Photons to Bits and Beyond
The Science and Technology of Digital Imaging

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Fall 2011

Versions of this talk have been presented at
People have been capturing and creating images by hand for a long time.

Cave drawing
~ 10,000 BC

Michelangelo
~1540

Klimt ~1912

Jackson ~2006
And using cameras for about 200 years to record images “automatically”

Giroux Daguerreotype ~1839

Kodak Brownie Camera ~ 1889

Steve Sasson and first portable digital camera (invented 1975)
Many kinds of digital cameras

- Photography
  - Digital single lens reflex (DSLR)
  - Point and shoot
  - Camera phone
- Video
  - TV (640x480) and HDTV (1920x1080)
  - Camcorder, broadcast
  - Webcam
  - High speed – slow motion
  - Motion capture
  - Gaming
- Medical
  - Endoscopy
  - Pill camera
  - X-ray camera
- Machine Vision
  - Automotive (e.g. “smart beam” headlight dimmer)
  - Security
  - Inspection
- 3D ranging
  - Gesture control
- Etc.
Congruent with Moore’s Law, cameras have become smaller, faster, cheaper and everywhere.

- 0.3 Mpixel CCD camera, Circa 1993
- 2 Mpixel Cell phone AF Camera, Circa 2007
- 0.06 Mpixel CMOS endoscopy camera, present day
- 16 Mpixel Cell phone Camera, Present day

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The ubiquitous nature of the mobile phone camera as a communications tool has led to new ways of interacting with each other, and “being there”.

1999 PB159 minicam Monument Valley Utah

2011 SBF and KEFL Stanford

2011 Fossum Farm New Hampshire

facebook

YouTube
Large Scale Social Change

- Rapid change due to “feedback” from nearly real-time visual images.

Arab Spring 2011
Too much visual information?

- Visual information overload from a few billion “overconnected” cameras.
  - God-like vision, participating yet helpless.

Japanese Tsunami 2011

see Bill Davidow, *Overconnected: The Promise and Threat of the Internet*
Privacy Issues

- Loss of privacy from networked security cameras and automatic facial recognition, tracking, and activity logging.
- Loss of privacy from “bad guys” and advertisers

Mall Scene Minority Report 2002
Inappropriate Use

- Inappropriate use like sexting, upskirting, spy cams, etc.

http://aftergroblog.blogs.com/rgb/2008/08/going-up-skirt.html
Gray-Area Defense Applications

- Very smart weapons, very personalized weapons.
  - “i-bullets”

Laser guided rifle

Micro Autonomous Systems and Technology (MAST) consortium
Science and Technology
Blackbody emission of photons (~6000K)
- With photon shot noise
- Plus atmospheric scatter
- Plus scene reflection

\[ \sim 10^{14-17} \text{ photons/cm}^2/\text{s} \]

Lens collects and bends EM waves and focuses image.

Photons strike image sensor and are absorbed by semiconductor.

http://www.societyofrobots.com/images/sensors_color_spectrum.gif
Photon Shot Noise

- Photon emission is a Poisson process. Stream of photons is NOT regularly spaced.

- Photon flux $\Phi$ characterized by:

$$\langle (\Phi - \langle \Phi \rangle)^2 \rangle \sim \Phi$$
Photon Shot Noise

- Let Signal be $N$, so Photon Shot Noise $n = \sqrt{N}$
- SNR=$\sqrt{N}$  Want SNR$>$10 and usually higher
- Effect for “uniform lighting” shown below (Nikon D3)

by Emil Martinec © 2008
Simulated effect of noise

Low noise

Noise impacts luminance and color


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Diffraction Limit

Airy Disk Diameter
\[ D = 2.44 \frac{\lambda}{F#} \]

Cheap Lens Resolution
(30 lp/mm)

High Performance Lens Resolution
(120 lp/mm)
Microlenses

- Main camera lens brings image to microlenses
- Microlens funnels photons to active detector area.
Color Filter Array (CFA)

• Each pixel gets covered by a colored filter
  – We use red, green, blue (RGB) CFA - best match for RGB displays
  – Pixel colors arranged in “Bayer” pattern
     \[ \begin{array}{cc}
     G & R \\
     B & G
     \end{array} \]

