Lesson 01. Introduction. Intensity transformations

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Modified by Ines Ayed

Module I.
Fundamentals of Image Processing

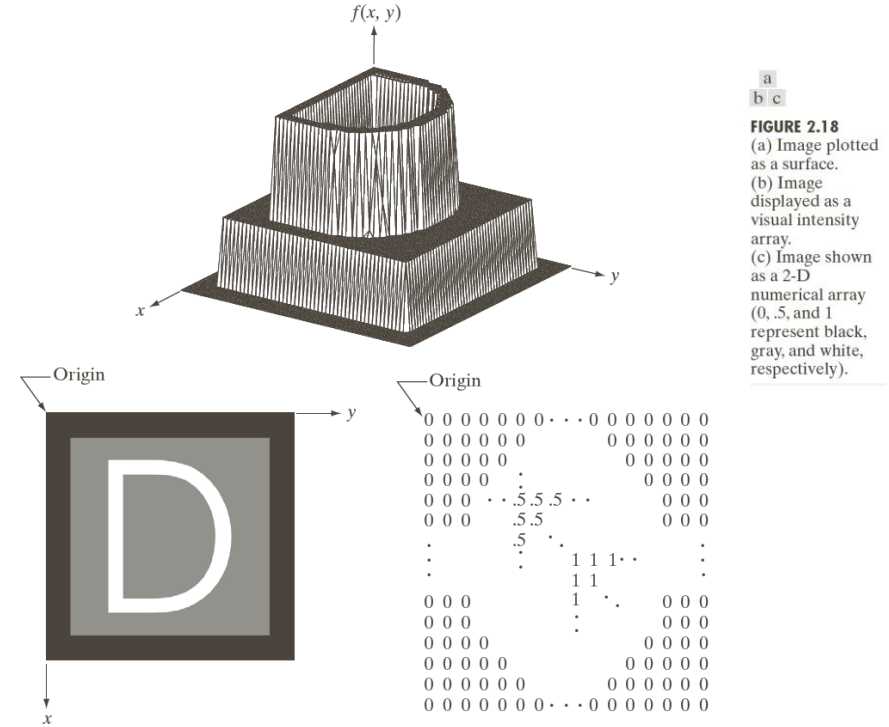
1. Introduction
2. Intensity transformations.
3. Spatial filtering.
4. Mathematical morphology.
5. Domain transformations.
6. Detection of basic shapes.
7. Image segmentation.

What is an image?

Dog under a table, Public Domain.

Chapter 2
Digital Image Fundamentals

- An image may be defined as a two-dimensional function, f (x, y), where x and y are spatial (plane) coordinates, and the amplitude of f at any pair of coordinates (x, y) is called the intensity or gray level of the image at that point.
- When x, y, and the intensity values of f are all finite, discrete quantities, we call the image a digital image.



a
b c

FIGURE 2.18
(a) Image plotted as a surface.
(b) Image displayed as a visual intensity array.
(c) Image shown as a 2-D numerical array (0, .5, and 1 represent black, gray, and white, respectively).

Image representation: conceptually

As a matrix (tensor)	As a function
$A = \begin{pmatrix} a_{1,1} & \dots & a_{1,w} \\ \vdots & & \vdots \\ a_{h,1} & \dots & a_{h,w} \end{pmatrix}$	$\boldsymbol{I} : \mathbb{Z}^n \rightarrow \mathbb{R}^d$

Image representation: in practice

Numeric values (for each pixel)

```
>>> image
array([[0, 1, 2],
       [1, 2, 3],
       [2, 3, 4]])
```

Tensor size (spatial size and number of channels)

```
>>> image.shape
(3, 3)
```

How values are stored internally

```
>>> image.dtype
dtype('uint8')
```

Image representation: in practice

Numeric values (for each pixel)

```
>>> image
array([[[0.03, 0.12, 0.32],
        ...,
        [0.42, 0.00, 0.82]]])
```

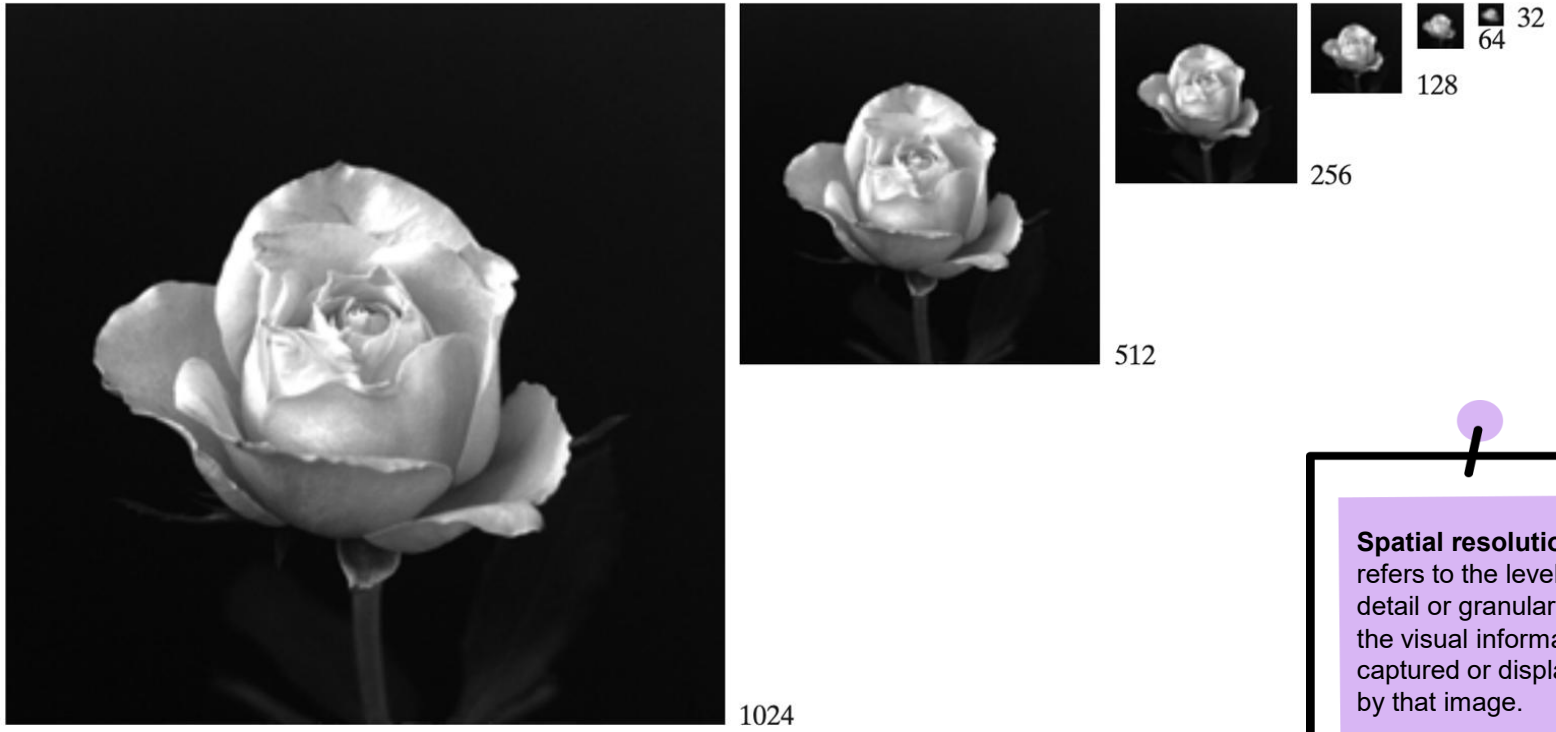
Tensor size (spatial size and number of channels)

```
>>> image.shape
(1024, 960, 3)
```

How values are stored internally

```
>>> image.dtype
dtype('float64')
```

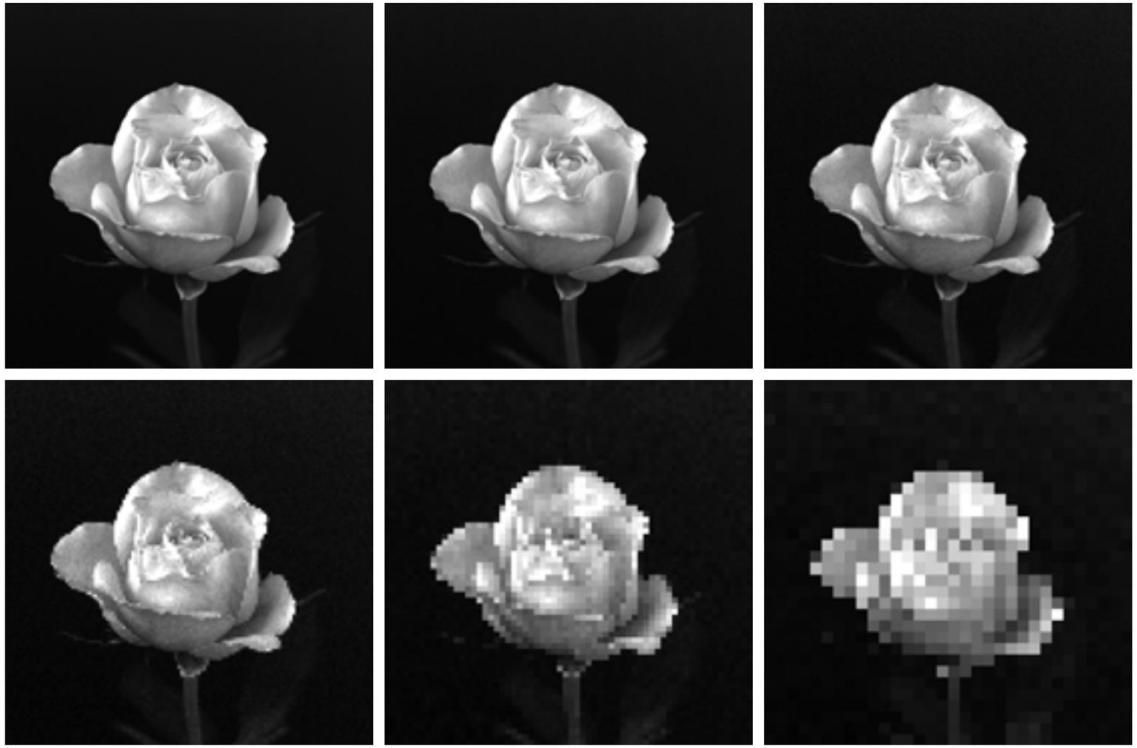
Spatial resolution



Digital Image Processing, González-Woods.

