb{R}^3 \mapsto \mathbb{R}^2.$





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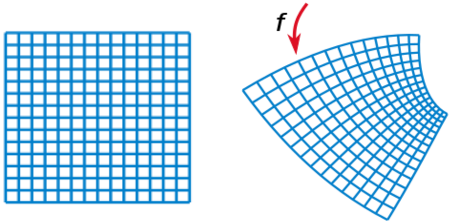

Retinal Image Plane Coordinates

Written in homogeneous form

$\boldsymbol{P} = (X, Y, Z)$

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Retinal Image Plane Coordinates

Written in homogeneous form

$$\begin{tikzcd}
\boldsymbol{P} = (X, Y, Z) \arrow[d, "{x = f\frac{X}{Z},\ y = f\frac{Y}{Z}}"] \\
\boldsymbol{p} = (x, y)
\end{tikzcd}$$

Retinal Image Plane Coordinates

Written in homogeneous form

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\boldsymbol{P} = (X, Y, Z) \arrow[d, "{x = f\frac{X}{Z},\ y = f\frac{Y}{Z}}"'] & \\
\boldsymbol{p} = (x, y) \arrow[r, "\text{homogeneous form}"'] & \tilde{\boldsymbol{p}} = (x', y', z')
\end{tikzcd}$$

$$x = \frac{x'}{z'},\ y = \frac{y'}{z'}$$

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Retinal Image Plane Coordinates

Written in homogeneous form

$$\begin{tikzcd}
\boldsymbol{P}=(X,Y,Z) \arrow[dd, "{x=f\frac{X}{Z},\ y=f\frac{Y}{Z}}"'] \arrow[ddrr, "{x'=\frac{fX}{z'},\ y'=\frac{fY}{z'},\ z'=Z}", "{\tilde{\boldsymbol{p}}=\begin{pmatrix} f & 0 & 0 \\ 0 & f & 0 \\ 0 & 0 & 1 \end{pmatrix}\begin{pmatrix} X \\ Y \\ Z \end{pmatrix}}"'] & & \\
& & \\
\boldsymbol{p}=(x,y) \arrow[rr, "\text{homogeneous form}"'] & & \tilde{\boldsymbol{p}}=(x',y',z')
\end{tikzcd}$$

$$x=\frac{x'}{z'},\ y=\frac{y'}{z'}$$

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Written in homogeneous form

$$\begin{tikzcd}
\mathbf{P} = (X, Y, Z) \arrow[rr, "\text{homogeneous form}"] \arrow[ddd, "{x = f\frac{X}{Z},\ y = f\frac{Y}{Z}}"'] \arrow[dr, dash] & & {}^{C}\tilde{\mathbf{P}} = (X, Y, Z, 1)^{T} \\
& x' = \frac{fX}{z'},\ y' = \frac{fY}{z'},\ z' = Z & \\
& \tilde{\mathbf{p}} = \begin{pmatrix} f & 0 & 0 \\ 0 & f & 0 \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} X \\ Y \\ Z \end{pmatrix} \arrow[dr] & \\
\mathbf{p} = (x, y) \arrow[rr, "\text{homogeneous form}"'] & & \tilde{\mathbf{p}} = (x', y', z')
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$$\begin{tikzcd}[ampersand replacement=\&]
\boldsymbol{P} = (X, Y, Z) \arrow[r, "\text{homogeneous form}"] \arrow[d, "{x = f\frac{X}{Z},\ y = f\frac{Y}{Z}}"'] \arrow[dr, "{x' = \frac{fX}{z'},\ y' = \frac{fY}{z'},\ z' = Z \quad \tilde{\boldsymbol{p}} = \begin{pmatrix} f & 0 & 0 \\ 0 & f & 0 \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} X \\ Y \\ Z \end{pmatrix}}"] \& {}^{C}\tilde{\boldsymbol{P}} = (X, Y, Z, 1)^T \arrow[d, "{\text{camera matrix} \quad \tilde{\boldsymbol{p}} = \begin{pmatrix} f & 0 & 0 & 0 \\ 0 & f & 0 & 0 \\ 0 & 0 & 1 & 0 \end{pmatrix} {}^{C}\tilde{\boldsymbol{P}}}"] \\
\boldsymbol{p} = (x, y) \arrow[r, "\text{homogeneous form}"'] \& \tilde{\boldsymbol{p}} = (x', y', z')
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& \begin{array}{c} x' = \frac{fX}{z'}, y' = \frac{fY}{z'}, z' = Z \\ \tilde{\boldsymbol{p}} = \begin{pmatrix} f & 0 & 0 \\ 0 & f & 0 \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} X \\ Y \\ Z \end{pmatrix} \end{array} \arrow[dr] & & \begin{array}{c} \text{camera matrix} \\ \tilde{\boldsymbol{p}} = \begin{pmatrix} f & 0 & 0 & 0 \\ 0 & f & 0 & 0 \\ 0 & 0 & 1 & 0 \end{pmatrix} {}^{C}\tilde{\boldsymbol{P}} \end{array} \arrow[d] \\
\boldsymbol{p} = (x, y) \arrow[rr, "\text{homogeneous form}"', "{x = \frac{x'}{z'}, y = \frac{y'}{z'}}"' near end, shift right=0] & & \tilde{\boldsymbol{p}} = (x', y', z') & \tilde{\boldsymbol{p}} = \begin{pmatrix} f & 0 & 0 \\ 0 & f & 0 \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \end{pmatrix} {}^{C}\tilde{\boldsymbol{P}}
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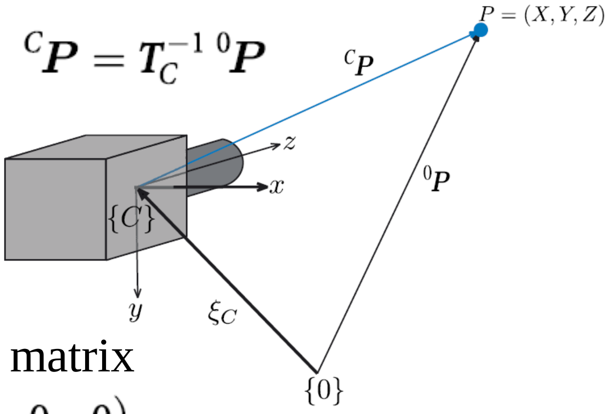

$${}^{C}\boldsymbol{P} = \boldsymbol{T}_C^{-1}\, {}^{0}\boldsymbol{P}$$

camera matrix

$$\tilde{\boldsymbol{p}} = \begin{pmatrix} f & 0 & 0 & 0 \\ 0 & f & 0 & 0 \\ 0 & 0 & 1 & 0 \end{pmatrix} {}^{C}\tilde{\boldsymbol{P}}$$

$$\tilde{\boldsymbol{p}} = \begin{pmatrix} f & 0 & 0 \\ 0 & f & 0 \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \end{pmatrix} {}^{C}\tilde{\boldsymbol{P}}$$

What about the physical coordinates on the actual image?

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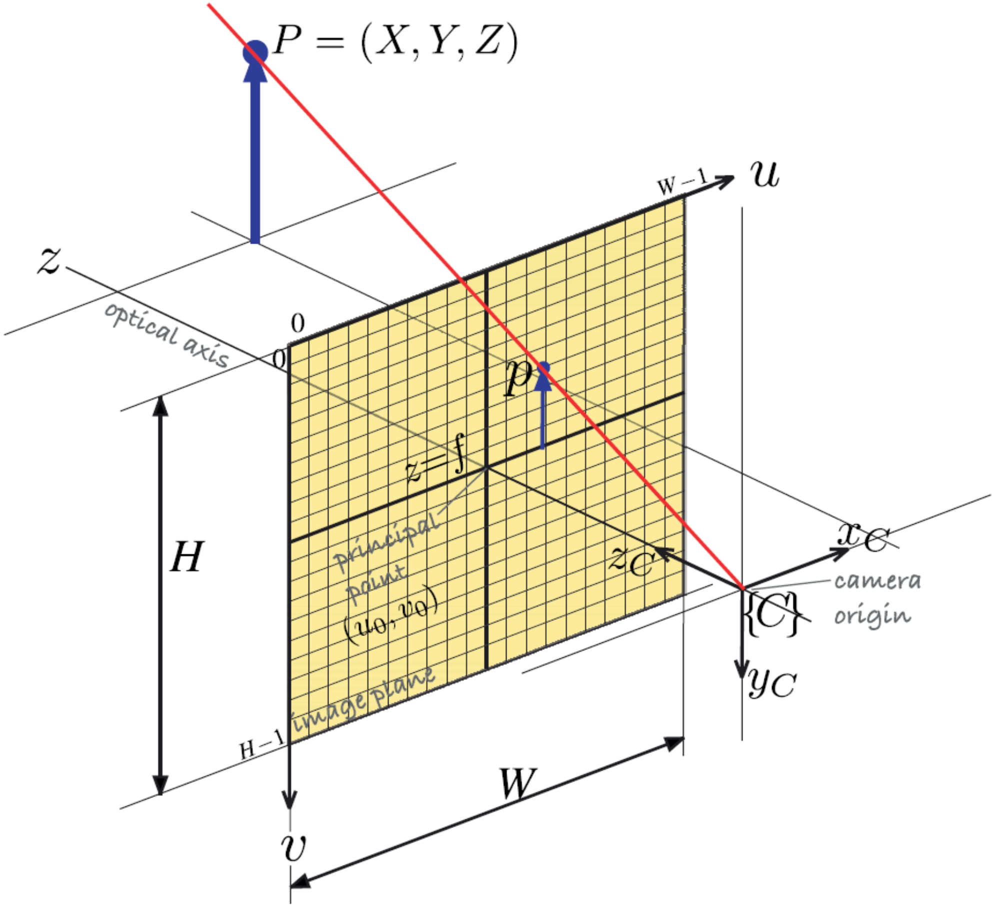
Express w.r.t the Camera

Physical Meanings of Camera Pixels

- A **camera sensor** with a **W**× **H** grid of image pixels
  - The pixel coordinates (*u*, *v*)



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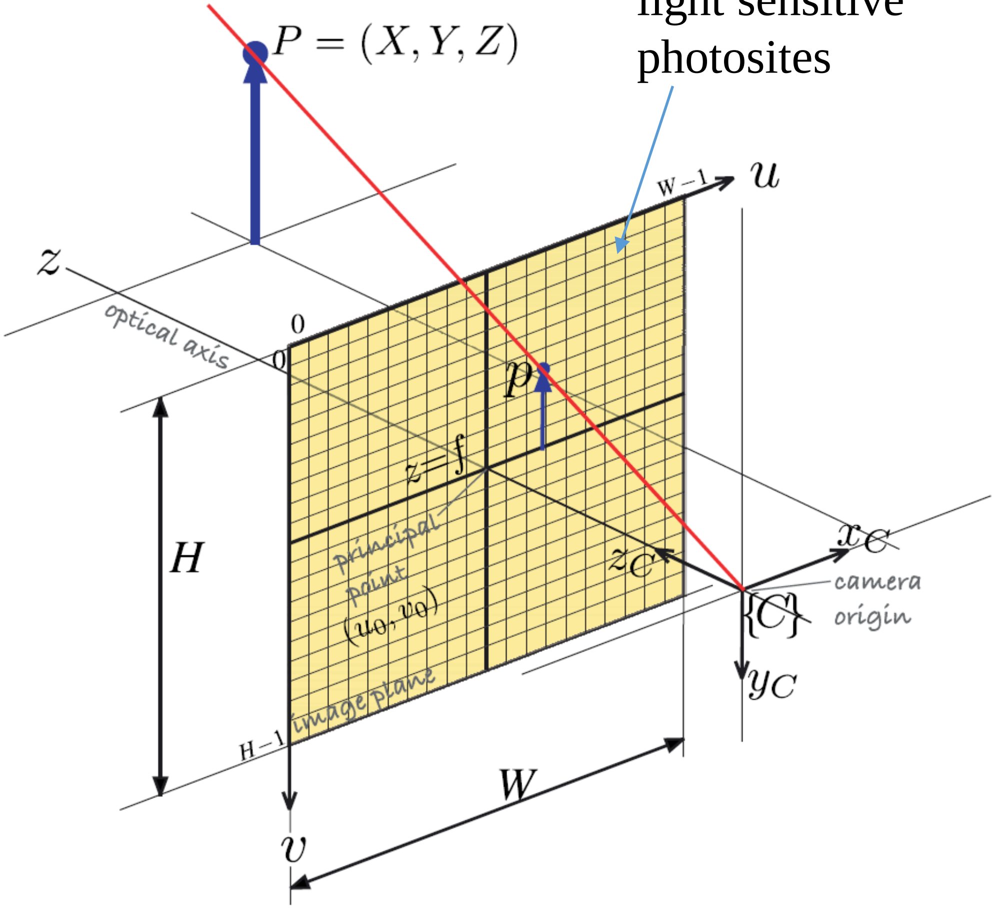

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Express w.r.t the Camera

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- A **camera sensor** with a **W**× **H** grid of image pixels
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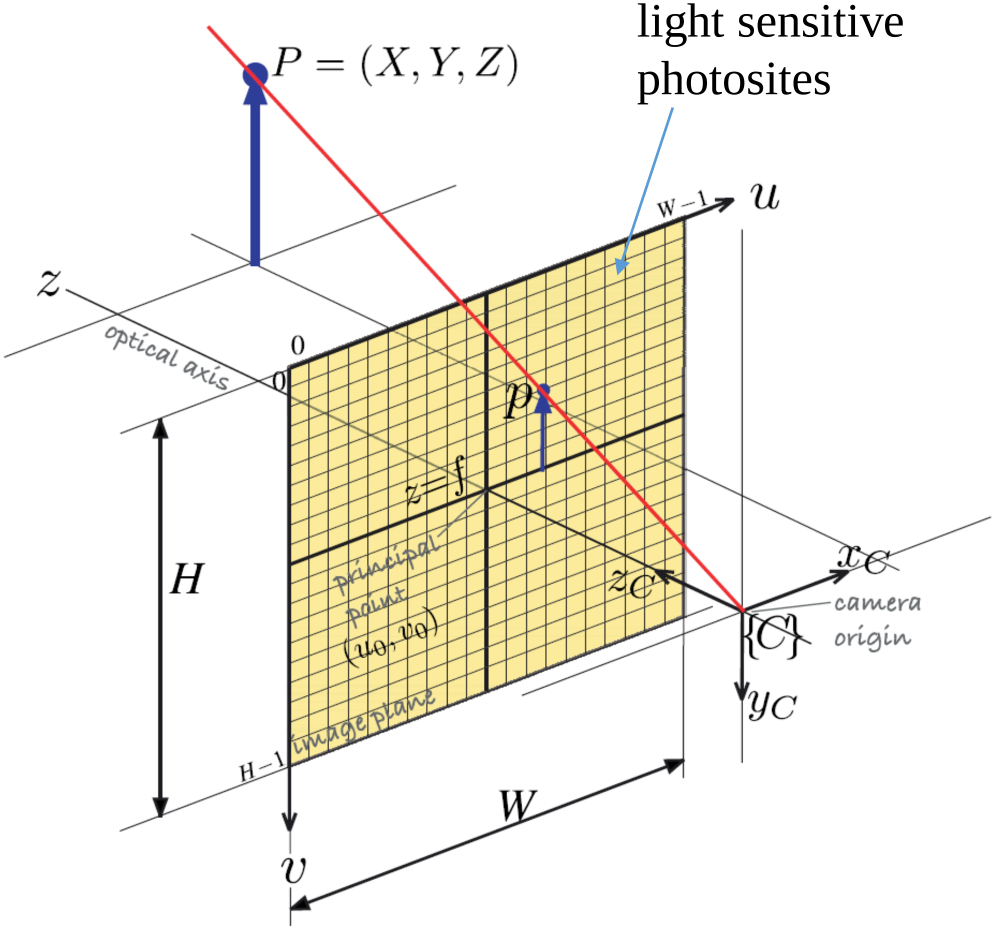
$$u = \frac{x}{\rho_w} + u_0,\ v = \frac{y}{\rho_h} + v_0$$



