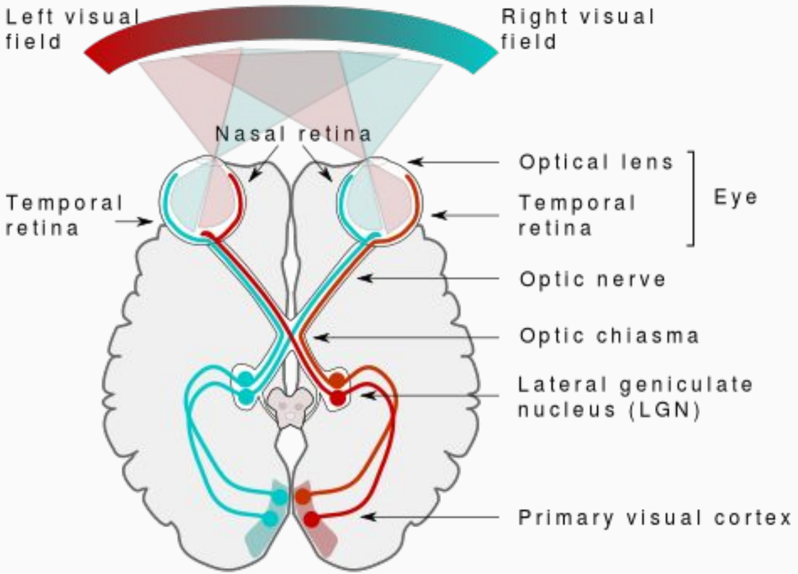
CSE428: Image Processing

Lecture 2: HVS and Digital Image Acquisition

Outline

- Human Visual System
- Digital Image Sensing
- Sampling and Quantization
- Digital Image Representation
- Upsampling, Downsampling, Interpolation

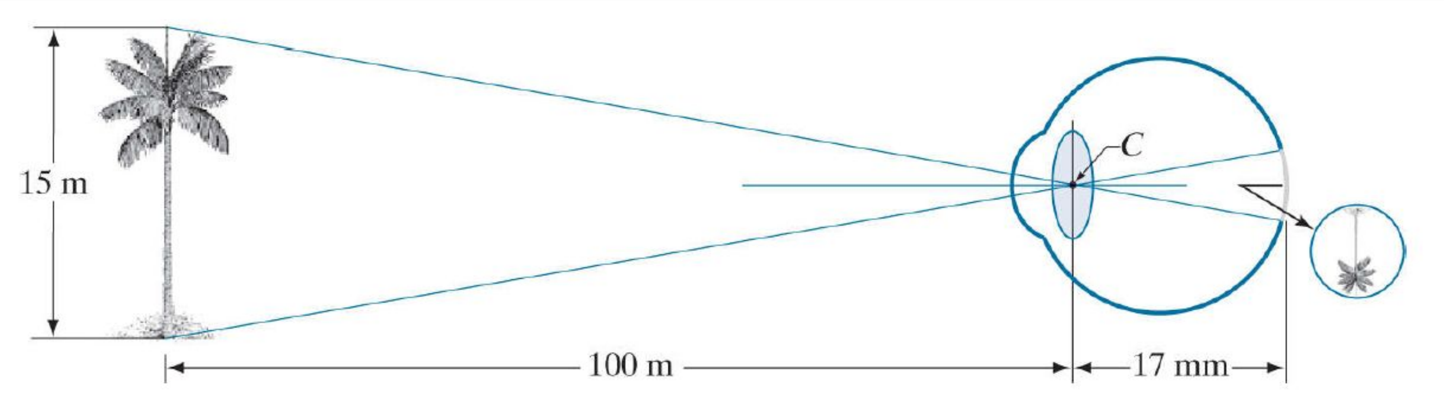
Human Visual System (HVS)



- Visual perception - key role in image processing
- **Eye** - sensor of the HVS
- **Brain** - image processing
  - Integrates intelligence and experience with input

Human Visual System (HVS)

Image formation in human eye



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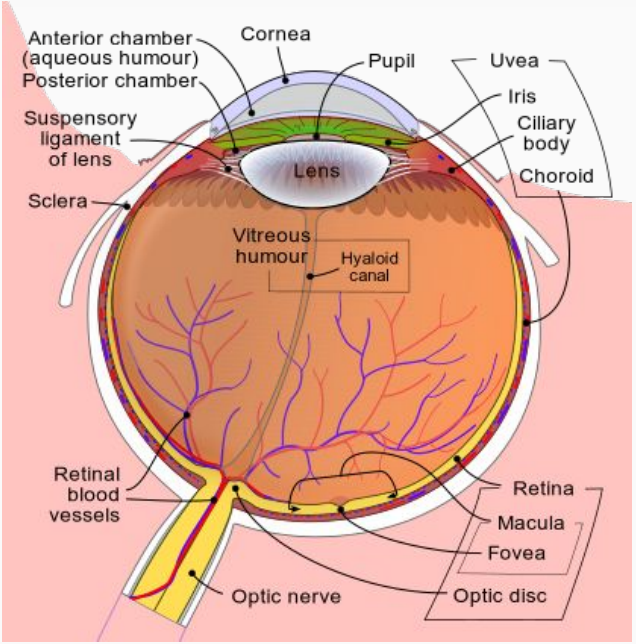
$$h/17\ \text{mm} = 15\ \text{m} / 100\ \text{m}$$

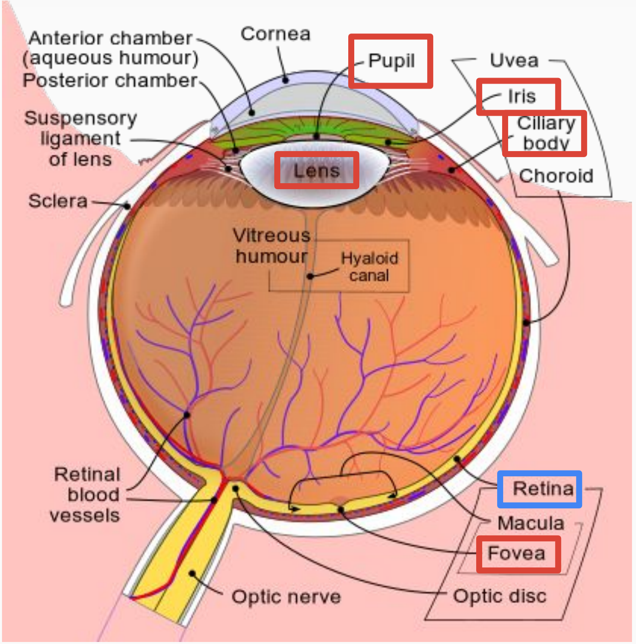
Human Visual System (HVS)

Structure of the eye



Human Visual System (HVS)