Spatial resolution refers to the level of detail or granularity in the visual information captured or displayed by that image.

Spatial resolution



Digital Image Processing, González-Woods.

- In digital images, spatial resolution is often quantified by the number of pixels or dots per unit of length, such as pixels per inch (PPI) or dots per inch (DPI).
- A higher spatial resolution means that there are more pixels or dots per unit of length, resulting in a finer level of detail and greater clarity in the image.

Spatial resolution

Numeric values (for each pixel)

```
>>> image
array([[[0.03, 0.12, 0.32],
        ...,
        [0.42, 0.00, 0.82]]])
```

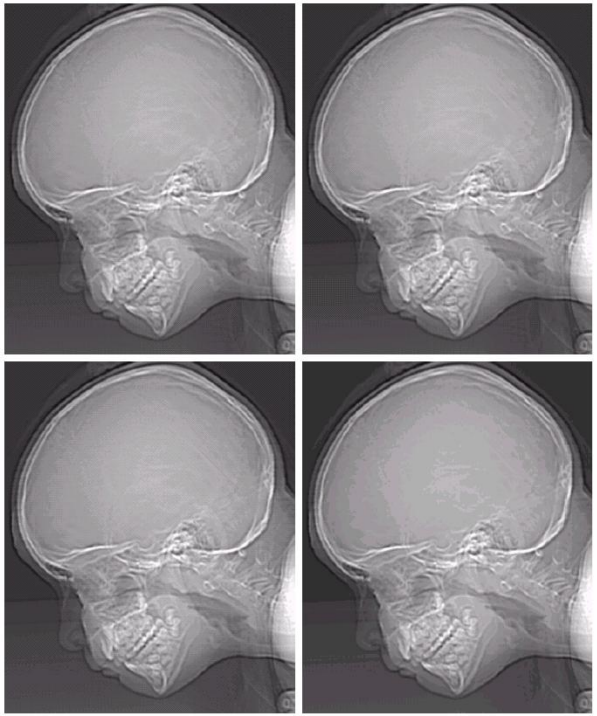
Tensor size (spatial size and number of channels)

```
>>> image.shape
(1024, 960, 3)
```

How values are stored internally

```
>>> image.dtype
dtype('float64')
```

Grayscale resolution



a b
c d

FIGURE 2.21
(a) 452 × 374, 256-level image. (b)–(d) Image displayed in 128, 64, and 32 gray levels, while keeping the spatial resolution constant.

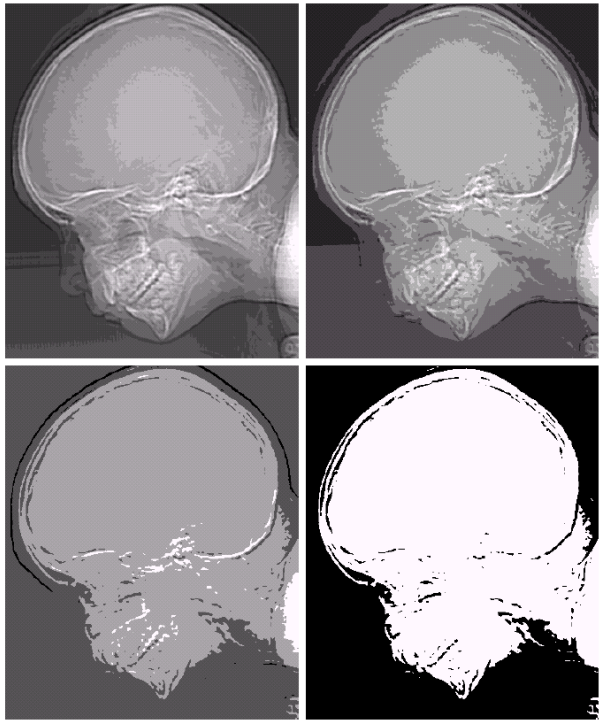
Digital Image Processing, González-Woods.

Intensity resolution similarly refers to the smallest discernible change in intensity level.

Grayscale resolution

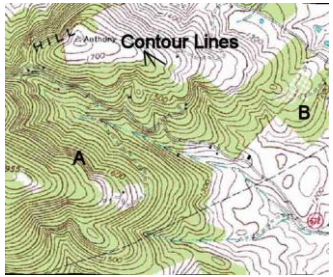
e f
g h

FIGURE 2.21
(Continued)
(e)–(h) Image displayed in 16, 8, 4, and 2 gray levels. (Original courtesy of Dr. David R. Pickens, Department of Radiology & Radiological Sciences, Vanderbilt University Medical Center.)



Digital Image Processing, González-Woods.

False contouring: artificial lines that appear in images with reduced number of gray levels.



Grayscale resolution

- The grayscale resolution of an image affects the quality of the image.
- A higher grayscale resolution will result in a smoother, more detailed image. However, a higher grayscale resolution will also require more storage space.

Numeric values (for each pixel)

```
>>> image
array([[[0.03, 0.12, 0.32],
        ...,
        [0.42, 0.00, 0.82]]])
```

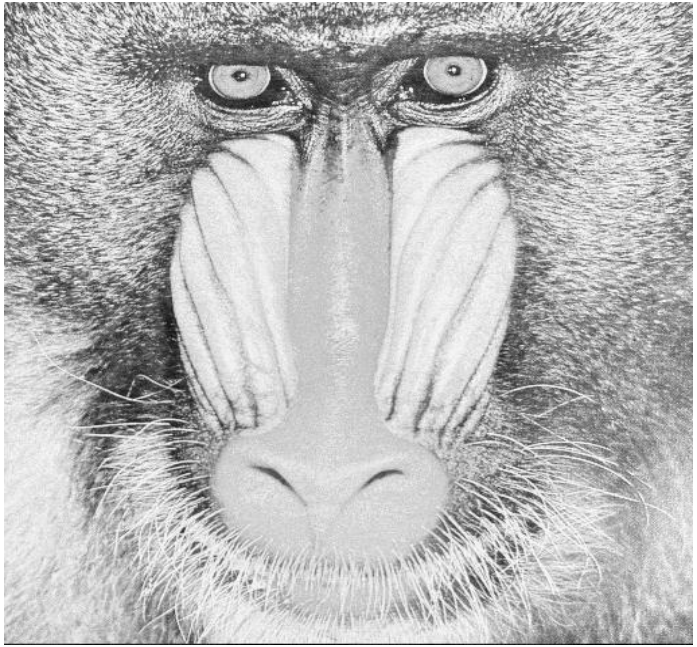
Tensor size (spatial size and number of channels)

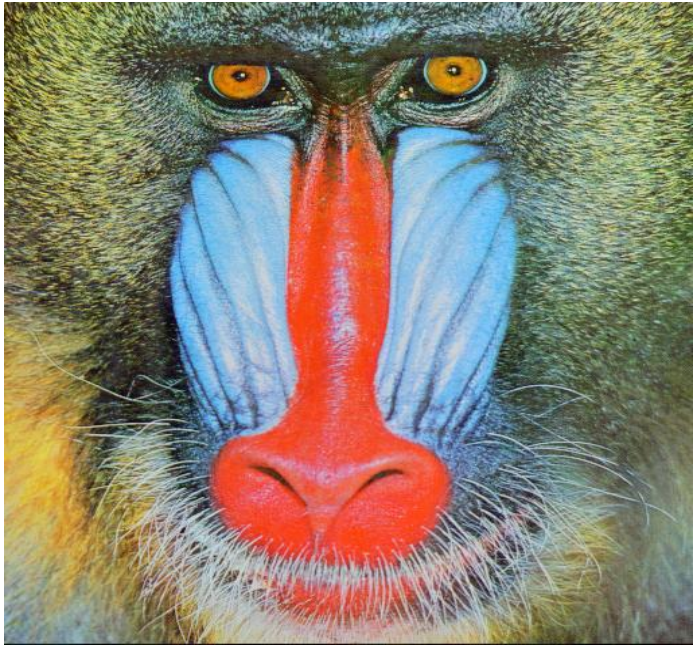
```
>>> image.shape
(1024, 960, 3)
```

How values are stored internally

```
>>> image.dtype
dtype('float64')
```

Color





Mandril (USC-SIPI Image Database)

Spatial resolution

Numeric values (for each pixel)

```
>>> image
array([[[0.03, 0.12, 0.32],
        ...,
        [0.42, 0.00, 0.82]]])
```

Tensor size (spatial size and number of channels)

```
>>> image.shape
(1024, 960, 3)
```

How values are stored internally

```
>>> image.dtype
dtype('float64')
```

What can we do **now** with an image?

