數位影像處理
Digital Image Processing

Chapter 2
Digital Image Fundamentals

Ming-Han Tsai
Department of Information Engineering and Computer Science,
Feng Chia University

2 數位影像基礎 Digital Image Fundamentals

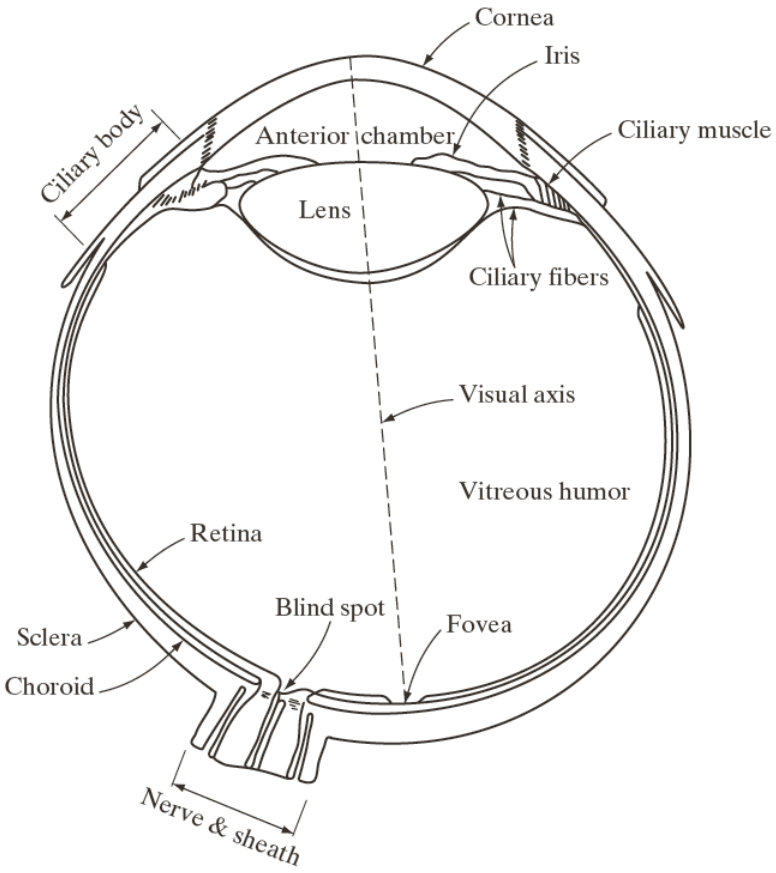
- 2.1 視覺感知要素 Elements of Visual Perception
- ~~2.2 光與電磁頻譜 Light and the Electromagnetic Spectrum~~
- 2.3 影像感知與獲取 Image Sensing and Acquisition
- 2.4 影像取樣與量化 Image Sampling and Quantization
- 2.5 像素間的基本關係 Basic Relationships between Pixels
- 2.6 數位影像處理的數學工具 Mathematical Tools Used in Digital Image Processing

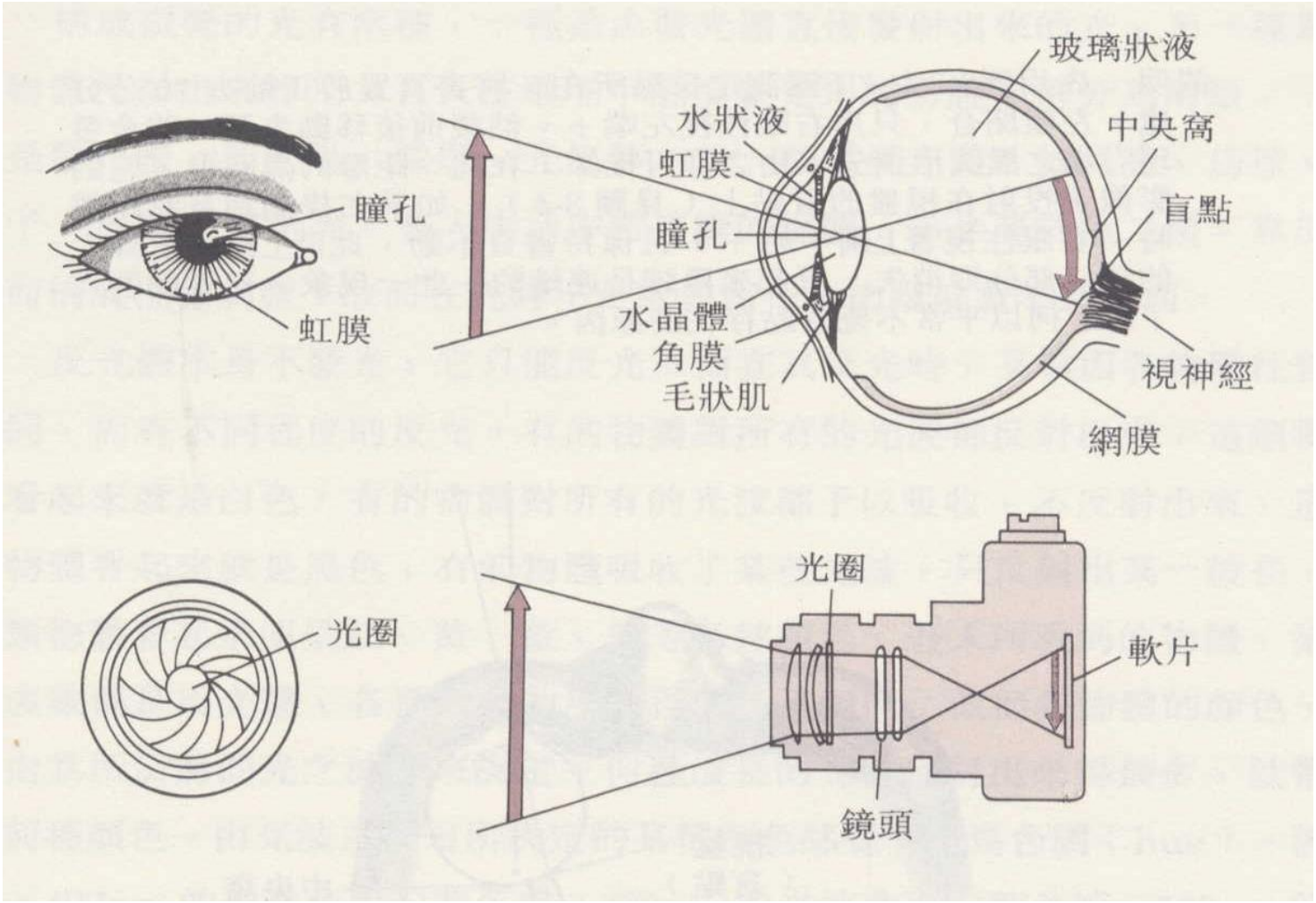
2.1 視覺感知要素 Elements of Visual Perception

- Goal: help an observer interpret the content of an image
- •Developing a basic understanding of the visual process is important
- •Brief coverage of human visual perception follows
  - Emphasis on concepts that relate to subsequent material

2.1 視覺感知要素 Elements of Visual Perception

- Eye characteristics
  - nearly spherical
  - approximately 20 mm in diameter
  - three membranes
    - cornea (transparent) & sclera(opaque) outer cover
    - choroid contains a network of blood vessels, heavily pigmented to reduce amount of extraneous light entering the eye. Also contains the iris diaphragm (2-8 mm to allow variable amount of light into the eye)
    - retina is the inner most membrane, objects are imaged on the surface



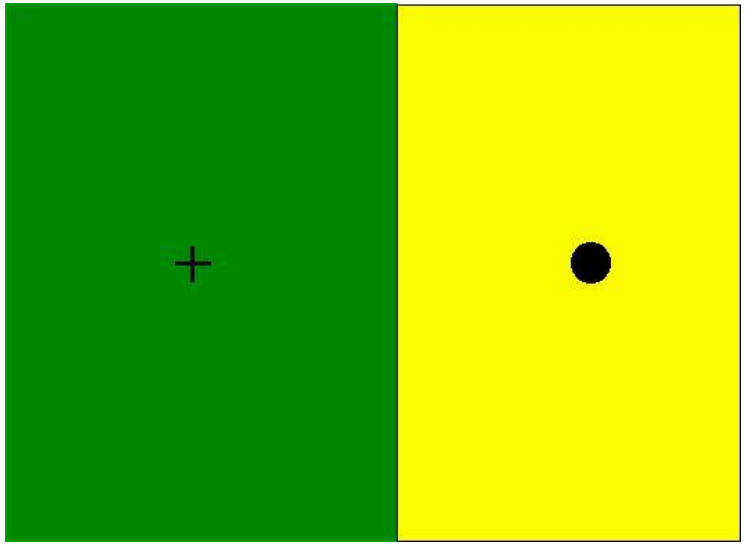

瞳孔
虹膜
玻璃狀液
水狀液
虹膜
中央窩
瞳孔
盲點
水晶體
角膜
毛狀肌
視神經
網膜
光圈
光圈
軟片
鏡頭

2.1 視覺感知要素 Elements of Visual Perception

- 盲點(blind spot)測試
  - Block left eye, watch the cross with right eye only
  - In a certain distance（15~30 cm），the right black point in right will disappear

2.1 視覺感知要素 Elements of Visual Perception

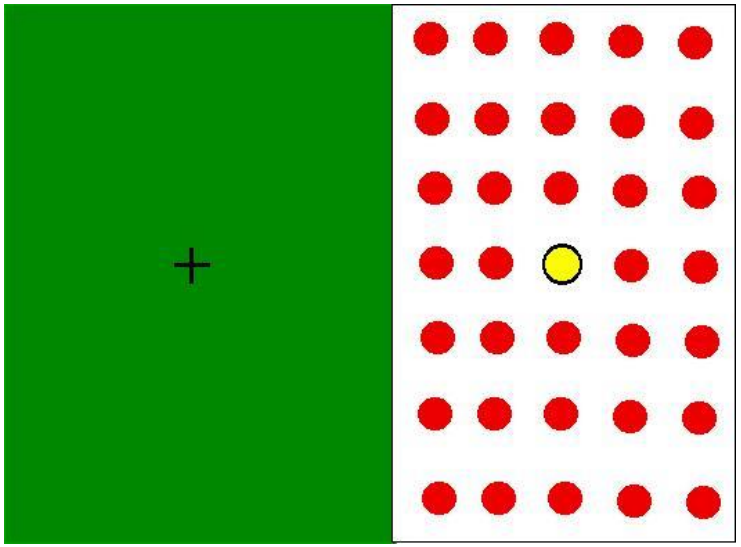
- 盲點(blind spot)測試
  - Block left eye, watch the cross with right eye only
  - In a certain distance（15~30 cm），the right black point in right will disappear



大腦會自動補上顏色

2.1 視覺感知要素 Elements of Visual Perception

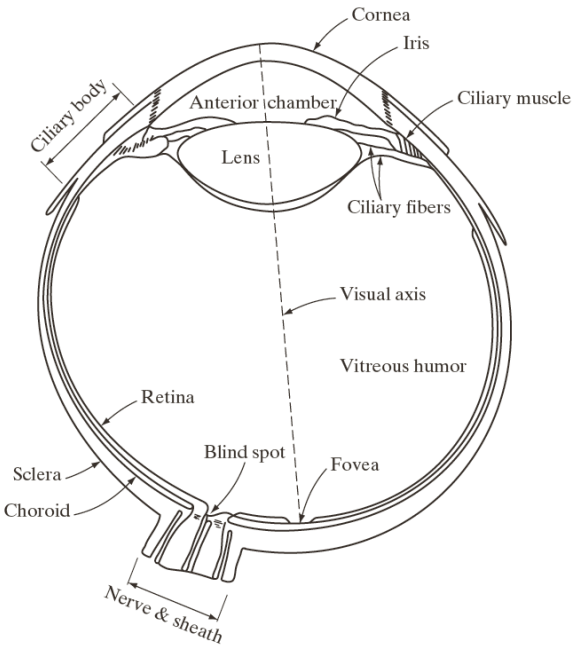
- 盲點(blind spot)測試
  - Block left eye, watch the cross with right eye only
  - In a certain distance（15~30 cm），the right black point in right will disappear

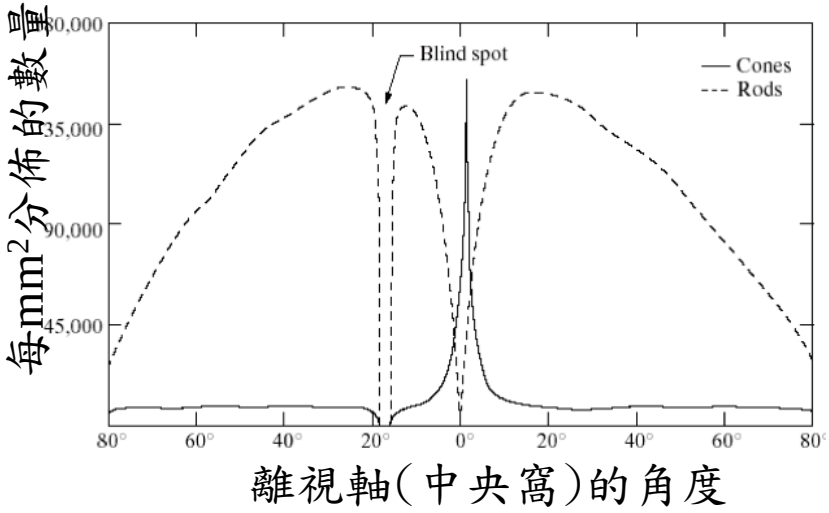


大腦會自動補上圖案

2.1 視覺感知要素 Elements of Visual Perception

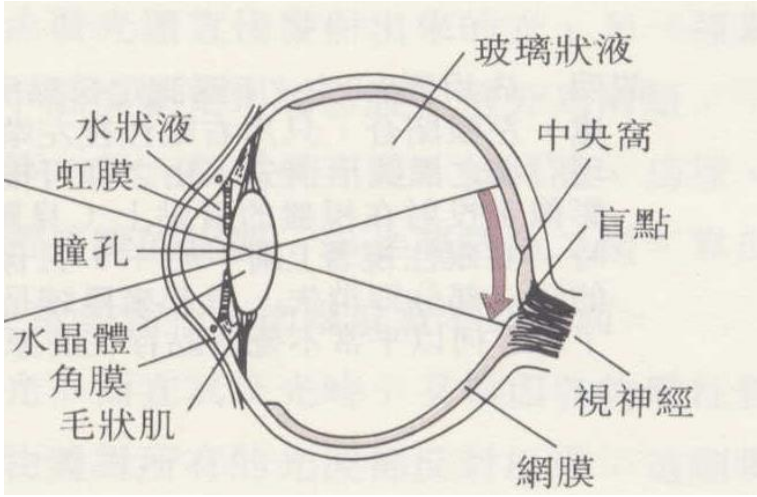
- Retinal surface is covered in discrete **light receptors**
  - Three types of Cones(錐狀體)：
  - 6-7 million located primarily near the center of the retina (the *fovea*)
  - highly sensitive to color
  - can resolve fine details because each is attached to a single nerve ending
  - Cone vision is called *photopic* or bright-light vision

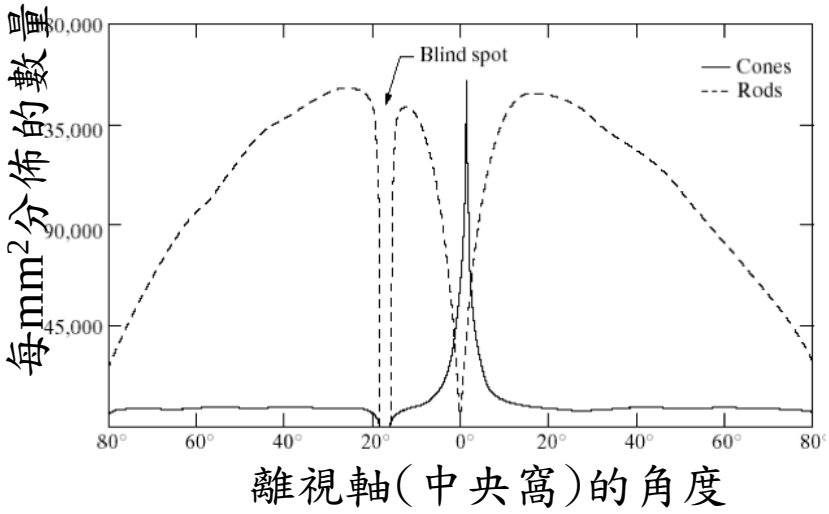




2.1 視覺感知要素 Elements of Visual Perception

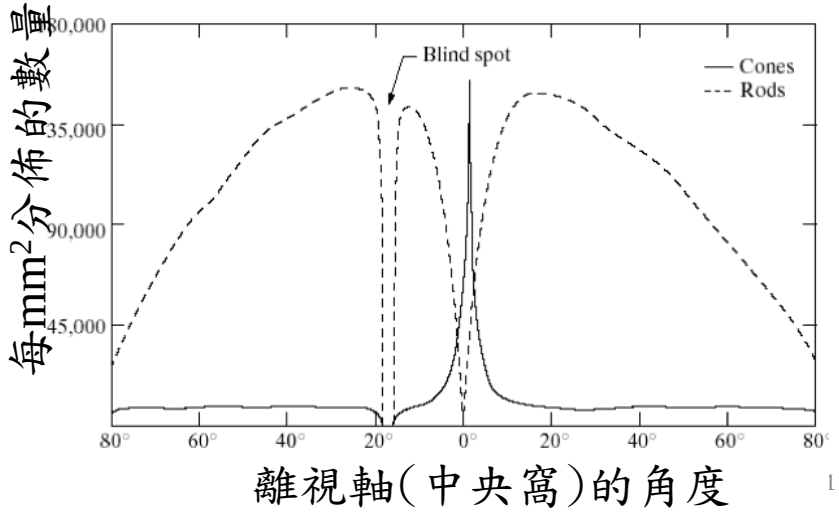
- Retinal surface is covered in discrete **light receptors**
  - Rods(桿狀體)：
  - 75-150 million distributed over the retinal surface
  - multiple rods connected to a single nerve ending
  - give a general overall picture of the field of illumination
  - not color sensitive but are sensitive to low levels of illumination
  - Rod vision is called *scotopic* or dim-light vision





2.1 視覺感知要素 Elements of Visual Perception

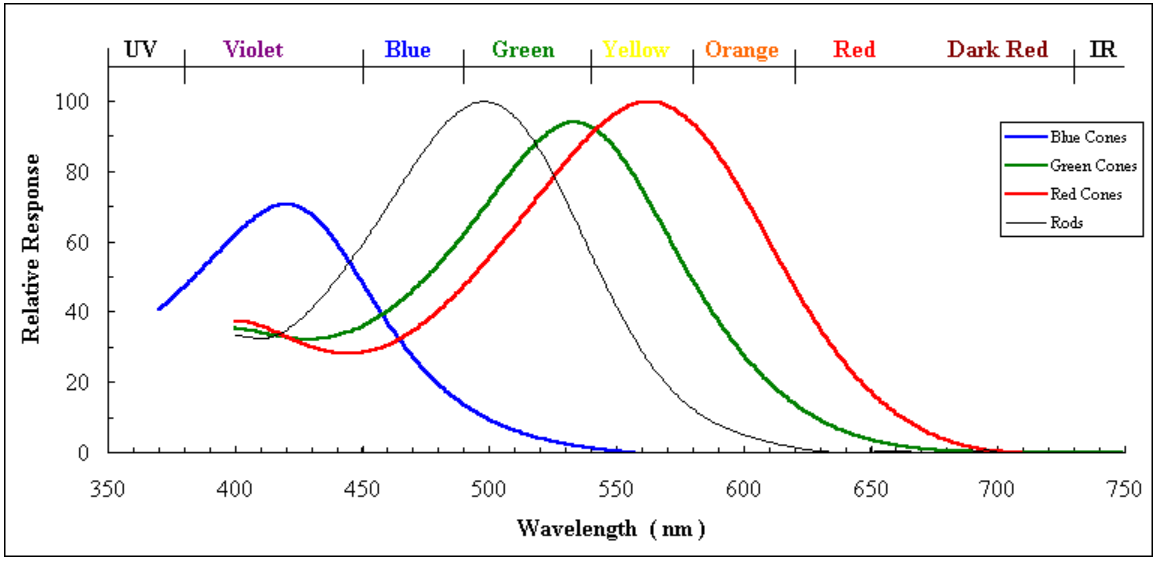
- Distribution is radially symmetric about the fovea
- Absence of receptors in the *blind spot* (emergence of the optic nerve)
- Receptor density measured in degrees from the fovea (the angle formed between the visual axis and a line extending from the center of the lens to the retina)
- Fovea:
  - basic ability of the eye to resolve detail is within the realm ofelectronic imaging sensors



2.1 視覺感知要素 Elements of Visual Perception

- Cones sense visual signal in light situation
- S-, M-, L- cones: sensitive to R、G、B
- The amount of S:M:L = 40: 20 : 1
- Rods sense visual signal in dark situation

