AuE 8930: Machine Perception and Intelligence

Lecture: Image formation and vehicle visual perception

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Outline

- Image Formation Steps
- Geometry
  - Pinhole camera model & Thin lens model
  - Perspective projection & Fundamental equation
- Radiometry
- Photometry
  - Color, human vision, & digital imaging
- Image Digitalization
  - Sampling, quantization & tessellations
- More on Digital Images
  - Neighbors, connectedness & distances
- Vehicle Visual Perception Intro

Abstract Image

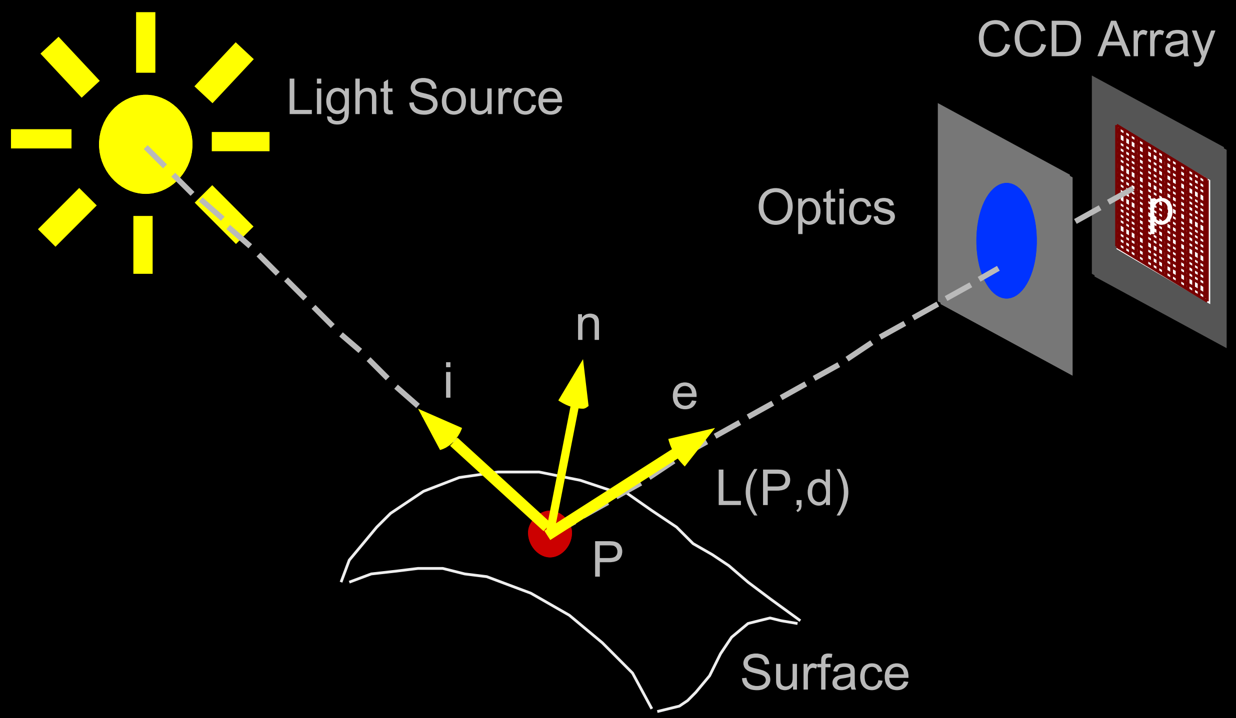
- An image can be represented by an image function whose general form is f(x,y).
- f(x,y) is a vector-valued function whose arguments represent a pixel location.
- The value of f(x,y) can have different interpretations in different kinds of images.

<u>Examples</u>

Intensity Image	- f(x,y) = intensity of the scene
Range Image	- f(x,y) = depth of the scene from imaging system
Color Image	- $f(x,y) = \{f_r(x,y), f_g(x,y), f_b(x,y)\}$
Video	- f(x,y,t) = temporal image sequence

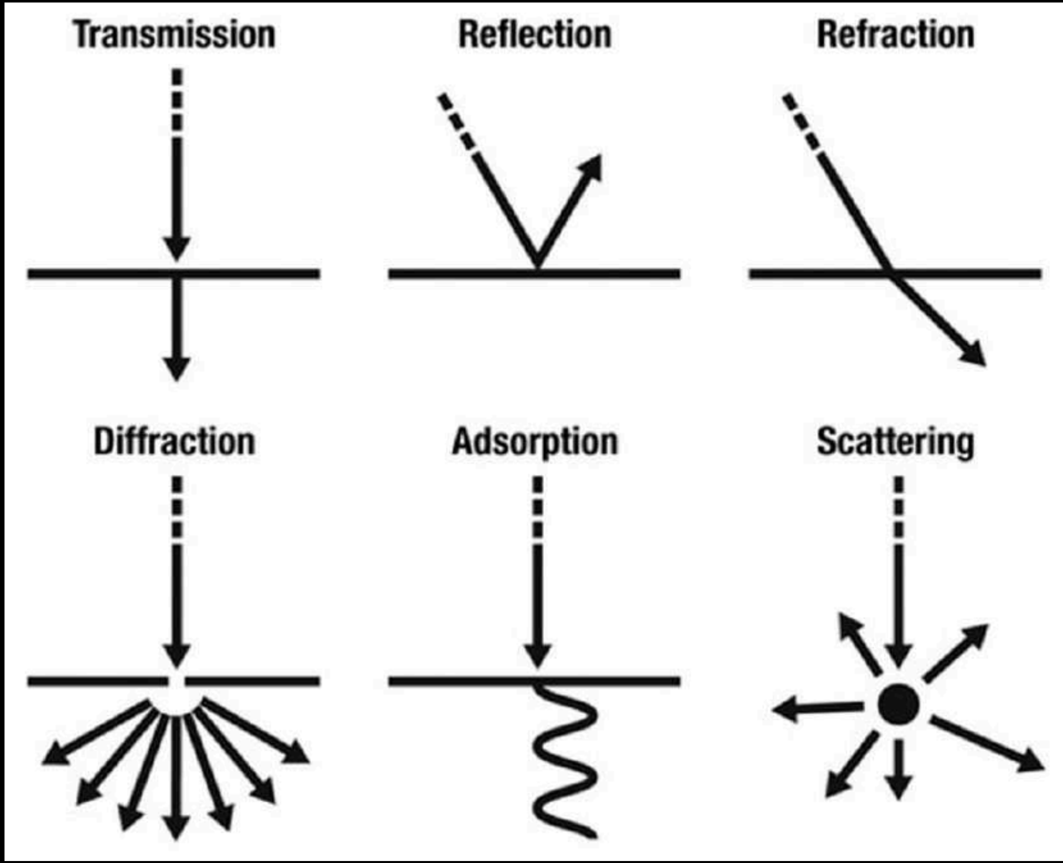
Basic Radiometry

- Radiometry is the part of image formation concerned with the relation among the amounts of light energy
  - emitted from light sources,
  - reflected from surfaces,
  - registered by sensors,



Light and Matter

- The interaction between light and matter can take many forms:
  - Transmission
  - Reflection
  - Refraction
  - Diffraction
  - Absorption
  - Scattering

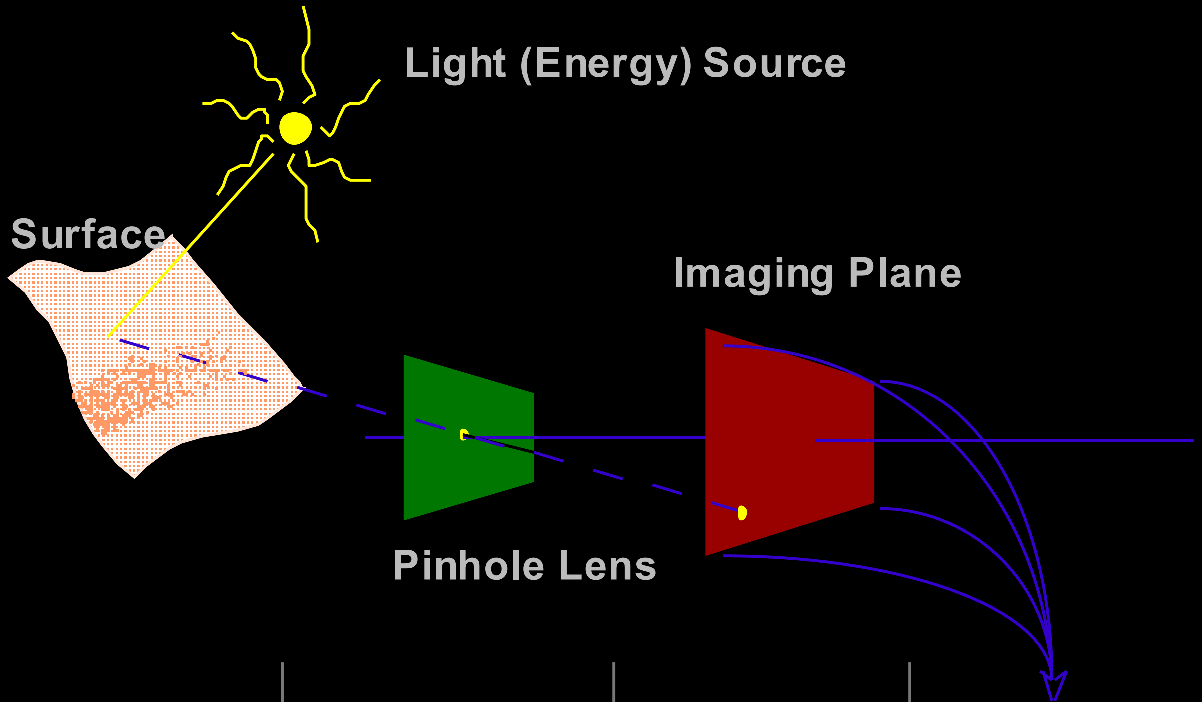


Lecture Assumptions

- Typical imaging scenario:
  - visible light
  - ideal lenses
  - Standard sensor (e.g. TV camera)
  - opaque objects

- The mechanism of image formation (from light $\rightarrow$ digital image) (be utilized to retrieve useful information and processed to recover some of the characteristics of the 3D world which was imaged.)

Image Formation



World	Optics	Sensor	Signal
		B&W Film	Silver Density
		Color Film	Silver density in three color layers
		TV Camera	Electrical

Steps

World → Optics → Sensor →
Signal → Digitizer →
Digital Representation

World	reality
Optics	focus {light} from world on sensor
Sensor	converts {light} to {electrical energy}
Signal	representation of incident light as continuous electrical energy
Digitizer	converts continuous signal to discrete signal
Digital Rep.	final representation of reality in computer memory

Factors in Image Formation

- Geometry
  - concerned with the relationship between points in the three-dimensional world and their images
- Radiometry
  - concerned with the relationship between the amount of light radiating from a surface and the amount incident at its image
- Photometry
  - concerned with ways of measuring the intensity of light
- Digitization
  - concerned with ways of converting continuous signals (in both space and time) to digital approximations

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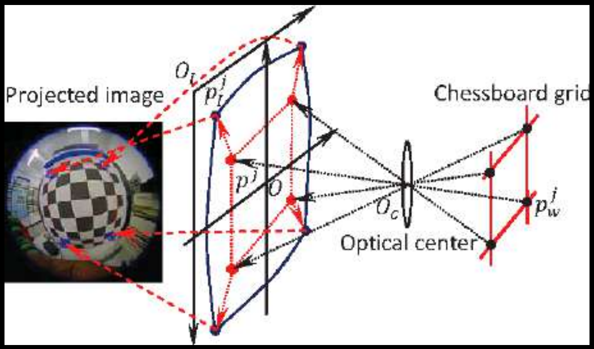
Geometry

- Geometry describes the projection of:

three-dimensional (3D) world → two-dimensional (2D) image plane.

- Typical Assumptions
  - Light travels in a straight line
- Optical Axis: the axis perpendicular to the image plane and passing through the pinhole (also called the central projection ray)
- Each point in the image corresponds to a particular direction defined by a ray from that point through the pinhole.
- Various kinds of projections:
  - perspective
  - orthographic
  - spherical
  - oblique
  - isometric

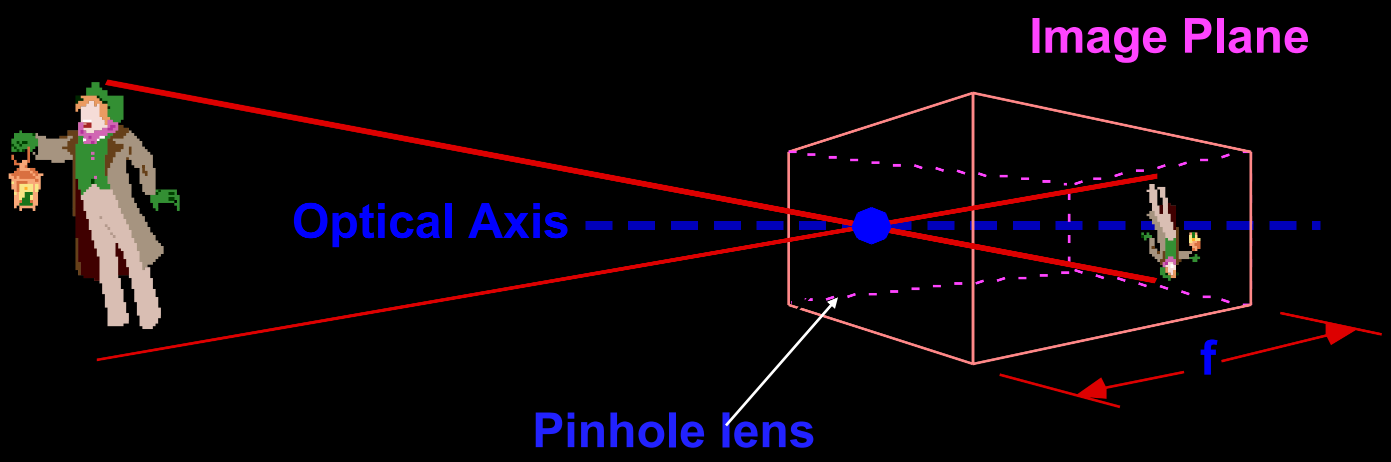
e.g.



Basic Optics

- Two models are commonly used:
  - Pin-hole camera
  - Optical system composed of lenses
- **Pin-hole** is the basis for most graphics and vision
  - Derived from physical construction of early cameras
  - Mathematics is very straightforward
- **Thin lens** model is first of the lens models
  - Mathematical model for a physical lens
  - Lens gathers light over area and focuses on image plane.