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Principal point in pixel coordinate

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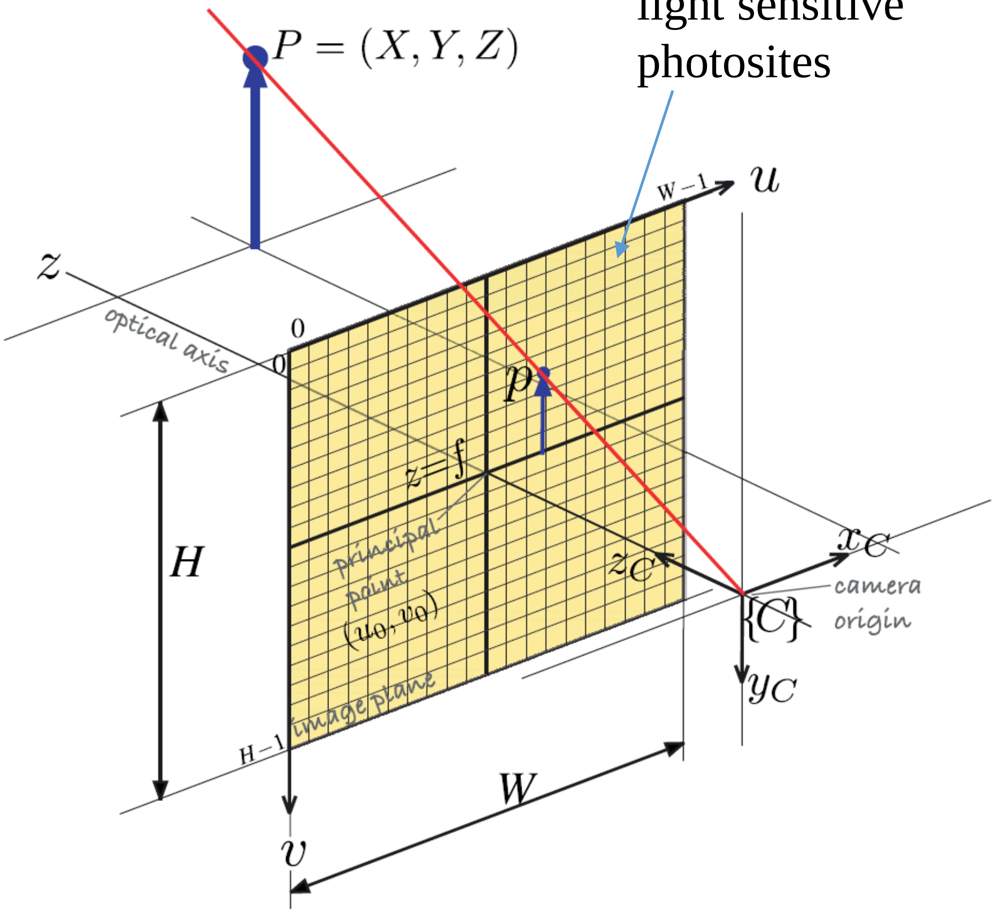

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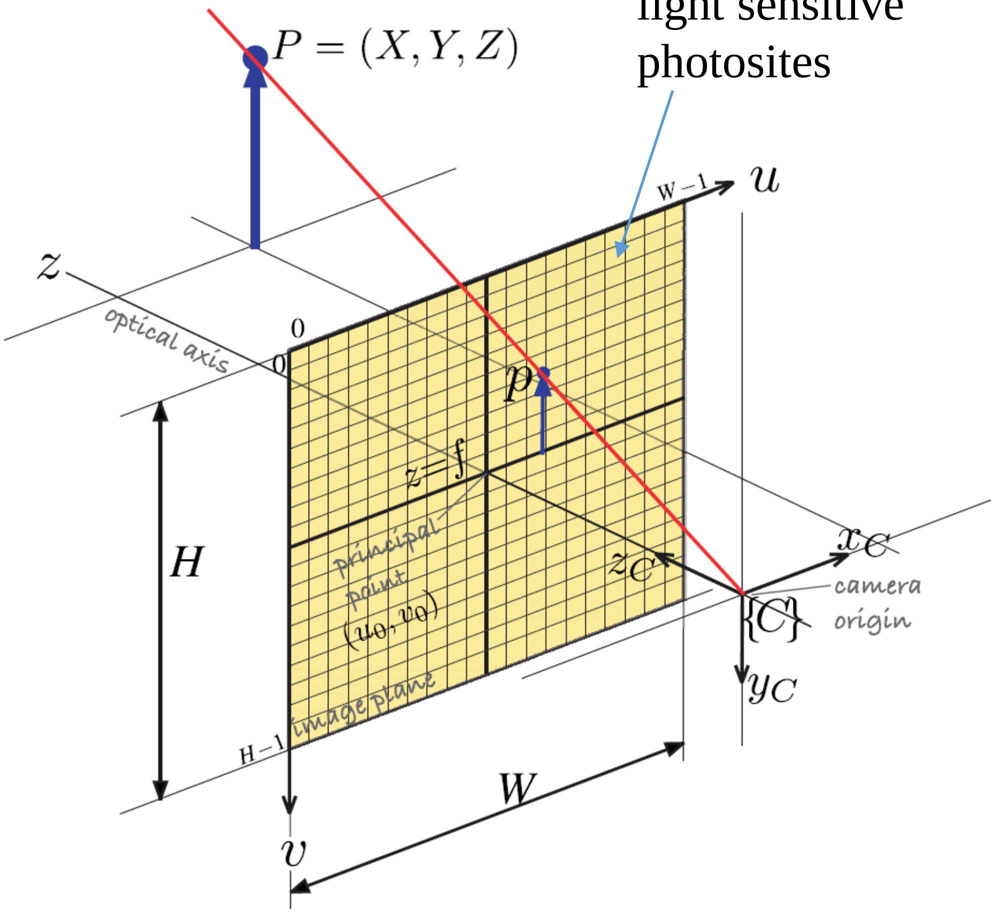
width and height of each pixel



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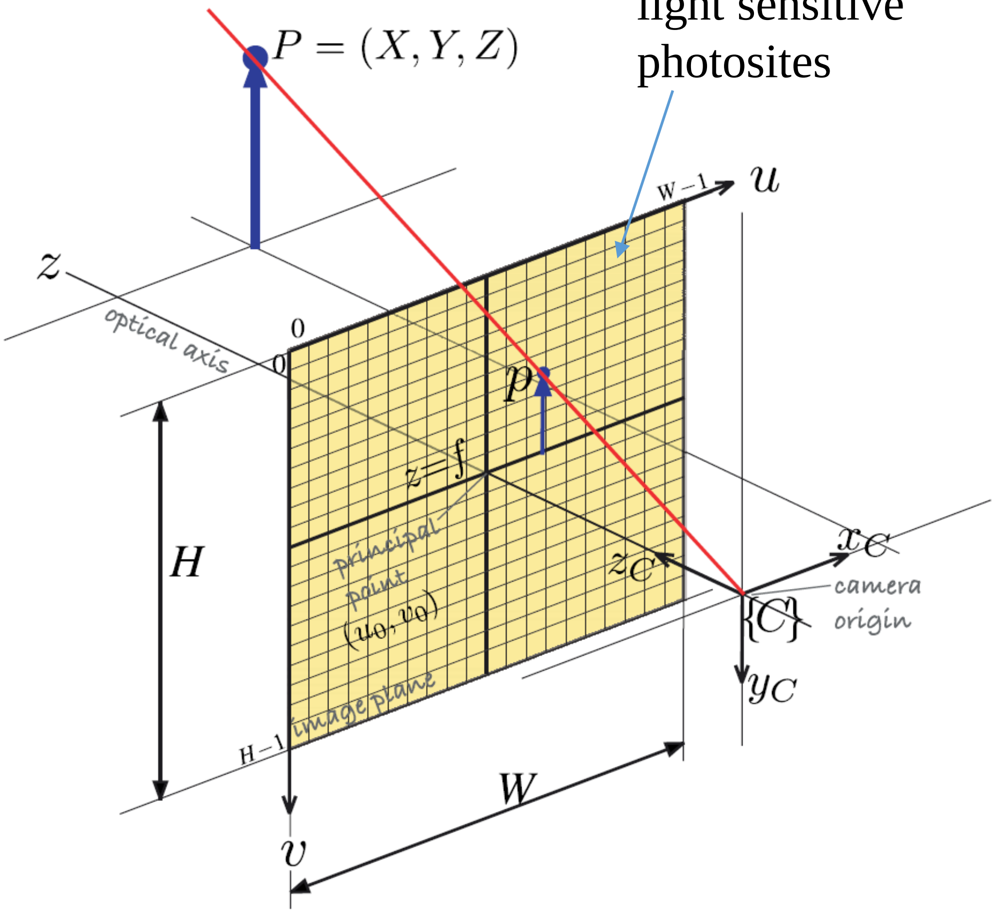
pixel coordinate



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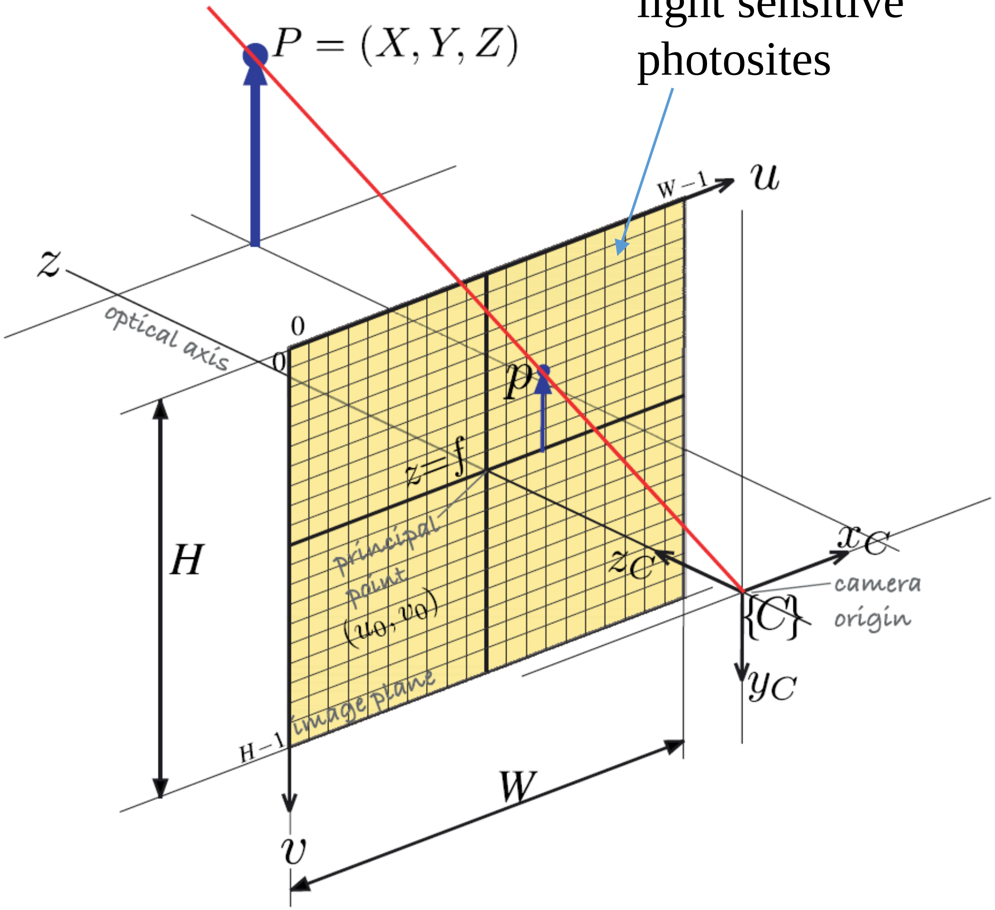

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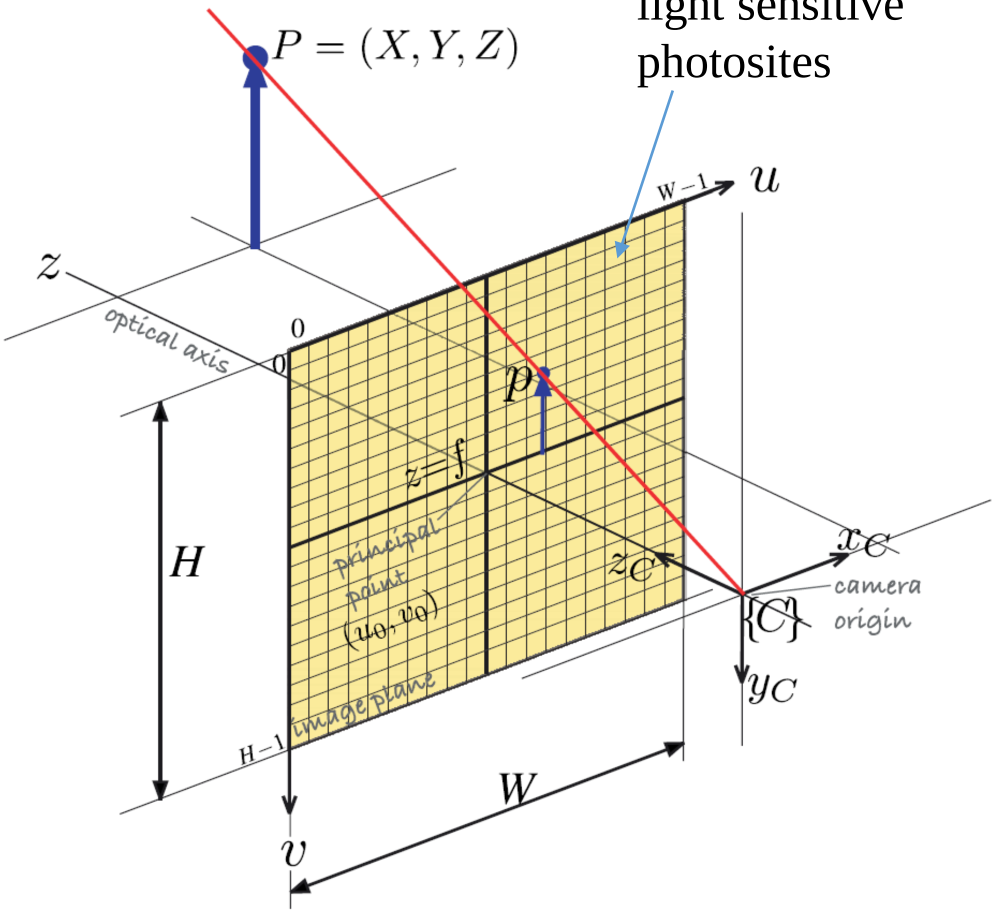
$$u = \frac{u'}{w'},\ v = \frac{v'}{w'}$$

$$\tilde{\boldsymbol{p}} = \underbrace{\begin{pmatrix} 1/\rho_w & 0 & u_0 \\ 0 & 1/\rho_h & v_0 \\ 0 & 0 & 1 \end{pmatrix}}_{K} \begin{pmatrix} f & 0 & 0 & 0 \\ 0 & f & 0 & 0 \\ 0 & 0 & 1 & 0 \end{pmatrix} {}^{C}\tilde{\boldsymbol{P}}$$



