Lecture 23:

Image Sensors

Computer Graphics and Imaging
UC Berkeley CS184/284A
Why Study Image Sensors?
A Quick, Sparse Random Sampling...
Imaging for Robotics

Google’s “Arm Farm”
Imaging for Computer Vision

ImageNet: 15M images, 22K categories
http://image-net.org
Imaging in Mapping

Maps, satellite imagery, street-level imaging,…
Imaging in Mapping

Maps, satellite imagery, street-level imaging,…
Ubiquitous Consumer Imaging

Cameras everywhere
Imaging for Virtual Reality

Imaging for Virtual Reality

Photon Capture
The Photoelectric Effect

Einstein’s Nobel Prize in 1921 “for his services to Theoretical Physics, and especially for his discovery of the law of the photoelectric effect"
Charge Coupled Devices (CCD)

Developed by Wilford Boyle (L) and George Smith (R) at Bells Labs in 1969
Nobel Prize 2009 - "for the invention of an imaging semiconductor circuit
– the CCD sensor"
Charge Coupled Devices (CCD)
CCD

Interline CCD

Integration of Photon-Induced Charge

Parallel Bucket Array

Serial Bucket Array

Parallel Register Shift (1 Row)

(a)

Serial Register Shift to Output

(b)

Figure 5

Conveyor Belt

Bucket Brigade CCD Analogy

Calibrated Measuring Container

(c)
CMOS APS (Active Pixel) Sensor
Anatomy of the Active Pixel Sensor Photodiode

http://www.olympusmicro.com/primer/digitalimaging/cmosimagesensors.html
Quantum Efficiency

Not all photons will produce an electron

- Depends on quantum efficiency of the device

\[ QE = \frac{\# \text{electrons}}{\# \text{photons}} \]

- Human vision: ~15%
- Smartphone camera: c ~60%
- Best back-thinned CCD: > 90%
- Scientific CMOS (sCMOS): 95%

Meynants et al. IISW 2013

QE of a 24MP CMOS full-frame sensor
Color Architectures
Color Filter Arrays (Mosaics)

Why more green pixels than red or blue?

- Because humans are most sensitive in the green portion of the visible spectrum
- Sensitivity given by the human luminous efficiency curve

Bayer pattern (most common)

Sony RGB+E wider color gamut

Kodak RGB+W higher dynamic range

Luminous Efficiency

400 700

Wavelength

0 1
Demosaicking Algorithms
Demosaicking Algorithms
Demosaicking Algorithms

Interpolate sparse color samples into RGB at every output image pixel

Simple algorithm: bilinear interpolation
  - Average 4 nearest neighbors of the same color

Consumer cameras use more sophisticated techniques
  - Try to avoid interpolating across edges

Due to demosaicking, 2/3 of image data is “made up”!
Demosaicking Based on Machine-Learning

3-Sensor Color Architecture

- Prismatic optics
- No demosaicking
- Three (smaller) sensors and optical alignment
Philips Total Internal Reflection Dichroic Prism

Light

R-sensor

Dichroic coating

Dichroic coating and air gap

B-sensor

G-sensor
Wavelengths Penetrate to Different Depths

Long-wavelength photons penetrate deeper than short in silicon

The spectral response of electrons at the surface differs from electrons deeper in the material
Dynamic Range
CCD & CMOS Response Functions Are Linear

Photoelectric effect in silicon:

- Response function from photons to electrons is linear
- May have some nonlinearity close to 0 due to noise, and near pixel saturation

Finite Dynamic Range: Real Sensor Pixels "Saturate"

Linear response until saturation (idealized)

https://www.ptgrey.com/white-paper/id/10912
Saturated Pixels: "Blown Out" Parts of Photo

Normal exposure
Saturated Pixels: "Blown Out" Parts of Photo

Overexposure ("blown-out" or "clipped" pixels)

Kanazawa & Ng
exposure: +0 stops
exposure: -8 stops
High Dynamic Range (HDR) Through Multiple Exposures

Figure 6: Sixteen photographs of a church taken at 1-stop increments from 30 sec to $\frac{1}{1000}$ sec. The sun is directly behind the rightmost stained glass window, making it especially bright. The blue borders seen in some of the image margins are induced by the image registration process.
HDR Through Multiple Exposures
HDR Through Multiple Exposures

Synthetic Motion Blur
Normal 8-bit image

Synthetic Motion Blur
HDR image

Real Photo
DIY HDR

- 2 shots
- Photoshop

Slide courtesy Marc Levoy
DIY HDR

Early morning in Zurich

- 2 shots
- Photoshop

CS184/284A  Early morning in Zurich  Kanazawa & Ng
DIY HDR

Early morning in Zurich

- 2 shots
- Photoshop

Slide courtesy Marc Levoy
HDR "Mode" On Smartphones
HDR By Pixel Mosaicking
HDR By Pixel Mosaicking
HDR By Pixel Mosaicking

(a) Exposure: T
(b) Exposure: 4T
(c) Exposure: 16T
(d) Exposure: 64T
HDR in Circuit Design of Image Sensor

• Many approaches tried: well adjusting, multiple capture, time to saturation, logarithmic, local adaptation, ...

