Computer Vision

Image Formation

Dr. Mrinmoy Ghorai

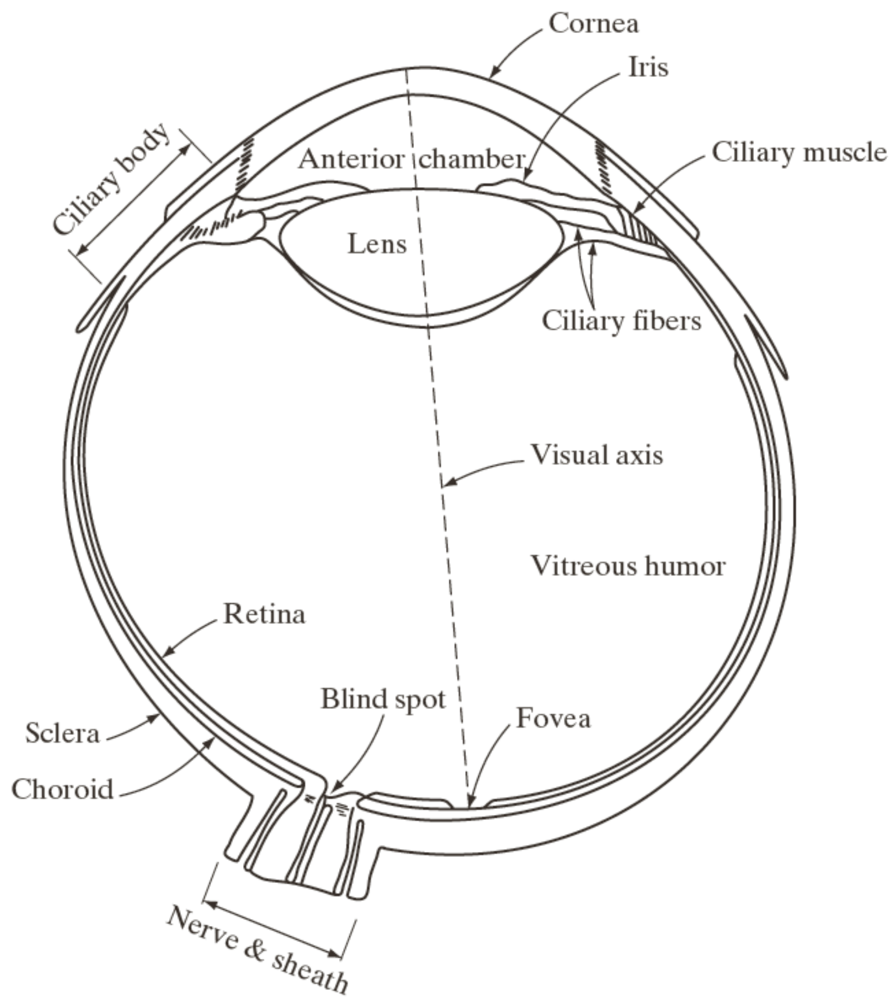
Indian Institute of Information Technology
Sri City, Chittoor

Today's Agenda

- Image Formation
  - Elements of Visual Perception
  - Image Sensing and Acquisition
  - Image Sampling and Quantization
  - Representing Digital Images
  - Fundamental Radiometric Relation

Elements of Visual Perception

Structure of the Human Eye



R. C. Gonzalez and R. E. Woods, Digital Image Processing, Prentice Hall, 4th edition, 2018.

Elements of Visual Perception

Image Formation in the Eye

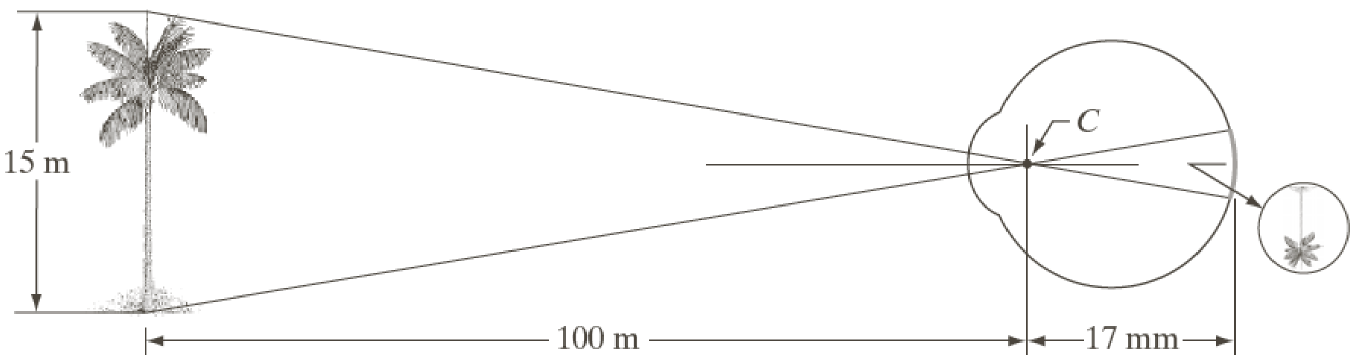


FIGURE 2.3 Graphical representation of the eye looking at a palm tree. Point C is the optical center of the lens.

a. If h is the height in mm of the that object in the retinal image then the figure yields $\frac{15}{100} = \frac{h}{17} \Rightarrow h = 2.55\ mm$.
b. The retinal image is reflected primarily in the area of the fovea.

