15-462 Computer Graphics I

Lecture 20

Image Processing

Display Color Models
Filters
Dithering
Image Compression

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http://www.cs.cmu.edu/~fp/courses/graphics/

Displays and Framebuffers

- Image stored in memory as 2D pixel array, called framebuffer
- Value of each pixel controls color
- Video hardware scans the framebuffer at 60Hz
- Depth of framebuffer is information per pixel
  - 1 bit: black and white display (cf. Smithsonian)
  - 8 bit: 256 colors at any given time via colormap
  - 16 bit: 5, 6, 5 bits (R,G,B), 2^{16} = 65,536 colors
  - 24 bit: 8, 8, 8 bits (R,G,B), 2^{24} = 16,777,216 colors

Fewer Bits: Colormaps

- Colormaps typical for 8 bit framebuffer depth
- With screen 1024 * 768 = 786432 = 0.75 MB
- Each pixel value is index into colormap
- Colormap is array of RGB values, 8 bits each
- All 2^{24} colors can be represented
- Only $2^8 = 256$ at a time
- Poor approximation of full color
- Who owns the colormap?
- Colormap hacks: affect image w/o changing framebuffer (only colormap)

More Bits: Graphics Hardware

- 24 bits: RGB
- + 8 bits: A (α-channel for opacity)
- + 16 bits: Z (for hidden-surface removal)
- * 2: double buffering for smooth animation
- = 96 bits
- For 1024 * 768 screen: 9 MB

Image Processing

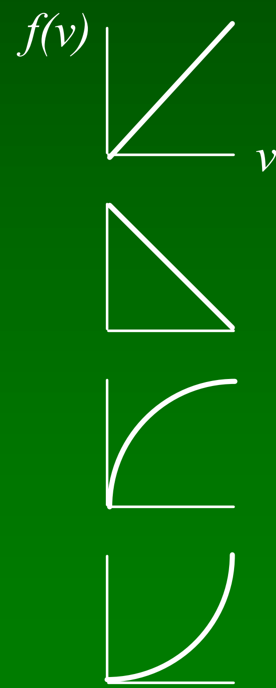
- 2D generalization of signal processing
- Image as a two-dimensional signal
- Point processing: modify pixels independently
- Filtering: modify based on neighborhood
- Compositing: combine several images
- Image compression: space-efficient formats
- Other topics (not in this course)
  - Image enhancement and restoration
  - Special effects (cf. Tuesday's lecture)
  - Computer vision

Outline

- Display Color Models
- Filters
- Dithering
- Image Compression

Point Processing

- Input: a(x,y); Output: b(x,y) = f(a(x,y))
- Useful for contrast adjustment, false colors
- Examples for grayscale, $0 \leq v \leq 1$
  - f(v) = v (identity)
  - f(v) = 1-v (negate image)
  - f(v) = v^p, p < 1 (brighten)
  - f(v) = v^p, p > 1 (darken)
- Gamma correction compensates monitor brightness loss



Gamma Correction Example

$\Gamma = 1.0; f(v) = v$

$\Gamma = 0.5; f(v) = v^{1/0.5} = v^2$

$\Gamma = 2.5; f(v) = v^{1/2.5} = v^{0.4}$

Signals and Filtering

- Audio recording is 1D signal: amplitude(t)
- Image is a 2D signal: color(x,y)
- Signals can be continuous or discrete
- Raster images are discrete
  – In space: sampled in x, y
  – In color: quantized in value
- Filtering: a mapping from signal to signal

Linear and Shift-Invariant Filters

- Linear with respect to input signal
- Shift-invariant with respect to parameter
- Convolution in 1D
  - a(t) is input signal
  - b(s) is output signal
  - h(u) is filter
  - Shorthand: b = a   h (= h   a, as an aside)

$$b(s) = \sum_{t=-\infty}^{+\infty} a(t)h(s-t)$$

- Convolution in 2D

$$b(x,y) = \sum_{u=-\infty}^{+\infty} \sum_{v=-\infty}^{+\infty} a(u,v)h(x-u,y-v)$$

Filters with Finite Support

- Filter h(u,v) is 0 except in given region
- Represent h in form of a matrix
- Example: 3×3 blurring filter

$$
\begin{aligned}
b(x,y) = \frac{1}{9} \; & (a(x-1,y-1) && +a(x,y-1) && +a(x+1,y-1) \\
& +a(x-1,y) && +a(x,y) && +a(x+1,y) \\
& +a(x-1,y+1) && +a(x,y+1) && +a(x+1,y+1))
\end{aligned}
$$

- As function

$$
h(u,v) = \begin{cases} \frac{1}{9} & \text{if } -1 \le u,v \le 1 \\ 0 & \text{otherwise} \end{cases}
$$

- In matrix form

$$
\frac{1}{9} \begin{bmatrix} 1 & 1 & 1 \\ 1 & 1 & 1 \\ 1 & 1 & 1 \end{bmatrix}
$$

Blurring Filters

- Average values of surrounding pixels
- Can be used for anti-aliasing
- Size of blurring filter should be odd
- What do we do at the edges and corners?
- For noise reduction, use median, not average
  - Eliminates intensity spikes
  - Non-linear filter

Examples of Blurring Filter

Original Image | Blur 3x3 mask | Blur 7x7 mask

Example Noise Reduction

Original image

Image with noise

Median filter (5x5?)

