Image Formation
Last Time

What is computer vision?

Input: digital images

Output: information about the world
Today

What is a digital image?
How does a camera capture a digital image?
What issues can we expect in digital images?
Today

What is a digital image?

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What is a Digital Image?
What is a Digital Image?

An image is a 2D rectilinear array of pixels

Continuous image

Digital image
What is a Pixel?

Digital image

Pixel

Digital image
What is a Pixel?

Sample of a continuous (color) function at a position

e.g., Color at (x,y)
What is a Color?
What is a Color?

Distribution of energies amongst frequencies in the visible light range

White Light

Orange Light
How Do We Represent Colors Digitally?
How Do We Represent Colors Digitally?

Common color models

• RGB
• CMY
• HLS
• HSV
• XYZ
• Others
How Do We Represent Colors Digitally?

Common color models

- **RGB**
- **CMY**
- **HLS**
- **HSV**
- **XYZ**
- **Others**

Spectral-response functions of each of the three types of cones on the human retina.
How Do We Represent Colors Digitally?

Common color models

- **RGB**
- **CMY**
- **HLS**
- **HSV**
- **XYZ**
- **Others**

Colors are additive
How Do We Represent Digital Images?

E.g., 2D arrays of red, green, and blue intensities
Note for Assignment 0

Color might be useful for skin detection

Image

R:239, G:208, B:207
Outline for Today

What is a digital image?
How does a camera capture a digital image?
What issues can we expect in digital images?
What Is a Photographic Image?

What does each pixel represent?
What Is a Photographic Image?

Conceptually, each pixel is a sample of radiance arriving at a camera viewpoint from a direction.
The plenoptic function $L(x,y,z, \theta, \phi, t, \lambda)$ describes the radiance arriving ...

- at any point $(x,y,z)$,
- in any direction $(\theta, \phi)$,
- at any time $(t)$,
- at any frequency $(\lambda)$
Photographic Image

Conceptually, a photographic image is a slice of the plenoptic function representing radiance arriving ...

- at a particular camera viewpoint,
- in the camera’s field of view,
- at a certain time,
- at RGB frequencies
Photography

Unfortunately, capturing such an image is difficult

- Sensors have limits on size, sensitivity, etc.
Pinhole Camera

Sensors on image plane behind “viewpoint” (pinhole)
Pinhole Camera

“Camera obscura” – idea known since antiquity
Pinhole Camera

Joseph Nicéphore Niépce: first recorded image
Digital Camera

Today: photon sensors are CCD, CMOS, etc.
Pinhole Camera

Problem?
Pinhole Camera

Problem: aperture should be infinitely small
What if aperture (pinhole size) is extremely small?

- diffraction through pinhole $\Rightarrow$ blurry image

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**2.18 DIFFRACTION LIMITS THE QUALITY OF PINHOLE OPTICS.** These three images of a bulb filament were made using pinholes with decreasing size. (A) When the pinhole is relatively large, the image rays are not properly converged, and the image is blurred. (B) Reducing the size of the pinhole improves the focus. (C) Reducing the size of the pinhole further worsens the focus, due to diffraction. From Ruechardt, 1958.
What if aperture (pinhole size) is very small?

- long exposure time (static scene)
- high intensity
Pinhole Camera

What if aperture (pinhole size) is too big?

- blurry image
No aperture is good!

• If large, blurry
• If small, not enough light
• There is no in-between
Lenses

Focus a bundle of rays from a scene point onto a single point on the imager

- Effective aperture is size of lens
- Sharp image (for small range of depths)
Thin Lens Optics

Rays emanating from one point on focus plane converge at one point on image plane.
Thin Lens Optics

All parallel rays converge to one point on a plane located at the focal length $f$

All rays going through the center are not deviated
  - Hence same perspective as pinhole
Thin Lens Optics

Tracing rays through lens

• Start by rays through the center
Tracing rays through lens

- Start by rays through the center
- Choose focal length, trace parallels
All rays coming from points on a plane parallel to the lens are focused on another plane parallel to the lens.
Thin Lens Optics

\[\frac{1}{D'} + \frac{1}{D} = \frac{1}{f}\]
Camera Terminology

Lens parameters:
- Focal length

Camera parameters:
- Focus depth
- Aperture

Camera properties:
- Depth of field
- Field of view
Focus Depth (D)

Can control D by changing D’

\[
\frac{1}{D'} + \frac{1}{D} = \frac{1}{f}
\]

Image plane

Focus plane
Focus Depth (D)

Can control by changing $D'$

$$\frac{1}{D'} + \frac{1}{D} = \frac{1}{f}$$

Image plane

Focus plane
Depth of Field

Only objects on focus plane are in “perfect” focus

D’