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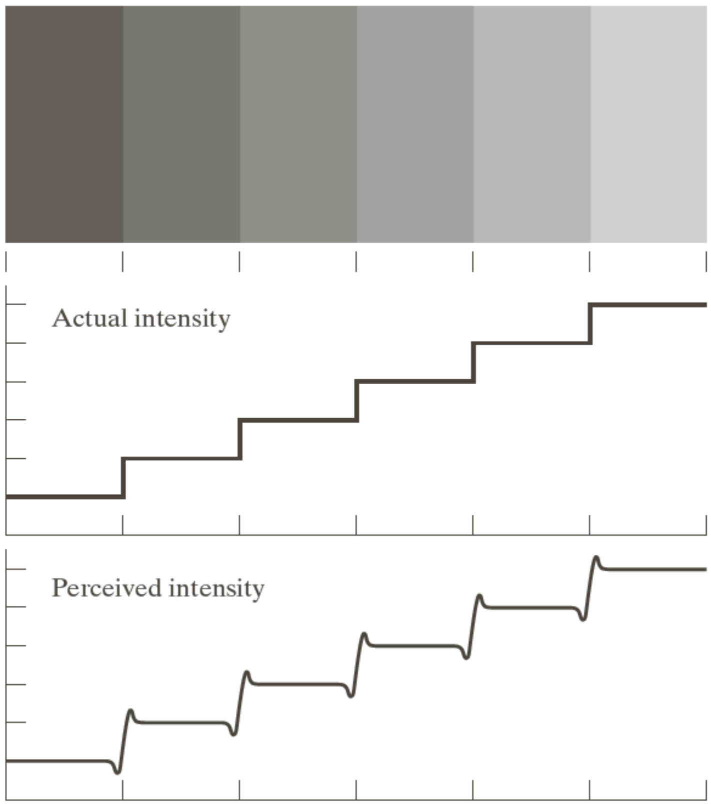
Elements of Visual Perception

Brightness Adaption and Discrimination



a
b
c

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

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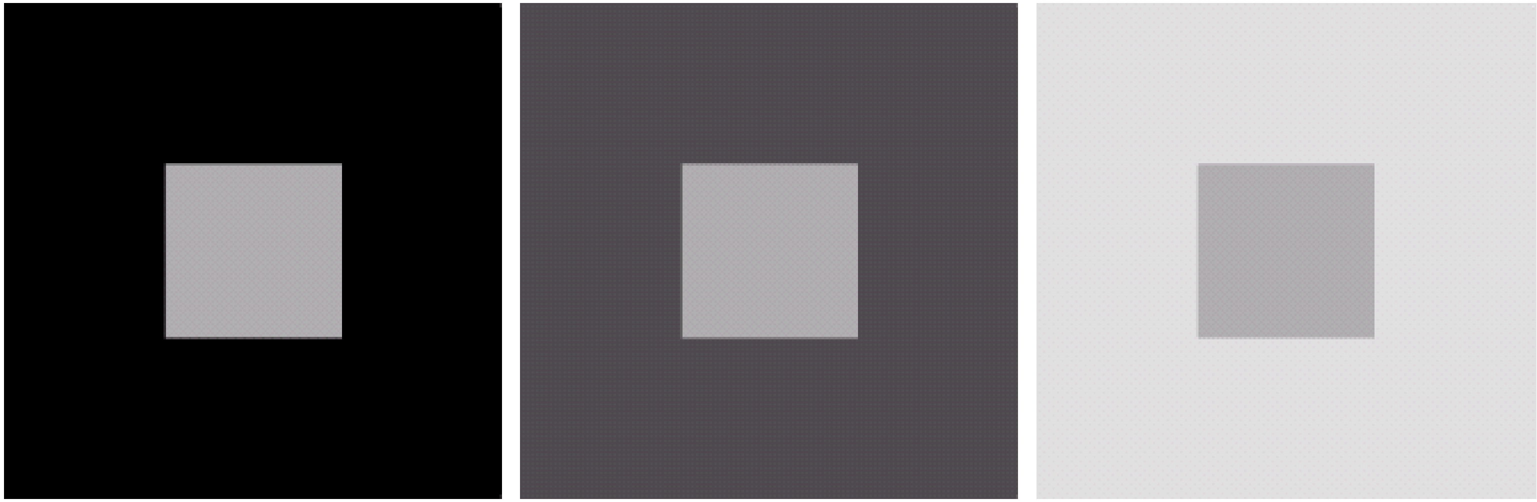
Elements of Visual Perception

Brightness Adaption and Discrimination



a b c

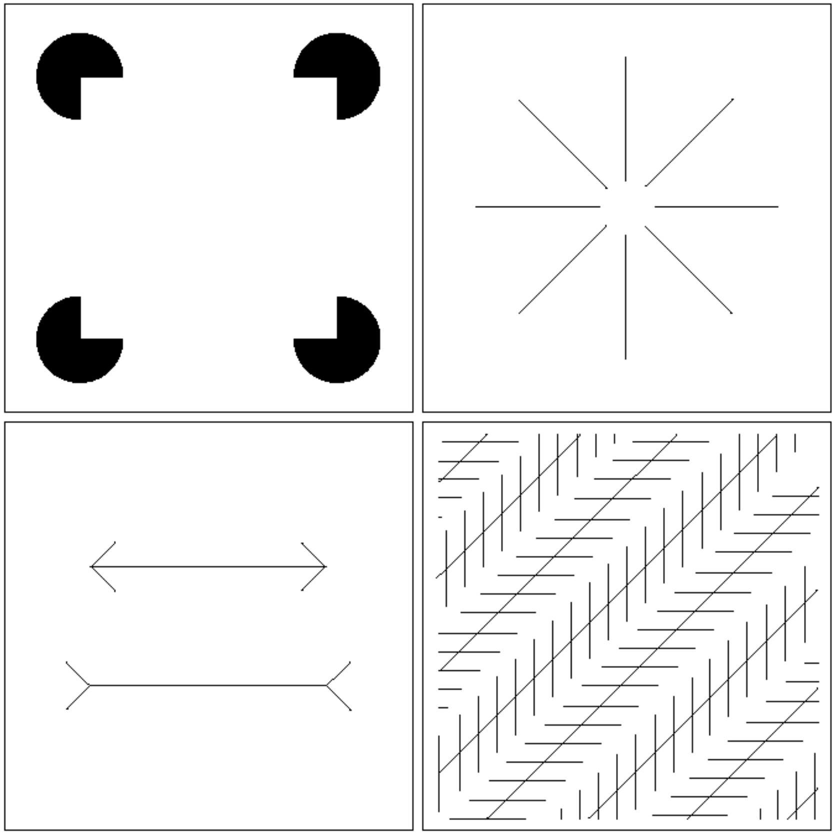
FIGURE 2.8 Examples of simultaneous contrast. All the inner squares have the same intensity, but they appear progressively darker as the background becomes lighter.