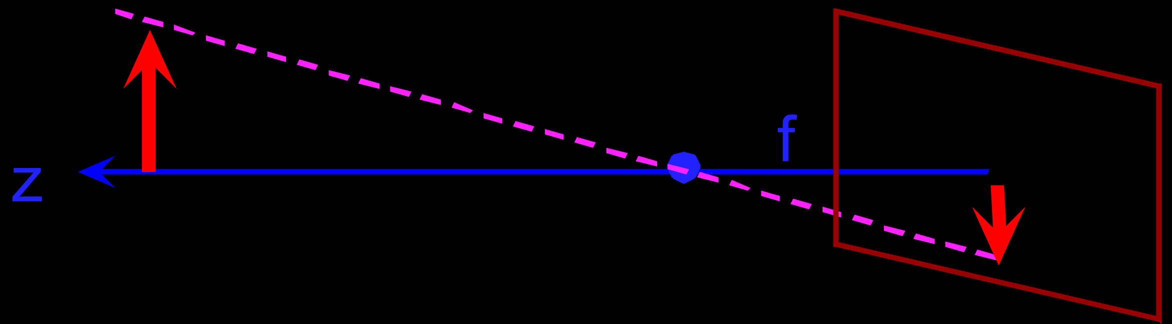
Pinhole Camera Model



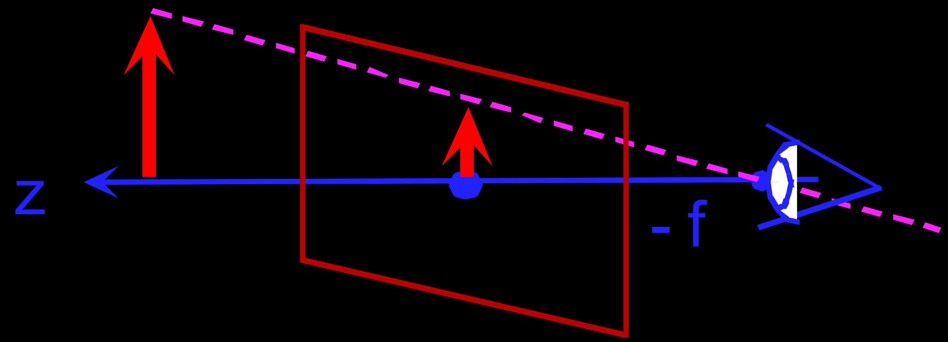
- World projected to 2D Image
  - Image inverted
  - Size reduced, (lost physical size)
  - Image is dim
  - No direct depth information
- f called the focal length of the lens
- Known as perspective projection

Equivalent Geometry

- Consider case with object on the optical axis:



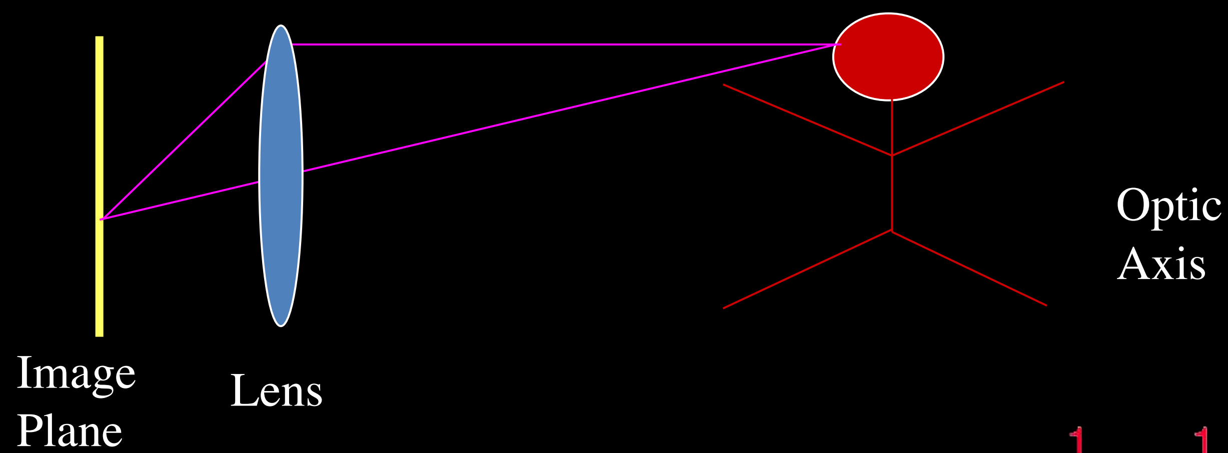
- More convenient with upright image:



- Equivalent mathematically

Thin Lens Model

- Rays entering parallel on one side converge at focal point.
- Rays diverging from the focal point become parallel.

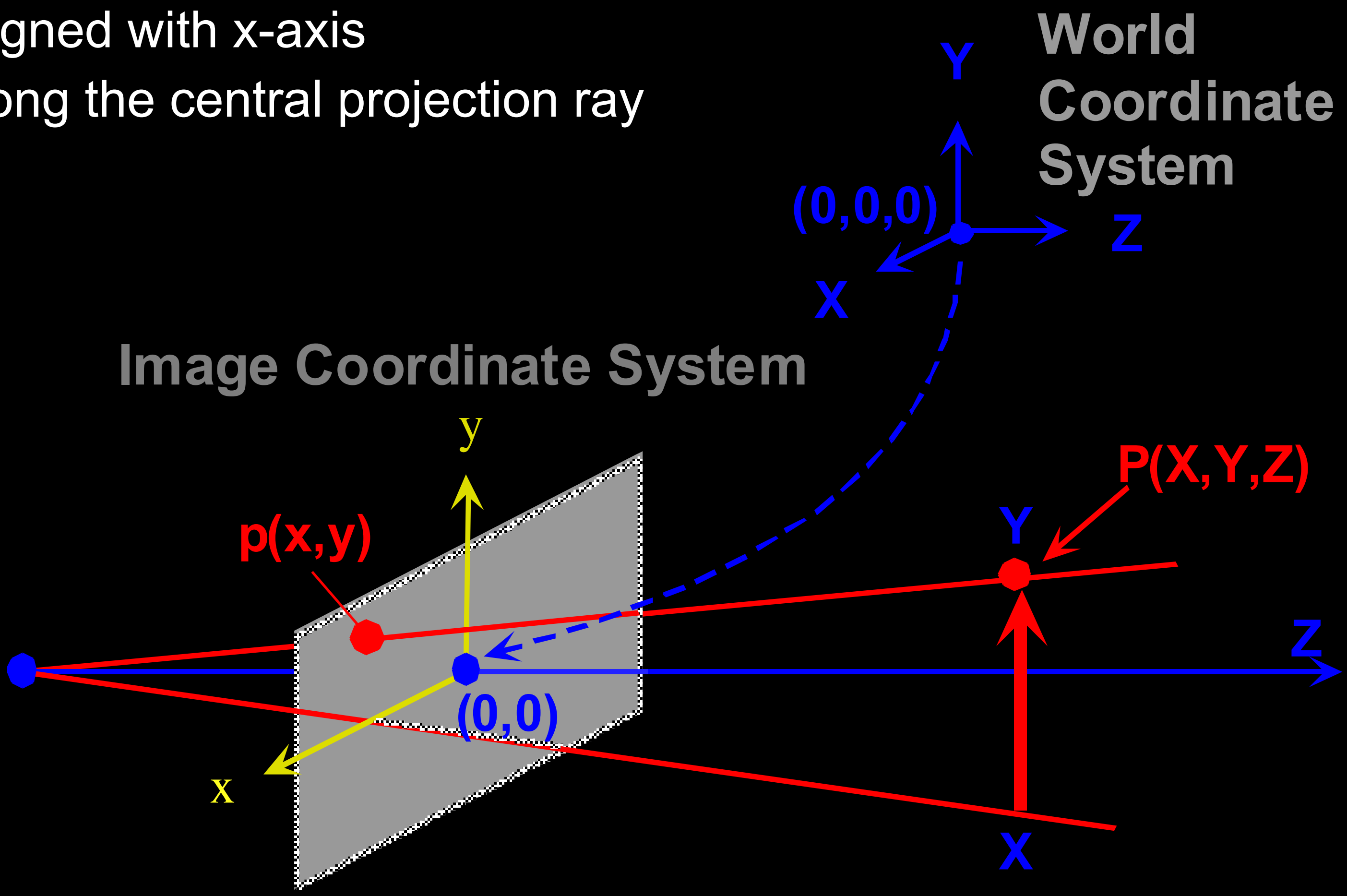


‘Thin Lens Law’

$$\frac{1}{o} + \frac{1}{i} = \frac{1}{f}$$

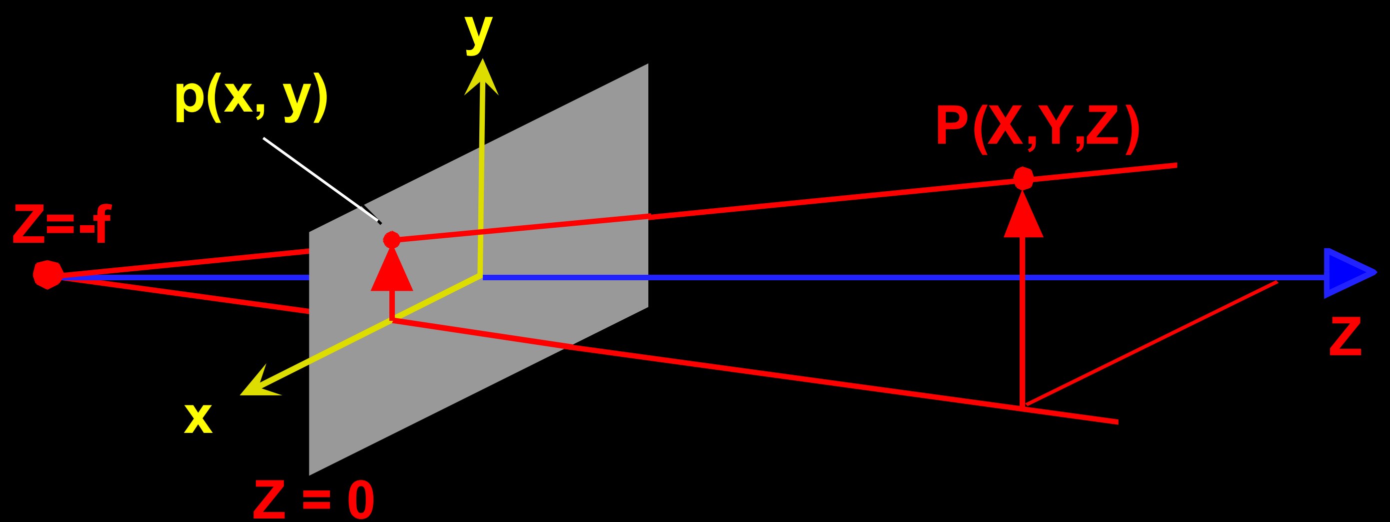
Coordinate Systems

- Simplified Case:
  - Origin of world and image coordinate systems coincide
  - Y-axis aligned with y-axis
  - X-axis aligned with x-axis
  - Z-axis along the central projection ray



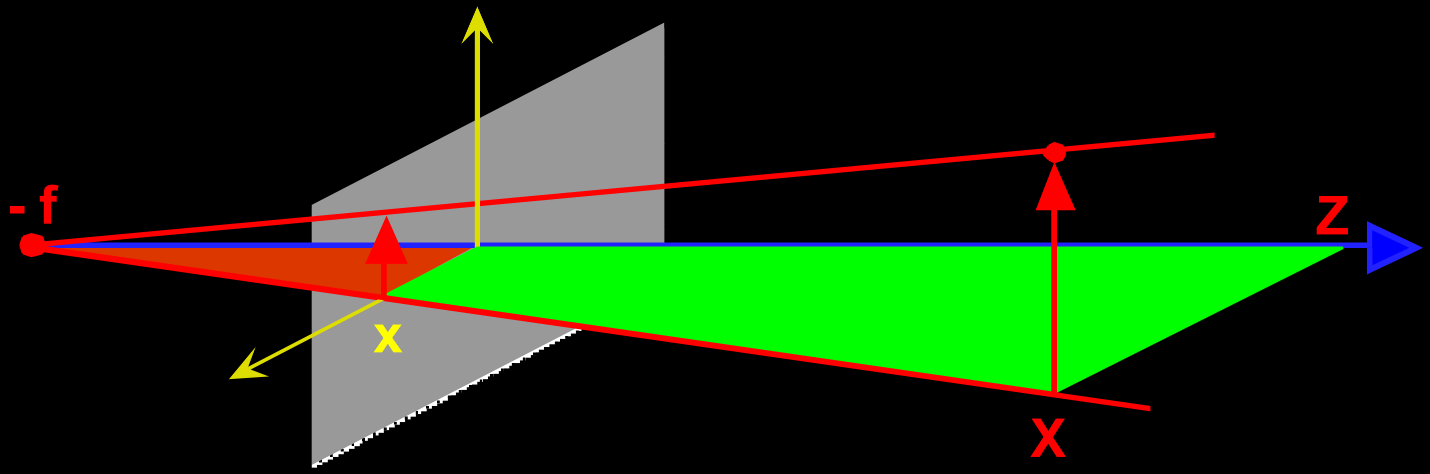
Perspective Projection

- Compute the image coordinates of p in terms of the world coordinates of P.



- Look at projections in x-z and y-z planes

X-Z Projection

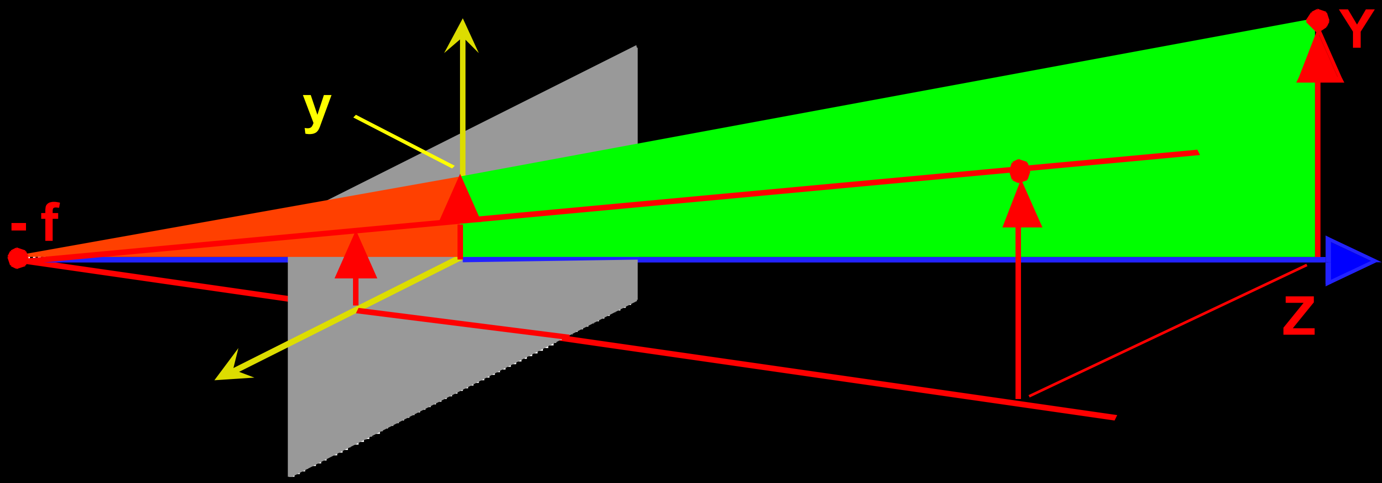


- By similar triangles:

$$\frac{x}{f} = \frac{X}{Z+f}$$

$$\boxed{x = \frac{fX}{Z+f}}$$

Y-Z Projection



- By similar triangles:

$$\frac{y}{f} = \frac{Y}{Z+f}$$

$$\boxed{y = \frac{fY}{Z+f}}$$

Perspective Equations

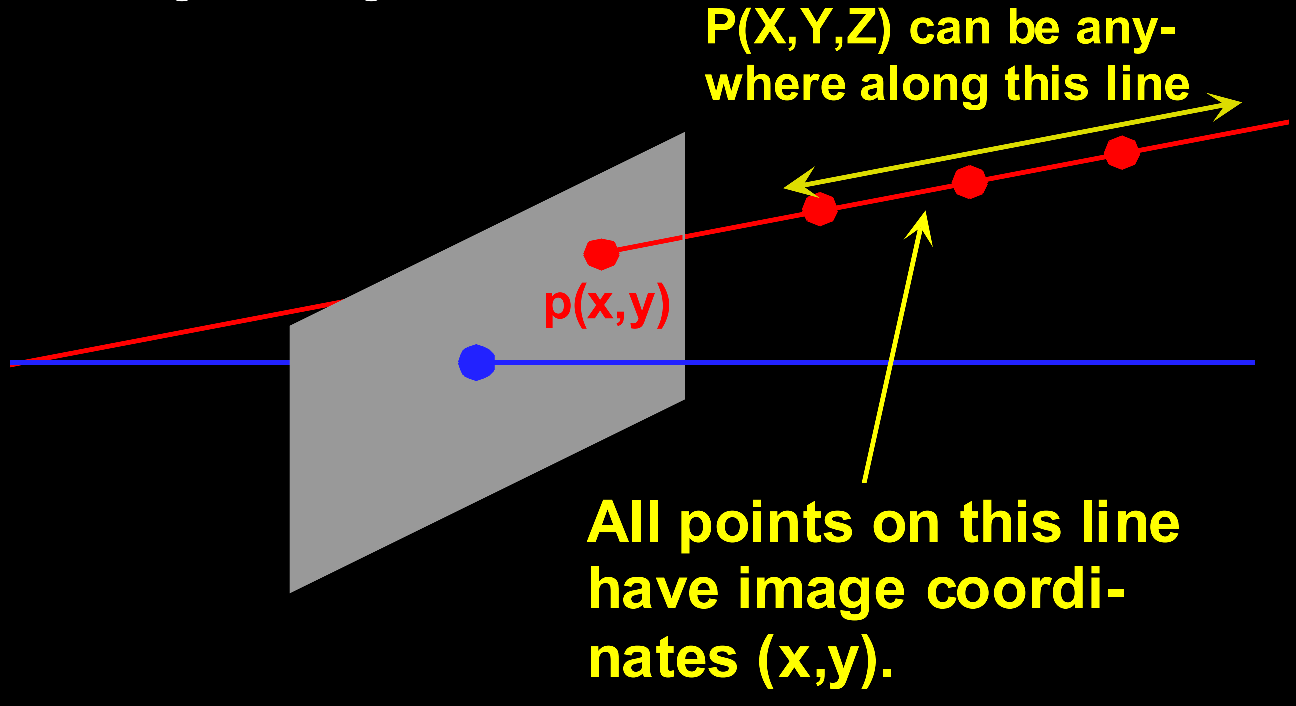
- Given point P(X,Y,Z) in the 3D world
- The two equations:

$$\boxed{x = \frac{fX}{Z+f}} \qquad \boxed{y = \frac{fY}{Z+f}}$$

- Transform world coordinates (X,Y,Z) into image coordinates (x,y)

