History and Future of Electronic Color Photography: *Where Vision and Silicon Meet*

Richard F. Lyon
Chief Scientist – Foveon, Inc.

FOVEON

Color Photographic History
– in a nutshell –

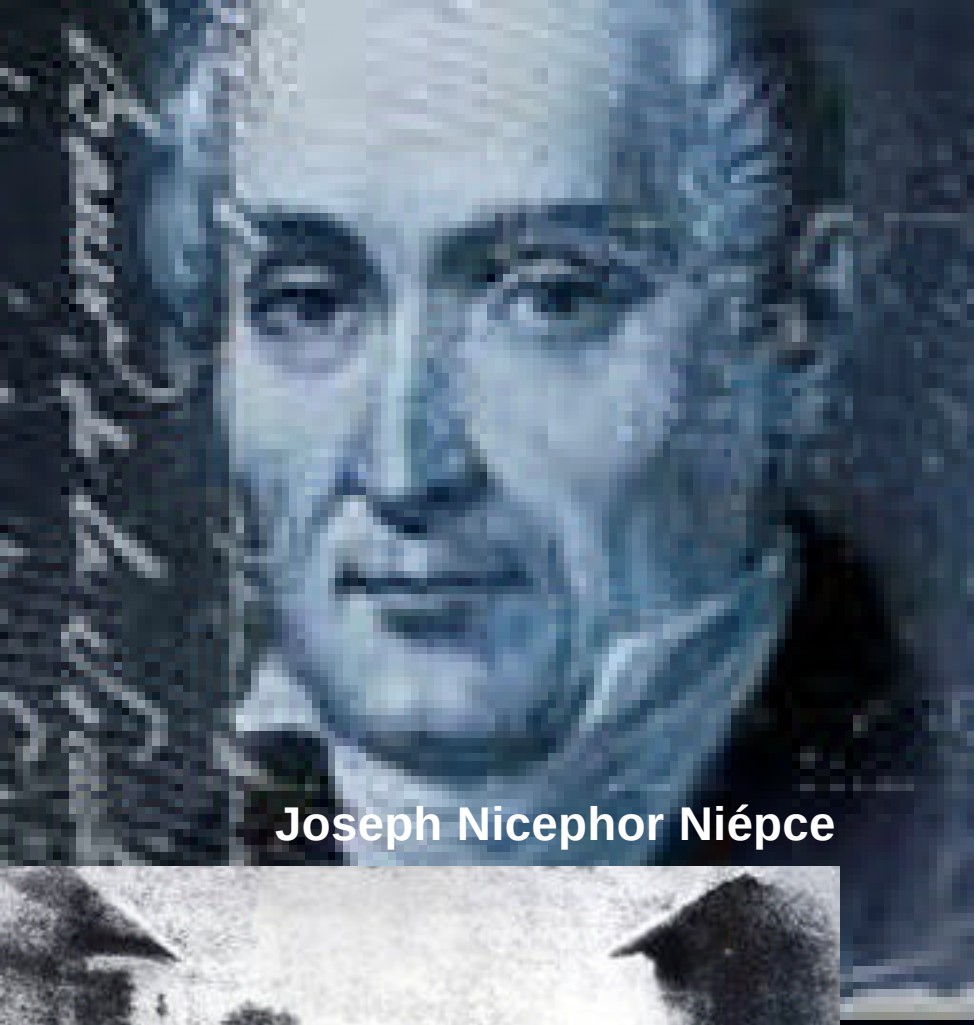
- Approaches to Silver-based Color
  - Three-shot
  - Filter mosaic
  - Color separation beam splitter
  - Stacked sensor layers

- Repeating the Cycle with Digital
  - Three-shot CCD cameras
  - Filter mosaic CCD sensors
  - Three-sensor prism-based cameras
  - The Foveon X3™ sensor technology

