Digital Image Processing

Digital Image Fundamentals

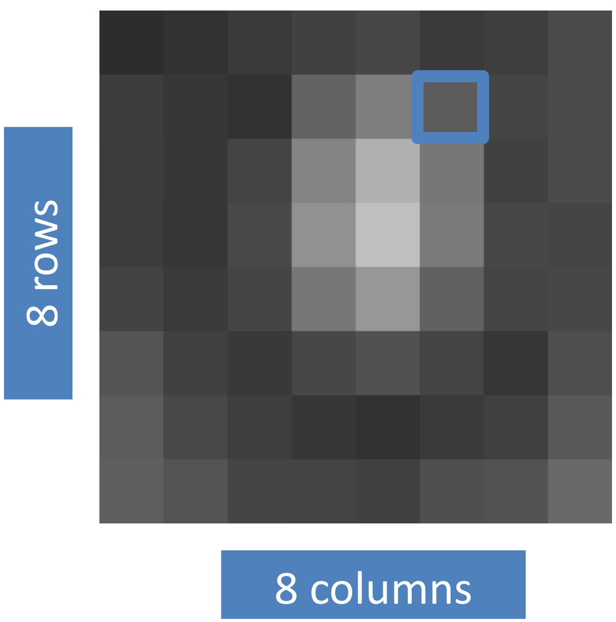
Suyash P. Awate

Digital Image

- Image = function
  - Domain = space
    - e.g., 2D photographs
    - e.g., 3D (volume) medical images
  - Range = scalar or vector
    - e.g., black-and-white photo (scalar)
    - e.g., color photo (RGB vector)
    - e.g., video (???)

Digital Image

- **Pixel** = a **coordinate** in the image domain
  - Displayed as a square / rectangle
  - Pixel **dimensions** depend on the dimensions of the **sensor element** during acquisition
  - Each pixel has an associated **value / intensity**



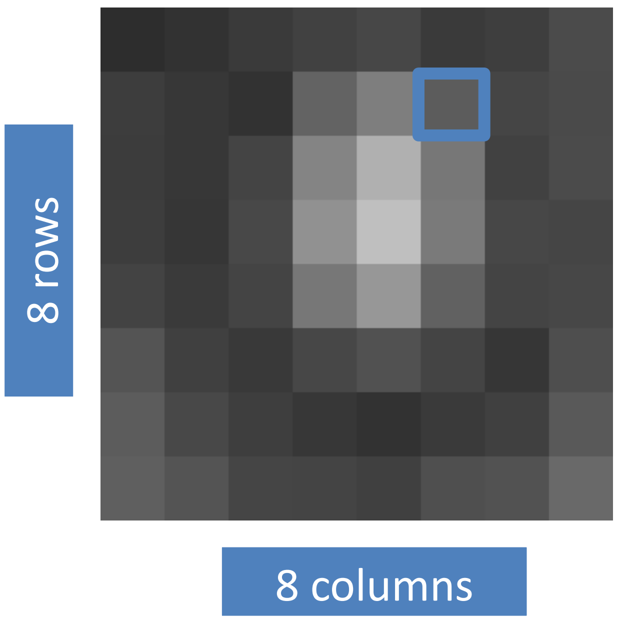
8 rows

$$\begin{bmatrix} 52 & 55 & 61 & 66 & 70 & 61 & 64 & 73 \\ 63 & 59 & 55 & 90 & 109 & \boxed{85} & 69 & 72 \\ 62 & 59 & 68 & 113 & 144 & 104 & 66 & 73 \\ 63 & 58 & 71 & 122 & 154 & 106 & 70 & 69 \\ 67 & 61 & 68 & 104 & 126 & 88 & 68 & 70 \\ 79 & 65 & 60 & 70 & 77 & 68 & 58 & 75 \\ 85 & 71 & 64 & 59 & 55 & 61 & 65 & 83 \\ 87 & 79 & 69 & 68 & 65 & 76 & 78 & 94 \end{bmatrix}$$

8 columns

Digital Image

- Displaying images
  - **Colormap** = function from intensities (scalars) to colors
  - Used purely for display purposes



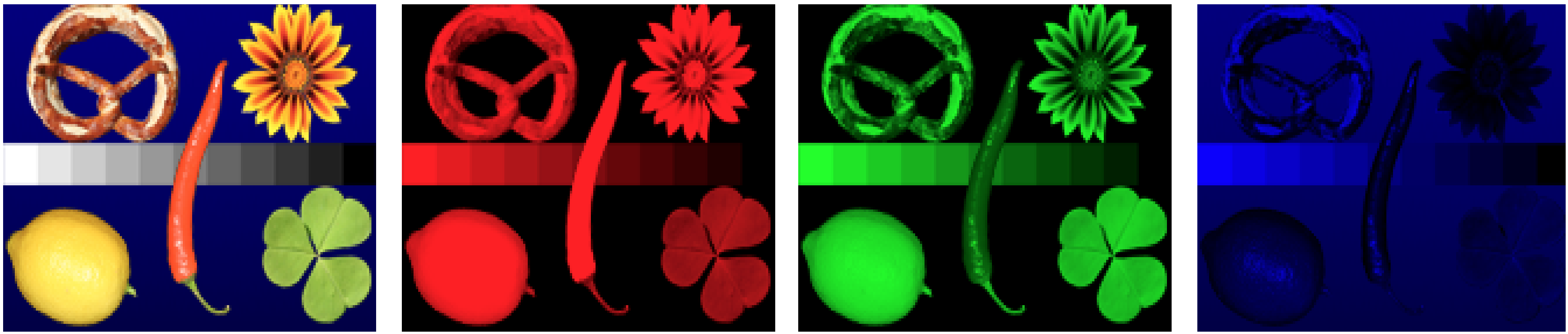
8 rows

$$\begin{bmatrix} 52 & 55 & 61 & 66 & 70 & 61 & 64 & 73 \\ 63 & 59 & 55 & 90 & 109 & \boxed{85} & 69 & 72 \\ 62 & 59 & 68 & 113 & 144 & 104 & 66 & 73 \\ 63 & 58 & 71 & 122 & 154 & 106 & 70 & 69 \\ 67 & 61 & 68 & 104 & 126 & 88 & 68 & 70 \\ 79 & 65 & 60 & 70 & 77 & 68 & 58 & 75 \\ 85 & 71 & 64 & 59 & 55 & 61 & 65 & 83 \\ 87 & 79 & 69 & 68 & 65 & 76 & 78 & 94 \end{bmatrix}$$

8 columns

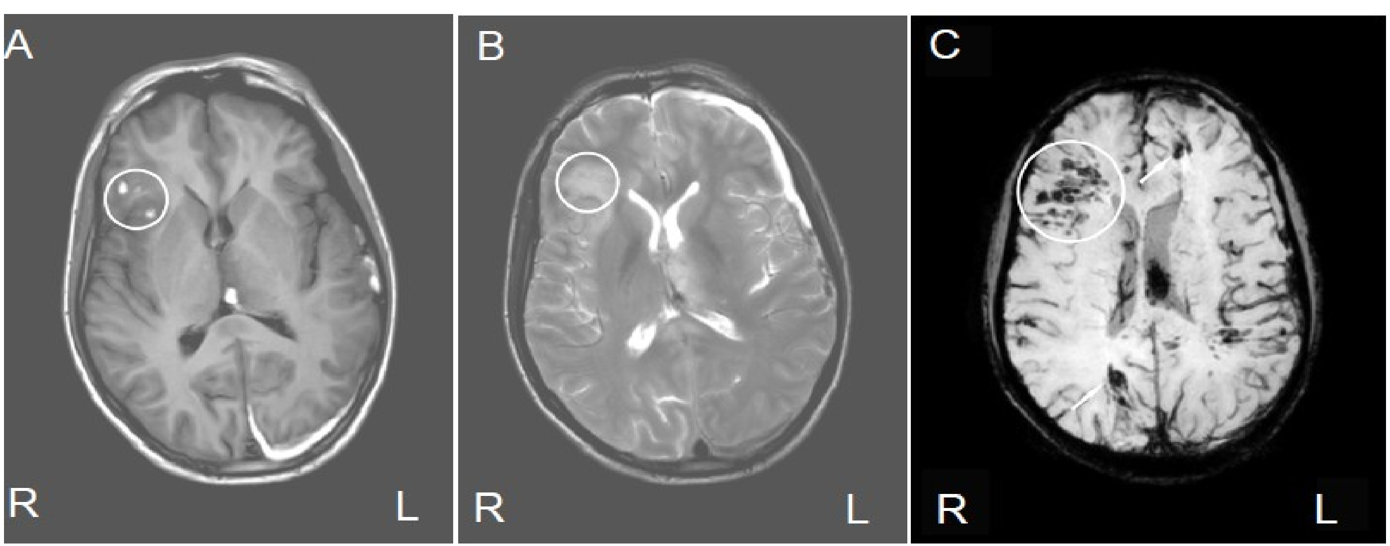
Multi-Component Image

- Vector-valued pixels
  - Color image: R,G,B components



Original Image | Red Color Component | Green Color Component | Blue Color Component

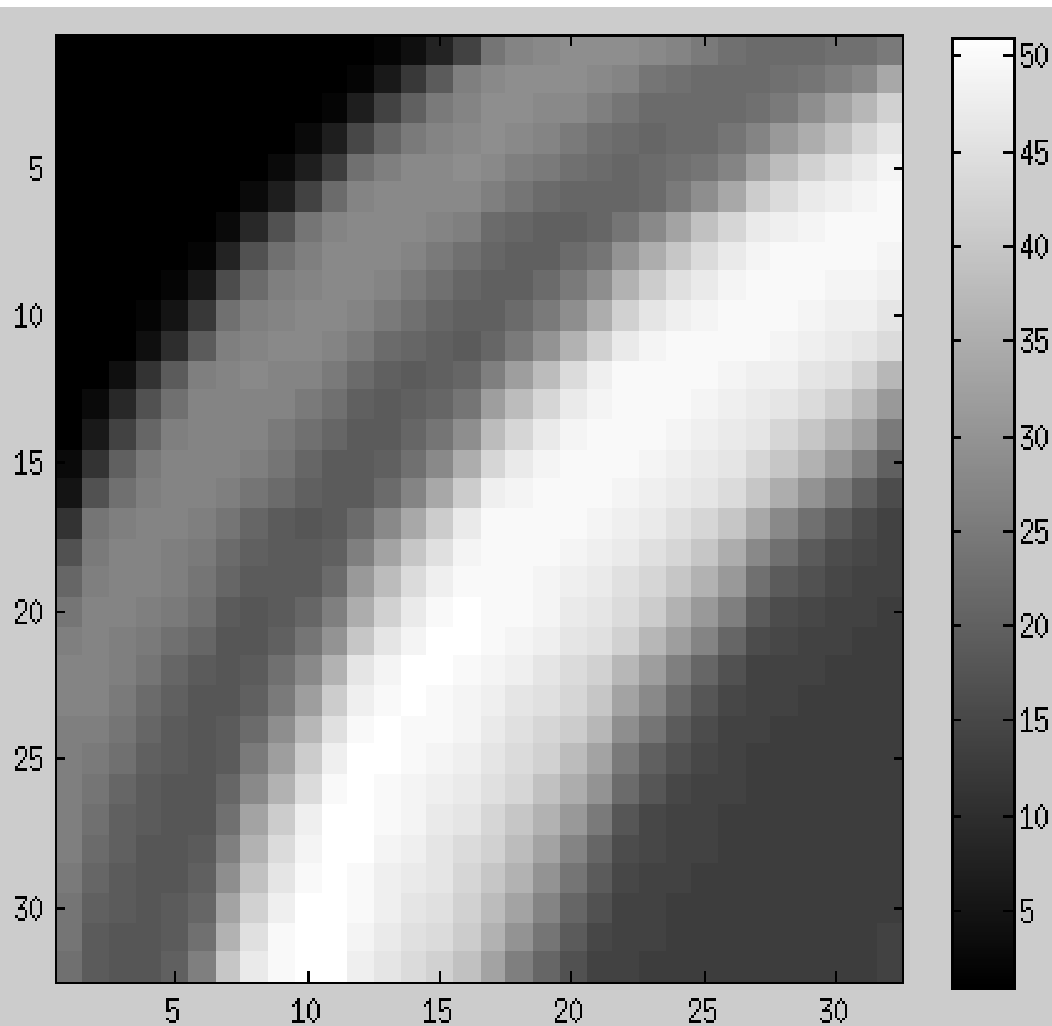
  - Multi-modal MRI

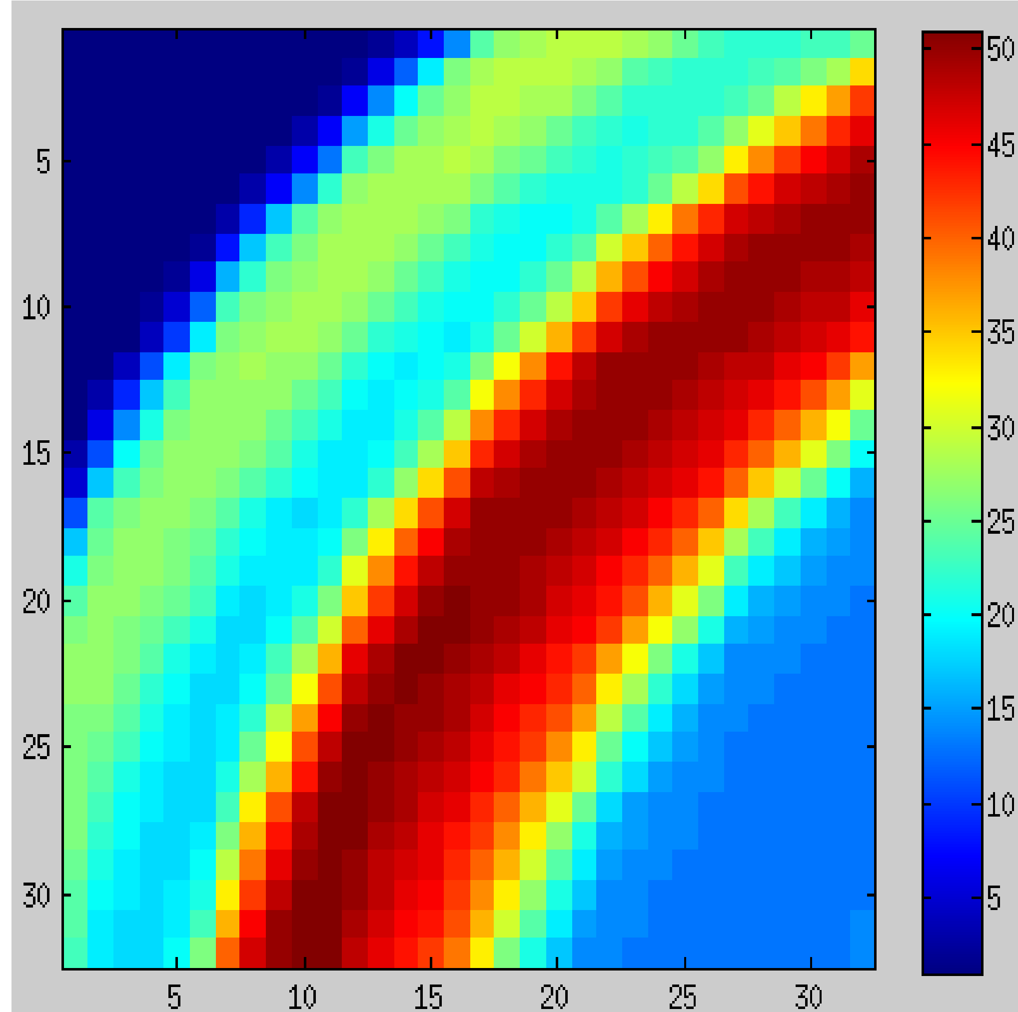


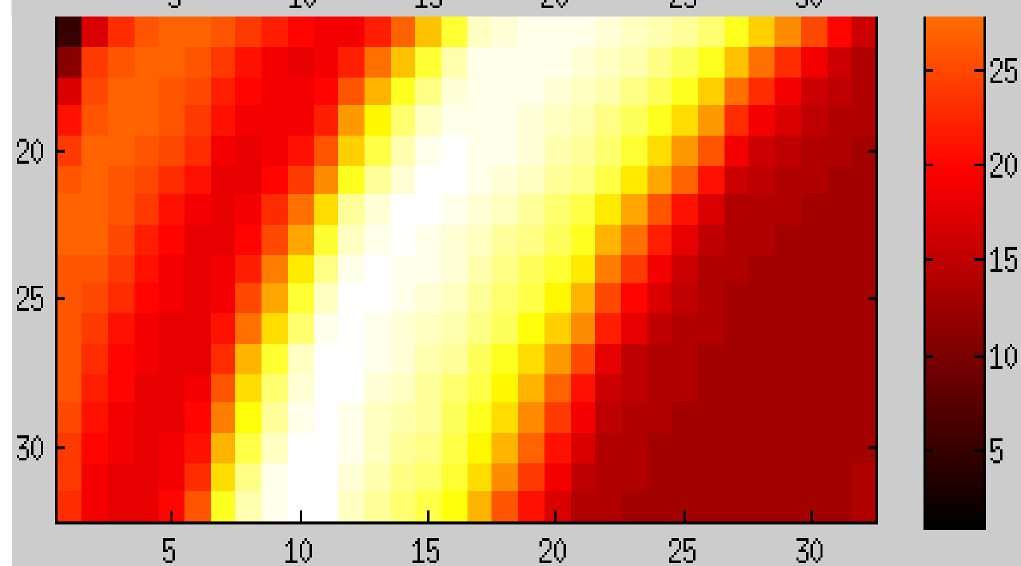
(A) A T1-weighted image shows high intensity lesions in the temporal lobe and left thalamus (white circle). (B) T2-weighted image shows low intensity hemorrhage and edema at the same location (white circle). (C) SWI shows more lesions at the same location and also other lesions in the left frontal lobe and right occipital lobe (white circle and white arrows). R: Right; L: left.

Digital Image

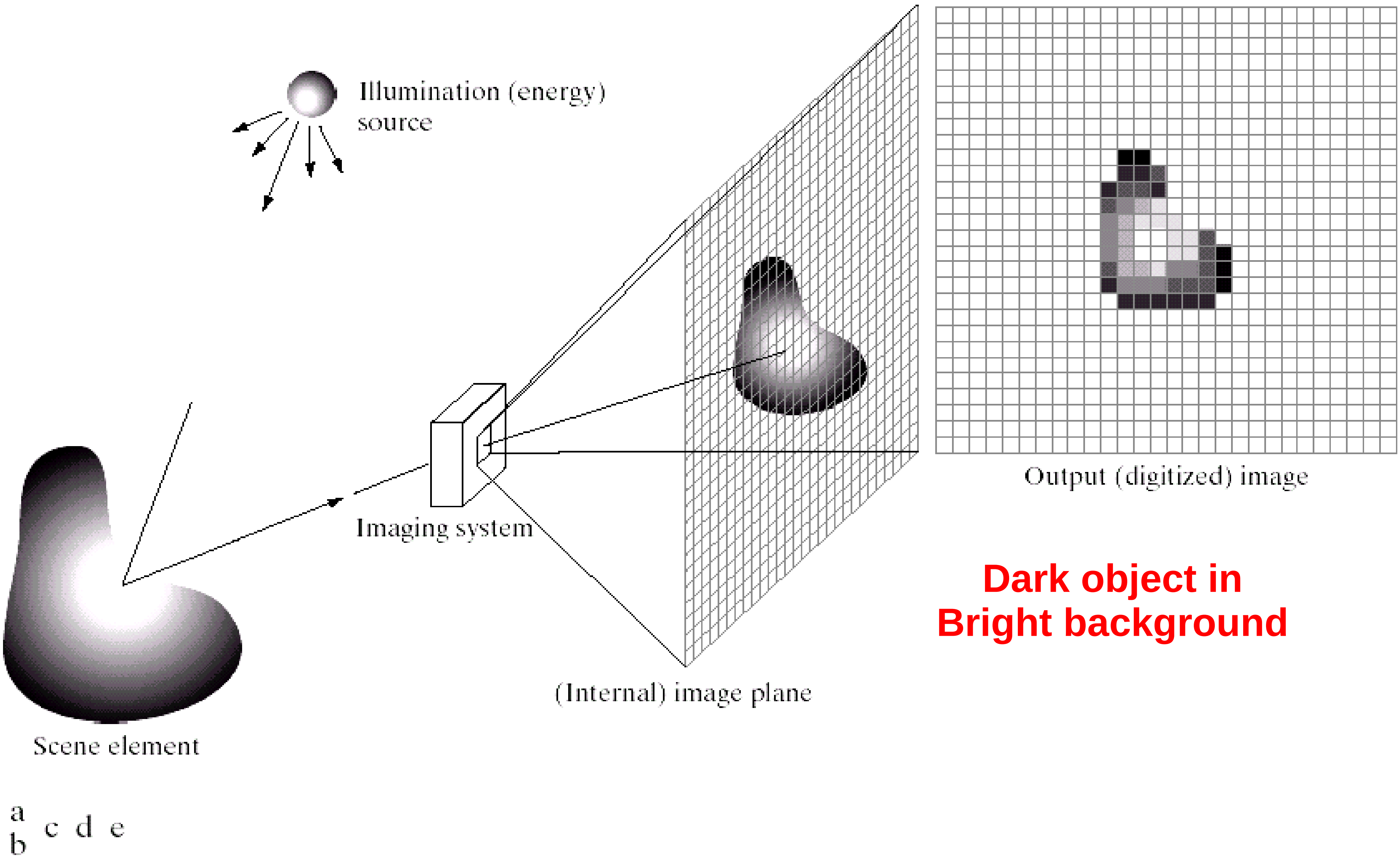
- Displaying images
  - Different colormaps







Digital Image Acquisition

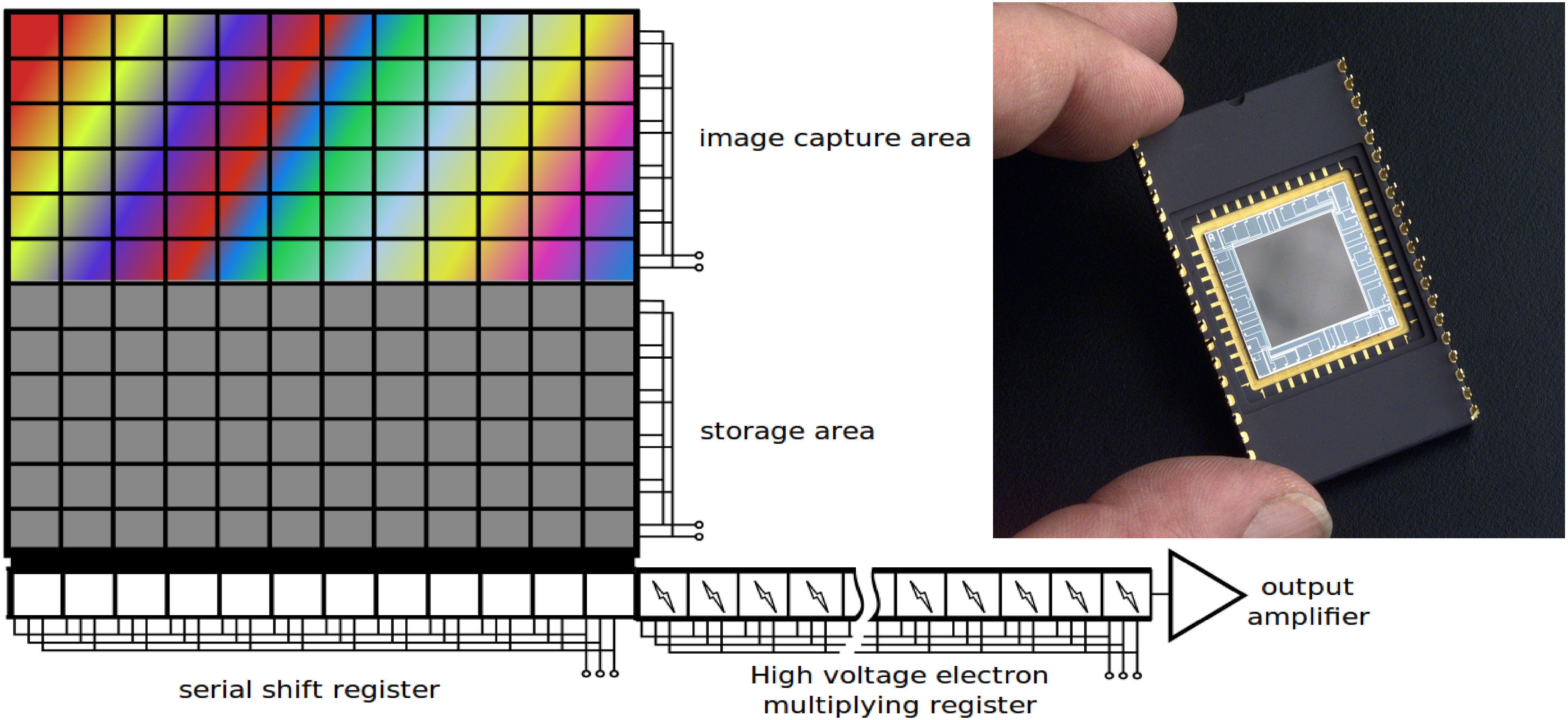


Dark object in Bright background

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.

