Scientific Images

Mars Expedition

Consumer Images and Videos

Movie Postproduction

Ocean's Eleven

Glass turns into plate (then glass again)

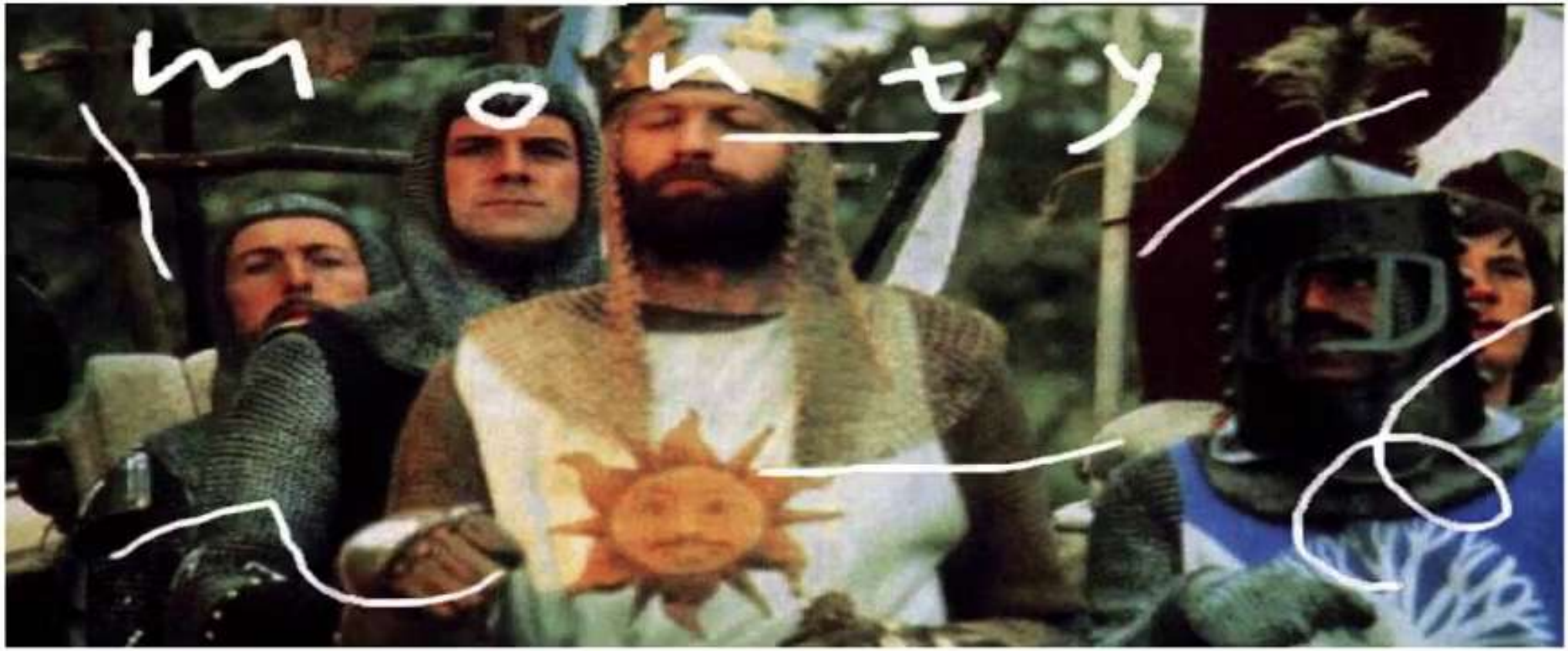
Pirates of the Caribbean: The Curse of the Black Pearl

Crew member visible

Just as Jack says, "On deck, you scabrous dogs," to the very left edge of the screen over Jack's shoulder is a grip crew member with a tan cowboy hat, white short sleeve tee shirt and sunglasses, just standing there looking

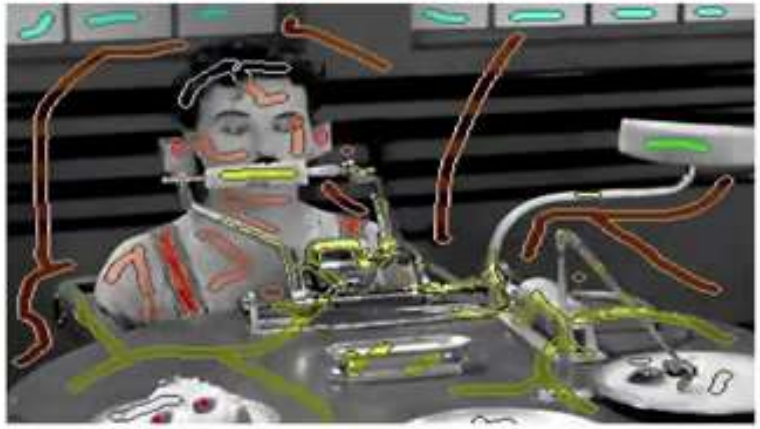
www.movie-mistakes.com

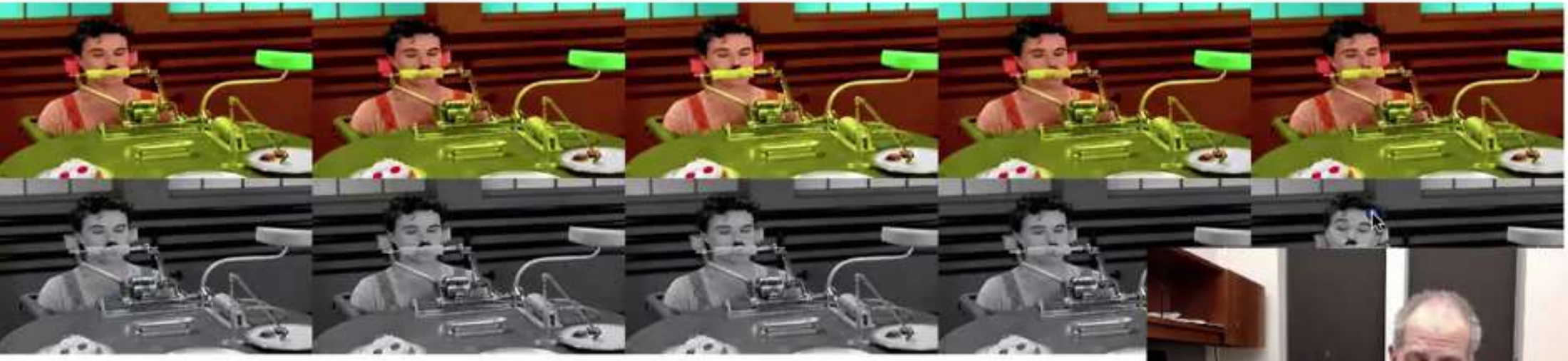
From D. King, “The Commissar vanishes”.



Single frame from a Monty Python movie

Single frame from a Monty Python movie



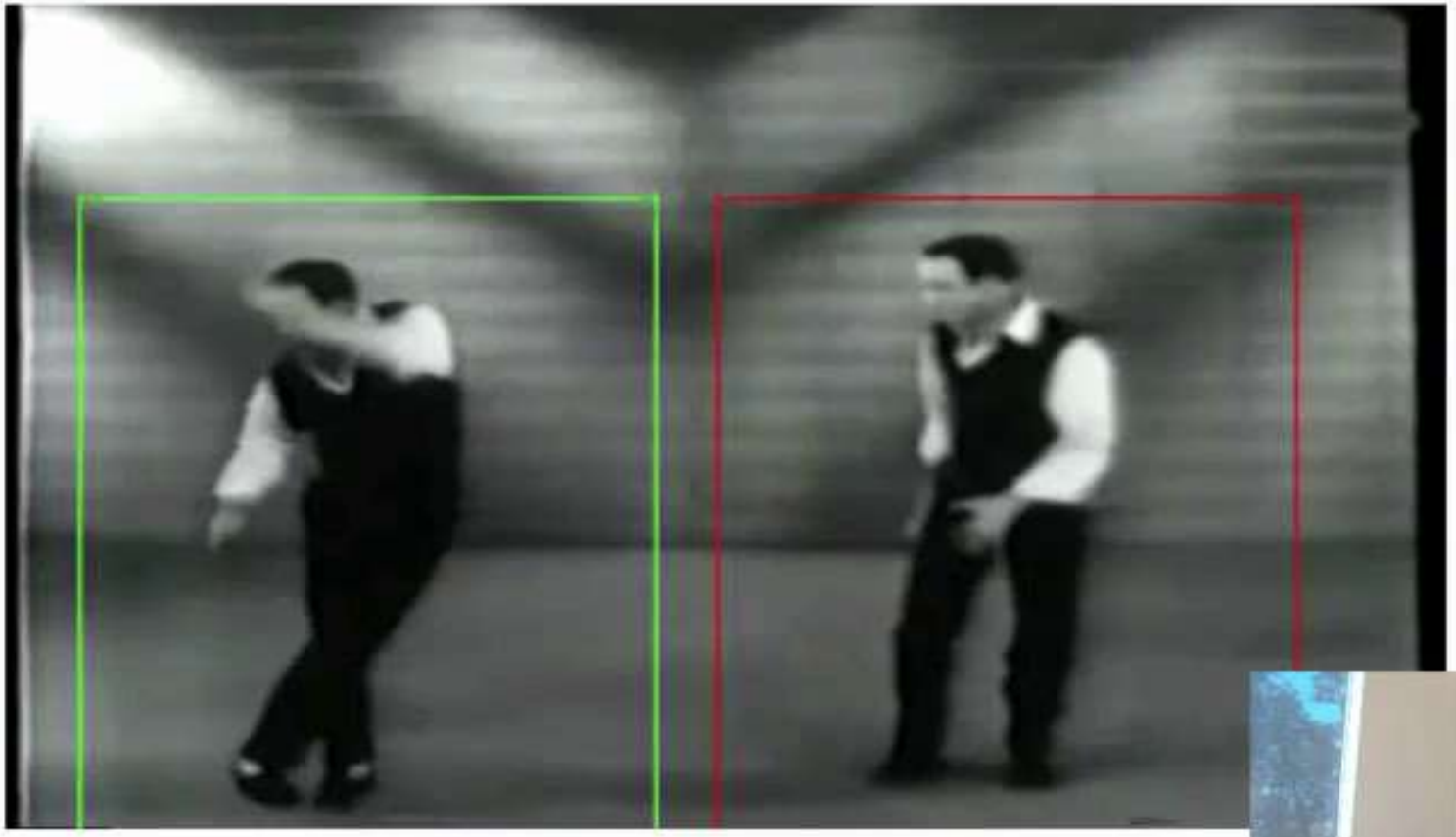


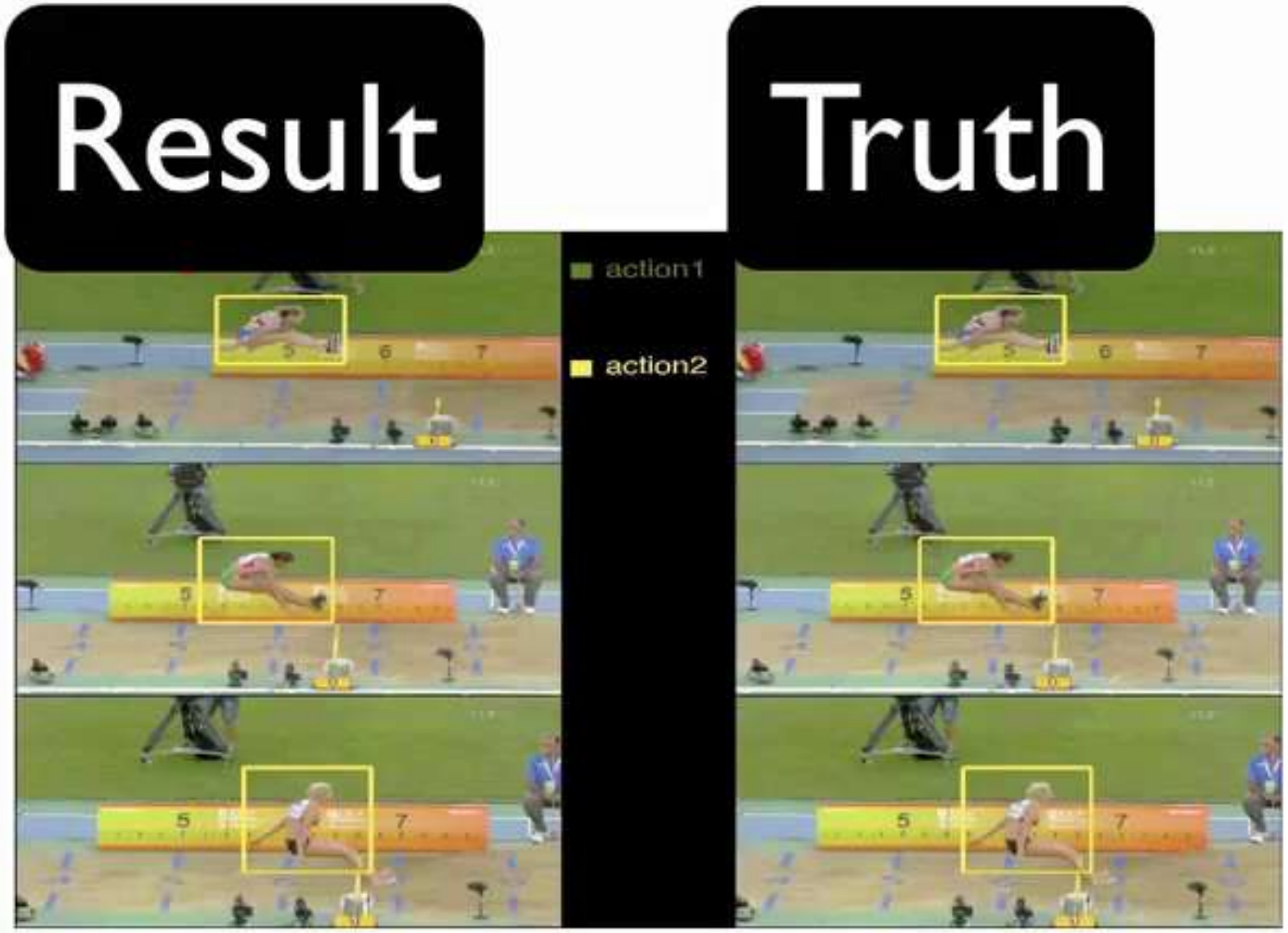
8

gettyimages

After Effects File Edit Composition Layer Effect Animation View Window Help

Consumer Images and Videos

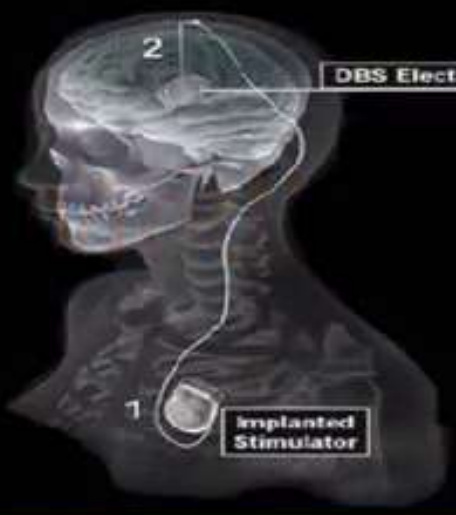


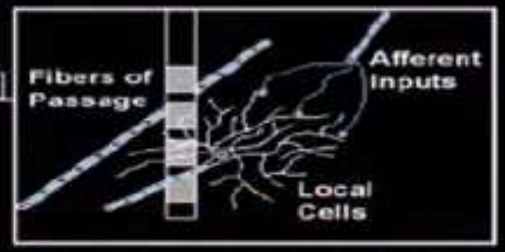

Result
Truth
action1
action2

Motivation

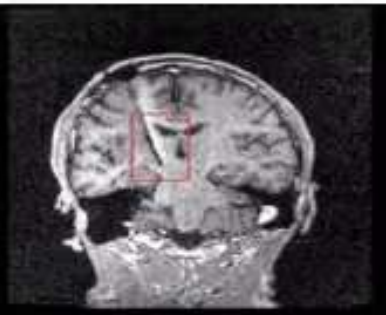
Medical and Biological Images

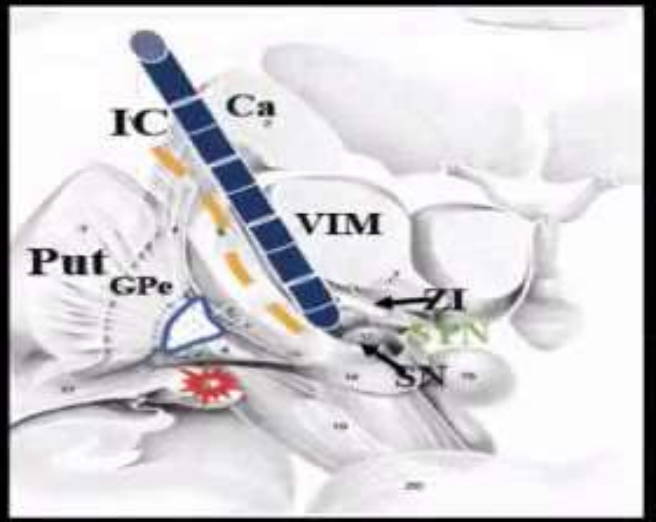
Deep Brain Stimulation (DBS)





