CS 370: Computer Imaging

Pushpak Karnick

Motivation to study Image Processing

Why Image Processing?

- Images are ubiquitous
- Casual and targeted output
  - Social Media …
  - Photoshop, Inkscape, …
  - Maya, ZBrush, Houdini …
- Output of the 3D Visualization Pipeline

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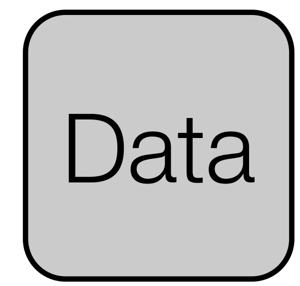

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Data
Processing

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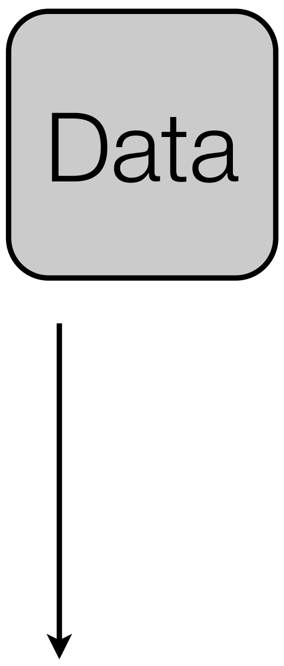
Data Processing



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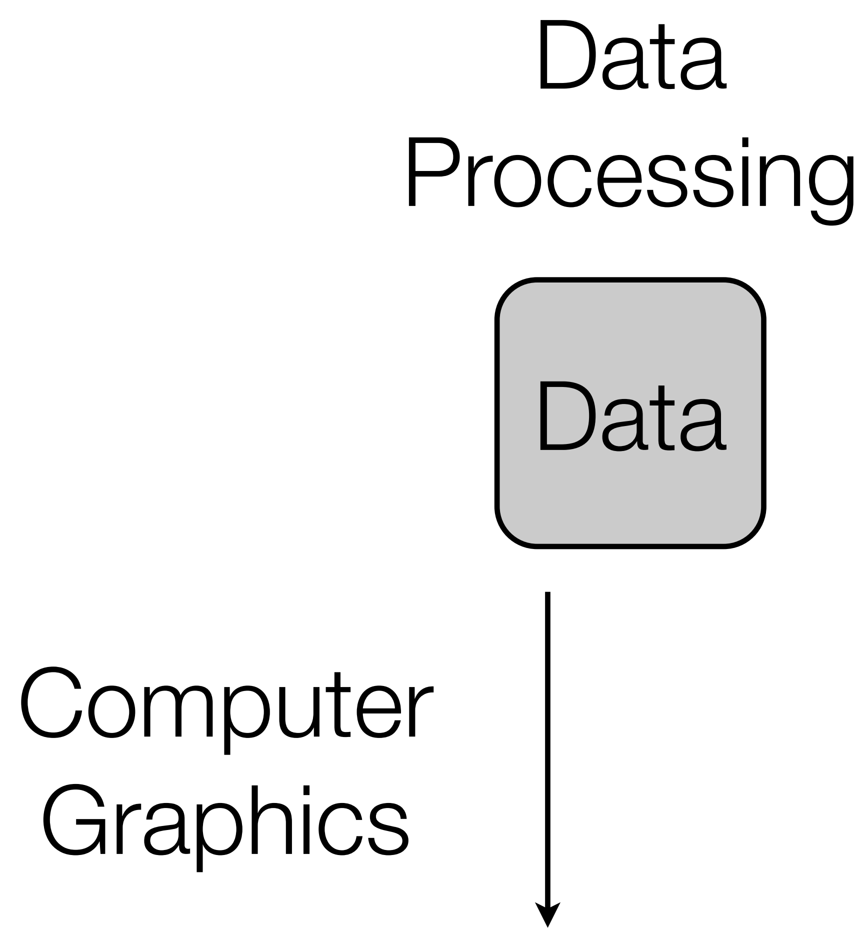

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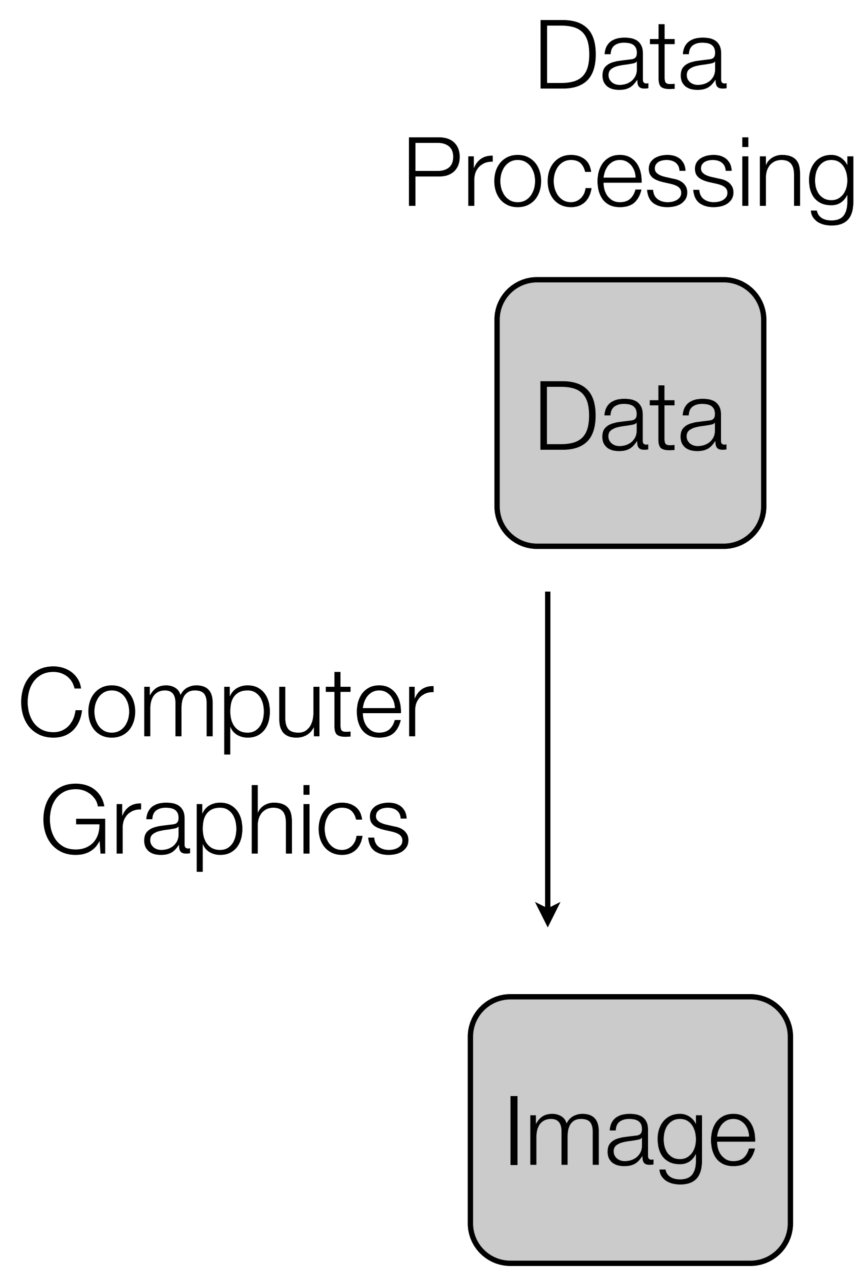

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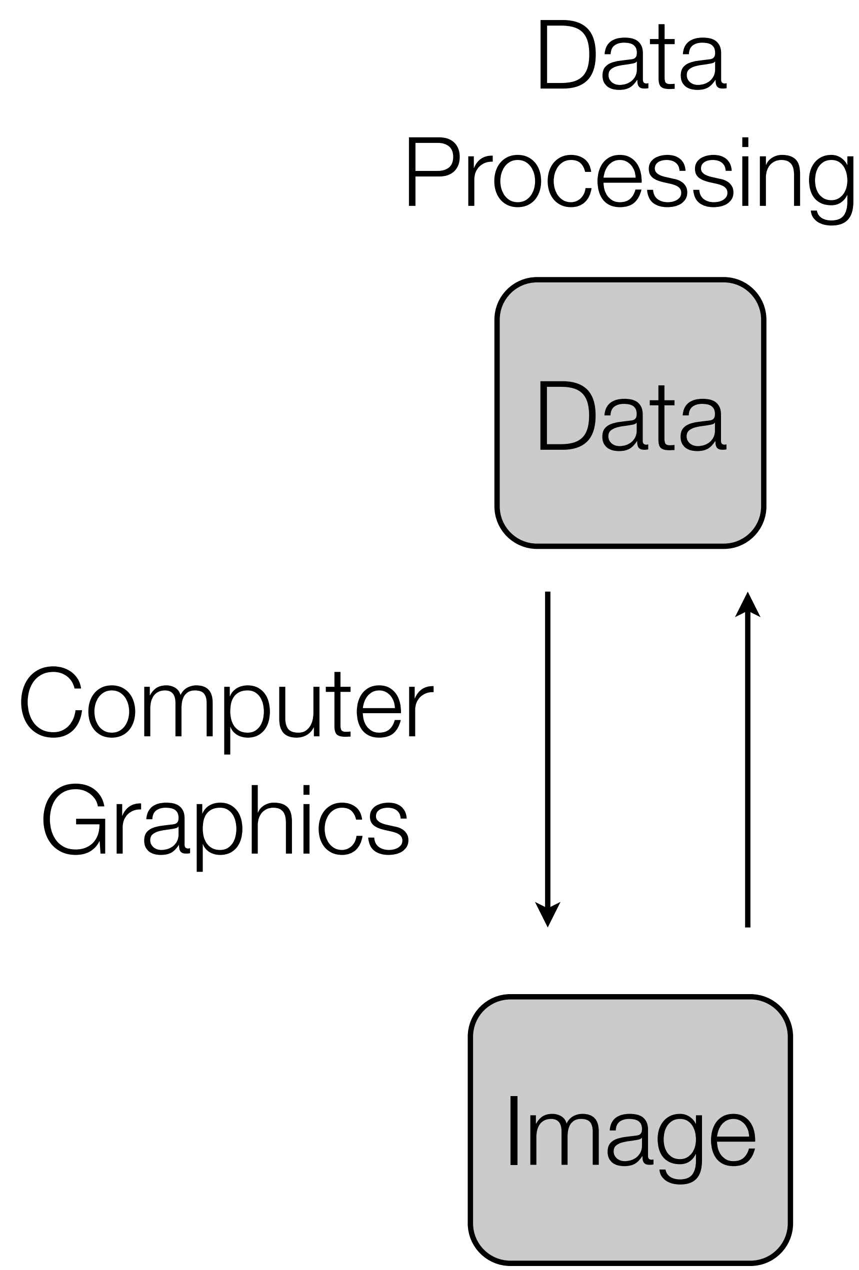

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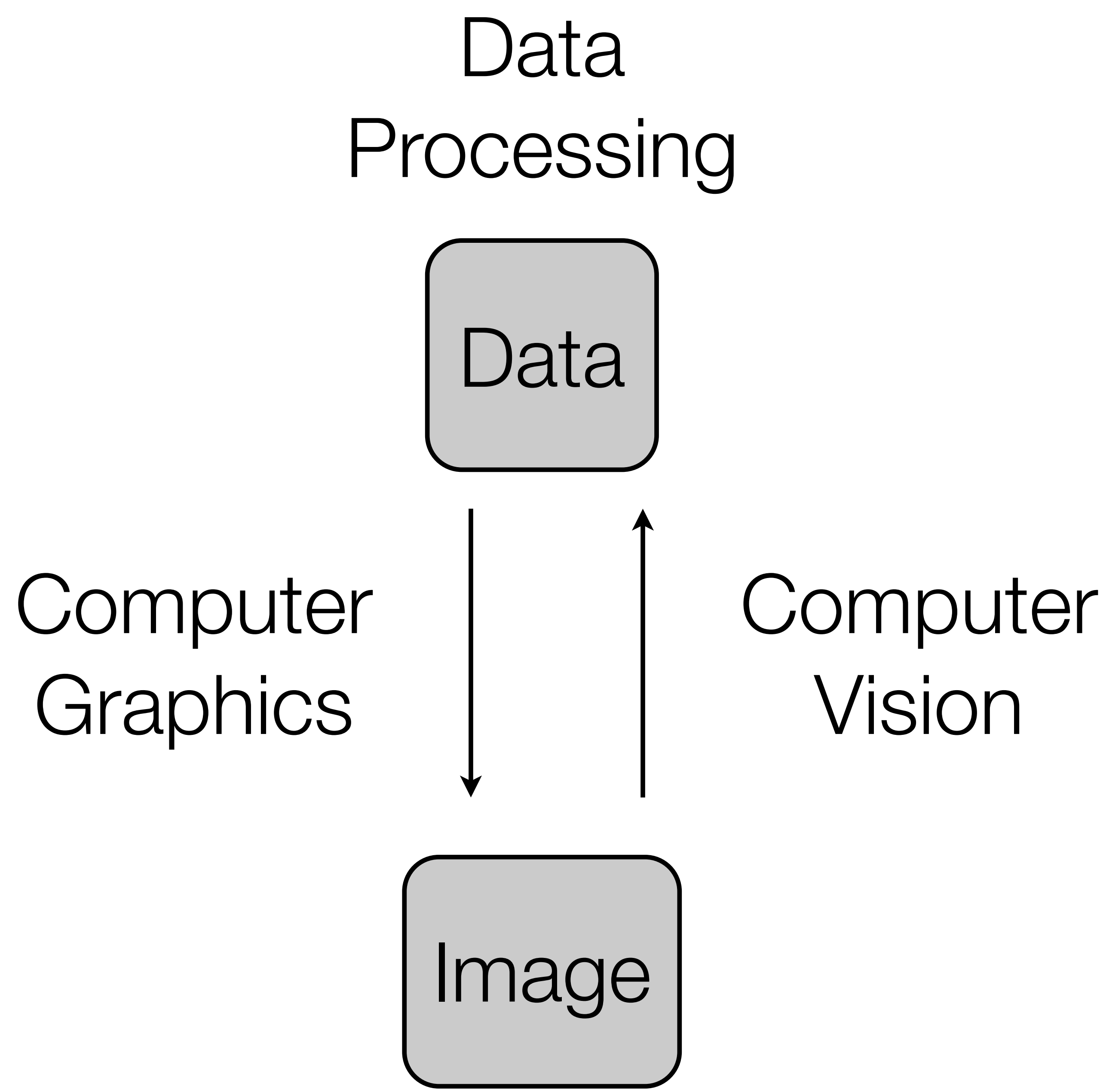

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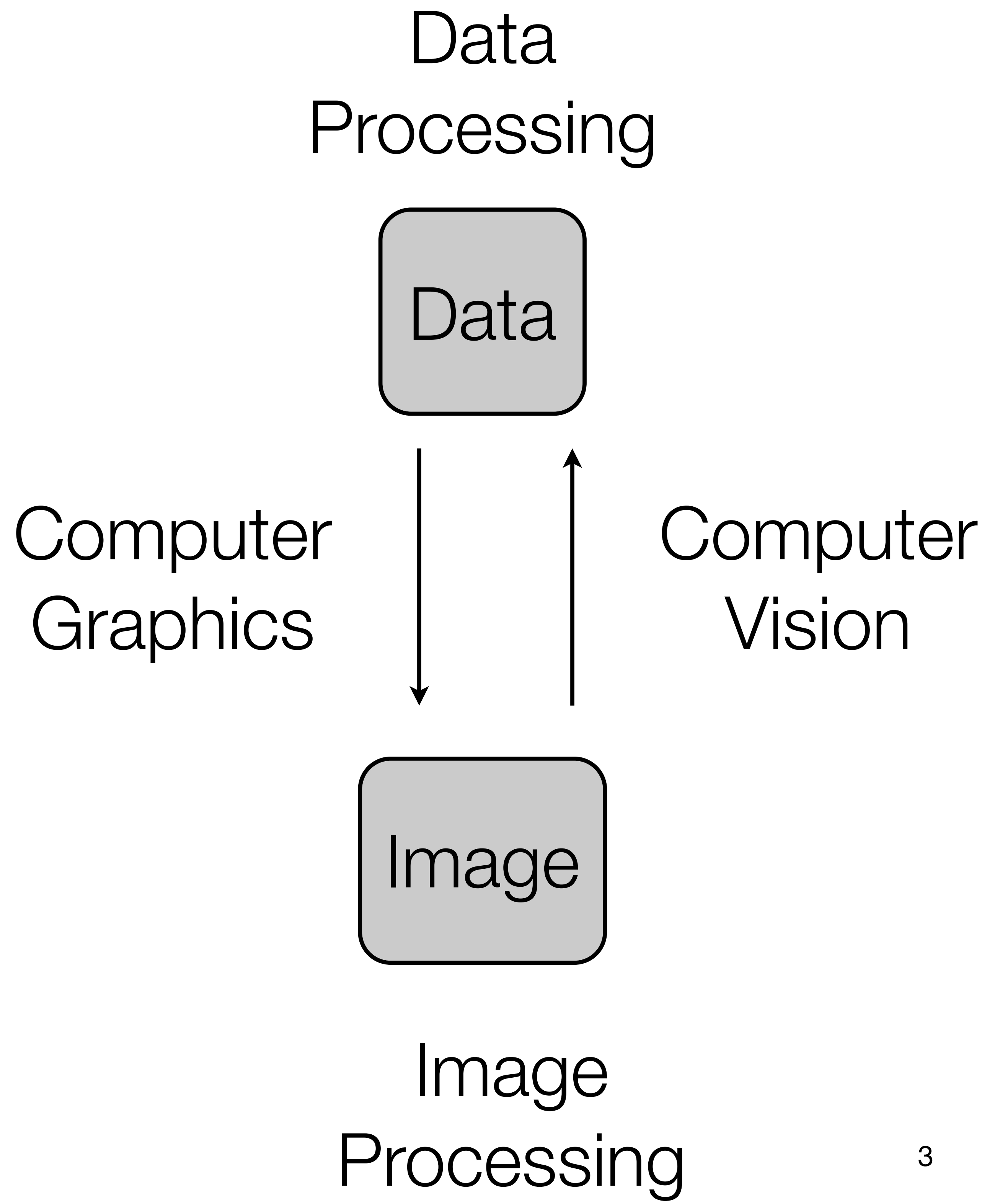
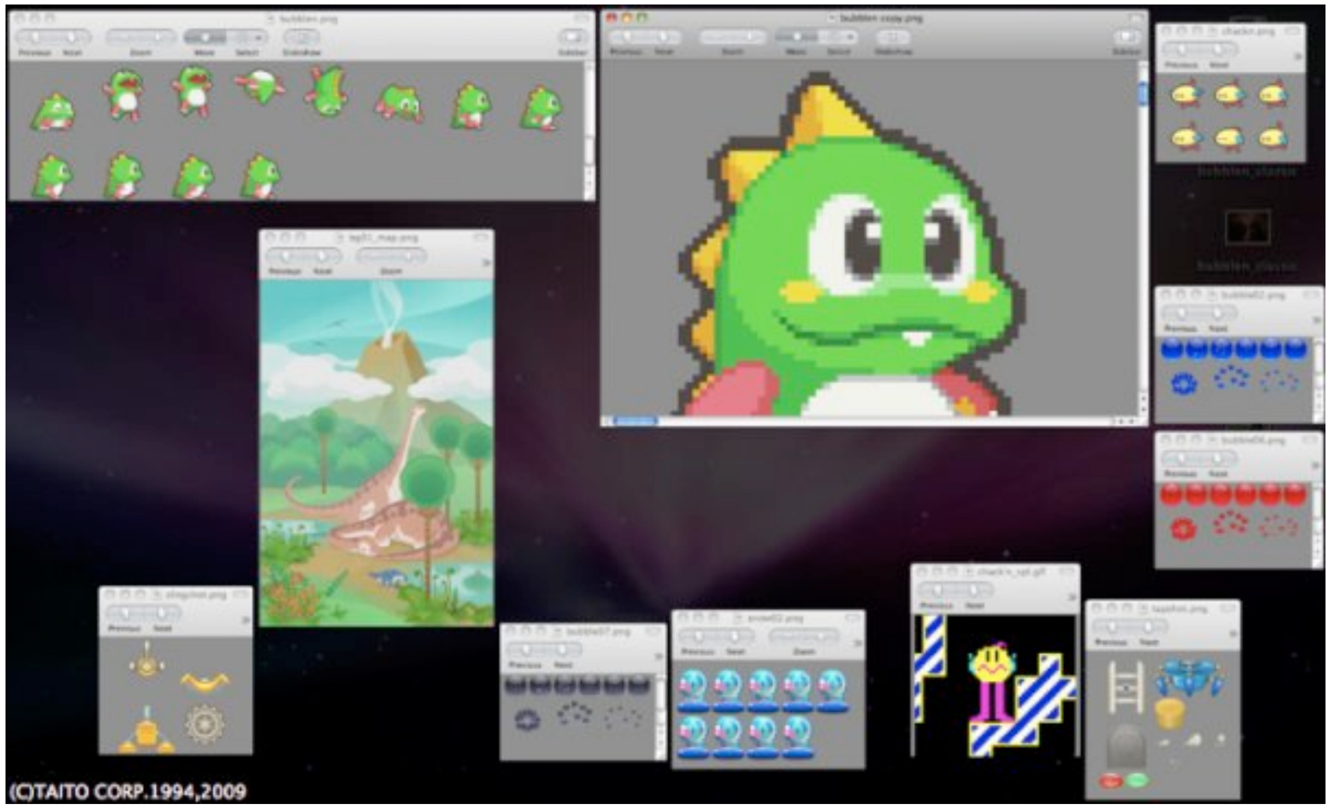
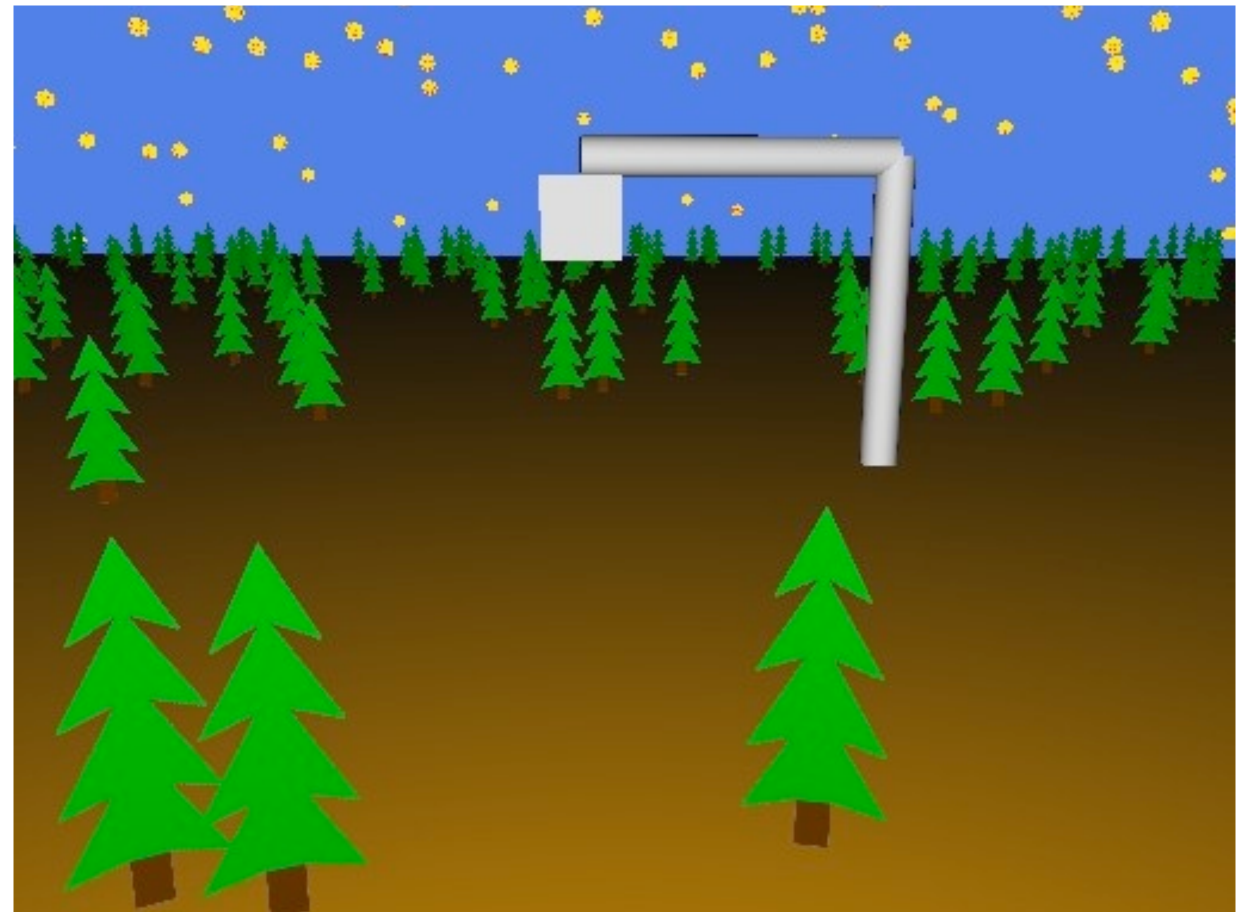


Image-based Methods in Games

- Sprites, billboards, HUDs
- Particle Systems
- Post-processing operations
  - Tone mapping - High Dynamic Range (HDR) Imaging
  - Real-time glow
  - Depth-of-field
  - Motion Blur

Sprites, Billboards





(c) Taito Corp, 2009

Figure courtesy www.gametrailers.com

Heads-up Displays (HUDs)

Metroid Prime

Mass Effect, BioWare

High Dynamic Range (HDR)




Images courtesy
wikipedia.org

High Dynamic Range (HDR)




Images courtesy
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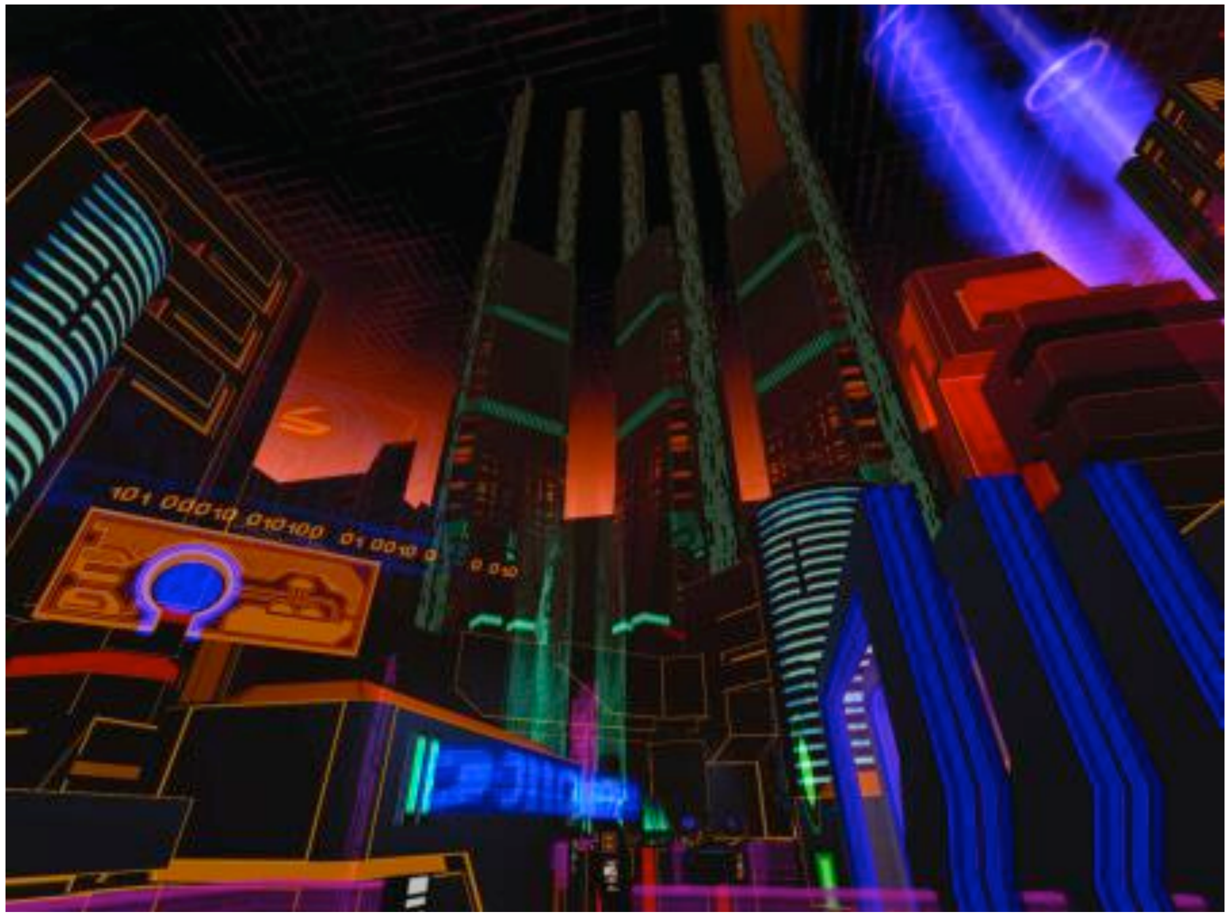
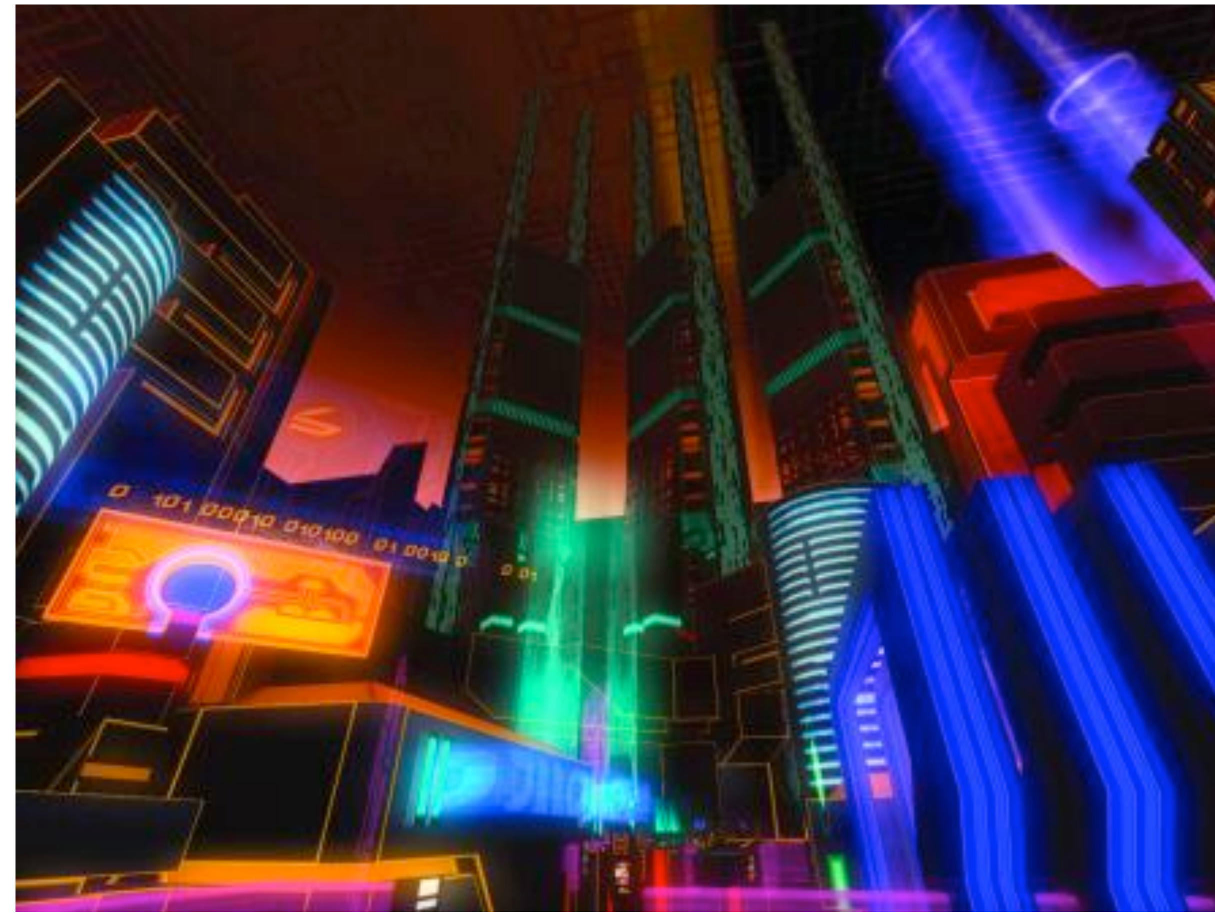
Real-time Glow (Bloom)





Tron 2.0 (c) Buena Vista Interactive / Disney Productions

Depth of Field Effects

Images courtesy www.gametrailers.com

But… what’s trending in “Image Processing and Computer Vision” **today**?

Edge AI, Vision Transformers (ViT), Generative AI
Multimodal, 3D Vision / Depth Estimation
Self-supervised Learning
Synthetic Data, Explainable AI (XAI)
Real-time Processing, Video Analysis
Federated Learning, Hyperspectral Imaging
Low-light Enhancement, Deepfake Detection
Event Cameras, Robotics, AR/VR
Ethical AI
Quantum Image, Energy-efficient/Efficient AI
Biomedical Imaging


light
Biomedical
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- **Event Cameras**, **Quantum Image Processing**, **Biomedical Imaging**, **Energy-efficient AI**: Cutting-edge techniques gaining traction in specialized research.

This is a LOT

- Yup!
- Most 4-year degrees would not be able to cover all of the topics mentioned in the previous slide**, to the depth and understanding required from a CS graduate**
- Our approach: First, get the fundamentals, then build on top
- Another view: ***First depth, then breadth***

How did we get ***here***?