Edge Filters

- Discover edges in image
- Characterized by large gradient

$$\nabla a = \left[\frac{\partial a}{\partial x} \;\; \frac{\partial a}{\partial y}\right], \qquad |\nabla a| = \sqrt{\left(\frac{\partial a}{\partial x}\right)^2 + \left(\frac{\partial a}{\partial y}\right)^2}$$

- Approximate square root

$$|\nabla a| \approx |\frac{\partial a}{\partial x}| + |\frac{\partial a}{\partial y}|$$

- Approximate partial derivatives, e.g.

$$\frac{\partial a}{\partial x} \approx a(x+1) - a(x-1)$$

Sobel Filter

- Edge detection filter, with some smoothing
- Approximate

$$\frac{\partial}{\partial x} \approx \begin{bmatrix} -1 & 0 & 1 \\ -2 & 0 & 2 \\ -1 & 0 & 1 \end{bmatrix}, \qquad \frac{\partial}{\partial y} \approx \begin{bmatrix} 1 & 2 & 1 \\ 0 & 0 & 0 \\ -1 & -2 & -1 \end{bmatrix}$$

- Sobel filter is non-linear
  - Square and square root (more exact computation)
  - Absolute value (faster computation)

Sample Filter Computation

- Part of Sobel filter, detects vertical edges

$\frac{1}{4}$

-1	0	1
-2	0	2
-1	0	1

h

0	0	0	0	0	25	25	25	25	25
0	0	0	0	0	25	25	25	25	25
0	0	0	0	0	25	25	25	25	25
0	0	0	0	0	25	25	25	25	25
0	0	0	0	0	25	25	25	25	25
0	0	0	0	0	25	25	25	25	25
0	0	0	0	0	25	25	25	25	25
0	0	0	0	0	25	25	25	25	25
0	0	0	0	0	25	25	25	25	25
0	0	0	0	0	25	25	25	25	25

a

0	0	0	0	25	25	0	0	0	0
0	0	0	0	25	25	0	0	0	0
0	0	0	0	25	25	0	0	0	0
0	0	0	0	25	25	0	0	0	0
0	0	0	0	25	25	0	0	0	0
0	0	0	0	25	25	0	0	0	0
0	0	0	0	25	25	0	0	0	0
0	0	0	0	25	25	0	0	0	0
0	0	0	0	25	25	0	0	0	0
0	0	0	0	25	25	0	0	0	0

b

Example of Edge Filter

Original image

Edge filter, then brightened

Image Compositing

- Use α-channel (RGBA)
- Already discussed in this course
- Used for retouching and special effects
- Other image compositing techniques
  - Morphing
  - See Steve Sullivan's talk

Outline

- Display Color Models
- Filters
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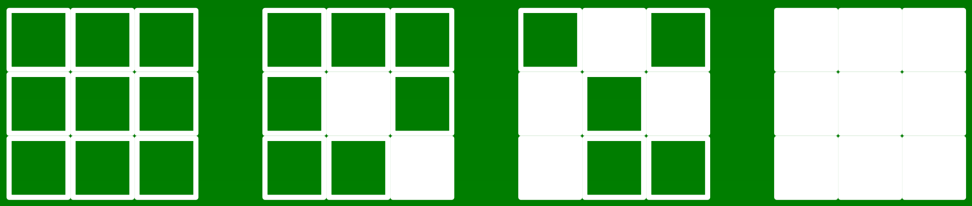
- Image Compression

Dithering

- Compensates for lack of color resolution
- Give up spatial resolution for color resolution
- Eye does spatial averaging
- Black/white dithering to achieve gray scale
  – Each pixel is black or white
  – From far away, color determined by fraction of white
  – For 3x3 block, 10 levels of gray scale



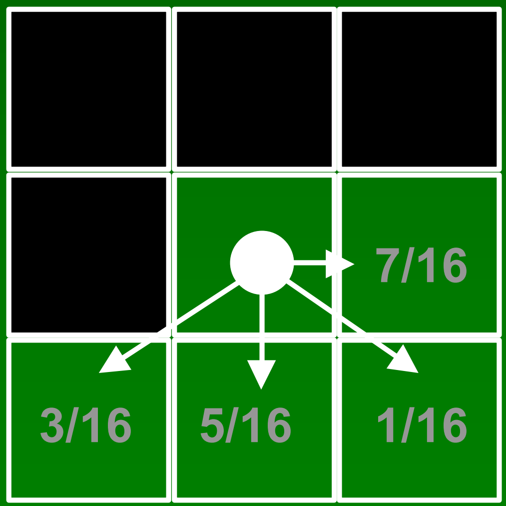
Halftone Screens

- Regular patterns create some artefacts
  - Avoid stripes
  - Avoid isolated pixels (e.g. on laser printer)
  - Monotonicity: keep pixels on at higher intensities
- Example of good 3×3 dithering matrix
  - For intensity n, turn on pixels 0..n–1

$$\begin{bmatrix} 6 & 8 & 4 \\ 1 & 0 & 3 \\ 5 & 2 & 7 \end{bmatrix}$$

Floyd-Steinberg Error Diffusion

- Approximation without fixed resolution loss
- Scan in raster order
- At each pixel, draw least error output value
- Divide error into 4 different fractions
- Add the error fractions into adjacent, unwritten pixels