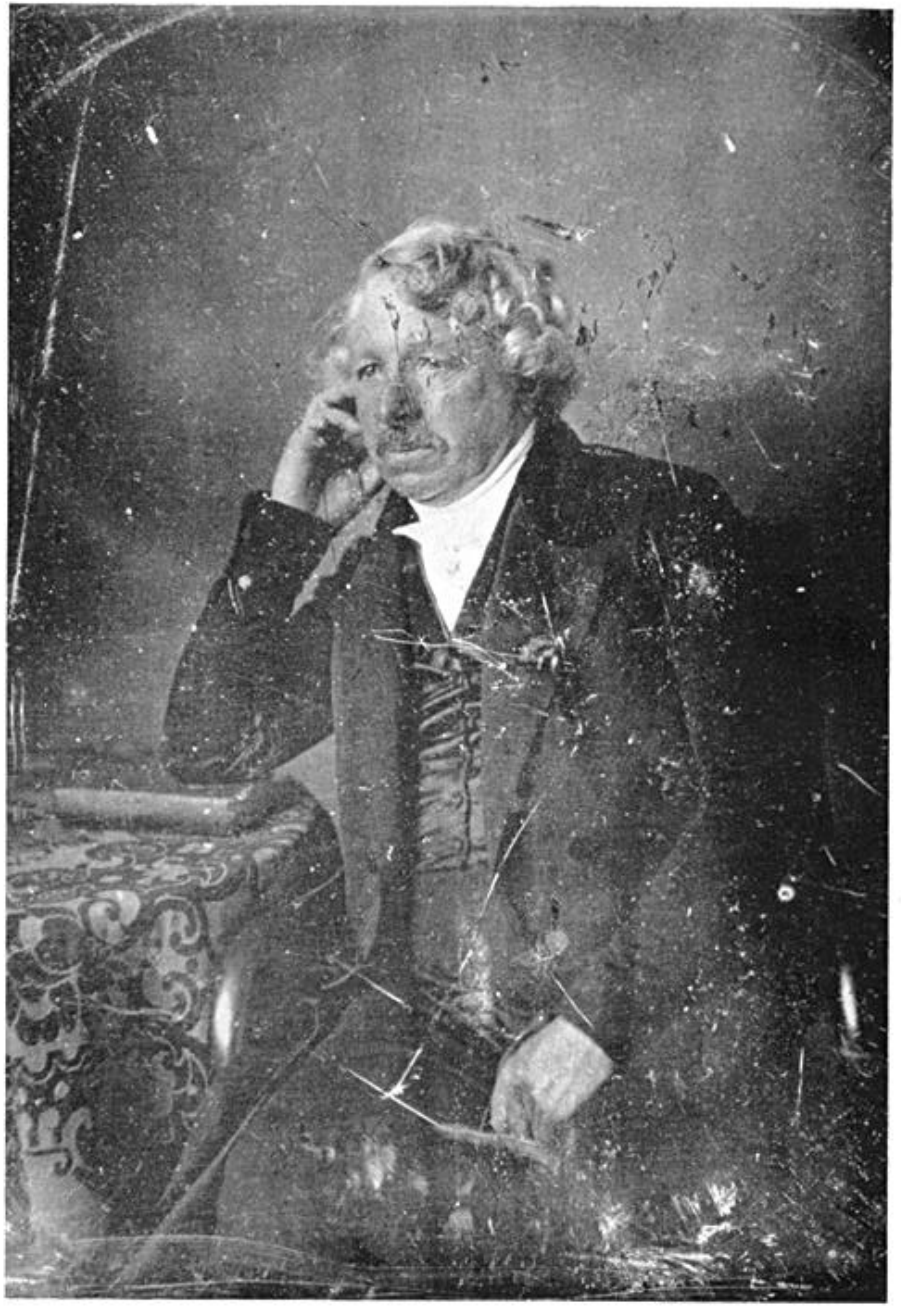
Repeating History

- "Those who cannot remember the past are condemned to repeat it." – *George Santayana*

- "Even if we do remember the past, we have to repeat it. But maybe we can fast forward to the good parts." – *Tom Lyon* (Creating the New Public Network)



