Computer Vision

Image Formation

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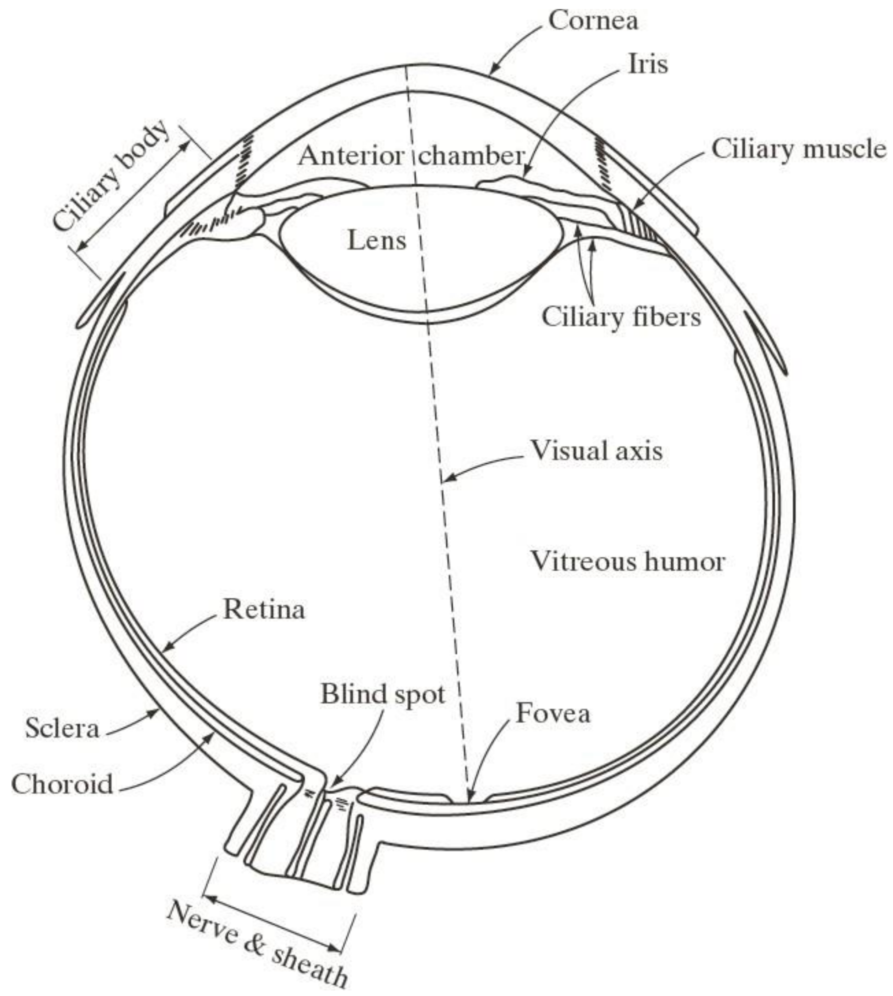
Today’s Agenda

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

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

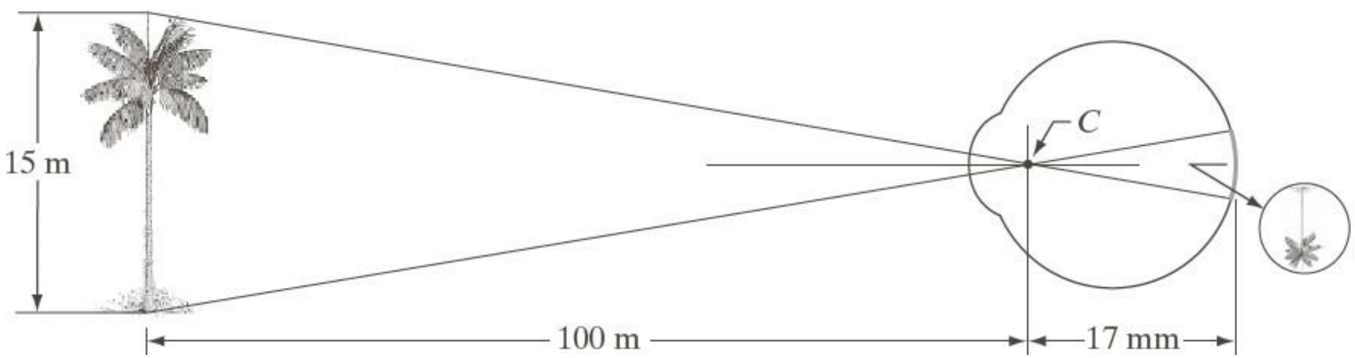
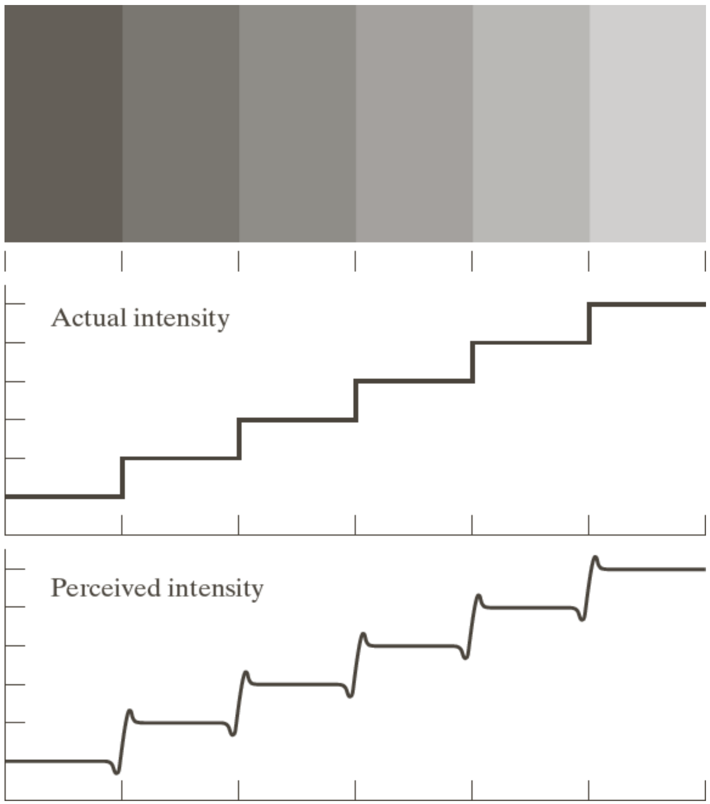


FIGURE 2.3 Graphical representation of the eye looking at a palm tree. Point C is the optical center of the lens.

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.

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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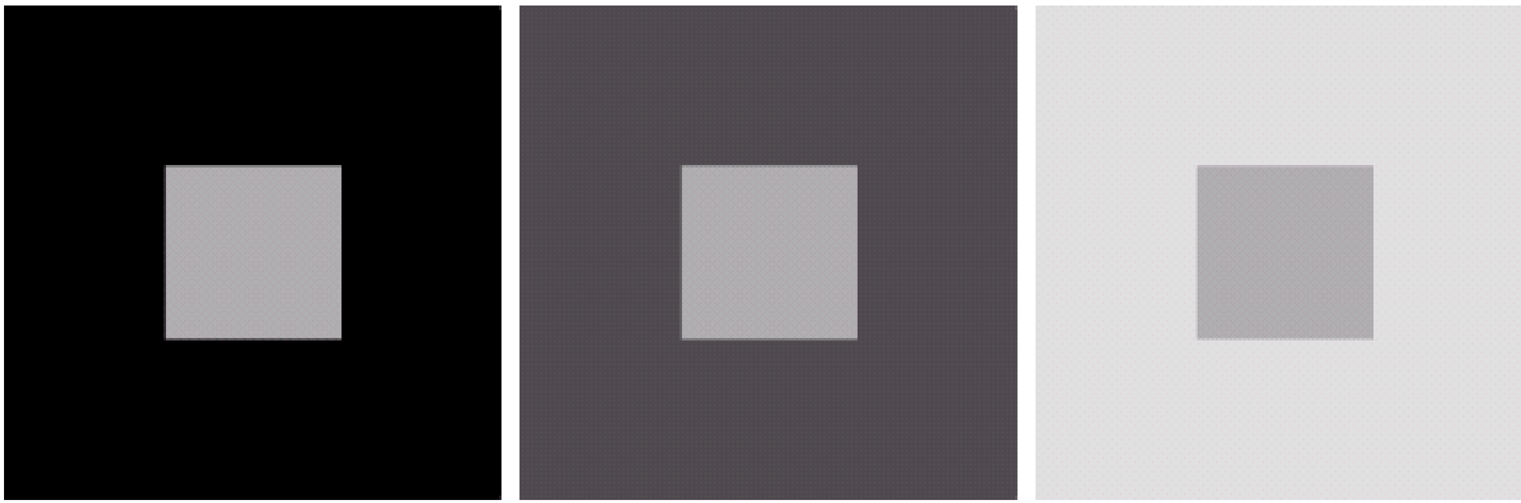
Elements of Visual Perception