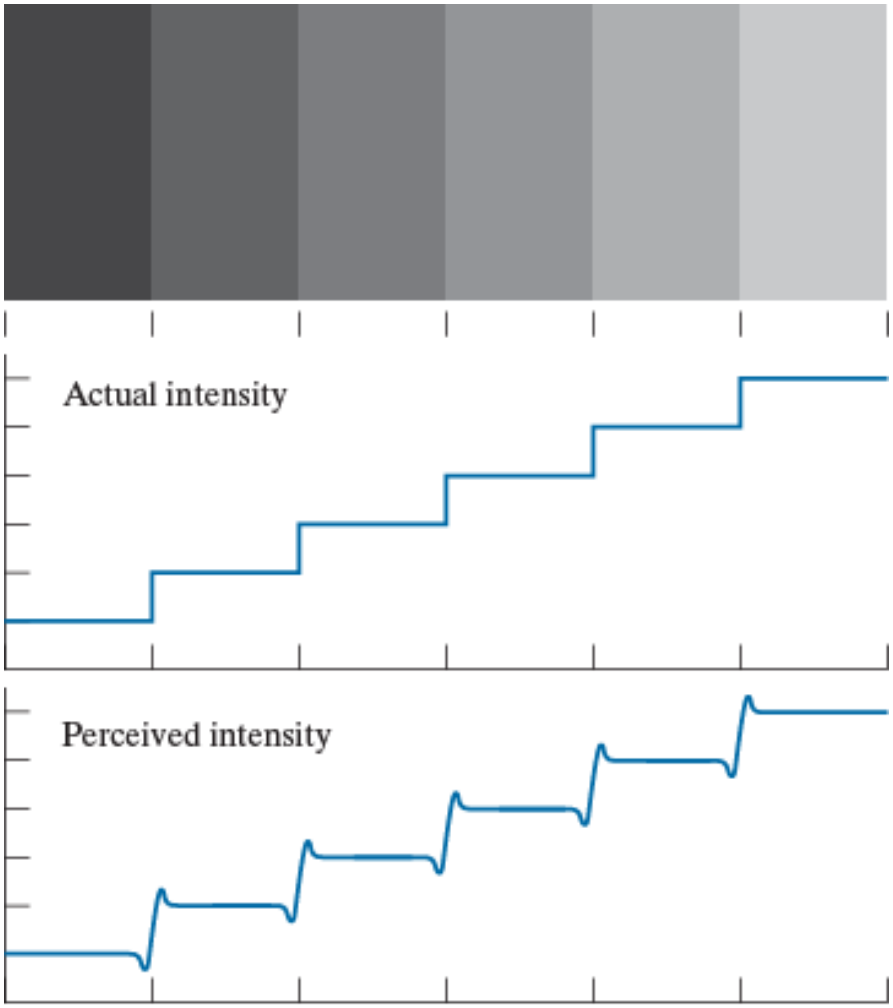
→Objects without color at night



(Ref: https://www.unm.edu/~toolson/human_cone_response.htm)

2.1 視覺感知要素 Elements of Visual Perception

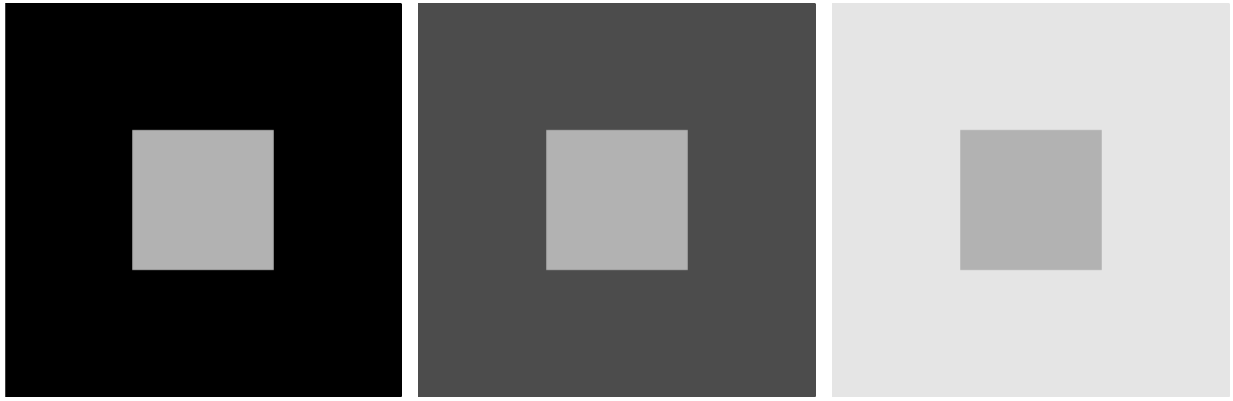
- 馬赫帶效應(Mach band effect)



Perceived intensity is not a simple function of actual intensity

2.1 視覺感知要素 Elements of Visual Perception

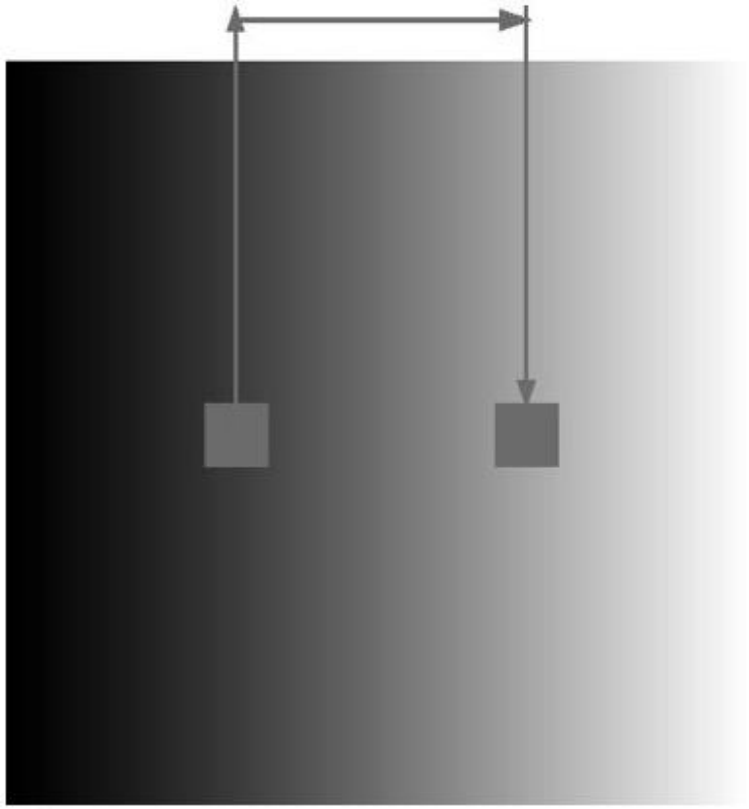
- 聯合對比度效應(Simultaneous contrast effect)
  - The sensed intensity is not only related to its illumination, but also the surrounded.



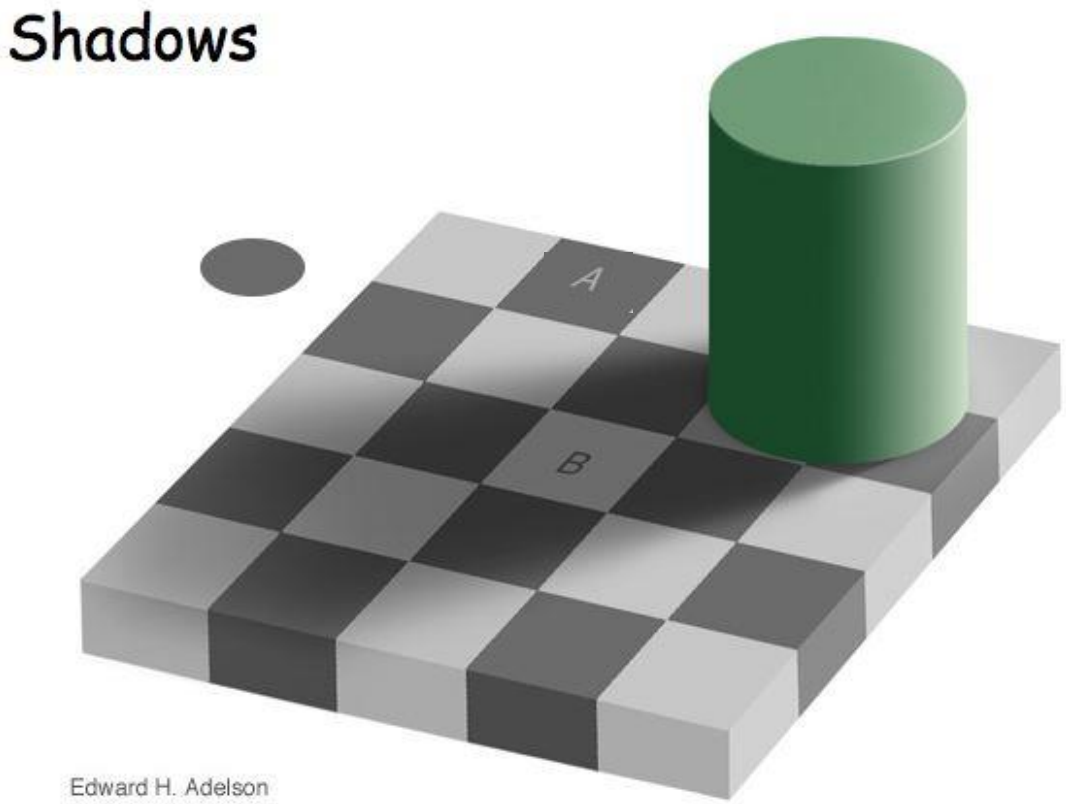
Brighter background, darker foreground

2.1 視覺感知要素 Elements of Visual Perception

- 聯合對比度效應(Simultaneous contrast effect)

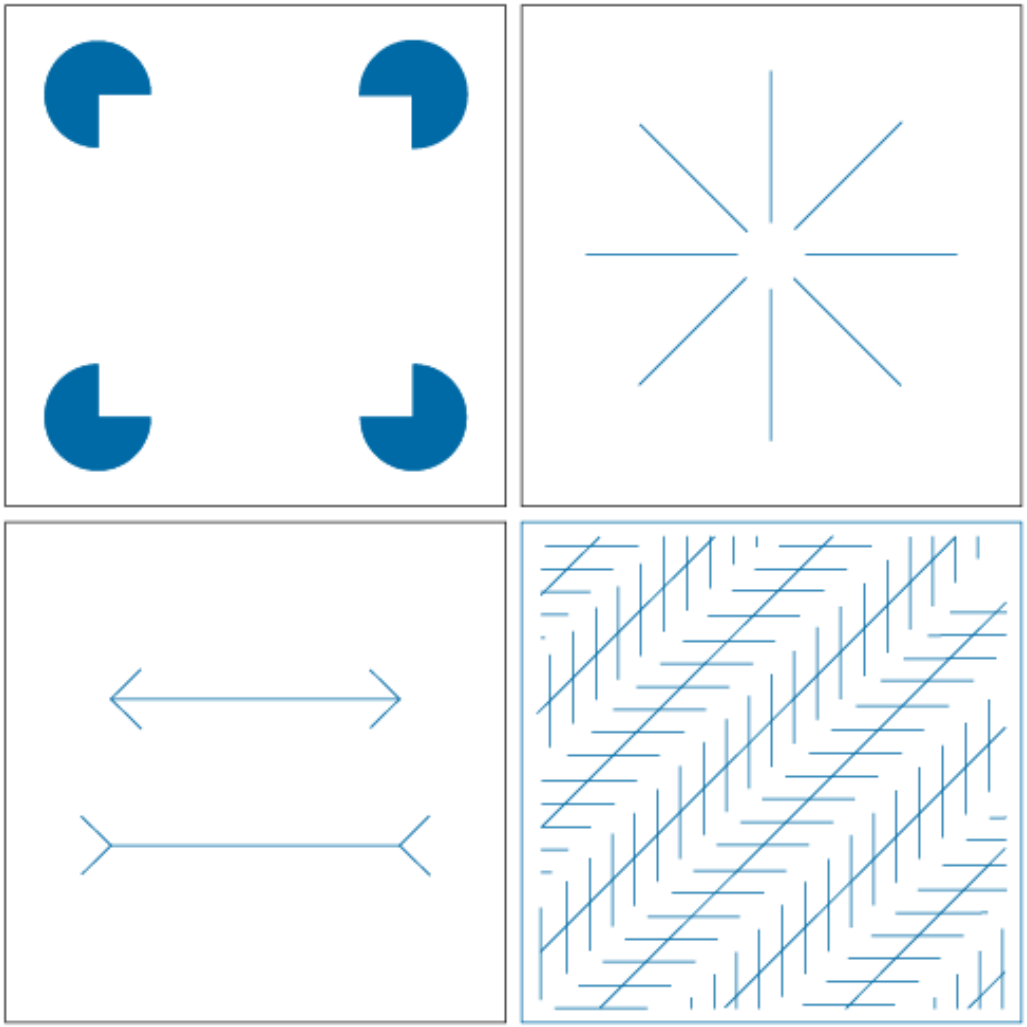


2.1 視覺感知要素 Elements of Visual Perception



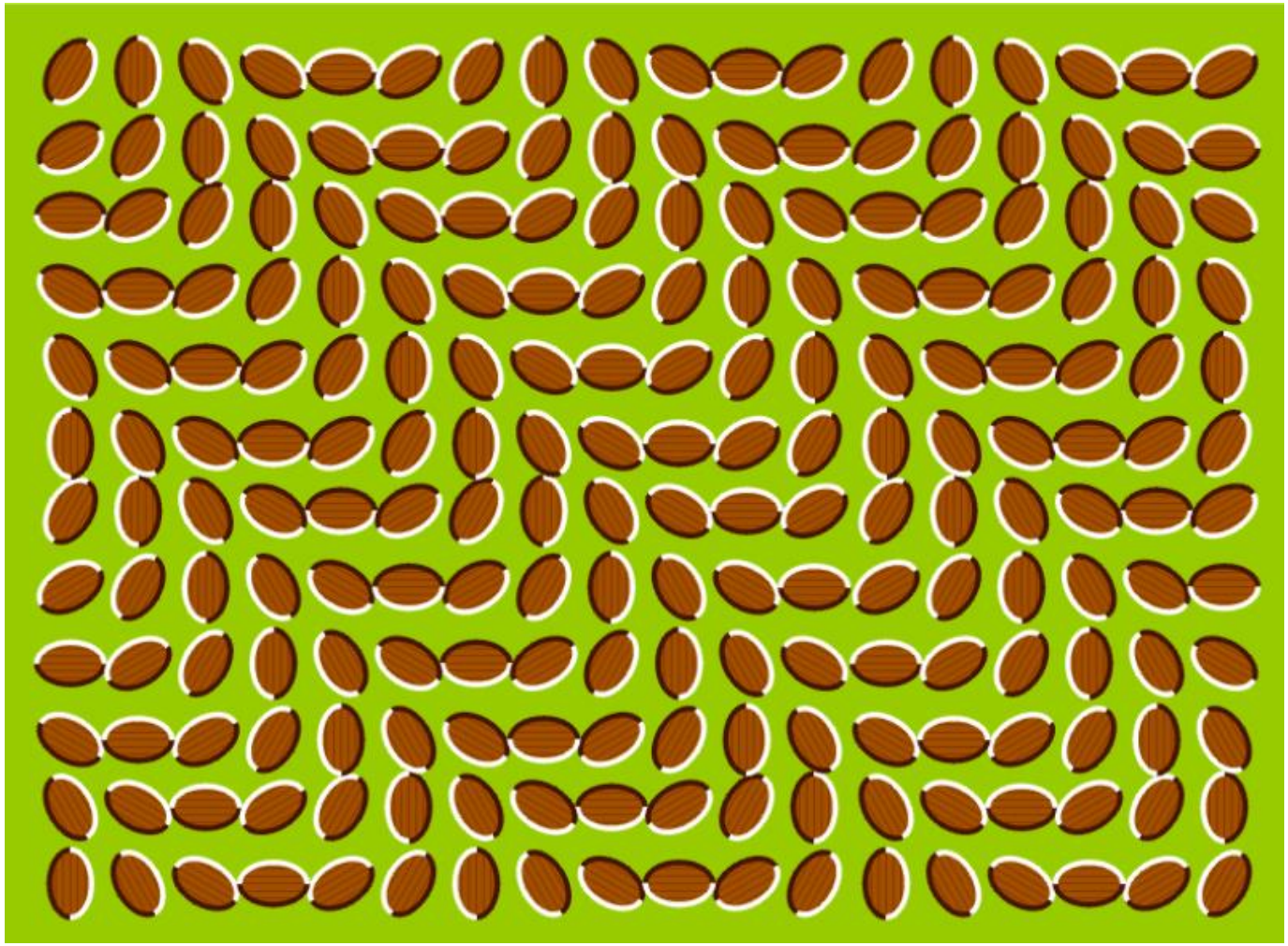
2.1 視覺感知要素 Elements of Visual Perception

- 光學錯覺



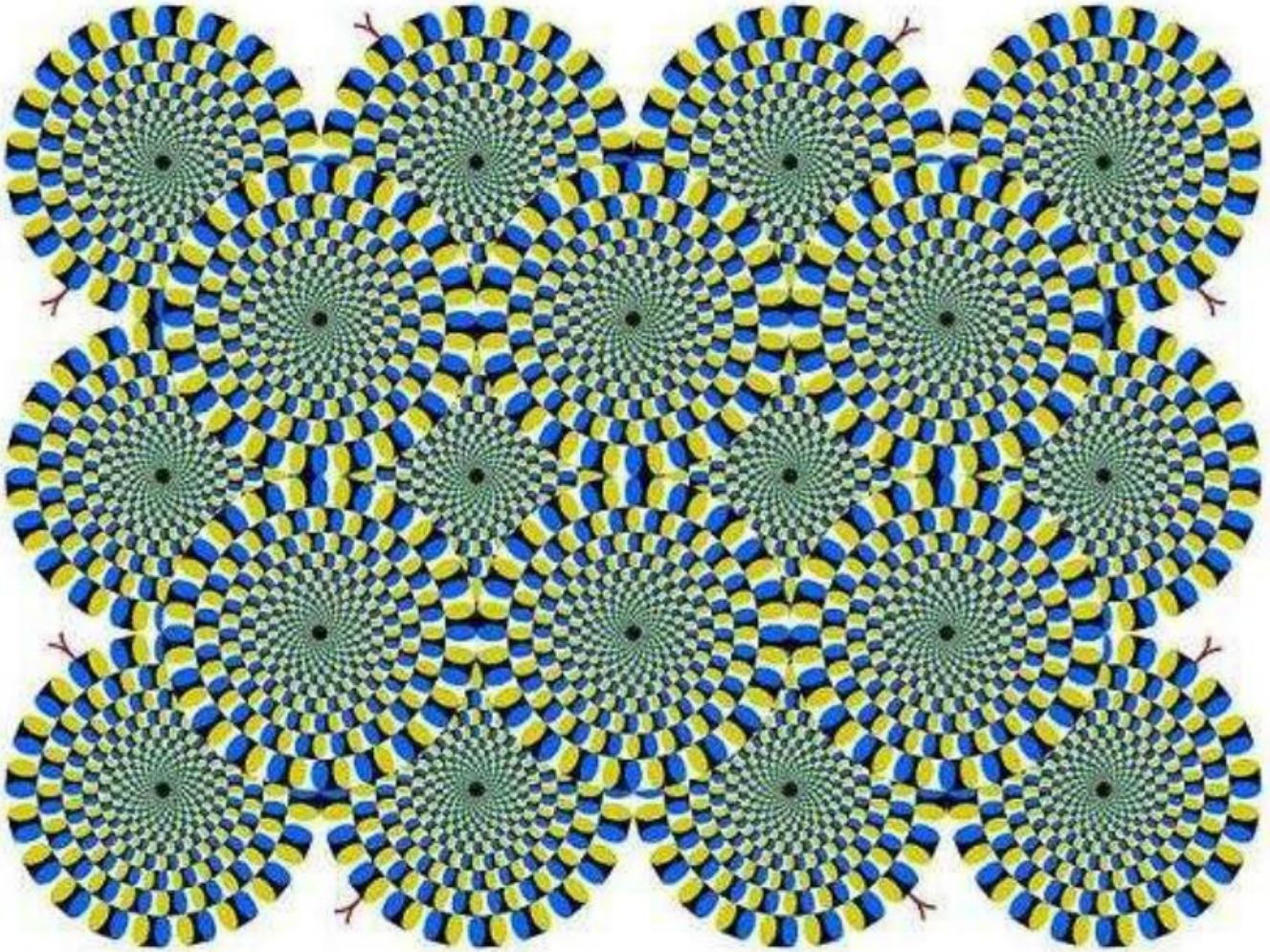
2.1 視覺感知要素 Elements of Visual Perception