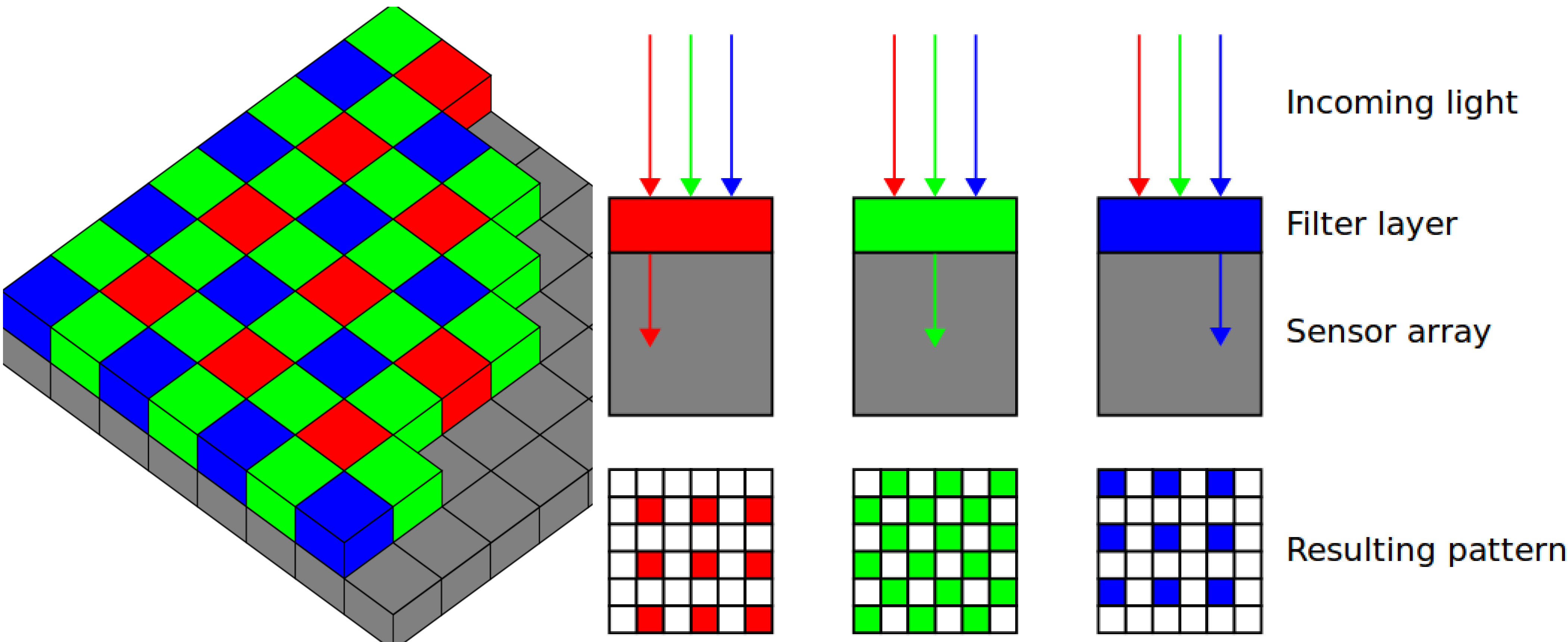
Digital Image Acquisition

- Charge-coupled device (CCD) array
  - Image projected through a lens onto a **capacitor** array
  - Each capacitor accumulates an electric **charge** proportional to the light **intensity** at that location



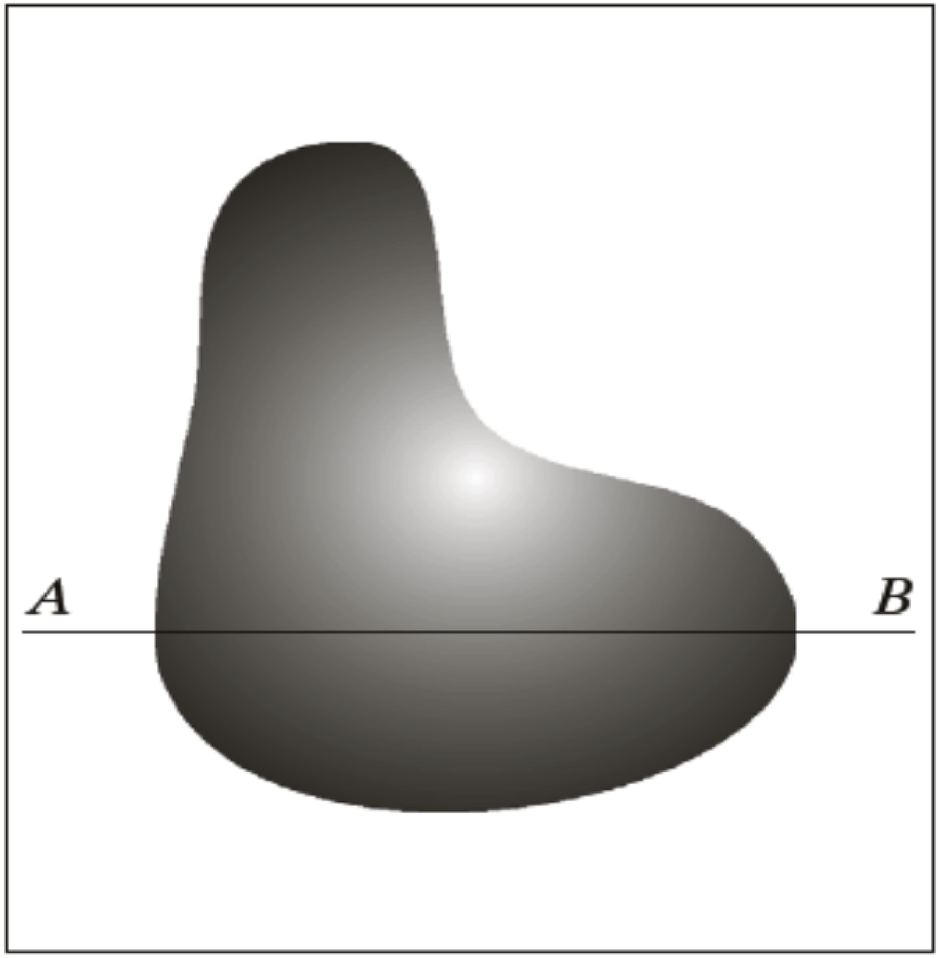
Digital Image Acquisition

- How to capture color ?
  - On CCD array, overlay a Bayer mask = Color filter array
    - Why more area for G ?
      - To capture G more accurately. Why ?
      - Because humans can distinguish subtly-different shades in G better than R or B (i.e., more “sensitive” to green; actually yellow-green)

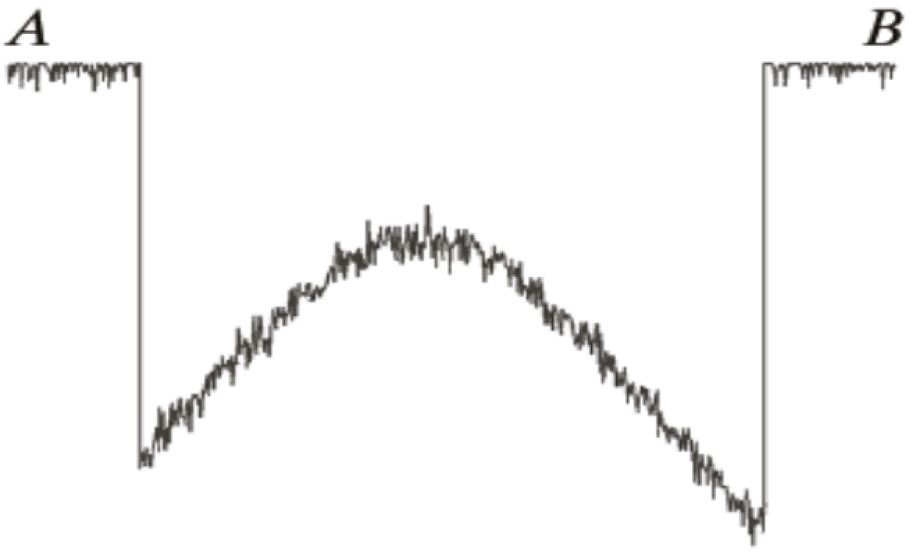


Digital Image Acquisition

Continuous Image

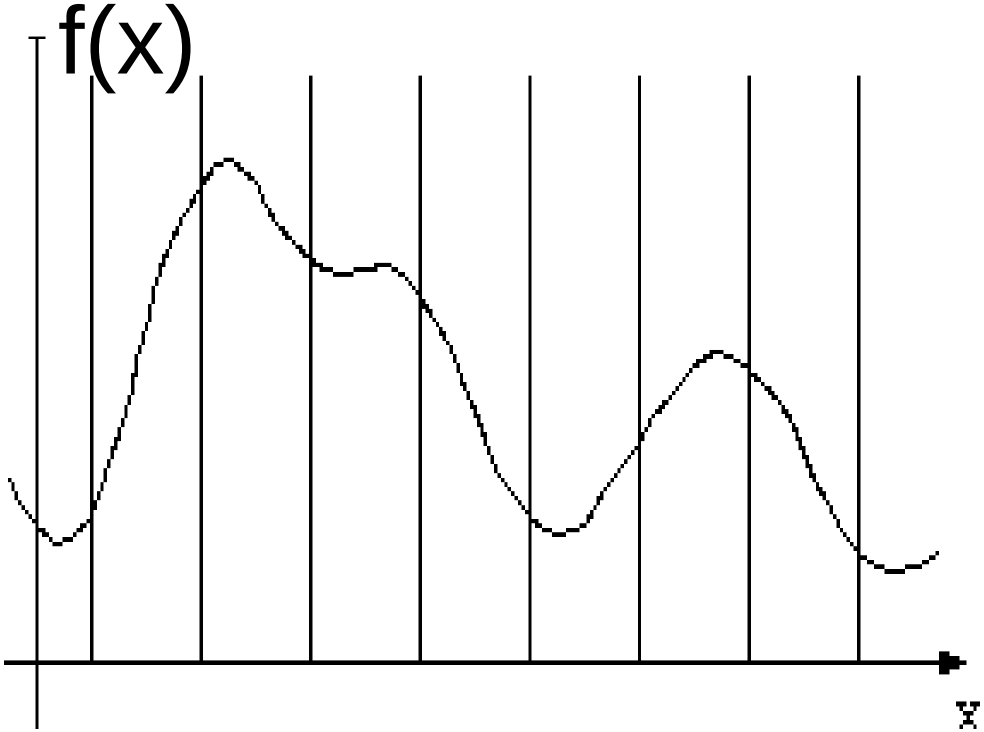


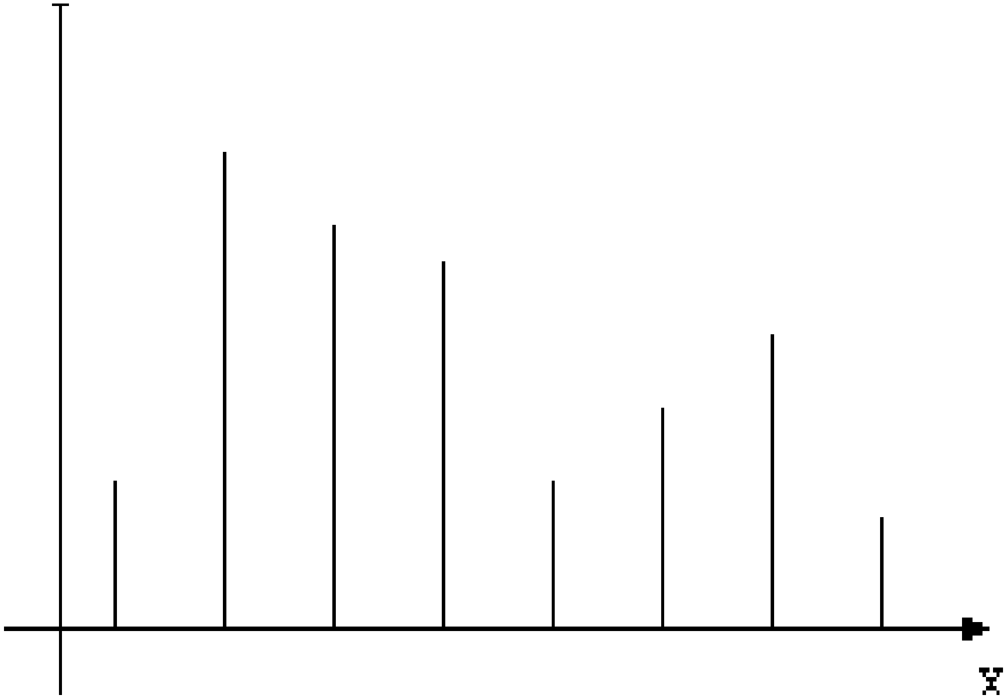
Continuous signal (e.g., voltage) measurements on 1 scan line



Digital Image Acquisition

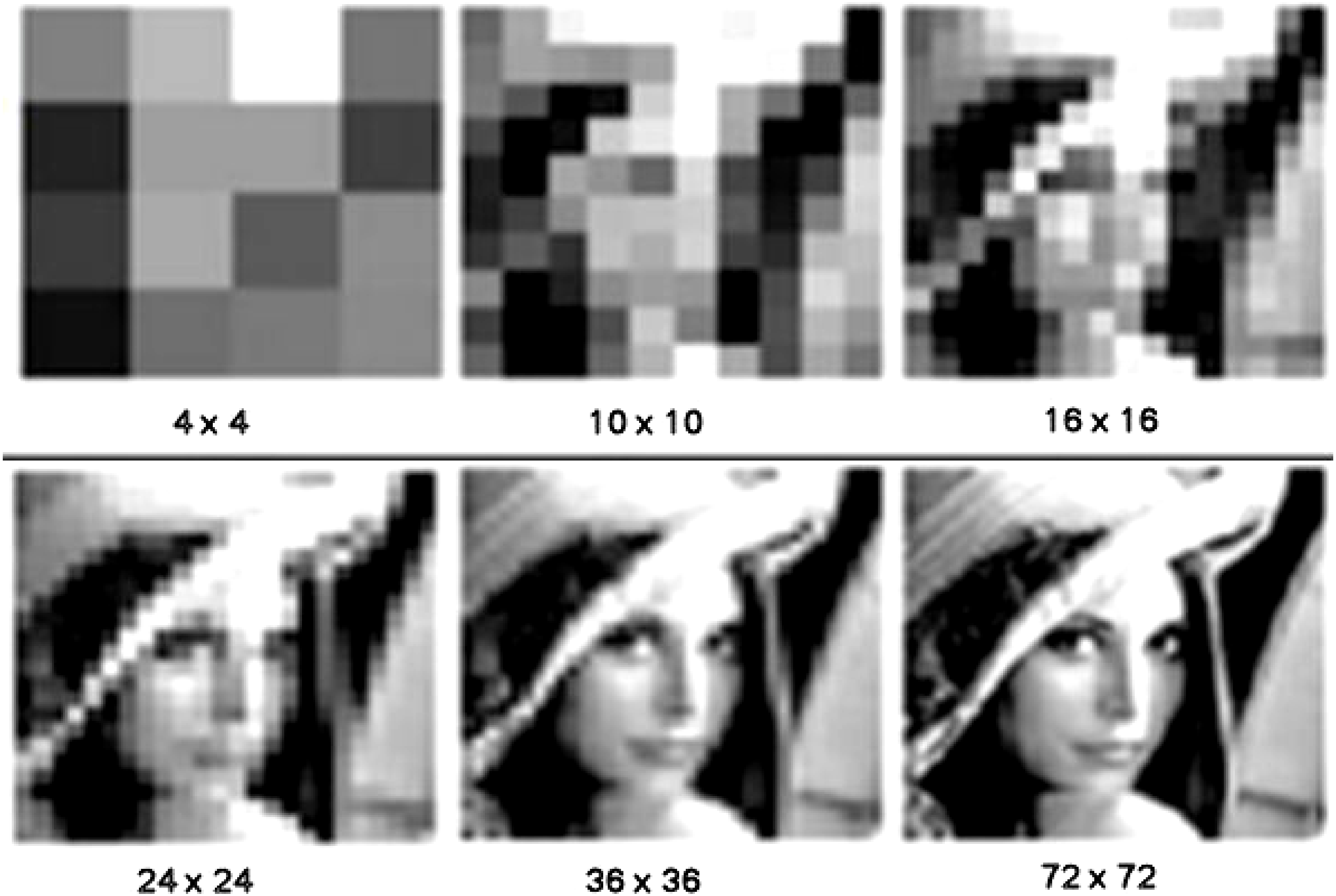
- *Spatial* **sampling**
  - Store function values at a discrete (finite) set of locations
  - Why ?
    - Finite amount of memory to store information





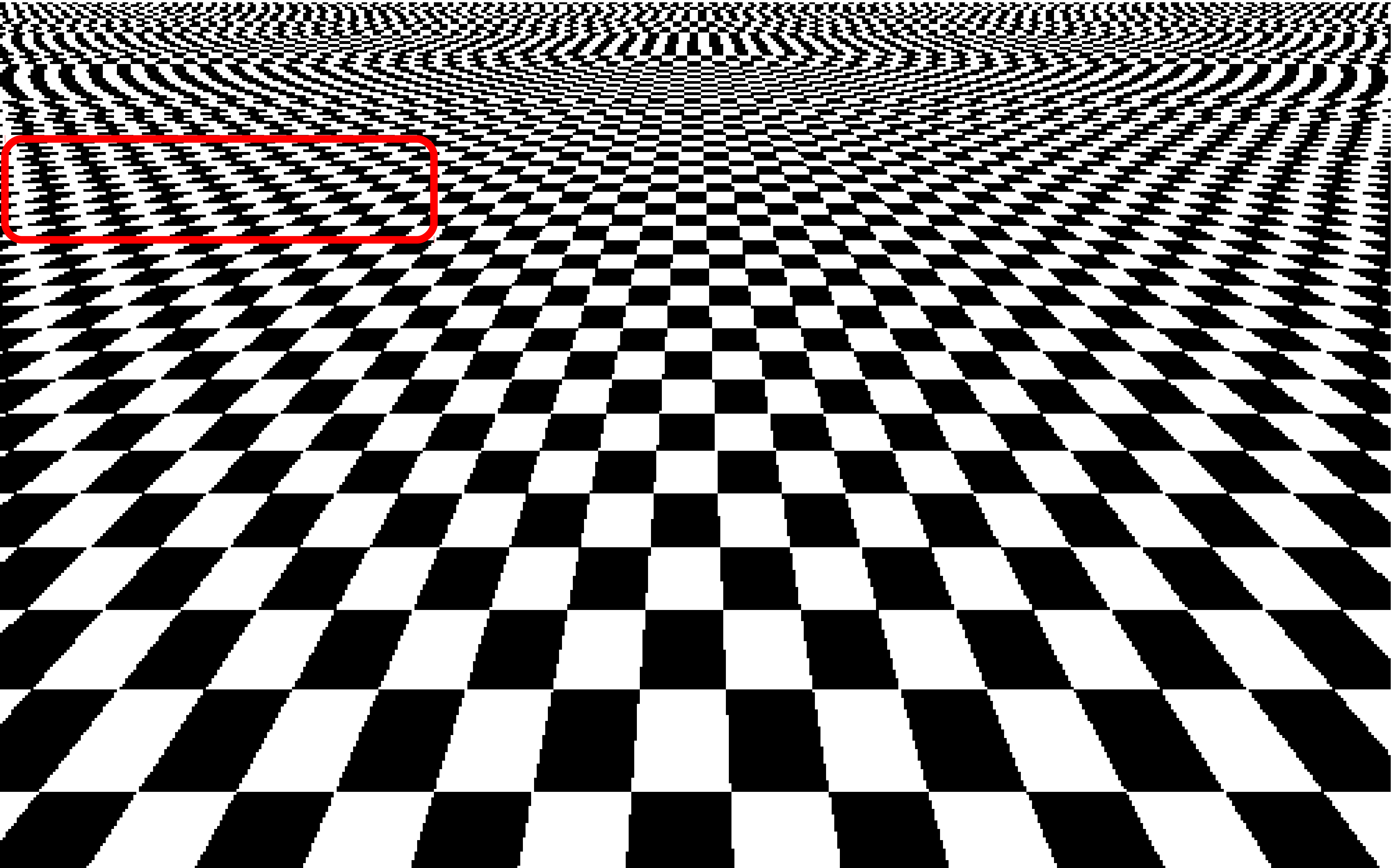
Digital Image Acquisition

- Image undersampling can lose information



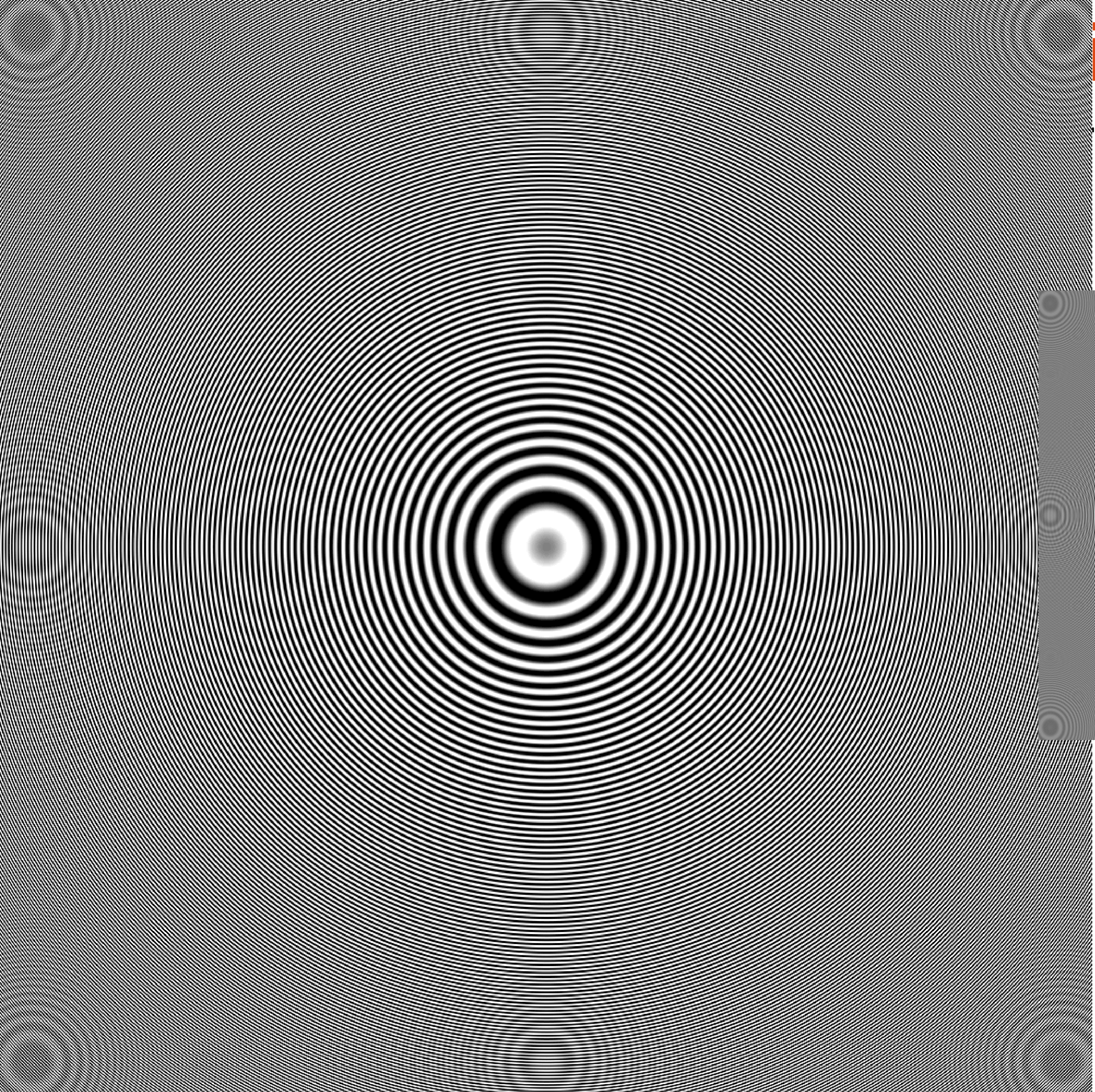
Digital Image Acquisition

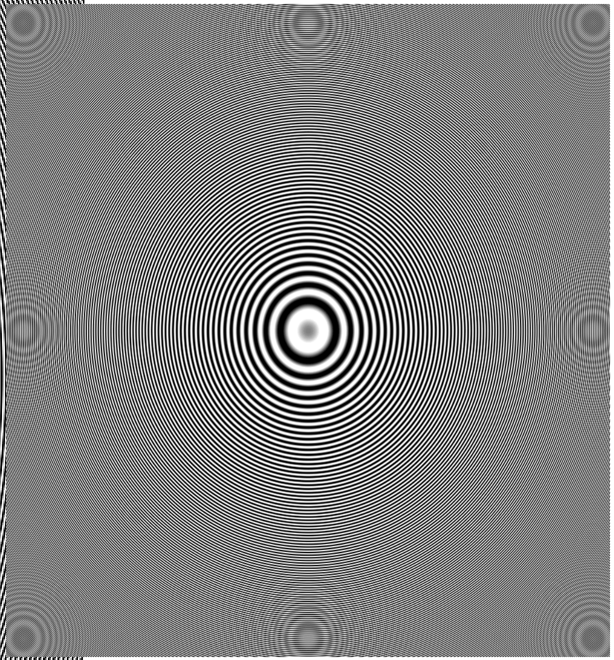
- Image undersampling can create a Moire pattern



ion

e pattern





Digital Image Acquisition

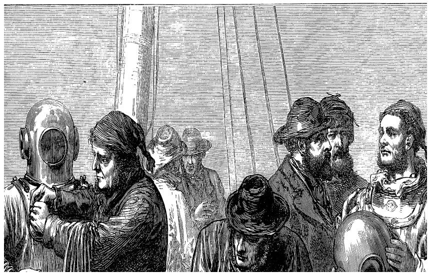
- Image undersampling can create a Moire pattern