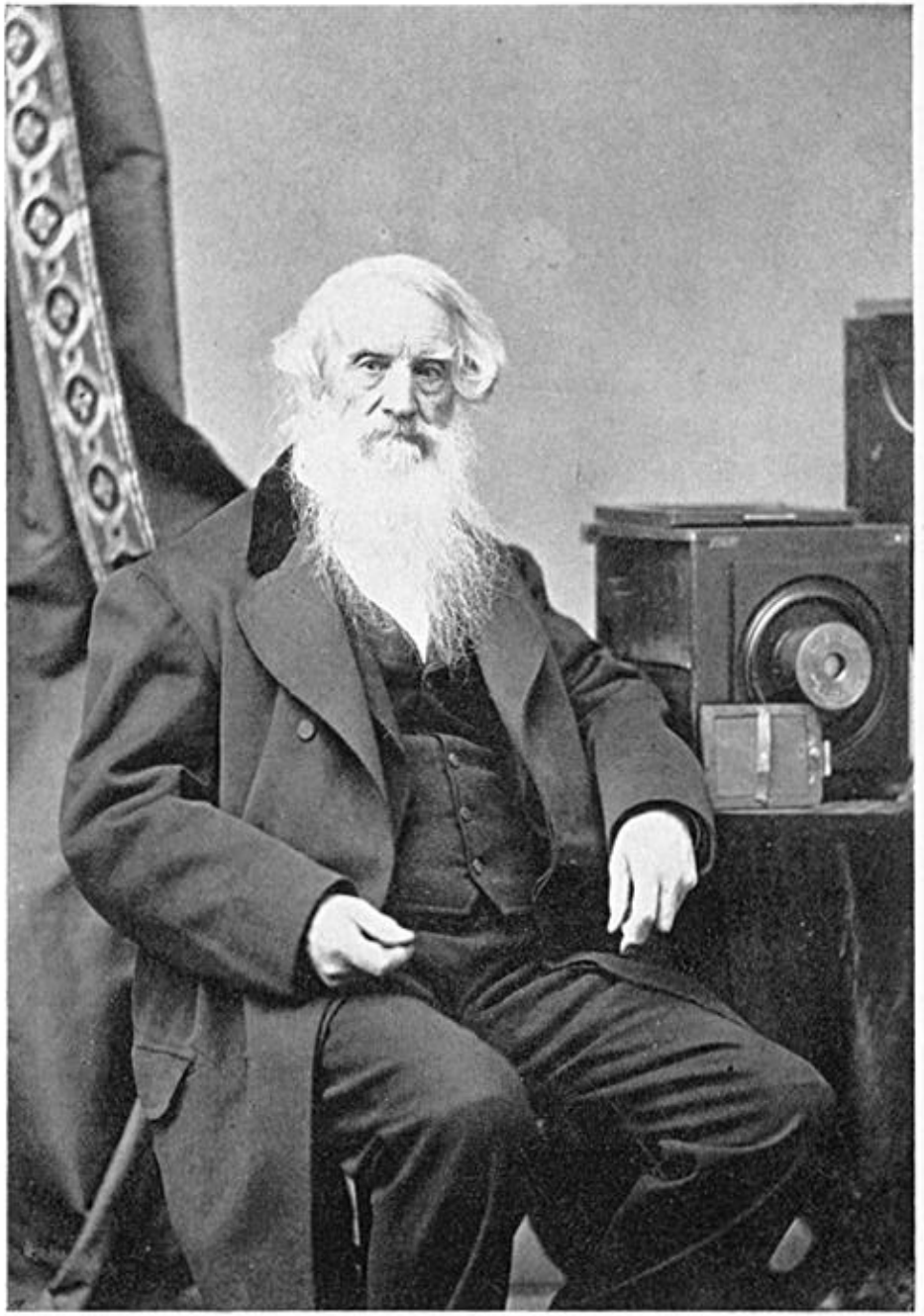
Joseph Nicephor Niépce



L. J. M. Daguerre. A photographic copy (1935) of an original daguerreotype made by Charles R. Meade of New York in 1848. The daguerreotype is now in the possession of the United States National Museum, through whose courtesy the copy is reproduced.