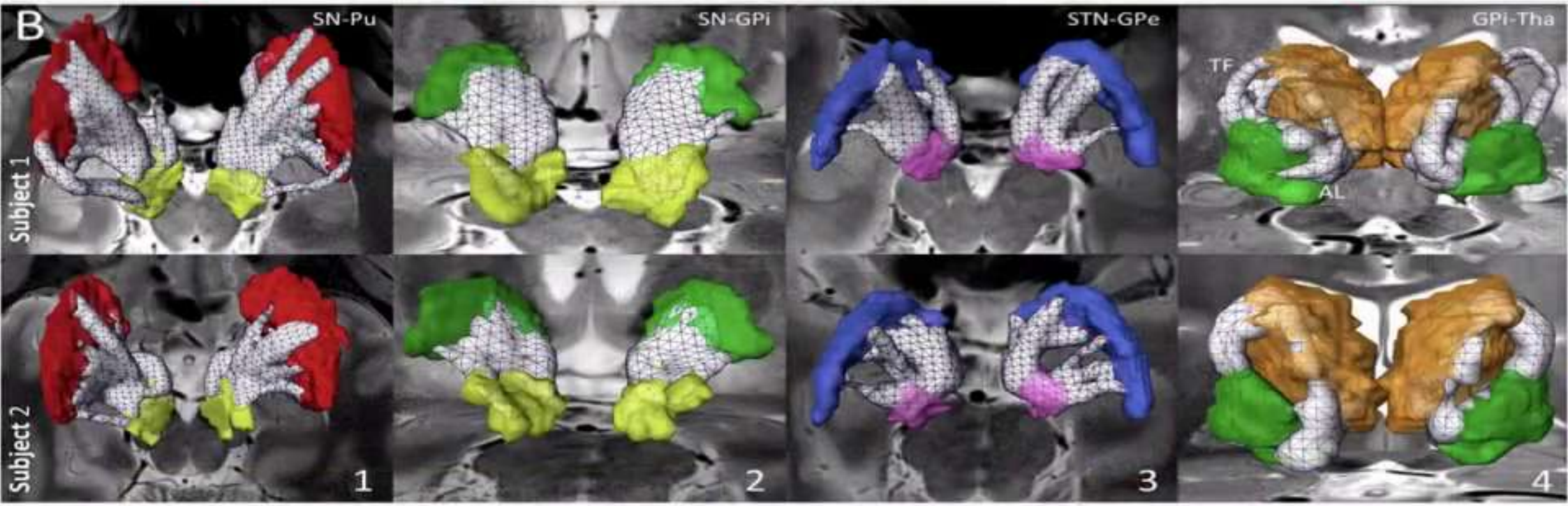
Cameron McIntyre, Cleveland Clinic Foundation





Successful DBS surgery is critically dependent on precise placement of DBS electrodes into target structures

Specific White Matter Pathways



Nigrostriatal

- Hard to reconstruct
- Consistency
- Some degree of variability between subjects

Nigropallidal

- Involved in PD (loss)

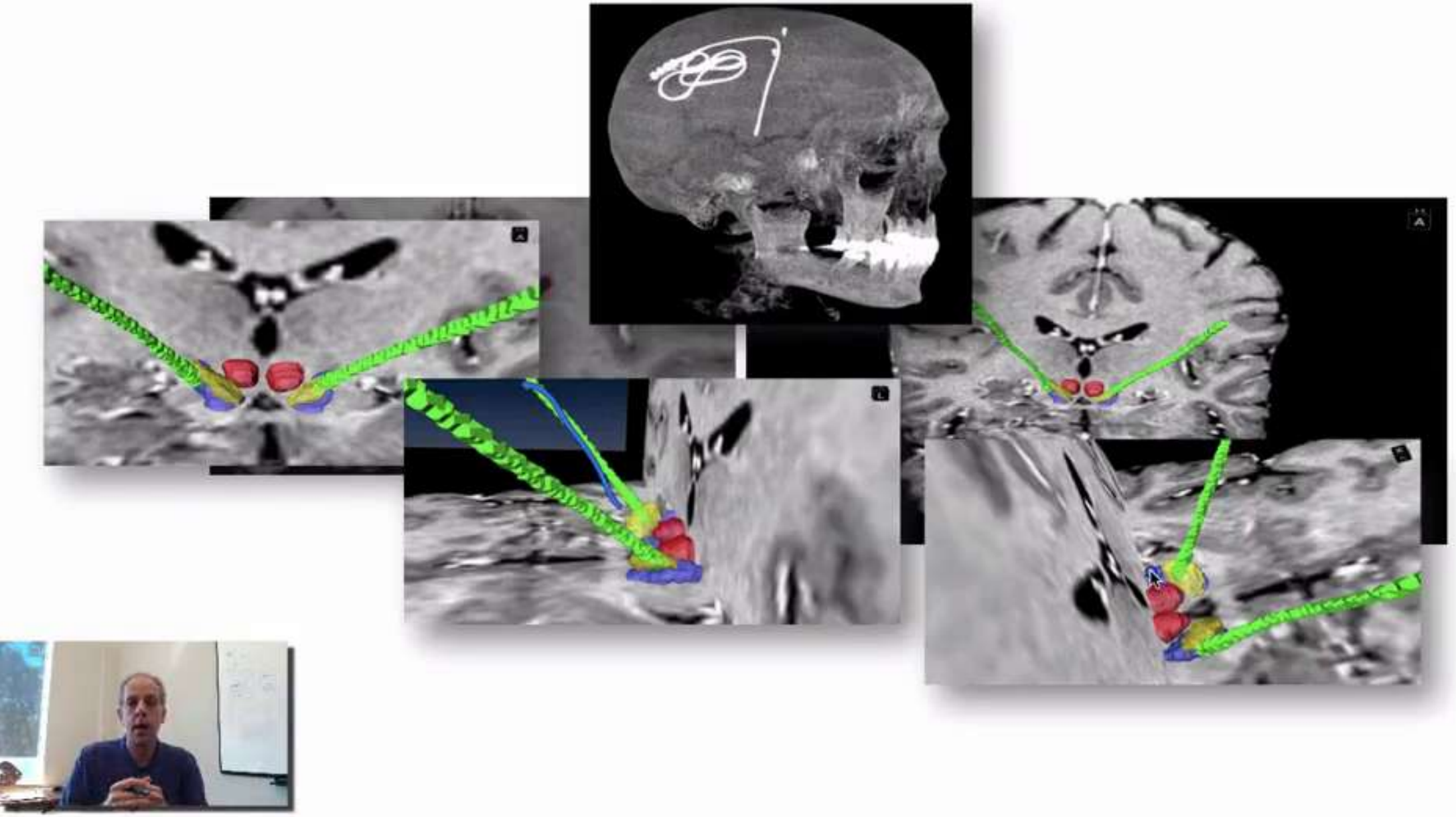
Subthalamopallidal

- Regulate burst activity in BG

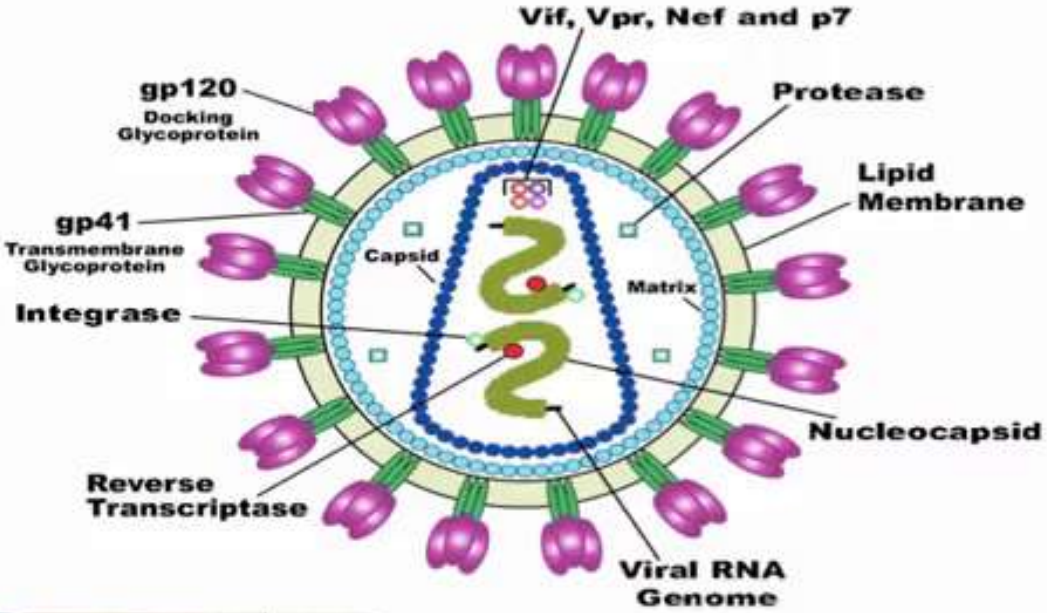
Pallidothalamic

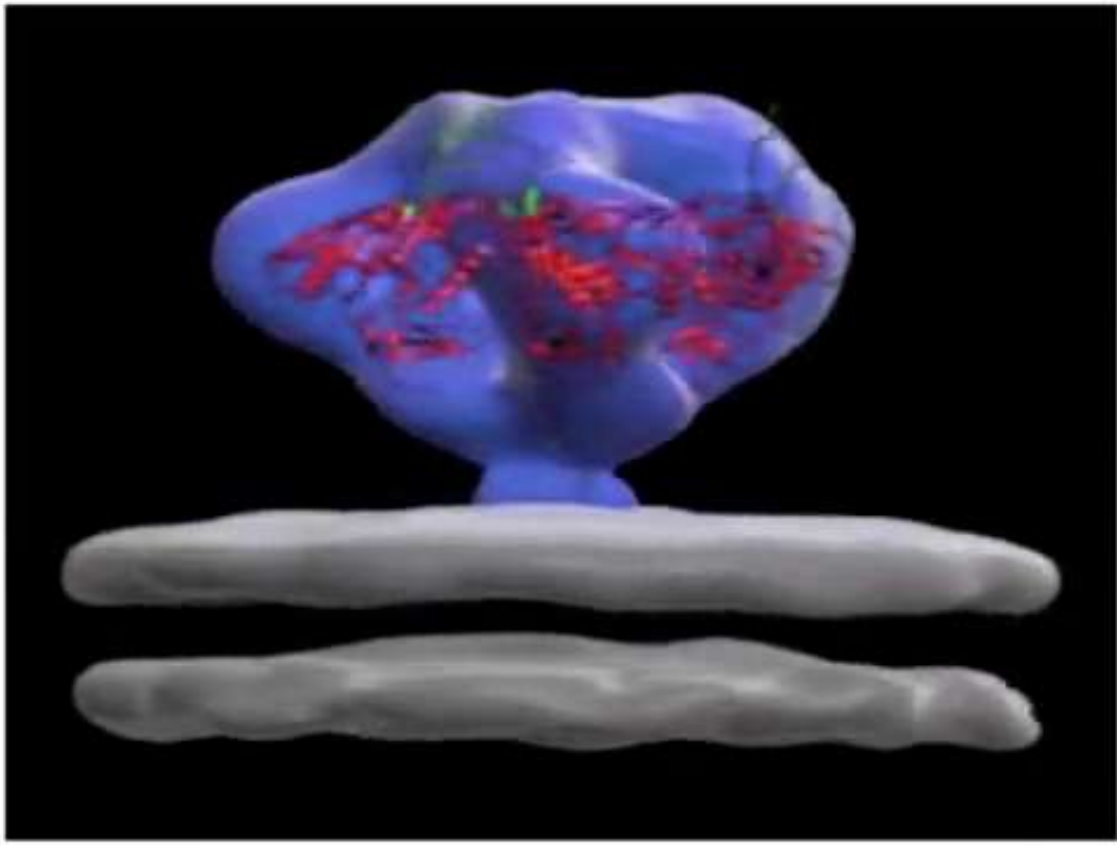
- Motor control
- Working memory
- To Lpo, Vo, CM/Pf, MD

CN Pu GPe GPi SN STN Tha

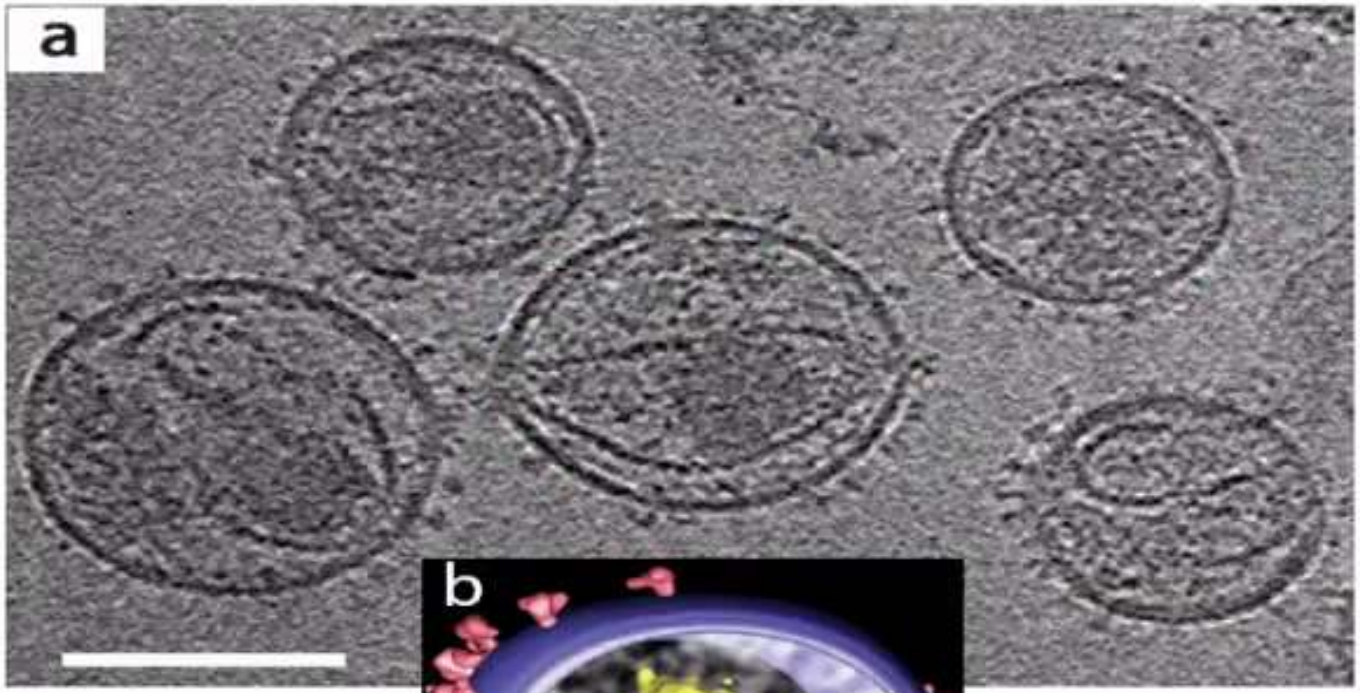


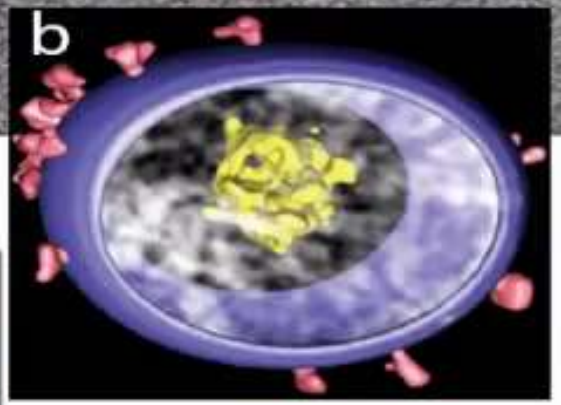
HIV Research

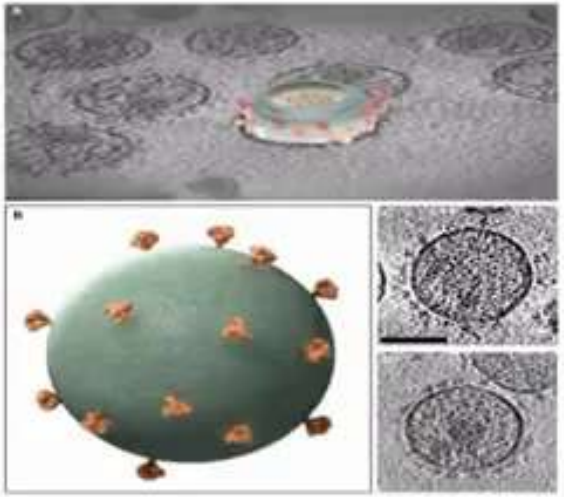


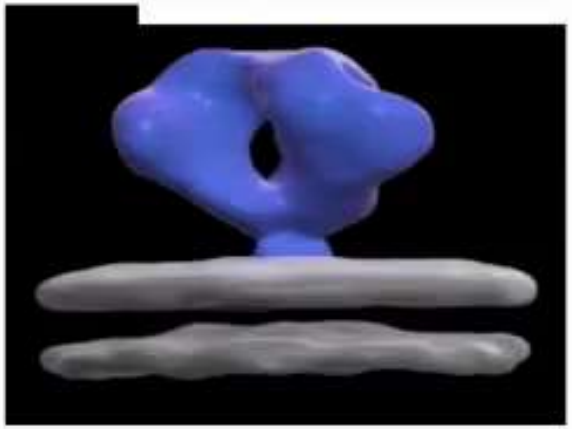


Behind the Scenes

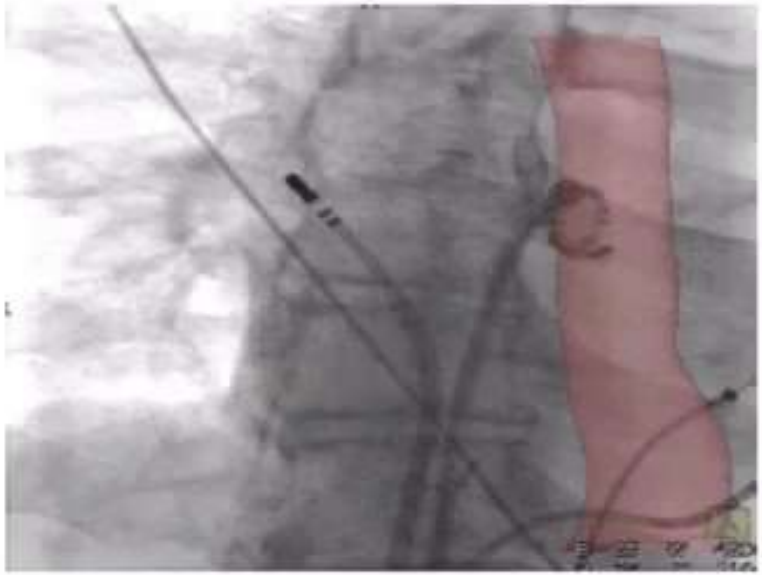








Esophagus Detection for Cardiac Ablation



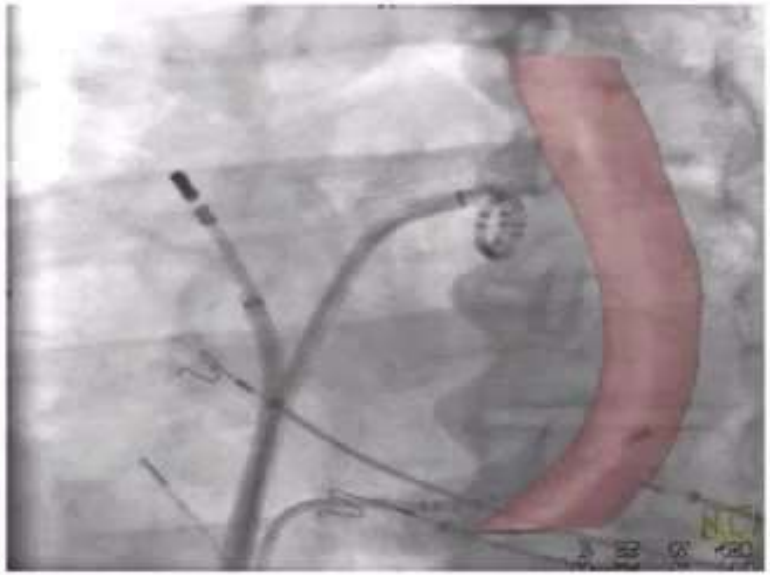


Image and Video Processing: From Mars to Hollywood with a Stop at the Hospital

Guillermo Sapiro

Duke
UNIVERSITY

Digital Image Processing, 3rd ed.