Structure of the eye

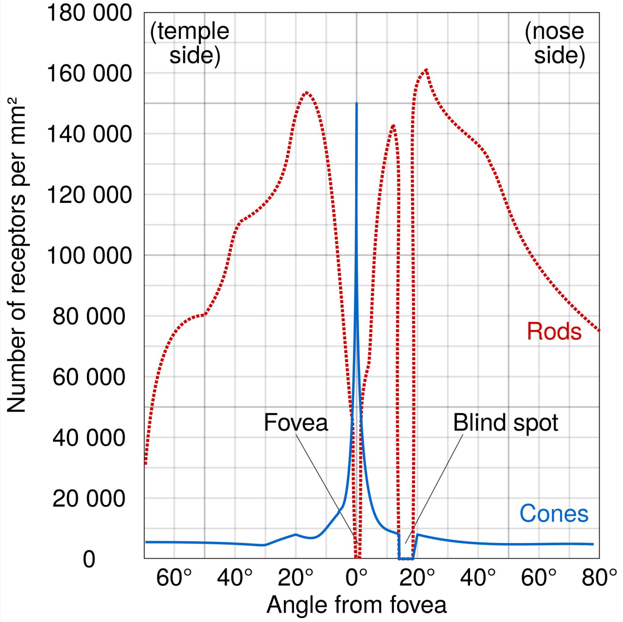


By Rhcastilhos. And Jmarchn. - Schematic_diagram_of_the_human_eye_with_English_annotations.svg, CC BY-SA 3.0, https://commons.wikimedia.org/w/index.php?curid=1597930

- **Iris & Pupil** - Controls the amount of light
- **Ciliary Body** - adjusts the focal length of optical **lens**
- **Retina** - Receptors (sensors) of 2 types, cones and rods
- **Fovea** - focusing region

Human Visual System (HVS)

Cones and Rods

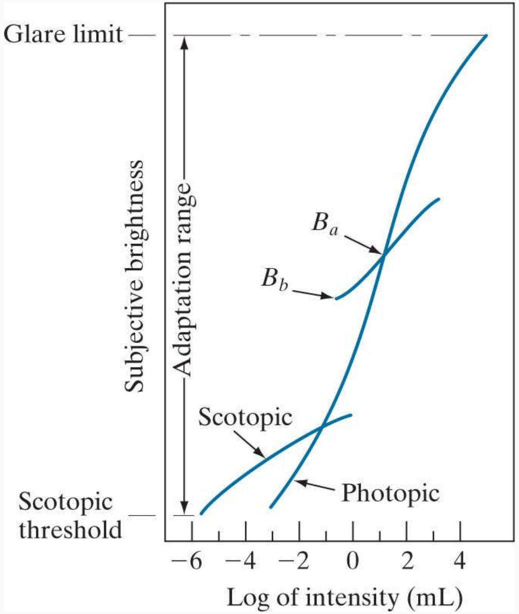


- **Cones** - Low in number. Concentrated on a central position called fovea. <u>Highly sensitive to color</u>. Fine details response since each cone connected with a nerve.

- **Rods** - High in number. Distributed over the optic globe. <u>Sensitive to low light</u> vision with <u>no color information</u>. Low resolution response since several rods connected with a nerve.

Human Visual System (HVS)

Brightness Adaptation



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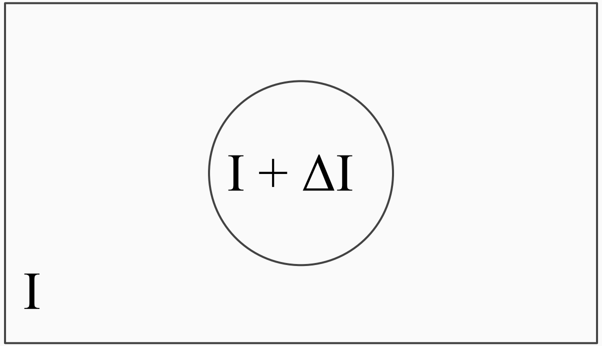
- Camera *captures* **intensity**, objective
- We *perceive* **brightness**, subjective
- Subjective brightness is a logarithmic function of light intensity
- Adaptation range for photopic vision is quite high, but overall adaptation due to scotopic vision is quite low.
- Thus, for a given set of brightness (say Ba) condition, the range of discriminative intensity level of HVS is rather small (shown as curve of Ba-Bb).

Human Visual System (HVS)

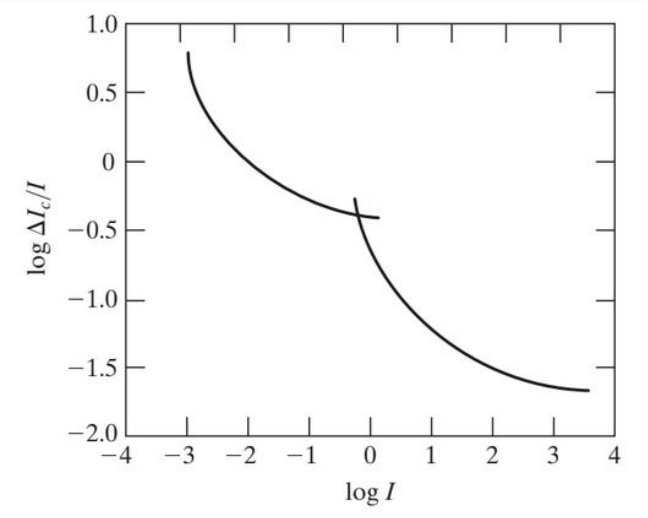
Brightness Discrimination



- I = background intensity
- ΔI = change in intensity required for "just noticeable difference"
- Weber ratio = $\Delta I / I$
- A smaller Weber ratio → only a small intensity change is distinguishable (good brightness discrimination)

Human Visual System (HVS)

Brightness Discrimination



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- Weber ratio as a function of intensity
- The power of brightness discrimination increases with the background intensity level
- Need "contrast stretching" for poorly illuminated images (Week 2)

Human Visual System (HVS)