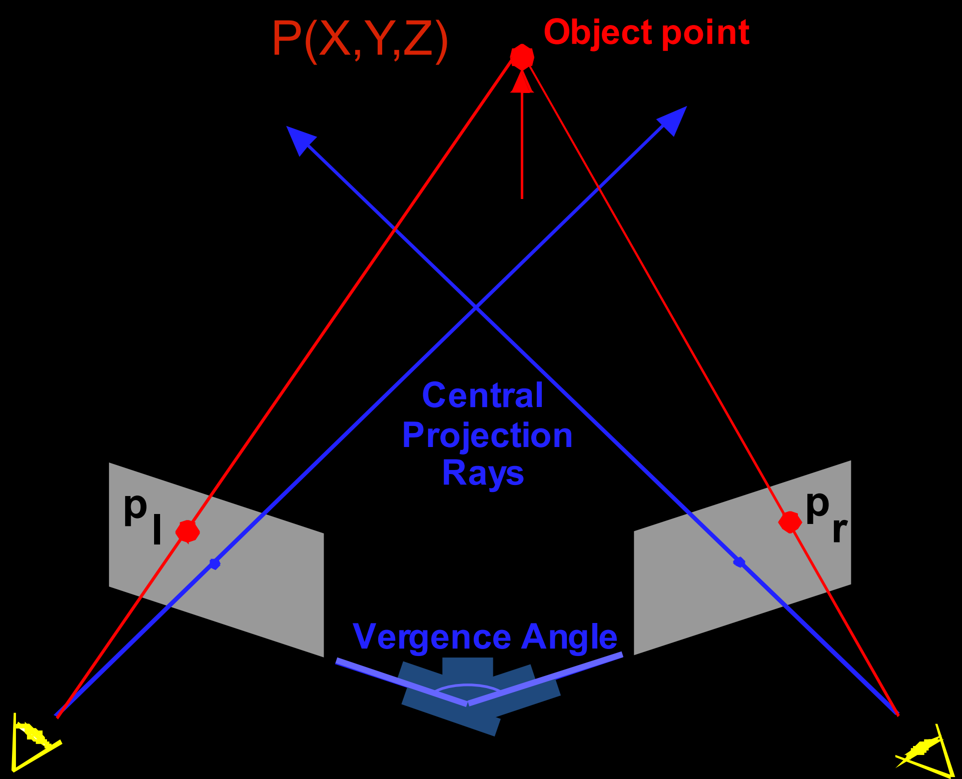
Reverse Projection

- Given a center of projection and image coordinates of a point, it is not possible to recover the 3D depth of the point from a single image.



In general, at least two images of the same point taken from two different locations are required to recover depth.

Stereo Geometry



- Depth obtained by triangulation
- Correspondence problem: p_l and p_r must correspond to the left and right projections of P, respectively.

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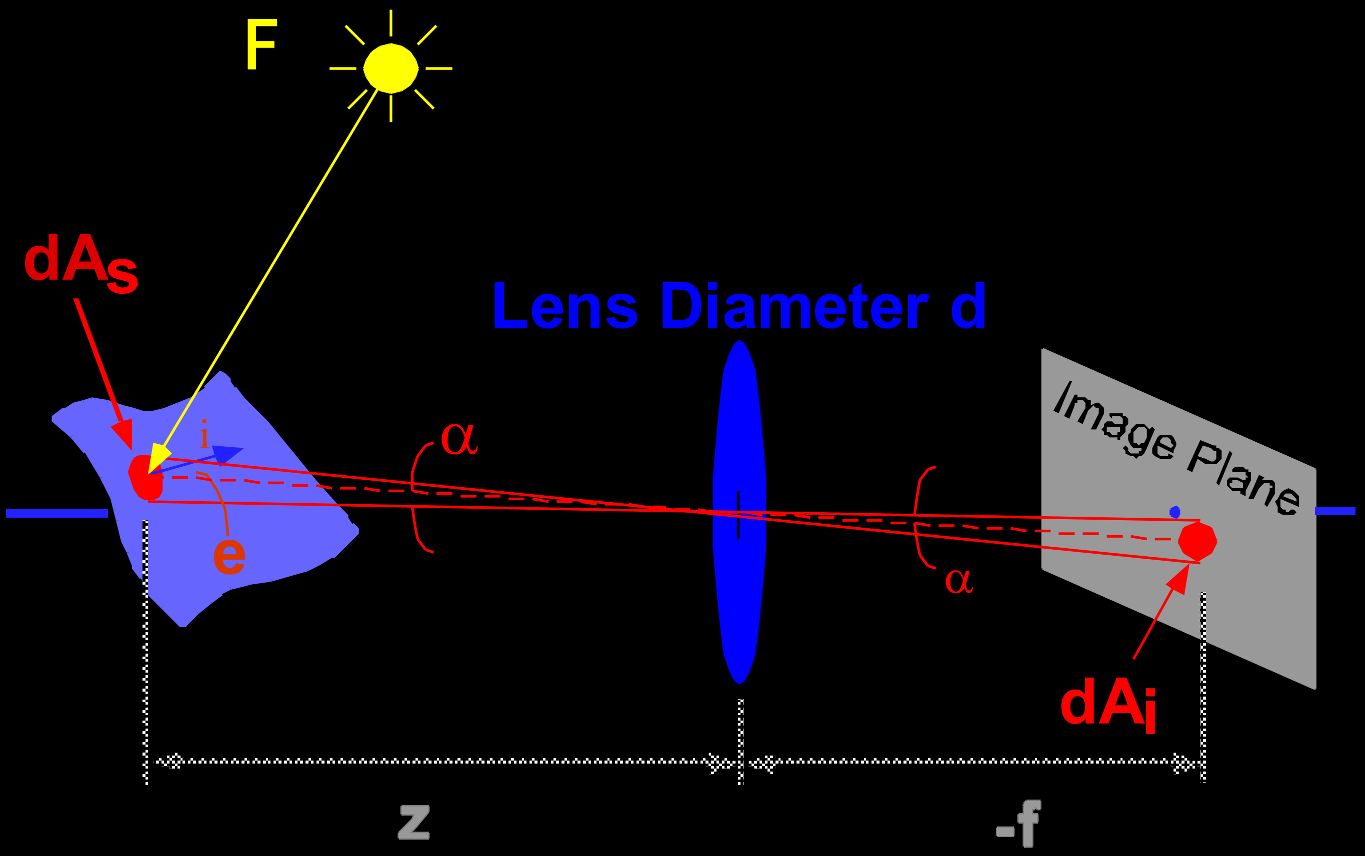
Radiometry

- Image: two-dimensional array of 'brightness' values.
- Geometry: where in an image a point will project.

- Radiometry: what the brightness of the point will be.
  - Brightness: informal notion used to describe both scene and image brightness.
  - Image brightness: related to energy flux incident on the image plane: => Irradiance
  - Scene brightness: brightness related to energy flux emitted (radiated) from a surface: => Radiance

Radiometry and Geometry

- Goal: Relate the radiance of a surface to the irradiance in the image plane of a simple optical system.



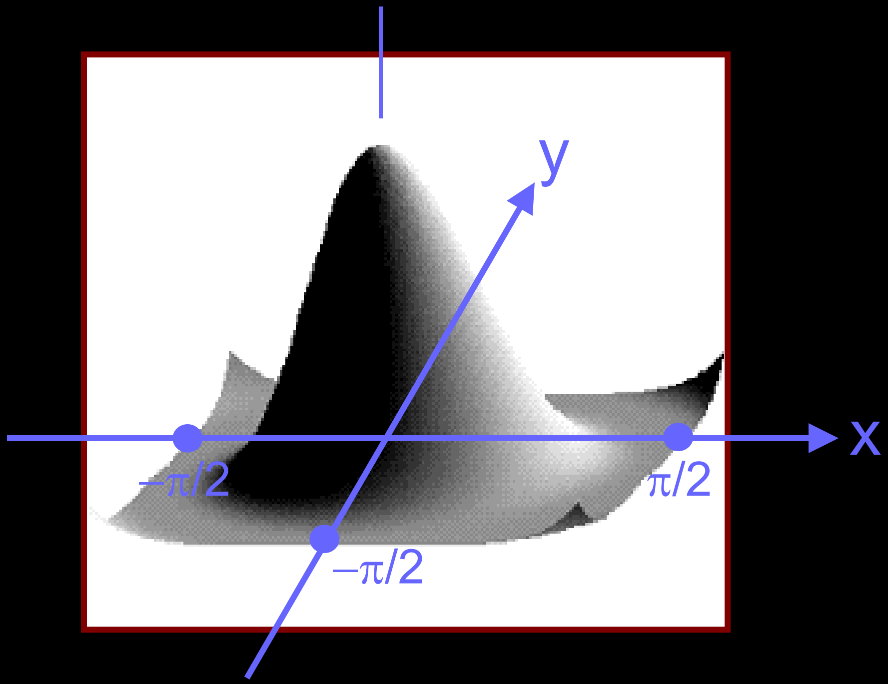
Radiometry Final Result

$$E_i = L_s \frac{\pi}{4}\left(\frac{d}{-f}\right)^2 \cos^4\alpha$$

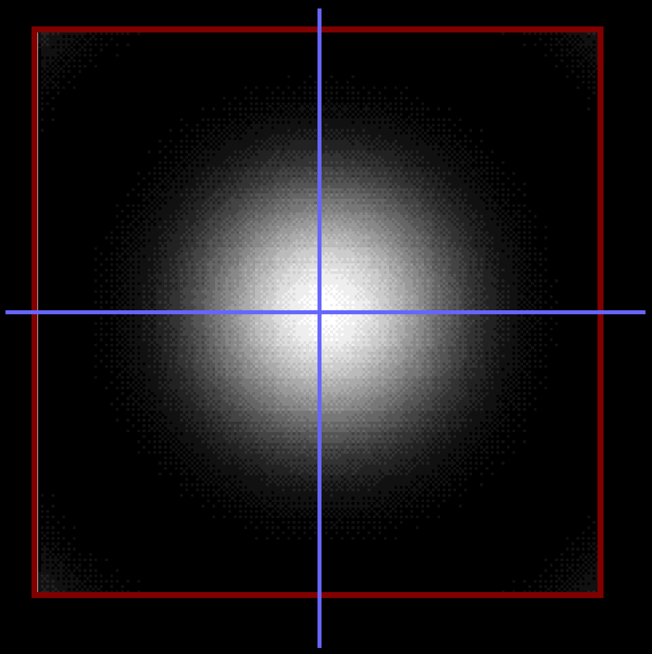
- Image irradiance is proportional to:
  - Scene radiance Ls
  - Focal length of lens f
  - Diameter of lens d
    - f/d is often called the **f-number** of the lens
  - Off-axis angle α

$Cos^4(\alpha)$ Light Falloff

Lens Center



Top view shaded by height



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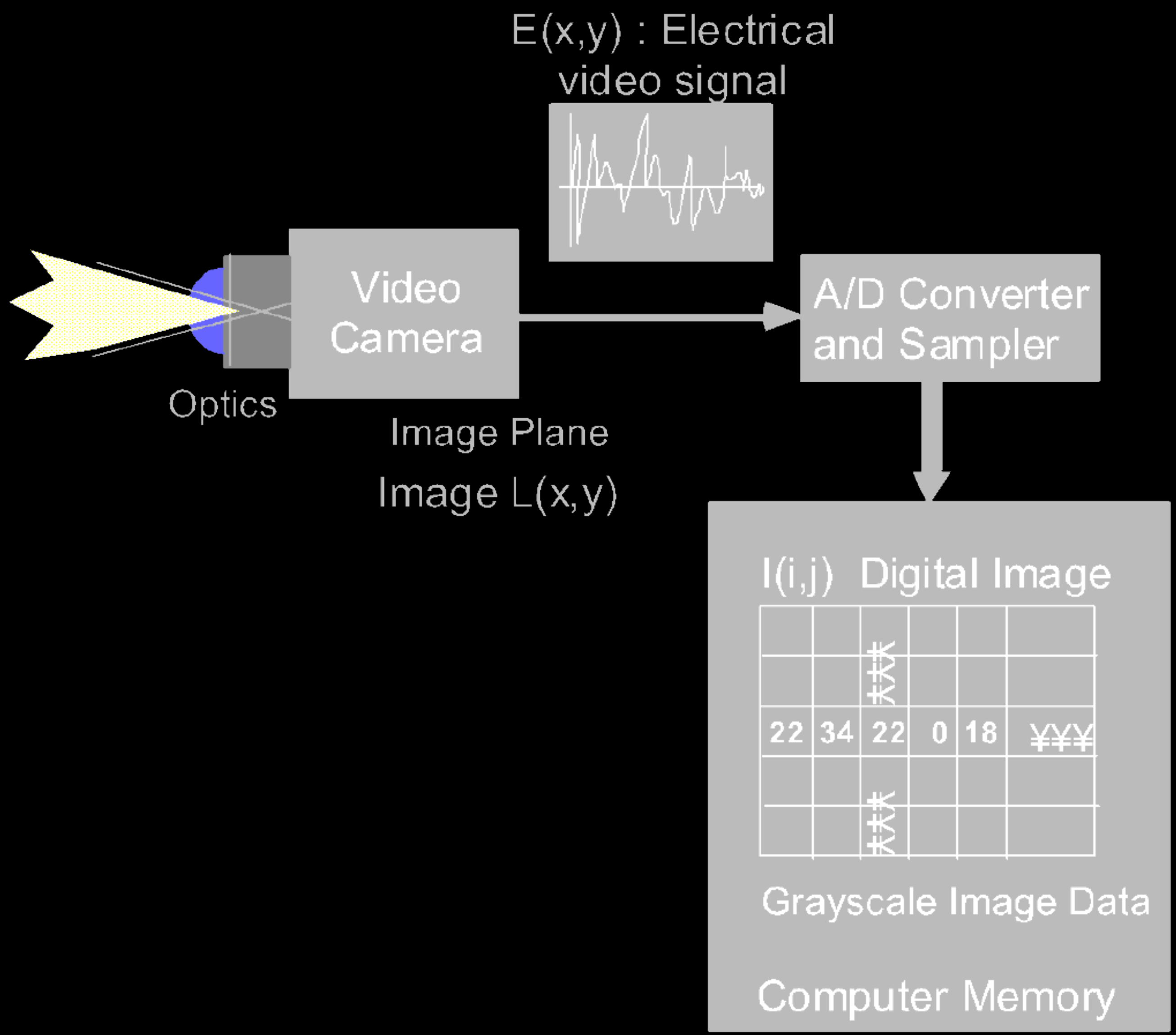
Photometry

- Photometry:

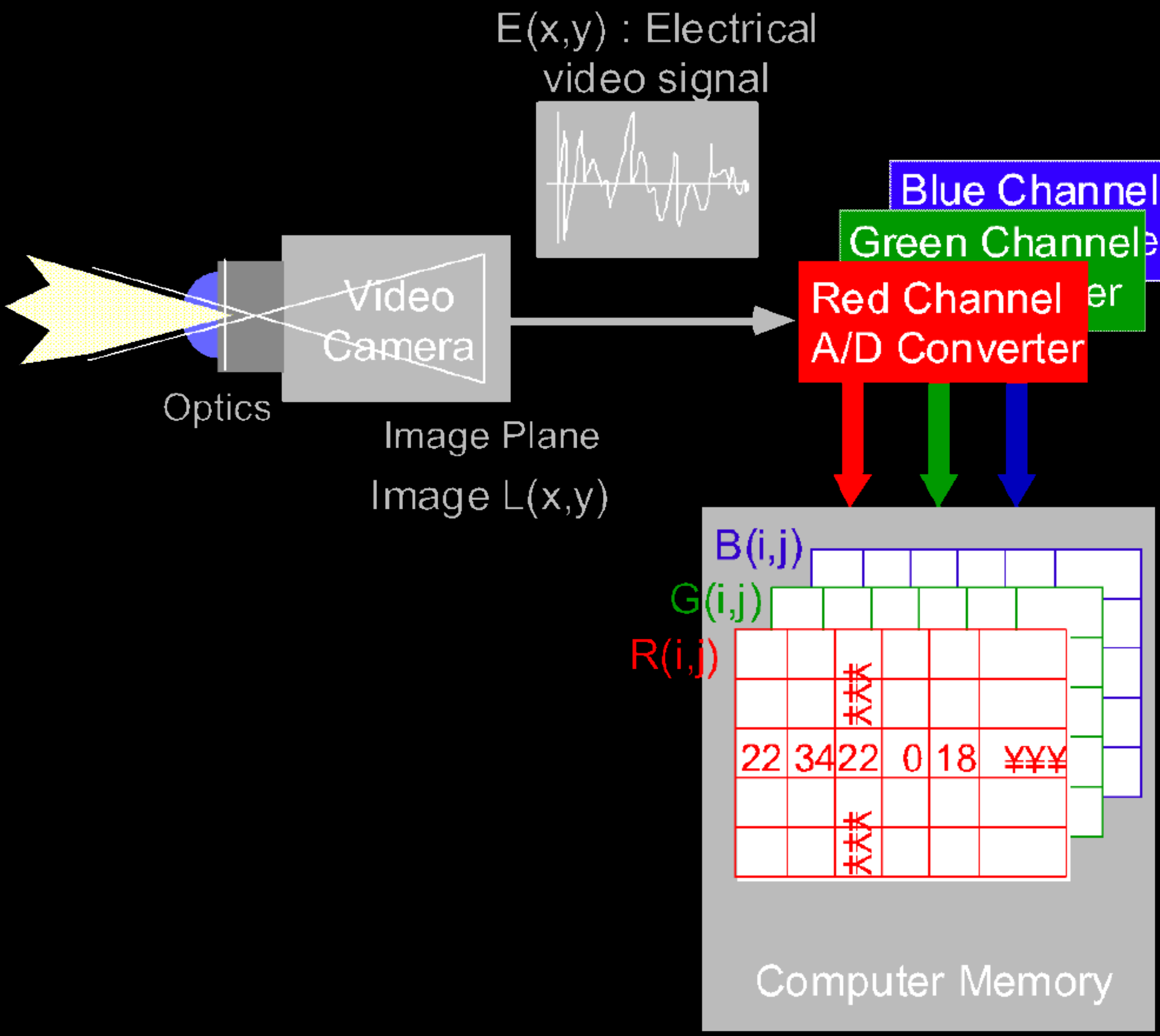
  Concerned with mechanisms for converting light energy into electrical energy.