A look through the history of Image Processing

FIGURE 1.1 A digital picture produced in 1921 from a coded tape by a telegraph printer with special typefaces. (McFarlane.) [References in the bibliography at the end of the book are listed in alphabetical order by authors' last names.]

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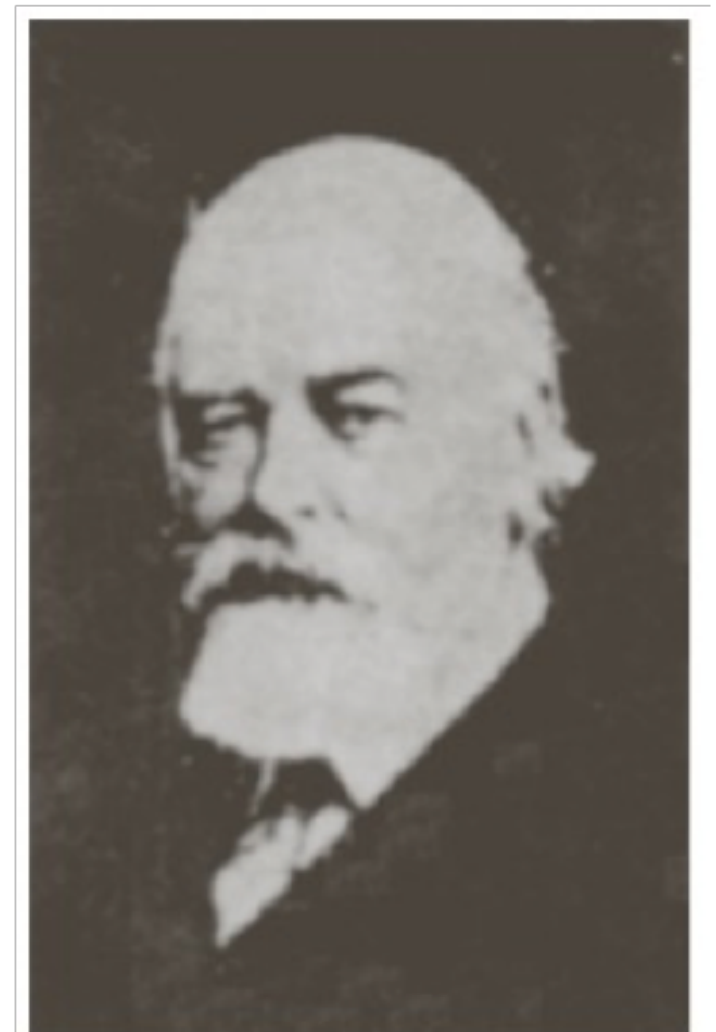
FIGURE 1.2 A digital picture made in 1922 from a tape punched after the signals had crossed the Atlantic twice. (McFarlane.)



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15 levels
of gray values

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A digital picture made in 1922 from a tape punched after the signals had crossed the Atlantic twice. (McFarlane.)

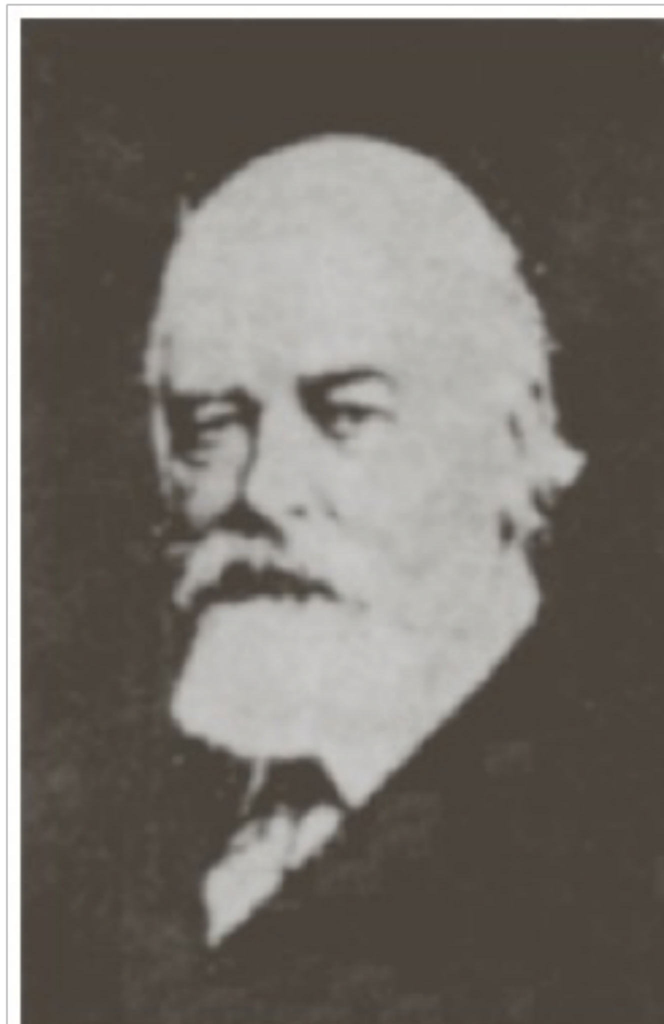
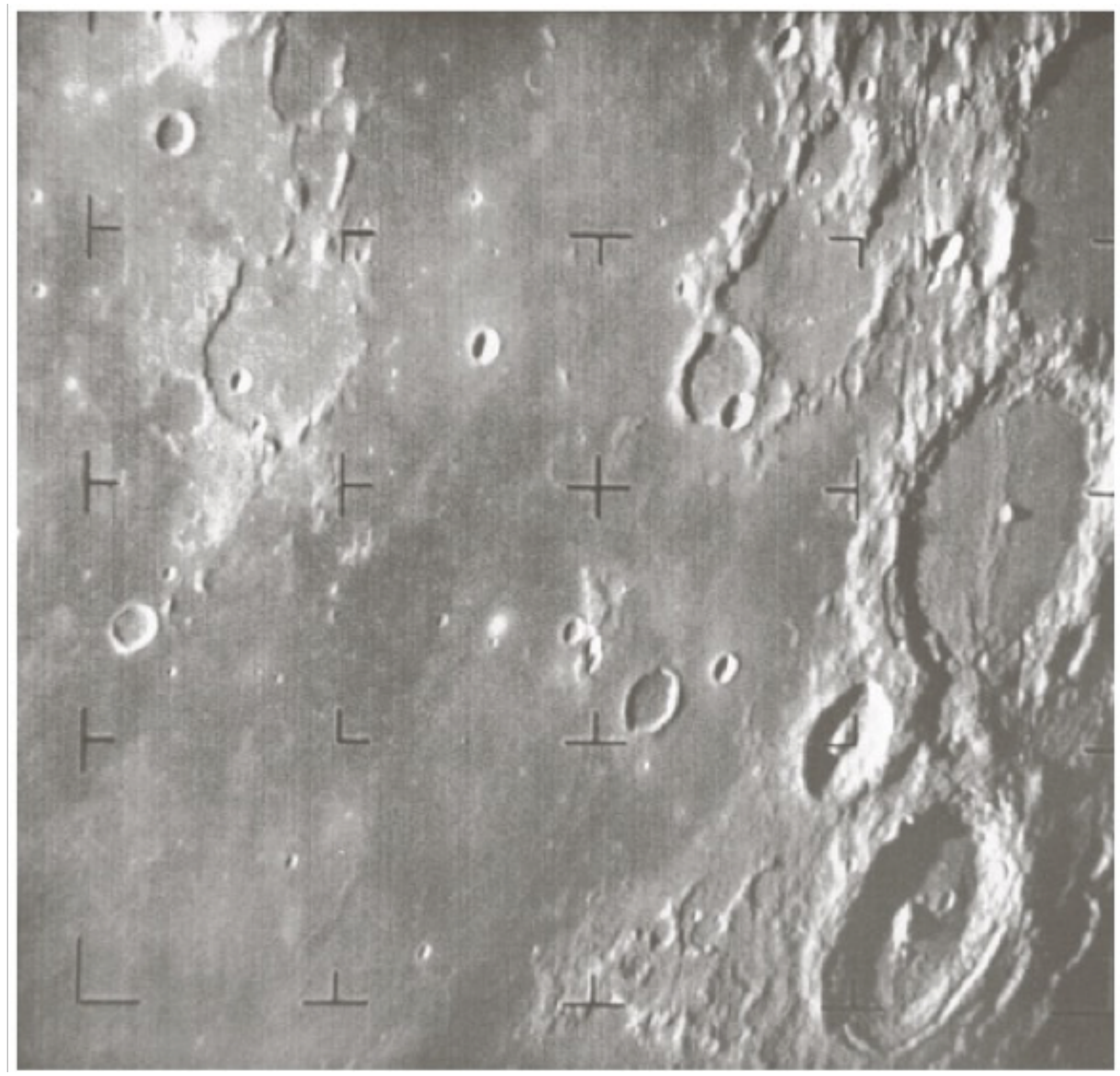
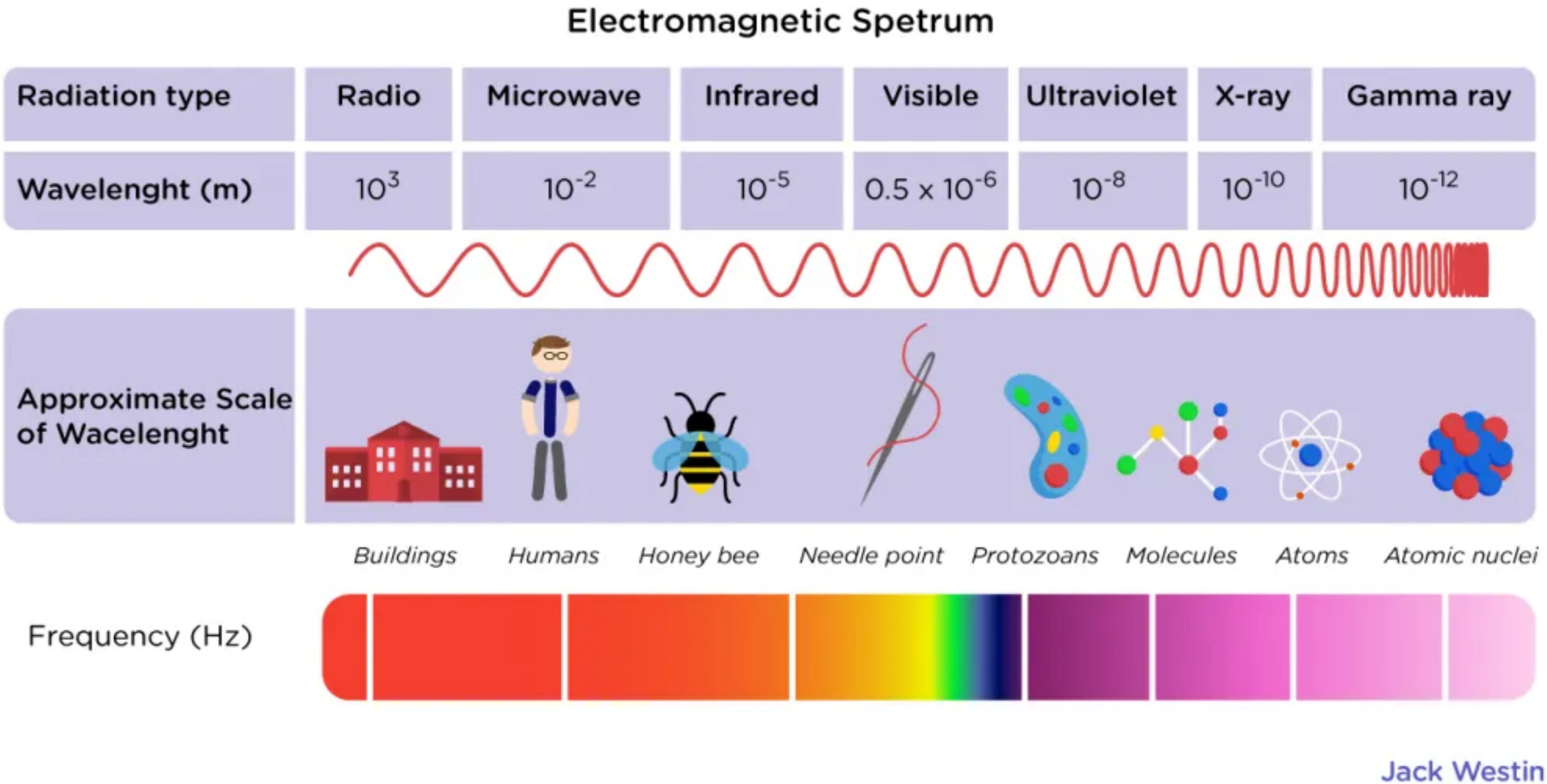


FIGURE 1.4 The first picture of the moon by a U.S. spacecraft. *Ranger 7* took this image on July 31, 1964 at 9:09 A.M. EDT, about 17 minutes before impacting the lunar surface. (Courtesy of NASA.)



Truly “digital” images



https://jackwestin.com/resources/mcat-content/light-and-electromagnetic-radiation/classification-of-electromagnetic-spectrum-photon-energy-e-hf

a d
c
b e

FIGURE 1.7 Examples of X-ray imaging. (a) Chest X-ray. (b) Aortic angiogram. (c) Head CT. (d) Circuit boards. (e) Cygnus Loop. (Images courtesy of (a) and (c) Dr. David R. Pickens, Dept. of Radiology & Radiological Sciences, Vanderbilt University Medical Center; (b) Dr. Thomas R. Gest, Division of Anatomical Sciences, Univ. of Michigan Medical School; (d) Mr. Joseph E. Pascente, Lixi, Inc.; and (e) NASA.)

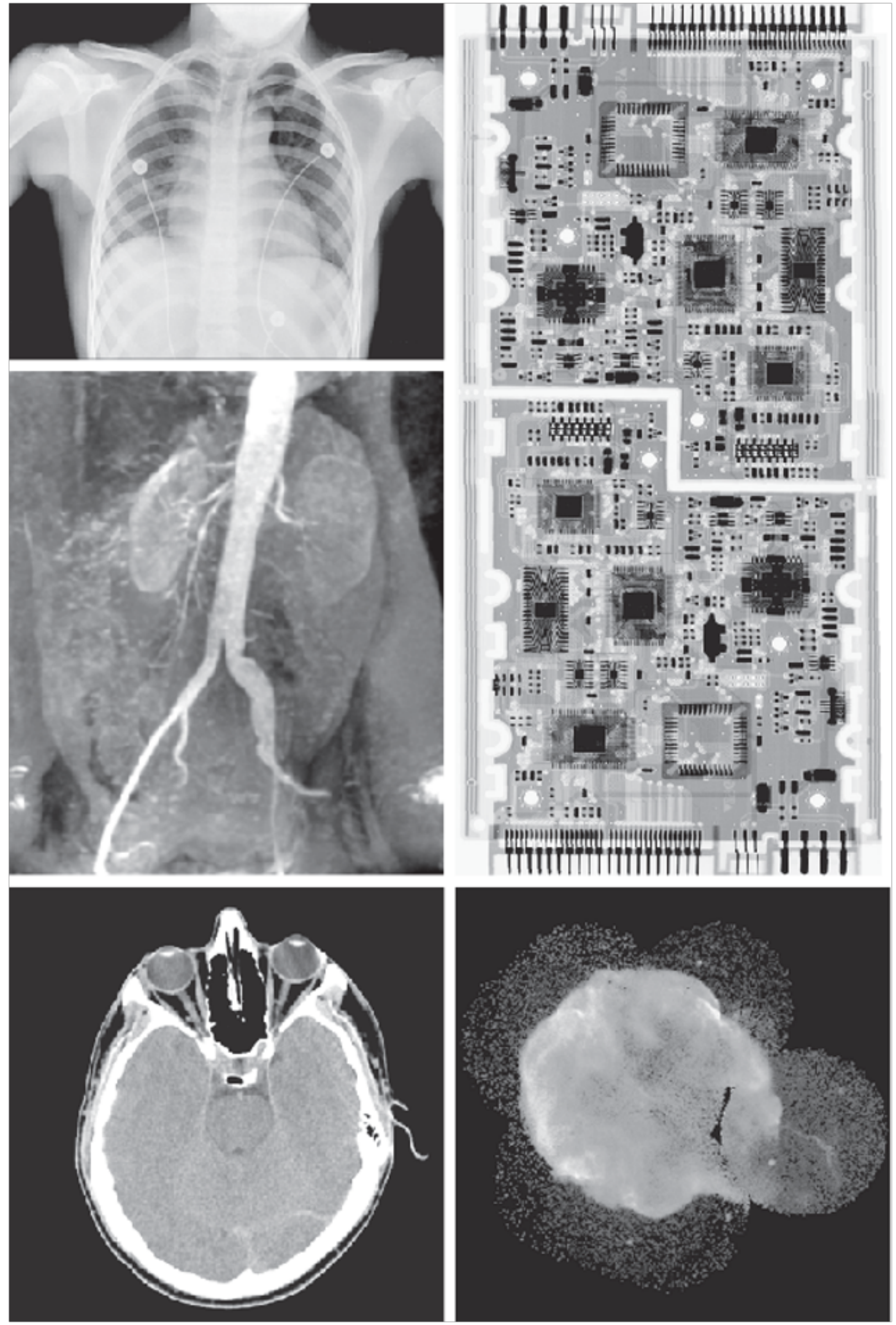


TABLE 1.1
Thematic bands of NASA's LANDSAT satellite.

Band No.	Name	Wavelength (μm)	Characteristics and Uses
1	Visible blue	0.45–0.52	Maximum water penetration
2	Visible green	0.53–0.61	Measures plant vigor
3	Visible red	0.63–0.69	Vegetation discrimination
4	Near infrared	0.78–0.90	Biomass and shoreline mapping
5	Middle infrared	1.55–1.75	Moisture content: soil/vegetation
6	Thermal infrared	10.4–12.5	Soil moisture; thermal mapping
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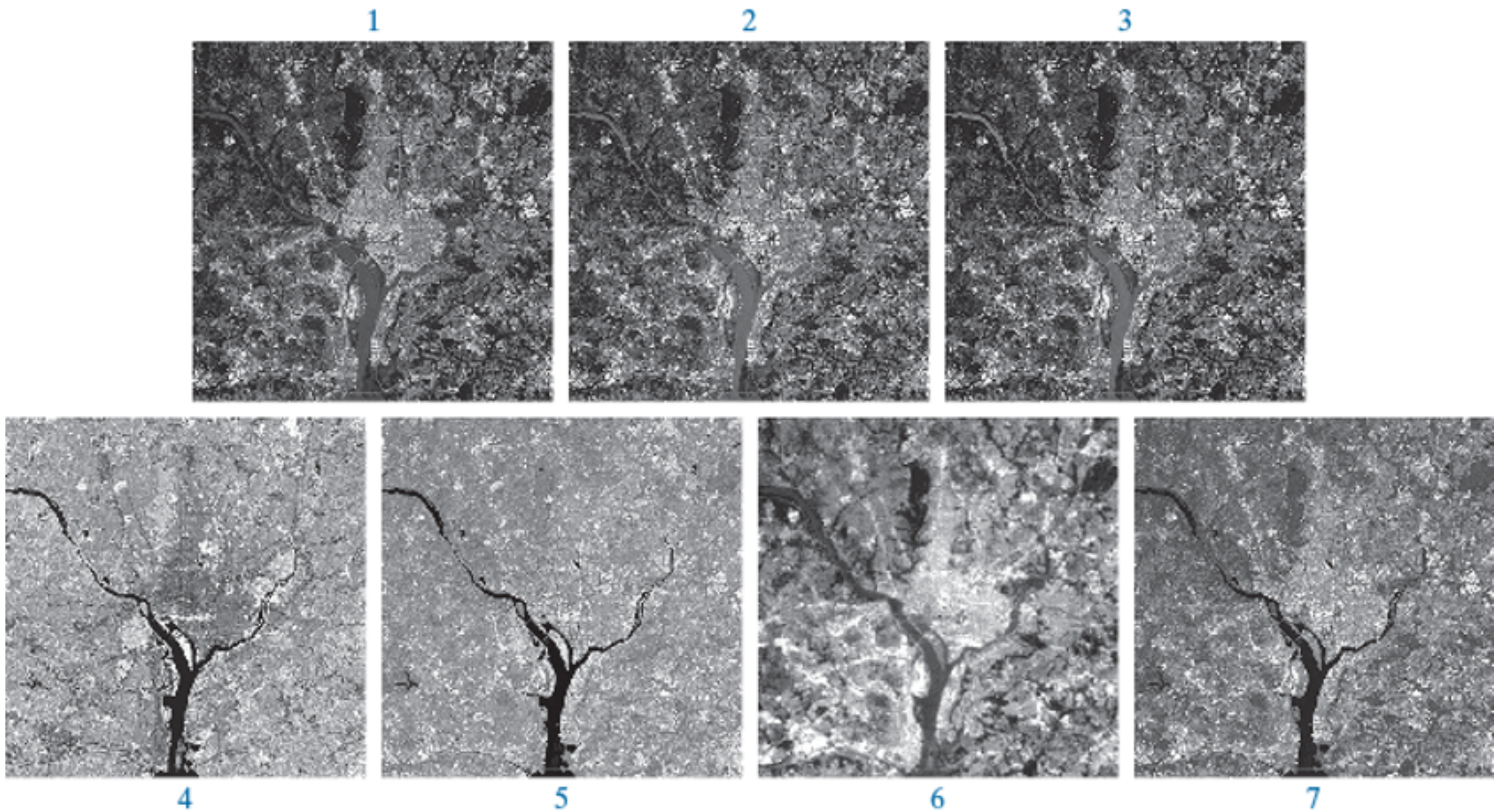


FIGURE 1.10 LANDSAT satellite images of the Washington, D.C. area. The numbers refer to the thematic bands in Table 1.1. (Images courtesy of NASA.)

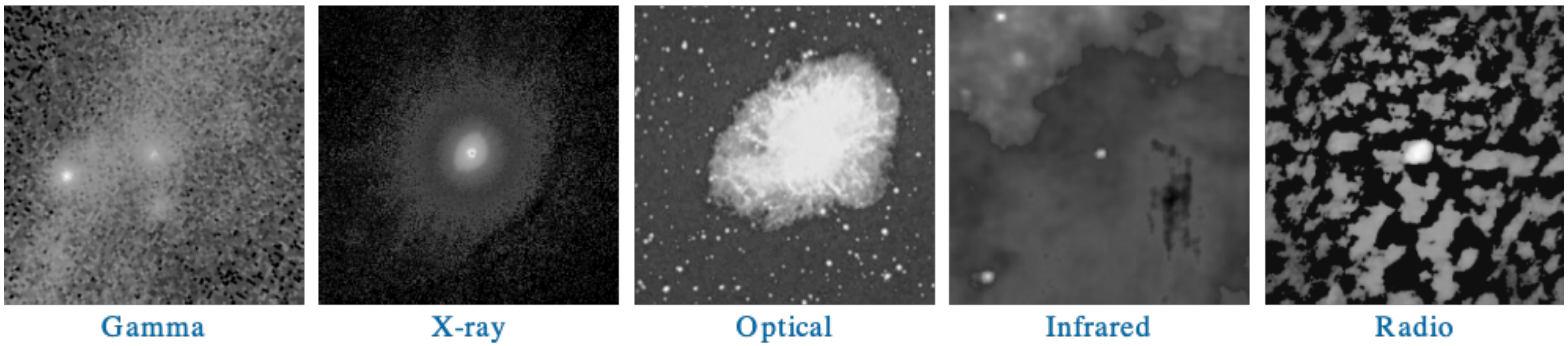


FIGURE 1.18 Images of the Crab Pulsar (in the center of each image) covering the electromagnetic spectrum. (Courtesy of NASA.)

Key Steps in Digital Image Processing

or

*“**What** can I do with this image?”*

FIGURE 1.23 Fundamental steps in digital image processing. The chapter(s) indicated in the boxes is where the material described in the box is discussed.

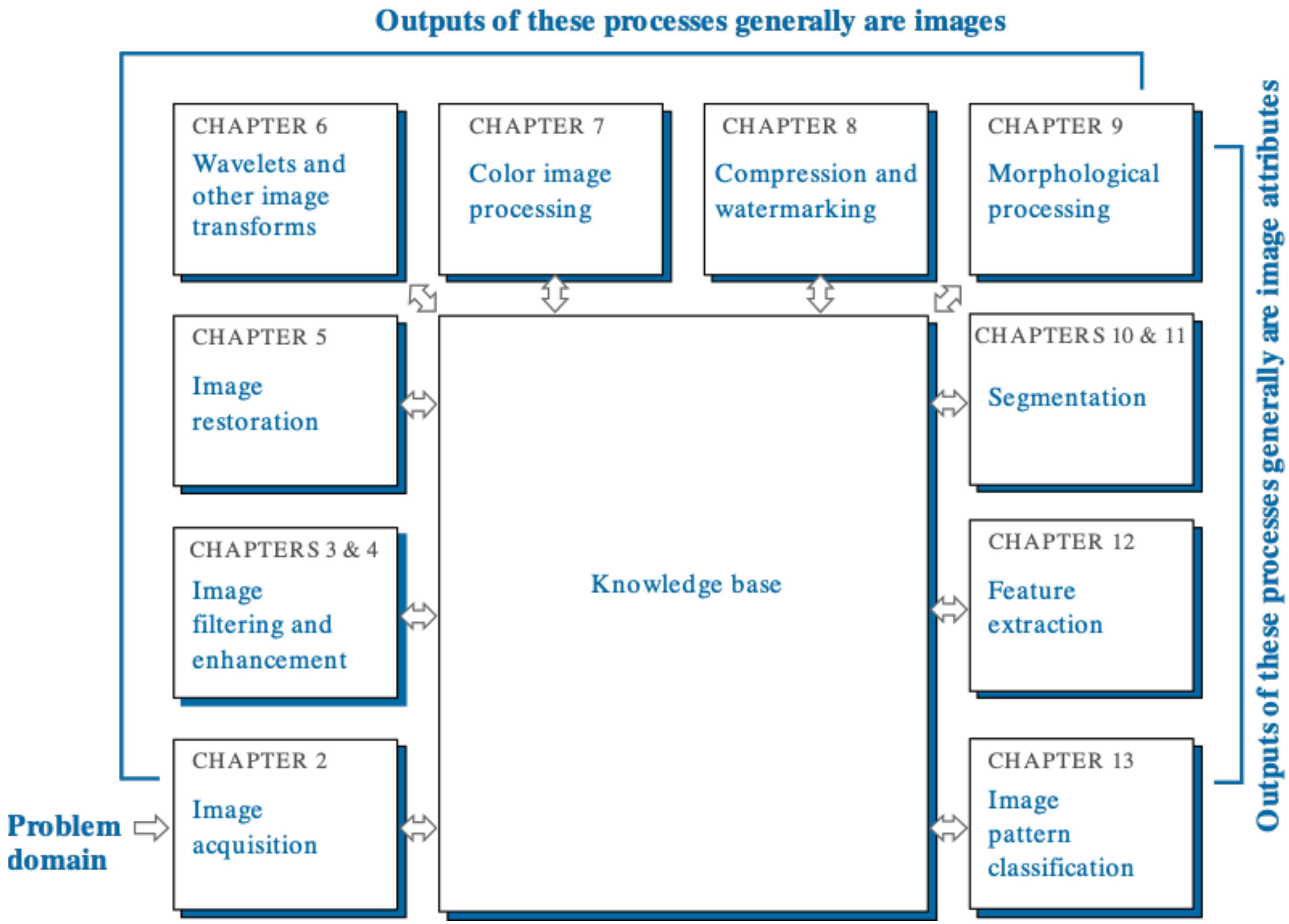
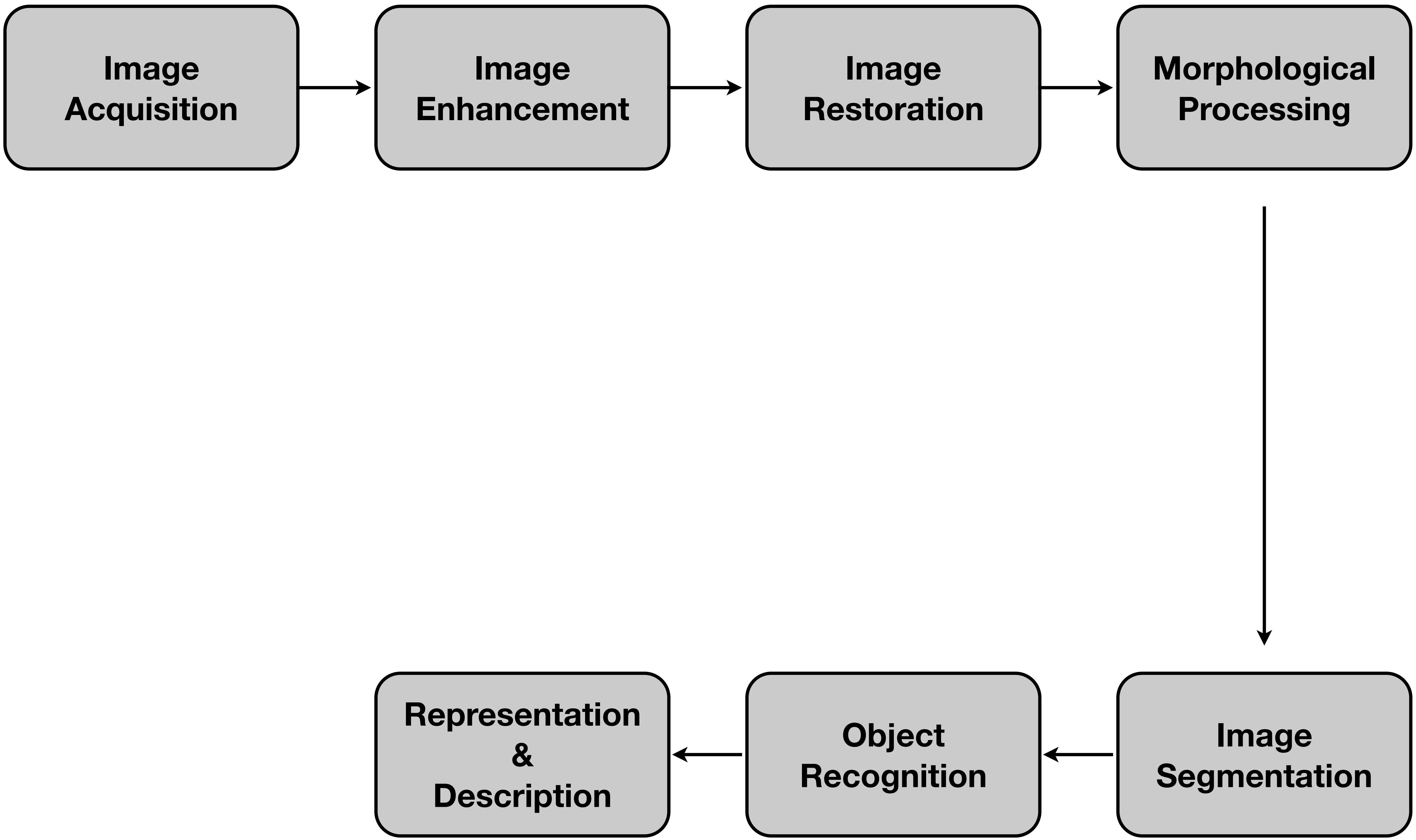


Image courtesy "Digital Image Processing," by Gonzalez & Woods, 4th ed.