Digital image processing

- The field of digital image processing refers to processing digital images by means of a digital computer.

- There are two main reasons for doing this:
  - Improvement of pictorial information for human interpretation
  - Processing of image data for tasks such as storage, transmission, and representation for autonomous machine perception

Digital image processing

- Three types of computerized processes can be considered in the continuum from image processing to computer vision : low-, mid-, and high level processes.

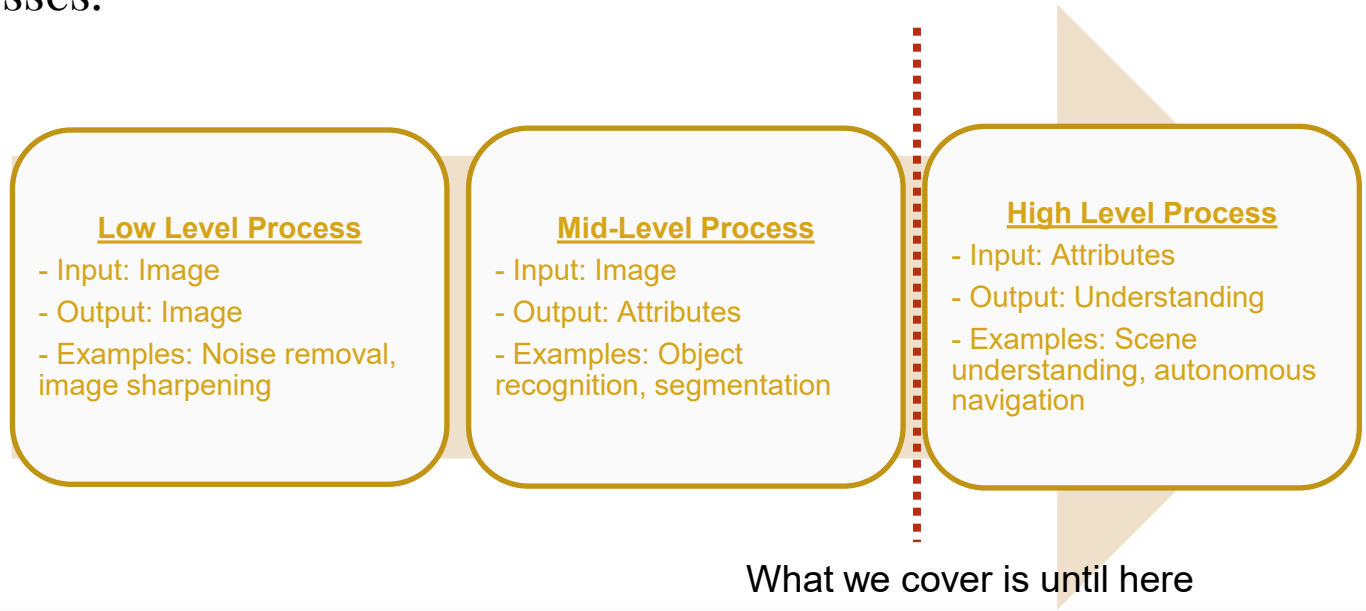
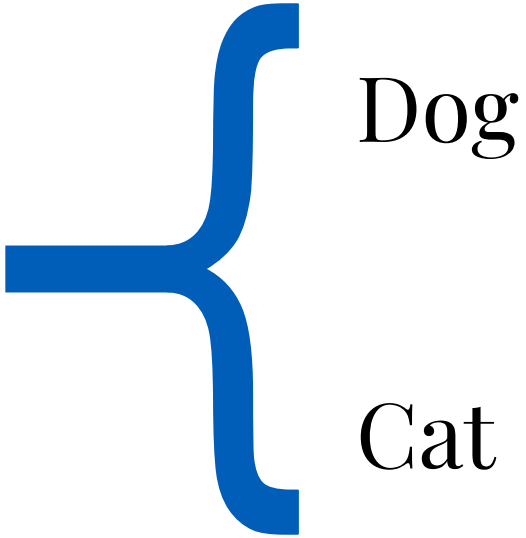
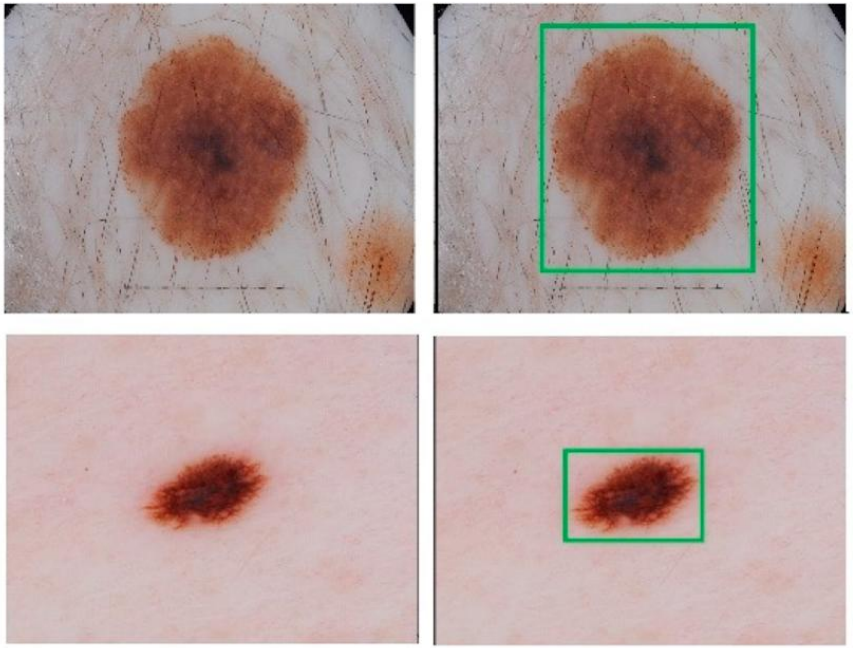


Image classification

Dog under a table, Public Domain.



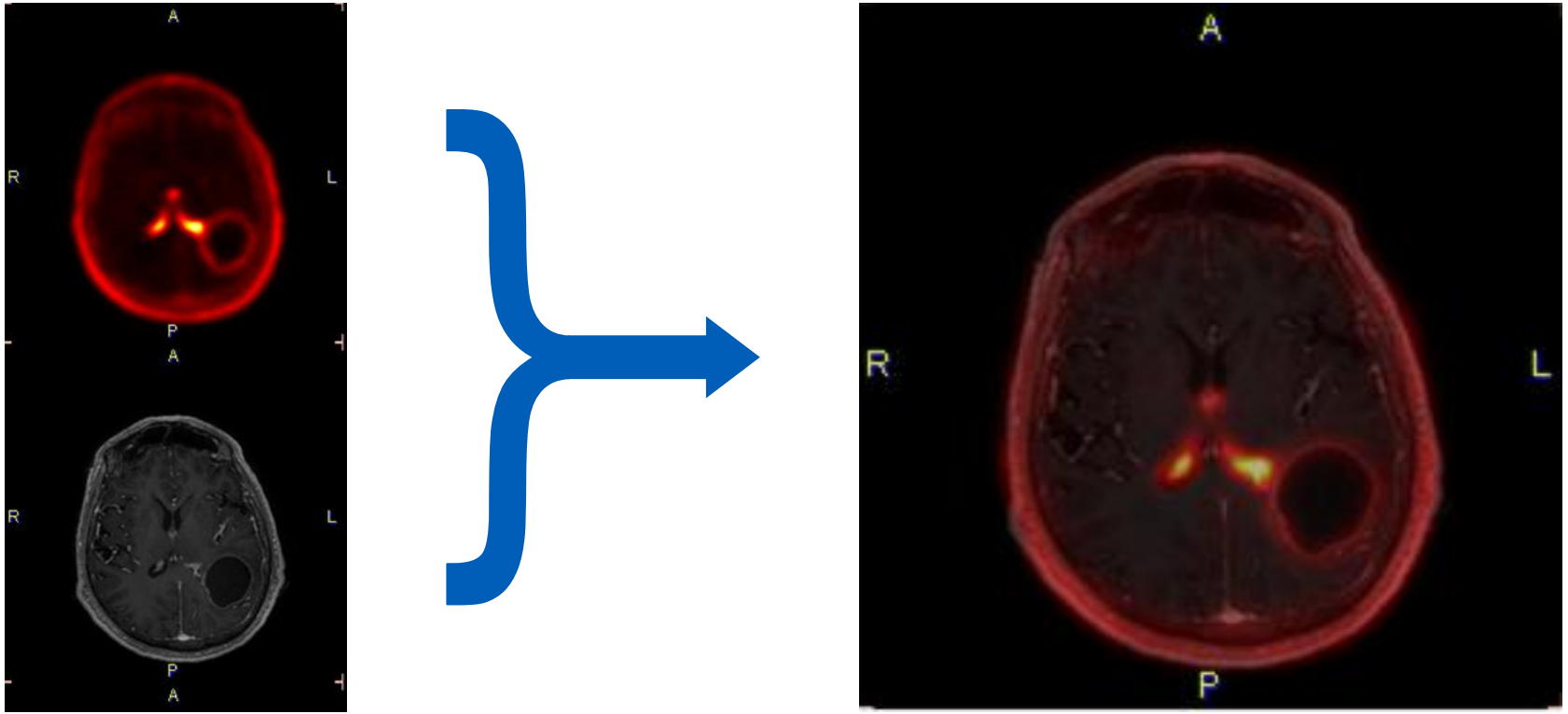
Object detection (bounding box)



