# Introduction to Image Processing

# Ch 2. Digital Image Fundamentals

Kuan-Wen Chen

# Ch 2. Digital Image Fundamentals

2.1 Elements of Visual Perception

2.2 Light and the Electromagnetic Spectrum

2.3 Image Sensing and Acquisition

2.4 Image Sampling and Quantization

2.5 Some Basic Relationships Between Pixels

2.6 Introduction to the Basic Mathematical Tools Used in Digital Image Processing

# 2.1 Elements of Visual Perception
# - Structure of the human eye

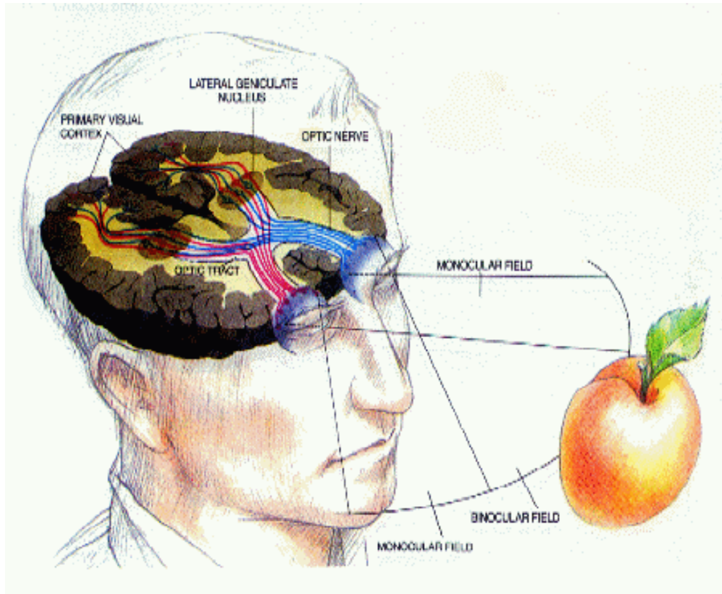
- Although DIP field is built on a foundation of mathematics, human intuition and analysis play a central role in choosing techniques.

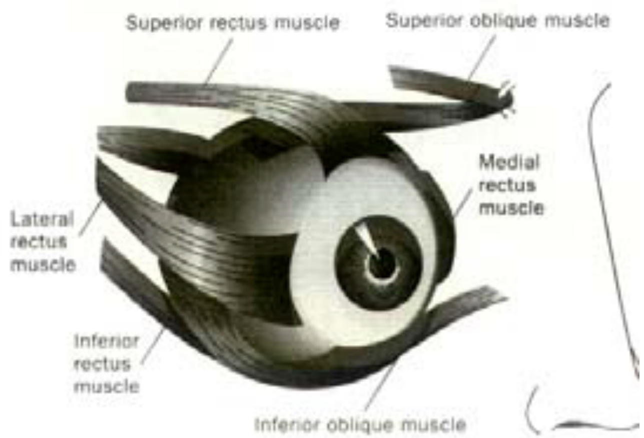
- We are interested in learning the physical limitation of human vision.

# 2.1 Elements of Visual Perception - Structure of the human eye

人類的眼球(~20mm):

- 三層膜 -- 鞏膜、脈絡膜、視網膜
- 兩個房 -- 前房Anterior chamber 、後房Posterior chamber
- • 六條控制眼動的肌肉 -- 包附著厚厚的保護性脂肪層， 使得眼球能安全地在眼窩裡轉動。

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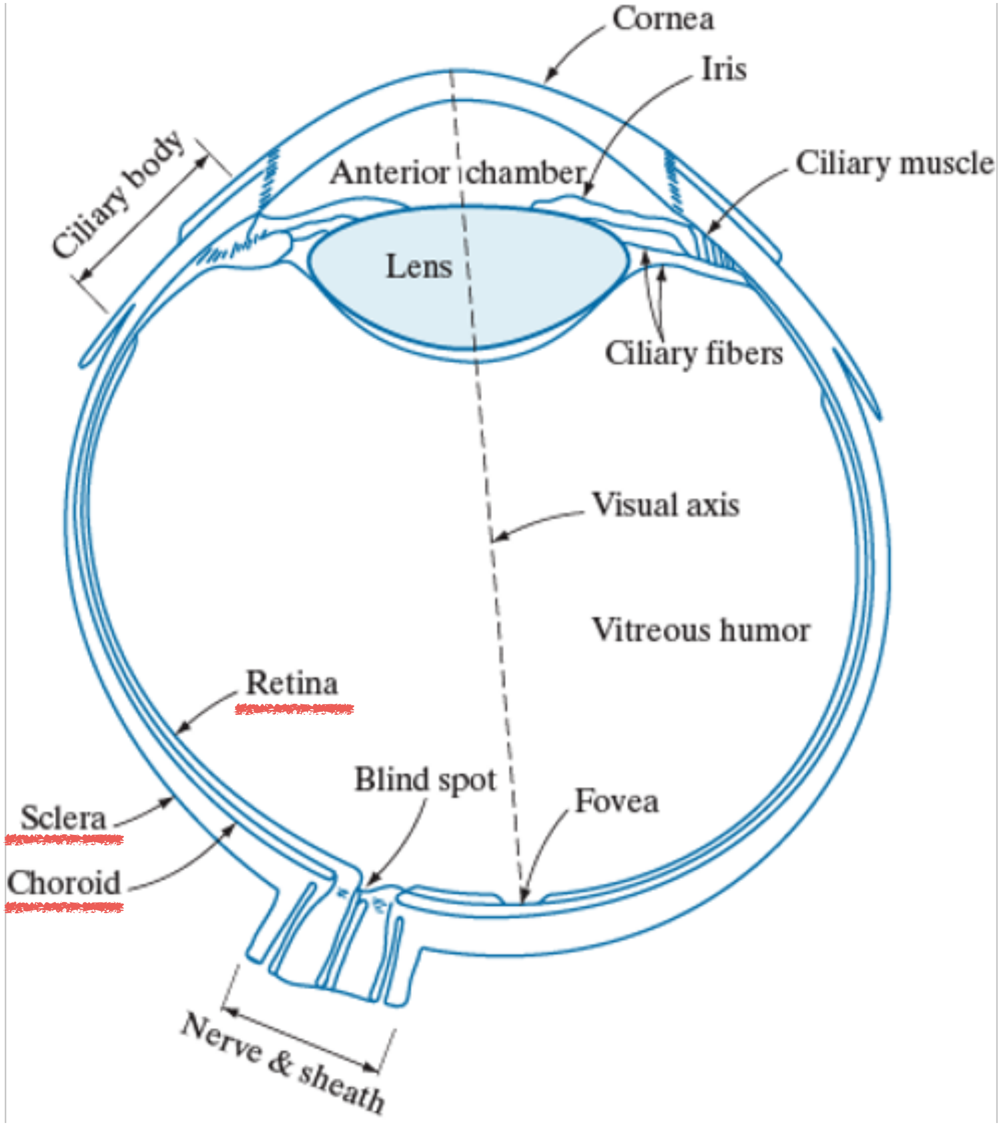
# 2.1 Elements of Visual Perception - Structure of the human eye




Three membranes(膜):

1. Sclera 鞏膜、“眼白” -- Cornea 角膜
2. Choroid 脈絡膜 (blood vessel) (heavily pigmented) -- Ciliary body 睫狀體 -- Iris diaphragm 虹膜 * Pupil 瞳孔
3. Retina 視網膜

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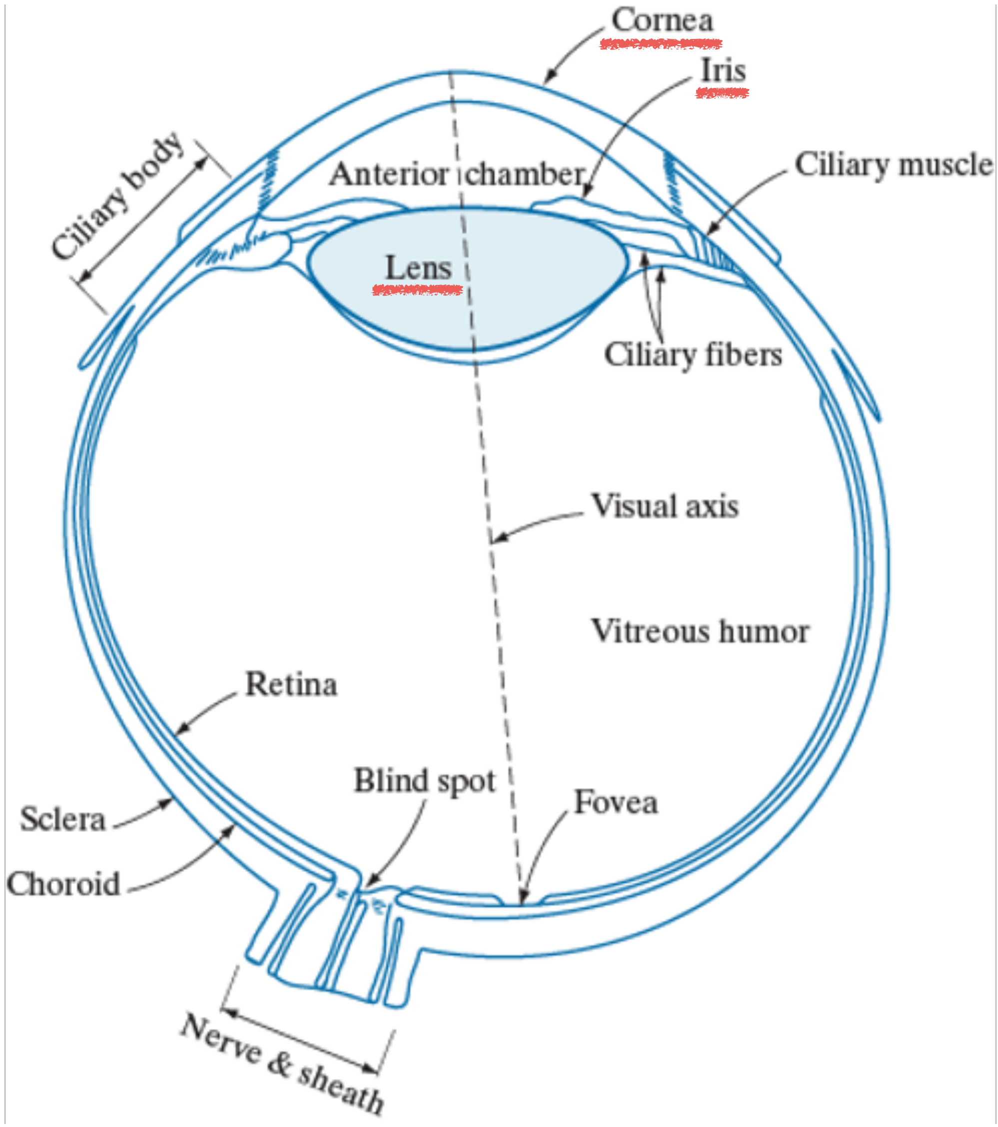
# 2.1 Elements of Visual Perception - Structure of the human eye




Lens: 水晶體

- 是眼球的主要屈光結構

Cornea: 角膜

- 初步集中進入眼球內的光
- 防止異物進入眼球

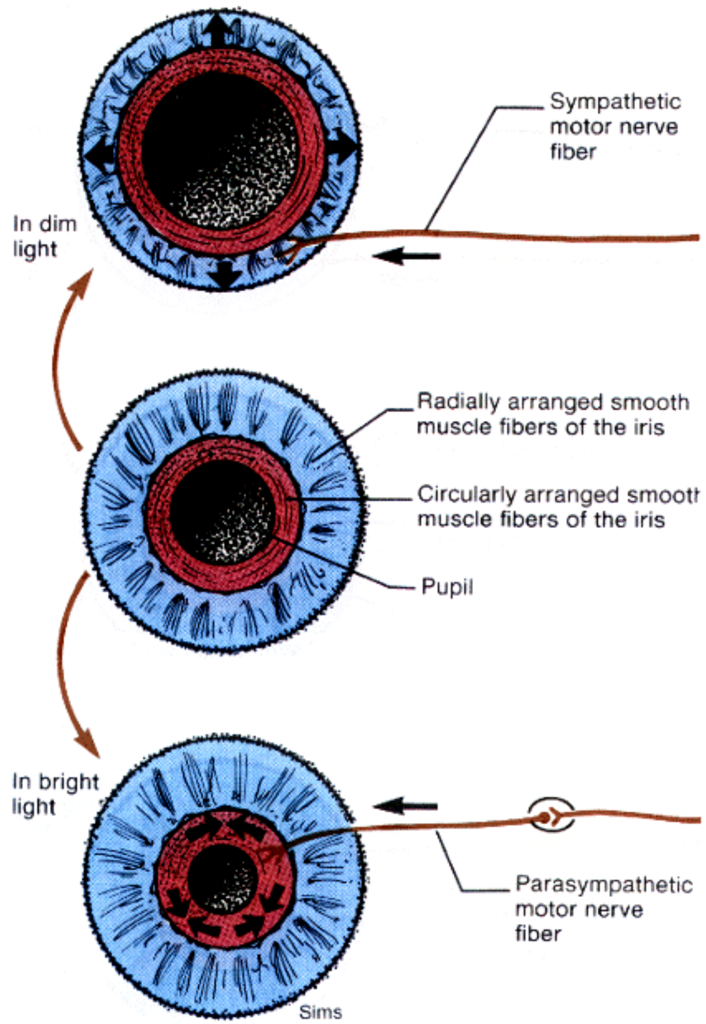
Iris: 虹膜

- 瞳孔大小可透過虹膜內肌肉的收緊放鬆調整，猶如相機當中的光圈

# 2.1 Elements of Visual Perception - Structure of the human eye

瞳孔大小的調節機制是根據環境的光亮強度(2-8mm) :

1. 瞳孔放大: 放射狀纖維(縱走肌)收縮、環狀纖維 (環狀肌)舒張，使得中間的孔徑放大
2. 瞳孔縮小: 放射狀纖維舒張、環狀纖維向內收縮

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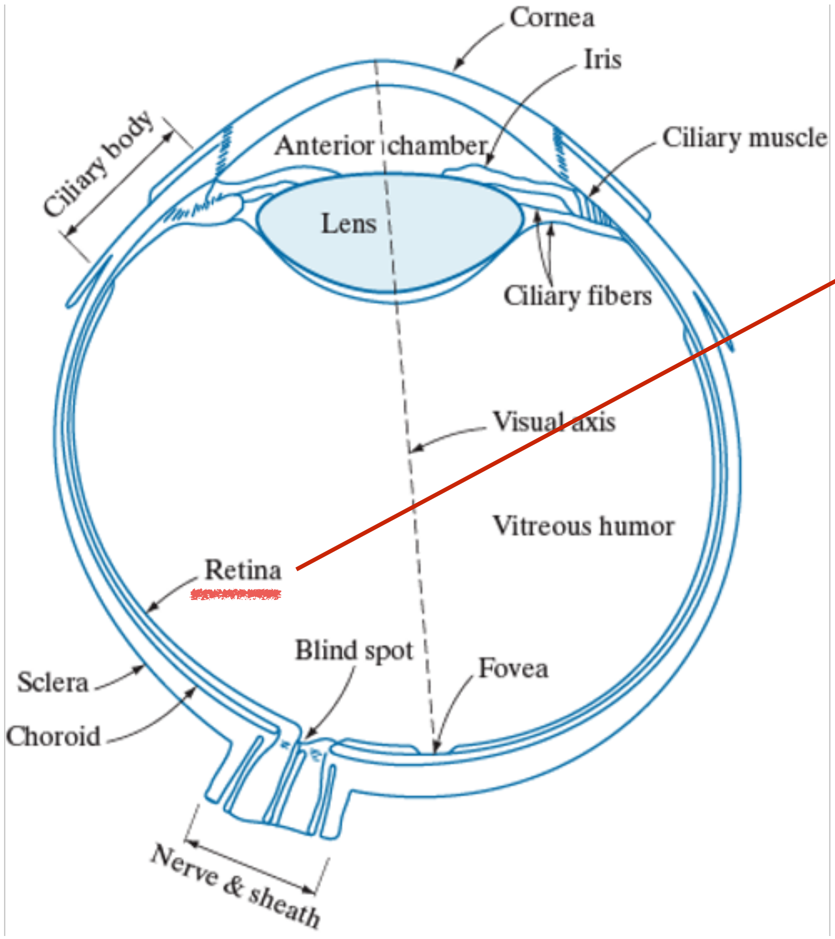
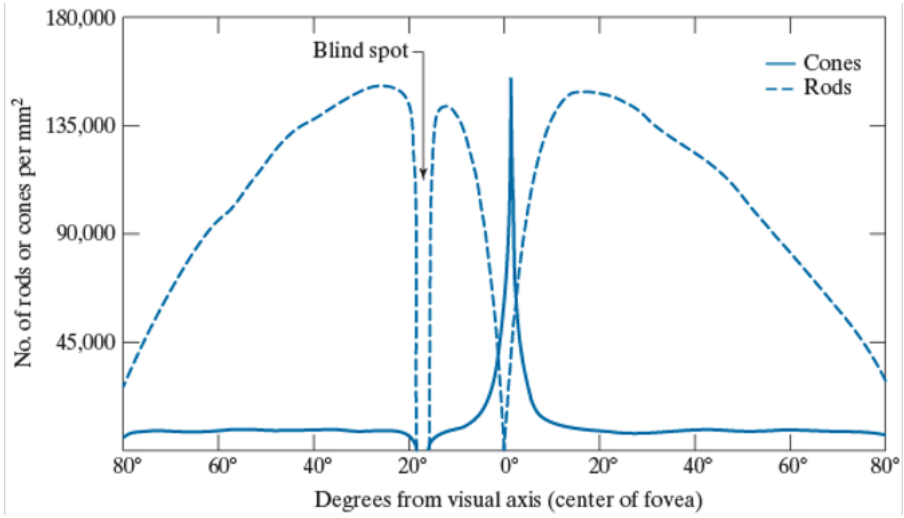
# 2.1 Elements of Visual Perception - Structure of the human eye

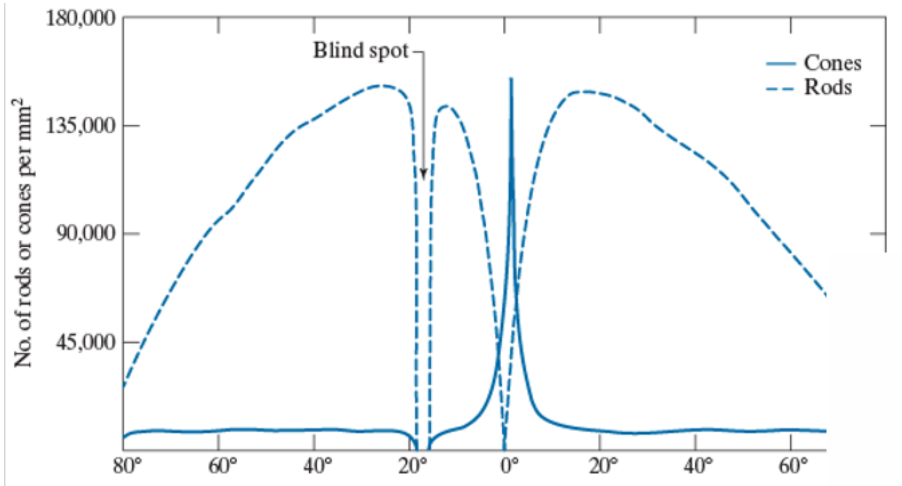



視網膜上最重要的兩種視覺接受器：

- 錐細胞(cone): 6~7 million
  - 主要負責顏色識別
- 桿細胞(rod): 75~150 million
  - 對光更敏感，幾乎主要全部用於夜視力

# 2.1 Elements of Visual Perception - Structure of the human eye



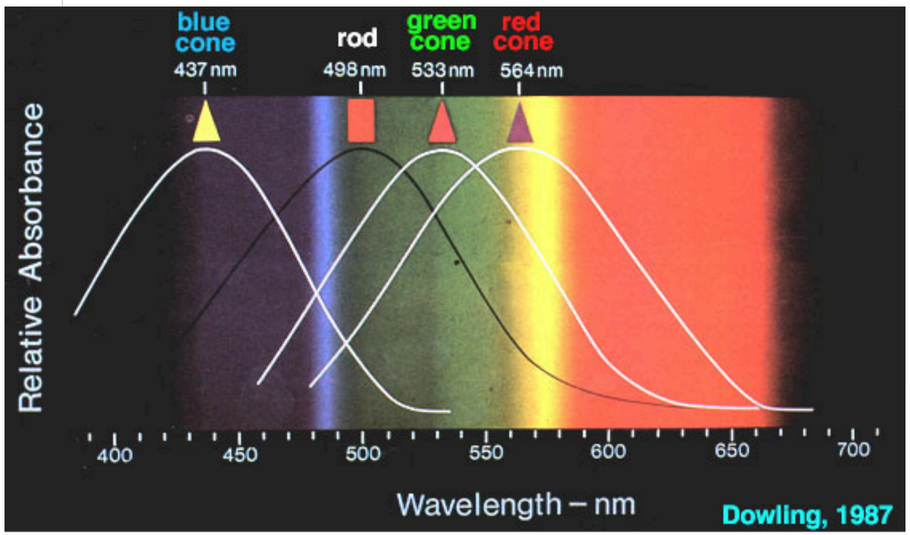
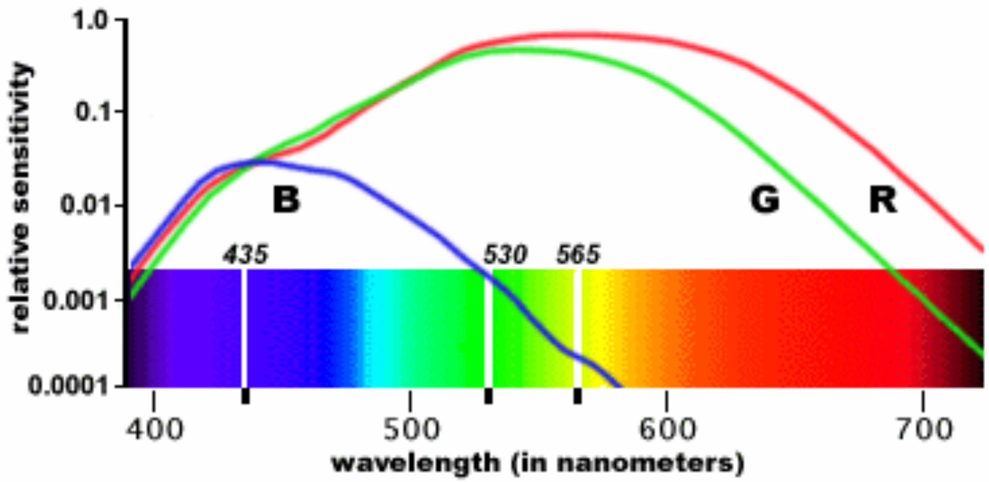




*Fig. 14.The peak spectral sensitivities of the the 3 cone types and the the rods in the primate retina (Brown and Wald, 1963). From Dowling's book (1987).*