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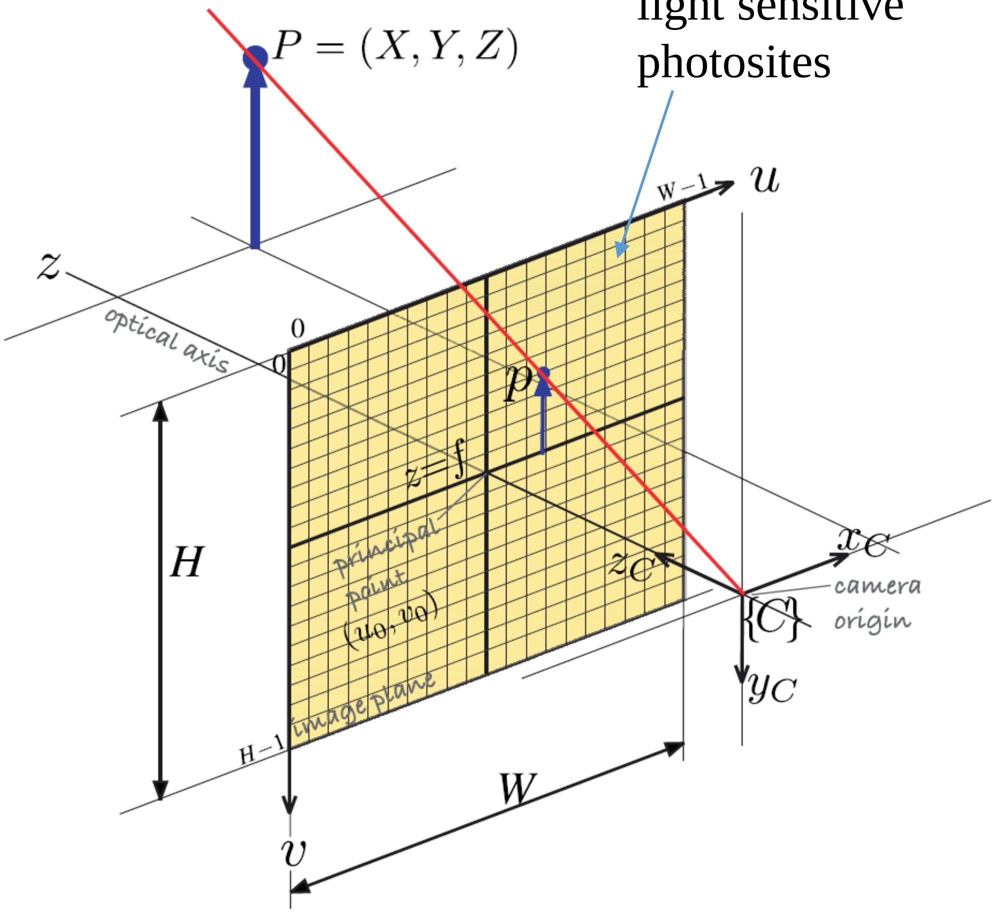
camera parameter matrix



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camera (projection) matrix

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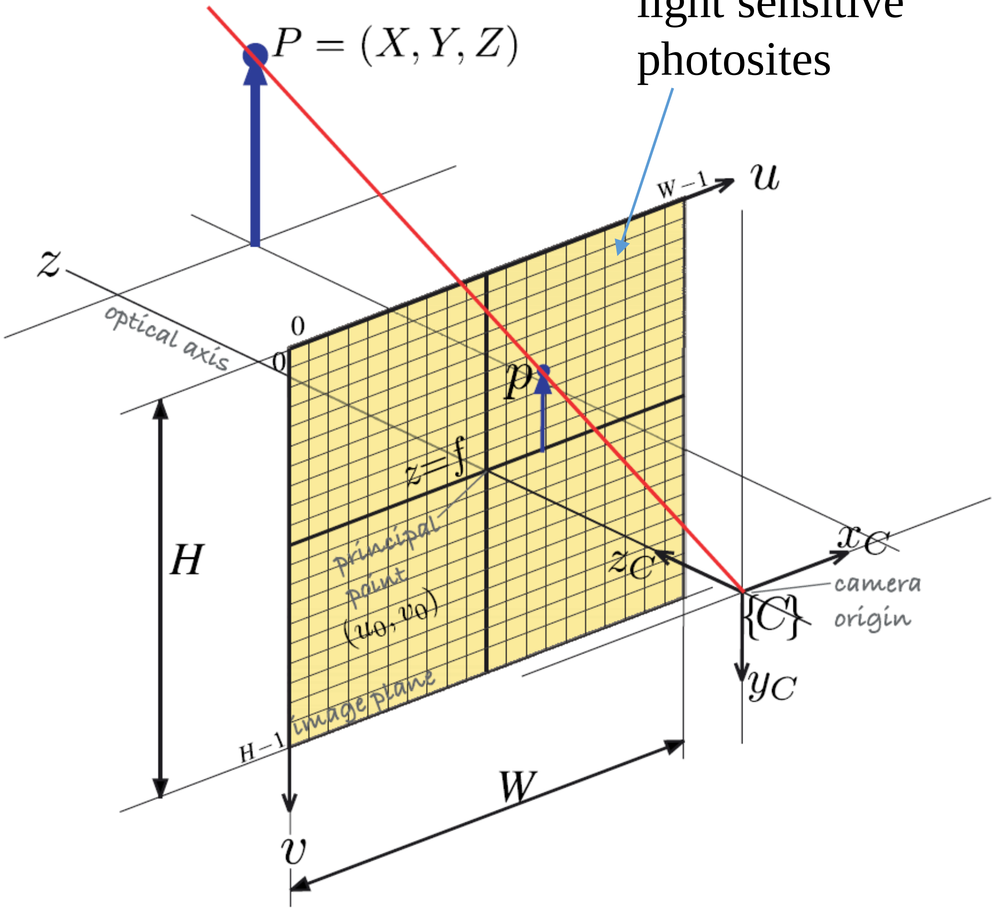
camera parameter matrix



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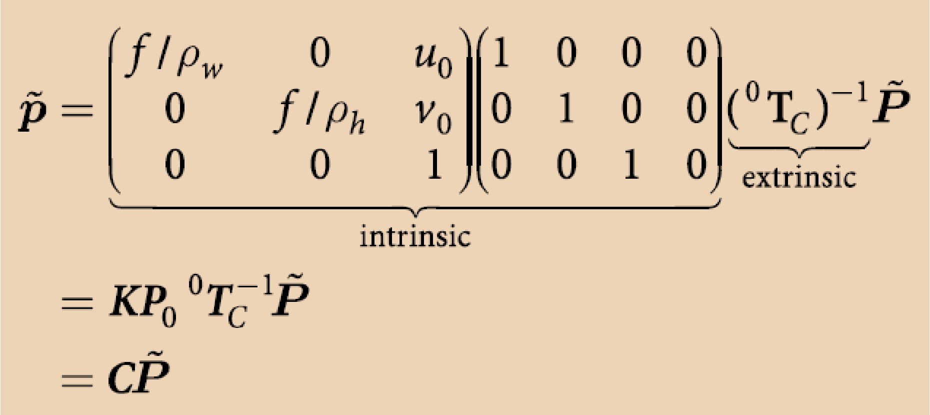
Camera Projection In General Form

Still, something is missing

- The 3x4 Camera Calibration Matrix
  - Performs scaling, translation and perspective projection



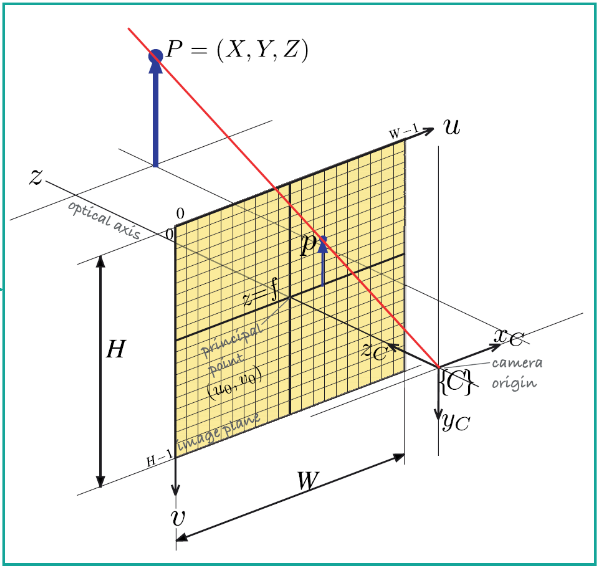
$$
\begin{aligned}
\tilde{\boldsymbol{p}} &= \underbrace{\begin{pmatrix} f/\rho_w & 0 & u_0 \\ 0 & f/\rho_h & v_0 \\ 0 & 0 & 1 \end{pmatrix}\begin{pmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \end{pmatrix}}_{\text{intrinsic}} \underbrace{({}^{0}\mathrm{T}_{C})^{-1}}_{\text{extrinsic}} \tilde{\boldsymbol{P}} \\
&= \boldsymbol{K}\boldsymbol{P}_0 \, {}^{0}\boldsymbol{T}_C^{-1} \tilde{\boldsymbol{P}} \\
&= \boldsymbol{C}\tilde{\boldsymbol{P}}
\end{aligned}
$$

Camera Projection In General Form

Still, something is missing

- The 3x4 Camera Calibration Matrix
  - Performs scaling, translation and perspective projection

$$
\begin{aligned}
\tilde{p} &= \underbrace{\begin{pmatrix} f/\rho_w & 0 & u_0 \\ 0 & f/\rho_h & v_0 \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \end{pmatrix}}_{\text{intrinsic}} \underbrace{({}^{0}\mathrm{T}_{C})^{-1}}_{\text{extrinsic}} \tilde{\boldsymbol{P}} \\
&= \boldsymbol{K}\boldsymbol{P}_0 \, {}^{0}\boldsymbol{T}_C^{-1} \tilde{\boldsymbol{P}} \\
&= \boldsymbol{C}\tilde{\boldsymbol{P}}
\end{aligned}
$$



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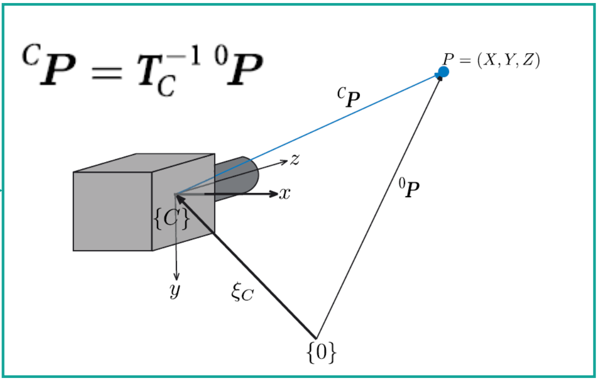
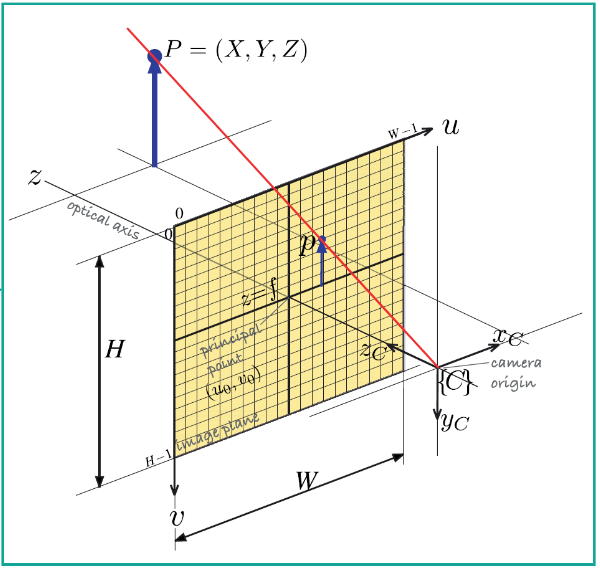
$$= KP_0\, {}^{0}T_C^{-1}\tilde{P}$$

$$= C\tilde{P}$$





Camera Projection In General Form

Still, something is missing

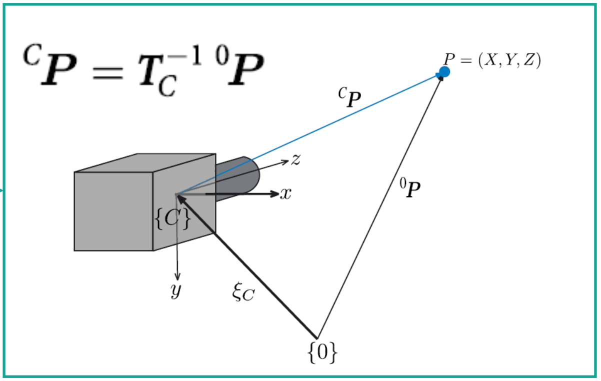
- The 3x4 Camera Calibration Matrix
  - Performs scaling, translation and perspective projection

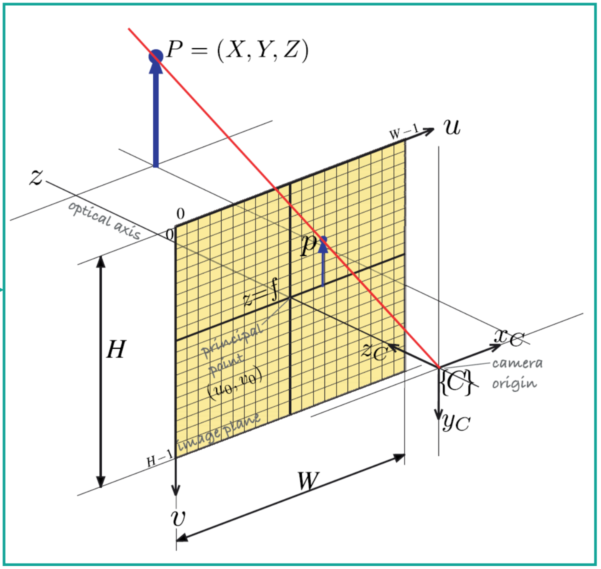
$$\tilde{p} = \underbrace{\begin{pmatrix} f/\rho_w & 0 & u_0 \\ 0 & f/\rho_h & v_0 \\ 0 & 0 & 1 \end{pmatrix}\begin{pmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \end{pmatrix}}_{\text{intrinsic}} \underbrace{\left({}^{0}\mathrm{T}_C\right)^{-1}}_{\text{extrinsic}} \tilde{P}$$

$$= KP_0\,{}^{0}T_C^{-1}\tilde{P}$$

$$= C\tilde{P}$$

$$p = \mathcal{P}(P, K, \xi_C)$$





Camera Projection In General Form

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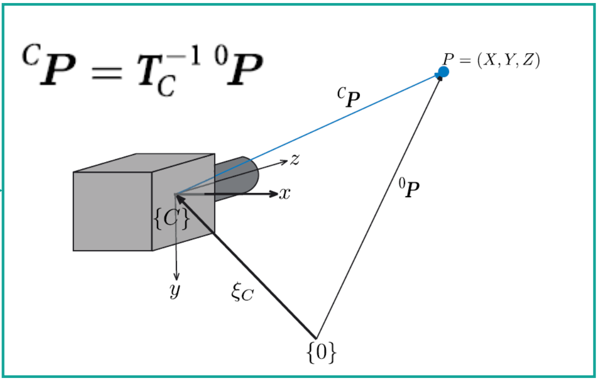
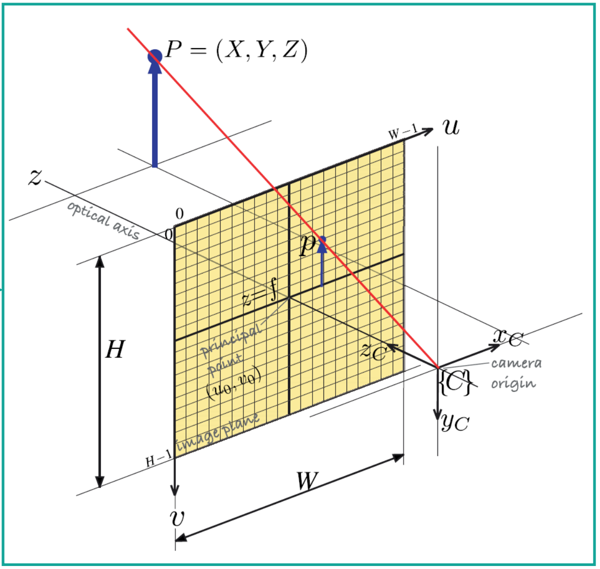
$$\tilde{p} = \underbrace{\begin{pmatrix} f/\rho_w & 0 & u_0 \\ 0 & f/\rho_h & v_0 \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \end{pmatrix}}_{\text{intrinsic}} \underbrace{\left({}^{0}\mathrm{T}_{C}\right)^{-1}}_{\text{extrinsic}} \tilde{P}$$

$$= K P_0\, {}^{0}T_C^{-1} \tilde{P}$$

$$= C\tilde{P}$$

$$p = \mathcal{P}(\boxed{P}, K, \xi_C)$$





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  - Performs scaling, translation and perspective projection