Elements of Visual Perception

Brightness Adaption and Discrimination

a b
c d

FIGURE 2.9 Some well-known optical illusions.



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Elements of Visual Perception

Light and the Electromagnetic Spectrum

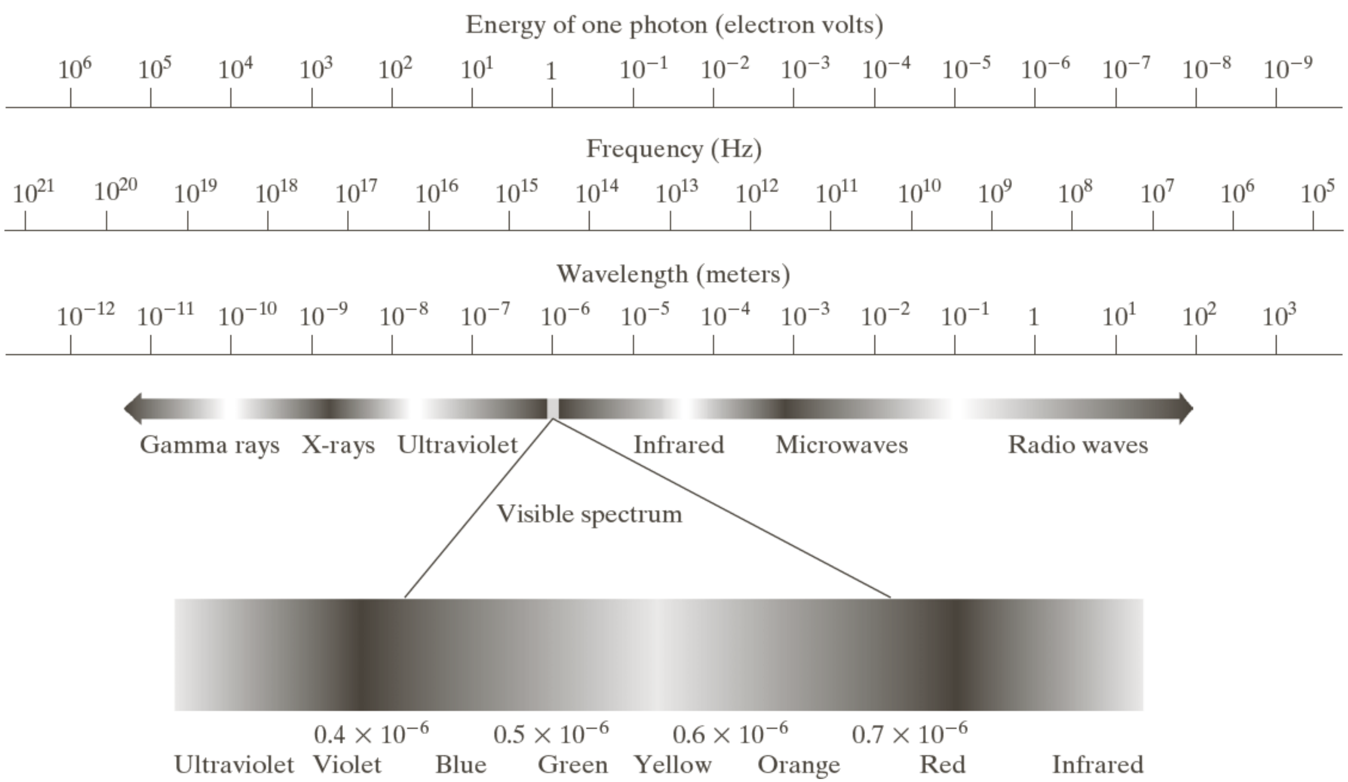

FIGURE 2.10 The electromagnetic spectrum. The visible spectrum is shown zoomed to facilitate explanation, but note that the visible spectrum is a rather narrow portion of the EM spectrum.

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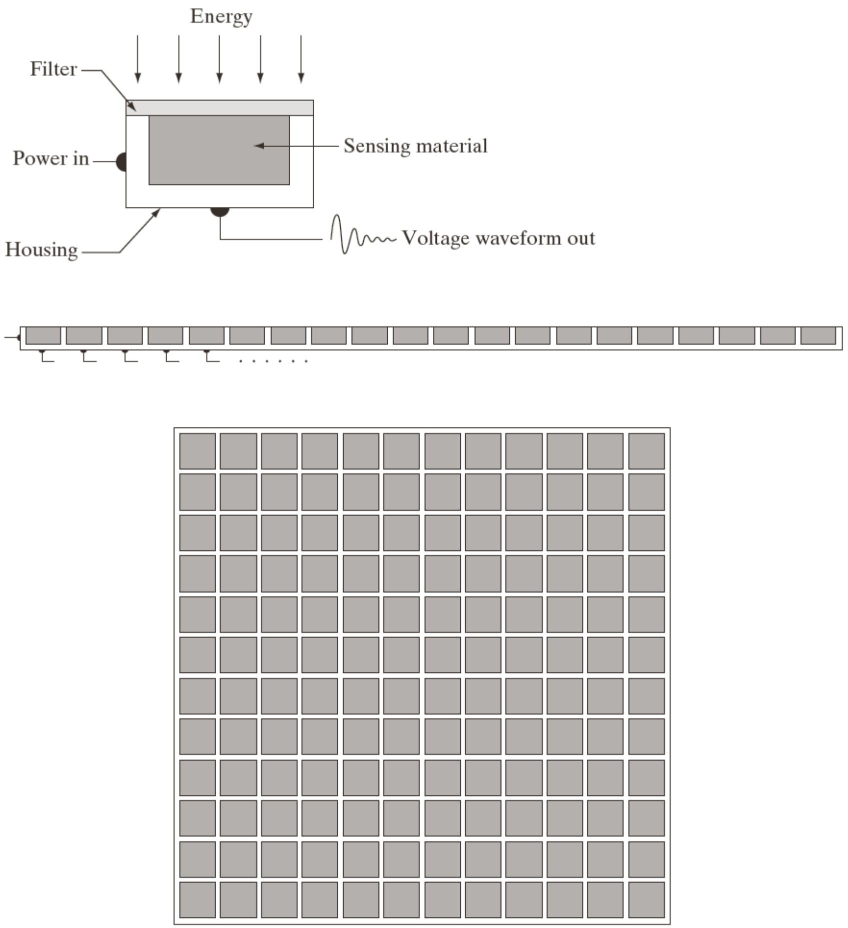
Image Sensing and Acquisition