Brightness Adaption and Discrimination



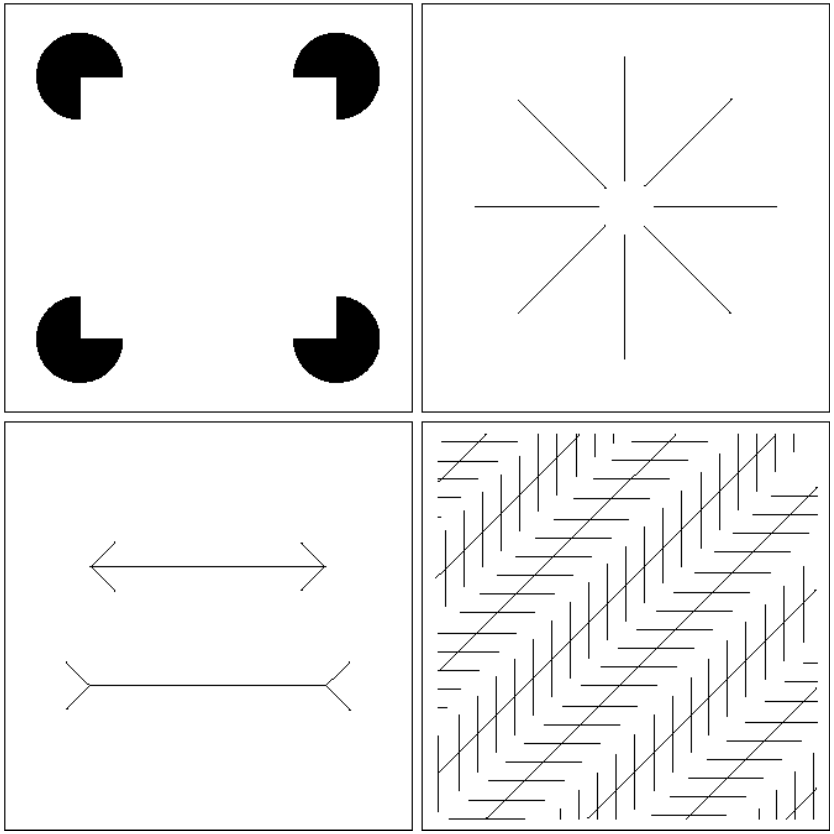
a b c

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.

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

Elements of Visual Perception

Brightness Adaption and Discrimination



a b
c d

FIGURE 2.9 Some well-known optical illusions.

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

Light and the Electromagnetic Spectrum

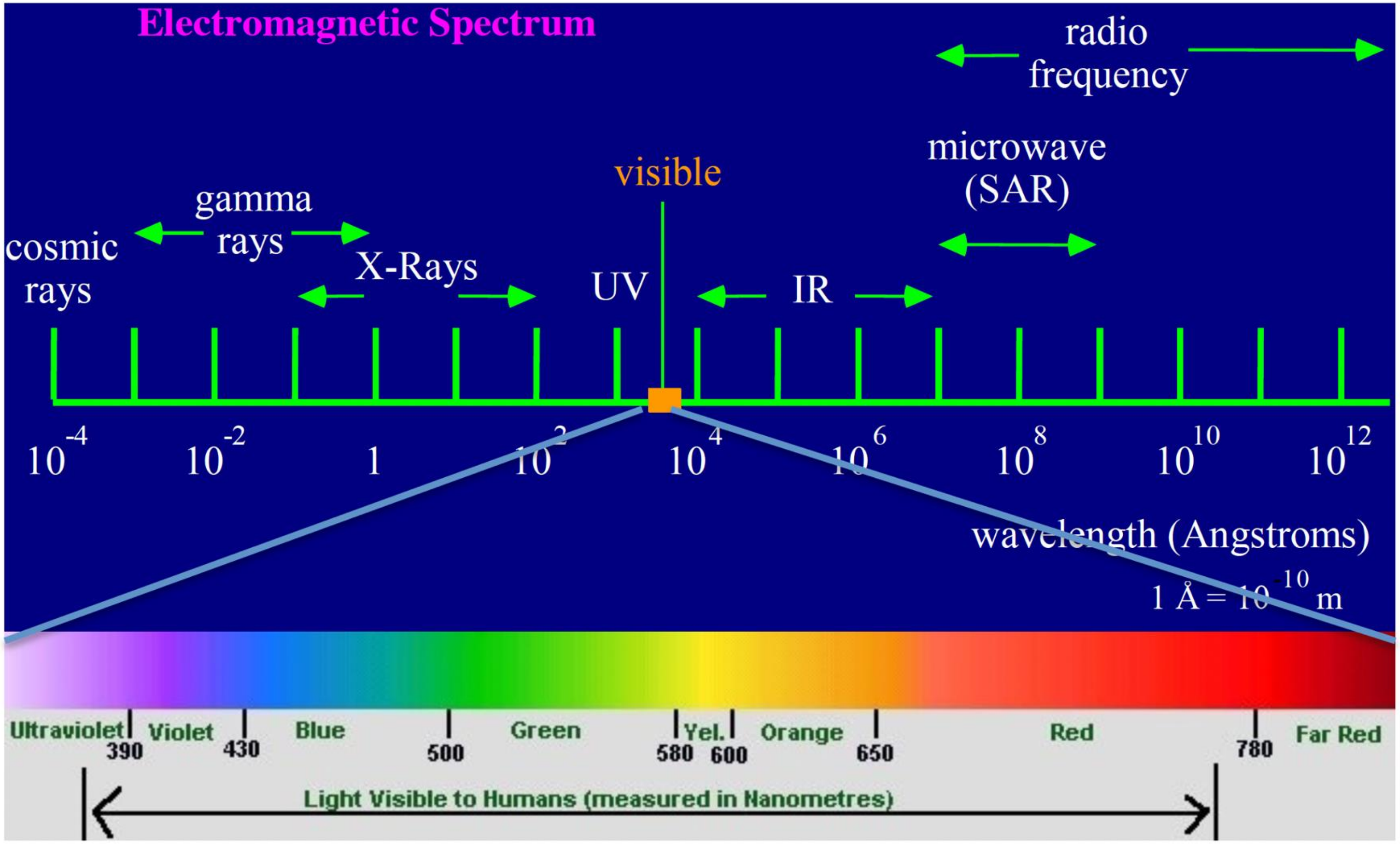


FIGURE 2.10 The electromagnetic spectrum. The visible spectrum is shown zoomed to facilitate explanation, but note that the visible spectrum is a rather narrow portion of the EM spectrum.

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

Imaging based on Frequency

Imaging done across the spectrum - from gamma rays to radio waves

- Gamma rays: nuclear medicine, astronomy
- X-rays: medical imaging
- UV rays: industrial inspection, fluorescence microscopy
- Visible spectrum: too many to list
- Radio waves: astronomy, medicine (magnetic resonance imagining)
- Recall $E = hv$, $c = \lambda v$ $\rightarrow$ implies short waves have high energy

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Image Sensing and Acquisition

Image Acquisition using Sensor Strips and Sensor Arrays

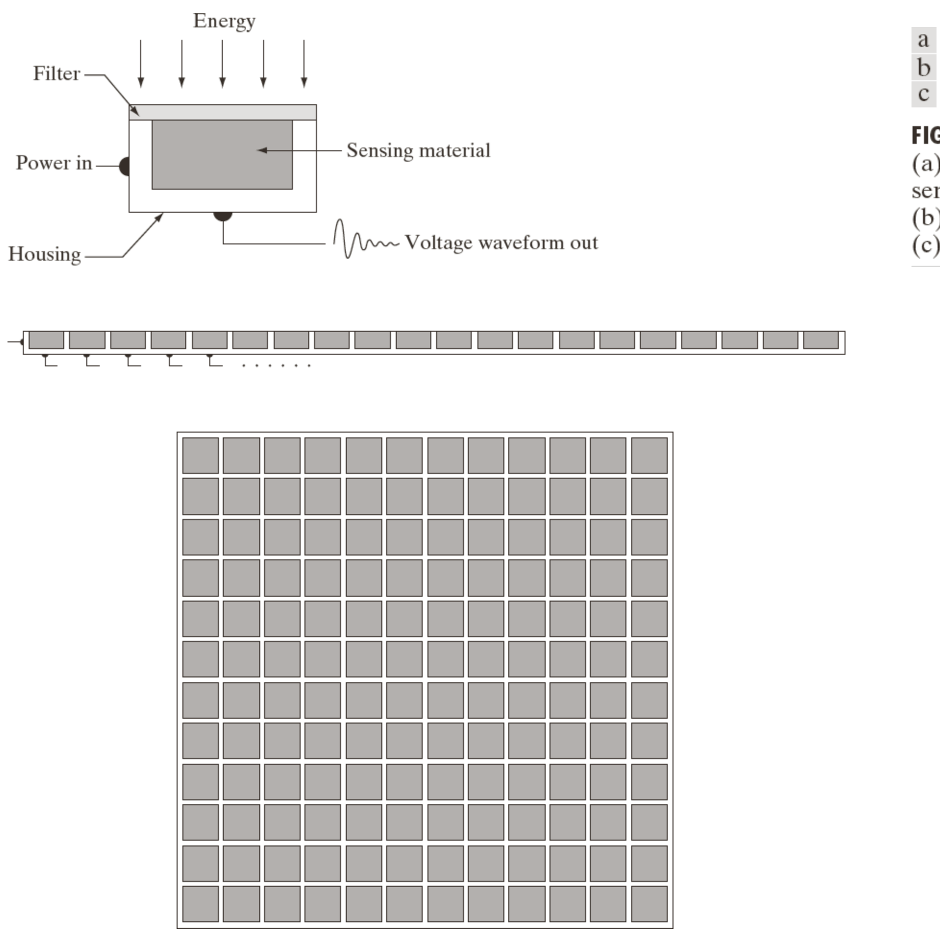

FIGURE 2.12
(a) Single imaging sensor.
(b) Line sensor.
(c) Array sensor.

