



ZJU-UIUC Institute

Zhejiang University / University of Illinois at Urbana-Champaign Institute



ECE 470: Introduction to Robotics

Lecture 22

Liangjing Yang


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Wechat ID: Liangjing_Yang

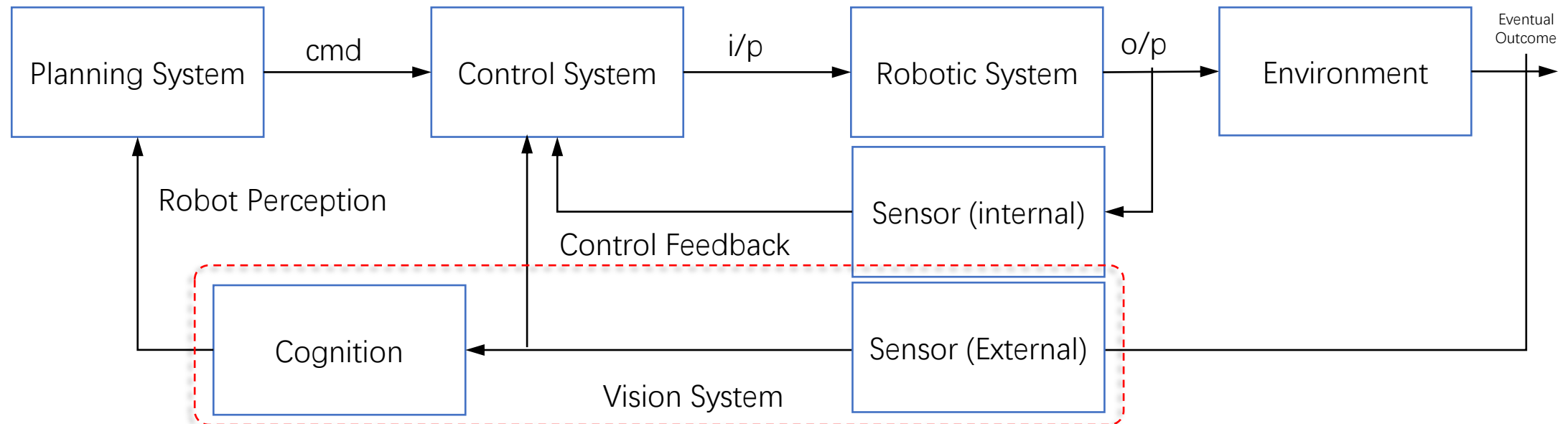
Our Learning Roadmap

• Schedule Check on our Learning Roadmap

O.	Overview	
	• Science & Engineering in Robotics	
I.	Spatial Representation & Transformation	Fundamentals
	• Coordinate Systems; Pose Representations; Homogeneous Transformations	Week 1-4
II.	Kinematics	
	• Multi-body frame assignment; D-H Convention; Joint-space; Work-space; Forward/Inverse Kinematics	Revision/ Quiz on Week 5
III.	Velocity Kinematics and Static Forces	
	• Translational/Rotational Velocity; Joint torque; Generalized Force Coordinates; Jacobian; Singularity	
IV.	Dynamics	Essentials
	• Acceleration of Body; Newton-Euler Equations of Motion; Lagrangian Formulation	
V.	Control	Week 6-9
	• Closed-Loop Control and Feedback, Control of 2 nd order system, Independent Joint Control, Force Control	Revision/ Quiz on Week 10
VI.	Planning	
	• Joint-Based Scheme; Cartesian-Based Scheme; Collision Free Path Planning	
	VII. Robot Vision (Perception)	Applied
	• Image Formation; Image Processing; Visual Tracking & Pose Estimation; Vision-based Control & Image-guided robotics	Week 11-14
		Reading Wk/ Exam on Week 15-16

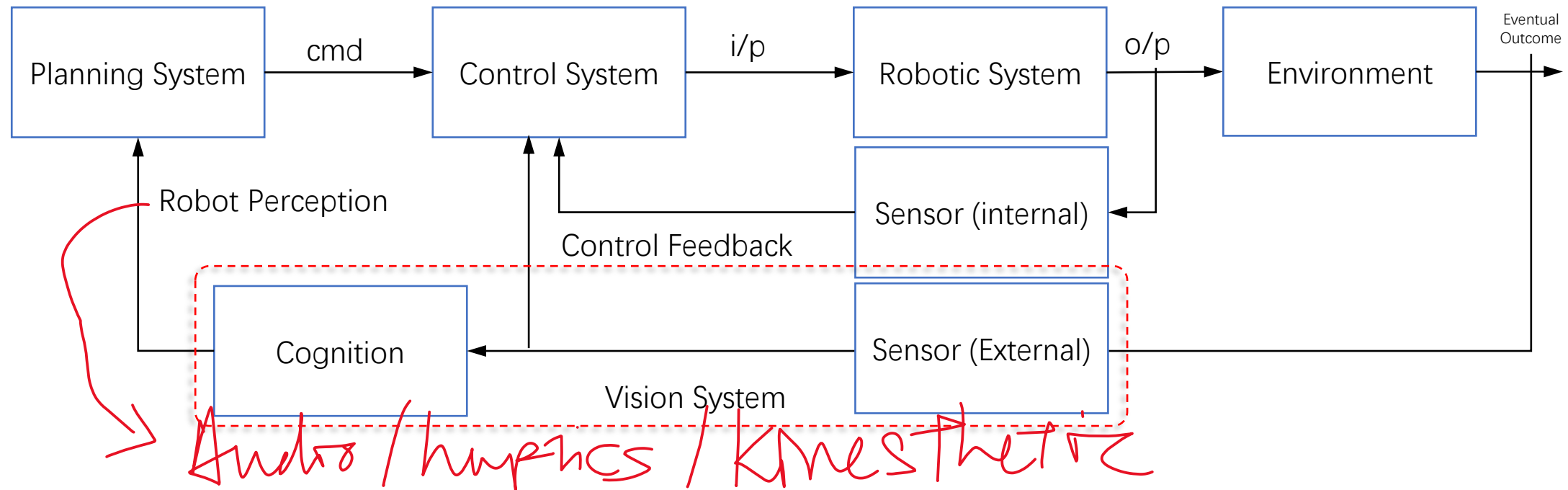
Robot Vision: Closing the final loop

- Model **kinematics** and **dynamics** of the robotic system
- Design **control** for appropriate input to achieve desired outcome
- **Planning system** to send the command to **control** system
- **Perceive** and interact with environment to achieve goal



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Overview of Robot Vision

✓ O. Introduction to Robot Vision

- What is Robot Vision? Imparting robots the capability of making sense of the scene

➔ I. Image Formation

- The science behind computer/machine vision

➔ II. Image Processing

- Common techniques to manipulate, enhance & analyse images

III. Robot Vision Applications

- 3D Vision; Photogrammetry → *obtaining info on physical objects or environment using photography* Vision-based techniques in robotics- visual servo, pose estimation, localization, mapping, navigation

Image Formation

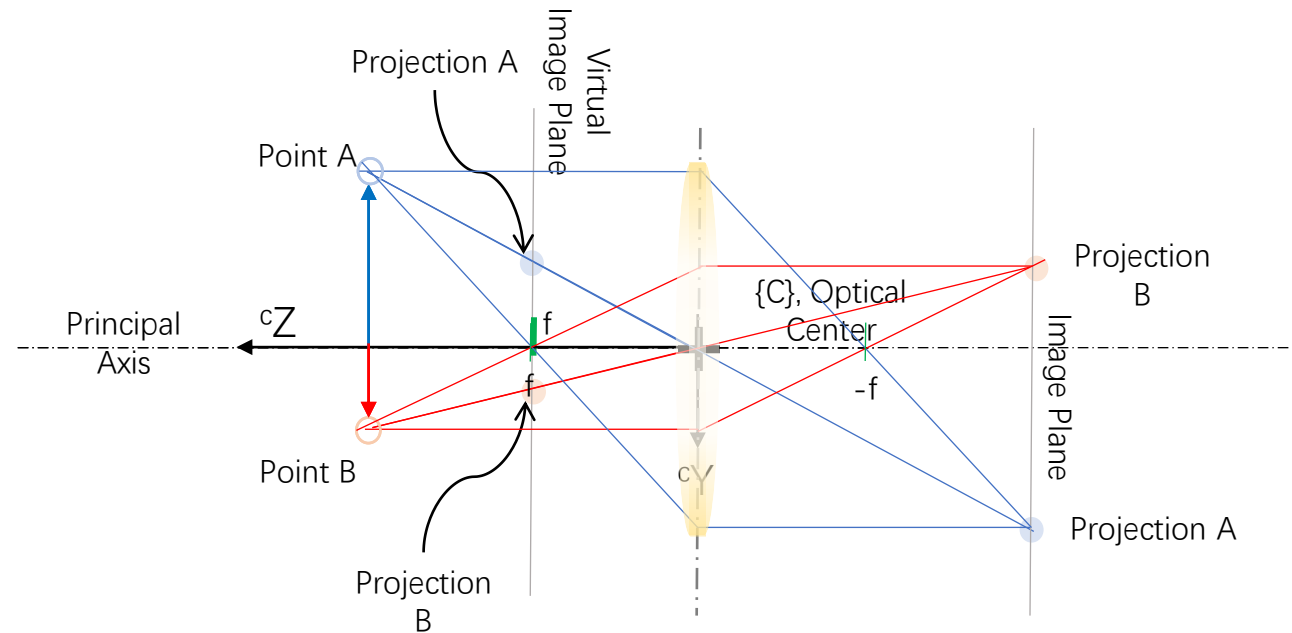
ECE 470 Introduction to Robotics

Image Formation

- Camera Model
 - How is image formed?
- Imaging System
 - How is it acquired?
- Digital Image Representation
 - How is it represented in computer?

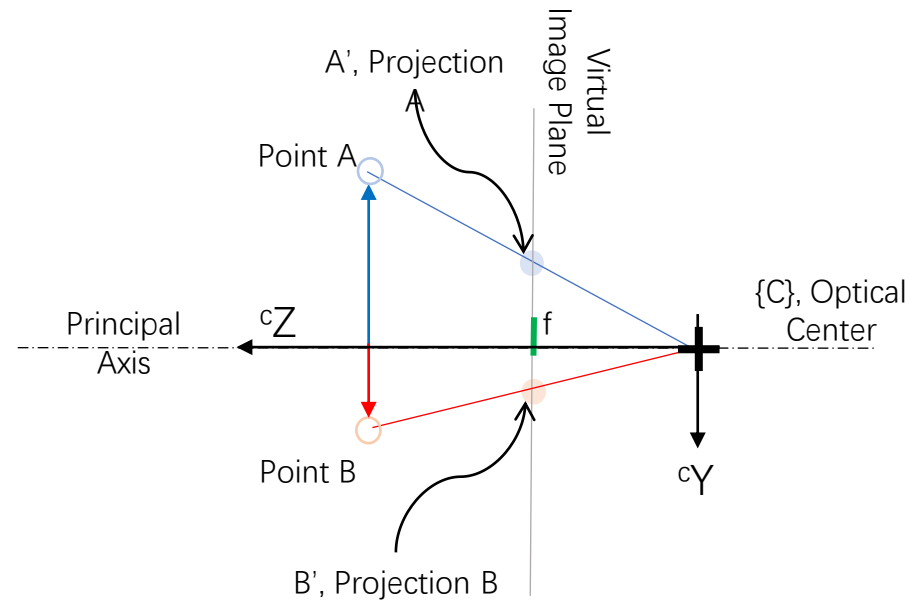
Camera Model


- Central Projection Camera Model
 - A simplified model for camera geometry



Camera Model

- Central Projection Camera Model
 - A simplified model for camera geometry



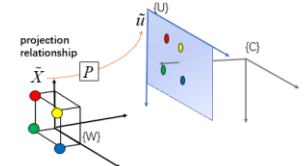
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Camera Model

- Camera Matrix, P
 - Relates world with image coord. System
 - 2 Components:
 - Extrinsic Matrix
 - Intrinsic Matrix

Camera Matrix, P
For a given set of points
 $^w X$ in 3D,
the projected set of points can be expressed as
 $u = P^w X$.

where $P = K [R | t]$,
 K = intrinsic matrix
 $[R | t]$ = extrinsic matrix



Computer Vision System Components

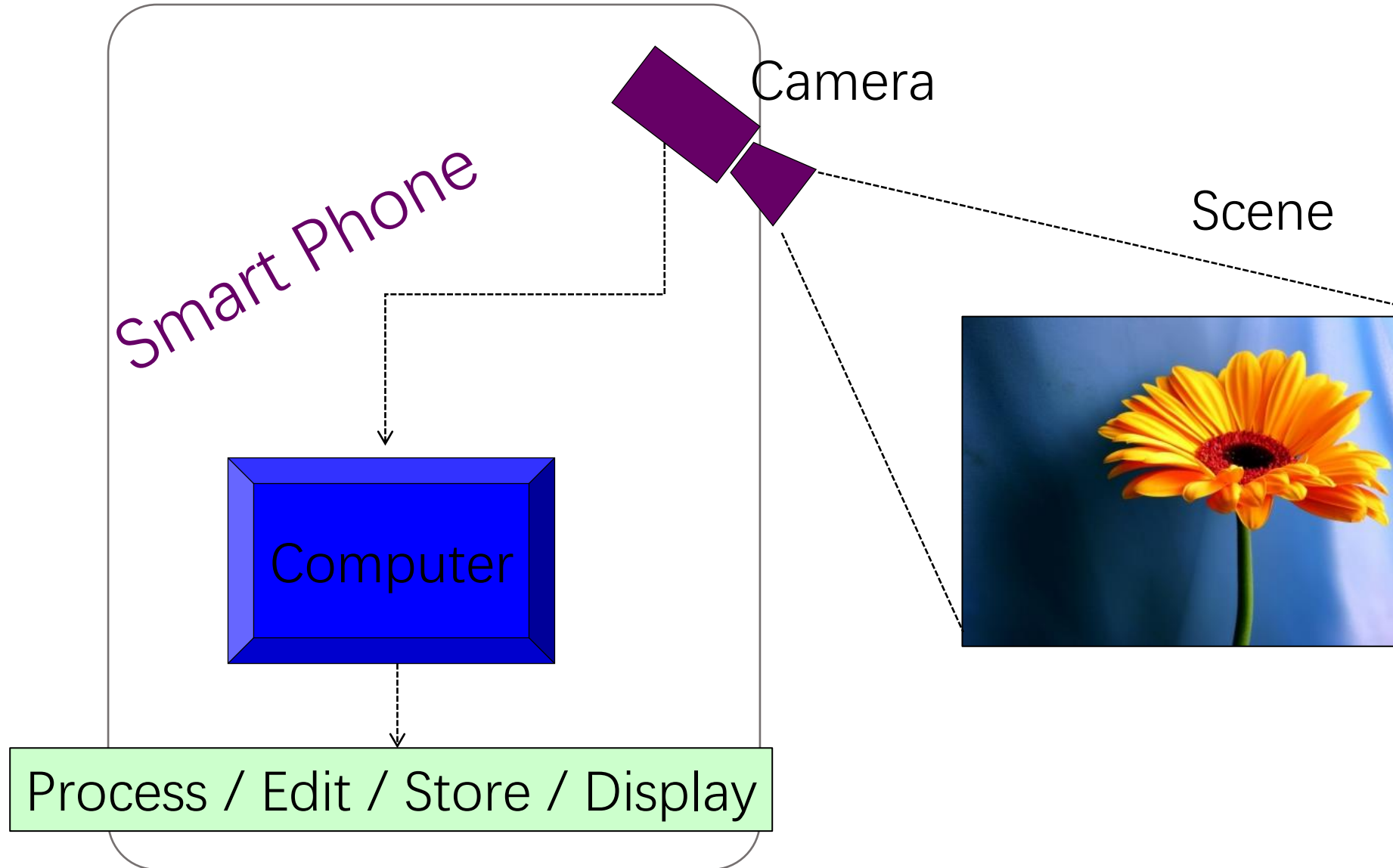


Image Representation

- Digital Image
- $N \times M$ Array of Pixels ()
 - Pixel Position ()
 - Pixel Values ()

Matrix \rightarrow Size \rightarrow Index \rightarrow Intensity

pixel (picture elem)
 \rightarrow elements in array

$I(i,j) = X$
 $0 \leq X \leq 255$
Black, $X=0$
White, $X=255$

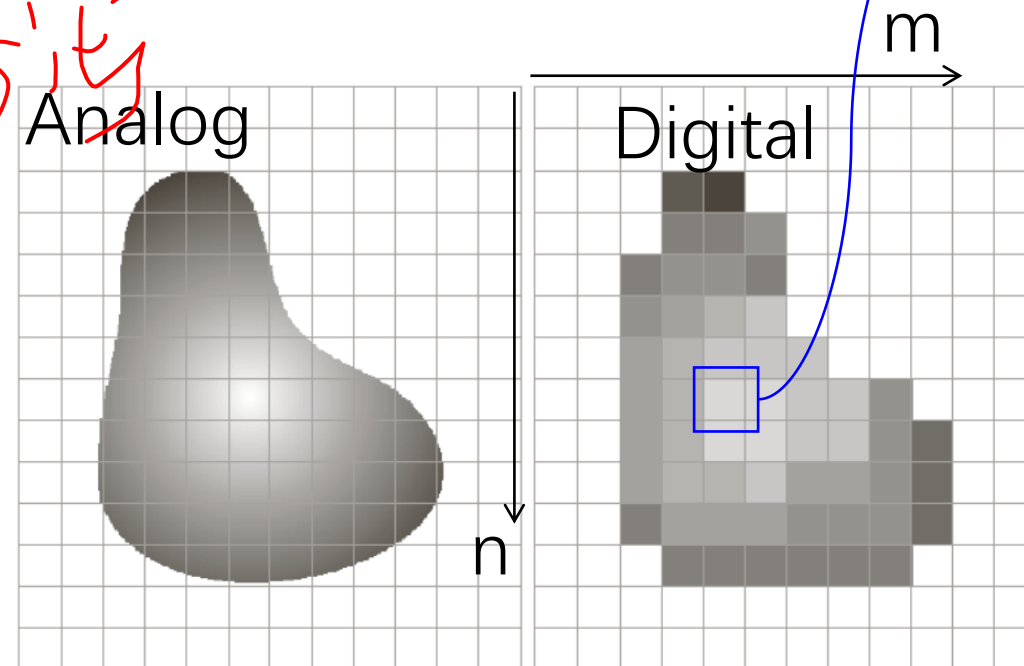
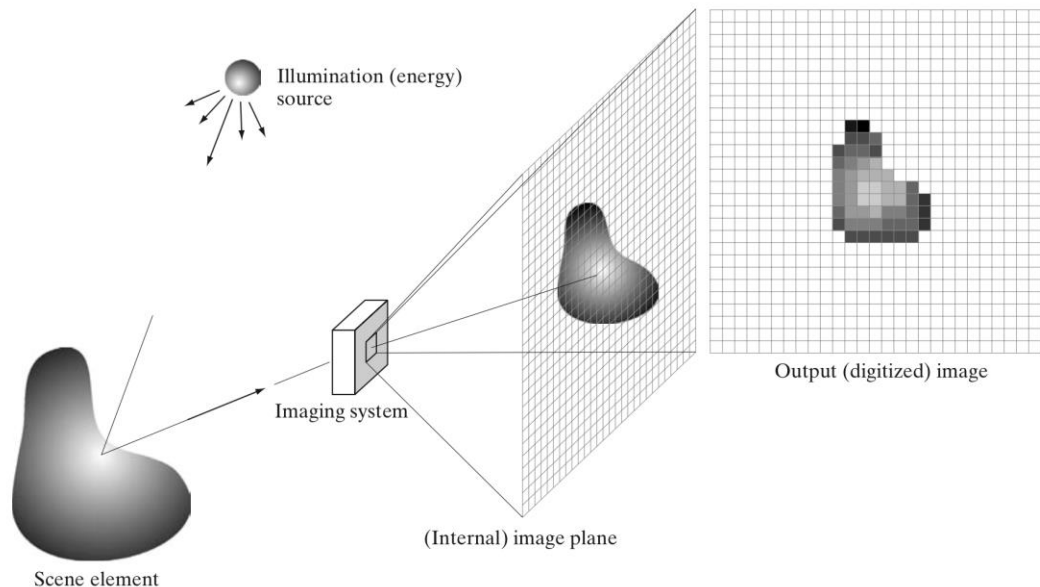