- 似動錯覺



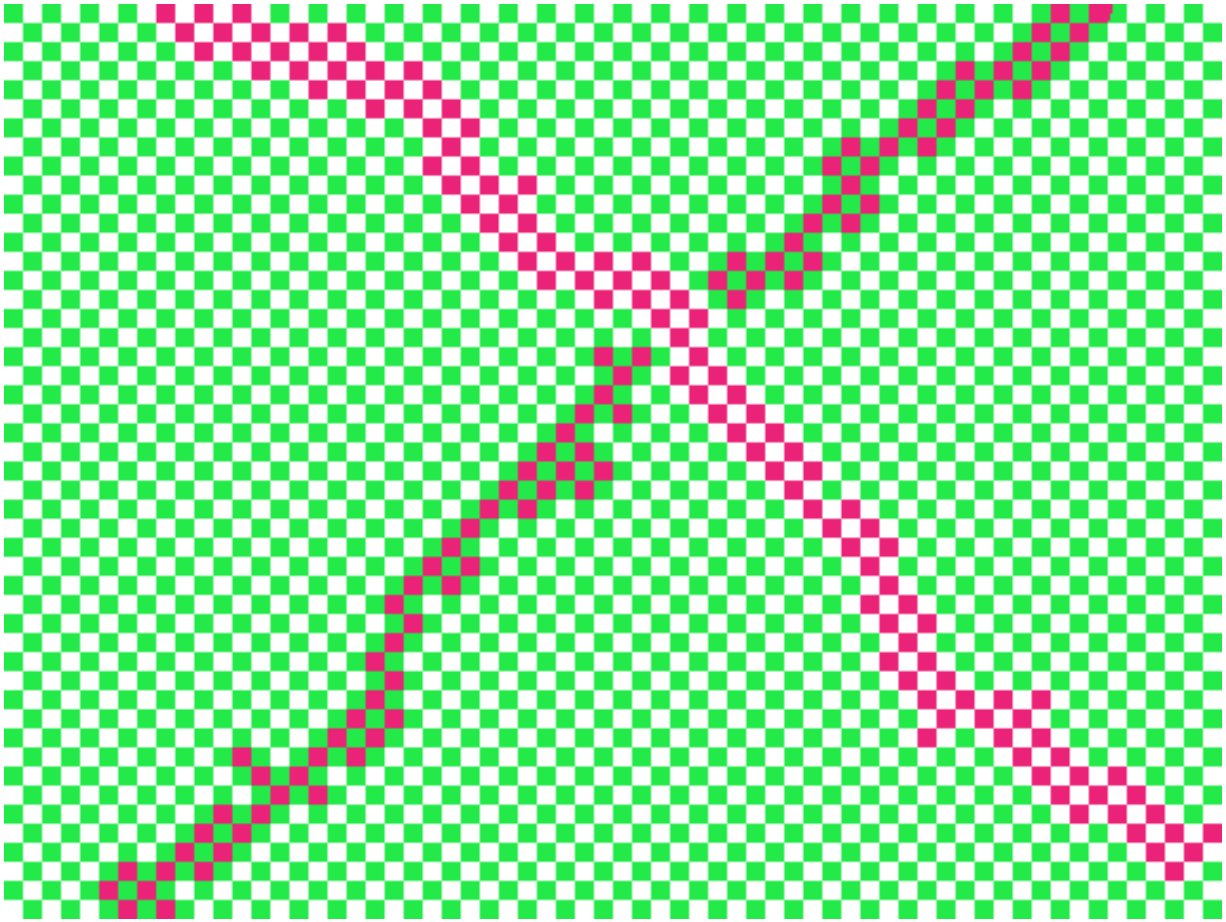
2.1 視覺感知要素 Elements of Visual Perception

- 似動錯覺



2.1 視覺感知要素 Elements of Visual Perception

- 有幾種顏色？



Imaging in eye

- Variable thickness lens: thick for close focus, thin for distant focus
- Distance of focal center of the lens to the retina (14-17 mm)
- Image of a 15m tree at 100m
  - 15/100 = X/17 or approximately 2.55 mm
- Image is almost entirely on the fovea

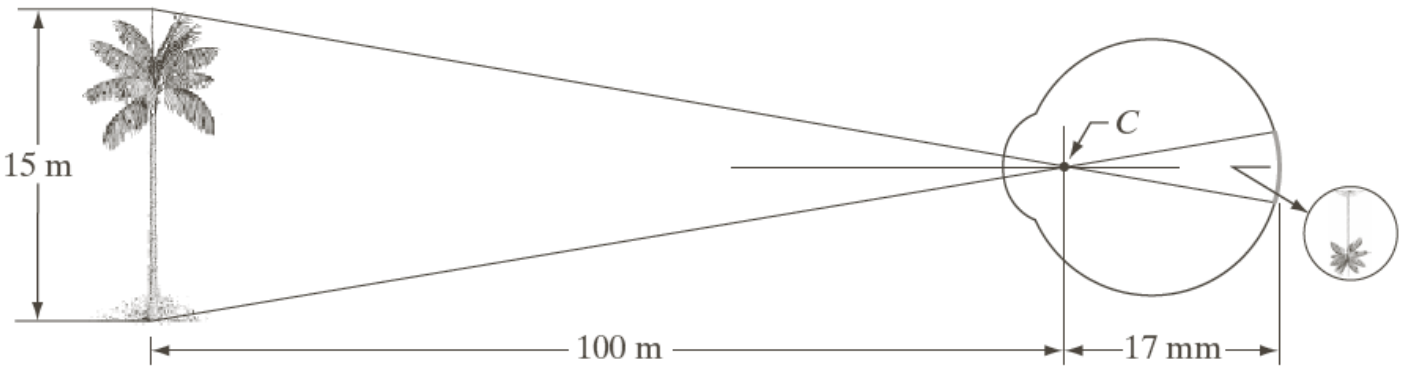


FIGURE 2.3 Graphical representation of the eye looking at a palm tree. Point *C* is the optical center of the lens.

Illusion Arts

Illusion Art Museum Prague

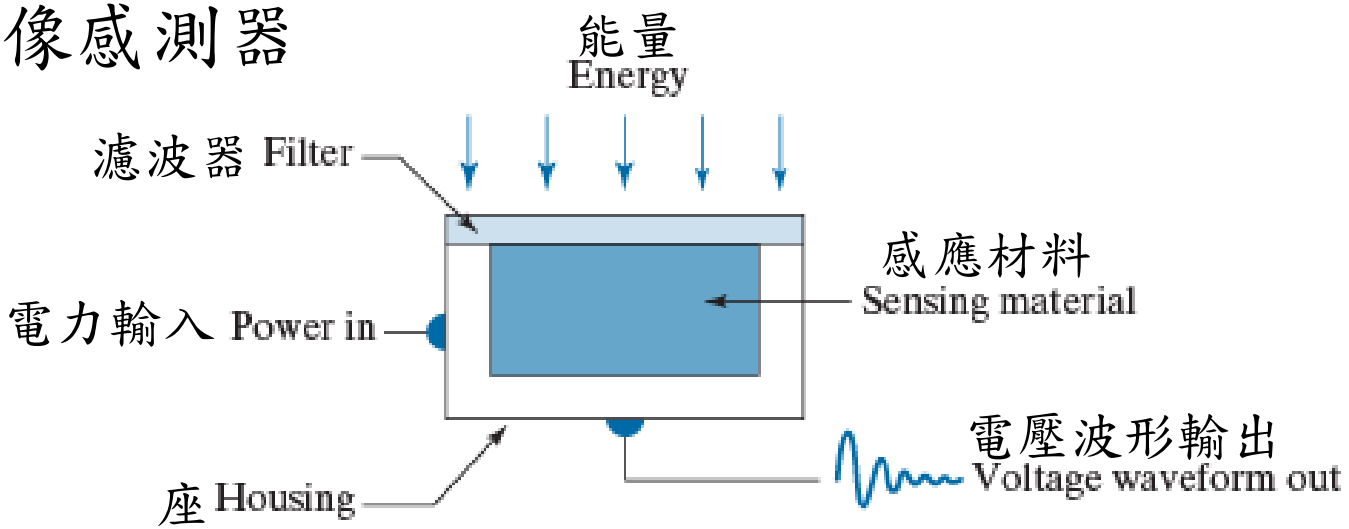
https://www.youtube.com/watch?v=LNikMG_9a9k

2 數位影像基礎 Digital Image Fundamentals

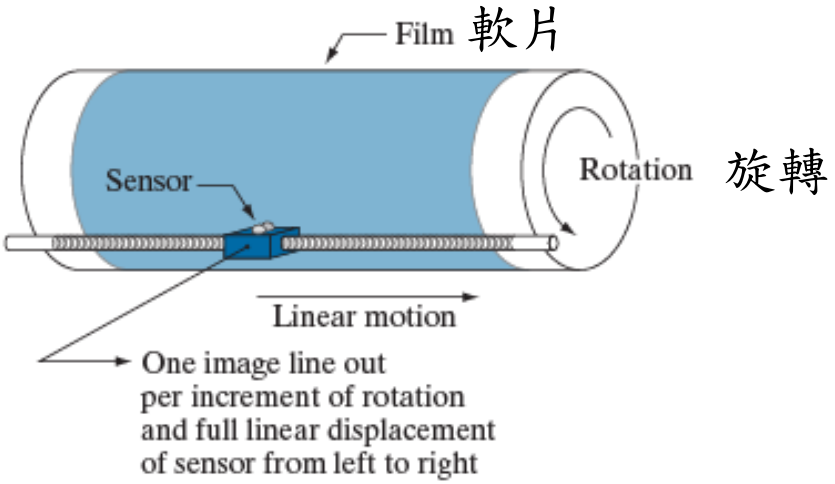
- 2.1 視覺感知要素 Elements of Visual Perception
- ~~2.2 光與電磁頻譜 Light and the Electromagnetic Spectrum~~
- 2.3 影像感知與獲取 Image Sensing and Acquisition
- 2.4 影像取樣與量化 Image Sampling and Quantization
- 2.5 像素間的基本關係 Basic Relationships between Pixels
- 2.6 數位影像處理的數學工具 Mathematical Tools Used in Digital Image Processing

2.3 影像感知與獲取 Image Sensing and Acquisition

- 單一影像感測器

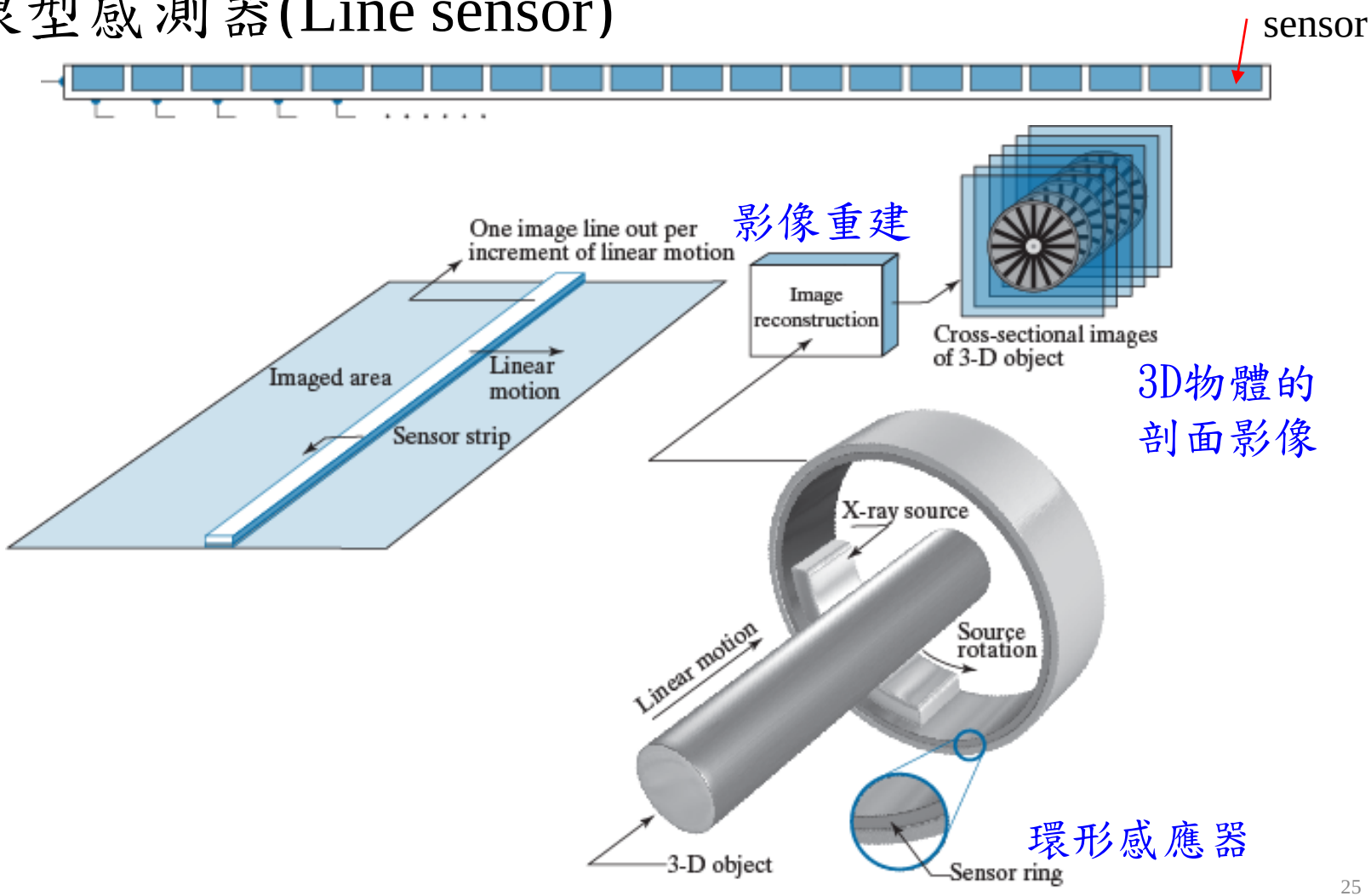


利用單一感應器來產生二維影像
→便宜獲許高解析度影像的方式，但速度慢。



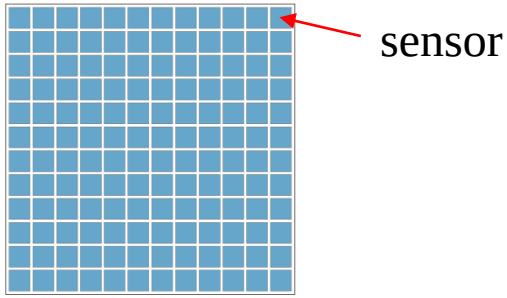
2.3 影像感知與獲取 Image Sensing and Acquisition

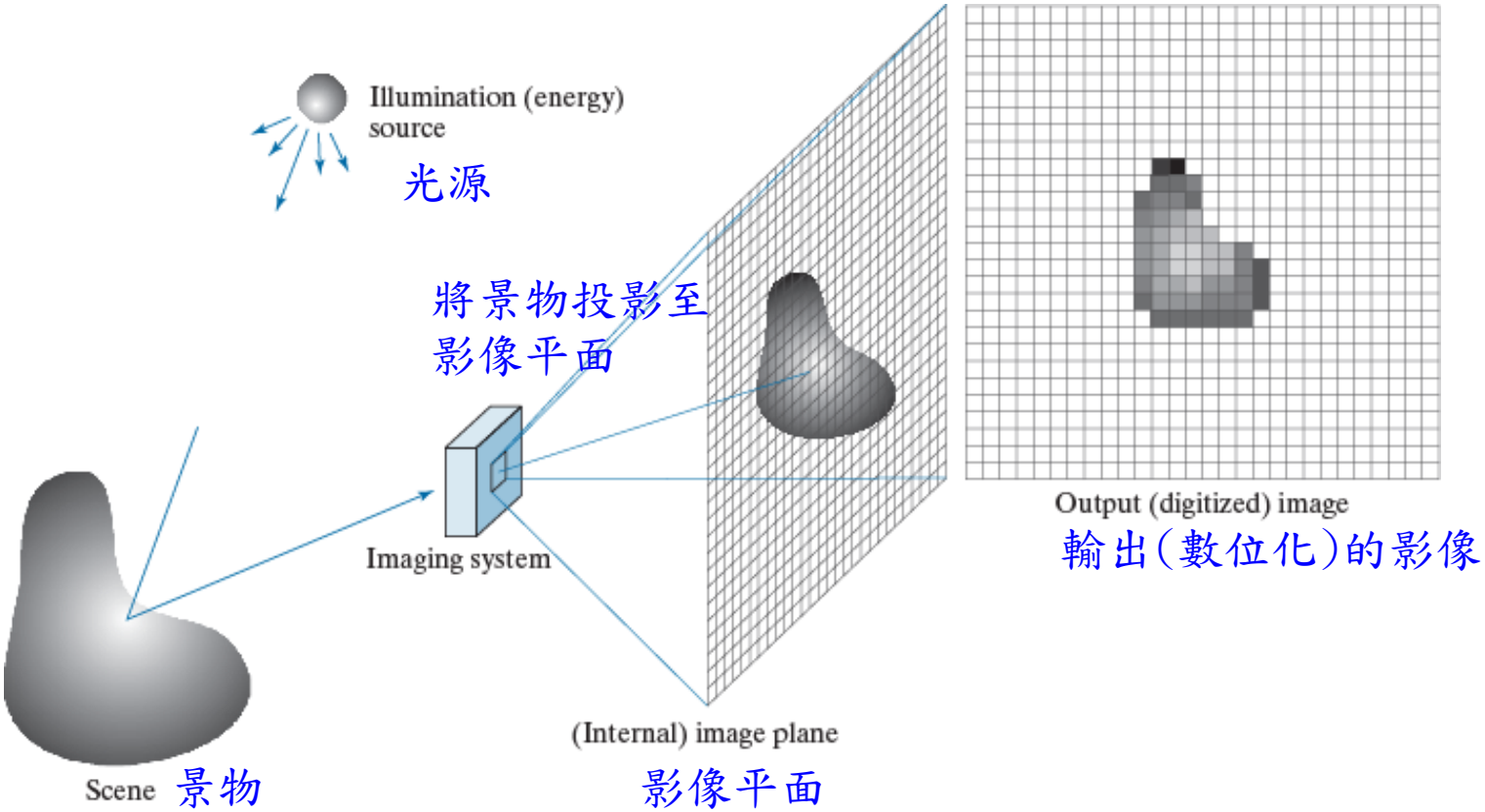
- 線型感測器(Line sensor)



2.3 影像感知與獲取 Image Sensing and Acquisition

- 感應器陣列 (Array sensor)
  - Mainly used in Digital Camera
  - CCD (Charge-coupled Device) Array



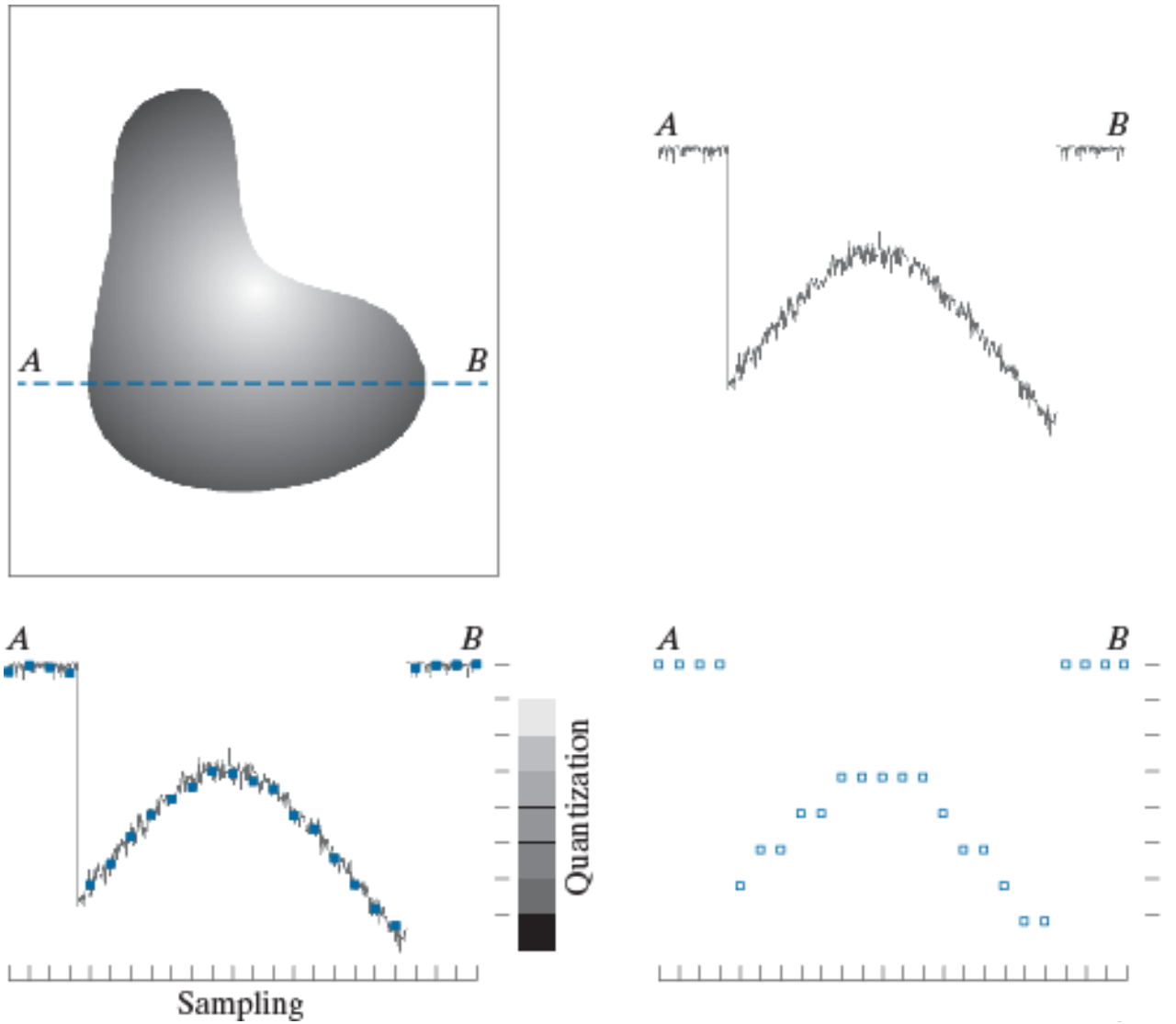


2 數位影像基礎 Digital Image Fundamentals

- 2.1 視覺感知要素 Elements of Visual Perception
- 2.2 光與電磁頻譜 Light and the Electromagnetic Spectrum
- 2.3 影像感知與獲取 Image Sensing and Acquisition
- 2.4 影像取樣與量化 Image Sampling and Quantization
- 2.5 像素間的基本關係 Basic Relationships between Pixels
- 2.6 數位影像處理的數學工具 Mathematical Tools Used in Digital Image Processing