World ➡ Optics ➡ Sensor ➡
Signal ➡ Digitizer ➡
Digital Representation

Image/Video Generating

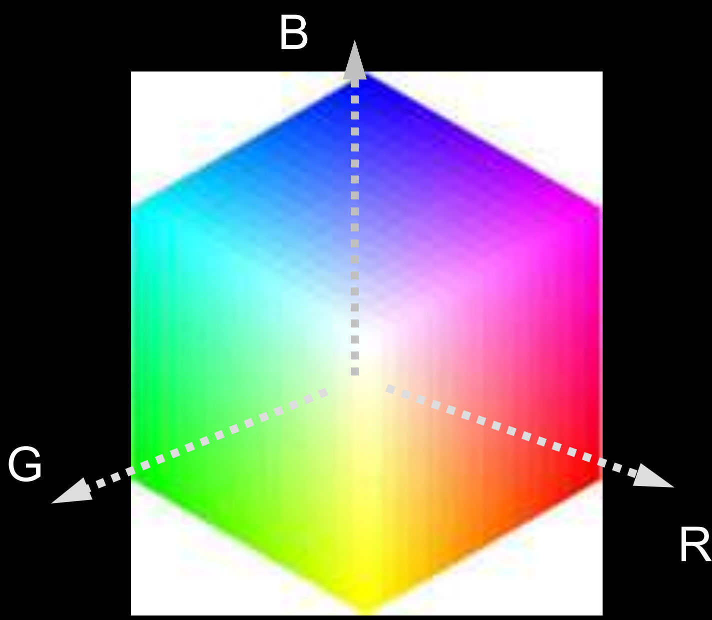


Color Image/Video Generating

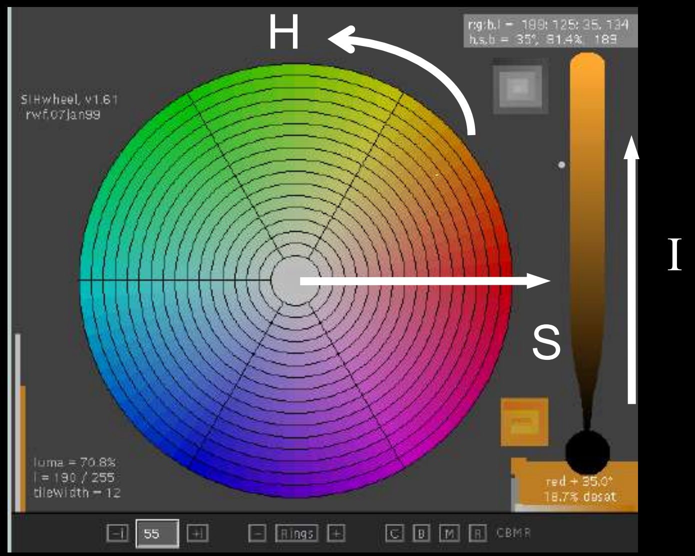


Color Representation

- Color Cube and Color Wheel



HSI
(hue, saturation, intensity)

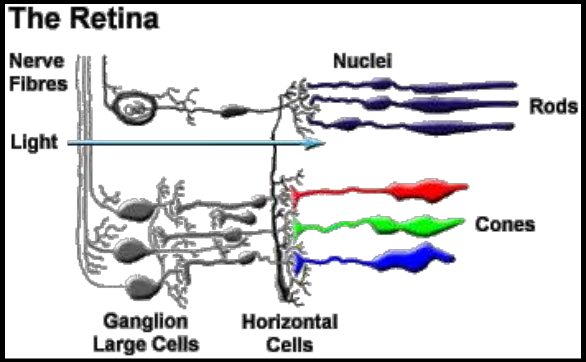


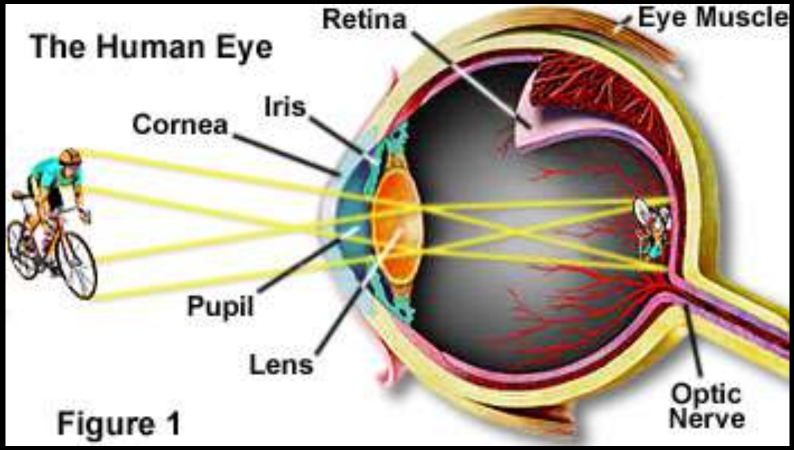
- For color spaces, please read
  - Color Cube http://www.morecrayons.com/palettes/webSmart/
  - Color Wheel http://r0k.us/graphics/SIHwheel.html
  - http://www-viz.tamu.edu/faculty/parke/ends489f00/notes/sec1_4.html

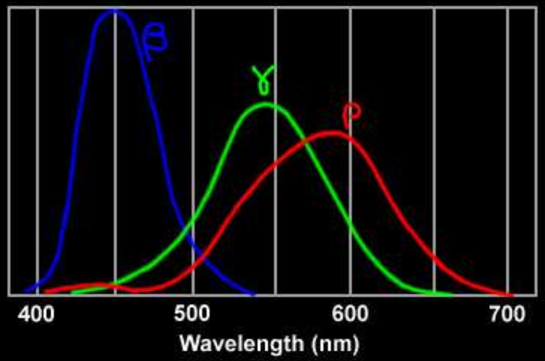
Digital Color Cameras

- Three CCD-chips cameras
  - R, G, B separately, AND digital signals instead analog video
- One CCD Cameras
  - RGB “Bayer” Color and MicroLenses
  - http://www.siliconimaging.com/RGB%20Bayer.htm

Human Eyes & Color Perception







- Visit a cool site with Interactive Java tutorial:
  - Human Vision and Color Perception
- Another site about human color perception:
  - Color Vision

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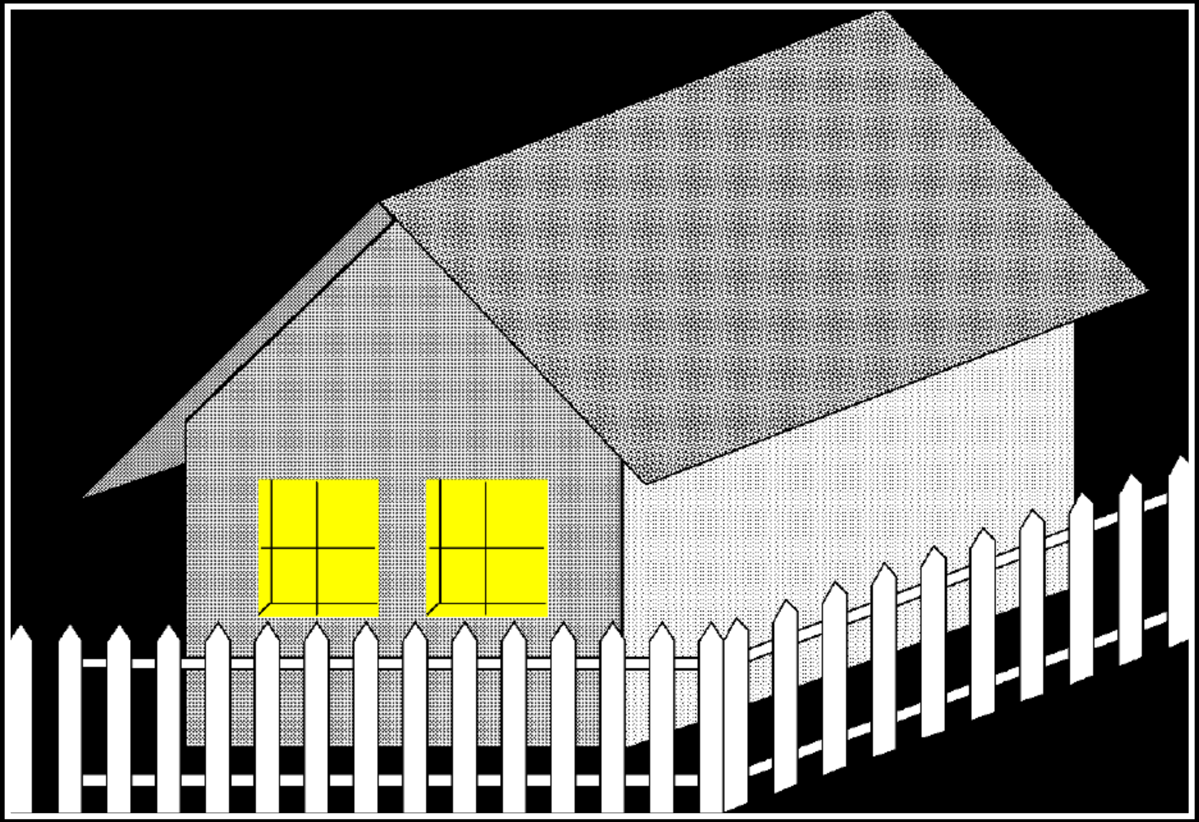
Image Digitization

World → Optics → Sensor →
Signal → Digitizer →
Digital Representation

- Digitization: conversion of the continuous (in space and value) electrical signal into a digital signal (digital image)

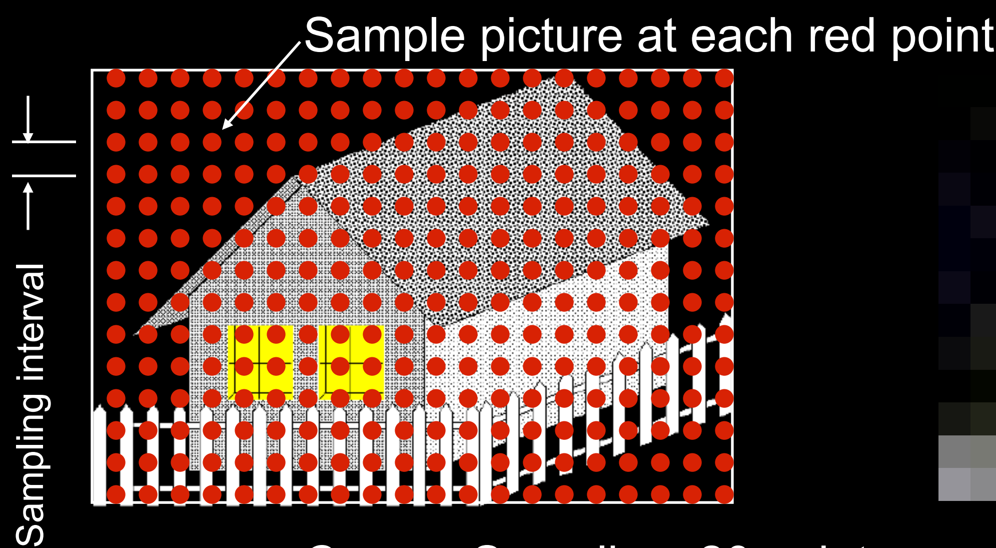
- Three decisions must be made:
  – Spatial resolution (how many samples to take)
  – Signal resolution (dynamic range of values- quantization)
  – Tessellation pattern (how to 'cover' the image with sample points)

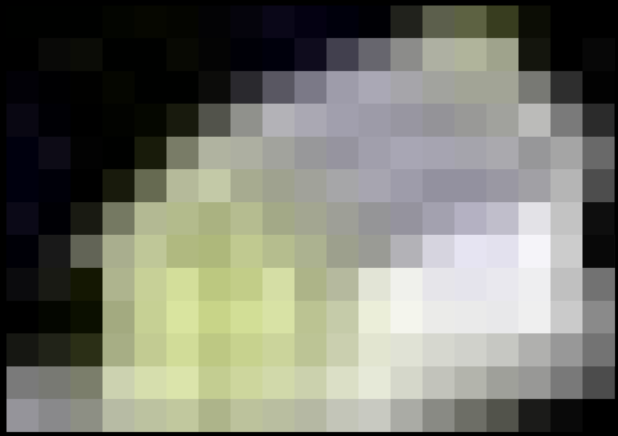
Digitization: Spatial Resolution



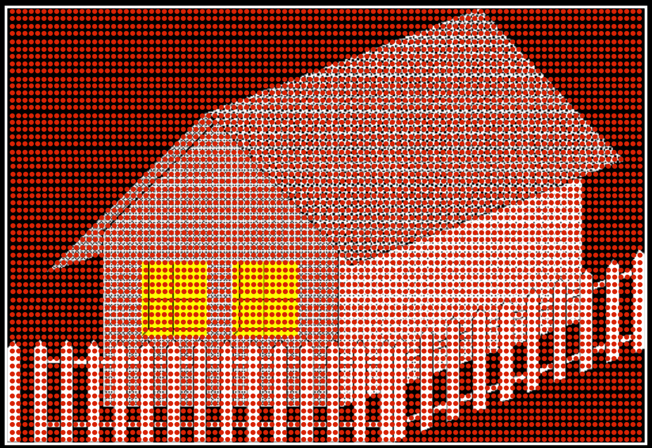
- Let's digitize this image
  - Assume a square sampling pattern
  - Vary density of sampling grid

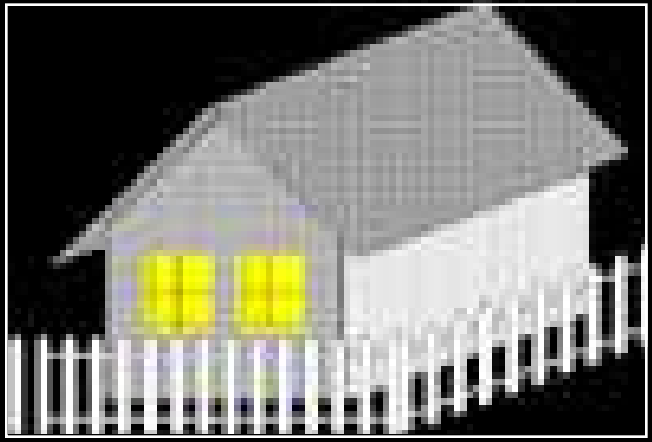
Spatial Resolution





Coarse Sampling: 20 points per row by 14 rows



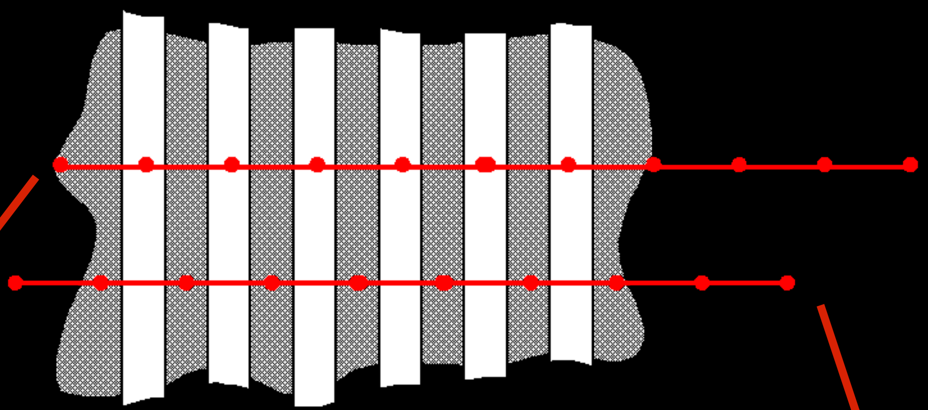


Finer Sampling: 100 points per row by 68 rows

Effect of Sampling Interval

- Look in vicinity of the picket fence:

Sampling Interval:



100	100	100	100	100	100
100	100	100	100	100	100
100	100	100	100	100	100
100	100	100	100	100	100

White Image!

