Digital Photography I
optics and sensors

CSC2529
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*slides adapted from Gordon Wetzstein, Fredo Durand, Ioannis Gkioulekas, Marc Levoy
Announcements

• HW 1 is due Wednesday at 11:59pm
• HW 2 is out (due next Wednesday 28/9)

• Instructor office hours today 1:30-2:30pm BA 7228
• TA office hours Tues/Fri 12:00-1:30pm BA 3201
• Problem session Wed 11:00am-12:00pm SS1071
Let’s say we have a sensor…

digital sensor (CCD or CMOS)
... and an object we like to photograph

What would an image taken like this look like?
Bare-sensor imaging

real-world object

digital sensor (CCD or CMOS)
Bare-sensor imaging

real-world object

digital sensor (CCD or CMOS)
Bare-sensor imaging

real-world object

digital sensor (CCD or CMOS)
Bare-sensor imaging

real-world object

All scene points contribute to all sensor pixels

digital sensor (CCD or CMOS)

What does the image on the sensor look like?
Bare-sensor imaging

All scene points contribute to all sensor pixels
What can we do to make our image look better?

real-world object

digital sensor (CCD or CMOS)
Let’s add something to this scene

real-world object

barrier (diaphragm)

pinhole (aperture)

digital sensor (CCD or CMOS)

What would an image taken like this look like?
Pinhole imaging

real-world object

digital sensor (CCD or CMOS)

most rays are blocked

one makes it through
Pinhole imaging

real-world object

digital sensor (CCD or CMOS)

most rays are blocked

one makes it through
Pinhole imaging

Each scene point contributes to only one sensor pixel

What does the image on the sensor look like?

real-world object
digital sensor (CCD or CMOS)
Pinhole imaging

real-world object

copy of real-world object (inverted and scaled)
Pinhole camera terms

- real-world object
- barrier (diaphragm)
- pinhole (aperture)
- digital sensor (CCD or CMOS)
Pinhole camera terms

- real-world object
- digital sensor (CCD or CMOS)
- barrier (diaphragm)
- pinhole (aperture)
- camera center (center of projection)
- image plane
Focal length

real-world object

focal length $f$
Focal length

What happens as we change the focal length?

classification of real-world object

focal length 0.5 f
Focal length

What happens as we change the focal length?

real-world object

focal length 0.5 f
Focal length

What happens as we change the focal length?

real-world object

object projection is half the size

focal length 0.5 f
Pinhole size

Ideal pinhole has infinitesimally small size
- In practice that is impossible.
Pinhole size

What happens as we change the pinhole diameter?
Pinhole size

What happens as we change the pinhole diameter?

real-world object
Pinhole size

What happens as we change the pinhole diameter?

real-world object
What happens as we change the pinhole diameter?

object projection becomes blurrier

real-world object
What happens as we change the pinhole diameter?

Will the image keep getting sharper the smaller we make the pinhole?
Diffraction limit

A consequence of the wave nature of light

What do geometric optics predict will happen?

What do wave optics predict will happen?
Diffraction limit

A consequence of the wave nature of light

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Diffraction limit

A consequence of the wave nature of light

What do geometric optics predict will happen?

What do wave optics predict will happen?
Diffraction limit

Diffraction pattern = Fourier transform of the pinhole.

- Smaller pinhole means bigger Fourier spectrum.
- Smaller pinhole means more diffraction.
What about light efficiency?

- What is the effect of doubling the pinhole diameter?
- What is the effect of doubling the focal length?
What about light efficiency?

- 2x pinhole diameter → 4x light
- 2x focal length → \(\frac{1}{4}\)x light
Pinhole Camera / Camera Oscura

Mo-Ti (Chinese Philosopher) 470-390 BC
Fun discovery - a small crack in the eastern facade of the Canada Malting Co silos has created a perfect pinhole camera. The result: real time projection of Toronto’s waterfront on the silo’s interior curved surfaces. An unplugged projection show!
J. Vermeer "The Milkmaid", 1658
Credit: ©Toppan Printing Co., Ltd.
Original photo data (Het melkmeisje [The Milkmaid] by Johannes Vermeer):
©Rijksmuseum Amsterdam. Purchased with the support of the Vereniging Rembrandt
Digital Photography - Overview

- optics
- aperture
- depth of field
- field of view
- exposure
- noise
- color filter arrays
- image processing pipeline
Camera Optics
Niepce “View from the Window at Le Gras”, 1826

1826
8h exp
Daguerrotype

- invented in 1836 by Louis Daguerre
- lenses focus light, better chemicals!
Daguerre “Boulevard du Temple”, 1838

exposure
10-12 mins
Lenses

- focus light
- magnify objects

Nimrud lens - 2700 years old
What is a lens?