錐細胞分為對長波、中波與短波敏感的三種類型(L-cone, M-cone, S-cone)，可感知色彩

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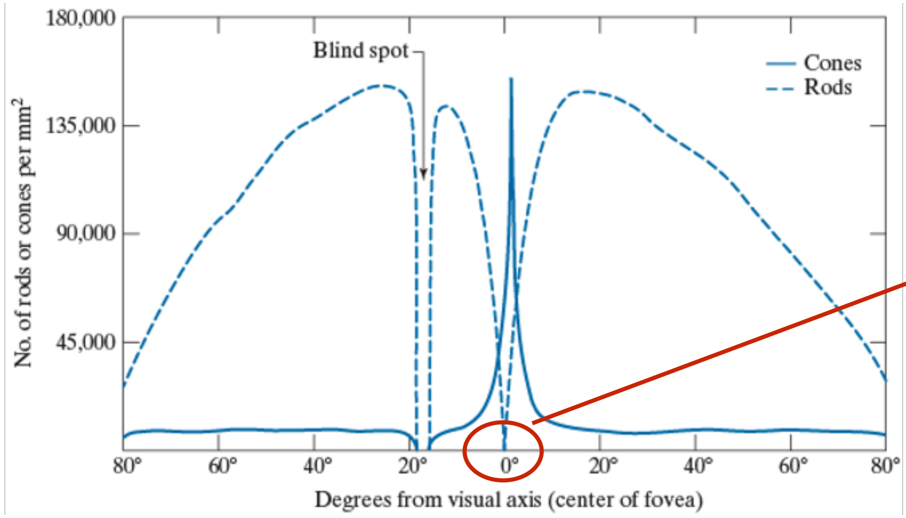
# 2.1 Elements of Visual Perception - Structure of the human eye




Fovea: 中央窩

- 神經層較薄，沒有阻礙光線的血管層
- 兩極細胞、水平細胞、 與節細胞等神經元都盡量地移到兩旁
- 此區的光線能更順利的 達到視覺受器上

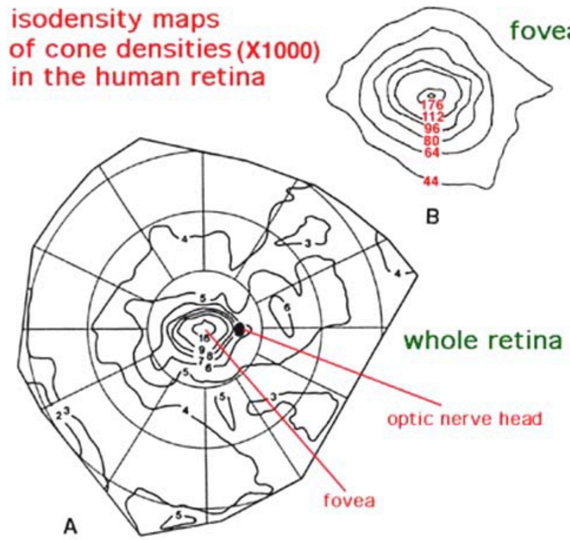
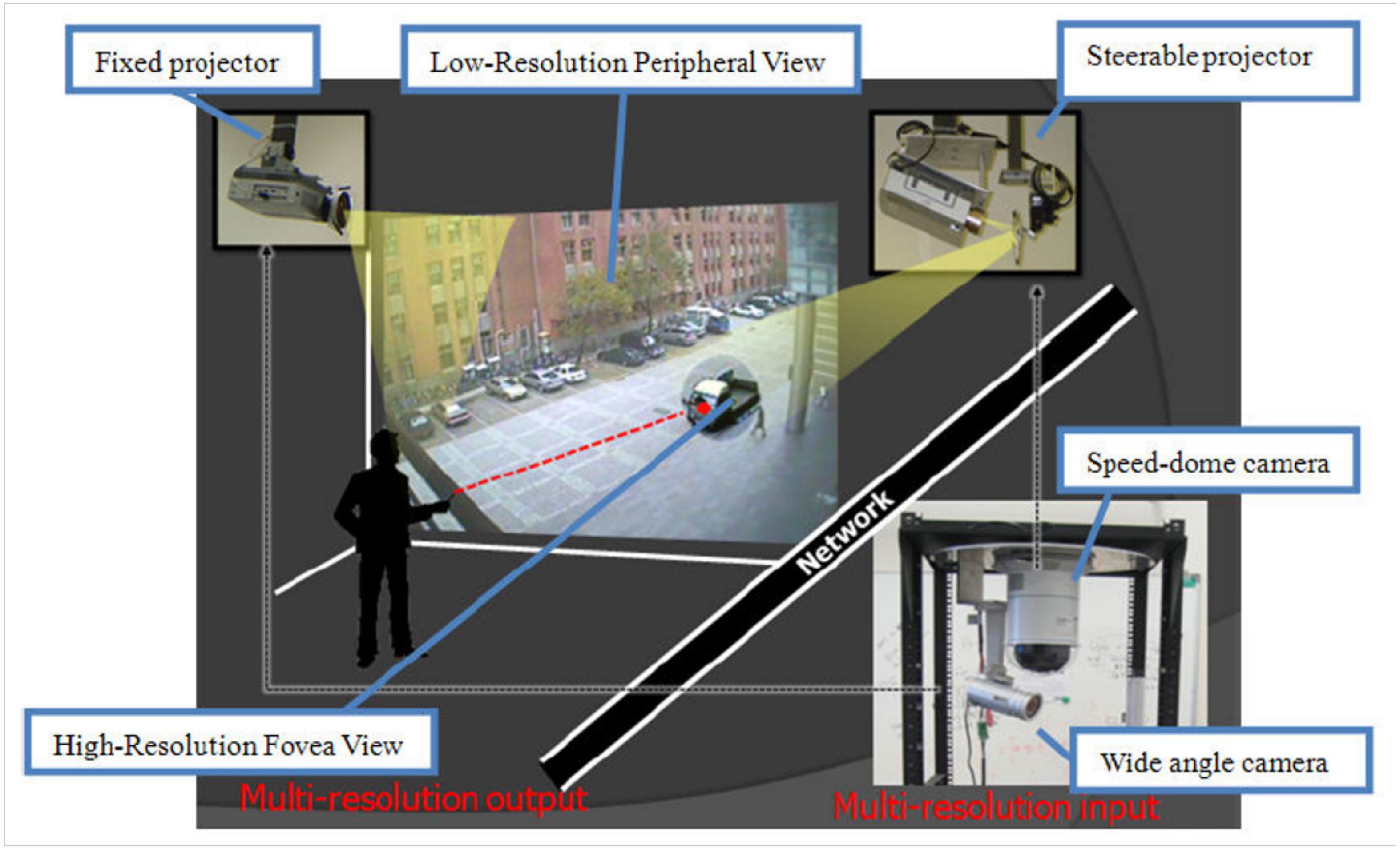



*Fig. 21. Cone densities in human retina as revealed in whole mount. The foveal area is enlaged in B. (from Curcio et al., 1987).*

# 2.1 Elements of Visual Perception - Structure of the human eye

e-Fovea




Kuan-Wen Chen, Chih-Wei Lin, Mike Y. Chen, and Yi-Ping Hung, "e-Fovea: A Multi-Resolution Approach with Steerable Focus to Large-Scale and High-Resolution Monitoring," ACM Multimedia, 2010. (Full Paper)

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e-Fovea

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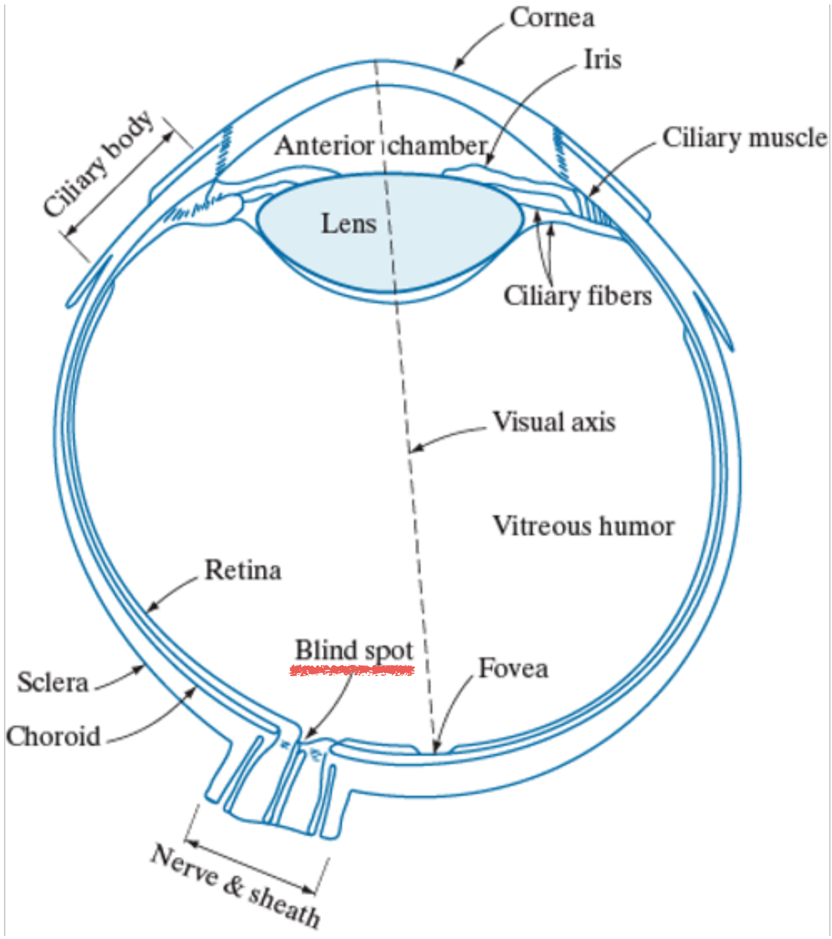
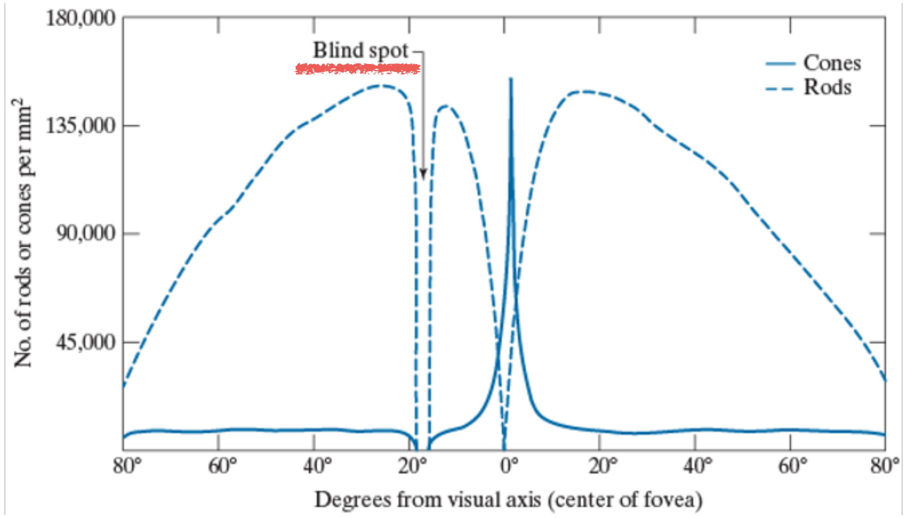



Blind spot: 盲點

- 此處是神經纖維進出的地方，沒有感光細胞，不能感應到光線

# 2.1 Elements of Visual Perception - Structure of the human eye

## Blind-spot Experiment

Draw an image similar to that below on a piece of paper (the dot and cross are about 6 inches apart)

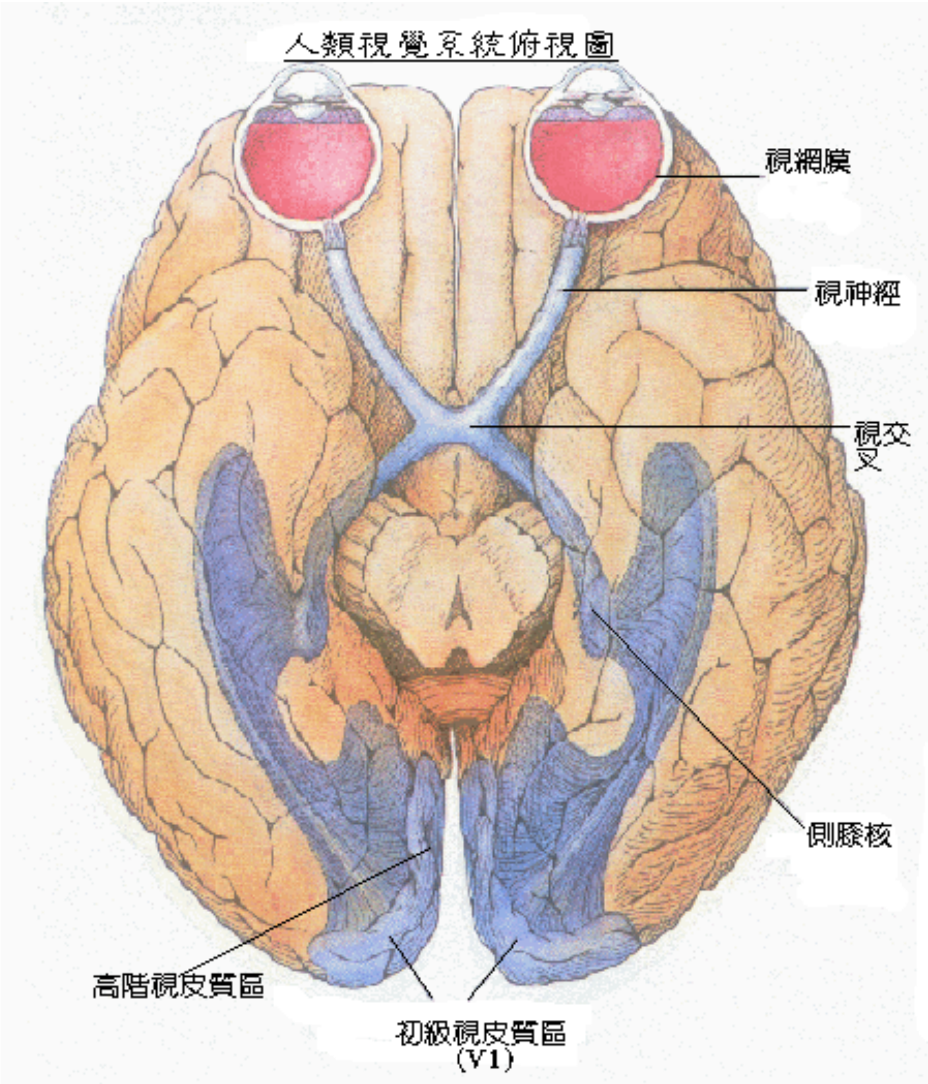
Close your right eye and focus on the cross with your left eye

Hold the image about 20 inches away from your face and move it slowly towards you

The dot should disappear!

credit of this slide: C. Nikou

# 2.1 Elements of Visual Perception - Structure of the human eye




人類的視覺神經路徑

視網膜→視神經→視交叉→側膝核→視皮質

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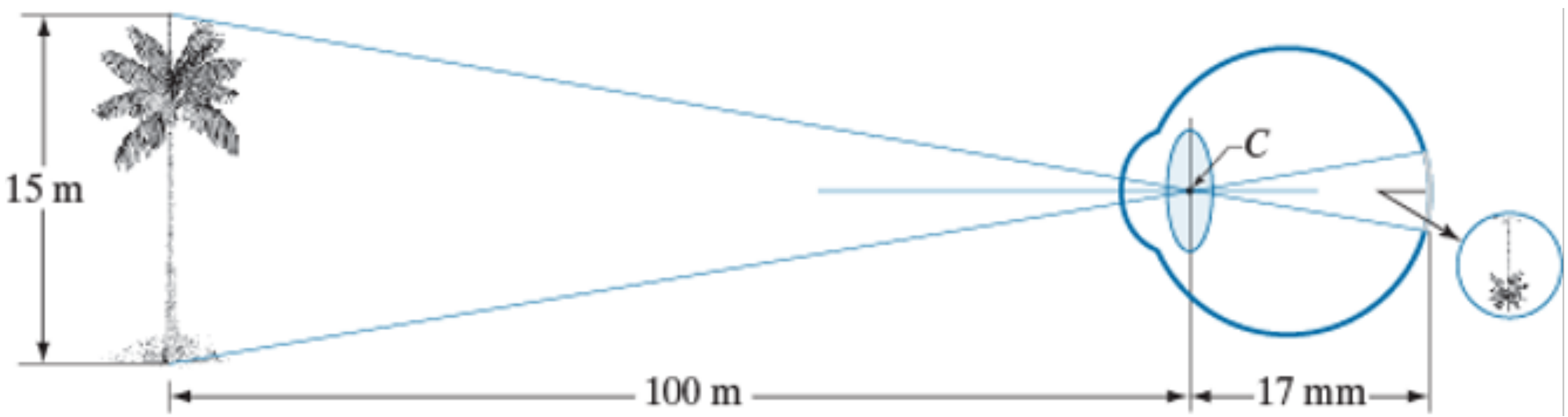
# 2.1 Elements of Visual Perception - Image Formation in the Eye

- Lens shape controlled by the tension of ciliary muscle (睫狀肌)
- Focal length: 17mm ~ 14mm

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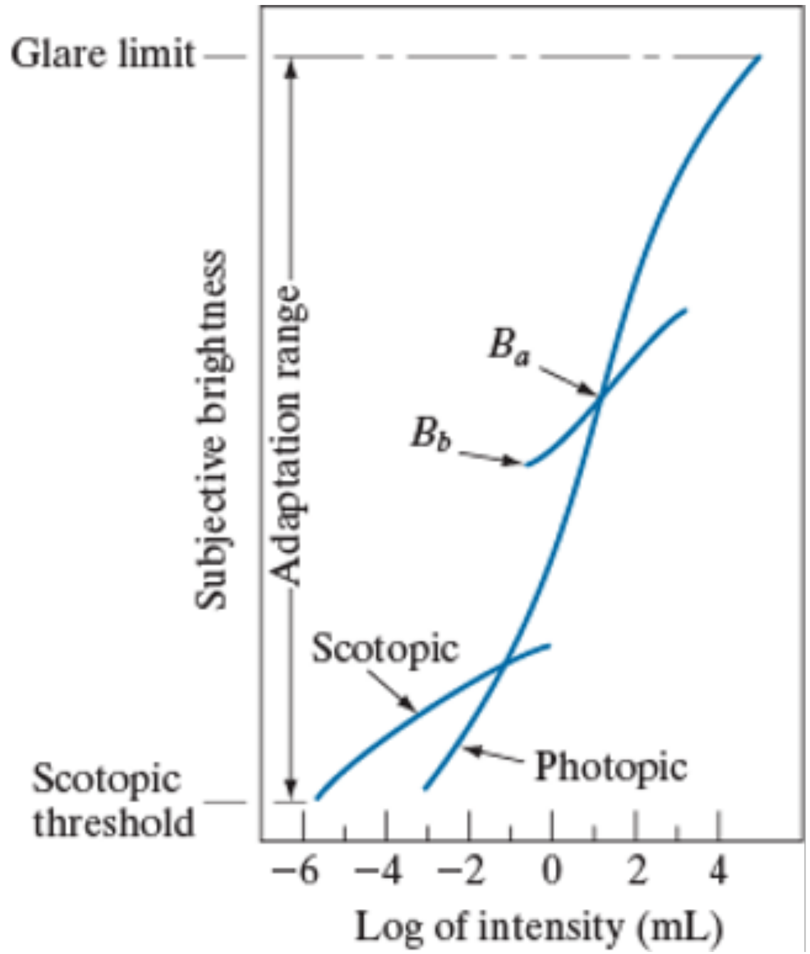
# 2.1 Elements of Visual Perception - Brightness Adaptation & Discrimination

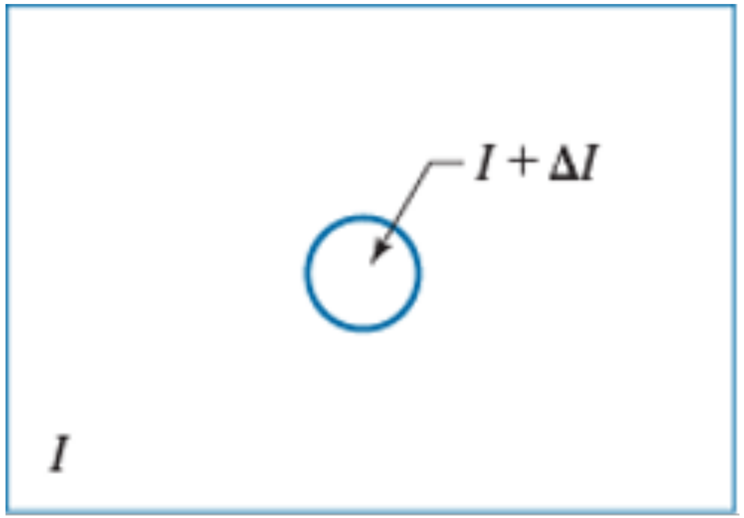
- Range of light intensity that human can adapt
  ➔ $10^{10}$
- Transition from scotopic to photopic vision is gradual
  ➔ from 0.001 to 0.1 millilambert (-3 to –1 in log)
- Vision System cannot operate over such a range simultaneously
- $B_a$ : Brightness adaptation level
- $B_b$ : at and below this level all stimuli are perceived as indistinguishable black



# 2.1 Elements of Visual Perception - Brightness Adaptation & Discrimination

Weber Ratio $\Delta I_c / I$

- Uniformly illuminated background, occupying entire field of view
- Add a short duration of flash $\Delta I$
- $\Delta I_c$: the increment of illumination discriminable 50% of the time

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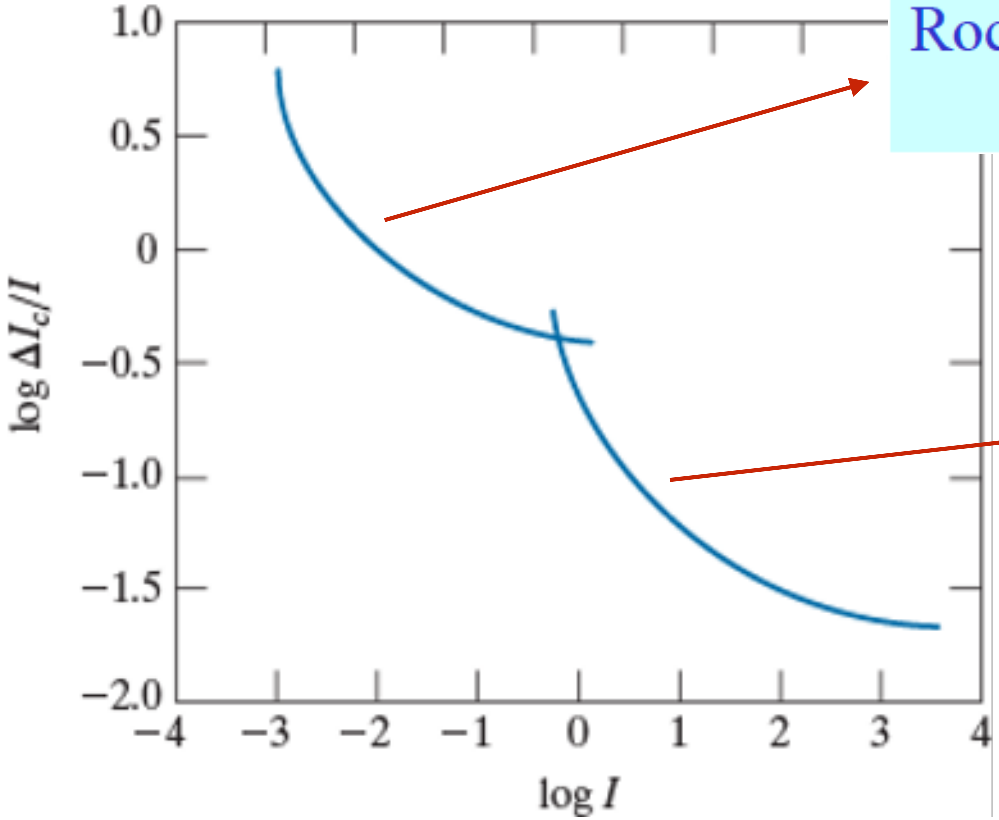
# 2.1 Elements of Visual Perception - Brightness Adaptation & Discrimination

