Image Acquisition and Representation

Some Details

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Lecture Objectives

- Previously
  - Image Acquisition and Generation
  - Image Display and Image Perception
  - HTML5 and Canvas
- Today
  - Brief summary of direction of study
  - What is a Digital Image?

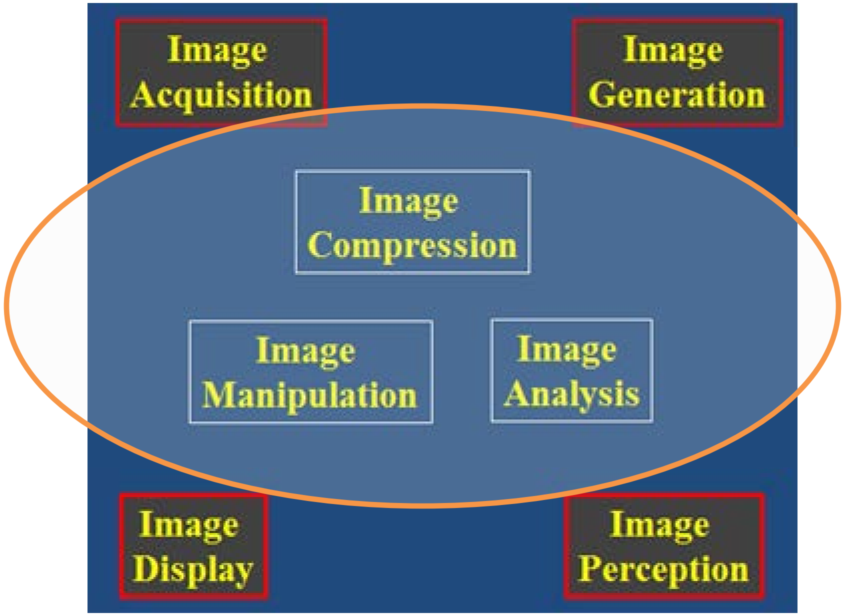
What we will Study

- Implicitly: **Visual Perception**
  - Light and EM Spectrum, Image Acquisition, Sampling, Quantization

- **Image Compression**
  - General Understanding

- **Image Manipulation/Enhancement**
  - in the Spatial Domain
    - noise models, noise filtering, image sharpening…
  - in the Frequency Domain
    - Fourier transform, filtering, restoration…

- **Image Analysis**
  - Object Identification,
  - Image Recognition,
  - Edge/corner detection,
  - Circle/line/ellipse detection…



What’s useful in this?

- Reasons for **Compression**
  - Image data needs to be accessed at different time or location
  - Limited storage space and transmission bandwidth
- Reasons for **Manipulation**
  - Image data acquisition was non-ideal, transmission was corrupted, or display device is less than optimal
    - reasons for restoration, enhancement, interpolation…
  - Image data may contain sensitive content
    - hide copyright, prevent counterfeit and forgery
- Reasons for **Analysis**
  - Reduce burden and error of human operators via automation
  - Allow a computer to “see” for various AI tasks

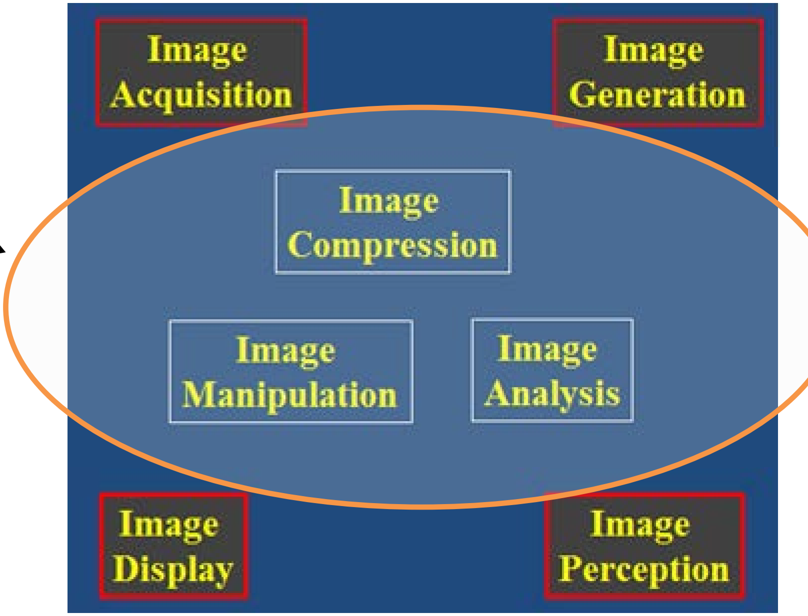
What **we will Discover**

- **Digital Image Processing connects many dots**
  - Linear Algebra, Matrix Theory and Statistics
  - Calculus and Fourier Transforms and Wavelets
  - AI, Neuroscience, and Psychology

Moving On

- How do we get to

DOING
this stuff ?



Must first understand WHAT a digital image is.

What is a Digital Image?

- Recall
  - **Digital Image Processing (DIP)**
    - **Is computer manipulation of pictures, or images, that have been converted into numeric form**

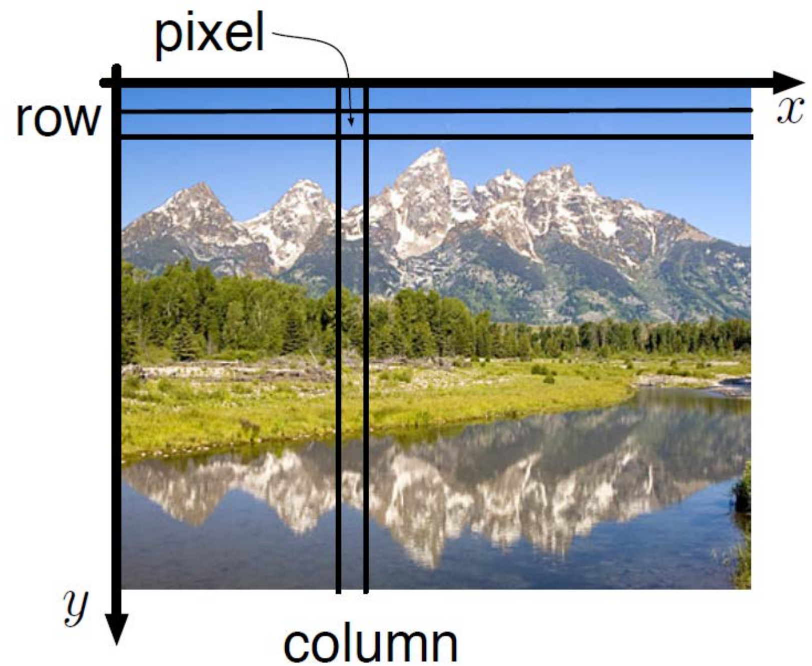
- Implies a **Digital Image**
  - **Is a picture or image converted to numeric form**

- Let us look at what that really means…

What is a Digital Image?

- 2D function f(x, y)
  or a matrix
  - x, y, and f(x, y)
    are discrete and finite
  - Image size = (x_{max}) by (y_{max})
    - e.g. 1024 x 768
  - Pixel Intensity Value = f(x,y)
    - bounded by 0 and 255

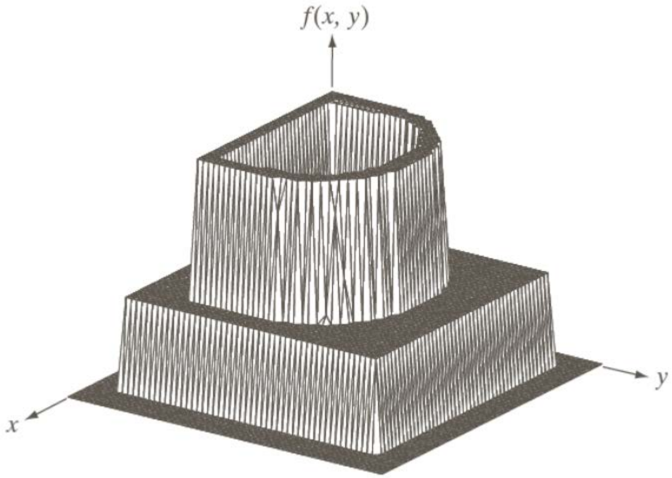
    hmm… how does color fit in?

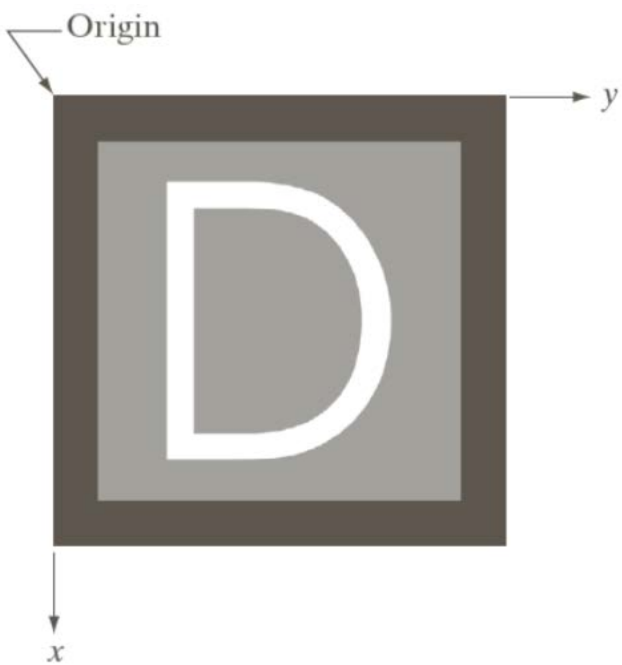


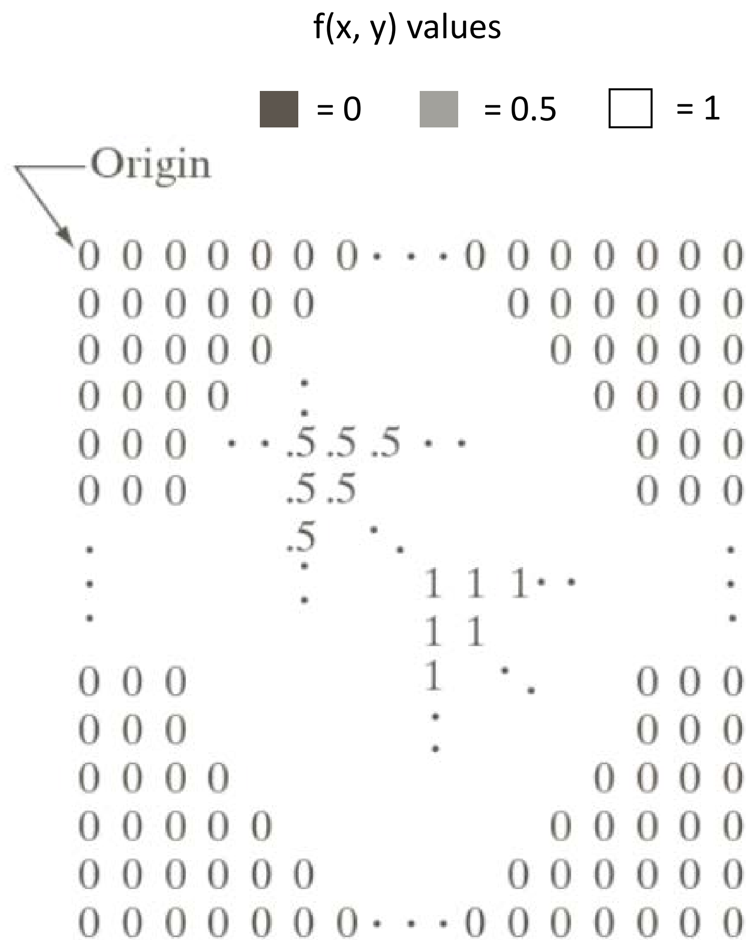
Think black and white for the moment

spoiler: for color think vector function

Pixel Values





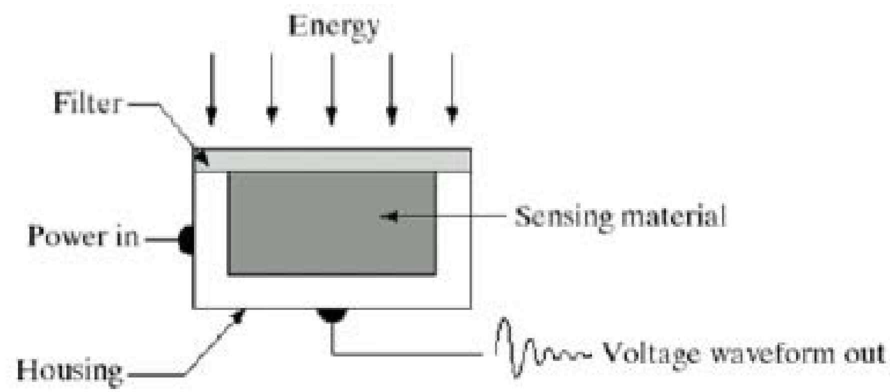


How do we get the numbers?

- Three principal sensor arrangements

How do we get the numbers?

- Three principal sensor arrangements
  - **Single**
  - Line
  - and Array



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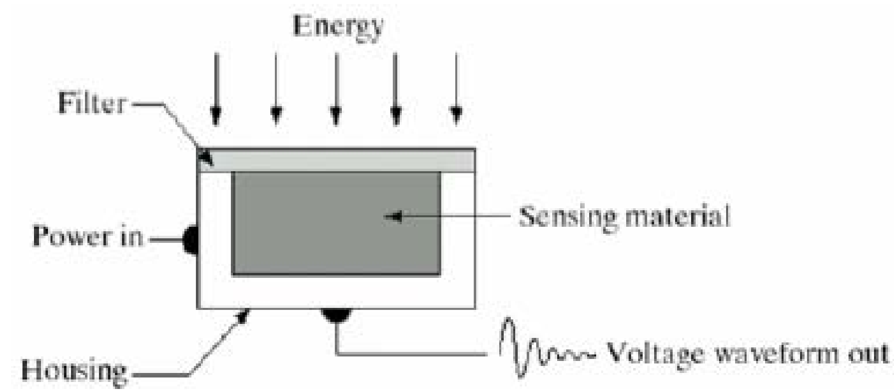

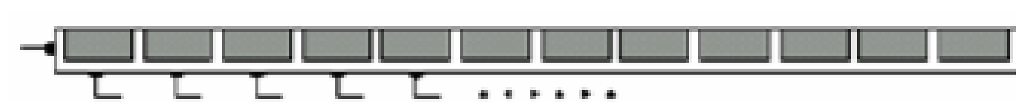

How do we get the numbers?