No evidence of the fence!

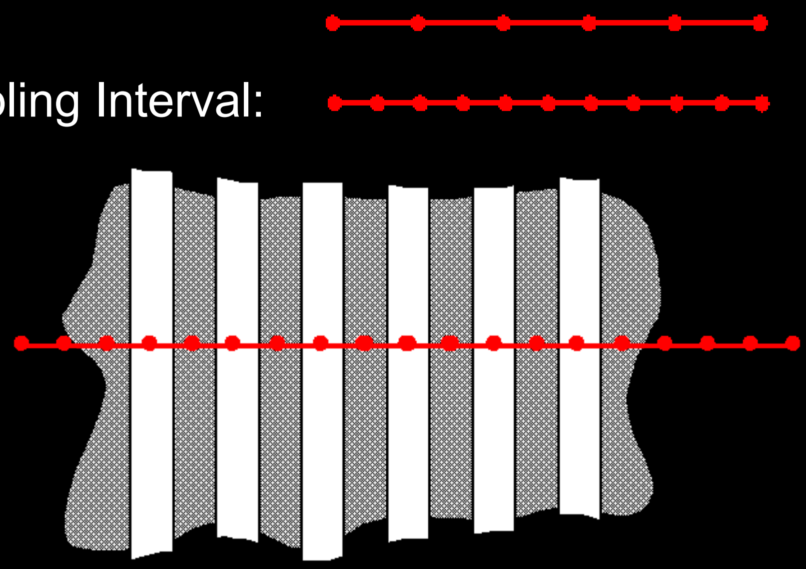
40	40	40	40	40	40
40	40	40	40	40	40
40	40	40	40	40	40
40	40	40	40	40	40

Dark Gray Image!

Effect of Sampling Interval

- Look in vicinity of picket fence:

Sampling Interval:



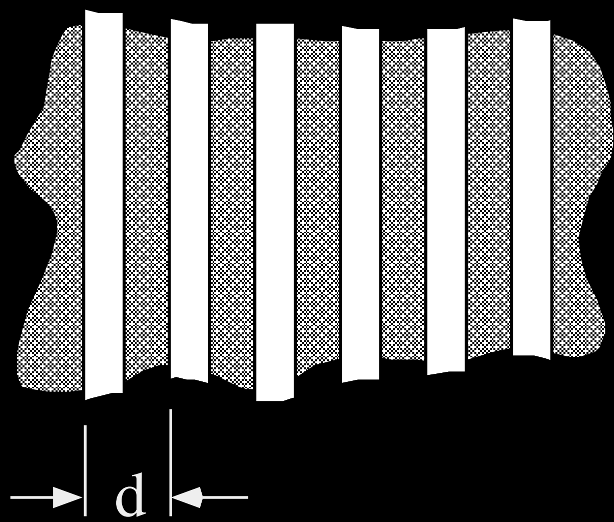
40	100	40	100	40
40	100	40	100	40
40	100	40	100	40
40	100	40	100	40

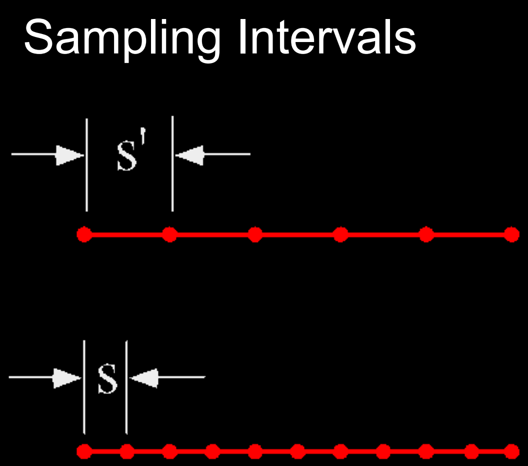
Now we've got a fence!

What's the difference between this attempt and the last one?

The Missing Fence Found

- Consider the repetitive structure of the fence:





Case 1: s' = d	The sampling interval is equal to the size of the repetitive structure	No Fence
Case 2: s = d/2	The sampling interval is one-half the size of the repetitive structure	Fence

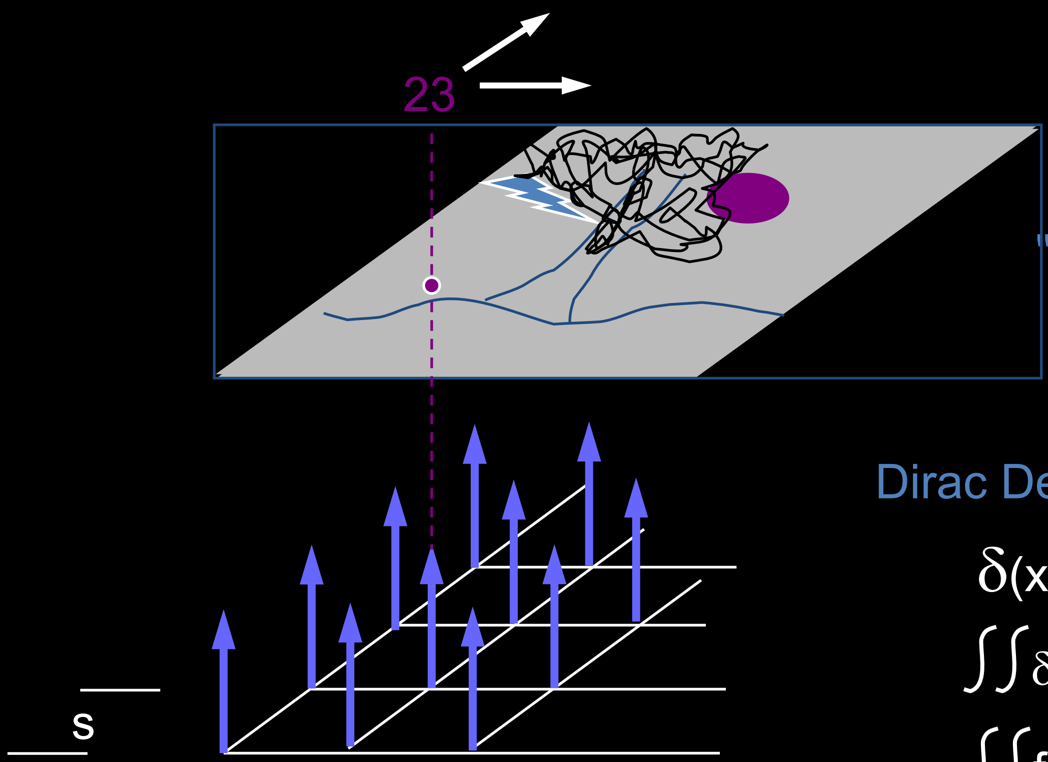
The Sampling Theorem

- IF: the size of the smallest structure to be preserved is d
- THEN: the sampling interval must not be larger than $d/2$

- Can be shown to be true mathematically
- Repetitive structure has a certain frequency
  – To preserve structure must sample at twice the frequency
  – Holds for images, audio CDs, digital television….
- Leads naturally to Fourier analysis

2D Sampling

- Rough Idea: Ideal Case



"Digitization"

"Continuous Image"

Dirac Delta Function 2D "Comb"

$\delta(x,y) = 0$ for $x \neq 0,\ y \neq 0$

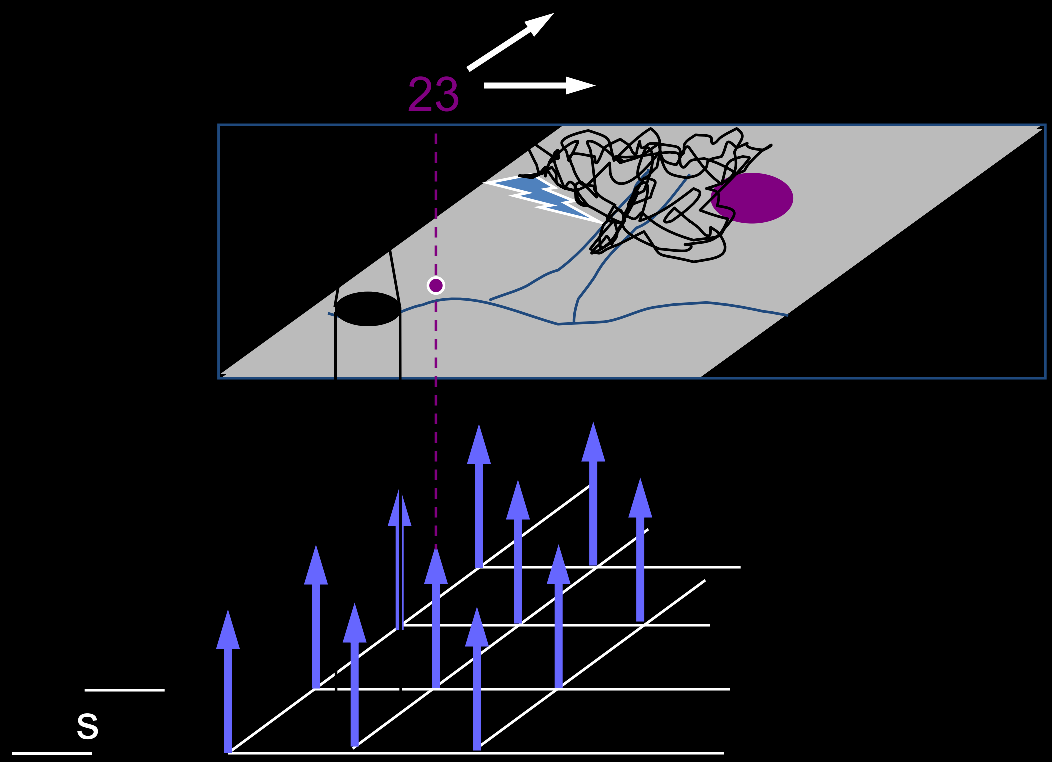
$\iint \delta(x,y)\,dx\,dy = 1$

$\iint f(x,y)\delta(x-a,y-b)\,dx\,dy = f(a,b)$

$\delta(x-ns,y-ns)$ for $n = 1\ldots.32$ (e.g.)

2D Sampling

- Rough Idea: Actual Case
  - Can't realize an ideal point function in real equipment
  - "Delta function" equivalent has an area
  - Value returned is the average over this area



Mixed Pixel Problem

Reflected energy

Image Quantization

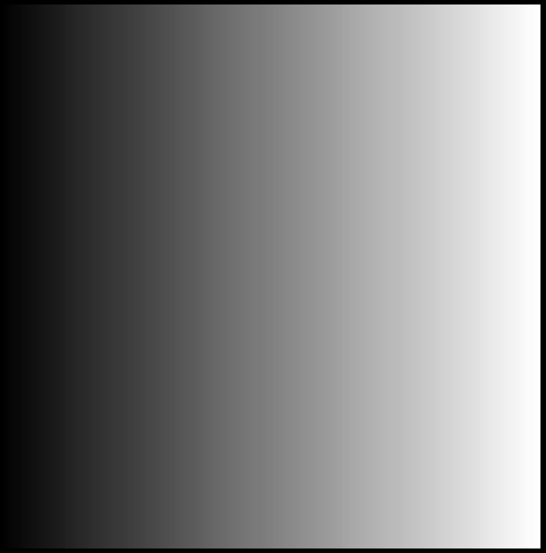
- $I(x,y)$ = continuous signal: $0 \le I \le M$
- Want to quantize to K values 0,1,....K-1
- K usually chosen to be a power of 2:

K	#Levels	#Bits
2	2	1
4	4	2
8	8	3
16	16	4
32	32	5
64	64	6
128	128	7
256	256	8

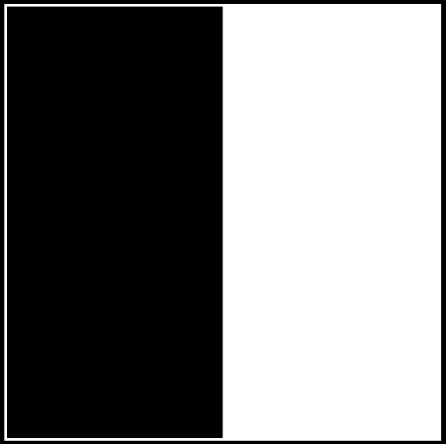
- Mapping from input signal to output signal is to be determined.
- Several types of mappings: uniform, logarithmic, etc.

Choice of K

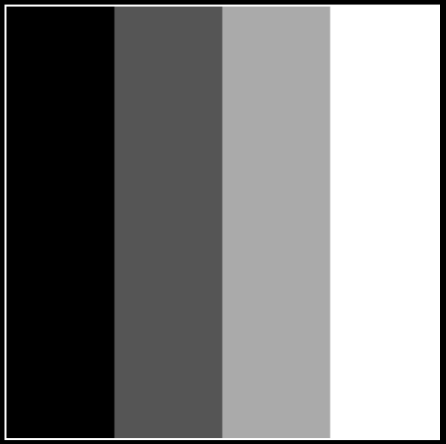
Original



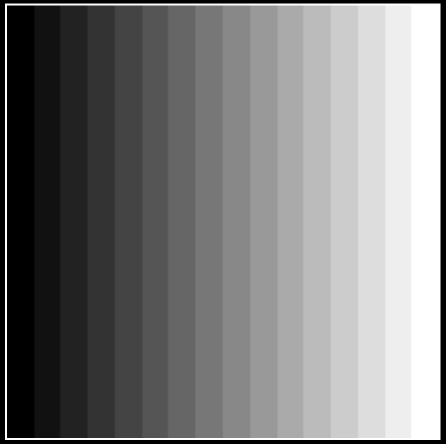
Linear Ramp



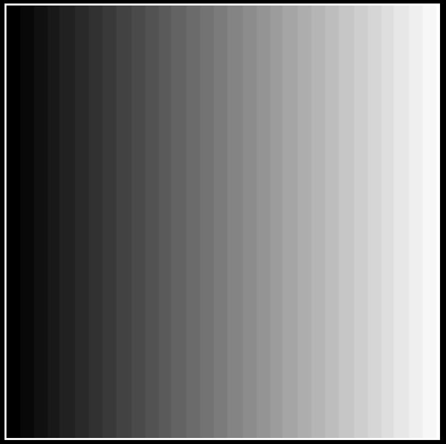
K=2



K=4



K=16



K=32

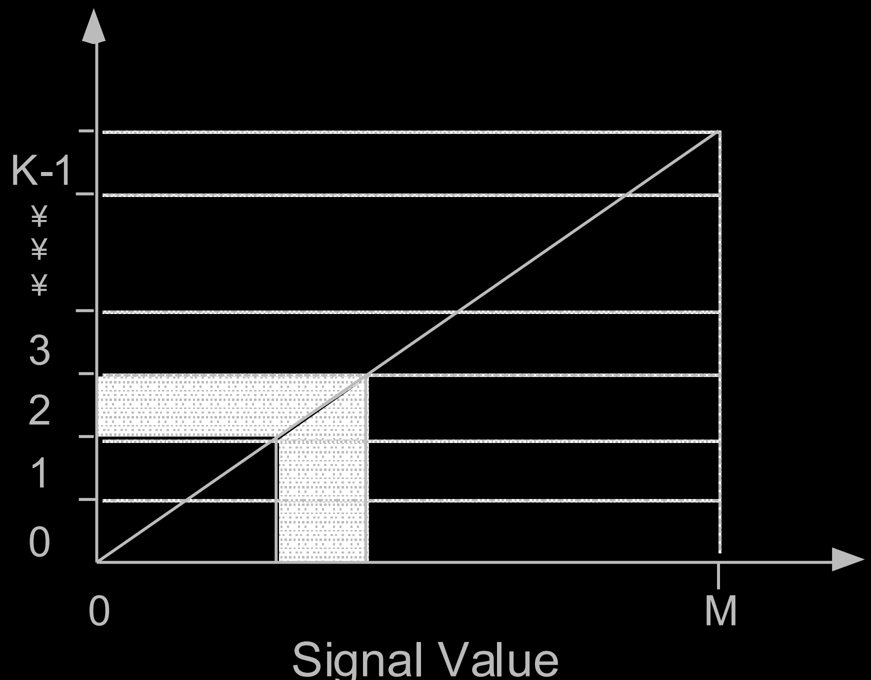
Choice of K

K=2 (each color)