Weber Ratio as a function of intensity




Rod vision: weber ratio large
→ brightness discrimination poor

Cone vision: weber ratio smaller
→ brightness discrimination better

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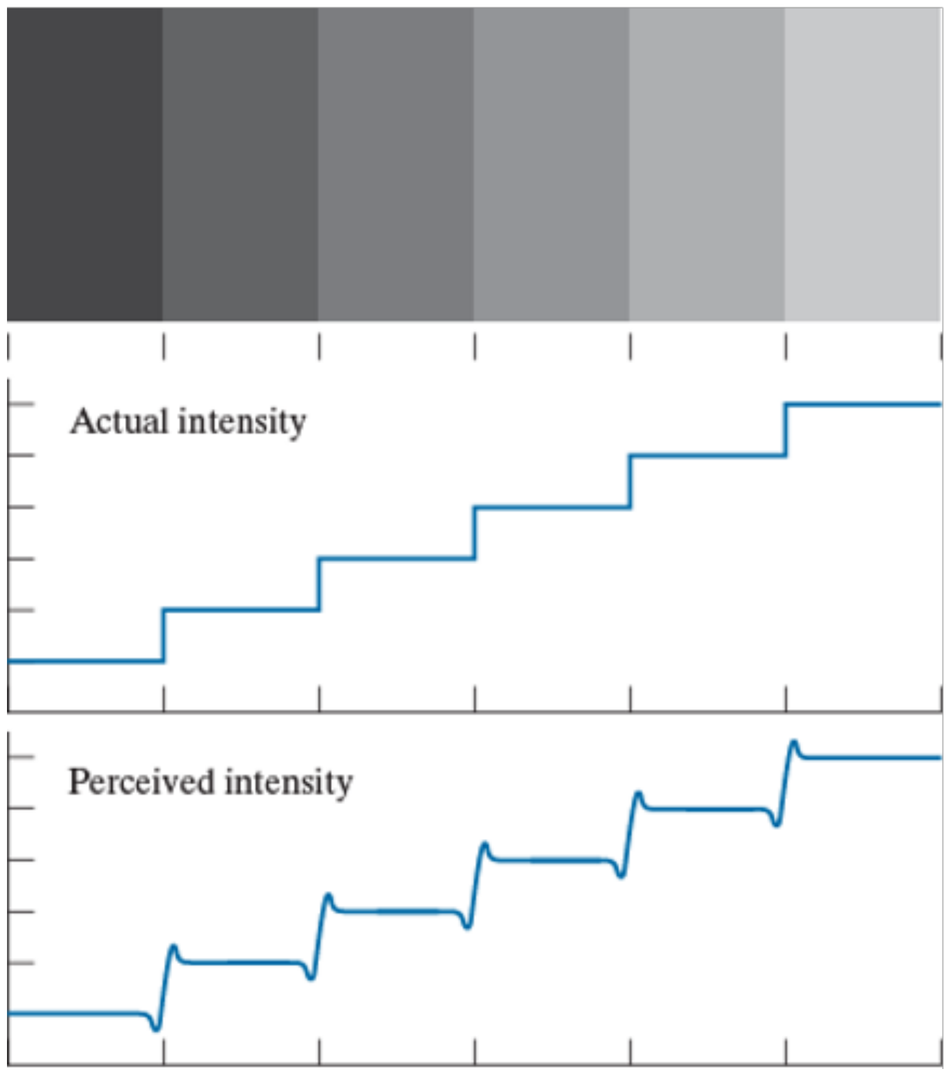
# 2.1 Elements of Visual Perception - Brightness Adaptation & Discrimination

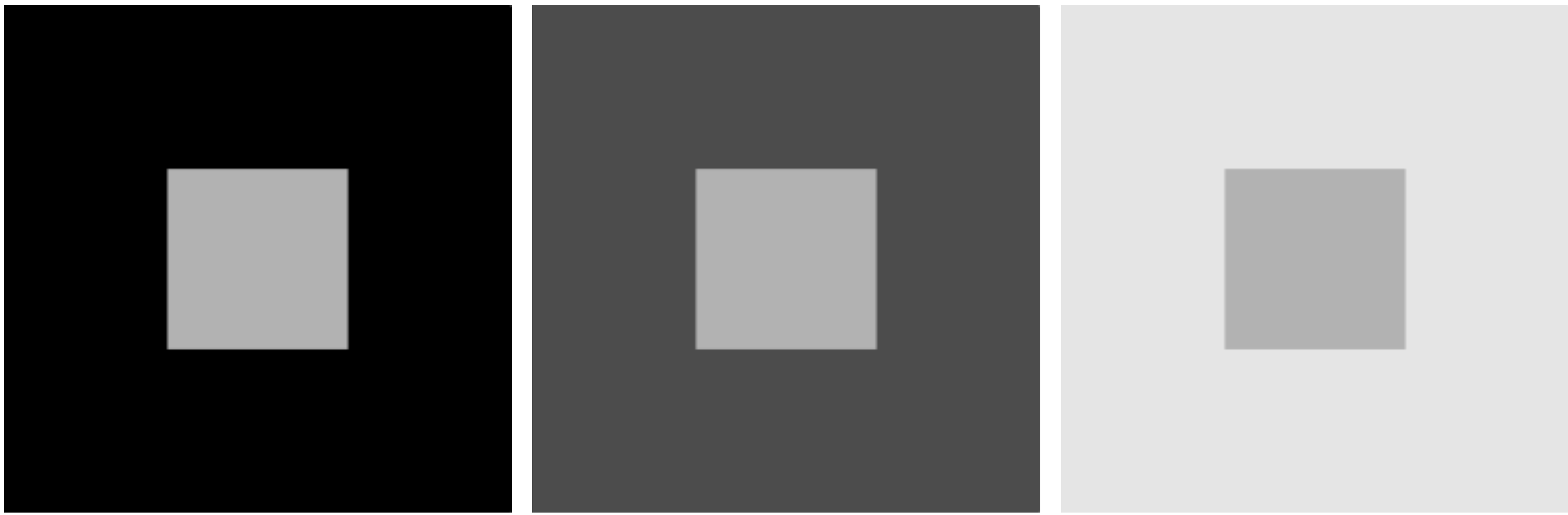
## Human Vision Phenomenon - Mach Band

Two phenomena demonstrate that perceived brightness is not a simple function of intensity



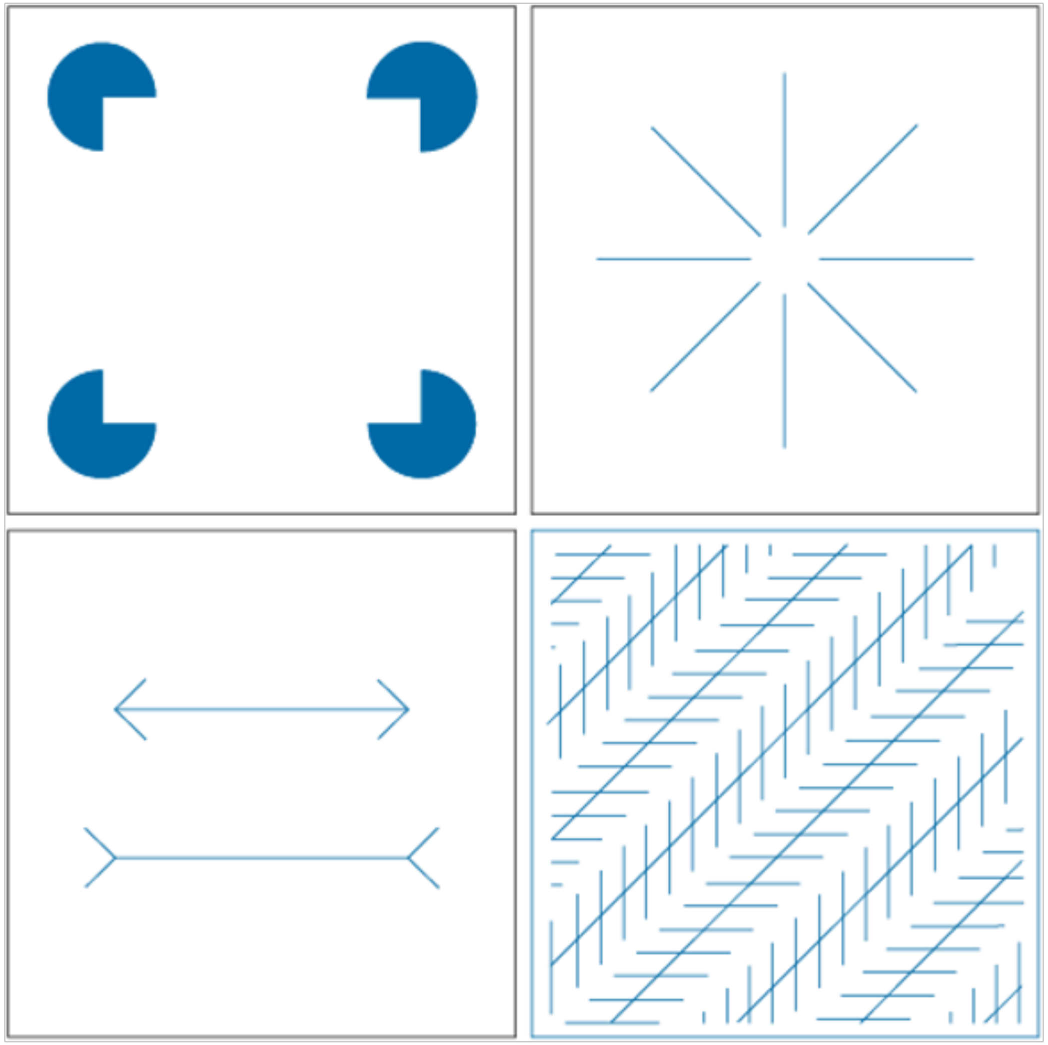
# 2.1 Elements of Visual Perception
# - Brightness Adaptation & Discrimination

## Human Vision Phenomenon - Simultaneous Contrast



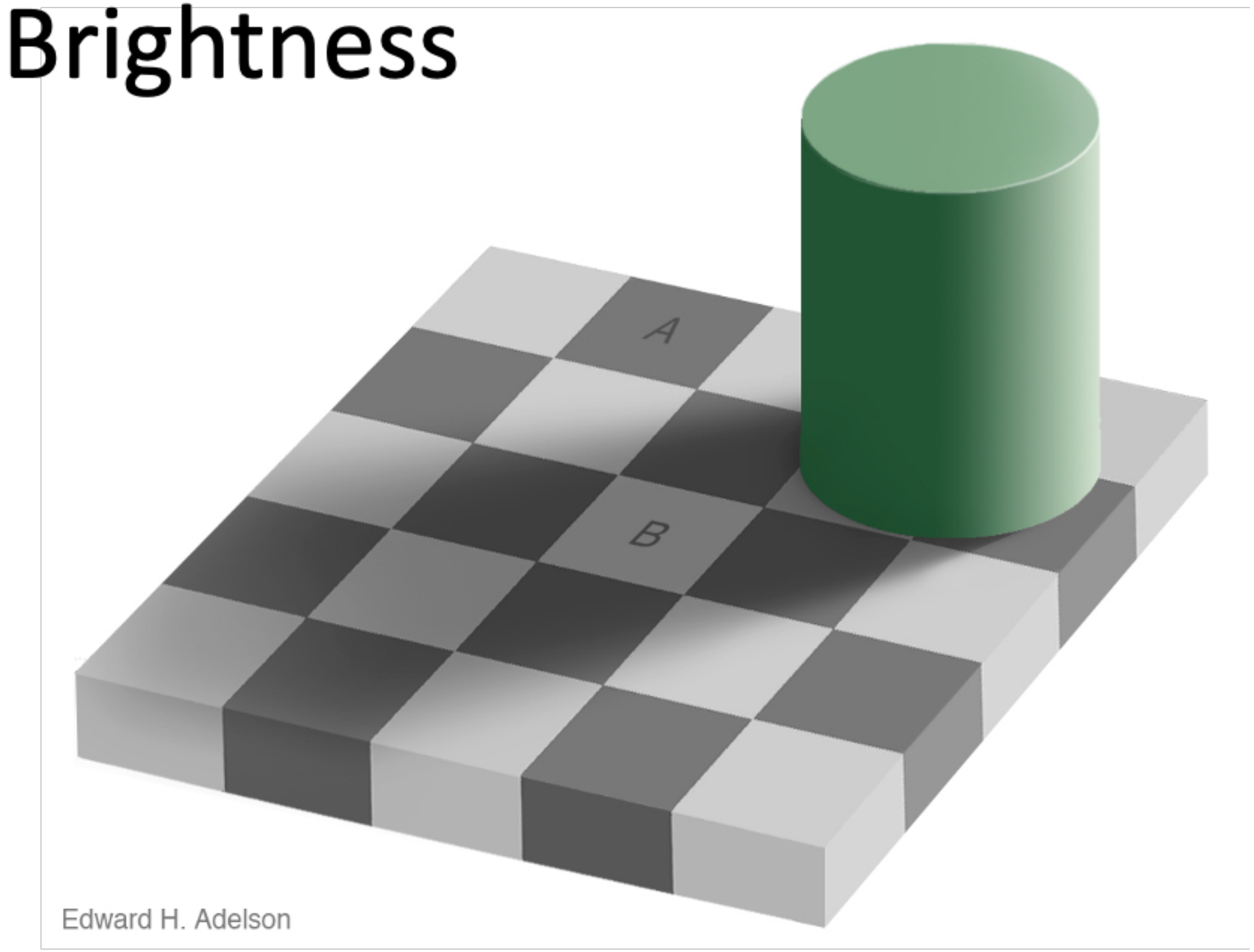
# 2.1 Elements of Visual Perception - Brightness Adaptation & Discrimination

Human Vision Phenomenon - Optical illusions



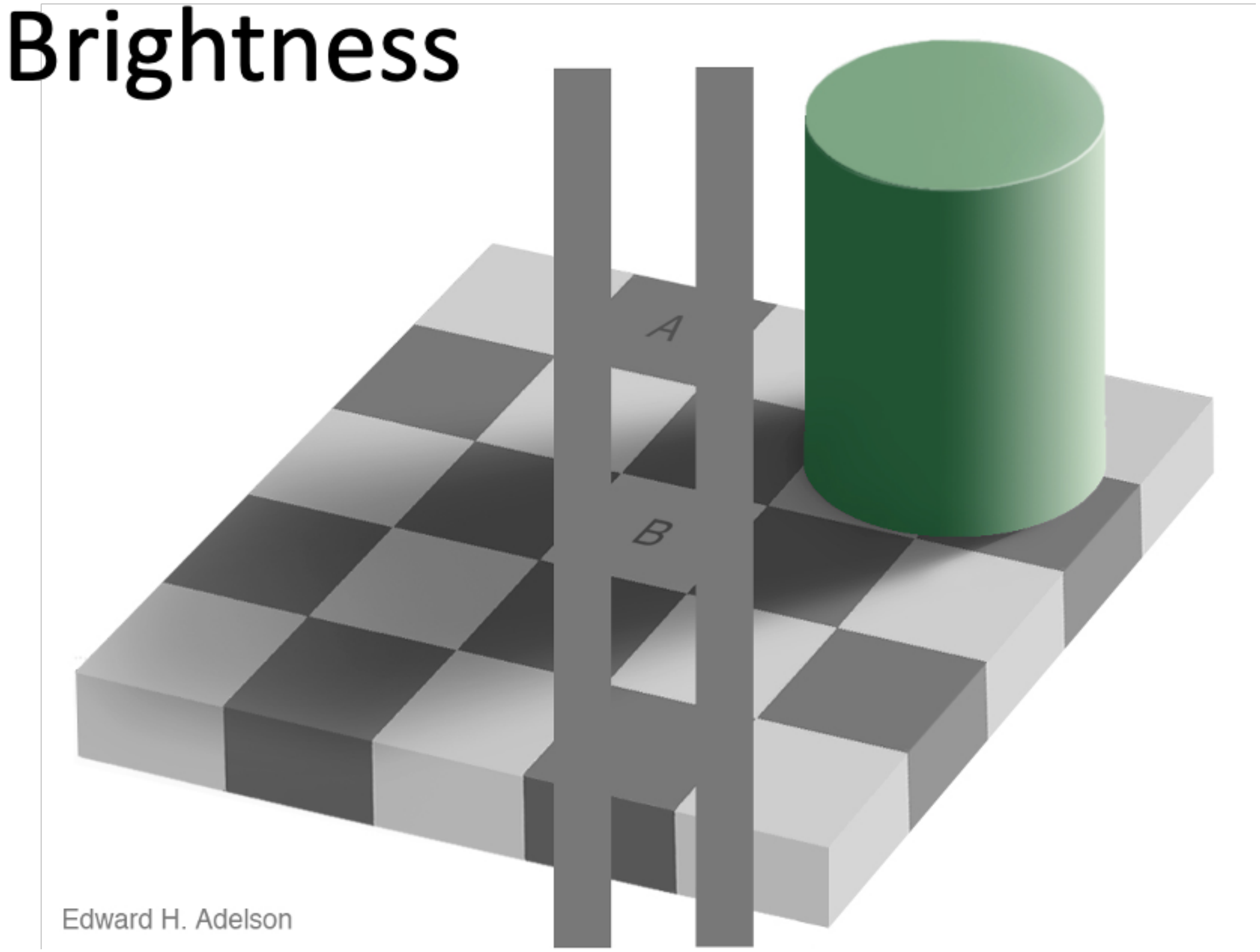
# 2.1 Elements of Visual Perception - Brightness Adaptation & Discrimination

Human Vision Phenomenon - Optical illusions



# 2.1 Elements of Visual Perception - Brightness Adaptation & Discrimination

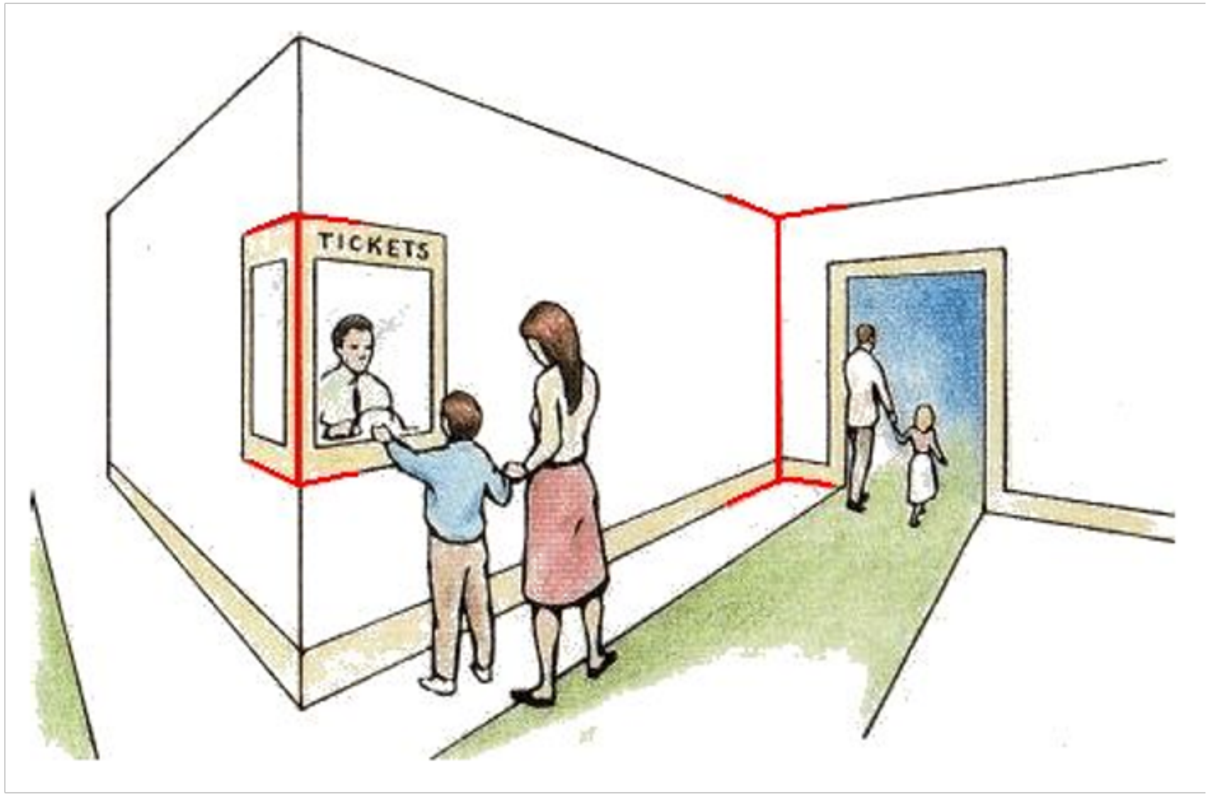
Human Vision Phenomenon - Optical illusions