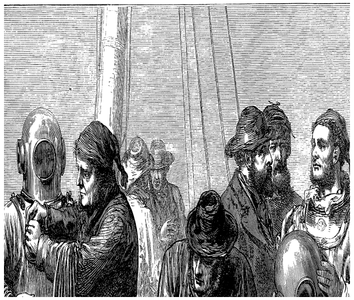
Digital Image Acquisition

- Image undersampling can create a Moire pattern
  - The pattern is actually made of parrallel equi-spaced lines

Digital Image Acquisition

- Image undersampling can create a Moire pattern





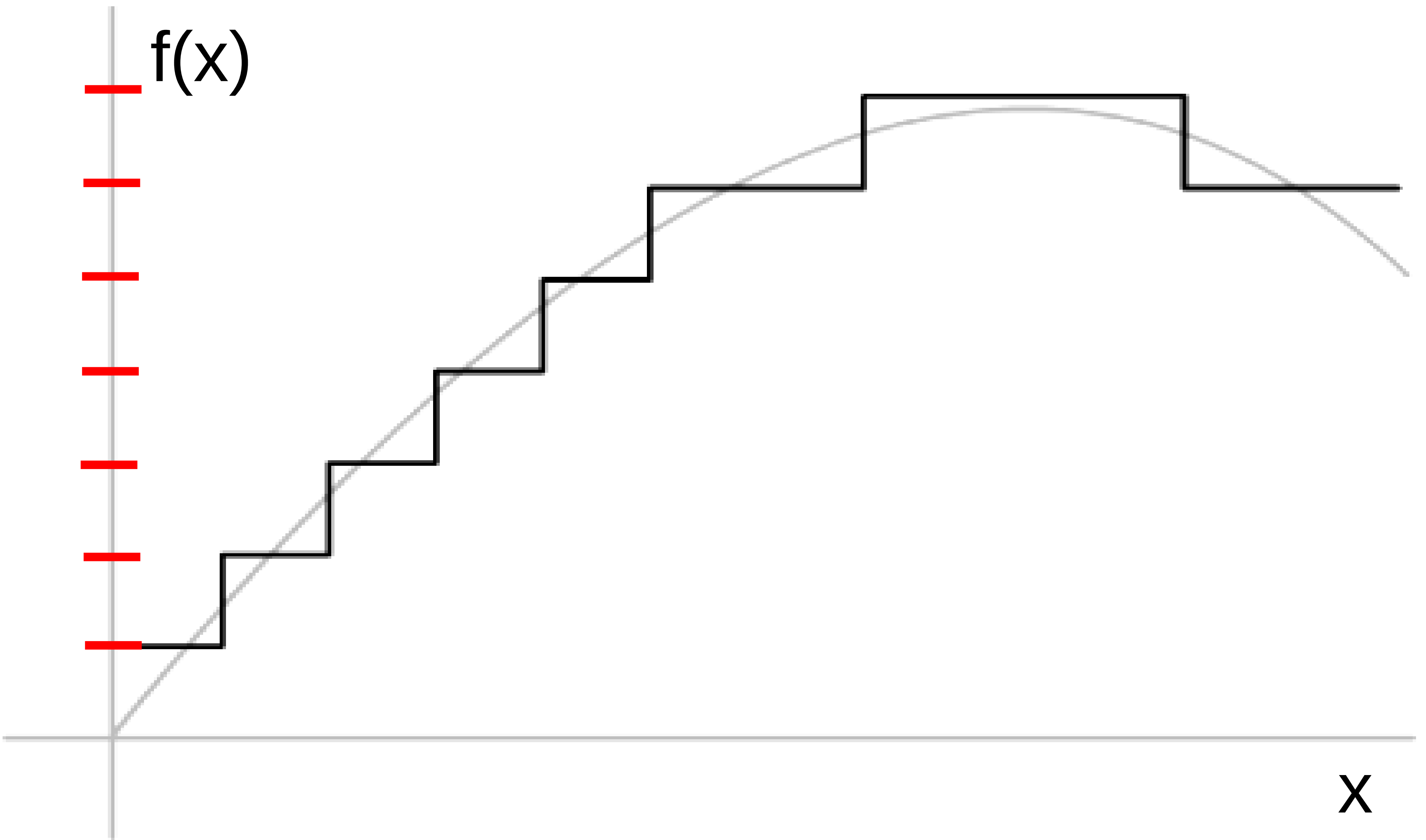
  - How fine of a sampling do we need to preserve all information ?
    - Depends on information content in image
    - Theory of Fourier analysis has some answers

Digital Image Acquisition

- *Intensity* / *color* **quantization**
  - What ?
    At any coordinate location,
    Limit the possible number of intensities / colors stored
    - Rounding real numbers
  - Why ?
    - Finite amount of memory to store information per pixel
    - 8 bits, 16 bits, 24 bits, 32 bits, etc.
  - N bits = 2^N intensities possible

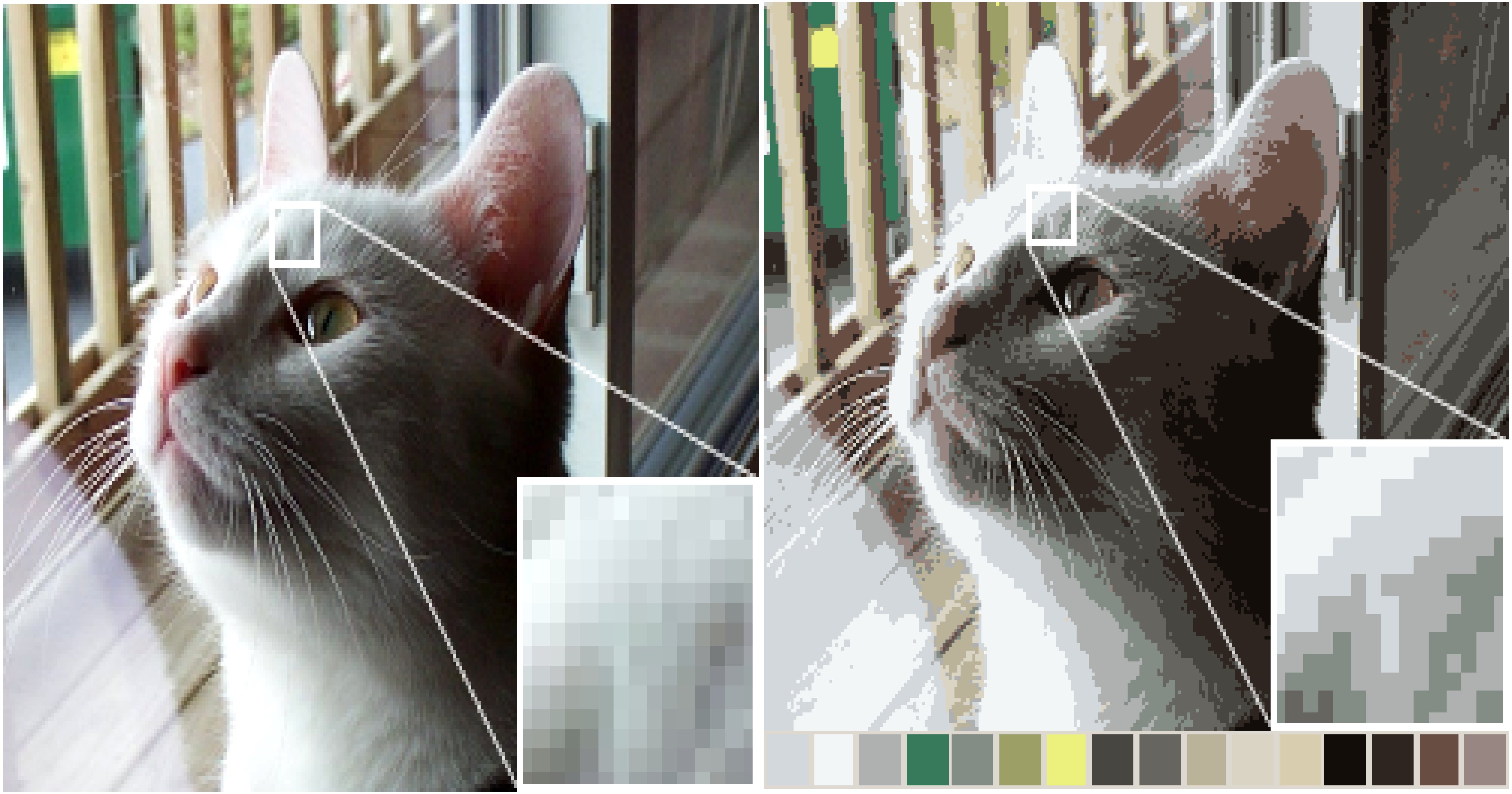
Digital Image Acquisition

- *Intensity / color* **quantization**



Digital Image Acquisition

- *Intensity / color* **quantization**
  - N bits = 2^N intensities possible

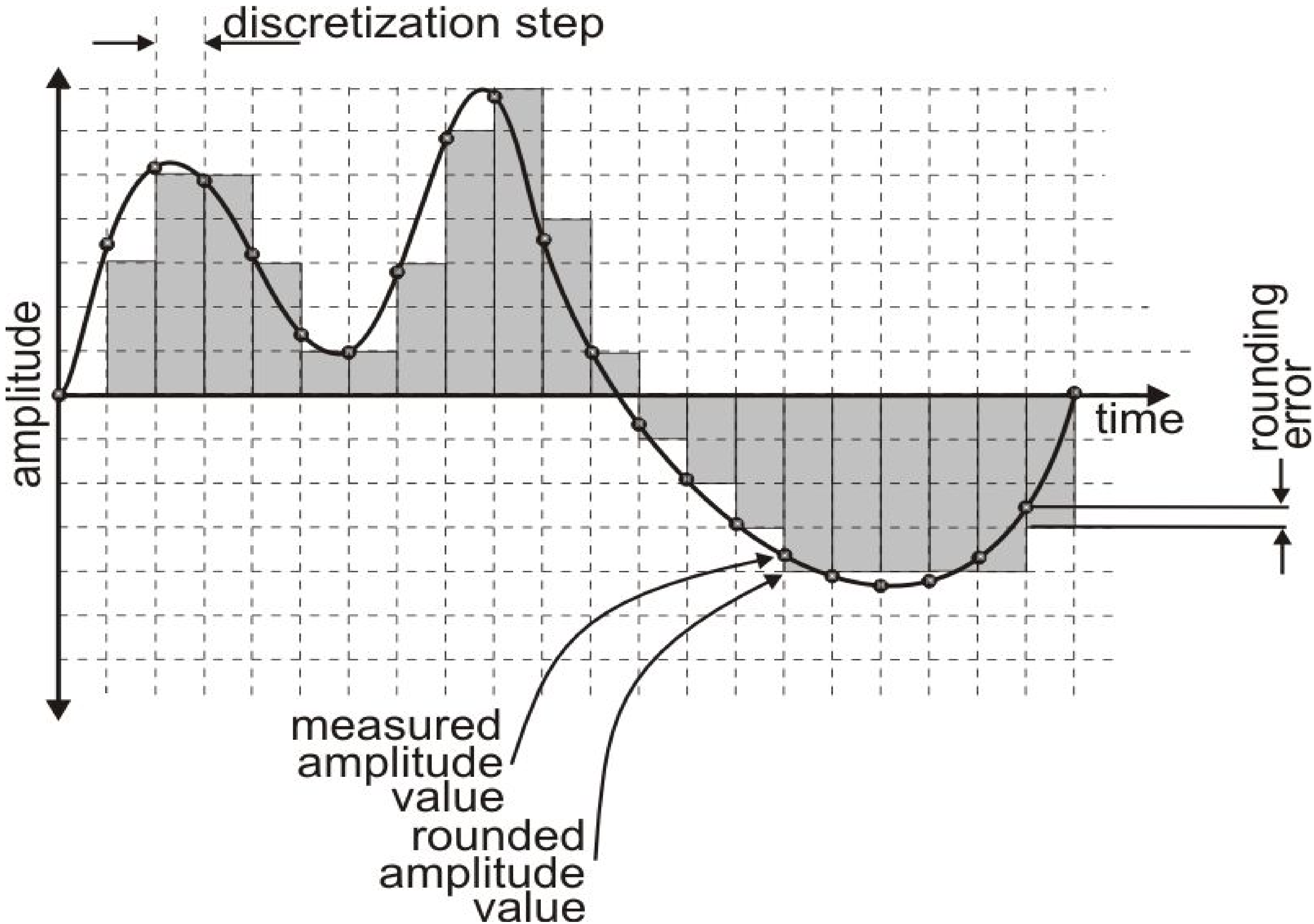


Digital Image Acquisition

- *Intensity / color* **quantization**
  - How finely quantized should intensity levels be ?
    - Depends on human perception, application

Digital Image Acquisition

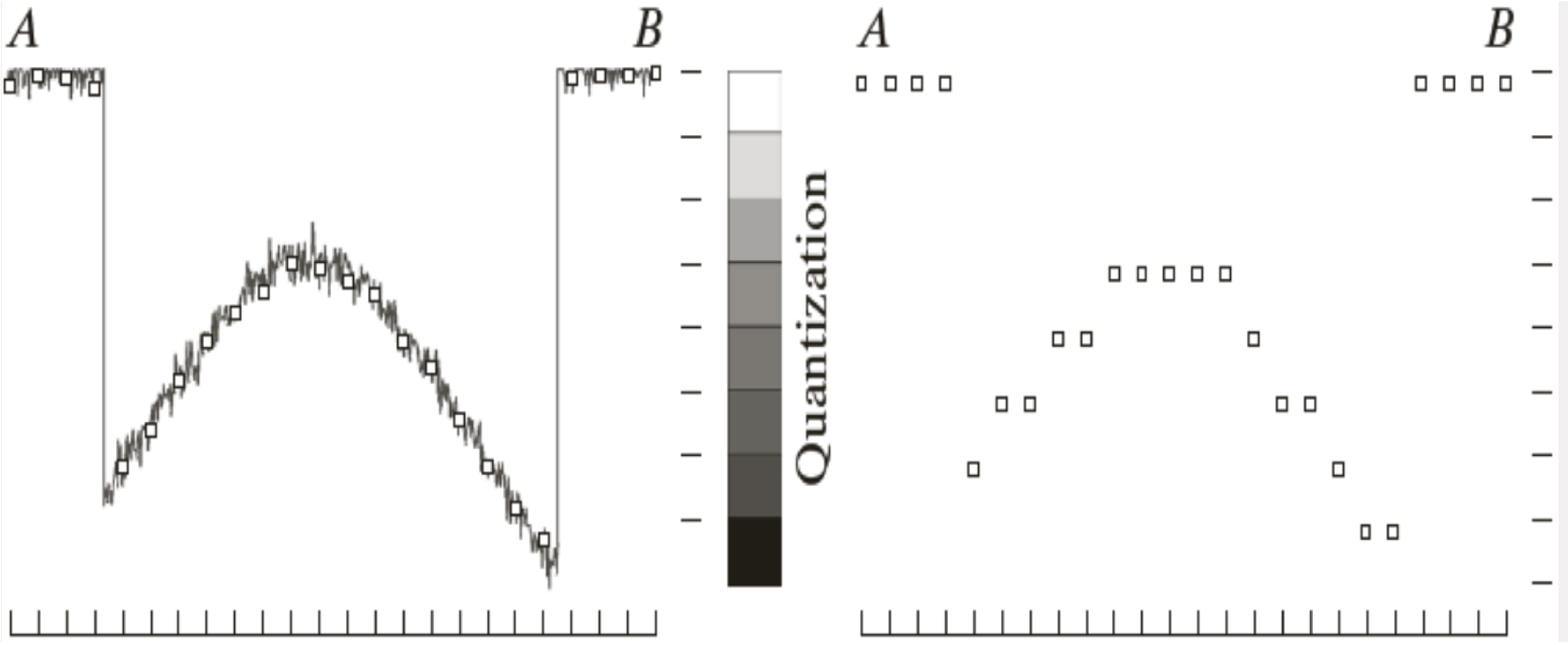
- **Sampling + Quantization**



Digital Image Acquisition

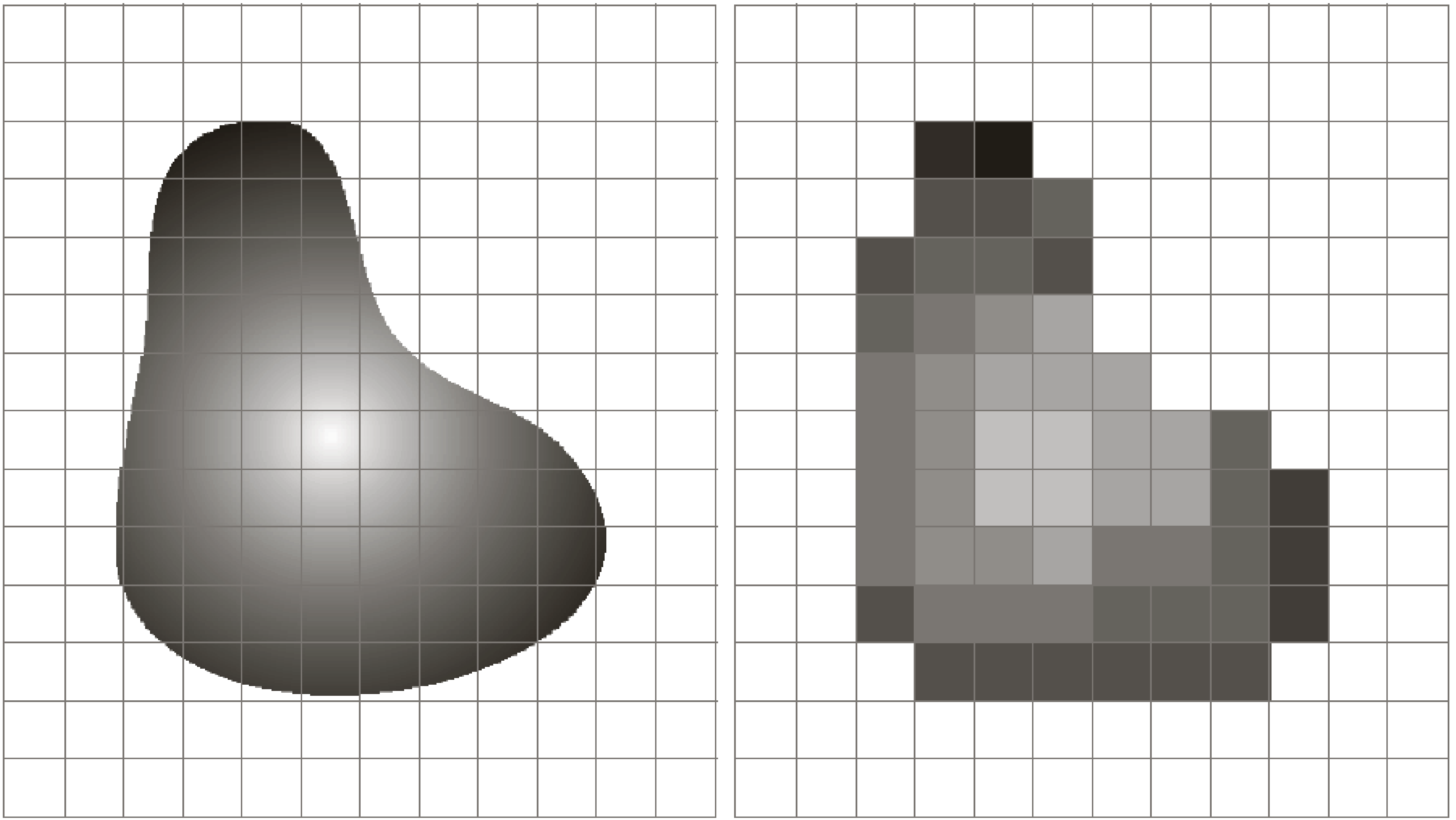
- Sampling (left) and Quantization (right)

Digital signal on 1 scan line



Digital Image Acquisition

- Continuous signal → Digital image (sample,quantize)