Gonzalez & Woods
www.ImageProcessingPlace.com

Chapter 1

Introduction

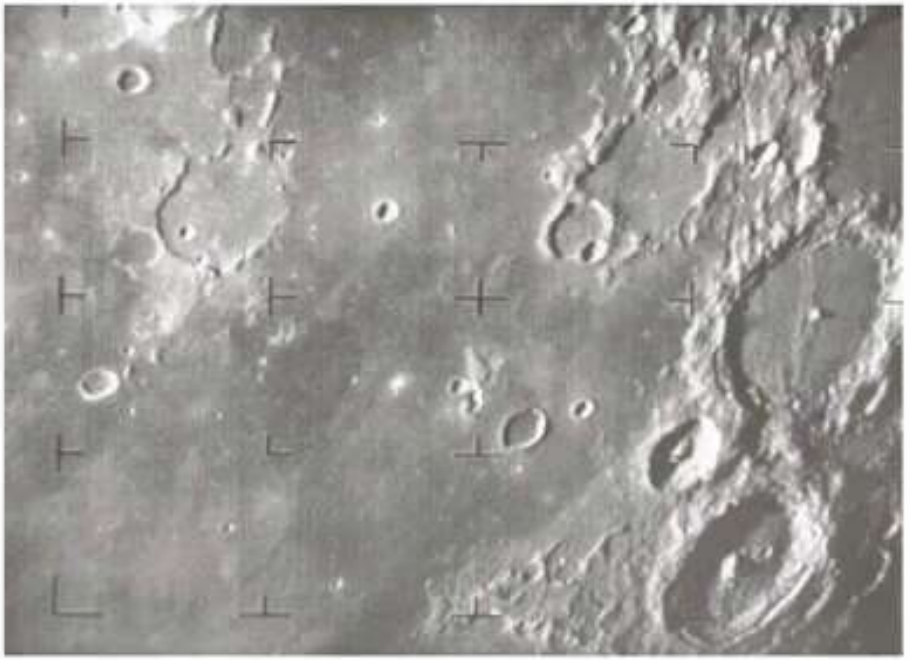


FIGURE 1.4 The first picture of the moon by a U.S. spacecraft. *Ranger 7* took this image on July 31, 1964 at 9:09 A.M. EDT, about 17 minutes before impacting the lunar surface. (Courtesy of NASA.)

© 1992–2008 R. C. Gonzalez & R. E. Woods

Digital Image Processing, 3rd ed.

Gonzalez & Woods
www.ImageProcessingPlace.com

Chapter 1

Introduction

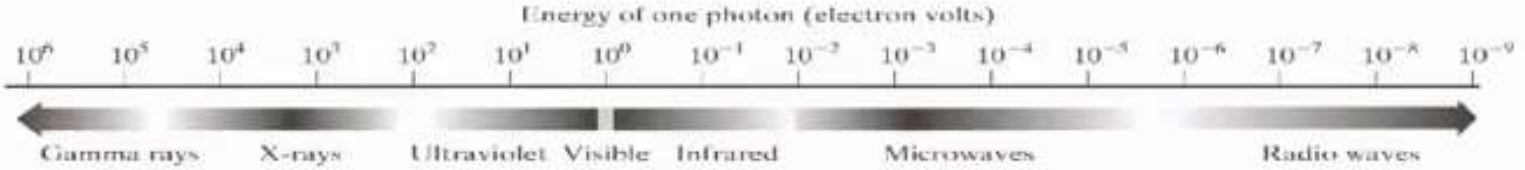


FIGURE 1.5 The electromagnetic spectrum arranged according to energy per photon.

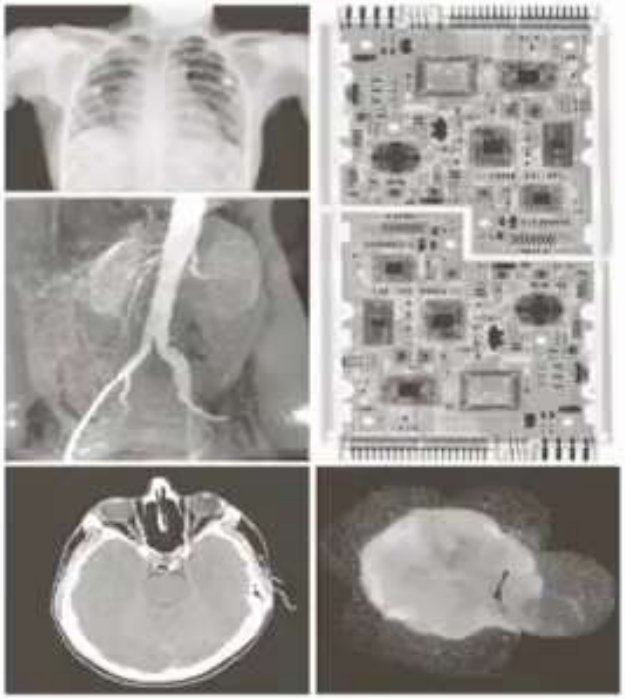
© 1992–2008 R. C. Gonzalez & R. E. Woods

Digital Image Processing, 3rd ed.

Gonzalez & Woods
www.ImageProcessingPlace.com

Chapter 1

Introduction



a b c d 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, University of Michigan Medical School; (d) Mr. Joseph E. Pascente, Lixi, Inc.; and (e) NASA.)

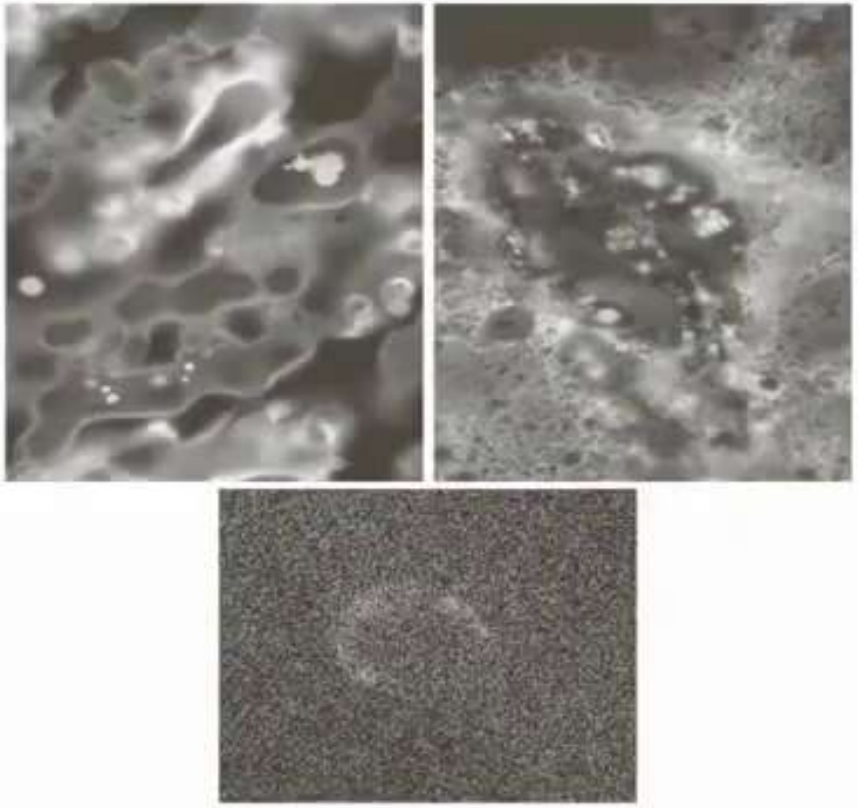
© 1992–2008 R. C. Gonzalez & R. E. Woods

Digital Image Processing, 3rd ed.

Gonzalez & Woods
www.ImageProcessingPlace.com

Chapter 1

Introduction



a b
c

FIGURE 1.8 Examples of ultraviolet imaging. (a) Normal corn. (b) Smut corn. (c) Cygnus Loop. (Images courtesy of (a) and (b) Dr. Michael W. Davidson, Florida State University, (c) NASA.)

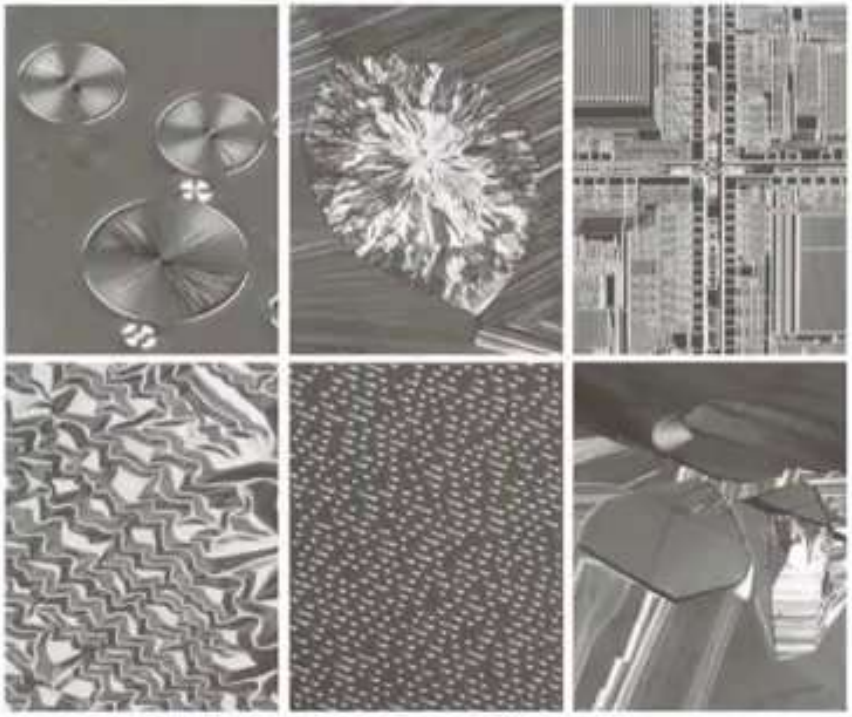
© 1992–2008 R. C. Gonzalez & R. E. Woods

Digital Image Processing, 3rd ed.

Gonzalez & Woods
www.ImageProcessingPlace.com

Chapter 1

Introduction



a b c
d e f

FIGURE 1.9 Examples of light microscopy images. (a) Taxol (anticancer agent), magnified 250×. (b) Cholesterol—40×. (c) Microprocessor—60×. (d) Nickel oxide thin film—600×. (e) Surface of audio CD—1750×. (f) Organic superconductor—450×. (Images courtesy of Dr. Michael W. Davidson, Florida State University.)

© 1992–2008 R. C. Gonzalez & R. E. Woods

Digital Image Processing, 3rd ed.

Gonzalez & Woods
www.ImageProcessingPlace.com

Chapter 1

Introduction

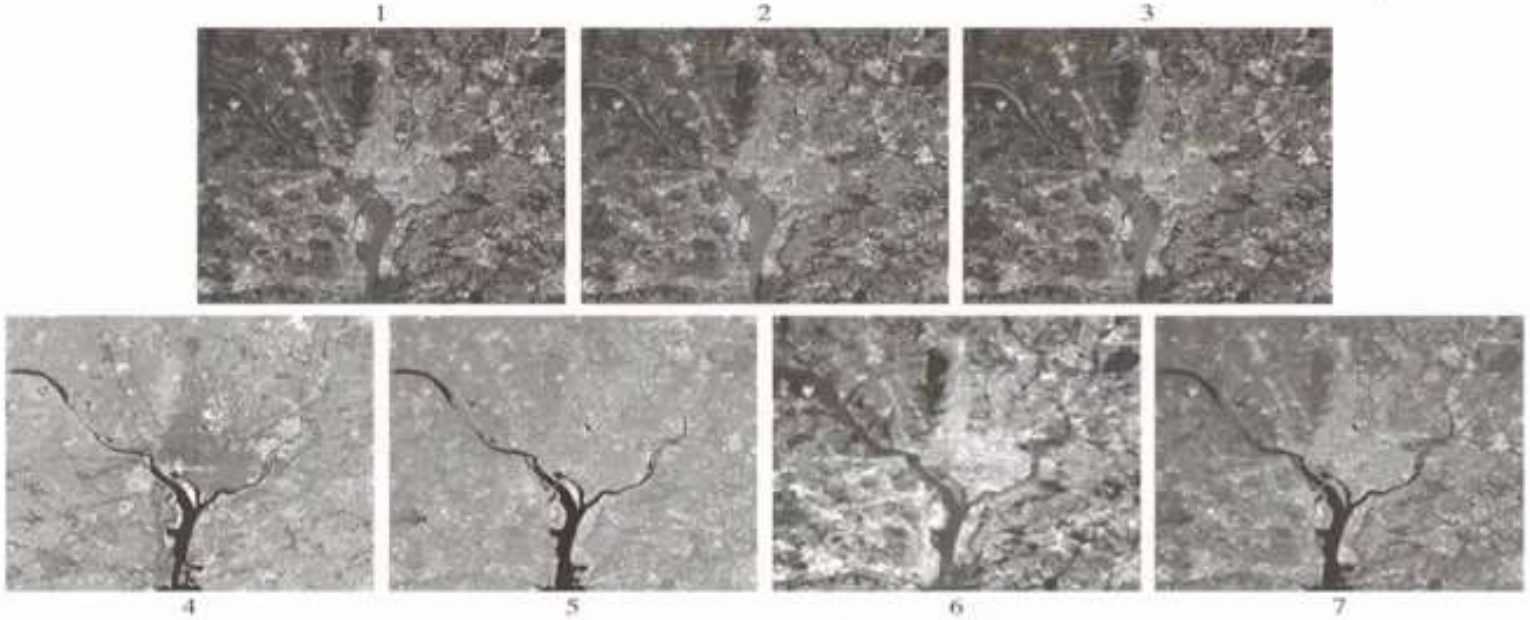


FIGURE 1.10 LANDSAT satellite images of the Washington, D.C. area. The numbers refer to the thematic bands in Table 1.1. (Images courtesy of NASA.)

© 1992–2008 R. C. Gonzalez & R. E. Woods

Digital Image Processing, 3rd ed.

Gonzalez & Woods

www.ImageProcessingPlace.com

Chapter 1

Introduction

FIGURE 1.11 Satellite image of Hurricane Katrina taken on August 29, 2005. (Courtesy of NOAA.)

© 1992–2008 R. C. Gonzalez & R. E. Woods

Digital Image Processing, 3rd ed.

Gonzalez & Woods

www.ImageProcessingPlace.com

Chapter 1

Introduction

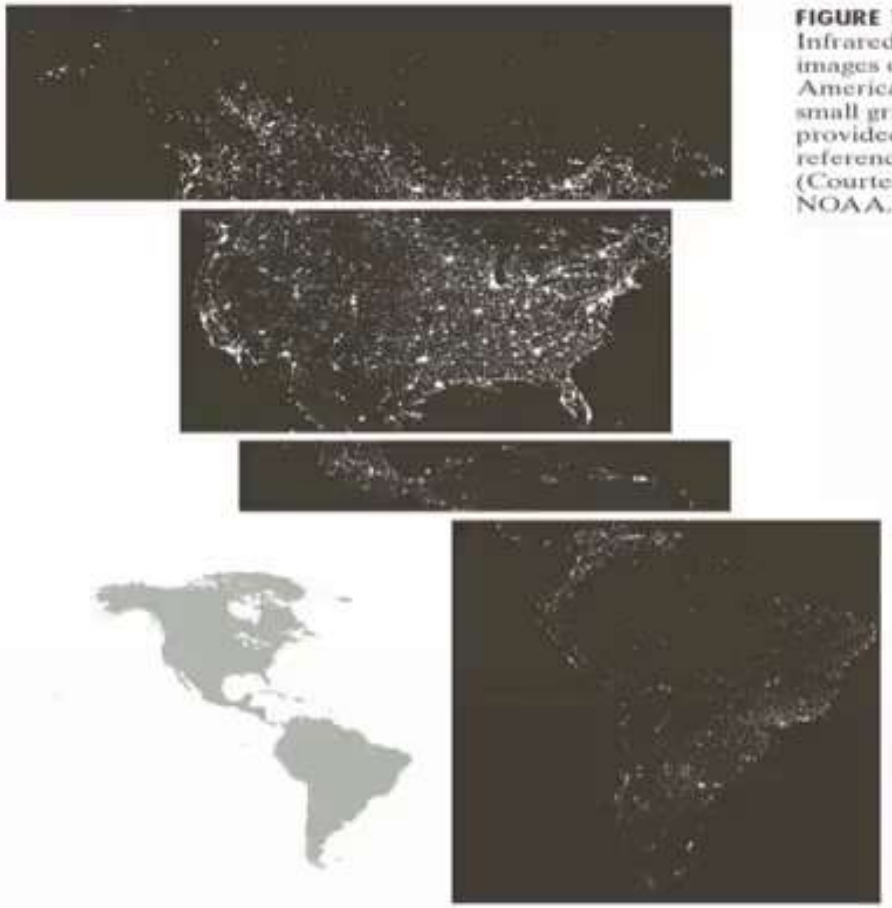


FIGURE 1.12 Infrared satellite images of the Americas. The small gray map is provided for reference. (Courtesy of NOAA.)