2.4 影像取樣與量化 Image Sampling and Quantization

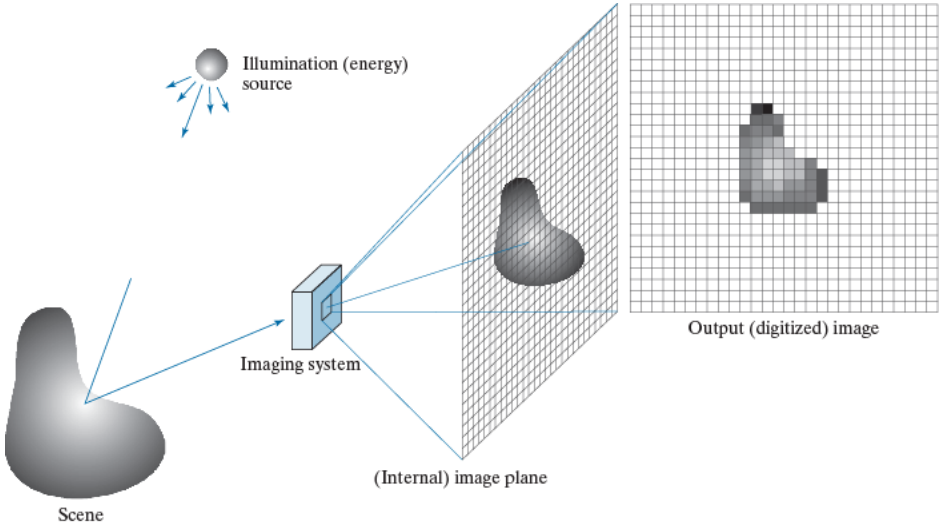
- 取樣(sampling)：digitalize the axis
- 量化(quantization)：digitalize the amplitude

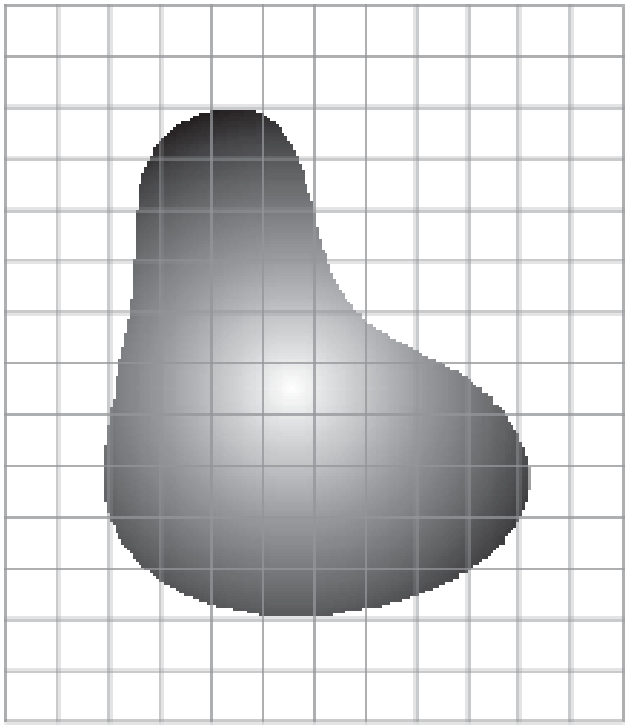


a b
c d

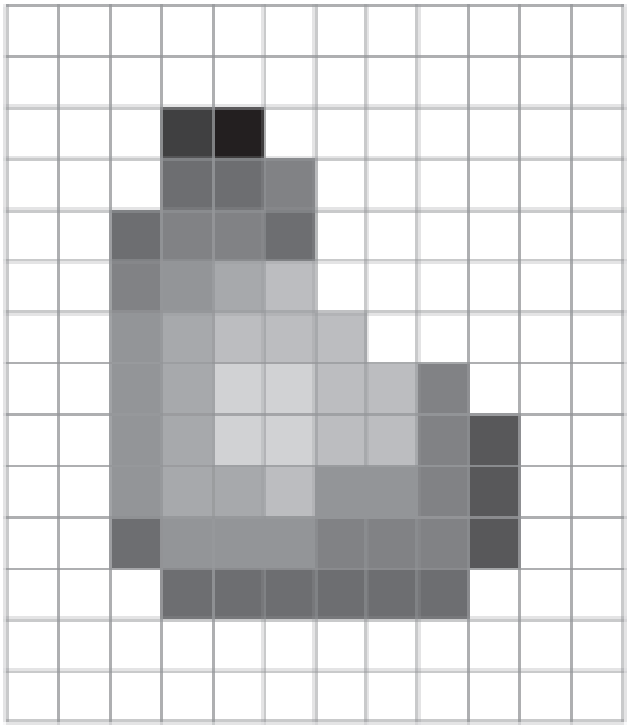
FIGURE 2.16 Generating a digital image. (a) Continuous image. (b) A scan line from *A* to *B* in the continuous image, used to illustrate the concepts of sampling and quantization. (c) Sampling and quantization. (d) Digital scan line.

2.4 影像取樣與量化





Continuous object projected on CCD array

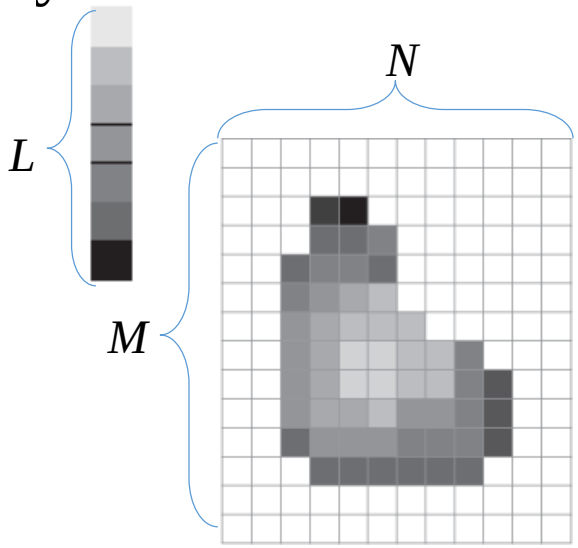


After digitalized: sampling and quantization

2.4.2 Digital Image Representation

- Image Digitalization：
  - M 、N : image width/Height， L : intensity level
- M、N：positive integer
- $L = 2^k$ (2, 4, 8, ..256…)
- Storage：# of *bits*

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



- k-bit image：an image with 2^k intensity level

→8-bit image：an image with 256 intensity level

from black to white, there are 256 levels

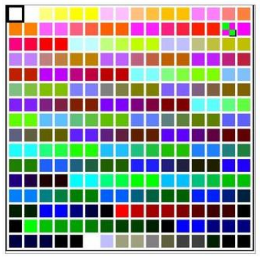
Different types of color image

- B/W：only Black and White(pure)，one bit each pixel 。
- 8-bit gray level：only Black and White，but from black to white, there are 256 levels
- Each pixel 8 bits=1 byte 。

8-bit gray level

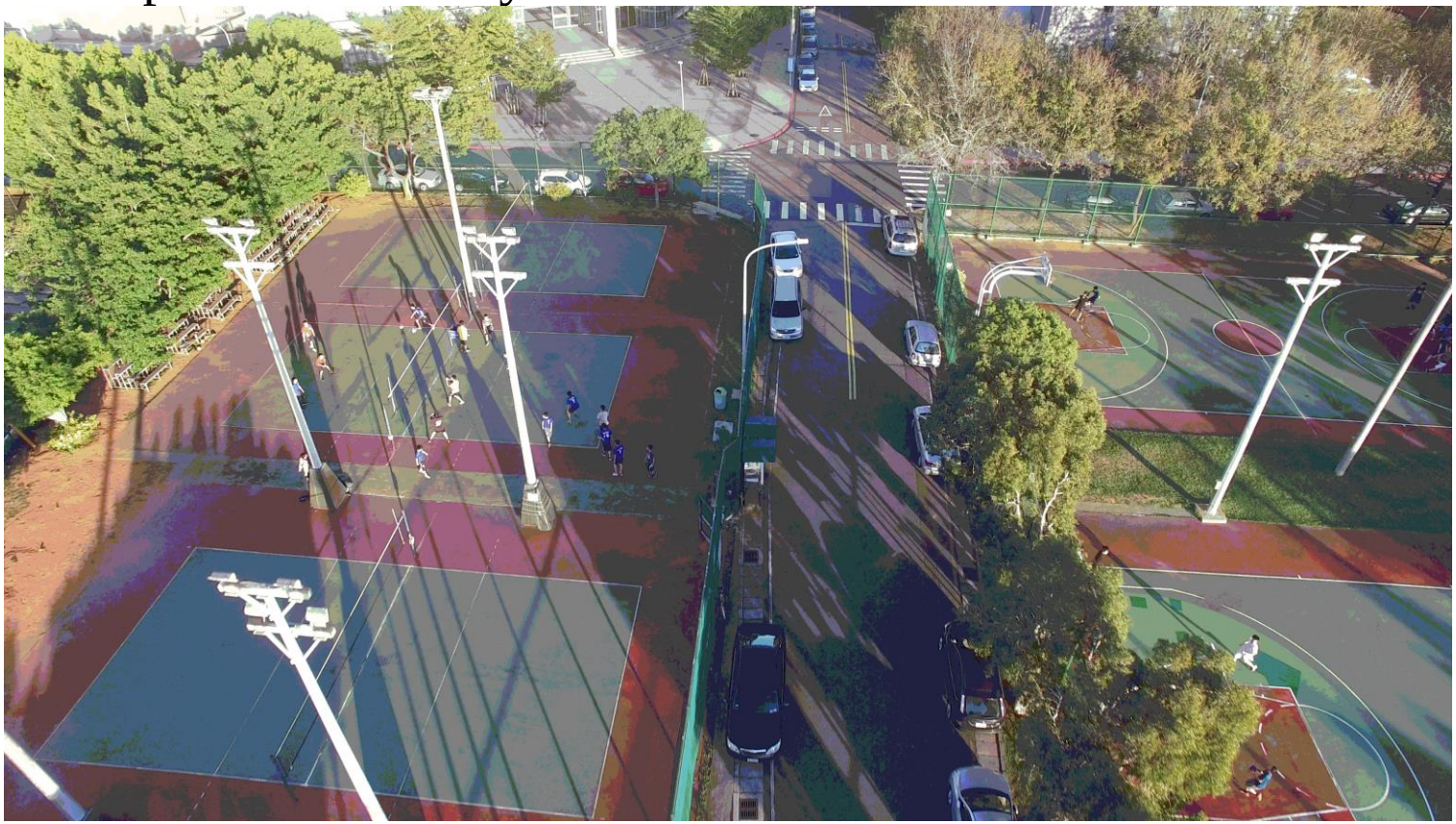
B/W

palette example



Different types of color image

- 8位元256 colors：at most 256 colors
- User defined palette or image dependent
- Each pixel 8 bits=1 byte →GIF



Different types of color image

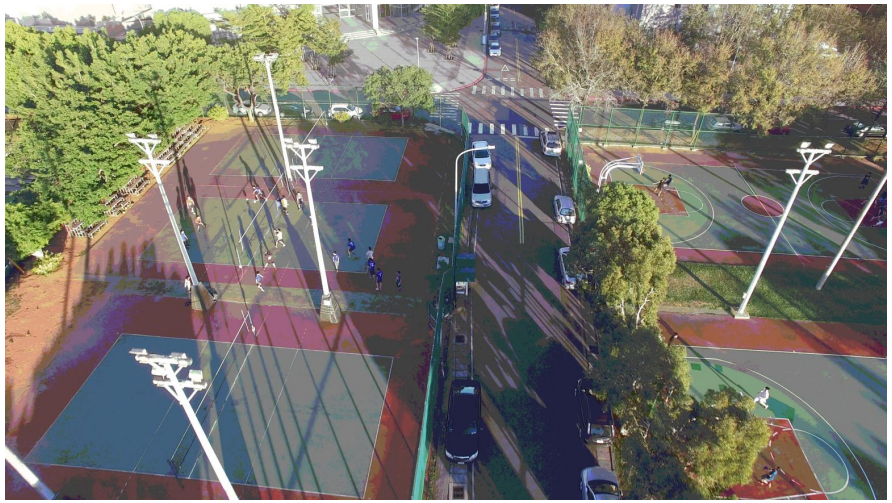
- 15bit high color：R、G、B：each 2^5=32 levels，32768 colors。
- 16bit high color：G：2^6=64 levels，R、B：2^5=32 levels，65536 colors。Each pixel 2 bytes = 16 bits
- **24bit full color： R、G、B：2^8=256 levels，256*256*256=1677216 colors，Each pixel 3 bytes=24bits**
- 32位元彩色：24bit full color + transparent channel。4 channels：R、G、B、Alpha (transparency) → 4x8 =32。

24-bit full color

影像的色彩類型

24 bit full color

8 bit 256 colors(GIF)



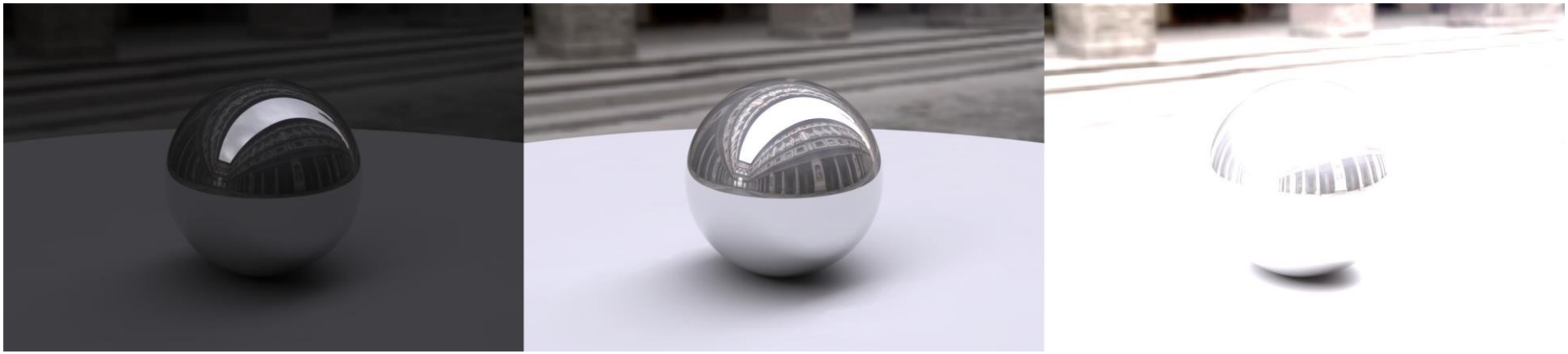
8 bit gray level

B/W

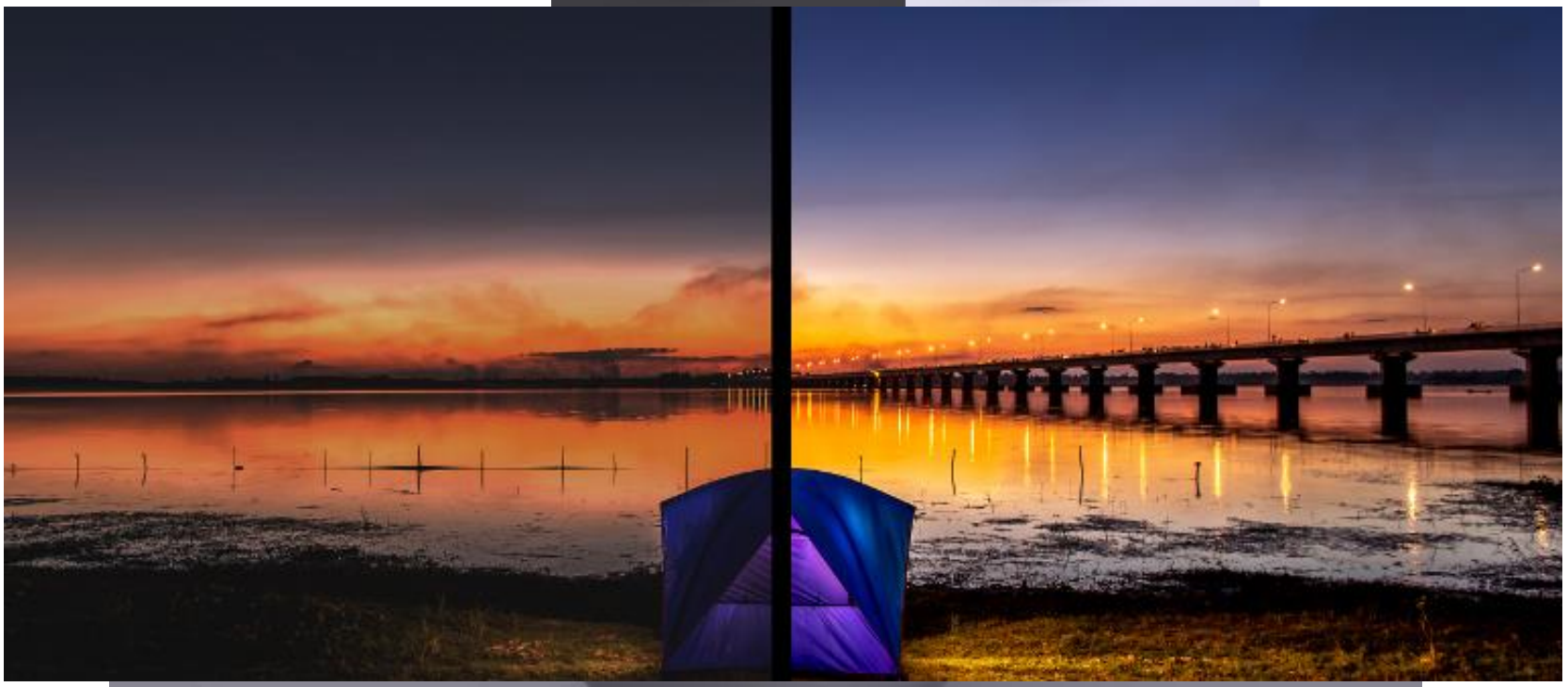
飽和度與雜訊 (Saturation and Noise)

- The dynamic range of an image system：

$$dynamic\ range = \frac{\max measurable\ intensity}{\min detectable\ intensity\ level}$$