K=4 (each color)

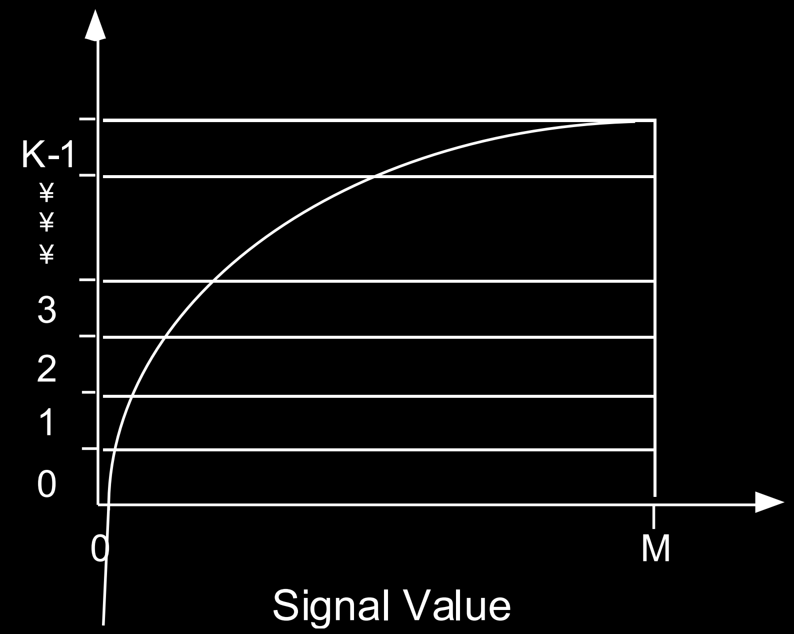
Choice of Function: Uniform

- Uniform quantization divides the signal range [0-M] into K equal-sized intervals.
- The integers 0,...K-1 are assigned to these intervals.
- All signal values within an interval are represented by the associated integer value.
- Defines a mapping:



Logarithmic Quantization

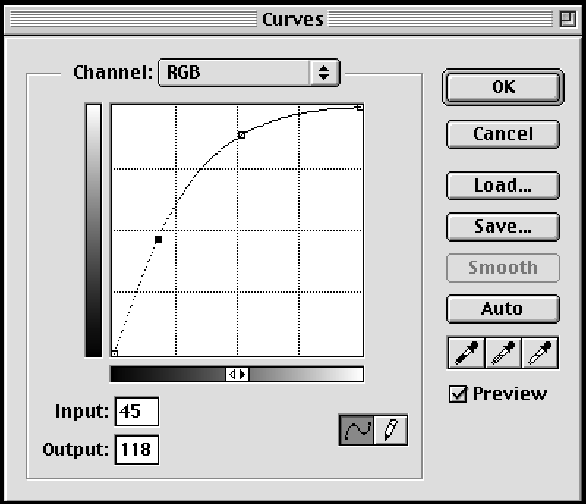
- Signal is log I(x,y).
- Effect is:



- Detail enhanced in the low signal values at expense of detail in high signal values.

Logarithmic Quantization

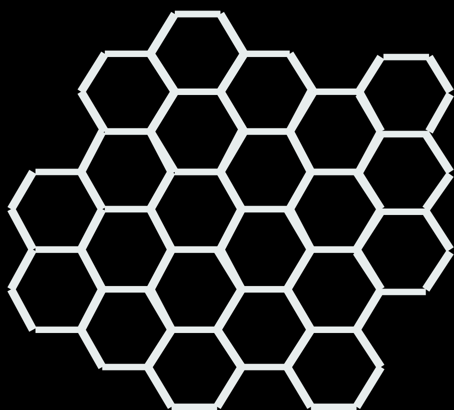
Original



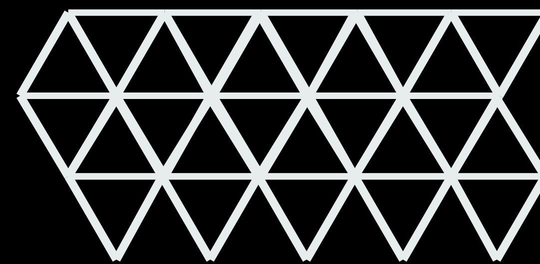
Quantization Curve

Logarithmic Quantization

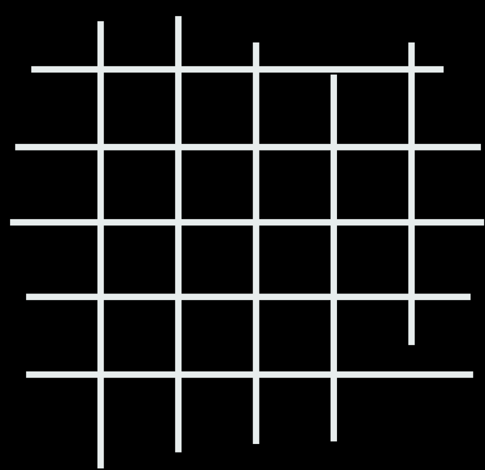
Tessellation Patterns



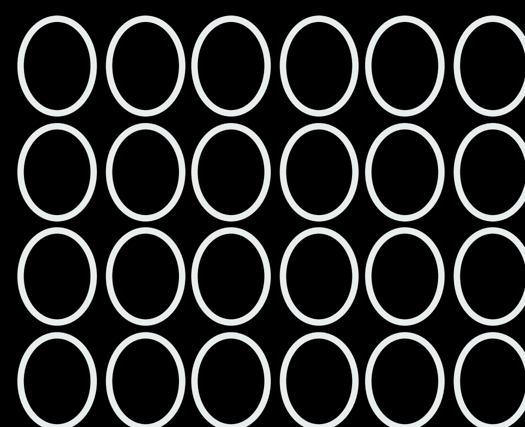
Hexagonal



Triangular



Rectangular

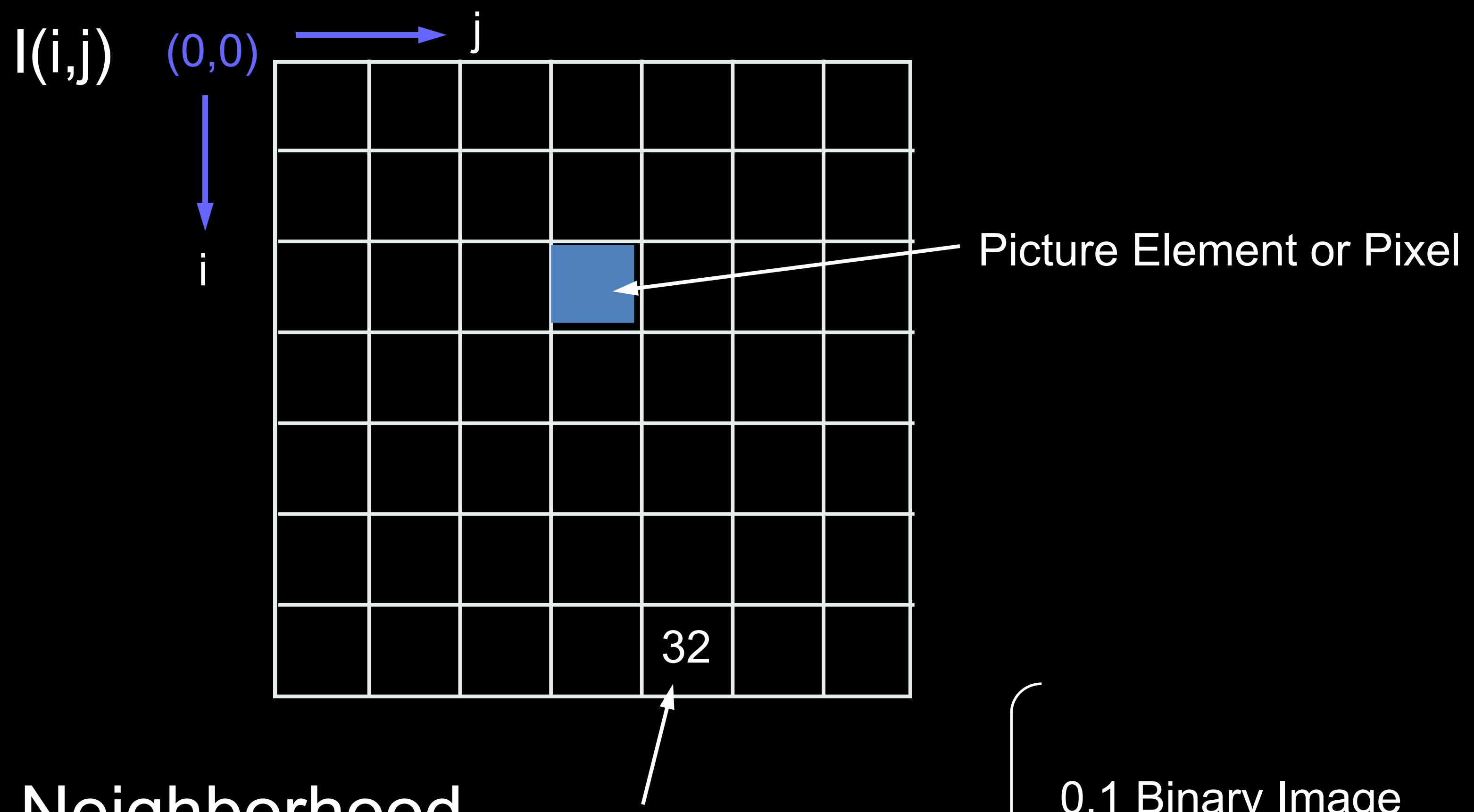


Typical

Outline

- Image Formation Steps
- Geometry
  - Pinhole camera model & Thin lens model
  - Perspective projection & Fundamental equation
- Radiometry
- Photometry
  - Color, human vision, & digital imaging
- Image Digitalization
  - Sampling, quantization & tessellations
- More on Digital Images
  - Neighbors, connectedness & distances
- Vehicle Visual Perception Intro

Digital Geometry

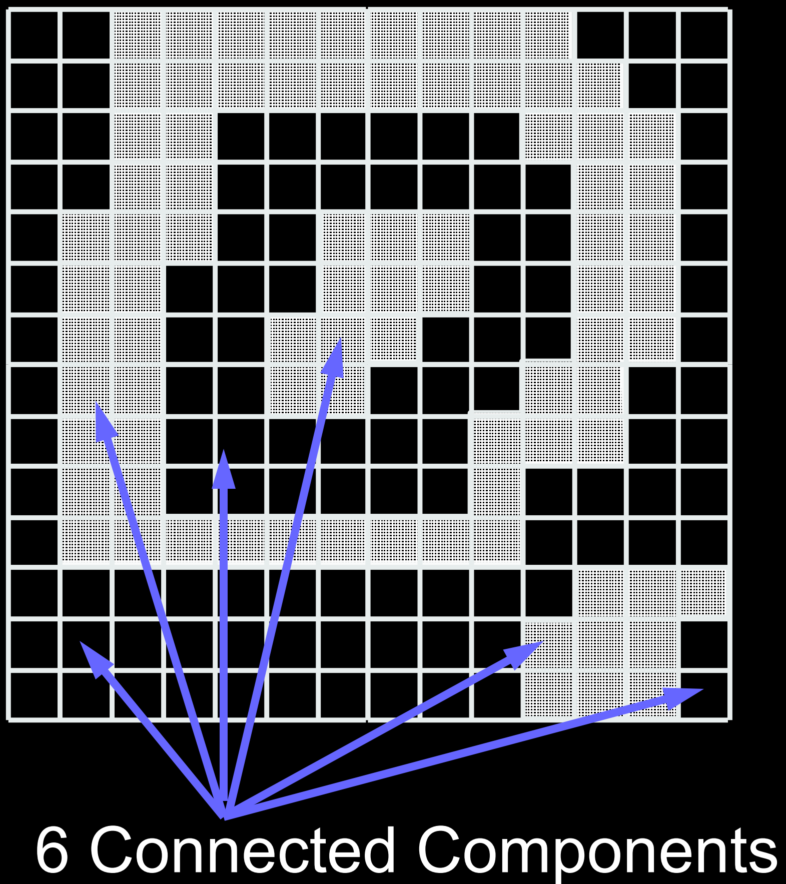


Pixel value I(I,j) =
- 0,1 Binary Image
- 0 ~ K-1 Gray Scale Image
- Vector: Multispectral Image

- Neighborhood
- Connectedness
- Distance Metrics

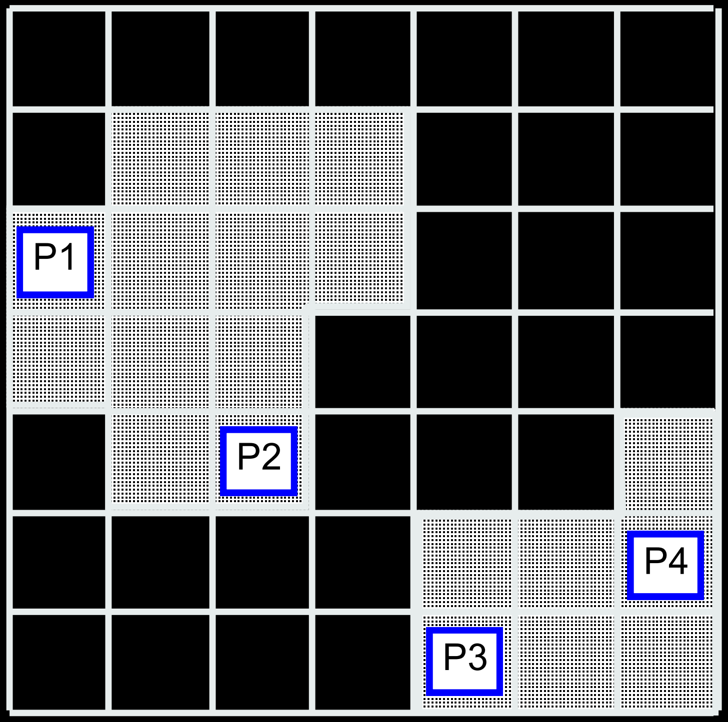
Connected Components

- Binary image with multiple 'objects'
- Separate 'objects' must be labeled individually



Find Connected Components

- Two points in an image are 'connected' if a path can be found for which the value of the image function is the same all along the path.