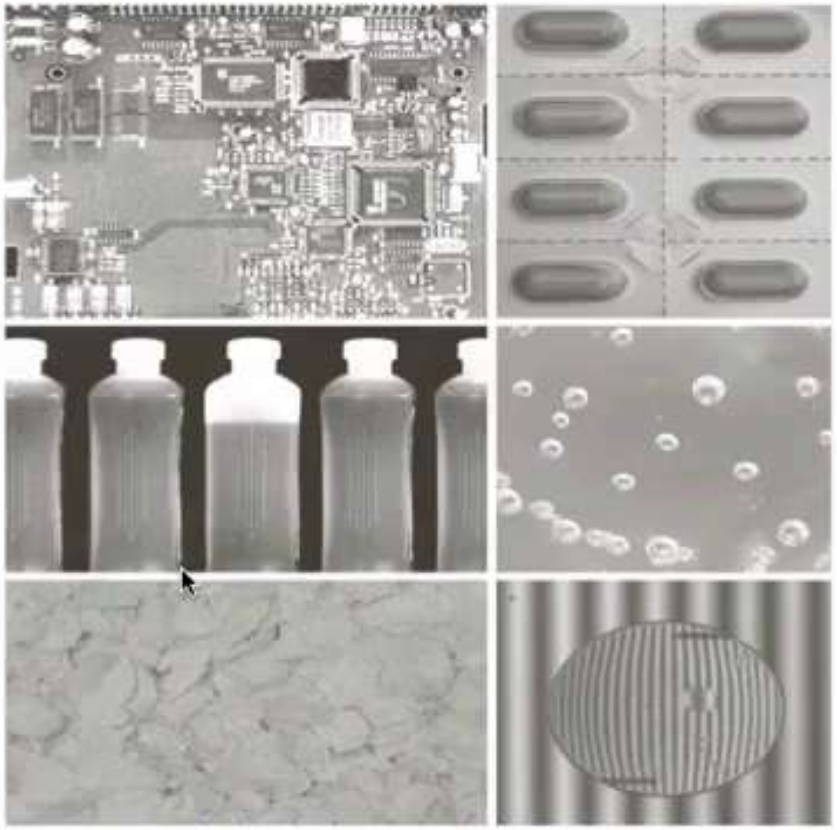
© 1992–2008 R. C. Gonzalez & R. E. Woods

Digital Image Processing, 3rd ed.

Gonzalez & Woods
www.ImageProcessingPlace.com

Chapter 1

Introduction



a b
c d
e f

FIGURE 1.14
Some examples of manufactured goods often checked using digital image processing.
(a) A circuit board controller.
(b) Packaged pills.
(c) Bottles.
(d) Air bubbles in a clear-plastic product.
(e) Cereal.
(f) Image of intraocular implant.
(Fig. (f) courtesy of Mr. Pete Sites, Perceptics Corporation.)

© 1992–2008 R. C. Gonzalez & R. E. Woods

Digital Image Processing, 3rd ed.

Gonzalez & Woods

www.ImageProcessingPlace.com

Chapter 1

Introduction

a b
c
d

FIGURE 1.15 Some additional examples of imaging in the visual spectrum. (a) Thumb print. (b) Paper currency. (c) and (d) Automated license plate reading. (Figure (a) courtesy of the National Institute of Standards and Technology. Figures (c) and (d) courtesy of Dr. Juan Herrera, Perceptics Corporation.)

© 1992–2008 R. C. Gonzalez & R. E. Woods

Digital Image Processing, 3rd ed.

Gonzalez & Woods

www.ImageProcessingPlace.com

Chapter 1

Introduction

Gamma | X-ray | Optical | Infrared | Radio

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

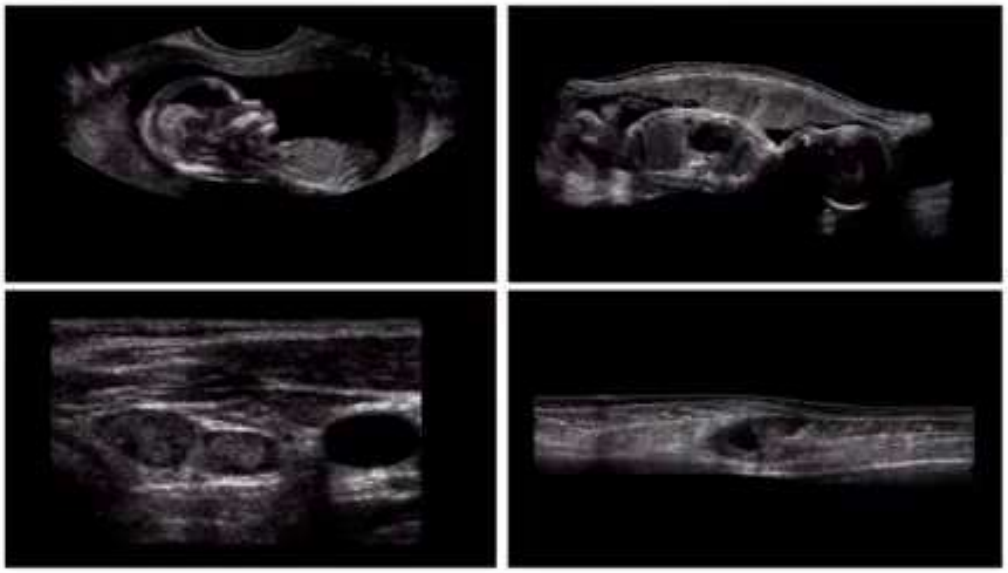
© 1992–2008 R. C. Gonzalez & R. E. Woods

Digital Image Processing, 3rd ed.

Gonzalez & Woods
www.ImageProcessingPlace.com

Chapter 1

Introduction



a b
c d

FIGURE 1.20 Examples of ultrasound imaging. (a) Baby. (2) Another view of baby. (c) Thyroids. (d) Muscle layers showing lesion. (Courtesy of Siemens Medical Systems, Inc., Ultrasound Group.)

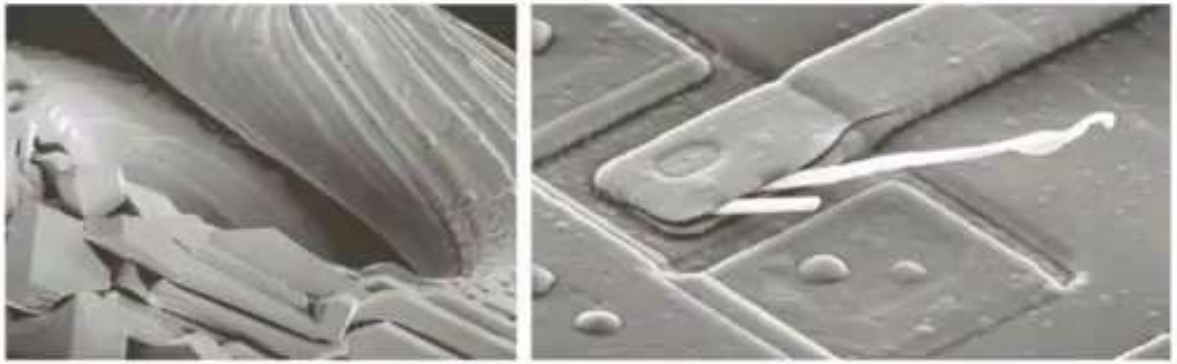
© 1992–2008 R. C. Gonzalez & R. E. Woods

Digital Image Processing, 3rd ed.

Gonzalez & Woods
www.ImageProcessingPlace.com

Chapter 1

Introduction



a b

FIGURE 1.21 (a) 250× SEM image of a tungsten filament following thermal failure (note the shattered pieces on the lower left). (b) 2500× SEM image of damaged integrated circuit. The white fibers are oxides resulting from thermal destruction. (Figure (a) courtesy of Mr. Michael Shaffer, Department of Geological Sciences, University of Oregon, Eugene; (b) courtesy of Dr. J. M. Hudak, McMaster University, Hamilton, Ontario, Canada.)

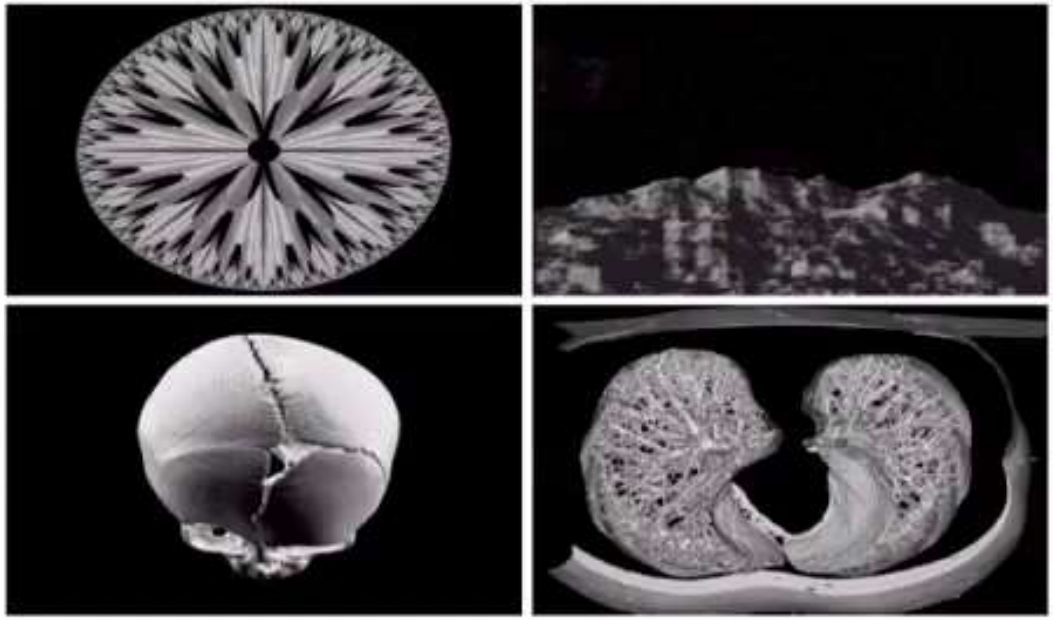
© 1992–2008 R. C. Gonzalez & R. E. Woods

Digital Image Processing, 3rd ed.

Gonzalez & Woods
www.ImageProcessingPlace.com

Chapter 1

Introduction



a b
c d

FIGURE 1.22 (a) and (b) Fractal images. (c) and (d) Images generated from 3-D computer models of the objects shown. (Figures (a) and (b) courtesy of Ms. Melissa D. Binde, Swarthmore College. (c) and (d) courtesy of NASA.)

© 1992–2008 R. C. Gonzalez & R. E. Woods

Image and Video Processing: From Mars to Hollywood with a Stop at the Hospital

Guillermo Sapiro

Duke
UNIVERSITY

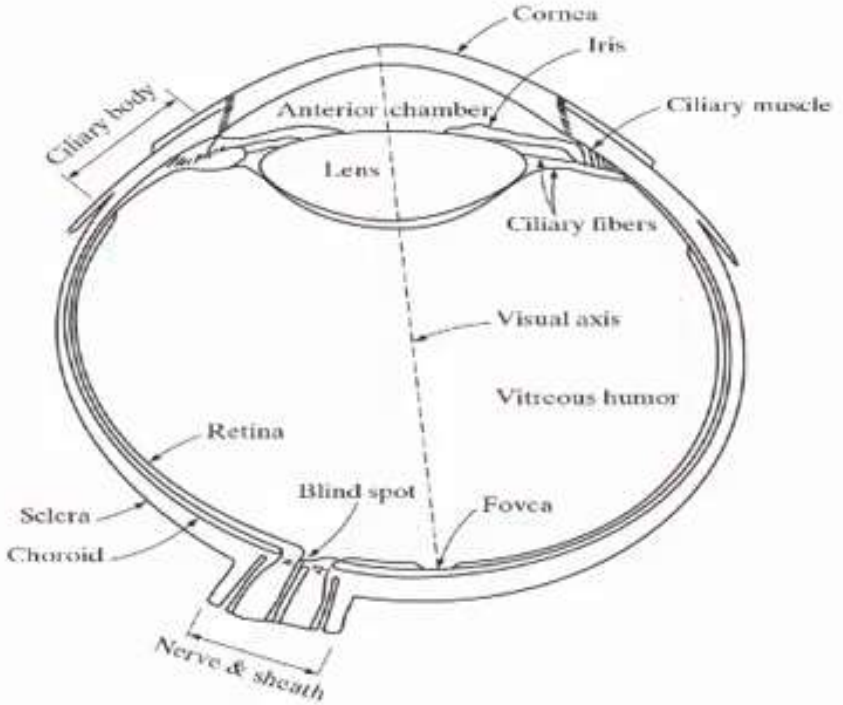
Digital Image Processing, 3rd ed.

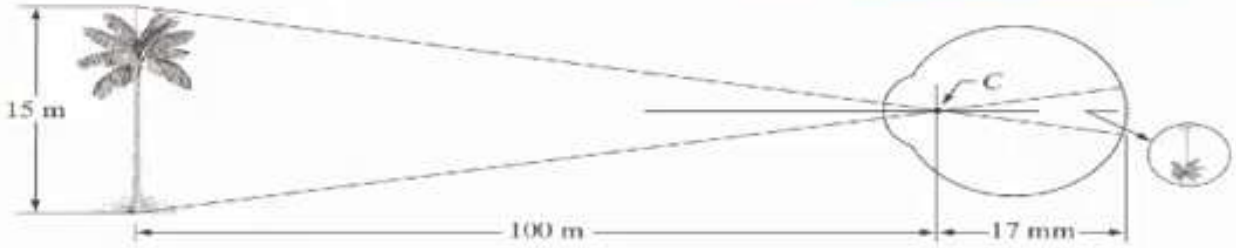
Gonzalez & Woods

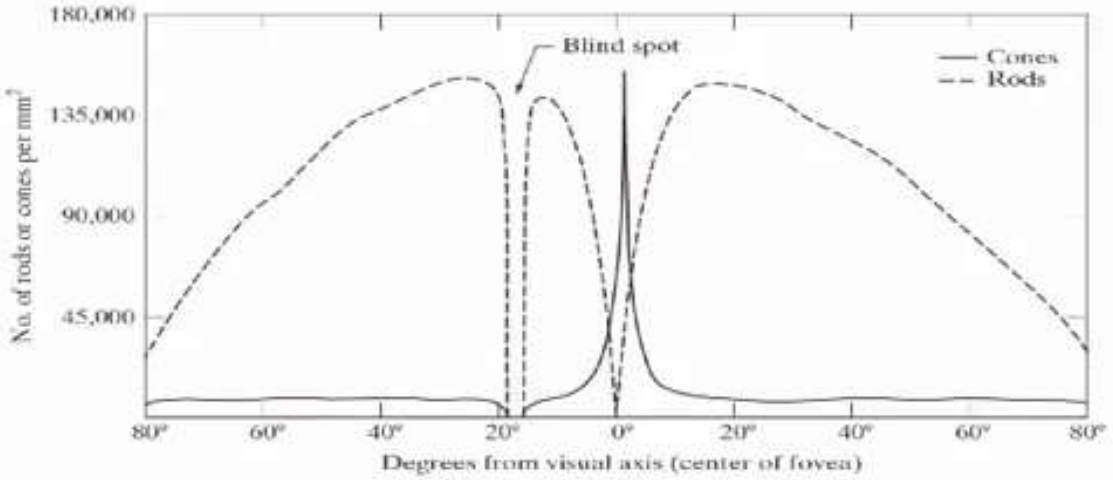
www.ImageProcessingPlace.com

Chapter 2

Digital Image Fundamentals







© 1992–2008 R. C. Gonzalez & R. E. Woods

Digital Image Processing, 3rd ed.

Gonzalez & Woods

www.ImageProcessingPlace.com

Chapter 2
Digital Image Fundamentals

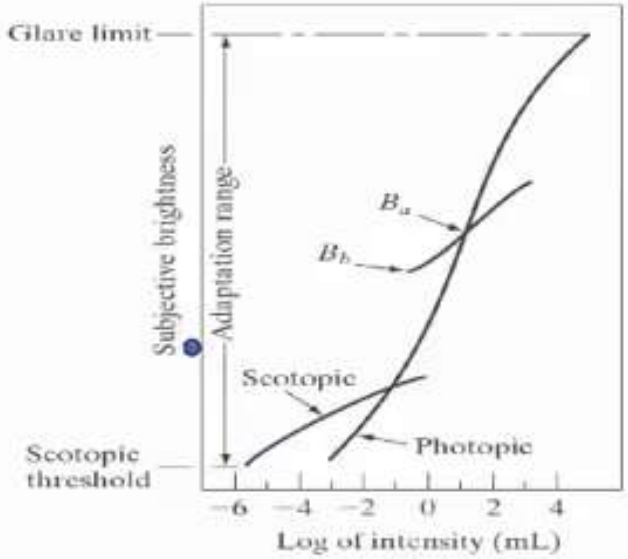


FIGURE 2.4 Range of subjective brightness sensations showing a particular adaptation level.

© 1992–2008 R. C. Gonzalez & R. E. Woods

Digital Image Processing, 3rd ed.

Gonzalez & Woods

www.ImageProcessingPlace.com

Chapter 2

Digital Image Fundamentals

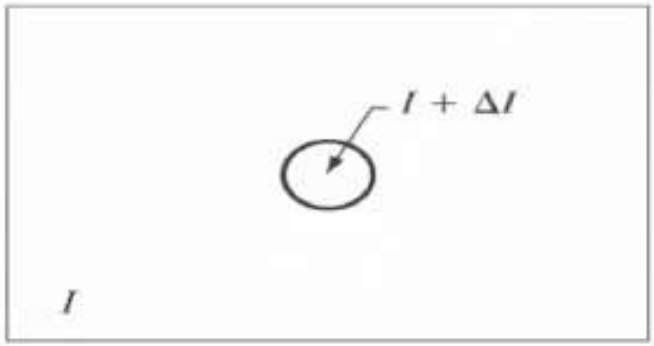


FIGURE 2.5 Basic experimental setup used to characterize brightness discrimination.