A piece of glass manufactured to have a specific shape
What is a lens?

A piece of glass manufactured to have a specific shape

- shape of surfaces (usually spherical)
- type of glass
- focal length $f$
- focal plane

Aperture limiting the extent of the lens

Focal length is determined by the lens’ shape and material
How does a lens work?
Refraction

Refraction is the bending of rays of light when they move from one material to another.
How does a lens work?
Lenses are designed so that their refraction makes light rays bend in a very specific way.
Thin lens model

Simplification of geometric optics for well-designed lenses.
Thin lens model

Simplification of geometric optics for well-designed lenses.

Two assumptions:
1. Rays passing through lens center are unaffected.
Thin lens model

Simplification of geometric optics for well-designed lenses.

Two assumptions:
1. Rays passing through lens center are unaffected.
2. Parallel rays converge to a single point located on focal plane.
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Thin Lens Model

Ray tracing example
- Parallel rays map to the focal plane
Thin Lens Model

Ray tracing example
- Parallel rays map to the focal plane
- The chief ray passes straight through the center

\[ S_1 \quad f \quad f \quad S_2 \]

Object \quad Real \: image
Thin Lens Model

Ray tracing example

- Parallel rays map to the focal plane
- The chief ray passes straight through the center
- The ray that passes through the near focal plane becomes parallel
Thin Lens Model

Thin lens formula: \[ \frac{1}{f} = \frac{1}{S_1} + \frac{1}{S_2} \]

Magnification: \[ M = -\frac{S_2}{S_1} = \frac{f}{f - S_1} \]
Lenses

$S_1 < f$: magnifying glass
Lenses

S1 < f: magnifying glass

minification
Yes, but…
Thin lenses are a fiction

The thin lens model assumes that the lens has no thickness, but this is rarely true…

To make real lenses behave like ideal thin lenses, we have to use combinations of multiple lens elements (compound lenses).
Thin lenses are a fiction

The thin lens model assumes that the lens has no thickness, but this is rarely true...

- Even though we have multiple lenses, the entire optical system can be (paraxially) described using a single thin lens of some equivalent focal length and aperture number.

To make real lenses behave like ideal thin lenses, we have to use combinations of multiple lens elements (compound lenses).
Lenses - Aberrations

Spherical aberration

Chromatic aberration

Coma

Achromatic doublet
Lenses - Aberrations

- Spherical aberration
- Chromatic aberration
- Coma
- Achromatic doublet
- Crown
- Flint
Refraction at interfaces of complicated shapes

What shape should an interface have to make parallel rays converge to a point?
Refraction at interfaces of complicated shapes

What shape should an interface have to make parallel rays converge to a point?

Single hyperbolic interface: point to parallel rays

Double hyperbolic interface: point to point rays

Therefore, lenses should also have hyperbolic shapes.
Spherical lenses

In practice, lenses are often made to have spherical interfaces for ease of fabrication.
- Two roughly fitting curved surfaces ground together will eventually become spherical.

Spherical lenses don’t bring parallel rays to a point.
- This is called spherical aberration.
- Approximately axial (i.e., paraxial) rays behave better.
Aberrations

Deviations from ideal thin lens behavior (e.g., imperfect focus).

- Example: spherical aberration.
Lenses - Aberrations

- Spherical aberration
- Chromatic aberration
- Coma
- Achromatic doublet
- Crown
- Flint
Oblique aberrations

These appear only as we move further from the center of the field of view.

- Contrast with spherical and chromatic, which appear everywhere.
- Many other examples (astigmatism, field curvature, etc.).
Distortion example
Lenses - Aberrations

- **Spherical aberration**
- **Chromatic aberration**
- **Coma**
- **Achromatic doublet**
Aberrations

Deviations from ideal thin lens behavior (e.g., imperfect focus).

- Example: chromatic aberration.

  focal length shifts with wavelength

  glass has dispersion (refractive index changes with wavelength)

  one lens cancels out dispersion of other

  glasses of different refractive index

Using a doublet (two-element compound lens), we can reduce chromatic aberration.
Chromatic aberration examples
Field of View

Hubble – what’s the focal length?