Image Representation

- Digital Image
- $N \times M$ Array of Pixels (Image size; 2D matrix)
 - Pixel Position (Coordinates)
 - Pixel Values (Intensity)

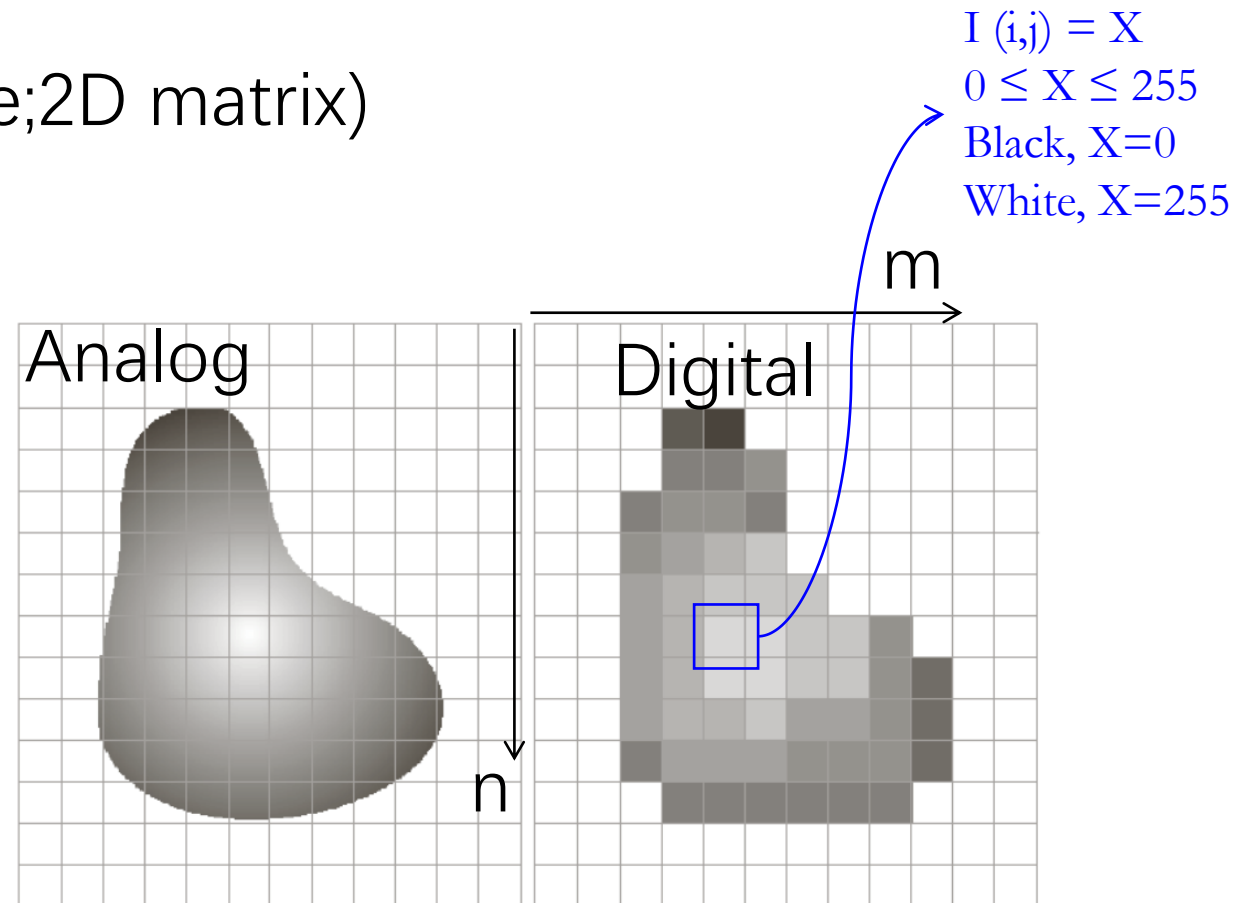
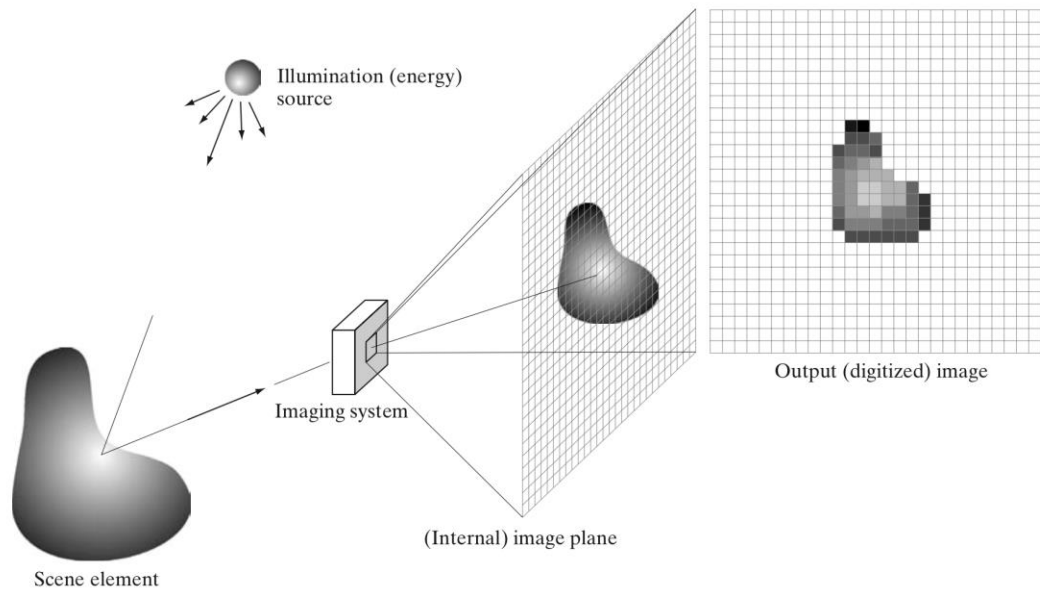
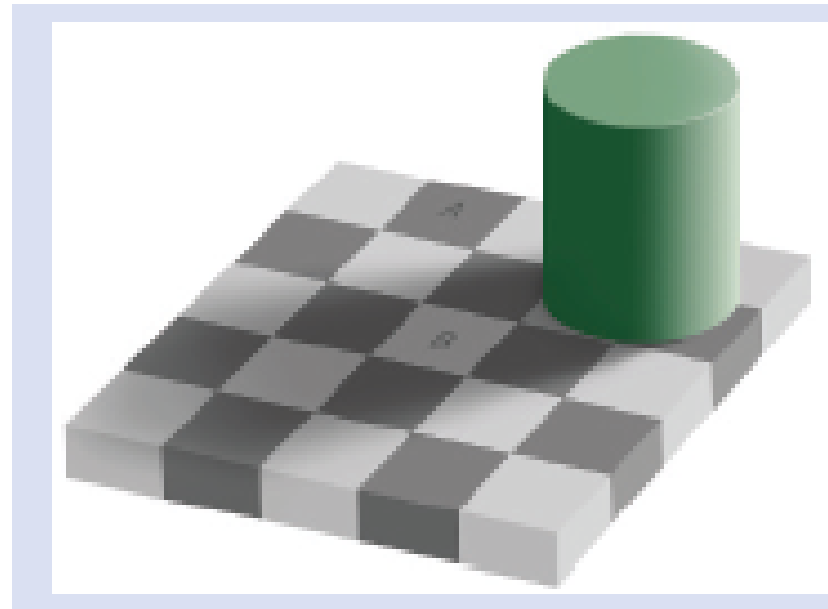


Image Representation

Which region of pixels have higher intensity values?
A or B?

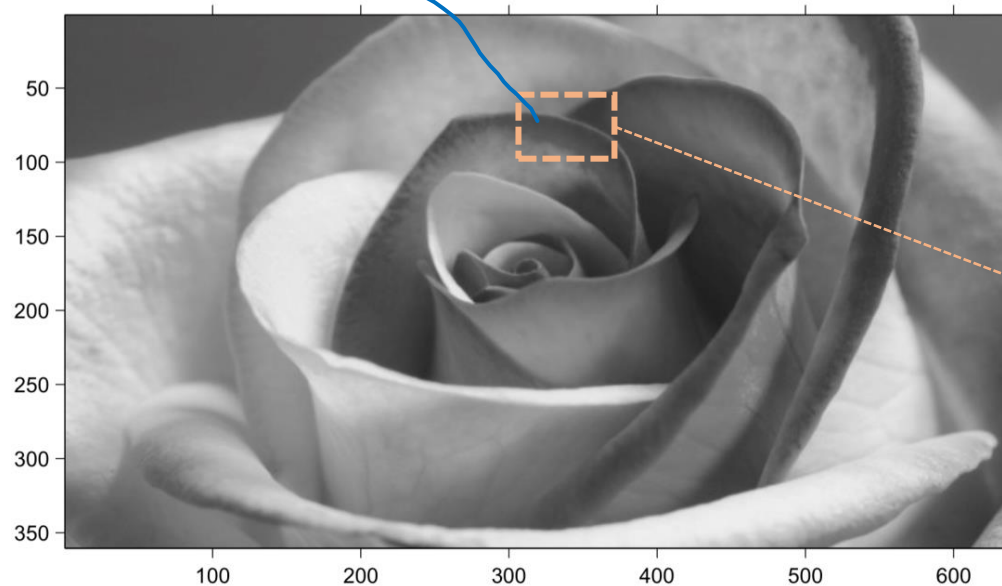


Computer Interpretation of Images

Region of interest
ROI

Gray scale Images

Image

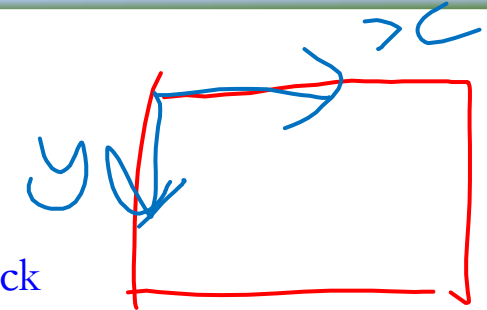


Intensity, $I(i,j)$

j →

i	345	346	347	348	349	350	351	352	353	354	355
70	67	64	61	61	60	59	60	61	60	59	59
71	74	69	65	63	63	61	60	60	61	60	59
72	86	79	72	70	68	66	64	63	63	62	61
73	96	97	94	87	81	77	72	67	66	64	62
74	75	83	91	97	98	95	88	81	69	65	63
75	72	74	75	78	84	93	101	104	92	84	75
76	68	68	68	69	73	81	88	92	101	101	96
77	67	67	67	69	71	72	73	74	81	94	102
78	69	67	65	66	67	68	71	74	73	80	85
79	67	67	68	69	70	68	67	68	74	74	71
80	70	69	68	68	67	66	66	69	70	70	73

0 = black
gray
255 = white



Matlab Commands:

`img_gray=rgb2gray(img1);`

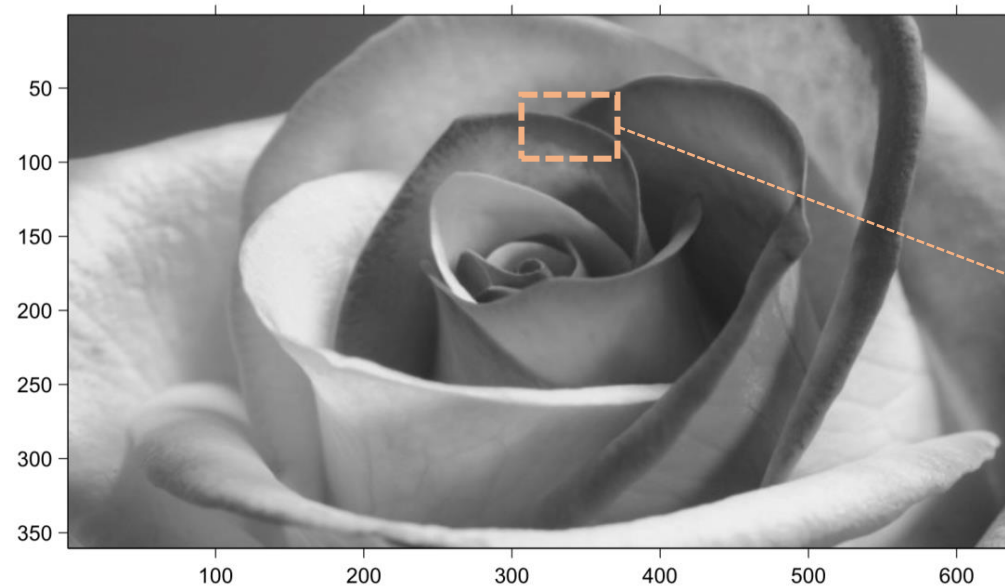
`imshow(img_gray)`

`imsub_gray=img_gray(40:80,345:355);` – for printing intensity matrix

Computer Interpretation of Images

Gray scale Images

Image



Intensity, $I(i,j)$

	$j \longrightarrow$										
$i \downarrow$	345	346	347	348	349	350	351	352	353	354	355
70	67	64	61	61	60	59	60	61	60	59	59
71	74	69	65	63	63	61	60	60	61	60	59
72	86	79	72	70	68	66	64	63	63	62	61
73	96	97	94	87	81	77	72	67	66	64	62
74	75	83	91	97	98	95	88	81	69	65	63
75	72	74	75	78	84	93	101	104	92	84	75
76	68	68	68	69	73	81	88	92	101	101	96
77	67	67	67	69	71	72	73	74	81	94	102
78	69	67	65	66	67	68	71	74	73	80	85
79	67	67	68	69	70	68	67	68	74	74	71
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```


Example 1: Spatial & Intensity Information

- A gray scale image **I** of our campus has a dimension of 945x1680 shown. A region of interest (ROI) from row 391 to 420 and column 1071 to 1100 is specified to encompass a window in the scene with an array of intensity values. This ROI is denoted as $I_{ROI} = \mathbf{I}(\text{ROI_array})$.



Example 1: Spatial & Intensity Information

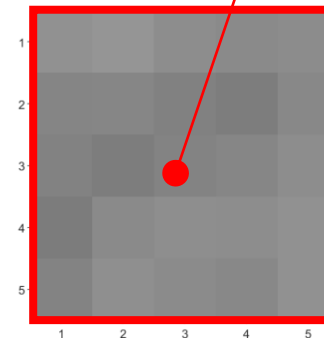
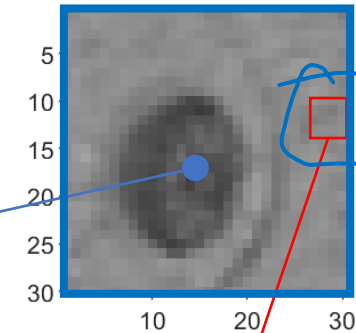
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→ Column
↓ row



	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	
1	134	140	148	150	148	145	143	141	141	141	139	141	146	146	142	132	131	132	143	150	152	143	139	146	144	138	137	139	137	135	
2	144	145	142	149	144	143	143	142	144	138	133	130	147	147	145	139	137	133	138	143	148	144	140	139	136	135	138	140	142	136	
3	151	146	138	138	143	143	146	143	138	135	132	143	147	142	137	137	137	139	140	143	149	146	147	143	146	147	149	145	146	146	
4	146	139	130	127	136	143	146	136	132	135	138	141	140	142	146	144	135	130	129	136	143	151	152	149	139	141	145	142	142	145	
5	143	140	131	137	144	139	139	140	137	132	139	139	139	142	146	143	141	146	141	143	147	149	144	139	134	135	140	145	143	134	
6	140	144	145	144	146	141	142	143	144	143	147	143	142	144	142	139	143	151	147	134	126	139	137	144	153	156	148	147	143	140	
7	143	153	144	137	138	142	148	145	145	148	141	137	140	141	136	137	145	151	148	132	132	140	145	151	154	151	148	144	140	143	
8	142	149	137	135	140	142	148	145	139	135	128	126	131	135	134	139	148	150	144	138	137	138	146	145	141	141	148	148	140	132	
9	148	147	141	136	143	145	144	135	128	127	132	124	117	117	122	132	142	145	142	144	138	127	134	136	139	147	156	150	141	135	
10	148	149	144	141	144	141	136	127	125	126	118	114	104	85	71	73	81	118	141	143	145	141	126	131	137	143	145	148	141	138	140
11	147	144	145	139	143	133	125	122	118	104	88	74	66	67	59	45	94	126	142	148	143	134	131	139	138	133	134	129	125	136	
12	144	145	147	147	144	132	130	118	100	86	74	68	73	82	82	81	90	98	120	149	151	140	131	138	137	130	125	131	134	141	
13	142	140	143	146	141	130	121	101	85	79	75	77	75	80	99	87	96	89	117	142	152	140	132	143	140	124	138	142	141	145	
14	142	145	139	135	131	126	109	87	79	77	74	83	82	89	103	96	101	91	105	136	151	137	122	133	139	131	143	139	136	145	
15	140	155	156	138	125	120	103	88	83	77	69	80	100	87	94	103	98	91	93	121	143	139	123	131	143	145	148	141	134	137	
16	142	152	163	147	129	114	94	87	85	80	78	88	108	85	76	83	81	84	106	119	132	132	119	126	141	148	152	152	145	138	
17	145	148	148	139	128	111	87	82	78	74	74	82	91	73	71	75	77	84	93	117	140	138	118	124	138	142	144	148	147	143	
18	142	148	145	130	122	109	85	83	78	68	81	107	85	59	56	89	75	75	82	126	155	143	116	126	144	146	145	144	136	136	
19	134	140	131	121	117	112	86	82	77	76	85	90	78	67	66	87	70	74	112	142	154	144	119	131	148	153	153	143	135	134	
20	141	135	140	132	122	114	93	81	69	72	76	91	90	82	81	73	68	84	111	146	156	140	117	130	146	144	143	140	141	147	
21	150	149	150	141	132	122	97	82	71	70	79	101	96	90	88	78	71	97	121	145	156	133	114	126	145	145	141	142	140	143	
22	145	150	148	133	125	125	109	91	77	74	77	86	89	98	101	97	83	97	129	132	138	122	122	133	139	131	143	139	137	136	
23	142	142	139	127	116	123	124	104	78	69	75	84	97	101	91	92	88	114	143	140	124	110	126	139	138	138	144	149	142	134	
24	150	141	132	133	130	130	119	94	89	65	81	89	94	84	96	106	131	145	151	121	115	134	140	142	141	147	146	141	142	142	
25	146	129	130	140	146	139	132	132	124	98	77	63	73	84	90	117	137	135	141	131	107	120	137	145	149	144	144	138	132	133	
26	136	123	134	142	145	141	137	134	126	132	122	90	80	119	133	126	148	143	131	102	104	126	142	147	144	138	140	136	130	133	
27	148	147	143	140	142	147	146	140	138	141	150	146	141	145	147	144	144	142	118	107	126	147	145	139	137	136	140	139	133	133	
28	146	153	141	140	143	148	147	143	140	140	143	142	136	144	149	149	145	121	113	123	125	141	142	138	137	144	145	144	138	139	
29	133	134	138	138	140	143	145	146	142	137	135	130	128	130	152	149	126	110	123	137	144	144	143	143	145	146	141	145	145	148	
30	137	133	145	143	140	138	140	146	147	140	136	131	137	138	138	129	118	127	139	144	146	149	144	139	141	136	140	144	145	147	