Brightness Discrimination

0	0	0
0	10	0
0	0	0

$I = 0$

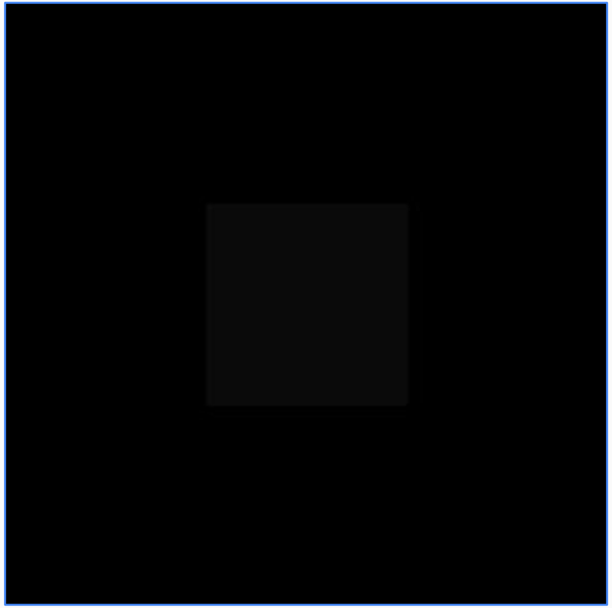
$\Delta I = 10$

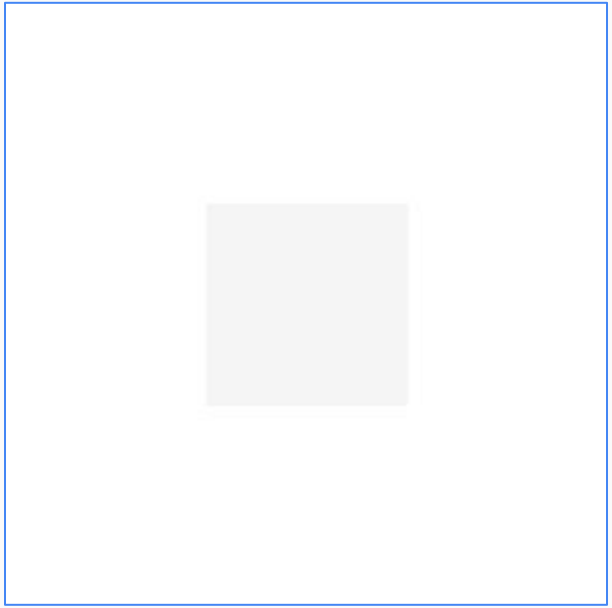
255	255	255
255	245	255
255	255	255

$I = 255$

Human Visual System (HVS)

Brightness Discrimination





Human Visual System (HVS)

Brightness Discrimination (Mach bands)

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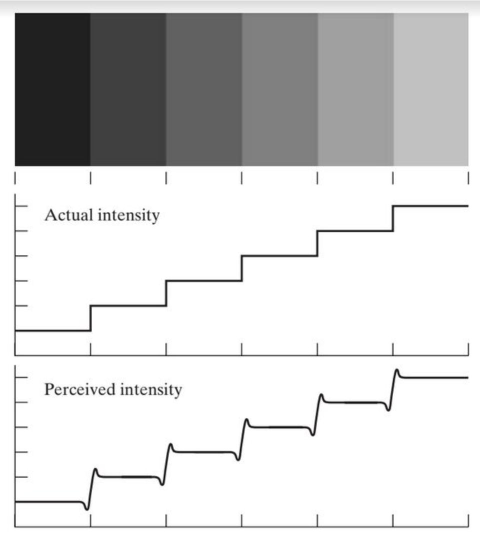

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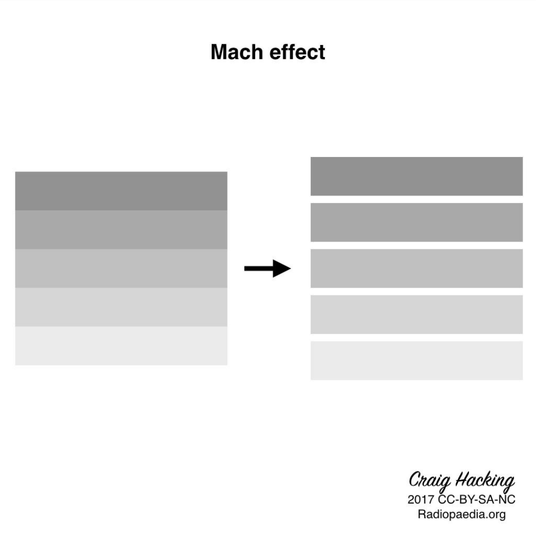
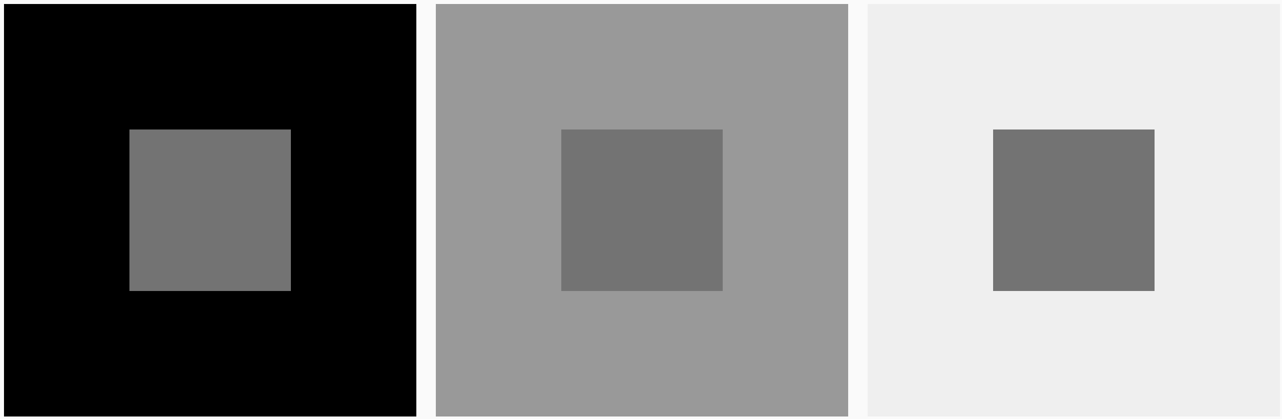


Human Visual System (HVS)

Optical Illusion Due to Perceived Brightness



Identify the middle-box with the highest intensity

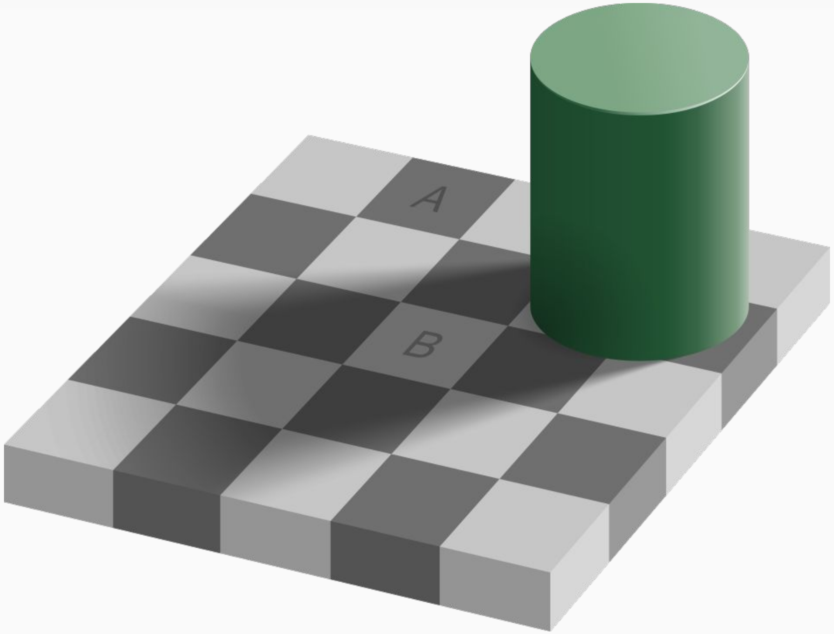
Human Visual System (HVS)

Optical Illusion Due to Perceived Brightness

They have the same intensity!