Image Acquisition using Sensor Strips and Sensor Arrays



a
b
c

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

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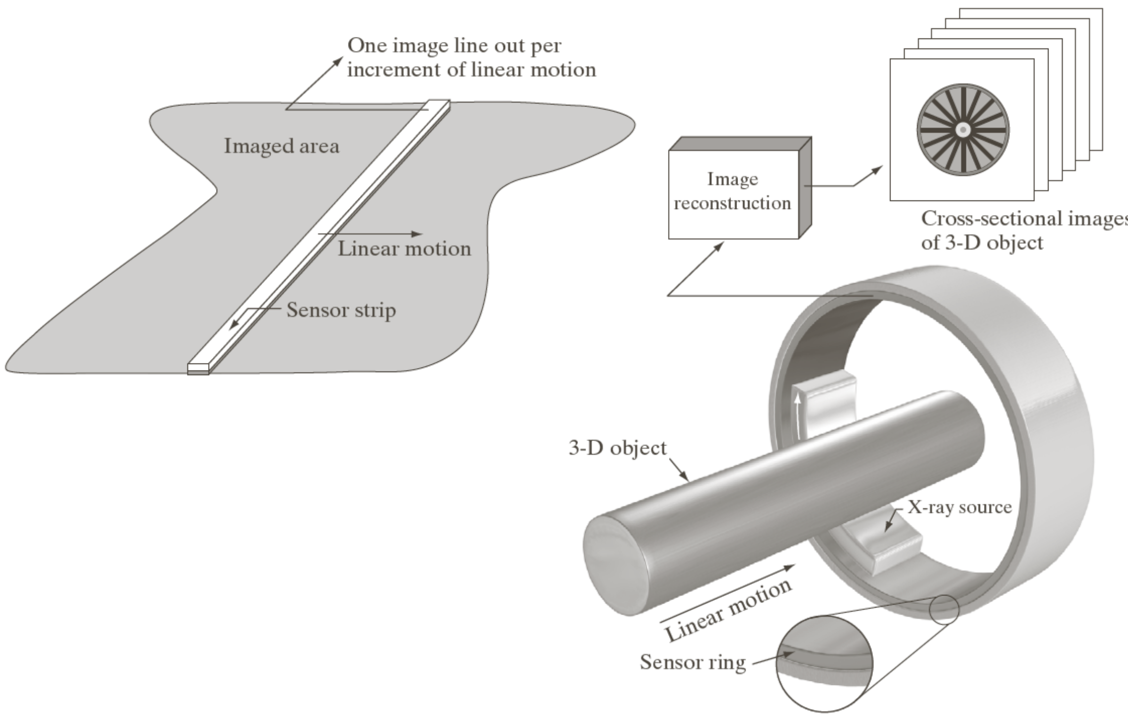
Image Sensing and Acquisition

Image Acquisition using Linear Sensor Strip and Circular Sensor Strip



a b

FIGURE 2.14 (a) Image acquisition using a linear sensor strip. (b) Image acquisition using a circular sensor strip.

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Image Sensing and Acquisition