(assumes UV and NIR filters)
Photons to Electrons

Covalently bonded silicon

Pinned photodiode
Backside Illumination

Front side of wafer

Example from Omnivision

1.4μm BSI Pixel Performance

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Example from Sony

Light

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• MOS-based charge-coupled devices (CCDs) shift charge one step at a time to a common output amplifier

20% fill factor boosted to 60% with microlens
Active Pixels

\[ \Delta V \propto \Phi \]

\[ \Delta t \]

\[ V_{pix}, V_{pd}, V_{rst}, C_{pd}, I_{pd} \]
Electronics Noise

- Many sources of electronics noise: pick-up, thermal, 1/f, trap-induced field effect (RTS), etc.
- "kTC" noise is fundamental – comes from Brownian-like motion of electrons in a conductor.
- Can be suppressed using CDS = correlated double sampling.

\[ V_1 = V_{rst} + v_n \]

Measure after reset

\[ V_2 = V_{rst} + v_n - \frac{Q_{pd}}{C} \]

Measure after photo-current subtracted

Take Difference

\[ \Delta V = V_1 - V_2 = \frac{Q_{pd}}{C} \]
**CMOS Active Pixel Sensor**

2nd Generation Image Sensor

Read pixel signals out thru switches and wires

- Photodetector converts photons to electrons
- Amplifier converts electrons to voltage after intrapixel complete charge transfer
- Analog signal processor suppresses noise and further amplifies signal
- Column multiplexer selects particular column(s) for routing to ADC(s)
- Analog-to-digital converters (ADC) converts signal from volts to bits (usually 10 bits resolution)

Row select logic chooses which row is selected for readout.

Timing and control logic controls the timing of the whole sensor.
CMOS Active Pixel Sensor
2nd Generation Image Sensor

Camera on a Chip
- Active pixel array
- Analog signal chain
- Analog-to-Digital Conv.
- VLSI Digital logic
  - I/O interface
  - Timing and control
  - Exposure control
  - Color processing
  - Ancillary circuits
On-Chip Image Signal Processing

- Camera System-on-a-Chip integration is extensive
  - Color interpolation
  - Color correction, white balance
  - Dark signal correction, gamma and other normal corrections
  - Lens shading corrections
  - Format conversion and compression
  - Exposure control
  - Flicker detection and avoidance
  - Defect identification and correction
  - Auto focus support (focus score, actuator control)
  - Etc.
Color Interpolation

- Goal is to get best approximation for RGB at each pixel site but we start with just red, green or blue, not all 3.
- Many ways to do color interpolation, for example:

  - Have blue, need green & red
    - \( G = \) average of 4 neighboring greens
    - \( R = \) average of 4 neighboring reds
  
  - Have green, need blue & red
    - \( B = \) average of 2 neighboring blues
    - \( R = \) average of 2 neighboring reds
  
  - Have red, need green & blue
    - \( G = \) average of 4 neighboring greens
    - \( B = \) average of 4 neighboring blues
Image on screen should look like image seen, but better

Human eye response to color

Silicon response and On-chip processing

Camera processing

Computer processing

LED LCD display color Spectrum and tuning

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State of the Art

- Pixel counts for consumers are in the 8-16 Mpixel range.
- Pixel counts for professional cameras are in the 20-40 Mpixel range.
- Pixel counts for aerospace application are approaching 100 Mpixels.
- Pixel size is 2.2 um to 1.1 um for common consumer applications.

UDTV or Super-High Vision
- 7680 x 4320
- 33 Mpixels, 60 fps
- 2 Gp/s
Science and Space Sensors

Fairchild Imaging sCMOS
• 2560 x 2160 pixels
• 6.5µm x 6.5µm pixel
• Readout noise less than 2 electrons at 30 f/s and less than 3 electrons at 100 f/s
• 100 f/s max at full-res
• Dynamic range: > 16000:1
• QE: >60% at 550 nm
• Rolling- or Global-Shutter readout (user selectable)

CMOSIS 70 Mpixel 3.5 um
8 analog outputs 3 fps

E2V 2Mpixel CMOS image sensor
In weather satellite

106-CCD Gigapixel
Gaia Sensor

High-Accuracy CMOS Image Sensors Fly Into Space On-Board European Space Agency’s Proba-2 Satellite
Coming Attractions
More Camera Phones