© 1992–2008 R. C. Gonzalez & R. E. Woods

Chapter 2
Digital Image Fundamentals

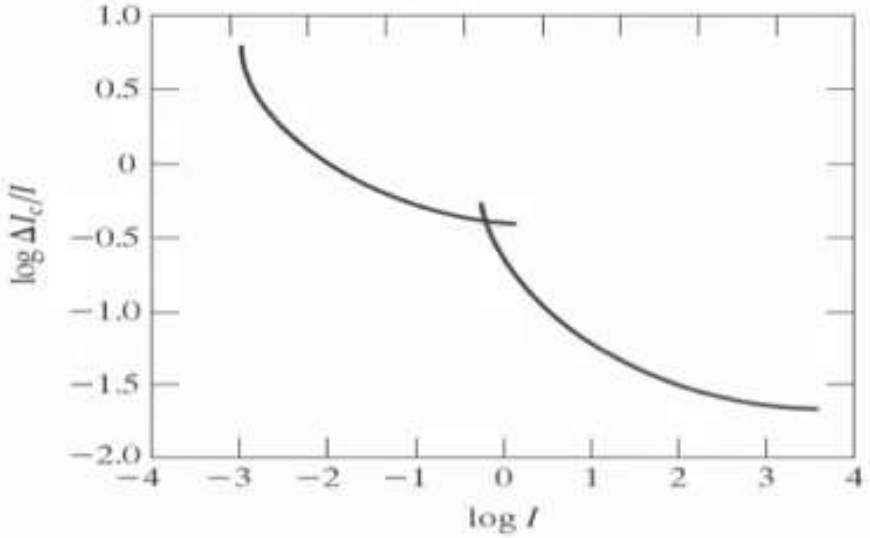


FIGURE 2.6 Typical Weber ratio as a function of intensity.

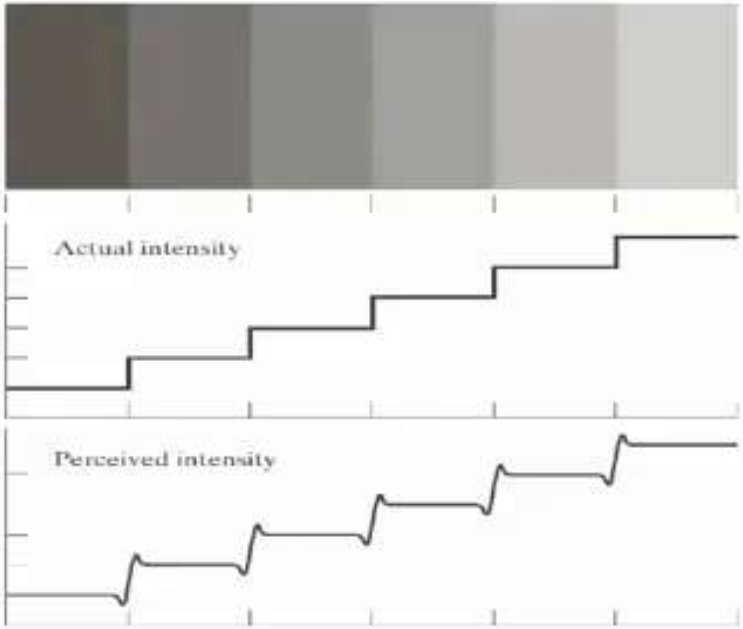
© 1992–2008 R. C. Gonzalez & R. E. Woods

Digital Image Processing, 3rd ed.

Gonzalez & Woods

www.ImageProcessingPlace.com

Chapter 2
Digital Image Fundamentals



a
b
c

FIGURE 2.7 Illustration of the Mach band effect. Perceived intensity is not a simple function of actual intensity.

© 1992–2008 R. C. Gonzalez & R. E. Woods

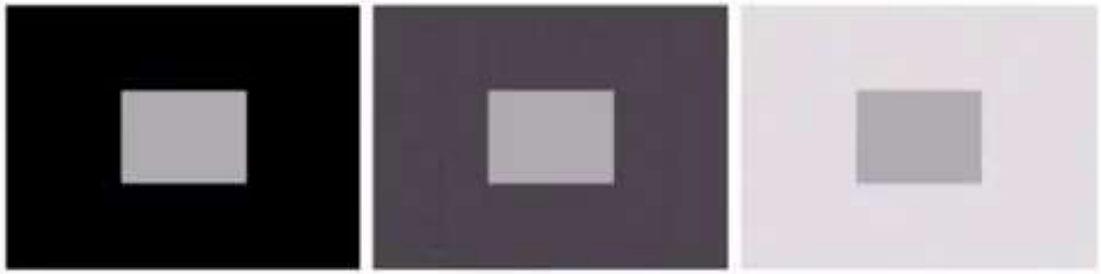
Digital Image Processing, 3rd ed.

Gonzalez & Woods

www.ImageProcessingPlace.com

Chapter 2

Digital Image Fundamentals



a b c

FIGURE 2.8 Examples of simultaneous contrast. All the inner squares have the same intensity, but they appear progressively darker as the background becomes lighter.

© 1992–2008 R. C. Gonzalez & R. E. Woods

Digital Image Processing, 3rd ed.

Gonzalez & Woods

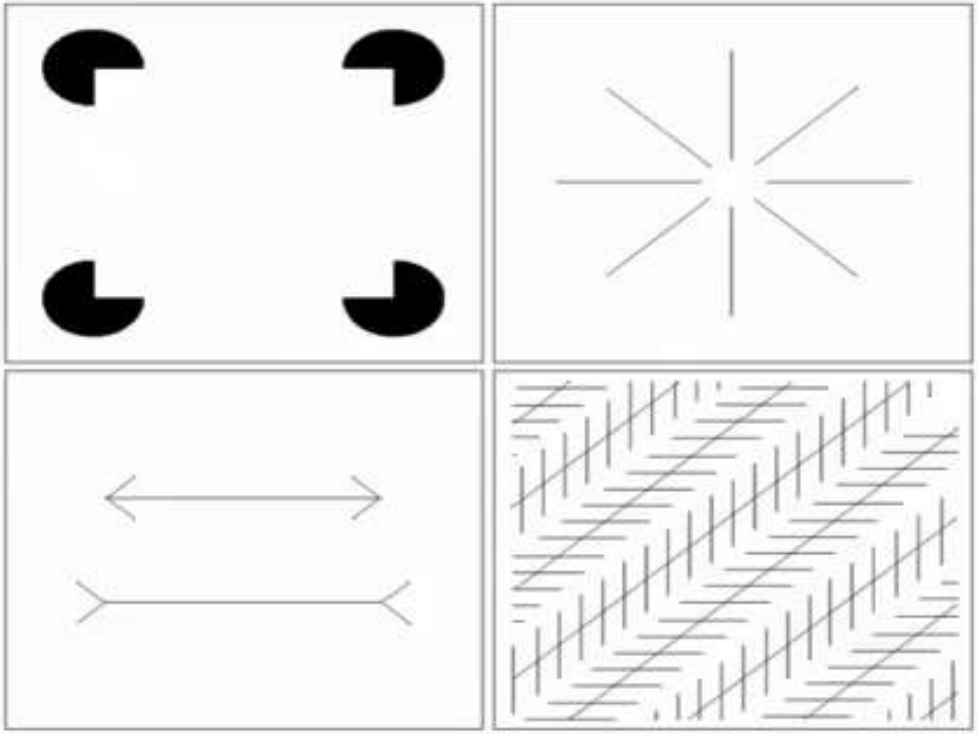
www.ImageProcessingPlace.com

Chapter 2

Digital Image Fundamentals

a b
c d

FIGURE 2.9 Some well-known optical illusions.



© 1992–2008 R. C. Gonzalez & R. E. Woods

Digital Image Processing, 3rd ed.

Gonzalez & Woods

www.ImageProcessingPlace.com

Chapter 2

Digital Image Fundamentals

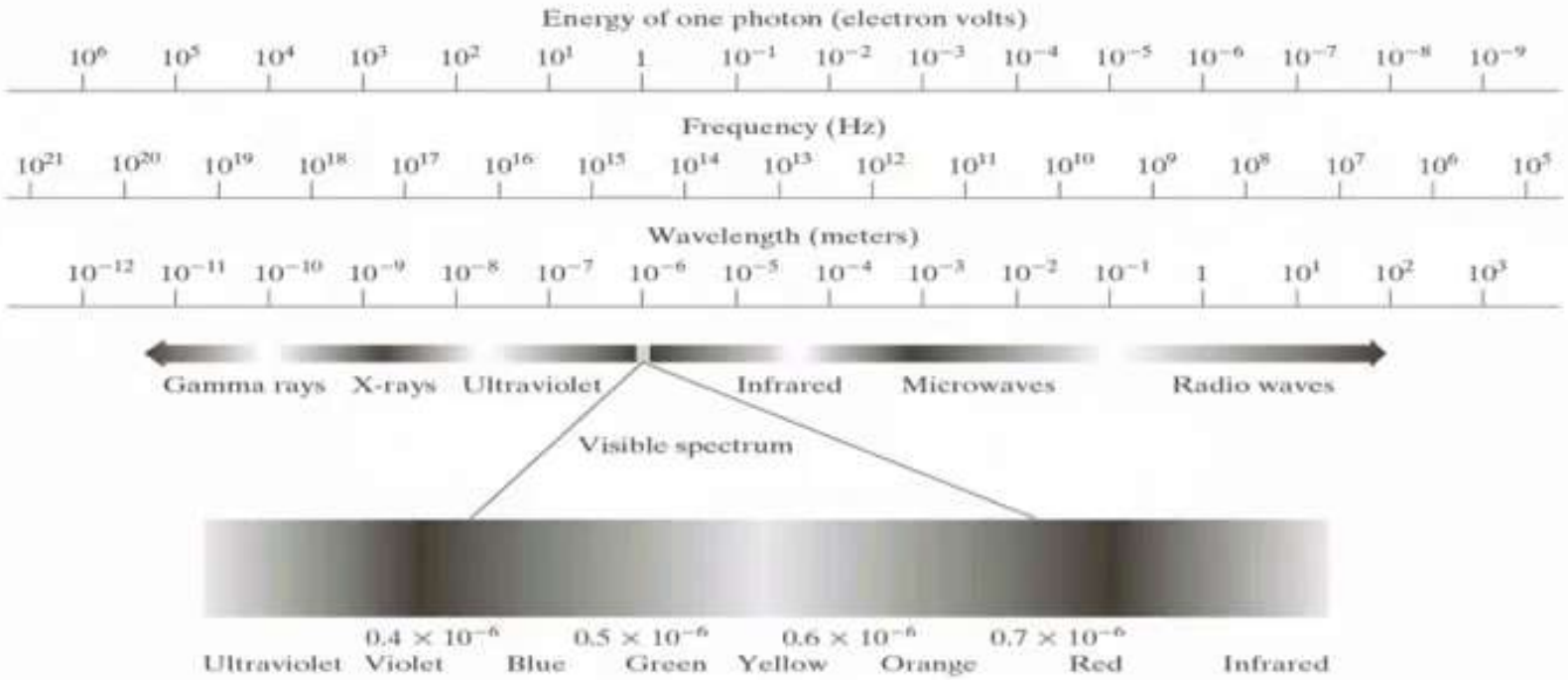


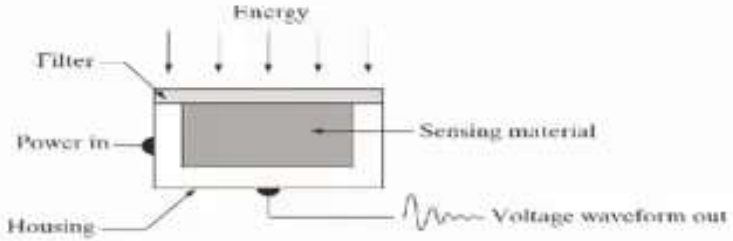
FIGURE 2.10 The electromagnetic spectrum. The visible spectrum is shown zoomed to facilitate explanation, but note that the visible spectrum is a rather narrow portion of the EM spectrum.

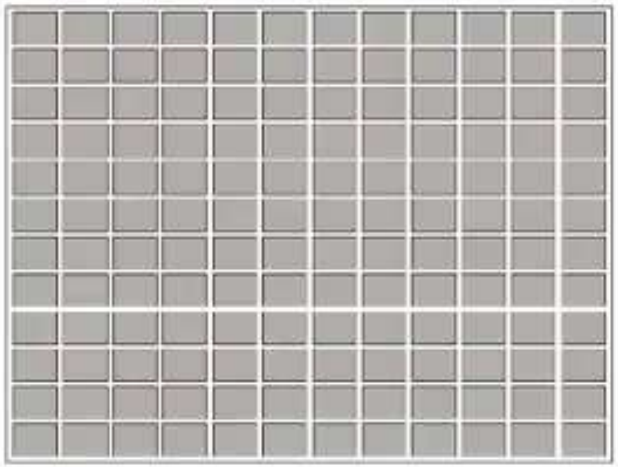
© 1992–2008 R. C. Gonzalez & R. E. Woods

Digital Image Processing, 3rd ed.

Gonzalez & Woods
www.ImageProcessingPlace.com

Chapter 2
Digital Image Fundamentals





a
b
c

FIGURE 2.12
(a) Single imaging sensor.
(b) Line sensor.
(c) Array sensor.

© 1992–2008 R. C. Gonzalez & R. E. Woods

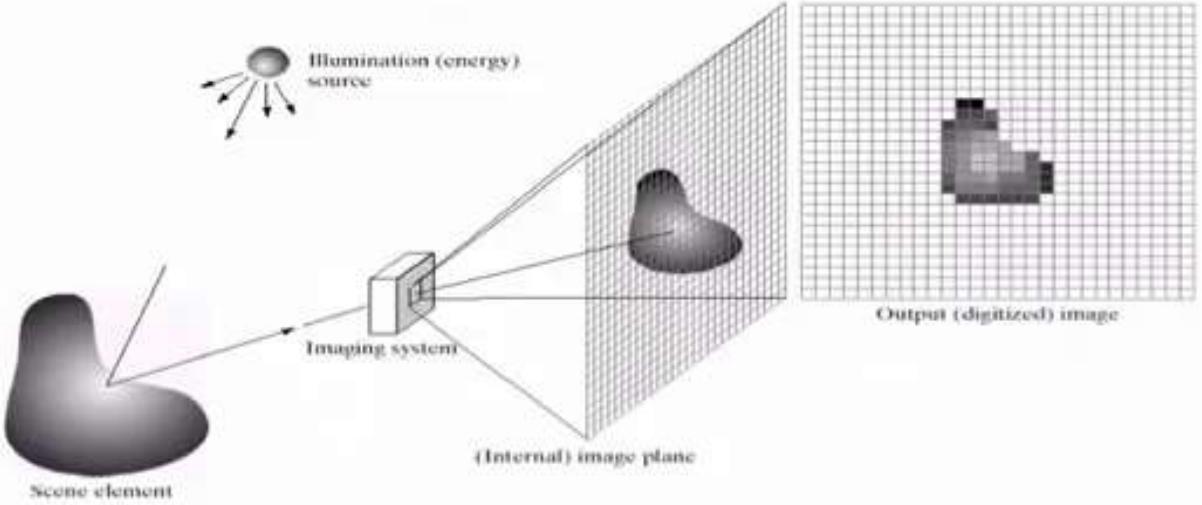
Digital Image Processing, 3rd ed.

Gonzalez & Woods

www.ImageProcessingPlace.com

Chapter 2

Digital Image Fundamentals



a b c d e

FIGURE 2.15 An example of the digital image acquisition process. (a) Energy ("illumination") source. (b) An element of a scene. (c) Imaging system. (d) Projection of the scene onto the image plane. (e) Digitized image.

© 1992–2008 R. C. Gonzalez & R. E. Woods

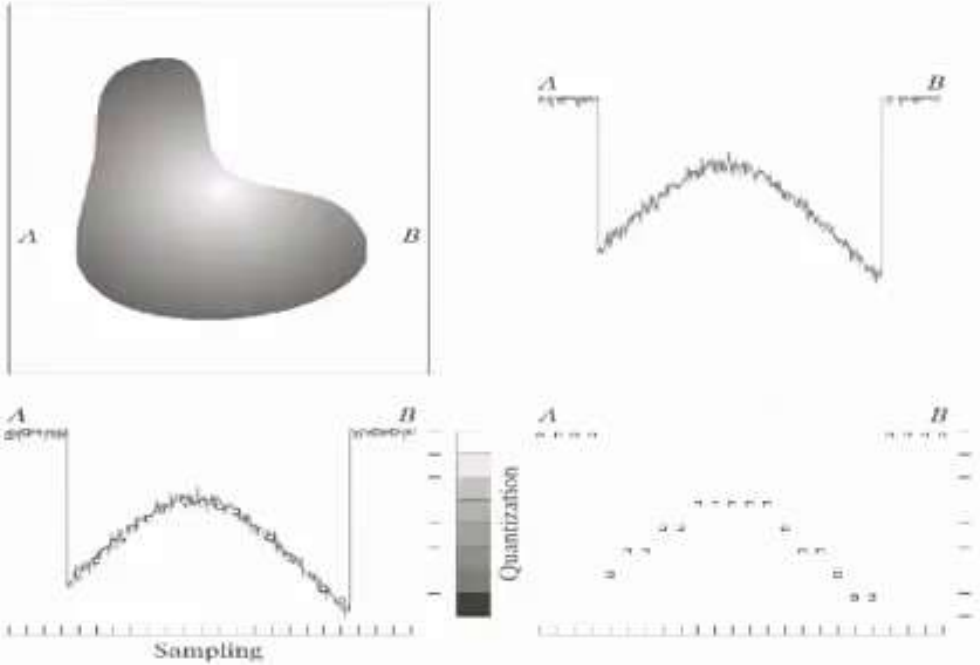
Digital Image Processing, 3rd ed.

Gonzalez & Woods

www.ImageProcessingPlace.com

Chapter 2

Digital Image Fundamentals



a b
c d

FIGURE 2.16 Generating a digital image. (a) Continuous image. (b) A scan line from A to B in the continuous image, used to illustrate the concepts of sampling and quantization. (c) Sampling and quantization. (d) Digital scan line.

