BBM 413
Fundamentals of Image Processing
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Erkut Erdem
Dept. of Computer Engineering
Hacettepe University

Image Formation and the Digital Camera

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What is an image?

- A photographic print
- A photographic negative?
- This projection screen
- Some numbers in RAM?
An image is:

• A 2D distribution of intensity or color
• A function defined on a two-dimensional plane

\[ I : \mathbb{R}^2 \rightarrow \ldots \]

• Note: no mention of pixels yet
• To process images, must:
  – obtain images—capture the scenes via hardware
  – represent images—encode them numerically
Image Formation

Three Dimensional World

Two Dimensional Image Space

• What is measured in an image location?
  – brightness
  – color

Figures: Francis Crick, The Astonishing Hypothesis,
Image Formation

Why is there no image on a white piece of paper?
- It receives light from all directions

From Photography, London et al.
Pinhole

From Pinhole Photography, London et al.
Pinhole
Pinhole Size?

Photograph made with small pinhole

Small pinhole—sharp but hard to collect enough light

Photograph made with larger pinhole

Larger pinhole—Blur

From Photography, London et al.
Pinhole Size

small hole => sharp, but don’t collect enough light (noise)
Solution: refraction!

From Photography, London et al.
Lenses

- gather more light!
- But need to be focused

Photograph made with small pinhole

To make this picture, the lens of a camera was replaced with a thin metal disk pierced by a tiny pinhole, equivalent in size to an aperture of f/182. Only a few rays of light from each point on the subject got through the tiny opening, producing a soft but acceptably clear photograph. Because of the small size of the pinhole, the exposure had to be 6 sec long.

Photograph made with lens

This time, using a simple convex lens with an f/16 aperture, the scene appeared sharper than the one taken with the smaller pinhole, and the exposure time was much shorter, only 1/100 sec.

The lens opening was much bigger than the pinhole, letting in far more light, but it focused the rays from each point on the subject precisely so that they were sharp on the film.

From Photography, London et al.
A lens is focused at a single depth

Object at focus depth

lens

sensor plane

All rays emerge from a single object point => The captured image is sharp
A lens is focused at a single depth

Object away from focus depth

Rays emerge from multiple object points => the captured image is blurred

sensor plane
A lens is focused at a single depth
Aperture

• Diameter of the lens opening (controlled by diaphragm)
• Expressed as a fraction of focal length, in f-number
  – f/2.0 on a 50mm means that the aperture is 25mm
  – f/2.0 on a 100mm means that the aperture is 50mm
• Disconcerting: small f number = big aperture
• What happens to the area of the aperture when going from f/2.0 to f/4.0?
• Typical f numbers are f/2.0, f/2.8, f/4, f/5.6, f/8, f/11, f/16, f/22, f/32
  – See the pattern?
Main effect of aperture

- Depth of field

From Photography, London et al.
Image of object in focus - sharp (all rays hitting a single sensor point emerge from a single point on the object)
Depth of field

Image of object in focus- sharp (all rays hitting a single sensor point emerge from a single point on the object)

Image of an object away from focus depth- blurred (rays hitting a single sensor point emerge from multiple points on the object)
Depth of field

- We allow for some tolerance

Max acceptable circle of confusion
Depth of Field
Depth of Field

Shallow Depth of Field

Large Depth of Field
Exposure

• Get the right amount of light to sensor/film

• Two main parameters:
  – Shutter speed
  – Aperture (area of lens)
Shutter speed

• Controls how long the film/sensor is exposed
• Pretty much linear effect on exposure
• Usually in fraction of a second:
  – 1/30, 1/60, 1/125, 1/250, 1/500
  – Get the pattern?
• On a normal lens, normal humans can hand-hold down to 1/60
  – In general, the rule of thumb says that the limit is the inverse of focal length, e.g. 1/500 for a 500mm
Shutter speed

- Short exposure - dark
- Medium exposure
- Long exposure - saturation
Shutter speed

Short exposure after contrast adjustment - noise

medium exposure

long exposure - saturation
Main effect of slower shutter speed

• Motion blur – camera shake

Image taken with a tripod

Image taken with a hand held camera
Main effect of slower shutter speed

- Motion blur - scene motion

From Photography, London et al.
Representative display technologies

Computer displays
• Raster CRT display
• LCD display

Printers
• Laser printer
• Inkjet printer
Effect of shutter speed

- Freezing motion

<table>
<thead>
<tr>
<th>Walking people</th>
<th>Running people</th>
<th>Car</th>
<th>Fast train</th>
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<tbody>
<tr>
<td>1/125</td>
<td>1/250</td>
<td>1/500</td>
<td>1/1000</td>
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Cathode ray tube

- First widely used electronic display
  - developed for TV in the 1920s–1930s
Raster CRT display

- Scan pattern fixed in display hardware
- Intensity modulated to produce image
- Originally for TV
  - (continuous analog signal)
- For computer, intensity determined by contents of framebuffer
LCD flat panel or projection display

- Principle: block or transmit light by twisting its polarization
- Intermediate intensity levels possible by partial twist
- Fundamentally raster technology
- Fixed format
Raster display system