• Multiple capture approach requires multiple, high-speed, non-destructive reads of the pixel's value during exposure

• Not common, not used in cameras for consumer photography today
Pixel Structure & Micro Optics
Front-Side-Illuminated (FSI) CMOS

Building up the CMOS imager layers
Photodiodes
~50% Fill Factor

Pixel pitch:
A few microns

Courtesy R. Motta, Pixim
Polysilicon & Via 1

Courtesy R. Motta, Pixim
Metal 1

Courtesy R. Motta, Pixim
Color filter array

Courtesy R. Motta, Pixim
Pixel Fill Factor

Fraction of pixel area that integrates incoming light.
Pixel Fill Factor

Fraction of pixel area that integrates incoming light.

Optimize with per-pixel microlenses.

Microlenses on a CMOS sensor

Microlenses on a CCD pixel
Pixel Fill Factor

Shifted microlenses on M9 sensor.

Leica M9
Optical Cross-Talk

With some CMOS sensors, rays of incoming light at large angles of incidence can fail to reach the photodiode of the corresponding pixel and reach only the adjacent pixel. Or they are shadowed or reflected on the way to the pixel with the effect that the overall amount of light received by the pixels is less than the amount arriving through the microlenses.

Pixel Optics for Minimizing Cross-Talk

Sensor architecture of the Leica Max 24 MP sensor (schematic diagram)

1. Microlens design with varying radius
2. Relatively short distance between color filter and photodiode

In the case of the Leica Max 24 MP sensor, and in contrast to standard CMOS sensors, even light rays with large angles of incidence, e.g. from wide-angle lenses or large apertures, are captured precisely by the photodiodes of the sensor. This is enabled by the special microlens design and the smaller distance between the colour filter and photodiode, which allows more light to enter the system, and ensures that it falls more directly on the respective photodiodes.

Image Example of Cross-Talk

Color desaturation due to pixel cross-talk

Kohyama et al. IISW 2009
Recall: FSI (Front-Side Illuminated) Pixel Structure

Humrick & Yankulin, tomshardware.com
BSI (Back-Side Illumination) Sensor Fabrication Process

Humrick & Yankulin, tomshardware.com
FSI vs BSI Pixel Structure

Humrick & Yankulin, tomshardware.com

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Kanazawa & Ng
Majority of CMOS Sensors are BSI Today

Smartphones
Some cameras

Good BSI sensors can provide higher QE and lower cross-talk.
Pixel Aliasing, Antialiasing
Pixel Fill Factor

Fraction of pixel area that integrates incoming light.

Photodiode area

Non photosensitive (circuitry)
What is going wrong in the image on the right?
Simulation of pixels with 25% fill factor
Pixel Sampling & Aliasing

Source of aliasing includes imperfect fill-factor, and color subsampling in color filter array.

Discussed techniques to improve fill-factor (e.g. microlenses)
Antialiasing Filter

Optical low-pass filter

- Use layer of birefringent material, splits each ray into two that overlaps each pixel
- Use two layers oriented at 90 degrees to split each ray over 2x2 pixels
With and Without Antialiasing Filter @ 36 MP

D800E JPEG (default settings)  D800 JPEG (default settings)
D800E JPEG (default settings)  D800 JPEG (default settings)
With and Without Antialiasing Filter @ 36 MP

Without AA Filter (D800E)

CS184/284A  https://www.dpreview.com/reviews/nikon-d800-d800e/28 Kanazawa & Ng
With and Without Antialiasing Filter @ 36 MP

With AA Filter (D800)

https://www.dpreview.com/reviews/nikon-d800-d800e/28 Kanazawa & Ng
Imaging Noise Fundamentals
(Most slides courtesy of Marc Levoy)
Image Noise

Grain in image. Generally worse in low light, long exposures, shadows in images.

Image credit: imaging-resources.com
Signal-to-Noise Ratio (SNR)

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

\[ SNR \text{ (dB)} = 20 \log_{10} \left( \frac{\mu}{\sigma} \right) \]

Example

- If SNR improves from 100:1 to 200:1, then it improves by
  \[ 20 \log_{10}(200) - 20 \log_{10}(100) = +6 \text{ dB} \]
Photon Shot Noise

The number of photons arriving during an exposure varies from exposure to exposure and from pixel to pixel, even if the scene is completely uniform. This number is governed by the Poisson distribution.
Poisson Distribution

Probability that a certain number of random events will occur during an interval of time:

- Known mean rate
- Independent events

If on average $\lambda$ events occur in an interval of time, the probability $p \text{ that } k$ events occur instead is

$$p(k; \lambda) = \frac{\lambda^k e^{-\lambda}}{k!}$$
Poisson Distribution Mean and Variance