Digital Image Processing Pipeline

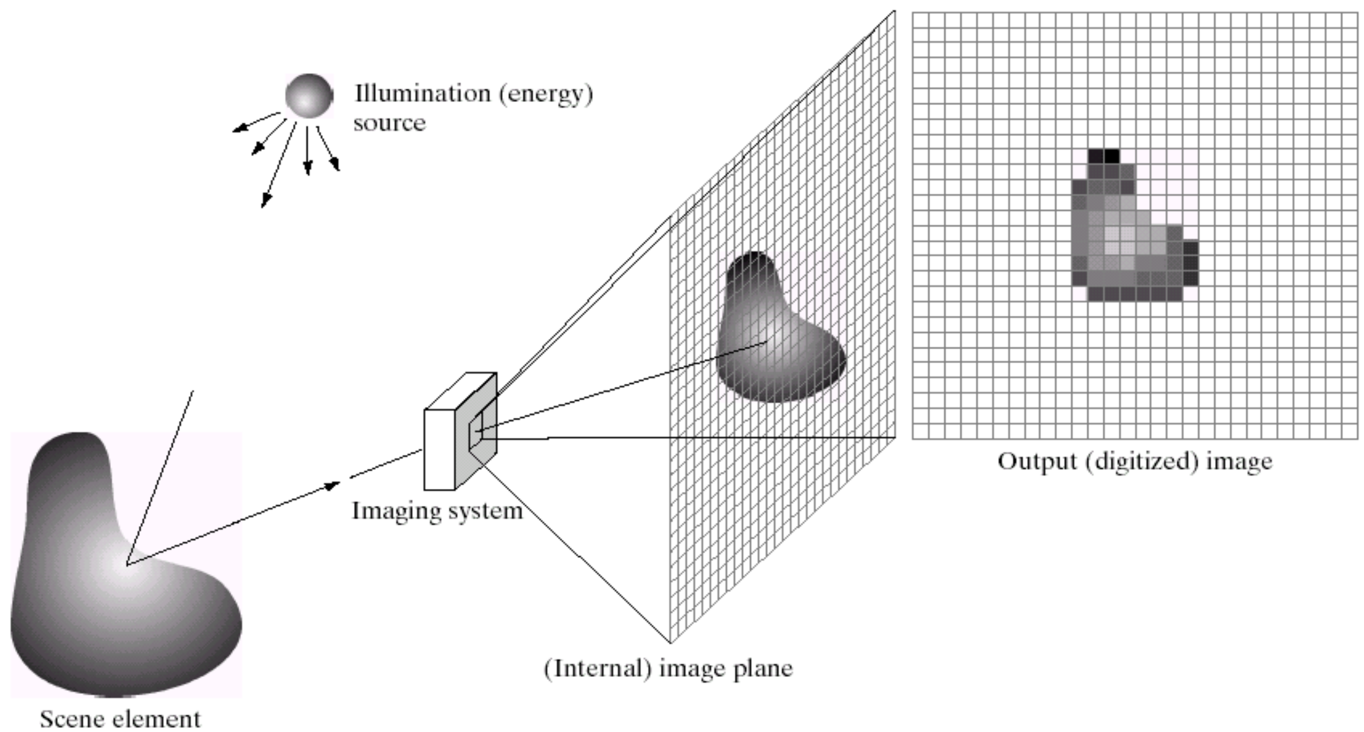


Digital Image Processing Pipeline

Image Acquisition → **Image Enhancement** → **Image Restoration** → **Morphological Processing**

↓

Image Segmentation → **Object Recognition** → **Representation & Description**



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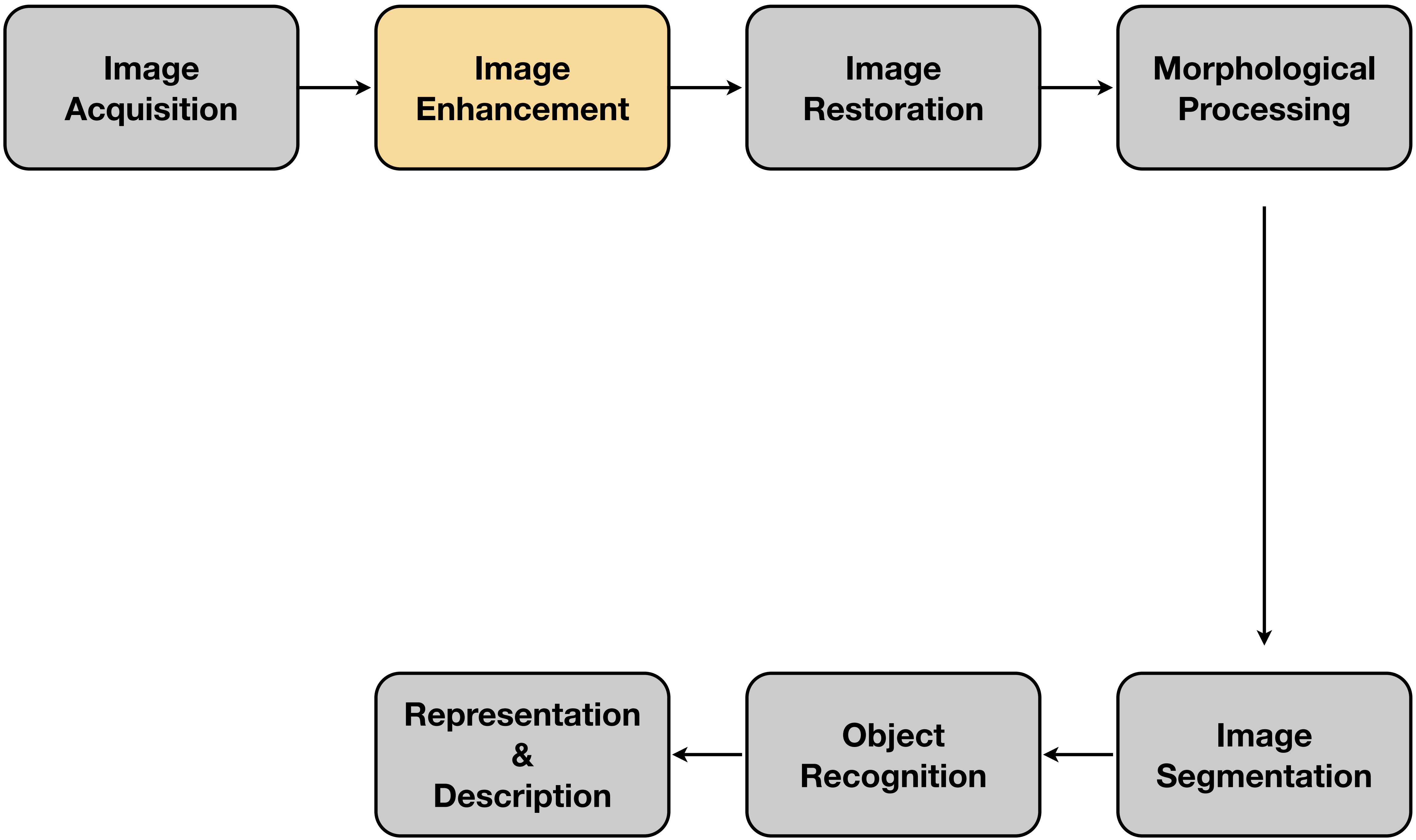

Images courtesy NASA

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Images courtesy of photo-restoration.jaincotech.com

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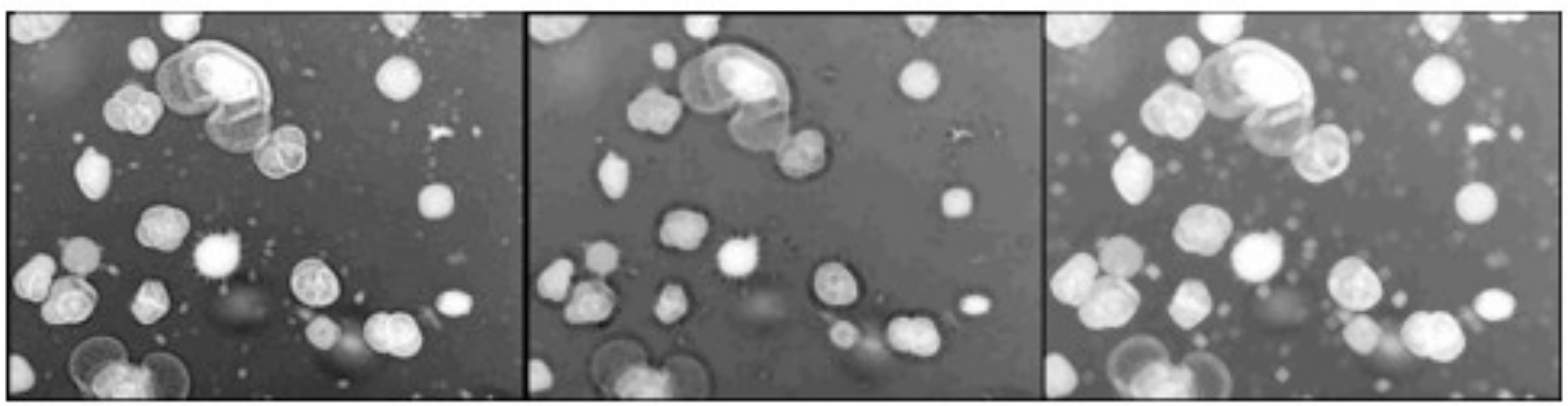

Erosion Dilation

Image Segmentation → **Object Recognition** → **Representation & Description**

Images courtesy NASA

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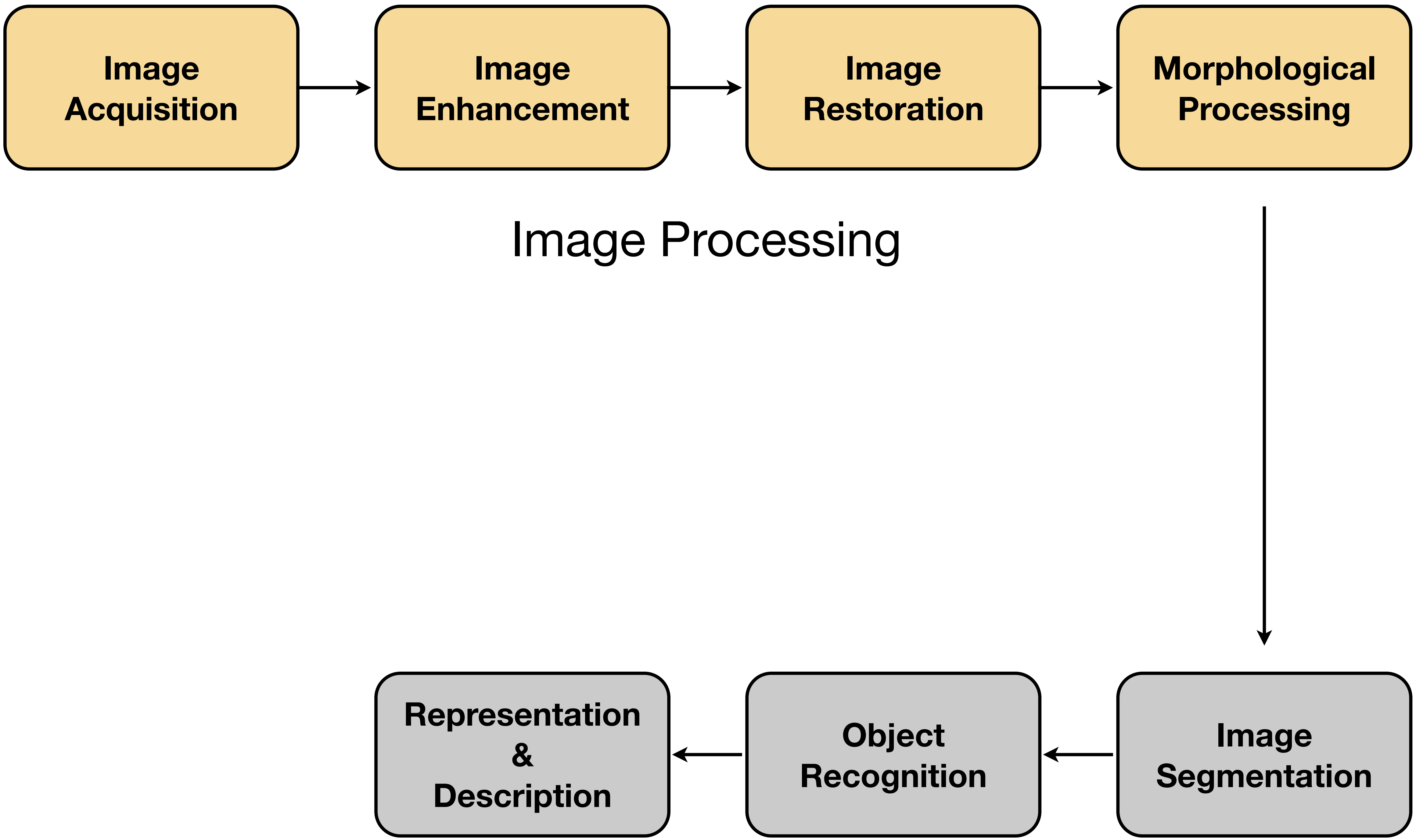

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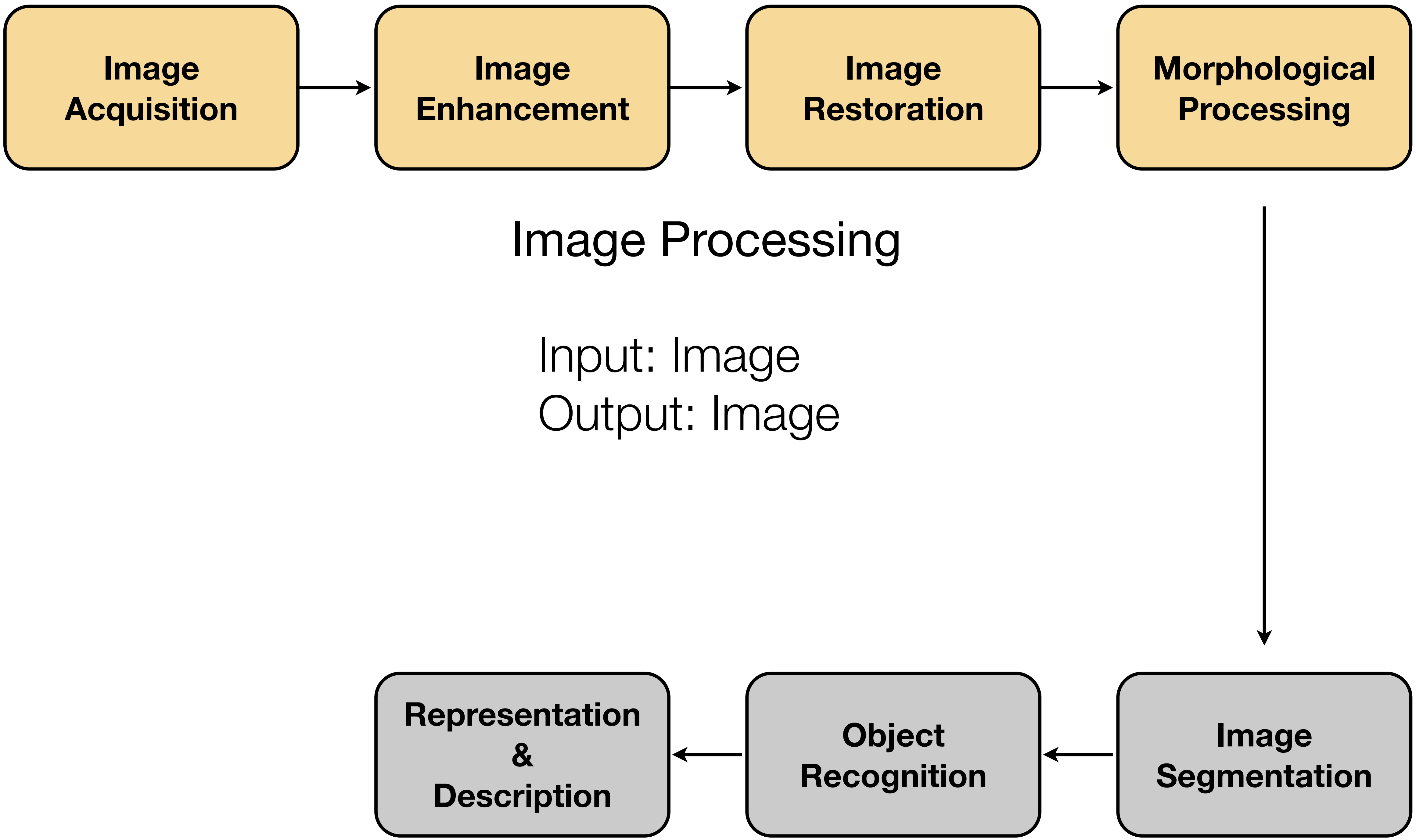

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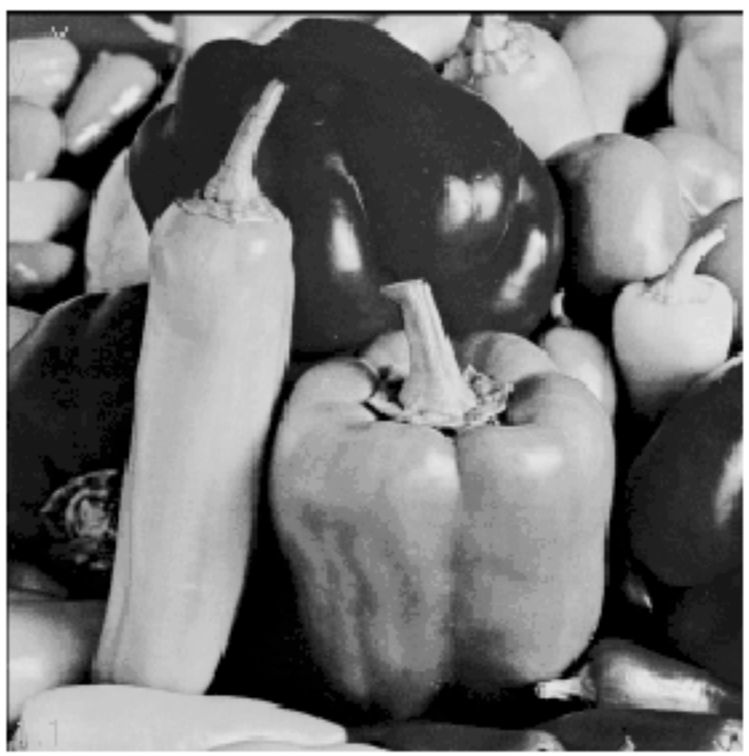

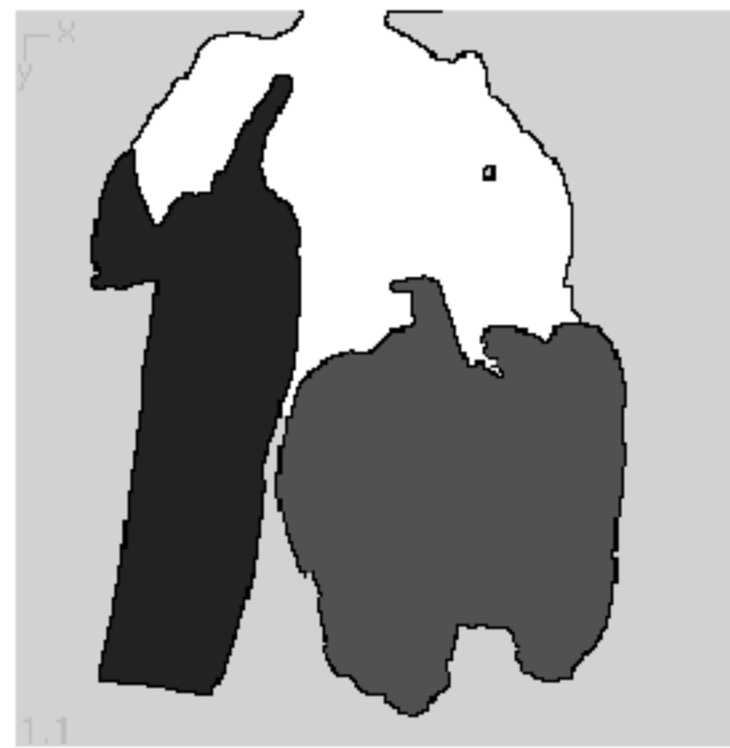

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Images courtesy University of Iowa

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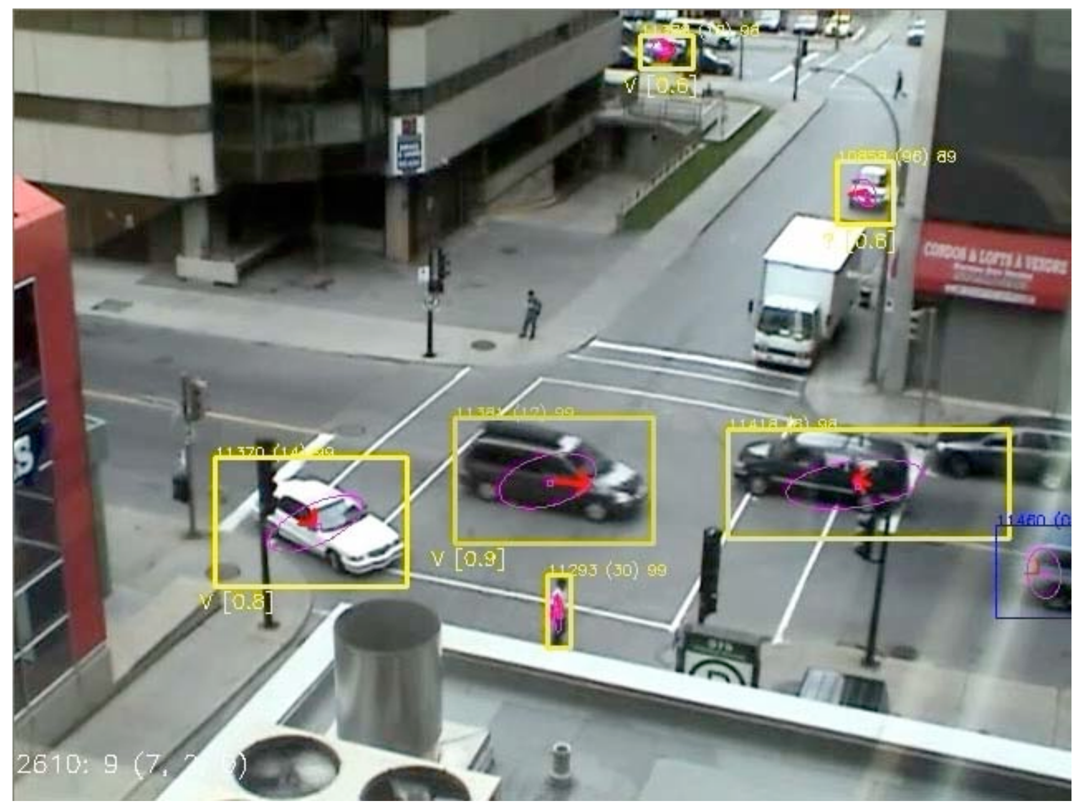

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Image Segmentation → **Object Recognition** → **Representation & Description**

Images courtesy www.crim.ca

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Representation & Description ← Object Recognition ← Image Segmentation

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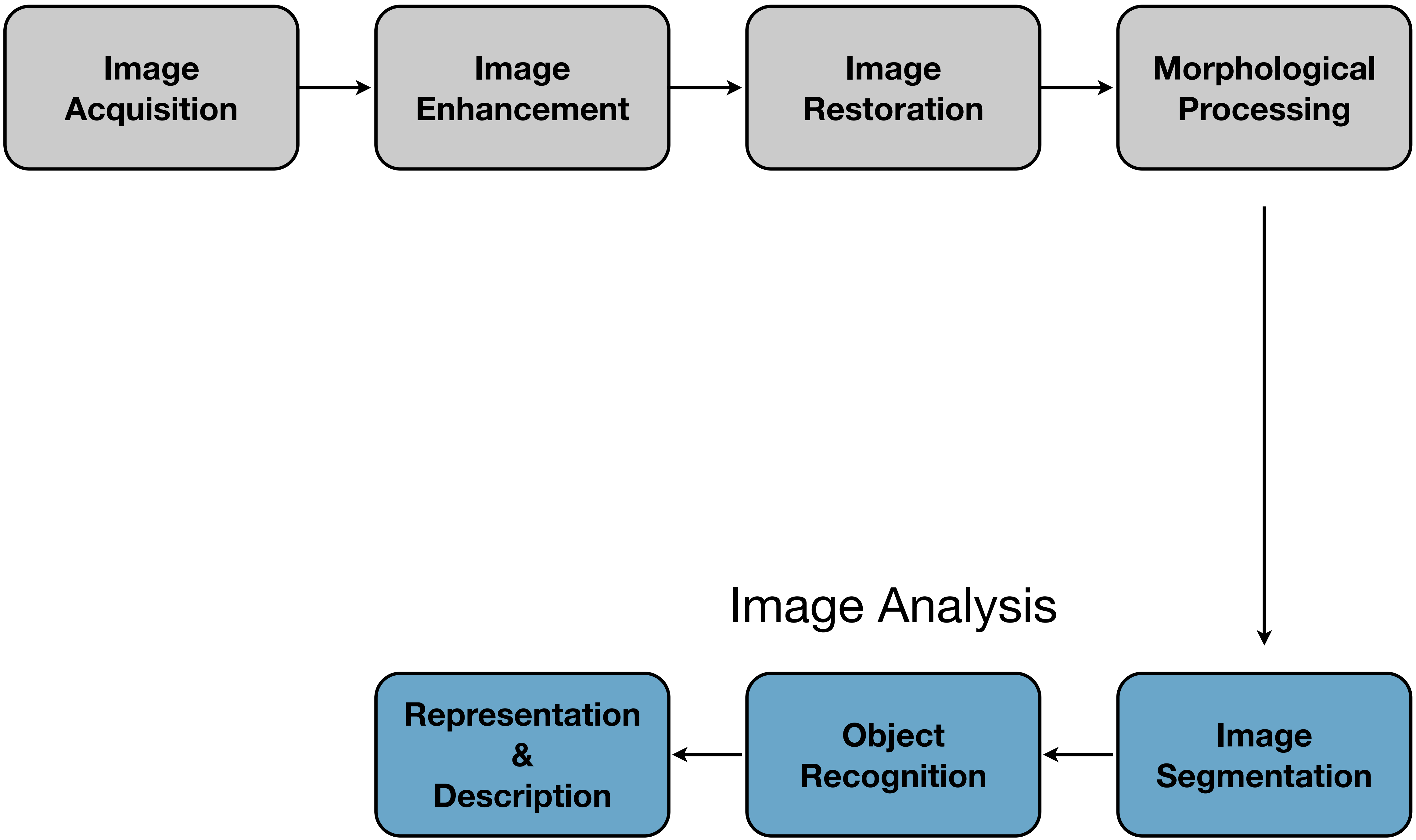

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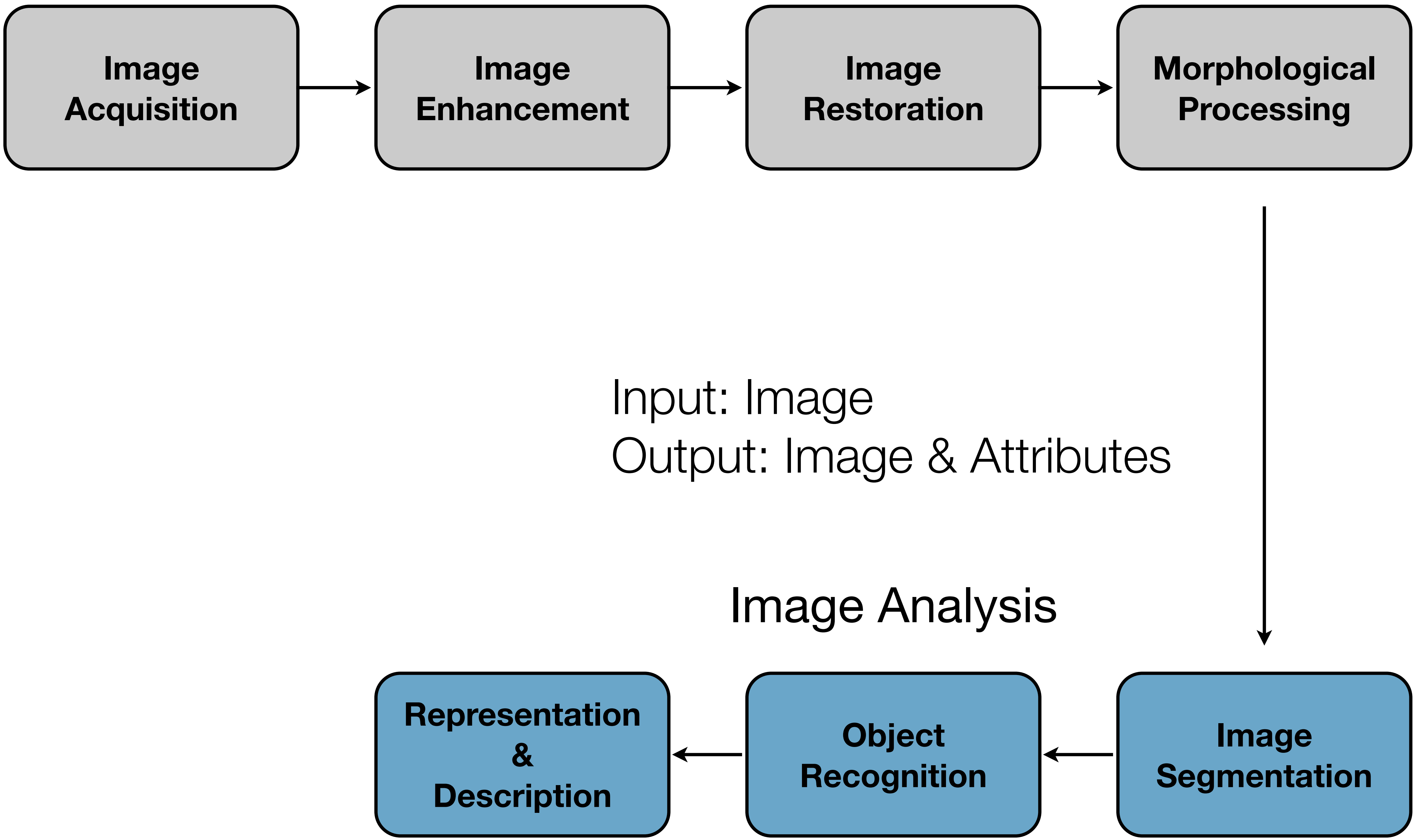

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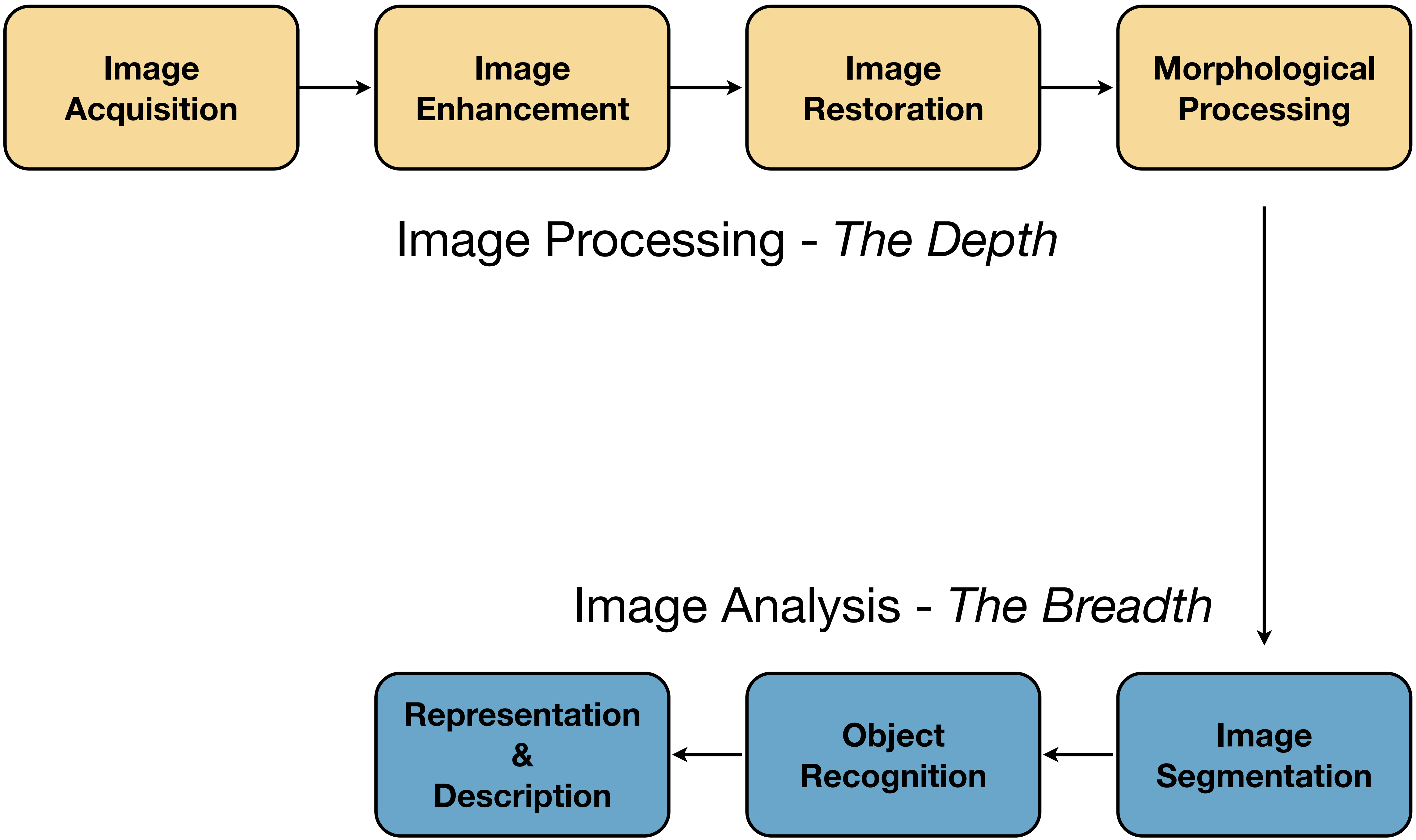

Image Processing - *The Depth*

Image Analysis - *The Breadth*

Key Components in Digital Image Processing
or
*“**How** is this stuff implemented?”*

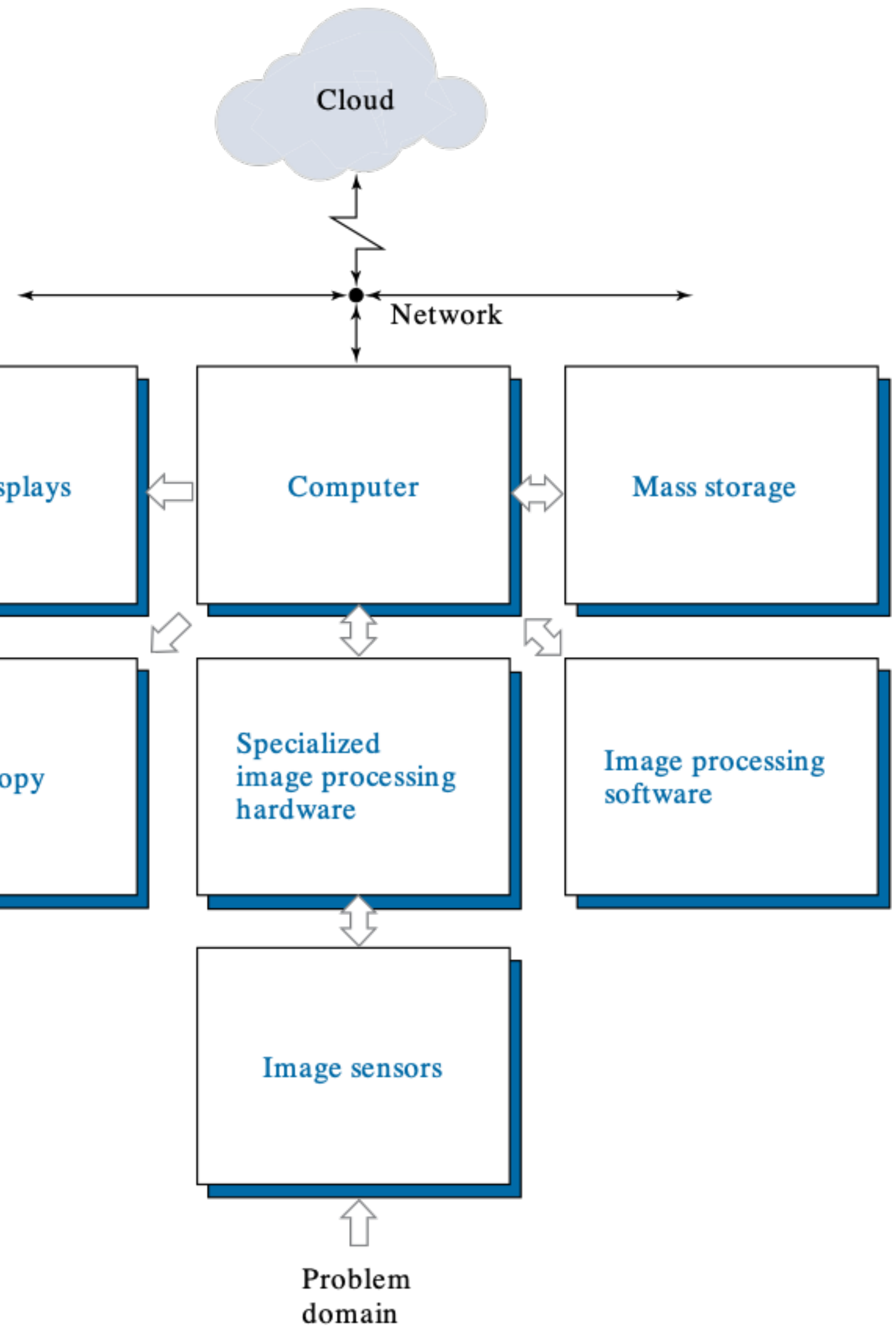

FIGURE 1.24 Components of a general-purpose image processing system.