- Screen image defined by a 2D array in RAM
  - for CRT, read out and convert to analog in sync with scan
- In most systems today, it’s in a separate memory
- The memory area that maps to the screen is called the *frame buffer*
Color displays

• Operating principle: humans are trichromatic
  – match any color with blend of three
  – therefore, problem reduces to producing 3 images and blending

• Additive color
  – blend images by sum
  – e.g. overlapping projection
  – e.g. unresolved dots
  – R, G, B make good primaries

[Image of color primaries: red, green, blue, yellow, cyan, magenta, white]
Color displays

• CRT: phosphor dot pattern to produce finely interleaved color images

• LCD: interleaved R,G,B pixels
Laser printer

- Xerographic process
- Like a photocopier but with laser-scanned raster as source image
- Key characteristics
  - image is binary
  - resolution is high
  - very small, isolated dots are not possible
Inkjet printer

- Liquid ink sprayed in small drops
  - very small—measured in picoliters
- Head with many jets scans across paper
- Key characteristics:
  - image is binary (drop or no drop; no partial drops)
  - isolated dots are reproduced well
Digital camera

- A raster input device
- Image sensor contains 2D array of photosensors
Digital camera

- Color typically captured using color mosaic
Raster image representation

• All these devices suggest 2D arrays of numbers
• Big advantage: represent arbitrary images
  – approximate arbitrary functions with increasing resolution
  – works because memory is cheap (brute force approach!)
Meaning of a raster image

• Meaning of a given array is a function on 2D

• Define meaning of array = result of output device?
  – that is, piecewise constant for LCD, blurry for CRT
  – but: we don’t have just one output device
  – but: want to define images we can’t display (e.g. too big)

• Abstracting from device, problem is reconstruction
  – image is a sampled representation
  – pixel means “this is the intensity around here”
    • LCD: intensity is constant over square regions
    • CRT: intensity varies smoothly across pixel grid
  – will discuss specifics of reconstruction later
• Discretization
  – in image space - sampling
  – In image brightness - quantization

Image Representation

- **Digital image**: 2D discrete function $f$
- **Pixel**: Smallest element of an image $f(x,y)$
Image Representation

- **Digital image**: 2D discrete function $f$
- **Pixel**: Smallest element of an image $f(x,y)$

Figure: M. J. Black
Datatypes for raster images

• Bitmaps: boolean per pixel (1 bpp): \( I : \mathbb{R}^2 \rightarrow \{0, 1\} \)
  – interp. = black and white; e.g. fax

• Grayscale: integer per pixel: \( I : \mathbb{R}^2 \rightarrow [0, 1] \)
  – interp. = shades of gray; e.g. black-and-white print
  – precision: usually byte (8 bpp); sometimes 10, 12, or 16 bpp

• Color: 3 integers per pixel: \( I : \mathbb{R}^2 \rightarrow [0, 1]^3 \)
  – interp. = full range of displayable color; e.g. color print
  – sometimes 16 (5+6+5) or 30 or 36 or 48 bpp
  – indexed color: a fading idea
Datatypes for raster images

• Floating point: $I : \mathbb{R}^2 \rightarrow \mathbb{R}_+$ or $I : \mathbb{R}^2 \rightarrow \mathbb{R}_+^3$
  – more abstract, because no output device has infinite range
  – provides high dynamic range (HDR)
  – represent real scenes independent of display
  – becoming the standard intermediate format in graphics processors

• Clipping and white point
  – common to compute FP, then convert to integer
  – full range of values may not “fit” in display’s output range
  – simplest solution: choose a maximum value, scale so that value becomes full intensity ($2^n-1$ in an $n$-bit integer image)
Intensity encoding in images

- What do the numbers in images (pixel values) mean?
  - they determine how bright that pixel is
  - bigger numbers are (usually) brighter
Datatypes for raster images

• For color or grayscale, sometimes add *alpha* channel
  – describes transparency of images
Storage requirements for images

• 1024x1024 image (1 megapixel)
  – bitmap: 128KB
  – grayscale 8bpp: 1MB
  – grayscale 16bpp: 2MB
  – color 24bpp: 3MB
  – floating-point HDR color: 12MB
Converting pixel formats

• Color to gray
  – could take one channel (blue, say)
    • leads to odd choices of gray value
  – combination of channels is better
    • but different colors contribute differently to lightness
    • which is lighter, full blue or full green?
    • good choice: gray = 0.2 R + 0.7 G + 0.1 B
    • more on this in color, later on
Converting pixel precision

- Up is easy; down loses information—be careful
Dithering

• When decreasing bpp, we quantize
• Make choices consistently: banding
• Instead, be inconsistent—dither
  – turn on some pixels but not others in gray regions
  – a way of trading spatial for tonal resolution
  – choose pattern based on output device
  – laser, offset: clumped dots required (halftone)
  – inkjet, screen: dispersed dots can be used
Dithering methods

• Ordered dither
  – based on traditional, optically produced halftones
  – produces larger dots

• Diffusion dither
  – takes advantage of devices that can reproduce isolated dots
  – the modern winner for desktop printing
Ordered Dither example

- Produces regular grid of compact dots
Diffusion dither

- Produces scattered dots with the right local density