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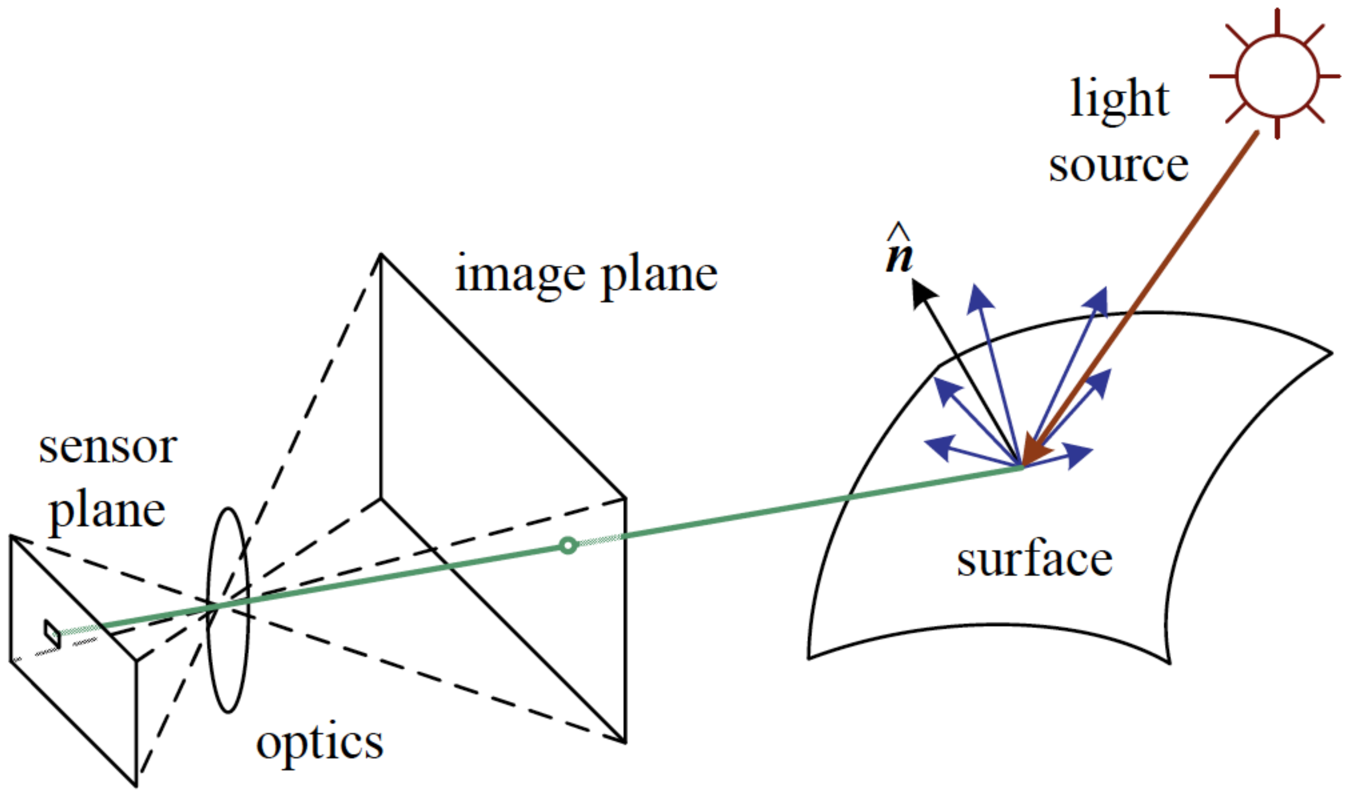
Image Formation



Factors

- *Light source strength and direction*
- *Surface geometry, material and nearby surfaces*
- *Sensor capture properties*
- *Image representation and colour*

1Credit: Szeliski, Computer Vision: Algorithms and Applications, 2010

Image Sensing and Acquisition

Image Acquisition Process

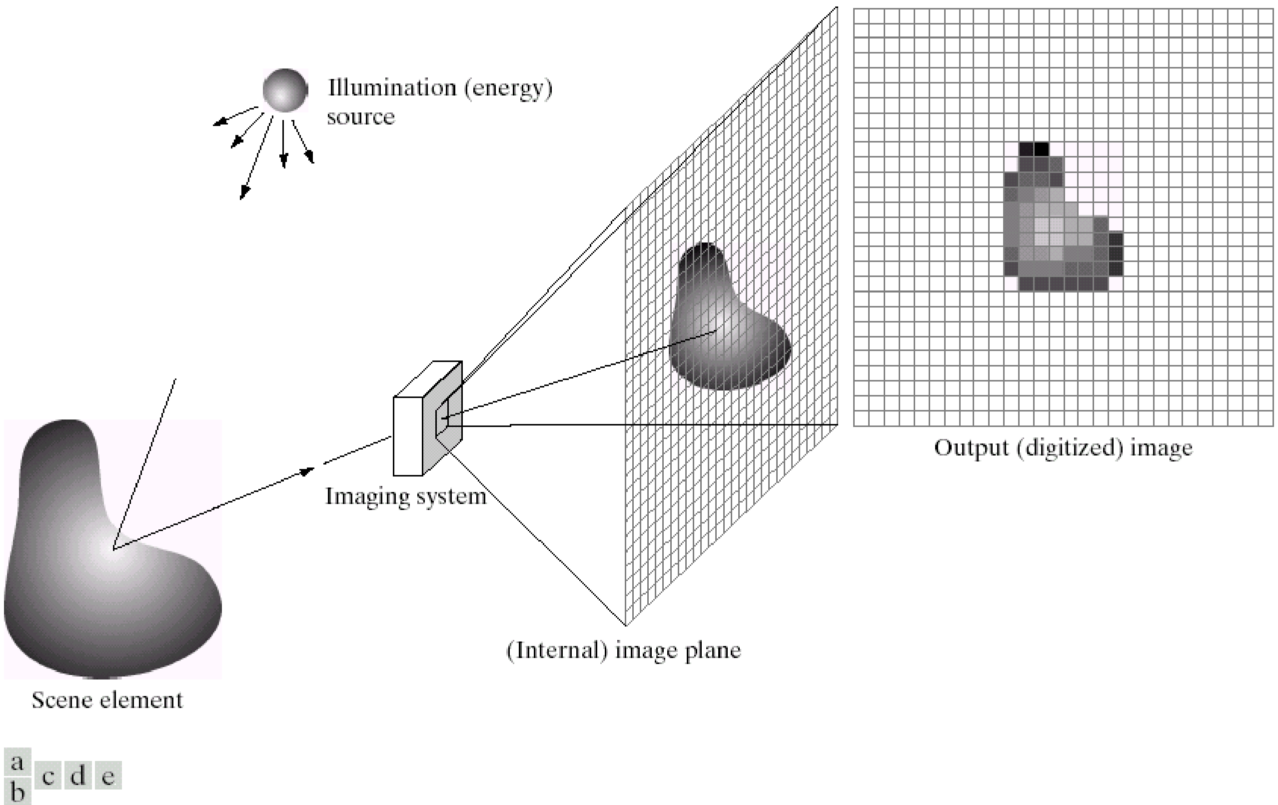


FIGURE 2.15 An example of the digital image acquisition process. (a) Energy ("illumination") source. (b) An element of a scene. (c) Imaging system. (d) Projection of the scene onto the image plane. (e) Digitized image.