- 1000 mm: 2.5°
- 500 mm: 5°
- 350 mm: 7.5°
- 250 mm: 10°
- 135 mm: 18°
- 85 mm: 29°
- 50 mm: 43°
- 35 mm: 63°
- 28 mm: 75°
- 8 mm: 180°
A costly aberration

Hubble telescope originally suffered from severe spherical aberration.
• COSTAR mission inserted optics to correct the aberration.
Aperture

- aperture controls amount of light

focal plane
Aperture

- aperture controls amount of light
Aperture size

Most lenses have variable aperture size.

- F-number notation: “f/1.4” means $f/ = 1.4$.
- Usually aperture sizes available at steps of one-half or one-third stops.
- Older lenses have separate manual aperture ring.
- Modern lenses control the aperture through a dial on the camera body (“gelded” lenses).

![f/1.4](image)
![f/2.8](image)
![f/4](image)
![f/8](image)
![f/16](image)
Aperture size

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Reminder: A “stop” changes the amount of light by a factor of 2.
Aperture

- out of focus blur

focal plane

circle of confusion
Aperture

- out of focus blur

focal plane

circle of confusion
Depth of Field

depth of field: max circle of confusion

focal plane

circle of confusion
Circle of Confusion

c = M \cdot D \cdot \frac{|S - S_1|}{S}

M = \frac{f}{S_1 - f}

focal plane: S₁

S

circle of confusion: c
Circle of Confusion

\[ c = M \cdot D \cdot \frac{|S - S_1|}{S} \]

Canon 5D Mark III: f=50mm, f/2.8 (N=2.8),
focused at 5m, pixel size=7.5um
Hyperfocal Distance

\[ H = \frac{f^2}{Nc} \]

**Canon 5D Mark III:** \( f=50\text{mm}, f/2.8 (N=2.8), \) focused at 5m, pixel size=7.5\( \mu \)m
Hyperfocal Distance

$$H = \frac{f^2}{Nc}$$

Canon 5D Mark III: $f=50\text{mm}, f/2.8 (N=2.8)$, focused at $5\text{m}$, pixel size=$7.5\text{um}$

Everything is in focus from $H/2$ to infinity

For this CoC threshold
Depth of Field

aperture...f 1.8
shutter......1/500
ISO.........100
distance...~3ft

aperture...f 4
shutter......1/125
ISO.........100
distance...~3ft

aperture...f 8
shutter......1/40
ISO.........125
distance...~3ft

http://photographywisdom.com/
Depth of Field & Motion Blur

London, Photography
Bokeh

artistic use

two delighted blog

coded aperture

Levin et al., SIGGRAPH 2007
Diffraction Limit

- Ernst Abbe 1873: \[ d = \frac{\lambda}{2n \sin \theta} \]

spot radius (image space)
Diffraction Limit

- Ernst Abbe 1873: 
  \[ d = \frac{\lambda}{2n \sin \theta} = \frac{\lambda}{2NA} \approx \lambda N \]

- Microscope objectives today: NA 1.4-1.6 \(\Rightarrow d = \lambda/2.8\)

- Small f-number (large NA) = high resolution but shallow depth of field
  - Inherent tradeoff between “3D” information and 2D resolution
  - Space-bandwidth product (uncertainty principle)
Fastest lens ever made?

Zeiss 50 mm f / 0.7 Planar lens

- Originally developed for NASA’s Apollo missions.
- Stanley Kubrick somehow got to use the lens to shoot Barry Lyndon under only candlelight.
Fastest lens ever made?

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• Stanley Kubrick somehow got to use the lens to shoot Barry Lyndon under only candlelight.
Sensors
What’s a Pixel?

photon to electron converter → photoelectric effect!

source: Molecular Expressions

wikipedia
What’s a Pixel?