© 1992–2008 R. C. Gonzalez & R. E. Woods

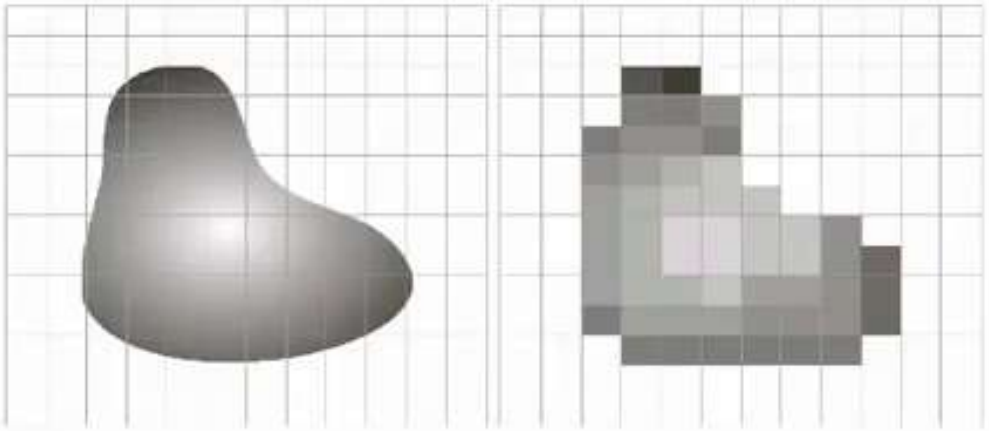
Digital Image Processing, 3rd ed.

Gonzalez & Woods

www.ImageProcessingPlace.com

Chapter 2

Digital Image Fundamentals



a b

FIGURE 2.17 (a) Continuous image projected onto a sensor array. (b) Result of image sampling and quantization.

© 1992–2008 R. C. Gonzalez & R. E. Woods

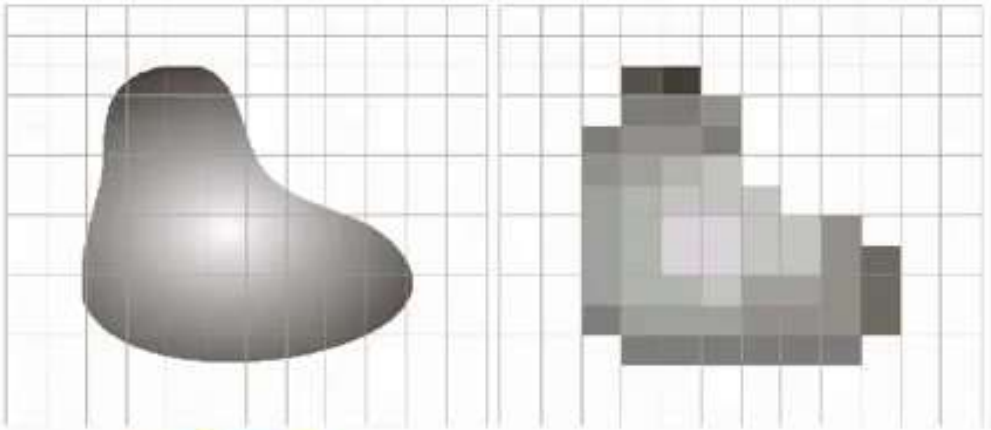
Digital Image Processing, 3rd ed.

Gonzalez & Woods

www.ImageProcessingPlace.com

Chapter 2

Digital Image Fundamentals



a b

FIGURE 2.17 (a) Continuous image projected onto a sensor array. (b) Result of image sampling and quantization.

Red R

Green G

Blue B

RGB

RGB

© 1992–2008 R. C. Gonzalez & R. E. Woods

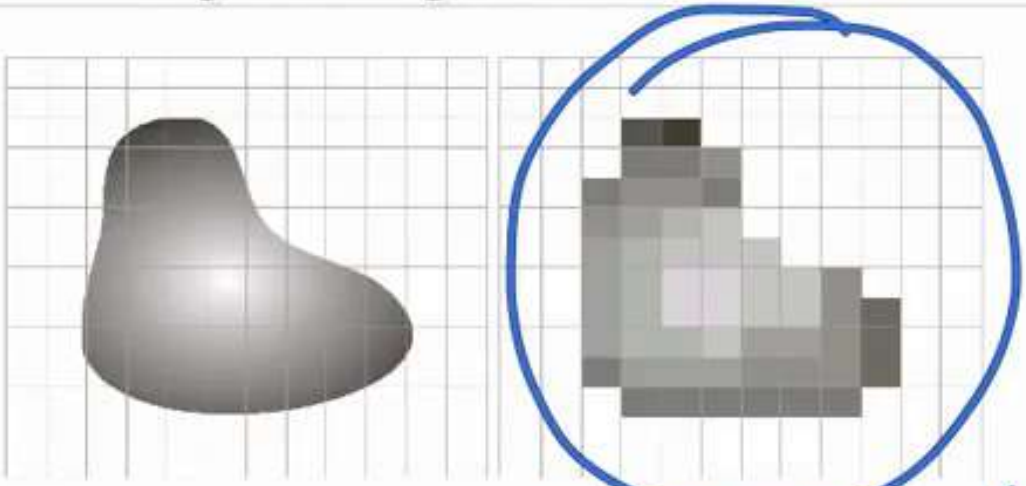
Digital Image Processing, 3rd ed.

Gonzalez & Woods

www.ImageProcessingPlace.com

Chapter 2

Digital Image Fundamentals



a b

FIGURE 2.17 (a) Continuous image projected onto a sensor array. (b) Result of image sampling and quantization.

RGB

30x(RGB)

30x3=90

90

512x512

8 bits

© 1992–2008 R. C. Gonzalez & R. E. Woods

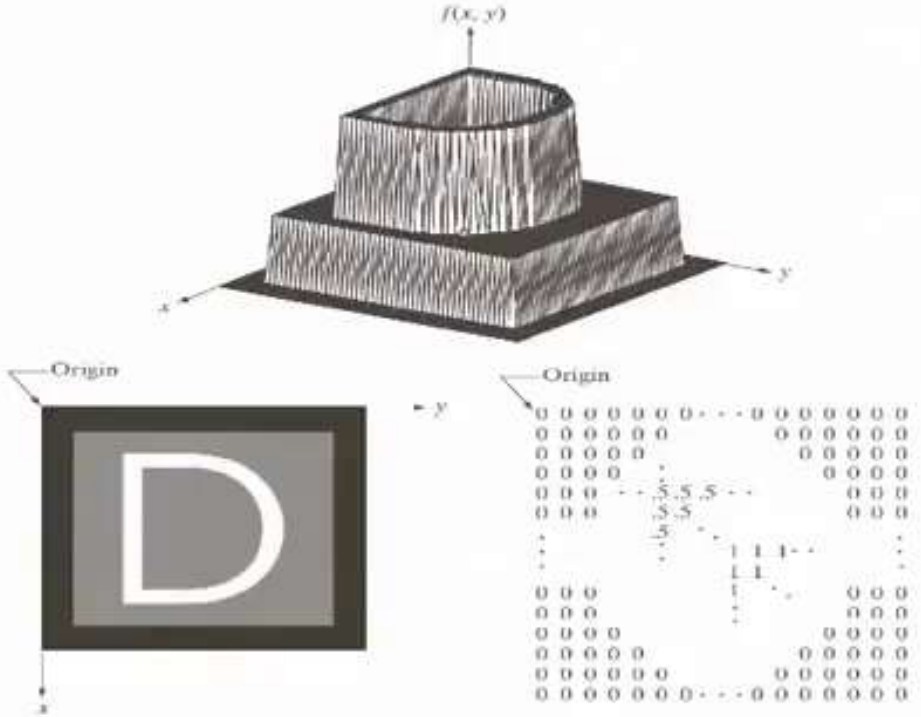
Digital Image Processing, 3rd ed.

Gonzalez & Woods

www.ImageProcessingPlace.com

Chapter 2

Digital Image Fundamentals



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).

© 1992–2008 R. C. Gonzalez & R. E. Woods

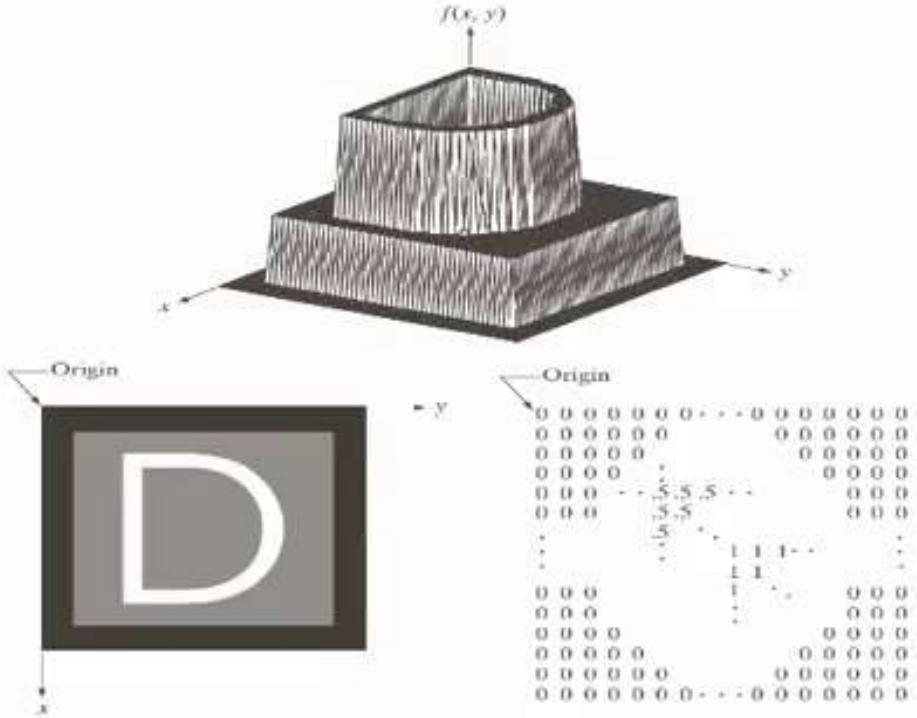
Digital Image Processing, 3rd ed.

Gonzalez & Woods

www.ImageProcessingPlace.com

Chapter 2

Digital Image Fundamentals



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).

8 bits

0 = black

255 = white

© 1992–2008 R. C. Gonzalez & R. E. Woods

Digital Image Processing, 3rd ed.

Gonzalez & Woods

www.ImageProcessingPlace.com

Chapter 2

Digital Image Fundamentals

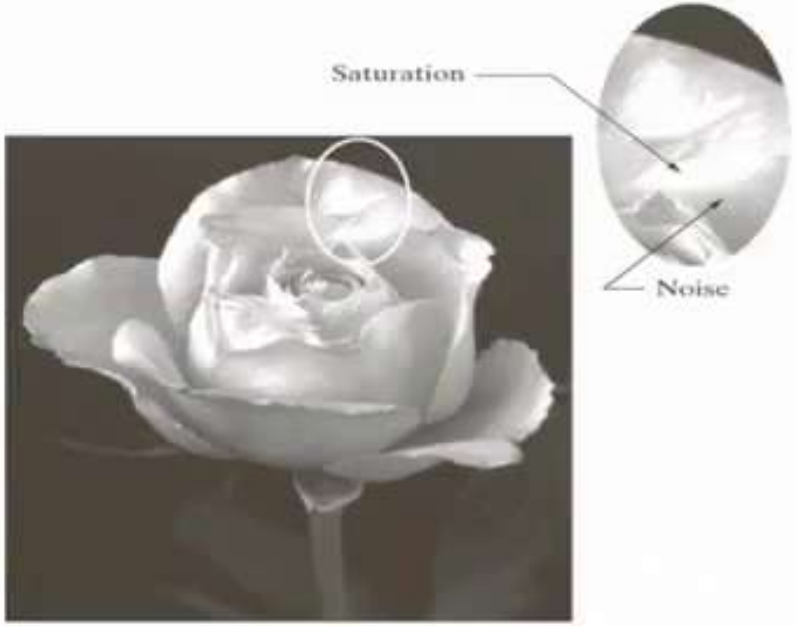


FIGURE 2.19 An image exhibiting saturation and noise. Saturation is the highest value beyond which all intensity levels are clipped (note how the entire saturated area has a high, *constant* intensity level). Noise in this case appears as a grainy texture pattern. Noise, especially in the darker regions of an image (e.g., the stem of the rose) masks the lowest detectable true intensity level.

© 1992–2008 R. C. Gonzalez & R. E. Woods

Digital Image Processing, 3rd ed.

Gonzalez & Woods

www.ImageProcessingPlace.com

Chapter 2

Digital Image Fundamentals

a b
c d

FIGURE 2.20 Typical effects of reducing spatial resolution. Images shown at: (a) 1250 dpi, (b) 300 dpi, (c) 150 dpi, and (d) 72 dpi. The thin black borders were added for clarity. They are not part of the data.

© 1992–2008 R. C. Gonzalez & R. E. Woods

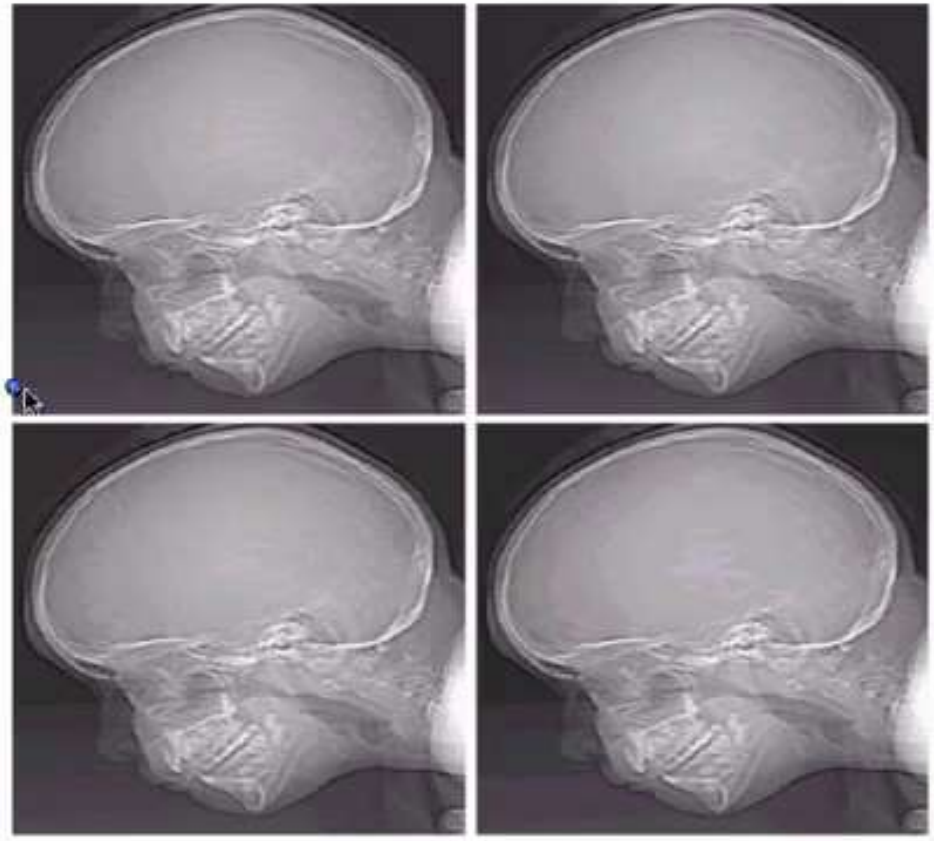
Digital Image Processing, 3rd ed.

Gonzalez & Woods

www.ImageProcessingPlace.com

Chapter 2

Digital Image Fundamentals



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.

© 1992–2008 R. C. Gonzalez & R. E. Woods

Digital Image Processing, 3rd ed.

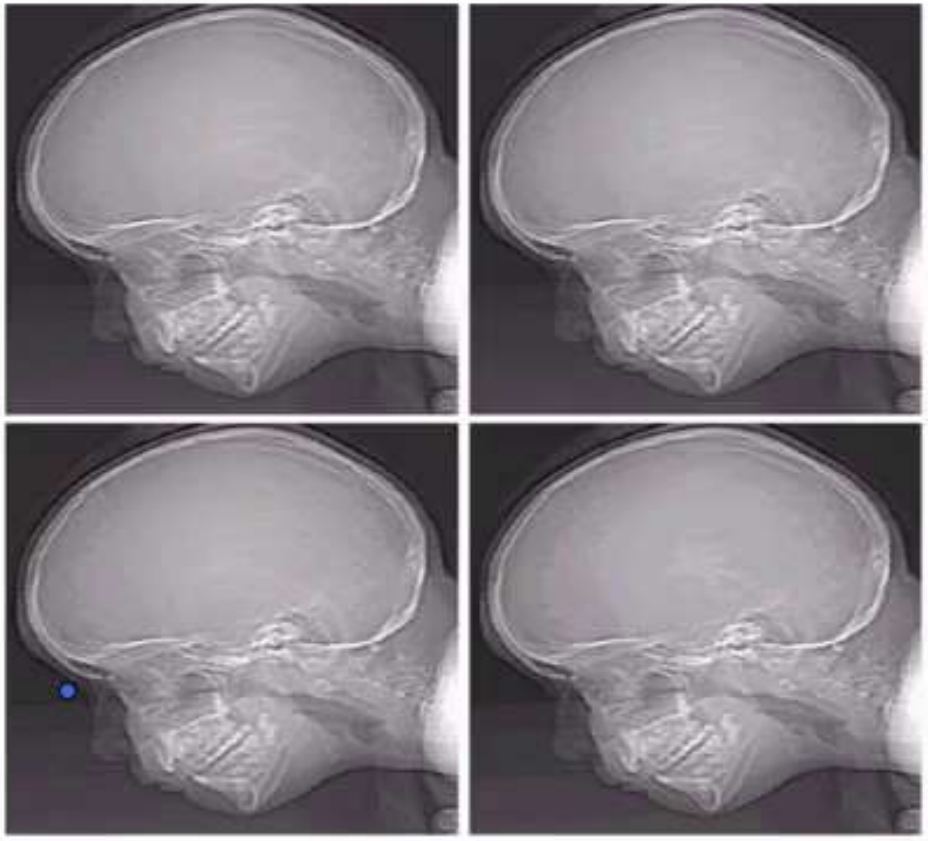
Gonzalez & Woods

www.ImageProcessingPlace.com

Chapter 2

Digital Image Fundamentals

$\left\lfloor \frac{9}{2} \right\rfloor \times 2 = 8$



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.