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

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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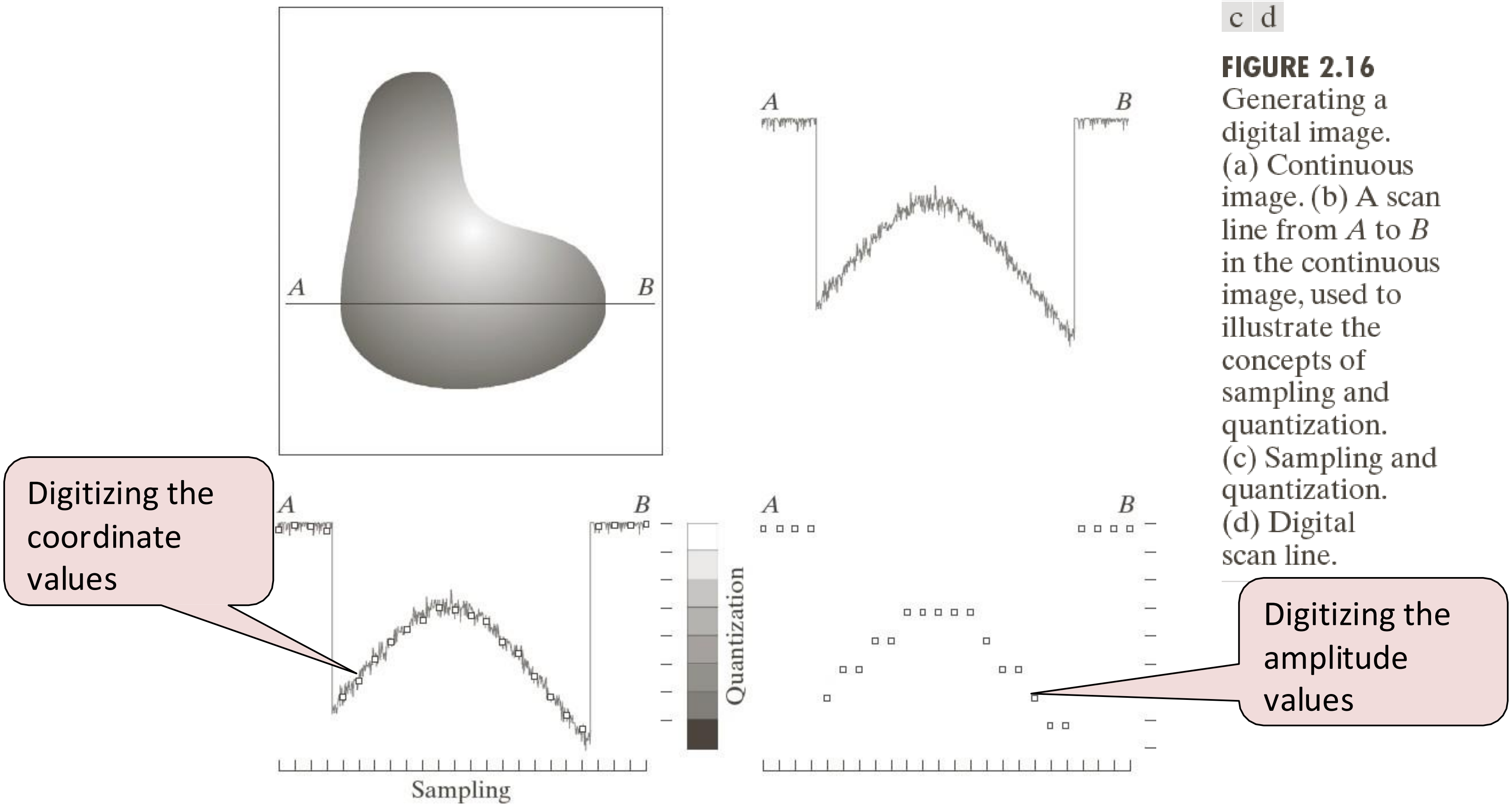
Image Sensing and Acquisition

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

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.

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

Image Sampling and Quantization

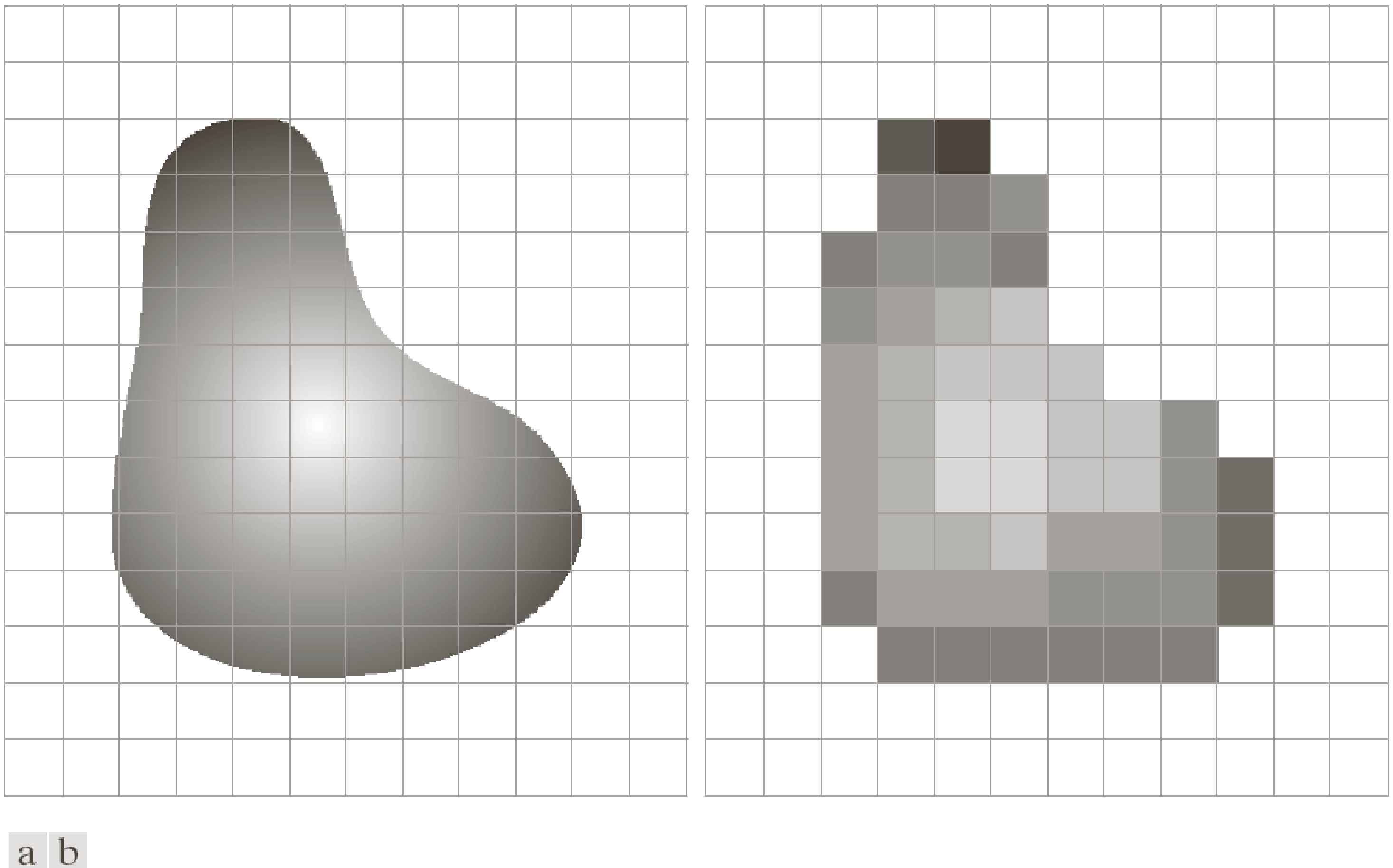


FIGURE 2.17 (a) Continuous image projected onto a sensor array. (b) Result of image sampling and quantization.

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Representing Digital Images

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

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

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

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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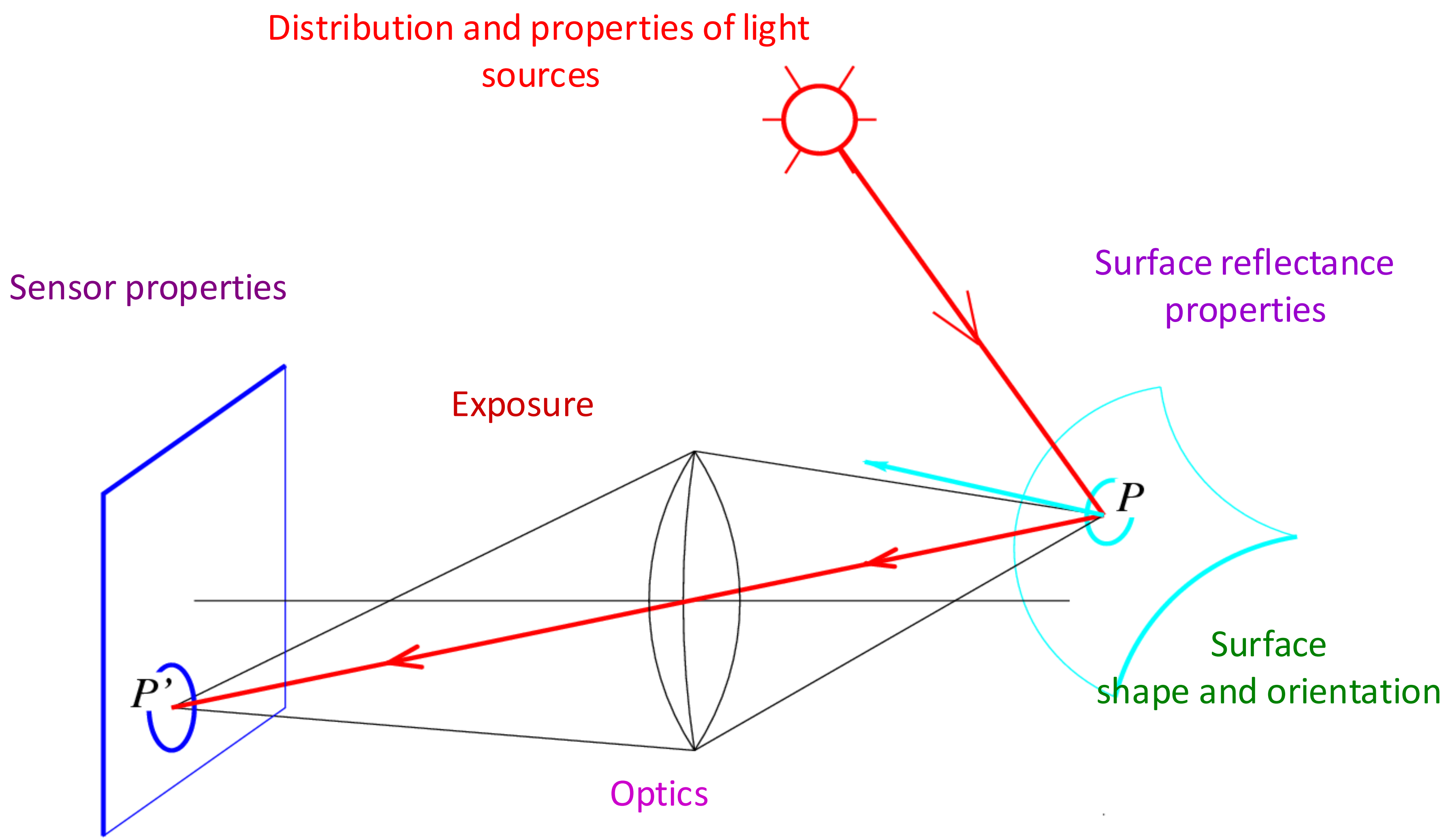
Spatial and Intensity Resolution

- **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.