Computer Interpretation of Images

Let us see how computer handles this image

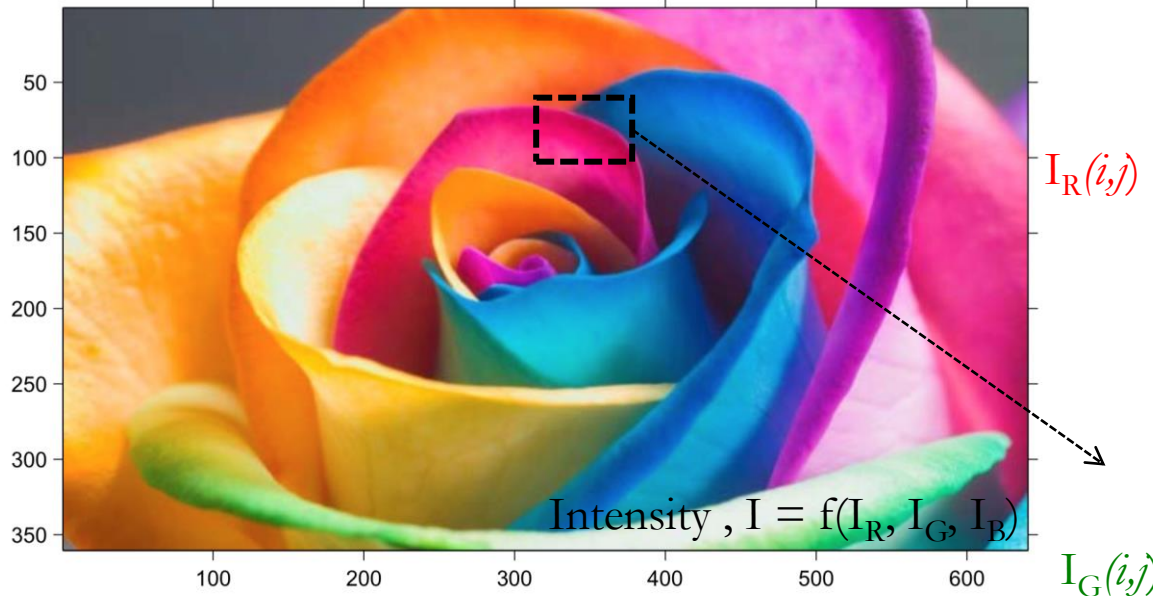


Matlab Commands:

```
img1=imread('filename.ext', 'ext');  
imshow(img1)
```


Computer Interpretation of Images

Color Images (RGB)



Matlab Commands:

`imshow(img1)`

`red=img1(:,:,1)`

`Isub_red=red(70:80,345:355,:)` – for printing
intensity matrix of red

$N \times M \times 3$

$j \longrightarrow$

	345	346	347	348	349	350	351	352	353	354	355
70	57	50	43	40	36	34	33	32	26	24	25
71	87	70	58	49	45	39	36	31	25	22	25
72	134	114	94	81	69	59	51	42	31	26	29
73	191	181	164	140	117	98	80	61	45	35	34
74	197	198	193	185	171	152	133	109	77	62	56
75	201	200	197	194	193	195	198	185	151	125	103
76	197	197	197	197	201	207	213	208	199	181	159
77	194	194	193	195	199	201	205	204	207	210	202
78	199	194	190	191	194	197	203	209	208	213	207
79	197	196	198	199	199	196	193	194	203	204	201
80	205	202	199	199	195	191	189	194	199	202	208

	345	346	347	348	349	350	351	352	353	354	355
70	64	63	61	62	62	62	63	65	66	66	65
71	60	60	60	62	63	63	62	65	69	69	65
72	55	54	53	56	59	60	61	64	69	70	67
73	42	48	52	53	55	58	59	61	67	69	66
74	8	20	34	46	54	58	57	58	56	57	57
75	3	6	9	14	23	35	45	55	54	55	52
76	0	0	0	0	4	12	19	27	44	53	57
77	0	0	0	2	3	3	1	3	11	29	45
78	1	0	0	0	0	0	0	2	0	7	18
79	0	0	0	1	2	1	0	1	5	4	1
80	0	0	0	0	0	0	1	3	2	0	1

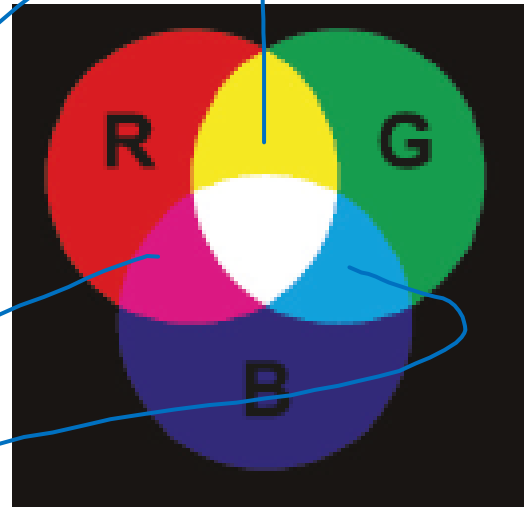
	345	346	347	348	349	350	351	352	353	354	355
70	110	108	107	109	111	112	115	116	115	114	116
71	113	110	108	107	111	111	113	113	114	113	114
72	121	116	111	111	112	114	114	114	114	115	114
73	126	127	126	122	120	120	118	115	116	115	113
74	98	108	118	127	132	132	129	125	115	113	111
75	90	92	96	103	112	125	136	141	133	127	118
76	79	81	83	87	96	106	116	124	136	136	133
77	76	77	79	83	89	91	96	99	109	124	134
78	78	75	73	76	78	83	89	93	94	105	110
79	73	71	73	78	81	80	81	84	92	93	90
80	79	74	73	74	75	74	77	81	84	84	89

$I_B(i,j)$

Computer Interpretation of Images

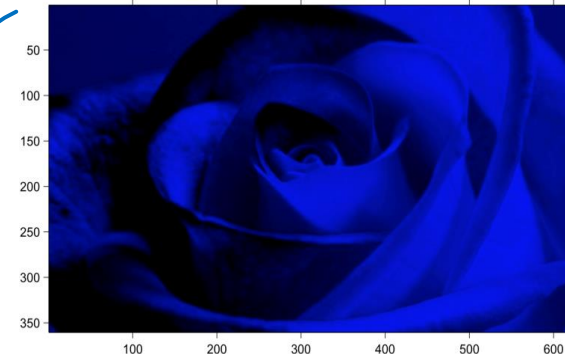
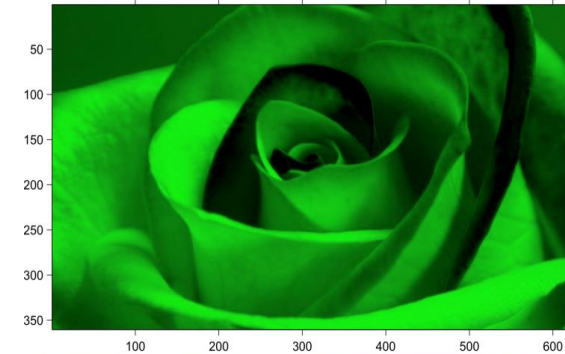
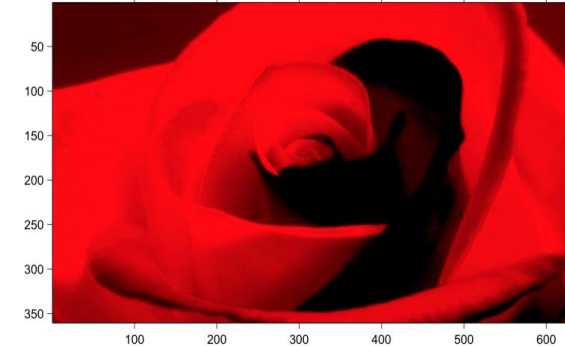
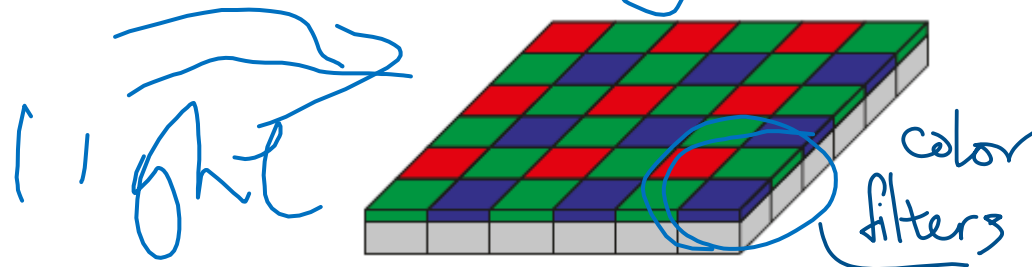
primary
colors

Color Images (RGB)



secondary
colors

array of sensor



Computer Interpretation of Images

Color Images (RGB)

Matlab Commands:

```
imshow(img1)
```

```
red=img1(:,:,1)
```

```
green=img1(:,:,2);
```

```
blue=img1(:,:,3);
```

```
a=zeros(size(img1,1),size(img1,2));
```

```
only_red=cat(3,red,a,a)
```

```
imshow(only_red)
```

```
only_green=cat(3,a,green,a)
```

```
imshow(only_green)
```

```
only_blue=cat(3,a,a,blue)
```

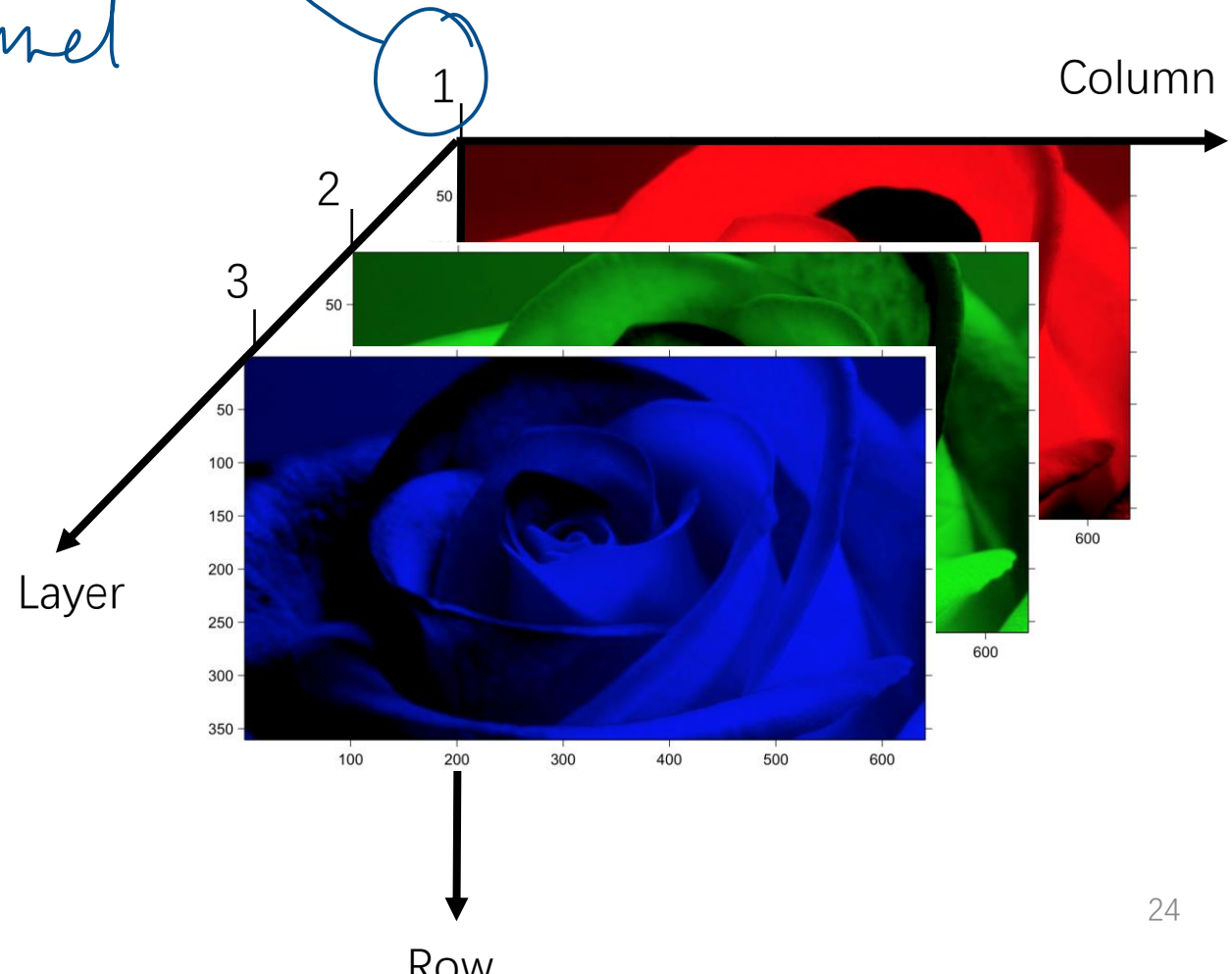
```
imshow(only_blue)
```

ends:
ng1)

channel
red layer

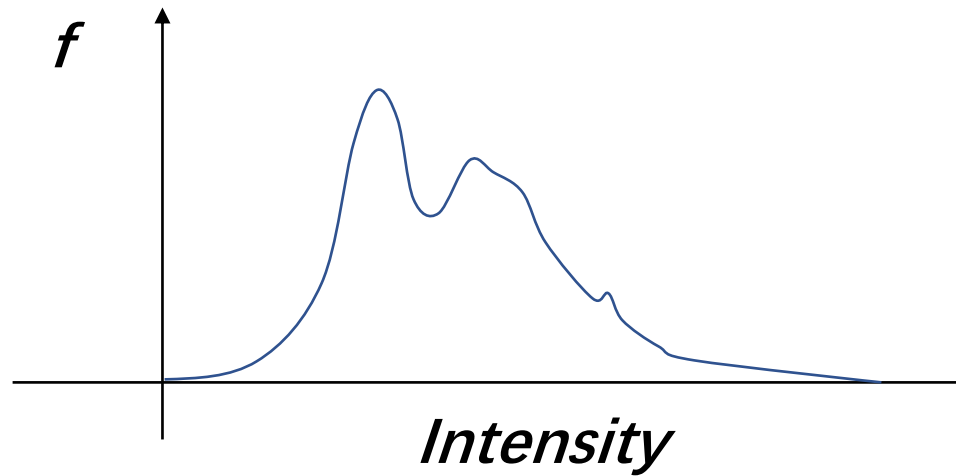
red layer
2); → green layer
); → blue layer

→ red layers



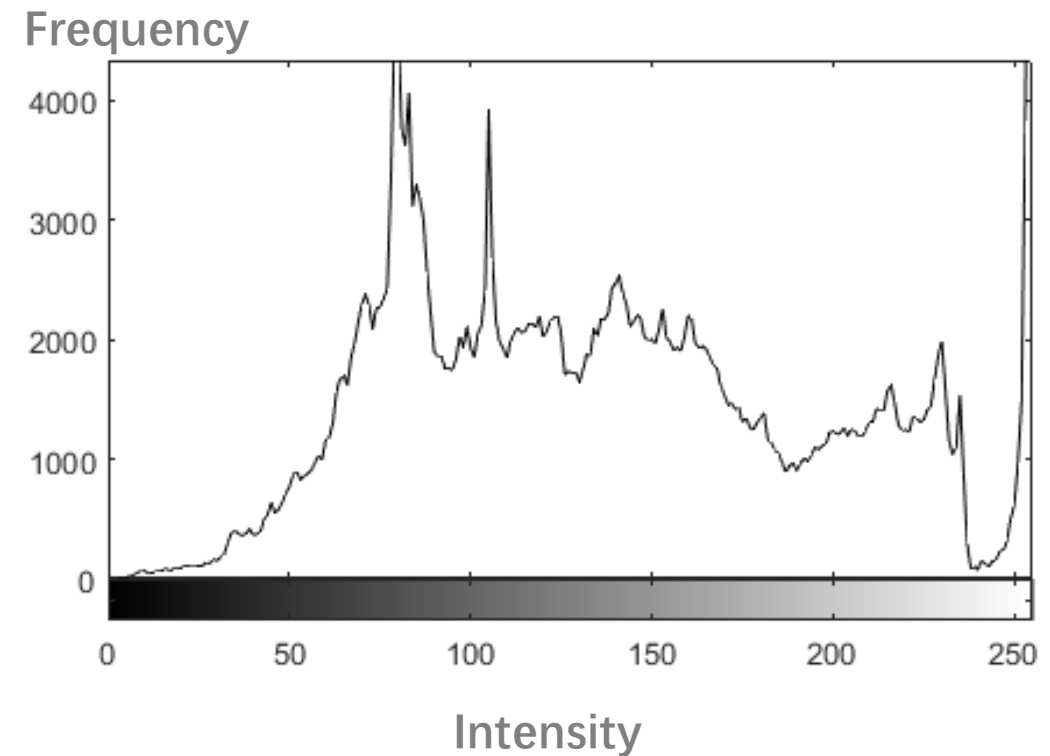
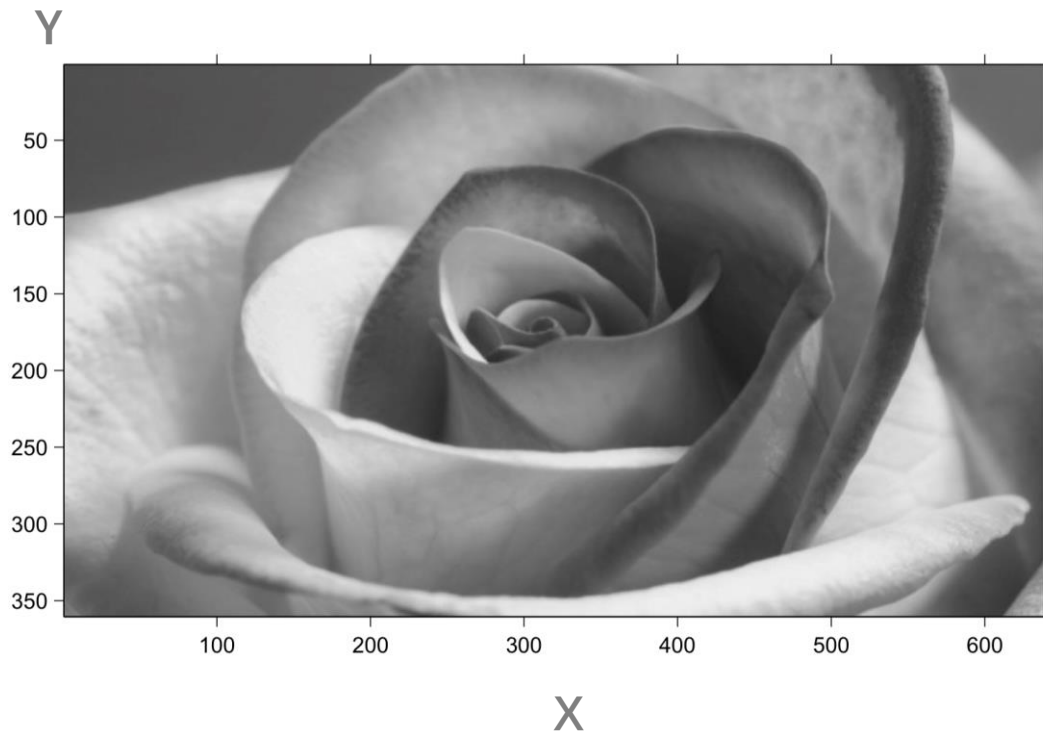
Histogram