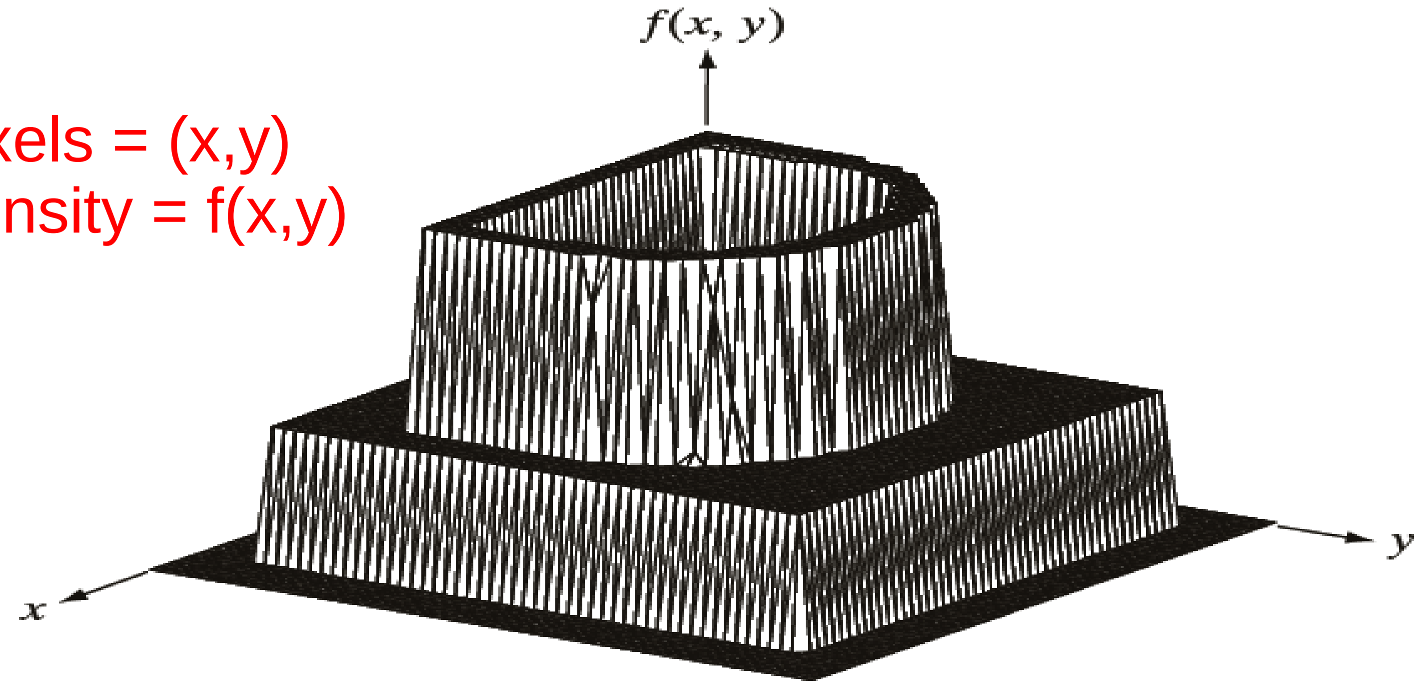


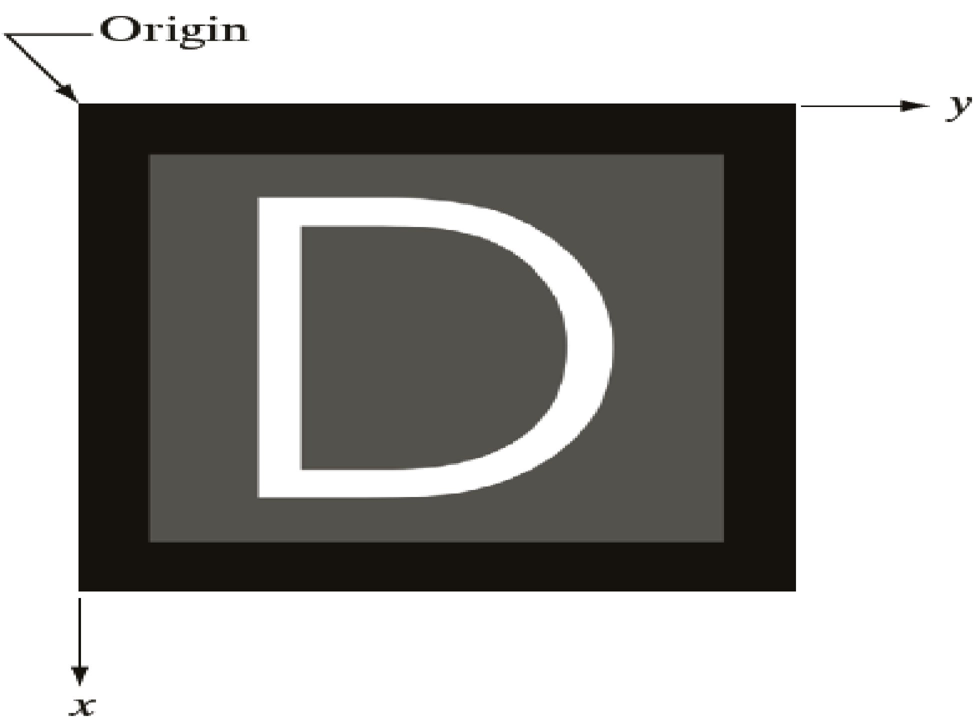
Digital Image Acquisition

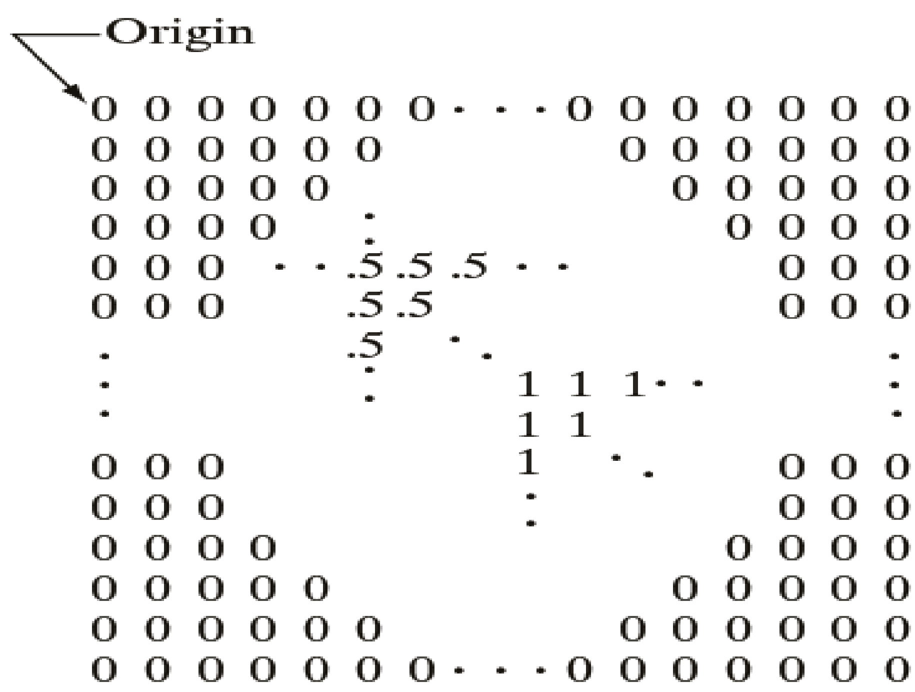
- Image storage: file size
  - Number of pixels in 2D image = M x N
  - Number of bits required to store each pixel value = L
  - Total number of bits required = M x N x L

Digital Image as a Function

Domain = pixels = (x,y)
Range = intensity = f(x,y)

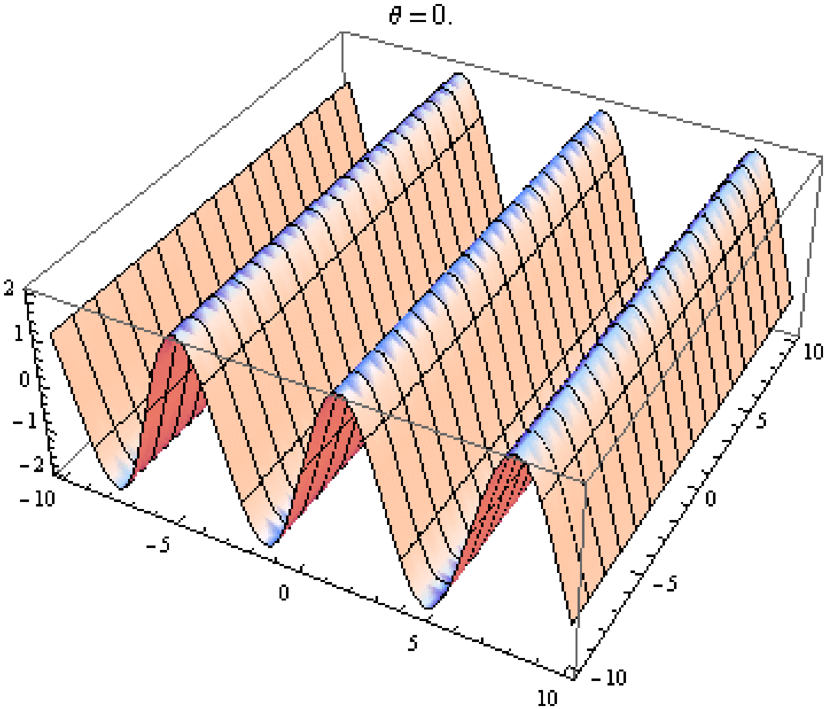




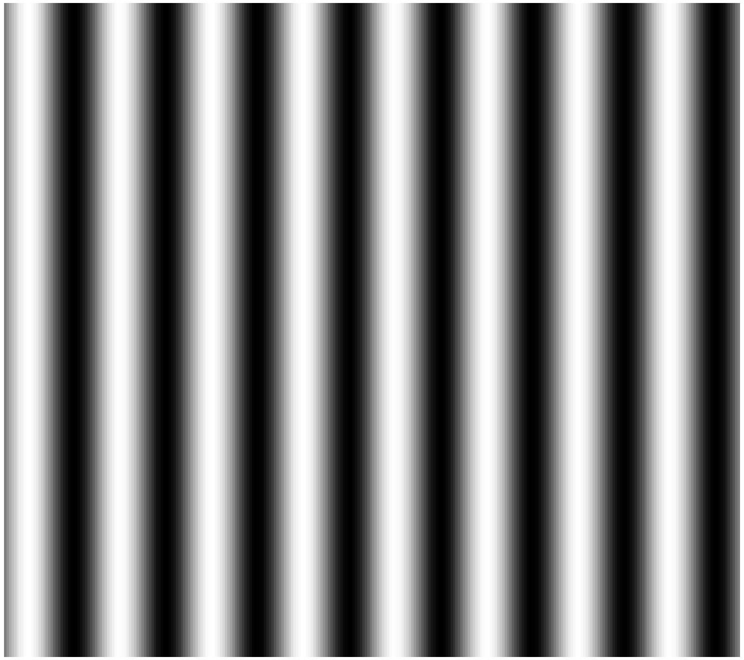


Digital Image as a Function

- Sinusoid function

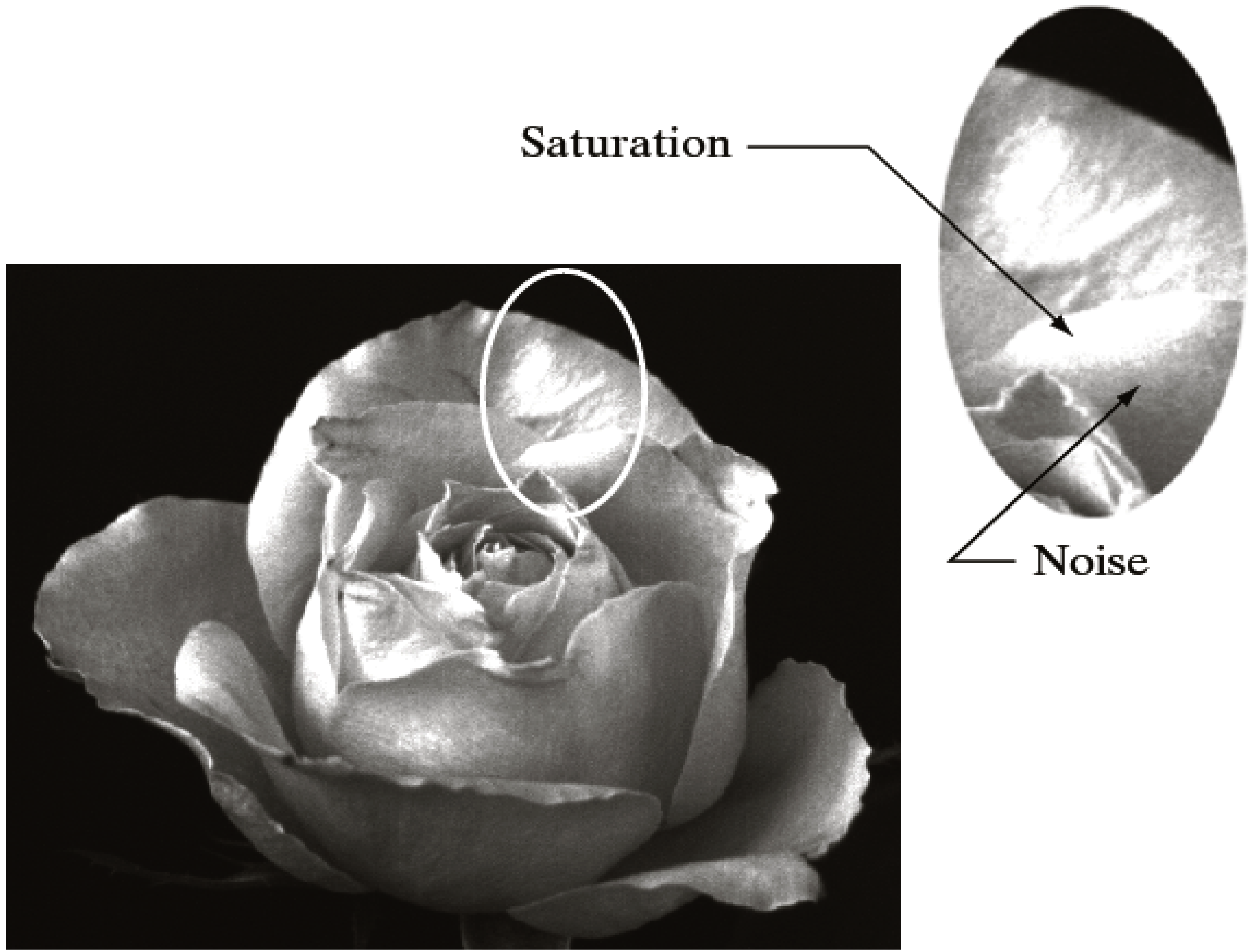


- Sinusoid function visualized as an image



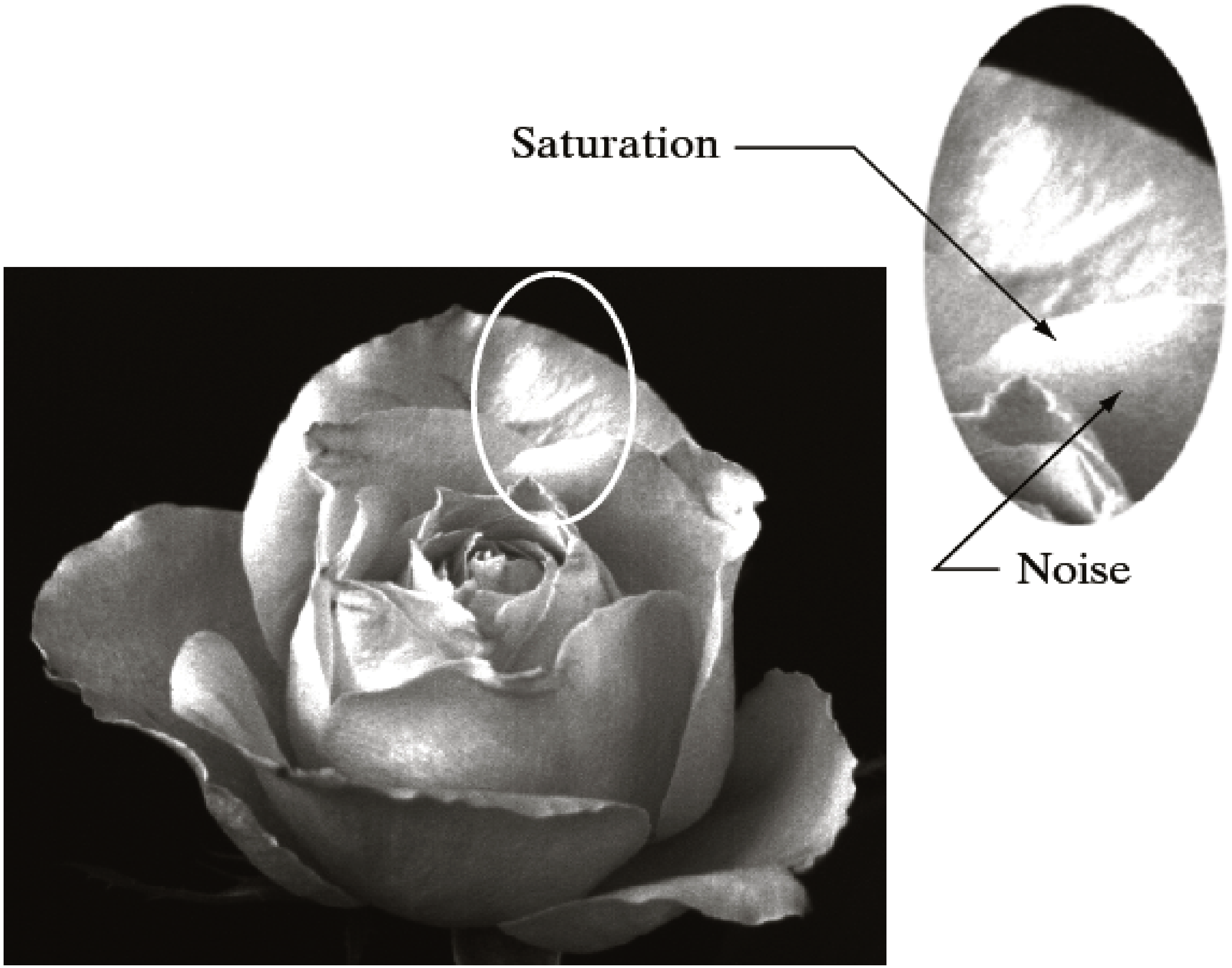
Digital Image

- An image exhibiting **saturation** and **noise**
  - **Saturation** = actual intensity > highest quantized intensity
    - Intensity gets clipped



Digital Image

- An image exhibiting **saturation** and **noise**
  - **Noise** = grainy texture
  - Noise can arise from:
    - Measurement errors
    - Imaging device properties
    - Physics underlying light-energy emission

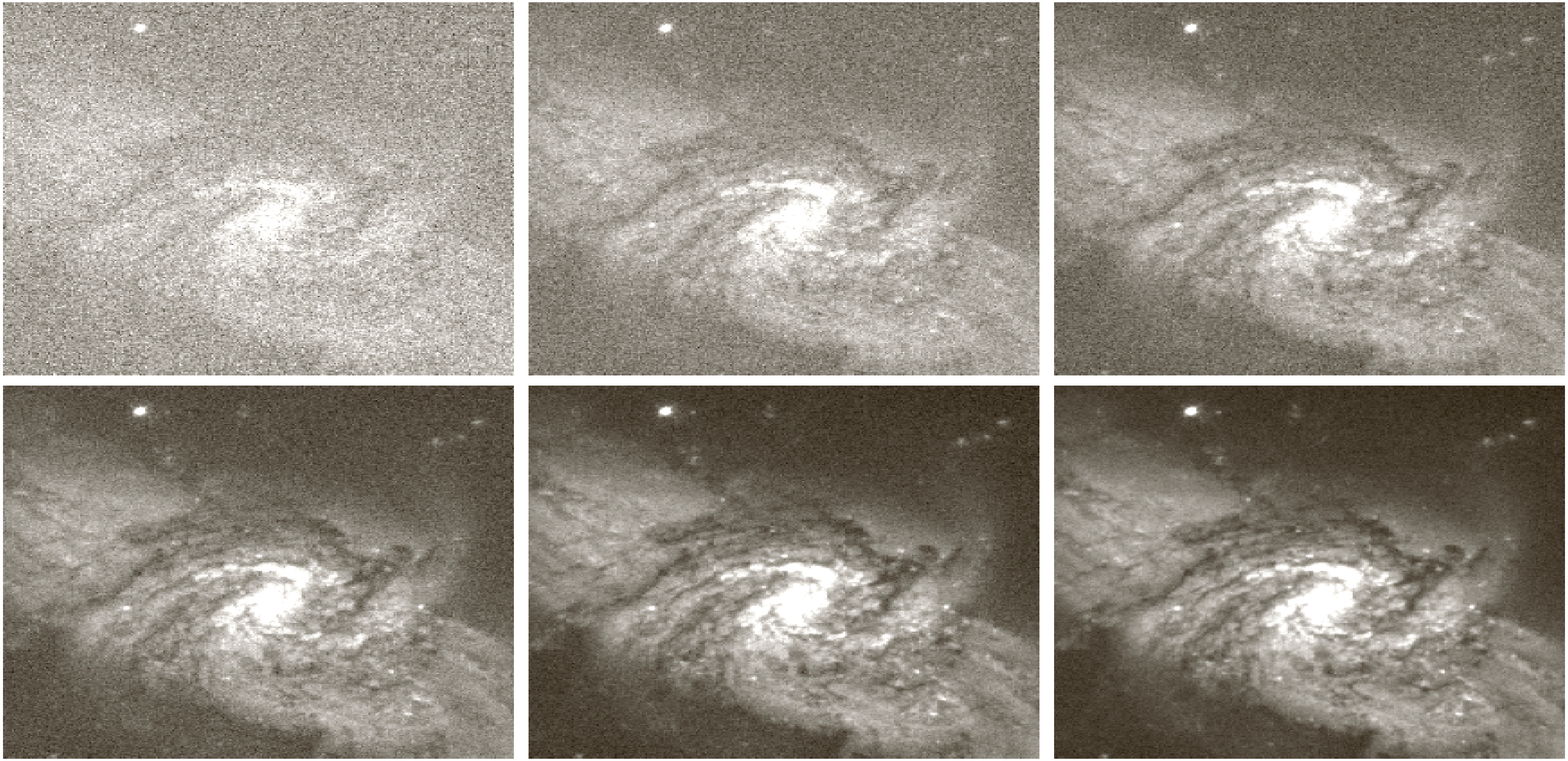


Digital Image

- Image noise
  - Low light intensity (weak signal) amplifies the effect of measurement errors (noise)

Digital Image

- Image noise
  - Can arise from random fluctuations in incoming signal



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.)

