History and Future of Electronic Color Photography:

Where Vision and Silicon Meet

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UC Berkeley Photography class
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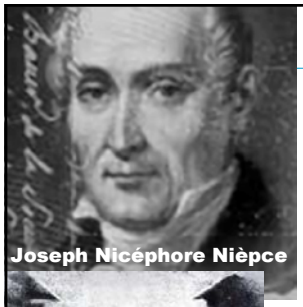
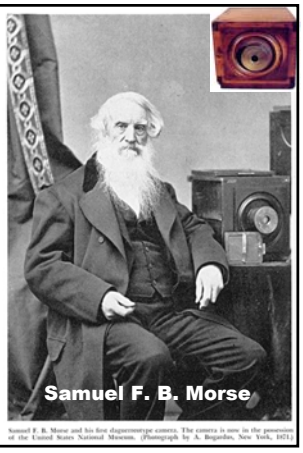
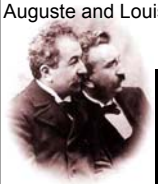
Color Photographic History
– in a nutshell –

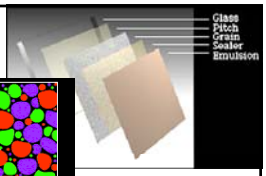
- **Approaches to Silver-based Color**
  - Three-shot
  - Filter mosaic
  - Color separation beam splitter
  - Stacked sensor layers
- **Repeating the Cycle with Digital**
  - Three-shot CCD cameras
  - Filter mosaic CCD sensors
  - Three-sensor prism-based cameras
  - The Foveon X3™ direct sensor technology

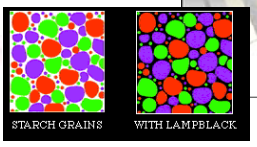




Auguste and Louis Lumière







1906: Autochrome, a photographic transparency plate patented by the Lumière brothers of Lyons, France.

Grains of potato starch dyed **orange**, **green**, and **violet**.

This screen of grains worked as a **filter mosaic**, exposing a panchromatic emulsion. The exposed plate was then reversal processed resulting in a transparency, and was viewed through the same filter grains.

http://www.bway.net/~jscruggs/auto.html

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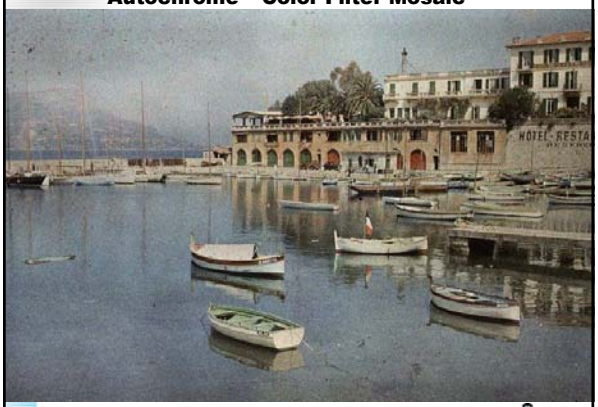
Autochrome – Color Filter Mosaic



http://www.ilford.com/html/us_english/autochrome/auto86.jpg

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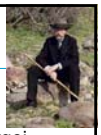
Three-shot color

http://www.loc.gov/exhibits/empire/gorskii.html



Sergei Mikhailovich Prokudin-Gorskii: Photographer to the Tsar 1908–1915

Austro-Hungarian Prisoners of World War I

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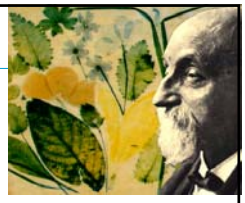
Color one-shot still cameras



1932
Devin Tri-Color

Louis Ducos du Hauron
1873

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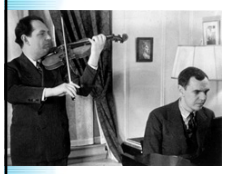
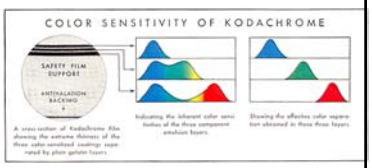
The Silver Solution: Kodachrome



Leopold Mannes and Leopold Godowsky, Jr. of Eastman Kodak Co.



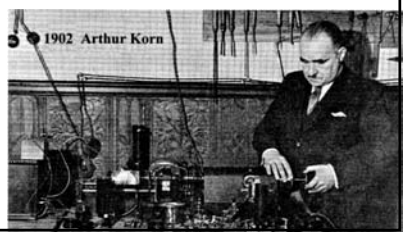
Senses colors in layers

- one shot
  - no motion problems
- all colors at all locations
  - no sampling artifacts
- one piece of film
  - no registration problem

Electronic Image Communication

1888: Telautograph,
Elisha Gray

1902: Telephotography
(photoelectric fax), Arthur Korn



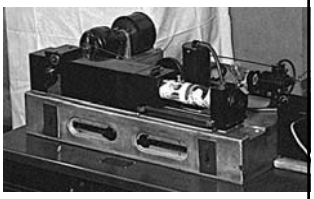
Nyquist and Telephotography

http://lucent.netlabs.net/minds/gallery/1944trw.html

Harry Nyquist (right) with John R. Pierce (left) and Rudi Kompfner (c. 1950).