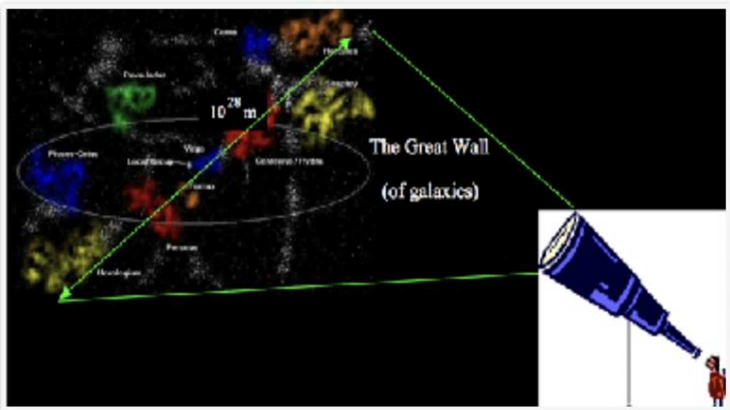
R. C. Gonzalez and R. E. Woods, Digital Image Processing, Prentice Hall, 4th edition, 2018.

What determines the brightness of an image pixel?

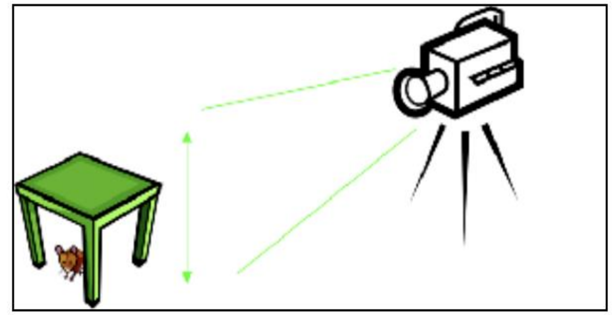


Slide by L. Fei-Fei

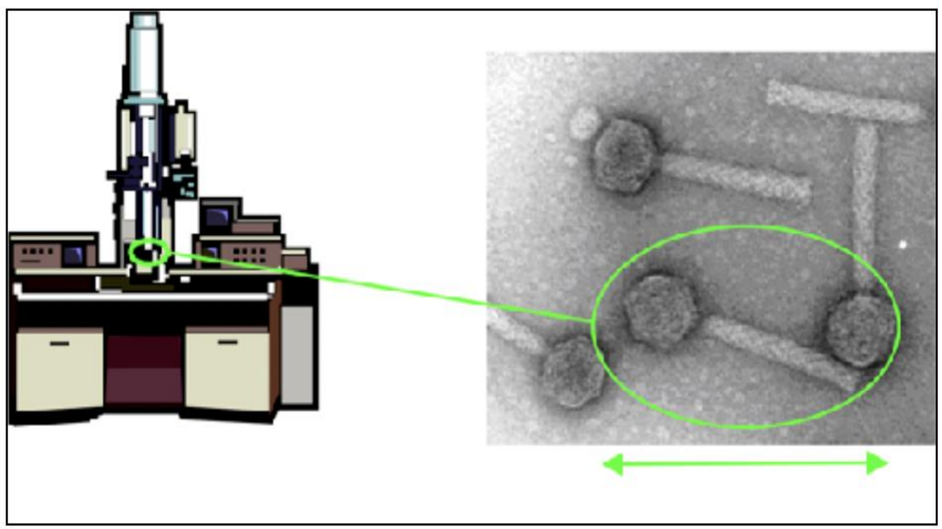
Image Scales



Gigantic



Everyday



Microscopic

Related topics

Geometry	2D Transformations, 3D Transformations, Camera Calibration, Distortion
Photometry	Lighting, Reflectance and Shading, Optics
Colour	Physics of Colour, Human Colour, Colour Representation
Sensor	Human Perception, Camera Design, Sampling and Aliasing, Compression

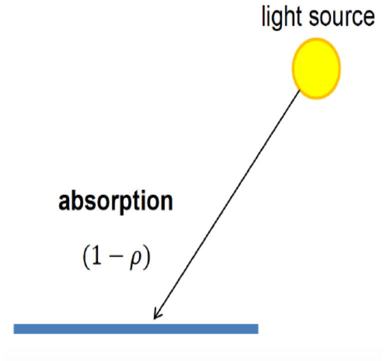
We will cover a few relevant topics from these

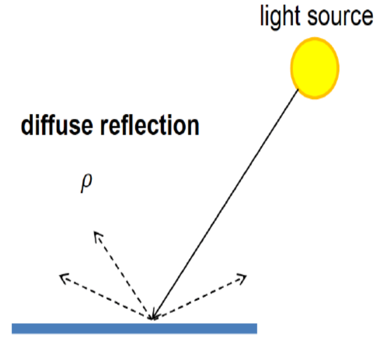
For a detailed understanding, read Chapters 1-5 of the book, *Computer Vision: A Modern Approach* by Forsyth and Ponce

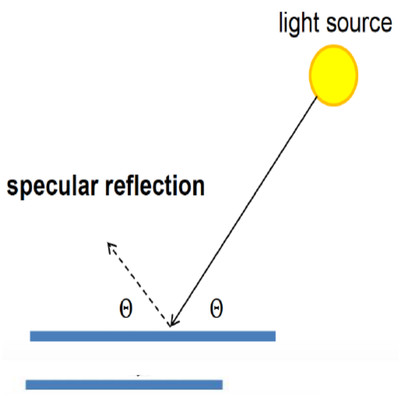
Models of reflection

When light hits a surface:

- Some light is absorbed ($1-\rho$, $\rho=$ albedo);
  - More absorbed for low albedos
- Some light is reflected diffusively, independent of viewing direction
  - E.g.: Brick, cloth, rough wood
  - **Lambert's cosine law:** Amount of reflected light proportional to $\cos(\theta)$
- Some light is reflected specularly, depends on viewing direction
  - E.g.: Mirror



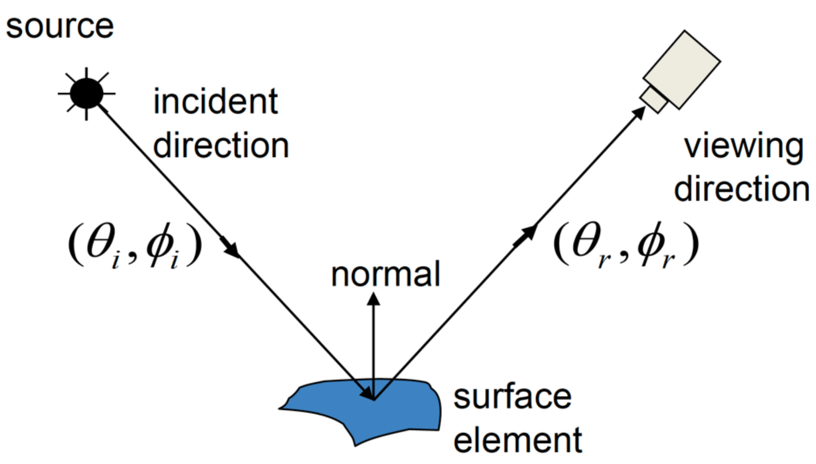




Credit: Derek Hoiem, UIUC

Models of reflection

- Most surfaces have both specular and diffuse components
- Intensity depends on illumination angle because less light comes in at oblique angles
- Other possible effects:
    - Transparency
    - Refraction
    - Subsurface scattering



BRDF - Bidirectional Reflectance Distribution Function: Model of local reflection that tells how bright a surface appears when viewed from one direction when light falls on it from another