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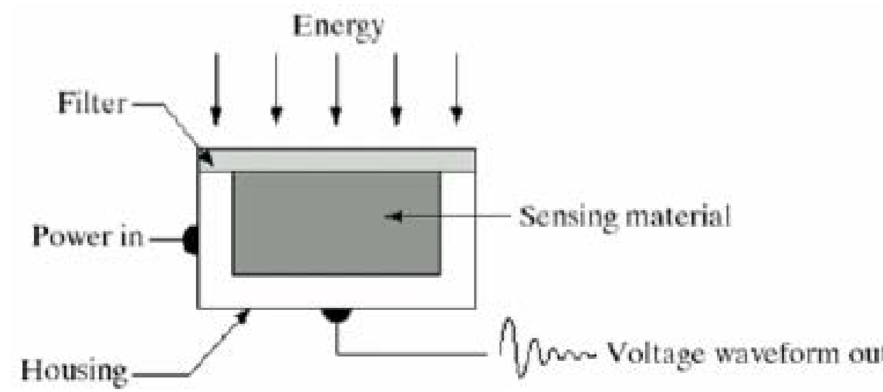
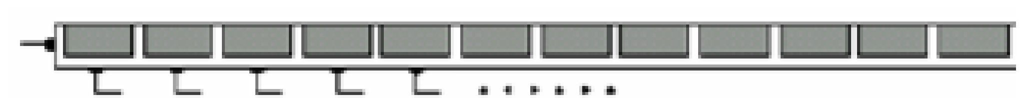
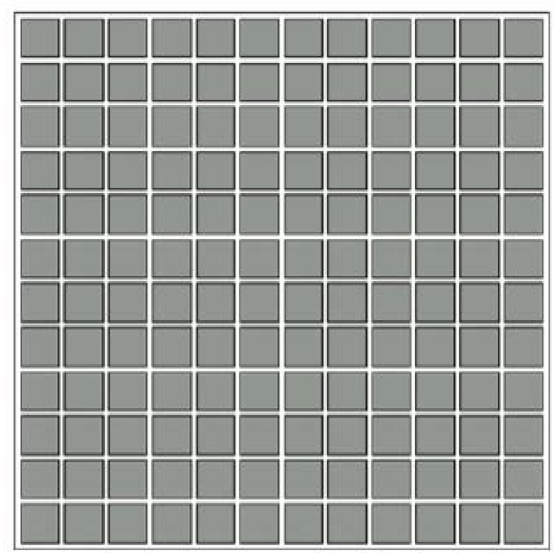
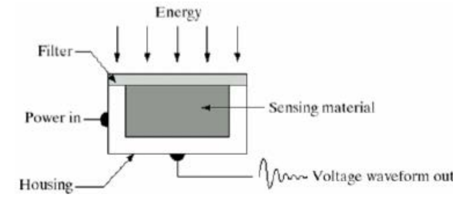






Single Sensor: Moving



- Photodiode
  - Constructed of silicon materials whose output voltage waveform is proportional to light
  - Generating a 2D image using a single sensor requires relative displacements in the horizontal and vertical directions between the sensor and area to be imaged

- Microdensitometers are mechanical digitizers that use a flatbed with the **sensor moving** in two linear directions

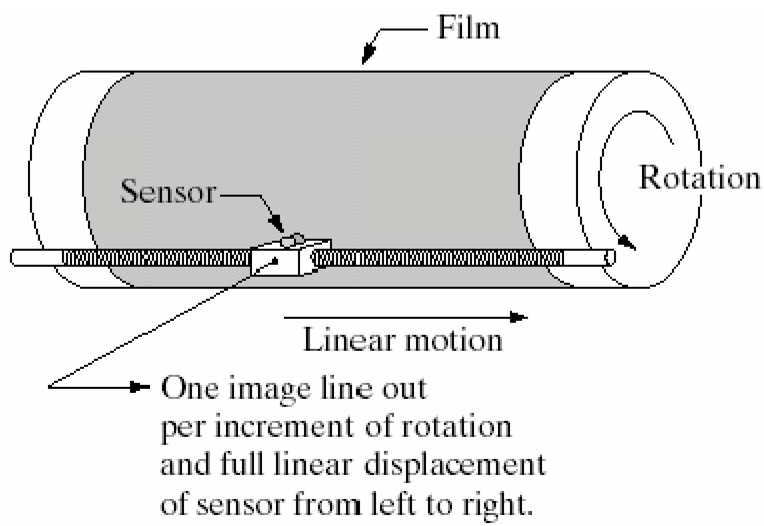
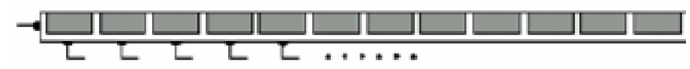
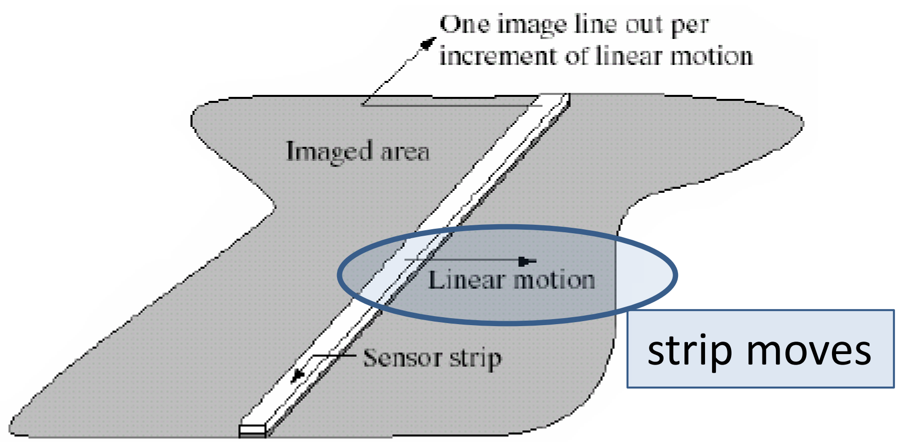


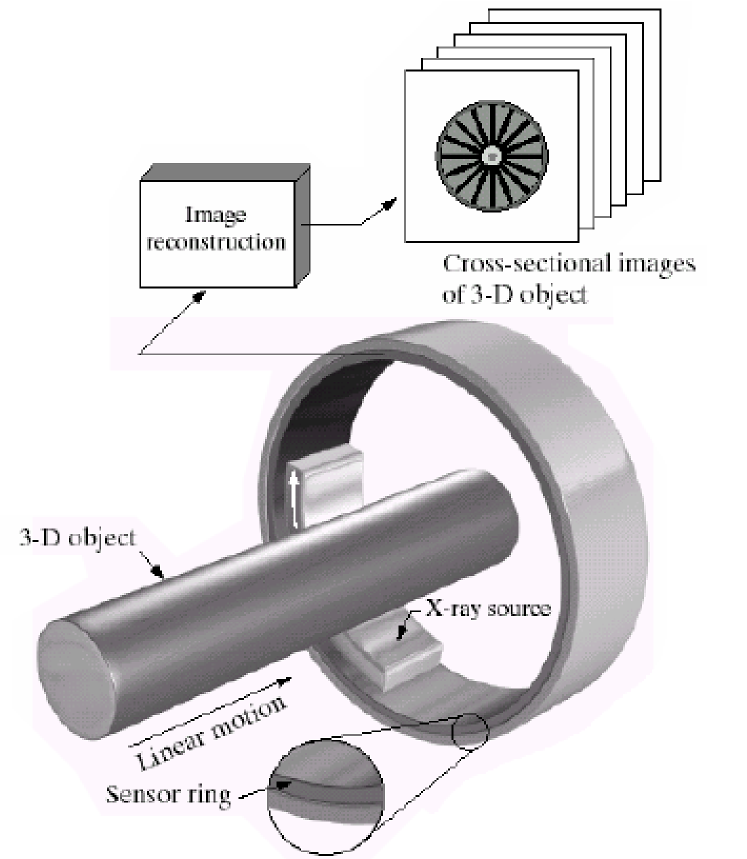
FIGURE 2.13 Combining a single sensor with motion to generate a 2-D image.

MOVING Sensor Strips

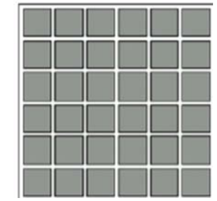
- In-line arrangement of sensors
    - i.e. a strip of sensors
  - Strip provides imaging elements in one direction
    - i.e. x direction
  - Motion perpendicular to the strip images in the other direction
    - i.e. y direction



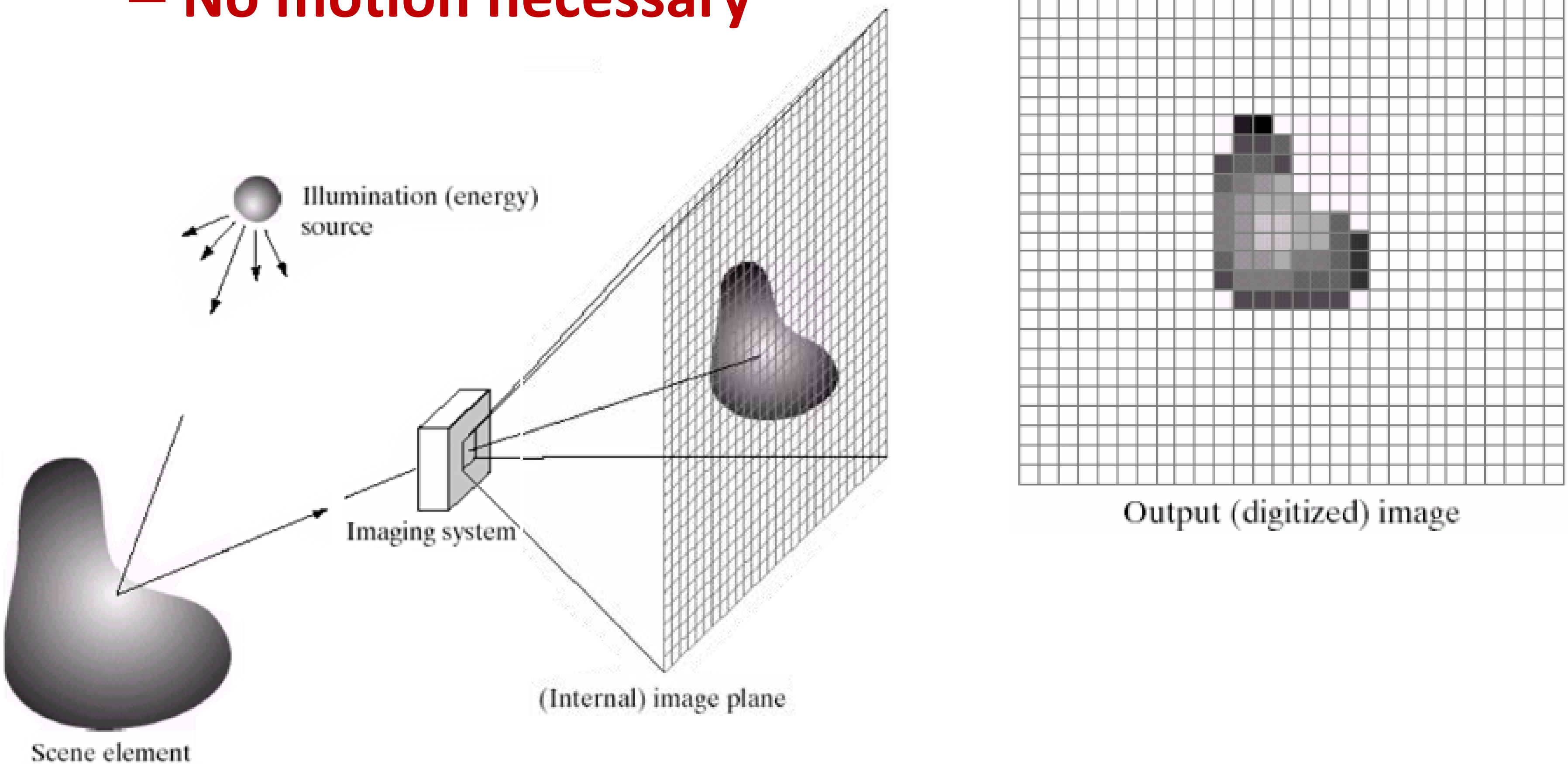




Sensor Arrays



- Individual sensors are arranged in a 2D array
  - Used in digital cameras
  - Entire image formed at once
  - **No motion necessary**



Signals

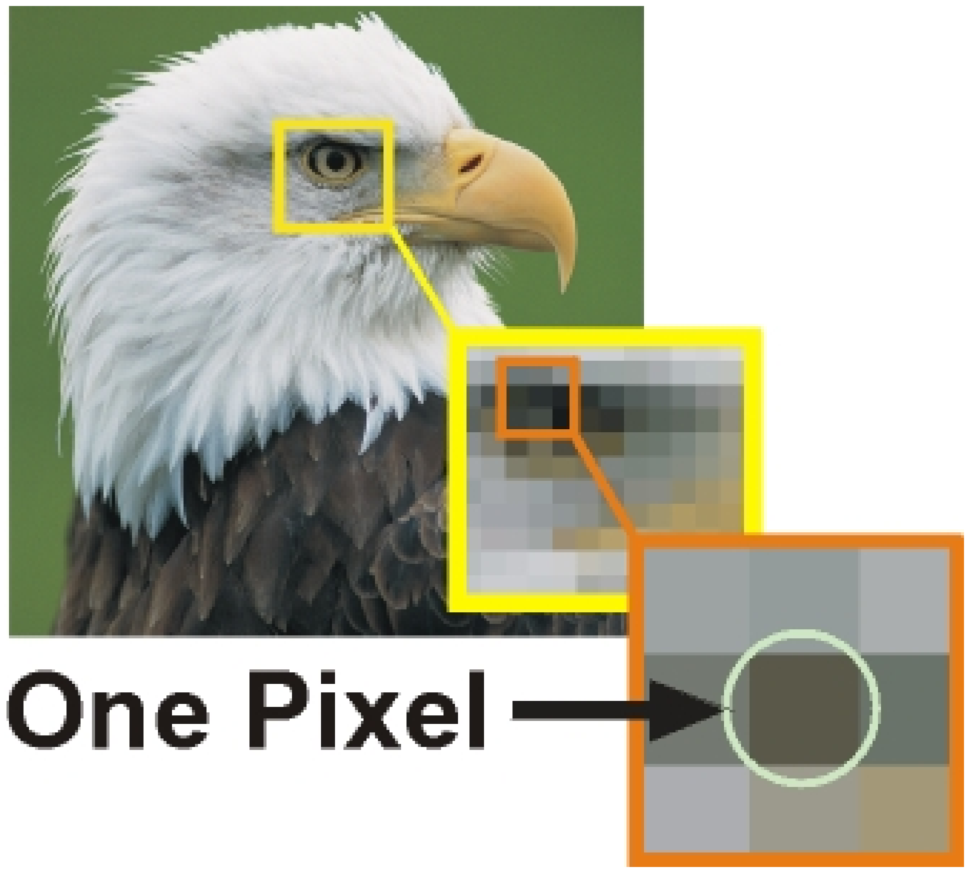
- A signal function conveys information
  - 1D signal: f(x) — waveform
  - 2D signal: f(x, y) — image
  - 3D signal: f(x, y, z) — volumetric data
    or f(x, y, t) — animation (spatiotemporal volume)
  - 4D f(x, y, z, t) — volumetric data over time