- 1924: Telephotography (Fax)
- 1925: AT&T Wirephoto System
- 1926: Sampling Theorem

Nyquist's fax machine



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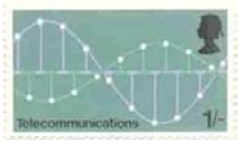
Pulse Code Modulation (PCM)

- **1937: Alec H. Reeves**
  PCM: Digital Represention and Communication of Telephone Signals



http://www.derivaz.fsnet.co.uk/ahr/pcm.htm

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PCM Tube

1948 – Vacuum-tube A-to-D converter

Raymond W. Sears holding his invention

http://lucent.netlabs.net/minds/gallery/1948pcm.html

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"The Philosophy of PCM"

John R. Pierce
1910–2002
with TWTA

- 1948: **The Philosophy of PCM**, by John Pierce, Claude Shannon, and Barney Oliver (Proc. IRE) led the way to media going digital, starting with the Bell System's voice transmission network
- 1951: Digital image coding kicked off by W. M. Goodall, **Television by Pulse Code Modulation**, BSTJ(30) 1951

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Three-Shot Color Photography with Vidicon TV Tube

Surveyor 1 – 1966

http://history.nasa.gov/SP-168/section2b.htm
http://nssdc.gsfc.nasa.gov/database/MasterCatalog?sc=1966-045A&ex=1

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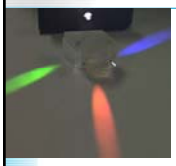
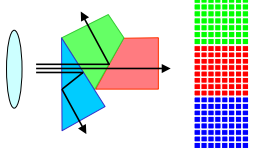
Prism-based Color Camera



2000 – Foveon II



100% green

100% red

100% blue

No guessing!

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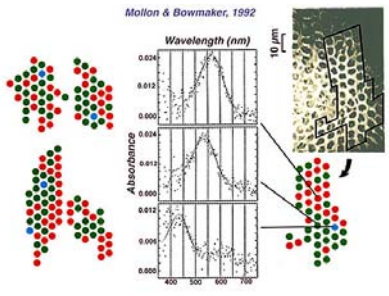
How do Humans See Color?

- **Packed mosaic of cones in the *fovea centralis* (few blue cones)**



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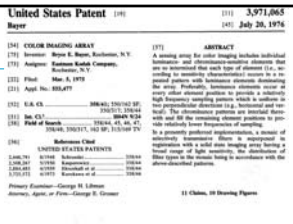
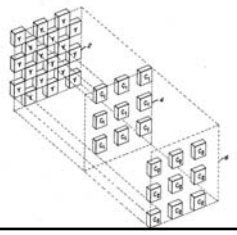


Bryce Bayer's US Patent #3,971,065



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Digital Camera Image Sensors

– A Return to Screen Plates

- **Light goes through lens and hits image sensor plane.**
- **Image sensor sees a mosaic pattern of color.**
- **Camera estimates image color from mosaic pattern.**

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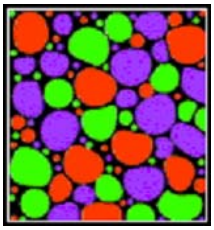
Tried and True?

1906
Potato starch on glass plates



1975
Bayer pattern on Silicon

G1	R2	G3	R4	G5
B6	G7	B8	G9	B10
G11	R12	G13	R14	G15
B16	G17	B18	G19	B20
G21	R22	G23	R24	G25

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Mosaic Sampling Artifacts

Recycled Color Techniques
in Electronic Cameras

- **Mosaics** (Bayer, in common use)
- **Three-shot** (e.g. Megavision)
- **Prism** (e.g. Foveon II)

What's left?

Can we copy multi-layered film?

Use a "vertical color filter" (VCF) in silicon?