Human Visual System (HVS)

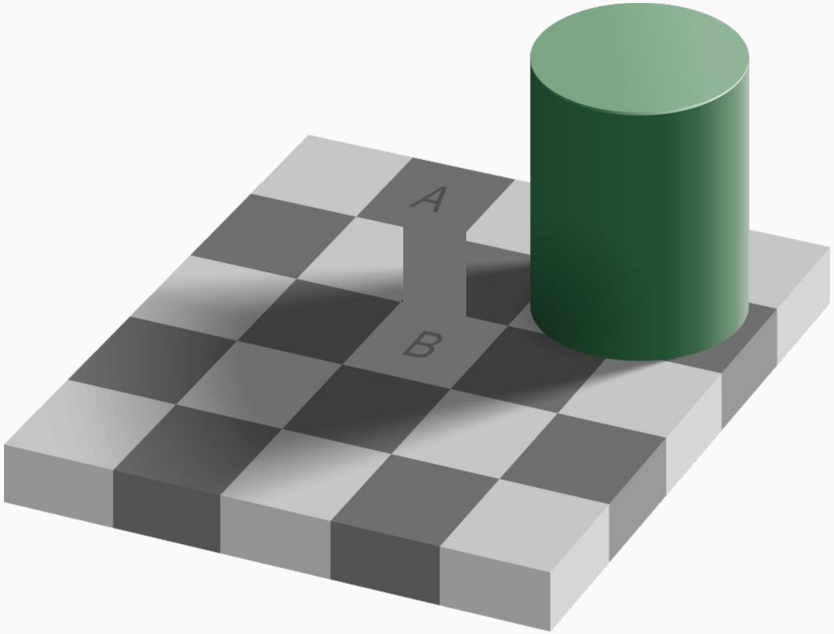
Optical Illusion Due to Experience



Which one has more intensity, A or B?

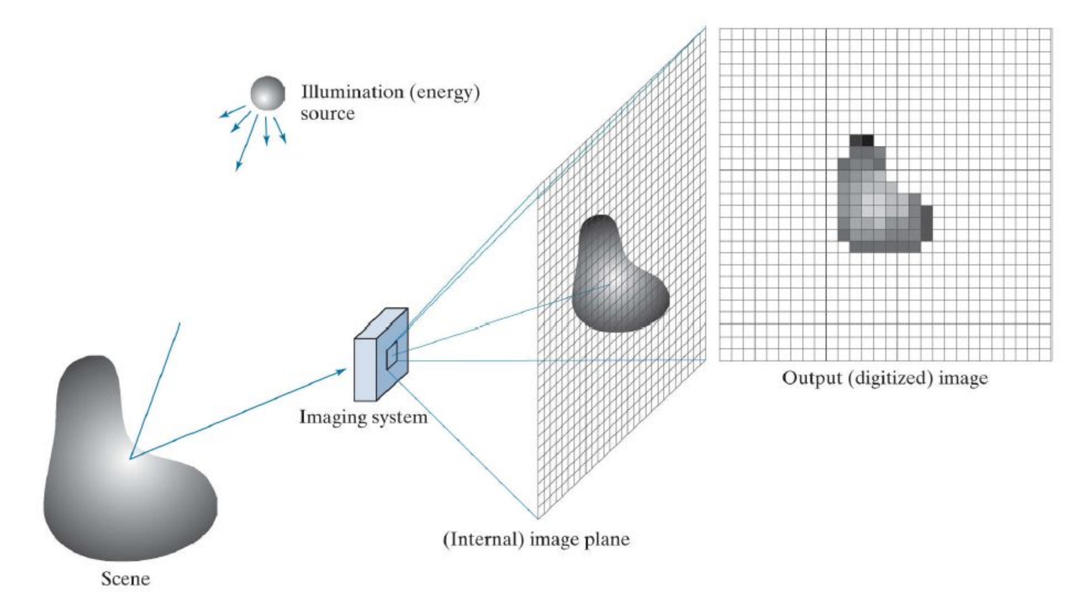
Human Visual System (HVS)

Optical Illusion Due to Experience



They have the exact same intensity!

Digital Image Acquisition



Example pipeline of digital image acquisition using a camera with CCD sensor array

- Image Formation
- Sensing
- Digitization
- Representation

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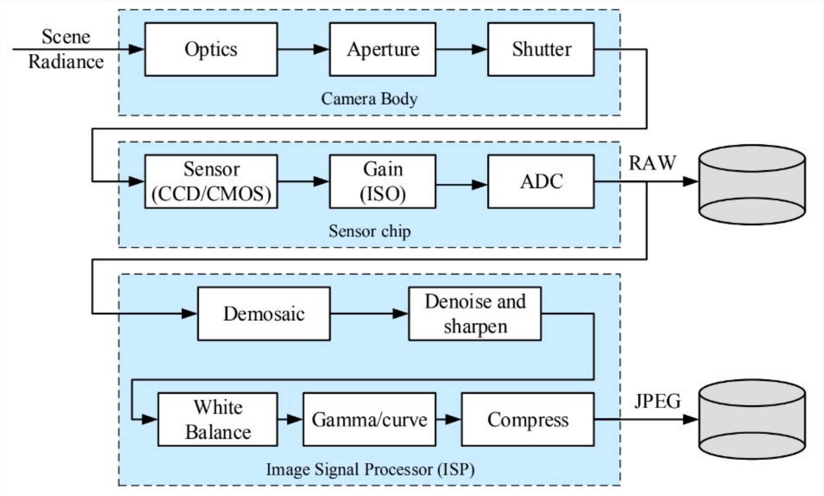
Image Sensing Pipeline



Example pipeline of digital image acquisition using a camera with CCD sensor array

- Image Formation
- Sensing
- Digitization
- Representation

Digital Image Acquisition

Image Formation Model

- The captured intensity $0 \leq f(x, y) < \infty$
- $f(x, y) = i(x, y)\, r(x, y)$
- Illumination, $0 \leq i(x, y) < \infty$
- Reflectance, $0 \leq r(x, y) \leq 1$
- $L_{min} \leq f(x, y) \leq L_{max}$. The ratio L_{max} / L_{min} is called the dynamic range.
- The interval $[L_{min}, L_{max}]$ is called gray scale. Typical indoor values, $L_{min} \approx 10$, $L_{max} \approx 1000$

Digital Image Acquisition
Image Formation Model

Clipped at L_{min}

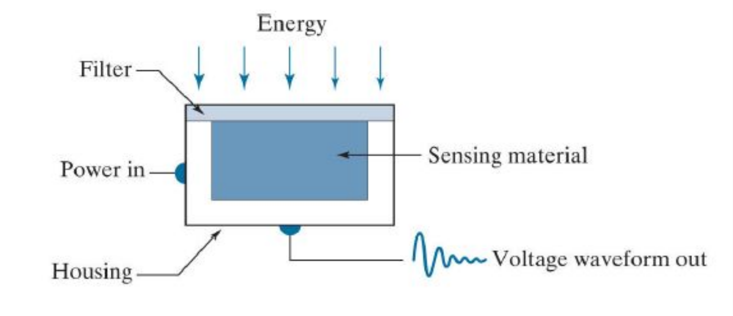
Clipped at L_{max} (saturated)