# 2.1 Elements of Visual Perception - Brightness Adaptation & Discrimination

Human Vision Phenomenon - Optical illusions

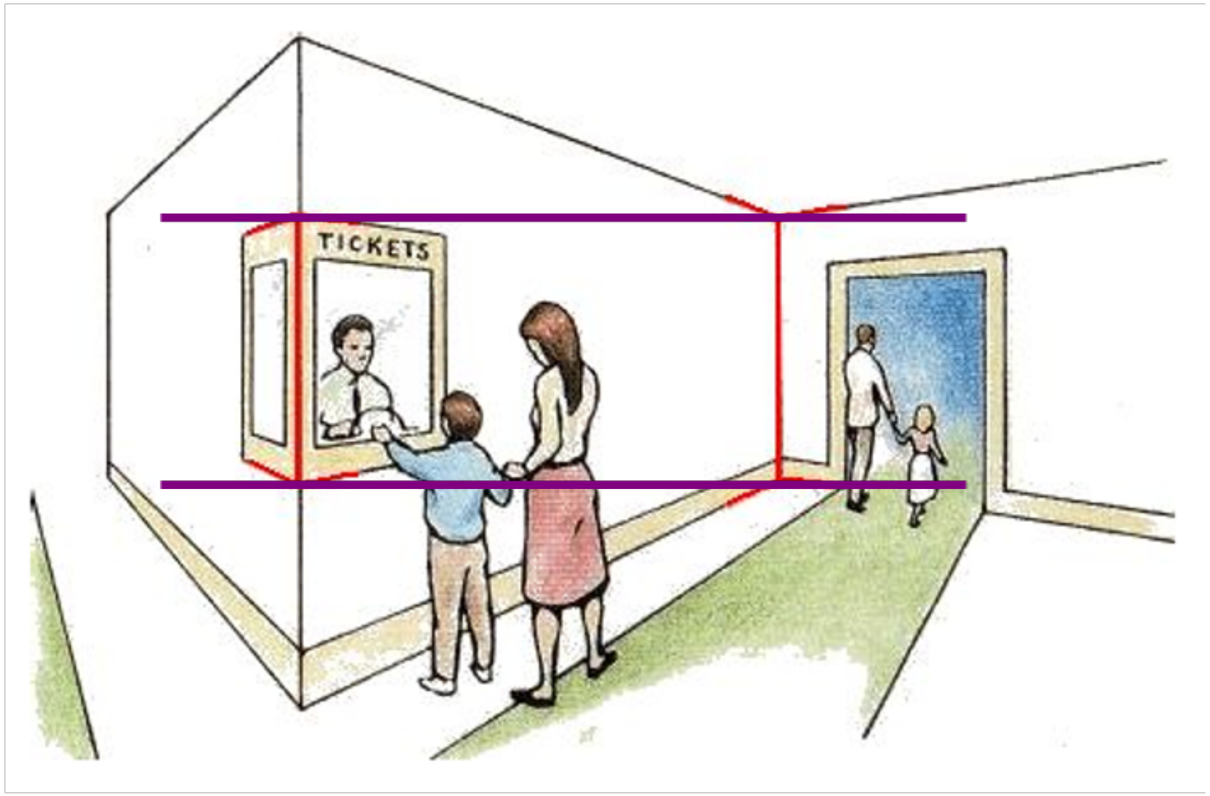
## Length



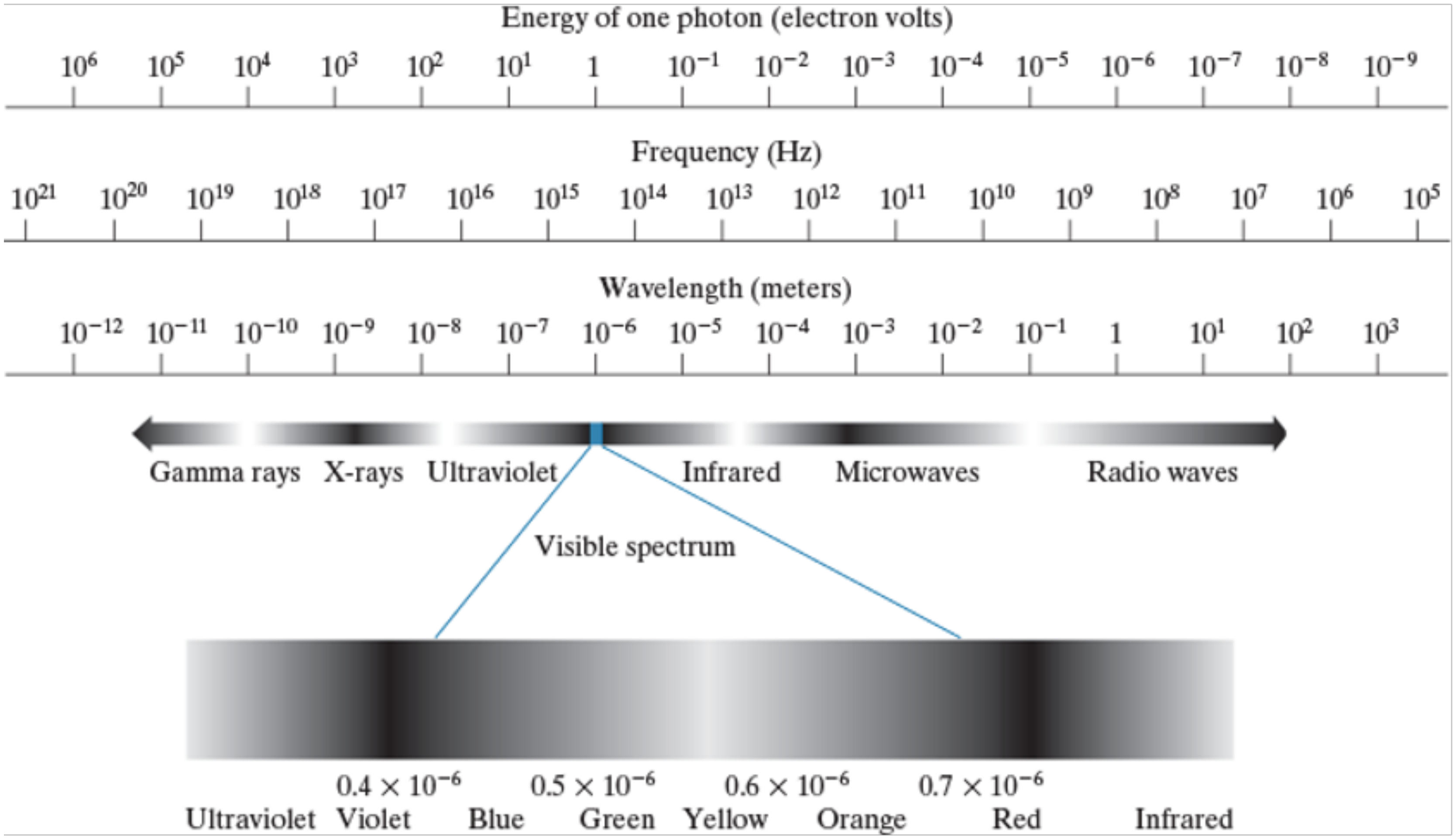
# 2.1 Elements of Visual Perception - Brightness Adaptation & Discrimination

Human Vision Phenomenon - Optical illusions

## Length



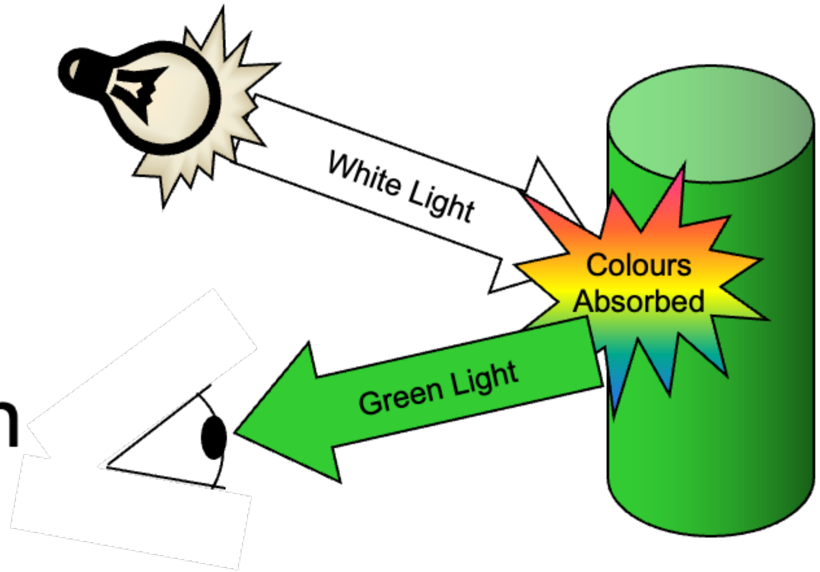
# 2.2 Light and the Electromagnetic Spectrum



# 2.2 Light and the Electromagnetic Spectrum

The colours that we perceive are determined by the nature of the light reflected from an object

For example, if white light is shone onto a green object most wavelengths are absorbed, while green light is reflected from the object

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# 2.2 Light and the Electromagnetic Spectrum

Visible band: 0.43 μm (violet) - 0.79 μm (red)

- Achromatic or monochromatic light
  → gray level, intensity

- Radiance: total energy from light source → watts
- Luminance: energy that an observer perceives → lumens
- Brightness: subjective descriptor of light perception
  → hard to measure

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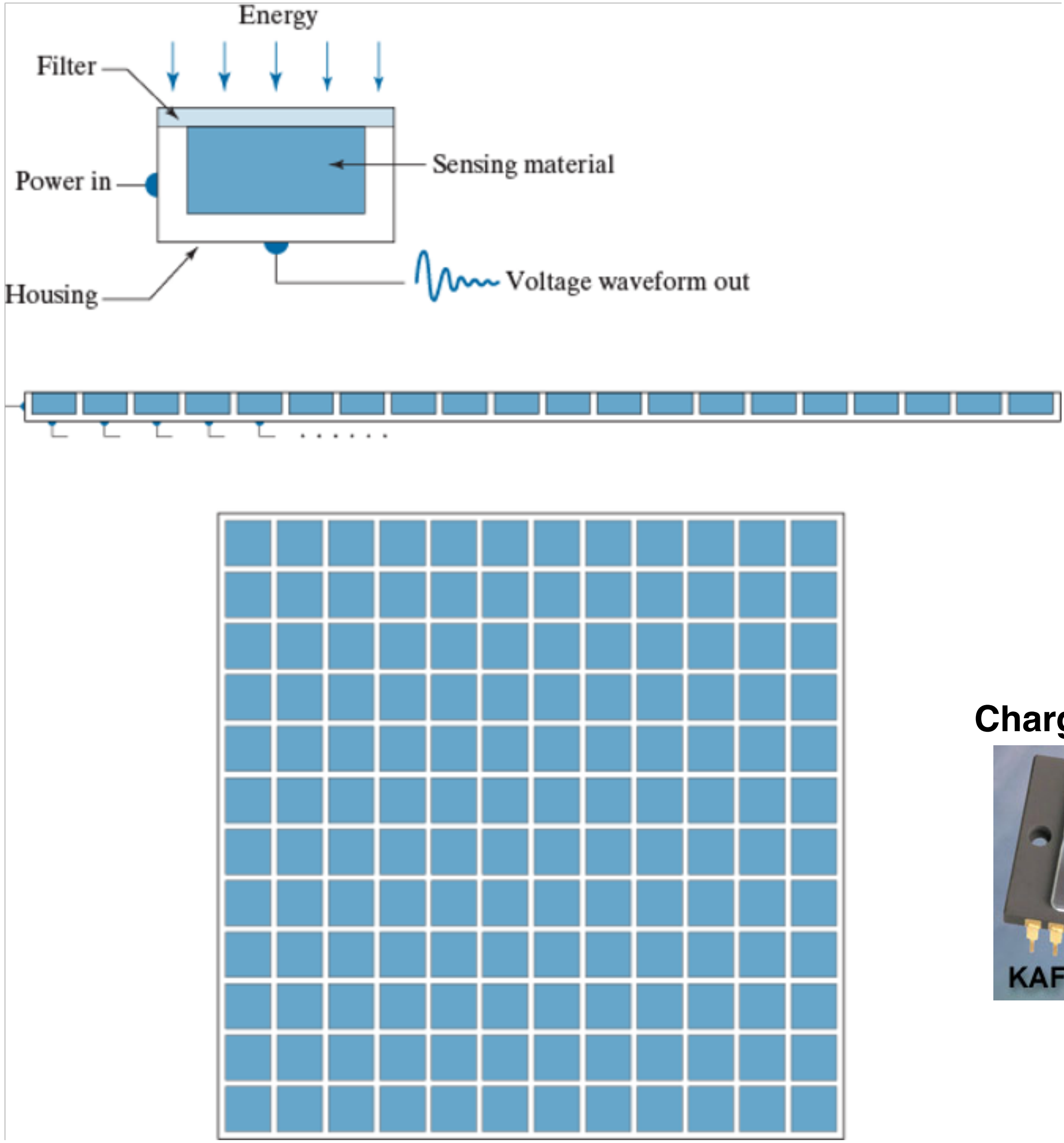
# 2.3 Image Sensing and Acquisition
# - Image Acquisition Using a Single Sensor

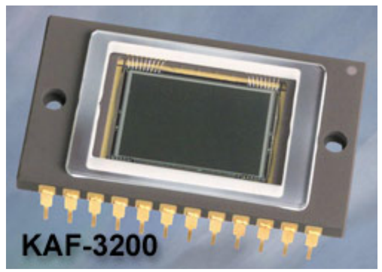
Single seising element

Line sensor

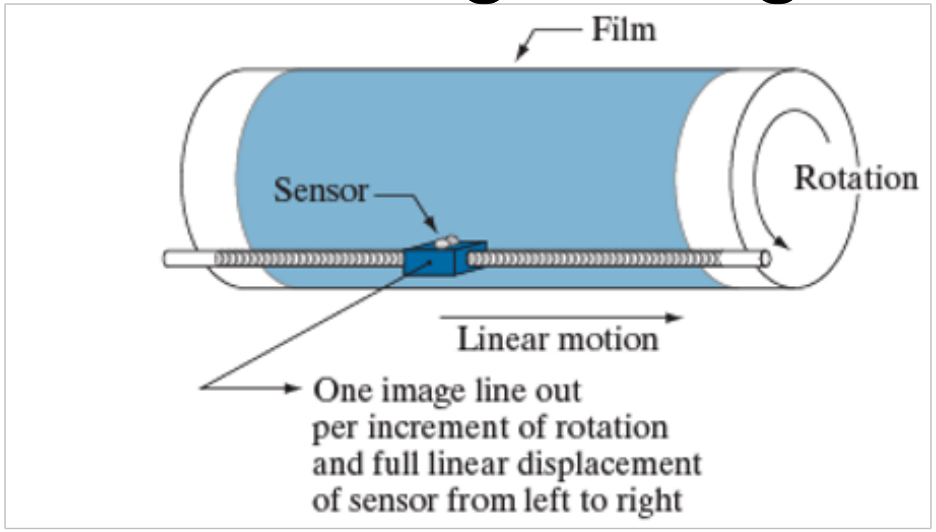
Array sensor




Charge-Coupled Device

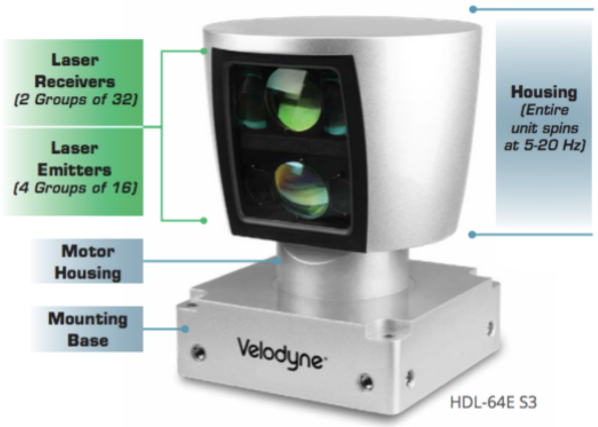


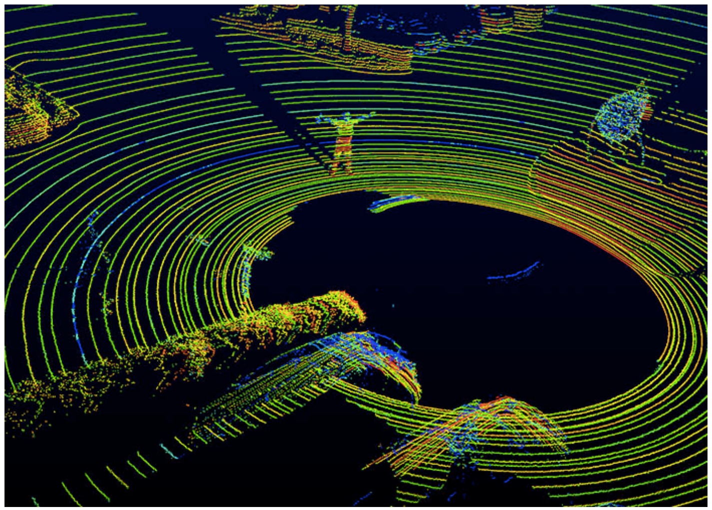
# 2.3 Image Sensing and Acquisition - Image Acquisition Using a Single Sensor



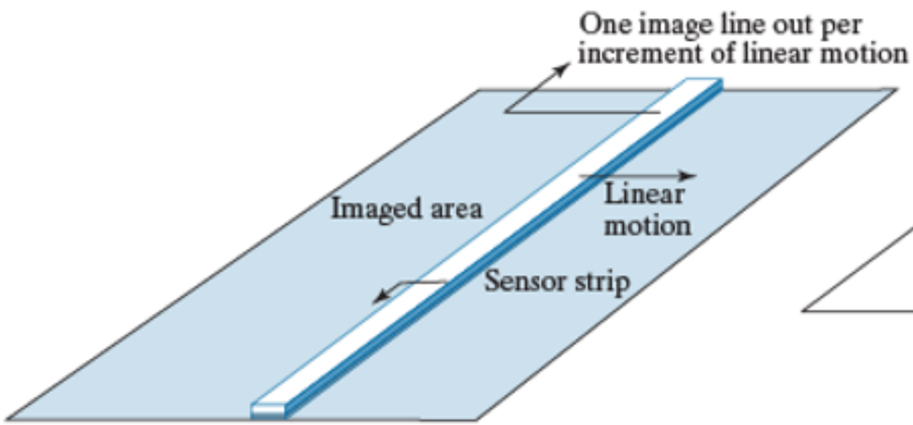

with mechanical motion to generate a 2D image, such as Microdensitometer (微密度計)

Current Laser Rangefinders, such as Lidar

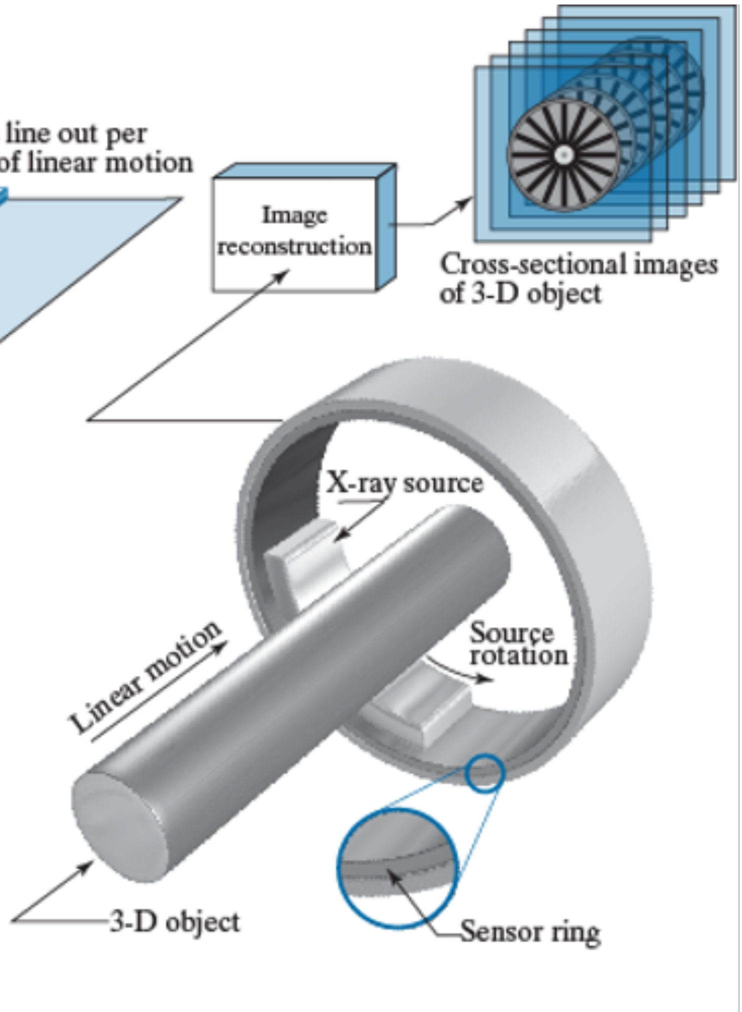


# 2.3 Image Sensing and Acquisition - Image Acquisition Using Sensor Strips

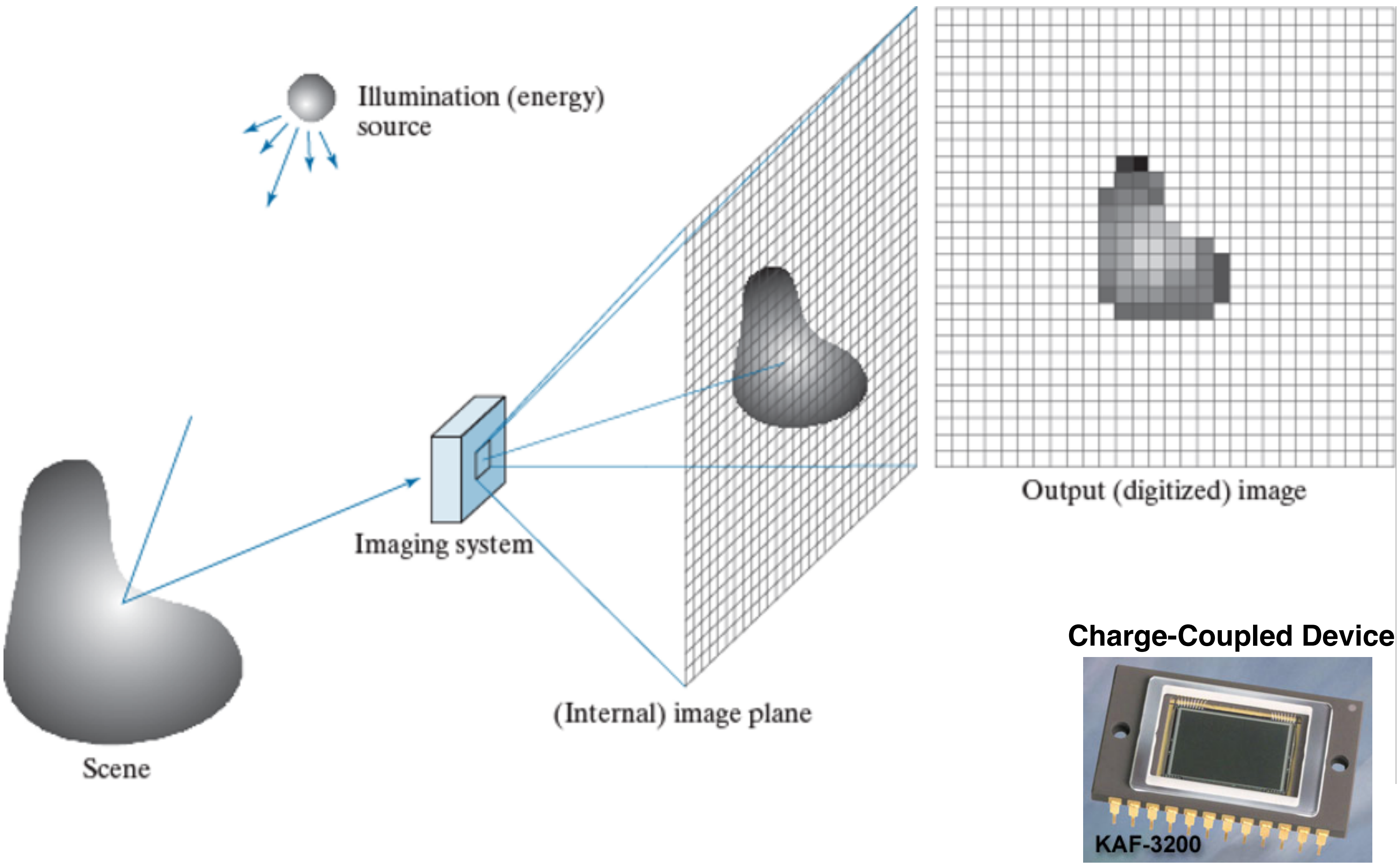



Linear sensor strip




Circular sensor strip

# 2.3 Image Sensing and Acquisition
# - Image Acquisition Using Sensor Arrays




Charge-Coupled Device

# 2.3 Image Sensing and Acquisition - A simple Image Formation Model

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

*i(x,y)*: the amount of source illumination incident on the scene

*r(x,y)*: the reflectivity function (or transmissivity function)