Image courtesy “Digital Image Processing,” by Gonzalez & Woods, 4th ed.

What to Expect from This Course?

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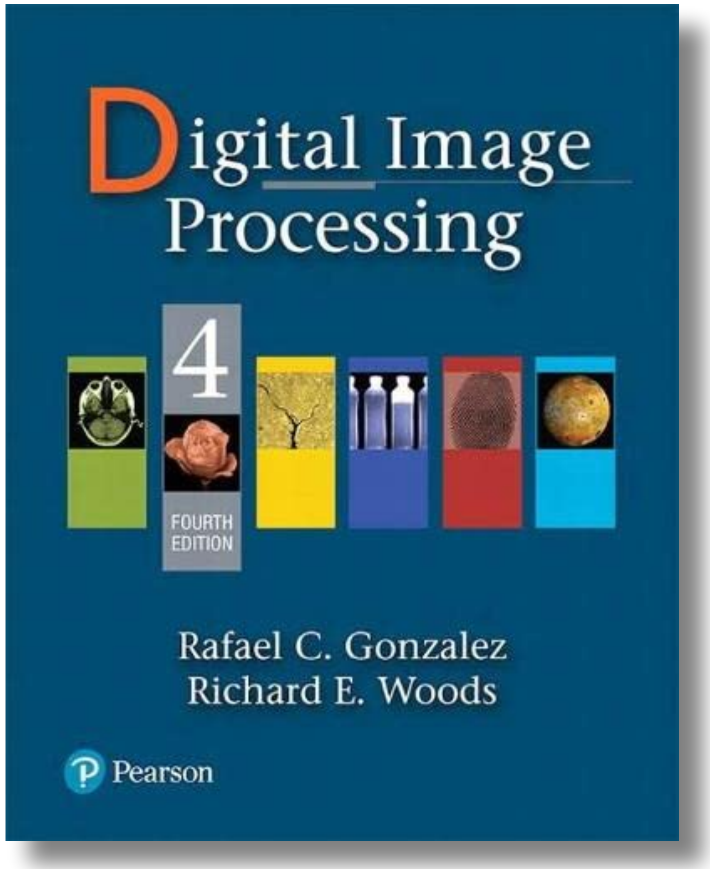
- Fundamentals of Image Processing
- Applications to real-world datasets
- Image processing implementation
  - Implement using Python / C++ / Compute Shaders
  - Course material presented in **Python**
- Student-based outcome
  - A configurable, extensible Image Processing toolset that YOU can showcase in your portfolio

Course Details

- Textbook **(NOT REQUIRED)**
- Reference Book (will be used in slides/examples)
  - Digital Image Processing, Gonzalez & Woods, 4th edition
- Online materials, as needed
  - Course Slides
  - Research and White papers
- Programming Assignments
  - **The Depth** - 3 Programming Assignments (2 weeks)
  - **The Breadth** - Group Project (due end of semester - monthly deliverables due)
- Mid-term Exam
- Final Exam



Programming Platform

Programming Platform

- Use … library to write applications

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    - E.g. OpenGL + GLFW + Compute Shaders

Programming Platform

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Programming Platform

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  - If you feel that you should know ***<XYZ>*** and no other class at DigiPen teaches that language/tool, feel free to explore it for CS 370

Programming Platform

- Use … library to write applications
  - E.g. OpenGL + GLFW + Compute Shaders
  - E.g. Python + CUDA + PyQT5 (Gui)
  - If you feel that you should know ***<XYZ>*** and no other class at DigiPen teaches that language/tool, feel free to explore it for CS 370
  - Caveat: DO NOT use any built-in image processing functions unless explicitly stated (e.g. OpenCV, PIL, …)

Programming Platform

- Use … library to write applications
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  - Caveat: DO NOT use any built-in image processing functions unless explicitly stated (e.g. OpenCV, PIL, …)
- Census assignment coming up
  - Write a small application that allows you to load and display images

Do’s and Don’ts for 3rd-party libraries

- Use third-party libraries for the following -
  - Load and save images
  - Display image data on screen
- DO NOT use them for -
  - image processing operations that are the outcomes of the assignment
  - e.g. addition, masking, histogram processing, edge detection etc.
- **When in doubt - consult the instructor**

Grade Distribution

Topic	Undergraduate	Graduate
Programming Assignments + Quizzes (2)	30%	15%
Midterm Exam	20%	15%
Group Project	30%	30%
Final Exam (Comprehensive)	20%	20%
Paper Implementation & Presentation	20%	20%
Total	100%	100%

Grade Levels

Points	Letter Grade
[93, 100]	A
[90, 93)	A-
[87, 90)	B+
[83, 87)	B
[80, 83)	B-
[77, 80)	C+
[73, 77)	C
[70, 73)	C-
[60, 73)	D
< 60	F

Pre-requisites

- Good implementation skills
- Linear Algebra
    - Matrices
    - 2D Transforms
- Enthusiasm to learn !

Lecture 01

Image Processing - The Fundamentals

Is this a “good” image?

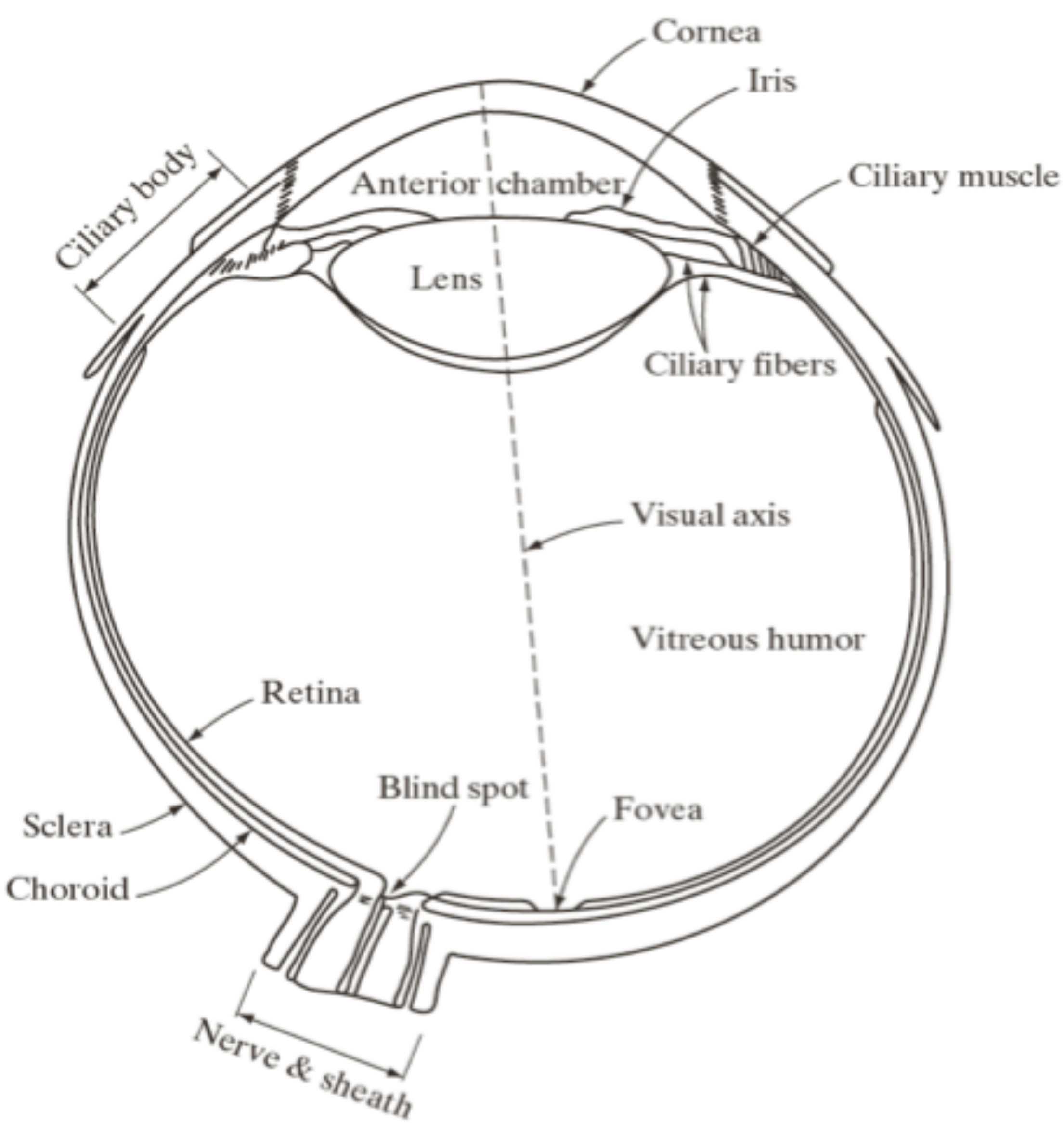
http://mynorthkorea.blogspot.com/2013/08/north-korea-and-satellite-resolution.html

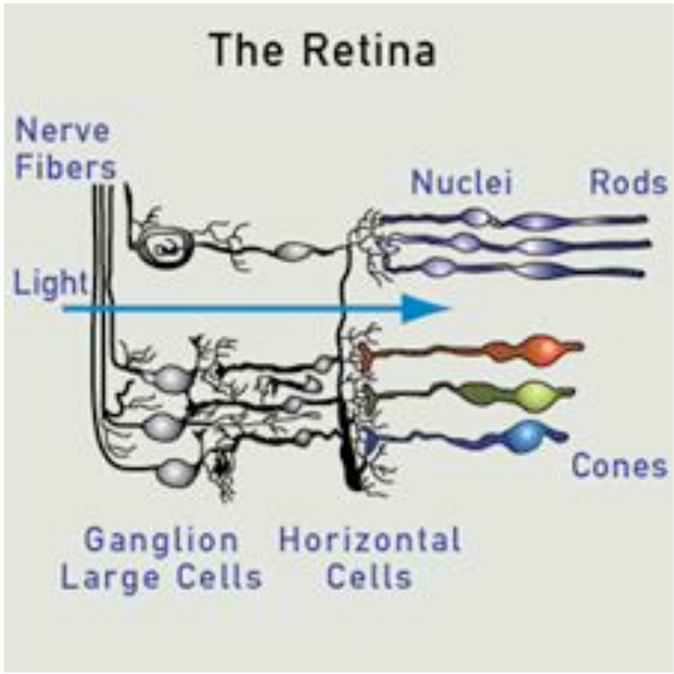
“Goal” of Image Processing

- Create images that “look good”
- What does the phrase “look good” imply?
  - One person’s good image may be another’s trash!
- VERY IMPORTANT TO REMEMBER
  - Image Processing quality assessment is largely subjective process
  - Typical mechanism : come up with a mathematical model/algorithm/ process that makes the image **appear desirable to the human observer for the specific operation or process in mind**

How do humans perceive images?

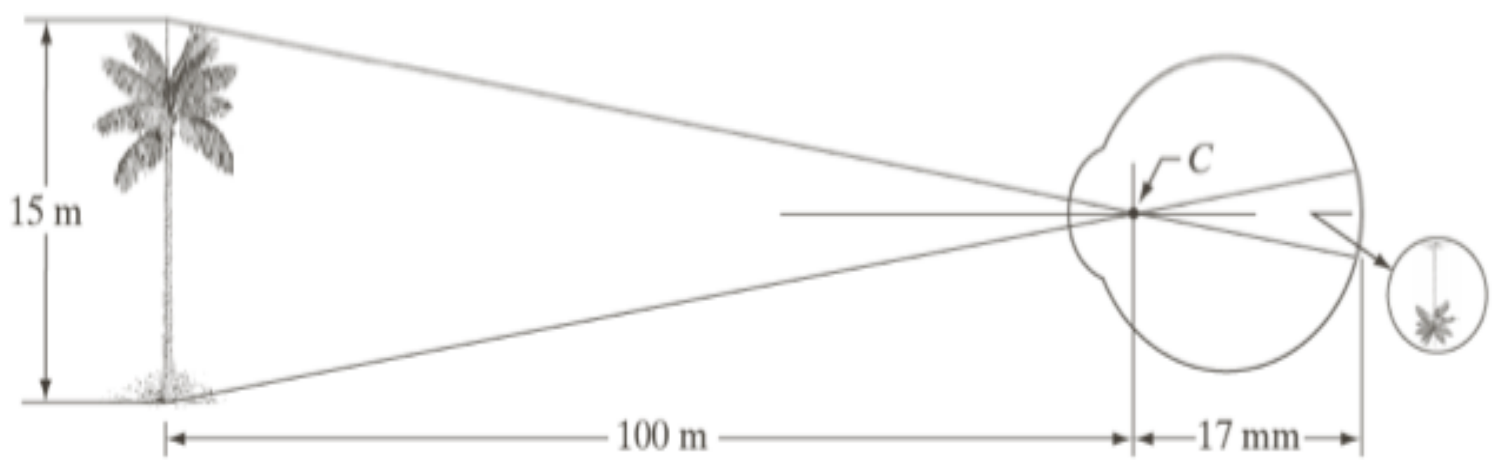
- Human Visual System





Images courtesy “Digital Image Processing,” by Gonzalez & Woods, 3rd ed.
www.webexhibits.org

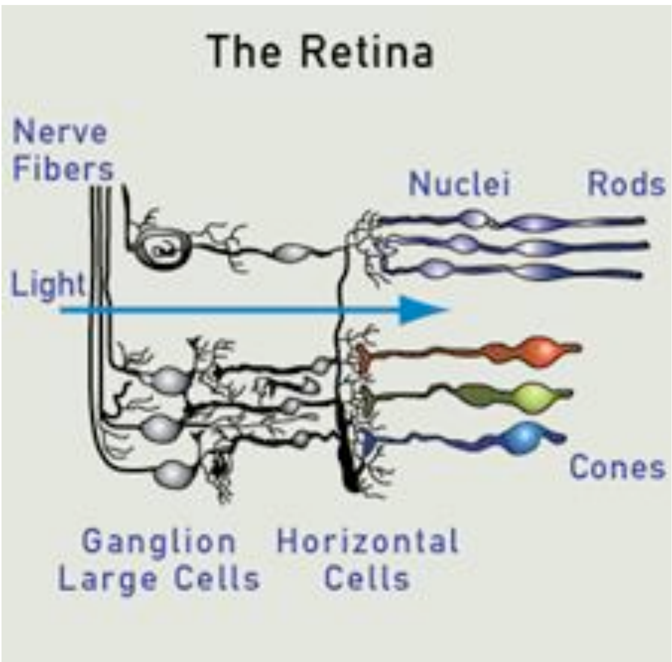
Image Formation - Lens based Model

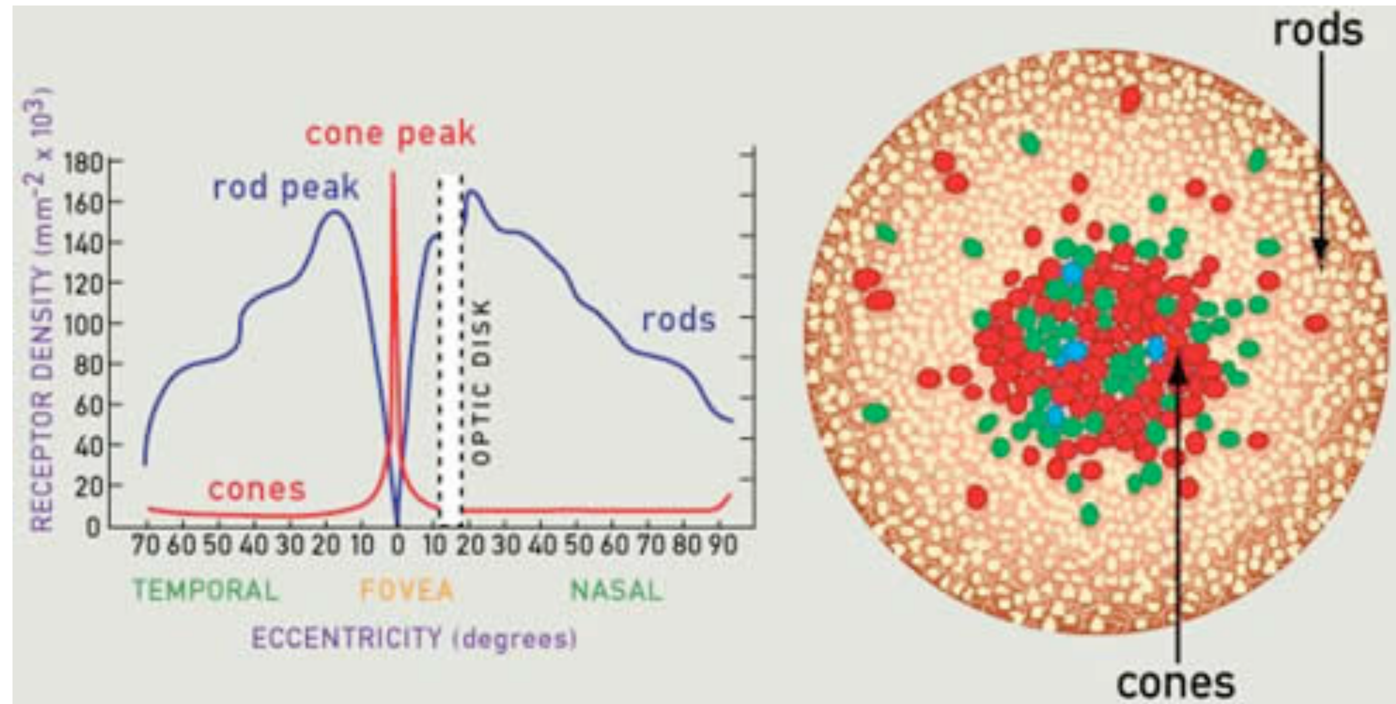


- Flexible lens - to allow focusing on variable distances
- Focal distance varies between 17 mm to 14 mm

Image courtesy "Digital Image Processing," by Gonzalez & Woods, 3rd ed.

Visual Perception





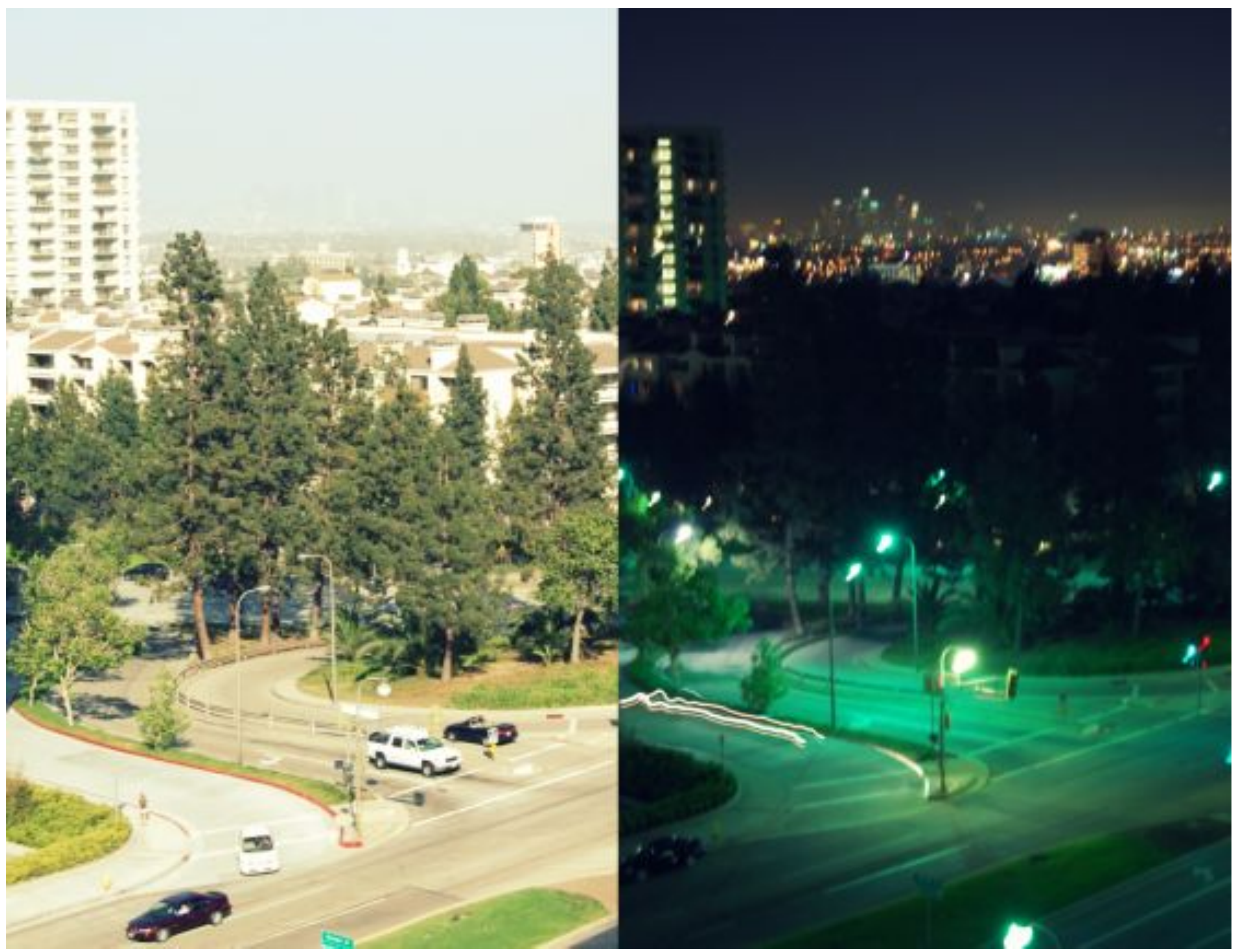
- More *rods* than *cones* (75-150 million Vs 6-7 million)
- *Rods* account for low-light, peripheral vision
  - Scotopic vision
- *Cones* help in frontal, color vision
  - Photopic vision

Image courtesy www.webexhibits.org

Day vs Night Vision

Day vs Night Vision

Objects identified by color



Day vs Night Vision

Objects identified by color

Objects identified by shape

Day vs Night Vision

Objects identified by color

Cones are activated

Objects identified by shape

Day vs Night Vision

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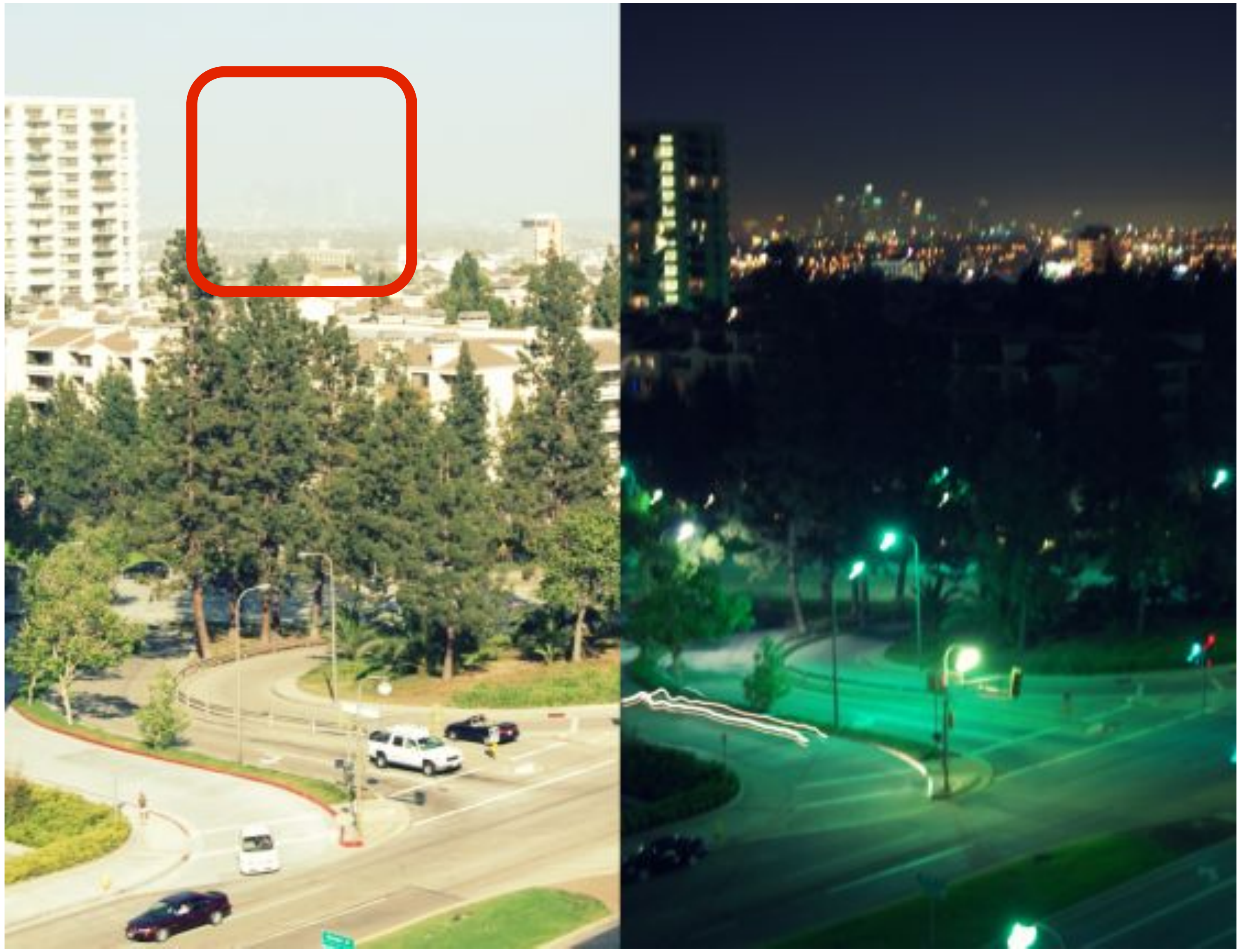

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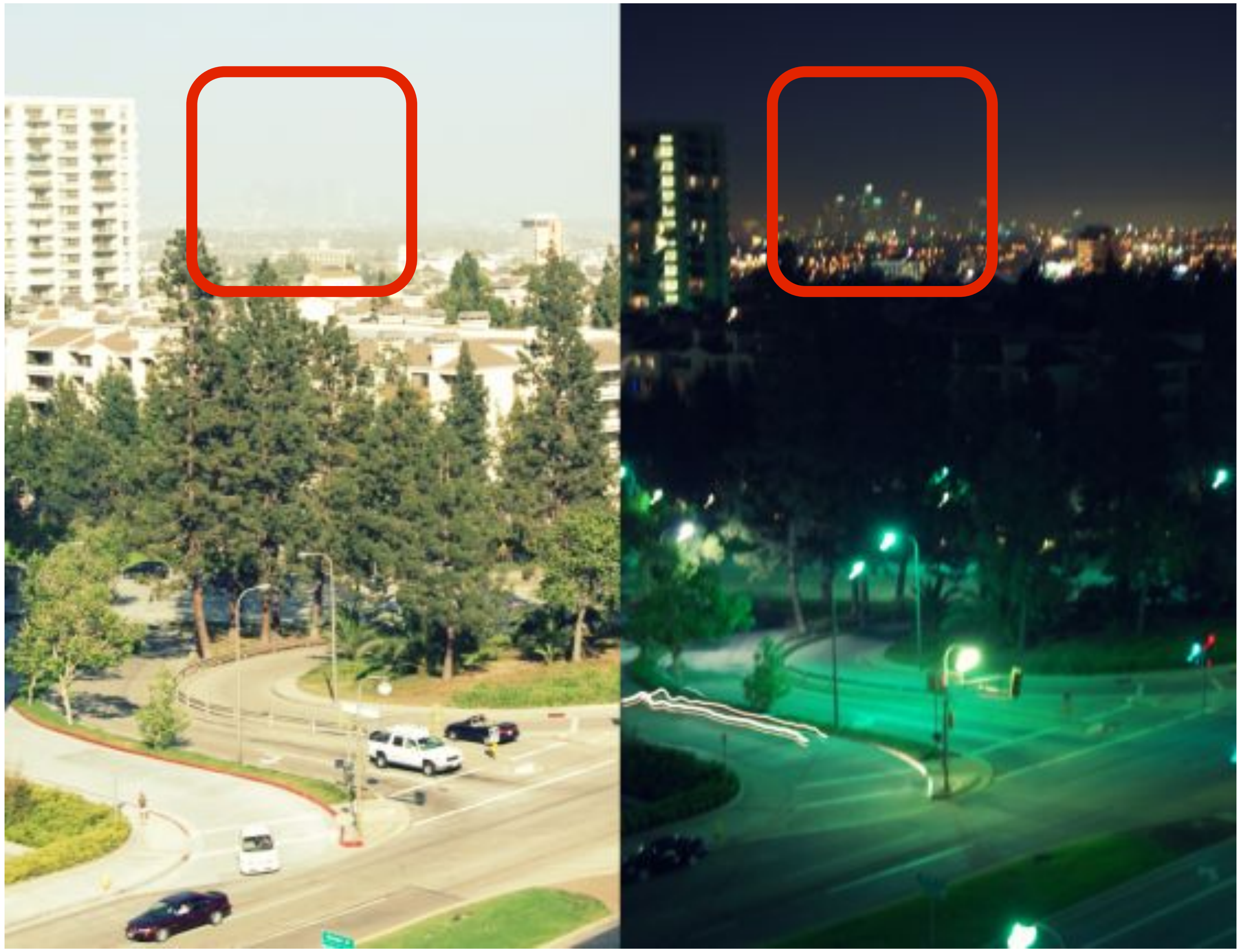

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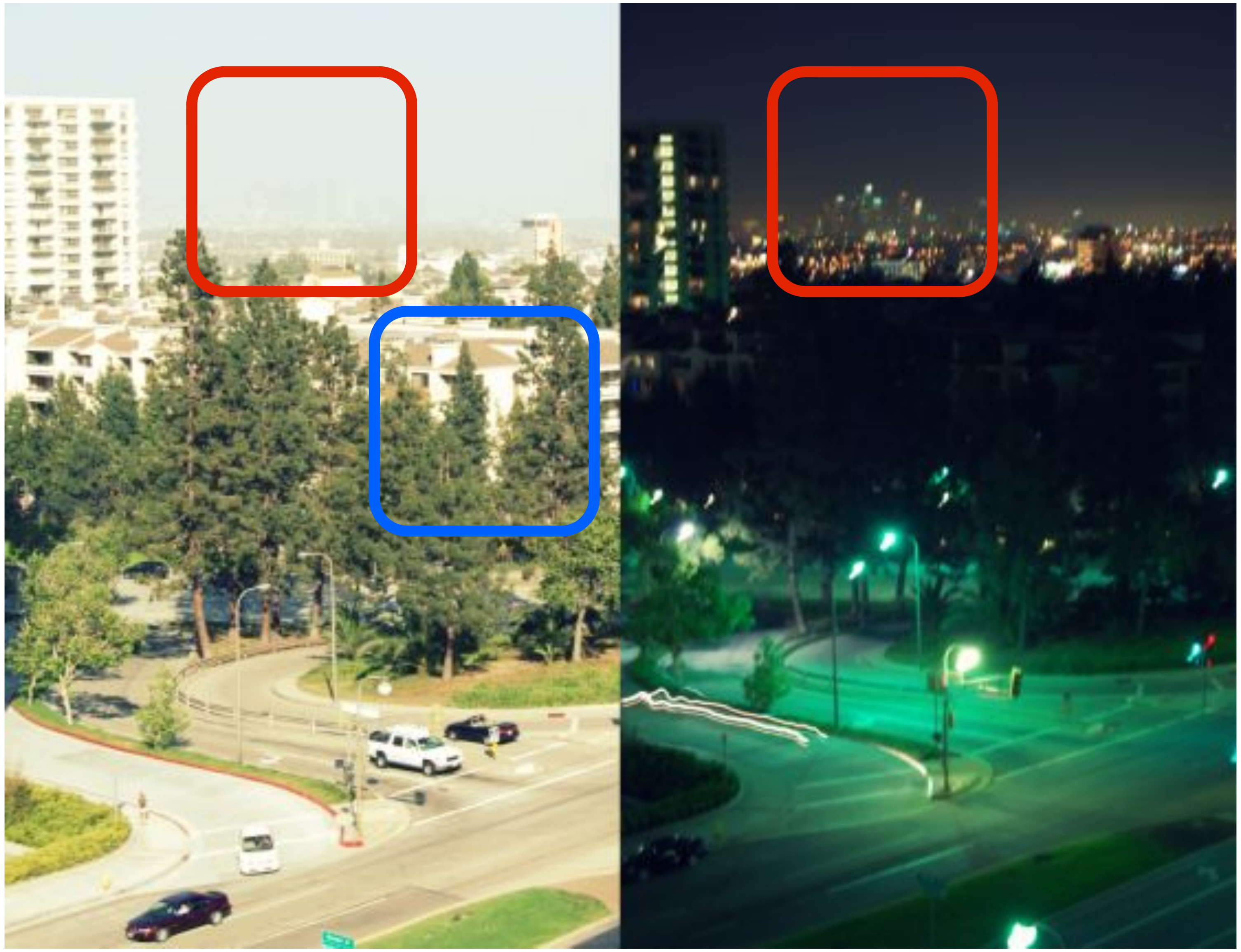


Objects identified by shape

Rods are activated

Day vs Night Vision

Objects identified by color

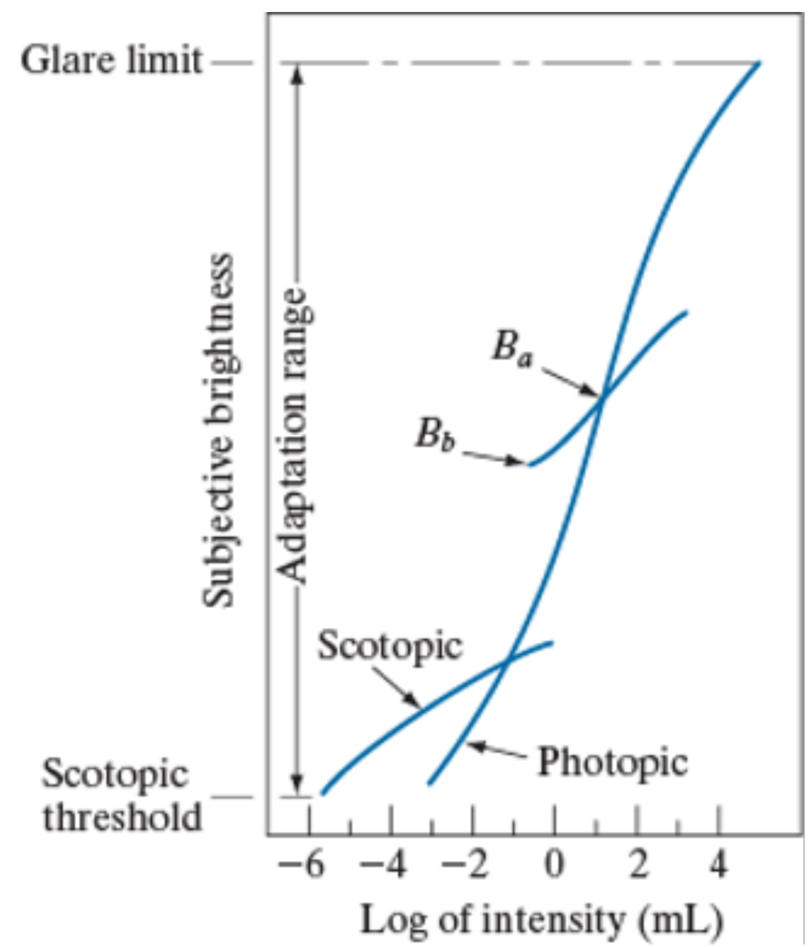
Cones are activated

Objects identified by shape

Rods are activated

Visual Response - Brightness Adaptation

- Brightness discrimination is crucial to image understanding
- Actual dynamic range of the human eye - order of 10^{10}
- Essential point: The human visual system cannot operate on the entire dynamic range *at once*
- Changes to overall sensitivity, known as “brightness adaptation”



B_a : Brightness adaptation level
B_b : Bottom threshold for discernible intensities

Image courtesy “Digital Image Processing,” by Gonzalez & Woods, 4th ed.