High Dynamic Range

Low Dynamic Range

Digital Image Acquisition

Image Sensing - Single Sensing Element



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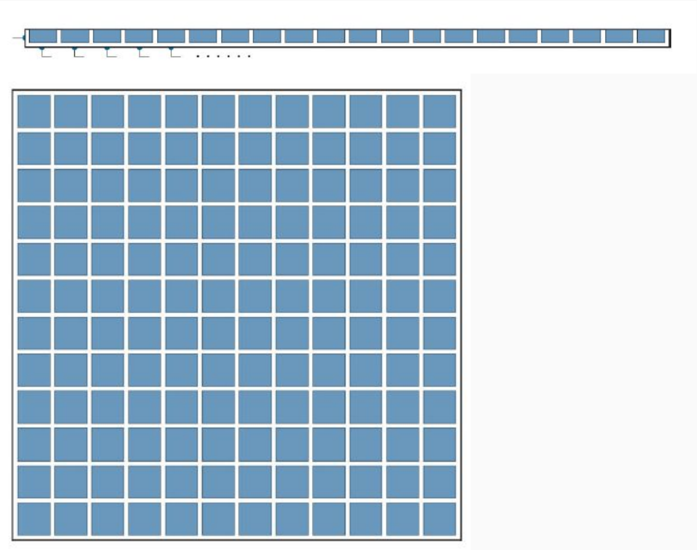
- A typical CCD camera has 4000×4000 sensors in array
- Electrical response to each sensor $\propto$ Integral of light intensity on surface over time, and thus reducing noise
- Electrical signal is stored in digitized form as a digital image

Digital Image Acquisition

Image Sensing - Sensor Array



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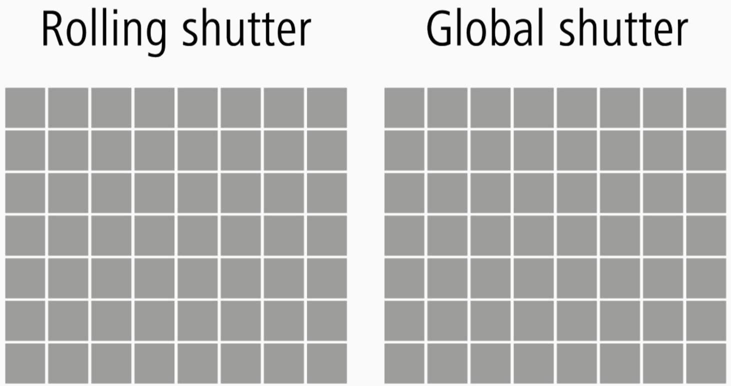
Line and grid Array of sensors



Exposure method - Rolling shutter vs global shutter

Digital Image Acquisition

Image Sensing - Rolling Shutter Effect

Ragsdale, S. 2009. “Airplane Prop + CMOS Rolling Shutter = WTF”. Online Image. <https://www.flickr.com/photos/sorenragsdale/3192314056/in/photostream/>

- Number of blades? (Assuming the scan direction is from left to right)
- Direction of rotation?
- Speed of rotation? (RPM)

Digital Image Acquisition

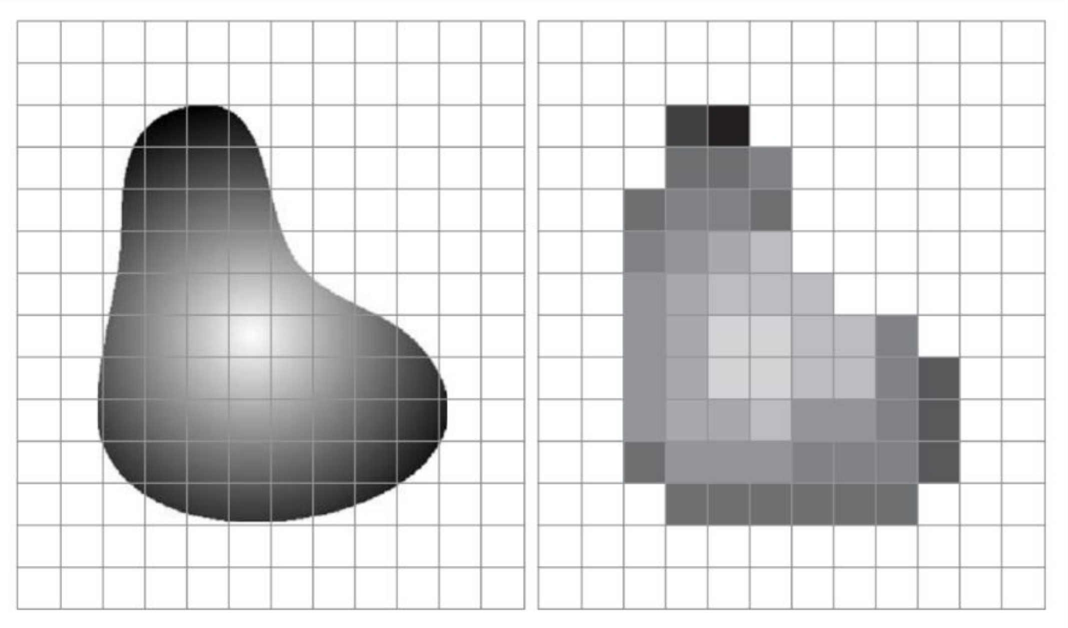
Image Sensing - Rolling Shutter Effect

Ragsdale, S. 2009. “Airplane Prop + CMOS Rolling Shutter = WTF”. Online Image. <https://www.flickr.com/photos/sorenragsdale/3192314056/in/photostream/>

Cole, J. 2014. “Rolling Shutters”. Online Image. <https://jasmcole.com/2014/10/12/rolling-shutters/>

Digital Image Acquisition

Digitization



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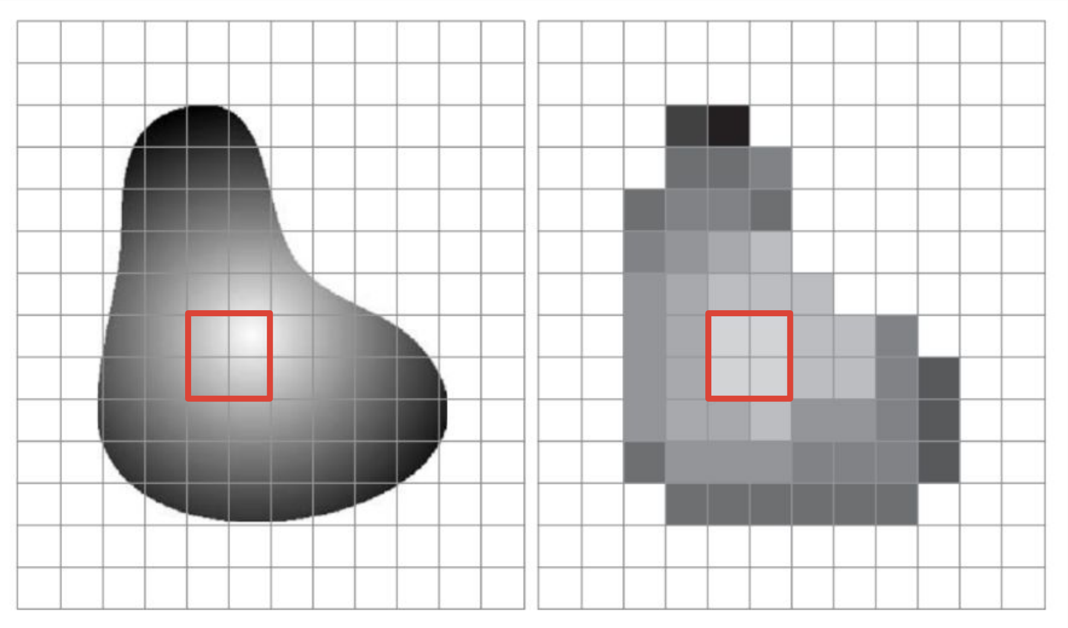
Two steps required:

- Sampling
- Quantization

Digital Image Acquisition
Digitization



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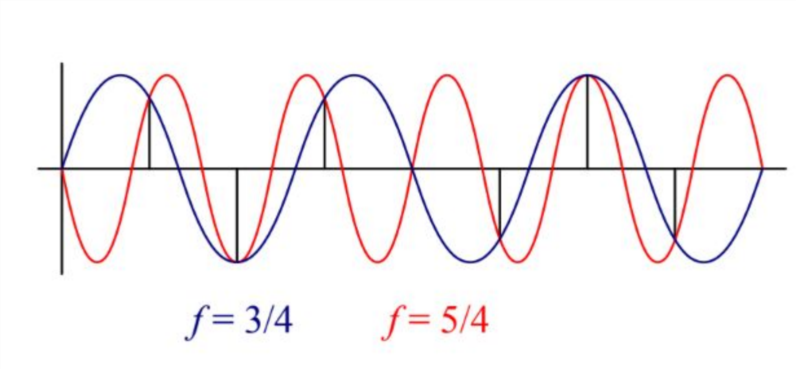
Two steps required:

- Sampling
- Quantization

Digital Image Acquisition

Sampling and Aliasing in 1D



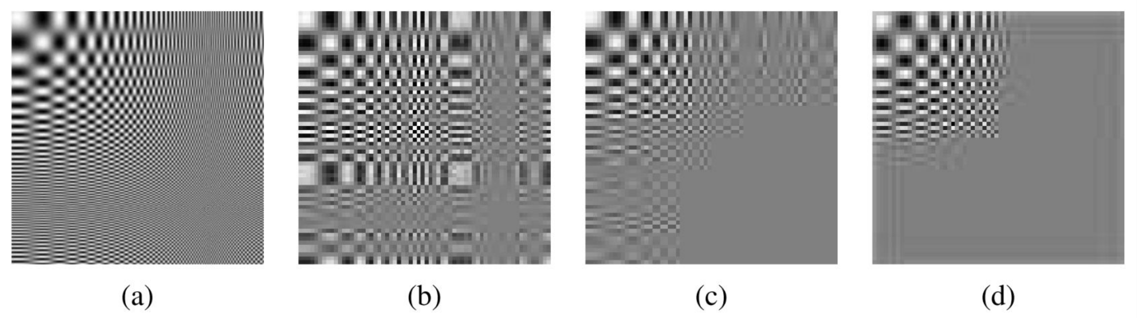
Aliasing of a one-dimensional signal:

- The blue sine wave at f = 3/4 and the red sine wave at f = 5/4 have the same digital samples, when sampled at f = 2
- These two signals are said to be "aliased"
- We are now no longer able to reconstruct the original signal

Shannon's Sampling Theorem: the minimum sampling rate required to reconstruct a signal from its instantaneous samples must be at least twice the highest frequency: $\mathbf{f_s \geq 2*f_{max}}$

Digital Image Acquisition

Sampling and Aliasing in 2D



Notice how the higher frequencies are aliased into visible frequencies with the lower quality filters, while the 9-tap filter completely removes these higher frequencies. (Anti-aliasing filter)

Aliasing of a two-dimensional signal:

- (a) original full-resolution image
- (b) downsampled 4 × with a 25% fill factor box filter
- (c) downsampled 4 × with a 100% fill factor box filter
- (d) downsampled 4 × with a high-quality 9-tap filter