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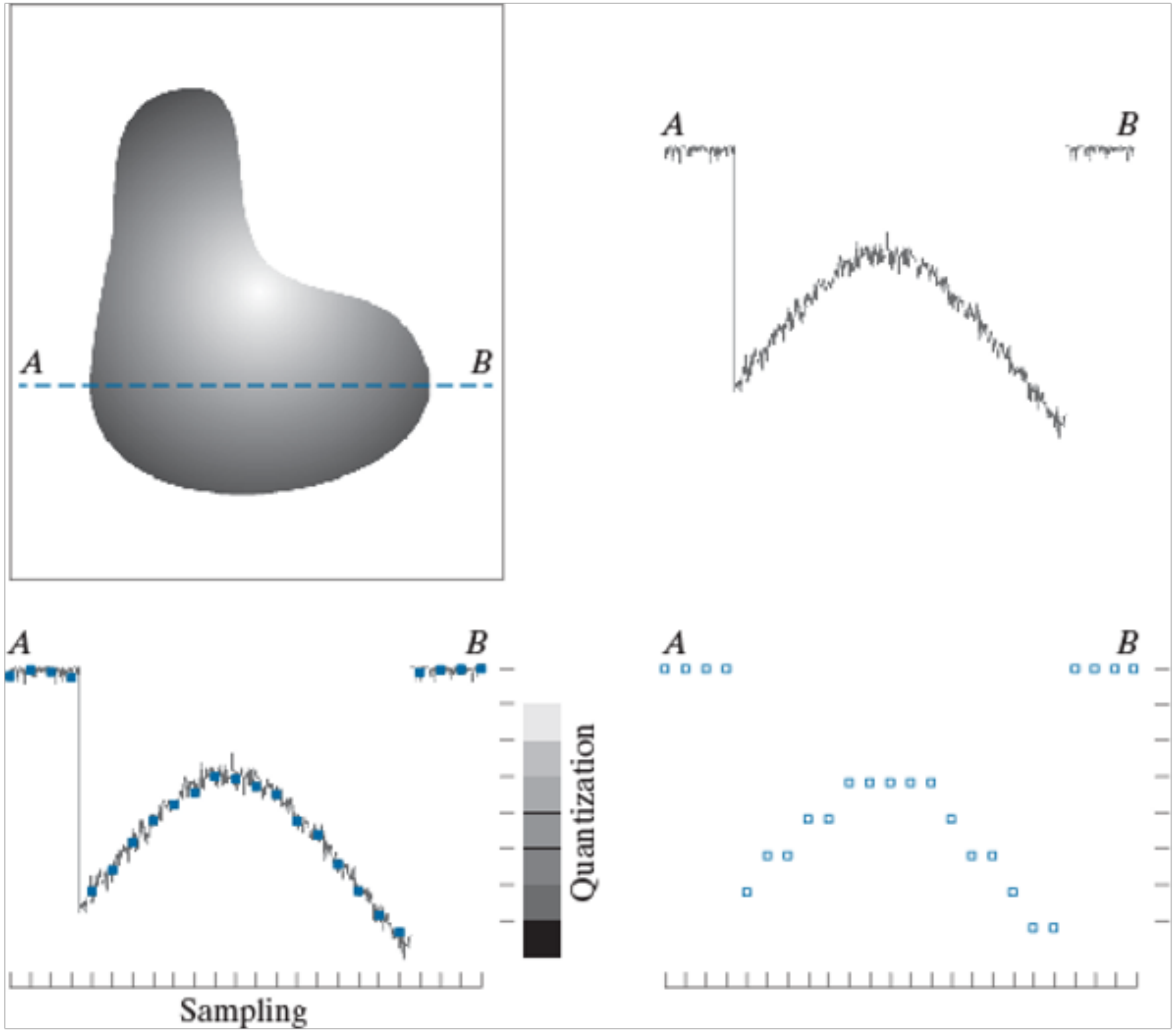
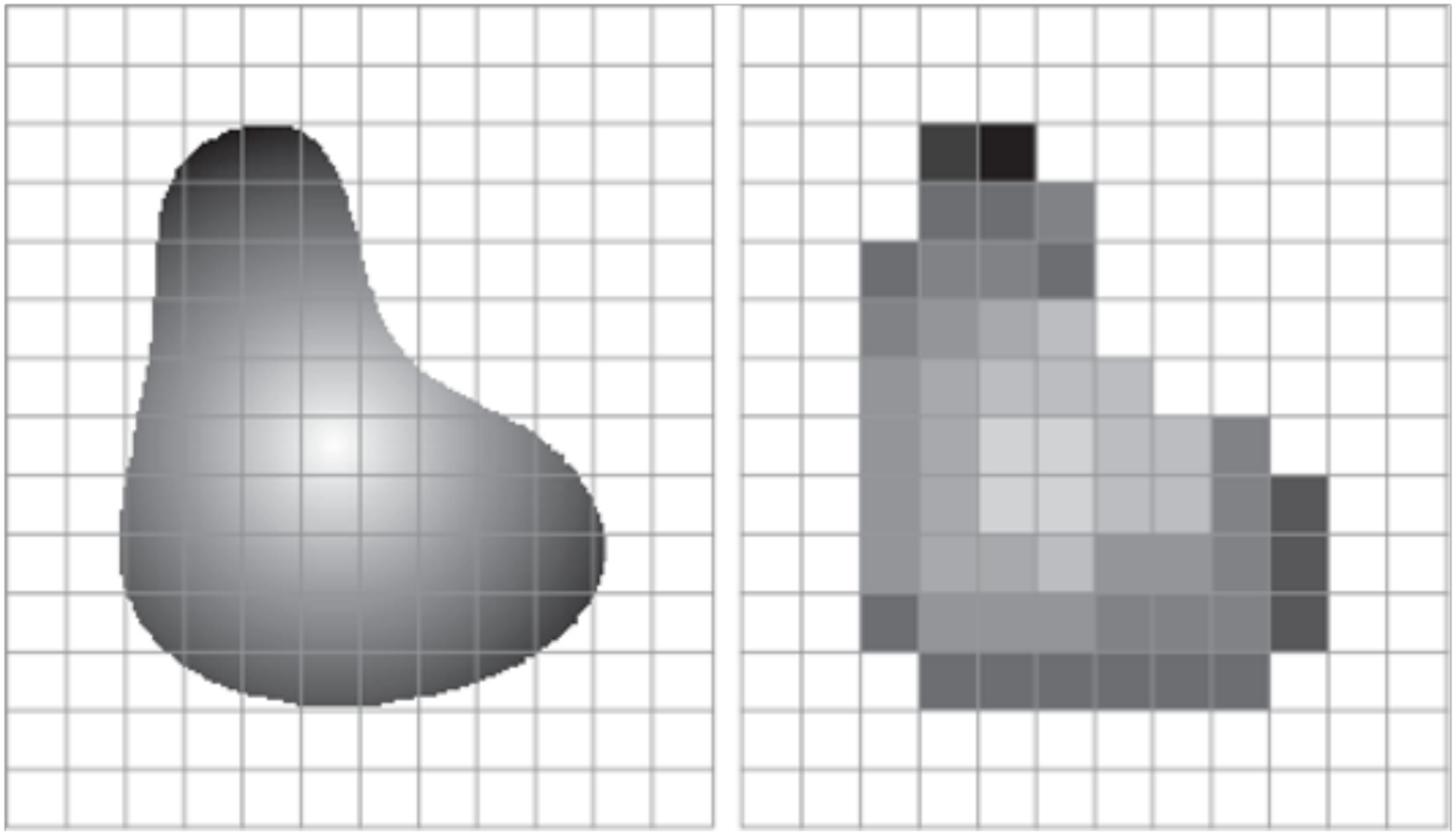
# 2.4 Image Sampling and Quantization



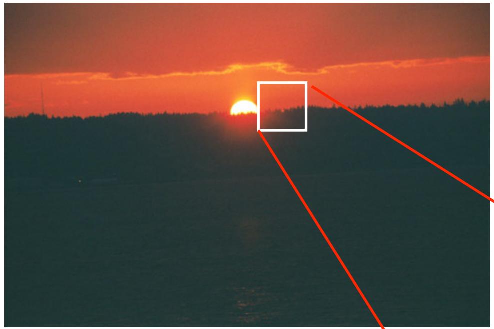

Digitizing the coordinate values is called **sampling**

Digitizing the amplitude is called **quantization**

# 2.4 Image Sampling and Quantization

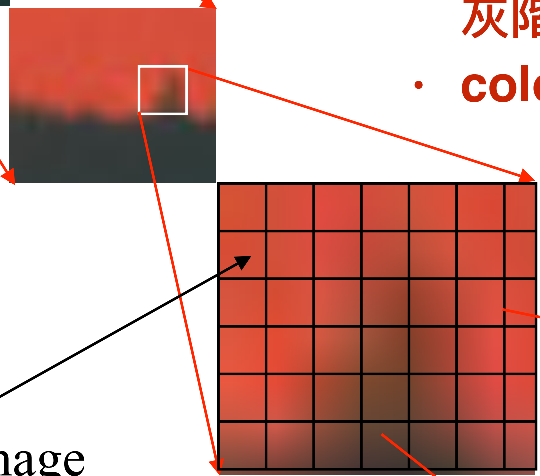


# 2.4 Image Sampling and Quantization - Representing Digital Images

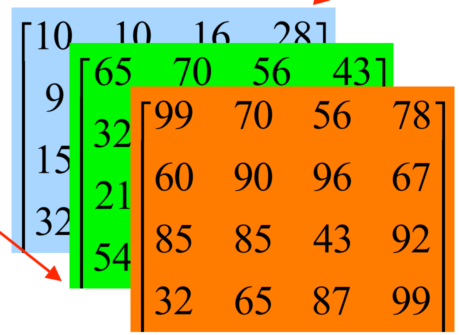


Digital image = a multidimensional array of numbers (such as intensity image) or vectors (such as color image)

- **grayscale image = intensity image: 灰階影像**
- **color image: 彩色影像**



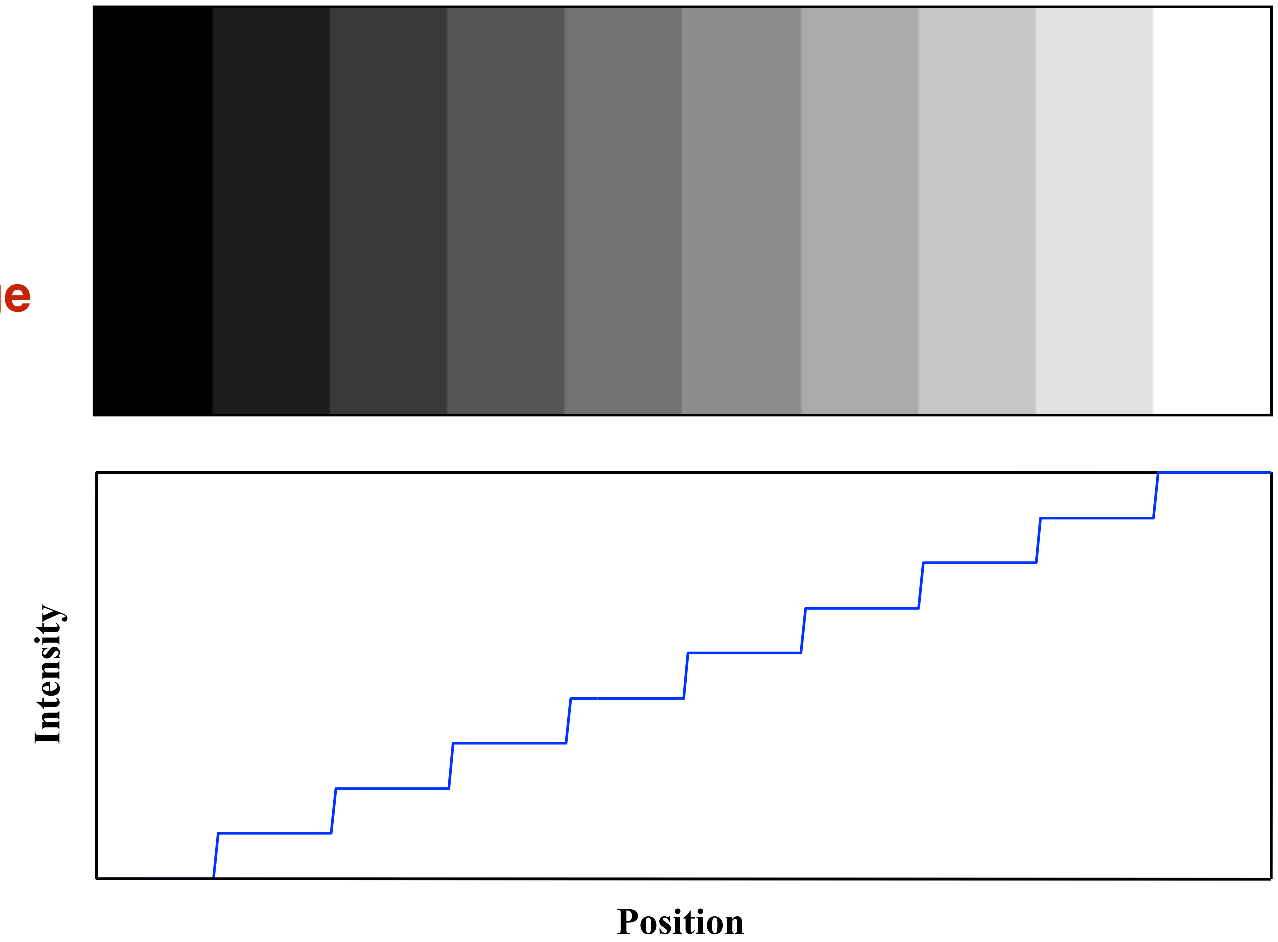
**Pixel: 像素**



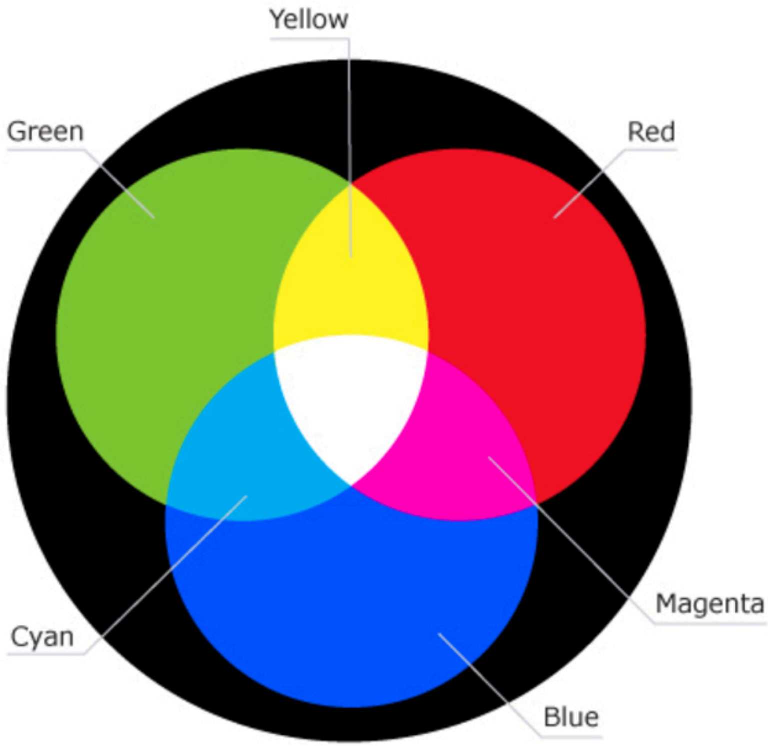

Each component in the image called pixel associates with the pixel value (a single number in the case of intensity images or a vector in the case of color images).

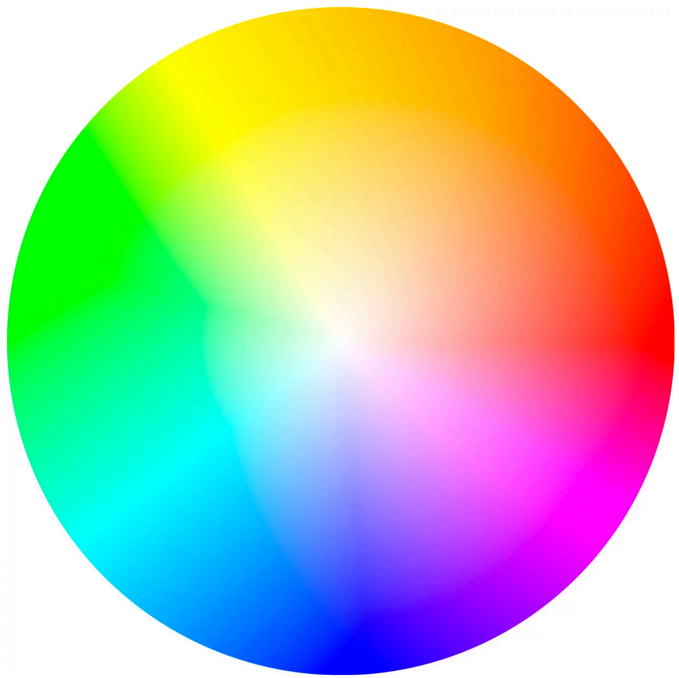
# 2.4 Image Sampling and Quantization - Representing Digital Images

**For grayscale image**
- **Intensity: 0 ~ 255**
- **1 byte for 1 pixel**



# 2.4 Image Sampling and Quantization - Representing Digital Images



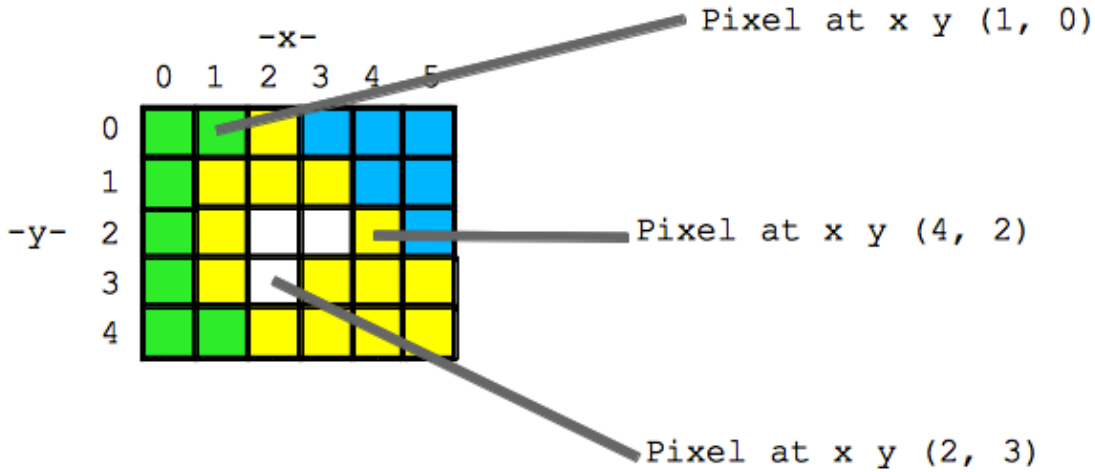



**For color image**

- **R: 0 ~ 255**
- **G: 0 ~ 255**
- **B: 0 ~ 255**
- **3 byte for 1 pixel, ex: 0x0000FF =** 

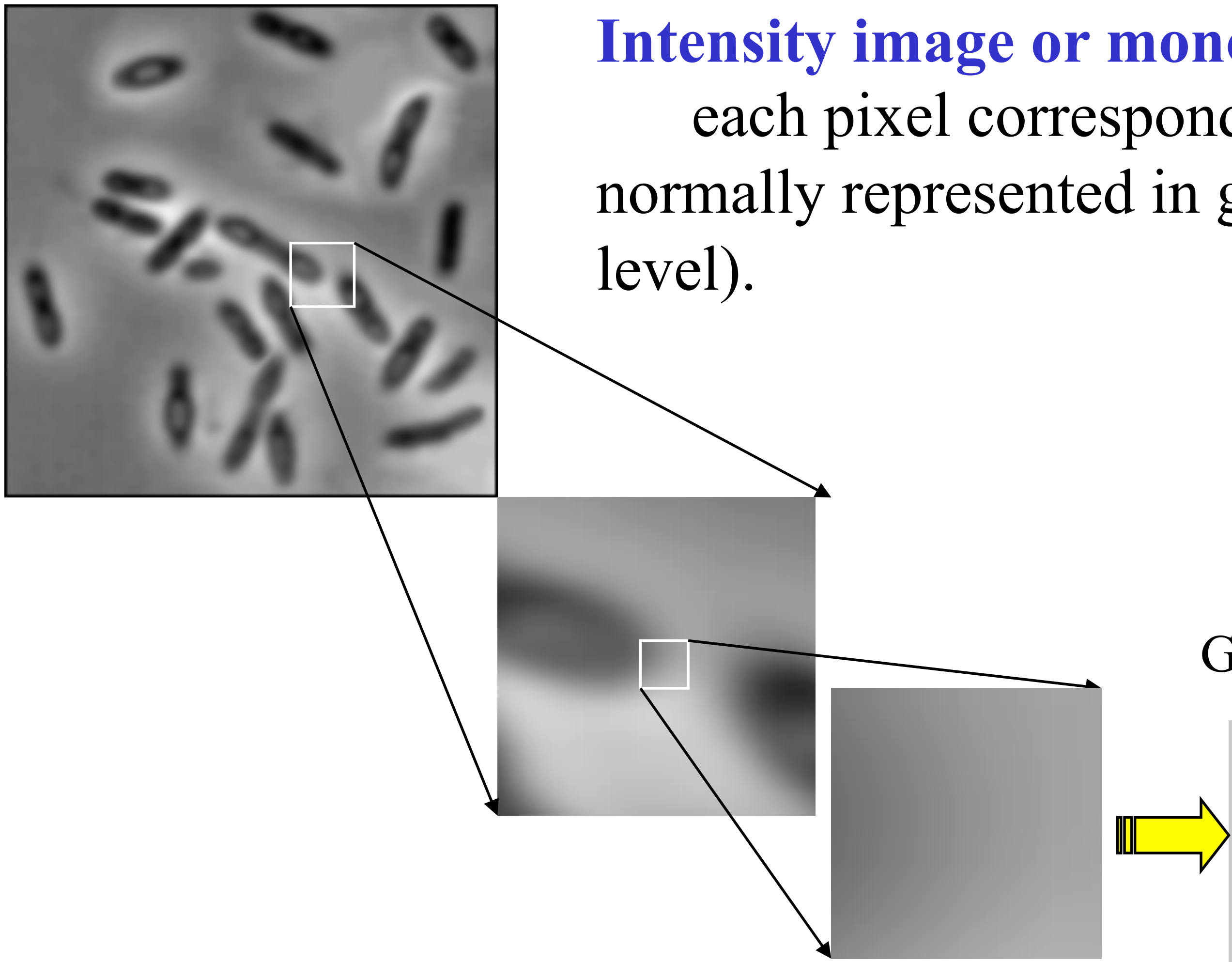
# 2.4 Image Sampling and Quantization - Representing Digital Images


Image "After snow storm"




- **An image**: **a multidimensional function of spatial coordinates**.
- **Spatial coordinate**: $(x,y)$ for 2D case such as photograph,
  $(x,y,z)$ for 3D case such as CT scan images
  $(x,y,t)$ for movies
- The function $f$ may represent intensity (for monochrome images) or color (for color images) or other associated values.