Image Acquisition Process

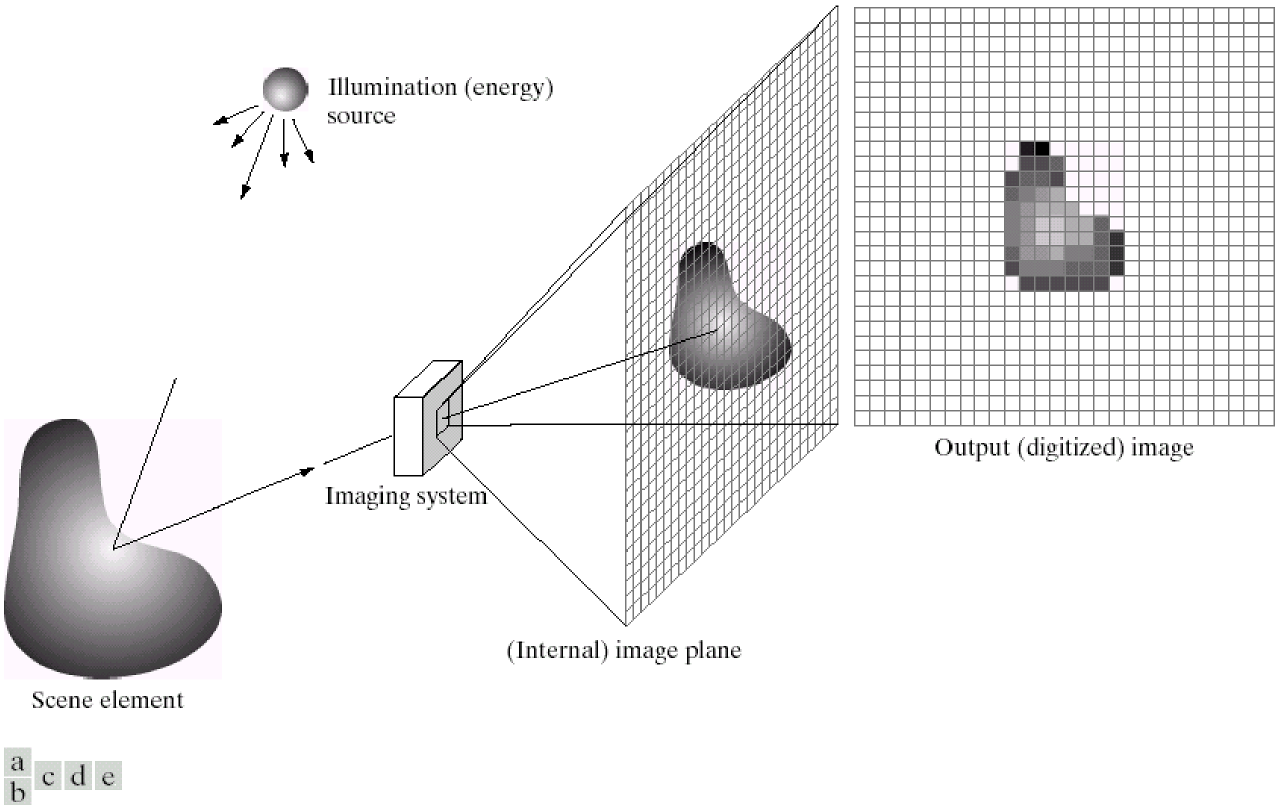

FIGURE 2.15 An example of the digital image acquisition process. (a) Energy ("illumination") source. (b) An element of a scene. (c) Imaging system. (d) Projection of the scene onto the image plane. (e) Digitized image.

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Image Sensing and Acquisition

A Simple Image Formation Model

$$\boldsymbol{f}(\boldsymbol{x},\boldsymbol{y}) = \boldsymbol{i}(\boldsymbol{x},\boldsymbol{y}) * \boldsymbol{r}(\boldsymbol{x},\boldsymbol{y})$$

$\boldsymbol{f}(\boldsymbol{x},\boldsymbol{y})$: intensity at the point $(\boldsymbol{x},\boldsymbol{y})$
$\boldsymbol{i}(\boldsymbol{x},\boldsymbol{y})$: illumination at the point $(\boldsymbol{x},\boldsymbol{y})$
(the amount of source illumination incident on the scene)
$\boldsymbol{r}(\boldsymbol{x},\boldsymbol{y})$: reflectance at the point $(\boldsymbol{x},\boldsymbol{y})$
(the amount of illumination reflected by the object)

where $\mathbf{0} < \boldsymbol{i}(\boldsymbol{x},\boldsymbol{y}) < \infty$ and $\mathbf{0} < \boldsymbol{r}(\boldsymbol{x},\boldsymbol{y}) < \mathbf{1}$

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Image Sensing and Acquisition

Some Typical Ranges of Illumination

- **Lumen -** a unit of light flow or luminous flux
- **Lumen per square meter (lm/m^2) -** the metric unit of measure for illuminance of a surface
- On a clear day, the sun may produce in excess of 90,000 lm/m^2 of illumination on the surface of the Earth
- On a cloudy day, the sun may produce less than 10,000 lm/m^2 of illumination on the surface of the Earth
- On a clear evening, the moon yields about 0.1 lm/m^2 of illumination

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Image Sensing and Acquisition

Some Typical Ranges of Reflectance

- 0.01 for black velvet
- 0.65 for stainless steel
- 0.80 for flat-white wall paint
- 0.90 for silver-plated metal
- 0.93 for snow

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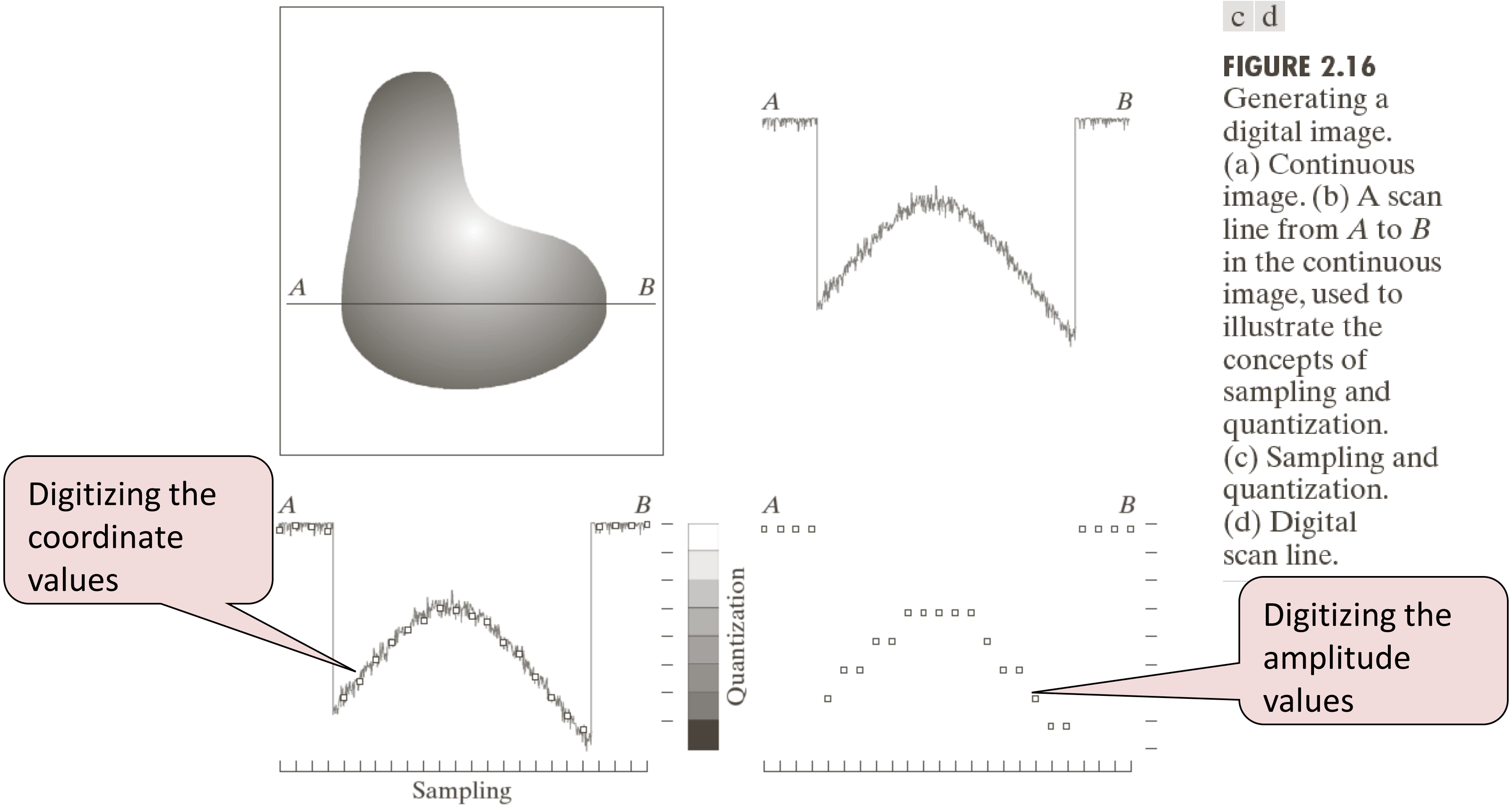
Image Sampling and Quantization