Global Market Trends for Camera-Equipped Cellular Devices (Breakdown by Resolution)

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Smaller Pixels and Backside Illumination (BSI)

From Wuu et al. 2009 IISW Bergen, Norway
Smaller Pixels, More Pixels

- Smaller pixels allow smaller chips
  + Reduces chip cost to camera module maker
  + Reduces optics size and cost
  + Smaller camera modules more desirable for integration into consumer products
  - NRE cost for chip higher
  - Performance of pixel usually degraded
    ▪ Lower quantum efficiency due to fill factor
    ▪ Reduced SNR under low light
    ▪ Smaller full-well so worse dynamic range
    ▪ Increased optoelectronic crosstalk
    ▪ Stack height and aperture degrades chief ray angle
    ▪ Lower voltages bad for analog circuits
Smaller Pixels, More Pixels (2)

- Smaller pixels means more megapixels.
  - Higher resolution images for same optics
  - Pixel count often sells cameras and gadgets.
  - More megapixels sells more cellular service traffic, bigger computers, better software, mass storage
  - Entering visible light diffraction limit zone with SOA pixel pitch so less return on resolution
  - More stringent requirements on optical system quality
  - More megapixels makes getting data off chip at same frame rate more challenging
  - More megapixels increases power requirements of sensor.
Sub-Diffraction Limit (SDL) Pixels

- Marginal return on shrink for real resolution improvement
- Sort of a spatial and color oversampling
- Anti-aliasing filter not needed

- Some real limit on how small is practical according to current pixel paradigm
Improved Functionality

- High dynamic range (HDR)
- Global electronic shutter
- Higher speed readout (slow motion, blur reduction)
- Handshake blur reduction
- Embedded focus pixels for mirrorless DSLRs
Paradigm Changing Research Activity

- Digital Integration Sensor
  - Signal integration in-pixel and digital off-array
- Quanta Image Sensor (QIS)
  - Counting individual photons
- 3D Range (Z) Image sensors
  - Range only
  - RGBZ
- Computational Imaging
  - Extended depth of field, refocusing
- Plenoptic Sensor
  - Multiple lenses and small arrays
- Stacked Sensor
  - Quantum dot film sensor, Organic film sensor
Digital Integration Sensor (DIS)

- Current paradigm: Integrate signal in well, readout. Full well needs to be as large as possible -> device and circuit constraints.
- DIS: Make smaller full well and higher conversion gain. Readout sensor 4x or 8x per final frame and sum (integrate) in digital memory. Can allow lower noise and higher dynamic range and easier pixel design. Lower ADC resolution needed. Needs faster readout circuit and increase in power.
Digital Integration Sensor (DIS)

- Break into multiple sub-integration periods
- Exposure sub-integration times can be varied to increase dynamic range
- Frames can be shifted to remove motion blur
Quanta Image Sensor (QIS)

Current paradigm:
- We collect photons for a predetermined amount of time in a silicon “rainbucket” determined by physical size and capacity of silicon pixel.

New paradigm:
- Let’s count each photogenerated carrier and record time and location, creating binary bit planes for each time slice, and then digitally form image by digital convolution over X,Y, t.

e.g. Non-linear 3D convolution
Need Gigapixels at Terabits/Sec

- Consider a tiny pixel ("jot") that is sensitive to a single photoelectron.
- Jot state changes from "0" to "1" when a photoelectron is present.
- Requires a single-electron amplifier or single-electron transistor.
- Want billions on a single chip so must be small, e.g. 0.1 - 0.5 um pitch.
- At 0.1 um jot pitch, 16:9 gigajot sensor would be 4.2 mm x 2.4 mm or about ¼” optical format.
Samsung

Status:
• TCAD model only
• Shows about 5 mV/e- signal
• More work required
# Pixels to Jots Equivalency