Digital Image

- Spatial **resolution**
  - More subtle concept
    - Depends on sampling (but it isn't the same concept)
    - Depends on process of image acquisition
      - e.g., focussing
  - **Measure of distance required between 2 lines (or points) to be distinguishable in the image**
  - Refers to number of **independent** intensities per unit length
    - Blurring artificially increases correlation between pixels

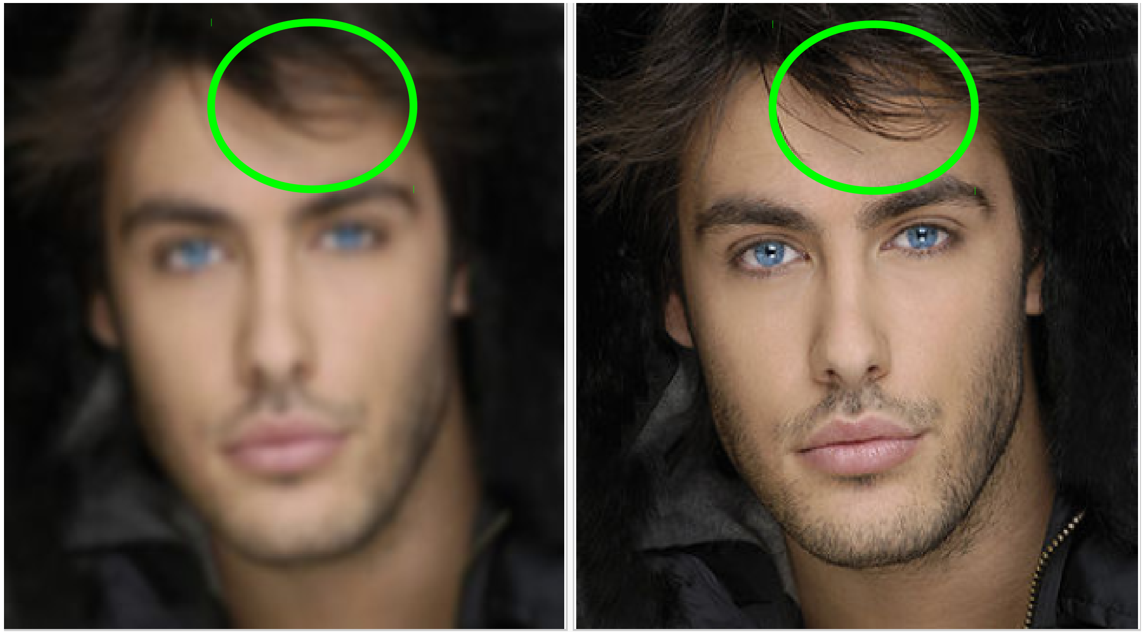


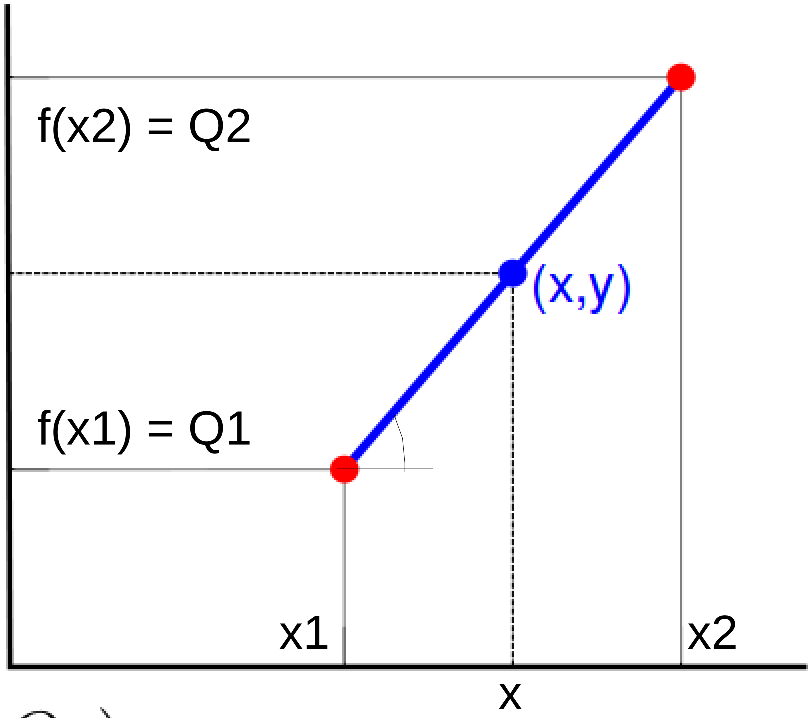
Image at left has a higher *pixel count* than the one to the right, but is still of worse spatial resolution.

Digital Image

- Zooming In = Oversampling
  - Pixel replication
    - Can increase the size of image an **integer** number of times
    - e.g., to replicate image size by 2x along each dimension: replicate rows, then replicate columns
  - Interpolation
    - Linear (1D)
      - Bilinear (2D)
      - Trilinear (3D)
    - Nearest neighbor

Digital Image

- Linear interpolation
  - Consider function $f(x)$
  - Given: $f(x_1) = Q_1,\ f(x_2) = Q_2$
  - Given: $x \in [x_1, x_2]$
  - Guess: $f(x)$



  - Draw a line joining (x_1, Q_1) and (x_2, Q_2)

$$f(x) = Q_1 \frac{x_2 - x}{x_2 - x_1} + Q_2 \frac{x - x_1}{x_2 - x_1}$$

f(x) is linear function of 'x' = polynomial function of degree 0 or 1. Don't confuse with linear 'map'.

Proof:

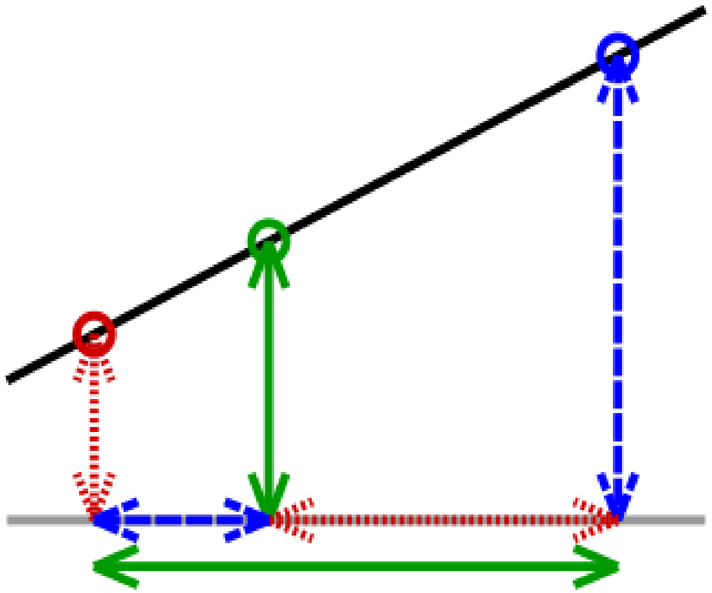
Equation of the line.

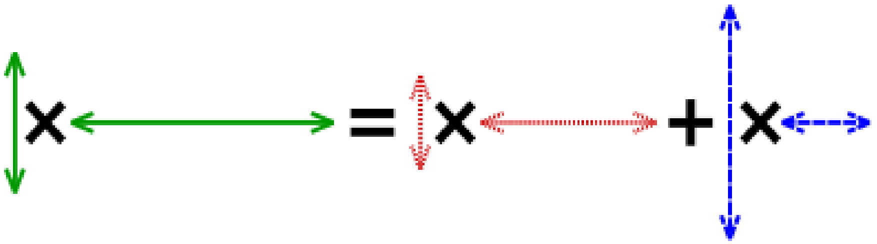
$$f(x) = Q_1 + (x - x_1)\tan(\theta) = Q_1 + (x - x_1)\frac{Q_2 - Q_1}{x_2 - x_1}$$

Simplify.

Digital Image

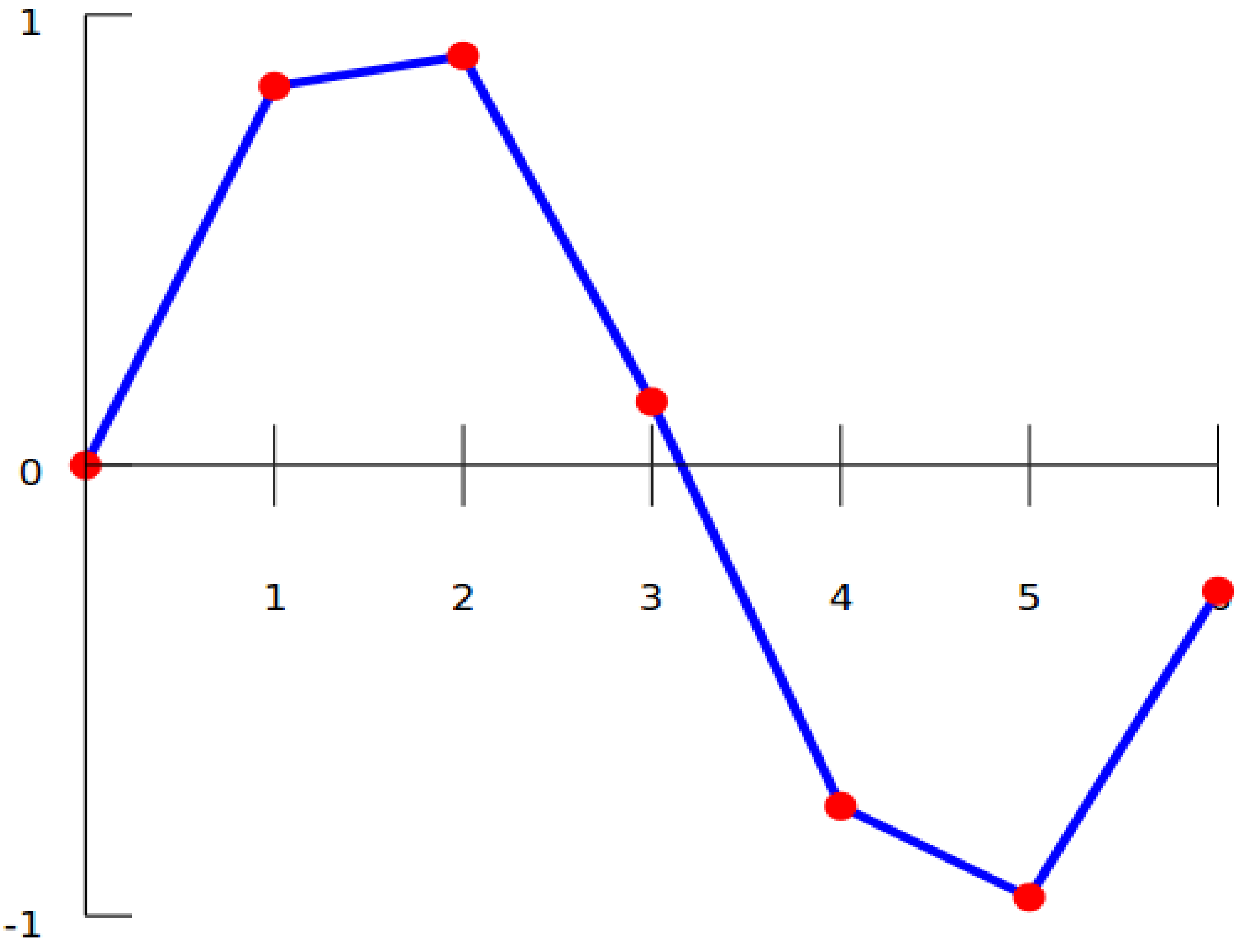
- Linear interpolation
  - Linearly-interpolated value at x is a linear function of x
    - Definition of linear function :
      f(x) = ax + b ;
      where a,b are constants
  - Q1 gets weighted by the fraction of length from the opposite end of x1
  - “Convex combination” of pixel intensities at the 2 ends
    - Interpolated intensity guaranteed to be between the intensities at the 2 ends





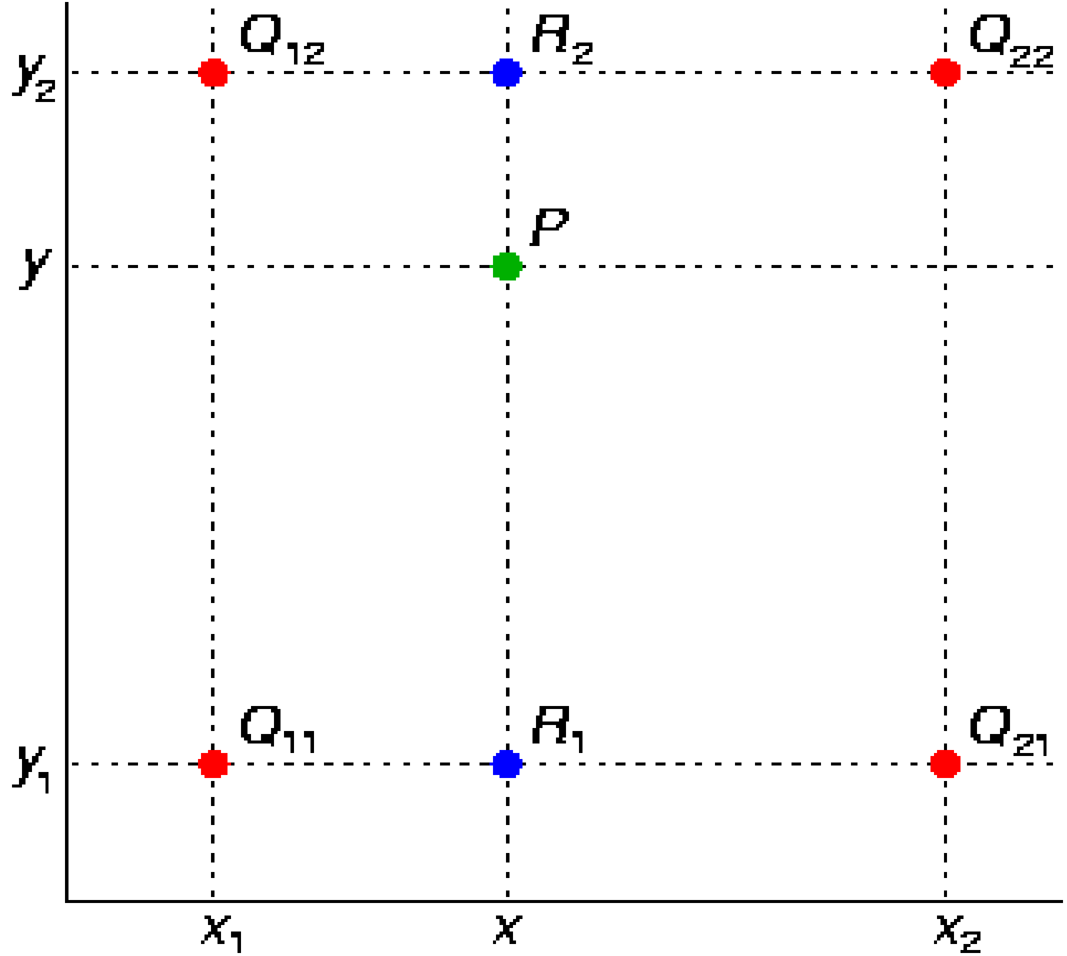
Digital Image

- Linear interpolation



Digital Image

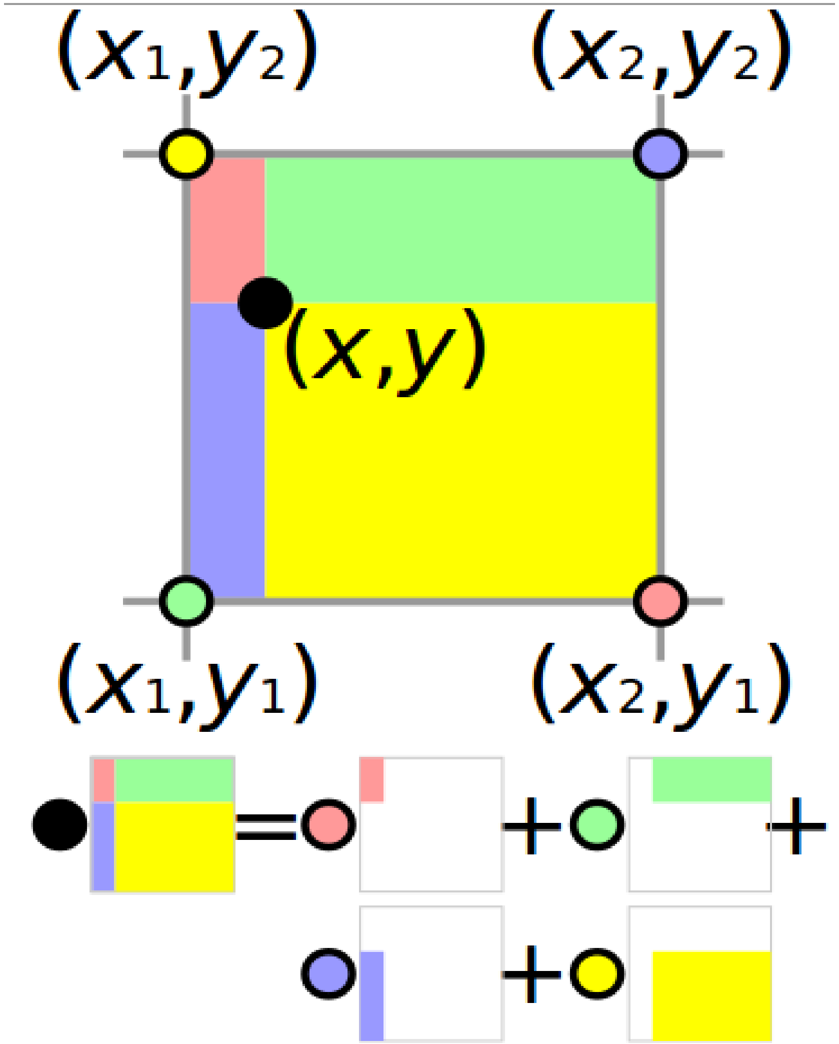
- Bilinear interpolation



  - Given: $f(x_1, y_1) = Q_{11}$, $f(x_1, y_2) = Q_{12}$, $f(x_2, y_1) = Q_{21}$, $f(x_2, y_2) = Q_{22}$
  - Find: $f(x, y)$ for $x \in [x_1, y_2]$ and $y \in [y_1, y_2]$
  - 2 linear interpolations along X axis ...
  - 1 linear interpolation along Y axis ...

$$f(x, y) = Q_{11} \frac{(x_2 - x)(y_2 - y)}{(x_2 - x_1)(y_2 - y_1)} + \dots$$

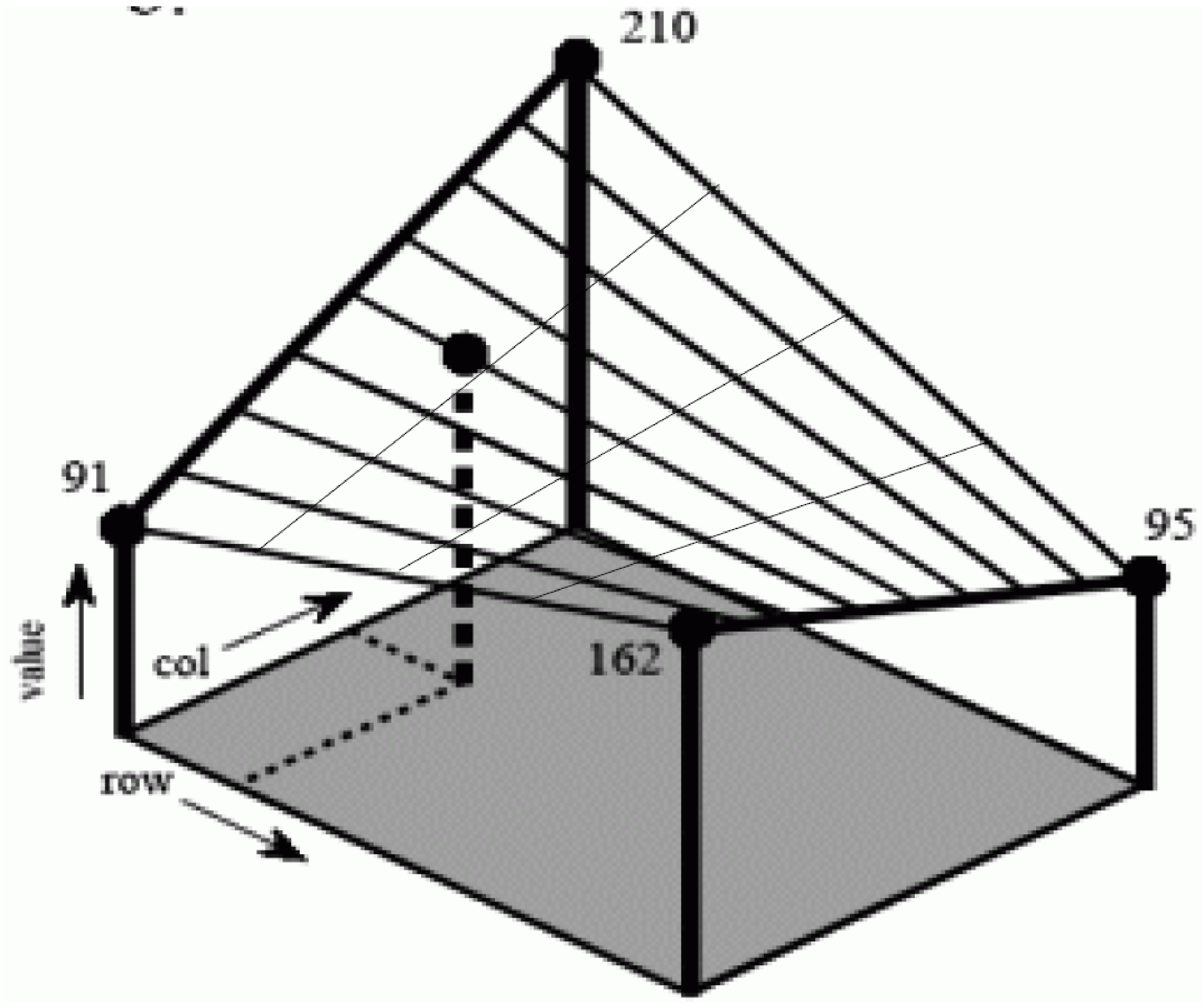
Digital Image



- Bilinear interpolation
  - Qij gets weighted by the fraction of area
    from the opposite end of xij
  - Bilinearly-interpolated value at (x, y) is:
    - a linear function of x alone
    - a linear function of y alone
    - but NOT x, y together
  - Bilinearly-interpolated value at (x, y)
    → linear function of Qij
  - "Convex combination" of pixel intensities Qij at corners
    - Interpolated intensity guaranteed to be between corner intensities