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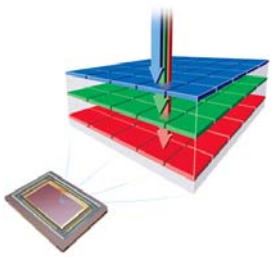
Direct Sensing – Each Location, All 3 Colors

- **Wavelengths of light are absorbed as different functions of depth in silicon.**
- **Detecting photocurrent at different depths can provide color information.**



Use ALL of the photons and capture ALL of the image information

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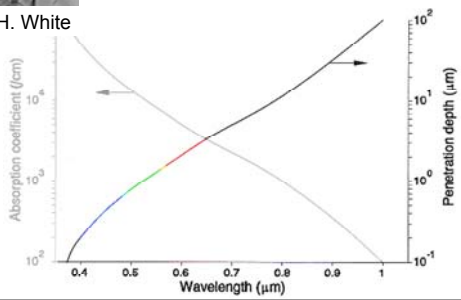
Silicon as a Color Filter

Marvin H. White

Absorption Coefficient and Penetration Depth in Silicon, vs. Wavelength

from Theuwissen, based on M. H. White 1976



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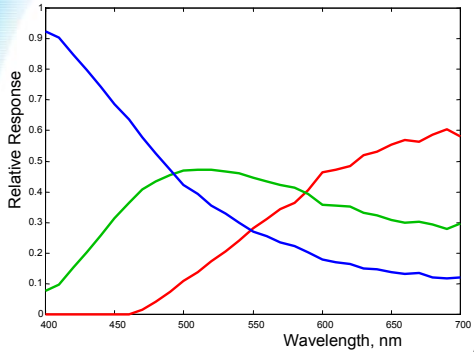
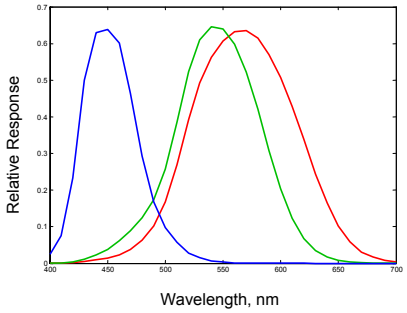
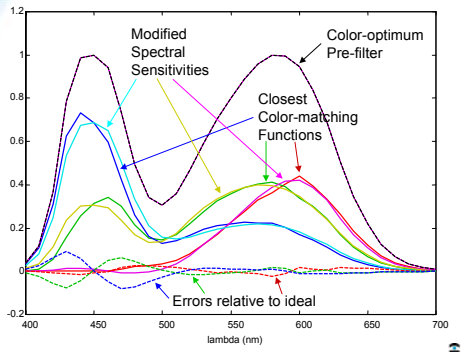
Spectral Response Curves



Human Cone Spectral Responses



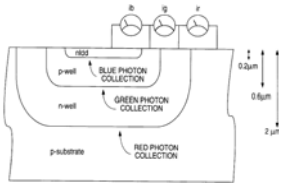
Color-Matching Functions



Film versus Direct VCF

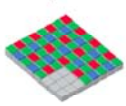
- **Kodachrome (left) versus a *vertical-color-filter* detector group in triple-well CMOS (right)**

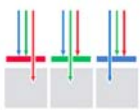
Dick Merrill



Mosaic vs. Direct VCF

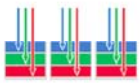
Mosaic Capture





sampling element is 2x2 'pixels'

Foveon® X3 Capture



sampling element is 1 'pixel'

works like color film

Moiré patterns

Mosaic Sensor

VCF (Foveon X3)

Chroma Resolution

Mosaic Sensor

Direct Sensor (Foveon X3)

The Silicon Solution: Direct Sensor using VCF

Single-Chip Full-Measured-Color Direct Image Sensor

- Has 3x the color information per location
  - About 1.7x the spatial resolution (1.4x luminance, 2.0x chrominance)
- Captures 3x the photons
  - Higher Sensitivity
- Eliminates color artifacts
  - Double the Nyquist frequency
- Enables new classes of camera designs
  - High flexibility, multi-function, low-cost

Like Having 3x the Silicon

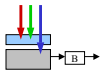
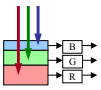
First Commercialization: Sigma SD9 SLR Camera

2268 x 1512 x 3 =
3 Layers x 3.4 MP per Layer =
10.2 Million Pixel Sensors

What's in a Megapixel?

Accepted definitions:

- **Picture Element (pixel):** RGB triple in a sampled color image
- **Pixel Sensor:** photodiode with readout circuit

Each 20th-century cell	Each Foveon X3 cell
1 pixel sensor	**3 pixel sensors**
1/3 picture element	**1 picture element**
	
1/3 pixel?	1 pixel?
1 pixel?	3 pixels?

Products with X3 Imagers

2002 – Sigma SD9 – 10.2 MP Digital SLR

2003 – Sigma SD10 – 10.2 MP Digital SLR

2004 – Polaroid x530 – 4.5 MP Point-and-shoot

Do Vision and Silicon Meet?

- Retina: photodetector mosaic in the human fovea for vision does not mean that a mosaic on silicon is good for photography
- Direct Image Sensor: multi-layer *vertical color filter* in silicon photographic sensor does not mean that biological vision should evolve a similar approach
- But silicon and vision need to work together, and take account of each other's properties