<table>
<thead>
<tr>
<th>Sensor</th>
<th>sCMOS</th>
<th>Aptina 8M</th>
<th>sCMOS</th>
<th>Aptina 8M</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pixel Pitch (nm)</td>
<td>6500</td>
<td>1400</td>
<td>6500</td>
<td>1400</td>
</tr>
<tr>
<td>Pixels H</td>
<td>2560</td>
<td>3264</td>
<td>2560</td>
<td>3264</td>
</tr>
<tr>
<td>Pixels V</td>
<td>2160</td>
<td>2448</td>
<td>2160</td>
<td>2448</td>
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<tr>
<td>Total (Mpix)</td>
<td>5.5</td>
<td>8.0</td>
<td>5.5</td>
<td>8.0</td>
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<tr>
<td>Full Well (e-)</td>
<td>31700</td>
<td>3000</td>
<td>31700</td>
<td>3000</td>
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<tr>
<td>Frame Rate (Hz)</td>
<td>30</td>
<td>15</td>
<td>30</td>
<td>15</td>
</tr>
<tr>
<td>Te-/sec</td>
<td>5.3</td>
<td>0.4</td>
<td>5.3</td>
<td>0.4</td>
</tr>
<tr>
<td>Jot Pitch (nm)</td>
<td>100</td>
<td>100</td>
<td>200</td>
<td>200</td>
</tr>
<tr>
<td>Jots/Pixel</td>
<td>4225</td>
<td>196</td>
<td>1056</td>
<td>49</td>
</tr>
<tr>
<td>Jots H</td>
<td>166400</td>
<td>45696</td>
<td>83200</td>
<td>22848</td>
</tr>
<tr>
<td>Jots V</td>
<td>140400</td>
<td>34272</td>
<td>70200</td>
<td>17136</td>
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<tr>
<td>Total (Gjot)</td>
<td>23.4</td>
<td>1.6</td>
<td>5.8</td>
<td>0.4</td>
</tr>
<tr>
<td>e-/jot/frame</td>
<td>7.5</td>
<td>15.3</td>
<td>30.0</td>
<td>61.2</td>
</tr>
<tr>
<td>Bit plane readout (Hz)</td>
<td>225.1</td>
<td>229.6</td>
<td>900.4</td>
<td>918.4</td>
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<tr>
<td>Column scan rate (MHz)</td>
<td>31.6</td>
<td>7.9</td>
<td>63.2</td>
<td>15.7</td>
</tr>
<tr>
<td>Total jot rate (Tb/sec)</td>
<td>5.3</td>
<td>0.4</td>
<td>5.3</td>
<td>0.4</td>
</tr>
<tr>
<td>After KP (Gb/s)</td>
<td>1.2</td>
<td>1.8</td>
<td>5.0</td>
<td>7.3</td>
</tr>
</tbody>
</table>
QIS Planar Architecture

- JOT ARRAY
  0.1-10 Gjots

- COLUMN SENSE AMPLIFIERS

- ACCUMULATING LOGIC+MEMORY

- KERNEL PROCESSOR

- OUTPUT MULTIPLEXER

- TIMING AND CONTROL

- ON-CHIP PROCESSOR PROGRAM

- BIT PLANE DATA
  n x n AGGREGATION

- TEMPORAL AGGREGATION

- OFF CHIP MEMORY

- 1-10 Tbits/sec

- READ POINTER

- RESET POINTER

- APERTURE

- QUANTA IMAGE SENSOR (QIS)

- ROW DRIVERS
Time of Flight Range Sensor

Single “Ping”  \[ Z = \frac{1}{2} c \Delta t \]

Improve SNR by using multiple pulses and lock-in method

\[ \Delta \phi = \left[ 4\pi f / c \right] \Delta Z \]

\[ \frac{1}{f} \]

\[ 1 \text{ cm} \leftrightarrow 66 \text{ ps} \]
Time-of-Flight Range Sensor

Lock-in single-tap pixel using pinned photodiode

![Lock-in single-tap pixel diagram]

- Conv. gain: 72 uV/e-
- Full well: 28ke-
- DC at 20 MHz: >50%

Range image

![Range image]

Samsung

T-Y Lee et al. IEDM 2011

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The Vision

Color-coded range image

RBGZ - 3D Color Image Sensor

3D Display

480x360 TOF embedded in 2Mpixel color sensor

2011 Samsung

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Conclusions

- Image sensors have come along way since the 1\textsuperscript{st} generation device – the CCD.
- The 2\textsuperscript{nd} generation device, the CMOS active pixel image sensor is going strong. “Billions and billions served”
- Much interesting work lies ahead as we move the digital divide as close as possible to the digital nature of photons.
- “Overconnection” of billions of massive-information gathering engines leads to interesting societal issues and questions.