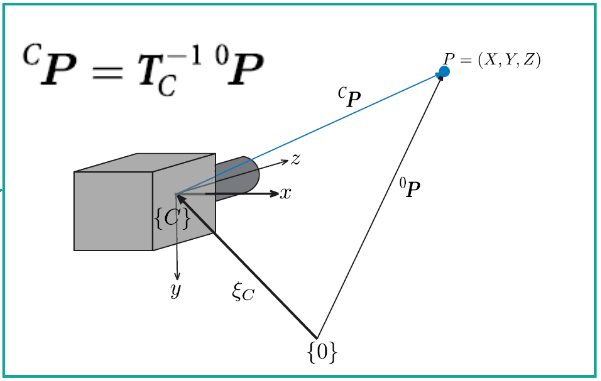
$$\tilde{\boldsymbol{p}} = \underbrace{\begin{pmatrix} f/\rho_w & 0 & u_0 \\ 0 & f/\rho_h & v_0 \\ 0 & 0 & 1 \end{pmatrix}\begin{pmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \end{pmatrix}}_{\text{intrinsic}} \underbrace{\left({}^{0}\mathbf{T}_C\right)^{-1}}_{\text{extrinsic}} \tilde{\boldsymbol{P}}$$

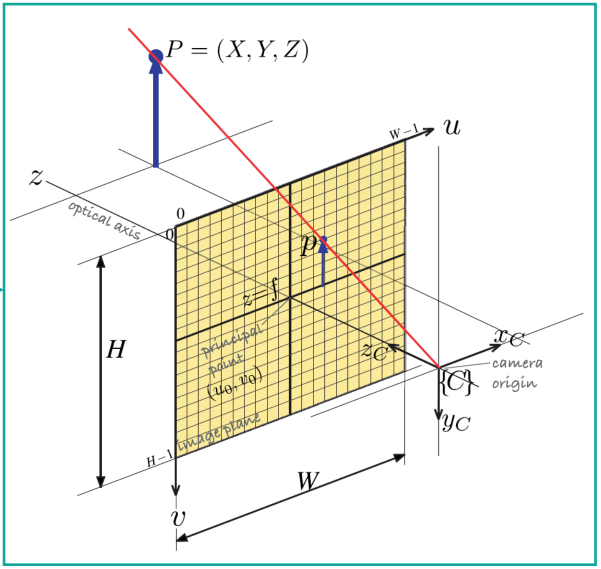
$$= \boldsymbol{K}\boldsymbol{P}_0\, {}^{0}\boldsymbol{T}_C^{-1} \tilde{\boldsymbol{P}}$$

$$= \boldsymbol{C}\tilde{\boldsymbol{P}}$$

$$\boldsymbol{p} = \mathcal{P}(\boxed{\boldsymbol{P}}, \boxed{\boldsymbol{K}}, \xi_C)$$

Camera parameter matrix: **5** parameters


${}^{C}\boldsymbol{P} = \boldsymbol{T}_C^{-1}\, {}^{0}\boldsymbol{P}$
$P = (X, Y, Z)$
${}^{C}P$
${}^{0}P$
z
x
y
$\{C\}$
ξ_C
$\{0\}$



Camera Projection In General Form

Still, something is missing

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    - Performs scaling, translation and perspective projection

$$\tilde{p} = \underbrace{\begin{pmatrix} f/\rho_w & 0 & u_0 \\ 0 & f/\rho_h & v_0 \\ 0 & 0 & 1 \end{pmatrix}\begin{pmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \end{pmatrix}}_{\text{intrinsic}} \underbrace{\left({}^{0}\mathrm{T}_C\right)^{-1}}_{\text{extrinsic}} \tilde{\boldsymbol{P}}$$

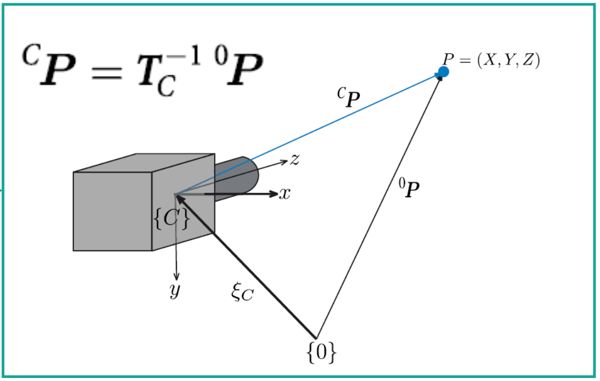
$$= \boldsymbol{K}\boldsymbol{P}_0 \, {}^{0}\boldsymbol{T}_C^{-1} \tilde{\boldsymbol{P}}$$

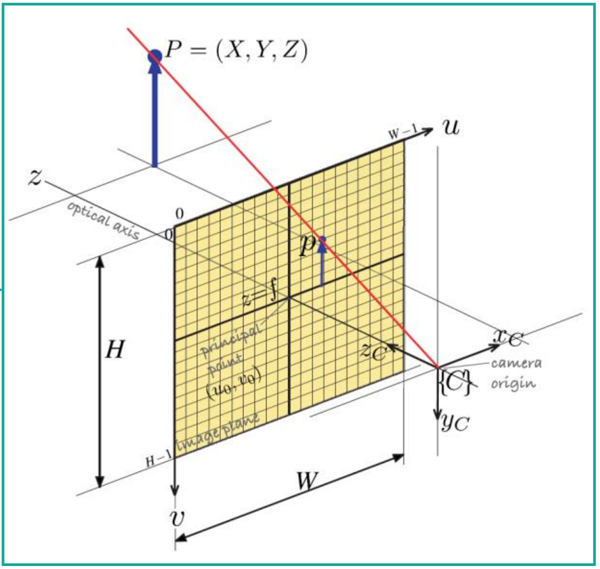
$$= \boldsymbol{C}\tilde{\boldsymbol{P}}$$

$$\boldsymbol{p} = \mathcal{P}(\boxed{\boldsymbol{P}}, \boxed{\boldsymbol{K}}, \boxed{\xi_C})$$

Camera pose: **6** parameters

Camera parameter matrix: **5** parameters


${}^{C}\boldsymbol{P} = \boldsymbol{T}_C^{-1}\,{}^{0}\boldsymbol{P}$
$P = (X, Y, Z)$
${}^{C}P$
z
x
${}^{0}P$
$\{C\}$
y
ξ_C
$\{0\}$



Camera Projection In General Form

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$$= KP_0\,{}^0T_C^{-1}\tilde{P}$$

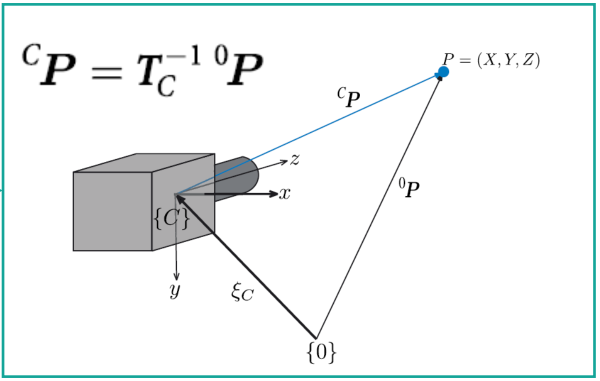
$$= C\tilde{P}$$

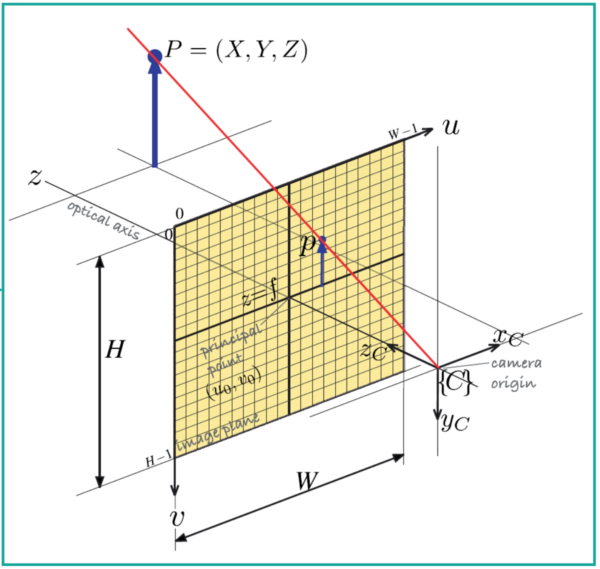
C is 3x4 with **12** elements

$$p = \mathcal{P}(\boxed{P}, \boxed{K}, \boxed{\xi_C})$$

Camera pose: **6** parameters

Camera parameter matrix: **5** parameters





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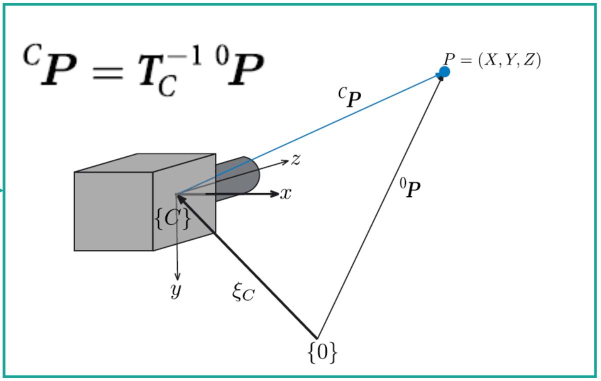
$$= KP_0 \, {}^{0}T_C^{-1} \tilde{P}$$

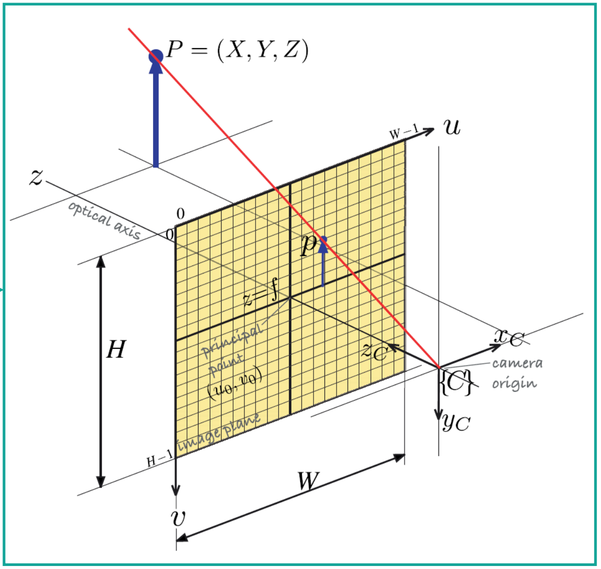
$$= C\tilde{P}$$

$$\tilde{p} = (CH^{-1})(H\tilde{P}) = C'\tilde{P}'$$

C is 3x4 with **12** elements

Unconstrained Overall Scale Factor





$$p = \mathcal{P}(\boxed{P}, \boxed{K}, \boxed{\xi_C})$$

Camera pose: **6** parameters

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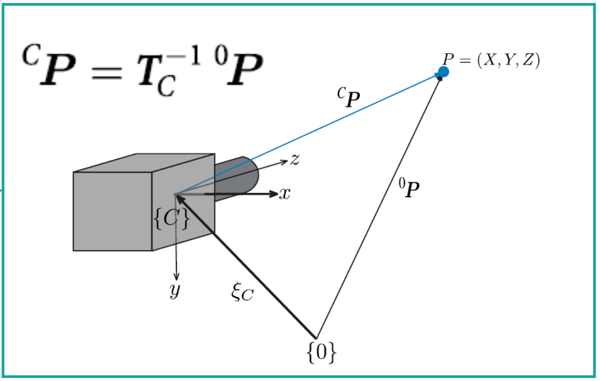

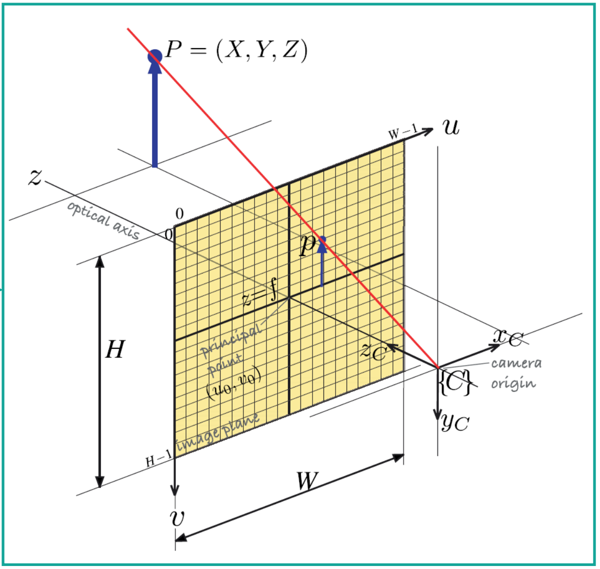

$$p = \mathcal{P}(P, K, \xi_C)$$

Camera pose: **6** parameters

Camera parameter matrix: **5** parameters

It can only be solved if we have information about the camera or the 3D object

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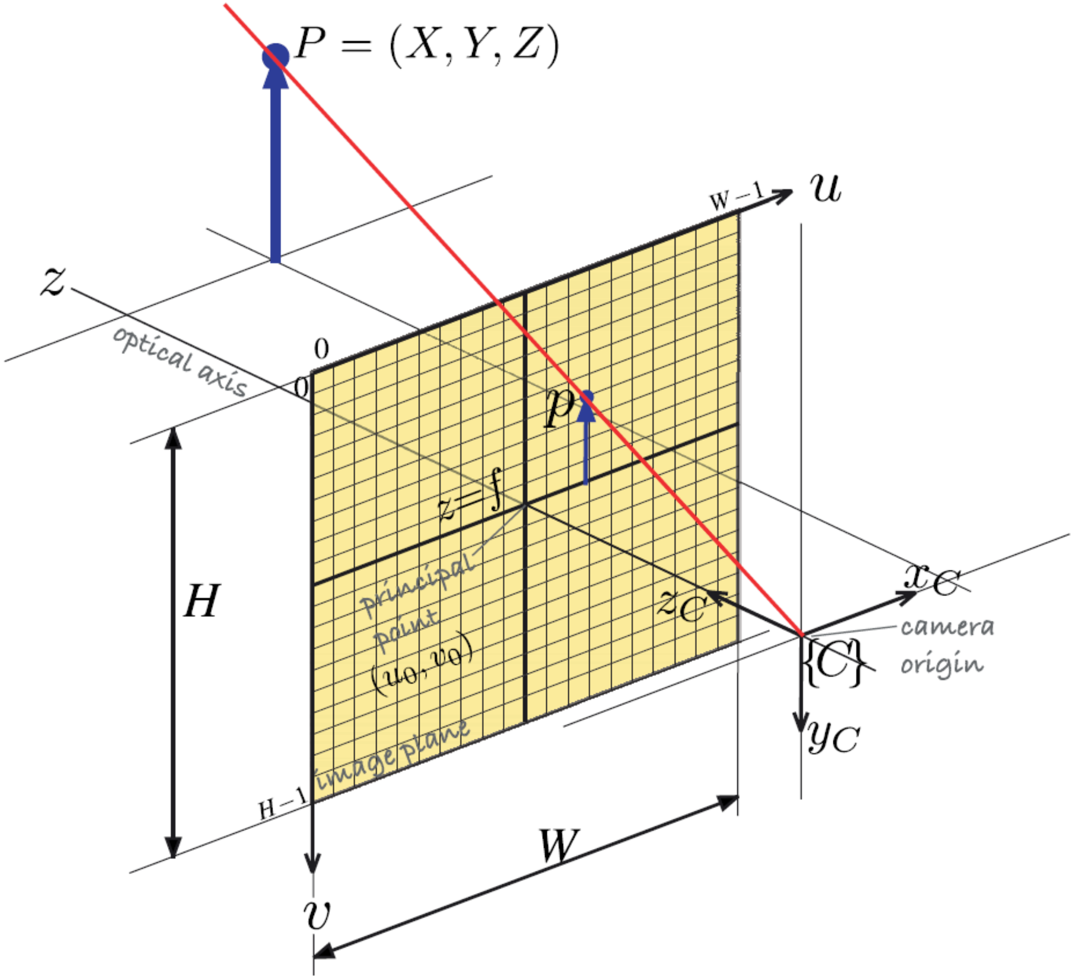
Camera Calibration