Floyd-Steinberg Example

Gray Scale Ramp

- Some worms
- Some checkerboards
- Enhance edges

Peter Anderson

Color Dithering

- Example: 8 bit framebuffer
  - Set color map by dividing 8 bits into 3,3,2 for RGB
  - Blue is deemphasized since we see it less well
- Dither RGB separately
  - Works well with Floyd-Steinberg
- Assemble results into 8 bit index into colormap
- Generally looks good

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Image Compression

- Exploit redundancy
  - Coding: some pixel values more common
  - Interpixel: adjacent pixels often similar
  - Psychovisual: some color differences imperceptible
- Distinguish lossy and lossless methods

Some Image File Formats

	Depth	File Size	Comments
JPEG	24	Small	Lossy compression
TIFF	8, 24	Medium	Good general purpose
GIF	1, 4, 8	Medium	Popular, but 8 bit
PPM	24	Big	Easy to read/write
EPS	1,2,4,8,24	Huge	Good for printing

Image Sizes

- 1024*1024 at 24 bits uses 3 MB
- Encyclopedia Britannica at 300 pixels/inch and 1 bit/pixes requires 25 gigabytes (25K pages)
- 90 minute movie at 640x480, 24 bits per pixels, 24 frames per second requires 120 gigabytes
- Applications: HDTV, DVD, satellite image transmission, medial image processing, fax, ...

Exploiting Coding Redundancy

- Not limited to images (text, other digital info)
- Exploit nonuniform probabilities of symbols
- Entropy as measure of information content
  - $H = -\Sigma_i \text{Prob}(s_i) \log_2 (\text{Prob}(s_i))$
  - If source is independent random variable need H bits
- Idea:
  - More frequent symbols get shorter code strings
  - Best with high redundancy (= low entropy)
- Common algorithms
  - Huffman coding
  - LZW coding (gzip)

Huffman Coding

- Codebook is precomputed and static
  - Use probability of each symbol to assign code
  - Map symbol to code
  - Store codebook and code sequence
- Precomputation is expensive
- What is “symbol” for image compression?

Lempel-Ziv-Welch (LZW) Coding

- Compute codebook on the fly
- Fast compression and decompression
- Can tune various parameters
- Both Huffman and LZW are lossless

Exploiting Interpixel Redundancy

- Neighboring pixels are correlated
- Spatial methods for low-noise image
  - Run-length coding:
    - Alternate values and run-length
    - Good if horizontal neighbors are same
    - Can be 1D or 2D (e.g. used in fax standard)
  - Quadtrees:
    - Recursively subdivide until cells are constant color
  - Region encoding:
    - Represent boundary curves of color-constant regions
- Combine methods
- Not good on natural images directly

Improving Noise Tolerance

- Predictive coding:
  - Predict next pixel based on prior ones
  - Output difference to actual
- Fractal image compression
  - Describe image via recursive affine transformation
- Transform coding
  - Exploit frequency domain
  - Example: discrete cosine transform (DCT)
  - Used in JPEG
- Transform coding for lossy compression

Discrete Cosine Transform

- Used for lossy compression (as in JPEG)

$$F(u,v) = c(u)c(v)\sum_{x=0}^{n-1}\sum_{y=0}^{n-1} f(x,y)\cos\frac{(2x+1)u\pi}{2n}\cos\frac{(2y+1)v\pi}{2n}$$

where $c(u) = 1/\sqrt{n}$ if $u = 0$, $c(u) = \sqrt{2/n}$ otherwise

- JPEG (Joint Photographic Expert Group)
  - Subdivide image into n $\times$ n blocks (n = 8)
  - Apply discrete cosine transform for each block
  - Quantize, zig-zag order, run-length code coefficients
  - Use variable length coding (e.g. Huffman)
- Many natural images can be compressed to 4 bits/pixels with little visible error

Summary

- Display Color Models
  - 8 bit (colormap), 24 bit, 96 bit
- Filters
  - Blur, edge detect, sharpen, despeckle
- Dithering
  - Floyd-Steinberg error diffusion
- Image Compression
  - Coding, interpixel, psychovisual redundancy
  - Lossless vs. lossy compression

Preview

- Assignment 6 graded
- Tuesday: Scientific Visualization
- Assignment 7 due Tuesday
- Assignment 8 (written) out Tuesday