Image Acquisition and Representation

Some Details
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 = $(x_{\text{max}})$ by $(y_{\text{max}})$
    • 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

The diagram illustrates the concept of pixel values in an image. The function $f(x, y)$ represents the intensity or value of a pixel at coordinates $(x, y)$. The image shows a 3D representation of a pixel value distribution, with the origin marked as the starting point.

The grid on the right side of the diagram represents the pixel values in a 2D space, where each cell corresponds to a pixel. The values are denoted using three symbols: black square for 0, gray square for 0.5, and empty square for 1. The grid values are as follows:

- Dark gray square = 0
- Gray square = 0.5
- Empty square = 1

The pattern shows a sequence of values, with specific arrangements indicating the distribution of pixel values across the image.
How do we get the numbers?

• Three principal sensor arrangements
How do we get the numbers?

• Three principal sensor arrangements
  – Single
  – Line
  – and Array
How do we get the numbers?

• Three principal sensor arrangements
  – Single
  – Line
  – and Array
How do we get the numbers?

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

![Diagram of single sensor with motion](image)

**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 \((\text{pixels})\) in the frame buffer
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

<table>
<thead>
<tr>
<th>Space</th>
<th>Image Values</th>
<th>Classification</th>
</tr>
</thead>
<tbody>
<tr>
<td>continuous</td>
<td>continuous</td>
<td>analog (continuous) image</td>
</tr>
<tr>
<td>continuous</td>
<td>discrete</td>
<td>intensity quantization</td>
</tr>
<tr>
<td>discrete</td>
<td>continuous</td>
<td>spatial quantization</td>
</tr>
<tr>
<td>discrete</td>
<td>discrete</td>
<td>digital (discrete) image</td>
</tr>
</tbody>
</table>
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) ∈ [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 = $(x_{\text{max}})$ by $(y_{\text{max}})$,
    » 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
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
• 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
• 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,
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
Sloppy Noise

- As charge moves from pixel to pixel, there is spillage
  - Which is one 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

\[ f(x,y) = i(x,y) \times r(x,y) + n(x, y) \]

<table>
<thead>
<tr>
<th></th>
<th>(0 &lt; f(x, y) &lt; \infty)</th>
<th>\textit{Intensity} which is proportional to the energy radiated by a physical source</th>
</tr>
</thead>
<tbody>
<tr>
<td>(i(x, y))</td>
<td>(0 &lt; i(x, y) &lt; \infty)</td>
<td>\textit{illumination} is amount of source illumination incident on the scene being viewed</td>
</tr>
<tr>
<td>(r(x, y))</td>
<td>(0 &lt; r(x, y) &lt; 1)</td>
<td>\textit{reflectance} is the amount of illumination reflected by objects in the scene</td>
</tr>
<tr>
<td>(n(x, y))</td>
<td></td>
<td>\textit{noise} is various measurement errors</td>
</tr>
</tbody>
</table>

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
  – Let's 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
Sampling and Quantization: 1D

(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

**Figure 2.17** (a) Continuous 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

![Diagram of Color Filter Arrays](image-url)
Bayer Filter

- Ordering of filter overlays on pixels is important

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

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%)
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

Presentation 1: https://courses.cs.washington.edu/courses/cse467/08au/pdfs/lectures/09-Demosaicing.pdf
Paper 4: https://hal.inria.fr/hal-00683233/PDF/AEIP_SOUMIS.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
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  – Sampling and Quantization

• Image representation
  – Spatial resolution
  – Bit-depth resolution
  – Local neighborhood
Images as Matrices

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”
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) $452 \times 374$, 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)

**FIGURE 2.21**
(Continued)
(c)–(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
\[ (2\text{-norm}) \]

\[
\begin{array}{cccc}
2\sqrt{2} & \sqrt{5} & 2 & \sqrt{5} \\
\sqrt{5} & \sqrt{2} & 1 & \sqrt{2} \\
2 & 1 & 0 & 1 \\
\sqrt{5} & \sqrt{2} & 1 & \sqrt{2} \\
2\sqrt{2} & \sqrt{5} & 2 & \sqrt{5} \\
\end{array}
\]

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

### \(D_4\) distance
\( (\text{city-block distance}) \)

\[
\begin{array}{cccccc}
4 & 3 & 2 & 3 & 4 \\
3 & 2 & 1 & 2 & 3 \\
2 & 1 & 0 & 1 & 2 \\
3 & 2 & 1 & 2 & 3 \\
4 & 3 & 2 & 3 & 4 \\
\end{array}
\]

\[ D_4(p, q) = |(x-s)| + |(y-t)| \]

### \(D_8\) distance
\( (\text{checkboard distance}) \)

\[
\begin{array}{cccccc}
2 & 2 & 2 & 2 & 2 \\
2 & 1 & 1 & 1 & 2 \\
2 & 1 & 0 & 1 & 2 \\
2 & 1 & 1 & 1 & 2 \\
2 & 2 & 2 & 2 & 2 \\
\end{array}
\]

\[ D_8(p, q) = \max(|(x-s)|, |(y-t)|) \]
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
• 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