Brightness Discrimination Test

Brightness discrimination is poor in low-light conditions

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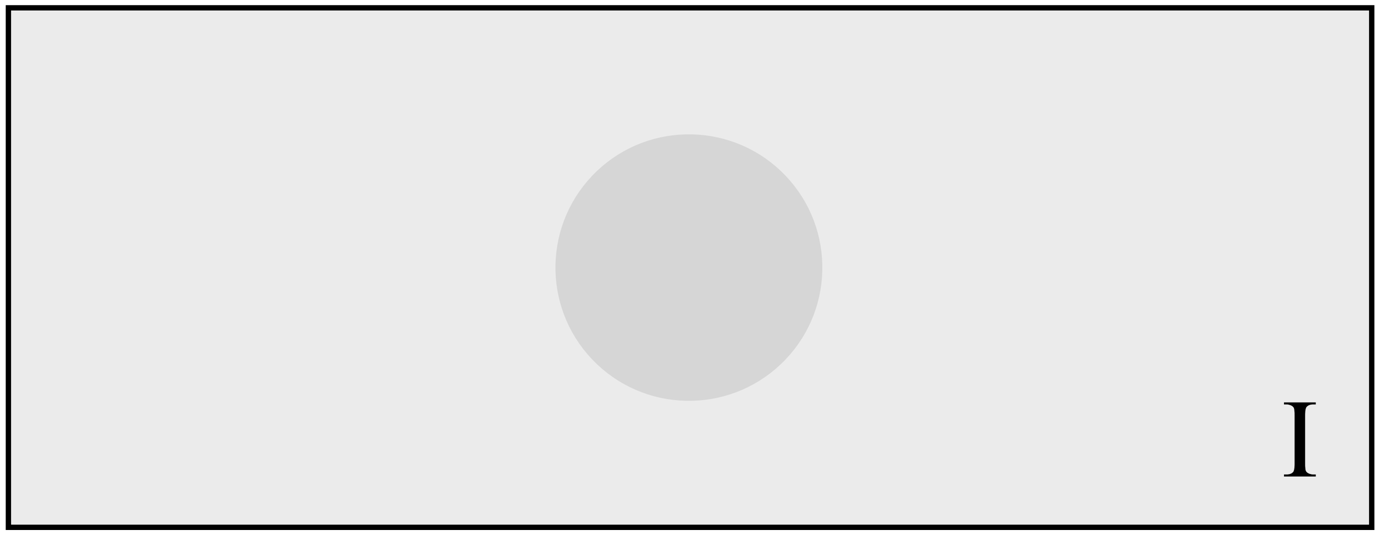
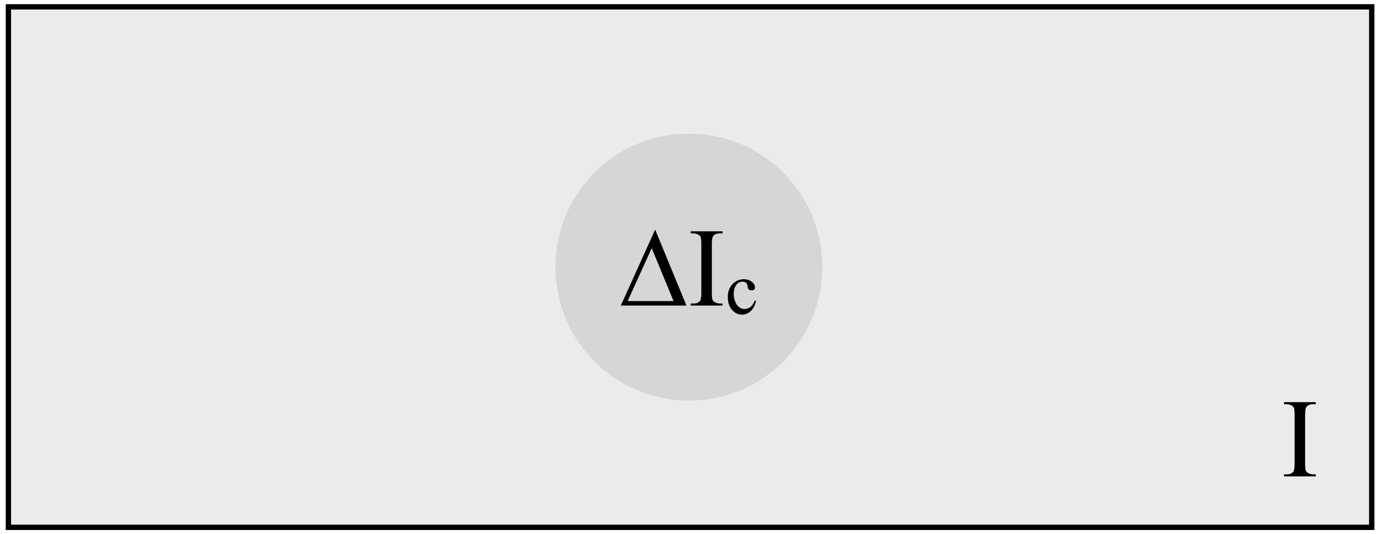


Brightness discrimination is poor in low-light conditions

Brightness Discrimination Test



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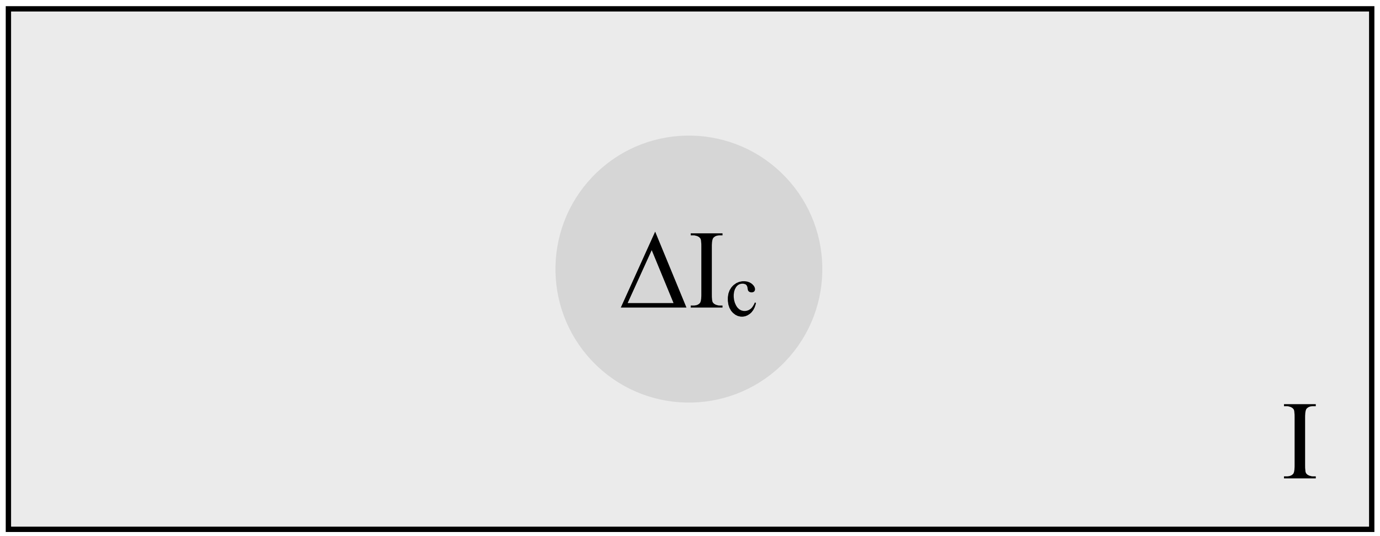
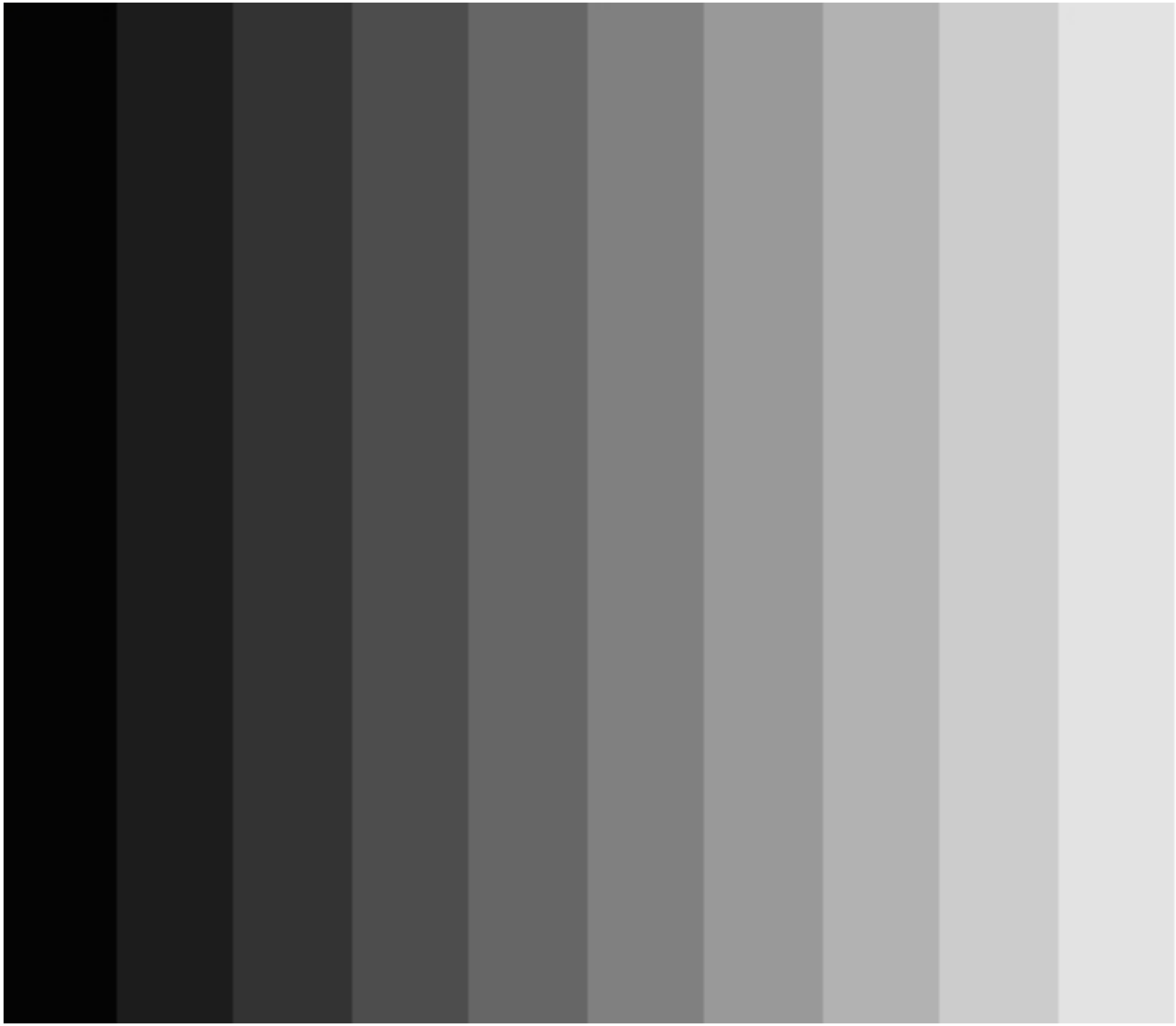


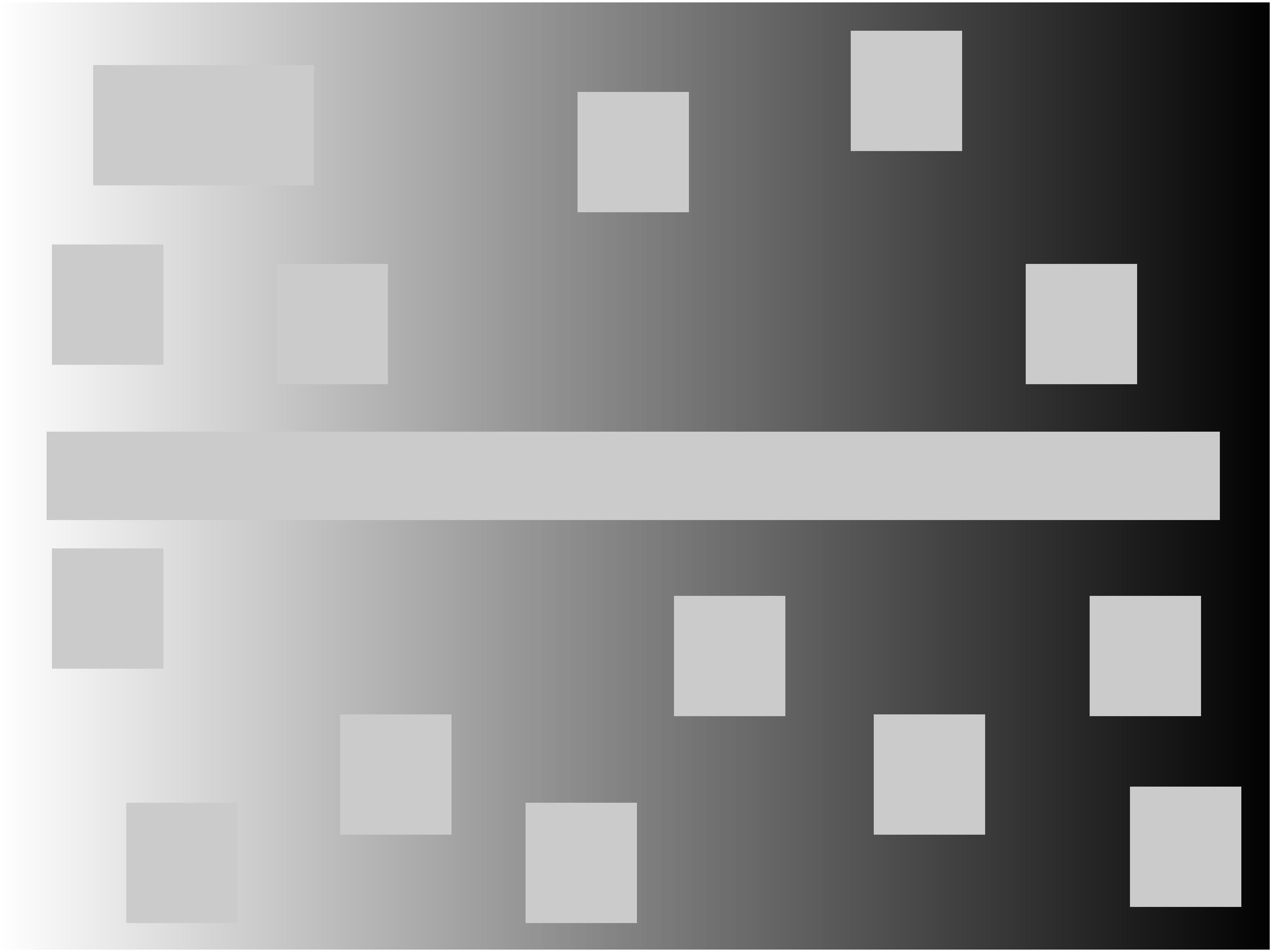
$\Delta I_c \,/\, I$: Weber Ratio

Brightness discrimination is poor in low-light conditions

Perception

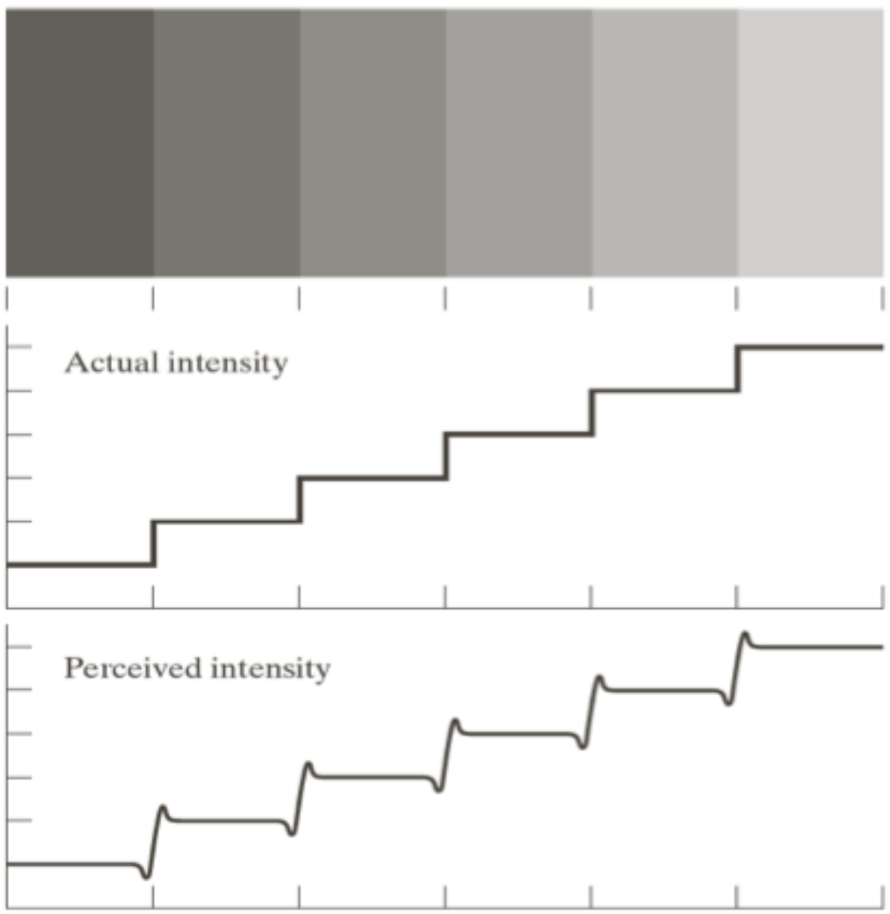


Contrast Perception



Contrast Perception

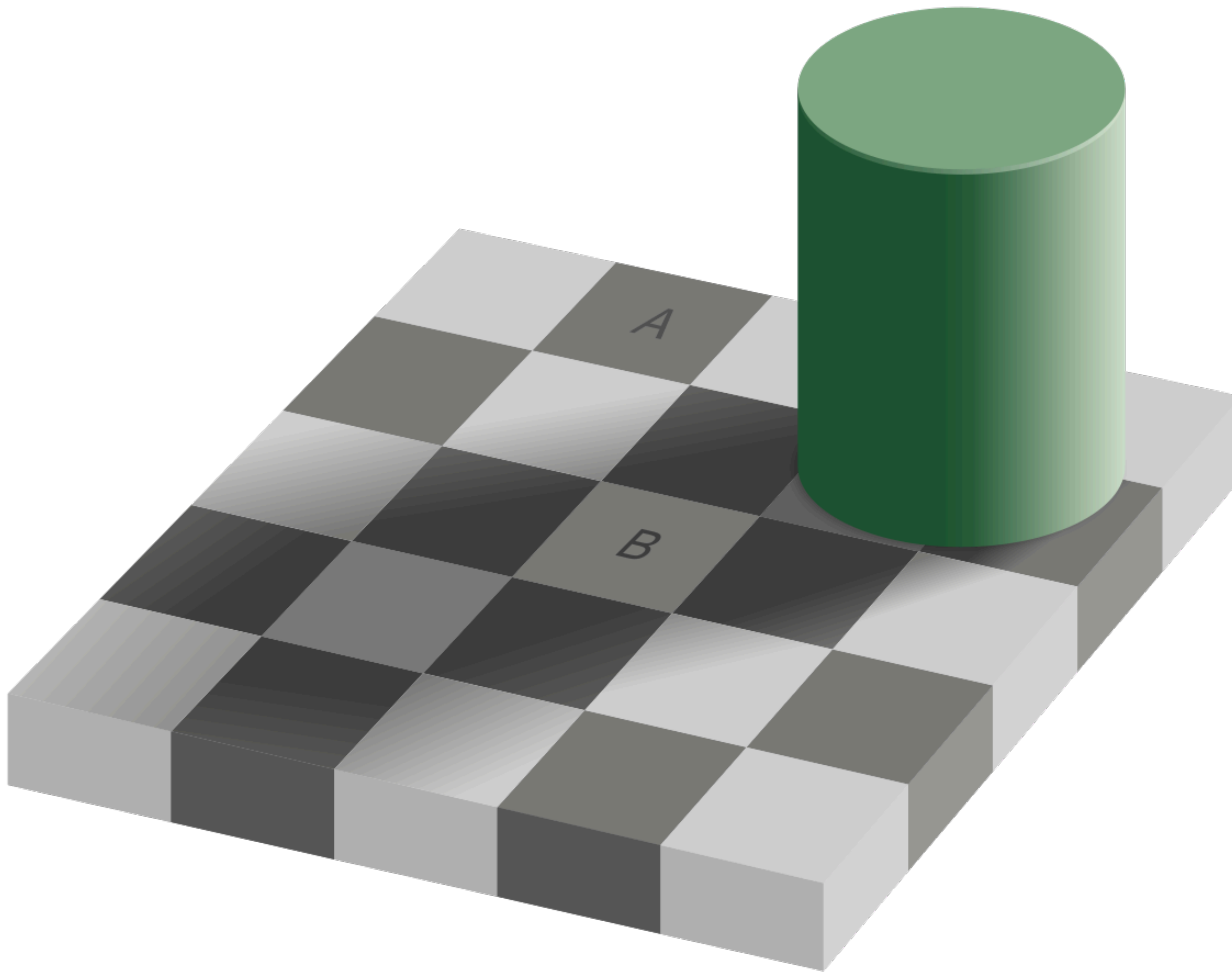
Perception



Perceived brightness is a function of intensity
Mach Bands (Ernst Mach, 1865)

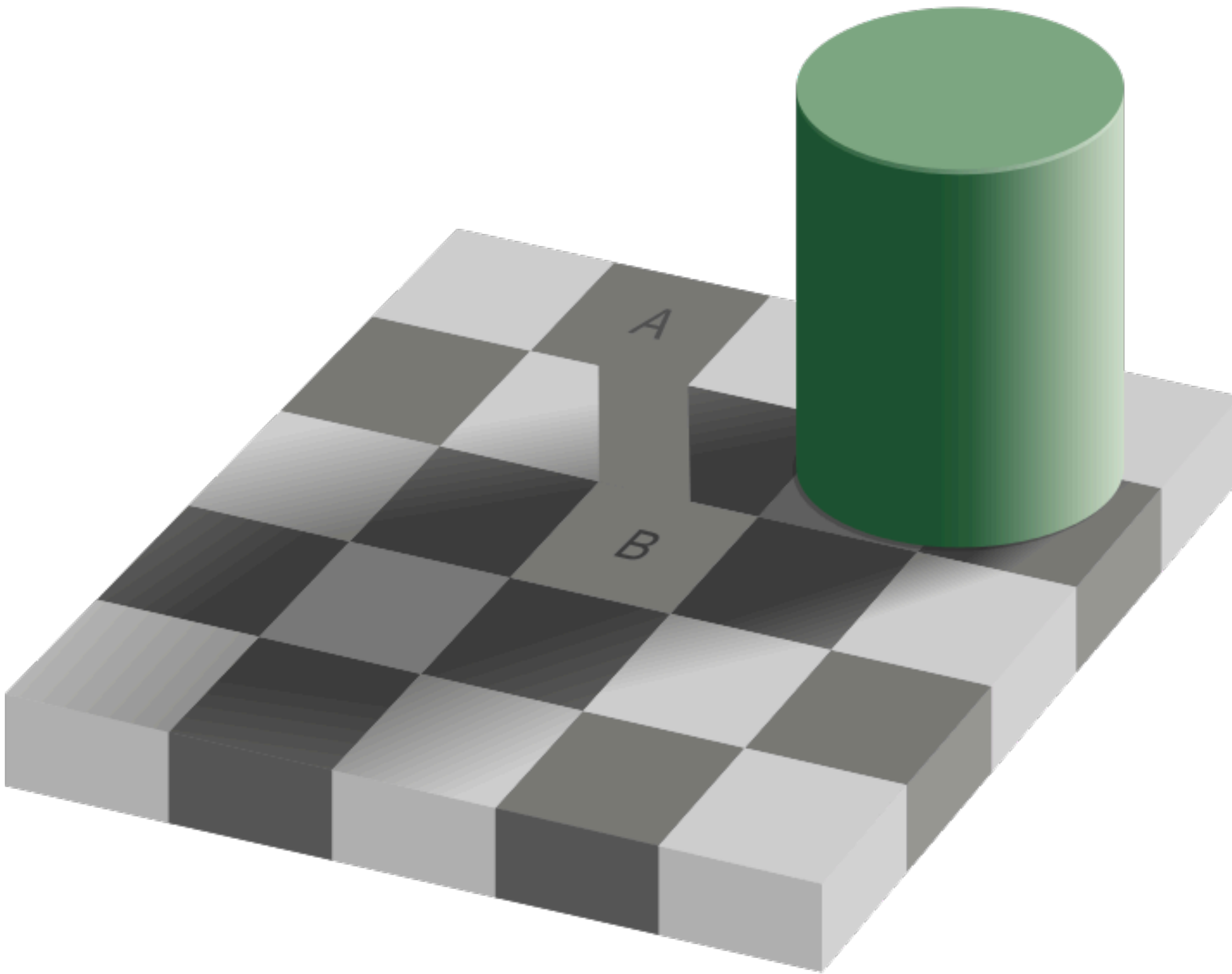
Images courtesy "Digital Image Processing," by Gonzalez & Woods, 3rd ed.

??

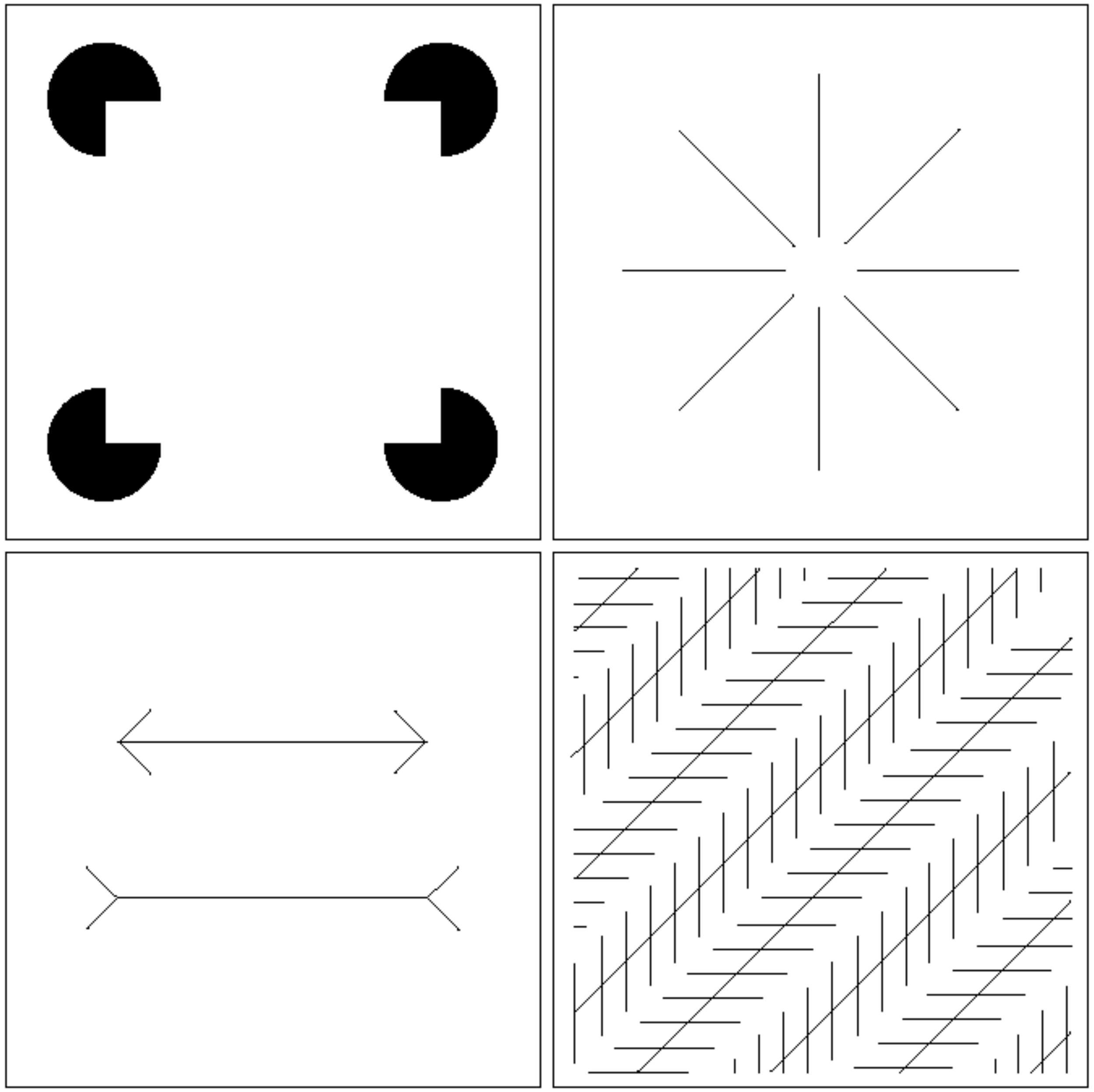

A
B

Shadow Illusion

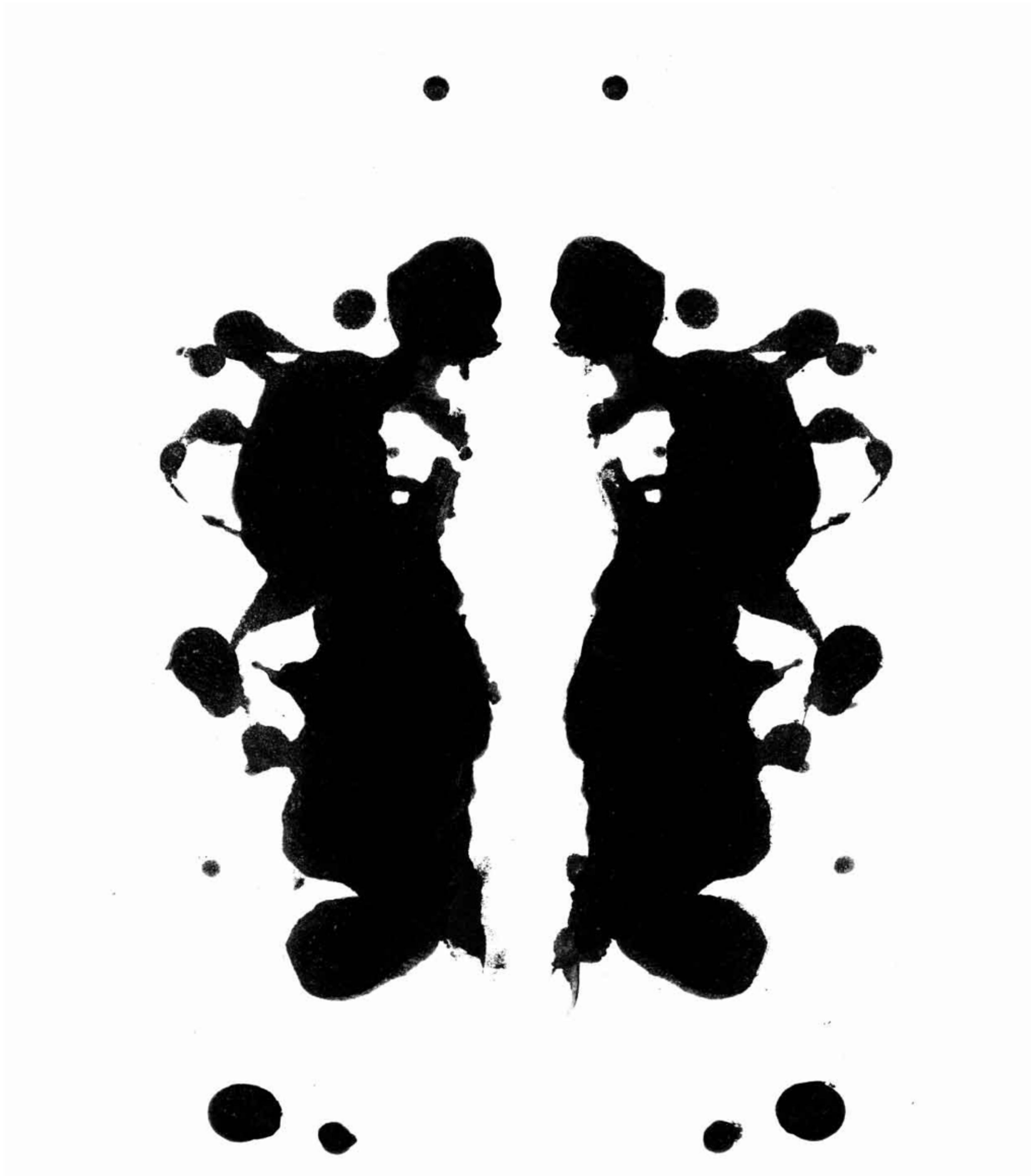
By Original by Edward H. Adelson - File created by Adrian Pingstone, based on the original created by Edward H. Adelson, Copyrighted free use, https://commons.wikimedia.org/w/index.php?curid=45737683



Optical Illusions



Images courtesy “Digital Image Processing,” by Gonzalez & Woods, 3rd ed.