High-dynamic range(HDR)



https://shield.nvidia.com/blog/what-is-hdr

2.4.3 Spatial & gray-level resolution

- spatial resolution←→sampling

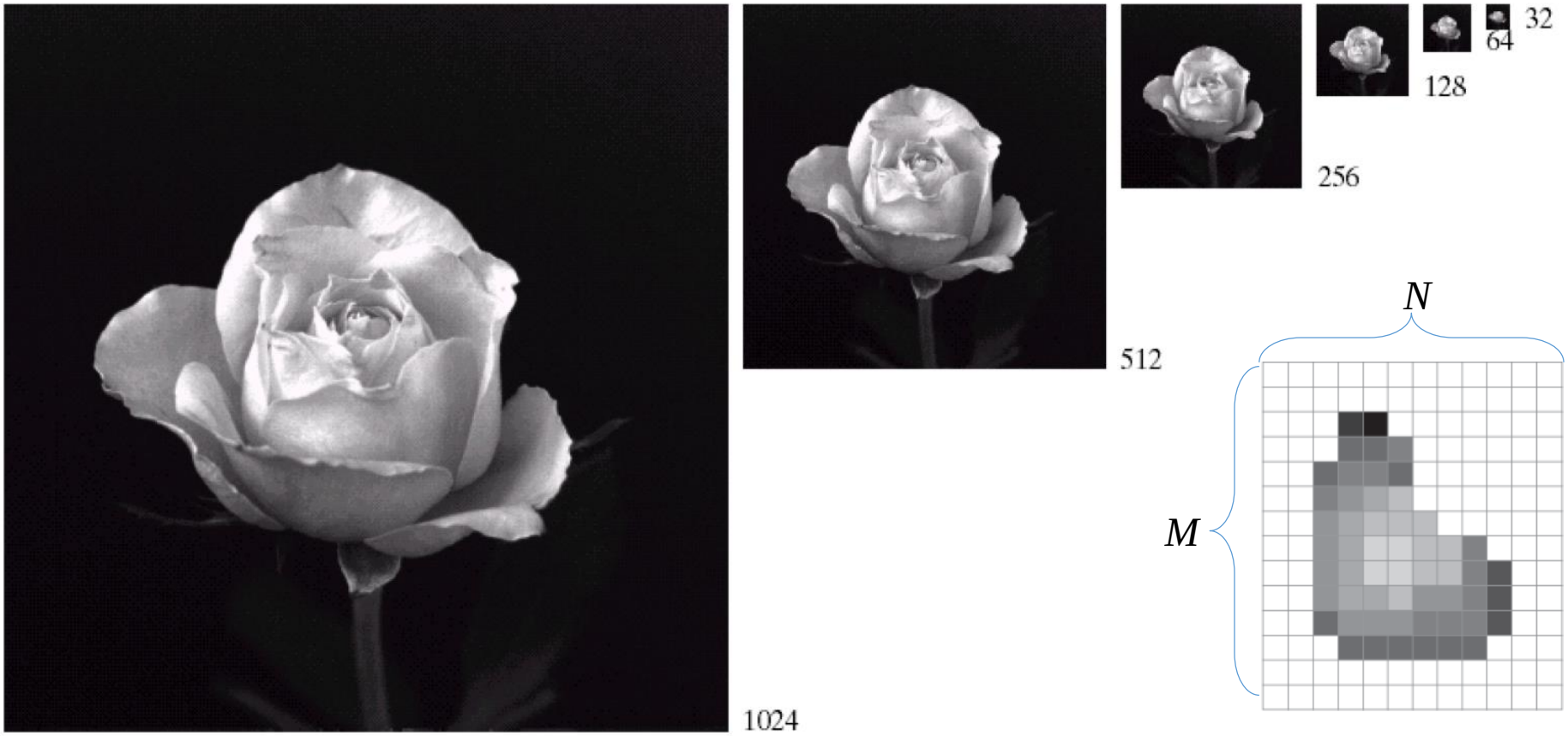
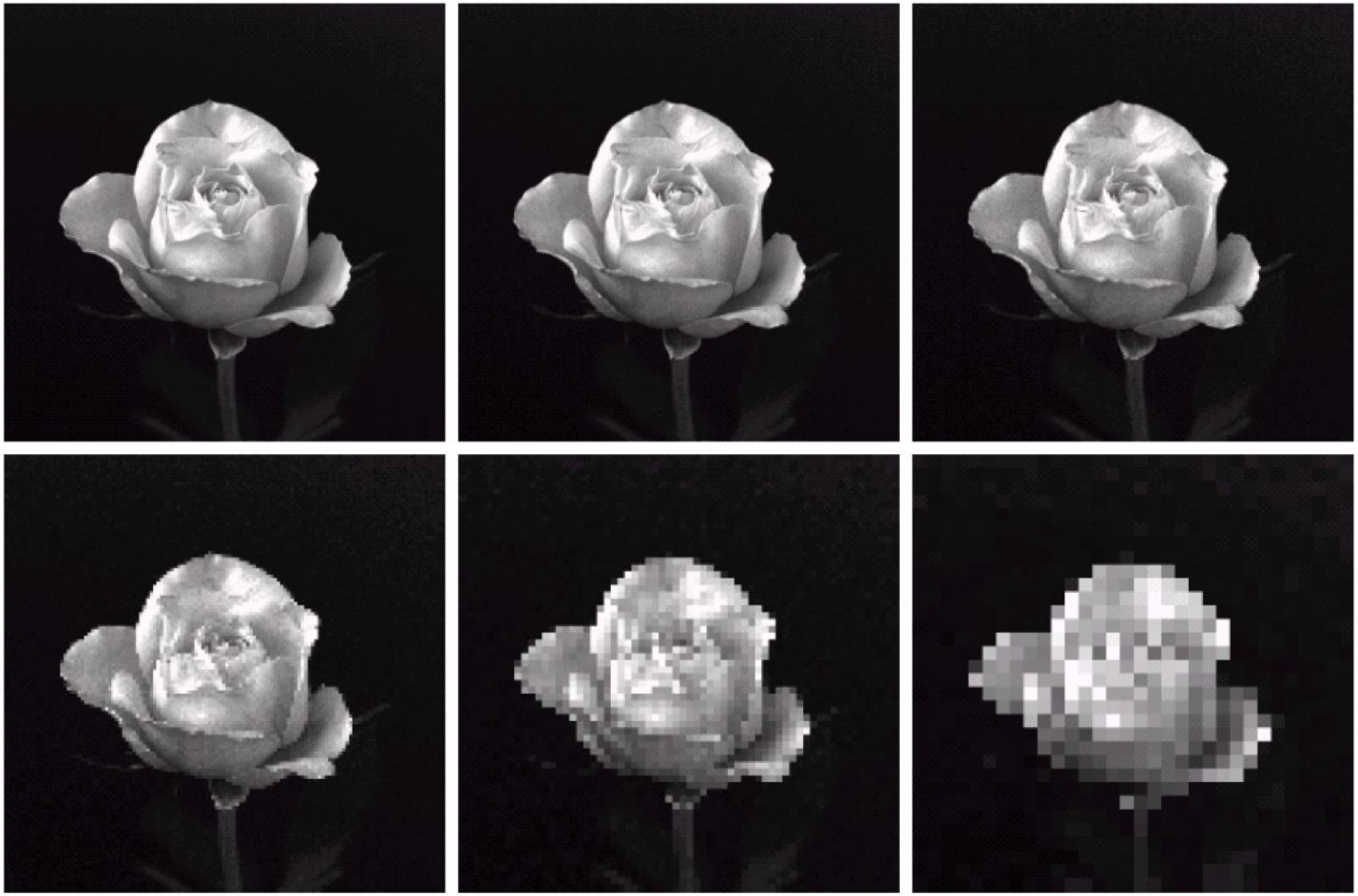


FIGURE 2.19 A 1024 × 1024, 8-bit image subsampled down to size 32 × 32 pixels. The number of allowable gray levels was kept at 256.

- spatial resolution

FIGURE 2.19 A 1024 × 1024, 8-bit image subsampled down to size 32 × 32 pixels. The number of allowable gray levels was kept at 256.



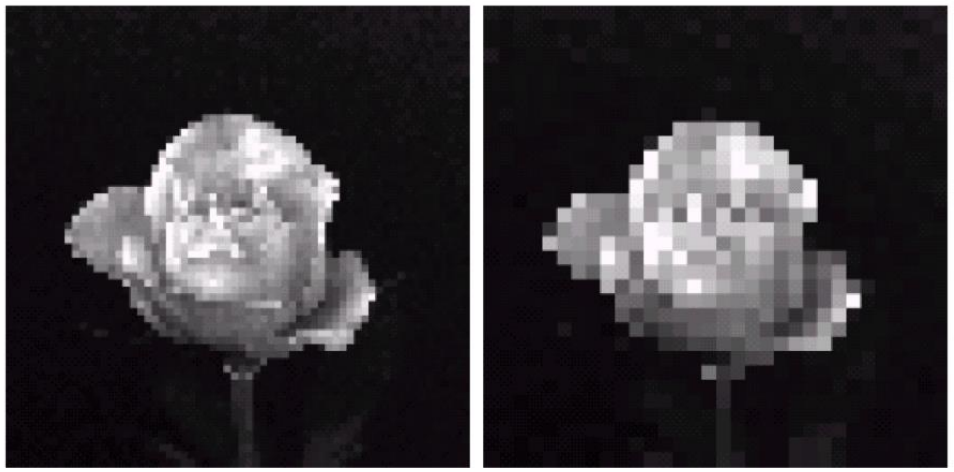
1024x1024 → 32x32

2.4.3 Spatial & gray-level resolution

- Spatial resolution
  - dots (pixels) per unit distance
  - dpi (dots per inch)
    - News: 75 dpi，Magazine：133 dpi，General use：300 or 600 dpi

one inch

one inch



64 dpi: 64 dots each row　32 dpi: 32 dots each row

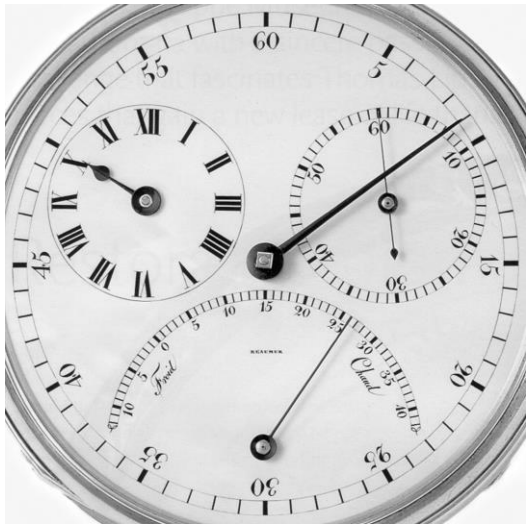
2.4.3 Spatial & gray-level resolution

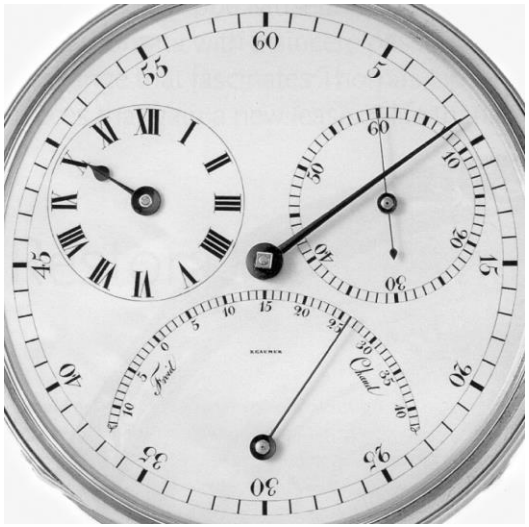
930 dpi

Image size: 2136x2140

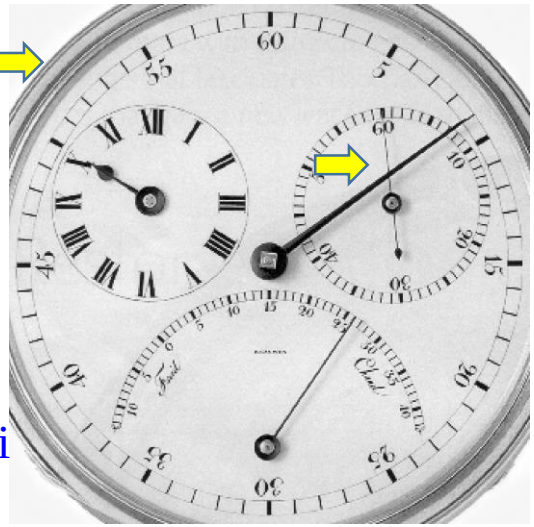
dpi: print in real life

Image size: only number of pixels

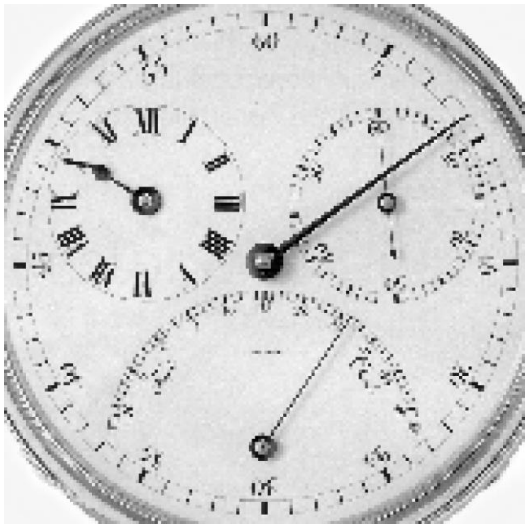




300 dpi posters



150 dpi

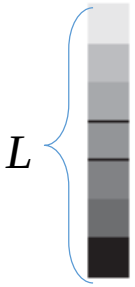


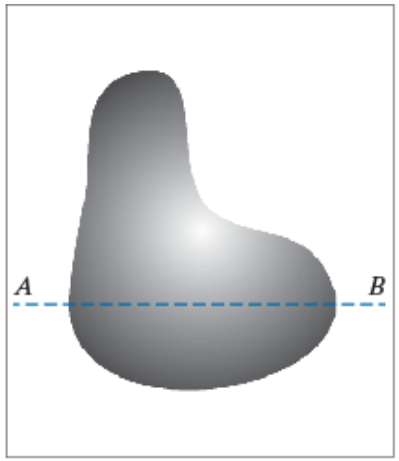
72 dpi

Image size: 165x166

2.4.3 空間與灰階解析度

- Gray-level resolution
  ←→
  Quantization





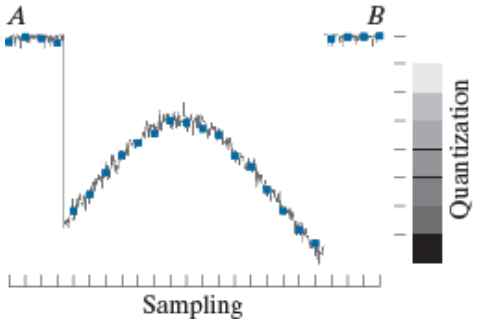


Image size:
774x640

256 levels

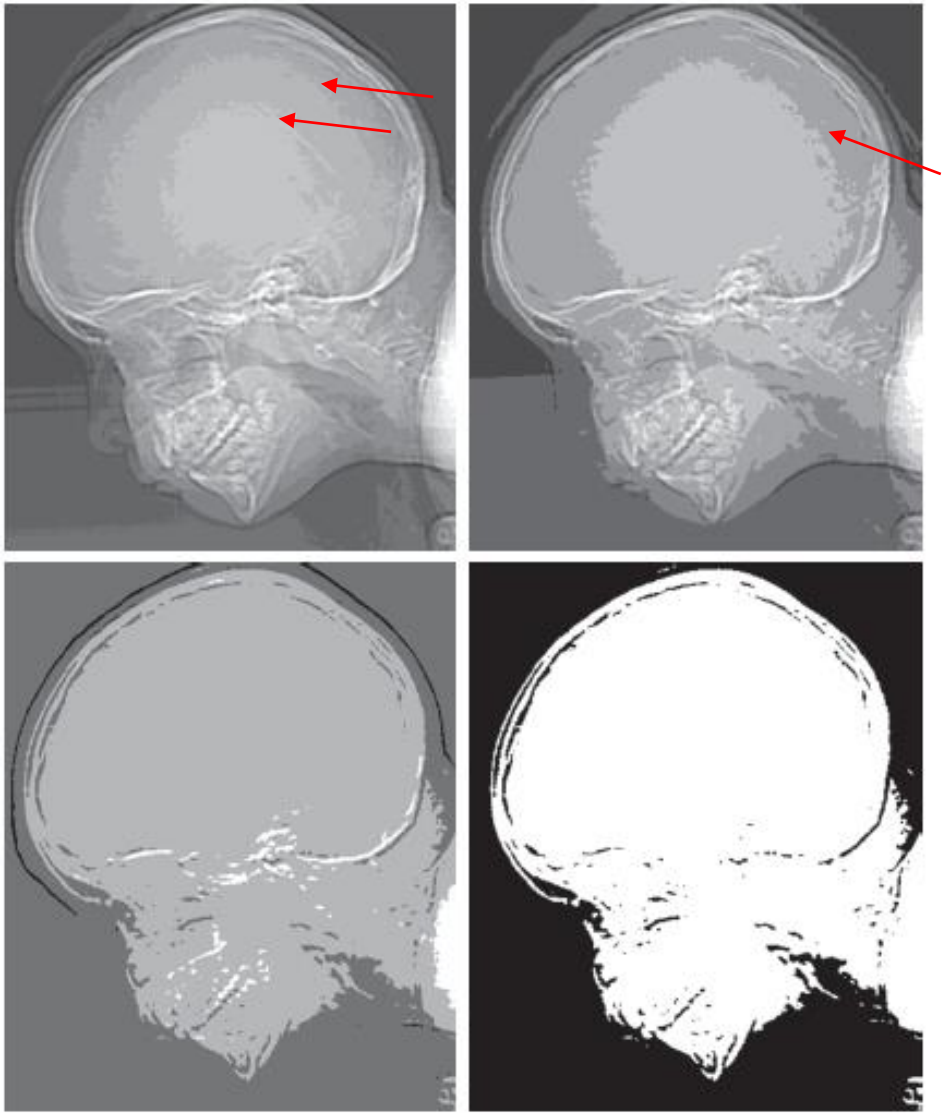
128 levels

64 levels

32 levels

2.4.3 空間與灰階解析度

Image size:
774x640



false contouring

16 levels

8 levels

4 levels

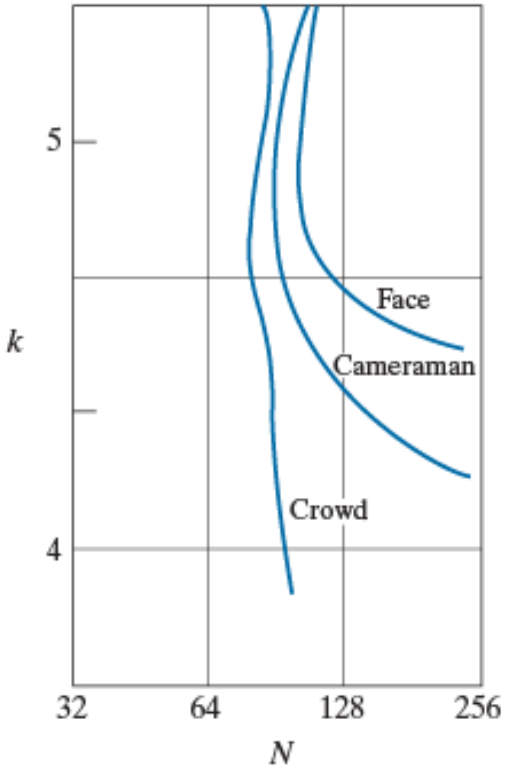
2 levels

2.4.3 空間與灰階解析度

- Less spatial resolution: bad quality
- Less gray-level resolution: bad quality
- What is the relation between spatial and gray-level resolution?

less←----------→more

details



Representative isopreference curves

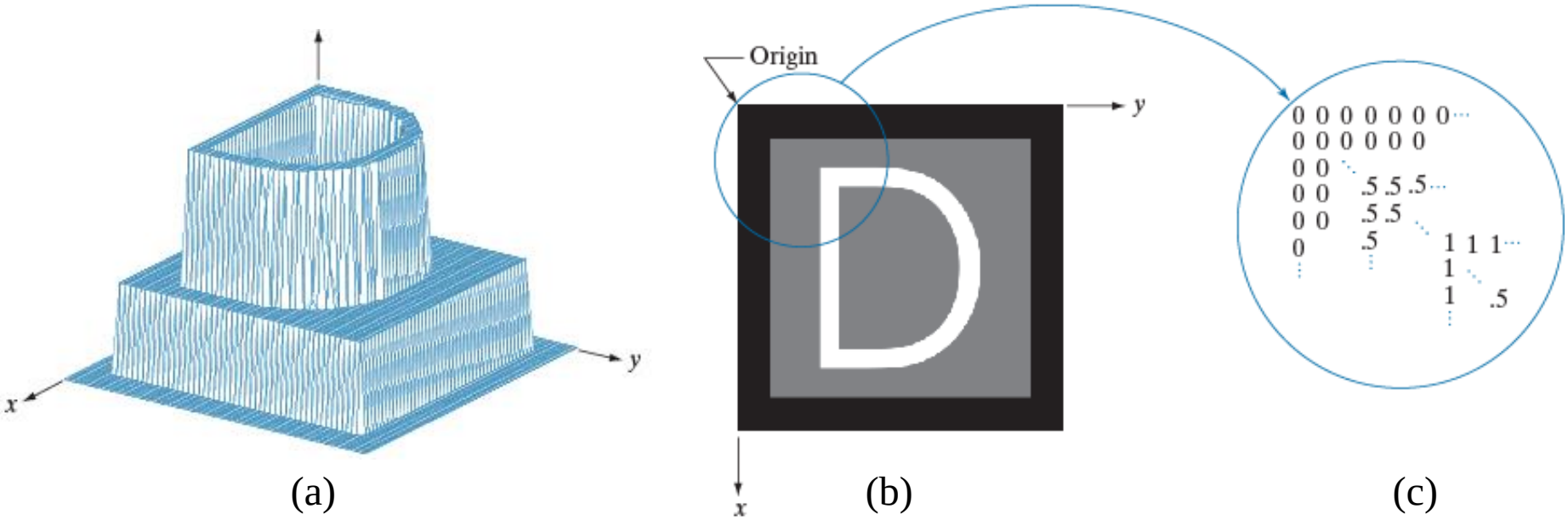
2.4.2 Digital Image Representation

(a) In 3D space：*x*, *y* as plane，z as intensity: *f*(*x*, *y*)。

f(.)：該座標點(pixel)的強度(intensity)或灰階(gray level)