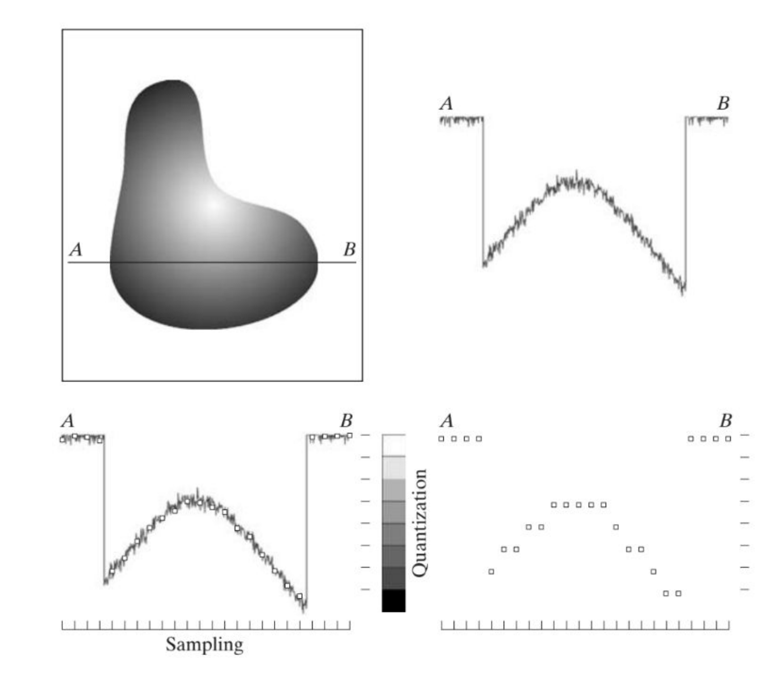
Digital Image Acquisition
Digitization

1) Image ➡

➡ 2) Scan line

3) Sampling ➡

➡ 4) Quantization



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Digital Image Acquisition

Effect of Sampling

400 x 400

200 x 200

100 x 100

50 x 50

25 x 25

Digital Image Acquisition
Effect of Quantization

256 levels	128 levels
64 levels	32 levels

Digital Image Acquisition

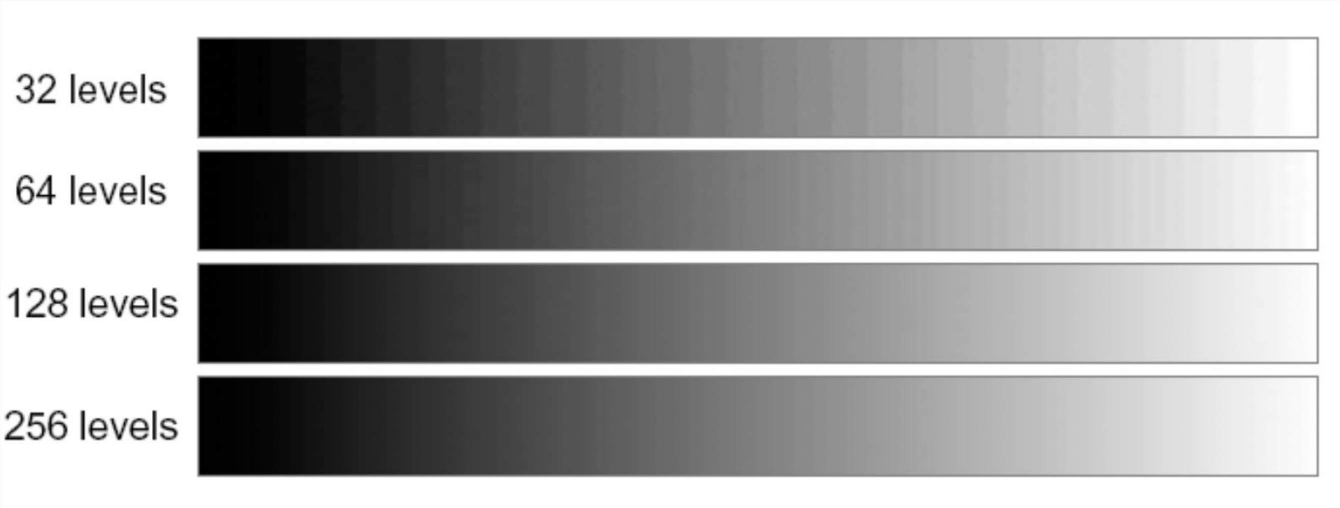
Effect of Quantization

16 levels	8 levels
4 levels	2 levels (binary)

False contouring

Digital Image Acquisition

Effect of Quantization



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Digital Image Acquisition

Representation

- $L_{min} \le f(x, y) \le L_{max}$
- $[L_{min}, L_{max}]$ often mapped to $[0, L-1]$ (for digital image)
- $[0, L-1]$ ➡ L quantization levels
- 0 is called black level, L-1 is called white level
- We choose $L = 2^k$, where k is the number of bits required
- 256 levels = 2^8, hence k = 8, called 8-bit image (most common)

Digital Image Acquisition
Representation

- For an image with M rows and N columns
  - x = 0, 1, 2, … , (M - 1) where M is the **height** of the image (also called H)
  - y = 0, 1, 2, … , (N - 1) where N is the **width** of the image (also called W)
- Numerical array form `[f(x, y)]`
- **(i, j)** th pixel value `[f(i, j)]` is the image intensity at point `(i, j)`
- In Python - `img[x, y]`, `img.shape = (H, W)`

y

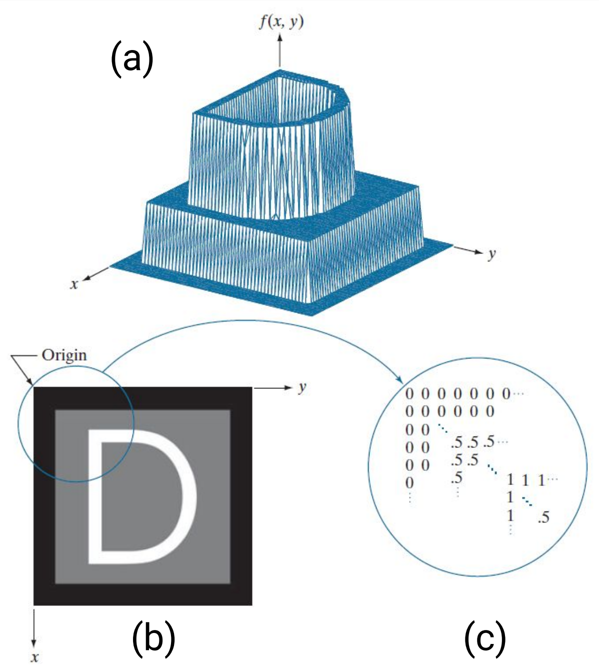
x

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

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

Digital Image Acquisition

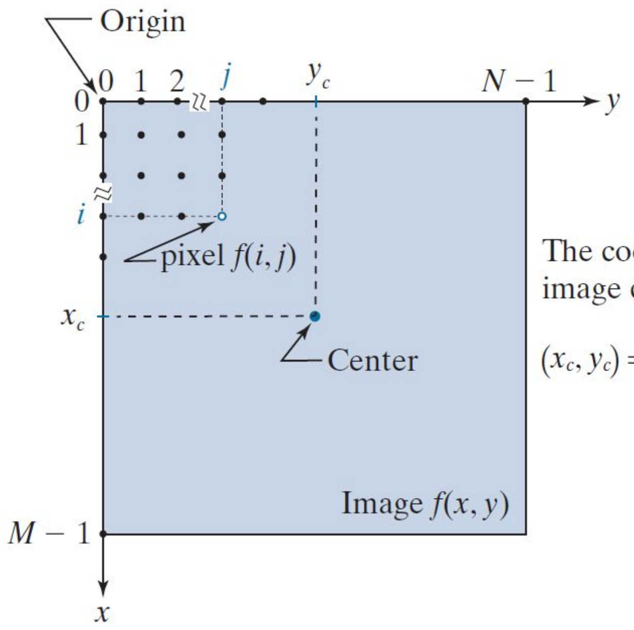
Representation



(a) Image plotted as a surface
(b) Image displayed as a visual intensity array
(c) Image shown as a 2-D numerical array. (The numbers 0, .5, and 1 represent black, gray, and white, respectively.)

Digital Image Acquisition

Coordinate Convention



The coordinates of the image center are

$$(x_c, y_c) = \left(\text{floor}\left(\frac{M}{2}\right), \text{floor}\left(\frac{N}{2}\right)\right)$$

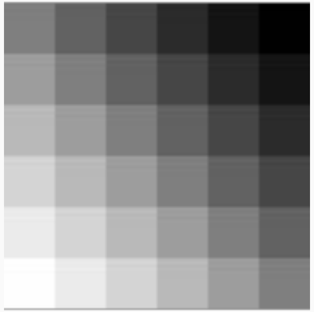
Image Resampling

Downsampling

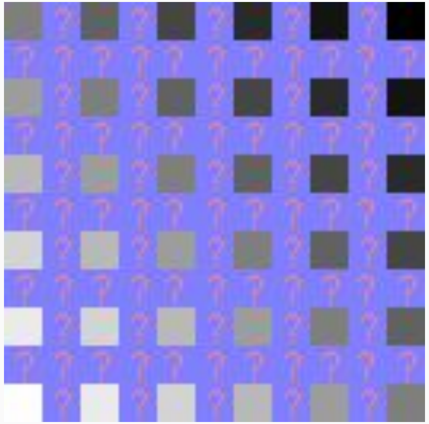
- k times downsample ➡ take the k’th sample
- In Python - `inp[y, x, n], inp.shape = (H, W, N)`
- `out[y, x, n], out.shape = (H//k, W//k, N)`
-
```
for y in range(0, H, k):
    for x in range(0, W, k):
        out[y//k, x//k, :] = inp[y, k, :]
```
- Or, thanks to numpy slicing, `out = inp[::k, ::k, ]`