# 2.4 Image Sampling and Quantization - Representing Digital Images



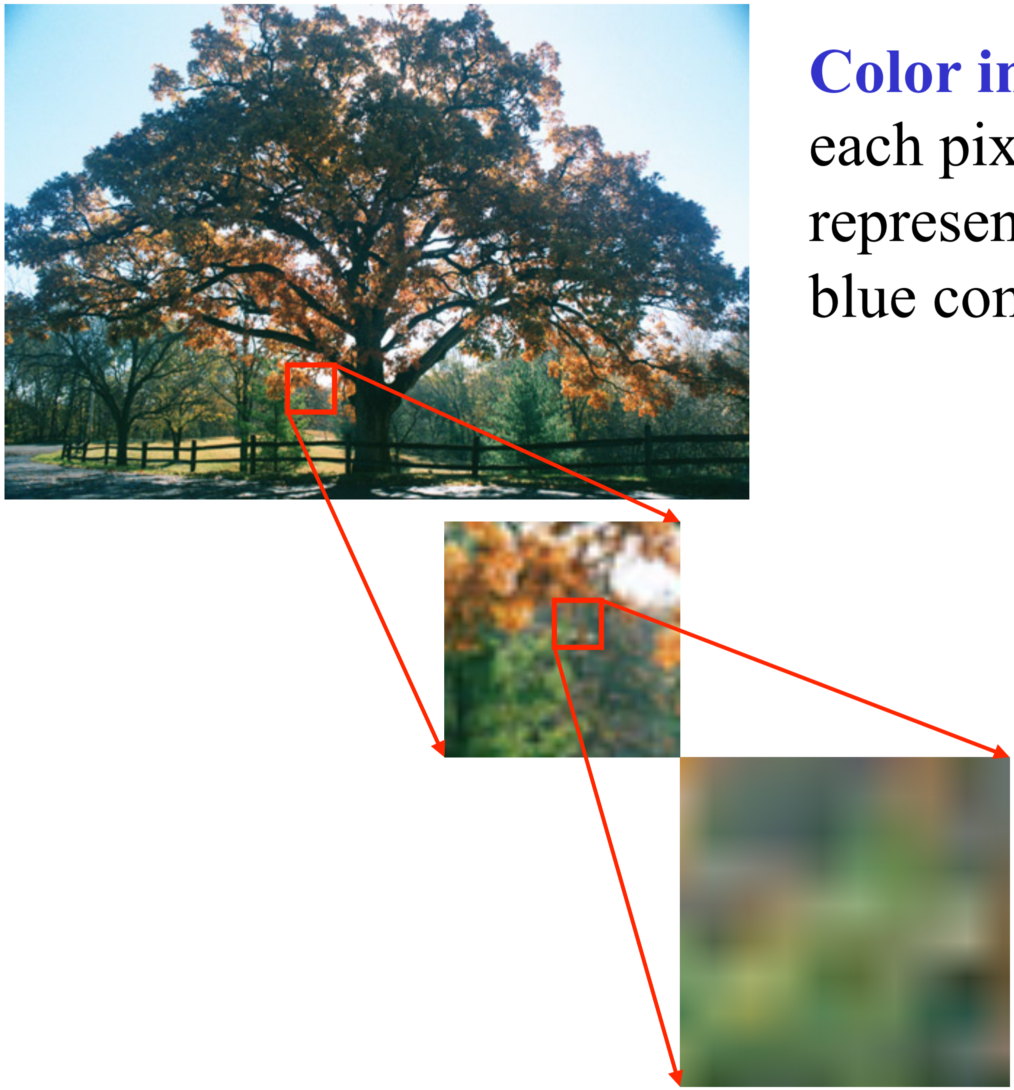
**Intensity image or monochrome image**

each pixel corresponds to light intensity normally represented in gray scale (gray level).

Gray scale values

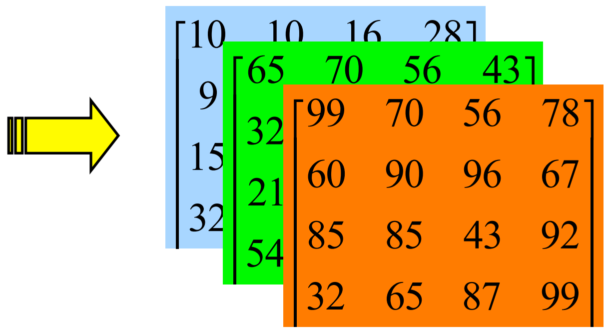
$$\begin{bmatrix} 10 & 10 & 16 & 28 \\ 9 & 6 & 26 & 37 \\ 15 & 25 & 13 & 22 \\ 32 & 15 & 87 & 39 \end{bmatrix}$$

# 2.4 Image Sampling and Quantization - Representing Digital Images



**Color image or RGB image**: each pixel contains a vector representing red, green and blue components.

RGB components



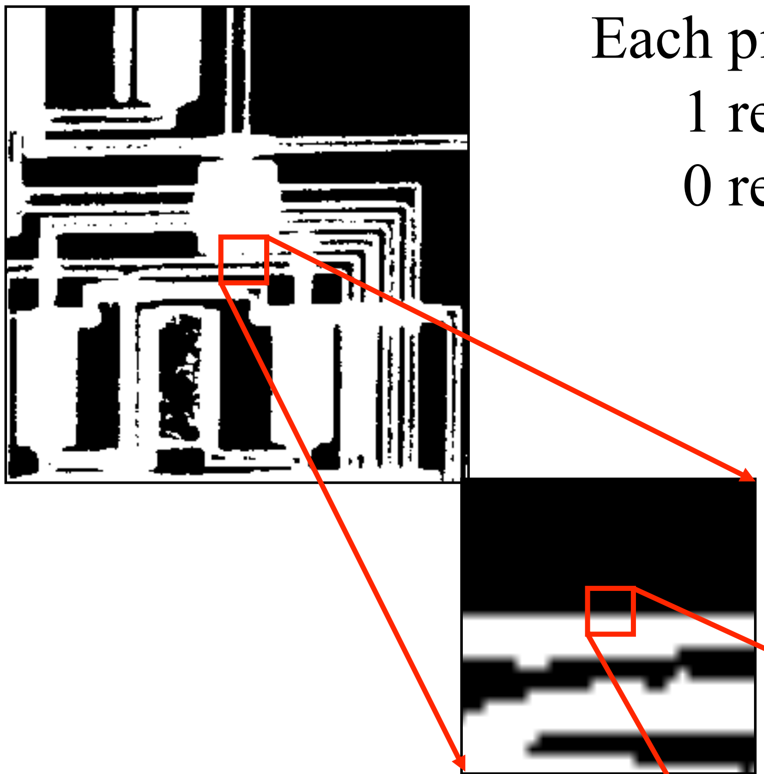
# 2.4 Image Sampling and Quantization - Representing Digital Images

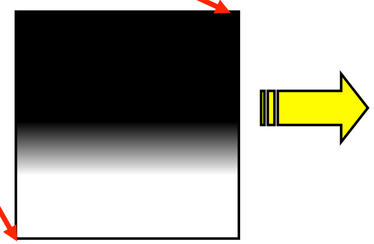
**Binary image or black and white image**

Each pixel contains one bit :

1 represent white

0 represents black





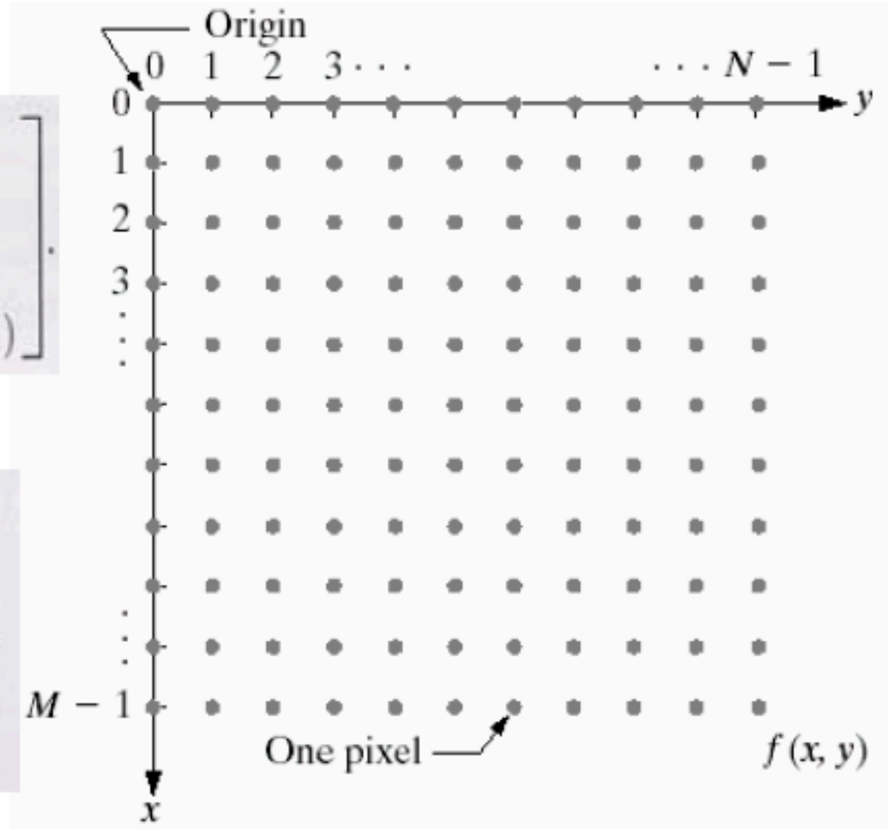
Binary data

$$\begin{bmatrix} 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ 1 & 1 & 1 & 1 \\ 1 & 1 & 1 & 1 \end{bmatrix}$$

# 2.4 Image Sampling and Quantization - Representing Digital Images

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

$$\mathbf{A} = \begin{bmatrix} a_{0,0} & a_{0,1} & \cdots & a_{0,N-1} \\ a_{1,0} & a_{1,1} & \cdots & a_{1,N-1} \\ \vdots & \vdots & & \vdots \\ a_{M-1,0} & a_{M-1,1} & \cdots & a_{M-1,N-1} \end{bmatrix}.$$



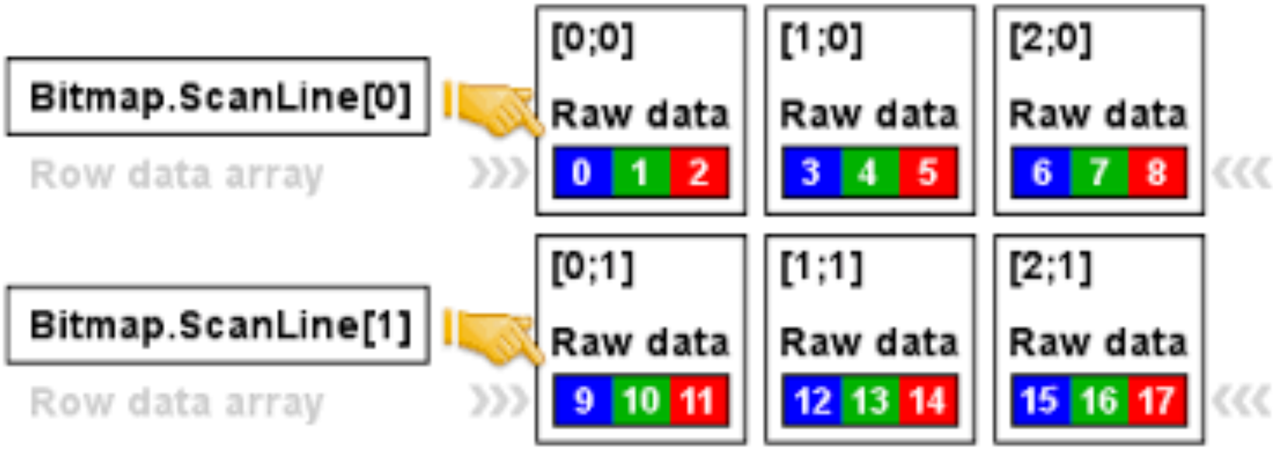

credit of this slide: Y. P. Hung

# 2.4 Image Sampling and Quantization - Representing Digital Images

## Bitmap (BMP)

A typical BMP file usually contains the following blocks of data:

- **BMP File Header:** Stores general information about the BMP file.
- **DIB header:** Stores detailed information about the bitmap image.
- **Color Palette:** Stores the definition of the colors being used for indexed color bitmaps.
    - Image pixels are stored with a color depth of 1, 4, 8, 16, 24, or 32 bits per pixel
- **Bitmap Data**: Stores the actual image, pixel by pixel.



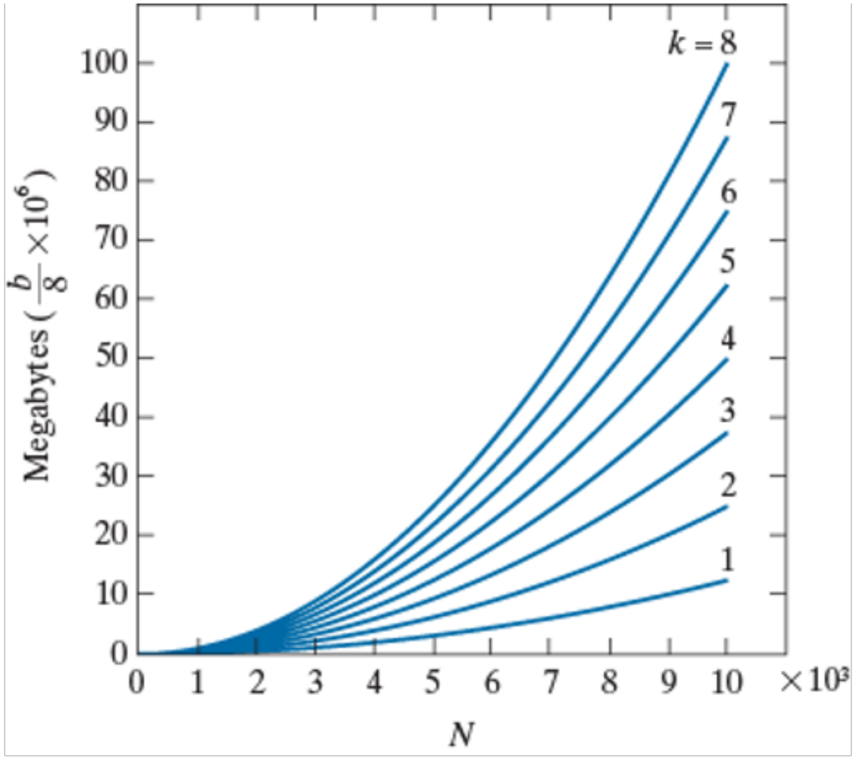
# 2.4 Image Sampling and Quantization - Image Size

Number of bits

bits per pixel

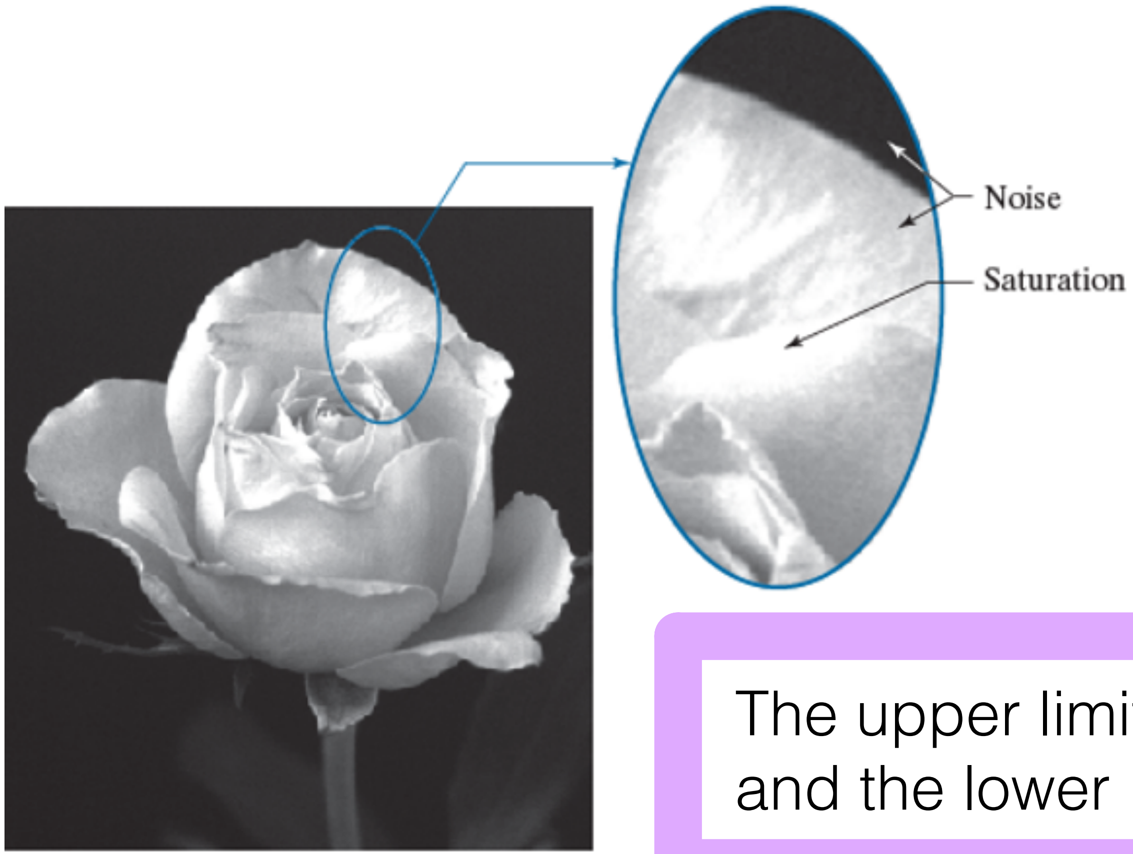
$$b = M \times N \times k$$

Number of megabytes required to store images with $M = N$



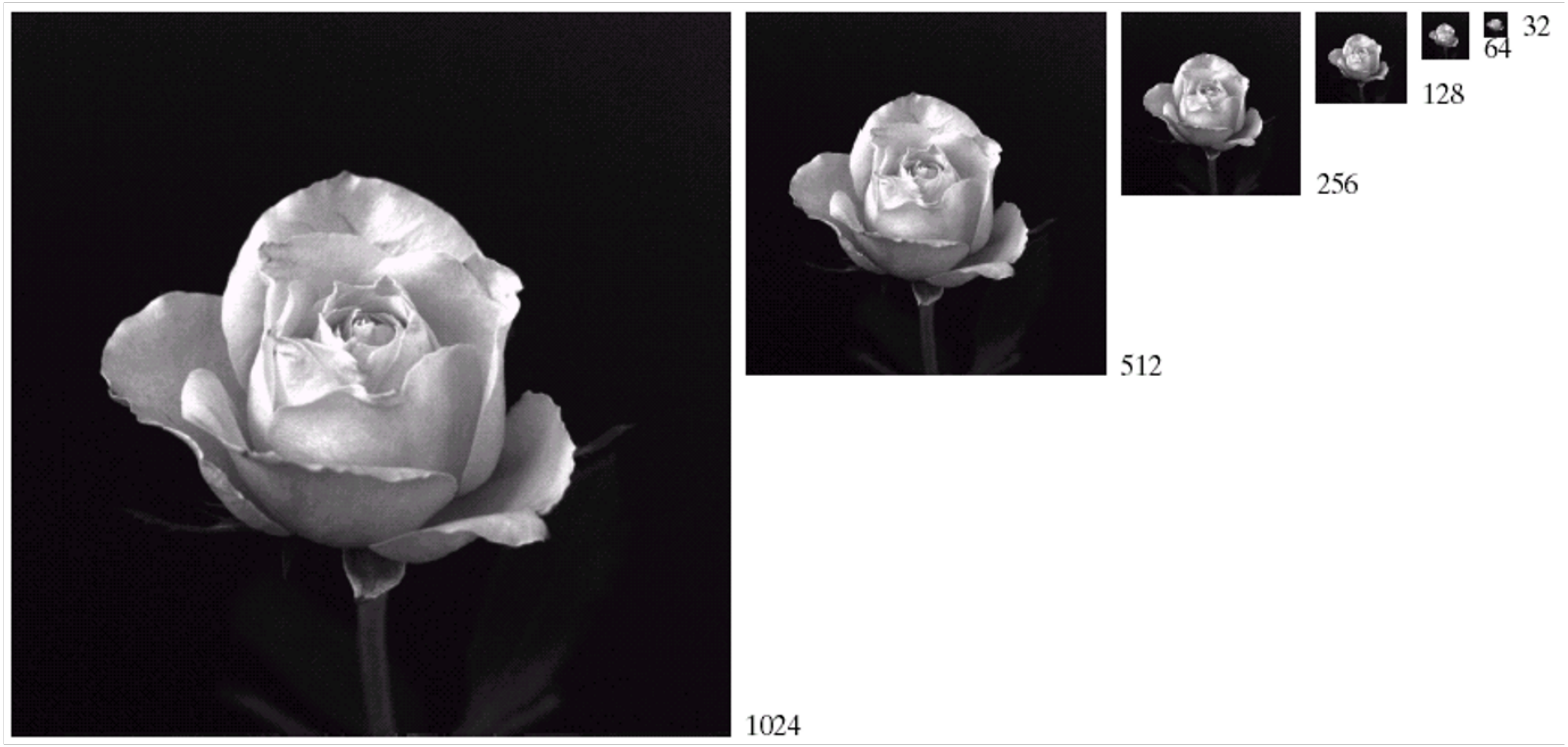
# 2.4 Image Sampling and Quantization - Image Saturation and Noise

Dynamic Range: the range of values spanned by gray scale

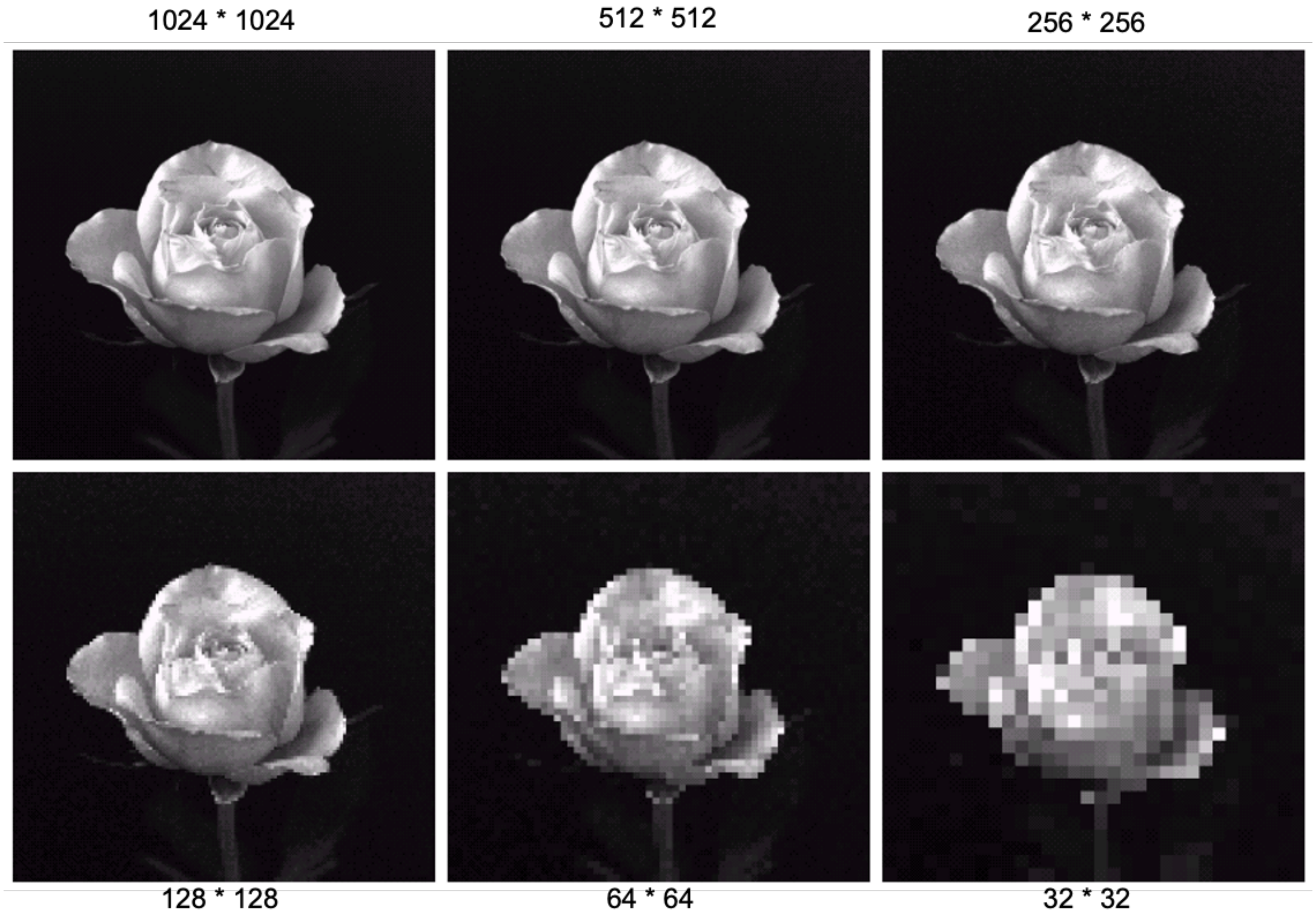



The upper limit is determined by *saturation* and the lower limit by *noise*.