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.

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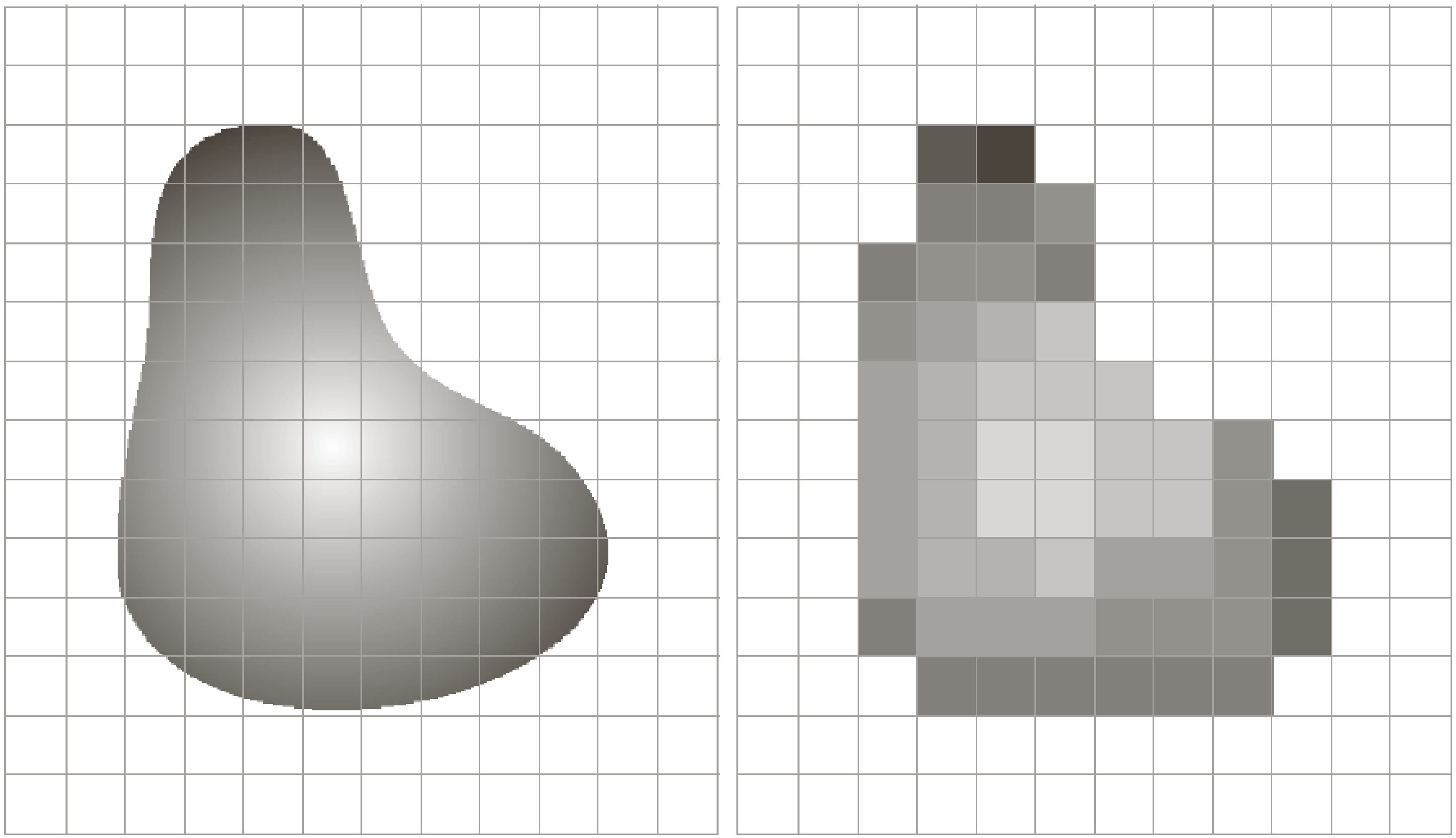
Image Sampling and Quantization



a b

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

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Representing Digital Images

The representation of a $M \times N$ numerical array as

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

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Representing Digital Images

- Discrete intensity interval $[\mathbf{0}, \boldsymbol{L} - \mathbf{1}]$, $\boldsymbol{L} = \mathbf{2}^{\boldsymbol{k}}$
- The number $\boldsymbol{b}$ bits required to store a $\boldsymbol{M} \times \boldsymbol{N}$ digitized Image

$$\boldsymbol{b} = \boldsymbol{M} \times \boldsymbol{N} \times \boldsymbol{k}$$

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Spatial and Intensity Resolution

- **Spatial Resolution**
  - a measure of smallest discernible detail in an image
  - stated with ***dots (pixels) per unit distance, dots per inch (dpi)***
- **Intensity Resolution**
  - the smallest discernible change in intensity level
  - stated with ***8 bits, 16 bits, 24 bits,*** etc.