452 x 374

256

128

$\left\lfloor \frac{value}{2} \right\rfloor \times 2$

$\left\lfloor \frac{8}{2} \right\rfloor \times 2 = 8$

© 1992–2008 R. C. Gonzalez & R. E. Woods

Digital Image Processing, 3rd ed.

Gonzalez & Woods

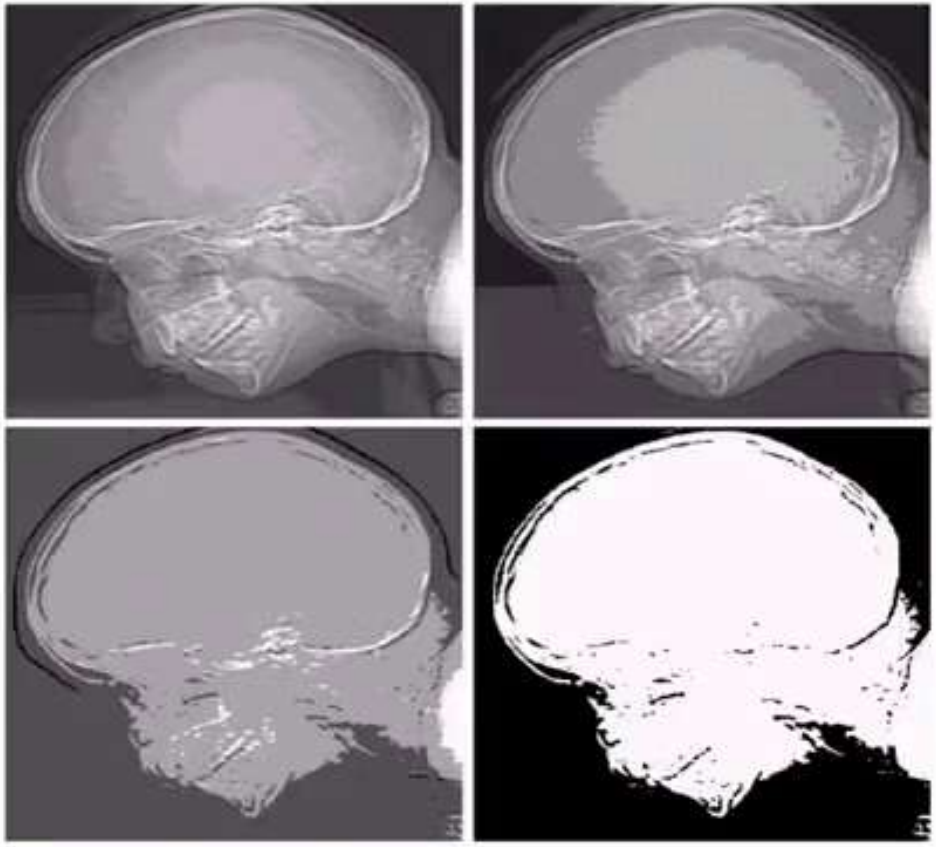
www.ImageProcessingPlace.com

Chapter 2

Digital Image Fundamentals

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.)



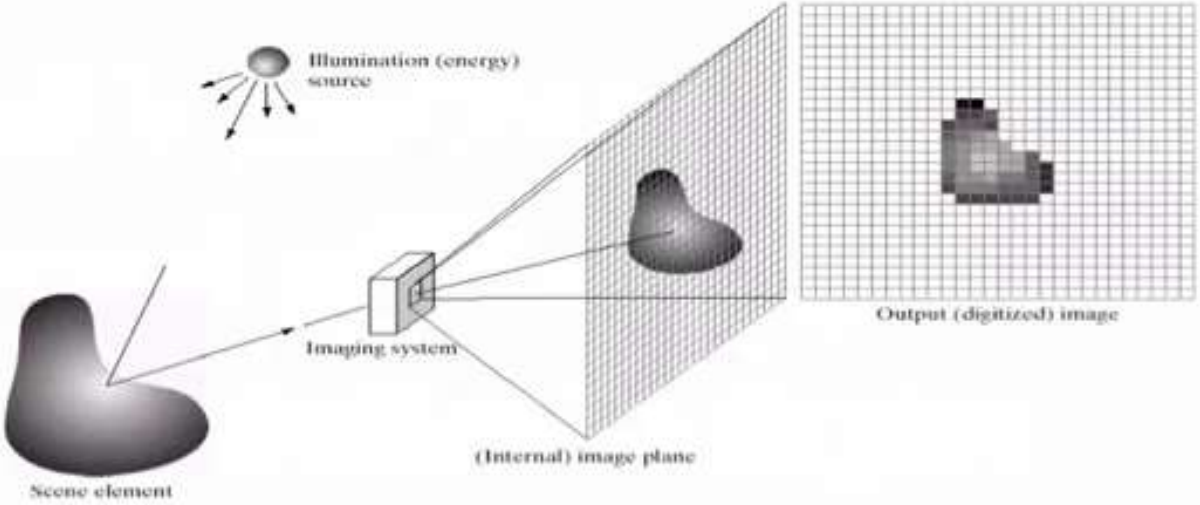
© 1992–2008 R. C. Gonzalez & R. E. Woods

Digital Image Processing, 3rd ed.

Gonzalez & Woods

www.ImageProcessingPlace.com

Chapter 2
Digital Image Fundamentals



a b c d e

FIGURE 2.15 An example of the digital image acquisition process. (a) Energy ("illumination") source. (b) An element of a scene. (c) Imaging system. (d) Projection of the scene onto the image plane. (e) Digitized image.

© 1992–2008 R. C. Gonzalez & R. E. Woods

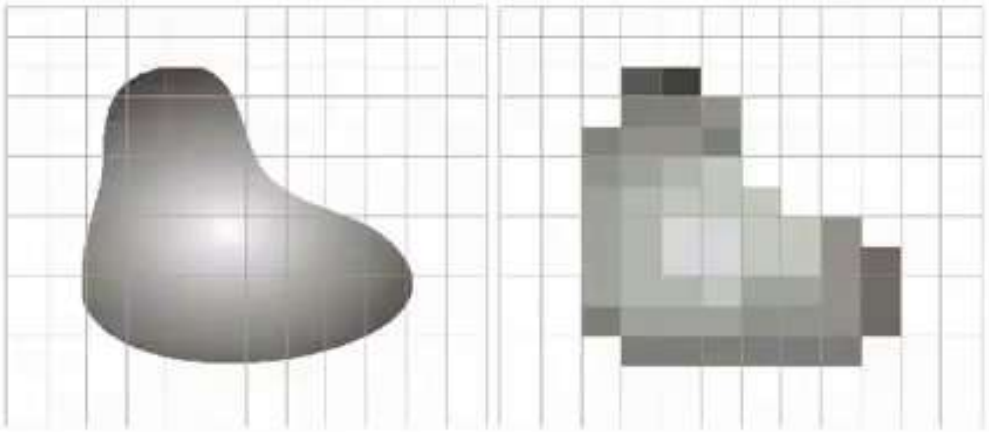
Digital Image Processing, 3rd ed.

Gonzalez & Woods

www.ImageProcessingPlace.com

Chapter 2

Digital Image Fundamentals



a b

FIGURE 2.17 (a) Continuous image projected onto a sensor array. (b) Result of image sampling and quantization.

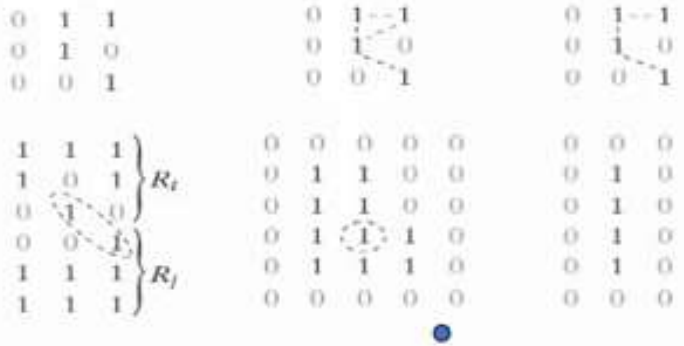
© 1992–2008 R. C. Gonzalez & R. E. Woods

Digital Image Processing, 3rd ed.

Gonzalez & Woods

www.ImageProcessingPlace.com

Chapter 2
Digital Image Fundamentals



a b c
d e f

FIGURE 2.25 (a) An arrangement of pixels. (b) Pixels that are 8-adjacent (adjacency is shown by dashed lines; note the ambiguity). (c) m-adjacency. (d) Two regions that are adjacent if 8-adjacency is used. (e) The circled point is part of the boundary of the 1-valued pixels only if 8-adjacency between the region and background is used. (f) The inner boundary of the 1-valued region does not form a closed path, but its outer boundary does.

© 1992–2008 R. C. Gonzalez & R. E. Woods

Digital Image Processing, 3rd ed.

Gonzalez & Woods

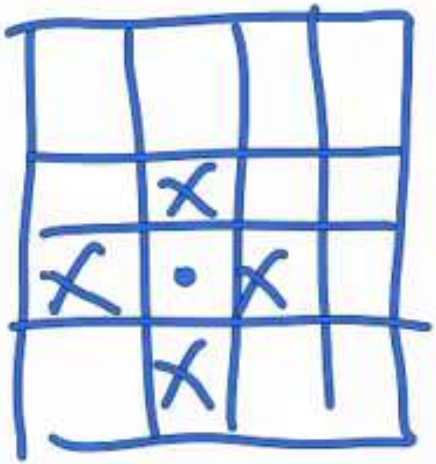
www.ImageProcessingPlace.com

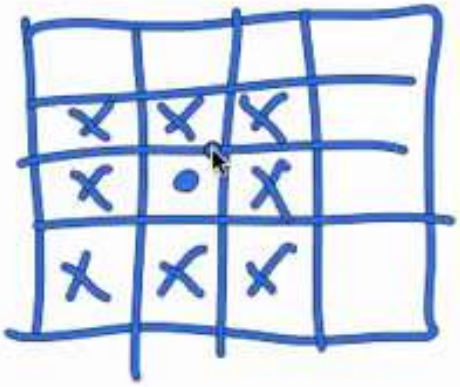
Chapter 2

Digital Image Fundamentals

a b c
d e f

FIGURE 2.25 (a) An arrangement of pixels. (b) Pixels that are 8-adjacent (adjacency is shown by dashed lines; note the ambiguity). (c) m-adjacency. (d) Two regions that are adjacent if 8-adjacency is used. (e) The circled point is part of the boundary of the 1-valued pixels only if 8-adjacency between the region and background is used. (f) The inner boundary of the 1-valued region does not form a closed path, but its outer boundary does.





© 1992–2008 R. C. Gonzalez & R. E. Woods

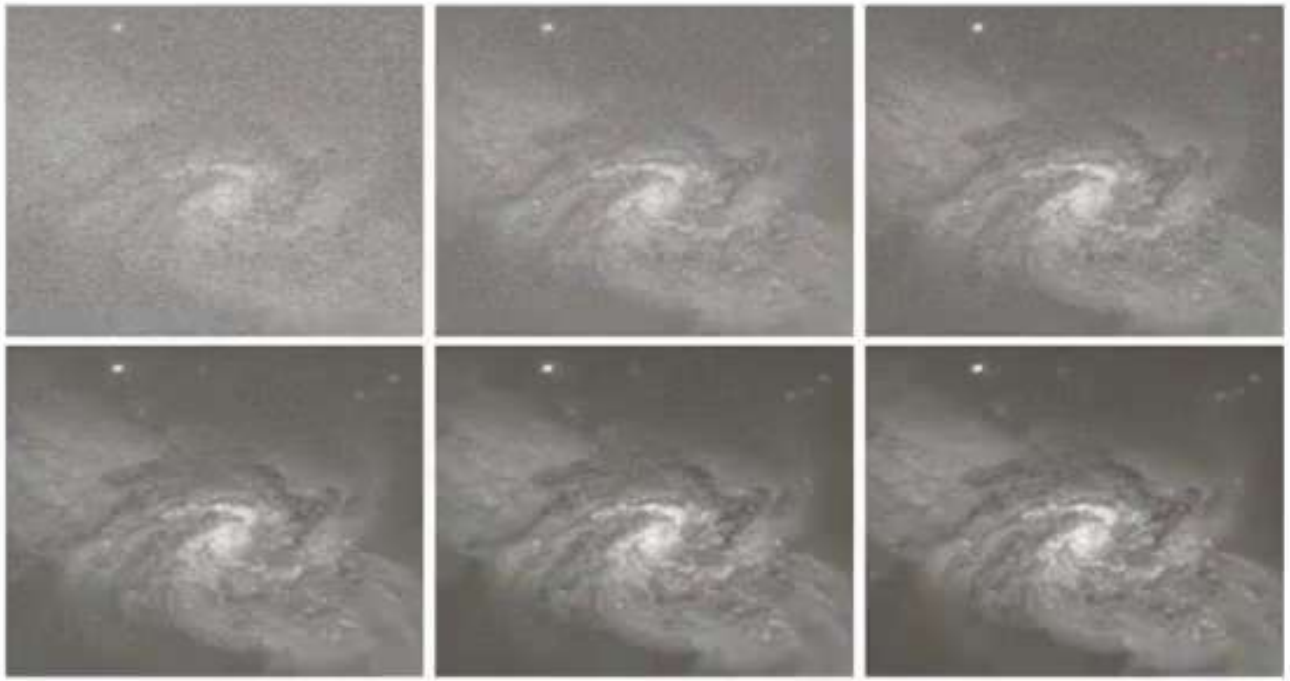
Digital Image Processing, 3rd ed.

Gonzalez & Woods

www.ImageProcessingPlace.com

Chapter 2

Digital Image Fundamentals



a b c
d e f

FIGURE 2.26 (a) Image of Galaxy Pair NGC 3314 corrupted by additive Gaussian noise. (b)–(f) Results of averaging 5, 10, 20, 50, and 100 noisy images, respectively. (Original image courtesy of NASA.)

© 1992–2008 R. C. Gonzalez & R. E. Woods

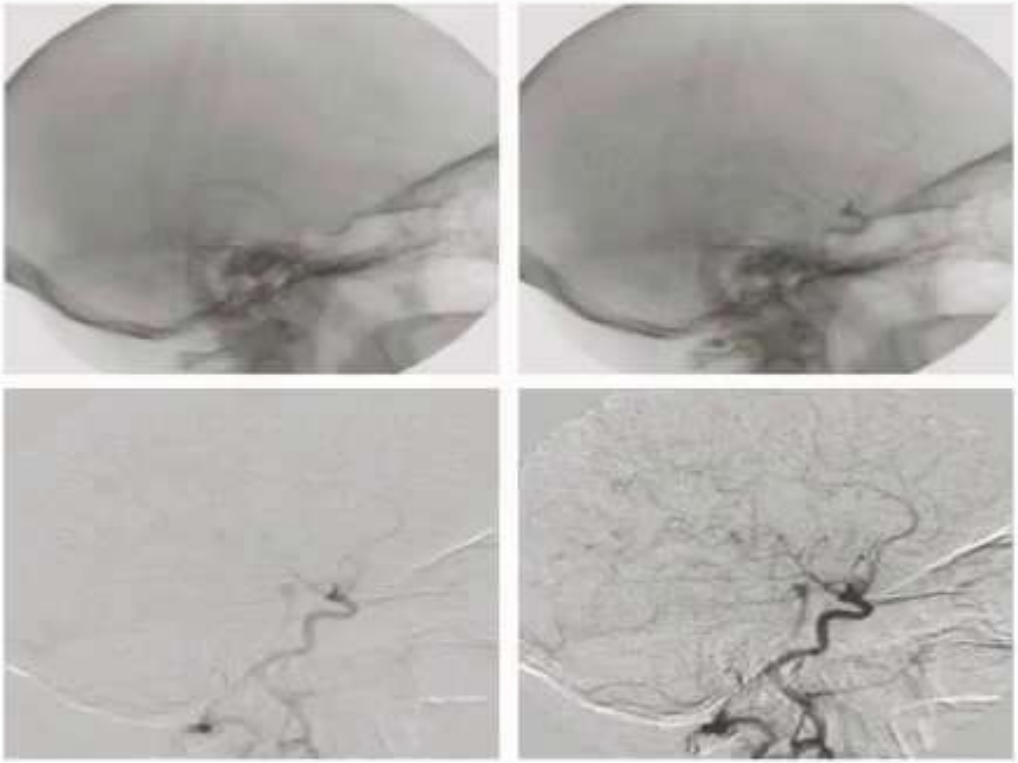
Digital Image Processing, 3rd ed.

Gonzalez & Woods

www.ImageProcessingPlace.com

Chapter 2

Digital Image Fundamentals



a b
c d

FIGURE 2.28 Digital subtraction angiography. (a) Mask image. (b) A live image. (c) Difference between (a) and (b). (d) Enhanced difference image. (Figures (a) and (b) courtesy of The Image Sciences Institute, University Medical Center, Utrecht, The Netherlands.)

© 1992–2008 R. C. Gonzalez & R. E. Woods

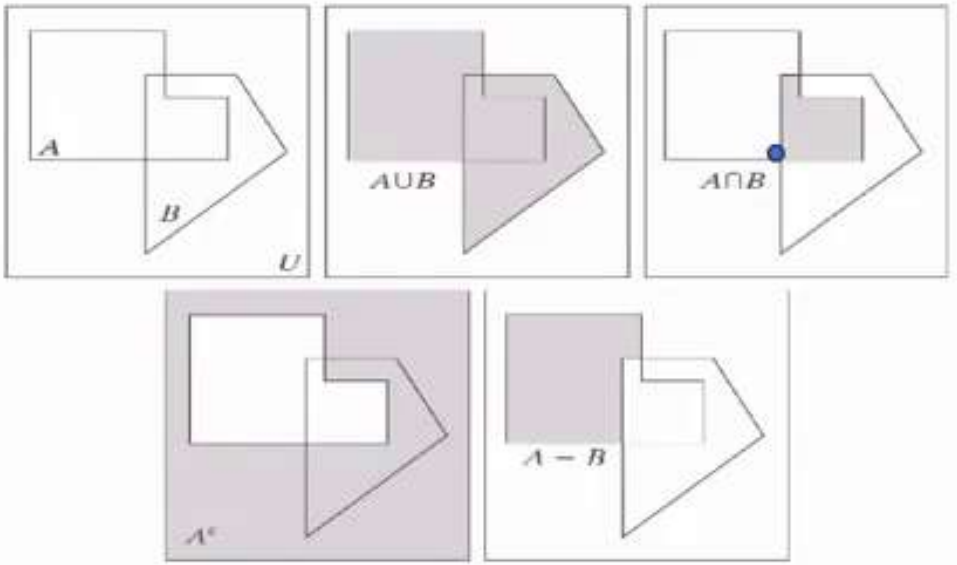
Digital Image Processing, 3rd ed.