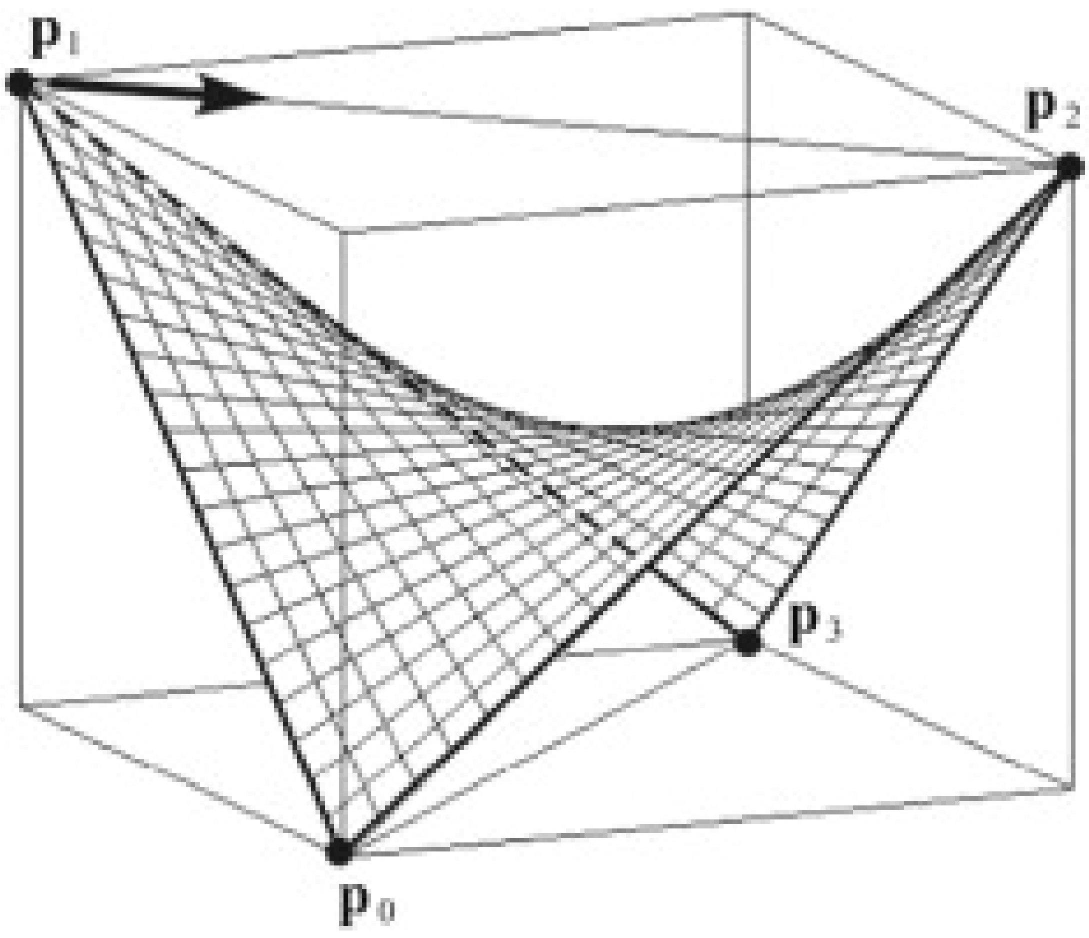
Digital Image

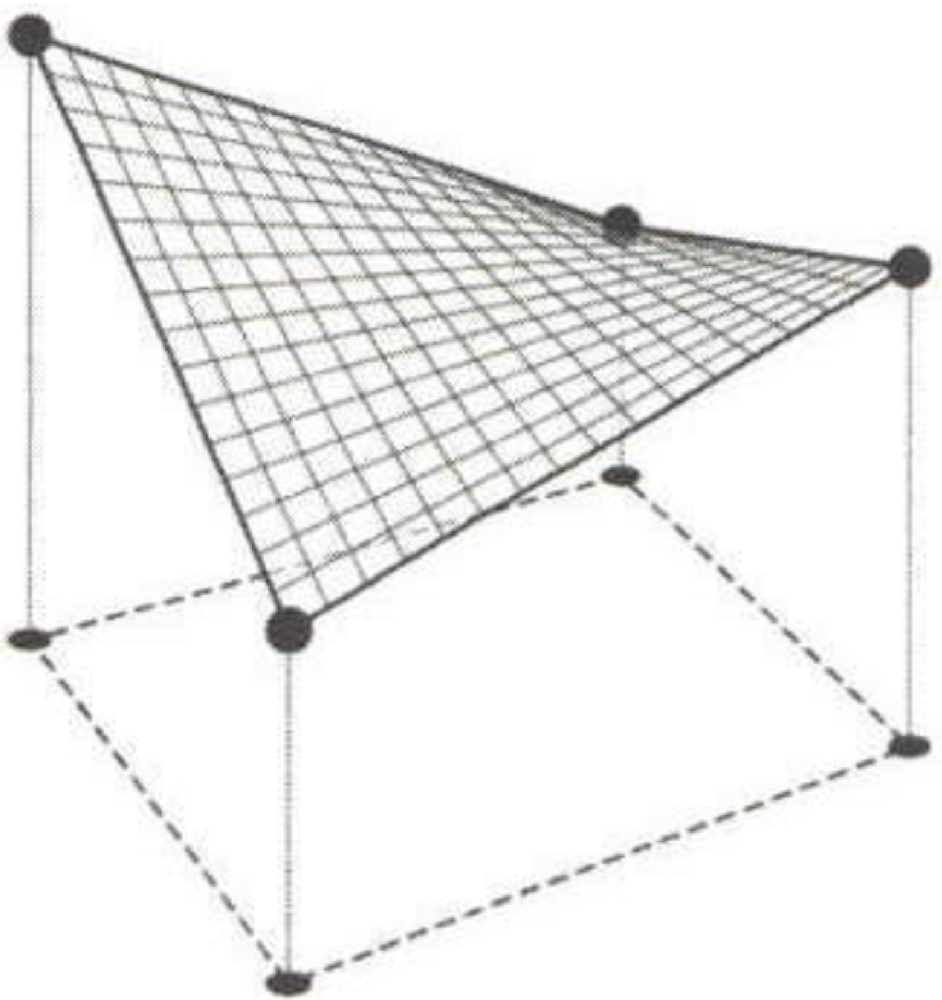
- Bilinear interpolation



Digital Image

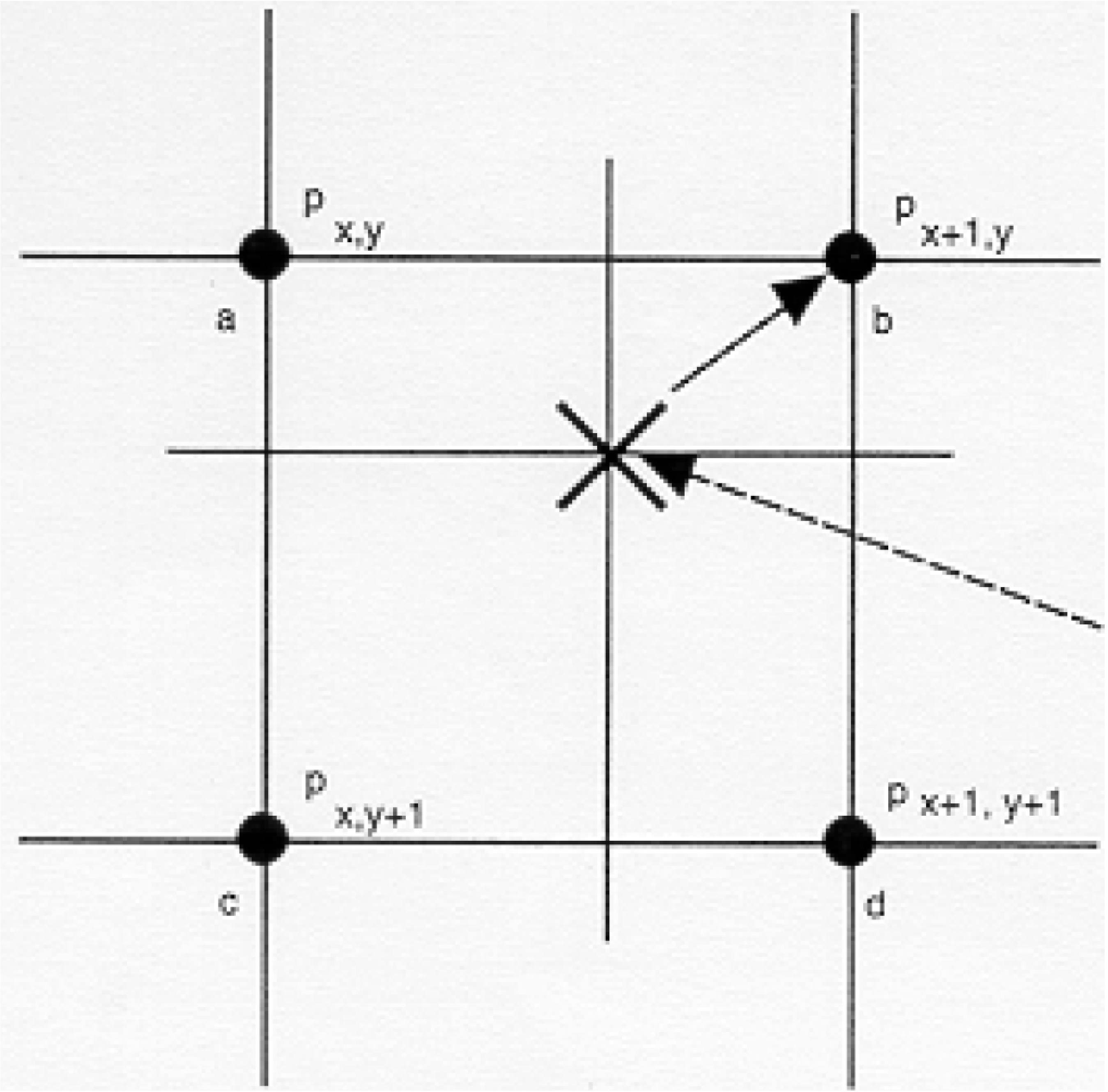
- Bilinear interpolation



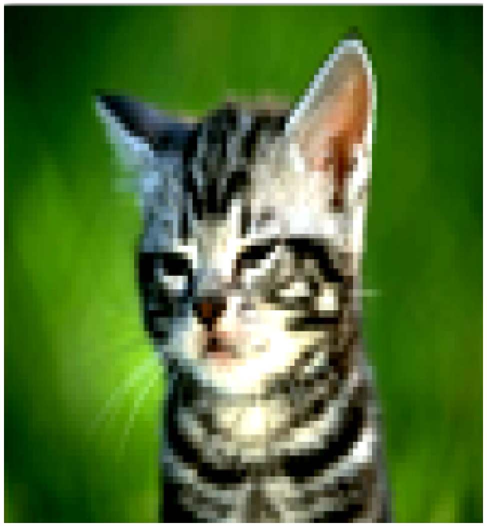


Digital Image

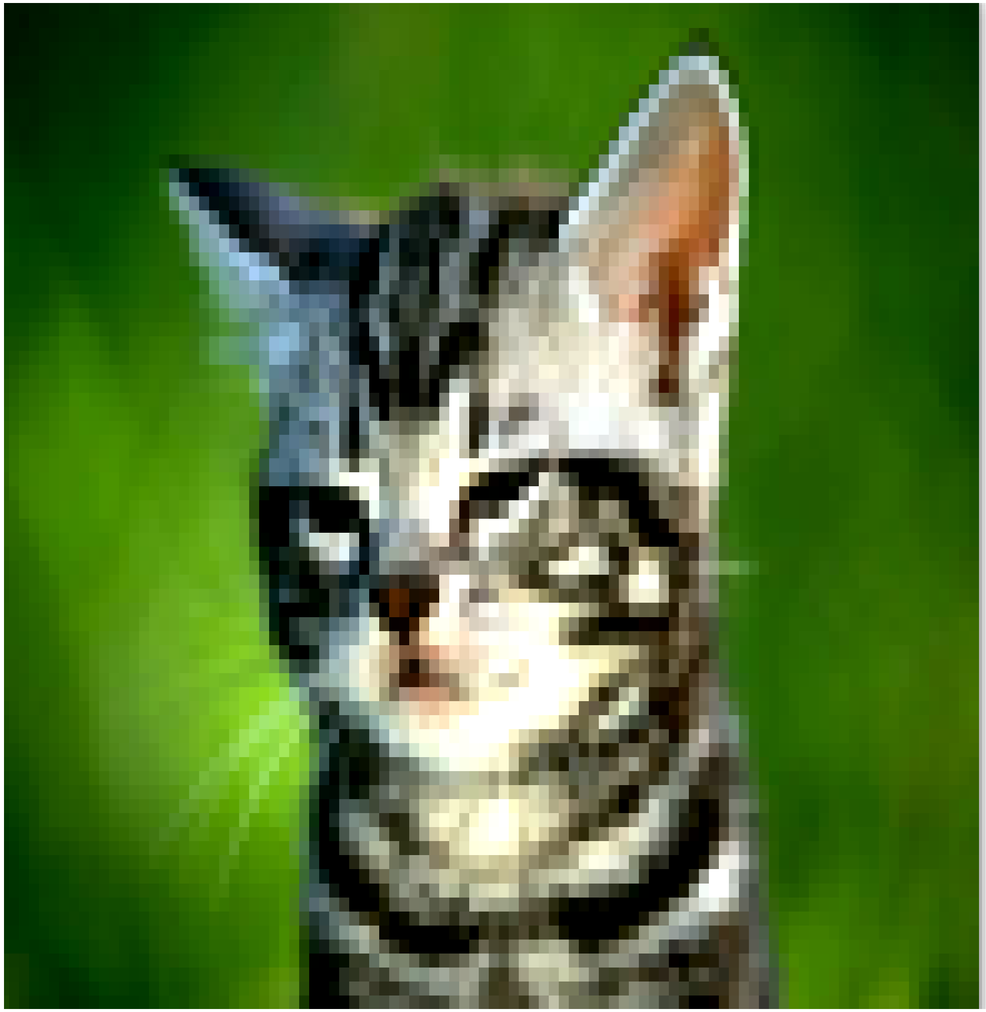
- Nearest neighbor interpolation



Digital Image

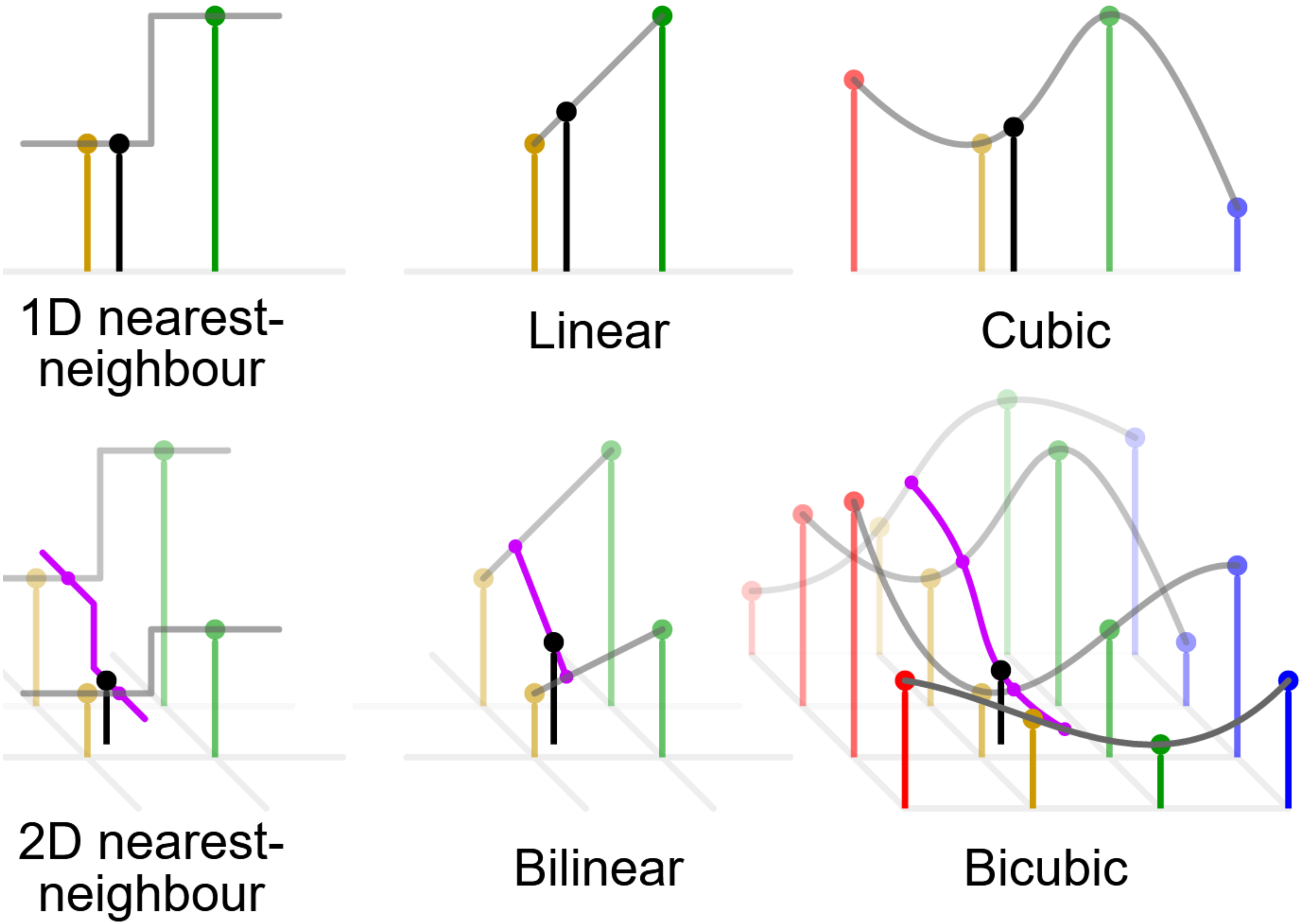


- Interpolation
  - Nearest neighbor vs. Bilinear
  - 2X along each dimension



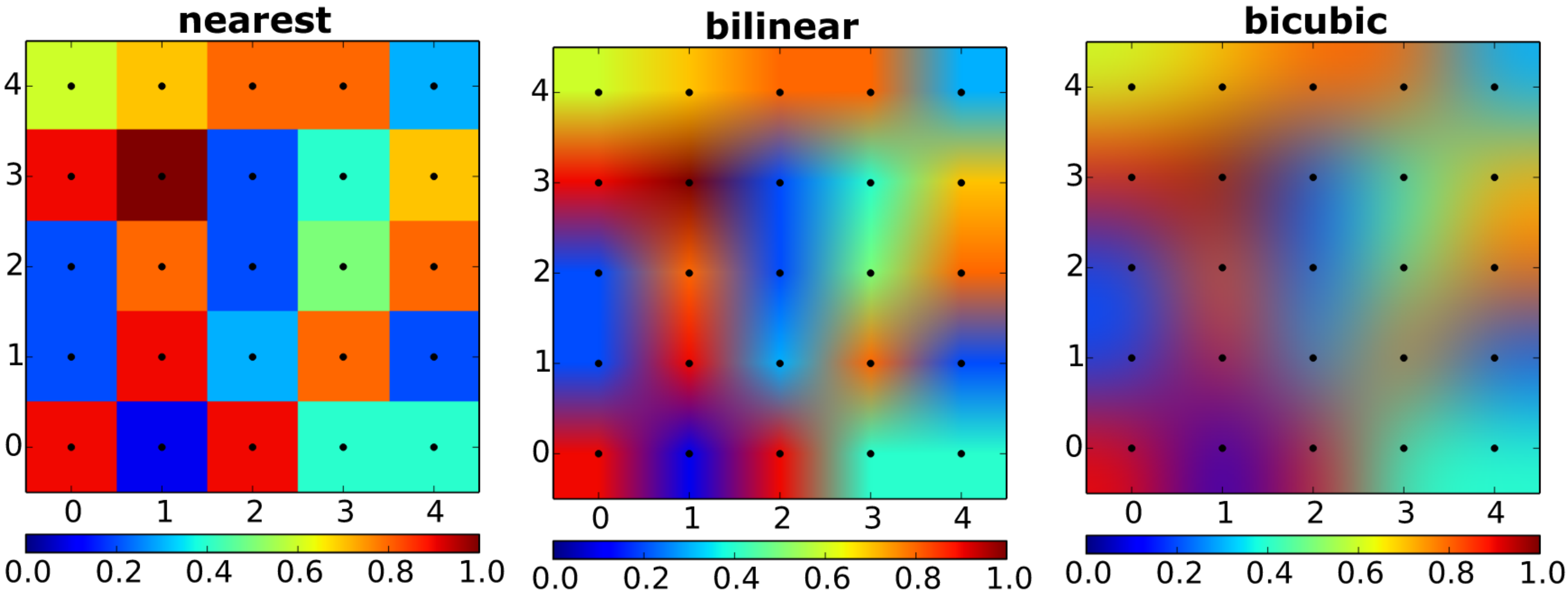
Digital Image

- Interpolation



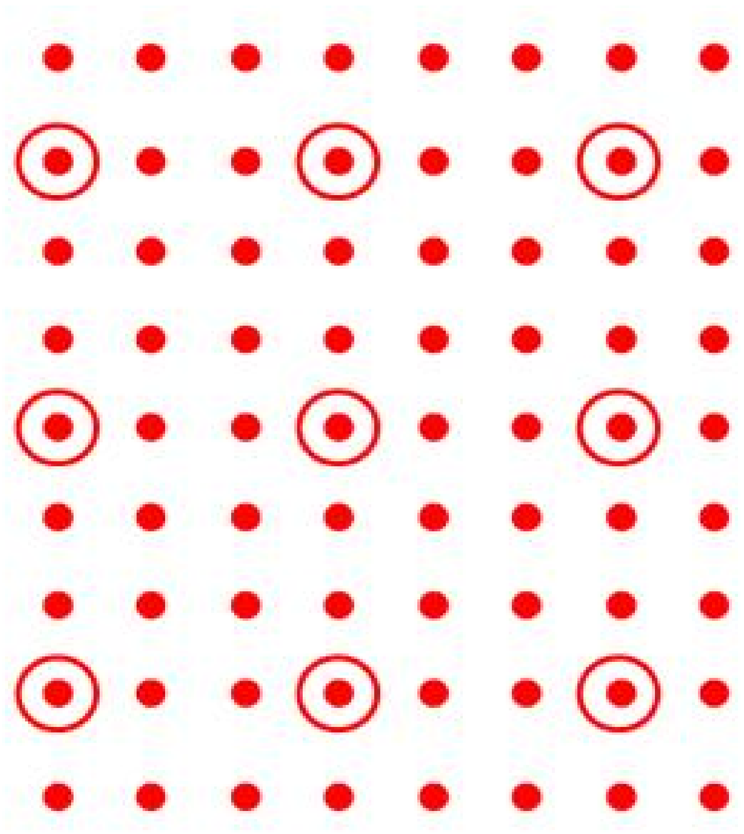
Digital Image

- Interpolation



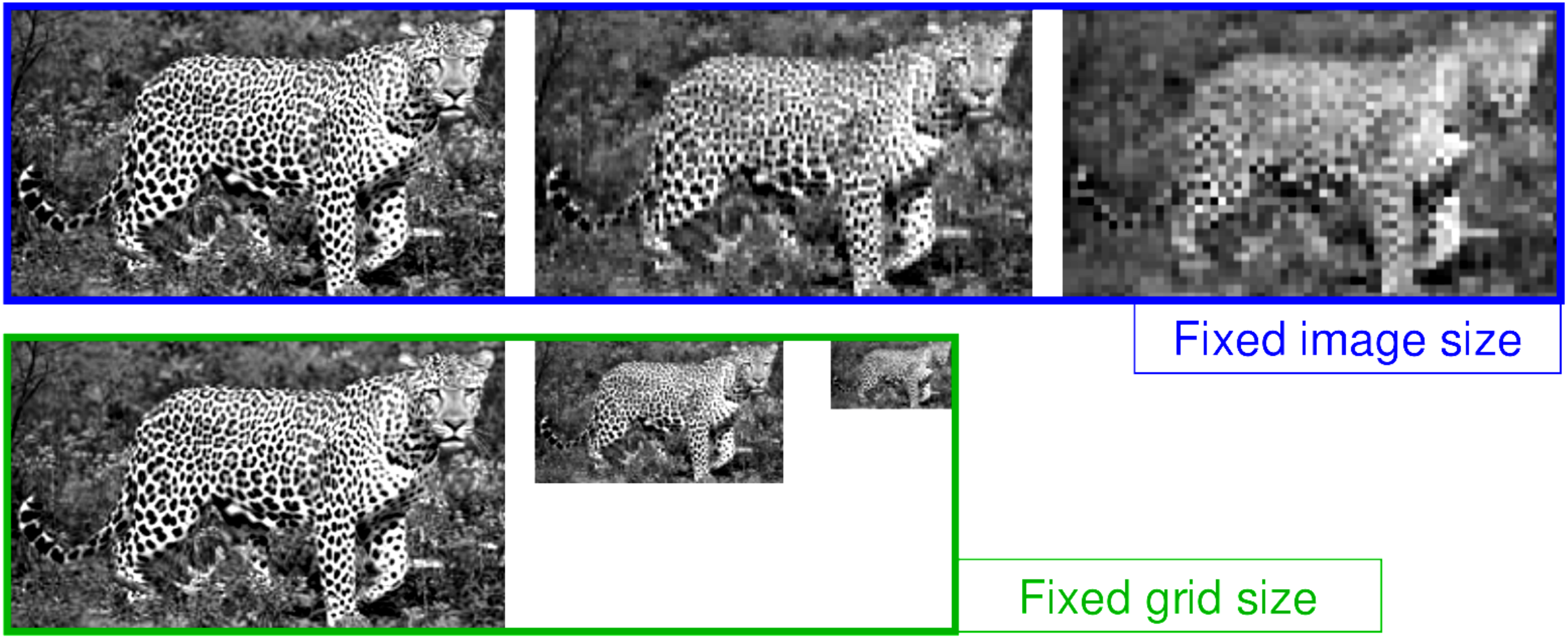
Digital Image

- Shrinking = undersampling
  - e.g., select every n-th pixel in a dimension



Digital Image

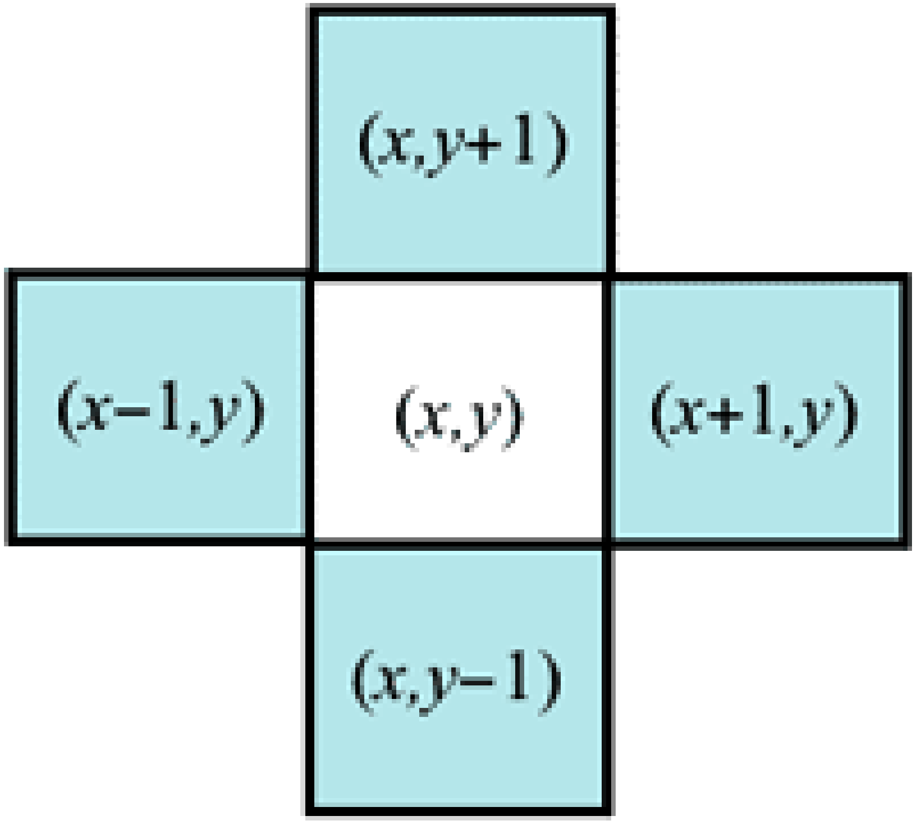
- Shrinking = undersampling



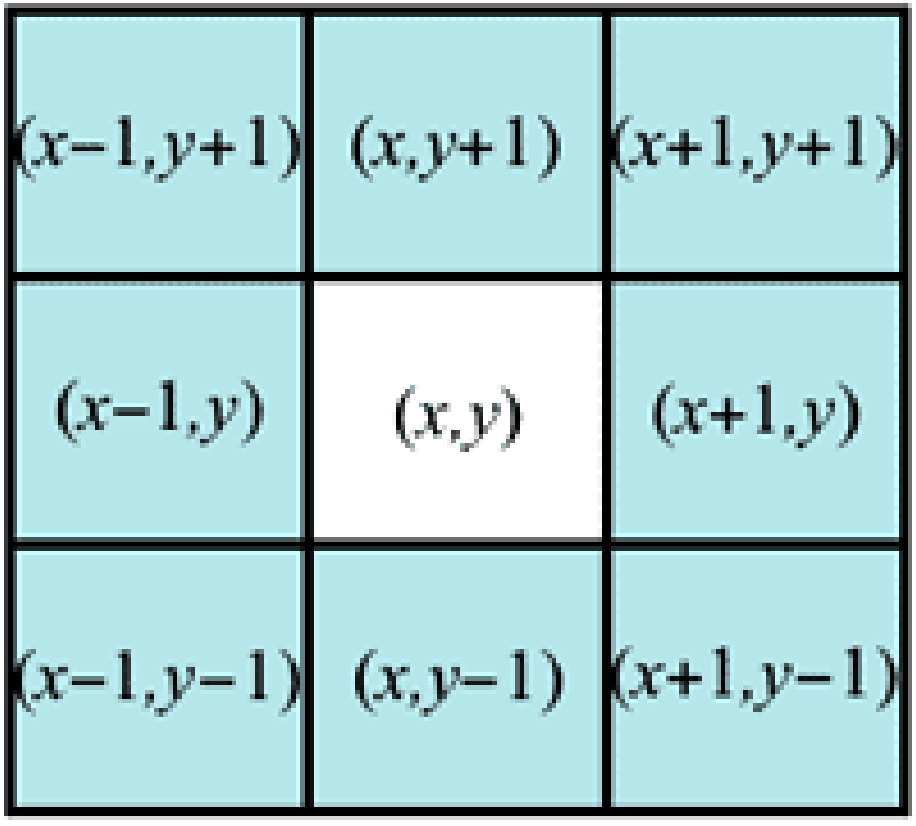
http://www.inf.tudresden.de/content/institutes/ki/is/VORLESUNGEN/BV_0708/ImageProcessing02.pdf

Digital Image

- **Neighborhood**
  - 4 **neighbors**
  - 8 neighbors



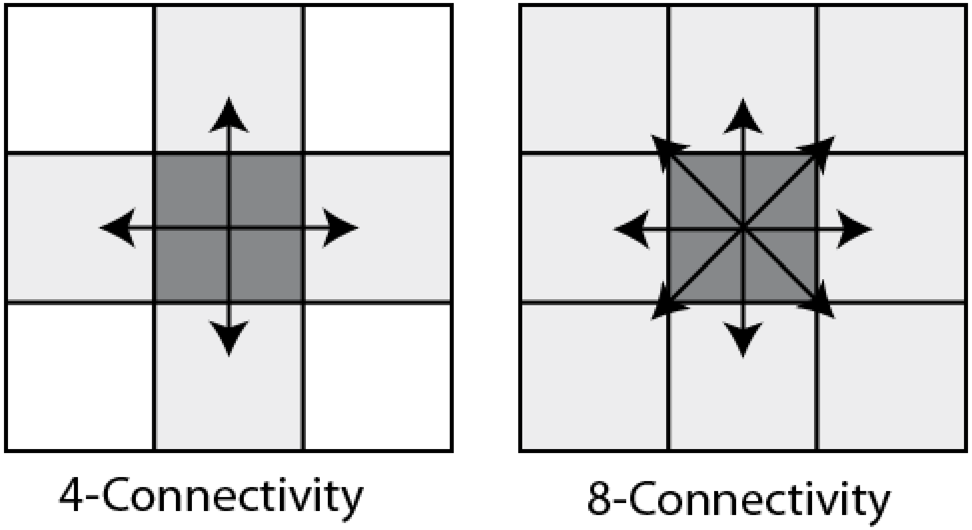
4-neighbourhood



8-neighbourhood

Digital Image

- Neighborhood connectivity
  - 4 connectivity / adjacency
  - 8 connectivity / adjacency