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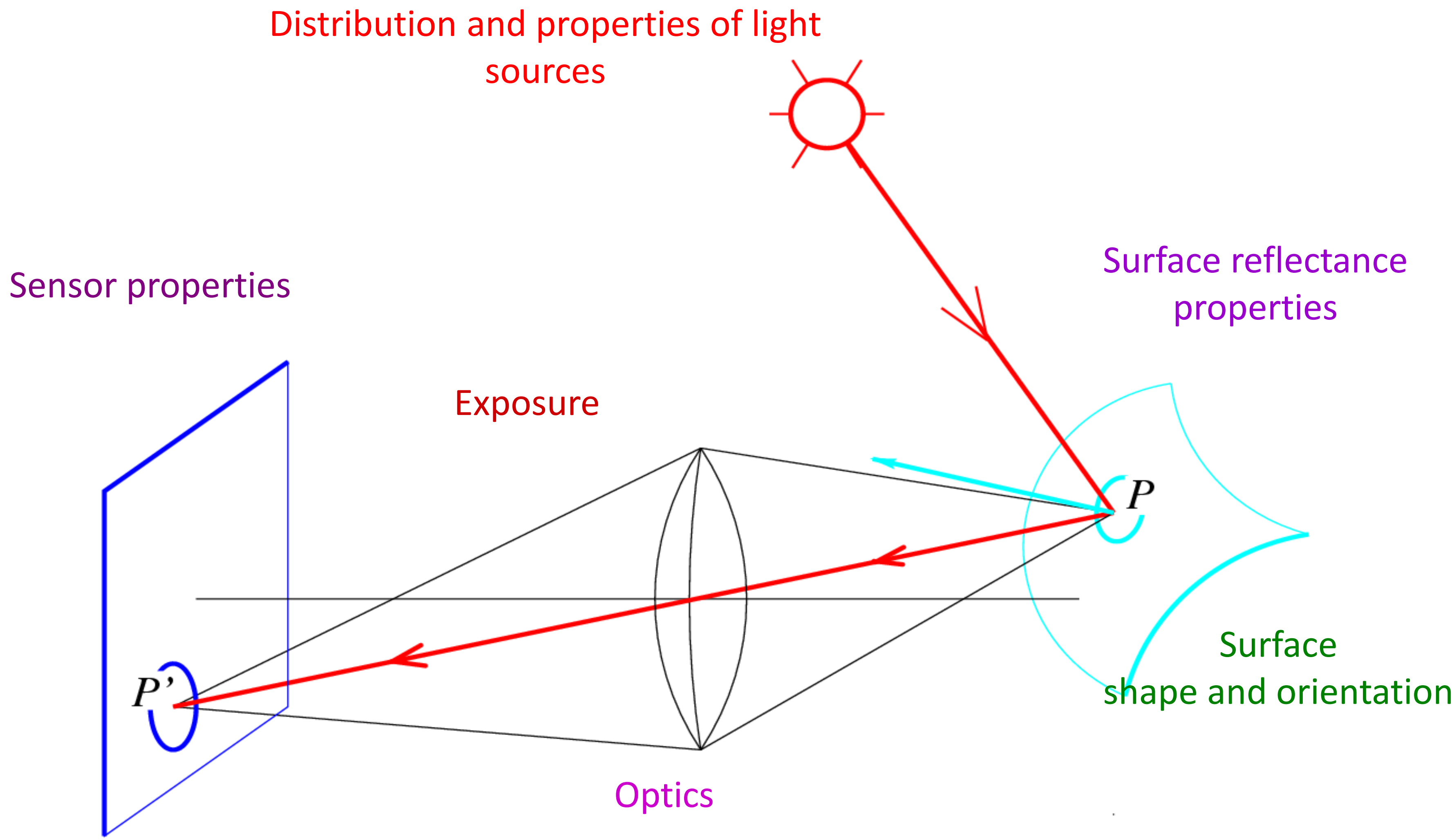
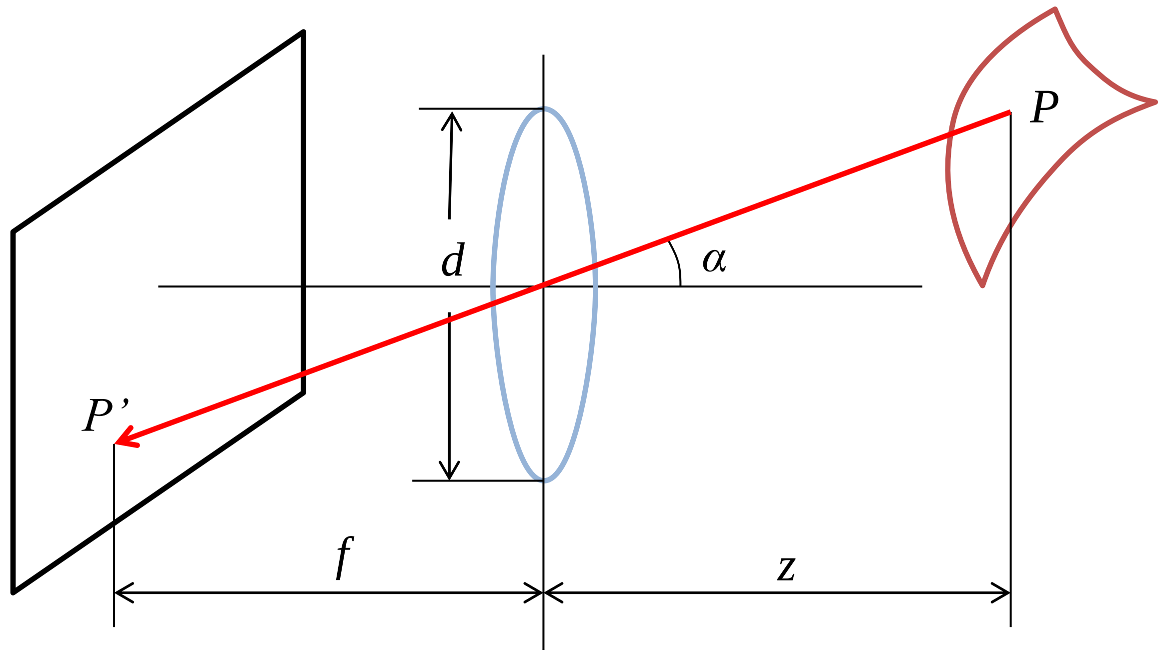
What determines the brightness of an image pixel?