In general, the cameras are not made as modeled



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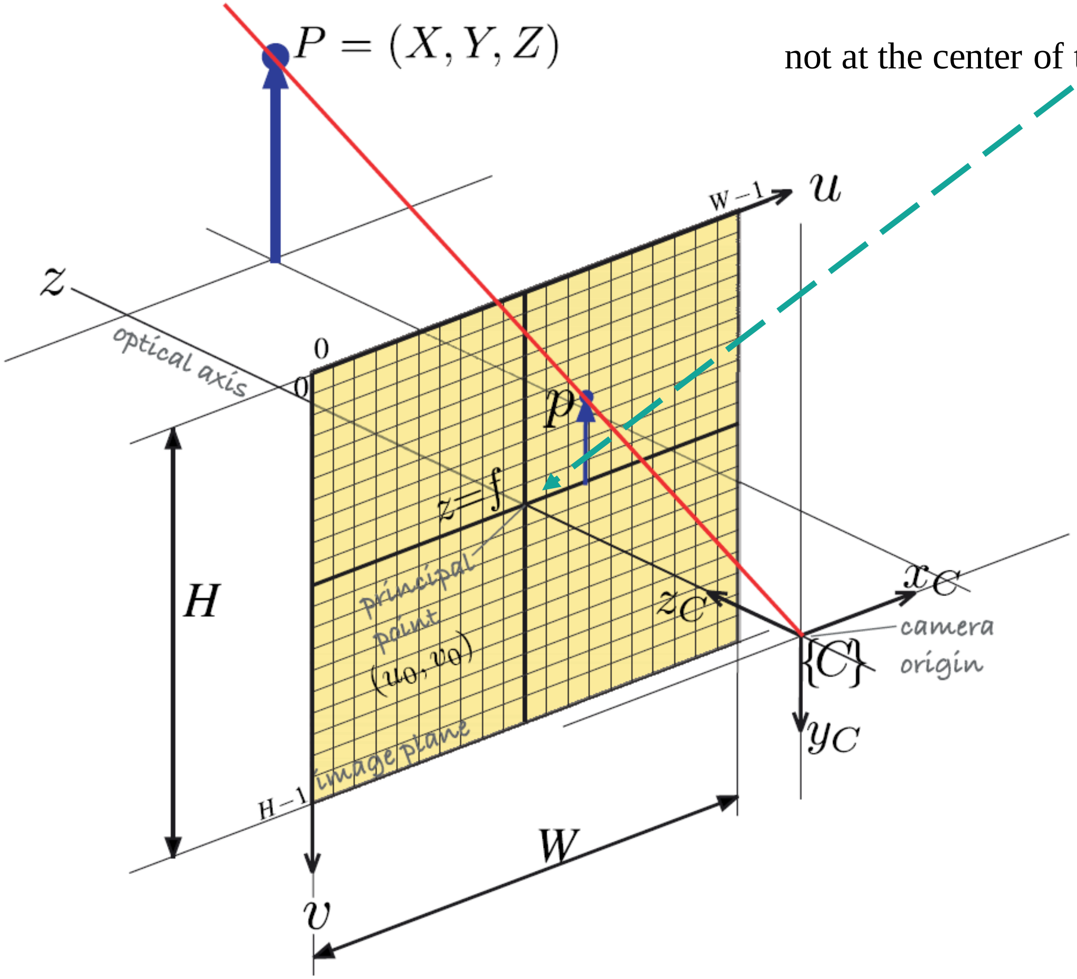
Camera Calibration

In general, the cameras are not made as modeled



not at the center of the photosite array

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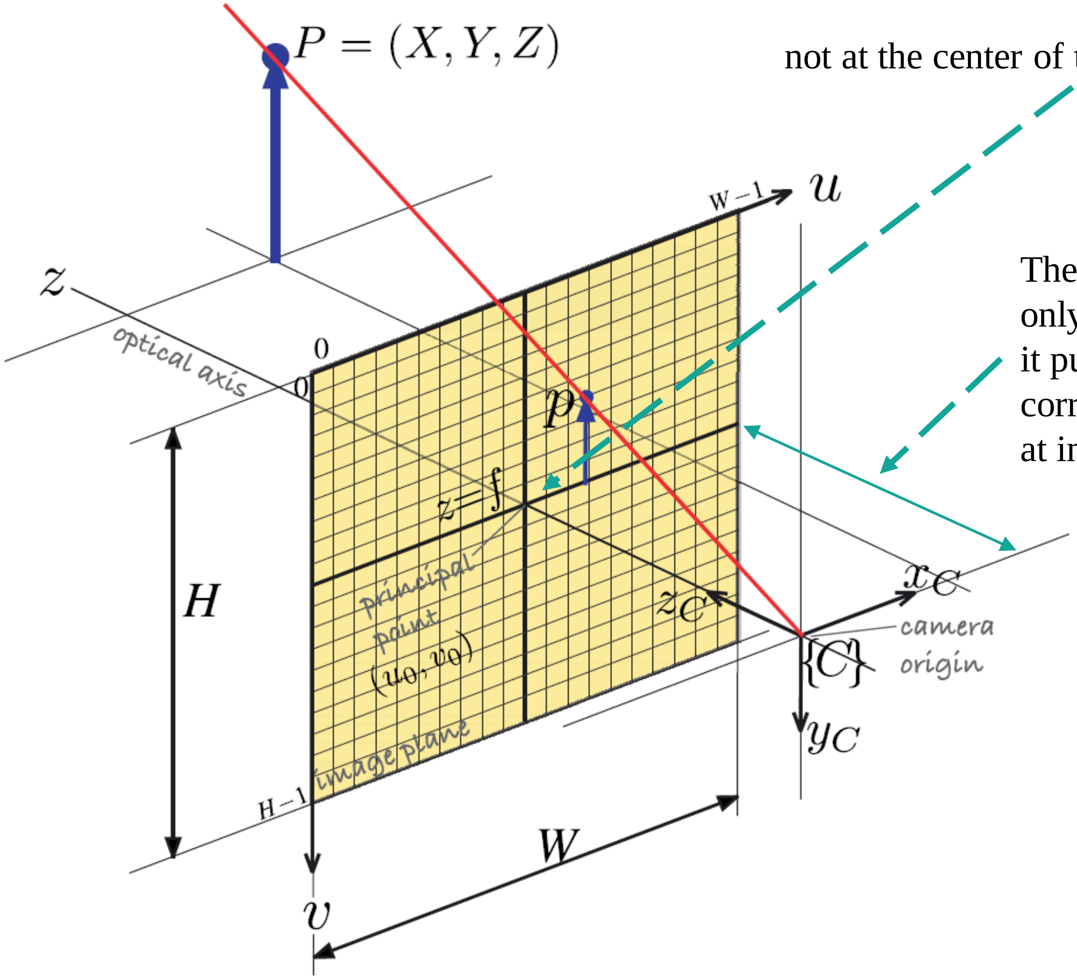

not at the center of the photosite array

The focal length of a lens is only accurate to 4% of what it purports to be, and is only correct if the lens is focused at infinity

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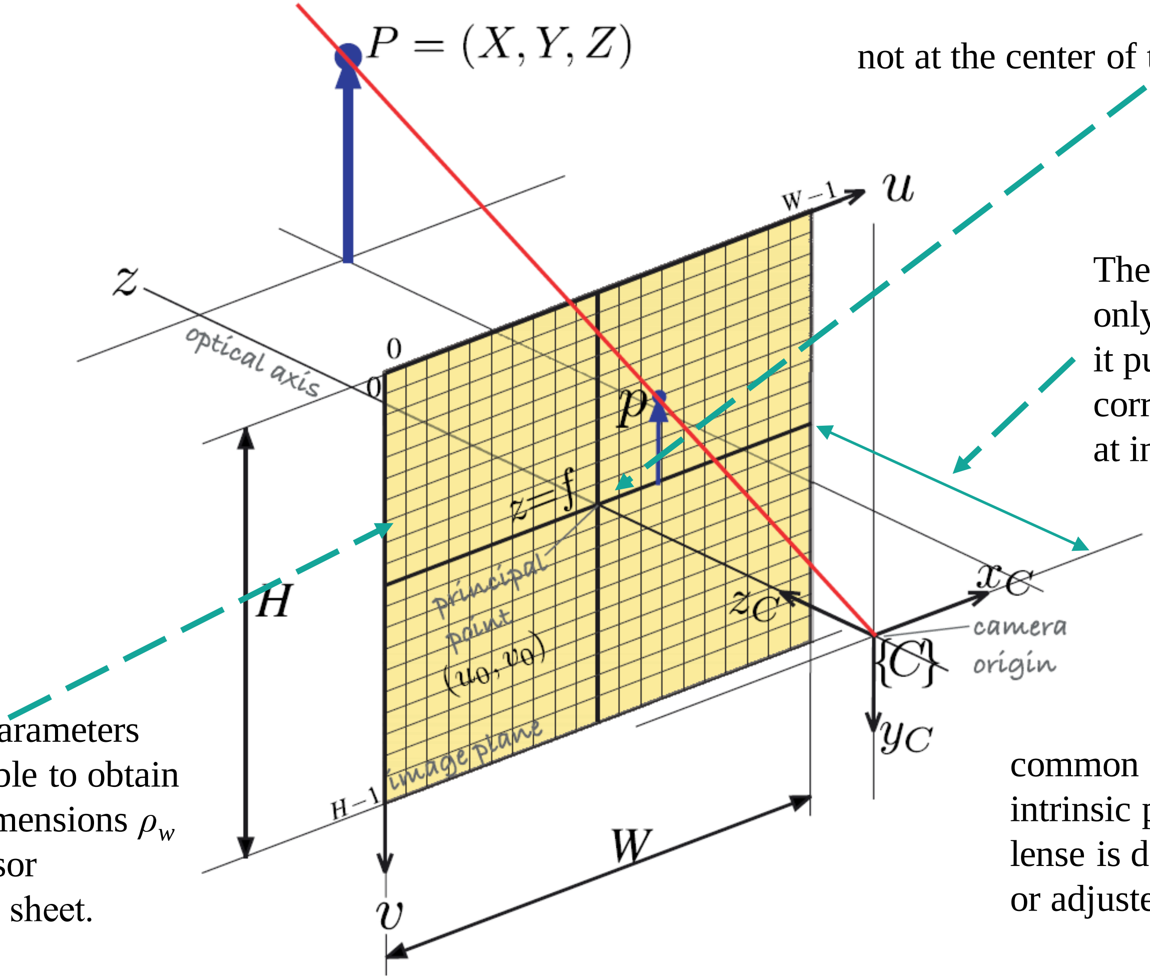
Camera Calibration

In general, the cameras are not made as modeled



not at the center of the photosite array

The focal length of a lens is only accurate to 4% of what it purports to be, and is only correct if the lens is focused at infinity

The only intrinsic parameters that it may be possible to obtain are the photosite dimensions ρ_w and ρ_h from the sensor manufacturer's data sheet.

common experience that the intrinsic parameters change if a lense is detached and reattached, or adjusted for focus or aperture.

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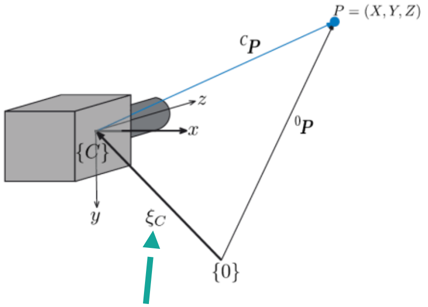

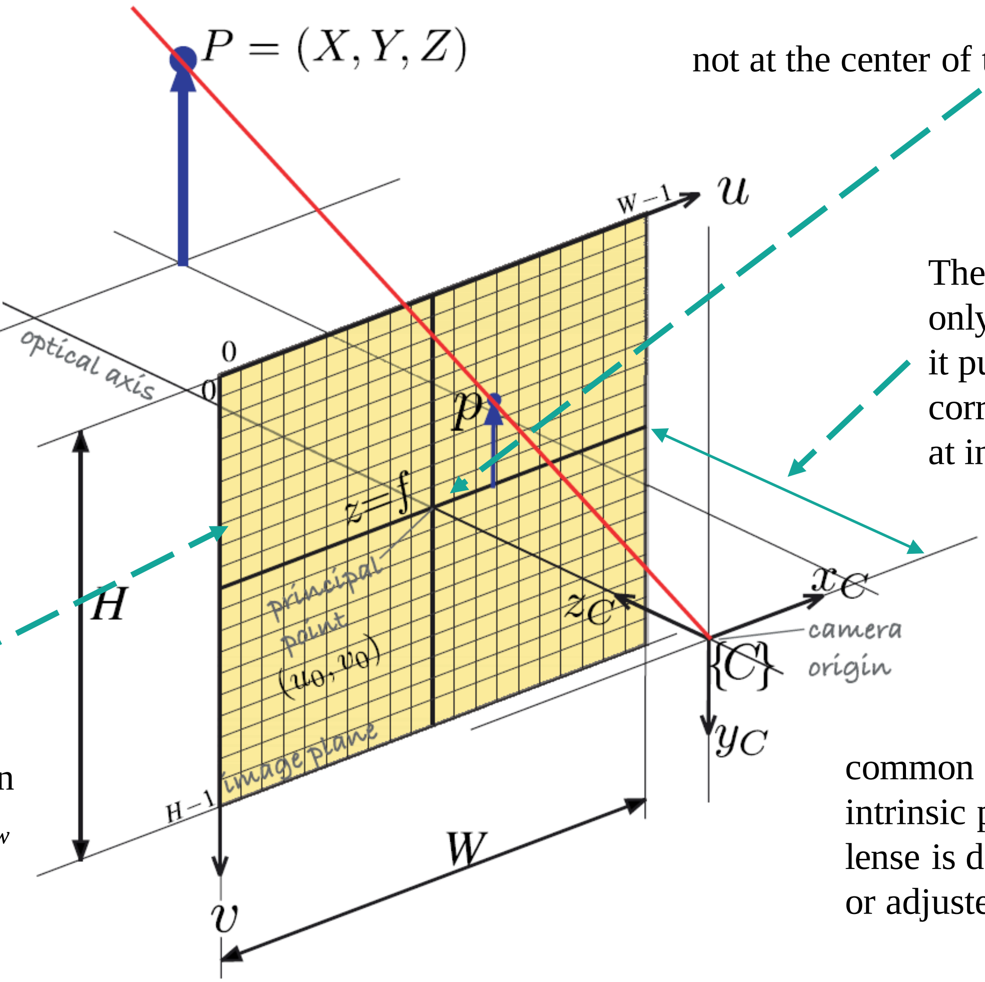

not at the center of the photosite array

The focal length of a lens is only accurate to 4% of what it purports to be, and is only correct if the lens is focused at infinity

The extrinsic parameters, the camera's pose, raises the question of where exactly is the center point of the camera.

The only intrinsic parameters that it may be possible to obtain are the photosite dimensions ρ_w and ρ_h from the sensor manufacturer's data sheet.

common experience that the intrinsic parameters change if a lense is detached and reattached, or adjusted for focus or aperture.