- The dimension of the signal
  is equal to its number of indices

- In this course we focus on 2D images: f(x, y)

Digital Image

- Image produced as an array of picture elements (pixels) in the frame buffer



http://digitalsafari.pbworks.com/w/page/84764749/02%20Pixel%20Art

Image Classification

- Images can be classified by
  - whether they are defined over all points in the spatial domain
  - and whether their image values have finite or infinite precision

  - If the position variables (x, y) are continuous
    then the function is defined over all points in the spatial domain

  - If (x,y) is discrete
    then the function can be sampled at only a finite set of points
    (i.e. the integers)

  - The value that a function returns can also be classified by its precision, independently of x and y

Image Classification

- *Quantization* refers to the mapping of real numbers onto a finite set
  - a many-to-one mapping
  - similar to casting a double precision to an integer

Space	Image Values	Classification
continuous	continuous	analog (continuous) image
continuous	discrete	intensity quantization
discrete	continuous	spatial quantization
discrete	discrete	digital (discrete) image

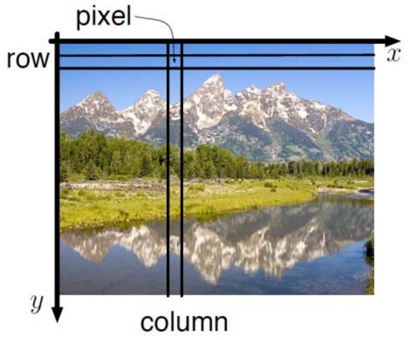
Digital Image: Summary

- Digital Image Processing (DIP)
  - Is computer manipulation of pictures, or images, that have been converted into numeric form

- A Digital Image
  - Is a picture or image converted to numeric form
  - In grey-scale the image can be thought of as
    - 2D function f(x, y) or a matrix
    - x, y, and f(x, y) are discrete and finite
    - Image size = (x_{max}) by (y_{max}), e.g. 1024 x 768
    - Pixel Intensity Value = $f(x,y) \in [0, 255]$

Summary So Far

- Digital Image Processing (DIP)
  - Is computer manipulation of pictures, or images, that have been converted into numeric form Previously
- **A Digital Image**
  - Is a picture or image converted to numeric form
  - In grey-scale the image can be thought of as
    - » **2D function f(x, y) or a matrix**
    - » x, y, and f(x, y) are discrete and finite
    - » Image size = (x_{max}) by (y_{max}),
    - » Pixel Intensity Value = $f(x,y) \in [0, 255]$
      - *for color f(x,y) returns a vector*
  - Digitally created by various physical devices



- **Next**
  - **Image Acquisition – part 2**
  - **Image Representation**

Grayscale (and Color) Imaging

- **Image Acquisition**
  - Light and Electromagnetic spectrum
  - Charge-Coupled Device (CCD) imaging
  - Sampling and Quantization
  - Bayer Filter
    - a common color filter array (CFA)
- Image Representation
  - Spatial resolution
  - Bit-depth resolution
  - Local neighborhood

Electromagnetic (EM) Spectrum

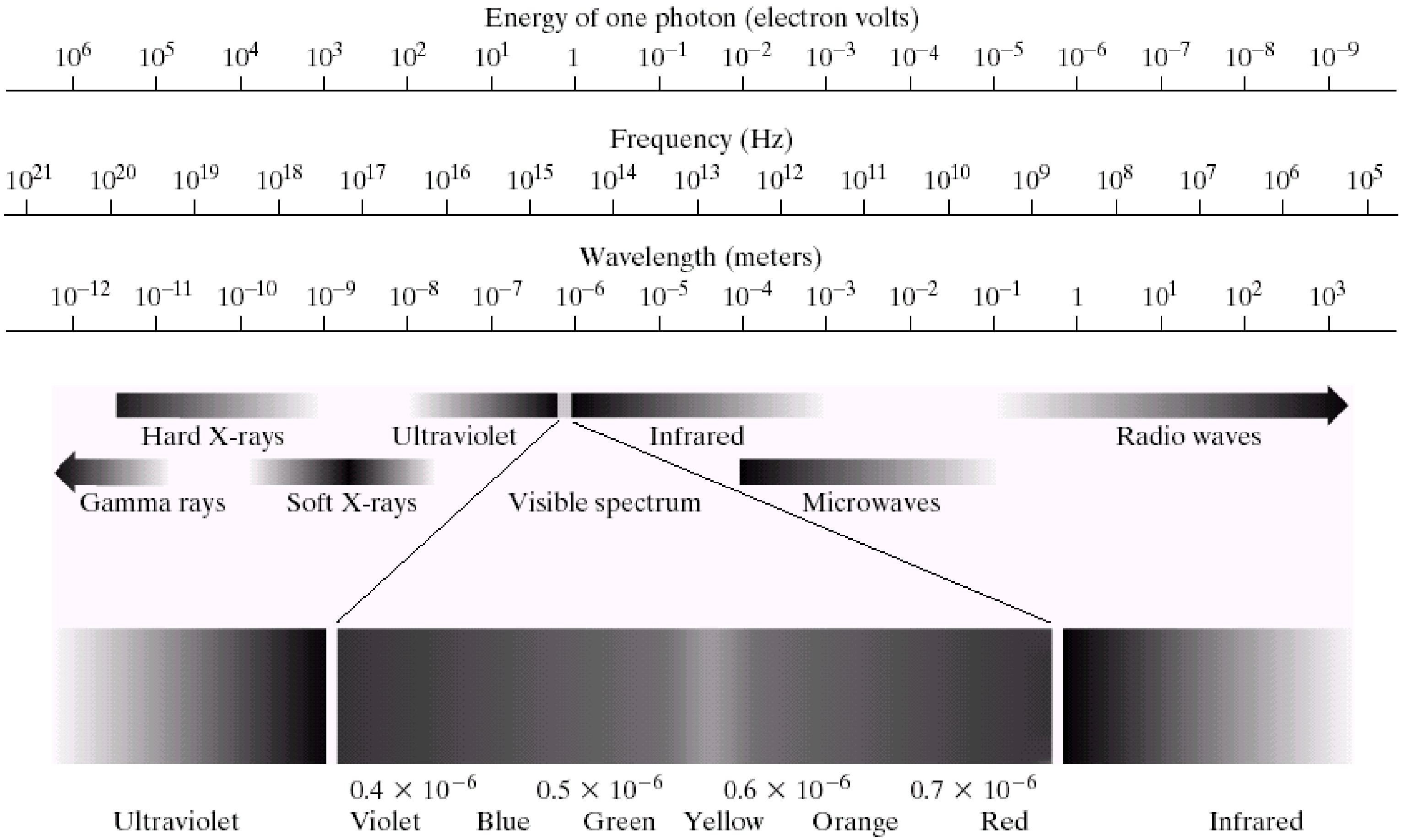


FIGURE 2.10 The electromagnetic spectrum. The visible spectrum is shown zoomed to facilitate explanation, but note that the visible spectrum is a rather narrow portion of the EM spectrum.

Visible Spectrum

- Visible range: 0.43μm(violet)-0.78μm(red)
- Six bands:
  - violet, blue, green, yellow, orange, red
- The color of an object is determined by the nature of the light *reflected* by the object
- Monochromatic light (gray level)
- Three elements measuring chromatic light
  - Radiance, luminance and brightness

Questions so far

- Questions on EM spectrum?

- Image Acquisition
  - Light and Electromagnetic spectrum
  - Charge-Coupled Device (CCD) imaging
  - Sampling and Quantization
  - Bayer Filter
    - a common color filter array (CFA)

CCD Imaging (Sensor Array)

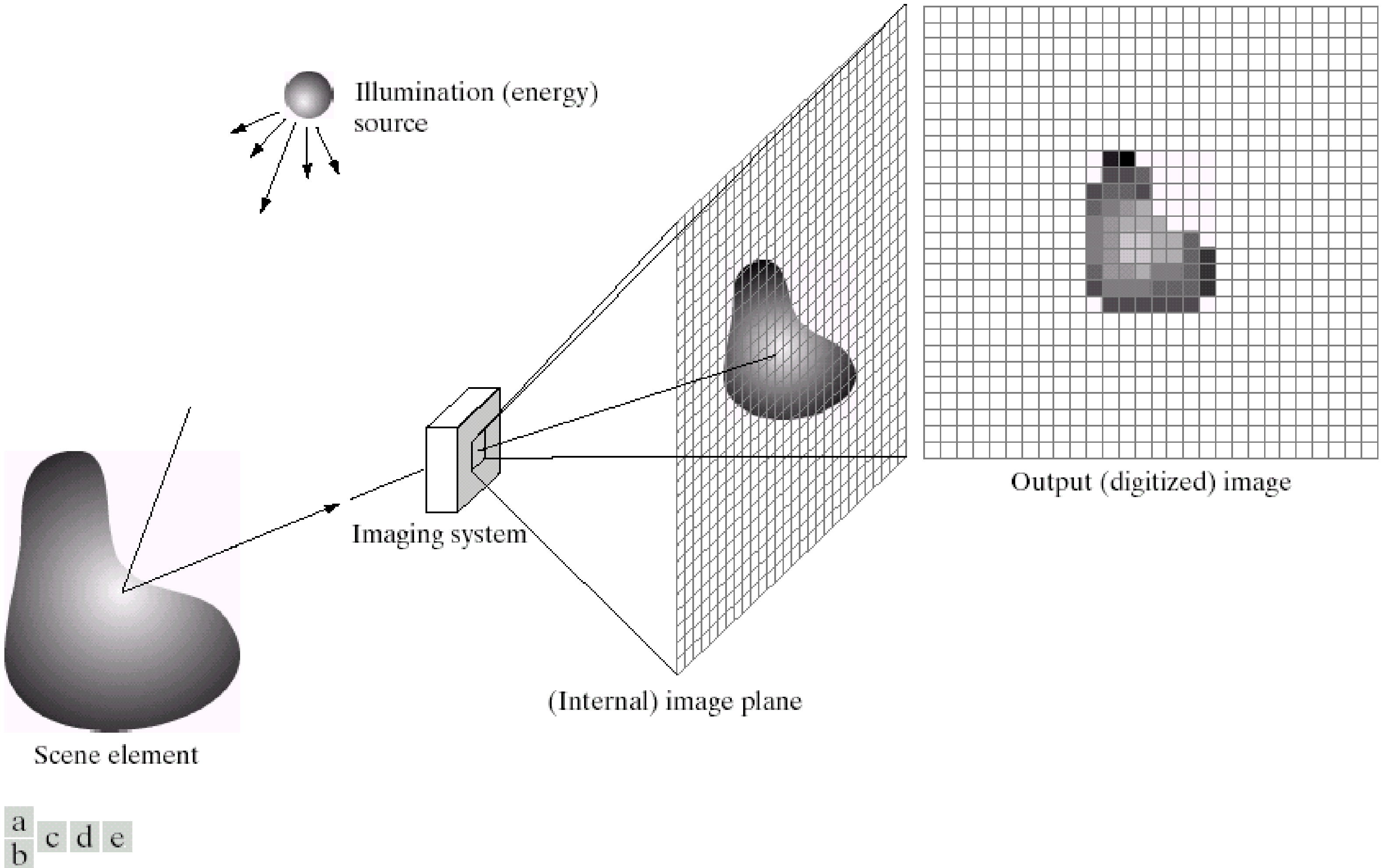
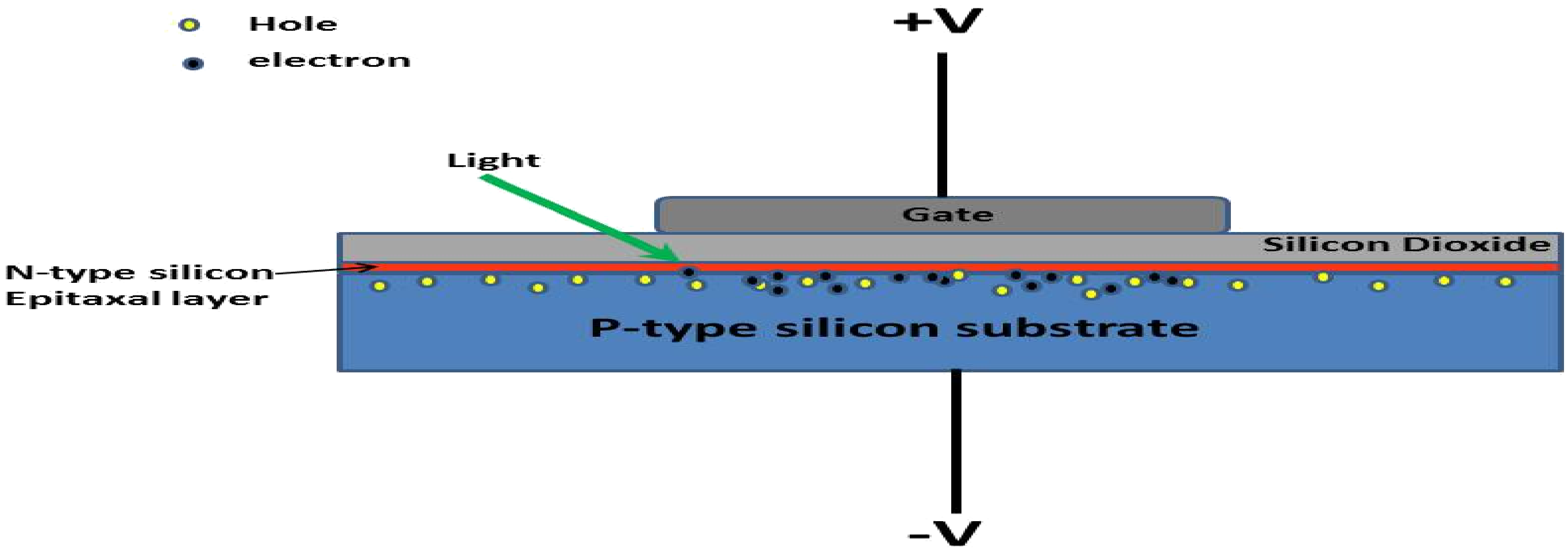


FIGURE 2.15 An example of the digital image acquisition process. (a) Energy ("illumination") source. (b) An element of a scene. (c) Imaging system. (d) Projection of the scene onto the image plane. (e) Digitized image.