H.M. Ünver, E. Ayan, Skin Lesion Segmentation in Dermoscopic Images with Combination of YOLO and GrabCut Algorithm

Object segmentation, instance segmentation

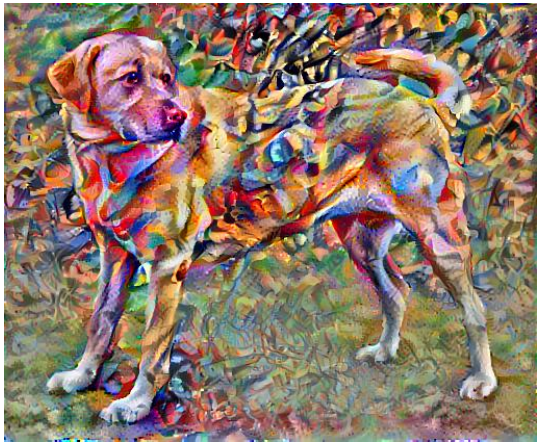
Co-registration



Transfer learning

Labrador, Wikimedia Commons (Elf)

Composition VII, Wassily Kandinsky



Google, CCA 4.0

Captioning (image-to-text)

COCO captioning dataset

“A large bus sitting next to a very tall building.”

Text-to-image

“Last selfie ever taken.”

@RobotOverlords (AI: midjourney)

- 3D reconstruction
- Facial identification
- Tracking (in video)
- Human pose detection
- Crowd counting
- ...

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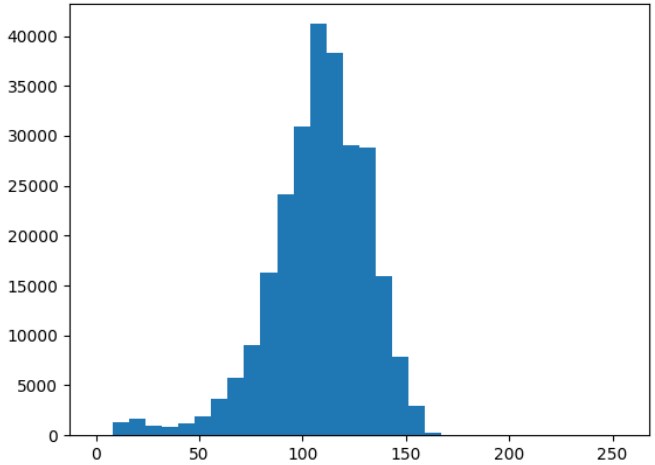
Spatial domain

- All the image processing techniques in the first chapters of the course are implemented in the spatial domain.
  - Spatial domain is the plane containing the pixels of an image.
  - Spatial domain techniques operate directly on the pixels of an image, as opposed, for example, to the frequency domain in which operations are performed on the Fourier transform of an image, rather than on the image itself.
- Some image processing tasks are easier or more meaningful to implement in the spatial domain, while others are best suited for other approaches.

What is the **histogram** of an image?

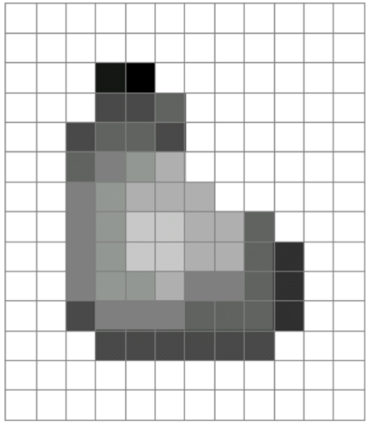
Histogram of an image

Tank (USC-SIPI Image Database)



$$h : \{0, \ldots, 255\} \longrightarrow \mathbb{N}$$

Histogram of an image



=

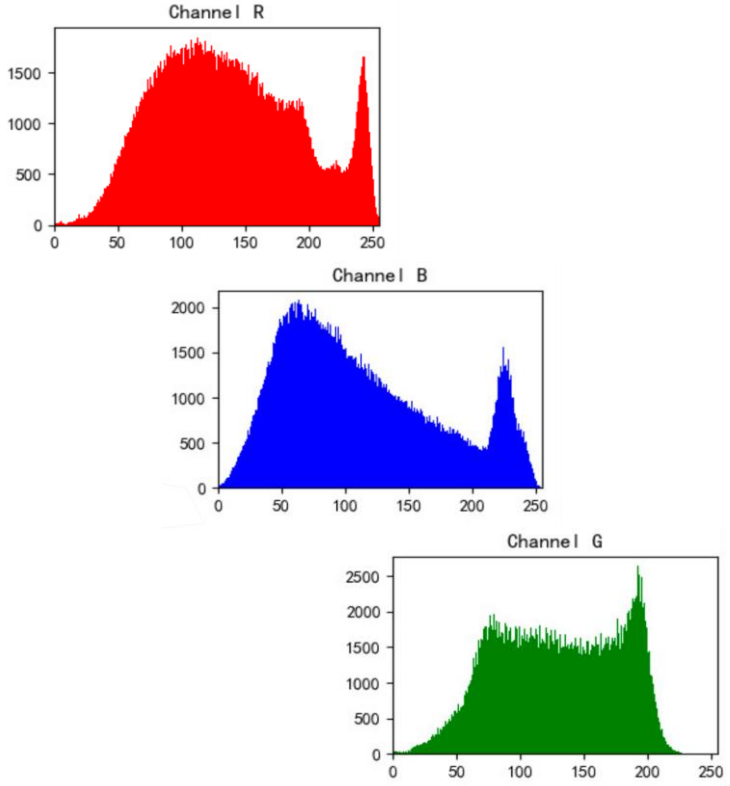
255	255	255	255	255	255	255	255	255	255	255	255
255	255	255	255	255	255	255	255	255	255	255	255
255	255	255	20	0	255	255	255	255	255	255	255
255	255	255	75	75	75	255	255	255	255	255	255
255	255	75	95	95	75	255	255	255	255	255	255
255	255	96	127	145	175	255	255	255	255	255	255
255	255	127	145	175	175	175	255	255	255	255	255
255	255	127	145	200	200	175	175	95	255	255	255
255	255	127	145	200	200	175	175	95	47	255	255
255	255	127	145	145	175	127	127	95	47	255	255
255	255	74	127	127	127	95	95	95	47	255	255
255	255	255	74	74	74	74	74	74	255	255	255
255	255	255	255	255	255	255	255	255	255	255	255
255	255	255	255	255	255	255	255	255	255	255	255

Histogram: a plot of gray values versus numbers of pixels at each gray value.

Noah Snavely, Cornell University

Histogram of an image

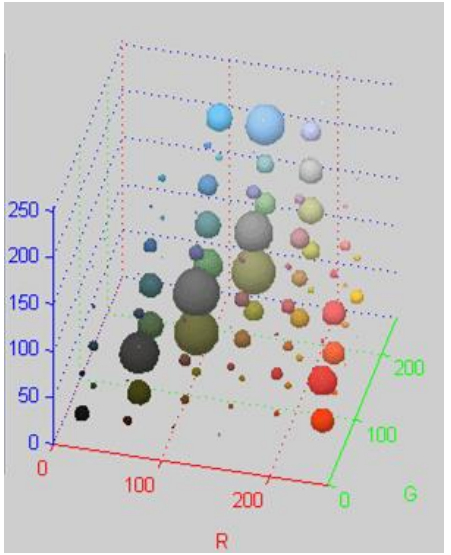
Mandril (USC-SIPI Image Database)