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Camera Calibration

Some are done before shipping, some are not, and some are provided with a software to do so

- The process of determining the camera’s intrinsic parameters and the extrinsic parameters with respect to the world coordinate system

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$$\tilde{p} = C\tilde{P}$$

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$$\tilde{p} = C\tilde{P}$$

$$\tilde{p} = (u, v, 1)$$

$$u = \frac{u'}{w'}, v = \frac{v'}{w'}$$

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$$\tilde{p} = C\tilde{P} \xrightarrow[u = \frac{u'}{w'},\ v = \frac{v'}{w'}]{\tilde{p} = (u, v, 1)} \begin{array}{l} C_{11}X + C_{12}Y + C_{13}Z + C_{14} - C_{31}uX - C_{32}uY - C_{33}uZ - C_{34}u = 0 \\ C_{21}X + C_{22}Y + C_{23}Z + C_{24} - C_{31}vX - C_{32}vY - C_{33}vZ - C_{34}v = 0 \end{array}$$

Camera Calibration

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Disregard overall scaling, set to 1

$$\tilde{p} = C\tilde{P}$$

$$\tilde{p} = (u, v, 1)$$

$$u = \frac{u'}{w'}, v = \frac{v'}{w'}$$

$$C_{11}X + C_{12}Y + C_{13}Z + C_{14} - C_{31}uX - C_{32}uY - C_{33}uZ - \boxed{C_{34}}u = 0$$
$$C_{21}X + C_{22}Y + C_{23}Z + C_{24} - C_{31}vX - C_{32}vY - C_{33}vZ - C_{34}v = 0$$

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Disregard overall scaling, set to 1

$$C_{11}X + C_{12}Y + C_{13}Z + C_{14} - C_{31}uX - C_{32}uY - C_{33}uZ - \boxed{C_{34}}u = 0$$

$$C_{21}X + C_{22}Y + C_{23}Z + C_{24} - C_{31}vX - C_{32}vY - C_{33}vZ - C_{34}v = 0$$

Increasing sampling for a solution

$$\begin{pmatrix} X_1 & Y_1 & Z_1 & 1 & 0 & 0 & 0 & 0 & -u_1X_1 & -u_1Y_1 & -u_1Z_1 \\ 0 & 0 & 0 & 0 & X_1 & Y_1 & Z_1 & 1 & -v_1X_1 & -v_1Y_1 & -v_1Z_1 \\ & & & & & \vdots & & & & & \\ X_N & Y_N & Z_N & 1 & 0 & 0 & 0 & 0 & -u_NX_N & -u_NY_N & -u_NZ_N \\ 0 & 0 & 0 & 0 & X_N & Y_N & Z_N & 1 & -v_NX_N & -v_NY_N & -v_NZ_N \end{pmatrix} \begin{pmatrix} C_{11} \\ C_{12} \\ \vdots \\ C_{33} \end{pmatrix} = \begin{pmatrix} u_1 \\ v_1 \\ \vdots \\ u_N \\ v_N \end{pmatrix}$$

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$$\tilde{p} = C\tilde{P}$$

$$\tilde{p} = (u, v, 1)$$

$$u = \frac{u'}{w'},\ v = \frac{v'}{w'}$$

$$C_{11}X + C_{12}Y + C_{13}Z + C_{14} - C_{31}uX - C_{32}uY - C_{33}uZ - \boxed{C_{34}}u = 0$$
$$C_{21}X + C_{22}Y + C_{23}Z + C_{24} - C_{31}vX - C_{32}vY - C_{33}vZ - C_{34}v = 0$$

Increasing sampling for a solution

11 unknows to be solved

$$\begin{pmatrix} X_1 & Y_1 & Z_1 & 1 & 0 & 0 & 0 & 0 & -u_1X_1 & -u_1Y_1 & -u_1Z_1 \\ 0 & 0 & 0 & 0 & X_1 & Y_1 & Z_1 & 1 & -v_1X_1 & -v_1Y_1 & -v_1Z_1 \\ & & & & & \vdots & & & & & \\ X_N & Y_N & Z_N & 1 & 0 & 0 & 0 & 0 & -u_NX_N & -u_NY_N & -u_NZ_N \\ 0 & 0 & 0 & 0 & X_N & Y_N & Z_N & 1 & -v_NX_N & -v_NY_N & -v_NZ_N \end{pmatrix} \boxed{\begin{pmatrix} C_{11} \\ C_{12} \\ \vdots \\ C_{33} \end{pmatrix}} = \begin{pmatrix} u_1 \\ v_1 \\ \vdots \\ u_N \\ v_N \end{pmatrix}$$

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Disregard overall scaling, set to 1

$$\begin{aligned} C_{11}X + C_{12}Y + C_{13}Z + C_{14} - C_{31}uX - C_{32}uY - C_{33}uZ - \boxed{C_{34}}u &= 0 \\ C_{21}X + C_{22}Y + C_{23}Z + C_{24} - C_{31}vX - C_{32}vY - C_{33}vZ - C_{34}v &= 0 \end{aligned}$$

Increasing sampling for a solution

11 unknows to be solved

$$\begin{pmatrix} X_1 & Y_1 & Z_1 & 1 & 0 & 0 & 0 & 0 & -u_1X_1 & -u_1Y_1 & -u_1Z_1 \\ 0 & 0 & 0 & 0 & X_1 & Y_1 & Z_1 & 1 & -v_1X_1 & -v_1Y_1 & -v_1Z_1 \\ & & & & & \vdots & & & & & \\ X_N & Y_N & Z_N & 1 & 0 & 0 & 0 & 0 & -u_NX_N & -u_NY_N & -u_NZ_N \\ 0 & 0 & 0 & 0 & X_N & Y_N & Z_N & 1 & -v_NX_N & -v_NY_N & -v_NZ_N \end{pmatrix} \boxed{\begin{pmatrix} C_{11} \\ C_{12} \\ \vdots \\ C_{33} \end{pmatrix}} = \begin{pmatrix} u_1 \\ v_1 \\ \vdots \\ u_N \\ v_N \end{pmatrix}$$

$N \geq 6$ for *a* solution, but usually more are used to solve using *least square*

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$$\tilde{p} = C\tilde{P}$$

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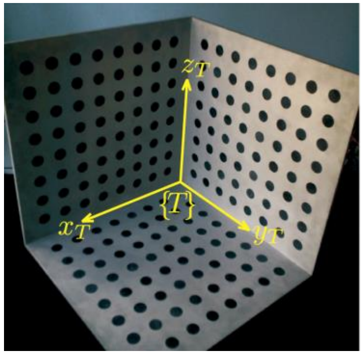
$$C_{11}X + C_{12}Y + C_{13}Z + C_{14} - C_{31}uX - C_{32}uY - C_{33}uZ - \boxed{C_{34}}u = 0$$

$$C_{21}X + C_{22}Y + C_{23}Z + C_{24} - C_{31}vX - C_{32}vY - C_{33}vZ - C_{34}v = 0$$

Increasing sampling for a solution

11 unknows to be solved

(u_i, v_i)



$$\begin{pmatrix} X_1 & Y_1 & Z_1 & 1 & 0 & 0 & 0 & 0 & -u_1X_1 & -u_1Y_1 & -u_1Z_1 \\ 0 & 0 & 0 & 0 & X_1 & Y_1 & Z_1 & 1 & -v_1X_1 & -v_1Y_1 & -v_1Z_1 \\ & & & & & \vdots & & & & & \\ X_N & Y_N & Z_N & 1 & 0 & 0 & 0 & 0 & -u_NX_N & -u_NY_N & -u_NZ_N \\ 0 & 0 & 0 & 0 & X_N & Y_N & Z_N & 1 & -v_NX_N & -v_NY_N & -v_NZ_N \end{pmatrix} \boxed{\begin{pmatrix} C_{11} \\ C_{12} \\ \vdots \\ C_{33} \end{pmatrix}} = \begin{pmatrix} u_1 \\ v_1 \\ \vdots \\ u_N \\ v_N \end{pmatrix}$$

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$$\tilde{p} = C\tilde{P}$$

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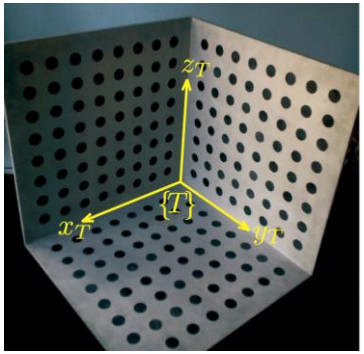
$$(u_i, v_i)$$

$$C_{11}X + C_{12}Y + C_{13}Z + C_{14} - C_{31}uX - C_{32}uY - C_{33}uZ - \boxed{C_{34}}u = 0$$

$$C_{21}X + C_{22}Y + C_{23}Z + C_{24} - C_{31}vX - C_{32}vY - C_{33}vZ - C_{34}v = 0$$

Increasing sampling for a solution

11 unknows to be solved



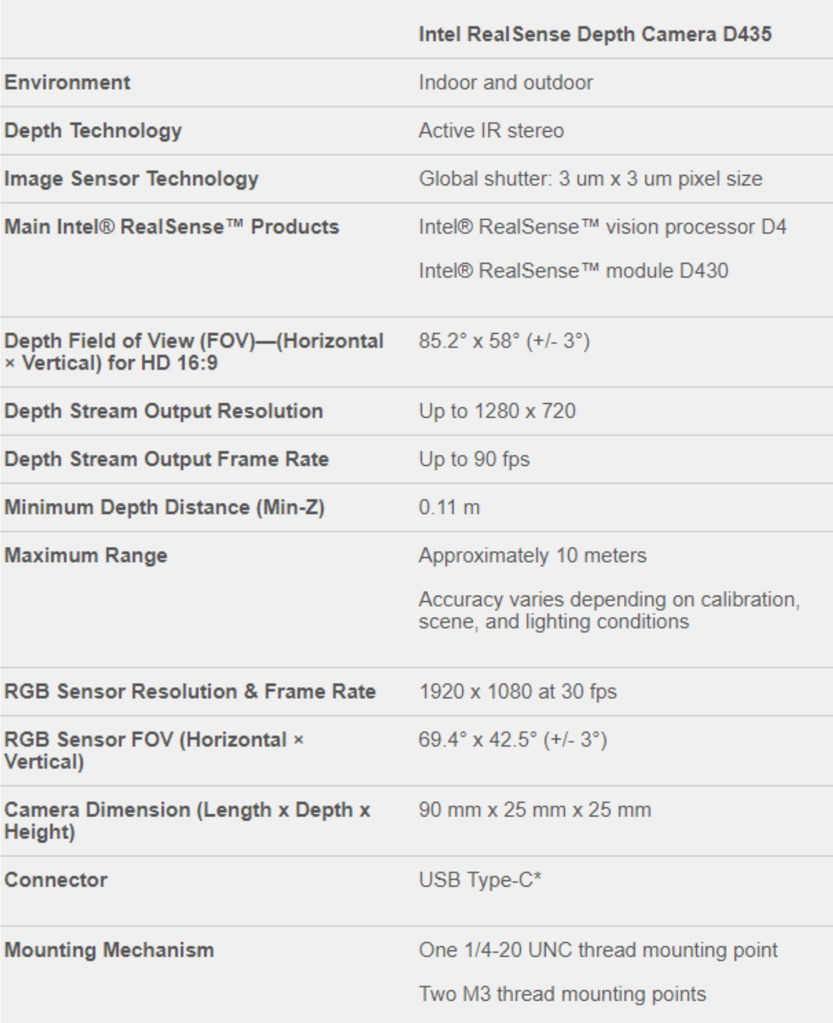
$$\begin{pmatrix} X_1 & Y_1 & Z_1 & 1 & 0 & 0 & 0 & 0 & -u_1X_1 & -u_1Y_1 & -u_1Z_1 \\ 0 & 0 & 0 & 0 & X_1 & Y_1 & Z_1 & 1 & -v_1X_1 & -v_1Y_1 & -v_1Z_1 \\ & & & & & \vdots & & & & & \\ X_N & Y_N & Z_N & 1 & 0 & 0 & 0 & 0 & -u_NX_N & -u_NY_N & -u_NZ_N \\ 0 & 0 & 0 & 0 & X_N & Y_N & Z_N & 1 & -v_NX_N & -v_NY_N & -v_NZ_N \end{pmatrix} \boxed{\begin{pmatrix} C_{11} \\ C_{12} \\ \vdots \\ C_{33} \end{pmatrix}} = \begin{pmatrix} u_1 \\ v_1 \\ \vdots \\ u_N \\ v_N \end{pmatrix}$$

$N \geq 6$ for *a* solution, but usually more are used to solve using *least square*

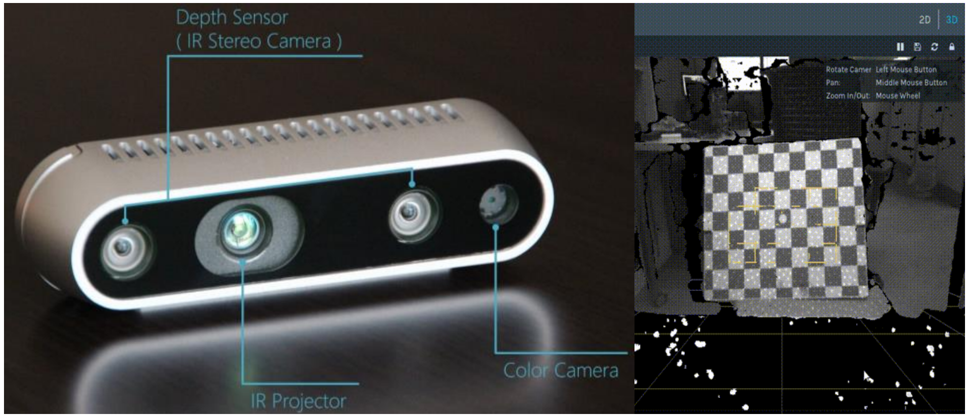
What if the points are coplanar?