Charged Coupled Device (CCD)

- A CCD is a device for the movement of electrical charge
  - usually from within the device to an area where the charge can be manipulated
    - often converted into a digital value
  - **CHARGE into digital value**
    - where charge is proportional to light exposure

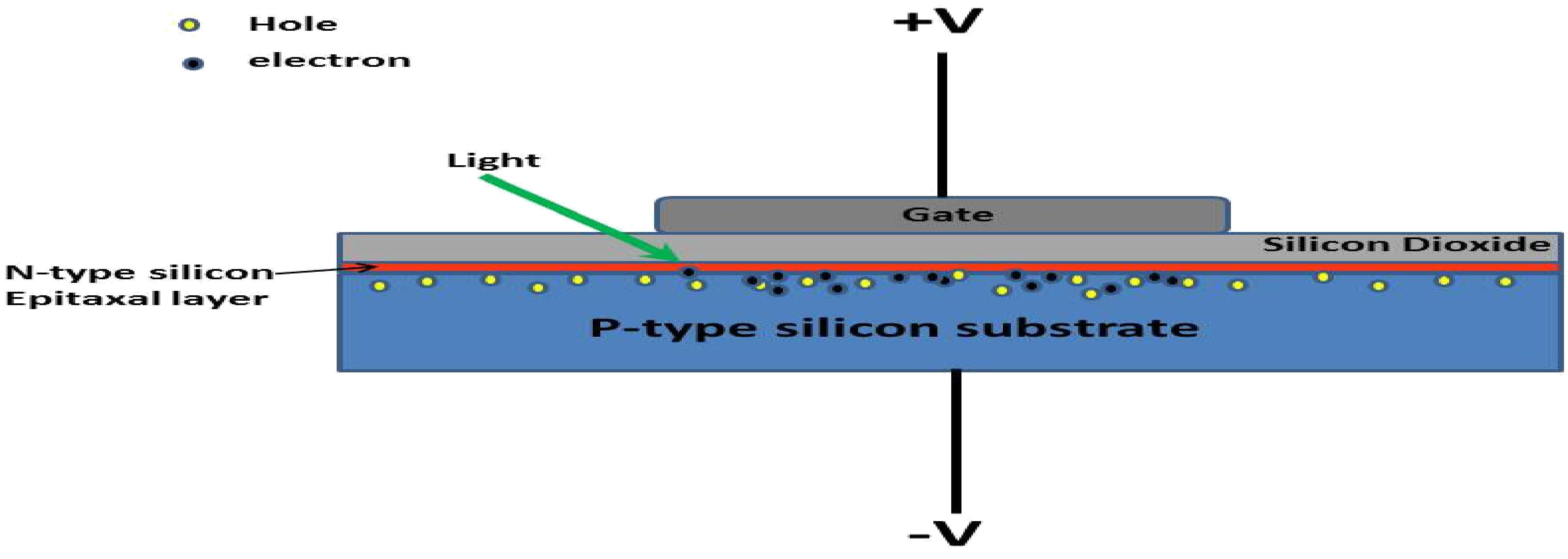
Single Pixel of a CCD Array



- The top gate is held at a positive voltage

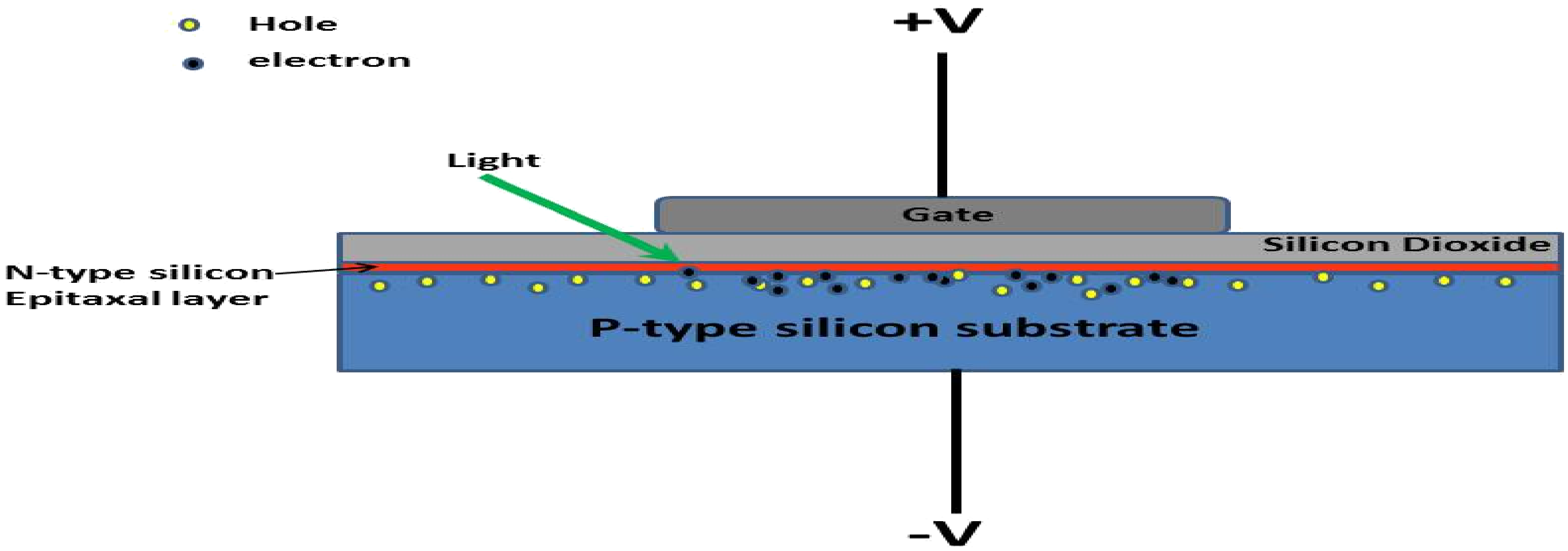
  gate = metal electrode

Single Pixel of a CCD Array



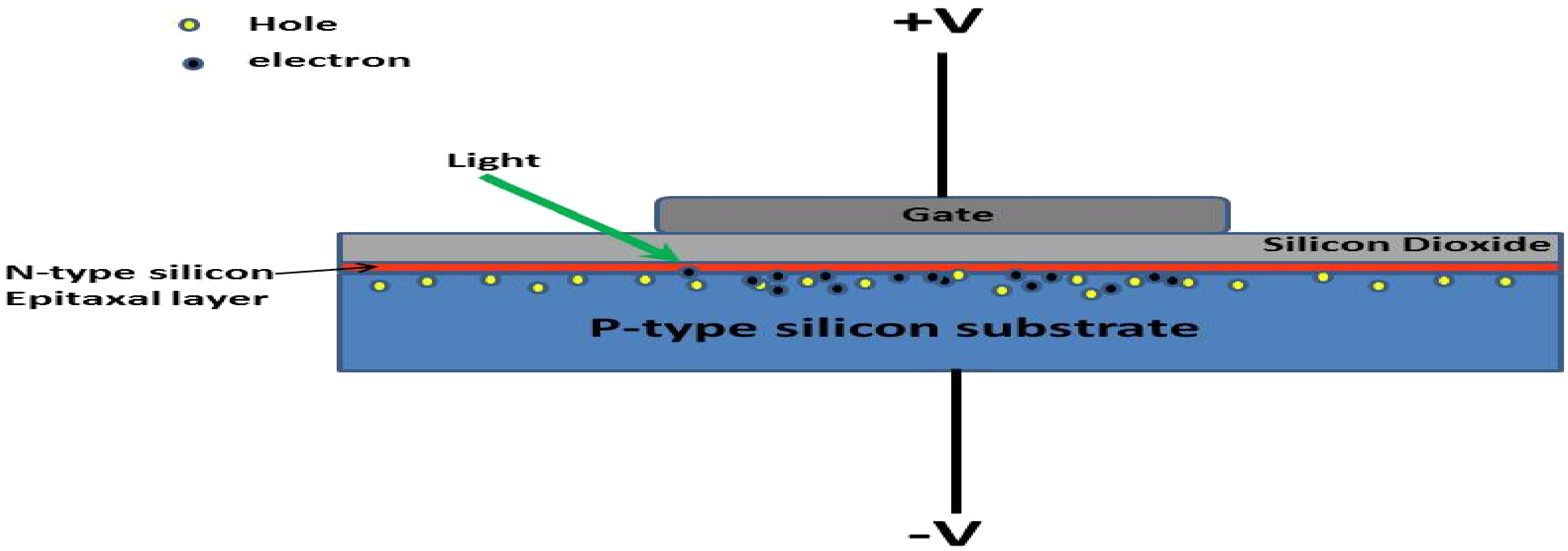
- Below the gate
  Silicon Dioxide = SAND
    - an insulator carrying no electrons
    - keeps electrons away from gate

Single Pixel of a CCD Array



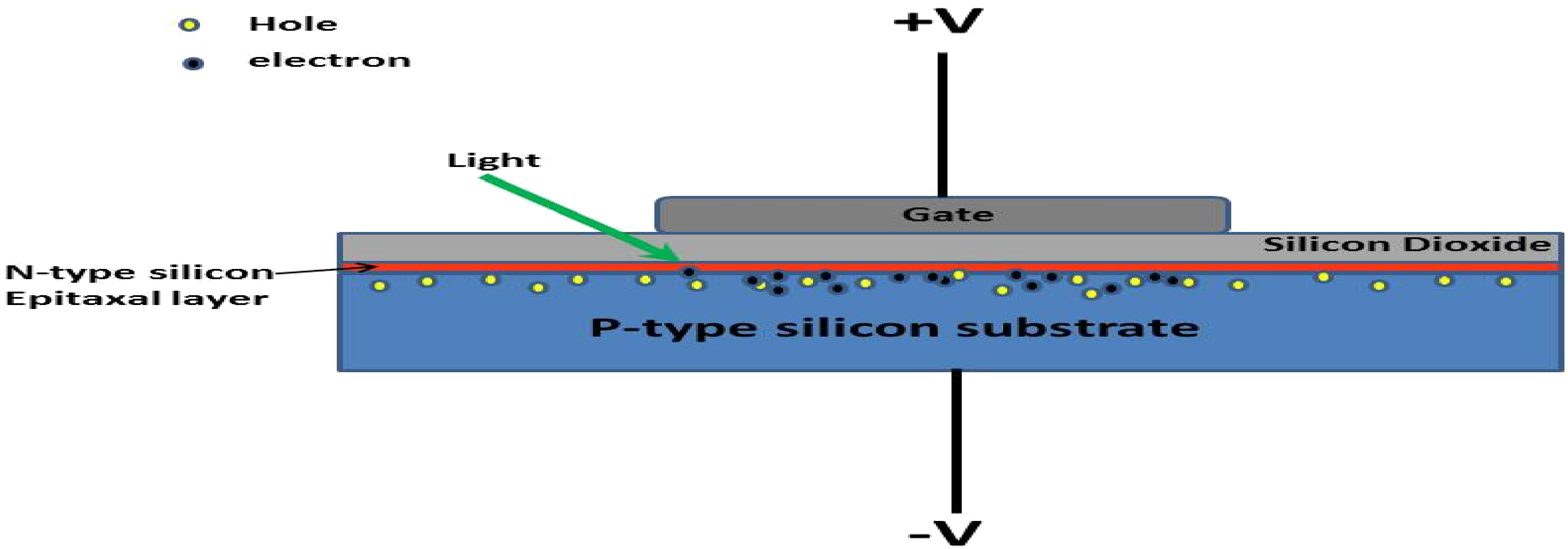
- Below the sand
- N-type silicon Epitaxal layer
  - photosensitive layer
  - light can knock electrons off of it

Single Pixel of a CCD Array



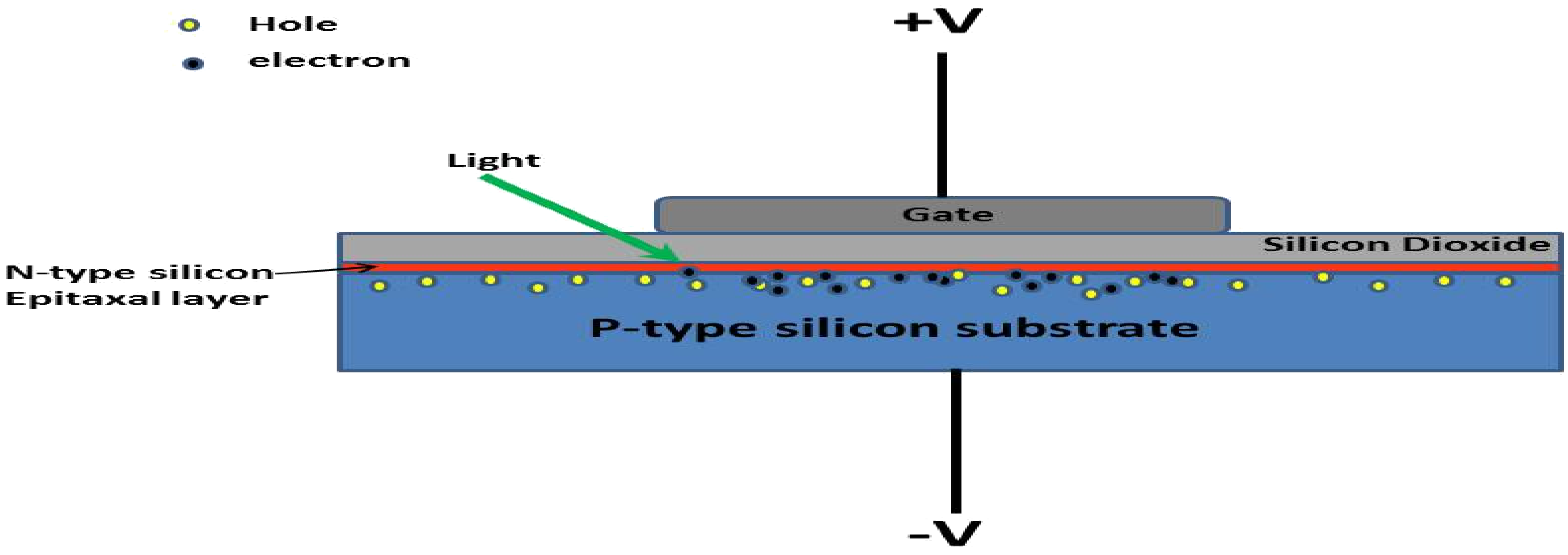
- Below the Epitaxal layer
- P-type silicon layer
  - kept at negative voltage