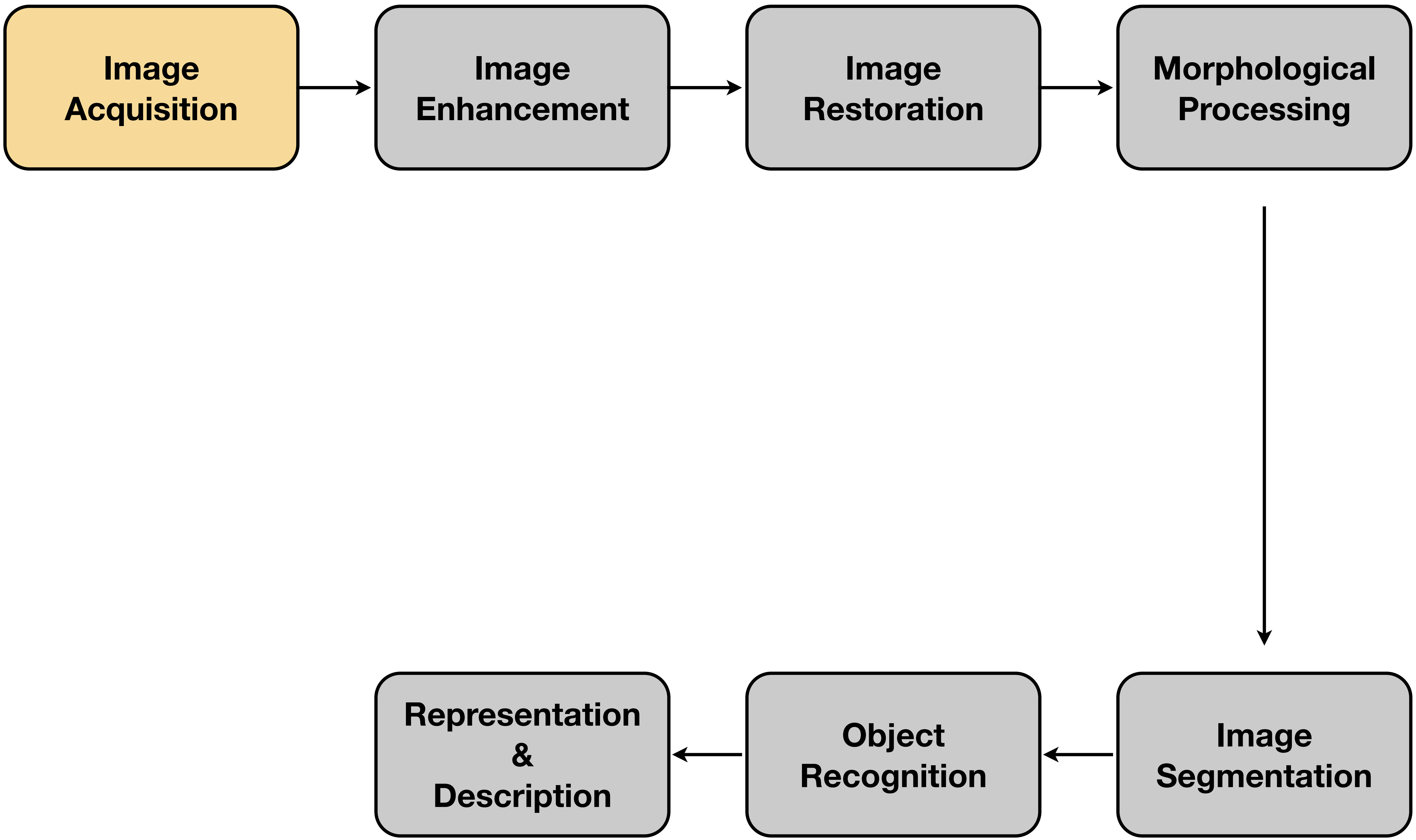
Key Idea

Pixel colors by themselves, **do not** correspond to “visual information.”

Images have to be **processed**, to be made **understandable** to humans.

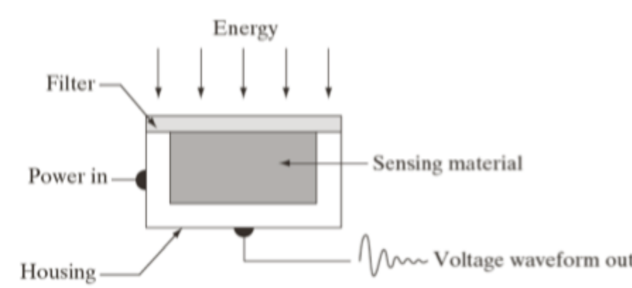
The Image Processing Pipeline

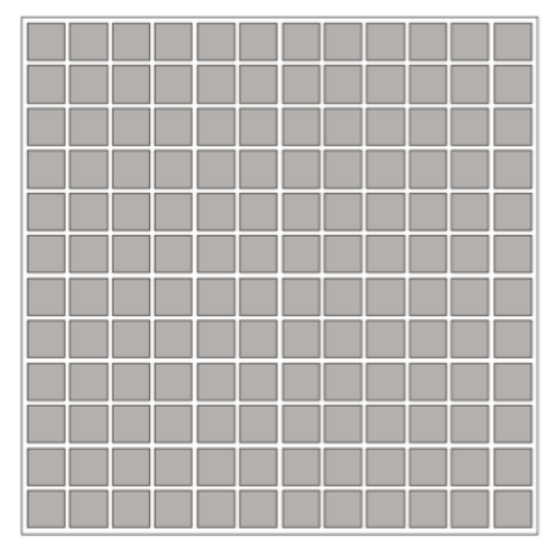
Digital Image Processing Pipeline



Capturing Digital Images

- Imaging sensors
  - Individual
  - Line-sensors
  - Array sensors





Images courtesy “Digital Image Processing,” by Gonzalez & Woods, 3rd ed.

Image Acquisition

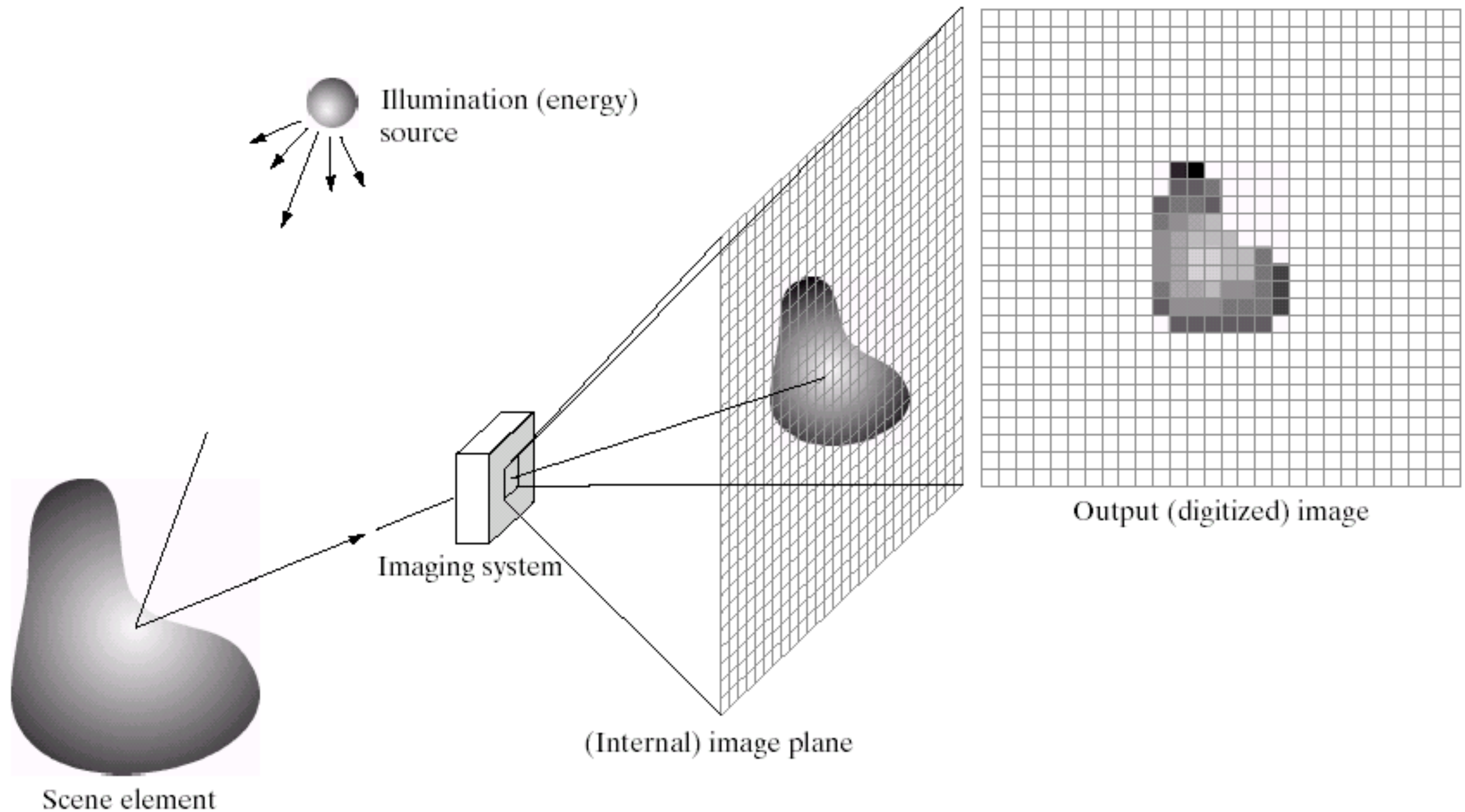
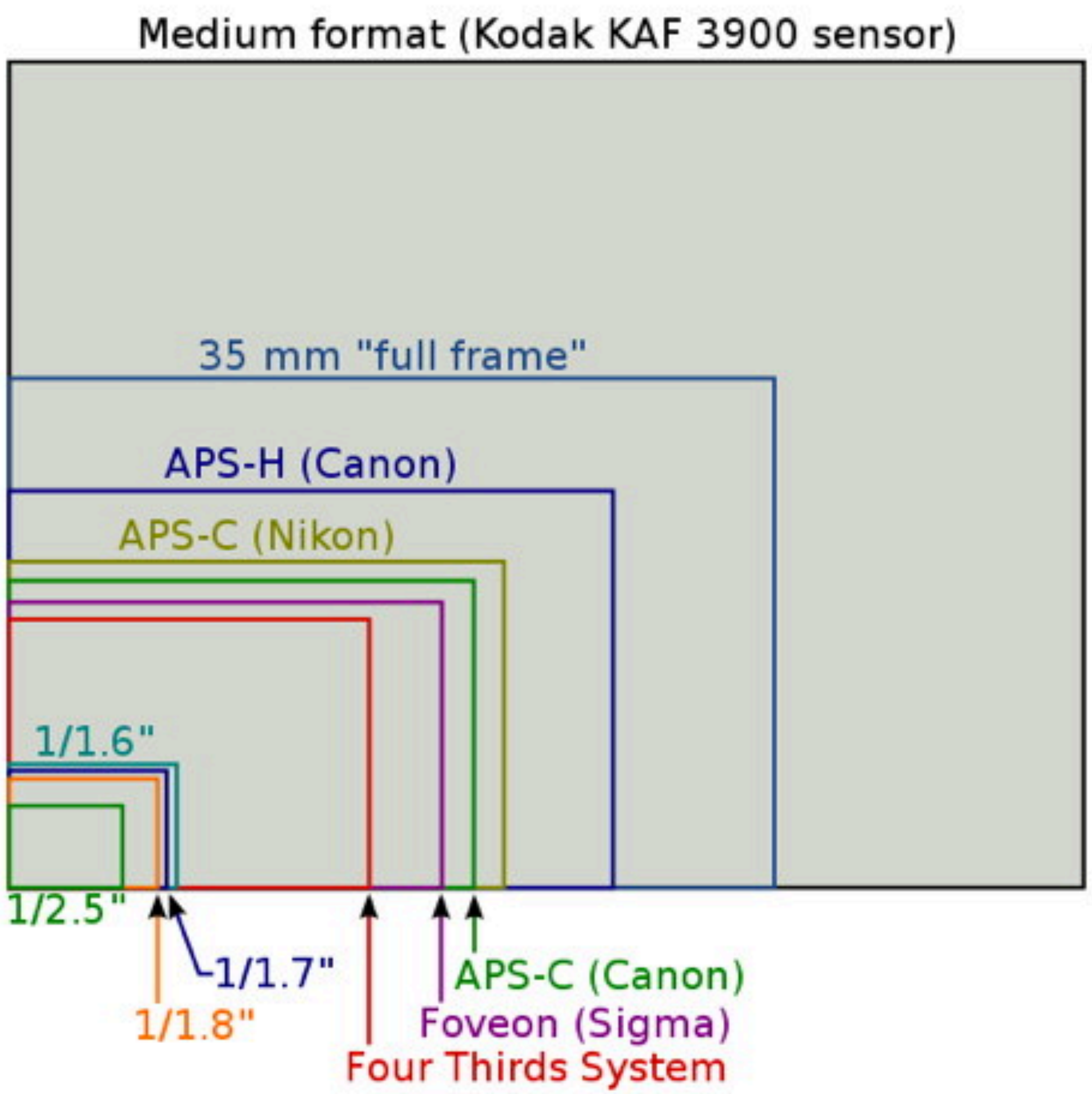


Image courtesy “Digital Image Processing,” by Gonzalez & Woods, 3rd ed.

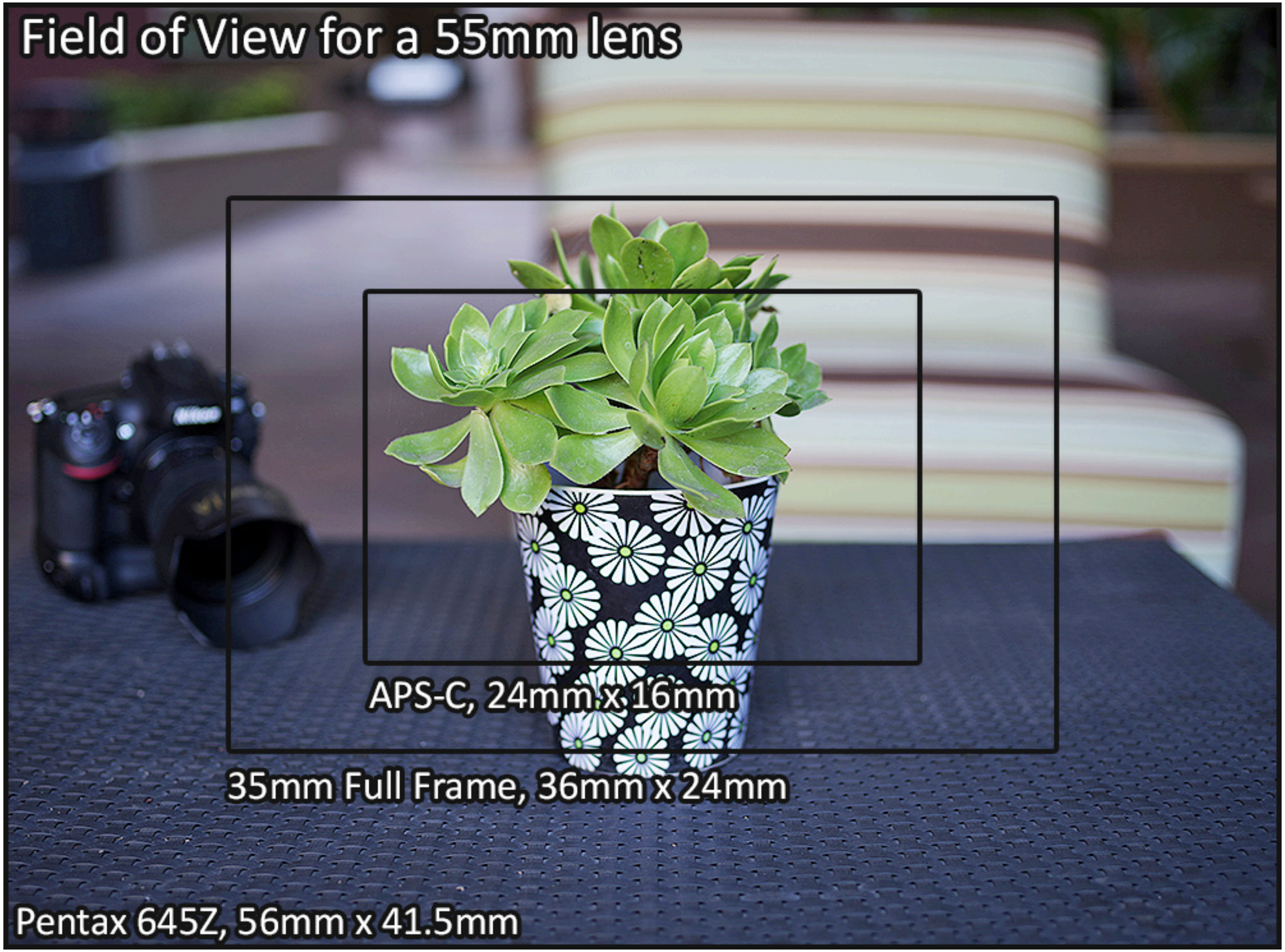
Imaging Plane

- Usually, the 2D planar receiver of the projected photons
- Film or glass plate
- This is the 2D plane where the image is “formed” by accumulation of photons

The Digital Imaging Plane == Image Sensor



FoV Comparison



Mathematical Model of the Image Plane

Illumination and Reflectance

- Image intensity is function of two phenomena
  - Incident light - Source illumination
  - Reflected light - Scene elements
- Resulting light energy can be modeled as follows:

$$f(x, y) = i(x, y)r(x, y)$$

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$$0 < i(x,y) < \infty$$ incident energy

$$0 < r(x,y) < 1$$ reflectance property

Practical Considerations

- Preceding bounds are theoretical
- In practice

Ambient Conditions	Incident energy
Bright daylight	9000 ft-cd
Cloudy day	≈ 1000 ft-cd
Lighted Office	100 ft-cd
Full moon	0.01 ft-cd

feet-candela

Material	Reflectance
Black velvet	0.01
Stainless Steel	0.65
Flat white wall paint	0.8
Silver plated metal	0.9

Gray Level Range

- Intensity of a monochrome image at location (x,y) -> Gray level, L
- For practical (indoor) situations

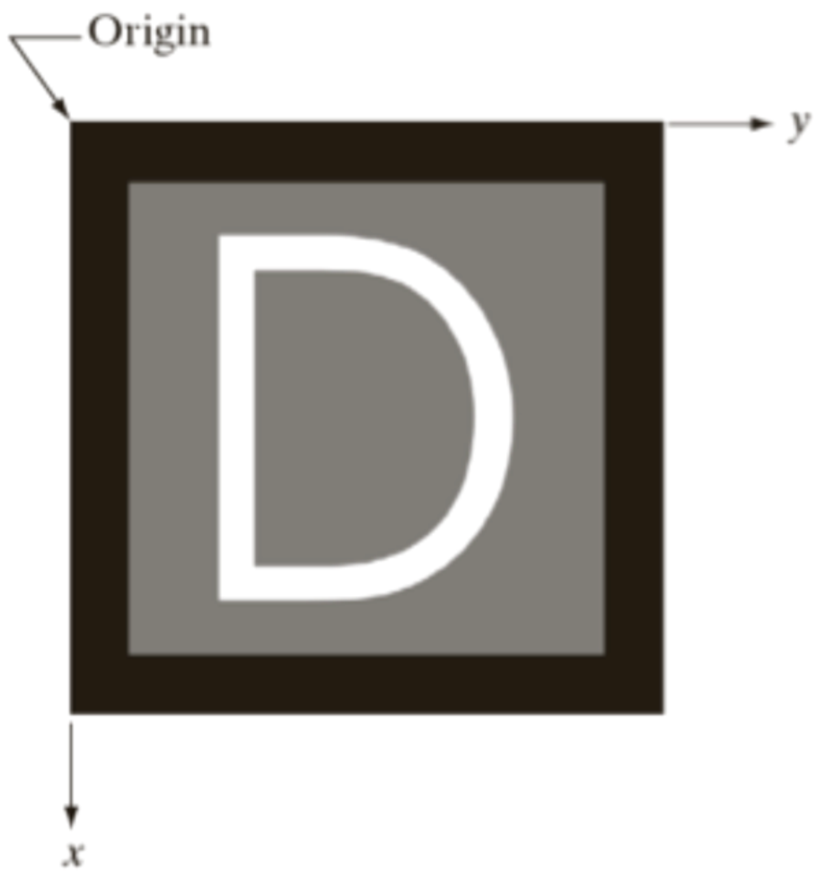
$$L_{min} \approx 0.05$$
$$L_{max} \approx 100$$

- The range $[\ L_{min}, L_{max}\ ]$ is called *Gray Scale* range
- In practice, the interval starts from “0” to a maximum value “L”
    - I = 0 is “black” / total absorption
    - I = L is “white” / total reflectance

Continuous Representation of Images

Image courtesy "Digital Image Processing," by Gonzalez & Woods, 3rd ed.

Continuous Representation of Images



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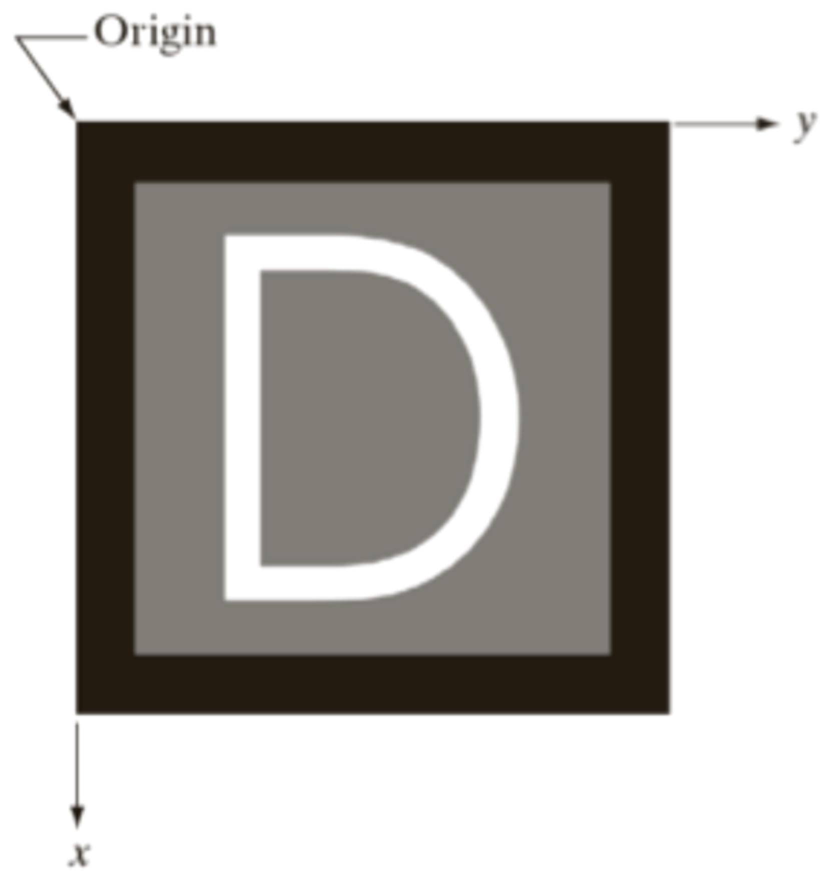

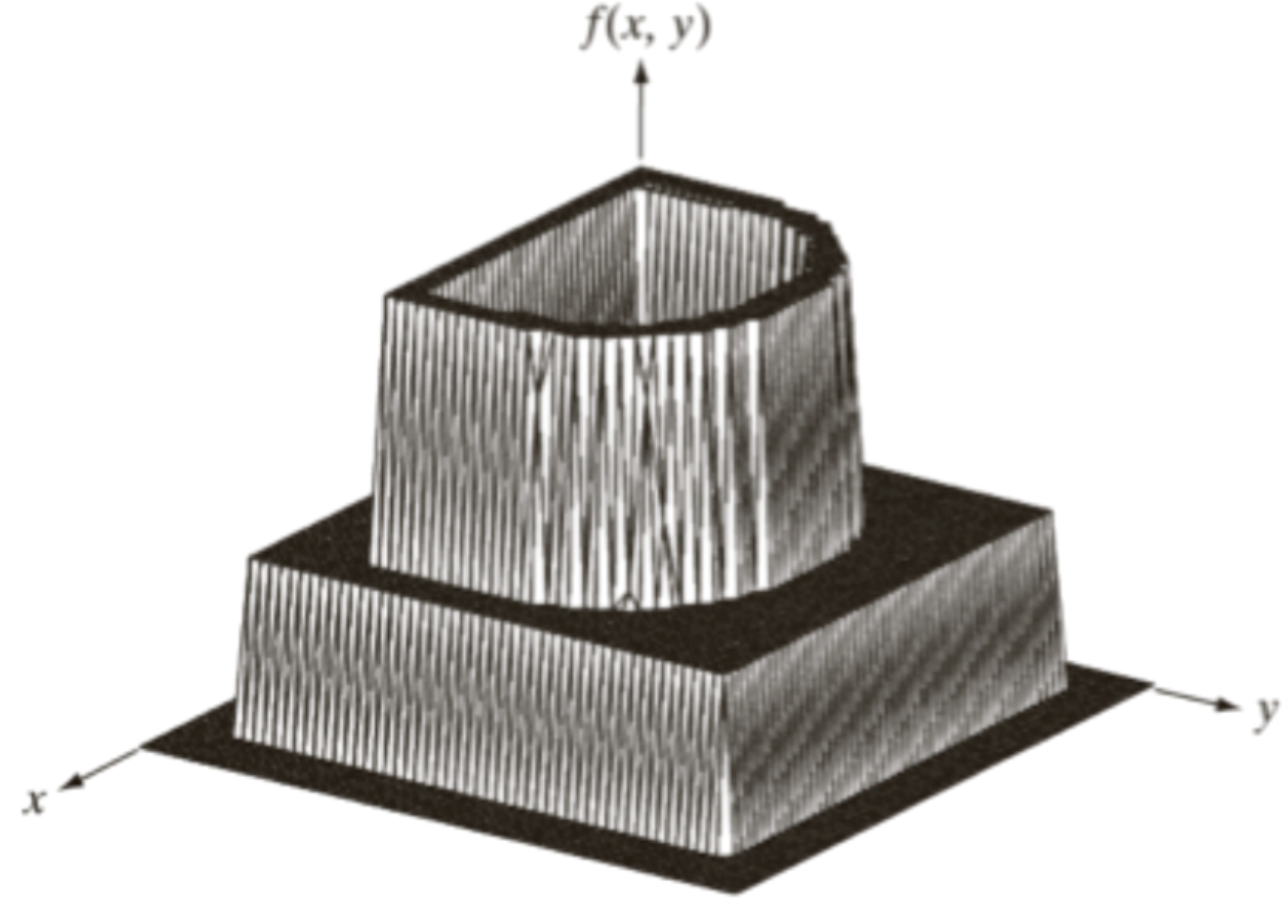

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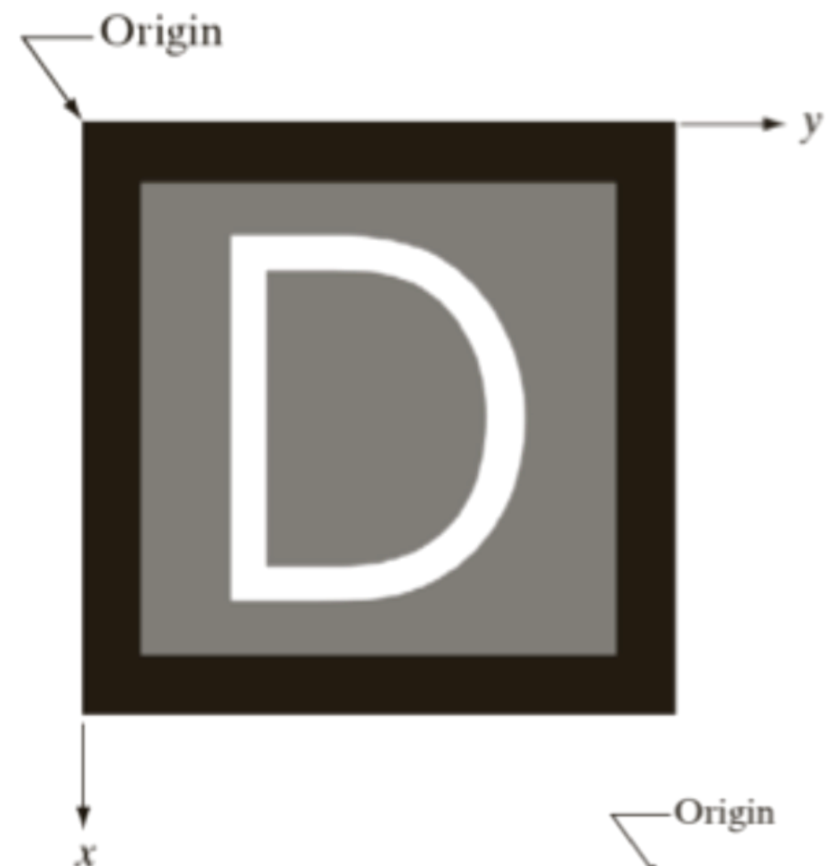
Continuous Representation of Images



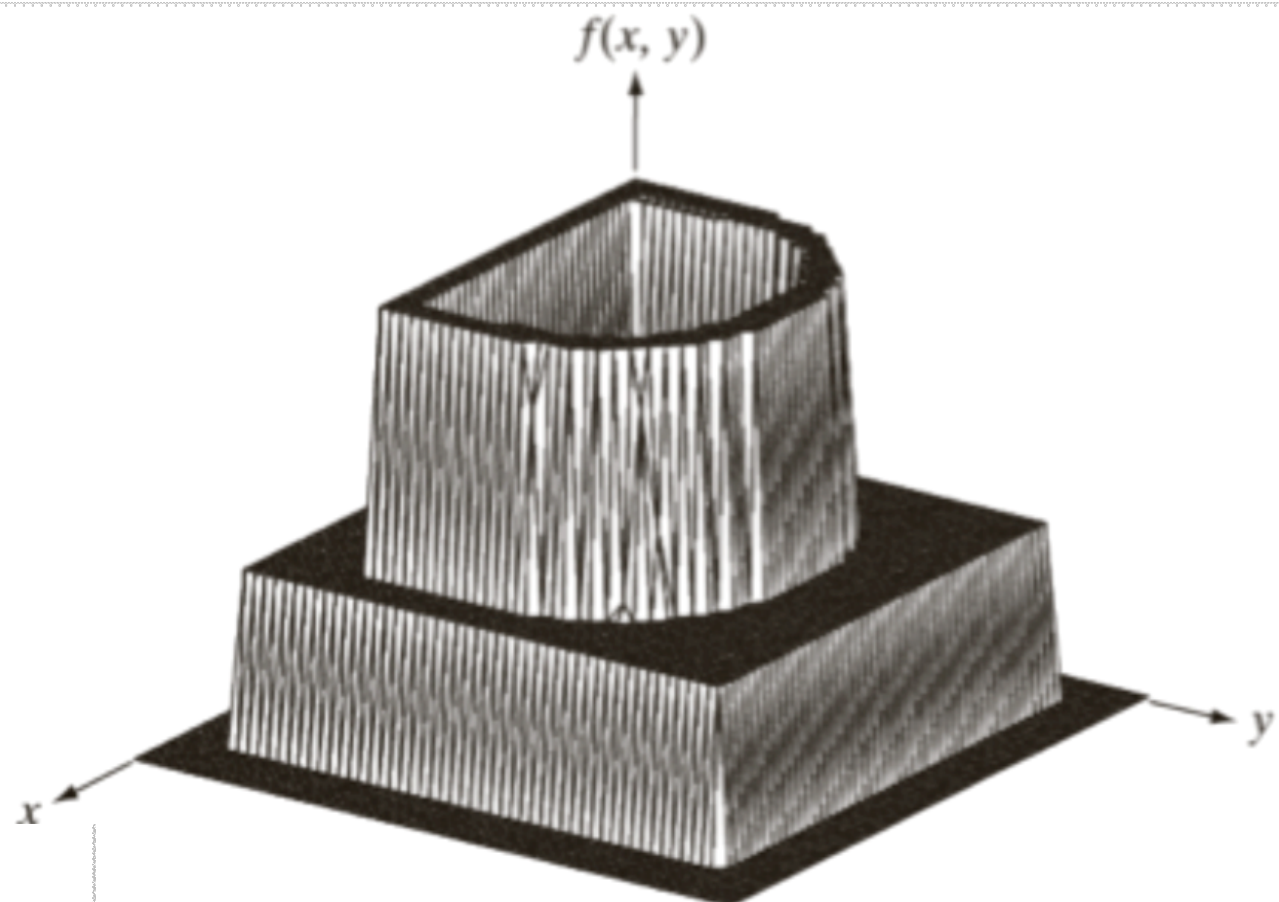


Image courtesy “Digital Image Processing,” by Gonzalez & Woods, 3rd ed.