- Distribution of the intensity levels



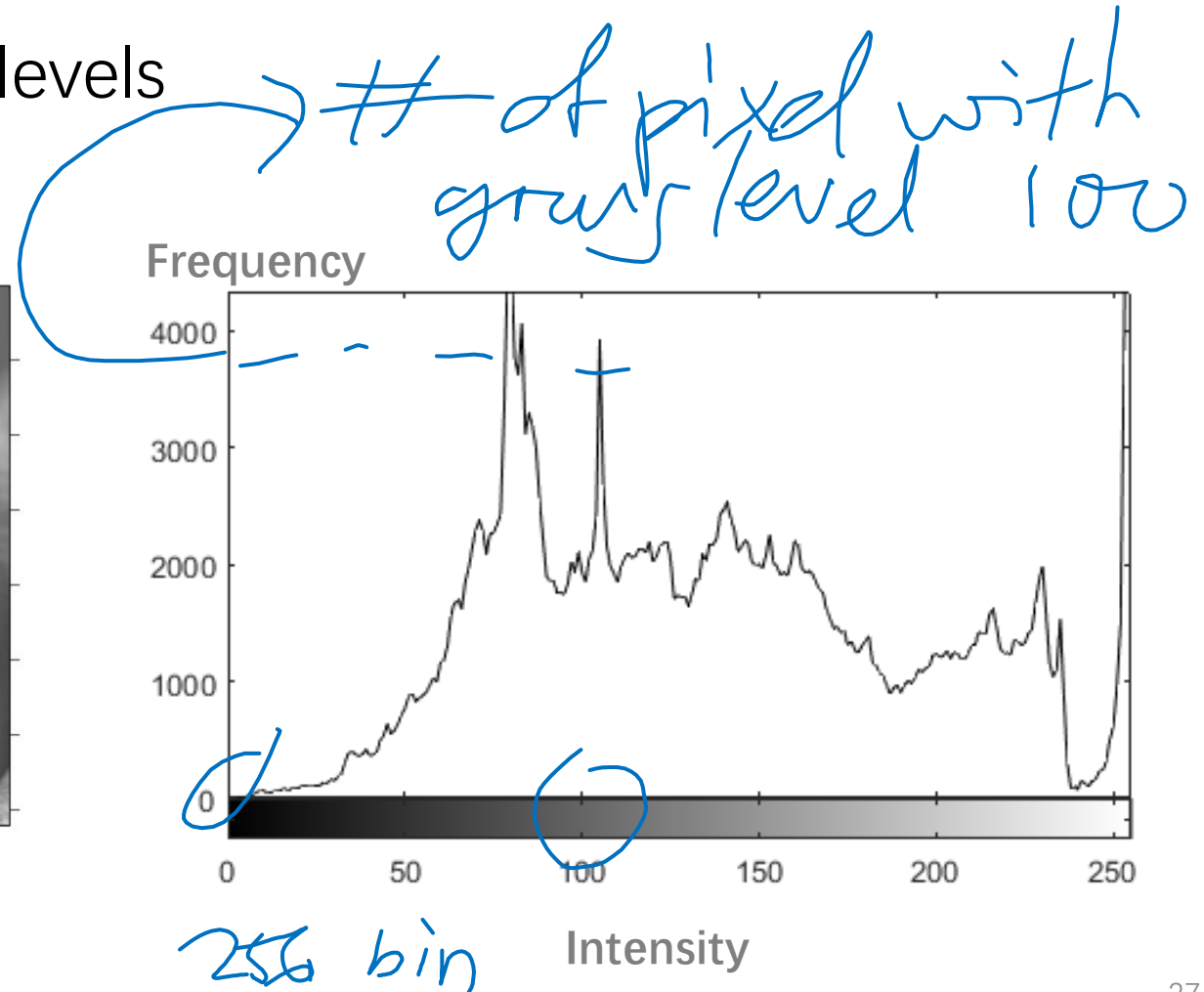
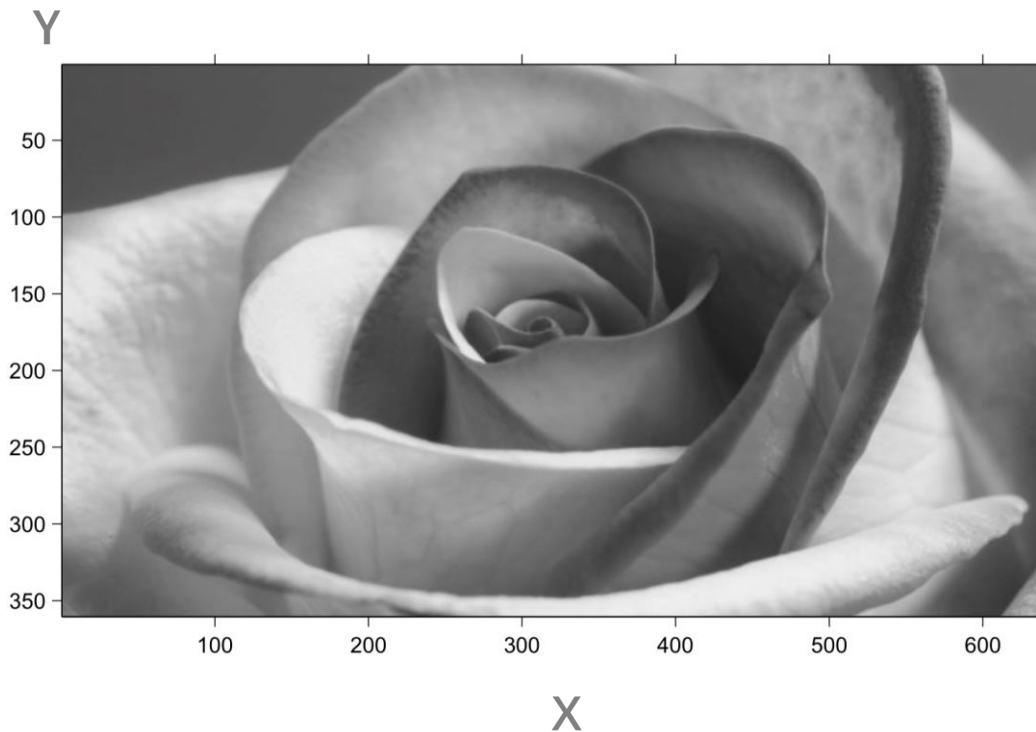
Histogram

- Distribution of the intensity levels

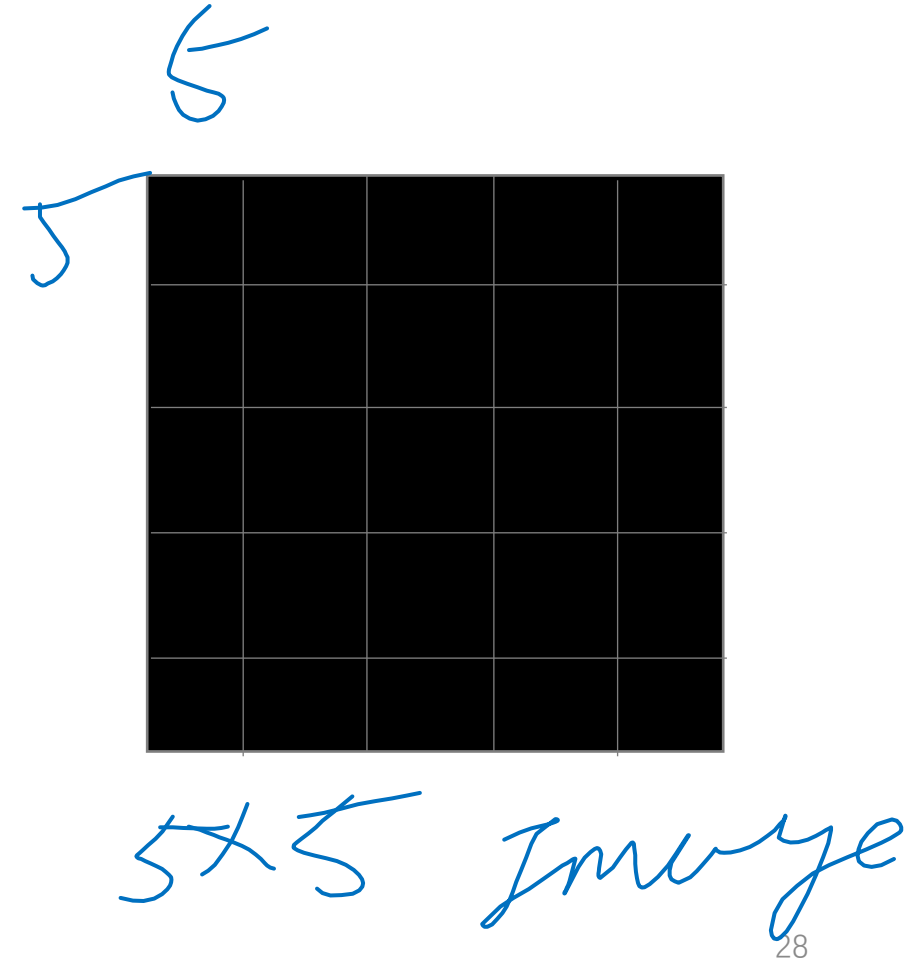
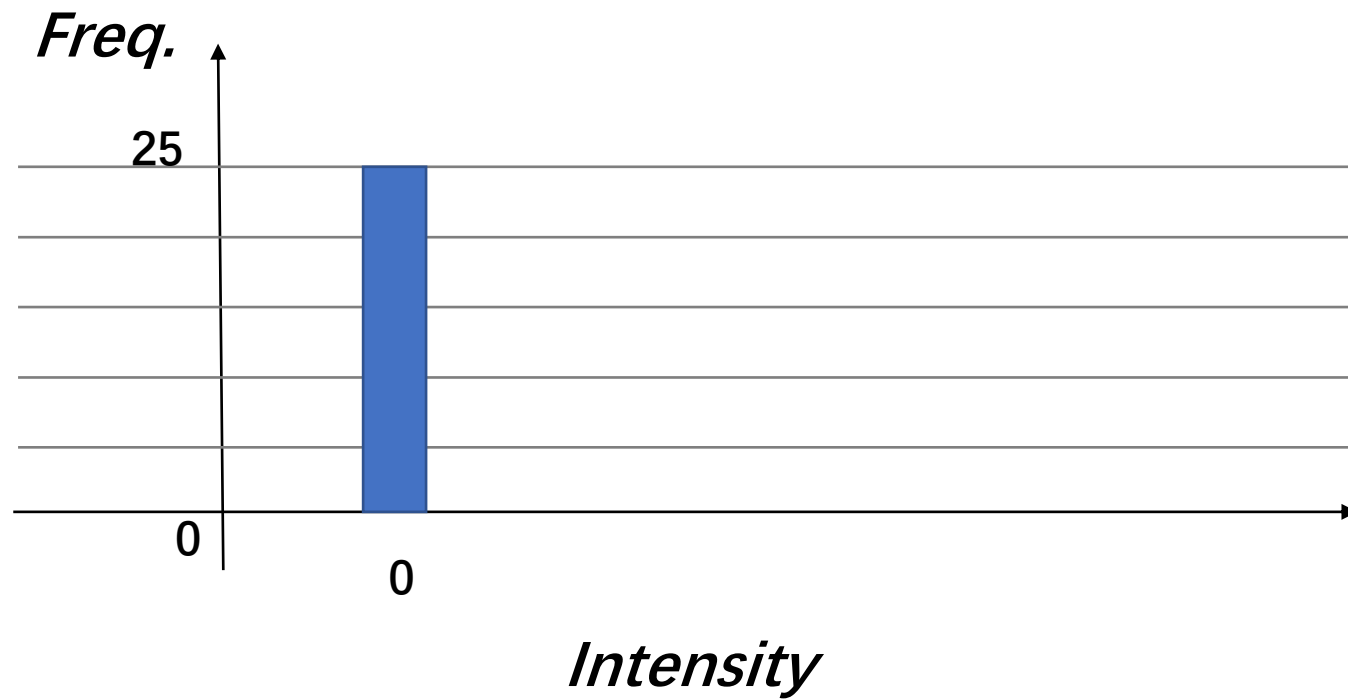


Histogram

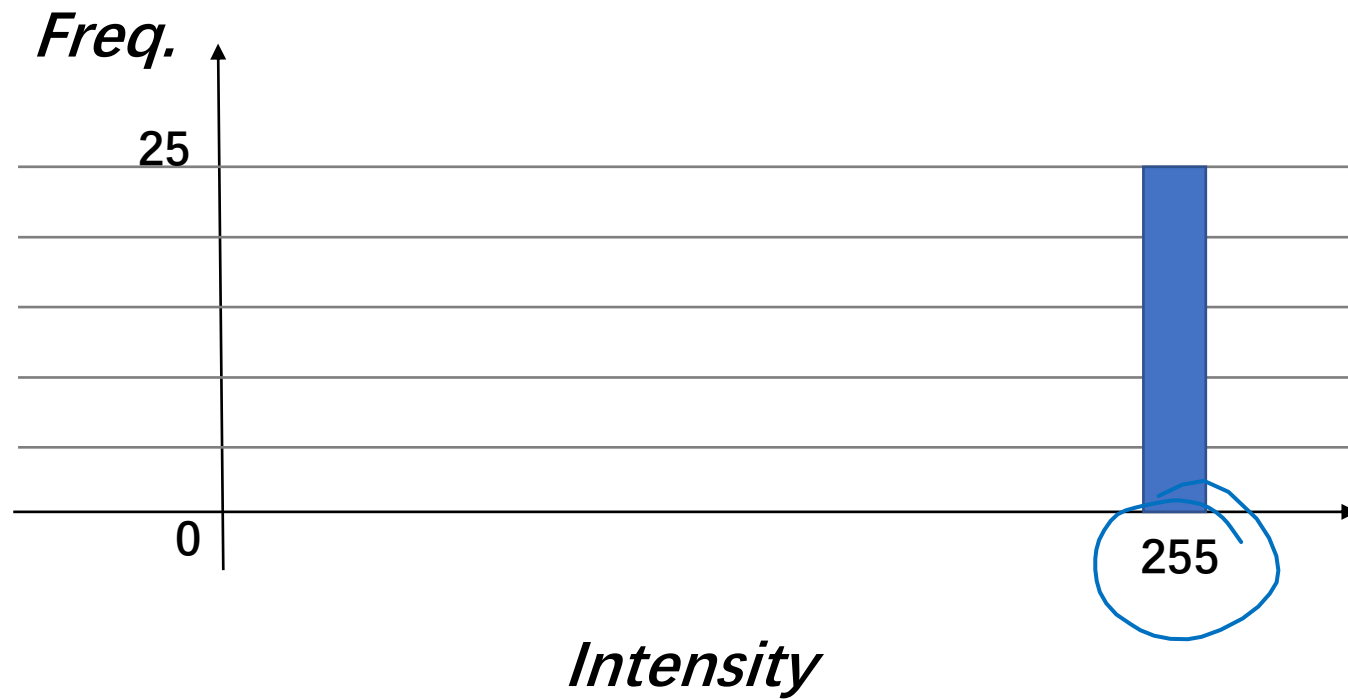
- Distribution of the intensity levels



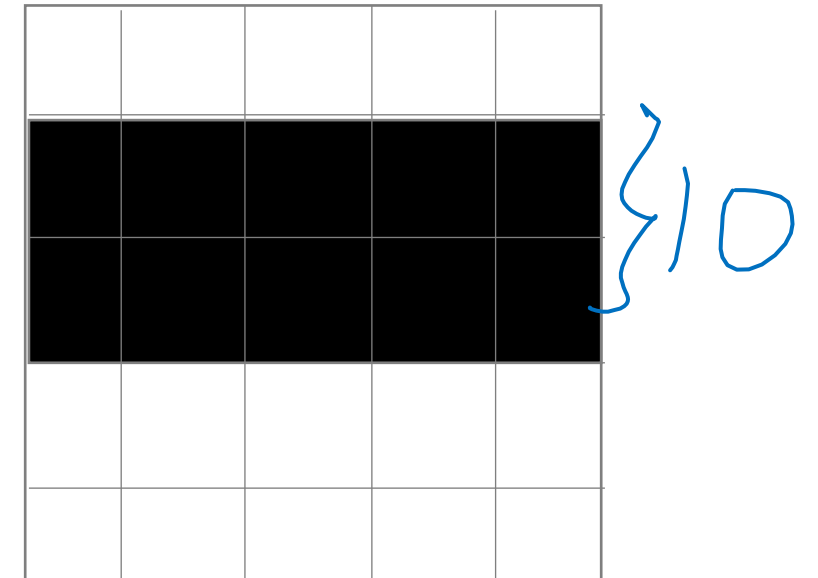
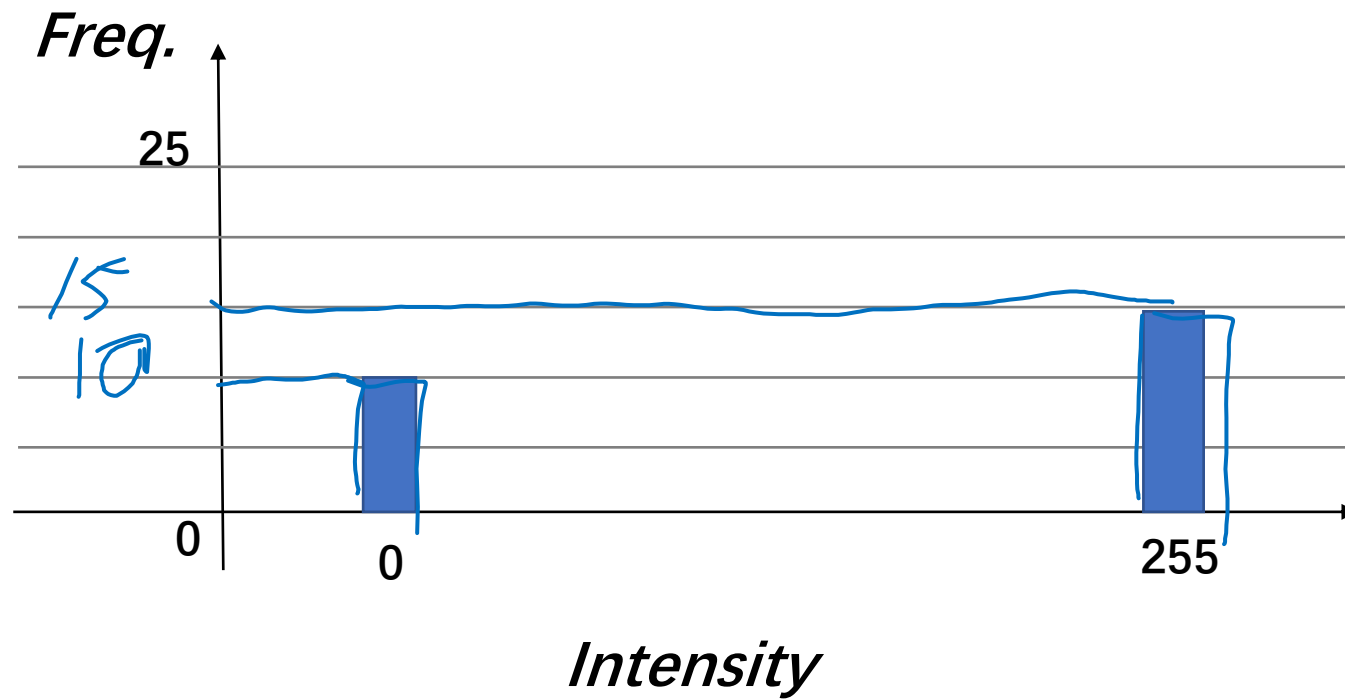
Histogram