Single Pixel of a CCD Array



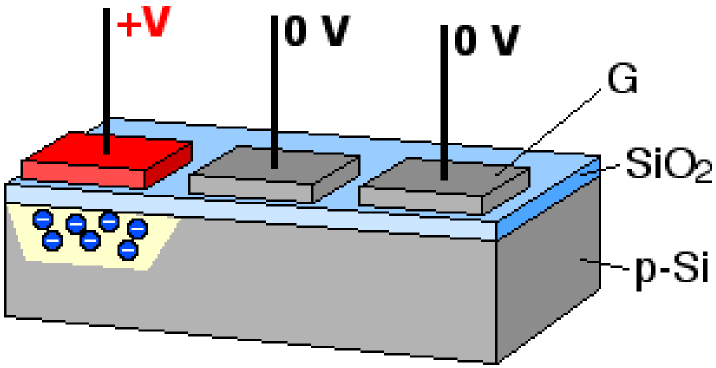
- Light hits the bottom side of this
  - Photoelectrons fill up the holes in the P-Type layer
    - longer exposure means more holes filled up
      - holes are "wells" to collect electrons
        - » maximum number of electrons a well can hold = well capacity

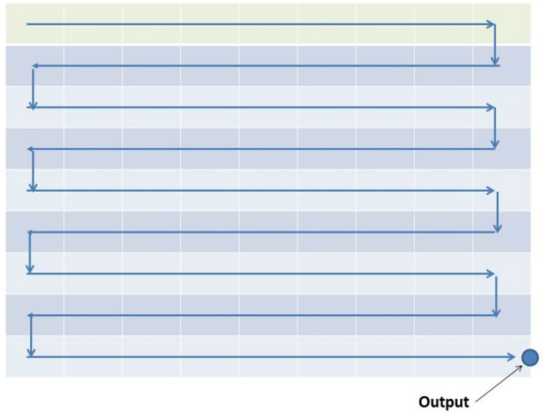
Single Pixel of a CCD Array



- End result
  - Device which stores charge proportional to light exposure
  - Make an array of them

Shift To Get Readout

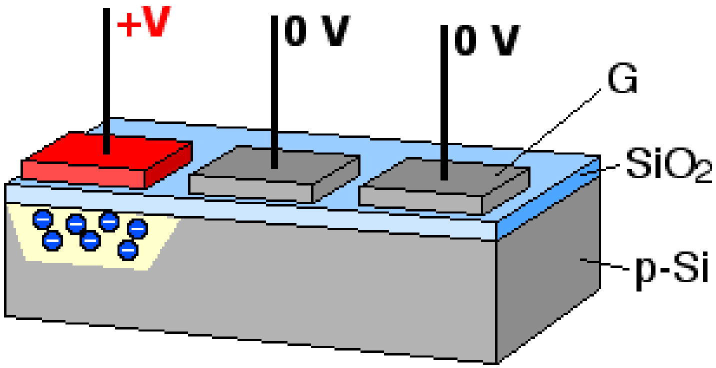


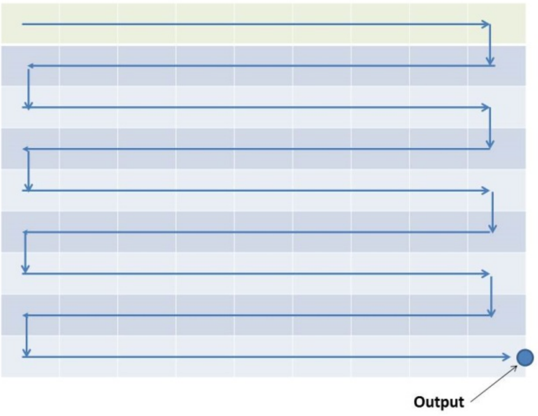


- CCD uses programmed voltages to shift the ***charge*** between pixels
  - Done by taking a pixel's voltage to zero
    - thus transferring it to adjacent pixel held at voltage V
  - Shift continues until it reaches the readout point

Left Image by: Michael Schmid from Wikicommons Creative Commons License,
Right Image: David E. Wolf, http://www.hatiandskoll.com/2013/04/10/more-secrets-of-charge-coupled-devices/

Shift To Get Readout

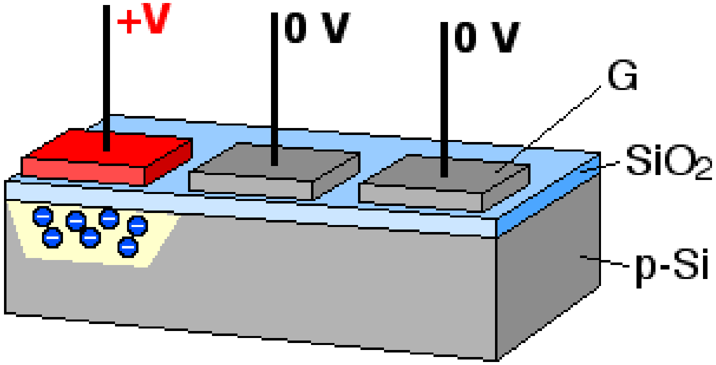




- At output point
  - accumulated charge acts as a voltage
  - Analog to Digital (A/D) converter converts voltage to digital signal
    - **Image is now digitized**

Left Image by: Michael Schmid from Wikicommons Creative Commons License,
Right Image: David E. Wolf, http://www.hatiandskoll.com/2013/04/10/more-secrets-of-charge-coupled-devices/

Sloppy Noise



- As charge moves from pixel to pixel, there is spillage
  - Which is <u>*one*</u> cause of “noise” in the signal
    - Noise can cause “errors” in readout/display

Questions so far

- Questions on
  CCD Hardware Aspects of Image Acquisition?

- Image Acquisition
  - Light and Electromagnetic spectrum
  - Charge-Coupled Device (CCD) imaging
  - Sampling and Quantization
  - Bayer Filter
    - a common color filter array (CFA)

Adding Some Math to The Picture

- Image Formation Model

$$f(x,y) = i(x,y) * r(x,y) + n(x, y)$$

$f(x, y)$	$0 < f(x, y) < \infty$	***Intensity*** which is proportional to the energy radiated by a physical source
$i(x, y)$	$0 < i(x, y) < \infty$	***illumination*** is amount of source illumination incident on the scene being viewed
$r(x, y)$	$0 < r(x, y) < 1$	***reflectance*** is the amount of illumination reflected by objects in the scene
$n(x, y)$		***noise*** is various measurement errors

nature of $i(x, y)$ is determined by the illumination source (light source)

nature of $r(x, y)$ is determined by the object(s) in the scene

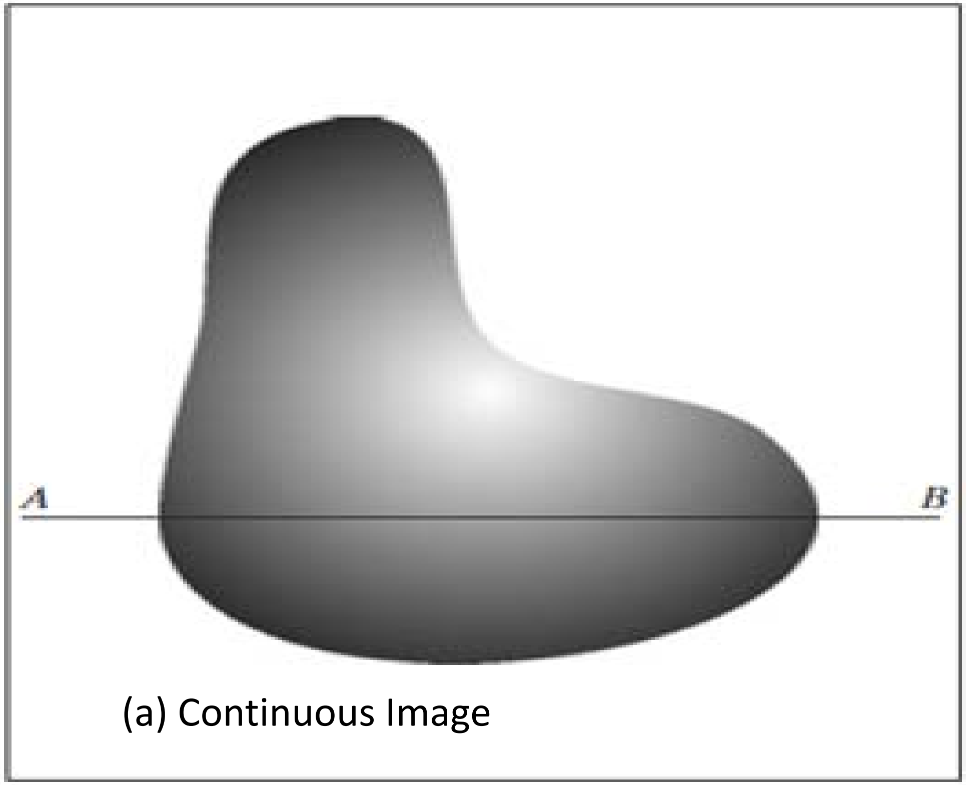
Continuous to Discrete

- f(x, y) in the “real” world is continuous
  - The sensors provide a continuous voltage waveform whose amplitude and spatial behavior are related to the physical phenomenon being sensed
- We must convert the continuous sensed data into digital form
  - The A/D converter helps
  - Lets look at some of the math behind it

Sampling and Quantization

- Sampling
  - Digitizing the coordinate values
    - this can be thought of as our "pixel" resolution
- Quantization
  - Digitizing the amplitude
    - A/D converter does most of this for us