- **Connected path** between pixels (x,y) and (s,t)
  - Sequence of pixels $(a_1,b_1), (a_2,b_2), \ldots, (a_n,b_n)$ such that:

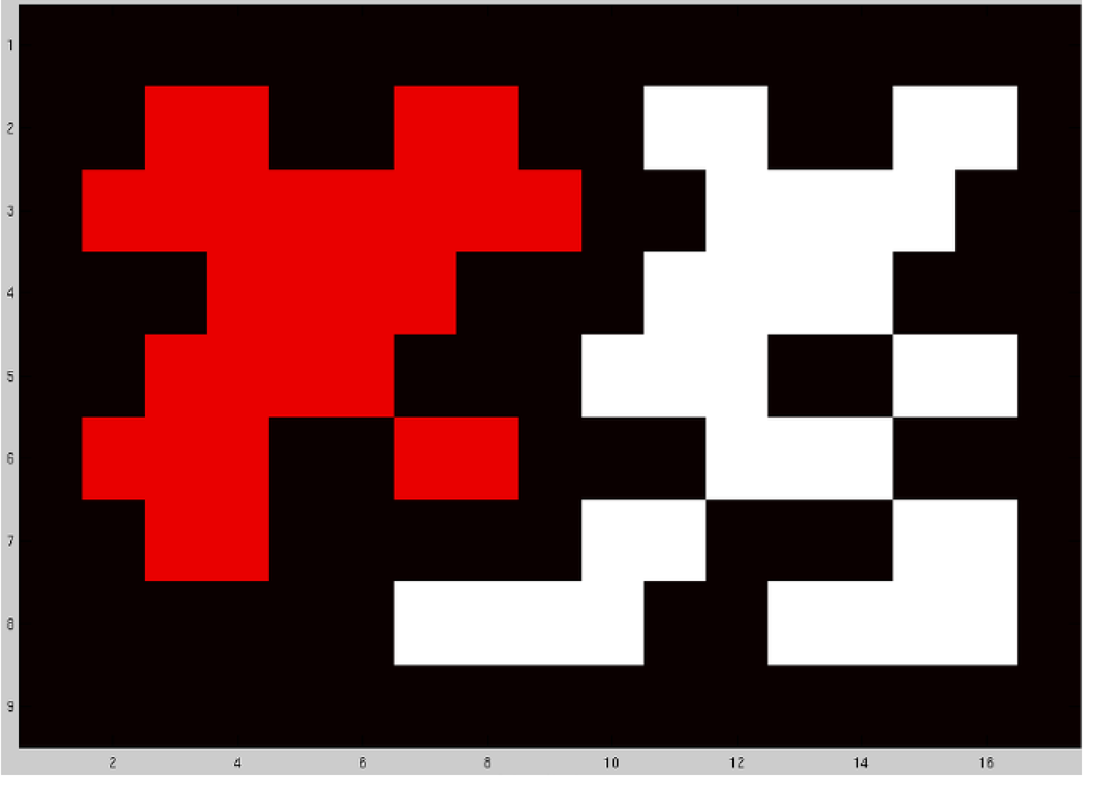
    (1) $(a_1,b_1) = (x,y)$

    (2) $(a_n,b_n) = (s,t)$

    (3) (a_{i-1},b_{i-1}) and (a_i,b_i) are **neighbors**, for i=2,...,n

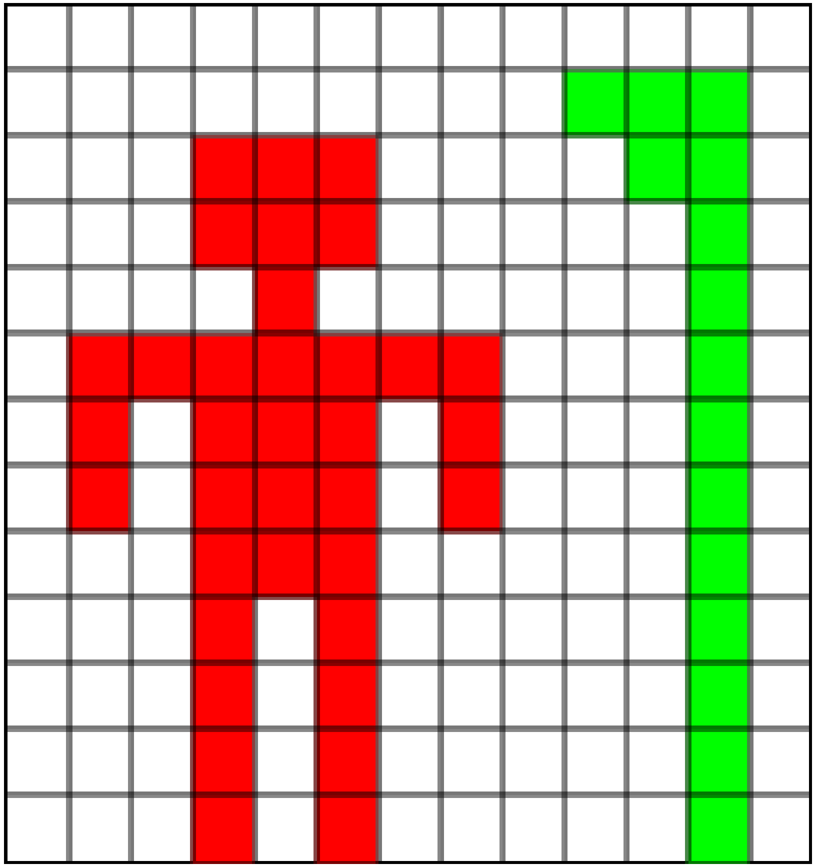
Digital Image

- **Connected subset** R
  - A set of pixels such that there exists a connected path between any 2 pixels within R,
    such that the path consists entirely of pixels within R
  - A connected subset is called a **region**
  - Is the set of red pixels
    a connected subset
    assuming
    4-neighbor connectivity ?



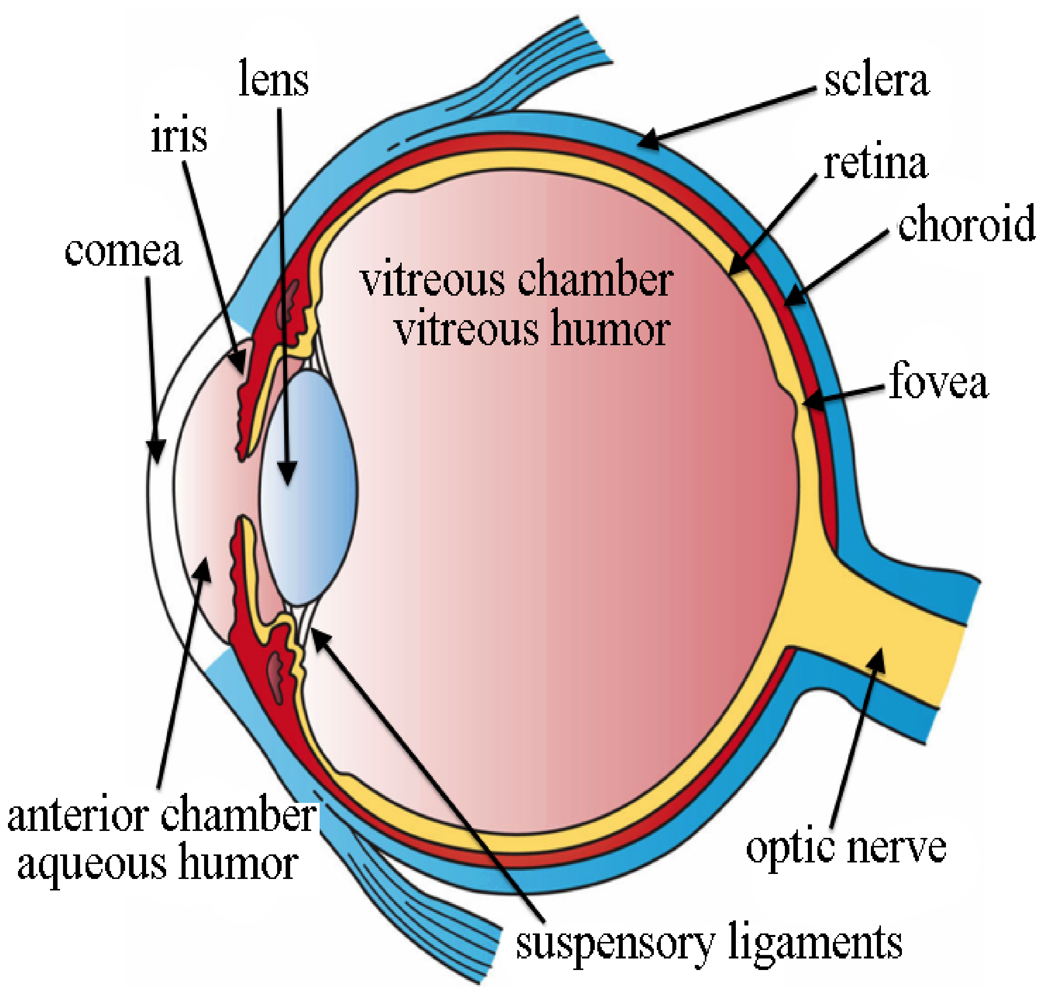
Digital Image

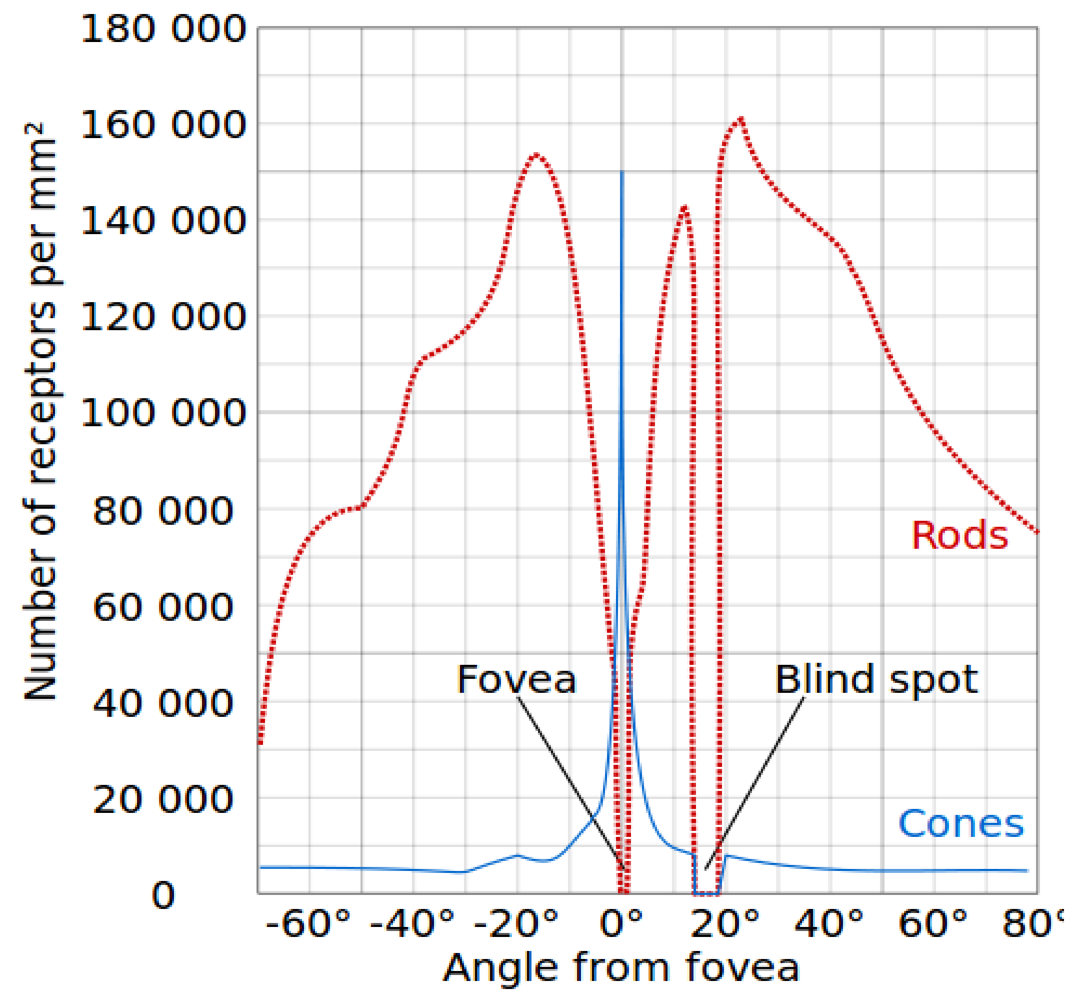
- **Boundary** of a region R
  - Set of pixels within R such that each pixel has a neighbor that is NOT in R
  - Which pixels in the green region are boundary pixels ?
    - Assuming 8 connectivity ?
    - Assuming 4 connectivity ?
  - What about the red region ?



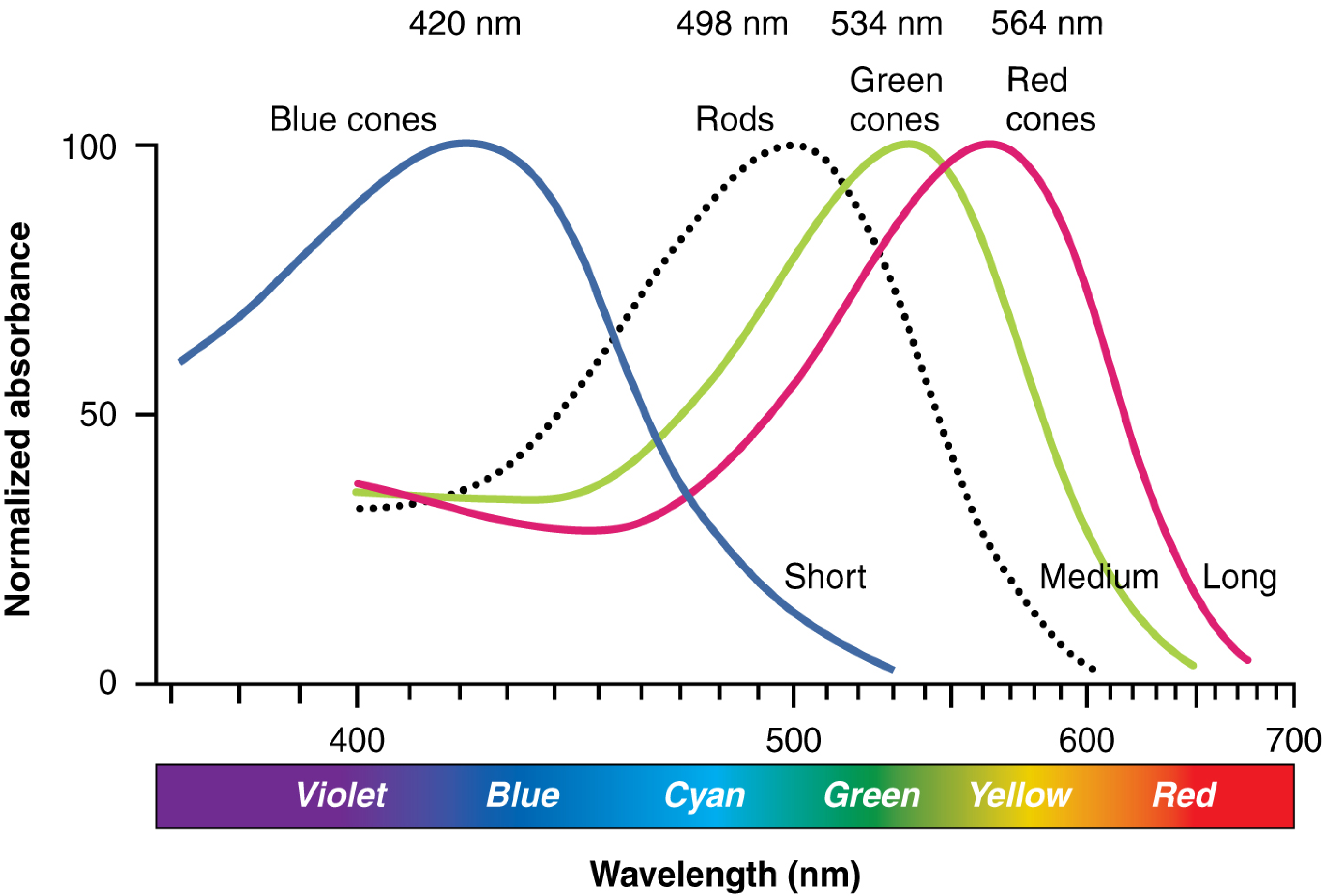
Human Visual System

- Cones → Color vision, visual acuity
- Rods → Low-light vision, more sensitive than cones to intensity but NOT color