$$h : \{0, \ldots, 255\} \longrightarrow \mathbb{N}$$

Histogram of an image

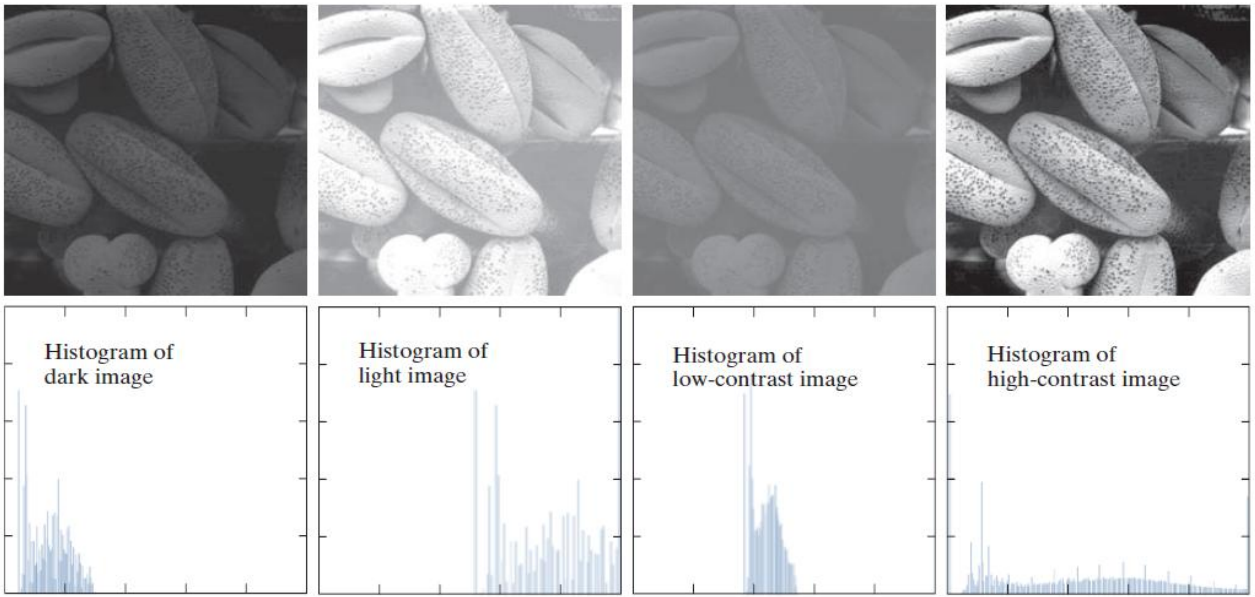
Mandril (USC-SIPI Image Database)



3D histogram of RGB image. Pavel Rajmic (2022).

$$h : \{0, \ldots, 255\}^3 \longrightarrow \mathbb{N}$$

What information contains the histogram?



a b c d

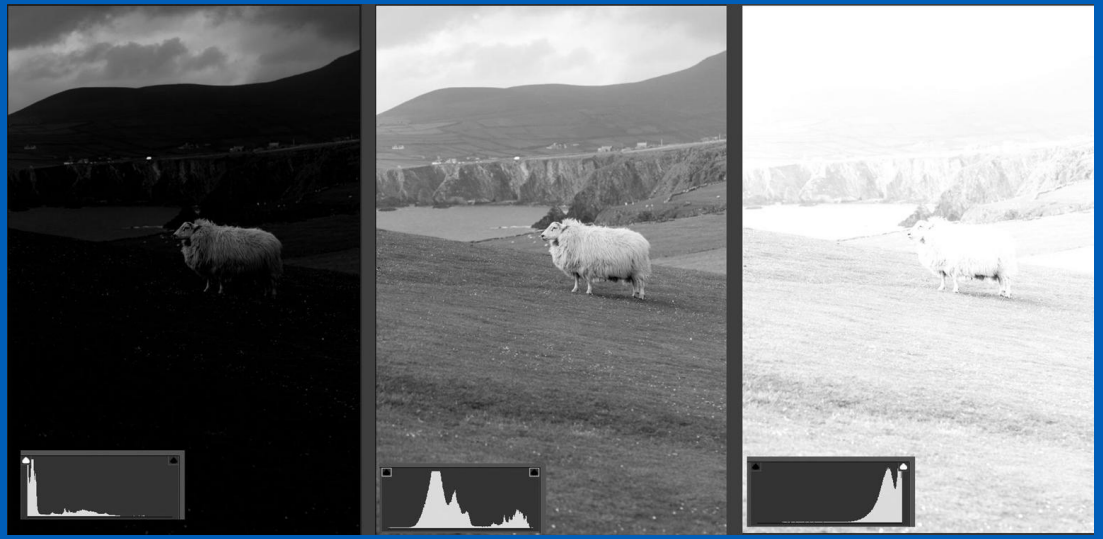
FIGURE 3.16 Four image types and their corresponding histograms. (a) dark; (b) light; (c) low contrast; (d) high contrast. The horizontal axis of the histograms are values of r_k and the vertical axis are values of $p(r_k)$.

Contrast: the difference in intensity between the highest and lowest intensity levels in an image.

Digital Image Processing, González-Woods.

What information contains the histogram?

Dali, The histogram in photography, 2019.
https://dalibro.com/what-is-histogram-in-photography/



Dali, The histogram in photography, 2019.

How can we “correct” these images?

Intensity transformation

Dali, The histogram in photography, 2019.

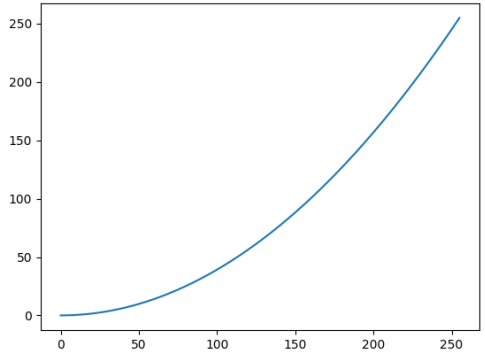
$$A = \begin{pmatrix} a_{1,1} & \dots & a_{1,w} \\ \vdots & & \vdots \\ a_{h,1} & \dots & a_{h,w} \end{pmatrix}$$

$$A' = \begin{pmatrix} f(a_{1,1}) & \dots & f(a_{1,w}) \\ \vdots & & \vdots \\ f(a_{h,1}) & \dots & f(a_{h,w}) \end{pmatrix}$$

Intensity transformation

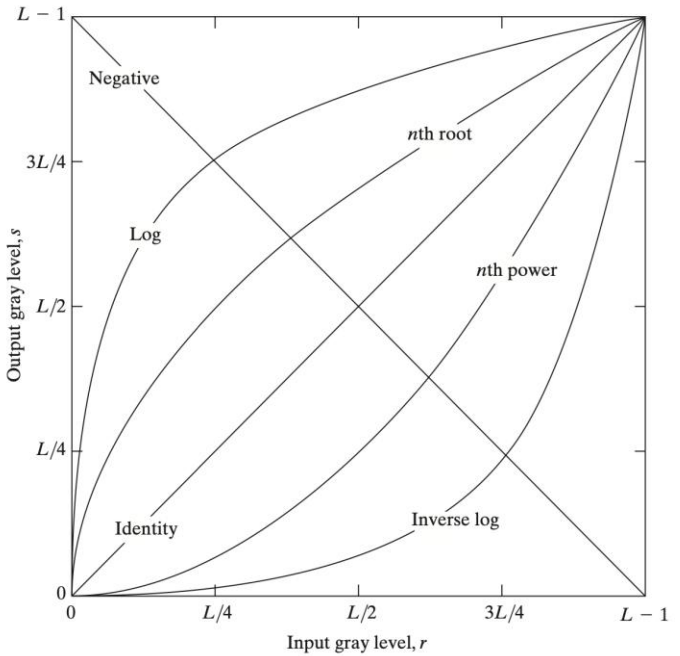
Dali, The histogram in photography, 2019.

x	f(x)
0	0
64	5
128	30
192	128
255	255



Intensity transformation

- Three basic types of functions used frequently in image processing:
  - linear (negative and identity transformations)
  - logarithmic (log and inverse-log transformations),
  - power-law (*n*th power and *n*th root transformations).

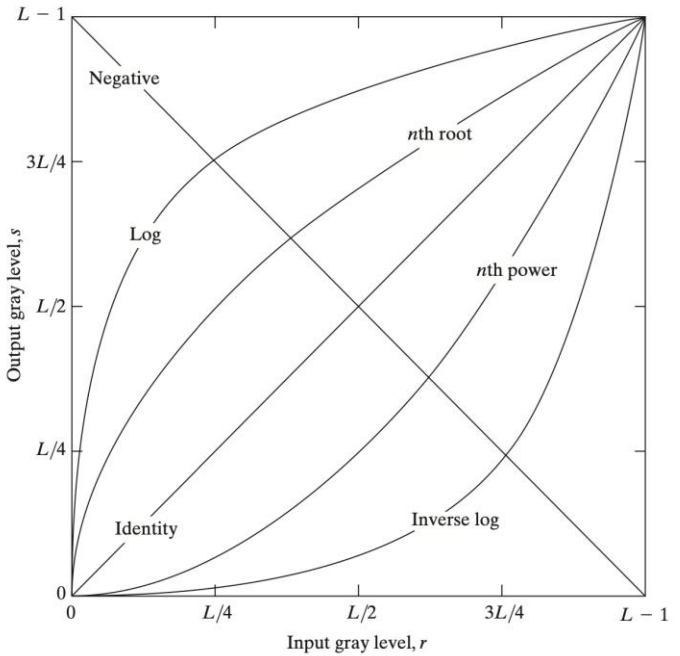


Digital Image Processing (González)

Identity (no transformation)

$$f(x) = x$$

Moon, Public domain.