Sampling and Quantization: 1D



(a) Continuous Image

FIGURE 2.16

Generating a digital image

Sampling and Quantization: 1D

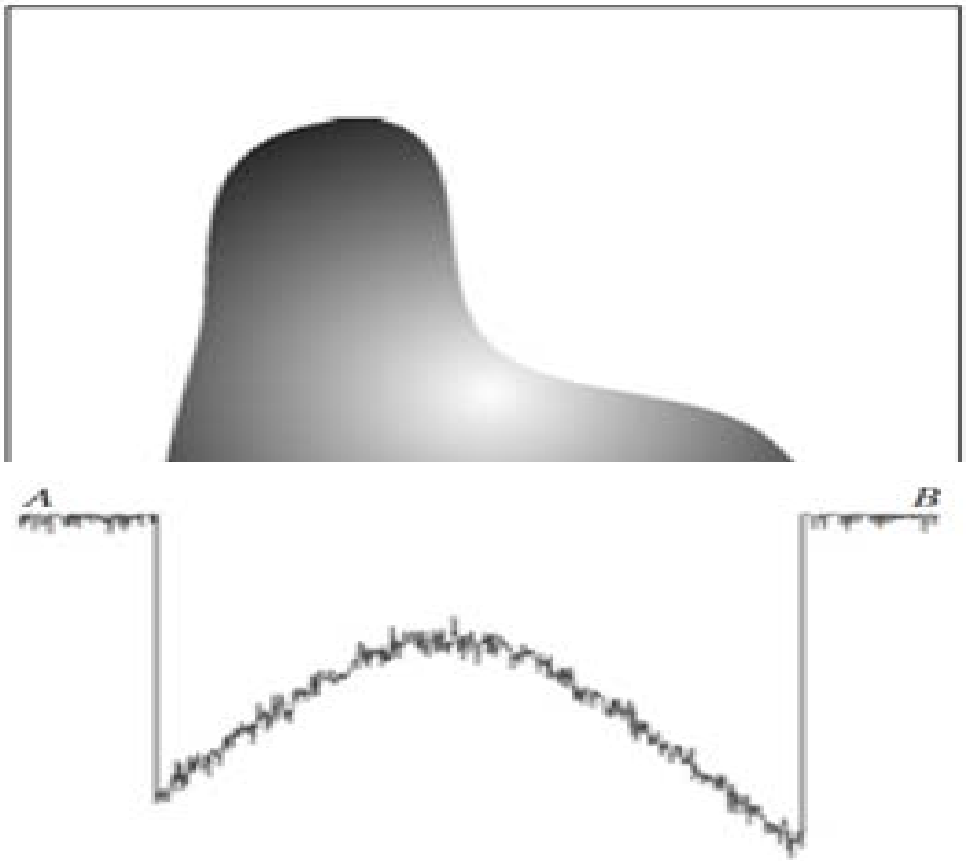


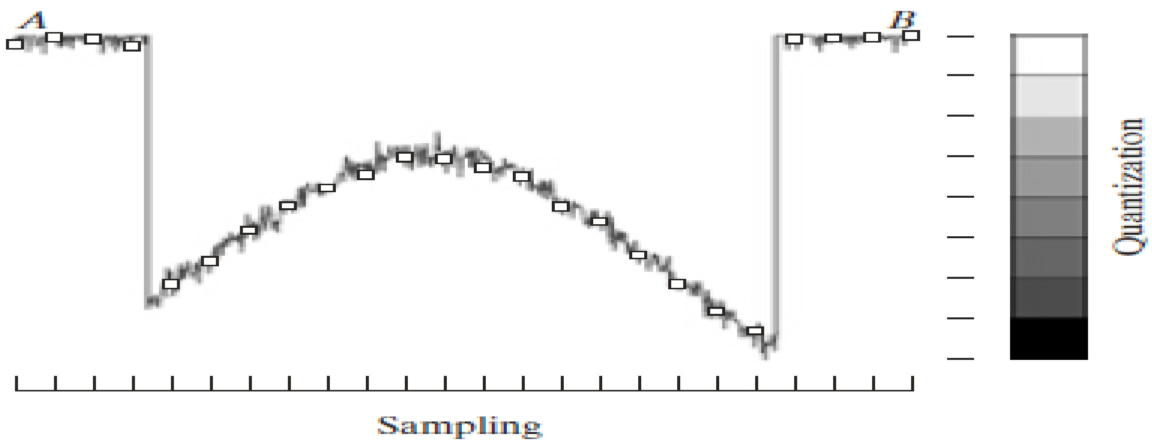
FIGURE 2.16
Generating a digital image

(b) A scan line from A to B
in the continuous image

Sampling and Quantization: 1D

FIGURE 2.16

Generating a digital image

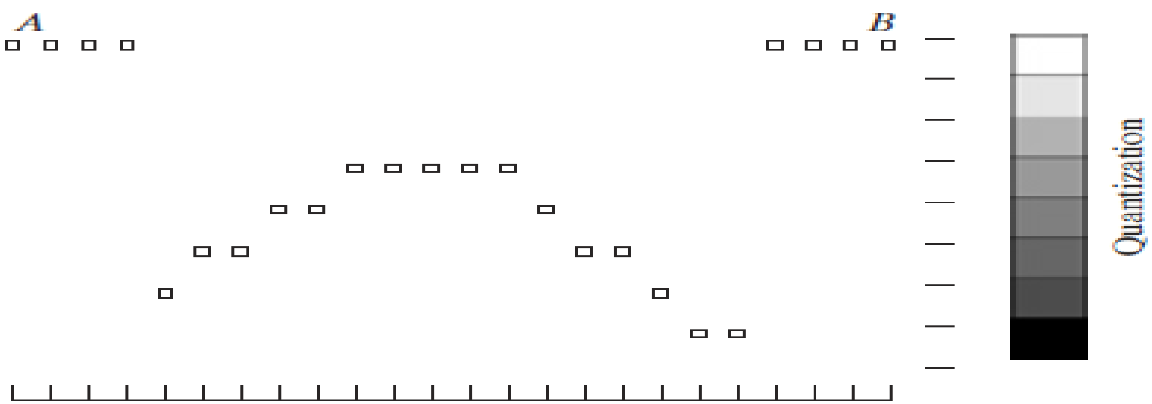


(c) Sampling and Quantization

Sampling and Quantization: 1D

FIGURE 2.16

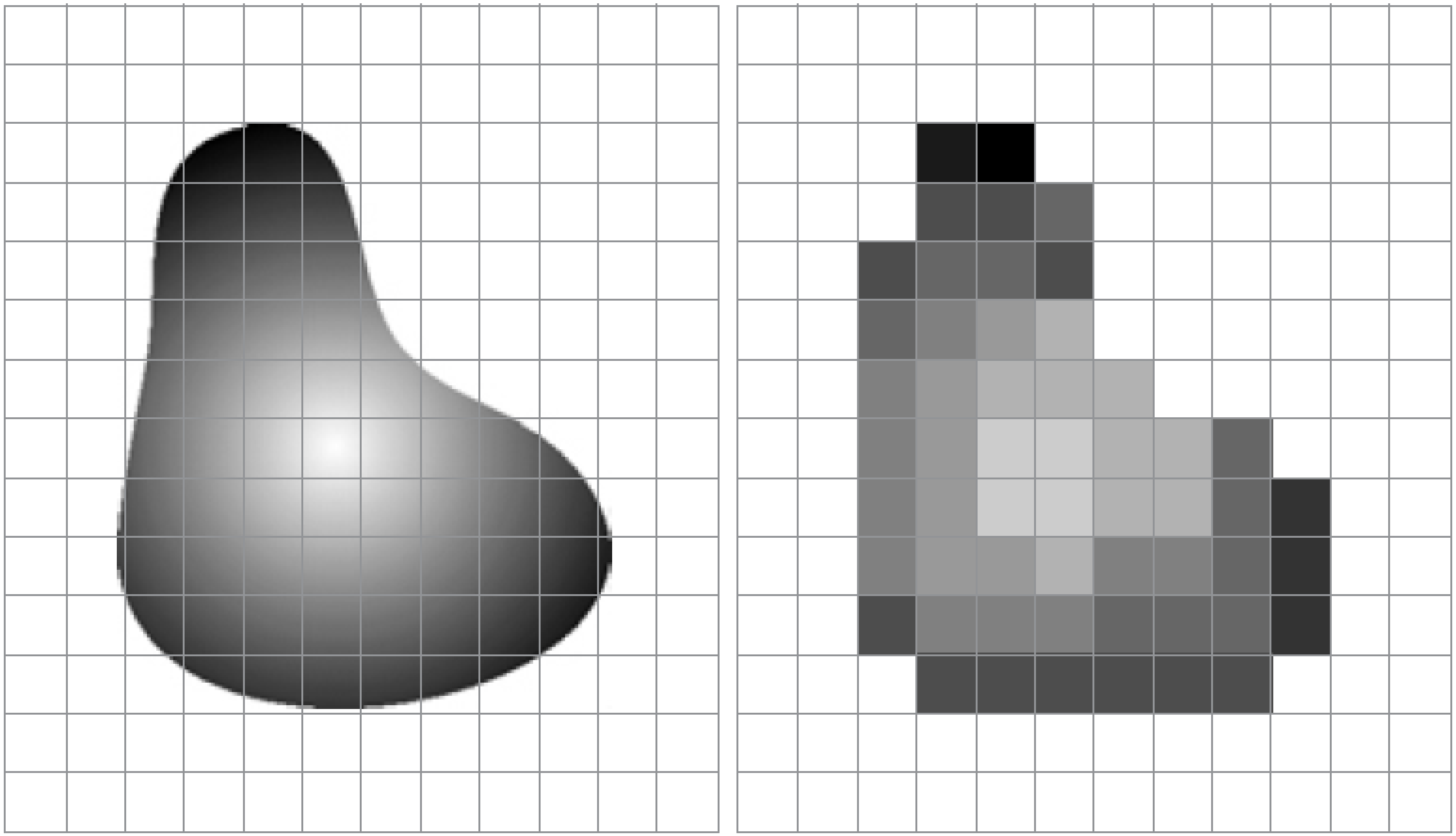
Generating a digital image



(d) Digital Scanline

(c) Sampling and Quantization

Onto 2D: Sampling and Quantization



a b

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

Questions so far

- Questions on Sampling or Quantization?

- Image Acquisition
  - Light and Electromagnetic spectrum
  - Charge-Coupled Device (CCD) imaging
  - Sampling and Quantization
  - Bayer Filter
    - a common color filter array (CFA)

Maxwell: Experiments in Color

- **How does one use black and white sensors to digitize color?**
  - *Experiments of Colour*, James Clerk Maxwell, 1855

- Answer (simplified)
  - **Color Filter Arrays (CFAs)**
    - Overlay the pixels with a set of Red, Green, and Blue filters

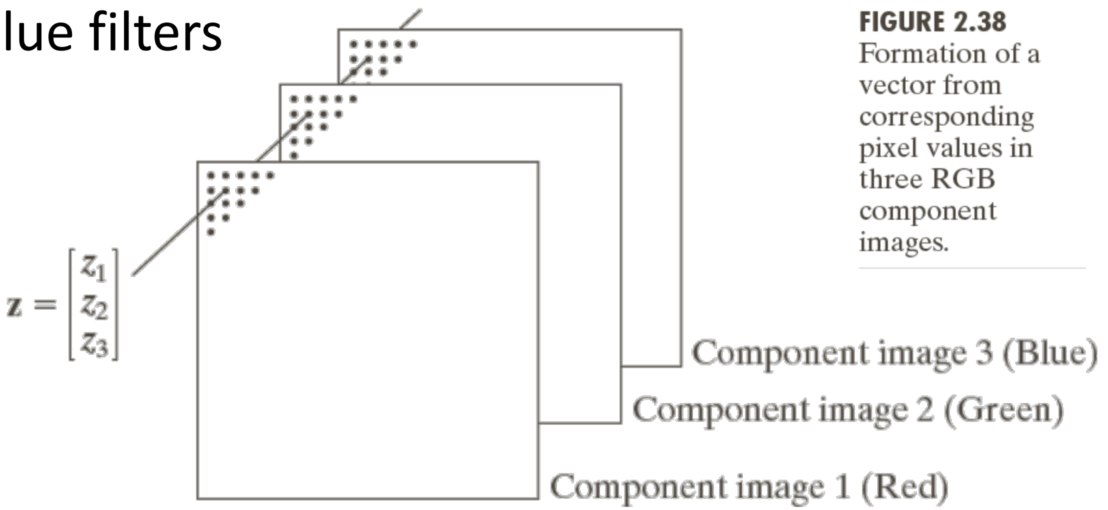
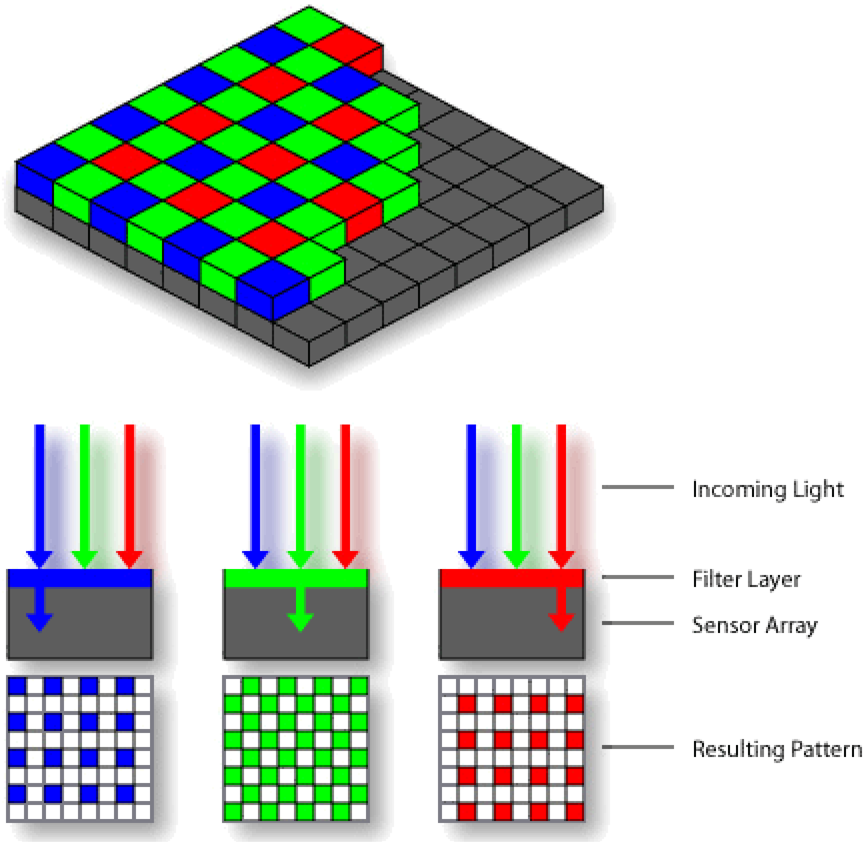


FIGURE 2.38 Formation of a vector from corresponding pixel values in three RGB component images.

Bayer Filter

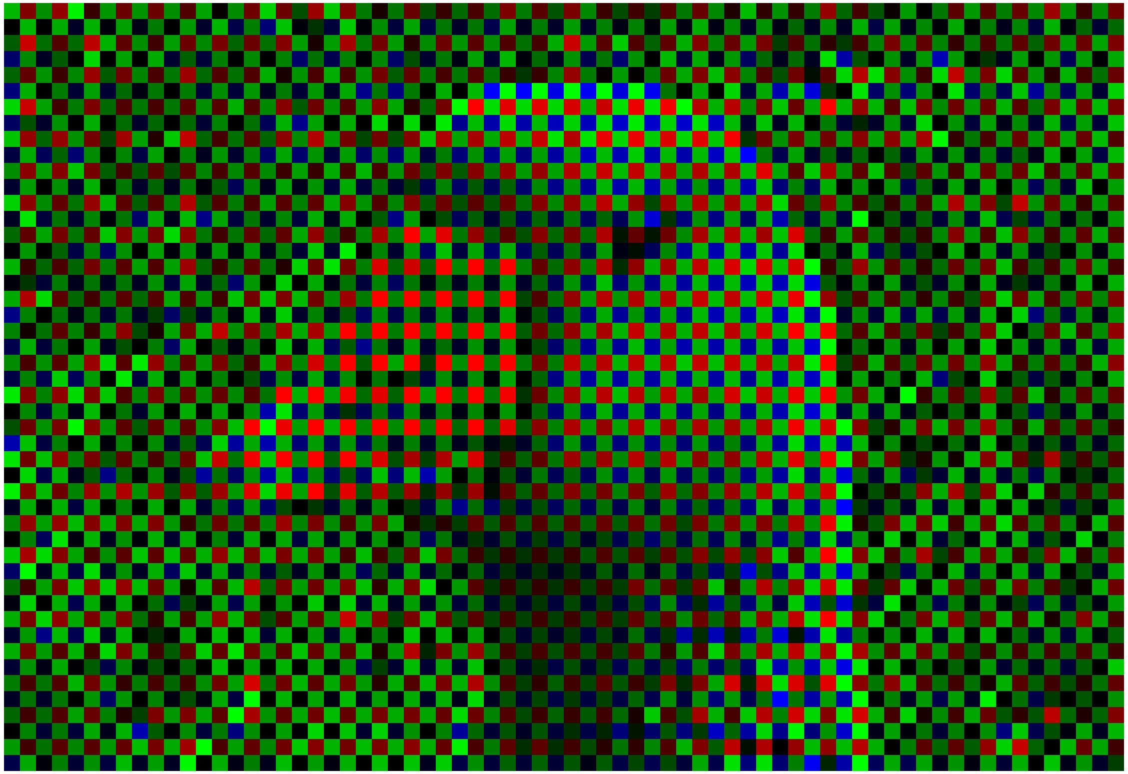


Bayer Filter overlaid on CCD
Public domain image from WikiCommons

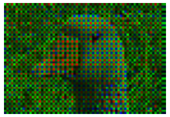
- Ordering of filter overlays on pixels is important

- Bayer Filter
  - Is one CFA option
  - Note that green has twice as many pixels
    - Why?