Human Visual System



Human Visual System

- Distribution of cone cells in fovea
  - Normal person Color-Blind person

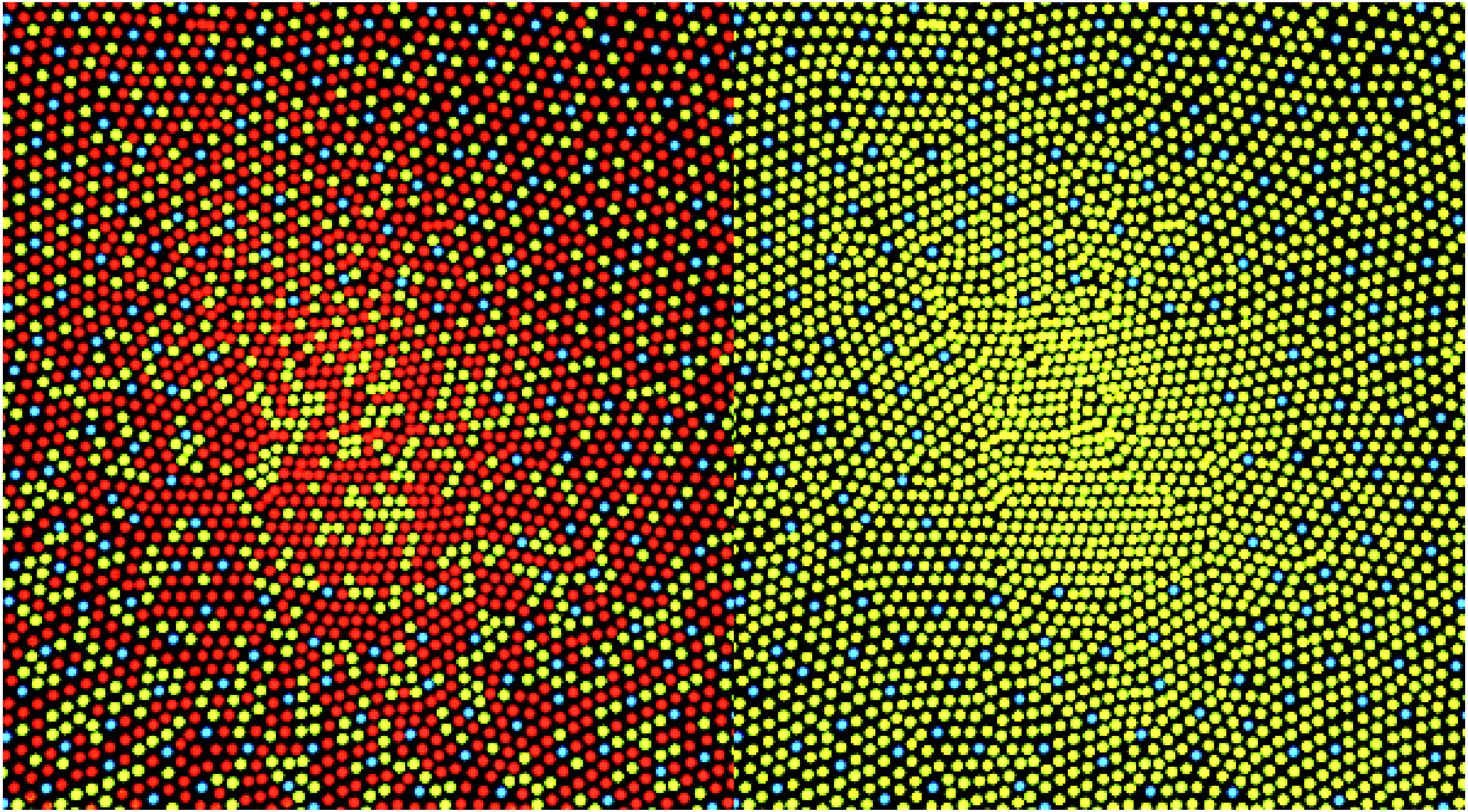


Image Perception

- Optical illusions
  - **Mach band** effect
    - Perceived intensity NOT a simple function of actual intensity
  - Due to post-processing of visual signals by our visual system

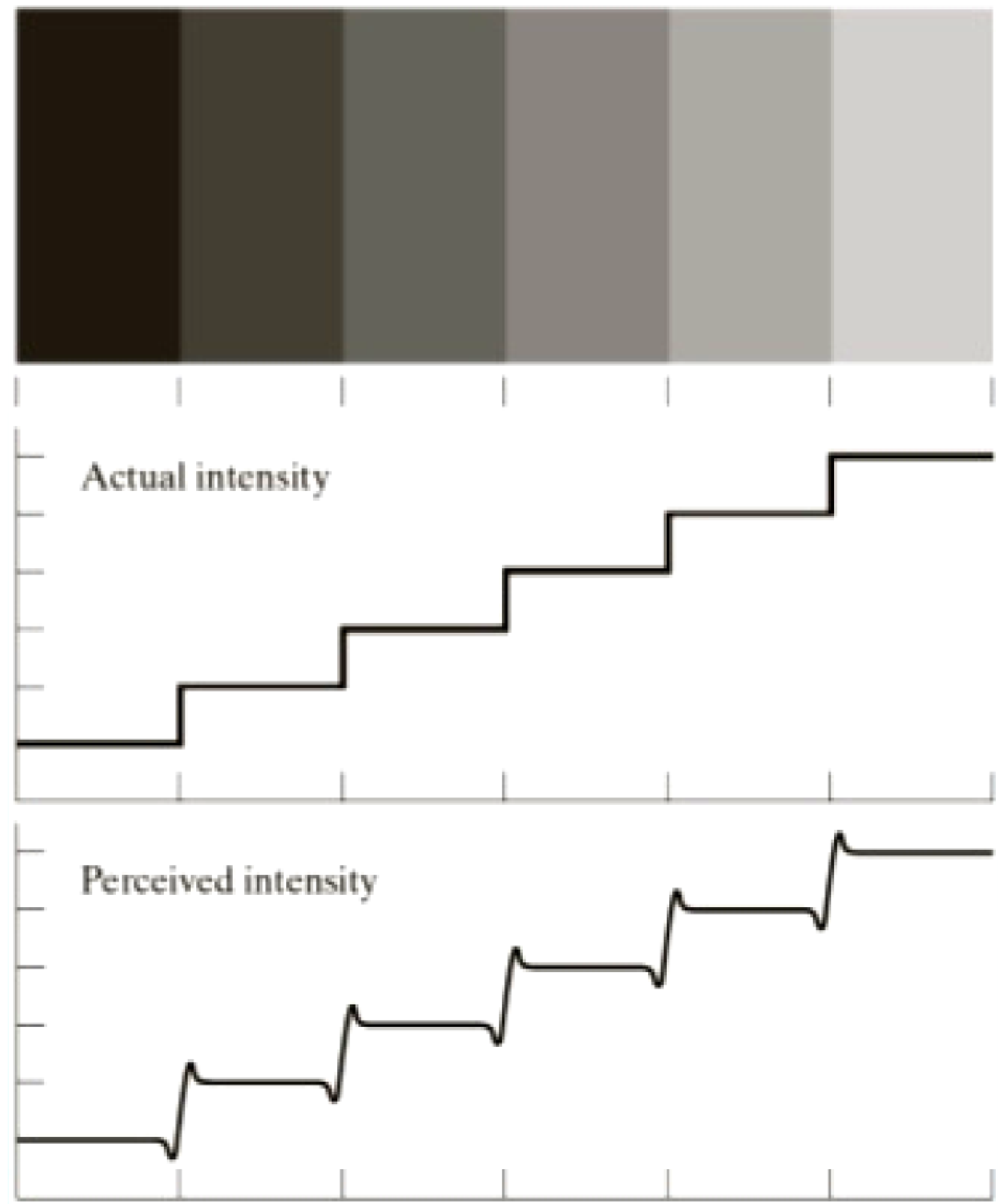


Image Perception

- Optical illusions
  - **Simultaneous contrast**

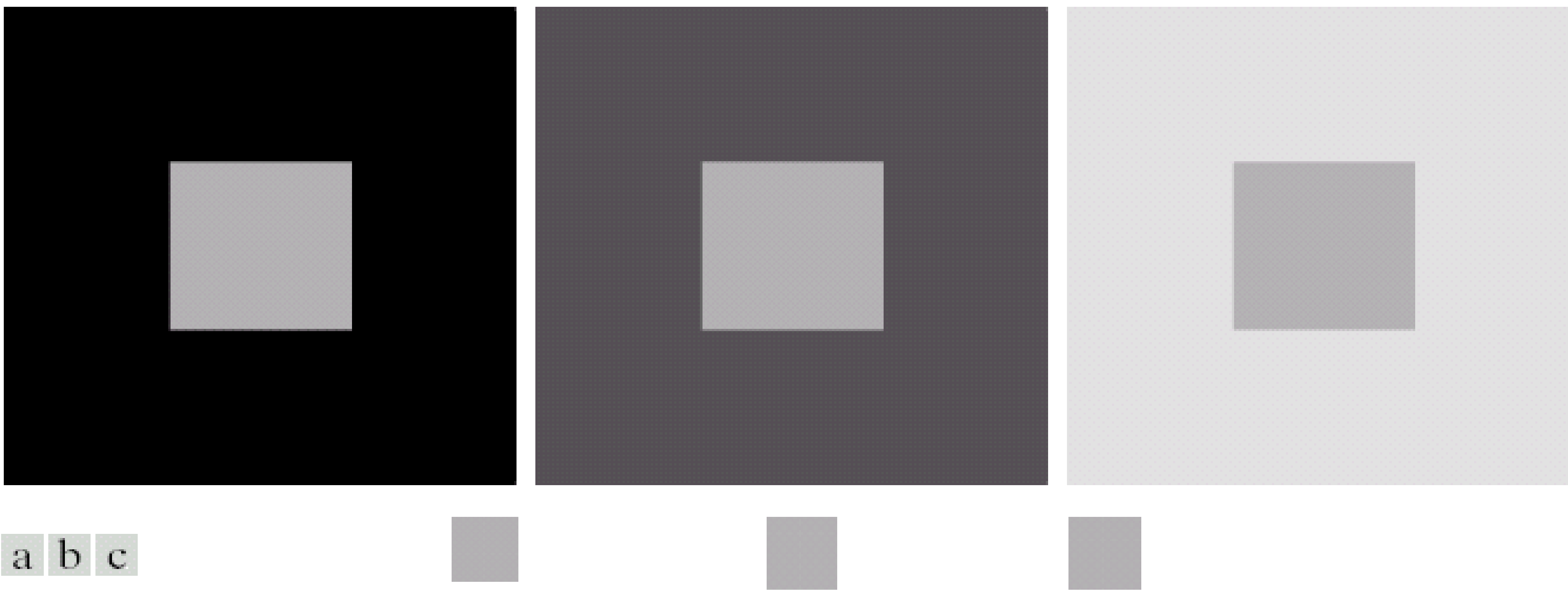
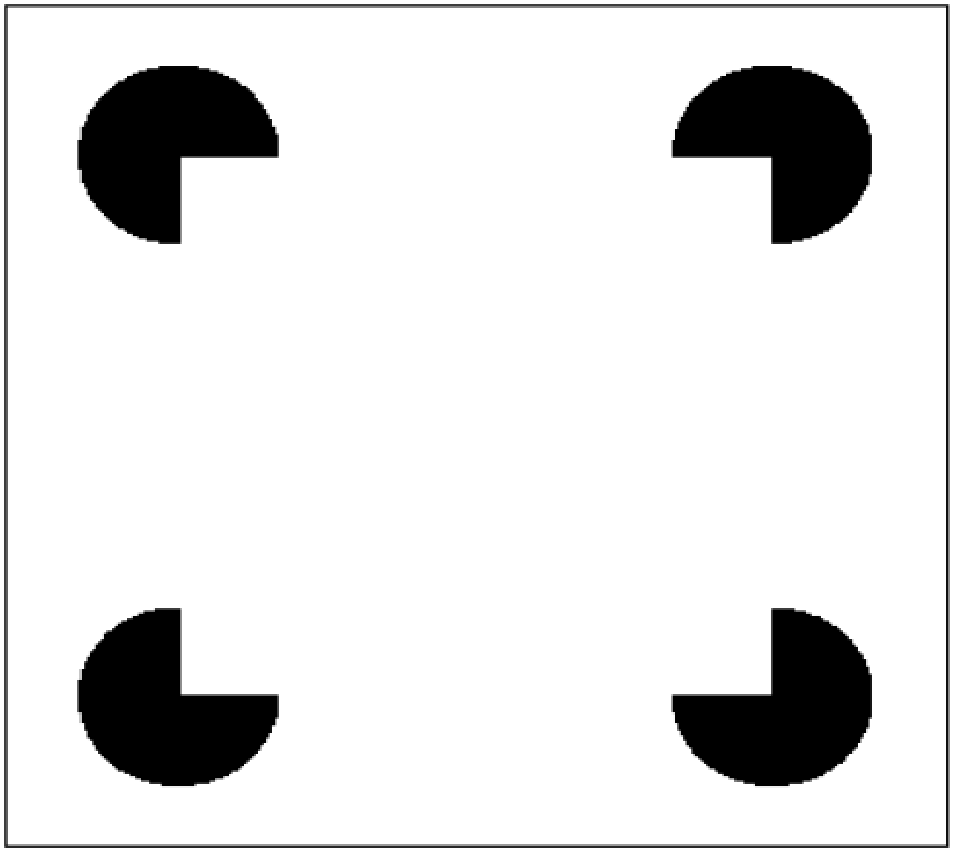


FIGURE 2.8 Examples of simultaneous contrast. All the inner squares have the same intensity, but they appear progressively darker as the background becomes lighter.

Image Perception

- Optical illusions
  - Filling in missing data



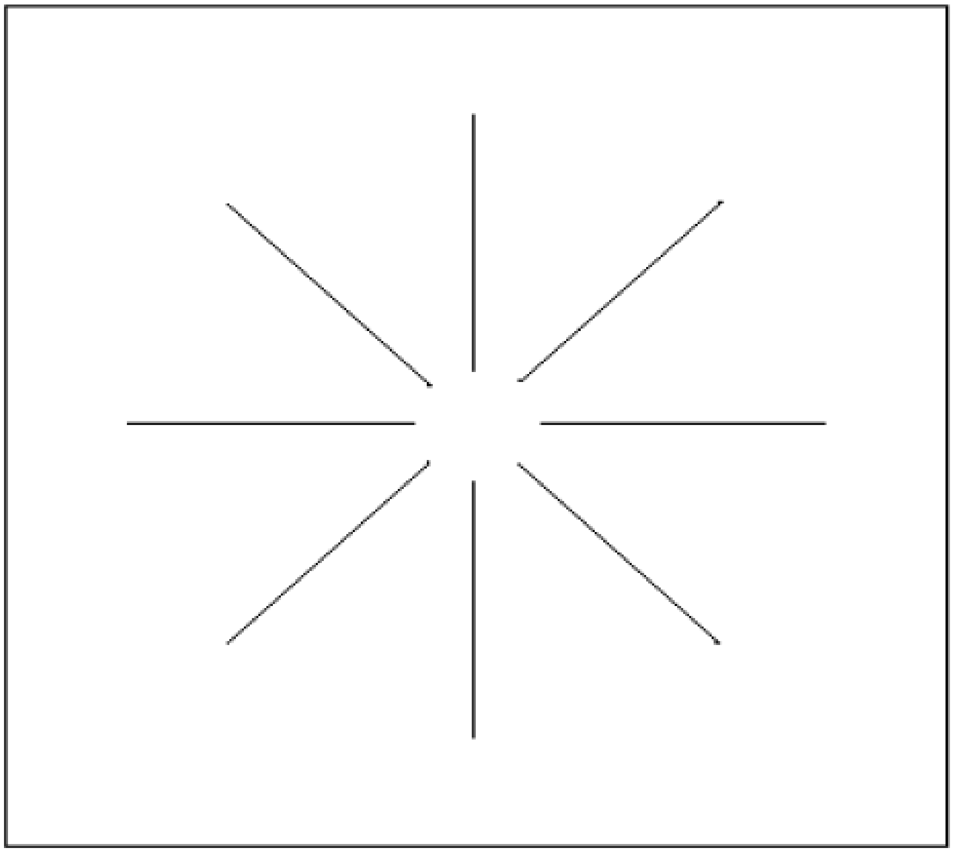


Image Perception

- Checkerboard illusion
  - The squares marked A and B are …
    - … the **same** shade of gray

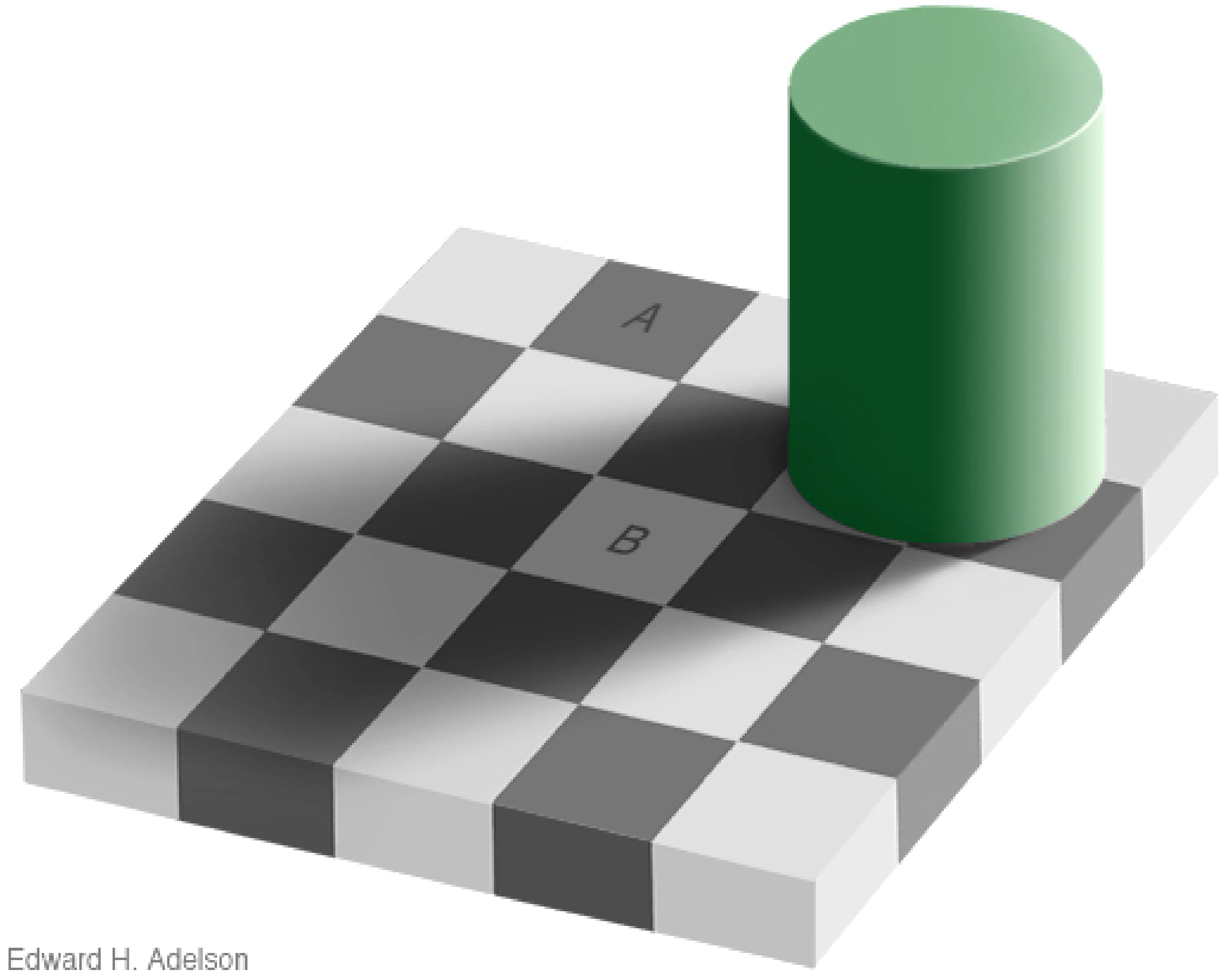
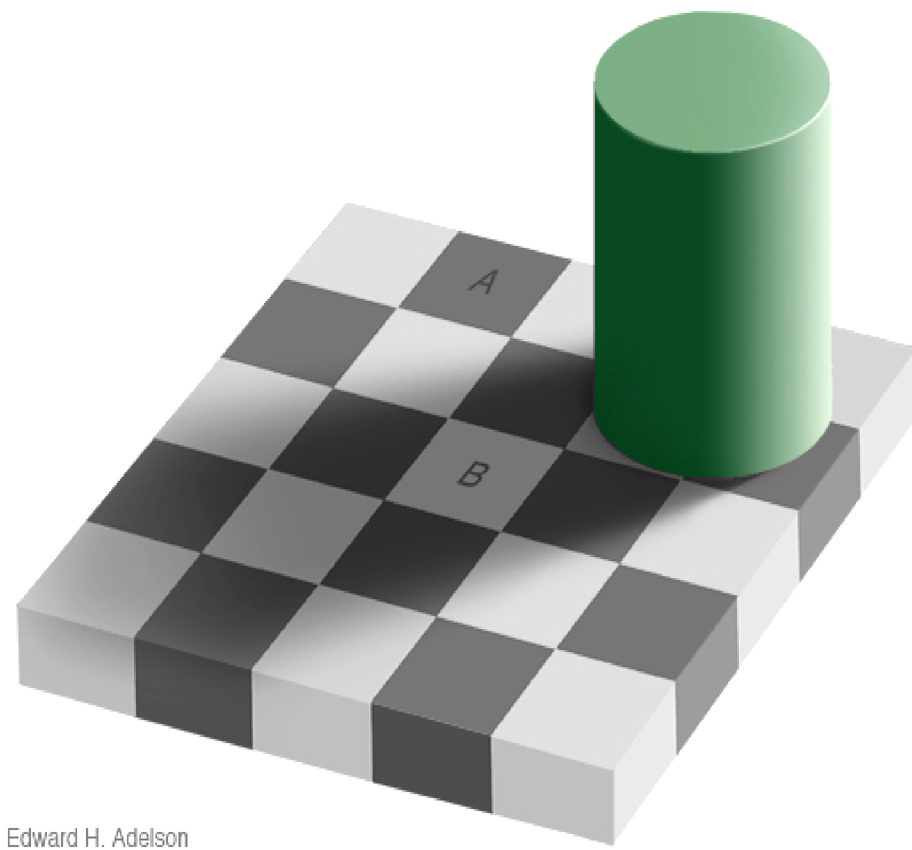


Image Perception

- Checkerboard illusion explanations
  - Simultaneous contrast
  - Checkerboard pattern
  - Shadows



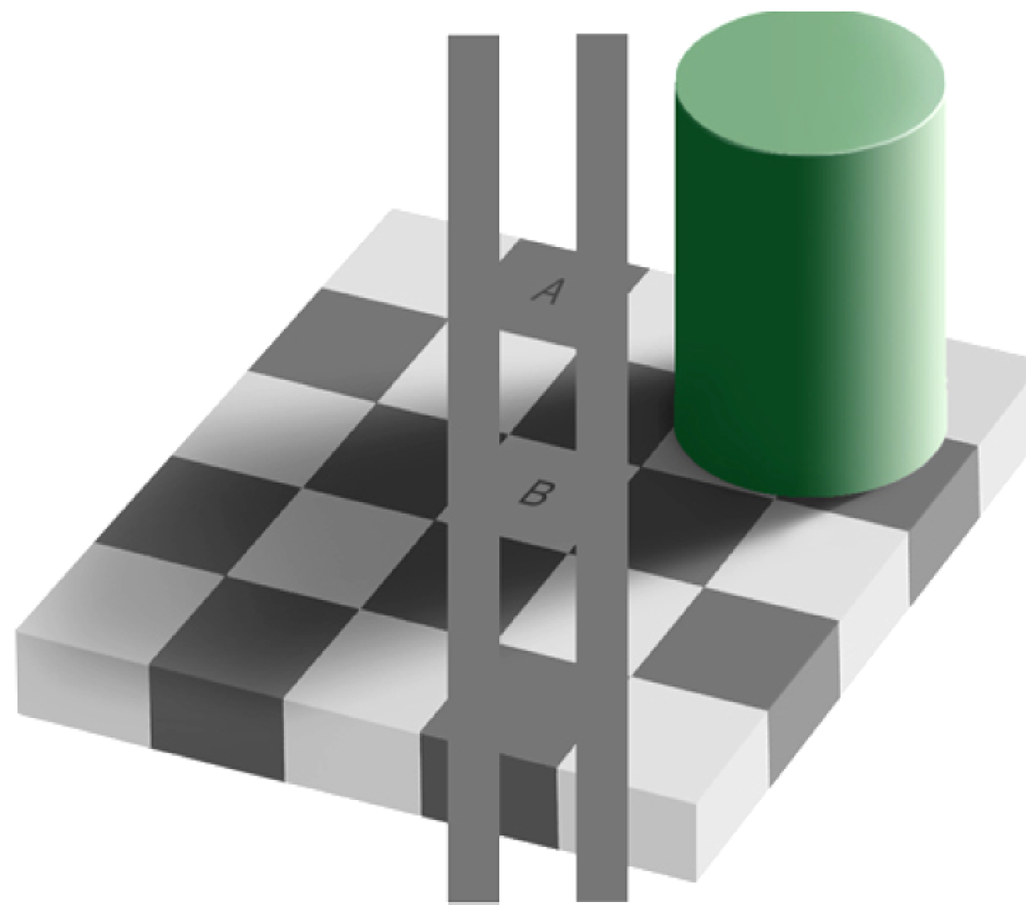


Image Perception

- Human visual system
  - Is NOT optimized for measuring the amount of light
  - Has evolved to achieve high-level understanding from limited data
    - e.g., object detection and recognition despite occlusion
    - e.g., object detection despite low light
- Be careful while interpreting the results of your algorithms !