(b) In intensity array in visual：different intensity *f* with different light

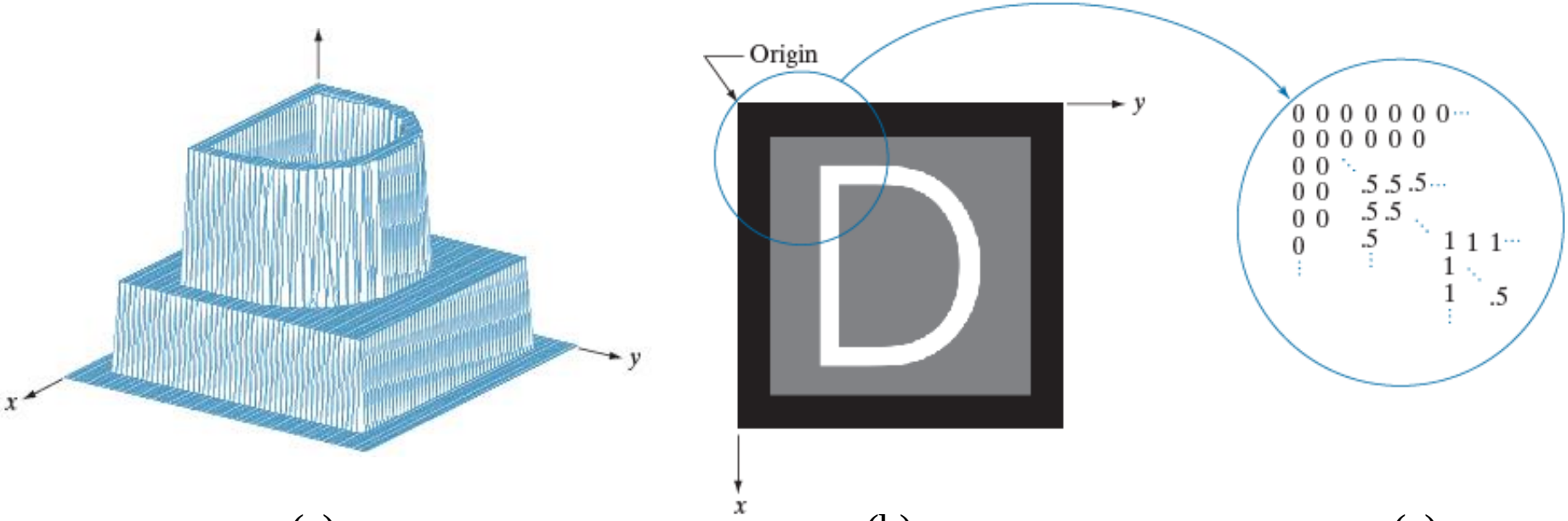
(c) In matrix：f(x,y)



(a) (b) (c)

2.4.2 Digital Image Representation

- Usually (b)(c)
- (b) shows the image result
- (c) is the raw data to be processed



(a) (b) (c)

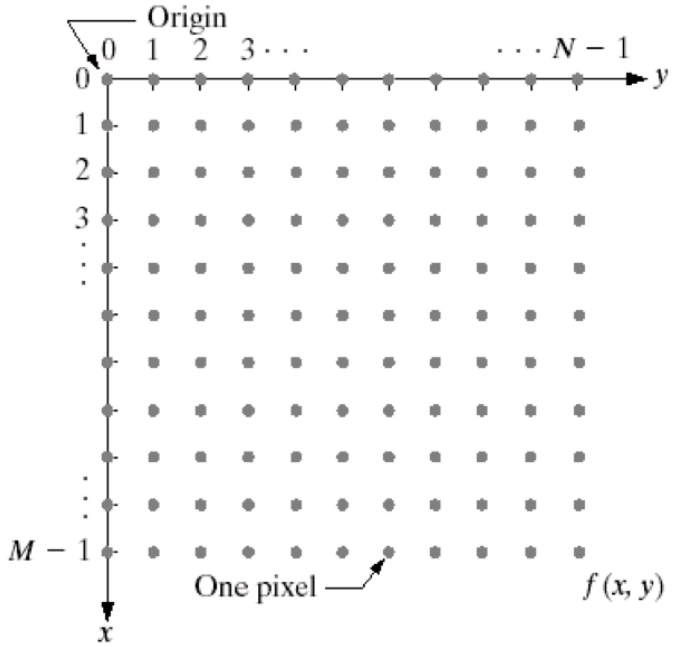
2.4.2 Digital Image Representation

- A $M \times N$ digital image can be represented as a function:

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

- or a matrix：

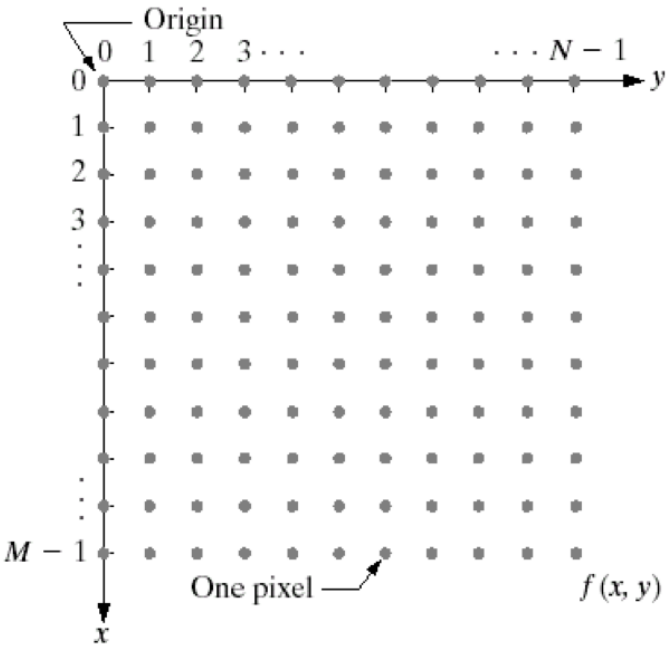
$$\mathbf{A} = \begin{bmatrix} a_{0,0} & a_{0,1} & \cdots & a_{0,N-1} \\ a_{1,0} & a_{1,1} & \cdots & a_{1,N-1} \\ \vdots & \vdots & \ddots & \vdots \\ a_{M-1,0} & a_{M-1,1} & \cdots & a_{M-1,N-1} \end{bmatrix}$$



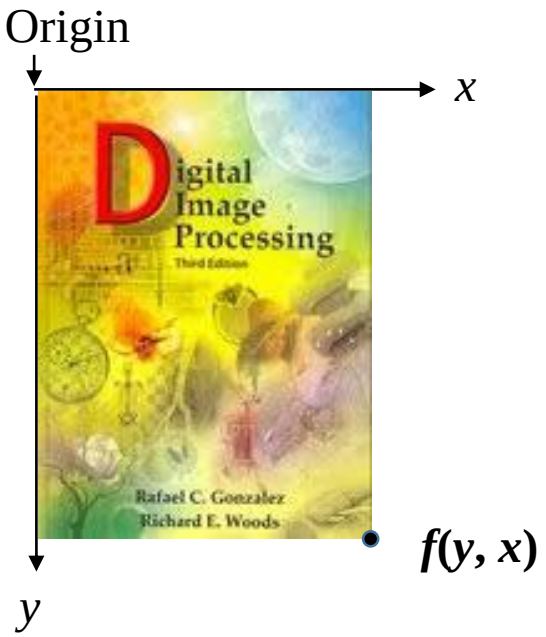
2.4.2 Digital Image Representation

- Different device with different origin

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



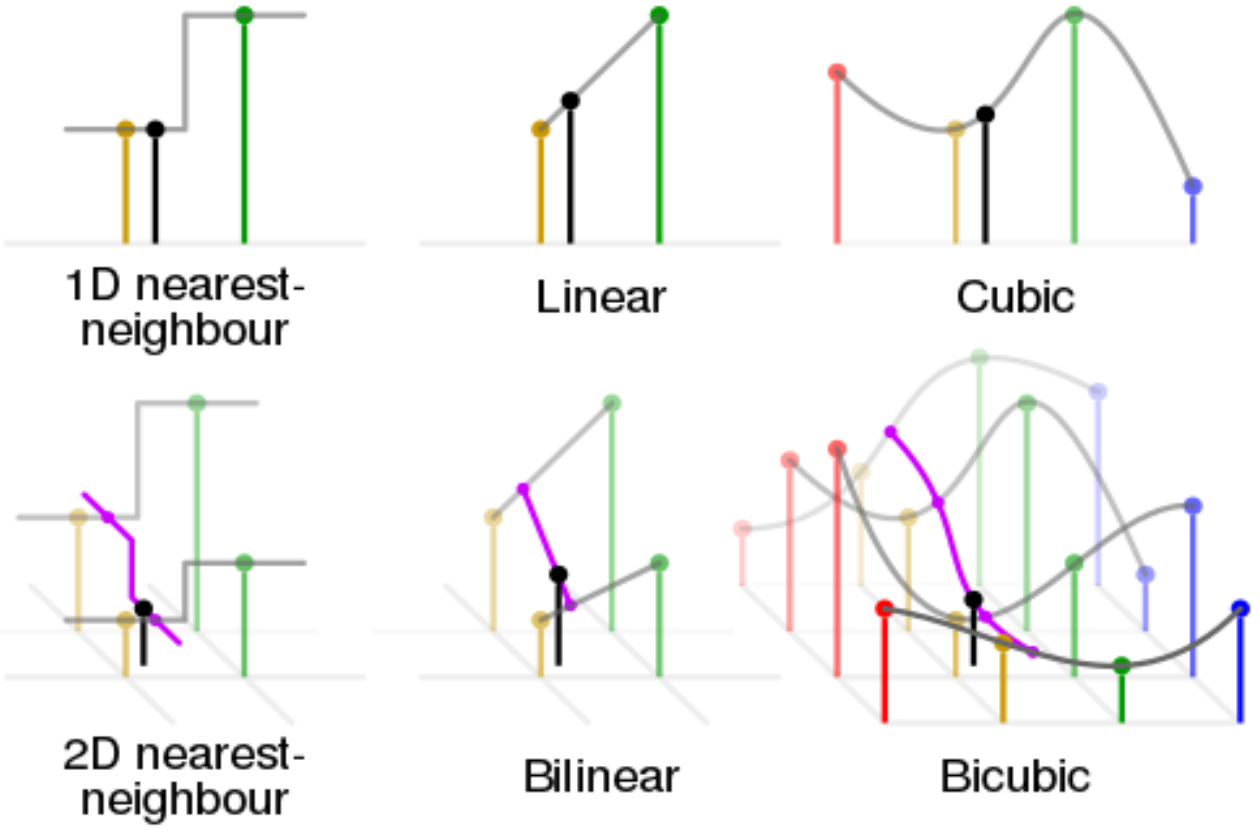
本書使用的表示方法



有些書籍使用的表示方法

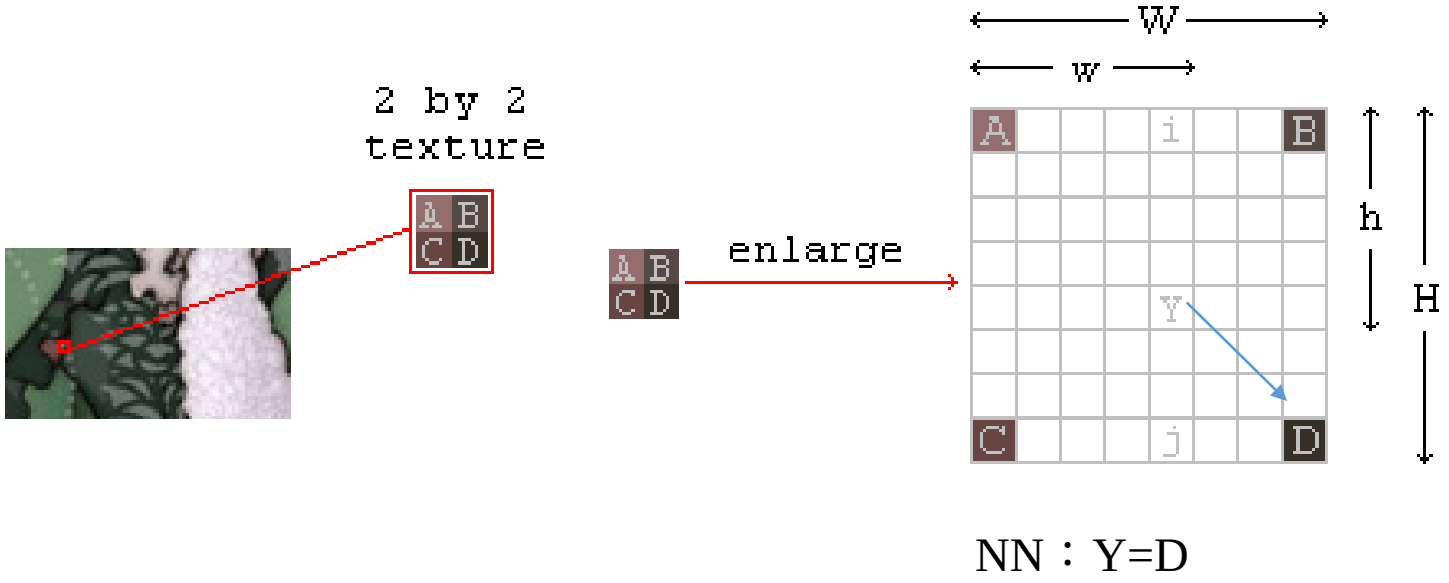
2.4.4 影像內插 (Interpolation)

- Interpolation：predict unknown data using known data
  - Nearest neighbor interpolation, NN interpolation
  - Linear interpolation：4 surrounding pixels
  - Bicubic interpolation：16 surrounding pixels



2.4.4 影像內插 (Interpolation)

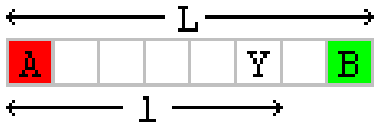
- Nearest neighbor interpolation, NN interpolation



NN：Y=D

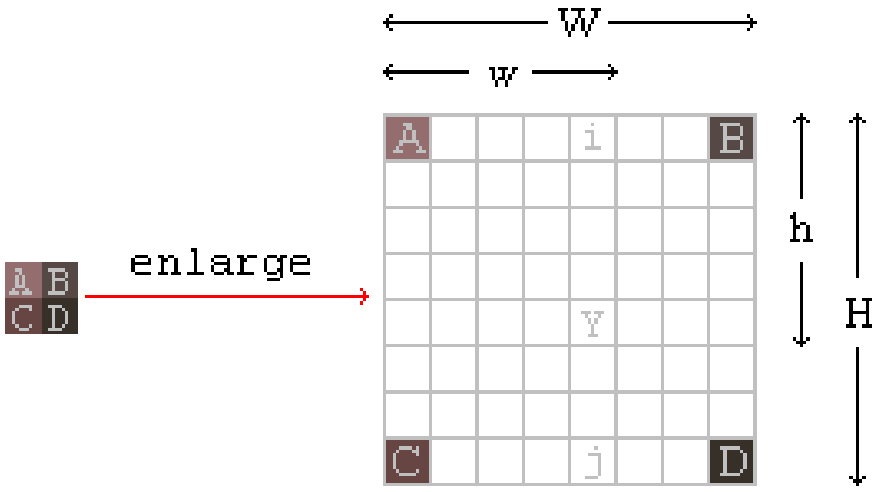
2.4.4 影像內插 (Interpolation)

- Linear interpolation：4 surrounding pixels



$$\frac{Y-A}{l}=\frac{B-A}{L}$$

$$Y=A+\frac{l(B-A)}{L}$$



W =1
H = 1

$$\frac{i-A}{w}=\frac{B-A}{W}$$

$$i=A+\frac{w(B-A)}{W}$$

$$i=A+w(B-A)\rightarrow 1$$

$$\frac{j-C}{w}=\frac{D-C}{W}$$

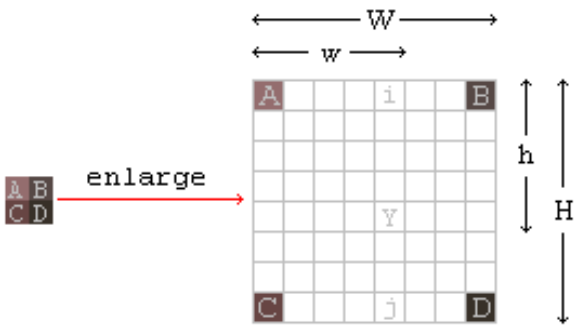
$$j=C+w(D-C)\rightarrow 2$$

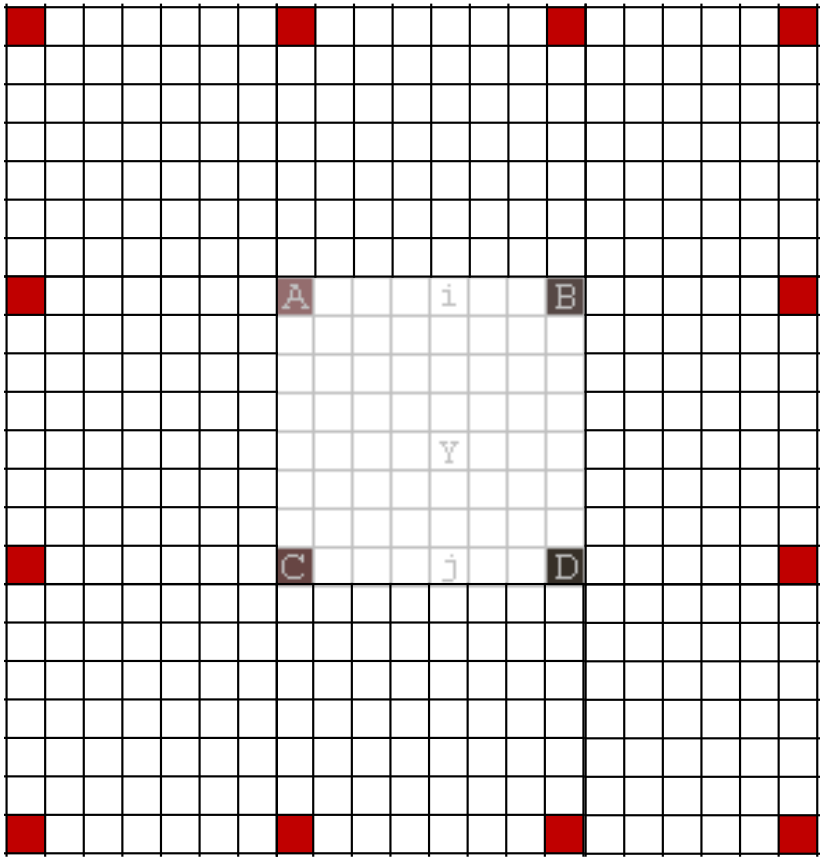
$$\frac{Y-i}{h}=\frac{j-i}{H}$$

$$Y=i+h(j-i)\rightarrow 3$$

2.4.4 影像內插 (Interpolation)

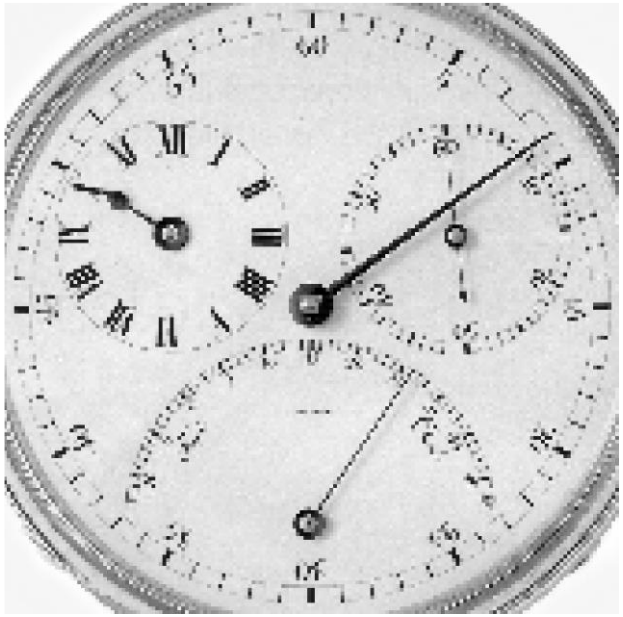
- Bicubic interpolation：16 surrounding pixels