The mean and variance of the Poisson distribution are:

\[ \mu = \lambda \]
\[ \sigma^2 = \lambda \]

The standard deviation is:

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

The error grows slower than the mean.
Photon Shot Noise SNR

Photons arrive in a Poisson distribution

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

so

\[ \text{SNR} = \frac{\mu}{\sigma} = \sqrt{\lambda} \]

Shot noise scales as the square root of number of photons

Examples:

- A pixel that collects 10,000 photoelectrons vs. 1,000 has an SNR improvement of \( \sqrt{10} \) or +10 dB
- Opening the aperture by 1 f/stop increases the number of photons by 2\( \times \), hence SNR by \( \sqrt{2} \) or +3 dB
Sensor Noise Sources
(Most slides courtesy of Marc Levoy)
Pixel Noise: Dark Current

• Electrons dislodged by random thermal activity
• Increases linearly with exposure time
• Increases exponentially with temperature
• Varies across sensor, and includes its own shot noise

(http://theory.uchicago.edu/~ejm/pix/20d/tests/noise/)

don’t confuse with photon shot noise

Canon 20D, 612 sec exposure
Pixel Noise: Hot Pixels

- Electrons leaking into well due to manufacturing defects
- Increases linearly with exposure time
- Increases with temperature, but hard to model
- Changes over time, and every camera has them

Canon 20D, 15 sec and 30 sec exposures
Pixel Noise: Fixing Dark Current & Hot Pixels

Example

- Aptina MT9P031 (in Nokia N95 cell phone)
- Full well capacity = ~8500 electrons/pix
- Dark current = 25 electrons/pix/sec at 55°C

Solution #1: chill the sensor

- Retiga 4000R bioimaging camera
- Peltier cooled 25°C below ambient
- Full well capacity = 40,000 electrons/pix
- Dark current = 1.64 electrons/pix/sec

Solution #2: dark frame subtraction

- Available on high-end SLRs
- Compensates for average dark current
- Also compensates for hot pixels and FPN
Pixel Noise: Fixed Pattern Noise (FPN)

- Manufacturing variations across pixels, columns, blocks
- Mainly in CMOS sensors
- Doesn’t change over time, so read once and subtract

Canon 20D, ISO 800, cropped

Zoomed Crop
Pixel Noise: Read Noise

- Thermal noise in readout circuitry
- Again, mainly in CMOS sensors
- Not fixed pattern, so only solution is cooling

Canon 1Ds Mark III, cropped

this image tainted by JPEG artifacts?
Effect of Downsizing on Image Noise

Levoy
Noise Reduction by Image Averaging

Single frame in dark room using iPhone 4
Noise Reduction by Image Averaging

Average of ~30 frames using SynthCam app by Marc Levoy

SNR increases as sqrt(# of frames) (neglecting read noise)
Things to Remember

Photoelectric effect
Imager revolution: CCD and CMOS sensors
Sensor saturation
High dynamic range (HDR) imaging
Color architectures, Bayer filter array, demosaicking
Pixel stack, fill factor, microlenses
FSI vs BSI pixel designs
Pixel sampling, aliasing, optical low-pass filters
Noise: photon shot, pixel noise sources, SNR
Acknowledgments

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Extras
Noise Recap

Photon shot noise

- Unavoidable randomness in number of photons arriving
- Grows as the square root of the number of photons, so brighter lighting and longer exposures will be less noisy

Dark current noise

- Grows with exposure time and sensor temperature
- Minimal for most exposure times used in photography
- Correct by subtraction, but only corrects for average dark current

Hot pixels, fixed pattern noise

- Caused by manufacturing defects, correct by subtraction

Read noise

- Electronic noise when reading pixels, unavoidable
Signal-to-Noise Ratio Revisited

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

\[
= \frac{P Q_e t}{\sqrt{P Q_e t + D t + N_r^2}}
\]

SNR changes with scene brightness, aperture, and exposure time

Where

- \(P\) = incident photon flux (photons/pixel/sec)
- \(Q_e\) = quantum efficiency
- \(t\) = exposure time (sec)
- \(D\) = dark current (electrons/pixel/sec), including hot pixels
- \(N_r\) = read noise (rms electrons/pixel), including fixed pattern noise

(formula from http://learn.hamamatsu.com/articles/ccdsnr.html)
ISO - Signal Gain

Doubling ISO doubles the signal

- Linear with light, so same as $2 \times$ exposure time, or brighten by one f-stop
- Implemented as analog or digital amplification
  - Analog before ADC on Canon 5D II up to ISO 6400; digital multiplication at higher ISOs?

Ideal to amplify as early as possible during readout

- If amplification occurs before read noise is added, and read-noise is independent of signal amplitude, then the amplified signal will have better SNR
Nikon D3S, ISO 25,600, denoised in Lightroom 3, photograph by Fredo Durand
RAW image from camera, before denoising in Lightroom
Tone mapped to show the scene as Fredo might have experienced it