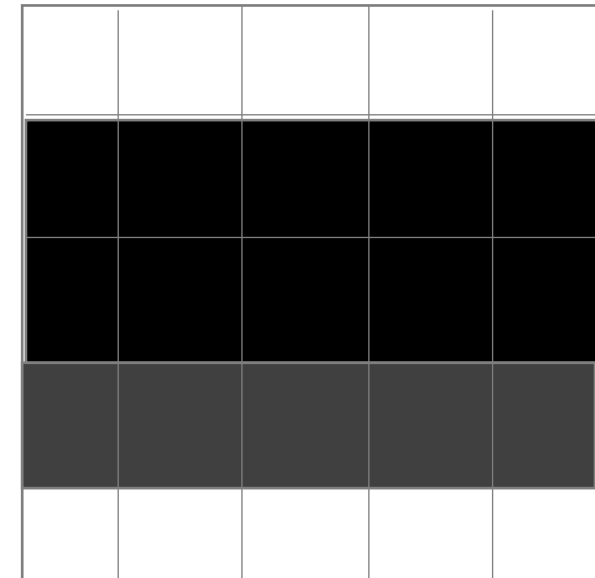
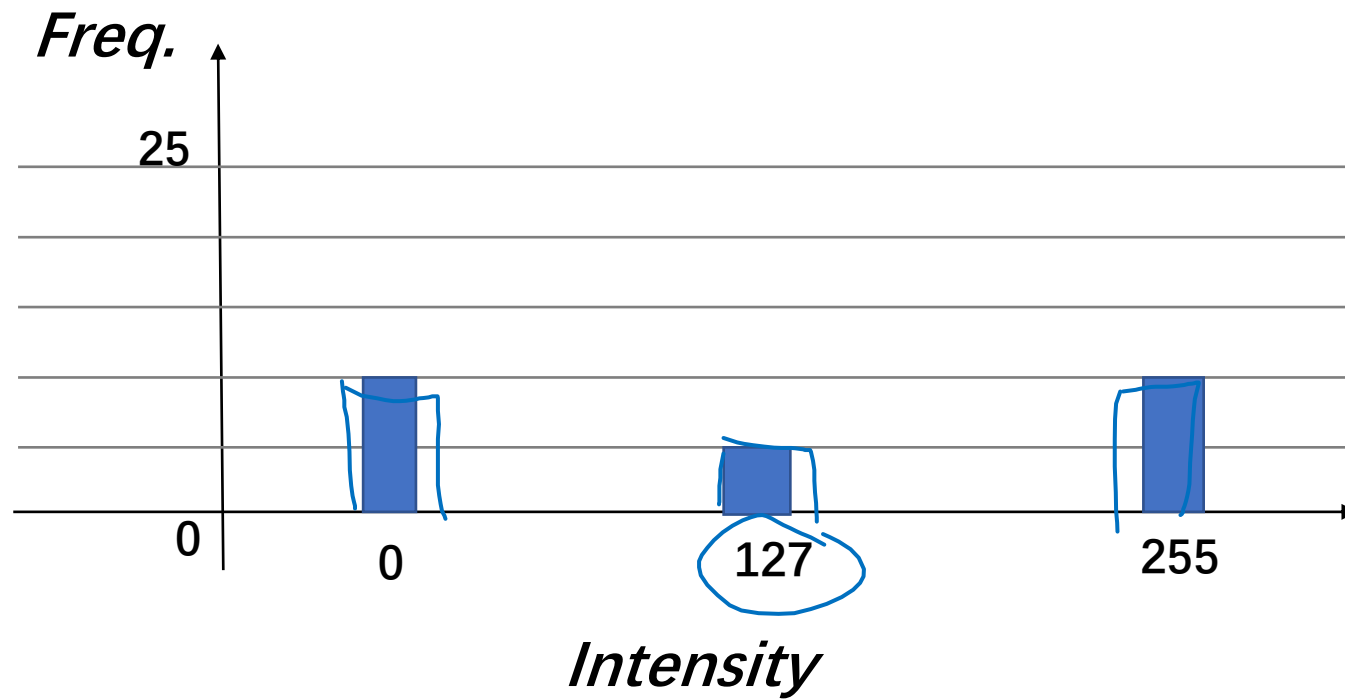
Histogram



Histogram

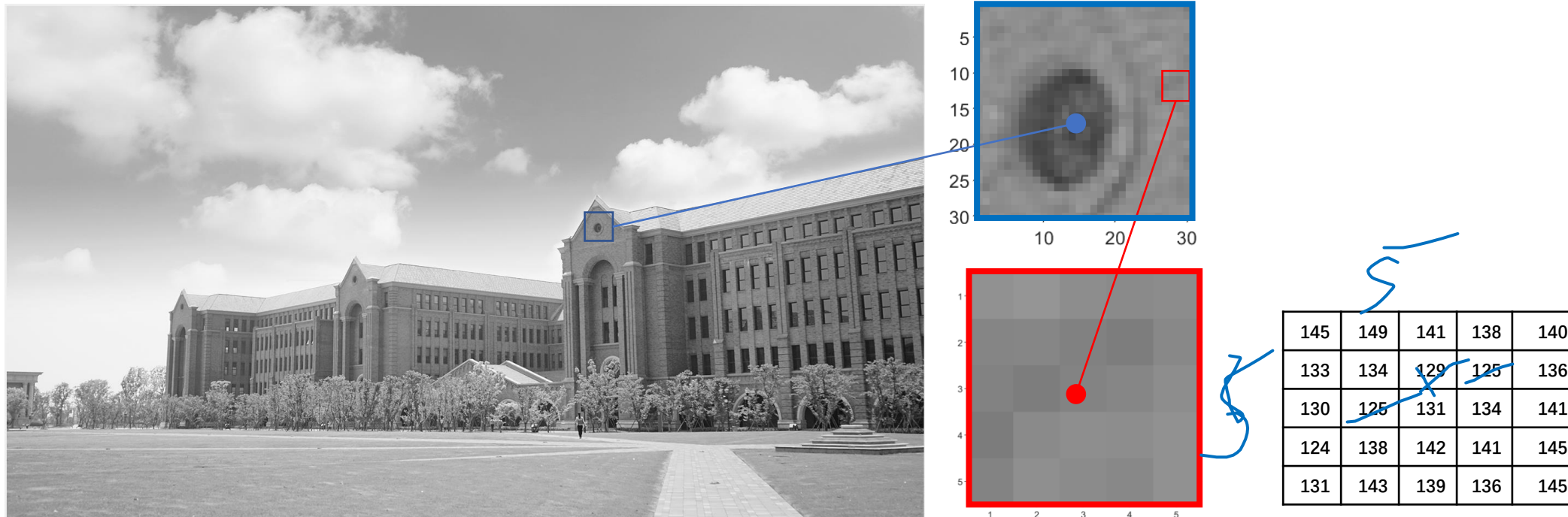


Histogram



Example 2: Histogram Representation

For a 5x5 sub-region $I_{\text{subROI}} = I_{\text{ROI}}(10:14, 26:30)$,



Gray Value

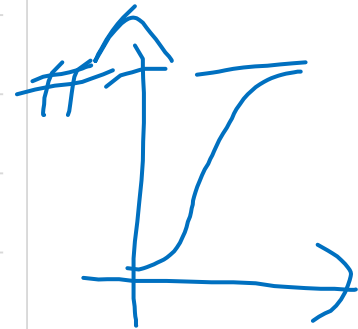
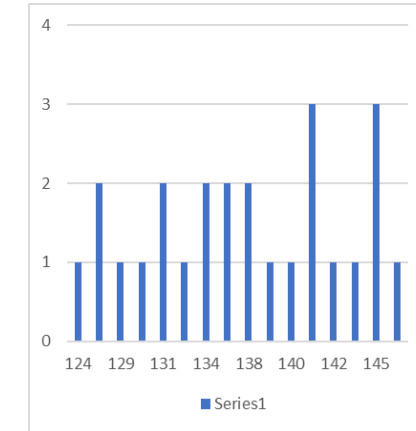
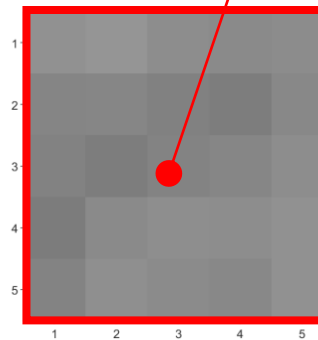
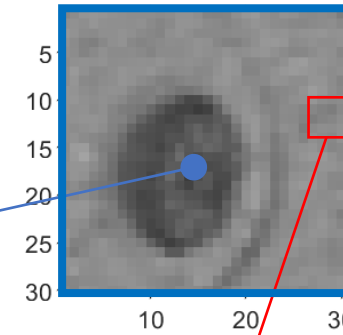
of occurrence

cumulative # of occurrence

Gray Value	124	125	129	130	131	133	134	136	138	139	140	141	142	143	145	149
# of occurrence	1	2	1													
cumulative # of occurrence	1	3	4													

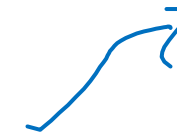
Example 2: Histogram Representation

For a 5x5 sub-region $I_{\text{subROI}} = I_{\text{ROI}}(10:14, 26:30)$,

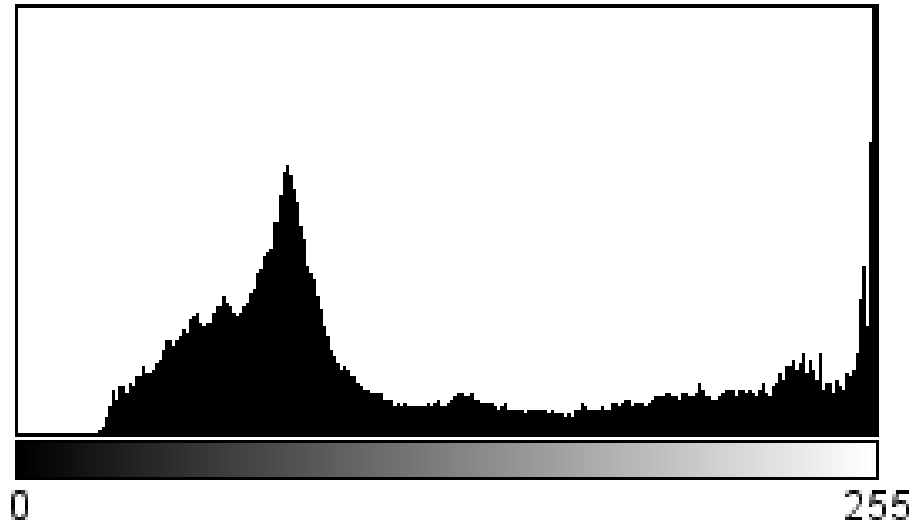


145	149	141	138	140
133	134	129	125	136
130	125	131	134	141
124	138	142	141	145
131	143	139	136	145

Gray Value	124	125	129	130	131	133	134	136	138	139	140	141	142	143	145	149
# of occurrence	1	2	1	1	2	1	2	2	2	1	1	3	1	1	3	1
cumulative # of occurrence	1	3	4	5	7	8	10	12	14	15	16	19	20	21	24	25



Histogram



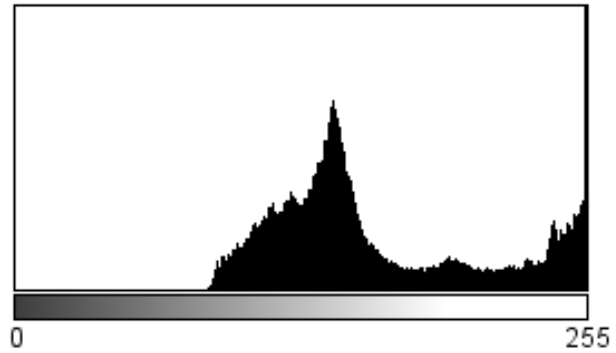
Count: 153436
Mean: 124.213
StdDev: 72.364

Min: 21
Max: 255
Mode: 255 (4159)

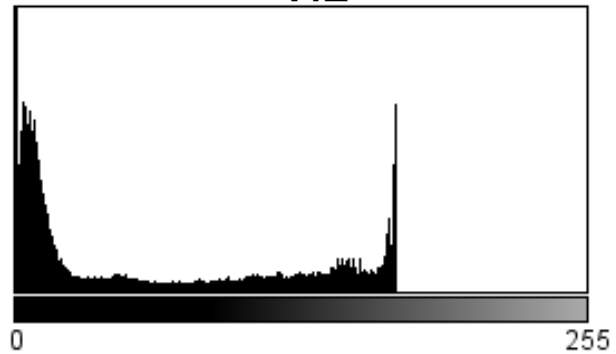


Histogram: Infer Brightness

H1



H2



A

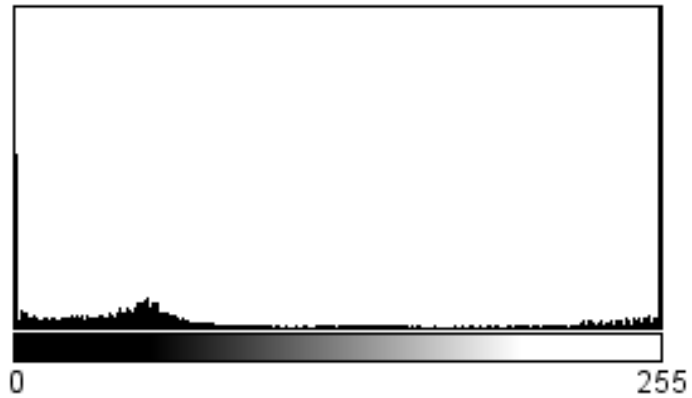


B

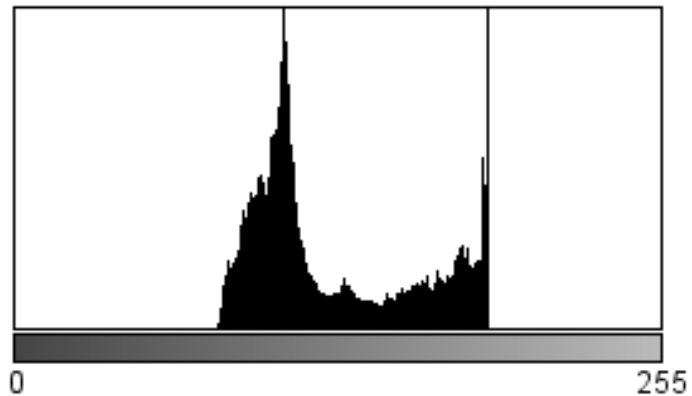


Histogram: Infer Contrast

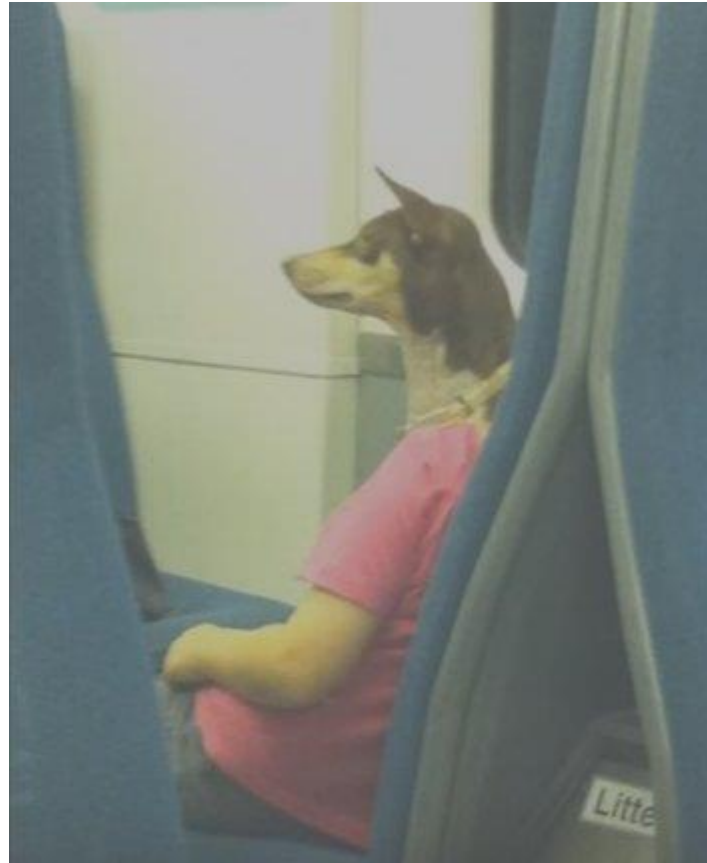
H1



H2



A

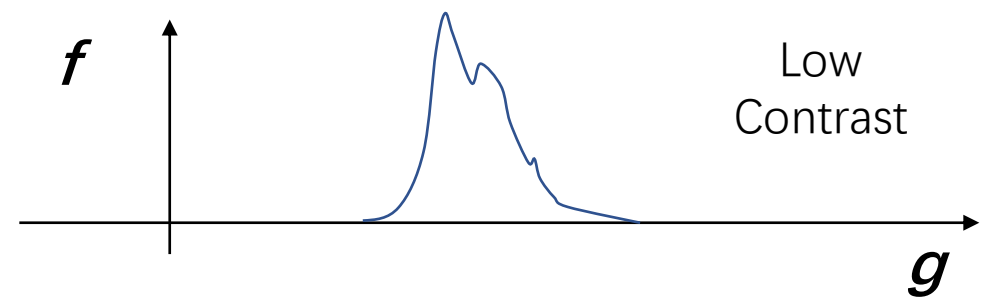
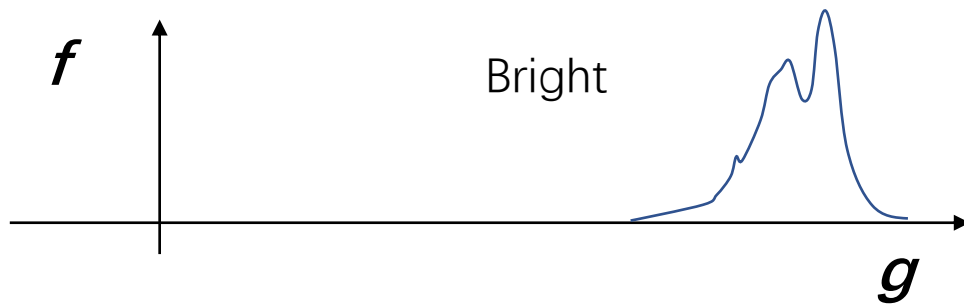
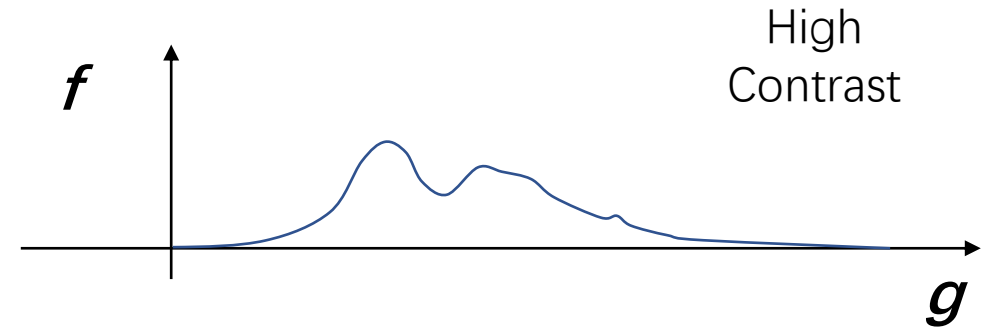
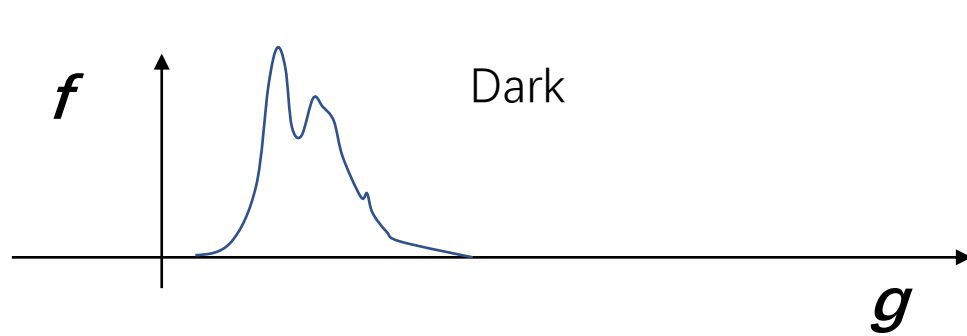


B



Histogram (Information available)

- Distribution of the intensity levels



What can you say about the image given its histogram?