Sampling & Quantization

“Welcome to the Digital World”

- Representing the image intensities in a computing device
- Digitizing in spatial and energy domains
  - Spatial digitization : Image Sampling
  - Energy digitization : Gray Level Quantization

Digital Image Representation

- Sample at regular intervals in the X and Y axes
- N = row samples, and M = column samples
- I = N x M array of intensity values

$$f(x,y) = \begin{bmatrix} f(0,0) & f(0,1) & \dots & f(0,M-1) \\ f(1,0) & f(1,1) & \dots & f(1,M-1) \\ \dots & \dots & \dots & \dots \\ f(N-1,0) & f(N-1,1) & \dots & f(N-1,M-1) \end{bmatrix}$$

Mathematical Model of a Digital Image

- 2D light intensity function

$$f(x, y) : \mathbb{Z} \, * \, \mathbb{Z} \rightarrow \mathbb{R}$$

Mathematical Model of a Digital Image

- 2D light intensity function

$$f(x, y) : \mathbb{Z} \ * \ \mathbb{Z} \rightarrow \mathbb{R}$$

Integer tuple - 2 values

Mathematical Model of a Digital Image

- 2D light intensity function

$$f(x, y) : \mathbb{Z} \ * \ \mathbb{Z} \rightarrow \mathbb{R}$$

Integer tuple - 2 values

Real values

Mathematical Model of a Digital Image

- 2D light intensity function

$$f(x, y) : \mathbb{Z} \ * \ \mathbb{Z} \rightarrow \mathbb{R}$$

Integer tuple - 2 values

Real values

$$f(3, 6) = 3.56$$

Quantization

- Quantum => discrete packets
    - Represent the continuous grayscale image with the help of discrete values
    - Lossy !!

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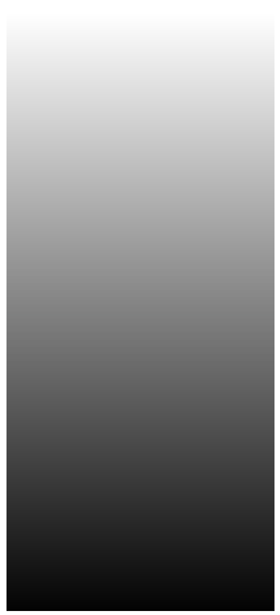

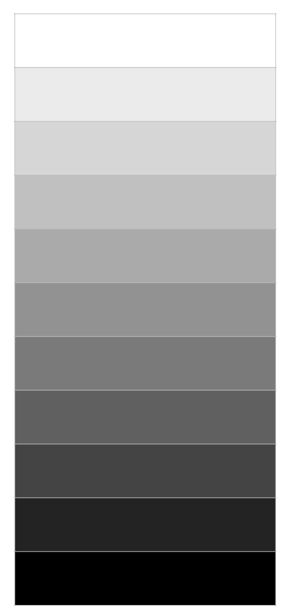

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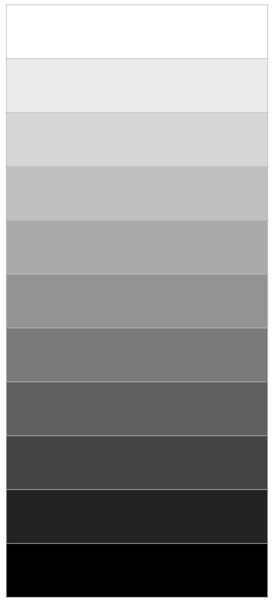
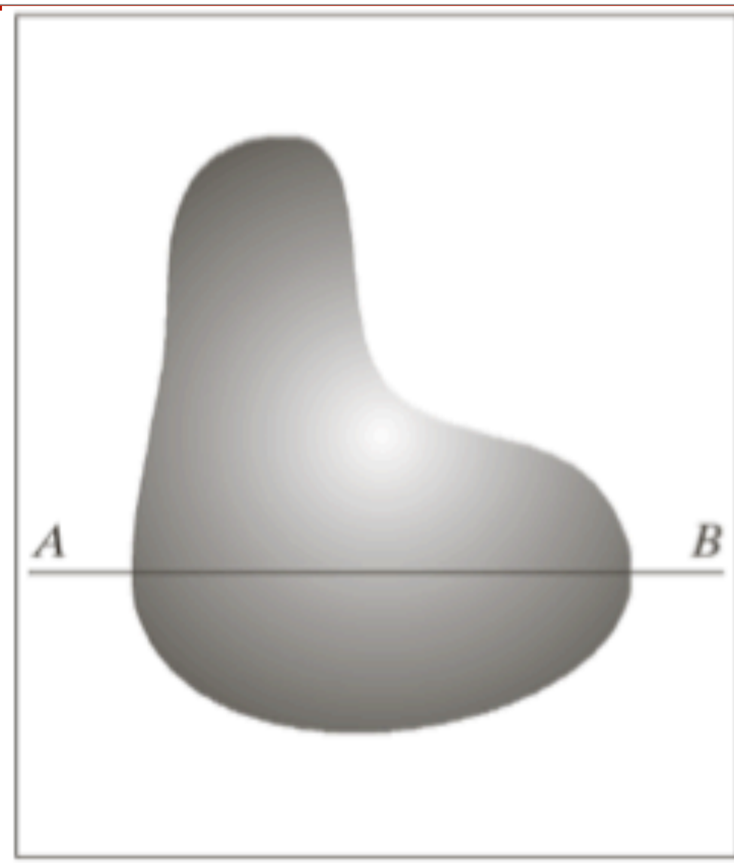


G, number of gray levels

From Analog to Digital



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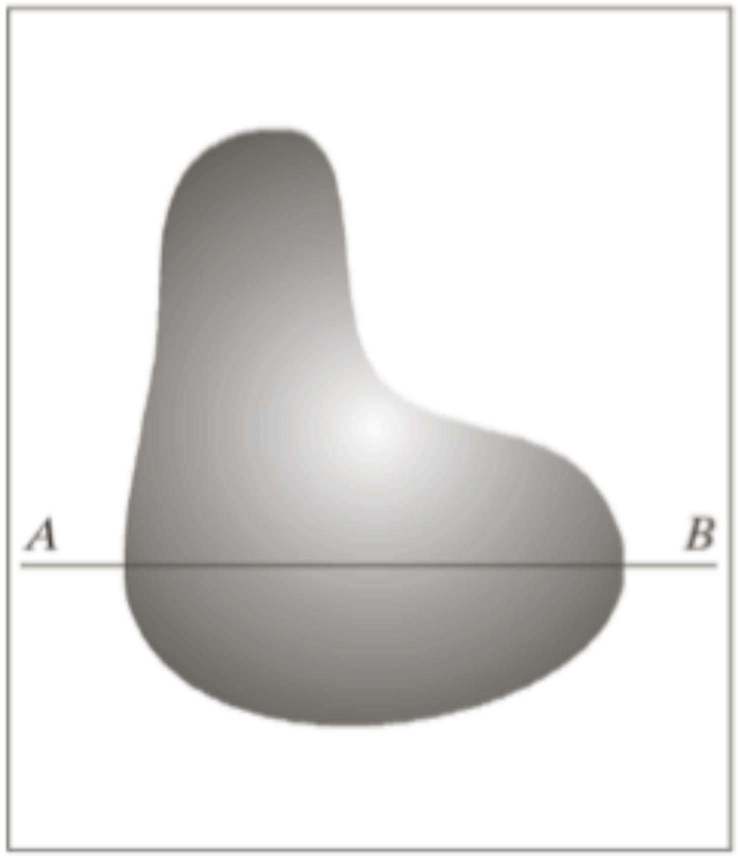

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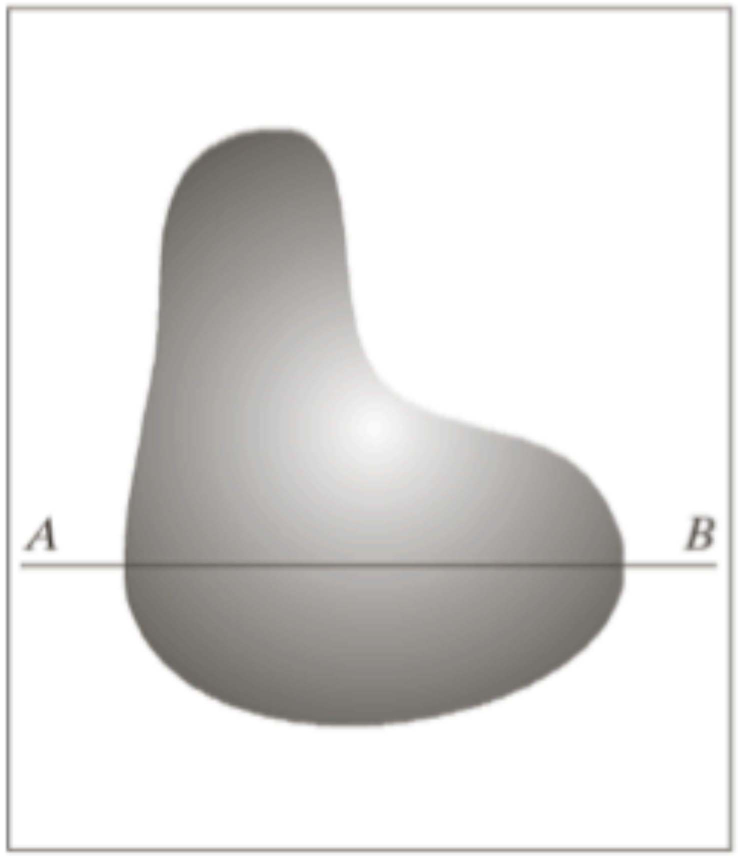

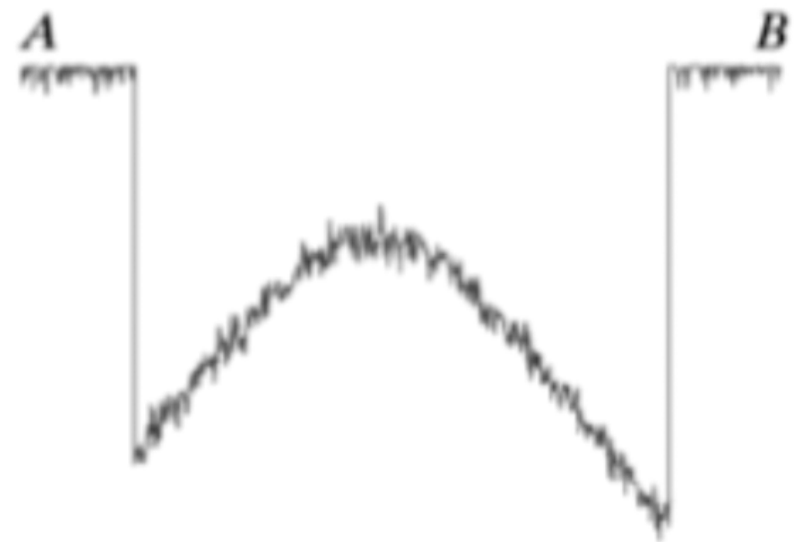

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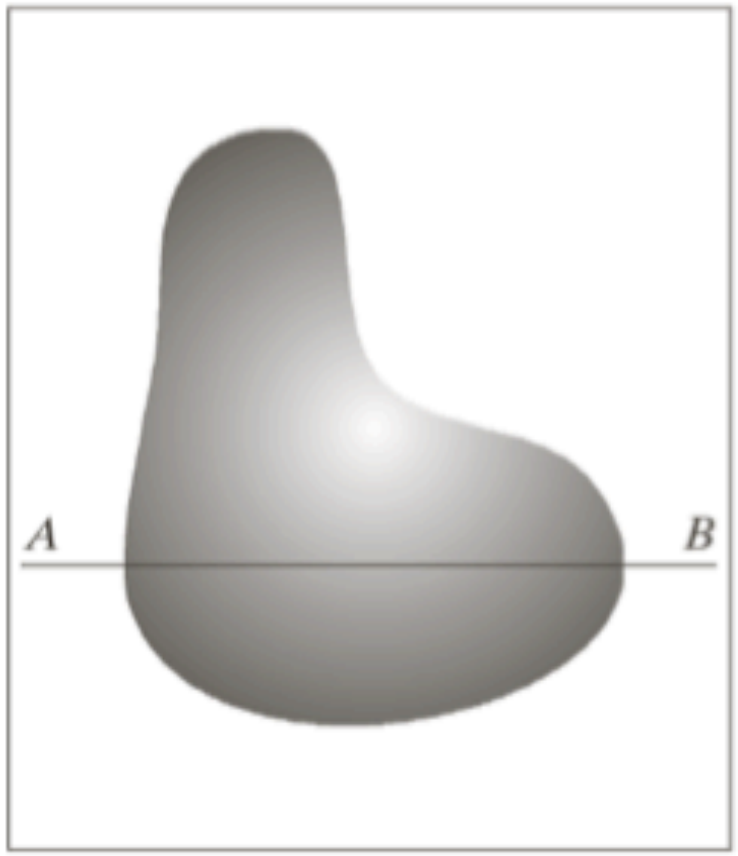

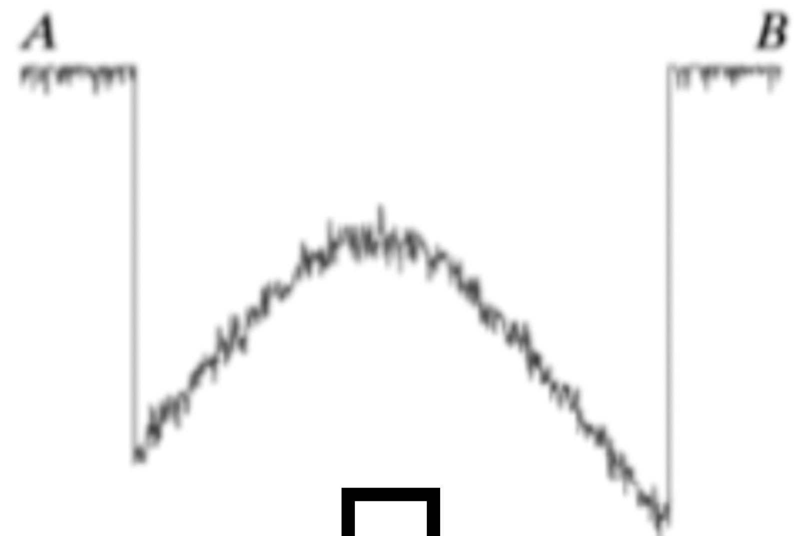

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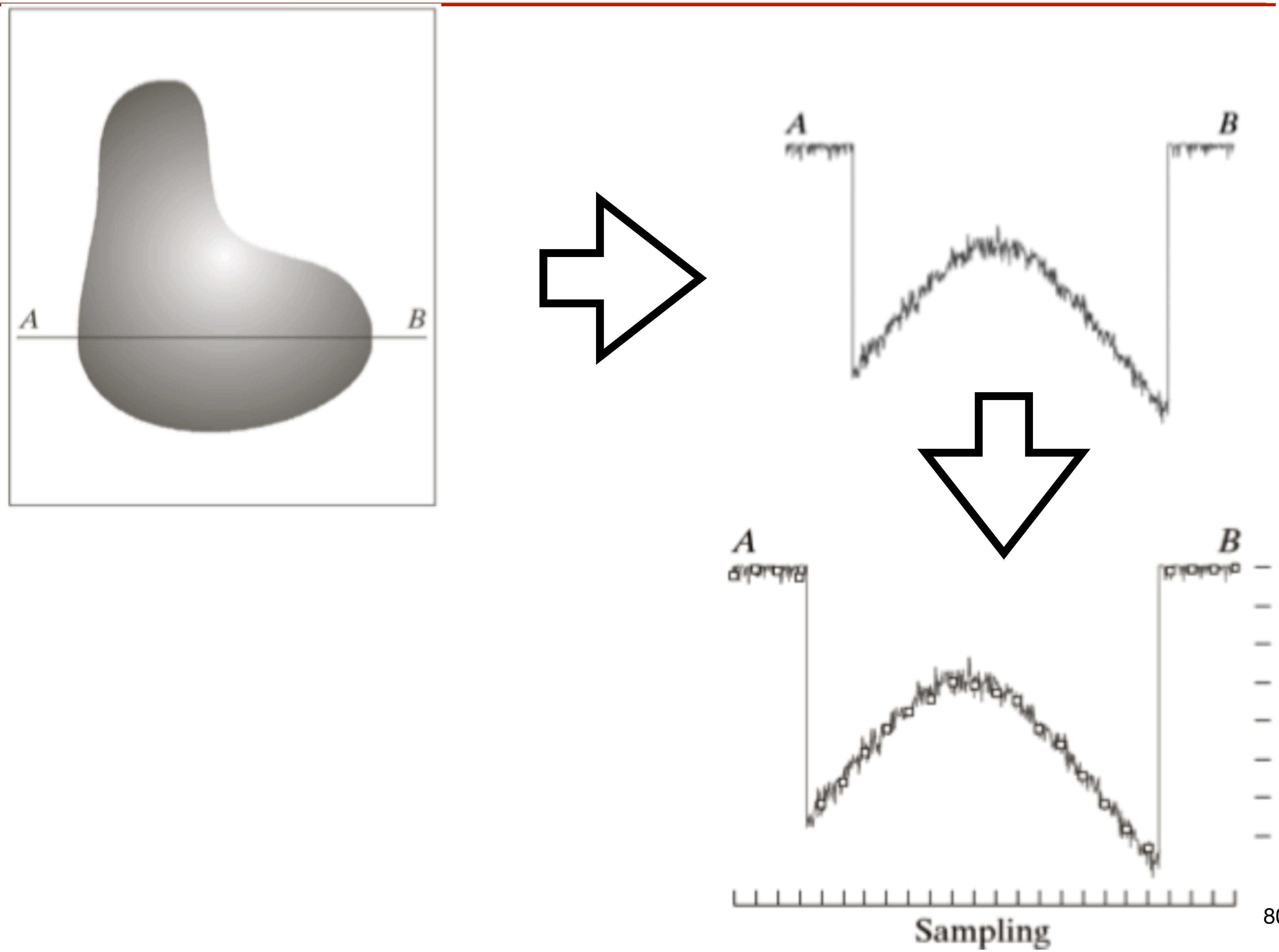

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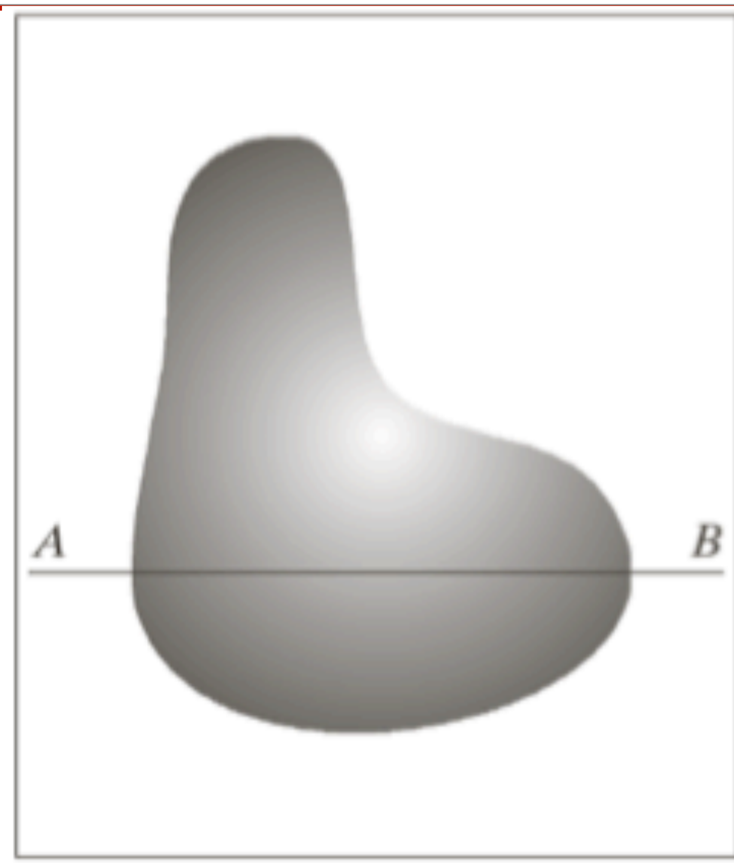
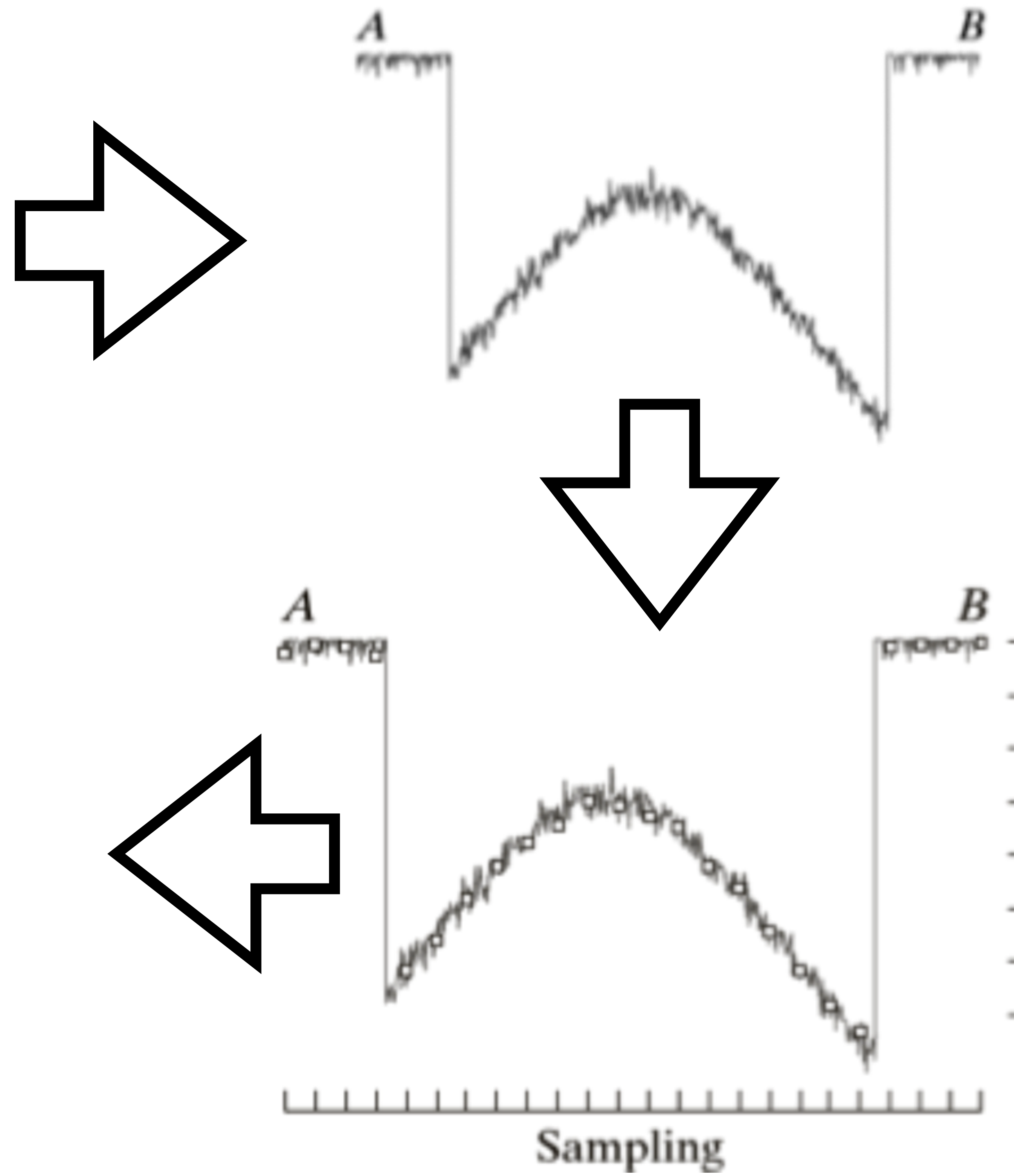
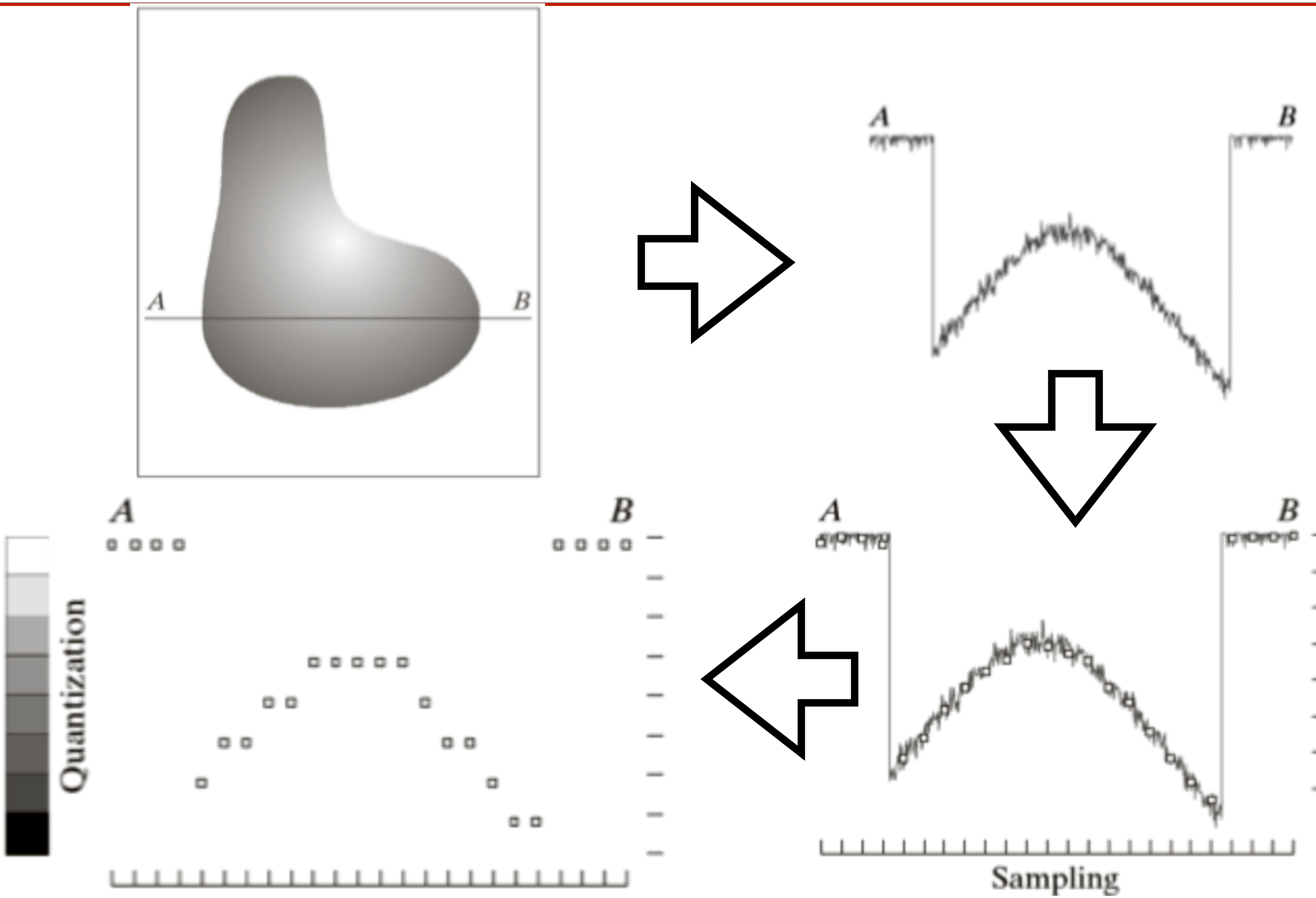
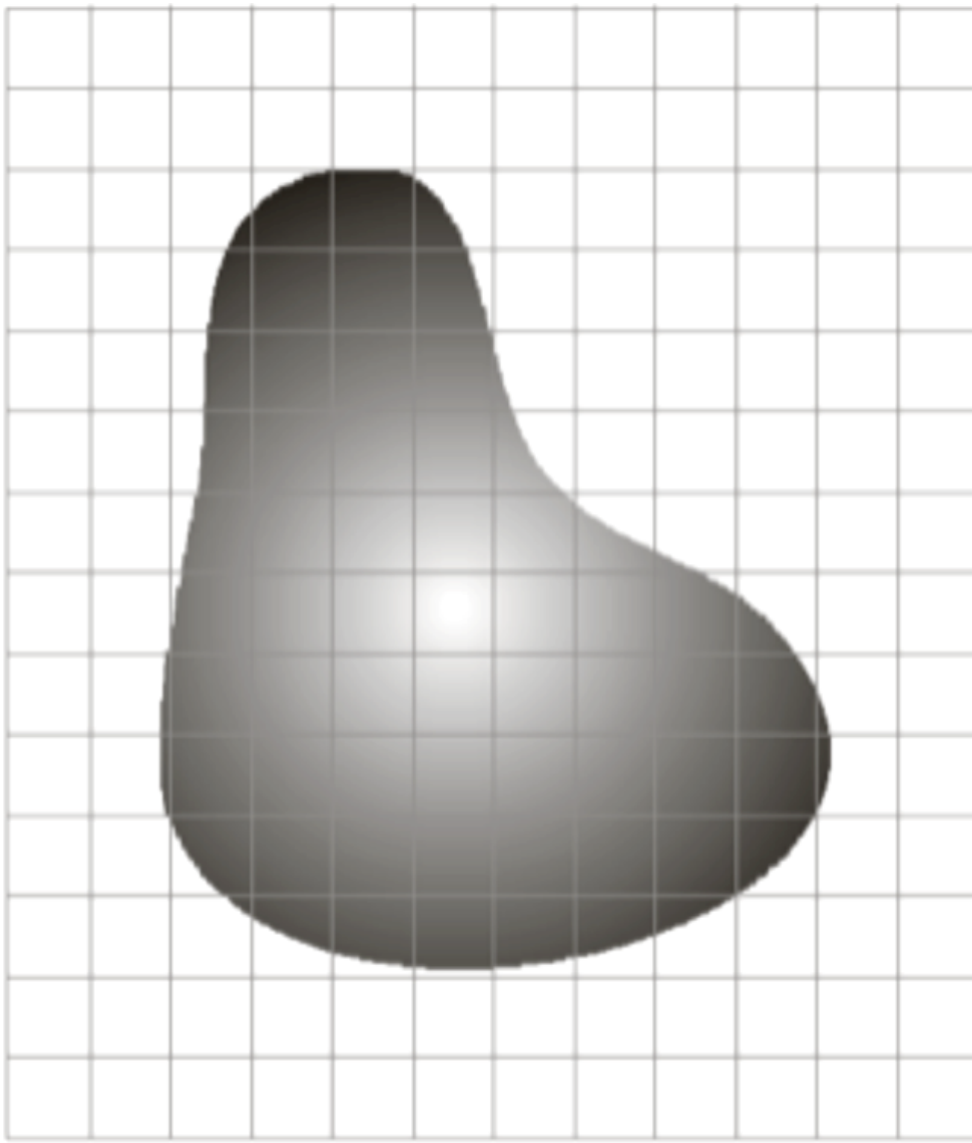




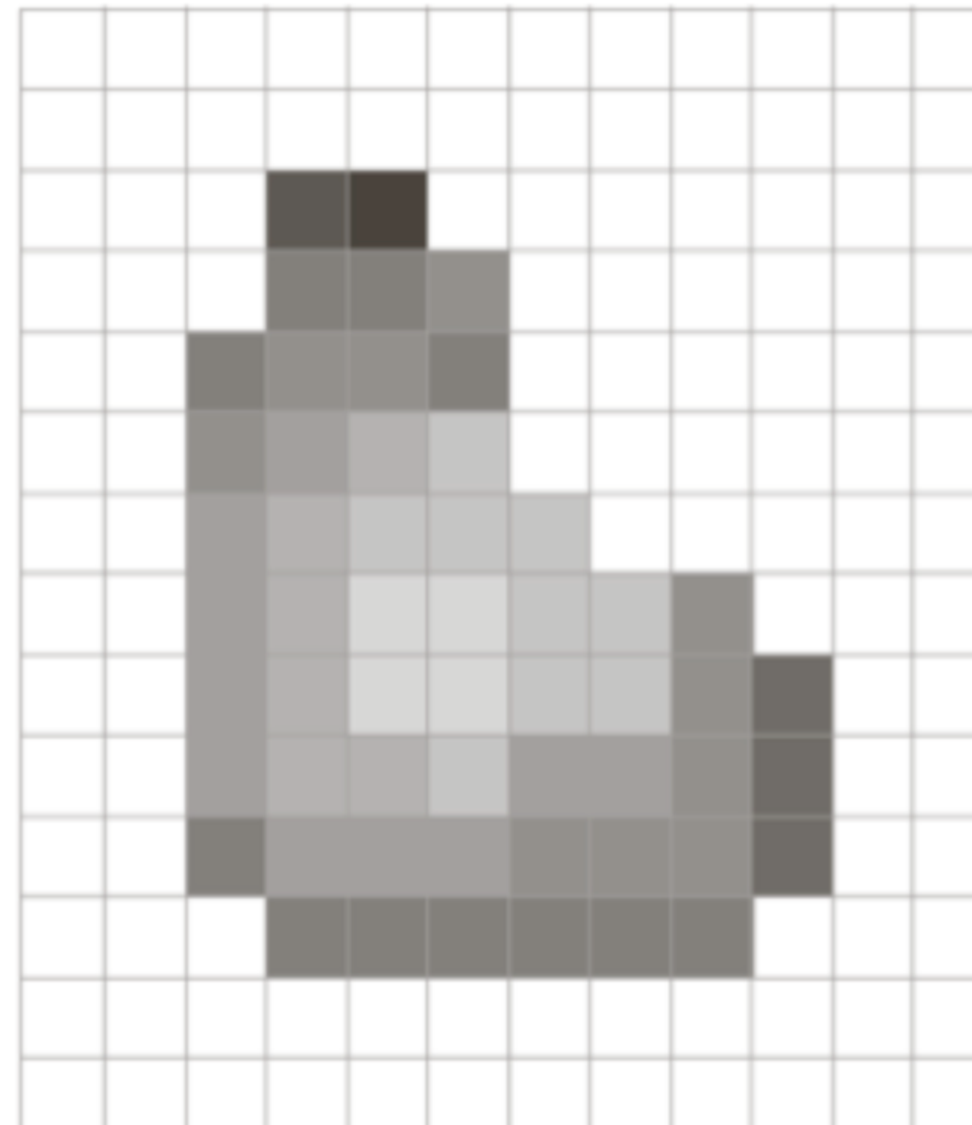
From Analog to Digital



From Analog to Digital (2)



Continuous input on the sensor



Result of Image Sampling and Quantization

Image courtesy “Digital Image Processing,” by Gonzalez & Woods, 3rd ed.