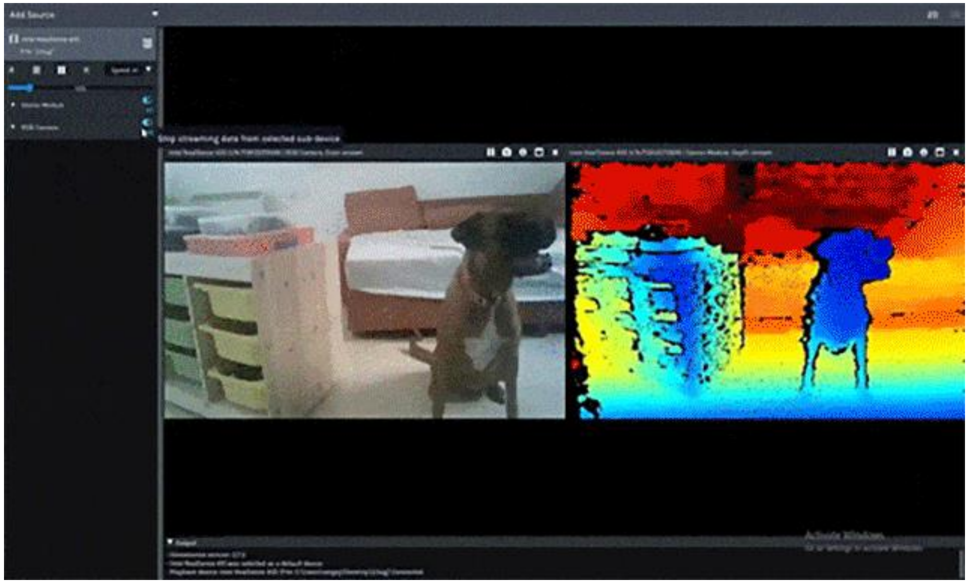
About Intel Realsense D435

Entry level stereo depth sensor with abundant resources at a low cost



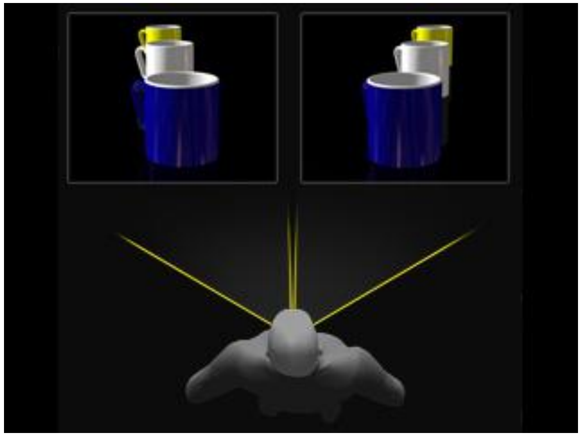
	Intel RealSense Depth Camera D435
Environment	Indoor and outdoor
Depth Technology	Active IR stereo
Image Sensor Technology	Global shutter: 3 um x 3 um pixel size
Main Intel® RealSense™ Products	Intel® RealSense™ vision processor D4 Intel® RealSense™ module D430
Depth Field of View (FOV)—(Horizontal × Vertical) for HD 16:9	85.2° x 58° (+/- 3°)
Depth Stream Output Resolution	Up to 1280 x 720
Depth Stream Output Frame Rate	Up to 90 fps
Minimum Depth Distance (Min-Z)	0.11 m
Maximum Range	Approximately 10 meters Accuracy varies depending on calibration, scene, and lighting conditions
RGB Sensor Resolution & Frame Rate	1920 x 1080 at 30 fps
RGB Sensor FOV (Horizontal × Vertical)	69.4° x 42.5° (+/- 3°)
Camera Dimension (Length x Depth x Height)	90 mm x 25 mm x 25 mm
Connector	USB Type-C*
Mounting Mechanism	One 1/4-20 UNC thread mounting point Two M3 thread mounting points





Stereo Vision

Triangulation Principle



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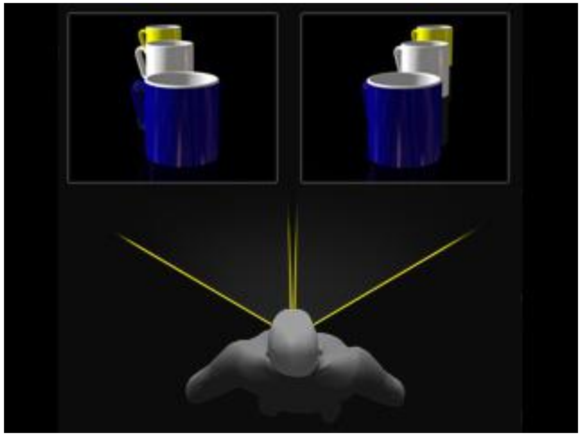
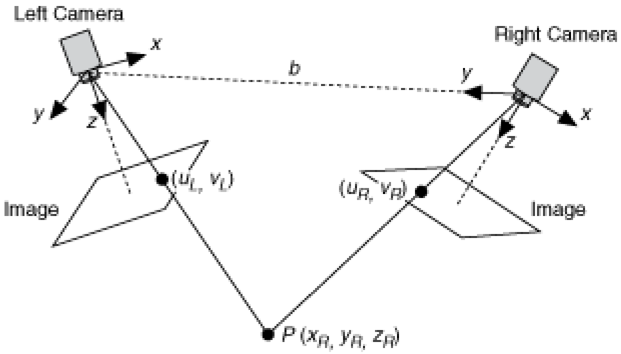
Stereo Vision

Triangulation Principle





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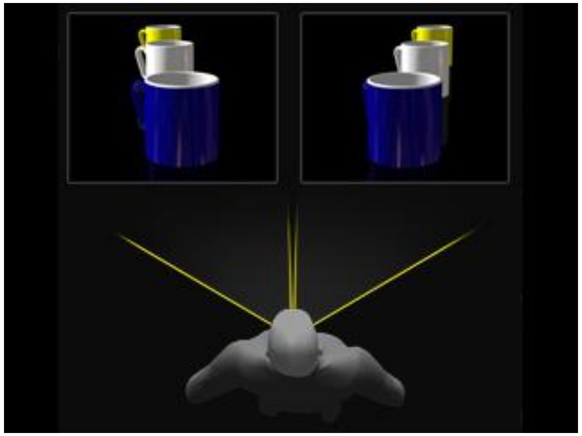
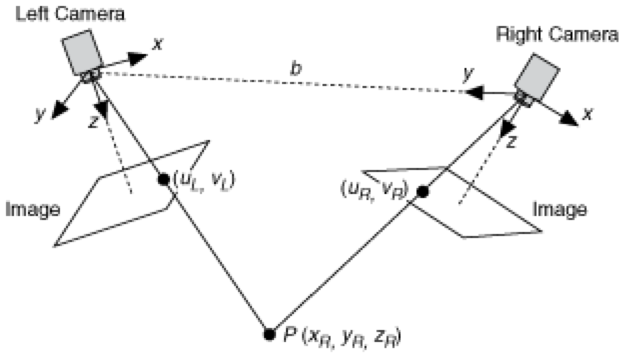
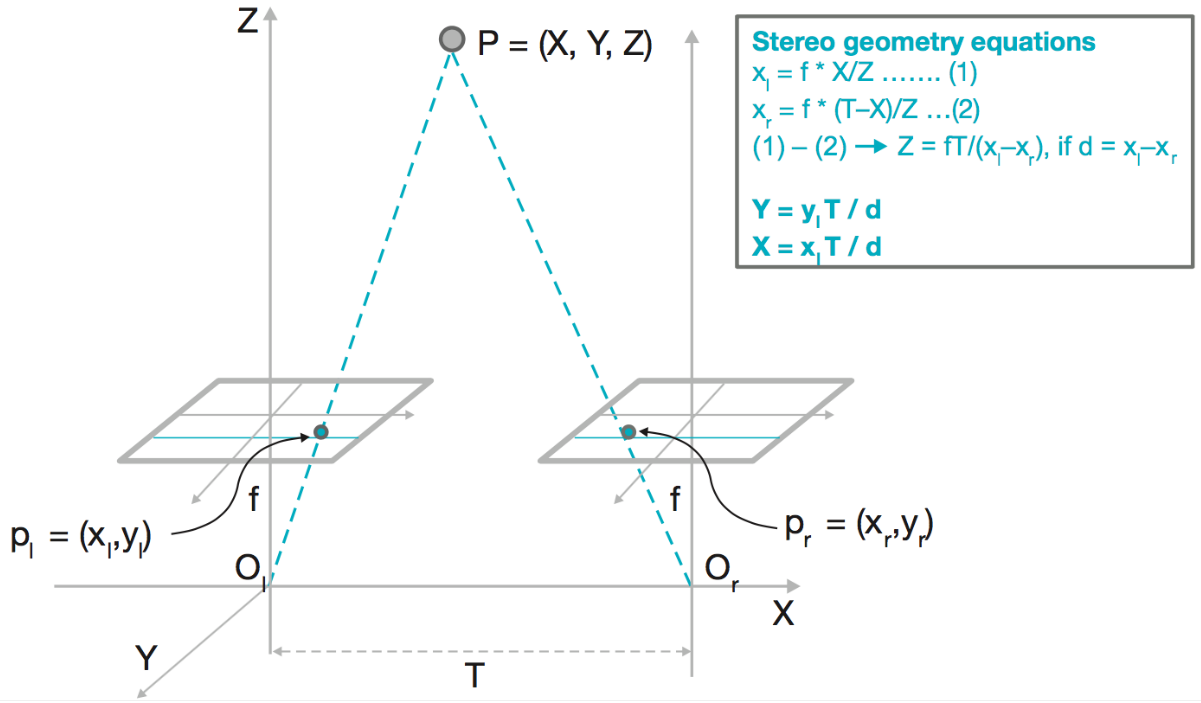
Stereo Vision

Triangulation Principle







Stereo geometry equations

$x_l = f * X/Z$ .... (1)

$x_r = f * (T–X)/Z$ ...(2)

(1) – (2) → $Z = fT/(x_l–x_r)$, if $d = x_l–x_r$

$Y = y_l T / d$

$X = x_l T / d$

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Interfacing Realsense with ROS

Installation

1. Connect the USB Type-C to your host PC.
2. Install the Intel® RealSense™ SDK V2.16(Please use the guidance here: https://realsense.intel.com/sdk-2/#install)
    1. Prep steps as instructed in the website
    2. sudo apt-get install librealsense2=2.16.0-0~realsense0.85
    3. sudo apt-get install librealsense2-utils=2.16.0-0~realsense0.85
    4. sudo apt-get install librealsense2-dev=2.16.0-0~realsense0.85
    5. sudo apt-get install librealsense2-dbg=2.16.0-0~realsense0.85
3. Run the Intel® RealSense™ Viewer (firmware upgrade may be needed if you encounter version error)

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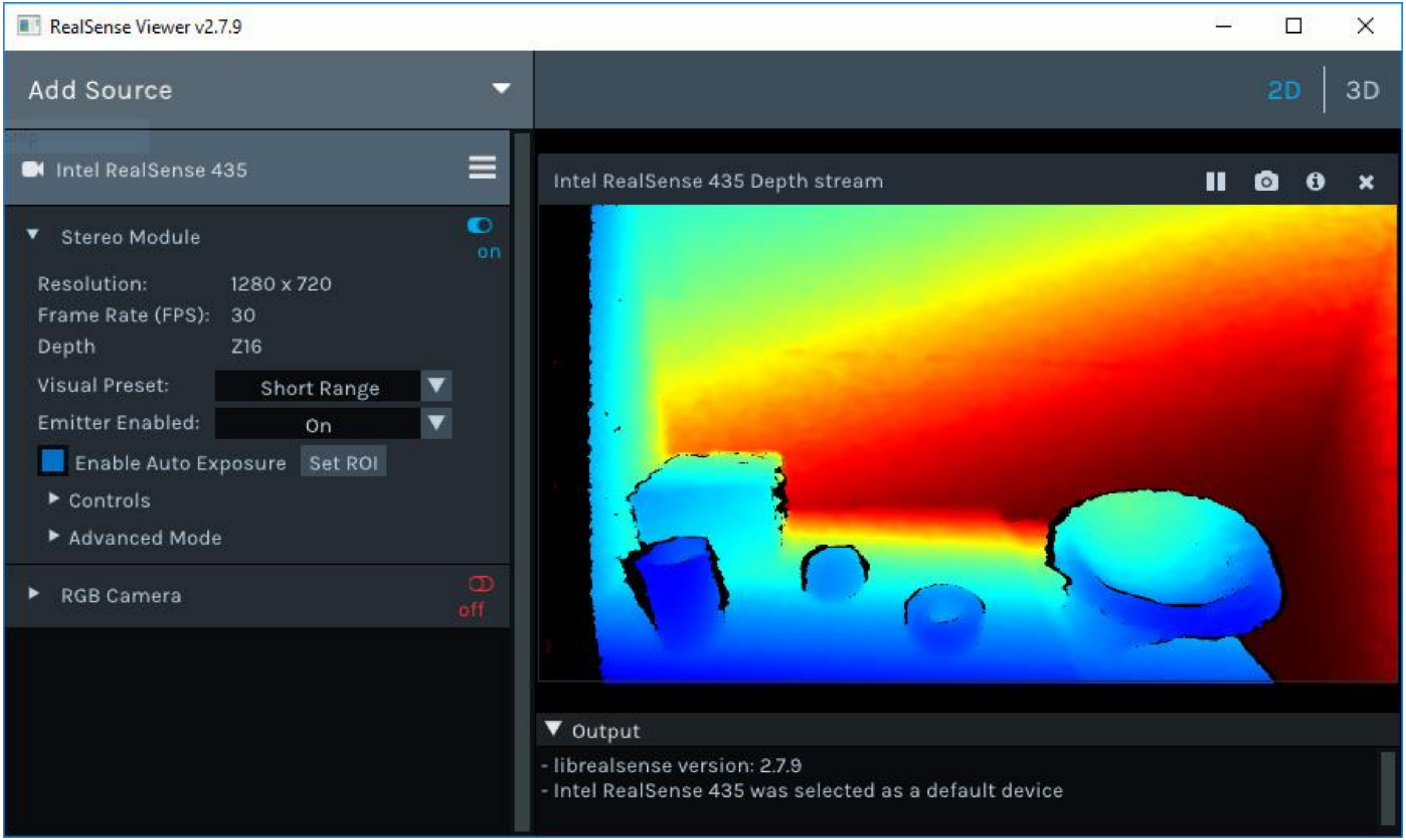
Interfacing Realsense with ROS



Stereo Module on

Resolution: 1280 x 720

Frame Rate (FPS): 30

Depth Z16

Visual Preset: Short Range

Emitter Enabled: On

■ Enable Auto Exposure Set ROI

RGB Camera off

Output

```
- librealsense version: 2.7.9
- Intel RealSense 435 was selected as a default device
```

Interfacing Realsense with ROS

Realsense ROS Package

- Installation
  1. cd ~/catkin_ws/src/
  2. git clone https://github.com/intel-ros/realsense.git
  3. git checkout tag/2.1.0
  4. catkin build & source ~/.bashrc
- Launch: roslaunch realsense2_camera rs_rgbd.launch

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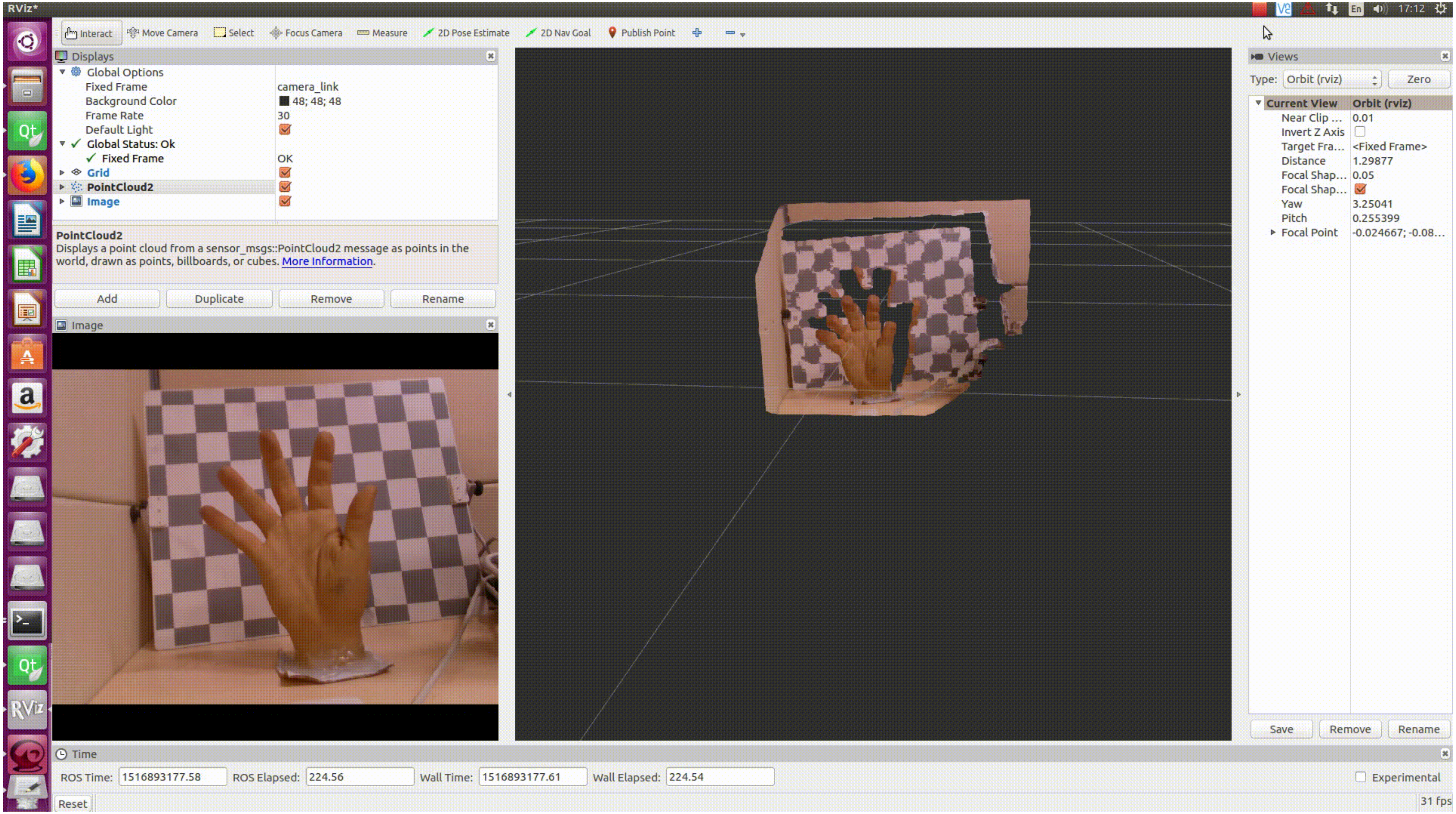
Interfacing Realsense with ROS

Point cloud in Rviz



Displays

Global Options	
Fixed Frame	camera_link
Background Color	■ 48; 48; 48
Frame Rate	30
Default Light	☑
✓ Global Status: Ok	
✓ Fixed Frame	OK
Grid	☑
PointCloud2	☑
Image	☑

PointCloud2
Displays a point cloud from a sensor_msgs::PointCloud2 message as points in the world, drawn as points, billboards, or cubes. More Information.