Image Processing

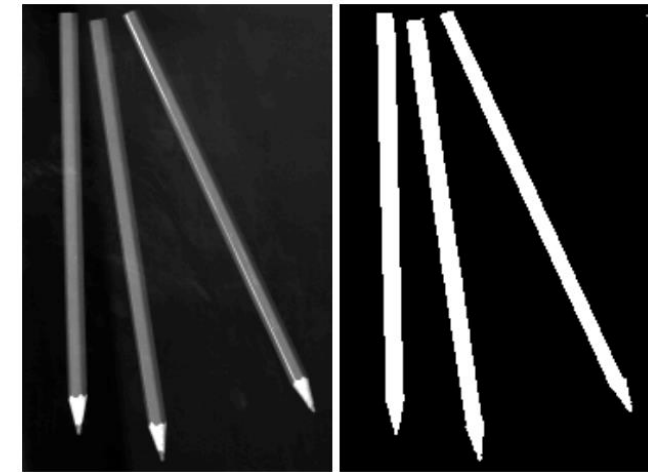
ECE 470 Introduction to Robotics

Image Processing

- Image Enhancement
 - Thresholding & Histogram Processing
 - Filtering
- Image Analysis
 - Feature Detection
 - Edges
 - Lines & Shapes
 - Interest points- Corners
- • Target Tracking

Thresholding

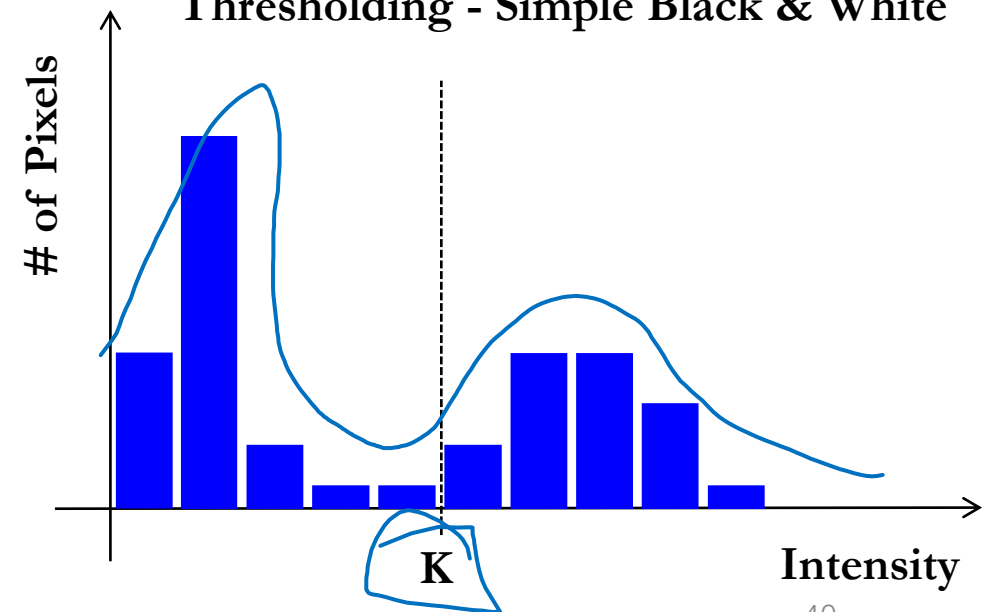
- A threshold parameter “K” is defined using intensity histogram
- Intensity of each pixel is changed to completely dark, “0” or completely bright “1” based on the “K” value
- If intensity of an image pixel, $p(m,n) \geq K$, then $p(m,n) = 1$
- Else, $p(m,n)=0$



Original

After Thresholding

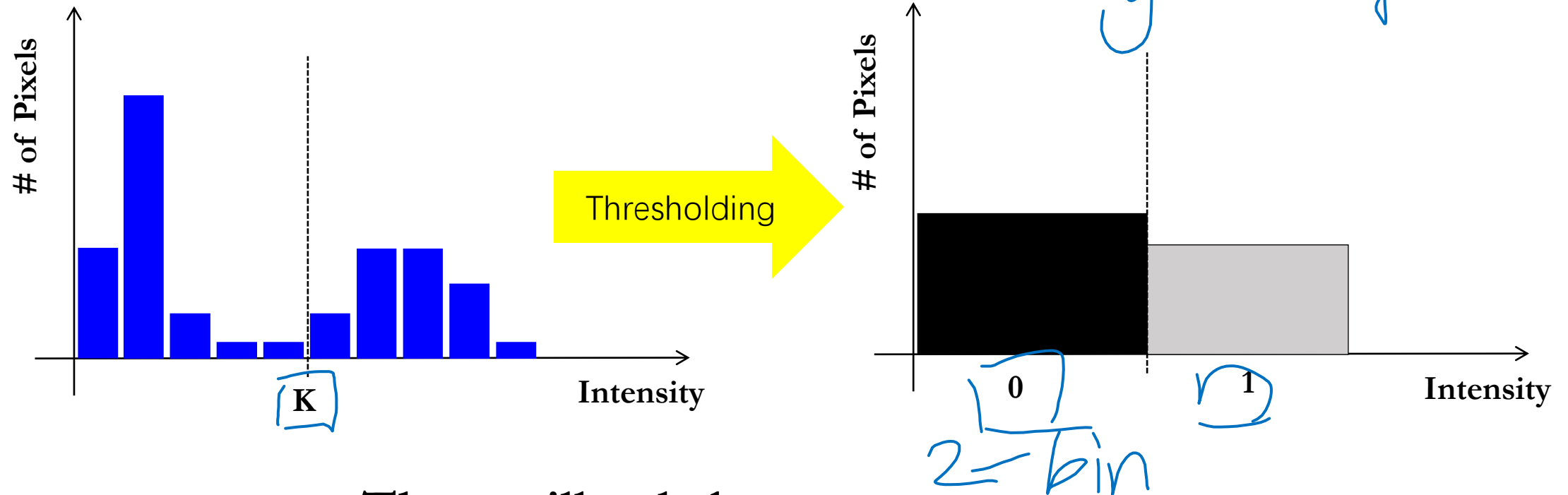
Thresholding - Simple Black & White



Ref: *Twan Maintz, Digital & Medical Image Processing, 2005*

Recap: Thresholding

What will the new histogram look like?



There will only be zeros or ones

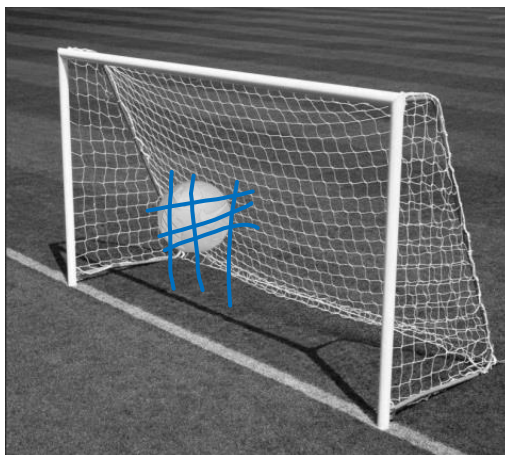
Background Removal

A difference image between two images taken at time i and time j may be defined as

$$d_{ij}(x, y) = \begin{cases} 1; & \text{if } |f(x, y, i) - f(x, y, j)| > T \\ 0; & \text{Otherwise} \end{cases}$$

where T is a threshold value, and $f(x, y, i)$ is the intensity of pixel at x, y , in the i -th image.

Current Image



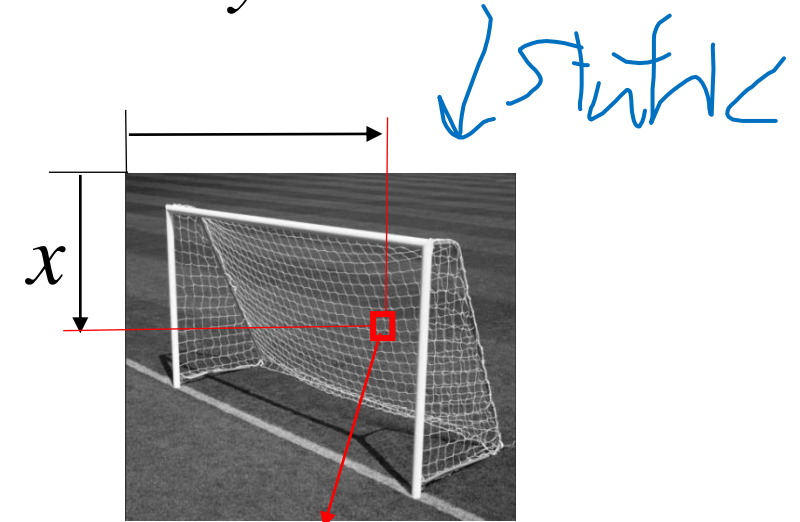
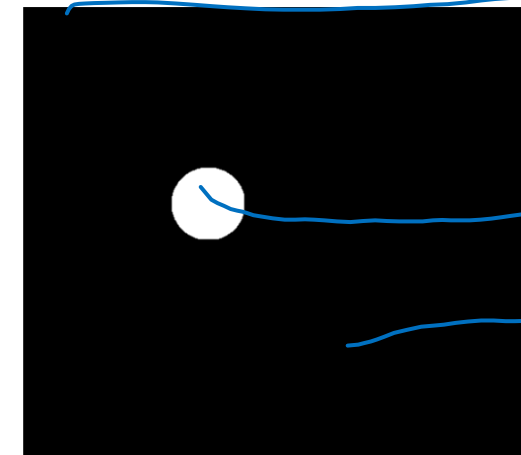
Background Image



—

=

Difference Image



$f(x, y, i)$

$f = 0$; Black, $f = 1$; White

Background Removal - Activity

Given:

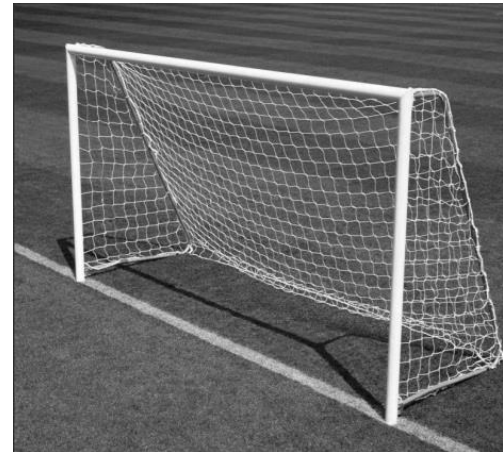
Two images in Gray scale, namely
BackgroundImage.jpeg and CurrentImage.jpeg

Write a code to determine the difference image DifferencelImage.
Compare with the original image and comment

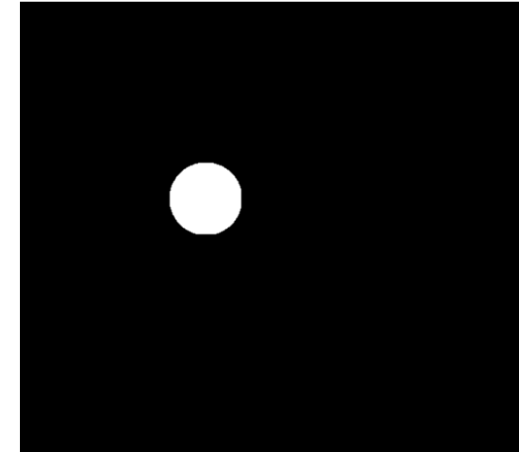
CurrentImage.jpeg



BackgroundImage.jpeg



DifferencelImage



Ref: *Computer Vision Handouts, Harry Asada, MIT*

Background Removal Activity

In Matlab,

```
CurrentImage = imread('CurrentImage.jpg');
```

```
BackgroundImage = imread('BackgroundImage.jpg');
```

```
DifferencelImage = CurrentImage - BackgroundImage;
```

```
DifferencelImage = im2bw(DifferencelImage, T);
```

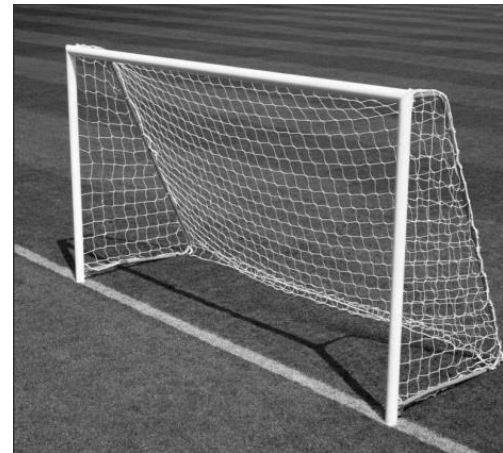
Matrix variable
image file

binarized

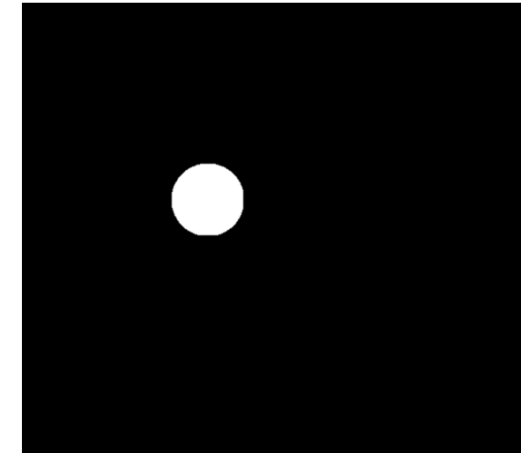
CurrentImage.jpeg



BackgroundImage.jpeg



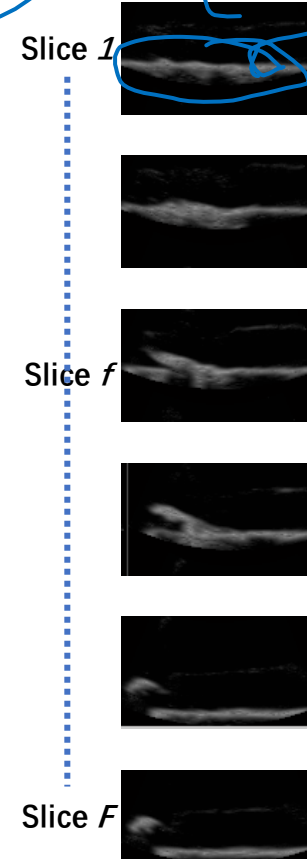
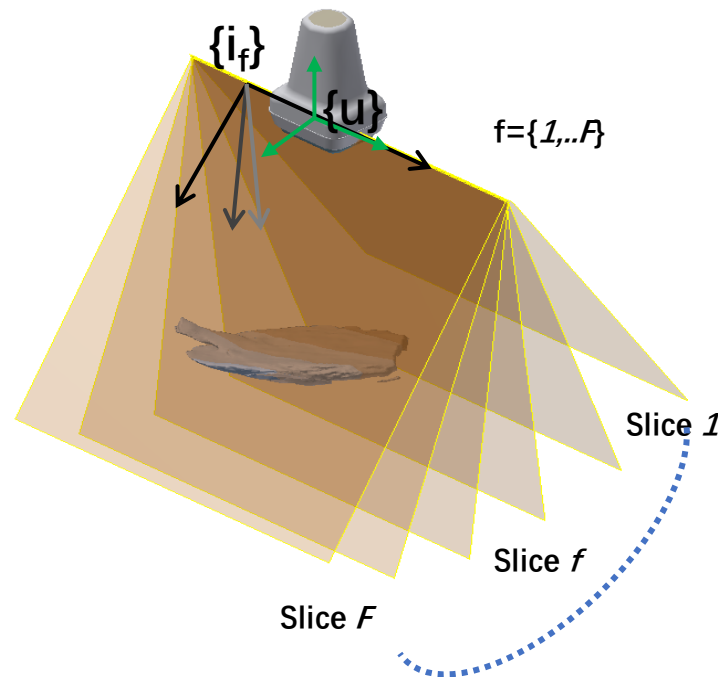
DifferencelImage



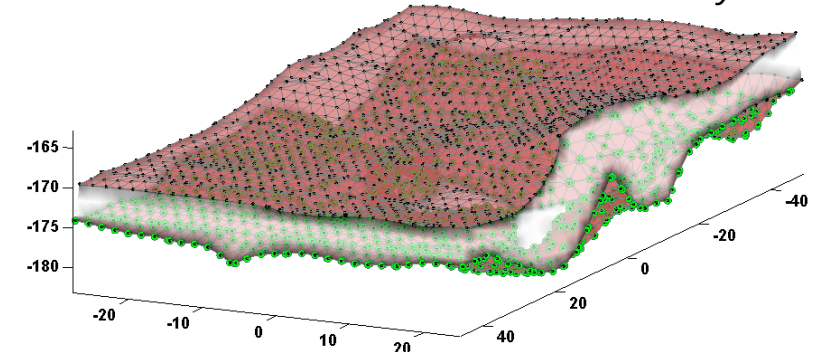
Ref: *Computer Vision Handouts, Harry Asada, MIT*

Thresholding

- Ultrasound Images Example
 - 3D reconstruction of hyperechoic organ from 2D images