- microlens: focus light on photodiode
- color filter: select color channel
- quantum efficiency: ~50%
- fill factor: fraction of surface area used for light gathering
Two main types of imaging sensors
Two main types of imaging sensors

**Charged coupled device (CCD):**
- row brigade shifts charges row-by-row
- amplifiers convert charges to voltages row-by-row

**Complementary metal oxide semiconductor (CMOS):**
- per-pixel amplifiers convert charges to voltages
- multiplexer reads voltages row-by-row

Can you think of advantages and disadvantages of each type?
Two main types of imaging sensors

Charged coupled device (CCD):
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Can you think of advantages and disadvantages of each type?
Two main types of imaging sensors

**Charged coupled device (CCD):**
- row brigade shifts charges row-by-row
- amplifiers convert charges to voltages row-by-row

- higher sensitivity
- lower noise

**Complementary metal oxide semiconductor (CMOS):**
- per-pixel amplifiers convert charges to voltages row-by-row
- multiplexer reads voltages row-by-row

- faster read-out
- lower cost
What’s a Pixel?
What’s a Pixel?
What’s a Pixel?
What’s a Pixel?
Most Common: Color Filter Arrays

Bayer pattern

any combination possible tradeoffs?

wikipedia
Assorted Pixels

- Narasimhan & Nayar @ Columbia
- multiplex anything: polarization, color, time, ND, …
Exposure (shutter speed)

- exposure = time (e.g. 1/250, 1/60, 1, 15, bulb)

wikipedia

\[
\frac{1}{4} \text{ sec, } f/3.3
\]

\[
2 \text{ sec, } f/6.3
\]
ISO ("film speed")

- sensor sensitivity
- analog gain
  applied before ADC!
Dynamic Range

- ratio between largest and smallest possible value
- bit depth also important! common bit depths: 12-14 bits RAW / 8 bits JPEG

high dynamic range

Kevin McCoy
Global Shutter vs. Rolling Shutter

All sensor pixels exposed at same time

Row-by-row readout of image
- shorter exposure times per pixel
- motion artifacts

http://ifa.mobivap.uva.es/~fradelg/phd/notes/global-shutter.html
What are these dark bands?
60 Hz AC power results in 120 Hz flicker!
Photons to RAW Image

- Photons
  - Photons to sensor
  - Sensor defects (fixed pattern noise)
- Sensor output
  - Amplifier (gain, ISO)
  - Additive noise
- ADC (quantization)
- RAW image

Equations:
- Photon noise = sensor defects
- Sensor defects = fixed pattern noise
- Additive noise = quantization

Noise types:
- Photons
- Sensor defects
- Additive noise
- Quantization

RAW image defects:
- Sensor defects
- Additive noise
- Quantization
Sensor Noise

- noise is (usually) bad!

- many sources of noise: heat, electronics, amplifier gain, photon to electron conversion, pixel defects, read, ...

- different noise follows different statistical distributions, two crucial ones:
  - Gaussian
  - Poisson
Gaussian Noise

- thermal, read, amplifier
- additive, signal-independent!
Photon or Shot Noise

- signal dependent

- Poisson distribution:

\[ f(k; \lambda) = \frac{\lambda^k e^{-\lambda}}{k!} \]

\[ \sigma = \sqrt{\lambda} \]

N photons: \( \sigma = \sqrt{N} \)

2N photons: \( \sigma = \sqrt{2\sqrt{N}} \)

nonlinear!
Signal-to-Noise Ratio (SNR)

\[ SNR = \frac{\text{mean pixel value}}{\text{standard deviation of pixel value}} = \frac{\mu}{\sigma} \]

\[ = \frac{PQ_e t}{\sqrt{PQ_e t + Dt + N_r^2}} \]

\[ P = \text{incident photon flux (photons/pixel/sec)} \]

\[ Q_e = \text{quantum efficiency} \]

\[ t = \text{exposure time (sec)} \]

\[ D = \text{dark current (electrons/pixel/sec), including hot pixels} \]

\[ N_r = \text{read noise (rms electrons/pixel), including fixed pattern noise} \]
Scientific Sensors

• e.g., Andor iXon Ultra 897: cooled to -100°C
• scientific CMOS & CCD
• reduce pretty much all noise, except for photon noise
Digital Photography

- optics
- aperture
- depth of field
- field of view
- exposure
- noise
- color filter arrays
- image processing pipeline
Digital Photography – Additional Resources

• What we left out: metering, autofocus, autoexposure, anti-aliasing filter, IR filter (and probably much more)

• Stanford CS 178 – Digital Photography: slides, applets, and other material online

• CMU Computational Photography 15-862

• looking for a camera? check dpreview.com
Next: The Image Processing Pipeline

- RAW images
- demosaicking
- denoising
- deblurring
- white balancing
- gamma correction
- compression
References and Further Reading

- Stanford CS 178, “Digital Photography”, Course Notes
- CMU Computational Photography course
- wikipedia