2.4.4 影像內插 (Interpolation)

- Original：2136x2140, downsize to 165*166



Enlarge with NN

Enlarge with Linear Interpolation

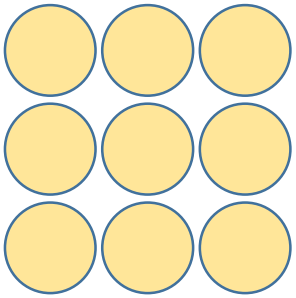
Enlarge with Bicubic Interpolation

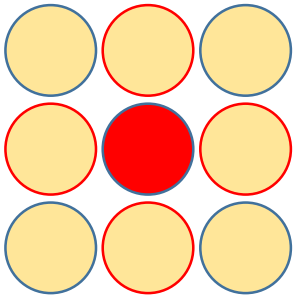
2 數位影像基礎 Digital Image Fundamentals

- 2.1 視覺感知要素 Elements of Visual Perception
- ~~2.2 光與電磁頻譜 Light and the Electromagnetic Spectrum~~
- 2.3 影像感知與獲取 Image Sensing and Acquisition
- 2.4 影像取樣與量化 Image Sampling and Quantization
- 2.5 像素間的基本關係 Basic Relationships between Pixels
- 2.6 數位影像處理的數學工具 Mathematical Tools Used in Digital Image Processing

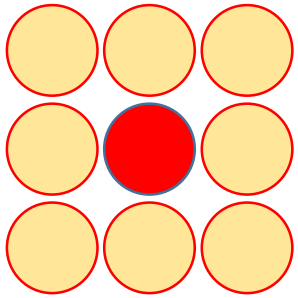
2.5.1 像素的近鄰 (neighbors)

- 對於一像素p (x, y):
  - $N_4(p)$：四近鄰(4-neighbors)
    - $(x+1, y)$、$(x, y+1)$、 $(x-1, y)$、$(x, y-1)$
  - $N_D(p)$：對角(diagonal)
    - $(x+1, y+1)$、$(x-1, y+1)$、 $(x-1, y-1)$、$(x+1, y-1)$
  - $N_8(p)$：八近鄰(8-neighbors)
    - $N_4(p) + N_D(p)$





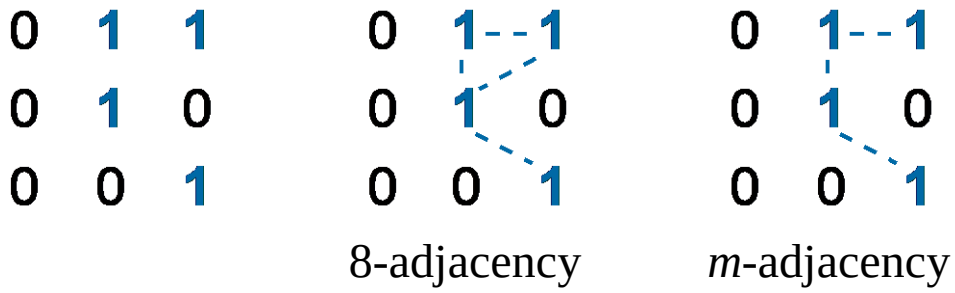
4-neighbors



8-neighbors

2.5.2 鄰接性、連通性、區域

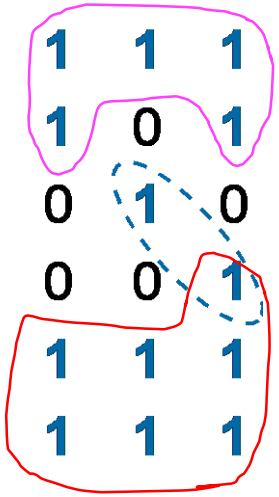
- 4-鄰接性(4-adjacency)
- 8-鄰接性(8-adjacency)
- *m*-鄰接性(*m*-adjacency)(混合鄰接性)



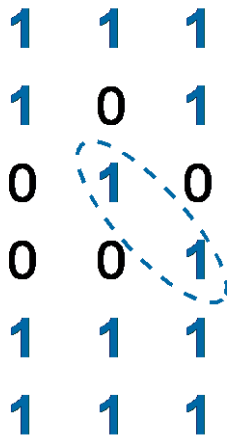
8-adjacency　　*m*-adjacency

2.5.2 鄰接性、連通性、區域

- 連通成份(connected component)
  - 依所採之鄰接性而不同
  - 形成區域(region)



4-adjacency



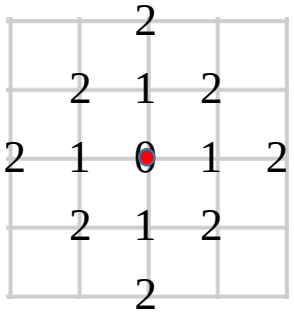
8-adjacency
所有的1都相連
(connected)

2.5.3 距離量測

- 假設有2像素p, q, 座標分別為: (x, y), (s, t)
- 歐基里德距離(*Euclidean distance*):

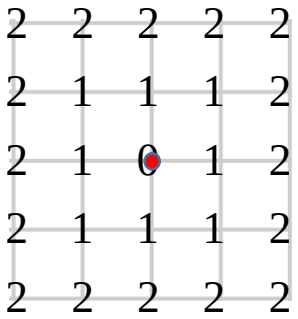
$$D_e(p,q) = [(x-s)^2 + (y-t)^2]^{\frac{1}{2}}$$

- 市街距離(*city-block distance*):



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

- 棋盤距離(*chessboard distance*):



$$D_8(p,q) = \max(|x-s|, |y-t|)$$

2 數位影像基礎 Digital Image Fundamentals

- 2.1 視覺感知要素 Elements of Visual Perception
- 2.2 光與電磁頻譜 Light and the Electromagnetic Spectrum
- 2.3 影像感知與獲取 Image Sensing and Acquisition
- 2.4 影像取樣與量化 Image Sampling and Quantization
- 2.5 像素間的基本關係 Basic Relationships between Pixels
- 2.6 數位影像處理的數學工具 Mathematical Tools Used in Digital Image Processing

2.6.1 Elementwise vs Matrix operations

- 影像可視為矩陣(matrix)，許多時候影像間的計算會用矩陣理論來執行。
- 因此必須先分清矩陣運算與點對點(Elementwise)運算
- 對影像進行Elementwise operation，指的是像素對像素(pixel-by-pixel)的運算。

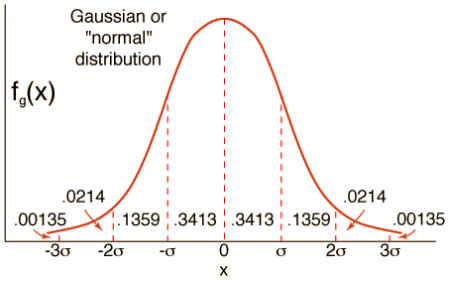
兩張2x2影像: $\begin{bmatrix} a_{11} & a_{12} \\ a_{21} & a_{22} \end{bmatrix}$ $\begin{bmatrix} b_{11} & b_{12} \\ b_{21} & b_{22} \end{bmatrix}$

matrix product (矩陣乘積) $\begin{bmatrix} a_{11} & a_{12} \\ a_{21} & a_{22} \end{bmatrix}\begin{bmatrix} b_{11} & b_{12} \\ b_{21} & b_{22} \end{bmatrix}=\begin{bmatrix} a_{11}b_{11}+a_{12}b_{21} & a_{11}b_{12}+a_{12}b_{22} \\ a_{21}b_{11}+a_{22}b_{21} & a_{21}b_{12}+a_{22}b_{22} \end{bmatrix}$

elementwise product ($\odot$ or $\otimes$) $\begin{bmatrix} a_{11} & a_{12} \\ a_{21} & a_{22} \end{bmatrix}\odot\begin{bmatrix} b_{11} & b_{12} \\ b_{21} & b_{22} \end{bmatrix}=\begin{bmatrix} a_{11}b_{11} & a_{12}b_{12} \\ a_{21}b_{21} & a_{22}b_{22} \end{bmatrix}$

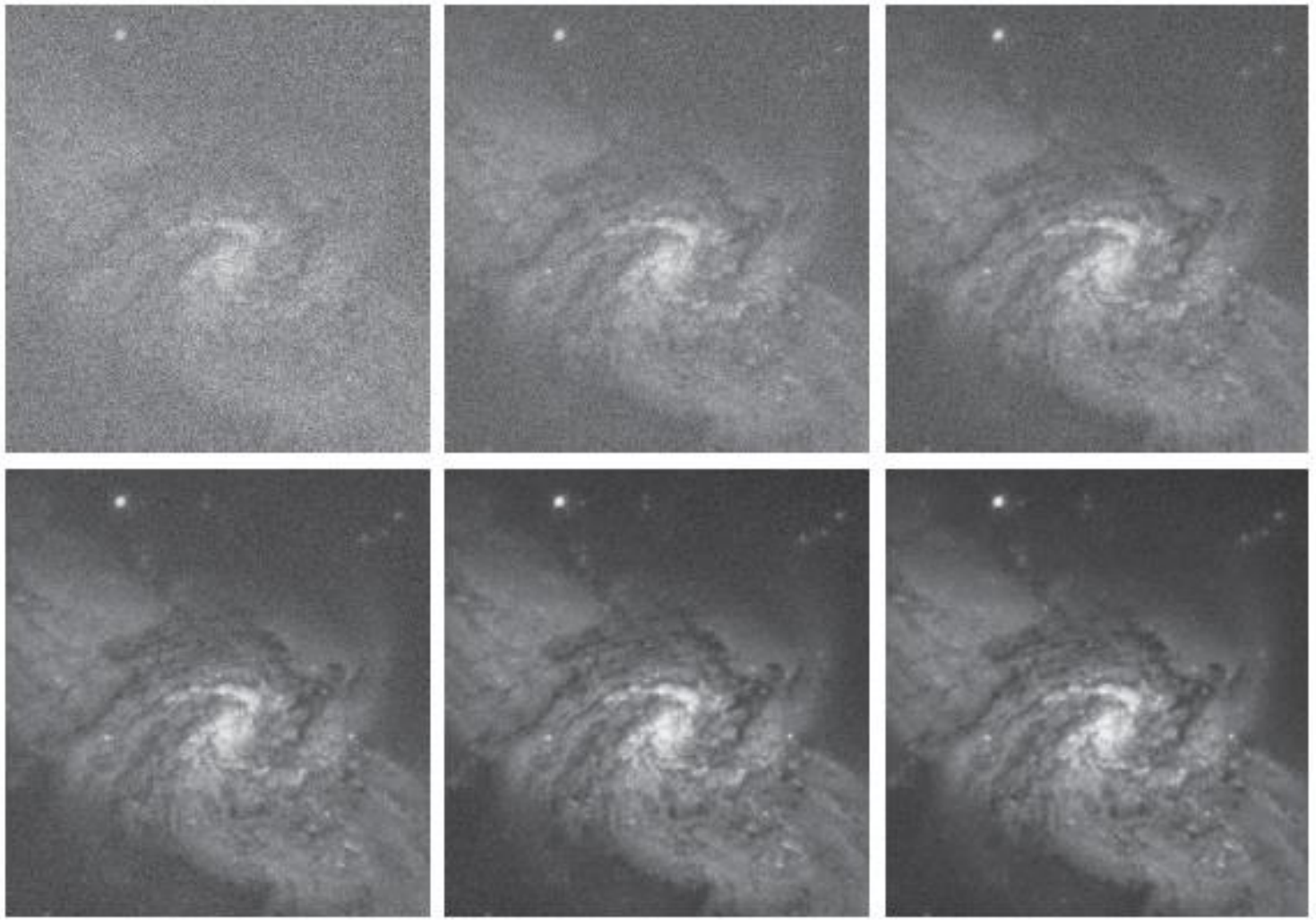
影像相加(平均)之應用

- 帶有雜訊的影像相加(平均)以降低雜訊

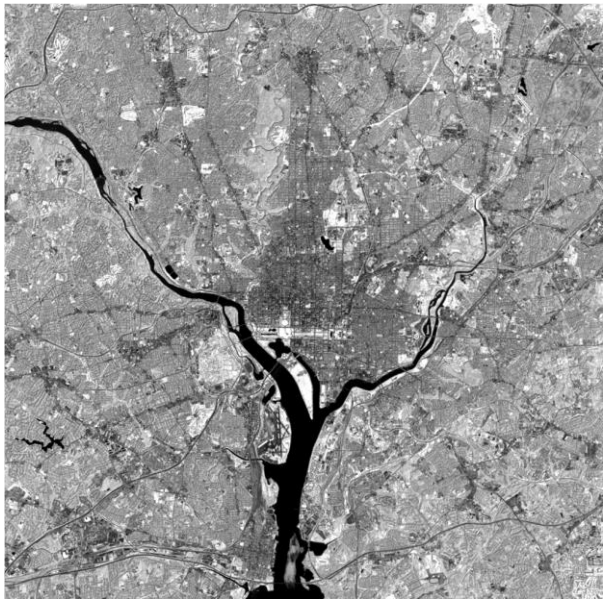
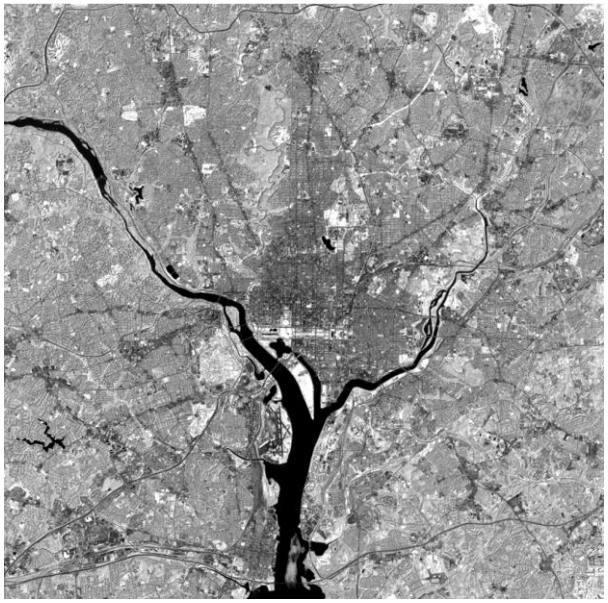
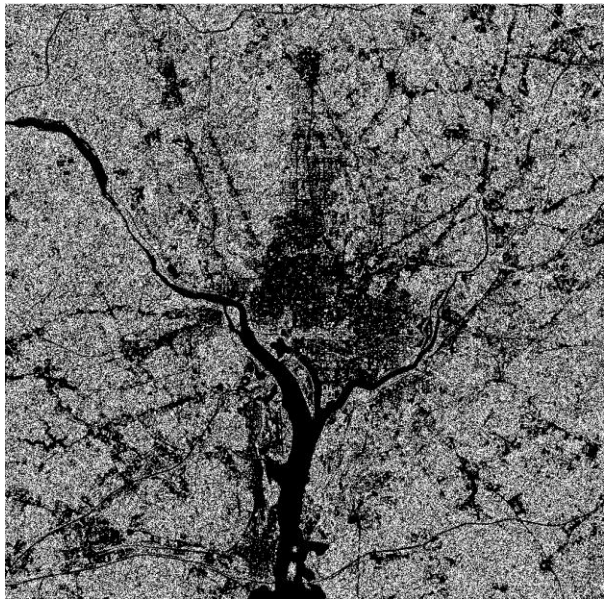


(a)帶有高斯雜訊的銀河系NGC 3314影像。

(b)~(f)分別平均5,10,20, 50, 100張帶有雜訊影像後的結果



影像相減之應用

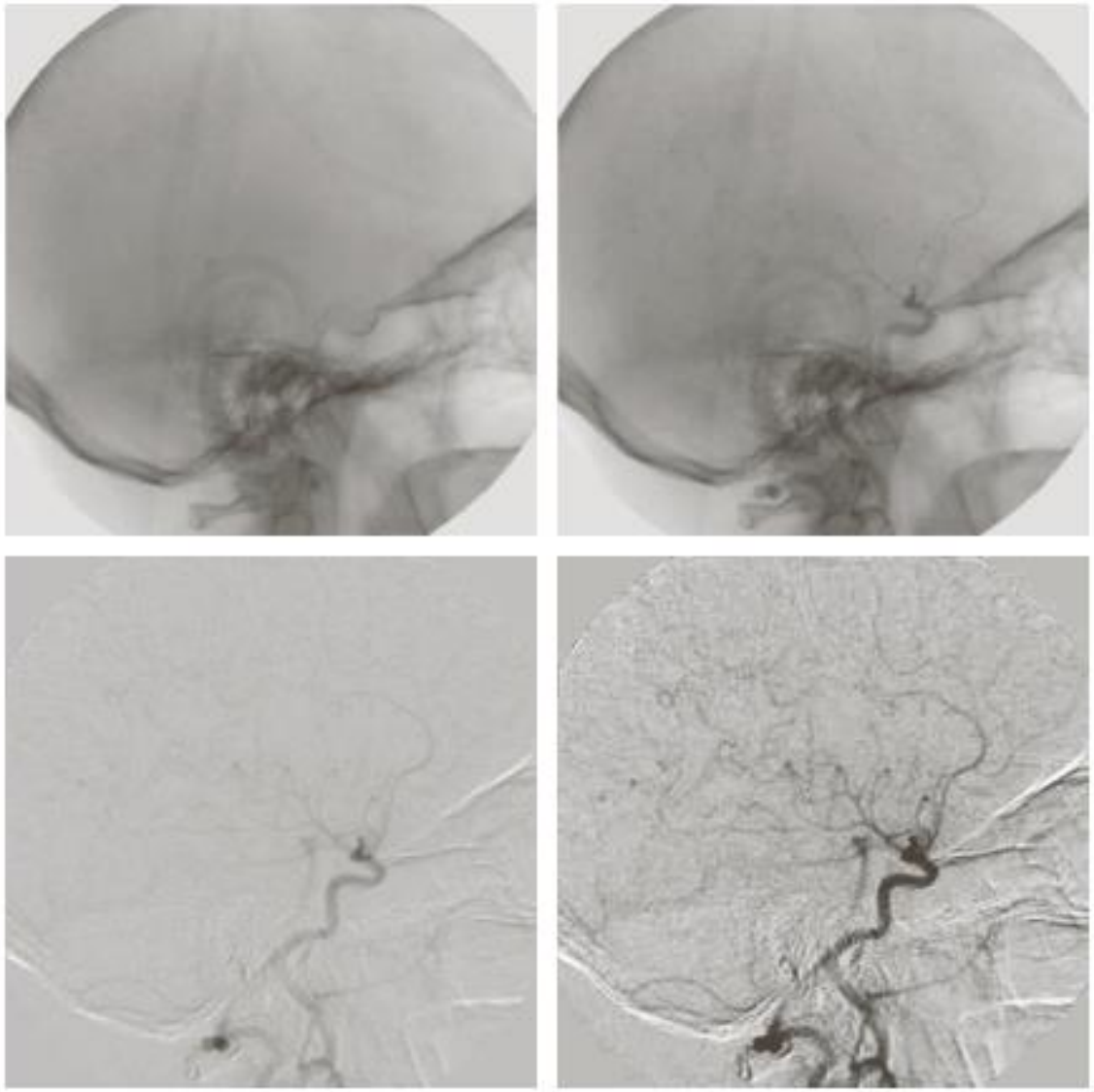




(a) 華盛頓DC區的紅外線影像　　8 bits: 10010111

(b) 將(a)中每個像素的最末位元(least significant bit)設為0，差異並不明顯

(c) 兩張影像的差值影像，為清楚呈現，調整至[0, 255]範圍
(黑像素表示「無差異」)