Zoomed in Result

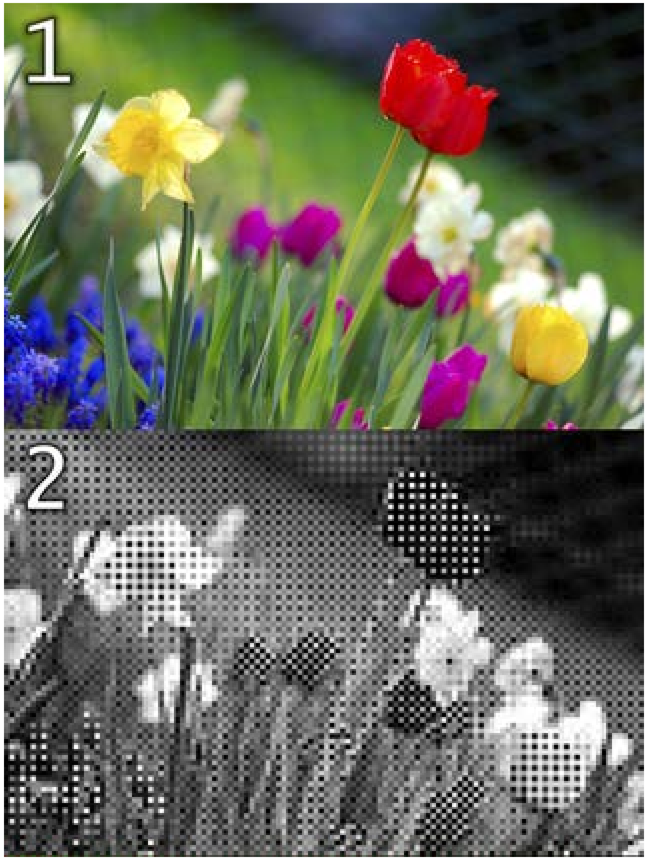


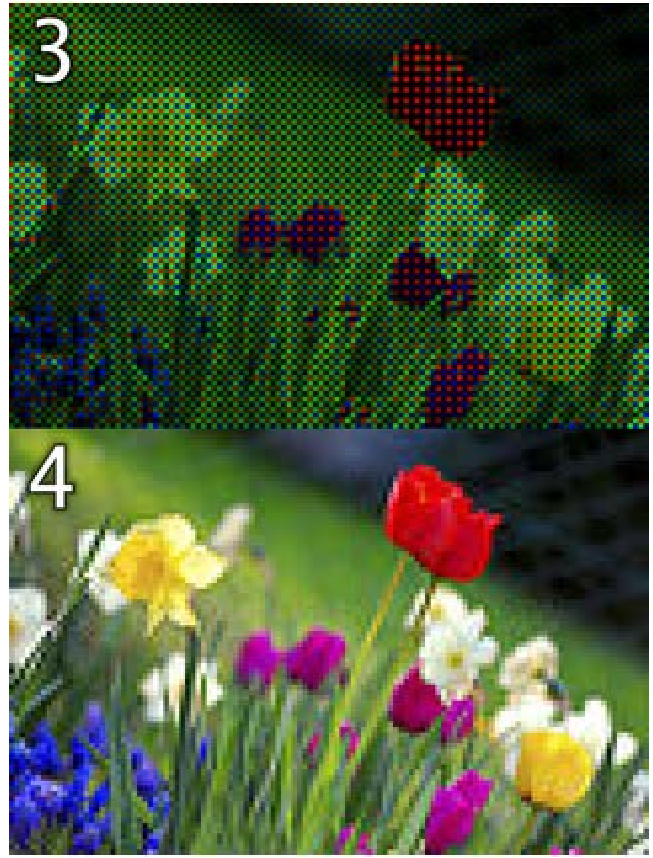
Public Domain image from WikiCommons



- Example Image acquired with a CCD chip using Bayer Filter
  - Mosaic Effect leaves something to be desired/fixed

Mosaic Effect



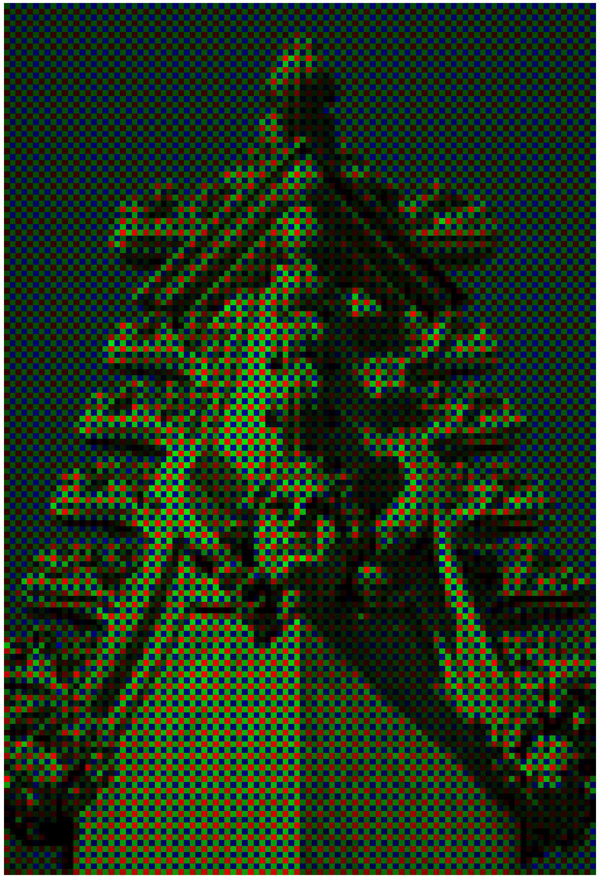


1. Original scene
2. Output of a
   120-pixel by 80-pixel
   sensor with Bayer Filter

3. Output color-coded with Bayer Filter colors
4. Reconstructed Image after interpolating missing
   color information

Another Example

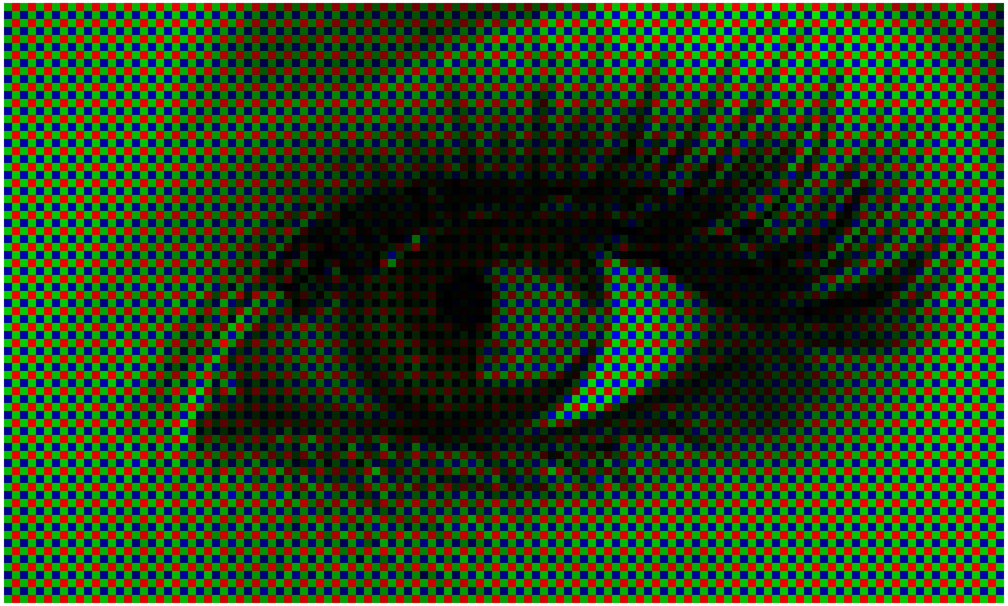
Original Scene



What the Camera Sees

Images from: http://www.cambridgeincolour.com/tutorials/camera-sensors.htm

Even More Examples



- Bayer Image (400%)

Image from: http://www.red.com/learn/red-101/bayer-sensor-strategy

Even More Examples

- Full Color Image (400%)

Image from: http://www.red.com/learn/red-101/bayer-sensor-strategy

Even More Examples

- Full Color Image (100%)

Image from: http://www.red.com/learn/red-101/bayer-sensor-strategy

Mosaic Removal: CFA Interpolation

- Bayer de-mosaicking is the process of translating a CFA (Bayer array) of primary colors into a final image that contains full color information
    - Interpolation methods
      will be discussed in a later lecture
    - The interested may check out various papers online

Paper 1: http://research.microsoft.com/en-us/um/people/lhe/papers/icassp04.demosaicing.pdf

Presentation 1: https://courses.cs.washington.edu/courses/cse467/08au/pdfs/lectures/09-Demosaicing.pdf

Paper 2: http://www.ece.ncsu.edu/imaging/Publications/2002/demosaicking-JEI-02.pdf

Paper 3: http://graphics.cs.williams.edu/papers/BayerJGT09/bayer-jgt09.pdf

Paper 4: https://hal.inria.fr/hal-00683233/PDF/AEIP_SOUMIS.pdf

Paper 5: http://research.microsoft.com/pubs/102068/Demosaicing_ICASSP04.pdf

Questions so far

- Questions on Bayer Filters?
  - Image Acquisition
    - Light and Electromagnetic spectrum
    - Charge-Coupled Device (CCD) imaging
    - Sampling and Quantization
    - Bayer Filter
      - a common color filter array (CFA)

Grayscale (and Color) Imaging

- Image acquisition
  - Light and Electromagnetic spectrum
  - Charge-Coupled Device (CCD) imaging
  - Bayer Filter
    - a common color filter array (CFA)
  - Sampling and Quantization

- **Image representation**
  - Spatial resolution
  - Bit-depth resolution
  - Local neighborhood

Images as Matrices

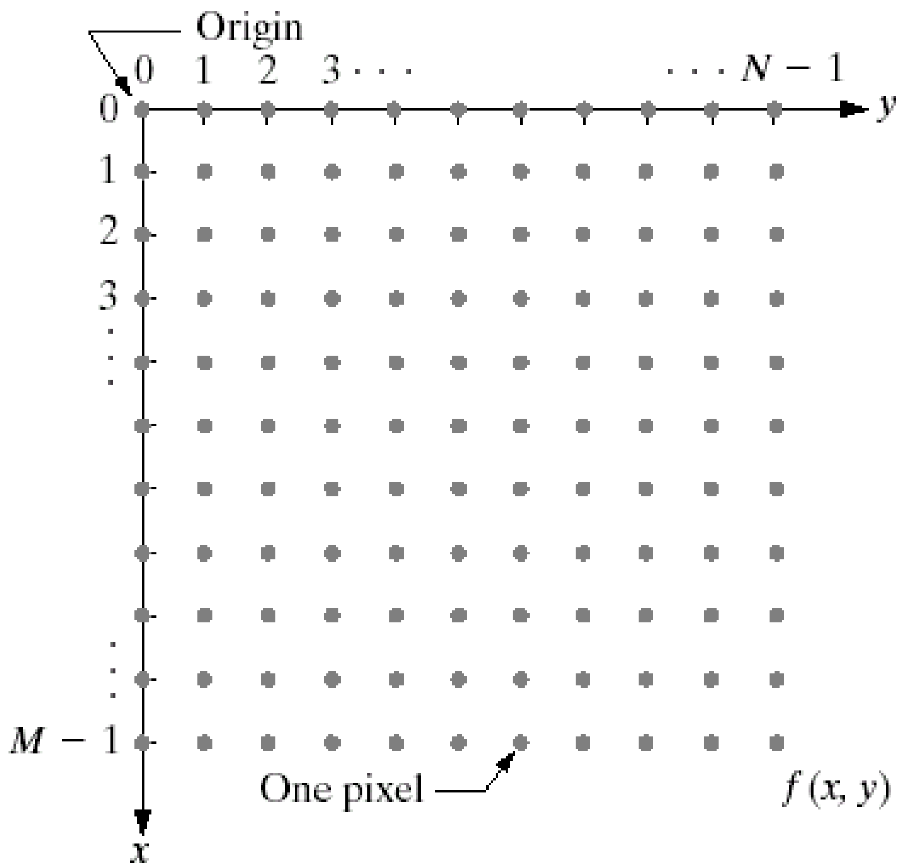


FIGURE 2.18 Coordinate convention used in this book to represent digital images.

Resolution in

Spatial (x, y) coordinates

and

Bit-Depth (pixel values)

Spatial Resolution: Subsampling

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.

Reducing image size by cutting out every other row/column
… appears mostly ok, w.r.t. appearance
… BUT what if we “zoom in” or keep image size “big”

Spatial Resolution: Resampling

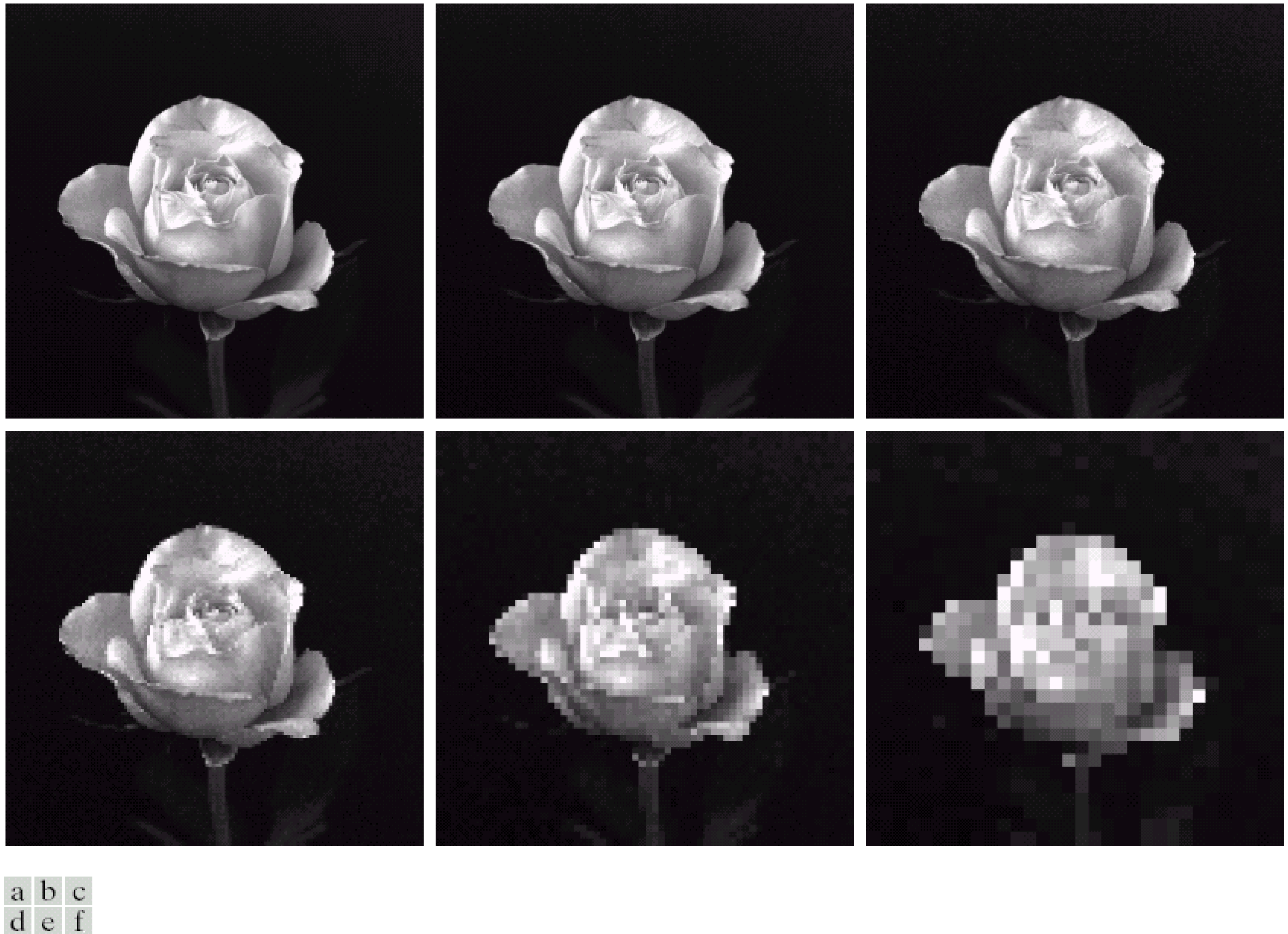


FIGURE 2.20 (a) 1024 × 1024, 8-bit image. (b) 512 × 512 image resampled into 1024 × 1024 pixels by row and column duplication. (c) through (f) 256 × 256, 128 × 128, 64 × 64, and 32 × 32 images resampled into 1024 × 1024 pixels.