D

f

Image plane

Focus plane
Depth of Field

Objects closer to focus plane are in better focus

Image plane

Focus plane

Circle of Confusion

Object Depth
Depth of Field

Objects closer to focus plane are in better focus

- $D'$
- $D$
- $f$
- Circle of Confusion
- Object Depth
- Image plane
- Focus plane
Depth of Field

Objects closer to focus plane are in better focus
Aperture

Controls radius of hole through which light can pass

f/1.4  f/5.6  f/16

F-number is diameter of aperture relative to focal length
Smaller apertures …

- Let in less light
- Have larger depth of field
Field of View

\[
\frac{1}{D} + \frac{1}{D'} = \frac{1}{f}
\]

\[
\tan \frac{\theta}{2} = \frac{1}{2} \frac{x_o}{D}
\]

\[
x_o \div D = x_i \div D'
\]

\[
\theta = 2 \tan^{-1} \frac{1}{2} x_i
\]

\[
(1/f - 1/D)
\]

Since typically \( D \gg f \),

\[
\theta \approx 2 \tan^{-1} \frac{1}{2} x_i / f
\]

\[
\theta \approx x_i / f
\]
Outline for Today

What is a digital image?

How does a camera capture digital images?

What issues can we expect in digital images?
Errors in Digital Images

What are some sources of error in this image?
Errors in Digital Images

What are some sources of error in this image?
Errors in Digital Images

Sensor effects
Lens effects
Processing effects
Errors in Digital Images

Sensor effects
Lens effects
Processing effects
Limited Resolution
Noise
Noise

Thermal noise: in all electronics

• Noise at all frequencies
• Proportional to temperature
• Special cooled cameras available for low noise

Shot noise: discrete photons / electrons

• Shows up at low intensities
• CCDs / CMOS can have high efficiency – approaching 1 electron per photon

$1/f$ noise: inversely proportional to frequency

• Amount depends on quality, manufacturing techniques
Limited Dynamic Range

**Cause:** common cameras have 8-bits per channel
- e.g., 255:1 intensity range

**Result:** saturation and/or underexposure
- Too bright: clamp to maximum
- Too dim: clamp to 0
Bloom

**Cause:** Overflow of charge in CCD buckets – spills to adjacent buckets

**Result:** Streaks (usually vertical) next to bright areas
Color Sampling

**Cause:** different photon sensors may capture different colors based on overlay filters of red, green, or blue

**Result:** colors are interpolated
Color Sampling

Original Scene (shown at 200%)

What Your Camera Sees (through a Bayer array)
Errors in Digital Images

- Sensor effects
- Lens effects
- Processing effects
Spherical Aberration

**Cause:** real lenses do not follow thin lens approximation because surfaces are spherical (due to manufacturing constraints)

**Result:** blurring of images
Radial Distortion

Cause: spherical lenses bend light more near the edge of the image

Result: warped images
Radial Distortion

**Correction:** can be approximated by polynomial (like Taylor series expansion):

\[ r' = r \left(1 + \kappa_1 r^2 + \kappa_2 r^4\right) \]

- \( r \) = ideal distance to center of image
- \( r' \) = distorted distance to center of image

Solve for \( \kappa_1 \) and \( \kappa_2 \) using calibration images

Use formula above to define image warp
Flare

**Cause:** light may reflect (often multiple times) from glass-air interface

**Result:** Ghost images or haziness (worse in multi-lens systems)

**Correction:** ameliorated by optical coatings (thin-film interference)
Vignetting

**Cause:** less power per unit area transferred for light at an oblique angle

**Result:** darkening of edges of image
Chromatic Aberration

**Cause:** dispersion in glass, since focal length varies with the wavelength of light

**Result:** color fringes (worst at edges of image)

**Correction:** build lens systems with multiple kinds of glass
Correcting for Aberrations

High-quality compound lenses use multiple lens elements to “cancel out” distortion and aberration.

Often 5-10 elements, potentially many more for zooms.
Errors in Digital Images

Sensor effects

Lens effects

Processing effects
Compression

Lossy compression introduces artifacts

Original

JPEG
Gamma Correction

**Cause:** CCDs and CMOS response is linear, but luminance scaled non-linearly during image capture to account for human visual perception

\[ \text{Signal} = \varepsilon^\gamma, \gamma \approx 1/2.5 \]

**Result:** must undo gamma correction before processing images
Summary of Today

Digital photos
• 2D array of pixels representing colors
• Colors represent frequency-dependent radiances arriving at camera viewpoint from directions in field of view

Capturing digital images
• Lenses required for normal lighting and exposure times
• Control focus depth, depth of field, aperture, etc.

Issues with digital photos:
• Sensor effects
• Lens effects
• Image processing
Next Time

Feature detection