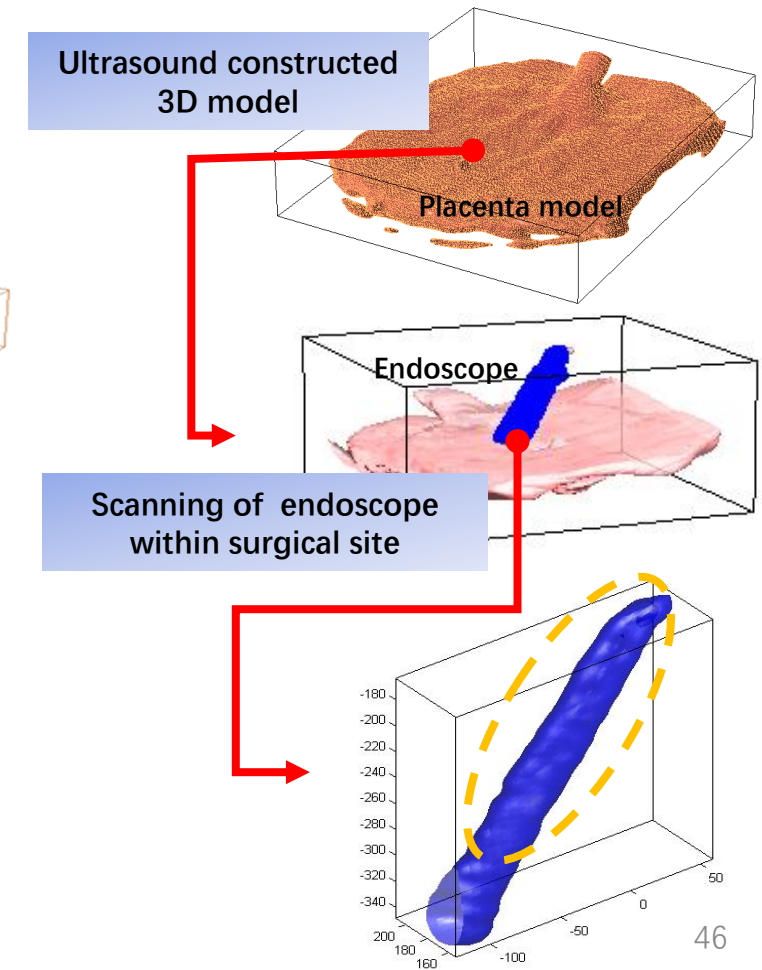
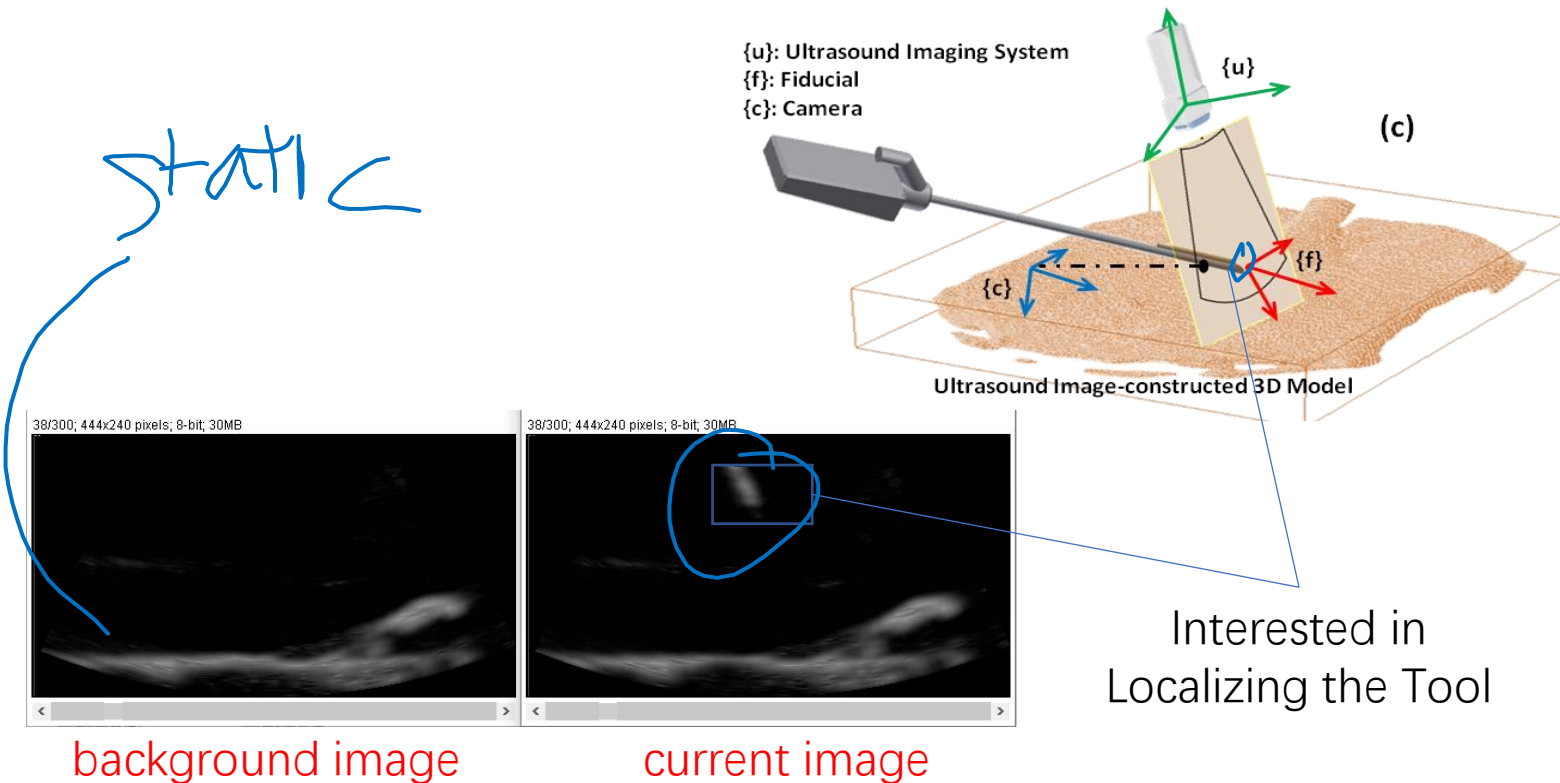


Interested in 3D Surface Geometry



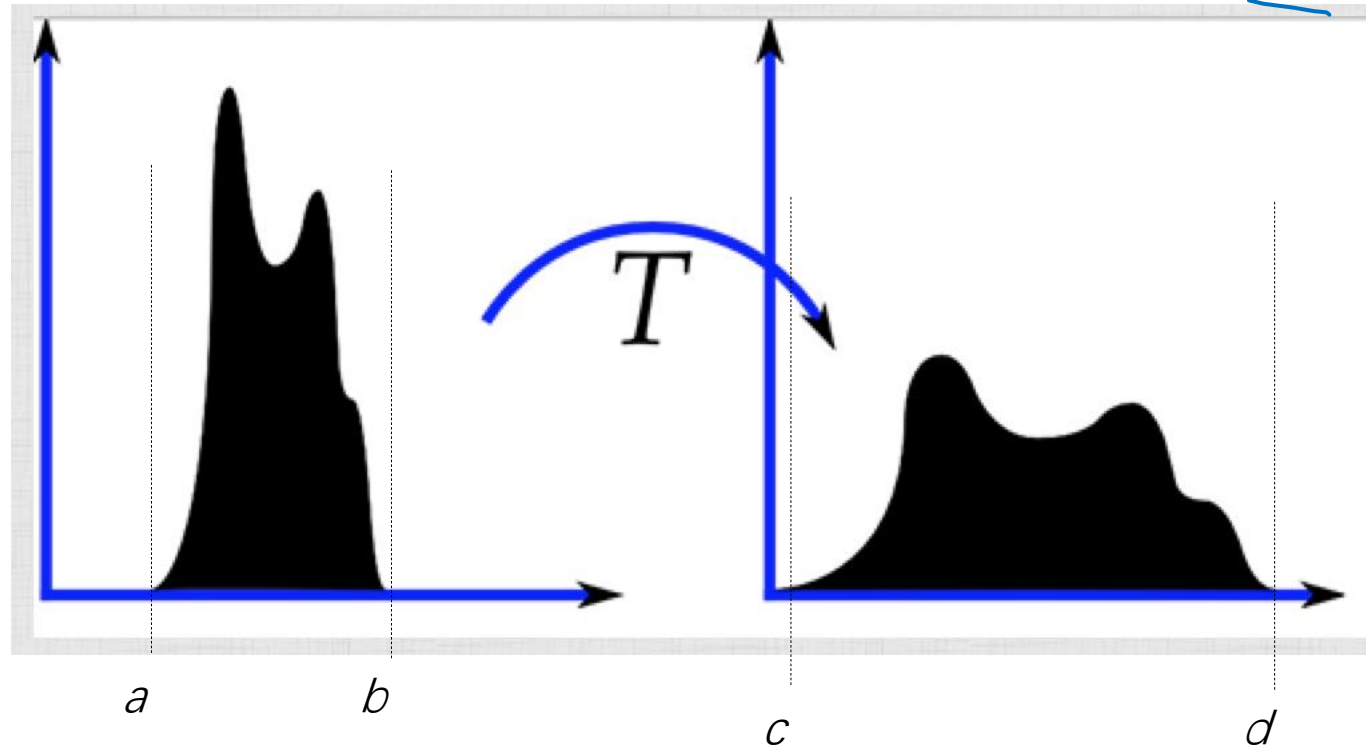
Background Removal

- Ultrasound Images Example
 - 3D reconstruction of moving surgical instrument

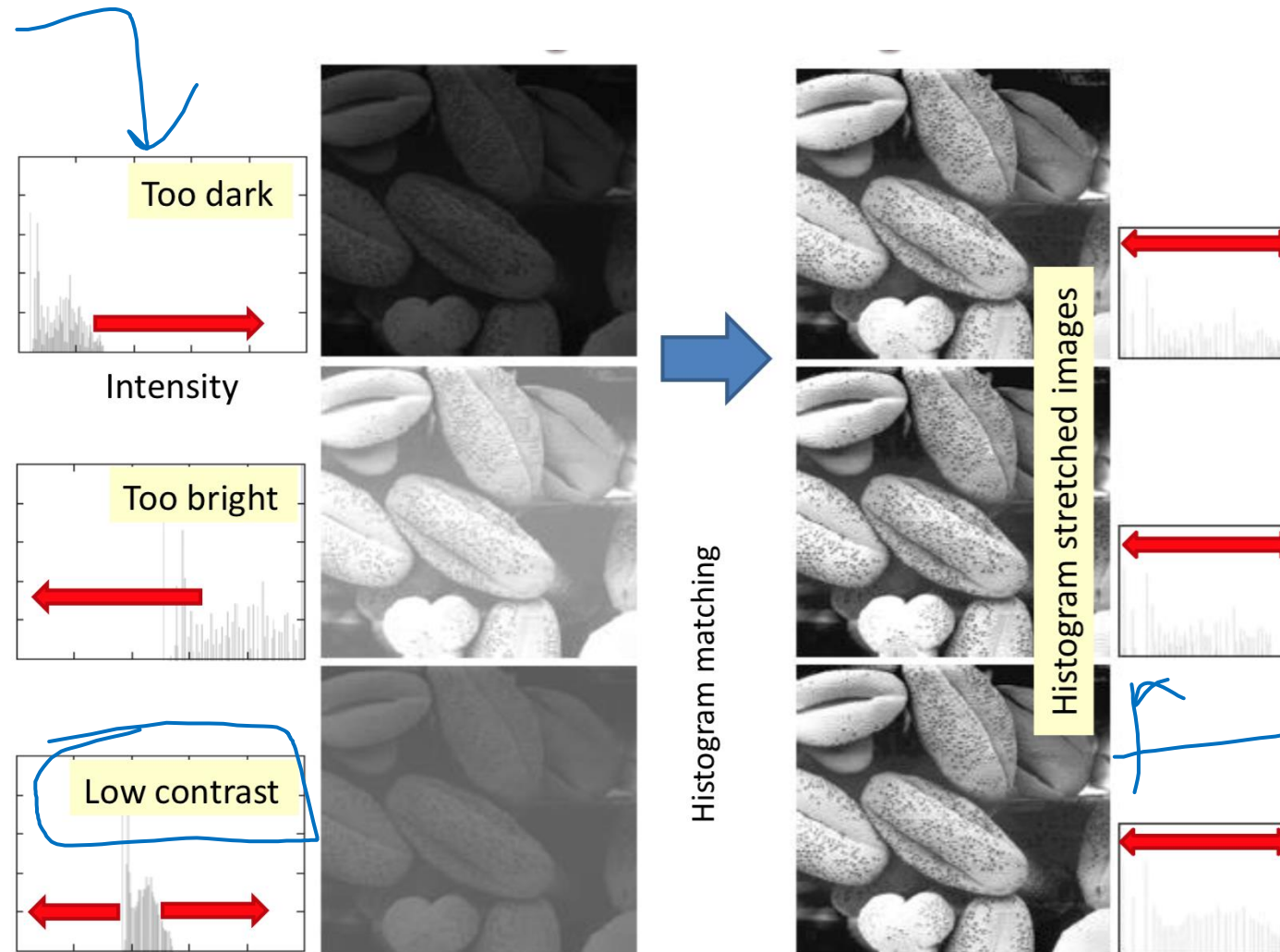


Histogram Processing - Stretching

Matlab Function for Histogram stretching:
 $EnhancedImage = Imadjust(Image, [a,b], [c,d], gamma)$



Histogram Processing - Stretching



Slide From: *Computer Vision Handouts, Harry Asada, MIT*

spread over larger range

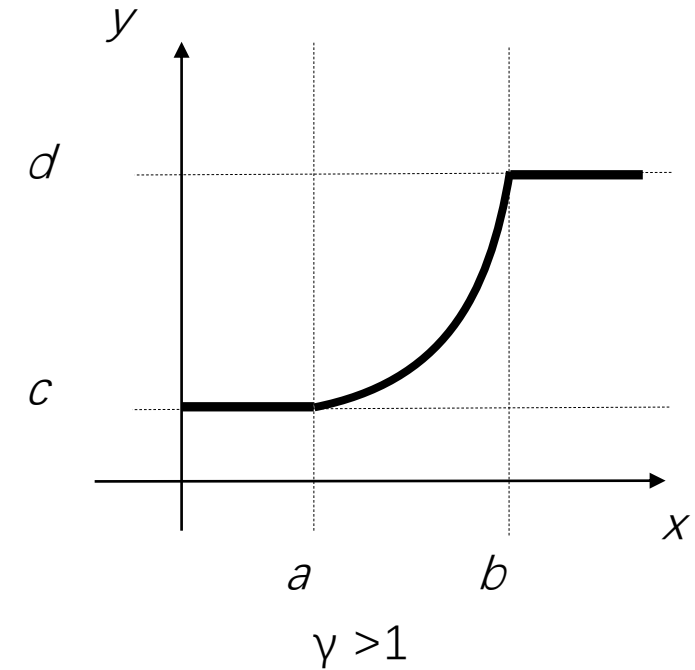
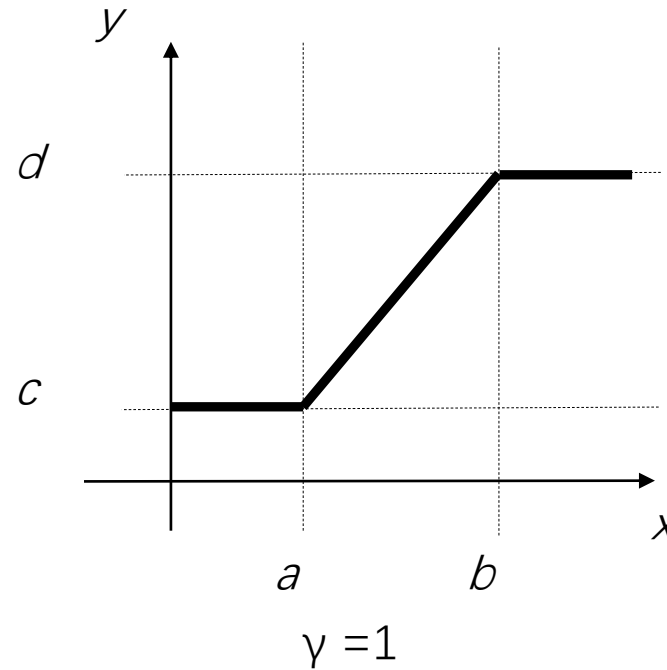
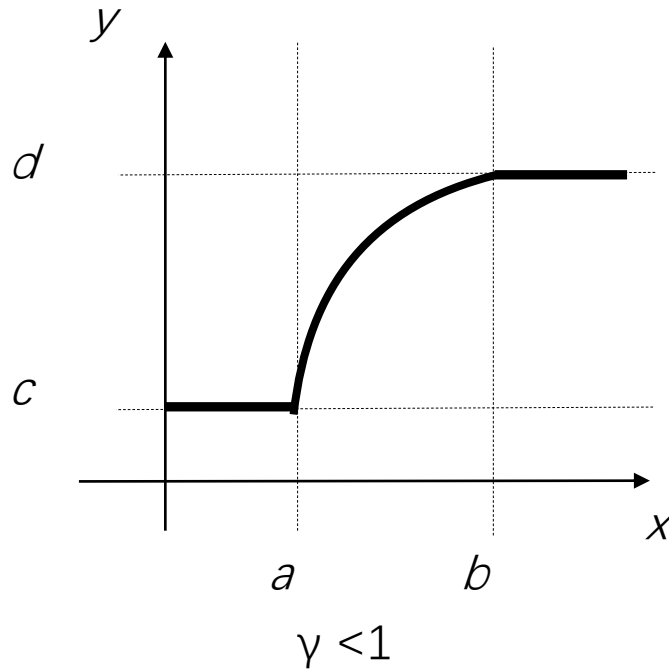
Histogram Processing - Stretching

$$y = \left(\frac{x-a}{b-a} \right)^\gamma (d-c) + c$$

x: input pixel

y: output pixel

- Pure stretching when $\gamma = 1$
- Combined stretching & gamma transform when $\gamma \neq 0$ and 1.