# 2.4 Image Sampling and Quantization - Spatial Resolution



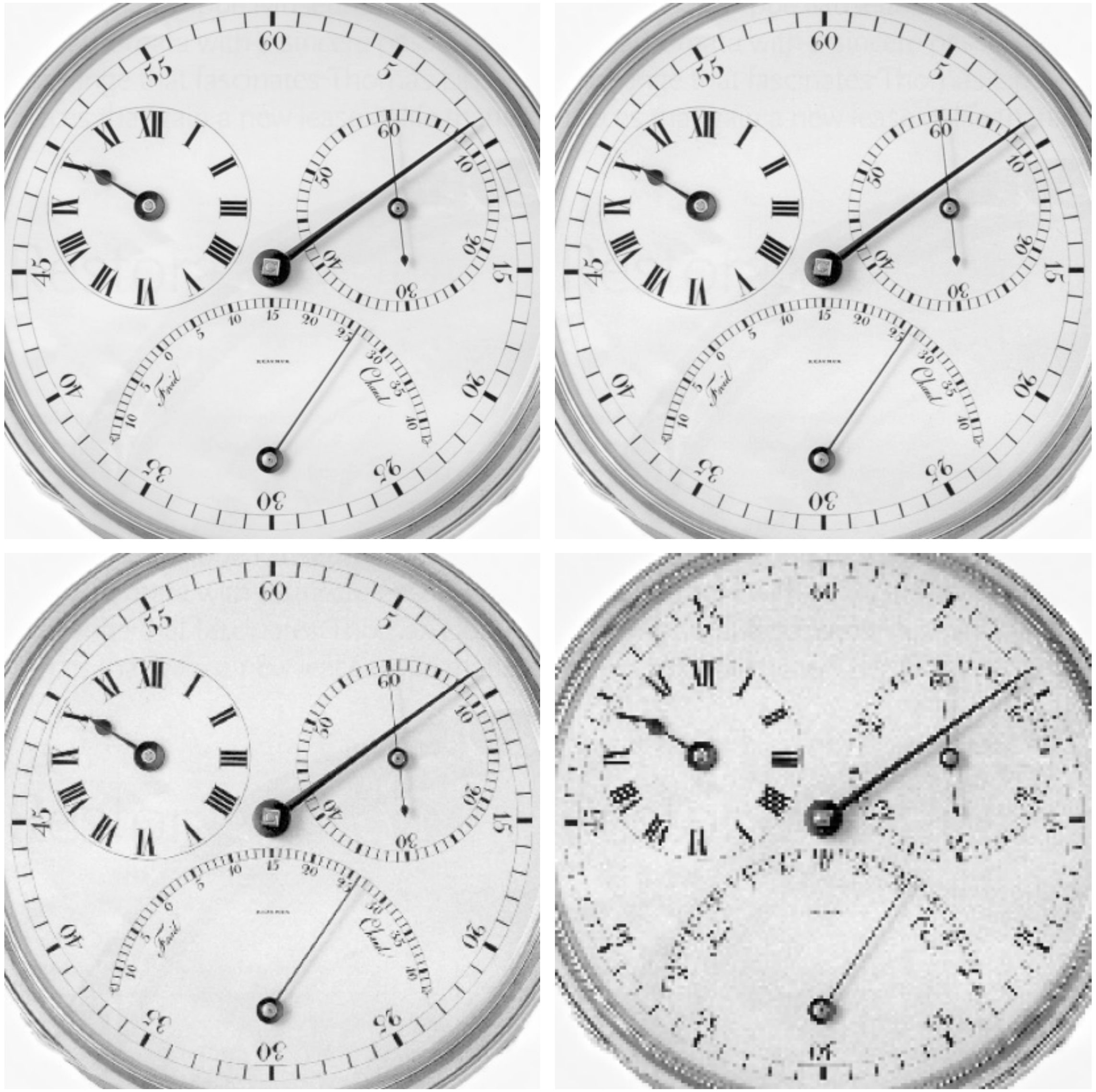
# 2.4 Image Sampling and Quantization - Spatial Resolution



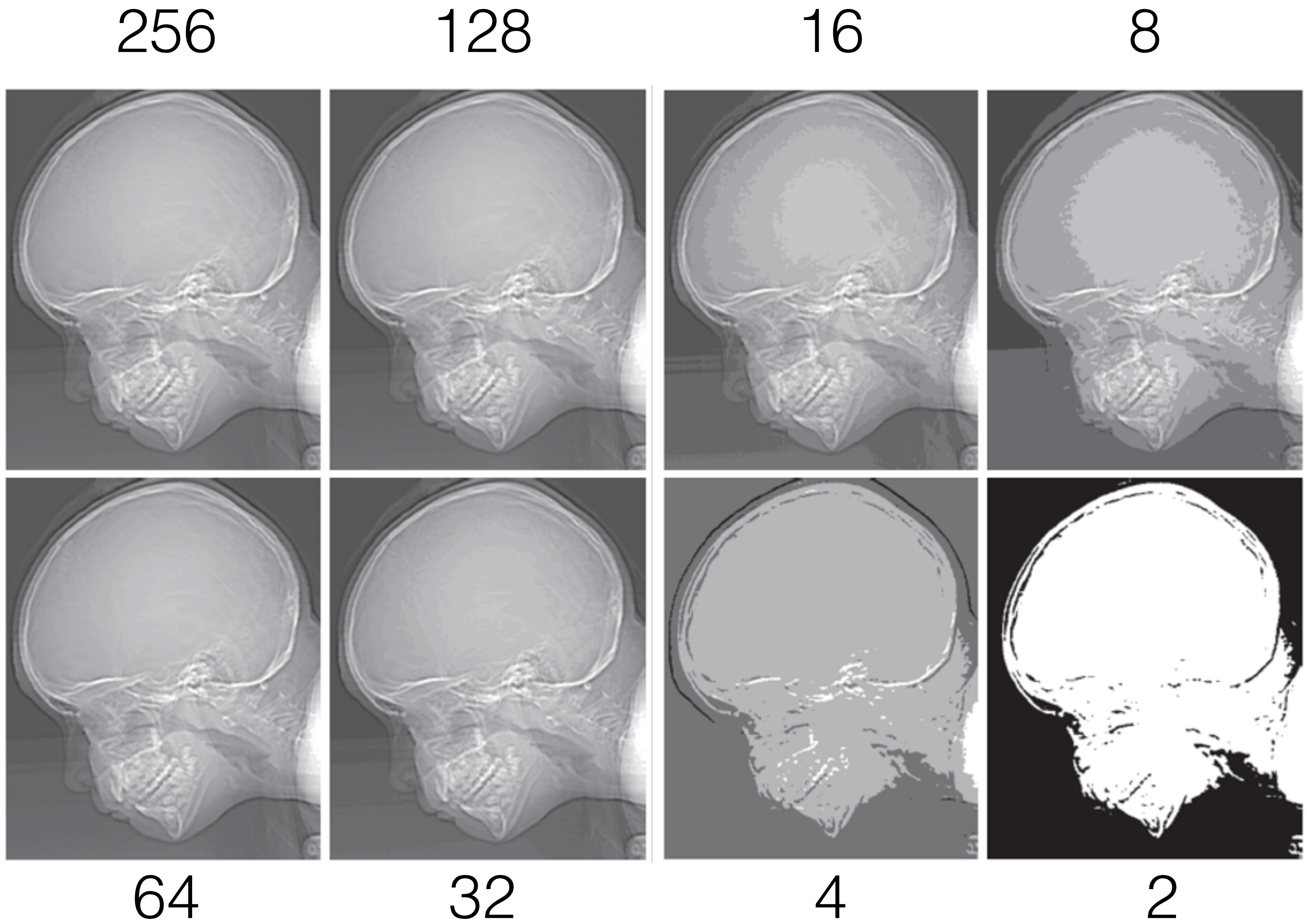
# 2.4 Image Sampling and Quantization - Spatial Resolution

a b
c d

**FIGURE 2.23** Effects of reducing spatial resolution. The images shown are at: (a) 930 dpi, (b) 300 dpi, (c) 150 dpi, and (d) 72 dpi.



# 2.4 Image Sampling and Quantization - Intensity Resolution



# 2.4 Image Sampling and Quantization - Spatial and Intensity Resolution

The big question with resolution is always *how much is enough*?

- This all depends on what is in the image and what you would like to do with it
- Key questions include
  - Does the image look aesthetically pleasing?
  - Can you see what you need to see within the image?

credit of this slide: C. Nikou

# 2.4 Image Sampling and Quantization - Spatial and Intensity Resolution


The picture on the right is fine for counting the number of cars, but not for reading the number plate

credit of this slide: C. Nikou

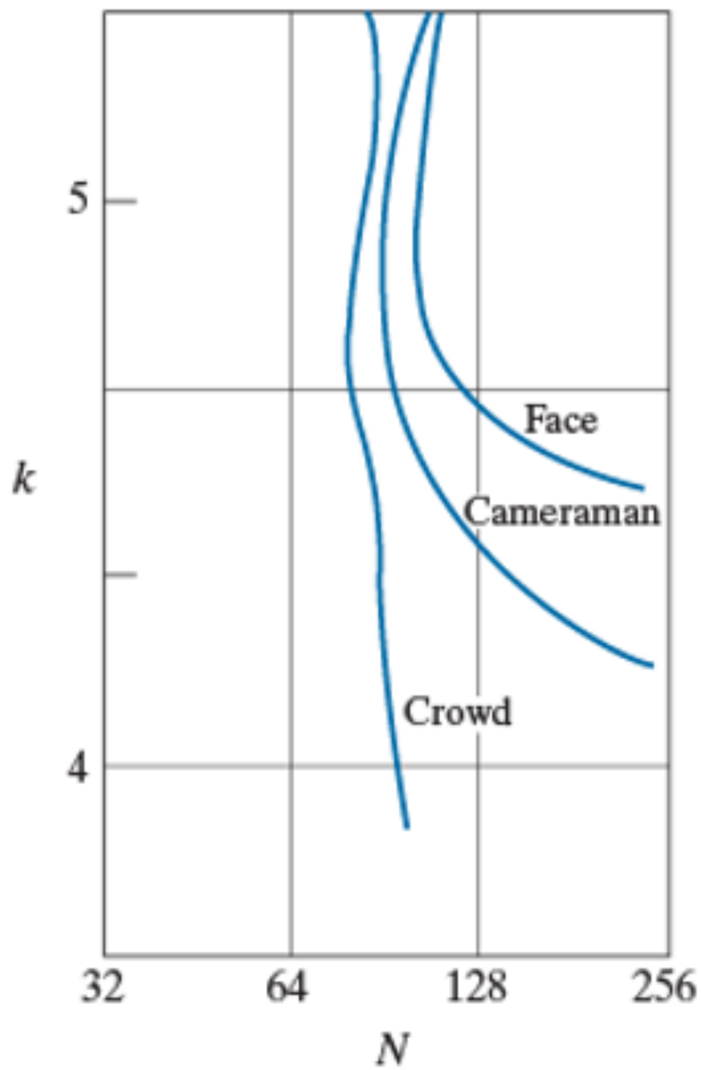
# 2.4 Image Sampling and Quantization - Spatial and Intensity Resolution

a b c

**FIGURE 2.25** (a) Image with a low level of detail. (b) Image with a medium level of detail. (c) Image with a relatively large amount of detail. (Image (b) courtesy of the Massachusetts Institute of Technology.)

# 2.4 Image Sampling and Quantization - Spatial and Intensity Resolution

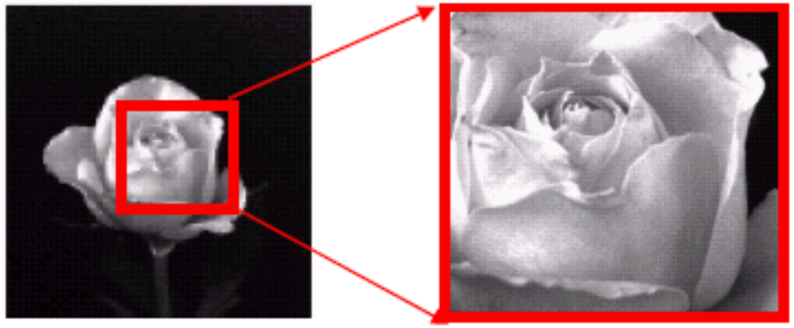
**Isopreference curves**.
Represent the dependence between intensity and spatial resolutions.
Points lying on a curve represent images of “equal” quality as described by observers.
They become more vertical as the degree of detail increases (a lot of detail need less intensity levels), e.g. in the *Crowd* image, for a given value of *N*, *k* is almost constant.



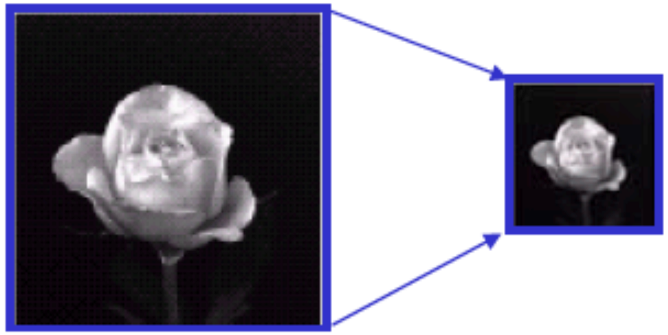

credit of this slide: C. Nikou

# 2.4 Image Sampling and Quantization - Image Interpolation

- Zooming: oversampling
  - Need *interpolation*
  - "superresolution"



- Shrinking: undersampling
  - Better to apply LPF before subsampling to avoid aliasing
  - Need *interpolation* for non-integer factor

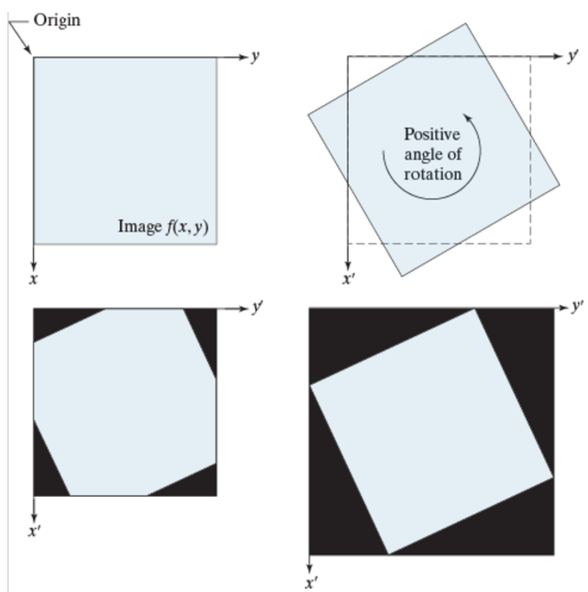


credit of this slide: Y. P. Hung

# 2.4 Image Sampling and Quantization
# - Image Interpolation

- Nearest Neighbor Interpolation
- Bilinear Interpolation
- Bicubic Interpolation
- etc

Applications

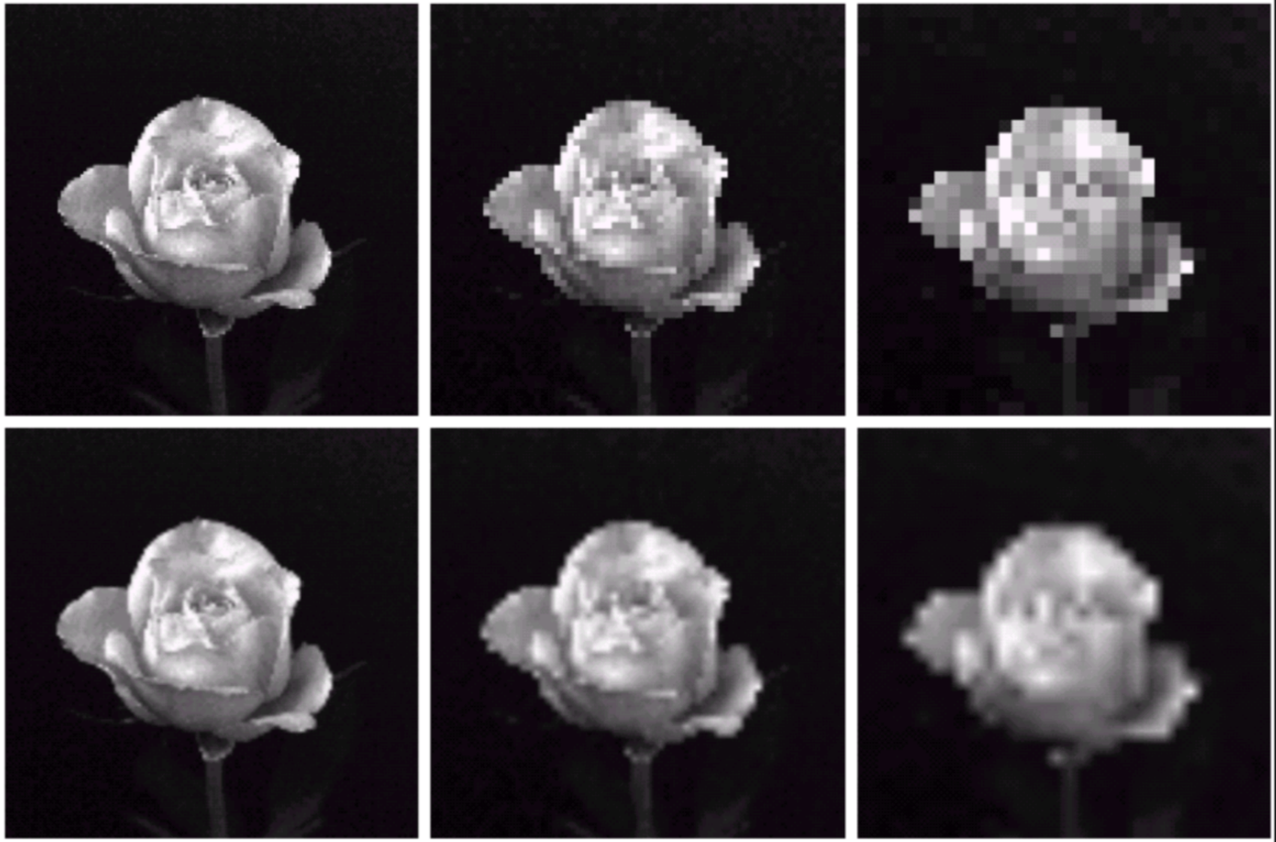



- Image Scaling/Resize
- Image Rotation
- Image Warping
- Image Morphing
- ……

credit of this slide: Y. P. Hung

# 2.4 Image Sampling and Quantization - Image Interpolation

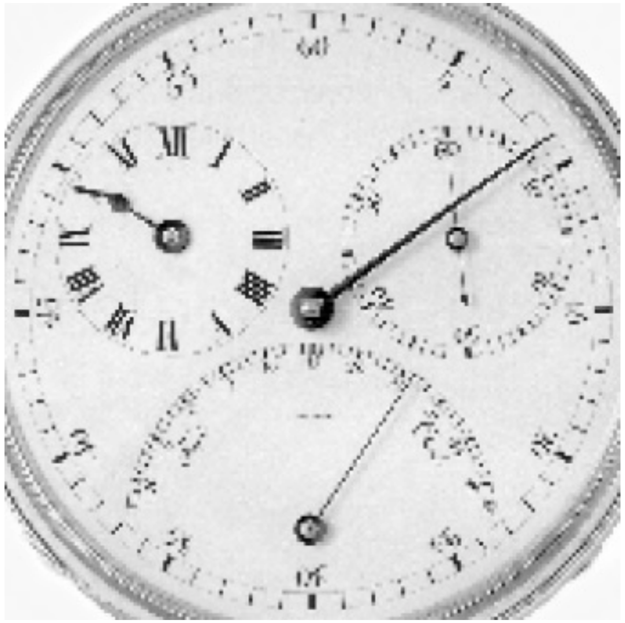
- Nearest-Neighbor Interpolation
- Bilinear Interpolation



| a | b | c |
|---|---|---|
| d | e | f |

**FIGURE 2.25** Top row: images zoomed from 128 × 128, 64 × 64, and 32 × 32 pixels to 1024 × 1024 pixels, using nearest neighbor gray-level interpolation. Bottom row: same sequence, but using bilinear interpolation.

# 2.4 Image Sampling and Quantization - Image Interpolation



Nearest Neighbor Interpolation

Bilinear Interpolation

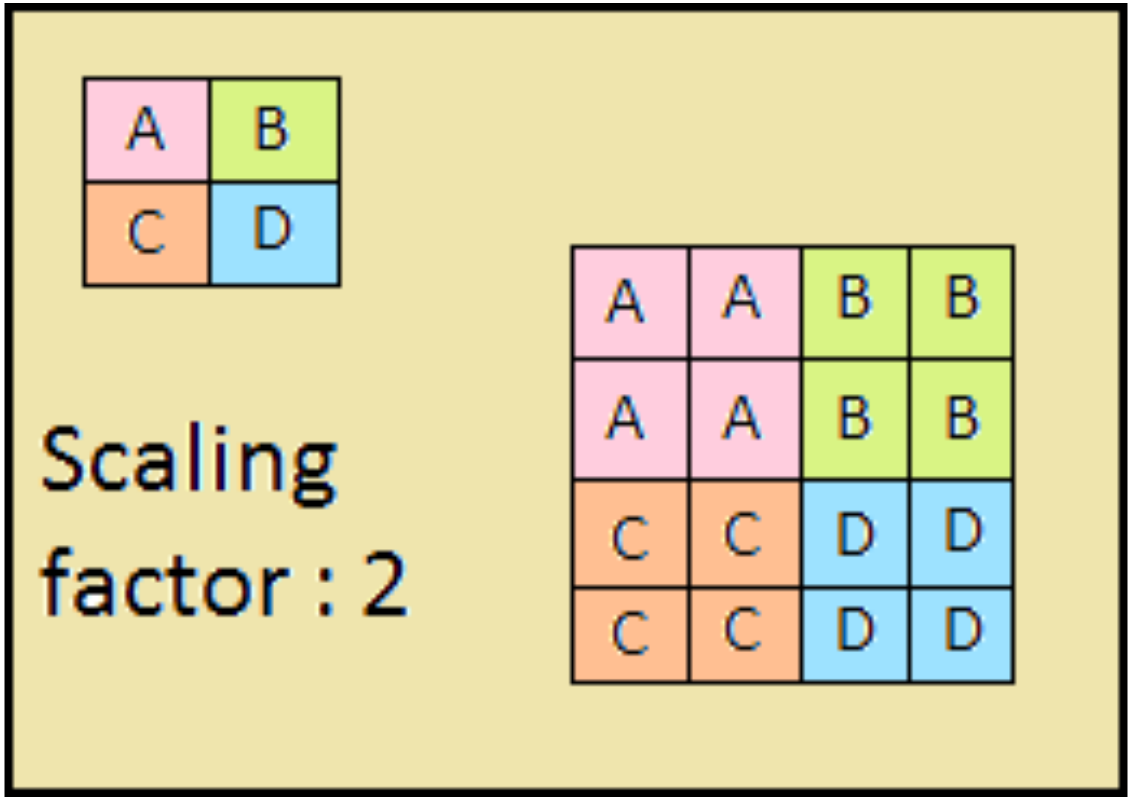
Bicubic Interpolation

a b c

**FIGURE 2.27** (a) Image reduced to 72 dpi and zoomed back to its original 930 dpi using nearest neighbor interpolation. This figure is the same as Fig. 2.23(d). (b) Image reduced to 72 dpi and zoomed using bilinear interpolation. (c) Same as (b) but using bicubic interpolation.