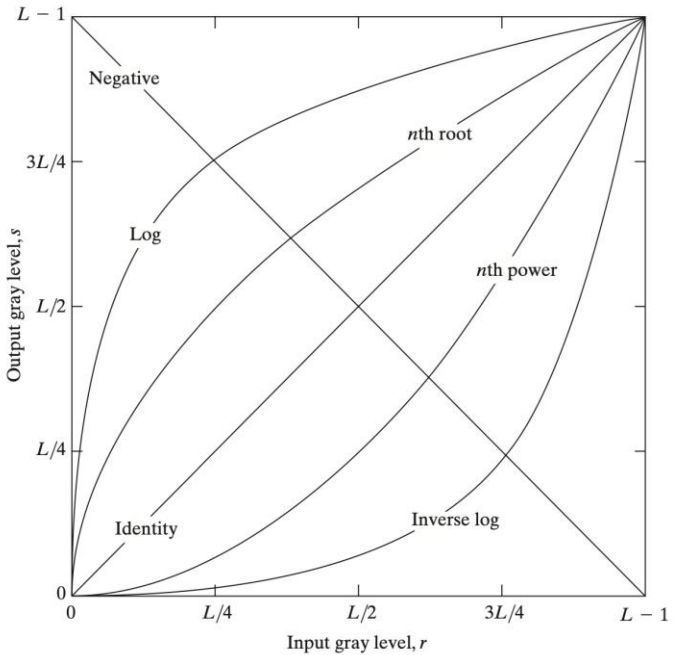


Digital Image Processing (González)

Negative

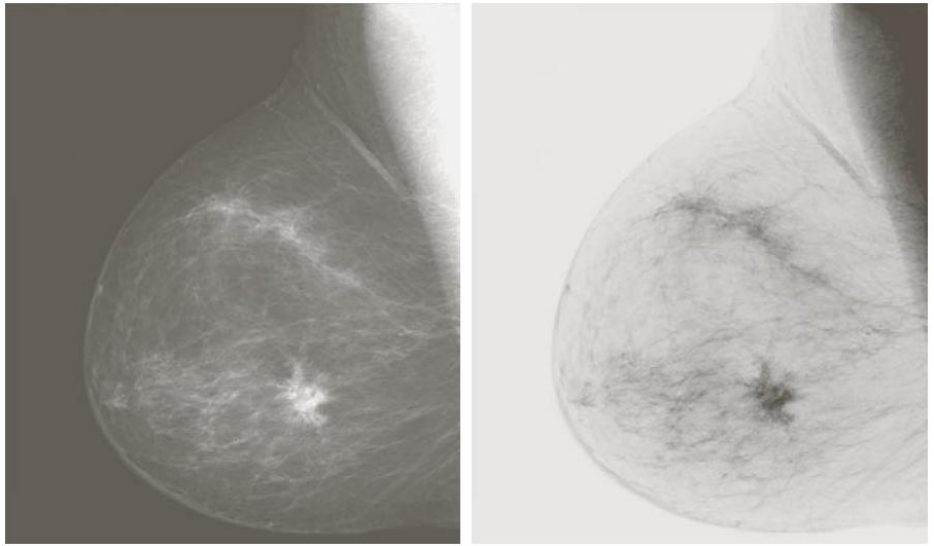
$$f(x) = -x$$

Moon, Public domain.



Digital Image Processing (González)

Negative – Use case



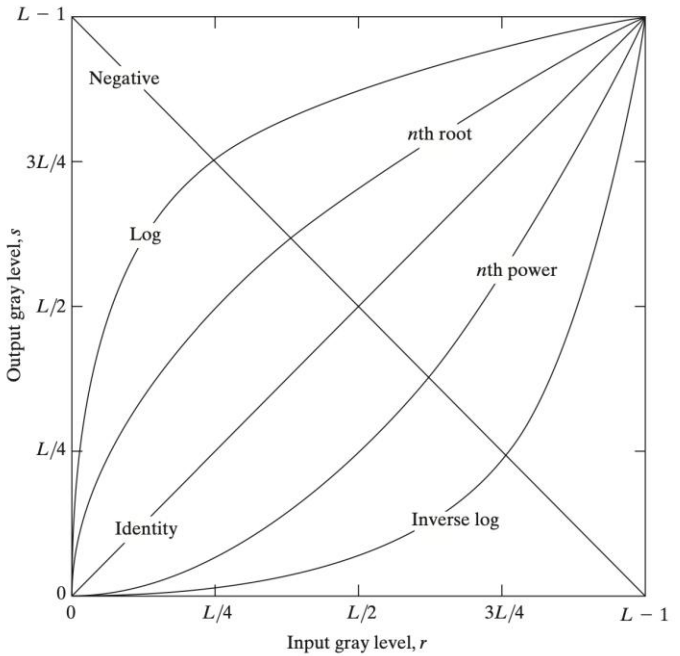
a b

FIGURE 3.4
(a) Original digital mammogram. (b) Negative image obtained using the negative transformation in Eq. (3.2-1). (Courtesy of G.E. Medical Systems.)

Log transform

$$f(x) = c \cdot \log(1 + x)$$

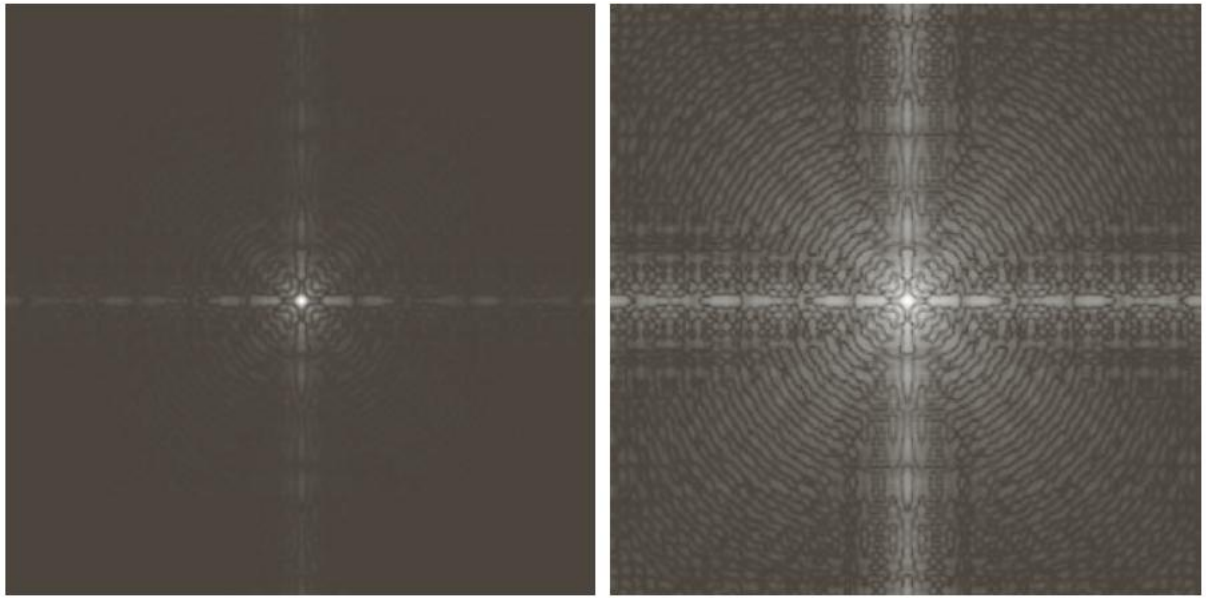
Moon, Public domain.



Digital Image Processing (González)

Log – Use case

Saturation is the highest value beyond which all intensity levels are clipped.

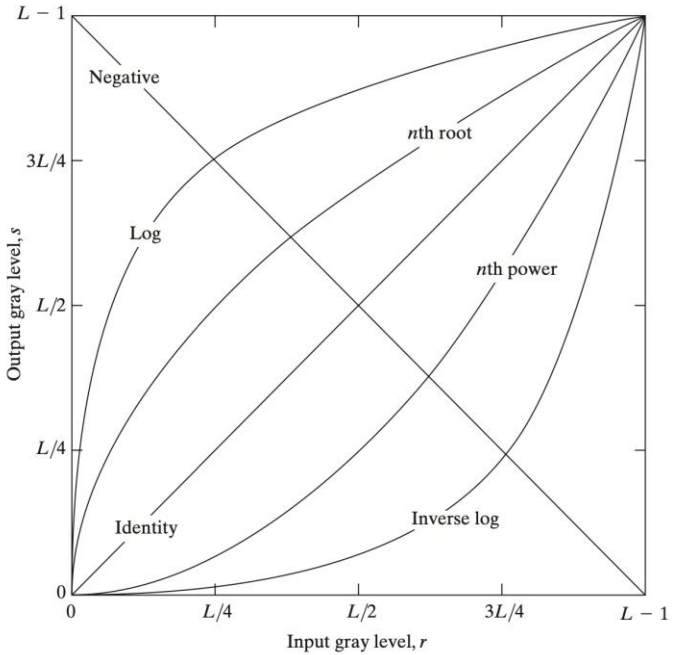


a b

FIGURE 3.5
(a) Fourier spectrum.
(b) Result of applying the log transformation in Eq. (3.2-2) with $c = 1$.

Exp transform (inverse log)

Moon, Public domain.