Color

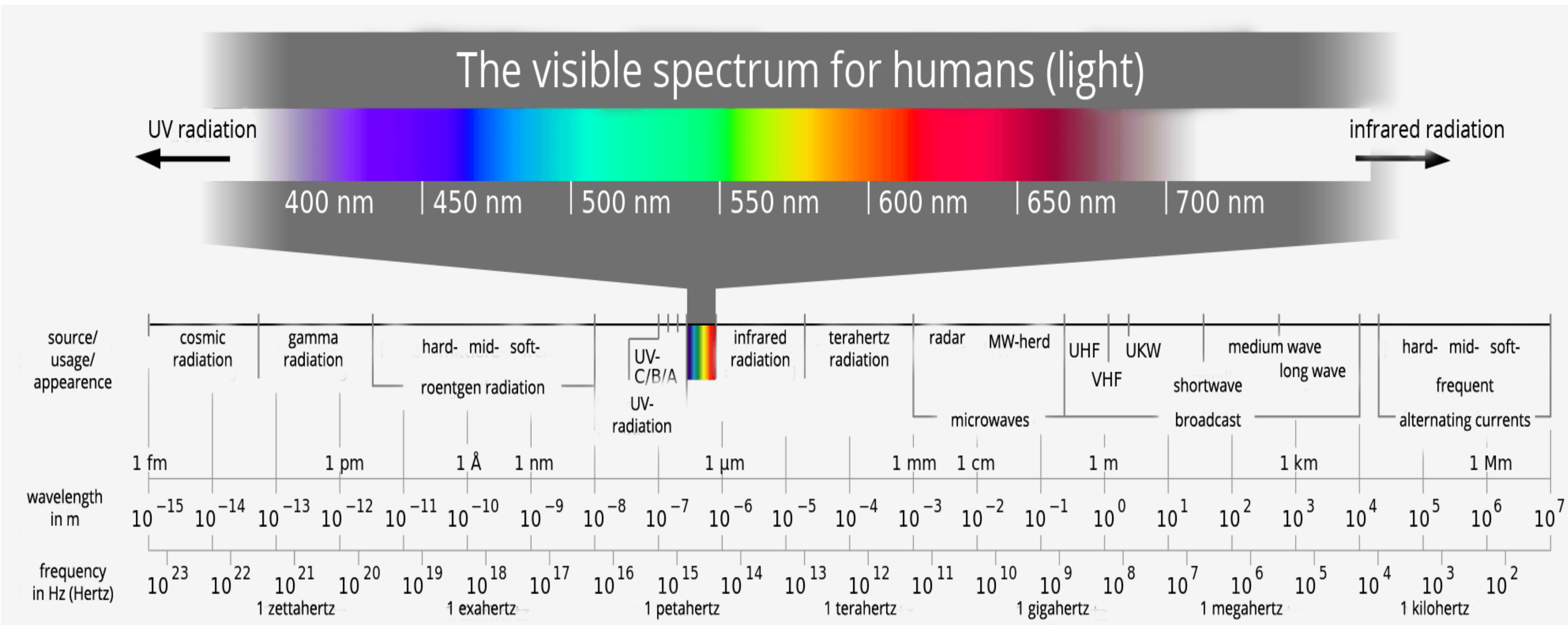
- An important aspect of images.
- At each pixel, the image has three values: Red, Green, and Blue.
- Can think of as three images: the Red, Green and Blue images: RGB representation.
- We can just process the intensity image I = R + G + B or
- Process R, G, B components separately like gray-scale images then add the results.
- Colour constancy: perceived colour of objects remain constant under varying illumination conditions

Colour: Can we function without it?

- RGB codes color video as three separate signals: R, G, and B.
- This is the representation captured by most color optical sensors.
- Color is important although perhaps not necessary for survival.

Colour

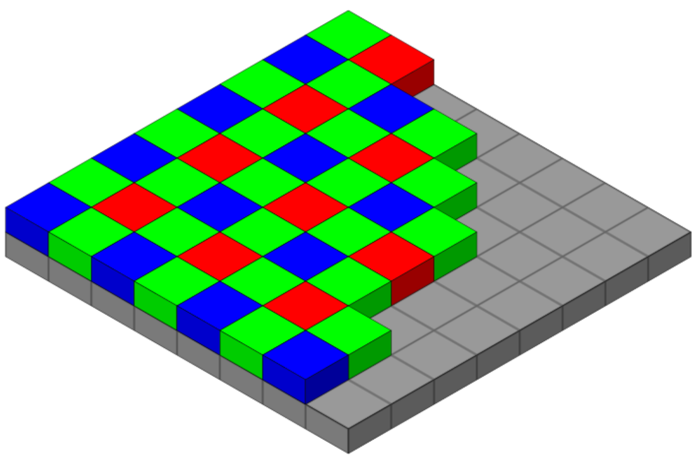
- Light is composed of a spectrum of wavelengths
- Coloured light arriving at sensor involves: (i) Colour of light source; (ii) Colour of surface

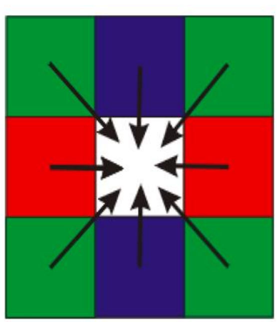


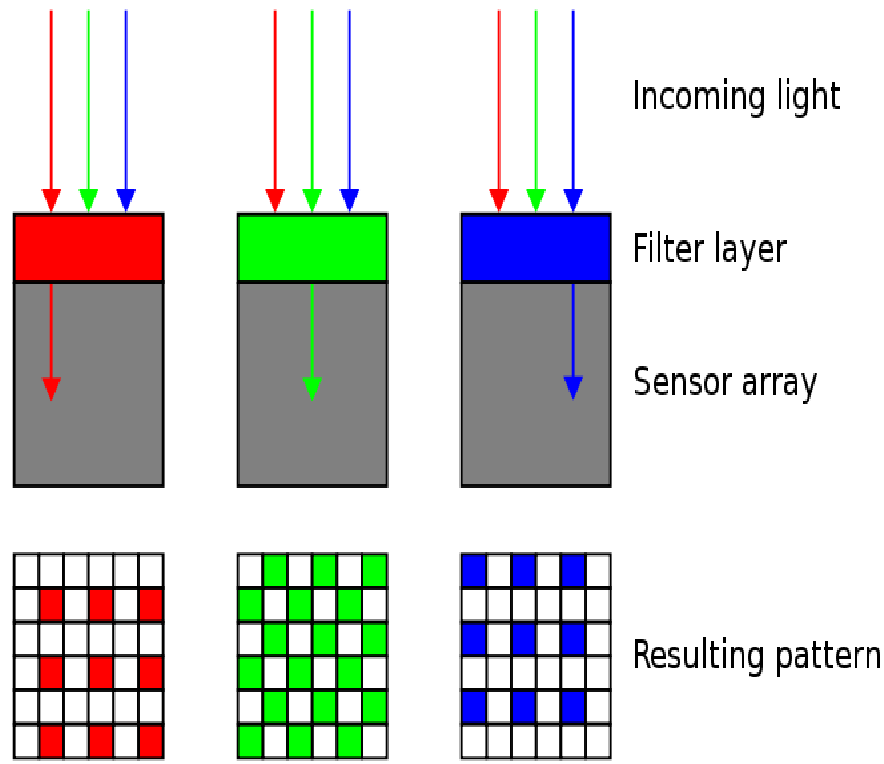
Credit: Electromagnetic spectrum by Horst Frank, Jailbird and Phrood. Under CC 3.0 License

Bayer Grid/Filter

- Bayer arrangement of color filters on a camera sensor
- Filter pattern is 50% green, 25% red and 25% blue
- To obtain full-colour image, demosaicing algorithms used - surrounding pixels used to estimate values for a particular pixel..







Question

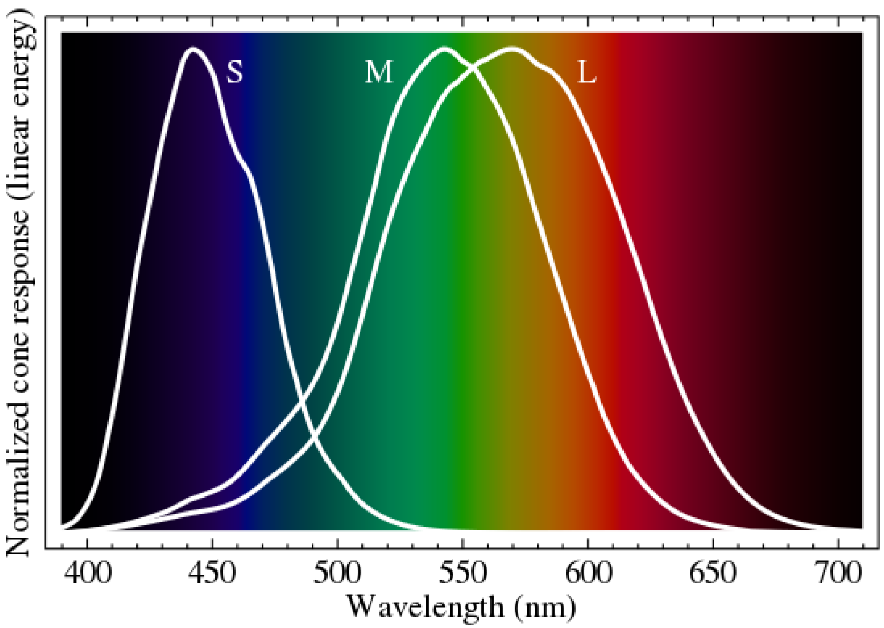
- If visible light spectrum is VIBGYOR, why RGB colour representation?