Image

Views

Type: Orbit (rviz)

Current View	Orbit (rviz)
Near Clip ...	0.01
Invert Z Axis	□
Target Fra...	<Fixed Frame>
Distance	1.29877
Focal Shap...	0.05
Focal Shap...	☑
Yaw	3.25041
Pitch	0.255399
Focal Point	-0.024667; -0.08...

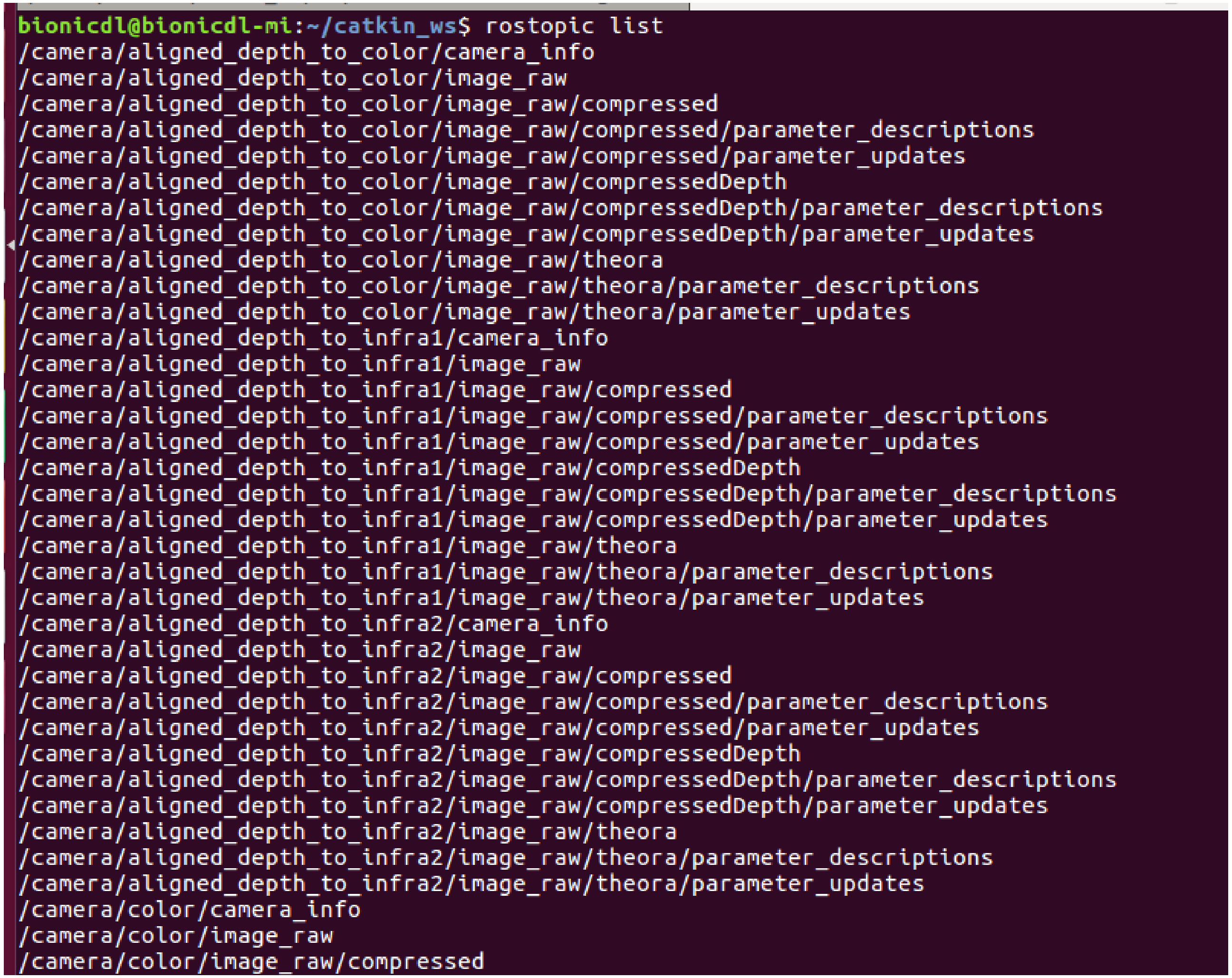
Time

ROS Time: 1516893177.58 ROS Elapsed: 224.56 Wall Time: 1516893177.61 Wall Elapsed: 224.54 □ Experimental

31 fps

Interfacing Realsense with ROS

ROS topics published

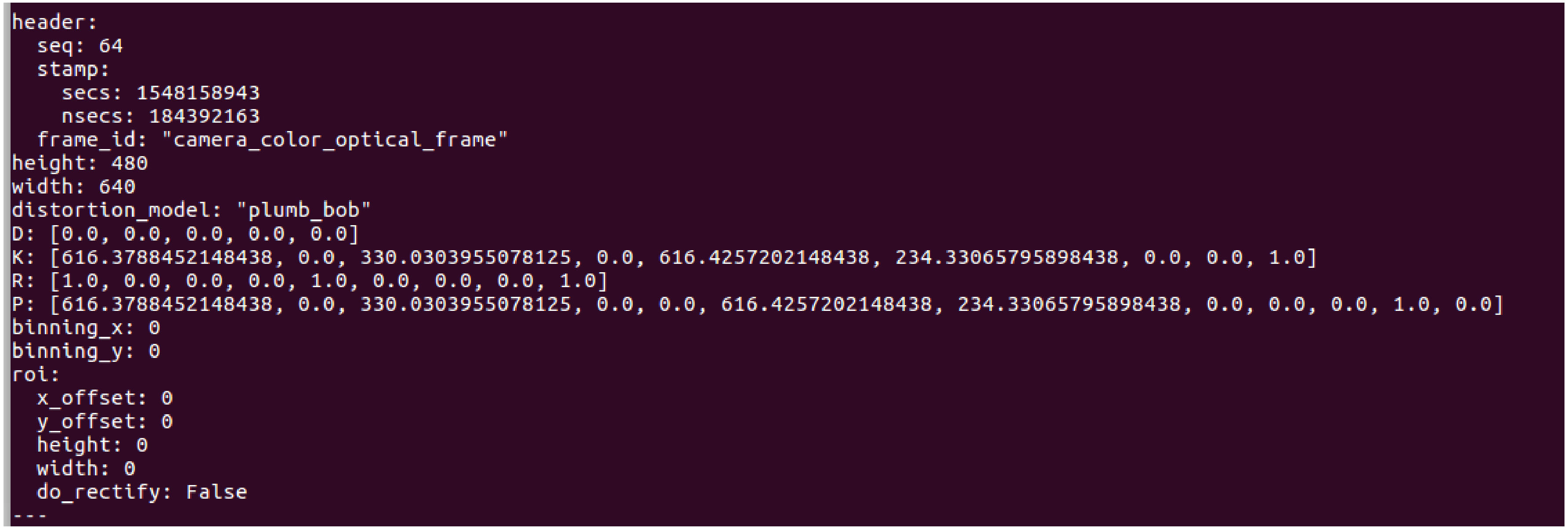


```
bionicdl@bionicdl-mi:~/catkin_ws$ rostopic list
/camera/aligned_depth_to_color/camera_info
/camera/aligned_depth_to_color/image_raw
/camera/aligned_depth_to_color/image_raw/compressed
/camera/aligned_depth_to_color/image_raw/compressed/parameter_descriptions
/camera/aligned_depth_to_color/image_raw/compressed/parameter_updates
/camera/aligned_depth_to_color/image_raw/compressedDepth
/camera/aligned_depth_to_color/image_raw/compressedDepth/parameter_descriptions
/camera/aligned_depth_to_color/image_raw/compressedDepth/parameter_updates
/camera/aligned_depth_to_color/image_raw/theora
/camera/aligned_depth_to_color/image_raw/theora/parameter_descriptions
/camera/aligned_depth_to_color/image_raw/theora/parameter_updates
/camera/aligned_depth_to_infra1/camera_info
/camera/aligned_depth_to_infra1/image_raw
/camera/aligned_depth_to_infra1/image_raw/compressed
/camera/aligned_depth_to_infra1/image_raw/compressed/parameter_descriptions
/camera/aligned_depth_to_infra1/image_raw/compressed/parameter_updates
/camera/aligned_depth_to_infra1/image_raw/compressedDepth
/camera/aligned_depth_to_infra1/image_raw/compressedDepth/parameter_descriptions
/camera/aligned_depth_to_infra1/image_raw/compressedDepth/parameter_updates
/camera/aligned_depth_to_infra1/image_raw/theora
/camera/aligned_depth_to_infra1/image_raw/theora/parameter_descriptions
/camera/aligned_depth_to_infra1/image_raw/theora/parameter_updates
/camera/aligned_depth_to_infra2/camera_info
/camera/aligned_depth_to_infra2/image_raw
/camera/aligned_depth_to_infra2/image_raw/compressed
/camera/aligned_depth_to_infra2/image_raw/compressed/parameter_descriptions
/camera/aligned_depth_to_infra2/image_raw/compressed/parameter_updates
/camera/aligned_depth_to_infra2/image_raw/compressedDepth
/camera/aligned_depth_to_infra2/image_raw/compressedDepth/parameter_descriptions
/camera/aligned_depth_to_infra2/image_raw/compressedDepth/parameter_updates
/camera/aligned_depth_to_infra2/image_raw/theora
/camera/aligned_depth_to_infra2/image_raw/theora/parameter_descriptions
/camera/aligned_depth_to_infra2/image_raw/theora/parameter_updates
/camera/color/camera_info
/camera/color/image_raw
/camera/color/image_raw/compressed
```

Interfacing Realsense with ROS

ROS topics published

- $rostopic ehco /camera/color/camera_info



```
header:
  seq: 64
  stamp:
    secs: 1548158943
    nsecs: 184392163
  frame_id: "camera_color_optical_frame"
height: 480
width: 640
distortion_model: "plumb_bob"
D: [0.0, 0.0, 0.0, 0.0, 0.0]
K: [616.3788452148438, 0.0, 330.0303955078125, 0.0, 616.4257202148438, 234.33065795898438, 0.0, 0.0, 1.0]
R: [1.0, 0.0, 0.0, 0.0, 1.0, 0.0, 0.0, 0.0, 1.0]
P: [616.3788452148438, 0.0, 330.0303955078125, 0.0, 0.0, 616.4257202148438, 234.33065795898438, 0.0, 0.0, 0.0, 1.0, 0.0]
binning_x: 0
binning_y: 0
roi:
  x_offset: 0
  y_offset: 0
  height: 0
  width: 0
  do_rectify: False
---
```

Interfacing Realsense with ROS

subscribe to ROS topic of relevant image

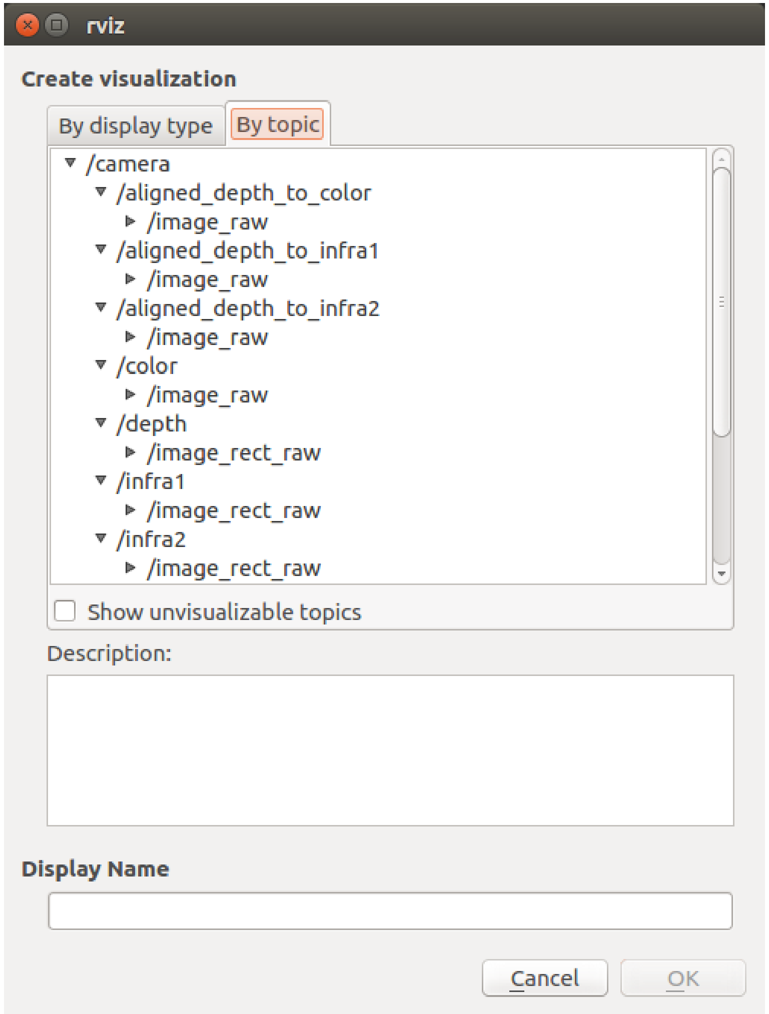
```
# TODO: Create Subscribers

depth_sub = message_filters.Subscriber("/camera/aligned_depth_to_color/image_raw", Image)


rgb_sub = message_filters.Subscriber("/camera/color/image_raw", Image)


ts = message_filters.TimeSynchronizer([depth_sub, rgb_sub], 1)

ts.registerCallback(callback)
```



```
▼ /camera
  ▼ /aligned_depth_to_color
    ▶ /image_raw
  ▼ /aligned_depth_to_infra1
    ▶ /image_raw
  ▼ /aligned_depth_to_infra2
    ▶ /image_raw
  ▼ /color
    ▶ /image_raw
  ▼ /depth
    ▶ /image_rect_raw
  ▼ /infra1
    ▶ /image_rect_raw
  ▼ /infra2
    ▶ /image_rect_raw
```

□ Show unvisualizable topics

Description:

Display Name

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Homework

- Write a perception ros node subscribing to ros topic of relevant image.
- Add a mover function to move the robot arm in the perception ros node.
- Prepare for the next lab session:
  - Install opencv and pcl

Thank you!

Prof. Song Chaoyang

- Dr. Wan Fang (sophie.fwan@hotmail.com)

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