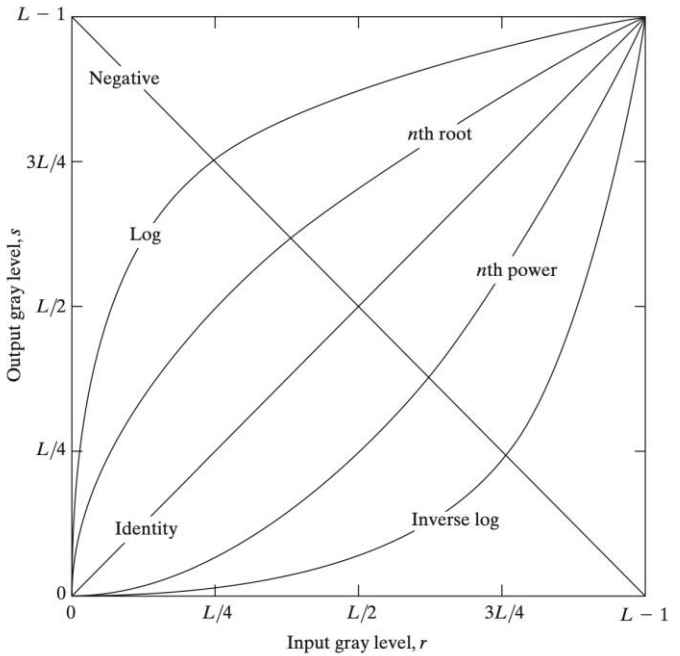
Digital Image Processing (González)

Gamma transform

$$f(x) = c \cdot x^{\gamma}$$

Moon, Public domain.

$$\gamma = 0.5$$



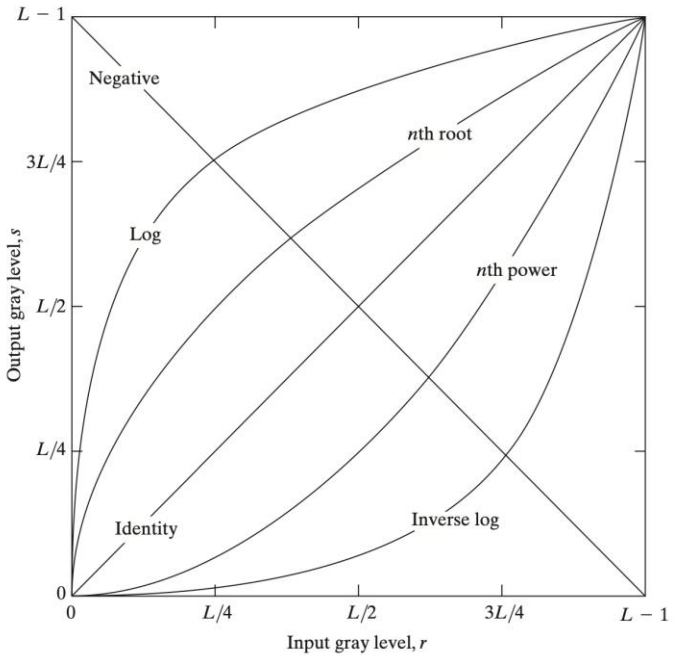
Digital Image Processing (González)

Gamma transform

$$f(x) = c \cdot x^{\gamma}$$

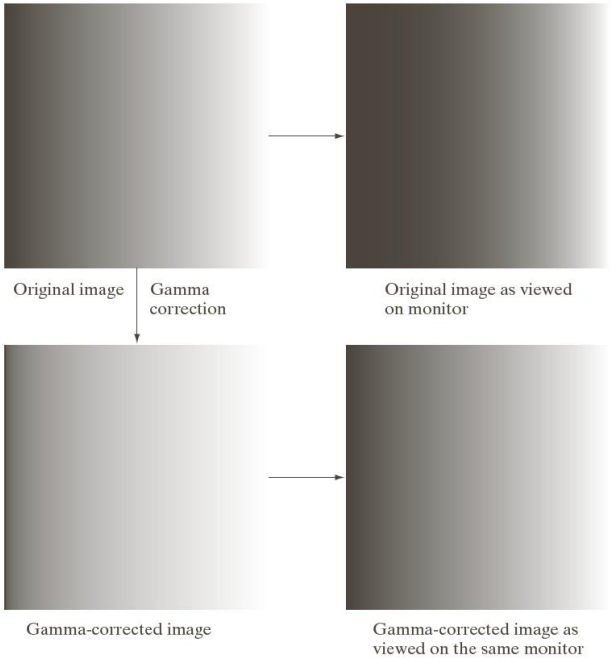
Moon, Public domain.

$$\gamma = 2$$



Digital Image Processing (González)

Gamma – Use case

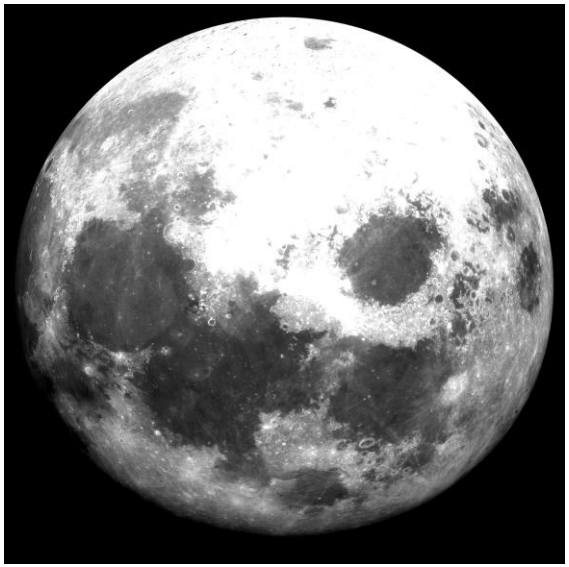


a b
c d

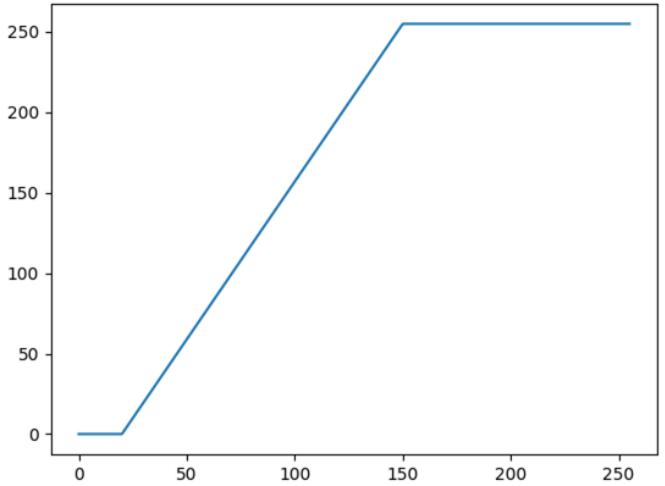
FIGURE 3.7
(a) Intensity ramp image. (b) Image as viewed on a simulated monitor with a gamma of 2.5. (c) Gamma-corrected image. (d) Corrected image as viewed on the same monitor. Compare (d) and (a).

Windowing

Moon, Public domain.



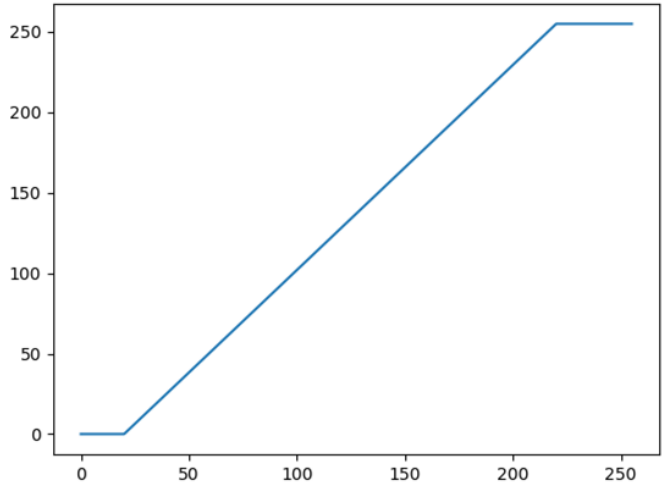
$$f(x) = \begin{cases} 0, & x < a, \\ k \cdot \frac{x-a}{b-a}, & a \le x \le b, \\ k, & x > b. \end{cases}$$



Min-max normalization

$$f(x) = \begin{cases} 0, & x < a, \\ k \cdot \frac{x-a}{b-a}, & a \leq x \leq b, \\ k, & x > b. \end{cases}$$

Moon, Public domain.

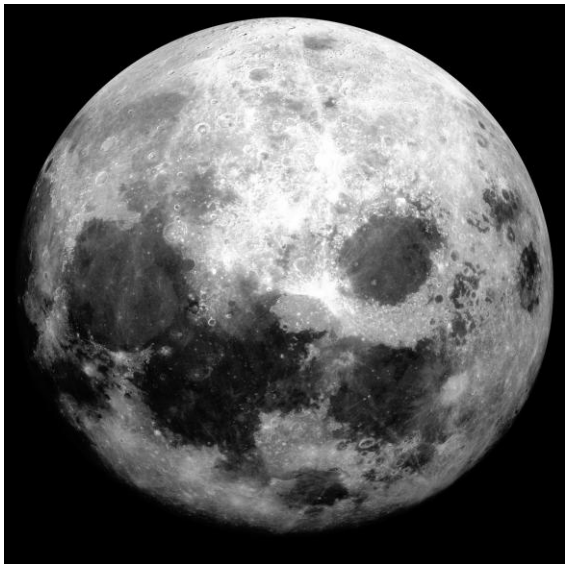


Histogram equalization

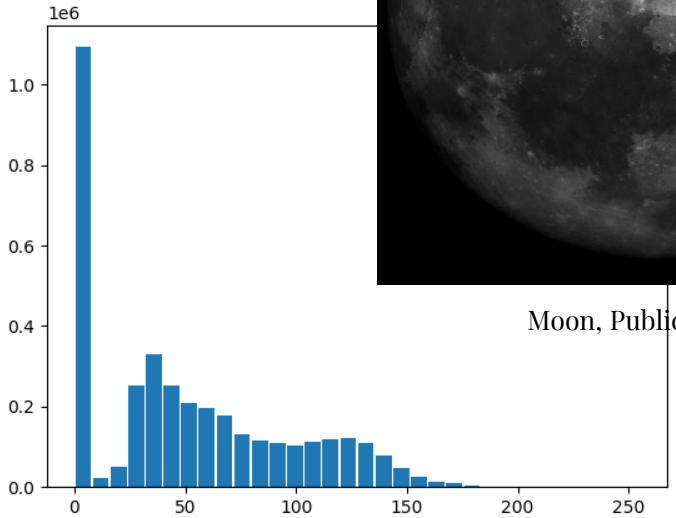
Output image should have a linear histogram

Mapping the original histogram to a uniform distribution.