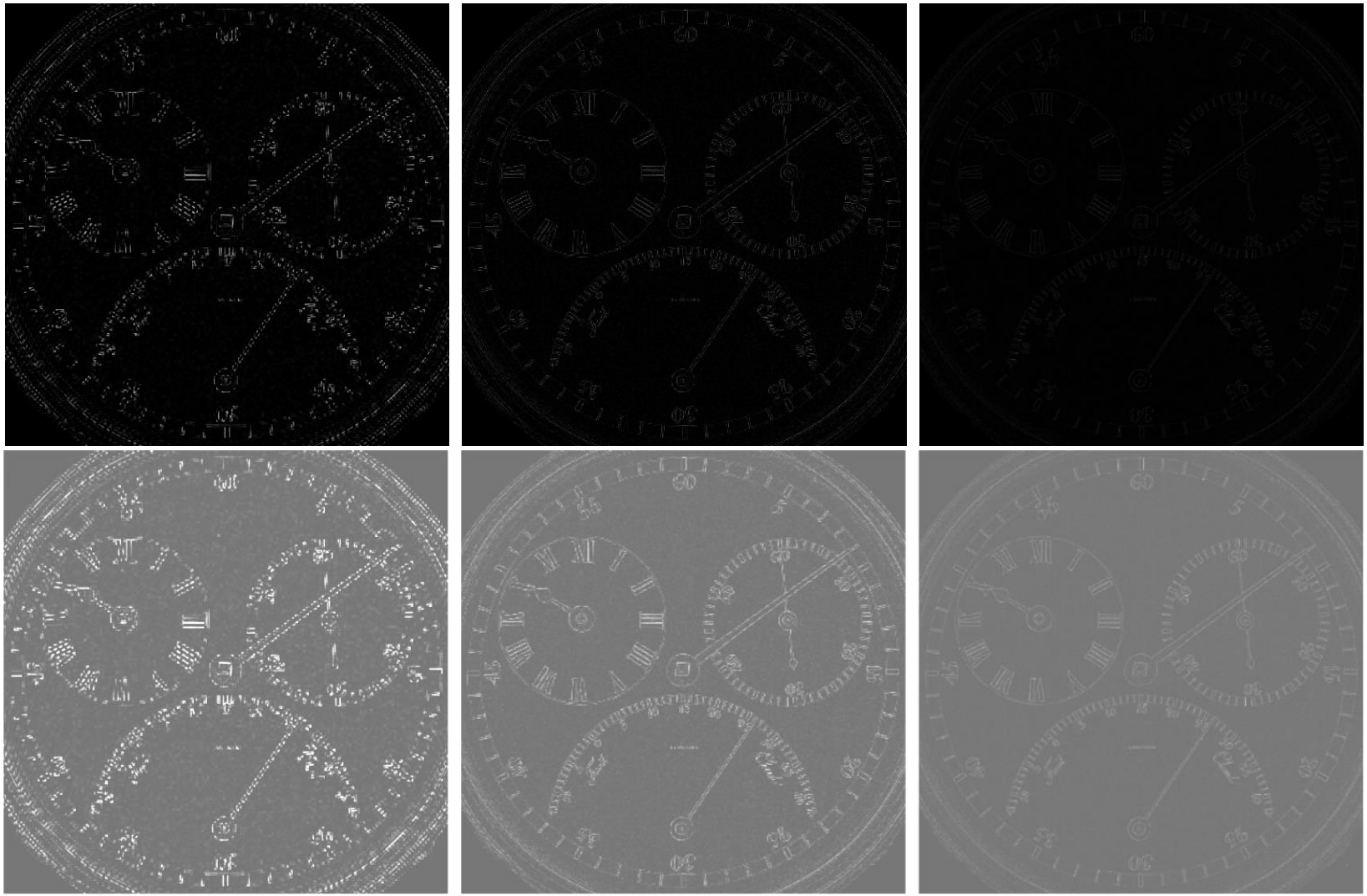
影像相減之應用



(a) 遮罩影像(mask image)
(b) 注射媒介溶液後之即時影像(live image)
(c) 差值影像
(d) 增強之差值影像

動態顯示出媒介溶液如何通過觀察區的各種動脈

影像相減之應用



加強對比亮度

(a) 930 dpi與72 dpi的差異 (b) 930 dpi與150 dpi的差異 (c) 930 dpi與300 dpi的差異

影像相減之應用

Background Model

Current Frame

Difference and thresholding

Absdiff (bg, frame, fg);

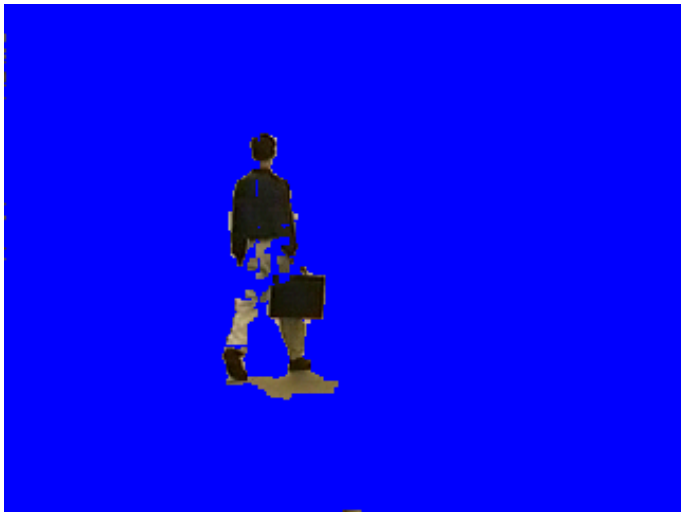
threshold (fg, white, 200, 255, THRESH_BINARY);

影像相減之應用

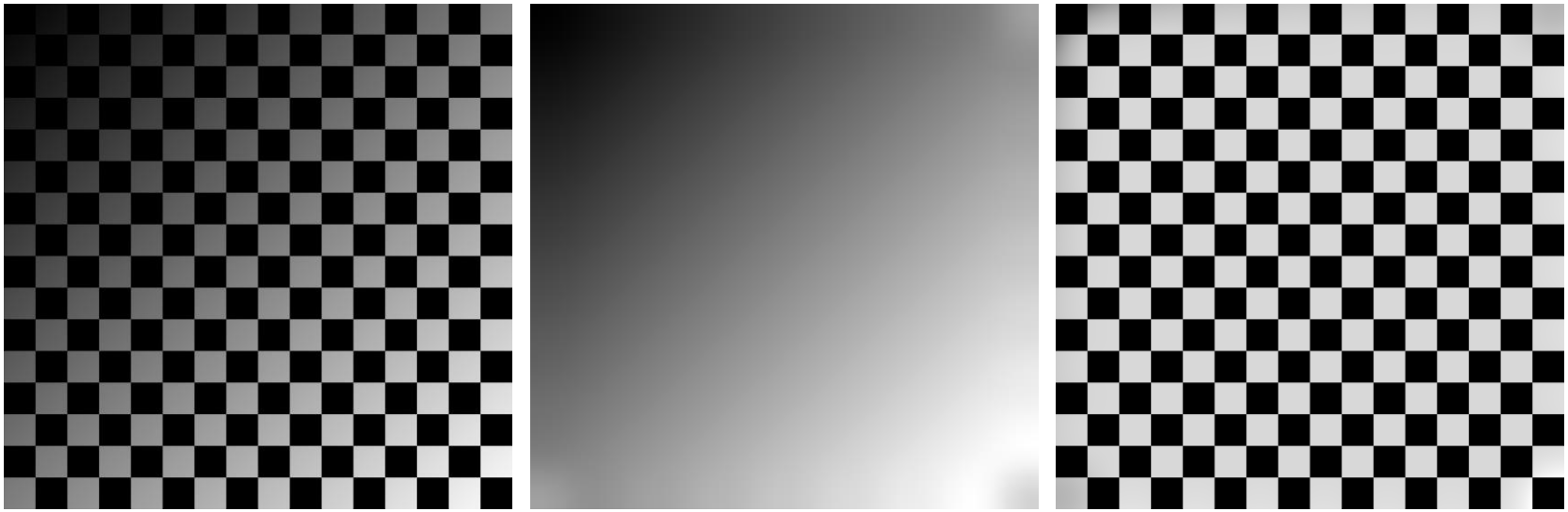
Background Model

Current Frame

Difference (subtraction) and thresholding

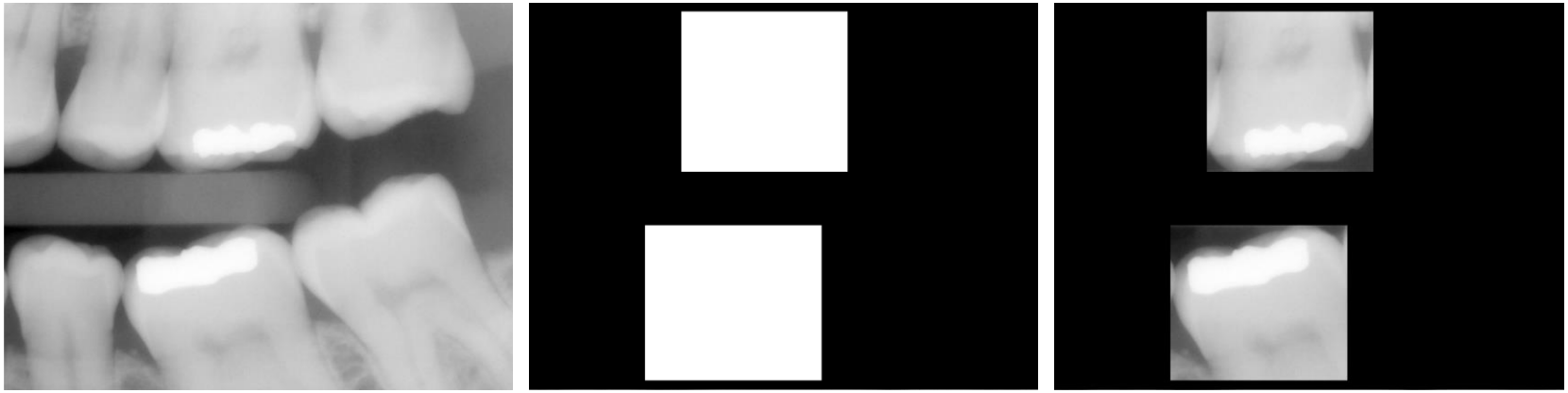


影像相乘/除做陰影修正



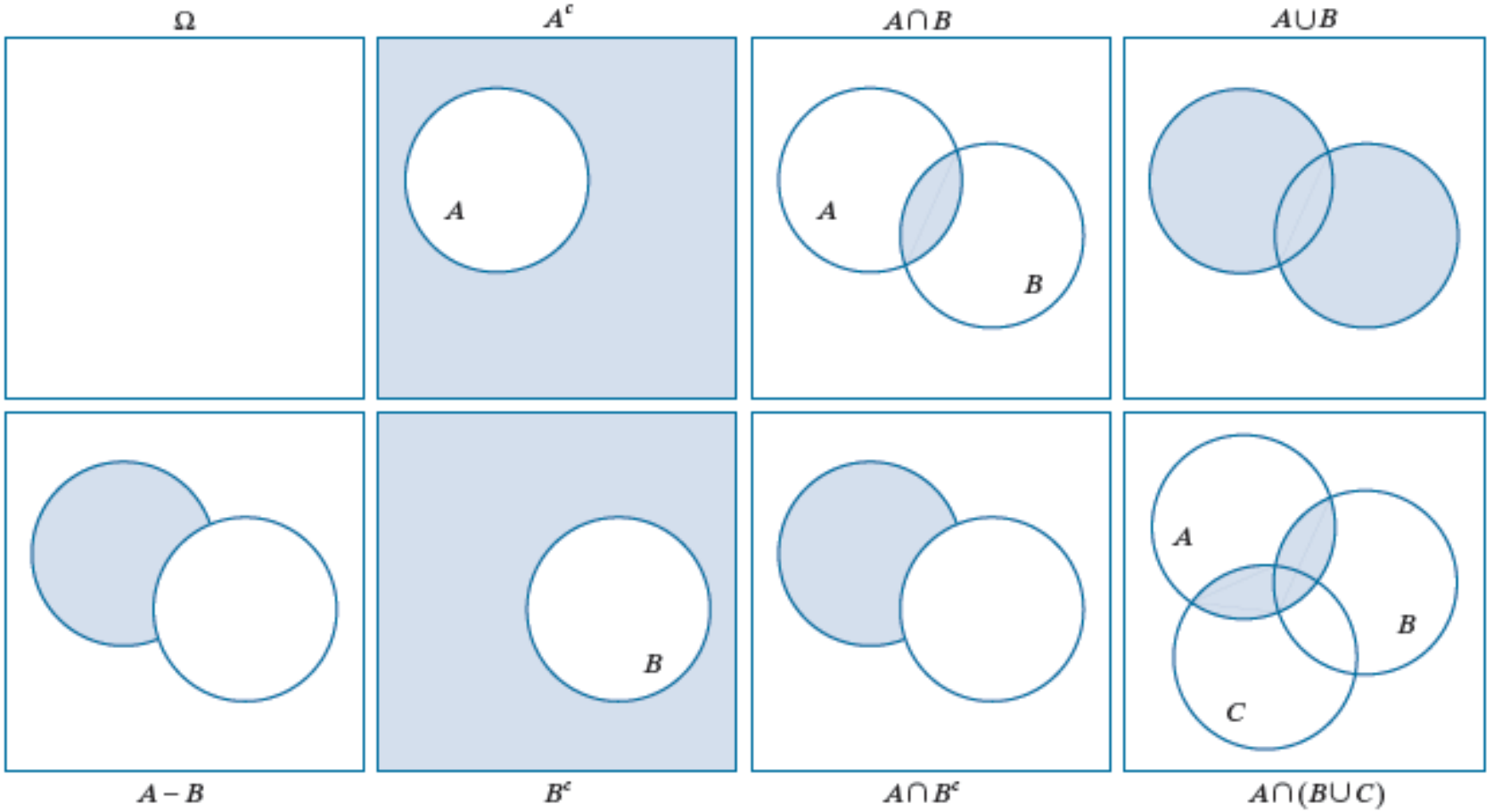
(a):有陰影的影像。
(b):估算出的陰影影像。
(c): (a)與(b)倒數相乘後的結果。

影像相乘作遮罩(masking)



(a):牙齒X光影像。
(b):ROI (region of interest)遮罩（1:白，0:黑）
(c): (a)與(b) 的乘積。

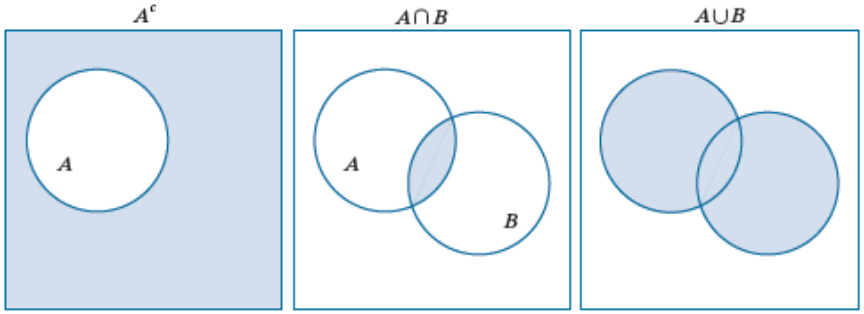
2.6.4 集合與邏輯運算



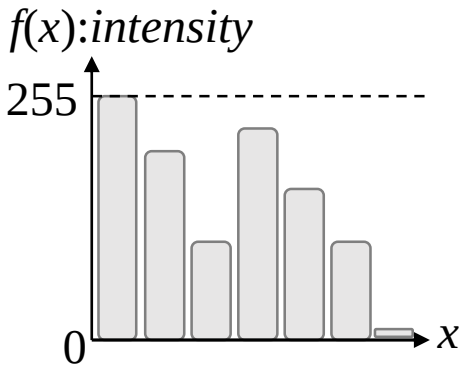
a b c d
e f g h

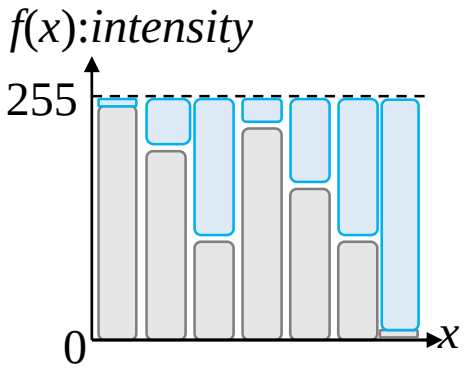
FIGURE 2.35 Venn diagrams corresponding to some of the set operations in Table 2.1. The results of the operations, such as A^c, are shown shaded. Figures (e) and (g) are the same, proving via Venn diagrams that $A - B = A \cap B^c$ [see Eq. (2-40)].

涉及影像強度的集合運算



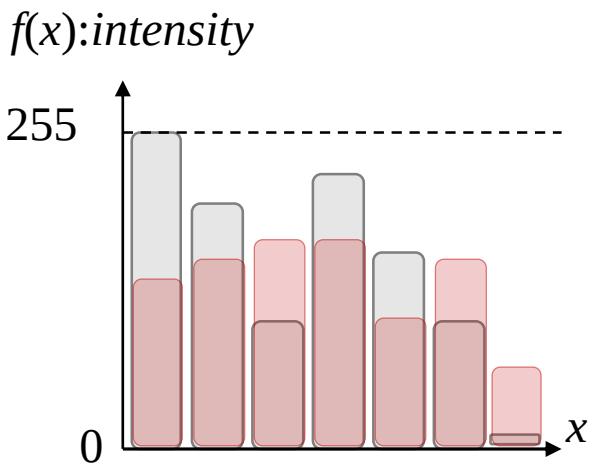
- 補集:
  $f^c(x, y) = 255 - f(x, y)$





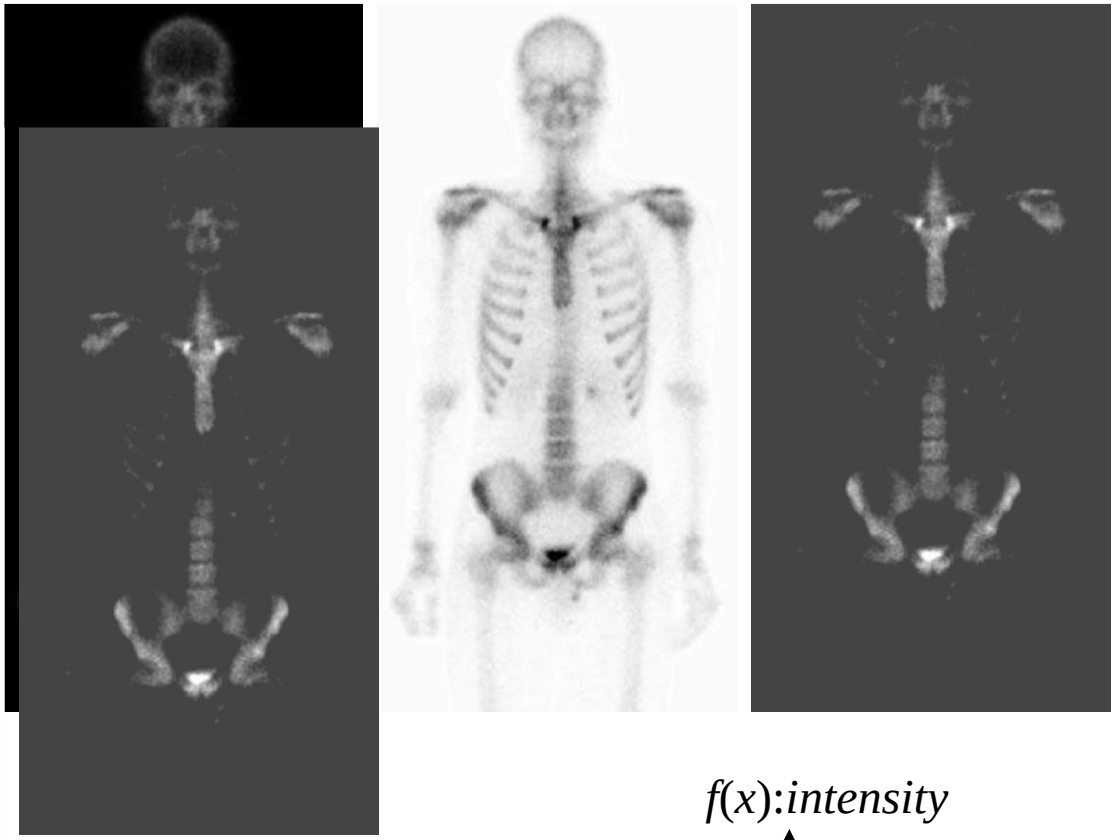
- 交集: $f_{A \cap B}(x, y) =$
  $\min(f_A(x, y),\ f_B(x, y))$

- 聯集: $f_{A \cup B}(x, y) =$
  $\max(f_A(x, y),\ f_B(x, y))$



涉及影像強度的集合運算

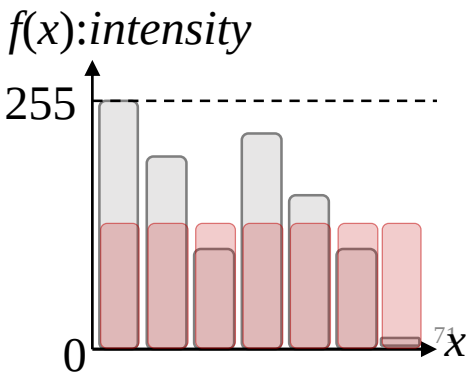
- 補集:
  $f^c(x, y) = 255\text{-}f(x, y)$
- 交集: $f_{A\cap B}(x, y) =$
  $\min(f_A(x, y),\ f_B(x, y))$
- 聯集: $f_{A\cup B}(x, y) =$
  $\max(f_A(x, y),\ f_B(x, y))$



(a)原影像 A

(b) 取補集所得之影像底片: $A^c = \{(x, y, 255\text{-}z) | (x, y, z) \in A\}$

(c) A與一常數影像取聯集: $A \cup B = \{\max_z(a, b) \mid a \in A, b \in B\}$



- Q&A