Histogram Processing - Stretching

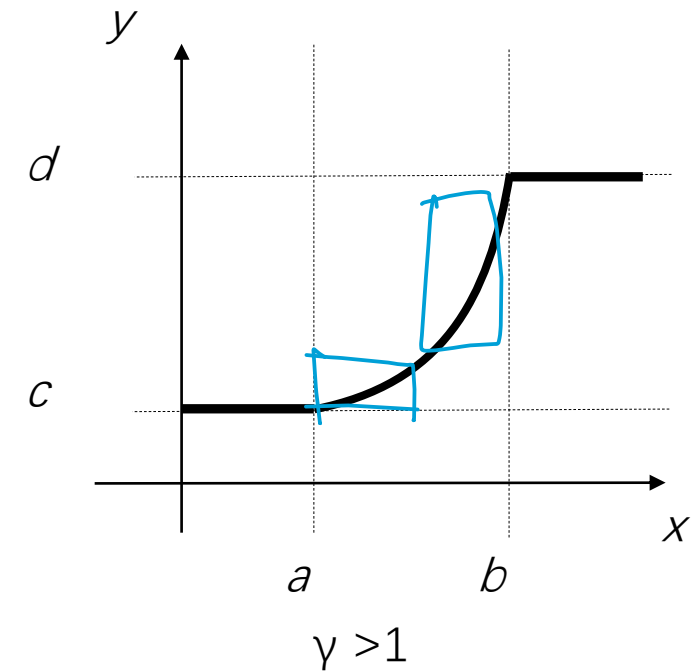
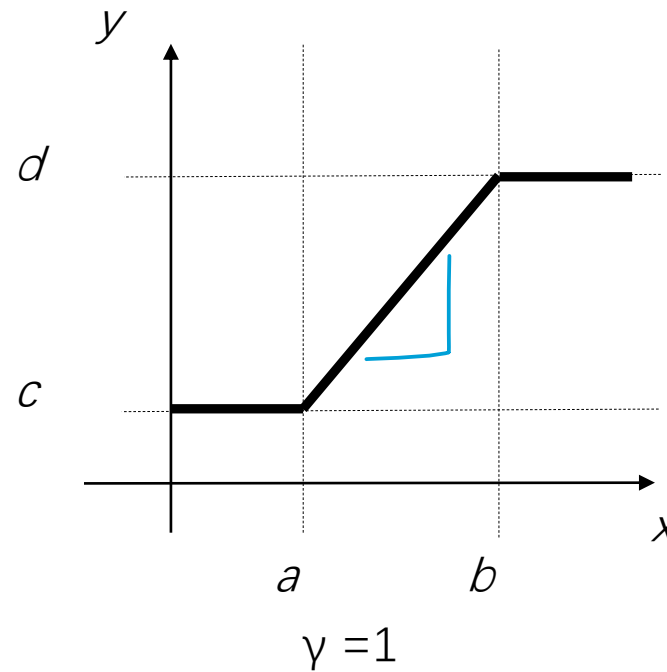
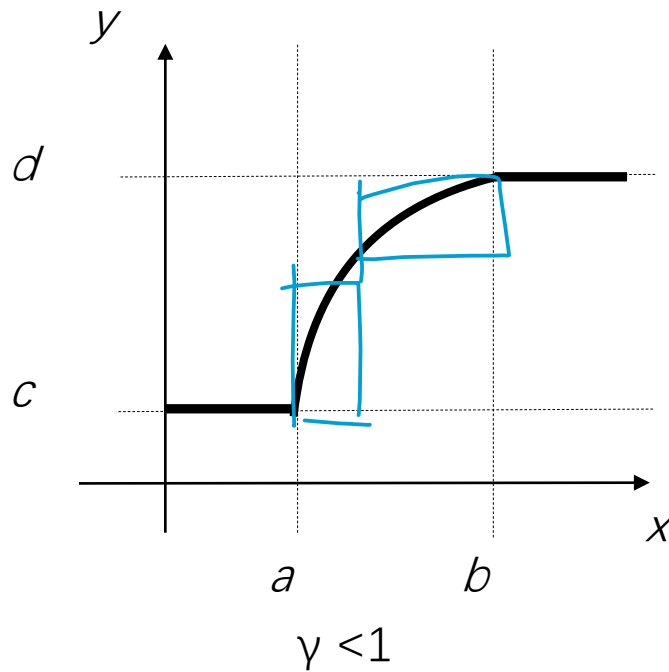
imadjust(I_m, ,)

$$y = \left(\frac{x-a}{b-a} \right)^\gamma (d-c) + c$$

x: input pixel

y: output pixel

- Pure stretching when $\gamma = 1$
- Combined stretching & gamma transform when $\gamma \neq 0$ and 1.



Histogram Processing - Stretching

- Is there a way to automatically determine the extent of histogram stretch?

Especially relevant for Robotics

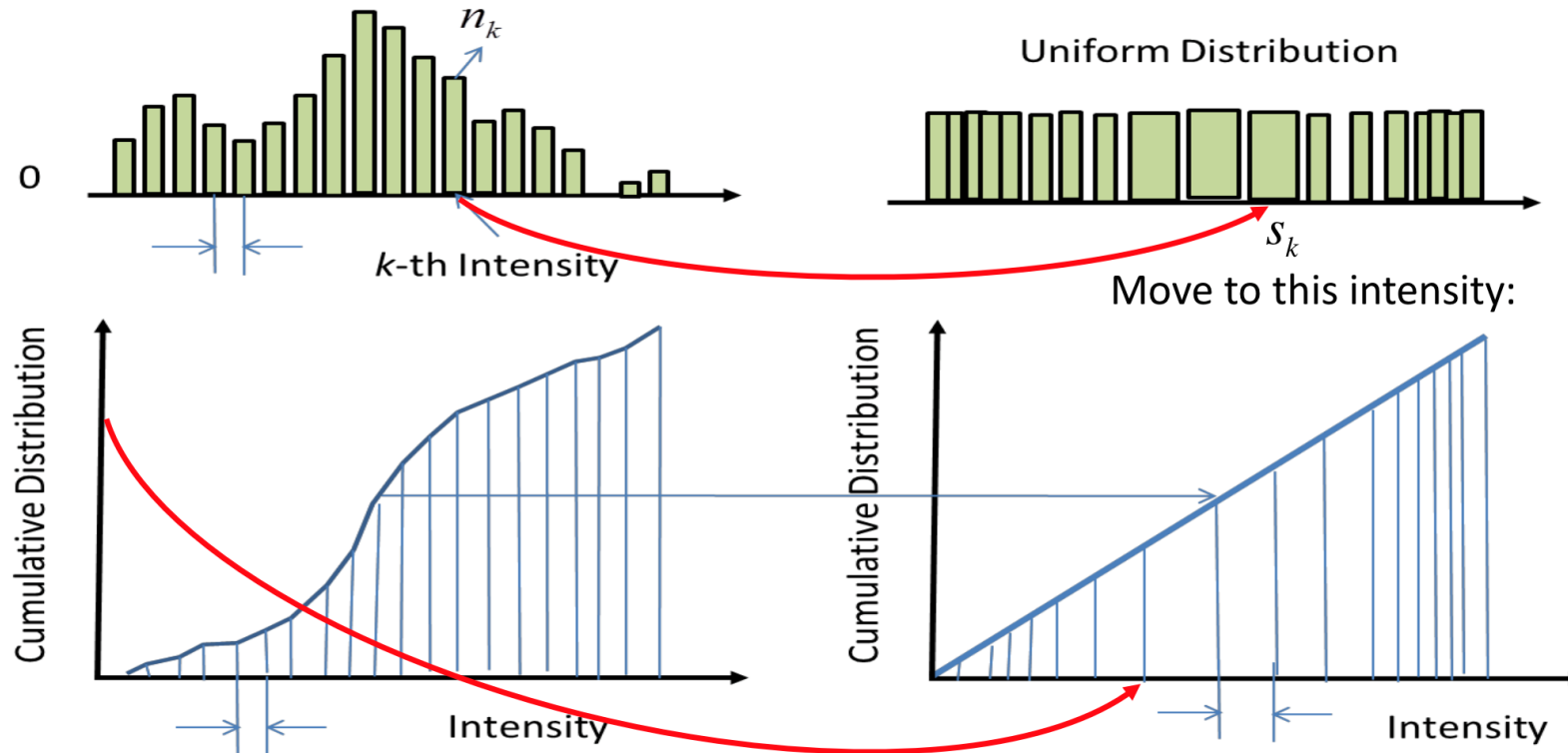
Histogram Processing - Equalization

- Histogram stretching **require user input**.
- Histogram equalization is an **entirely automatic**.
- Histogram equalization can **Stretch/Compress** an image such that:
 - Pixel values (intensity) that occur more frequently get stretched and become more visible.
 - Pixel values that occur infrequently get compressed and become less visible.

Ref: *Computer Vision Handouts, Harry Asada, MIT*

Histogram Processing - Equalization

Treat it as a type of probability: $p_k \approx \frac{n_k}{n}$, $n = MN$

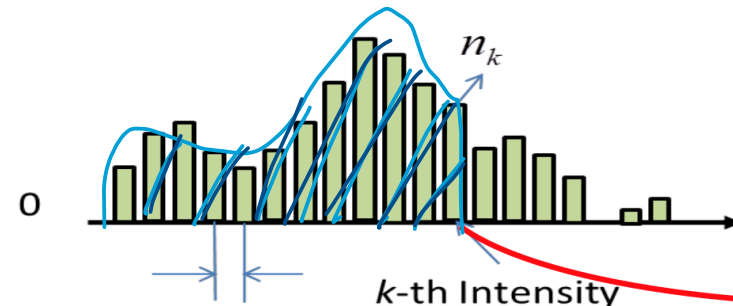


It transforms the histogram to be flat keeping area of individual blocks same

$$s_k = \frac{n_1 + n_2 + \dots + n_k}{n} (L - 1)$$

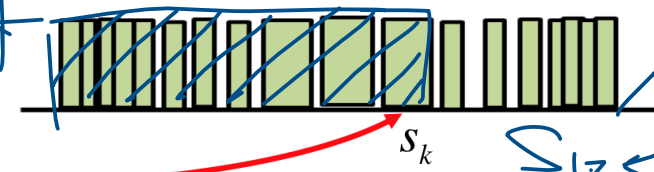
Histogram Processing - Equalization

Treat it as a type of probability: $p_k \approx \frac{n_k}{n}$, $n = MN$

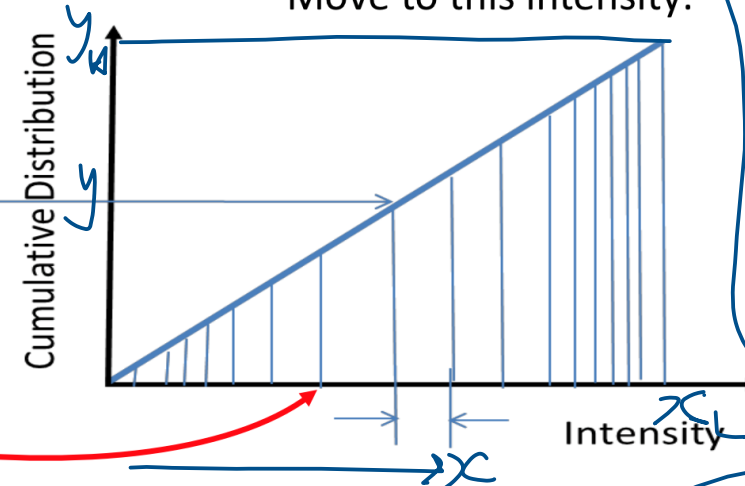
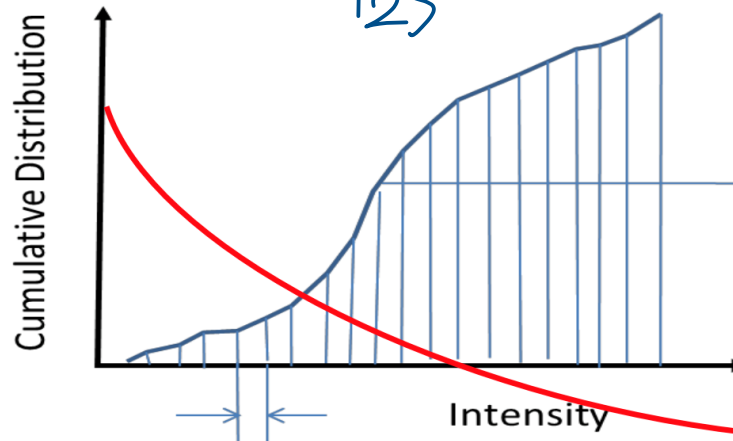


 $\frac{n}{L-1}$

Uniform Distribution



Move to this intensity:



It transforms the histogram to be flat keeping area of individual blocks same

$$s_k = \frac{n_1 + n_2 + \dots + n_k}{n} (L-1)$$

Typically $L = 256$

Handwritten notes:

$$A_1 = A_2$$

$$\sum n_k = \left(\frac{n}{L-1}\right) s_k$$

$$s_k = \frac{\sum n_k}{L-1}$$

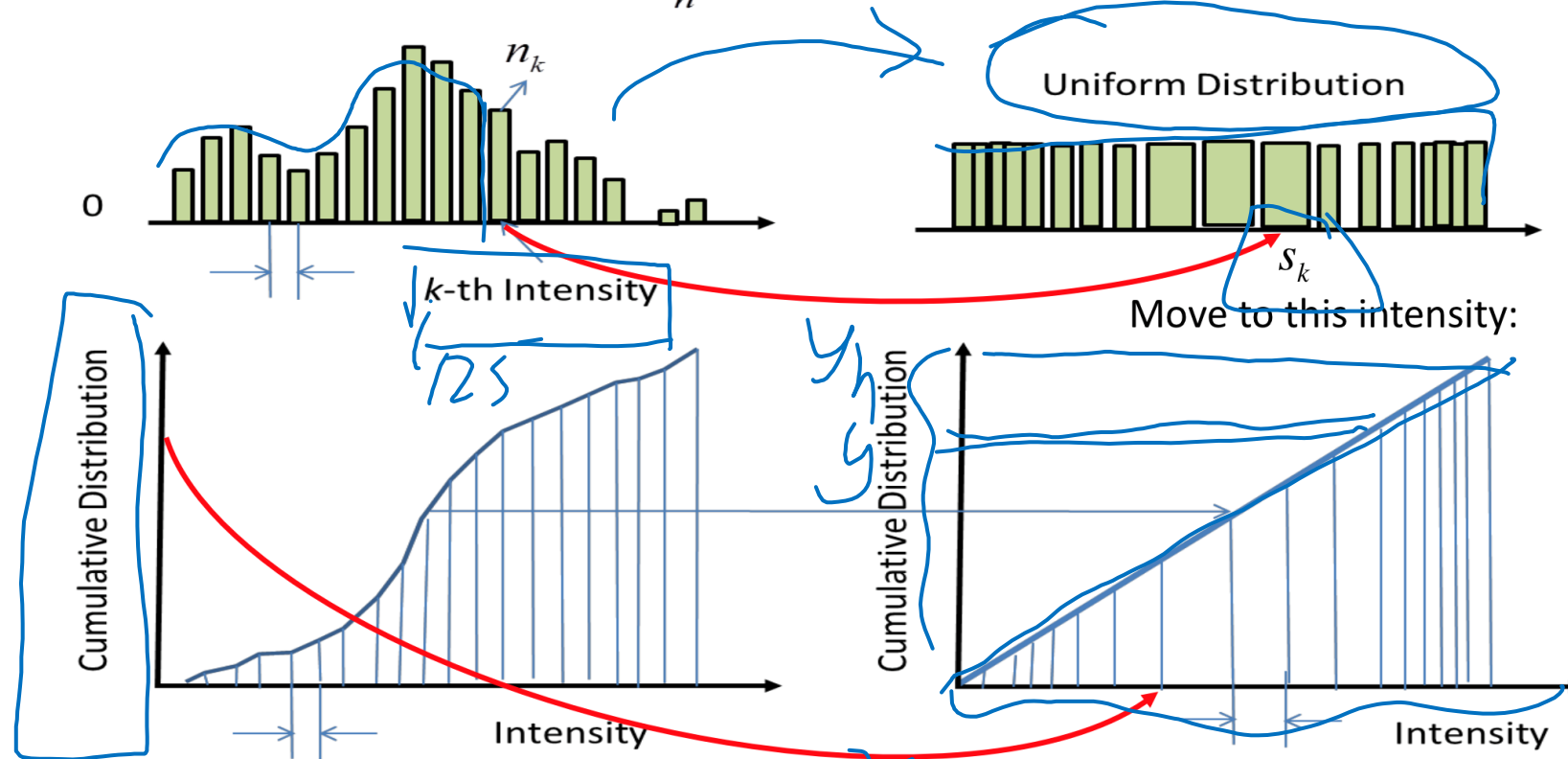
or

$$\frac{x}{x_L} = \frac{y}{y_H}$$

$$x = \frac{y}{y_H} x_L$$

Histogram Processing - Equalization

Treat it as a type of probability: $p_k \approx \frac{n_k}{n}$, $n = MN$



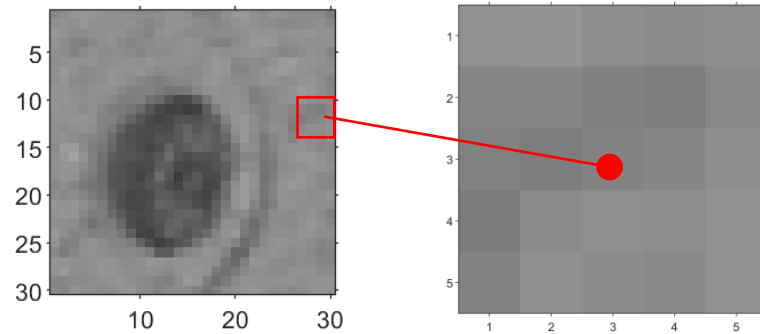
It transforms the histogram to be flat keeping area of individual blocks same

$$s_k = \frac{n_1 + n_2 + \dots + n_k}{n} (L - 1)$$

Typically $L = 256$

Example 3: Histogram Equalization

Perform histogram equalization and plot the new histogram



Transformation for histogram equalization:

$$S_k = \left(\frac{n_1 + n_2 + \dots + n_k}{n} \right) (L - 1)$$

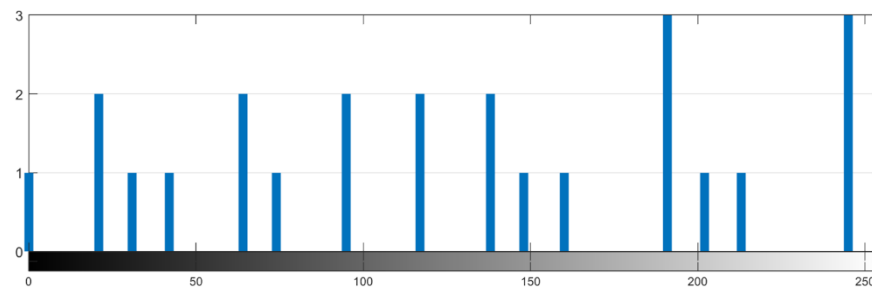
Substitute $L-1=255$, $n=5 \times 5$,

$$S_k = \left(\frac{n_1 + n_2 + \dots + n_k}{25} \right) (255)$$

Rounding off to nearest integer,

n	1	2	1	1	2	1	2	2	2	1	1	3	1	
lup	11	31	41	51	72	82	102	123	143	153	164	194	204	21
lwn	10	30	40	51	71	81	102	122	142	153	163	193	204	21

**Rounding up or down are both acceptable



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Example 2: Histogram Representation

For a 5x5 sub-region $I_{subROI} = I_{ROI}(10:14, 26:30)$,

Gray Value	124	125	129	130	131	133	134	136	138	139	140	141	142	143	145	149	
# of occurrence	1	2	1	1	2	1	2	1	2	2	1	1	3	1	1	3	1
cumulative # of occurrence	1	3	4	5	7	8	10	12	14	15	16	19	20	21	24	25	

Image Processing (Next Lecture)

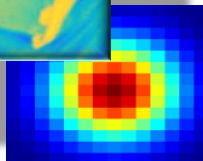
- Image Enhancement
 - Thresholding & Histogram Processing
 - Filtering
- Image Analysis
 - Feature Detection
 - Edges
 - Lines & Shapes
 - Interest points- Corners
 - Target Tracking

Filtering (Next Lecture)

- Operation that modify pixels based on their neighbourhood values



Original

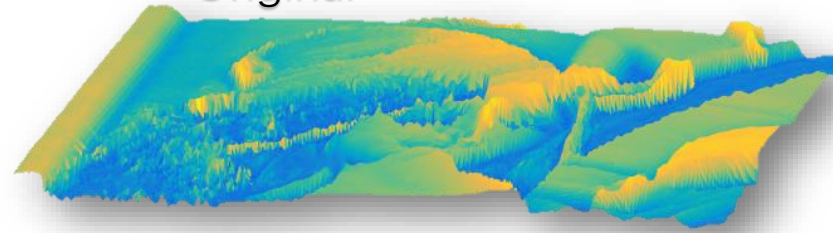


Filter

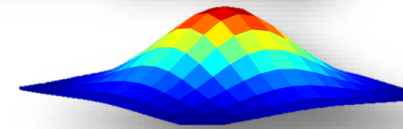


Filtered

Original



Filter



Filtered