# 2.4 Image Sampling and Quantization - Image Interpolation

**Nearest Neighbor Interpolation**

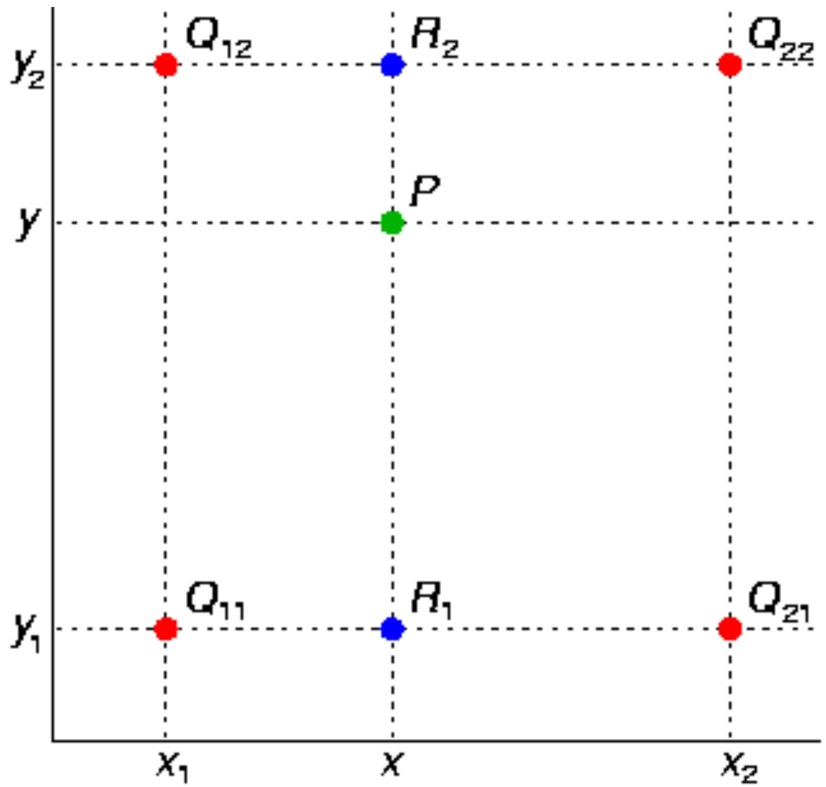


# 2.4 Image Sampling and Quantization - Image Interpolation

**Bilinear Interpolation**

$$f(x, y_1) \approx \frac{x_2 - x}{x_2 - x_1} f(Q_{11}) + \frac{x - x_1}{x_2 - x_1} f(Q_{21}),$$
$$f(x, y_2) \approx \frac{x_2 - x}{x_2 - x_1} f(Q_{12}) + \frac{x - x_1}{x_2 - x_1} f(Q_{22}).$$

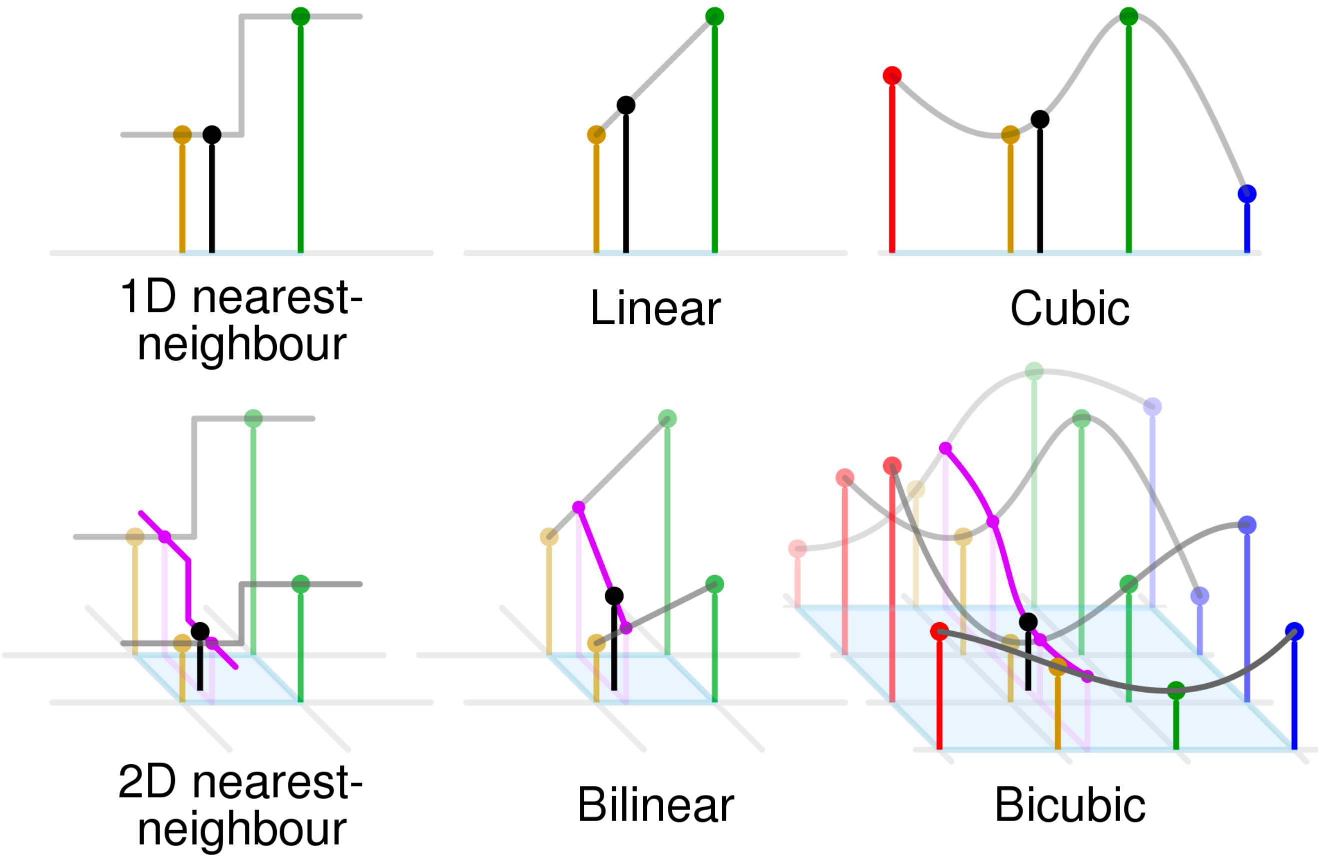
$$f(x, y) \approx \frac{y_2 - y}{y_2 - y_1} f(x, y_1) + \frac{y - y_1}{y_2 - y_1} f(x, y_2)$$



# 2.4 Image Sampling and Quantization - Image Interpolation

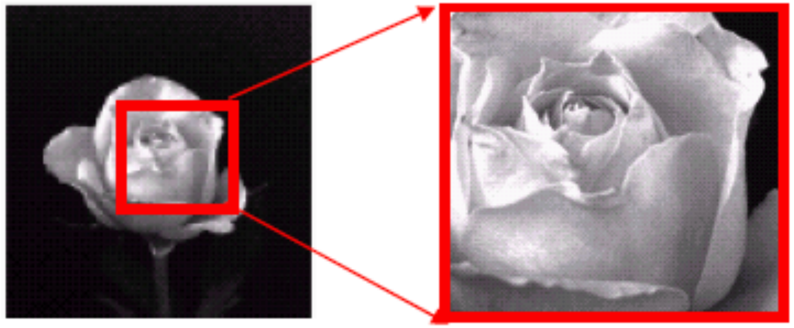
**Bicubic Interpolation**

$$p(x,y) = \sum_{i=0}^{3} \sum_{j=0}^{3} a_{ij} x^i y^j.$$

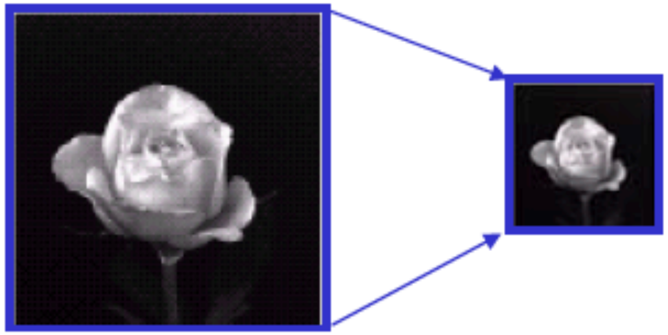



https://en.wikipedia.org/wiki/Bicubic_interpolation

# 2.4 Image Sampling and Quantization - Image Interpolation



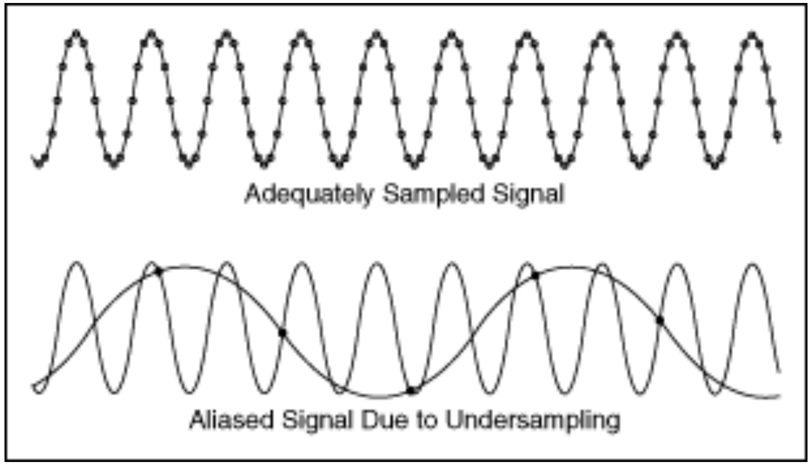
- Zooming: oversampling
  - Need *interpolation*
  - "superresolution"

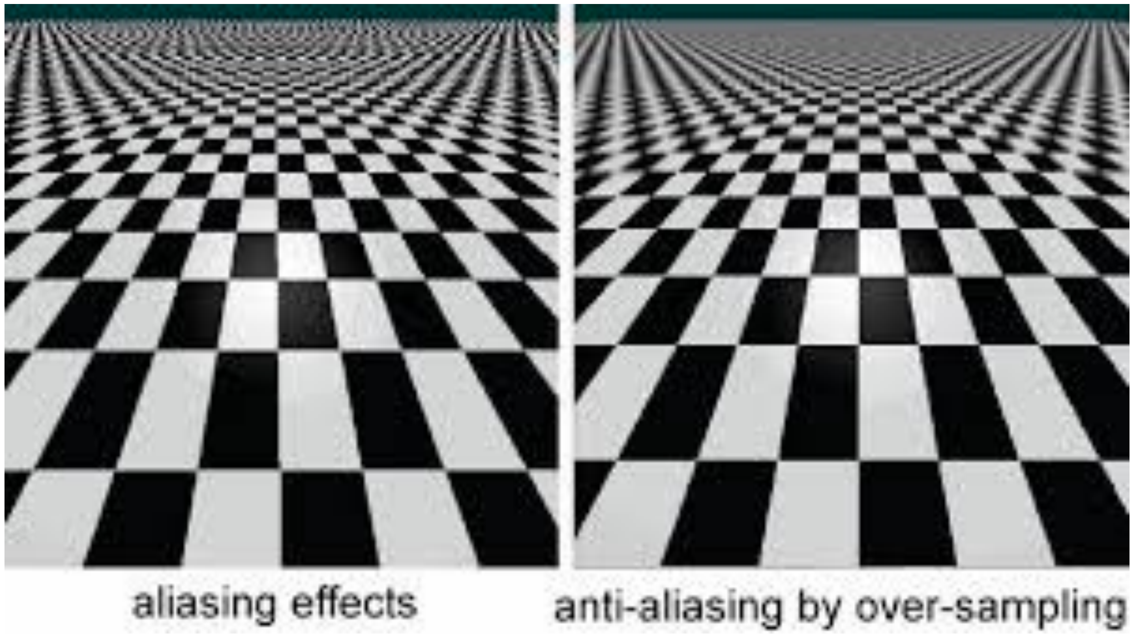


- Shrinking: undersampling
  - Better to apply LPF before subsampling to avoid aliasing
  - Need *interpolation* for non-integer factor

credit of this slide: Y. P. Hung

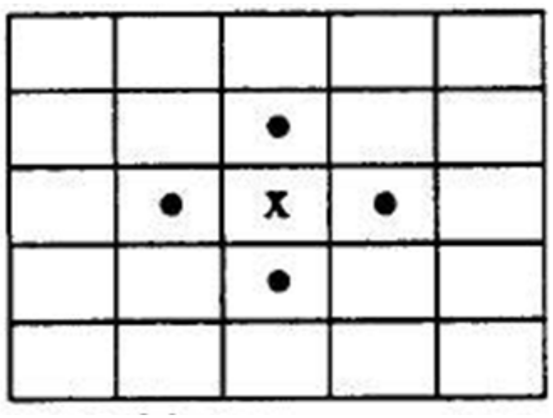
# 2.4 Image Sampling and Quantization - Aliasing



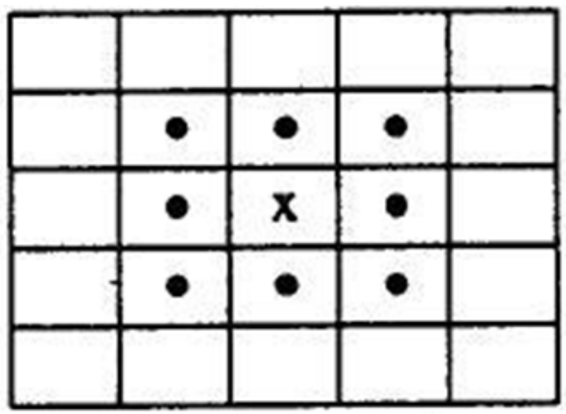



# 2.5 Some Basic Relationships Between Pixels - Neighbors of a Pixel

- 4-neighbors of $p$, $N_4(p)$



- 8-neighbors of $p$, $N_8(p)$



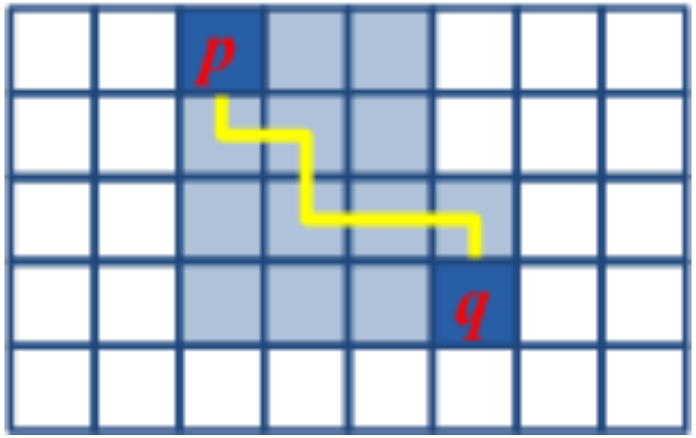
- Four diagonal neighbors of $p$, $N_D(p)$

# 2.5 Some Basic Relationships Between Pixels - Adjacency

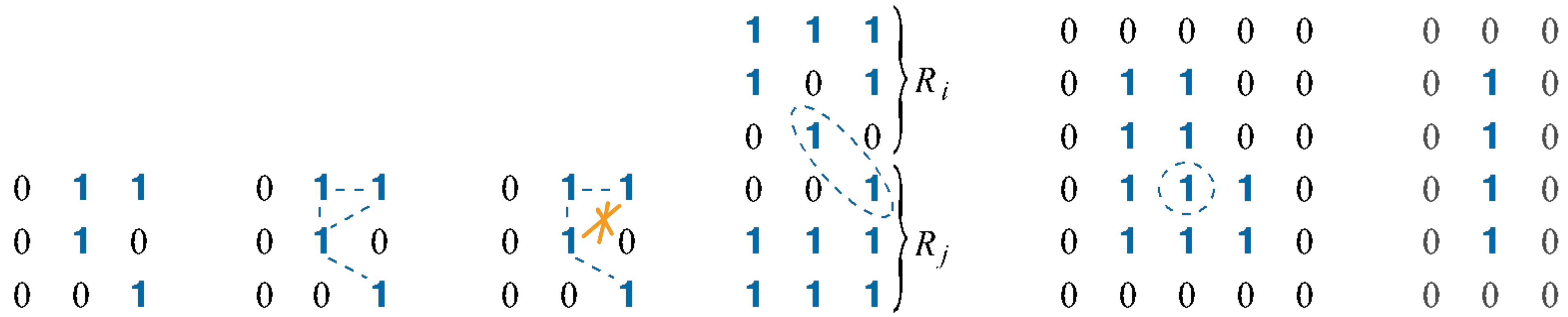
- ***4-adjacency***
  - Two pixels *p* and *q* are 4-adjacent if *q* is in the set $N_4(p)$.
- ***8-adjacency***
  - Two pixels *p* and *q* are 8-adjacent if *q* is in the set $N_8(p)$.
- ***m-adjacency*** (*mixed adjacency*)
  - Two pixels *p* and *q* are *m*-adjacent if
    - (a) *q* is in $N_4(p)$, or
    - (b) *q* is in $N_D(p)$ and the set $N_4(p) \cap N_4(q) = \varnothing$

# 2.5 Some Basic Relationships Between Pixels - Connectivity, Regions, and Boundaries

- **Connected component**
  - Definition of Connected Component
    - Two pixels $p$ and $q$ belong to the same connected component $C$ if there is a sequence of 1-pixels $(p_0, p_1, \ldots p_n)$, where
      - $p_0 = p$
      - $p_n = q$
      - $p_{i-1}, p_i : i = 1, \ldots, n$ are neighbor



# 2.5 Some Basic Relationships Between Pixels - Connectivity, Regions, and Boundaries




a b c d e f

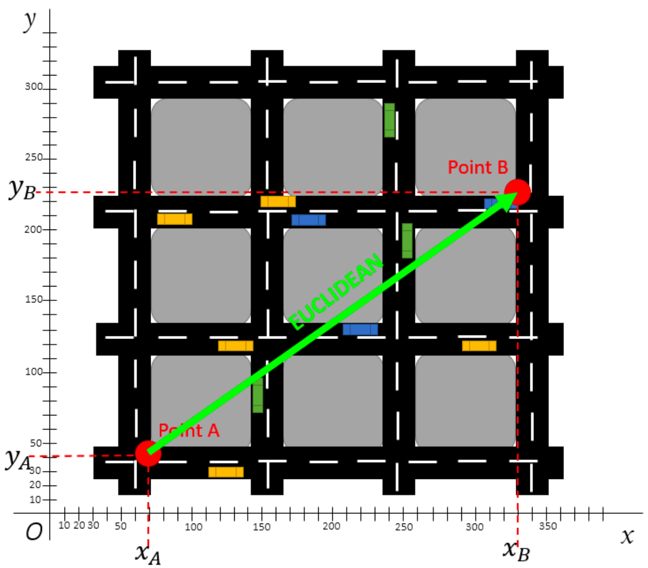
**FIGURE 2.28** (a) An arrangement of pixels. (b) Pixels that are 8-adjacent (adjacency is shown by dashed lines). (c) $m$-adjacency. (d) Two regions (of 1's) that are 8-adjacent. (e) The circled point is on the boundary of the 1-valued pixels only if 8-adjacency between the region and background is used. (f) The inner boundary of the 1-valued region does not form a closed path, but its outer boundary does.

# 2.5 Some Basic Relationships Between Pixels - Distance Measures

For pixels $p(x,y)$, $q(s,t)$

- Euclidean distance (L2 distance)

$$D_e(p,q) = \left[ (x-s)^2 + (y-t)^2 \right]^{\frac{1}{2}}$$




| | | |
|---|---|---|
| 1.41 | 1.0 | 1.41 |
| 1.0 | 0.0 | 1.0 |
| 1.41 | 1.0 | 1.41 |

Distance Transform

# 2.5 Some Basic Relationships Between Pixels - Distance Measures

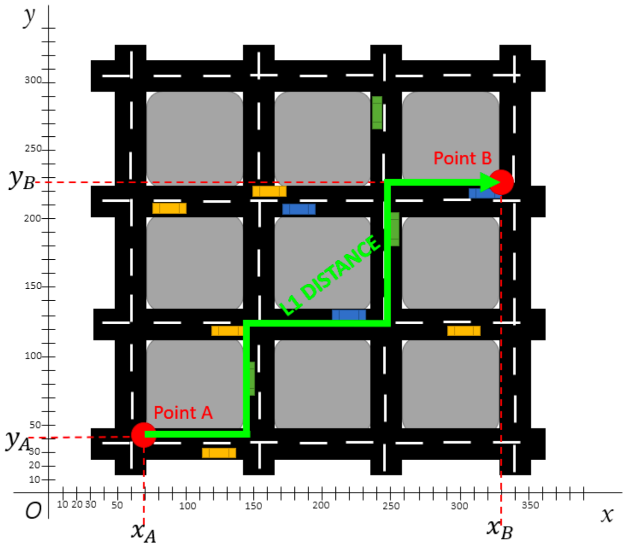
For pixels $p(x,y)$, $q(s,t)$

- Euclidean distance

$$D_e(p,q) = \left[(x-s)^2 + (y-t)^2\right]^{\frac{1}{2}}$$

- City-block or $D_4$ distance (L1 distance)

$$D_4(p,q) = |x-s| + |y-t|$$



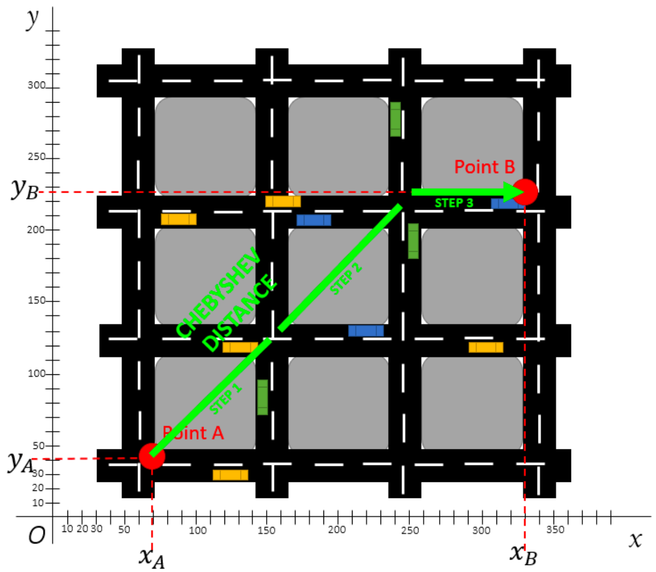

| | | |
|---|---|---|
| 2 | 1 | 2 |
| 1 | 0 | 1 |
| 2 | 1 | 2 |

Distance Transform

# 2.5 Some Basic Relationships Between Pixels - Distance Measures

For pixels $p(x,y)$, $q(s,t)$

- Euclidean distance $$D_e(p,q) = \left[(x-s)^2 + (y-t)^2\right]^{\frac{1}{2}}$$
- City-block or $D_4$ distance $$D_4(p,q) = |x-s| + |y-t|$$
- Chessboard or $D_8$ distance $$D_8(p,q) = \max(|x-s|, |y-t|)$$




| | | |
|---|---|---|
| 1 | 1 | 1 |
| 1 | 0 | 1 |
| 1 | 1 | 1 |

Distance Transform