Image Resampling

Upsampling and Interpolation



Original

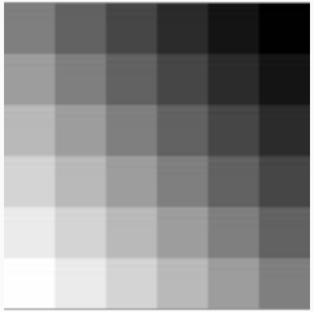


Upscaled - Before interpolation

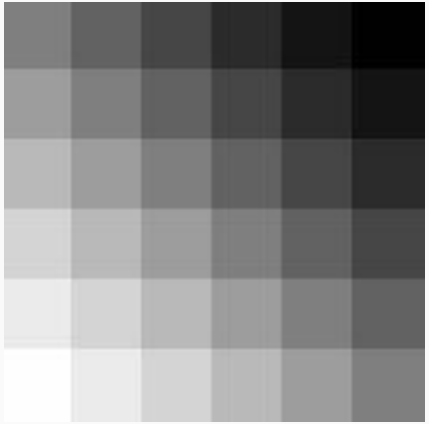
Cambridge in Color. Digital Image Interpolation. https://www.cambridgeincolour.com/tutorials/image-interpolation.htm

Image Resampling

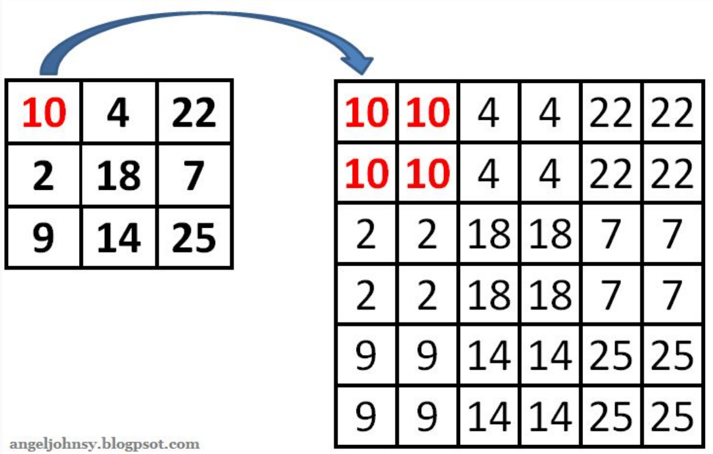
Upsampling and Interpolation



Original

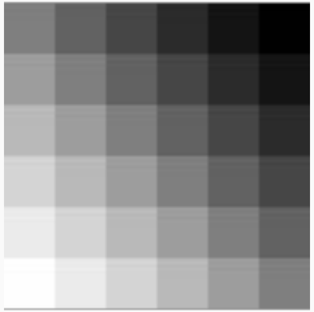


Upscaled - Nearest neighborhood

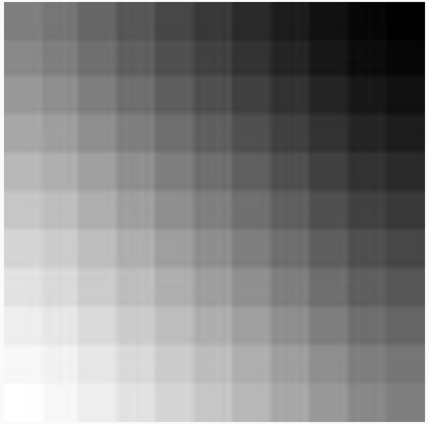


Cambridge in Color. Digital Image Interpolation. https://www.cambridgeincolour.com/tutorials/image-interpolation.htm

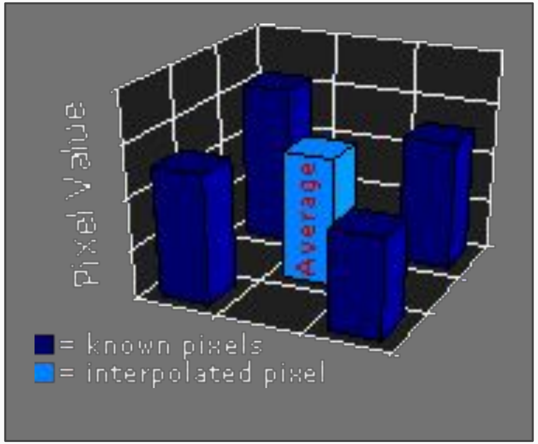
Image Resampling
Upsampling and Interpolation



Original



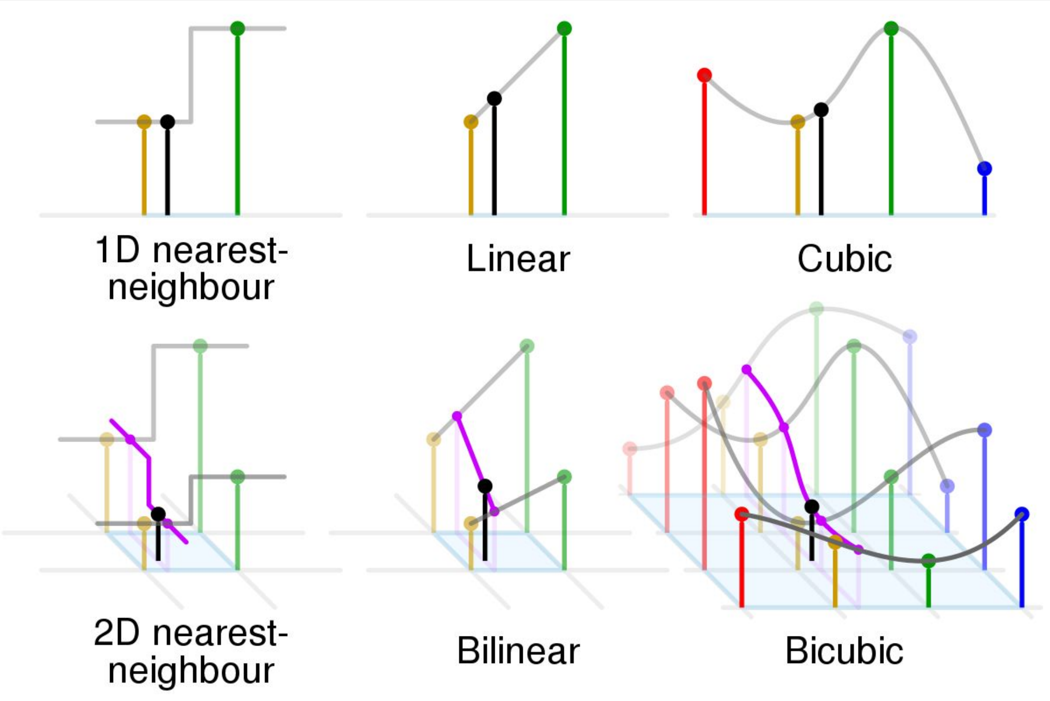
Upscaled - Bi-linear interpolation



Bi-linear interpolation

Cambridge in Color. Digital Image Interpolation. https://www.cambridgeincolour.com/tutorials/image-interpolation.htm

Image Resampling
Upsampling and Interpolation



Questions?