P_1 connected to P_2

P_3 connected to P_4

P_1 not connected to P_3 or P_4

P_2 not connected to P_3 or P_4

P_3 not connected to P_1 or P_2

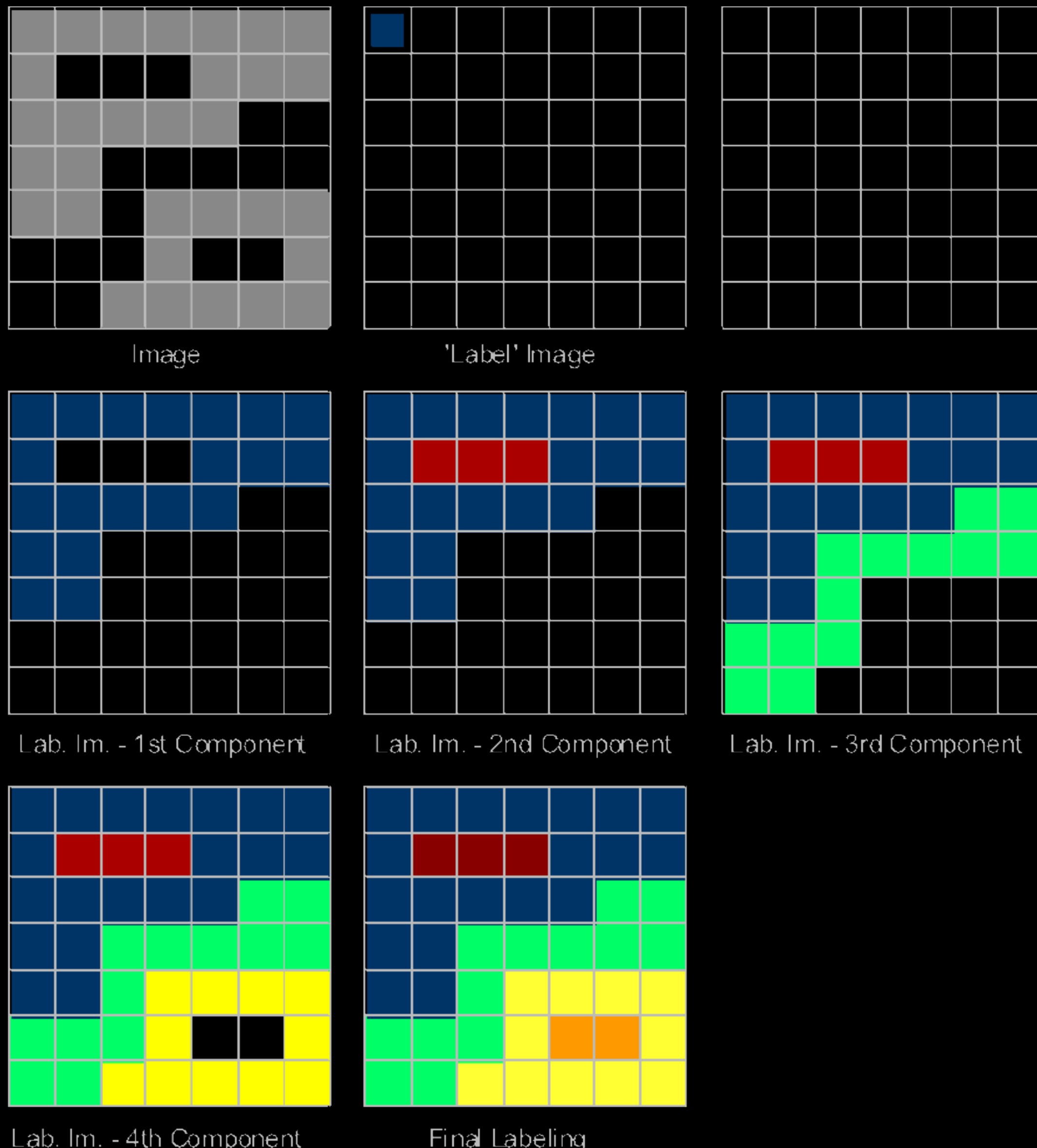
P_4 not connected to P_1 or P_2

Algorithm Steps

- Pick any pixel in the image and assign it a label
- Assign same label to any neighbor pixel with the same value of the image function
- Continue labeling neighbors until no neighbors can be assigned this label
- Choose another label and another pixel not already labeled and continue
- If no more unlabeled image points, stop.

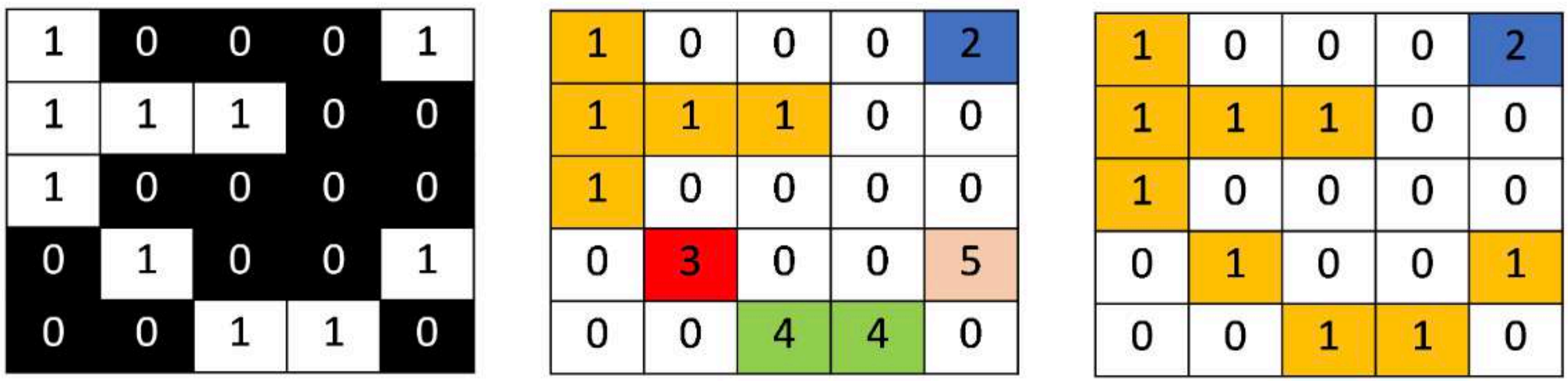
Who's my neighbor?

Algorithm Example: Region Growing



Algorithm Example: CCL

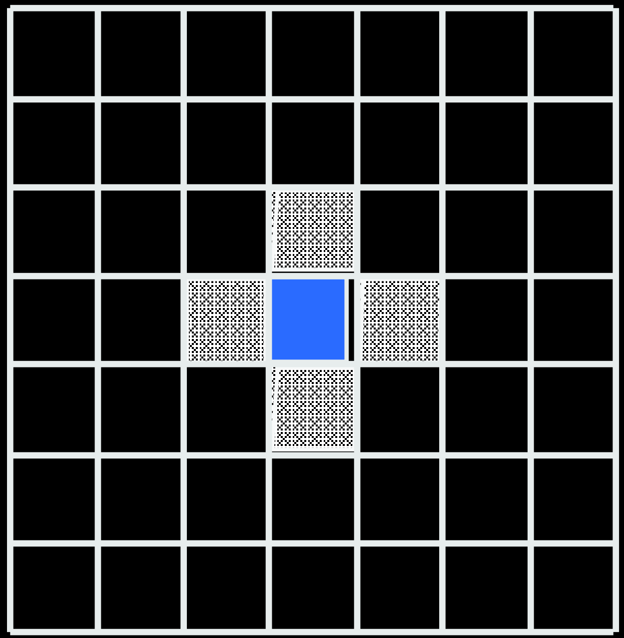
CCL (Connected Component Labelling)



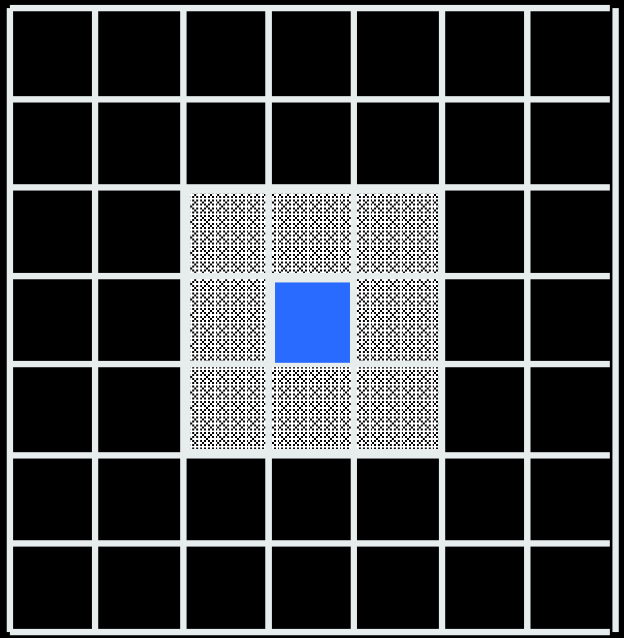
(a) (b) (c)

Neighbor

- Consider the definition of the term 'neighbor'
- Two common definitions:



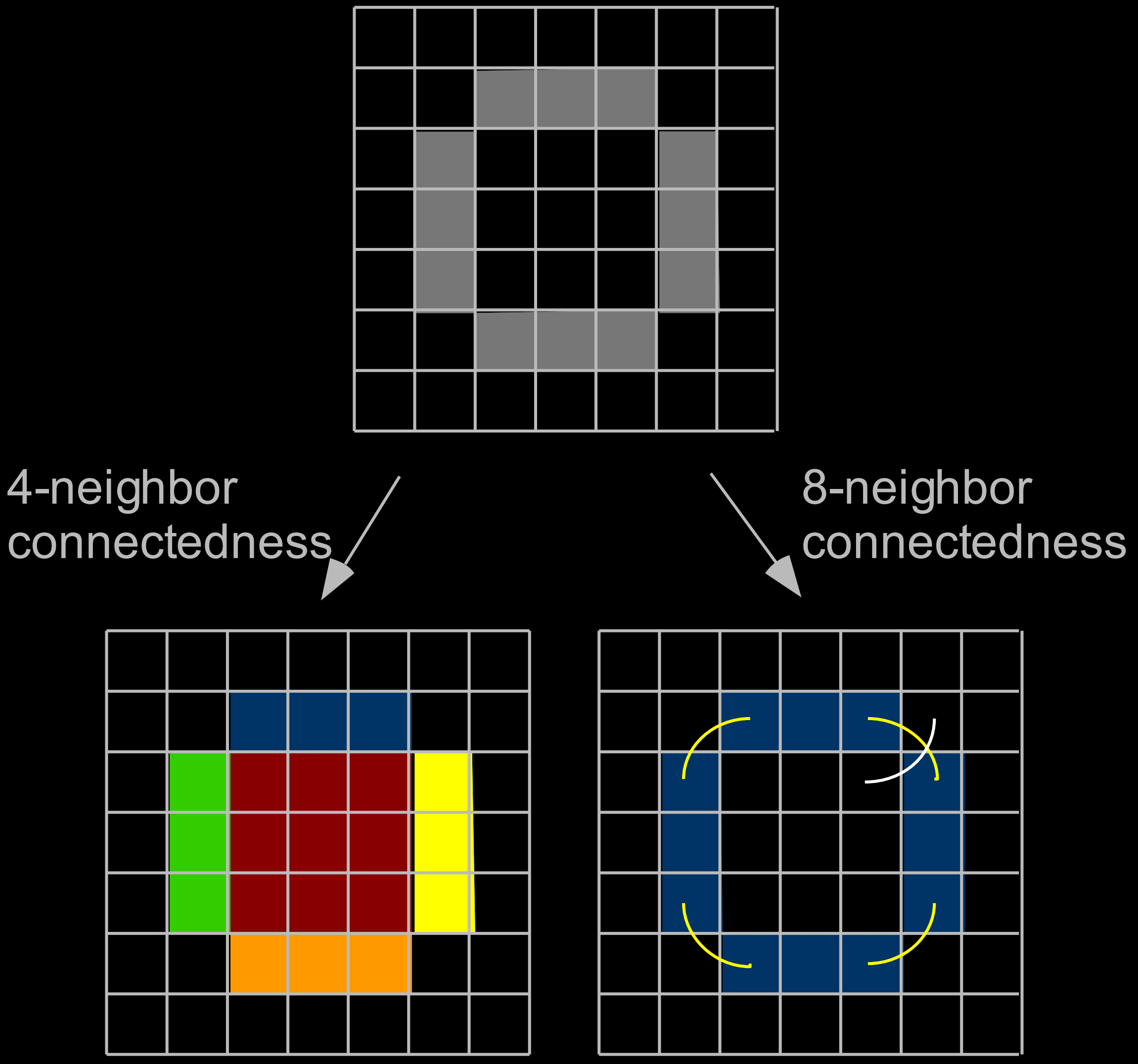
Four Neighbor



Eight Neighbor

- Consider what happens with a closed circle.
- One would expect a closed curve to partition the plane into two connected regions.

Alternate Neighborhood Types

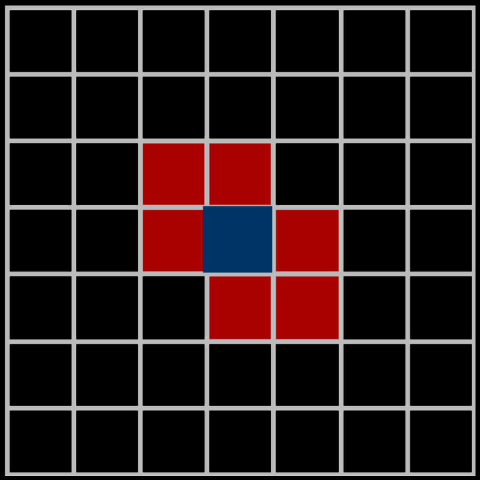


Neither neighborhood definition satisfactory!

Possible Solutions

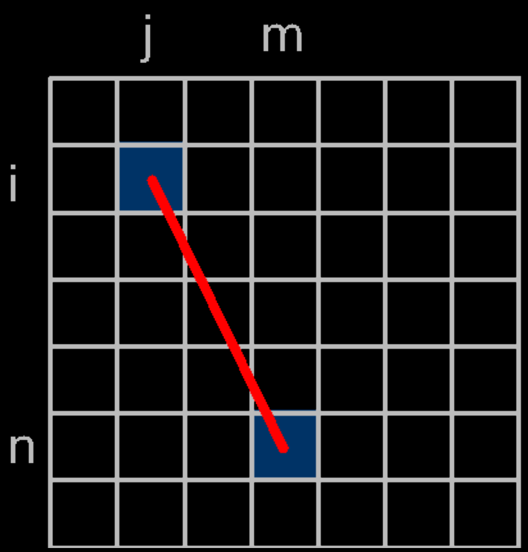
- Use 4-neighborhood for object and 8-neighborhood for background
  - requires a-priori knowledge about which pixels are object and which are background

- Use a six-connected neighborhood:



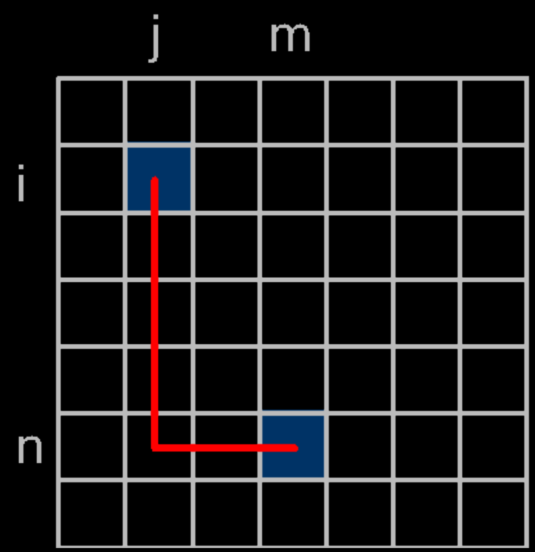
Digital Distances

- Alternate distance metrics for digital images



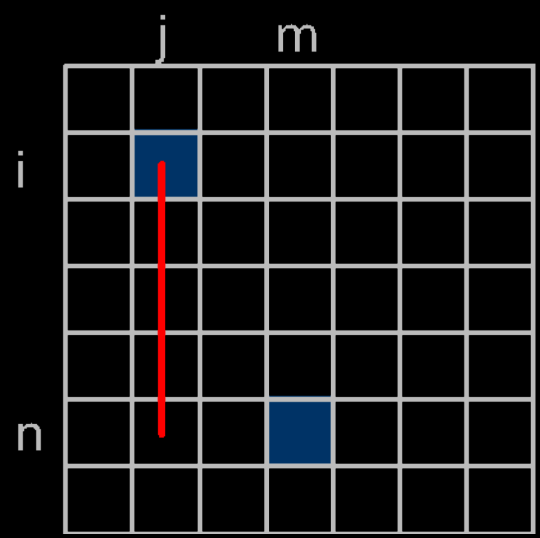
Euclidean Distance

$$=\sqrt{(i-n)^2 + (j-m)^2}$$



City Block Distance

$$= |i-n| + |j-m|$$



Chessboard Distance

$$= \max[\ |i-n|, |j-m|\ ]$$

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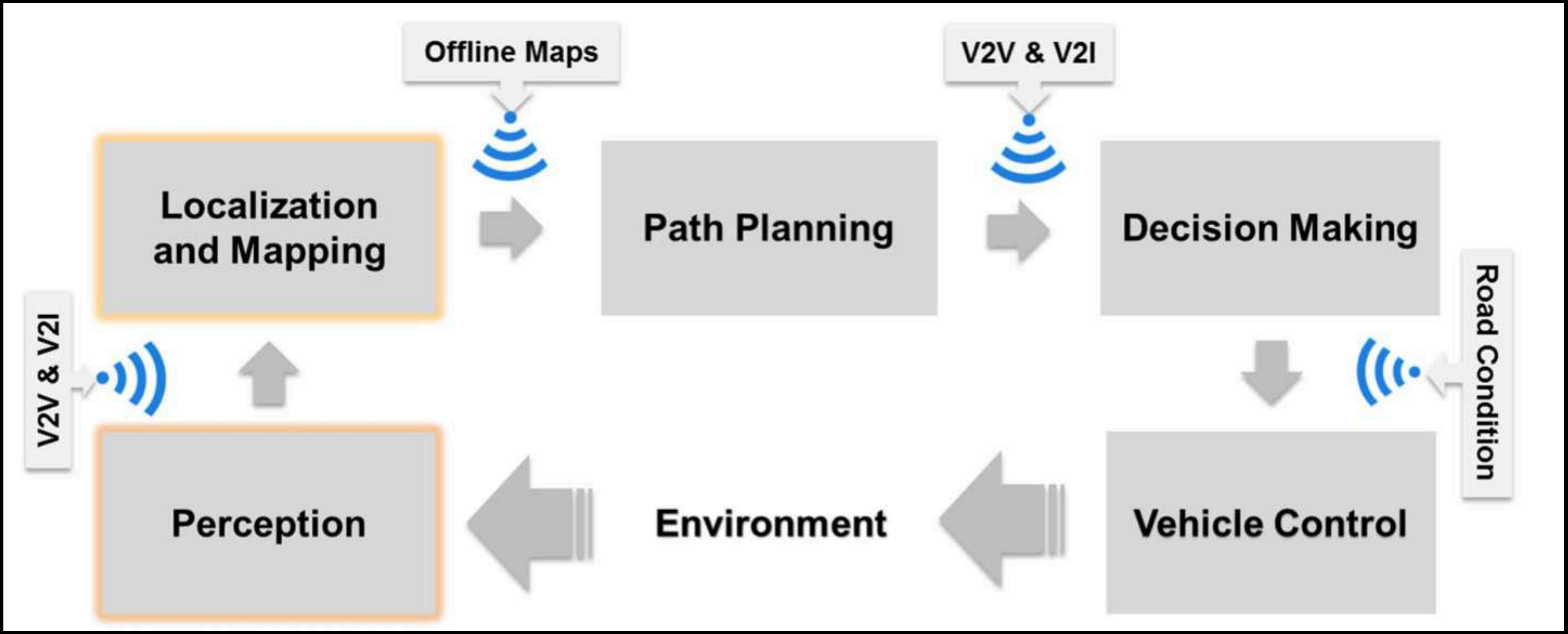
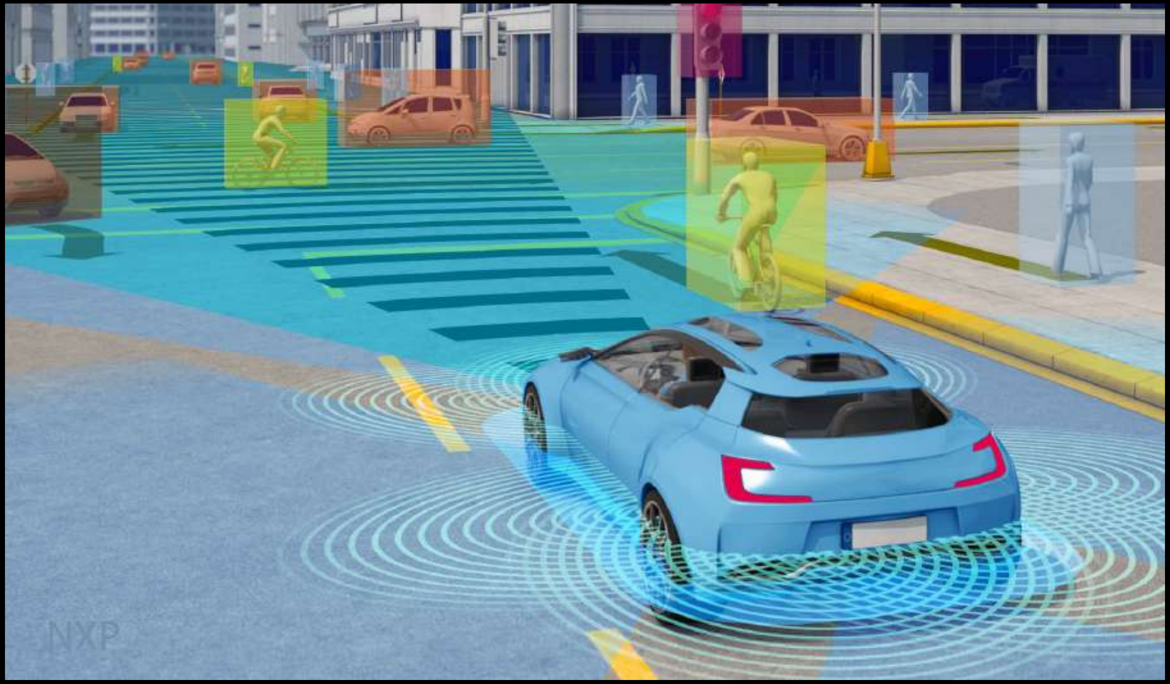
Vehicle Visual Perception Intro

- Inside of the Autonomous Vehicle big picture



Vehicle Visual Perception Problems

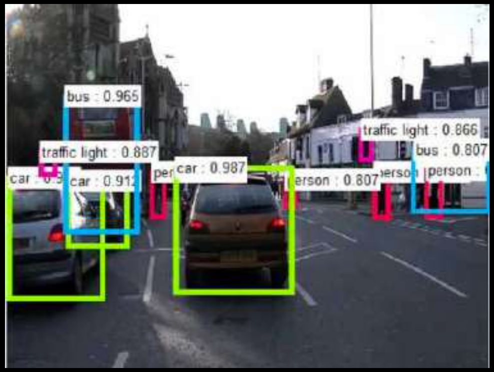
- Perceive what?
  - Road
    - Lane
    - Edge
  - Traffic
    - Traffic light
    - Sign
    - …
  - Object
    - Pedestrian
    - Vehicle
    - Cyclist
    - …
  - Object tracking

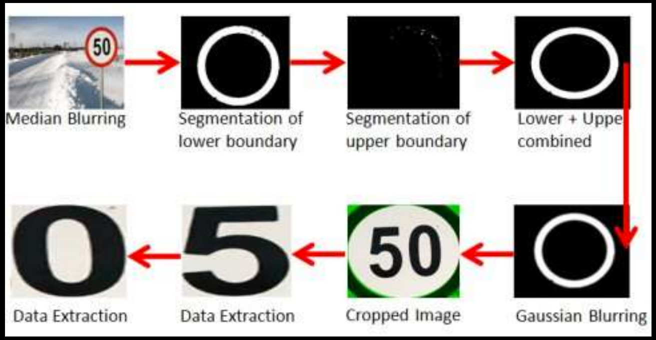


Detection, Segmentation, Tracking in 2D/3D

Vehicle Visual Perception Problems

- Detection

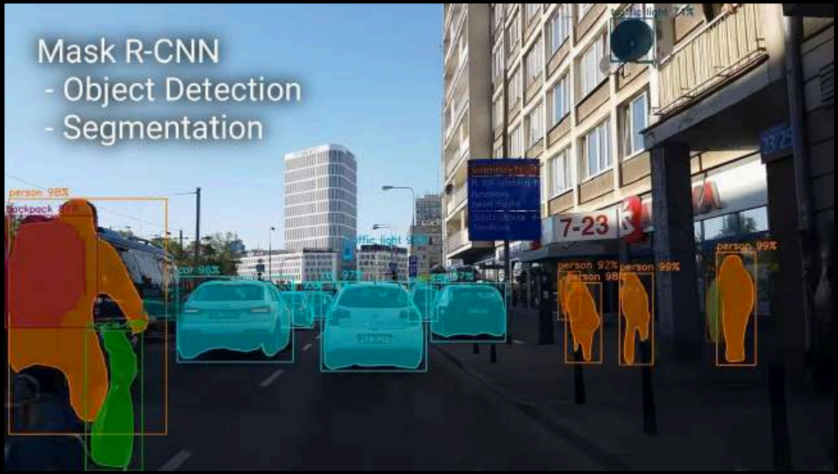




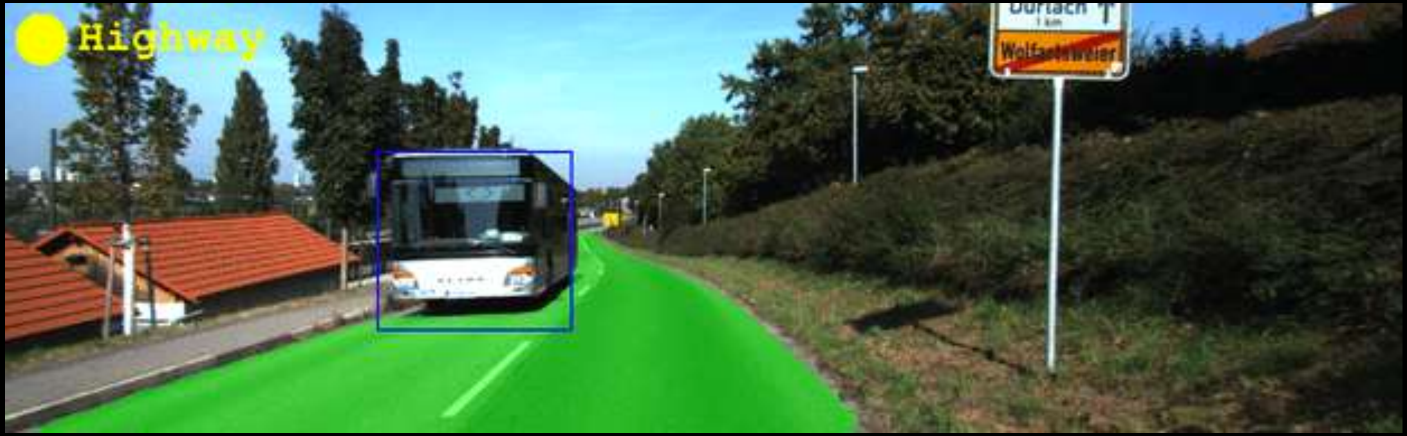
Vehicle Visual Perception Problems

- Segmentation

Object

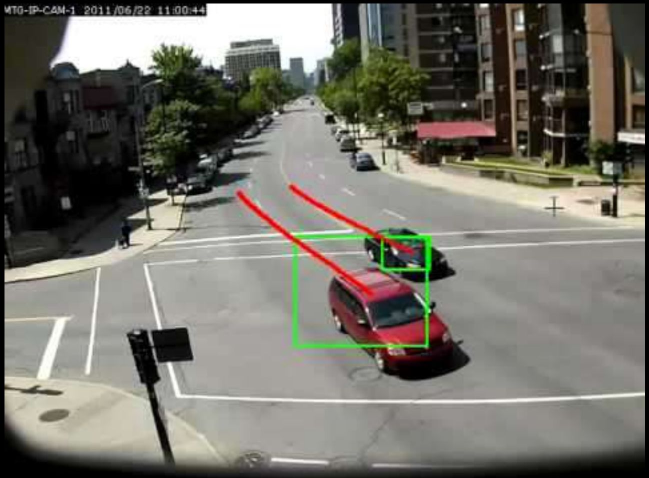


Road

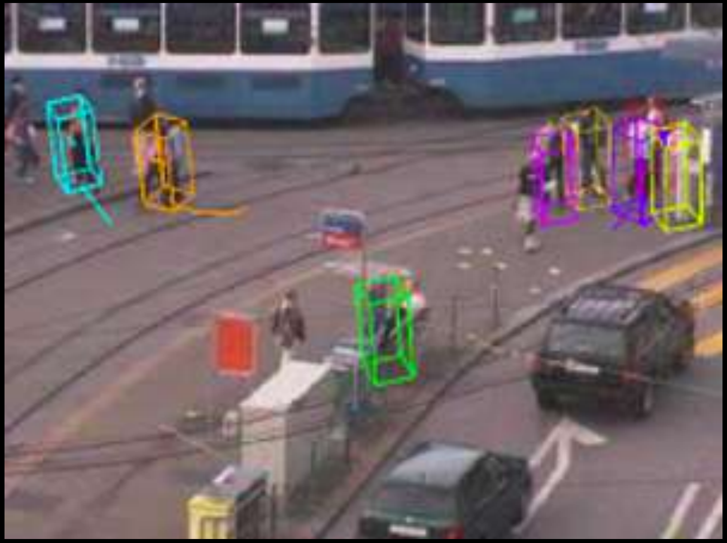


Vehicle Visual Perception Problems

- Tracking



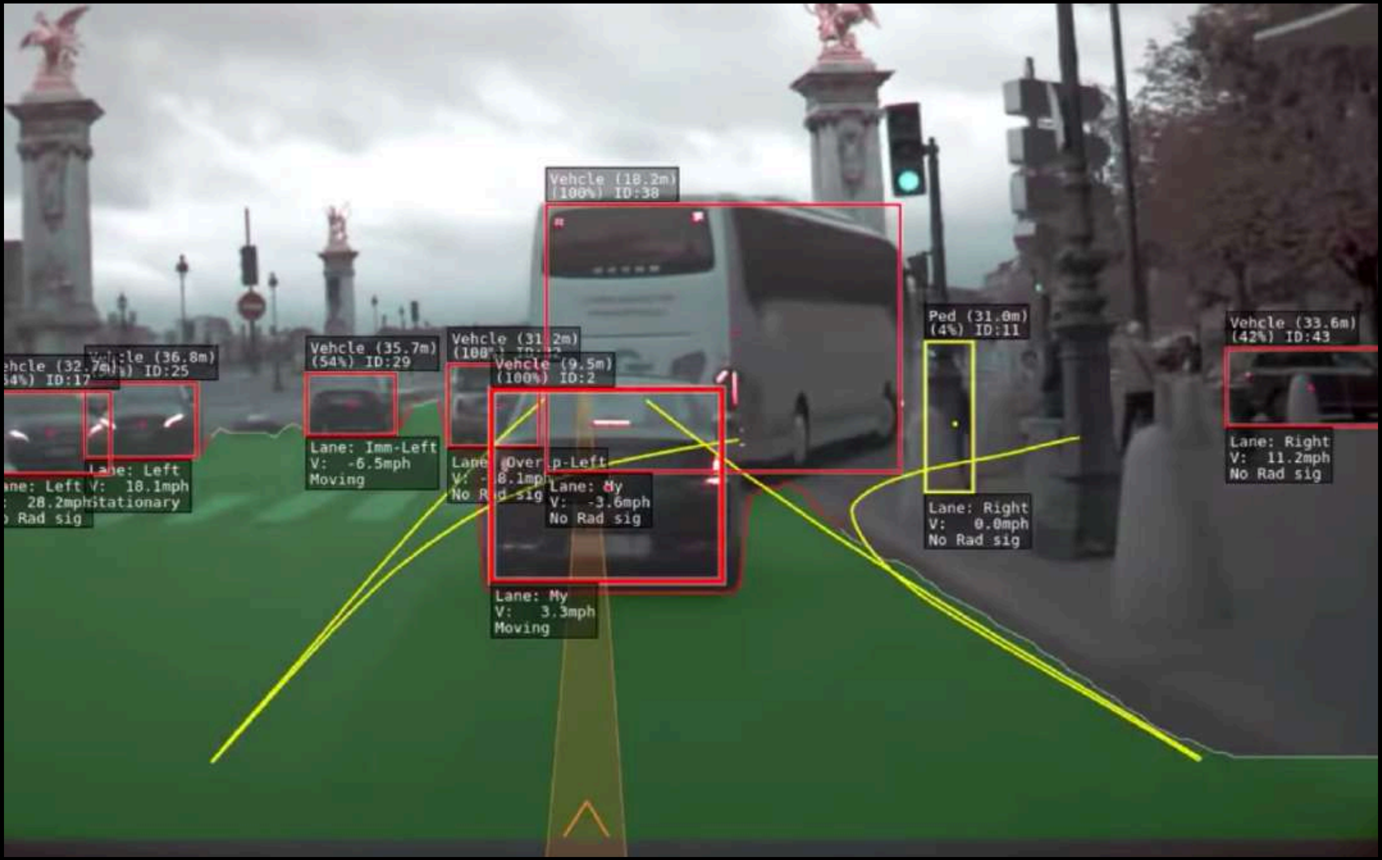
Vehicles



Pedestrians

Vehicle Visual Perception Problems

- Paris streets in the eyes of Tesla Autopilot



Summary Highlights

- Image formation steps
- Optical pinhole model
- Perspective projection
- Image sampling and resolution
- Image digitalization
- Color cube: RGB, HSI, ...
- Digital image geometry: connectivity
- Digital image: distance
- Vehicle visual perception problems

Acknowledgements

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