Instead of discarding rows and columns (reducing image size) – Resample to 1024x1024
i.e. Duplicate rows and columns with what previously was "kept" (keep image size)

Bit-Depth Resolution

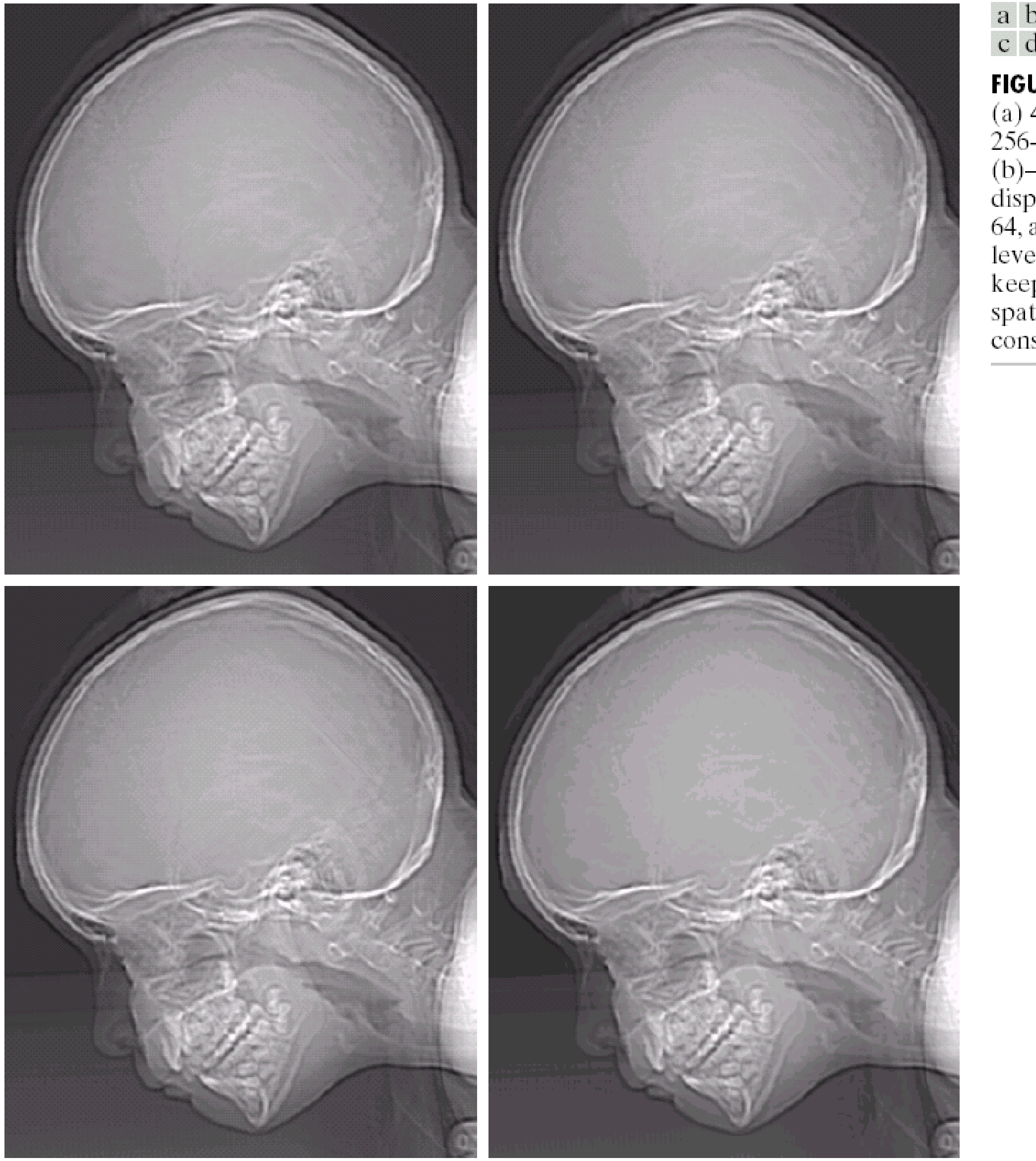
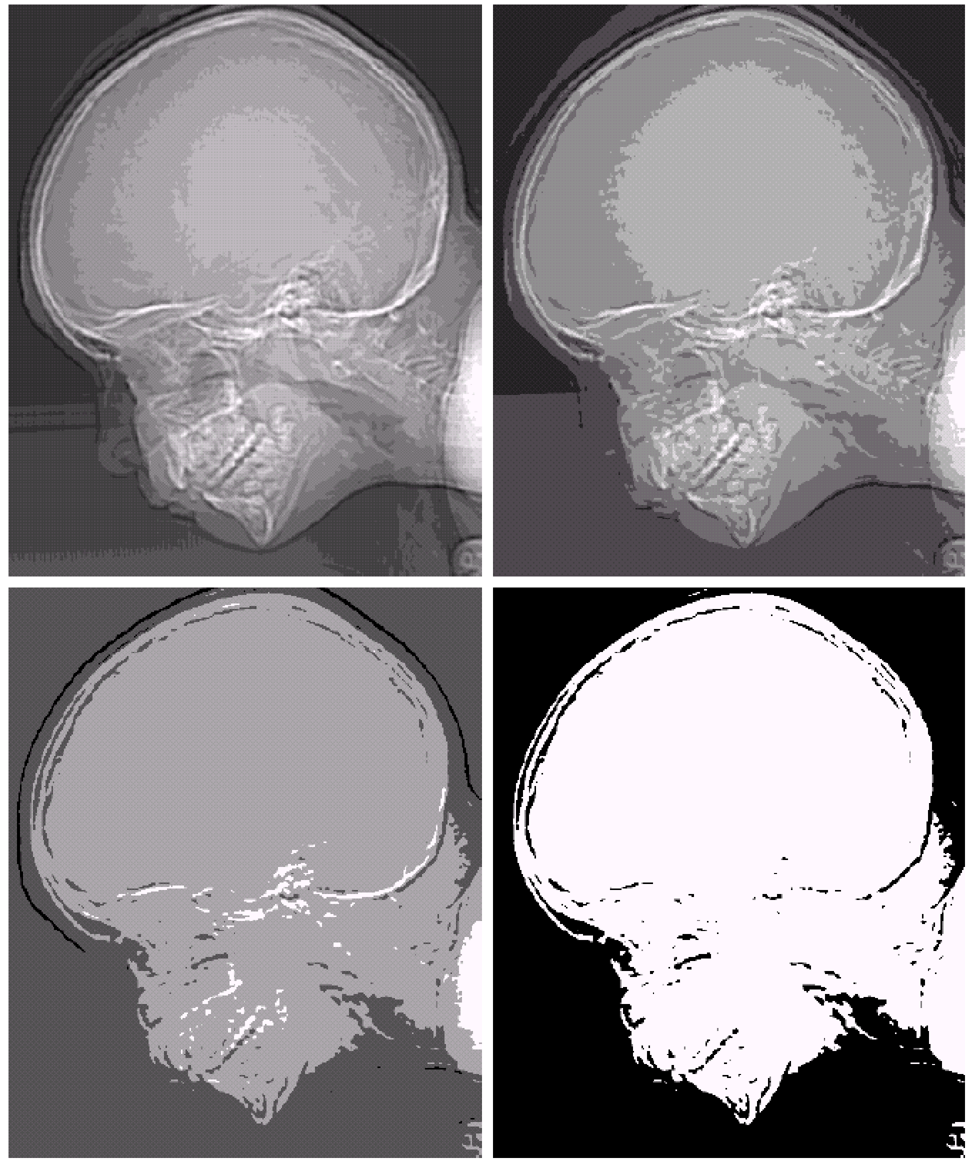


FIGURE 2.21
(a) 452 × 374, 256-level image. (b)–(d) Image displayed in 128, 64, and 32 gray levels, while keeping the spatial resolution constant.

Bit Depth Resolution (fewer bits)

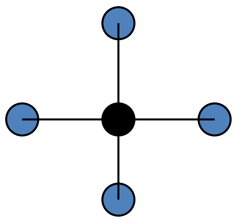
e f
g h

FIGURE 2.21 *(Continued)* (e)–(h) Image displayed in 16, 8, 4, and 2 gray levels. (Original courtesy of Dr. David R. Pickens, Department of Radiology & Radiological Sciences, Vanderbilt University Medical Center.)

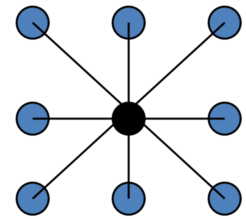


Neighborhoods

Neighbors of a pixel $p=(i,j)$



$N_4(p)=\{(i-1,j),(i+1,j),(i,j-1),(i,j+1)\}$



$N_8(p)=\{(i-1,j),(i+1,j),(i,j-1),(i,j+1),$
$(i-1,j-1),(i-1,j+1),(i+1,j-1),(i+1,j+1)\}$

Adjacency

4-adjacency: p,q are 4-adjacent if p is in the set $N_4(q)$

8-adjacency: p,q are 8-adjacent if p is in the set $N_8(q)$

Note that if p is in $N_{4/8}(q)$, then q must be also in $N_{4/8}(p)$

Distance Definitions

Euclidean distance
(2-norm)

$2\sqrt{2}$	$\sqrt{5}$	2	$\sqrt{5}$	$2\sqrt{2}$
$\sqrt{5}$	$\sqrt{2}$	1	$\sqrt{2}$	$\sqrt{5}$
2	1	0	1	2
$\sqrt{5}$	$\sqrt{2}$	1	$\sqrt{2}$	$\sqrt{5}$
$2\sqrt{2}$	$\sqrt{5}$	2	$\sqrt{5}$	$2\sqrt{2}$

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

D_4 distance
(city-block distance)

4	3	2	3	4
3	2	1	2	3
2	1	0	1	2
3	2	1	2	3
4	3	2	3	4

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

D_8 distance
(checkboard distance)

2	2	2	2	2
2	1	1	1	2
2	1	0	1	2
2	1	1	1	2
2	2	2	2	2

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

Summary

- Image acquisition
  - Light and Electromagnetic spectrum
  - Charge-Coupled Device (CCD) imaging
  - Sampling and Quantization
  - Bayer Filter

- Image representation
  - Spatial resolution
  - Bit-depth resolution
  - Local neighborhood

We understand digital images!
How and Why!

Questions?

- Beyond D2L
  - Examples and information can be found online at:
    - *http://docdingle.com/teaching/cs.html*
    - *Continue to more stuff as needed*

Extra Reference Stuff Follows

United States Patent [19]

Bayer

[11] **3,971,065**

[45] **July 20, 1976**

[54] **COLOR IMAGING ARRAY**

[75] Inventor: **Bryce E. Bayer**, Rochester, N.Y.

[73] Assignee: **Eastman Kodak Company,** Rochester, N.Y.

[22] Filed: **Mar. 5, 1975**

[21] Appl. No.: **555,477**

[52] **U.S. Cl.** .... **358/41;** 350/162 SF; 350/317; 358/44

[51] **Int. Cl.**[2] **H04N 9/24**

[58] **Field of Search** .... 358/44, 45, 46, 47, 358/48; 350/317, 162 SF; 315/169 TV

[56] **References Cited**

UNITED STATES PATENTS

2,446,791	8/1948	Schroeder	358/44
2,508,267	5/1950	Kasperowicz	358/44
2,884,483	4/1959	Ehrenhaft et al.	358/44
3,725,572	4/1973	Kurokawa et al.	358/46

Primary Examiner—George H. Libman

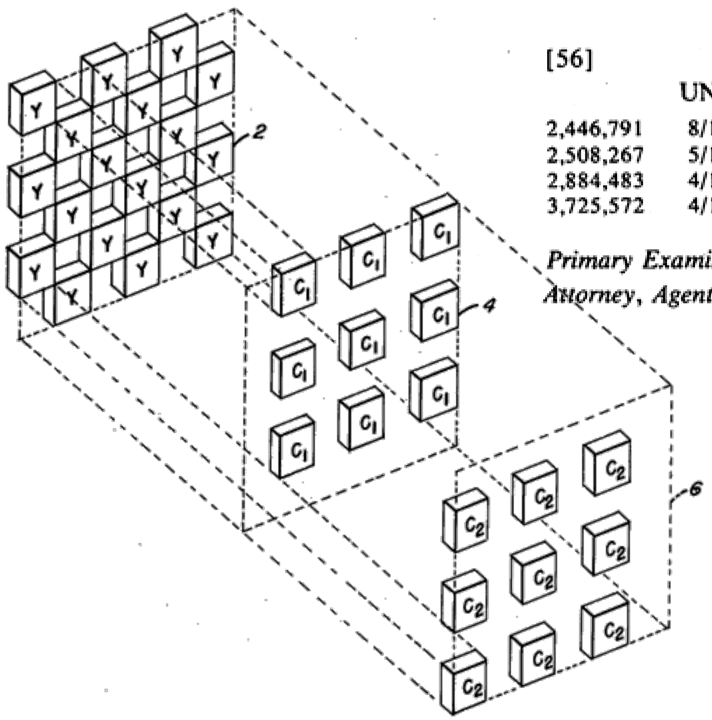
Attorney, Agent, or Firm—George E. Grosser

[57] **ABSTRACT**

A sensing array for color imaging includes individual luminance- and chrominance-sensitive elements that are so intermixed that each type of element (i.e., according to sensitivity characteristics) occurs in a repeated pattern with luminance elements dominating the array. Preferably, luminance elements occur at every other element position to provide a relatively high frequency sampling pattern which is uniform in two perpendicular directions (e.g., horizontal and vertical). The chrominance patterns are interlaid therewith and fill the remaining element positions to provide relatively lower frequencies of sampling.

In a presently preferred implementation, a mosaic of selectively transmissive filters is superposed in registration with a solid state imaging array having a broad range of light sensitivity, the distribution of filter types in the mosaic being in accordance with the above-described patterns.

11 Claims, 10 Drawing Figures



- Bryce Bayer's 1976 patent
  - Front Page
  - Demonstrates his terminology of luminance and chrominance sensitive elements

Credits

- Much of the content derived/based on slides for use with the book:
  - *Digital Image Processing,* Gonzalez and Woods

- Some layout and presentation style derived/based on presentations by
  - Donald House, Texas A&M University, 1999
  - Bernd Girod, Stanford University, 2007
  - Shreekanth Mandayam, Rowan University, 2009
  - Igor Aizenberg, TAMUT, 2013
  - Xin Li, WVU, 2014
  - George Wolberg, City College of New York, 2015
  - Yao Wang and Zhu Liu, NYU-Poly, 2015
  - Sinisa Todorovic, Oregon State, 2015