Answer

- Human eye has Long (red), Medium (green), and Short (blue) cones, plus intensity rods

Interesting facts

- “M" and “L" on the X-chromosome => men are more likely to be colour blind!
- Some animals have 1 (night animals), 2 (e.g., dogs), 4 (fish, birds), 5 (pigeons, some reptiles/amphibians), or even 12 (mantis shrimp) types of cones

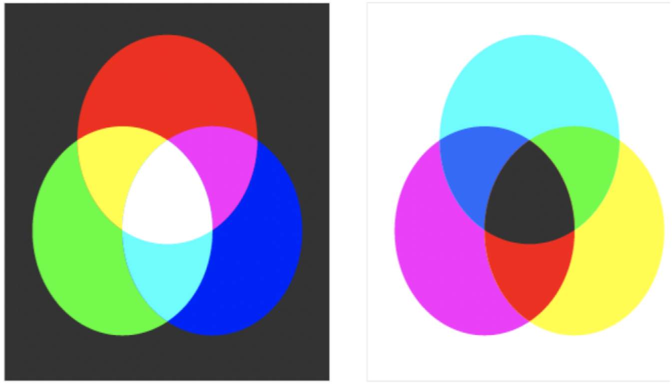


Credit: Derek Hoiem, UIUC

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

Colour Space Representation

- Popular colour spaces: RGB, CMYK
- Additive colours: R, G, B
- Subtractive colours: C, M, Y
- Other colour spaces: XYZ, YUV, Lab, YCbCr, HSV
- Standards established by Commission Internationale d'Eclairage (CIE)
- Understanding of colour spaces important in printing industry

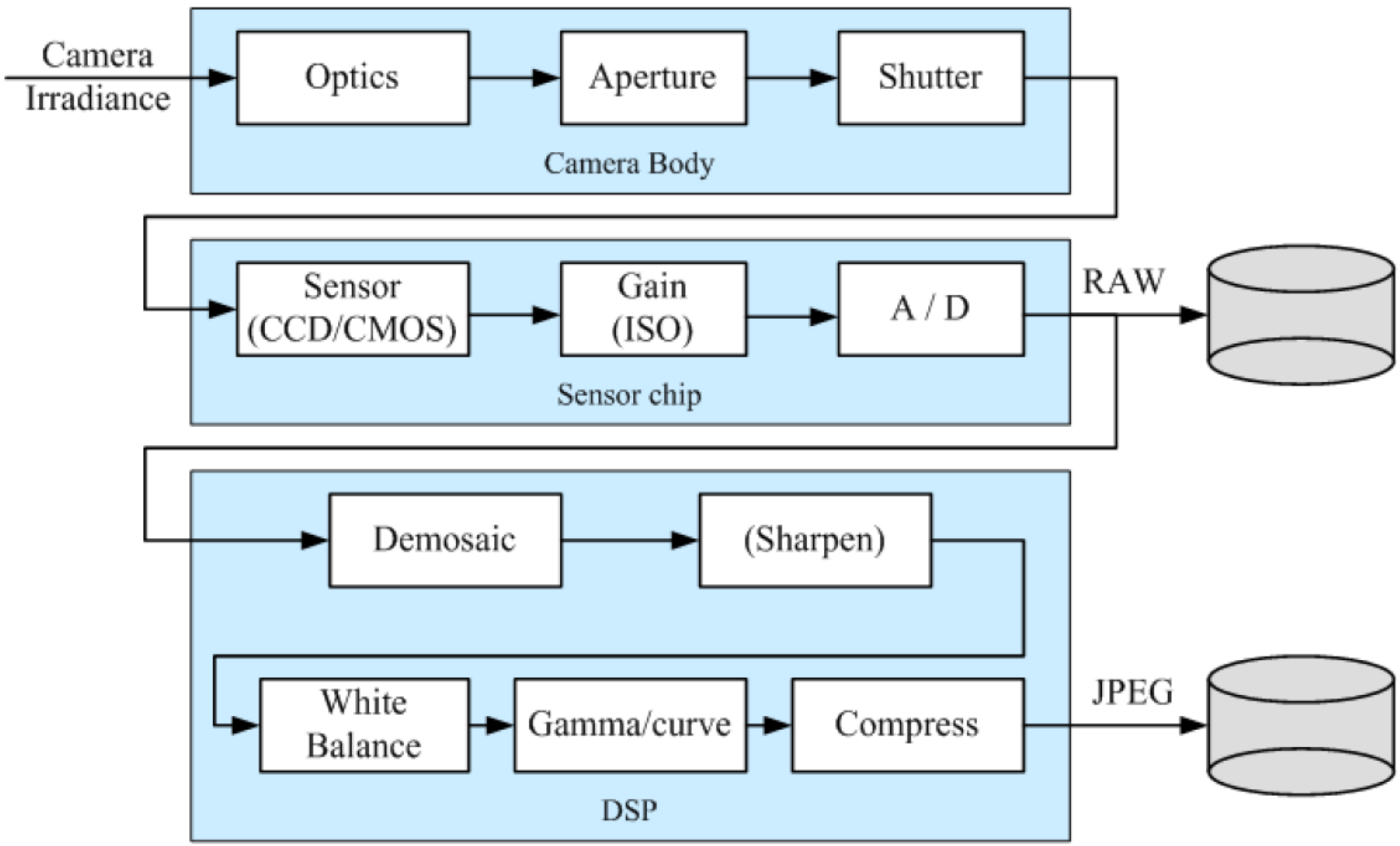


Credit: Szeliski, Computer Vision: Algorithms and Applications, 2010

For more information:

- https://www.tutorialspoint.com/dip/introduction_to_color_spaces.htm
- https://ciechanow.ski/color-spaces/

Image Sensing Pipeline



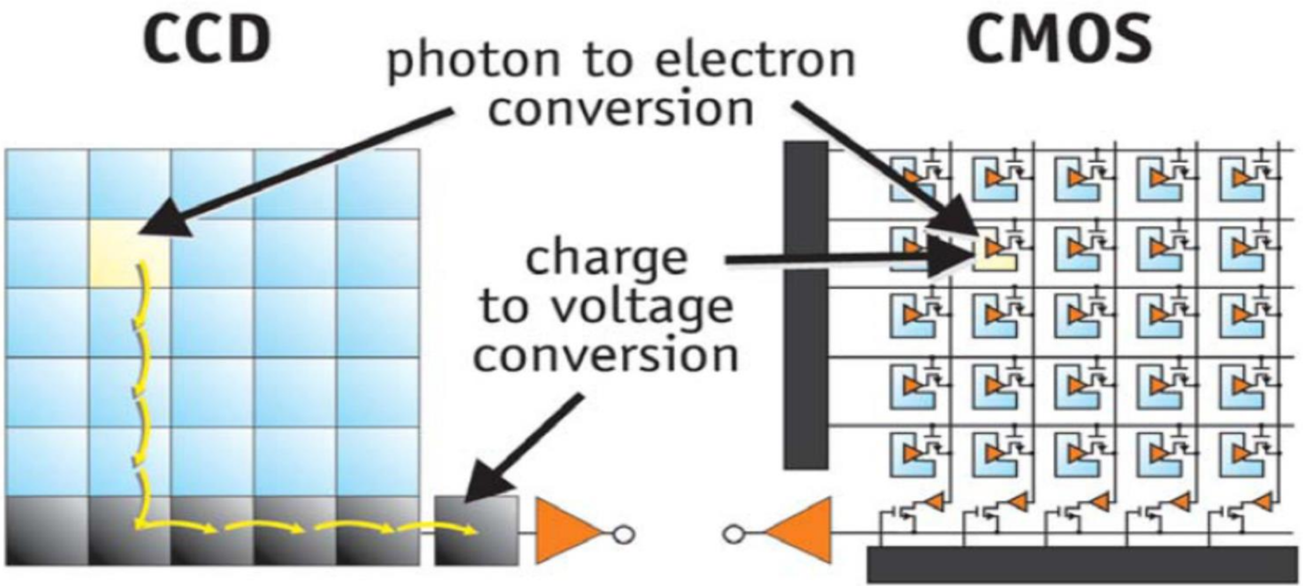
Credit: Szeliski, Computer Vision: Algorithms and Applications, 2010

Imaging Sensors

- Sensors: Charge Coupled Device (CCD), Complementary Metal Oxide Semiconductor (CMOS)

CCD

- Photon strike creates electron
- Move photogenerated charge from pixel to pixel, and convert it to voltage at output node
- An ADC then turns each pixel's value into a digital value
- Number of electrons proportional to number of photons
- Output voltage proportional to number of electrons
- High quality, high power, low noise

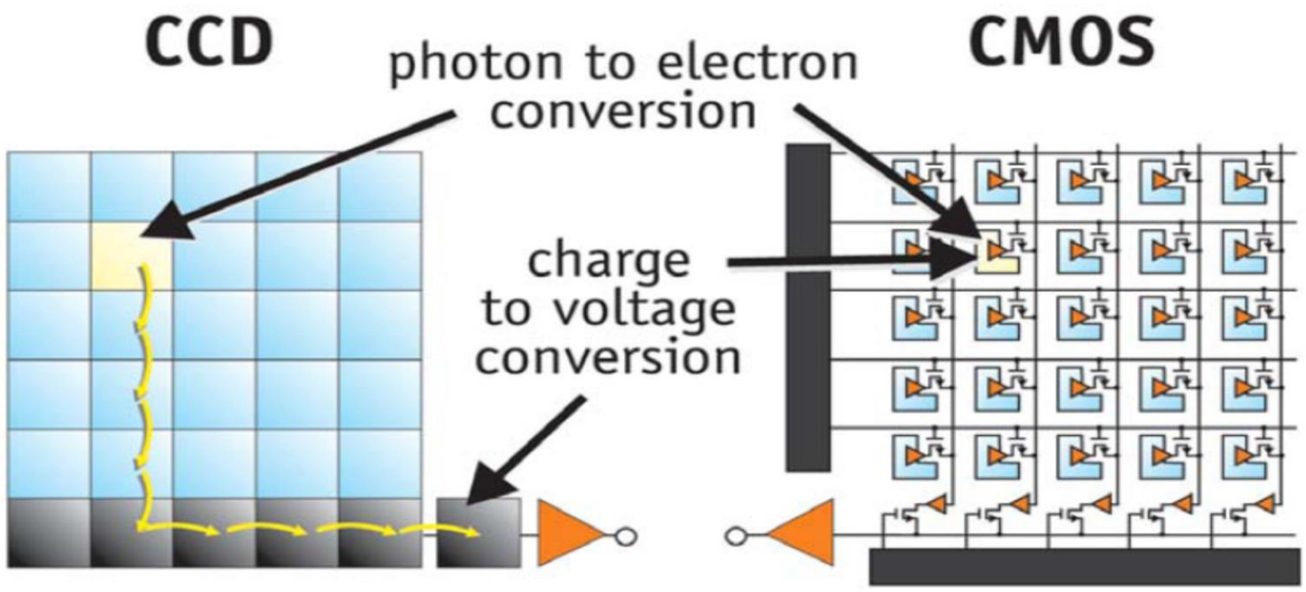


Imaging Sensors

- Sensors: Charge Coupled Device (CCD), Complementary Metal Oxide Semiconductor (CMOS)

