Lecture 29:

Image Sensors

Computer Graphics and Imaging
UC Berkeley CS184/284A, Spring 2017
Photon Capture
The Photoelectric Effect

Incident photons

Ejected electrons

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

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

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%
- Typical digital camera: < 50%
- Mobile camera: 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

Why more green pixels than red or blue?
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”!
3-Sensor Color Architecture

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

Dichroic coating

Dichroic coating and air gap

R-sensor

G-sensor

B-sensor

Light
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
Pixel Structure & Micro Optics
Front-Side-Illuminated (FSI) CMOS

Building up the CMOS imager layers

Courtesy R. Motta, Pixim
A few microns

Photodiodes
~50% Fill Factor

Pixel pitch:
A few microns

Courtesy R. Motta, Pixim
Polysilicon & Via 1

Courtesy R. Motta, Pixim
Color filter array

Courtesy R. Motta, Pixim
Pixel Fill Factor

Fraction of pixel area that integrates incoming light.

Photodiode area

Non photosensitive (circuitry)
Pixel Fill Factor

Fraction of pixel area that integrates incoming light.

Optimize with per-pixel microlenses.
Pixel Fill Factor

Shifted microlenses on M9

Leica M9
Optical Cross-Talk

Pixel Optics for Minimizing Cross-Talk

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
BSI (Back-Side Illumination) Sensor Fabrication Process

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

Humrick & Yankulin, tomshardware.com
Majority of CMOS Sensors are BSI Today

Smartphones

Some cameras

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

http://kenrockwell.com/nikon/d800/vs-d800e.htm
To Be Continued
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