Slide by L. Fei-Fei

Fundamental Radiometric Relation

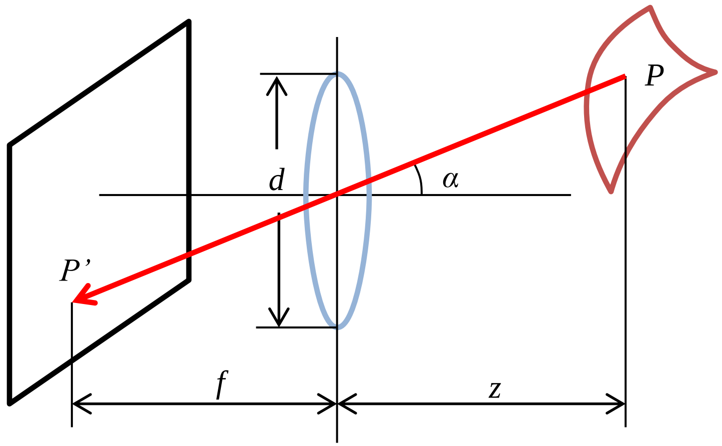
- *L*: *Radiance* emitted from *P* toward *P'*
  - Energy carried by a ray (Watts per sq. meter per steradian)
- *E*: *Irradiance* falling on *P'* from the lens
  - Energy arriving at a surface (Watts per sq. meter)



What is the relationship between *E* and *L*?

Szeliski 2.2.3

Fundamental Radiometric Relation



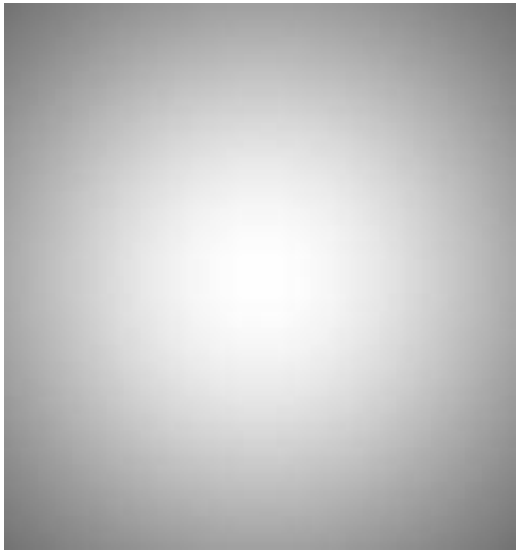
$$E = \left[\frac{\pi}{4} \left(\frac{d}{f} \right)^2 \cos^4 \alpha \right] L$$

- Image irradiance is linearly related to scene radiance
- Irradiance is proportional to the area of the lens and inversely proportional to the squared distance between the lens and the image plane
- The irradiance falls off as the angle between the viewing ray and the optical axis increases

Szeliski 2.2.3

Fundamental Radiometric Relation

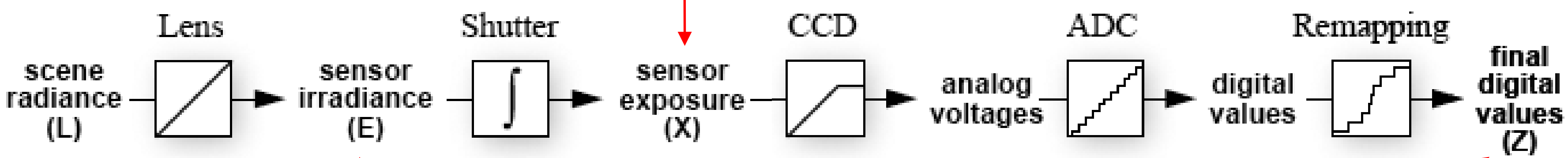
$$E = \left[\frac{\pi}{4} \left(\frac{d}{f} \right)^2 \cos^4 \alpha \right] L$$



S. B. Kang and R. Weiss. [Can we calibrate a camera using an image of a flat, textureless Lambertian surface?]() ECCV 2000

From light rays to pixel values

$$X = E \cdot \Delta t$$

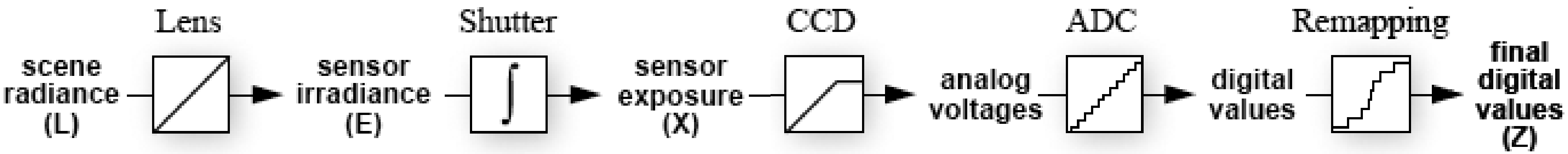


$$E = \left[\frac{\pi}{4} \left(\frac{d}{f} \right)^2 \cos^4 \alpha \right] L$$

$$Z = f\left(E \cdot \Delta t\right)$$

- Camera response function: the mapping f from irradiance to pixel values
  - Useful if we want to estimate material properties
  - Enables us to create *high dynamic range (HDR) images*
  - Classic reference: P. E. Debevec and J. Malik, *Recovering High Dynamic Range Radiance Maps from Photographs*, *SIGGRAPH 97*

From light rays to pixel values



– For more information:
  - M. Brown, Understanding the In-Camera Image Processing Pipeline for Computer Vision, CVPR 2016 Tutorial

Thank you: Question?