CMOS

- CMOS convert charge to voltage inside each element
- Uses several transistors at each pixel to amplify and move the charge using more traditional wires
- CMOS signal is digital, so it needs no ADC
- Cheaper, low power, noisier



Digital Image Sensor Properties

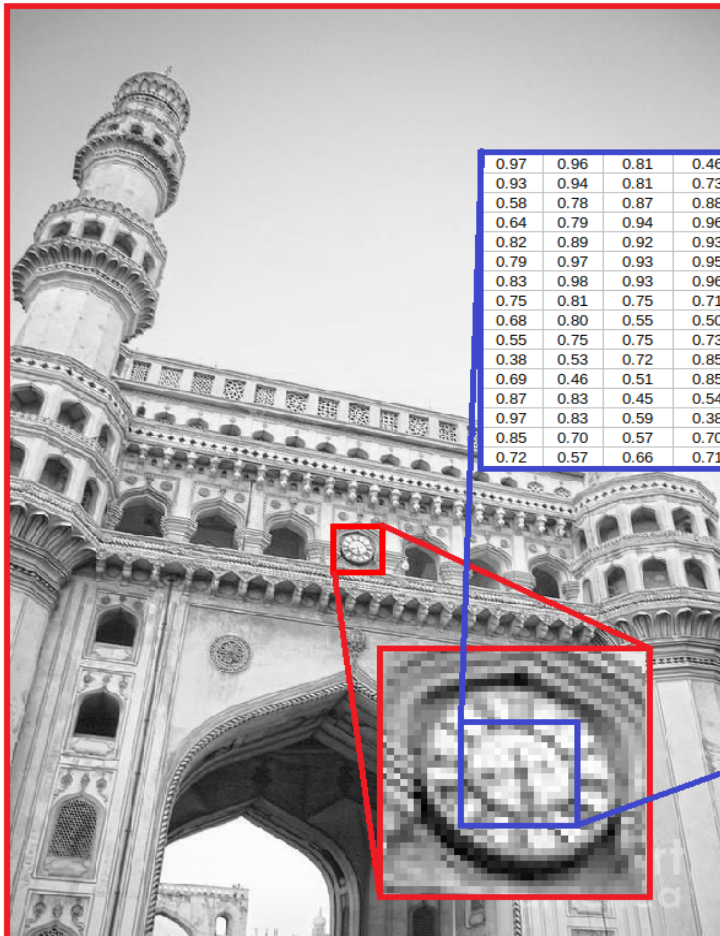
Shutter speed:	Controls the amount of light reaching the sensor (also called *exposure time*)
Sampling pitch:	Physical spacing between adjacent sensor cells on the imaging chip
Fill factor:	Active sensing area size as a fraction of the theoretically available sensing area (product of horizontal and vertical sampling pitches)
Chip size:	Size/area of the chip
Analog gain:	Amplification of the sensed signal using automatic gain control (AGC) logic (controlled using ISO setting on cameras)
Sensor noise:	Noise from various sources in the sensing process
Resolution:	How many bits for each pixel, decided by analog-to-digital conversion module
Post-processing:	Digital image enhancement methods often used before compression and storage of captured image

Question ?

With Smart phone do you need DSLR Cameras ?

Image as a matrix

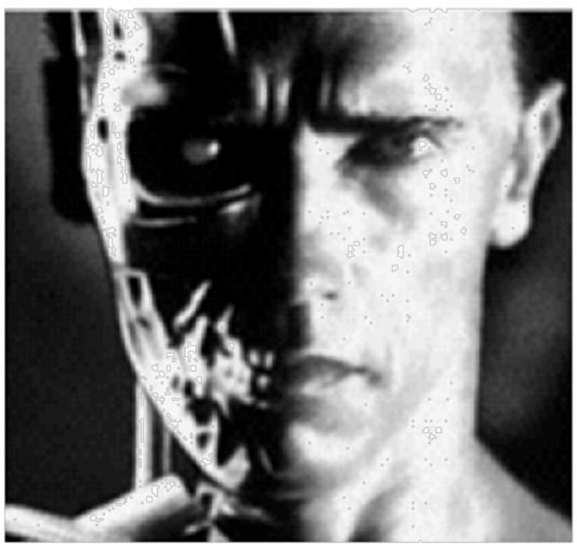
- Common to use one byte per value: 0 = black, 255 = white
- One such matrix for every channel in colour images

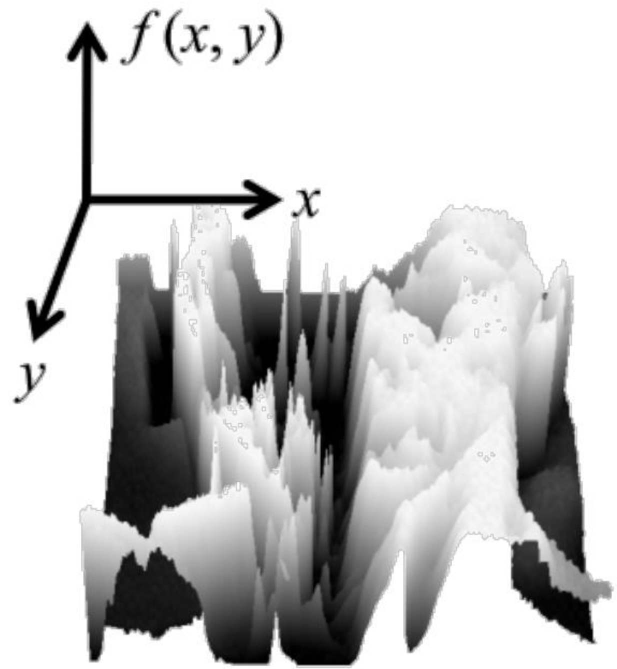


0.97	0.96	0.81	0.46	0.55	0.78	0.70	0.56	0.58	0.55	0.94	0.97	0.92	0.83	0.91	0.95
0.93	0.94	0.81	0.73	0.80	0.83	0.84	0.86	0.73	0.55	0.73	0.87	0.91	0.86	0.94	0.96
0.58	0.78	0.87	0.88	0.94	0.95	0.97	0.97	0.96	0.97	0.80	0.57	0.55	0.96	0.96	0.92
0.64	0.79	0.94	0.96	0.91	0.95	0.96	0.90	0.91	0.93	0.94	0.98	0.62	0.75	0.97	0.97
0.82	0.89	0.92	0.93	0.97	0.93	0.81	0.77	0.98	0.92	0.90	0.93	0.96	0.67	0.66	0.80
0.79	0.97	0.93	0.95	0.89	0.97	0.86	0.64	0.90	0.98	0.98	0.92	0.97	0.88	0.52	0.64
0.83	0.98	0.93	0.96	0.93	0.95	0.97	0.75	0.82	0.93	0.83	0.69	0.92	0.93	0.86	0.77
0.75	0.81	0.75	0.71	0.85	0.77	0.83	0.55	0.51	0.88	0.86	0.77	0.76	0.97	0.94	0.69
0.68	0.80	0.55	0.50	0.78	0.77	0.81	0.59	0.53	0.92	0.95	0.91	0.90	0.95	0.97	0.60
0.55	0.75	0.75	0.73	0.75	0.86	0.95	0.83	0.67	0.89	0.97	0.93	0.93	0.93	0.97	0.74
0.38	0.53	0.72	0.85	0.90	0.91	0.93	0.90	0.66	0.70	0.92	0.95	0.97	0.96	0.90	0.72
0.69	0.46	0.51	0.85	0.96	0.92	0.90	0.83	0.55	0.54	0.84	0.94	0.89	0.88	0.89	0.69
0.87	0.83	0.45	0.54	0.75	0.85	0.97	0.91	0.63	0.61	0.84	0.93	0.79	0.70	0.66	0.40
0.97	0.83	0.59	0.38	0.52	0.58	0.76	0.83	0.72	0.59	0.69	0.75	0.62	0.54	0.47	0.61
0.85	0.70	0.57	0.70	0.61	0.55	0.47	0.58	0.64	0.49	0.60	0.58	0.77	0.88	0.59	0.54
0.72	0.57	0.66	0.71	0.93	0.96	0.64	0.54	0.61	0.60	0.82	0.65	0.77	0.94	0.93	0.80

Image as a function

- We can think of a (grayscale) image as a function $f : R^2 \rightarrow R$, giving the intensity at position (x; y)
- A digital image is a discrete (sampled, quantized) version of this function





Credit: Noah Snavely, Cornell Univ

Thank you!
Question?