Gonzalez & Woods

www.ImageProcessingPlace.com

Chapter 2

Digital Image Fundamentals



a b c
d e

FIGURE 2.31
(a) Two sets of coordinates, A and B, in 2-D space. (b) The union of A and B. (c) The intersection of A and B. (d) The complement of A. (e) The difference between A and B. In (b)–(e) the shaded areas represent the member of the set operation indicated.

© 1992–2008 R. C. Gonzalez & R. E. Woods

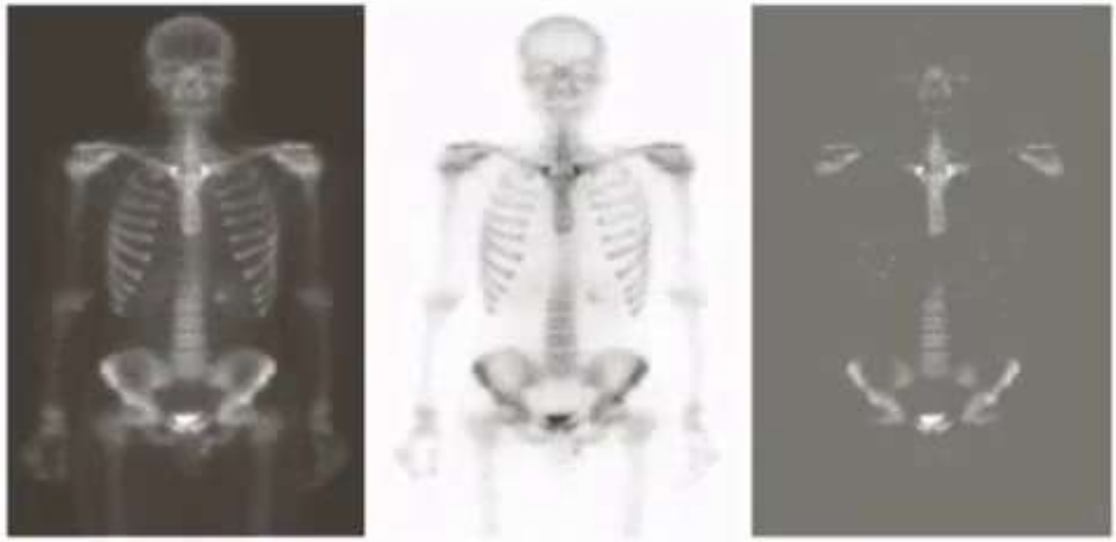
Digital Image Processing, 3rd ed.

Gonzalez & Woods

www.ImageProcessingPlace.com

Chapter 2

Digital Image Fundamentals



a b c

FIGURE 2.32 Set operations involving gray-scale images. (a) Original image. (b) Image negative obtained using set complementation. (c) The union of (a) and a constant image. (Original image courtesy of G.E. Medical Systems.)

© 1992–2008 R. C. Gonzalez & R. E. Woods

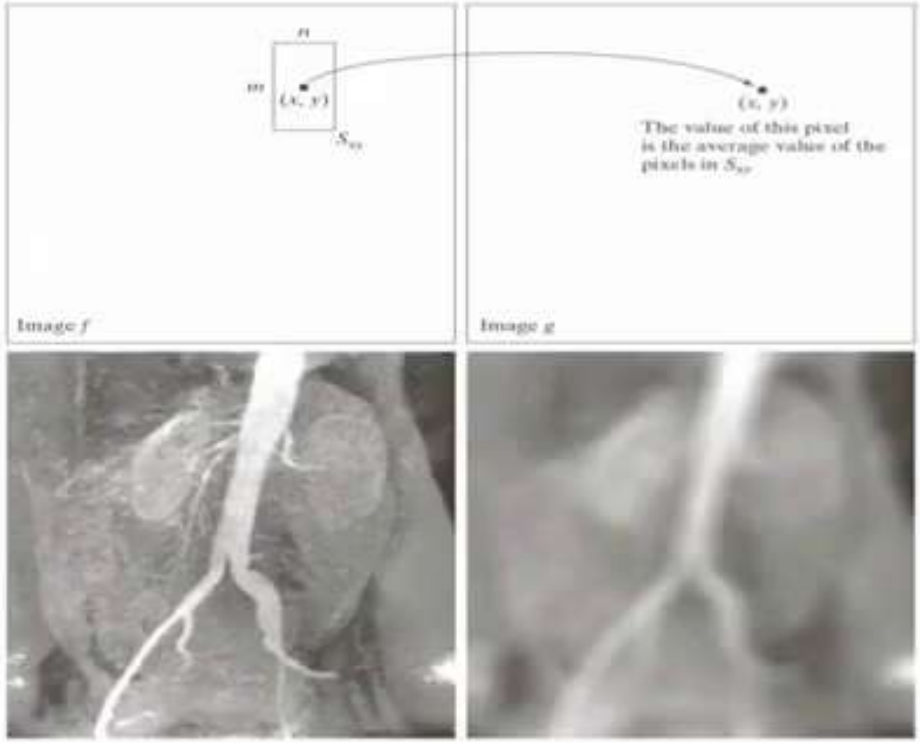
Digital Image Processing, 3rd ed.

Gonzalez & Woods

www.ImageProcessingPlace.com

Chapter 2

Digital Image Fundamentals



a b
c d

FIGURE 2.35 Local averaging using neighborhood processing. The procedure is illustrated in (a) and (b) for a rectangular neighborhood. (c) The aortic angiogram discussed in Section 1.3.2. (d) The result of using Eq. (2.6-21) with $m = n = 41$. The images are of size 790 × 686 pixels.

© 1992–2008 R. C. Gonzalez & R. E. Woods

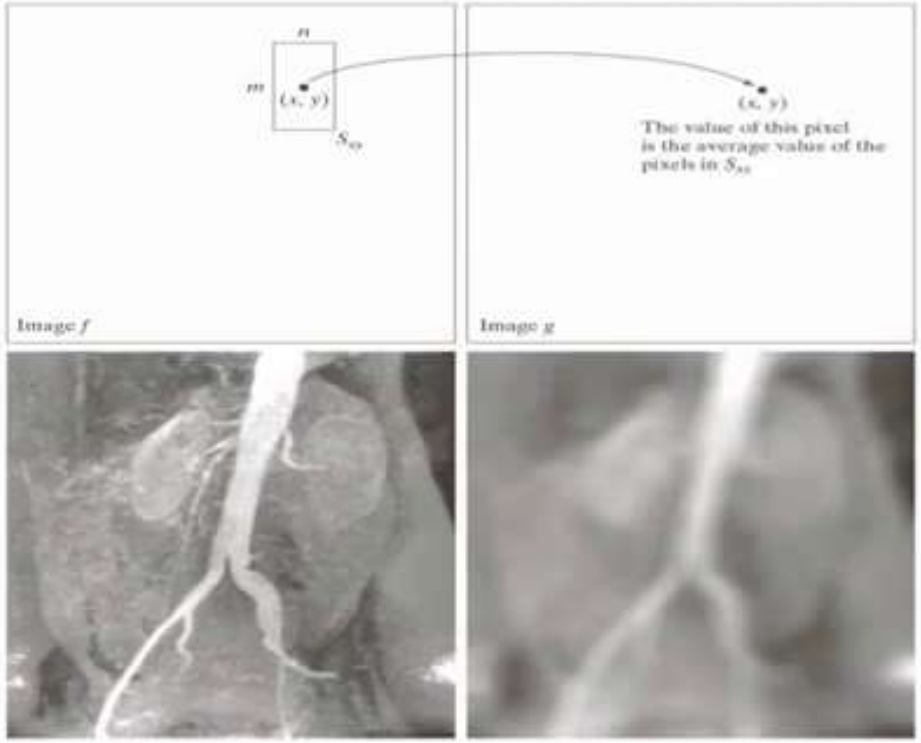
Digital Image Processing, 3rd ed.

Gonzalez & Woods

www.ImageProcessingPlace.com

Chapter 2

Digital Image Fundamentals



a b
c d

FIGURE 2.35 Local averaging using neighborhood processing. The procedure is illustrated in (a) and (b) for a rectangular neighborhood. (c) The aortic angiogram discussed in Section 1.3.2. (d) The result of using Eq. (2.6-21) with $m = n = 41$. The images are of size 790 × 686 pixels.

© 1992–2008 R. C. Gonzalez & R. E. Woods

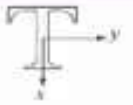
Digital Image Processing, 3rd ed.

Gonzalez & Woods

www.ImageProcessingPlace.com

Chapter 2
Digital Image Fundamentals

TABLE 2.2
Affine transformations based on Eq. (2.6.–23).

Transformation Name	Affine Matrix, T	Coordinate Equations	Example
Identity	$\begin{bmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{bmatrix}$	$x = v$ $y = w$	
Scaling	$\begin{bmatrix} c_x & 0 & 0 \\ 0 & c_y & 0 \\ 0 & 0 & 1 \end{bmatrix}$	$x = c_x v$ $y = c_y w$	
Rotation	$\begin{bmatrix} \cos\theta & \sin\theta & 0 \\ -\sin\theta & \cos\theta & 0 \\ 0 & 0 & 1 \end{bmatrix}$	$x = v\cos\theta - w\sin\theta$ $y = v\cos\theta + w\sin\theta$	
Translation	$\begin{bmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ t_x & t_y & 1 \end{bmatrix}$	$x = v + t_x$ $y = w + t_y$	
Shear (vertical)	$\begin{bmatrix} 1 & 0 & 0 \\ s_v & 1 & 0 \\ 0 & 0 & 1 \end{bmatrix}$	$x = v + s_v w$ $y = w$	
Shear (horizontal)	$\begin{bmatrix} 1 & s_h & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{bmatrix}$	$x = v$ $y = s_h v + w$	

© 1992–2008 R. C. Gonzalez & R. E. Woods

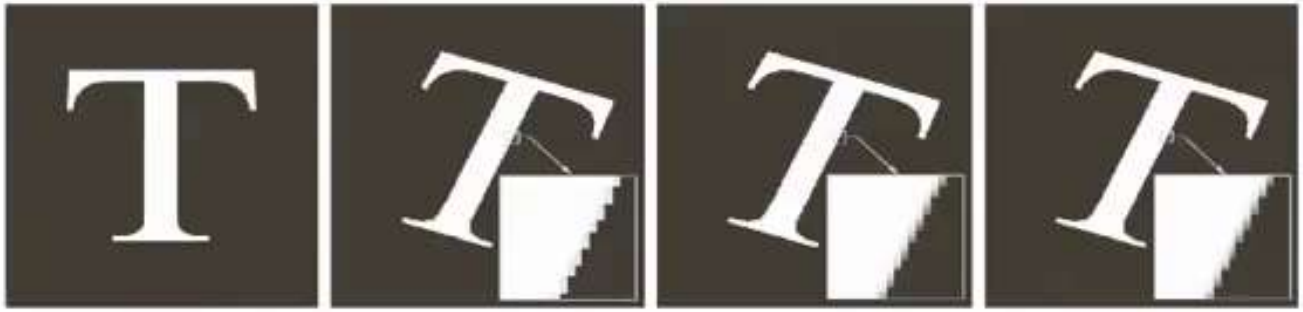
Digital Image Processing, 3rd ed.

Gonzalez & Woods

www.ImageProcessingPlace.com

Chapter 2

Digital Image Fundamentals



a b c d

FIGURE 2.36 (a) A 300 dpi image of the letter T. (b) Image rotated 21° clockwise using nearest neighbor interpolation to assign intensity values to the spatially transformed pixels. (c) Image rotated 21° using bilinear interpolation. (d) Image rotated 21° using bicubic interpolation. The enlarged sections show edge detail for the three interpolation approaches.

© 1992–2008 R. C. Gonzalez & R. E. Woods

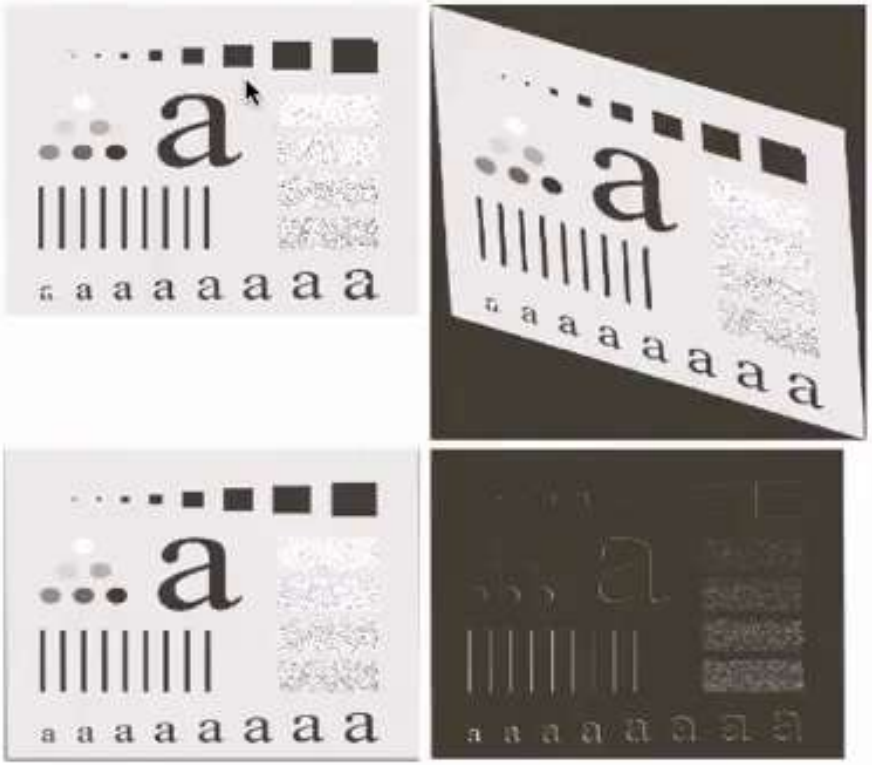
Digital Image Processing, 3rd ed.

Gonzalez & Woods

www.ImageProcessingPlace.com

Chapter 2

Digital Image Fundamentals



a b
c d

FIGURE 2.37 Image registration. (a) Reference image. (b) Input (geometrically distorted image). Corresponding tie points are shown as small white squares near the corners. (c) Registered image (note the errors in the borders). (d) Difference between (a) and (c), showing more registration errors.

© 1992–2008 R. C. Gonzalez & R. E. Woods

Digital Image Processing, 3rd ed.

Gonzalez & Woods

www.ImageProcessingPlace.com

Chapter 2

Digital Image Fundamentals

FIGURE 2.39 General approach for operating in the linear transform domain.

© 1992–2008 R. C. Gonzalez & R. E. Woods

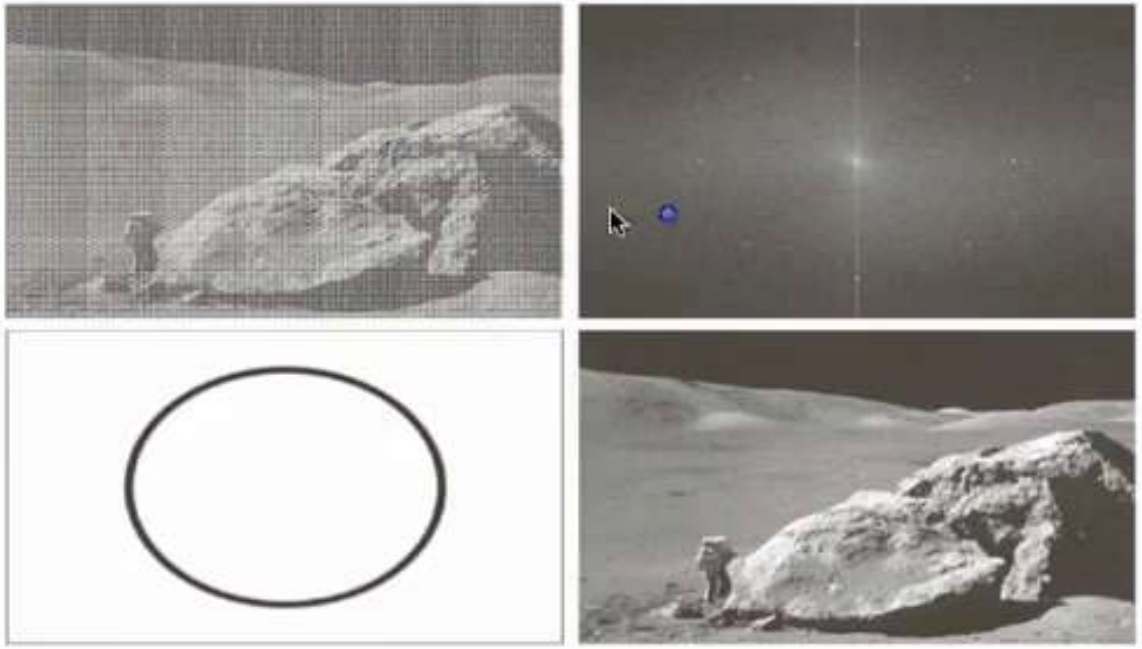
Digital Image Processing, 3rd ed.

Gonzalez & Woods

www.ImageProcessingPlace.com

Chapter 2

Digital Image Fundamentals



a b
c d

FIGURE 2.40
(a) Image corrupted by sinusoidal interference. (b) Magnitude of the Fourier transform showing the bursts of energy responsible for the interference. (c) Mask used to eliminate the energy bursts. (d) Result of computing the inverse of the modified Fourier transform. (Original image courtesy of NASA.)

© 1992–2008 R. C. Gonzalez & R. E. Woods