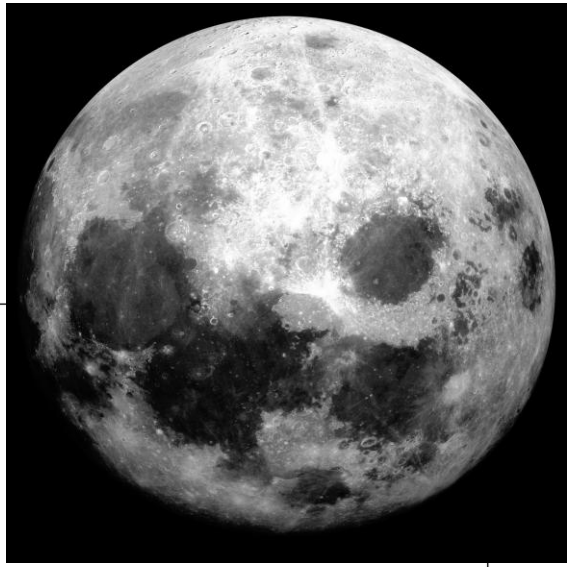
Moon, Public domain.

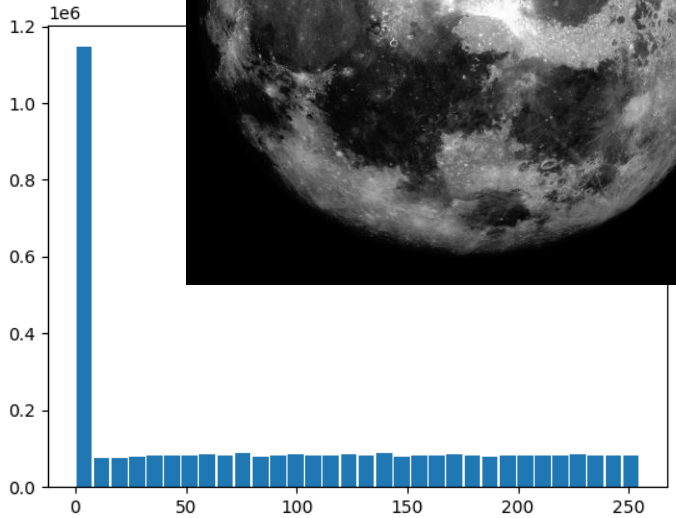


Histogram equalization

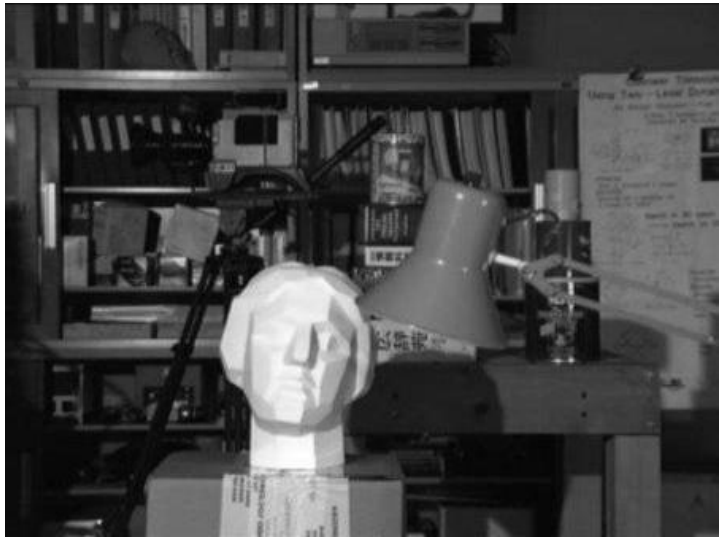


Moon, Public domain.

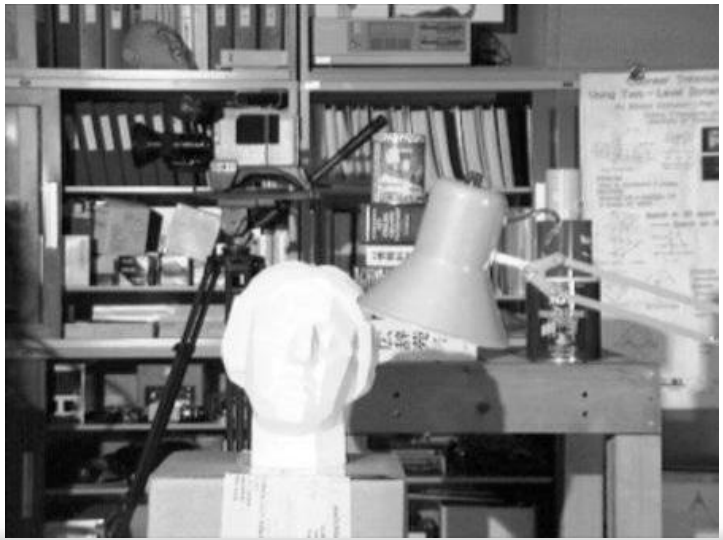




Histogram equalization



Statue, Public domain.



Problems:

1. Greatly increases noise from flat regions
2. “Small" parts might be worsened

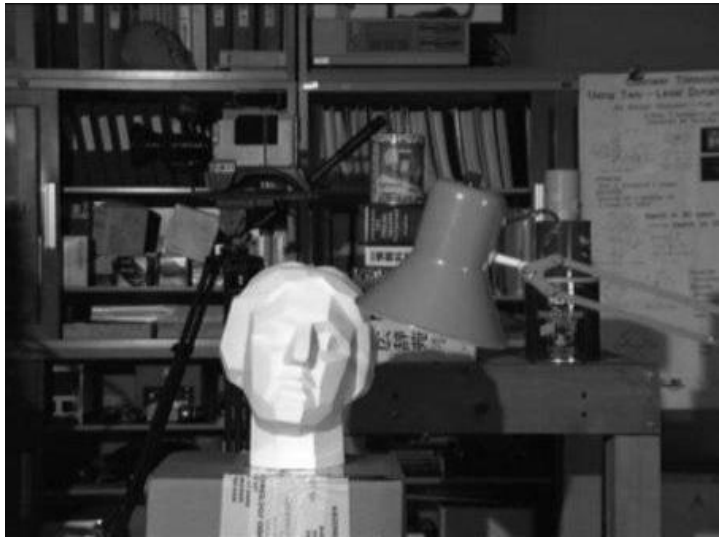
CLAHE (Contrast-limited adaptive histogram equalization)

Moon, Public domain.

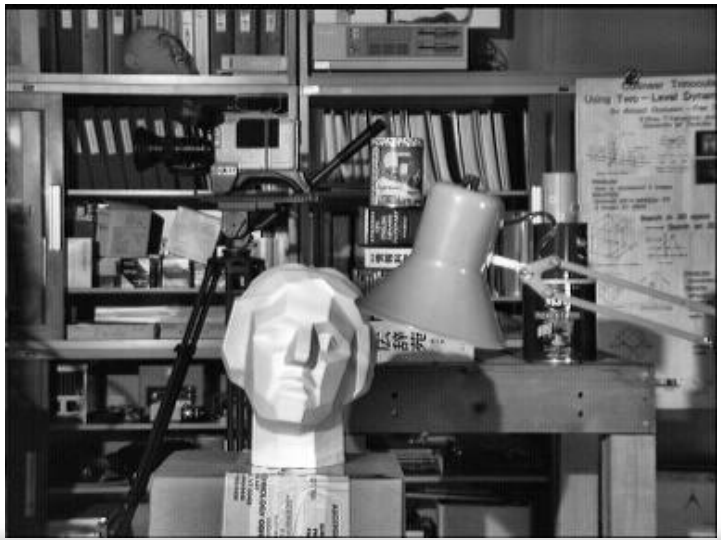
Solutions:

1. Contrast-limited: avoid making the histogram “too linear”
2. Adaptive: treat each part of the image differently

CLAHE (Contrast-limited adaptive histogram equalization)



Statue, Public domain.



Solutions:

1. Contrast-limited: avoid making the histogram “too linear”
2. Adaptive: treat each part of the image differently

Exercise:

For a `uint8` grayscale image (0-255), find the mathematical expressions to apply the following intensity transformations:

- Negative
- Log
- Exponential
- Gamma transform
- Windowing
- Max-Normalization
- Histogram