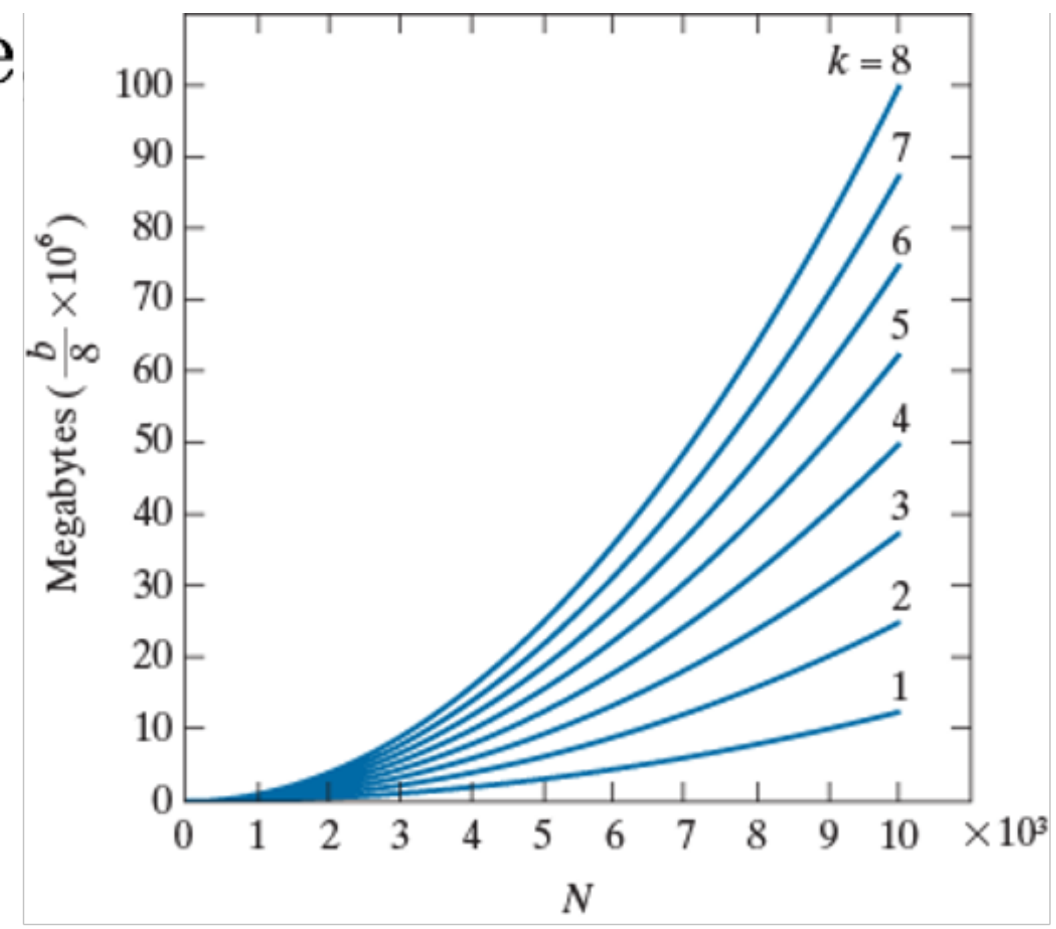
Image Resolution

$$G = 2^k$$

$$N = rows$$

$$M = columns$$

Number of bits to store the image
$b = N * M * k$



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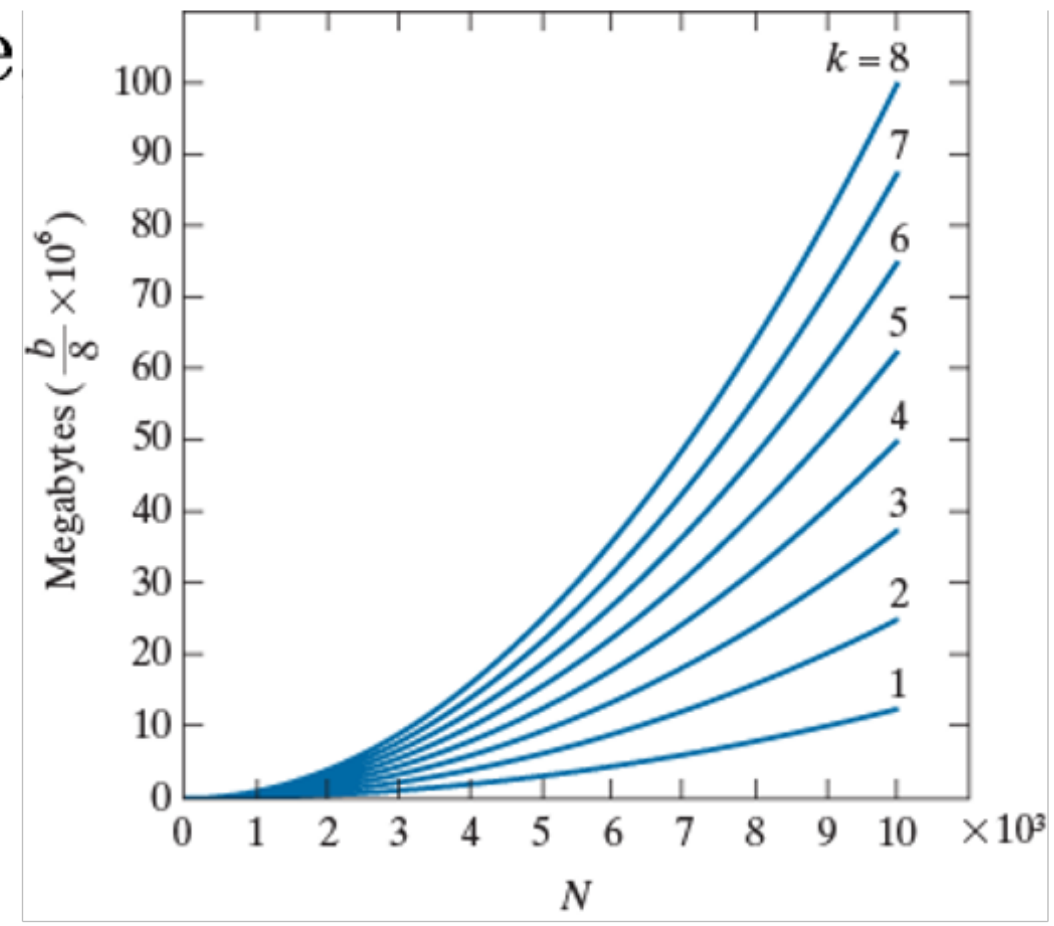
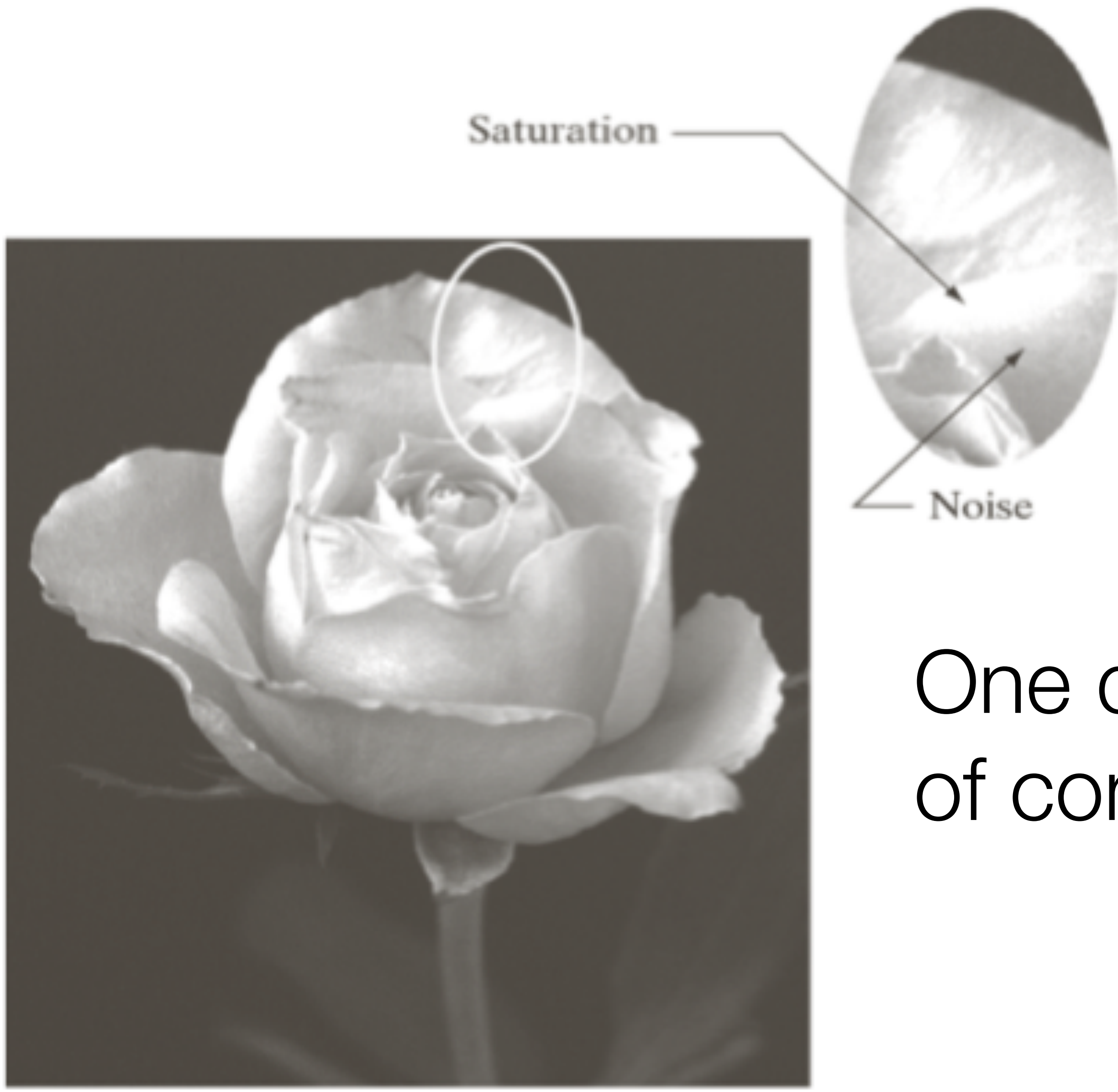
Number of bits to store the image

$$b = N * M * k$$



- How many megapixels on an analog media?

Acquisition Artifacts - Noise & Saturation



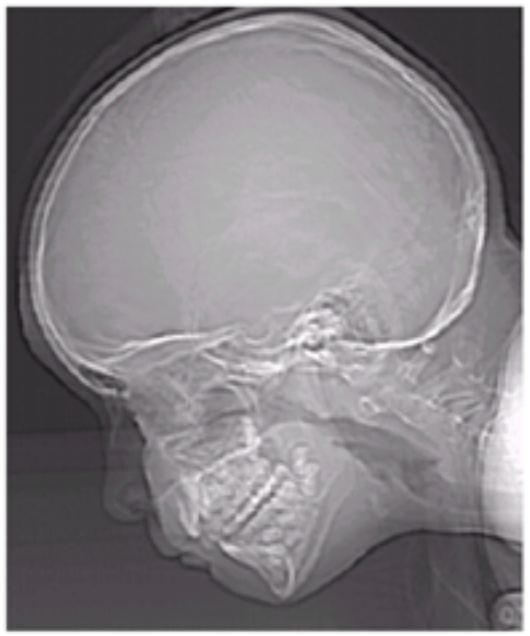
One digital value represents a range of continuous values

Image courtesy "Digital Image Processing," by Gonzalez & Woods, 3rd ed.

How many levels of Quantization are enough?

Image courtesy "Digital Image Processing," by Gonzalez & Woods, 3rd ed.

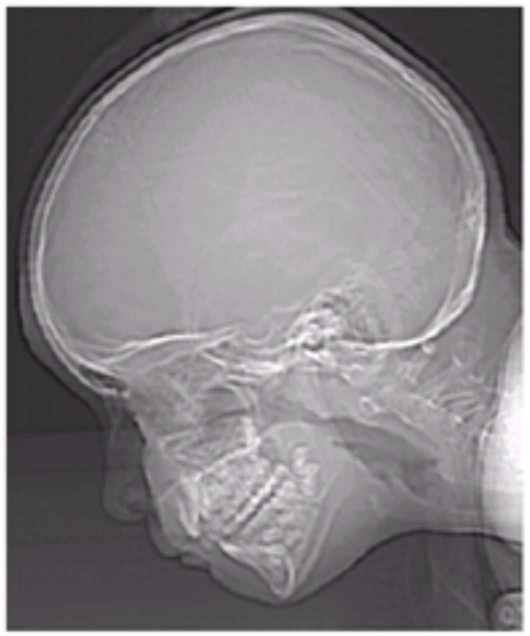
How many levels of Quantization are enough?



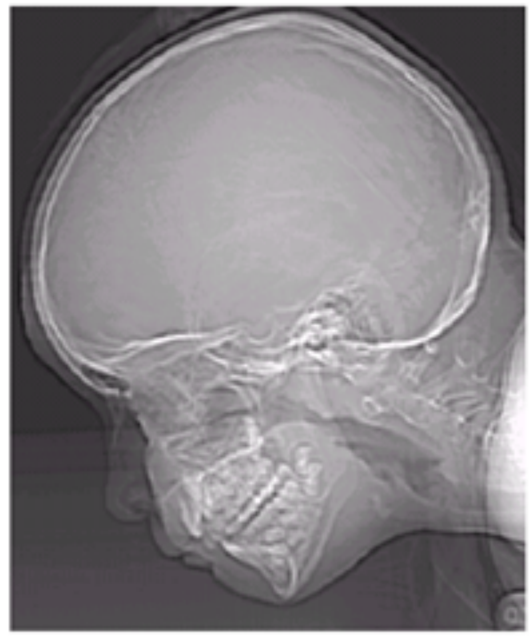
256

Image courtesy "Digital Image Processing," by Gonzalez & Woods, 3rd ed.

How many levels of Quantization are enough?



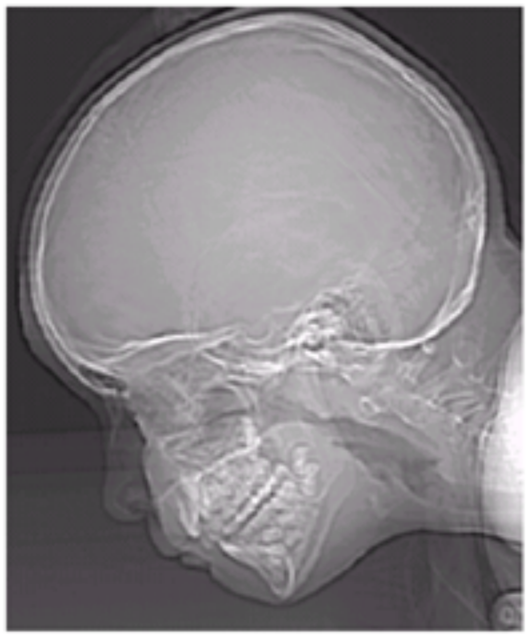
256



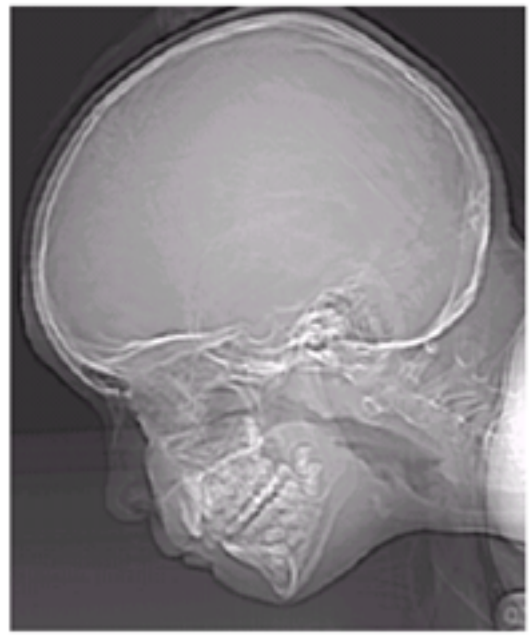
128

Image courtesy “Digital Image Processing,” by Gonzalez & Woods, 3rd ed.

How many levels of Quantization are enough?



256

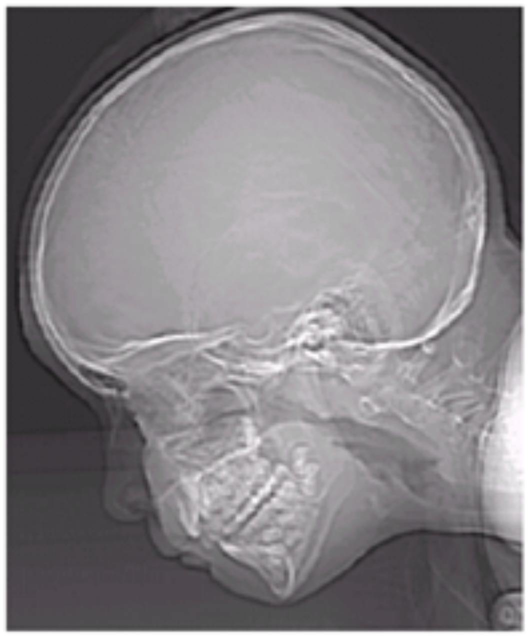


128

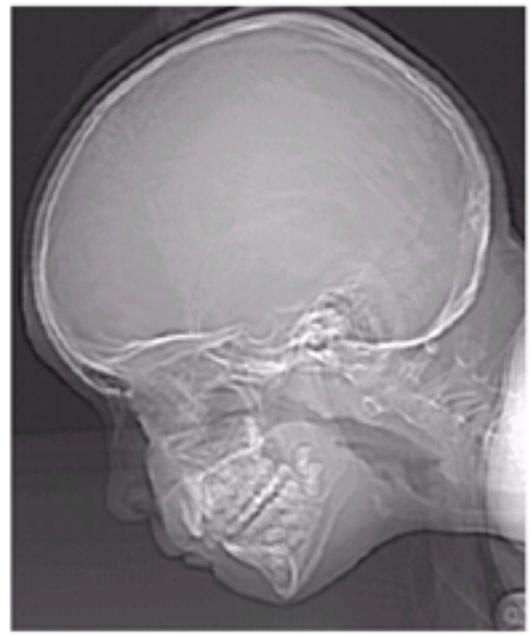
64

Image courtesy "Digital Image Processing," by Gonzalez & Woods, 3rd ed.

How many levels of Quantization are enough?

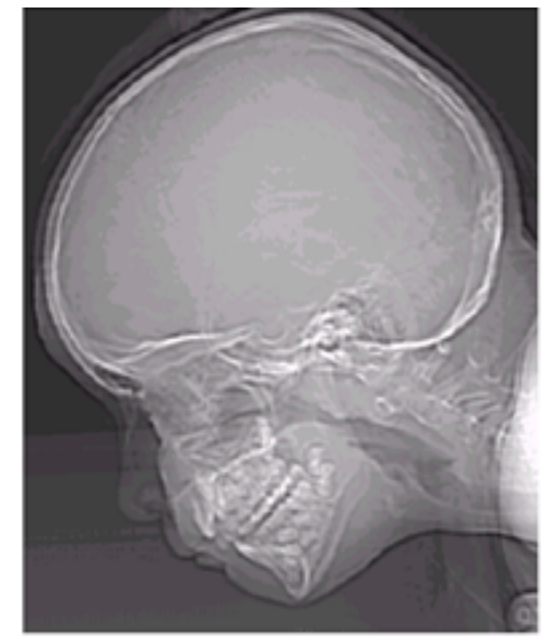


256



128

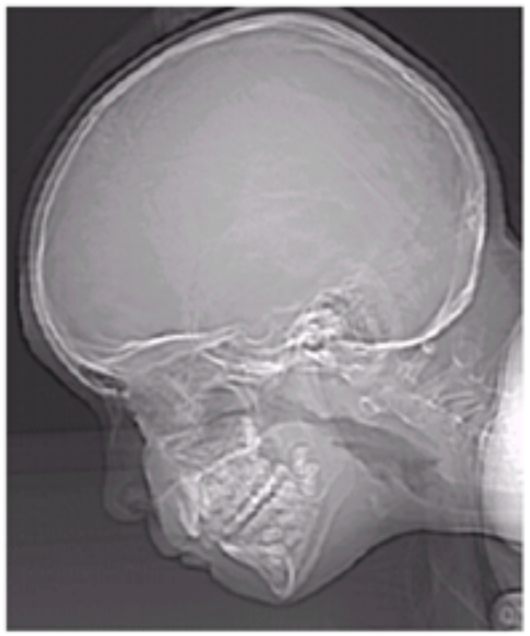
64

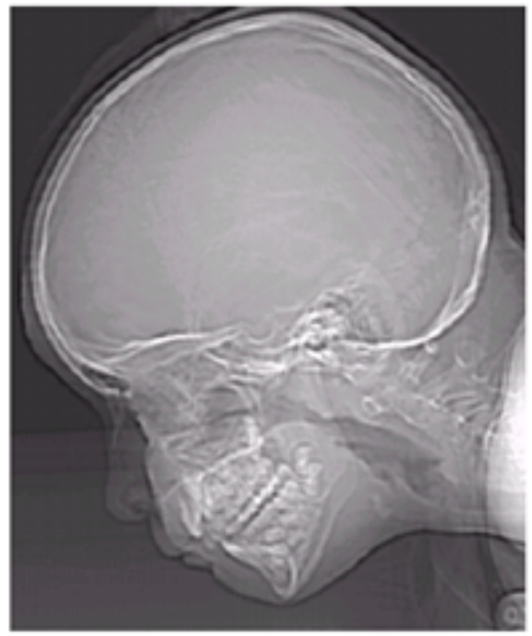


32

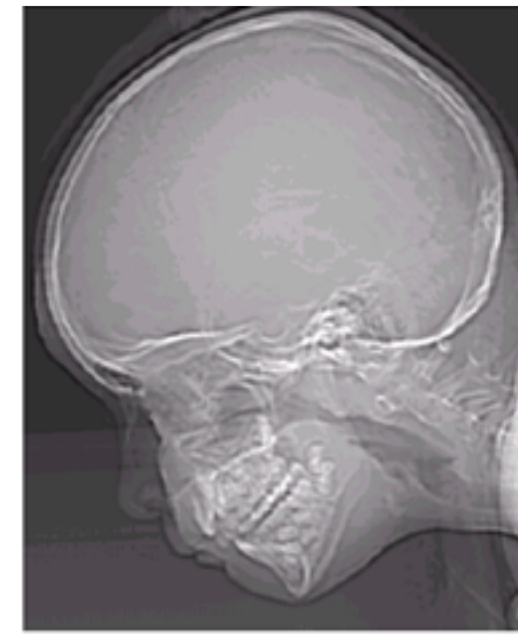
Image courtesy “Digital Image Processing,” by Gonzalez & Woods, 3rd ed.

How many levels of Quantization are enough?


256

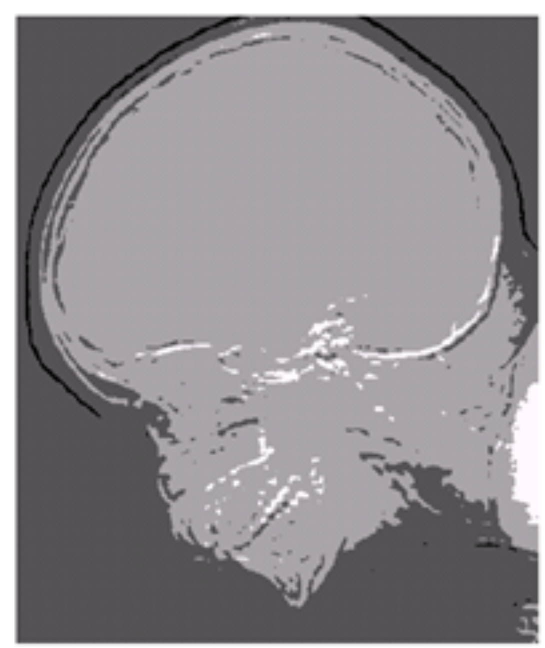

128


64


32


16

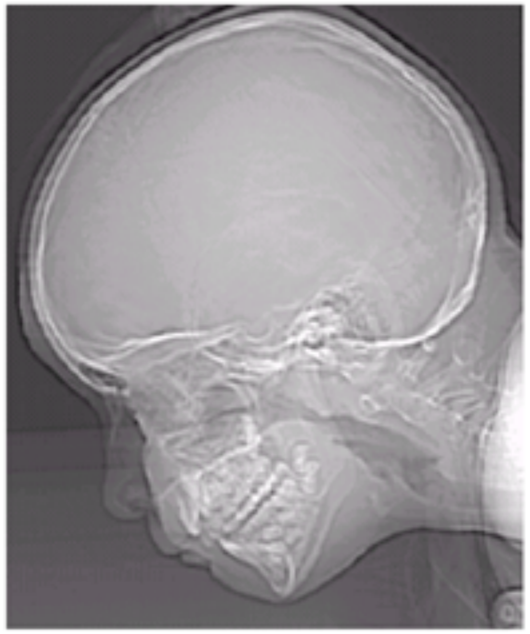

8


4


2

Image courtesy “Digital Image Processing,” by Gonzalez & Woods, 3rd ed.

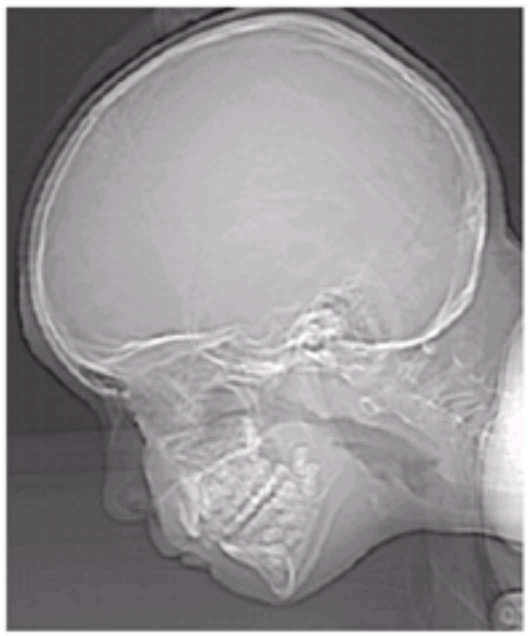
How many Pixels are enough?



100%

Image courtesy “Digital Image Processing,” by Gonzalez & Woods, 3rd ed.

How many Pixels are enough?

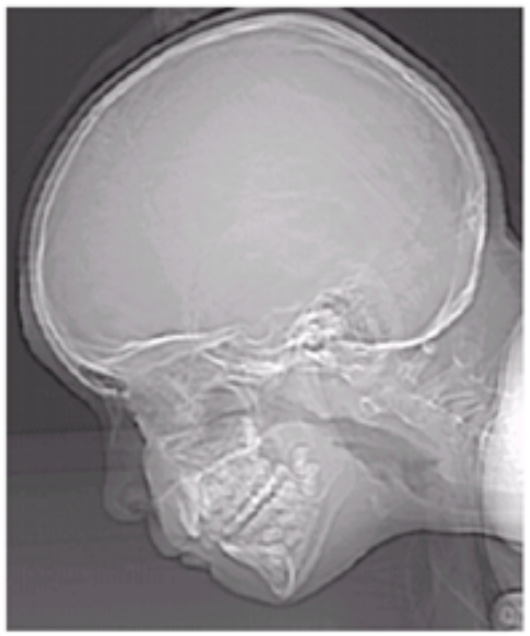


100%

50%

Image courtesy "Digital Image Processing," by Gonzalez & Woods, 3rd ed.

How many Pixels are enough?



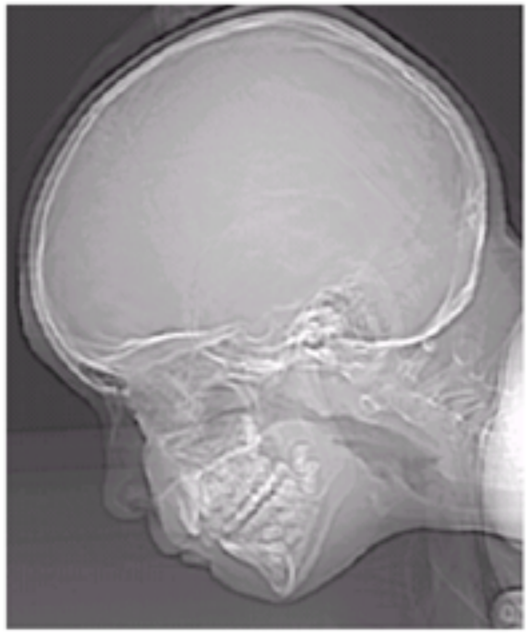
100%

50%

25%

Image courtesy “Digital Image Processing,” by Gonzalez & Woods, 3rd ed.

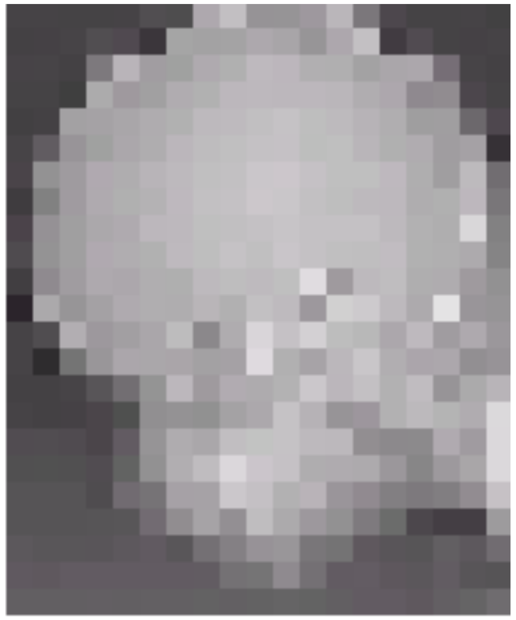
How many Pixels are enough?



100%

50%

25%



10%

Image courtesy “Digital Image Processing,” by Gonzalez & Woods, 3rd ed.

Non-uniform Sampling & Quantization

- Sample more points in regions of details
    - Change of intensity level
    - Edges

Low-detail

Mid-detail

High-detail

Non-uniform sampling - low detail image

Non-uniform sampling - low detail image

Input Image

Non-uniform sampling - low detail image

Input Image

Non uniform
Sampling

Non-uniform sampling - low detail image

Input Image

Non uniform
Sampling

Output Image

Non-uniform sampling - low detail image

Input Image

Non uniform Sampling

Output Image

Difference image

Sampling with Details

- Not feasible for **dense** images - **crowd** example
  - Too much detail/edge information to encode
- Requires extra storage
- Non-uniform quantization
  - Use more bits for frequently occurring values
  - Huffman encoding

Summary

- Digital Image Processing - Steps & Components
  - Image Operations (Image Processing)
  - Image Analysis (Computer Vision)
- Real-world images are 2D continuous signals
- Digitization Process
  - Sampling - choosing discrete points in the Spatial Domain
  - Quantization - ‘snapping’ to specific energy values in Image Intensity Range

Thank You.