J. Clerk Maxwell

Emery Walker ph. sc.



Samuel F. B. Morse and his first daguerreotype camera. The camera is now in the possession of the United States National Museum. (Photograph by A. Bogardus, New York, 1871.)

Late Nineteenth Century: Steps Toward Color

1861: Three-shot color and additive color projection, James Clerk Maxwell

1869: Screen plates, Louis Ducos du Hauron (implemented 1894 by J. Joly)

1892: Three-negative color by separation mirrors, Frederic Ives

All three of these obsolete ways of capturing color re-emerge about 100 years later as steps toward electronic photography

Twentieth Century Color

1906: Autochrome, Lumiére brothers

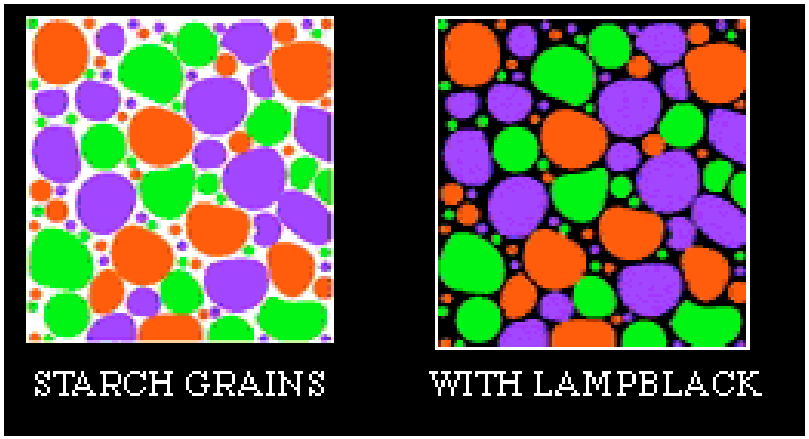
1908: Micro-lens film, Berthon (filters on lens; became “Kodacolor” movie film in 1928)

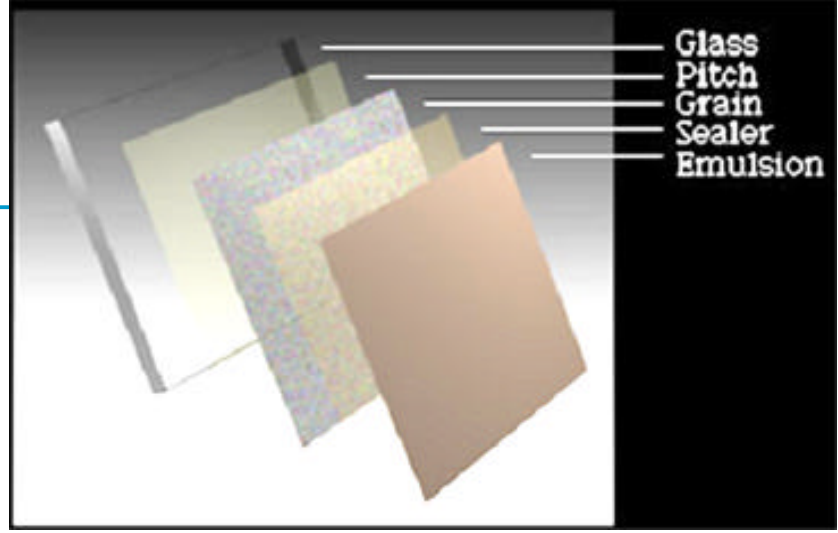
1932: Technicolor three-color movie camera with color-separation prism

1935: Kodachrome, multi-layered film, Leopold Mannes and Leo Godowsky

- Kodachrome’s three-layered sensing was revolutionary and lasting; only evolutionary improvements to film since then.

Autochrome





1906: AUTOCHROME, a photographic transparency film patented by Auguste and Louis Lumiére of Lyons, France.

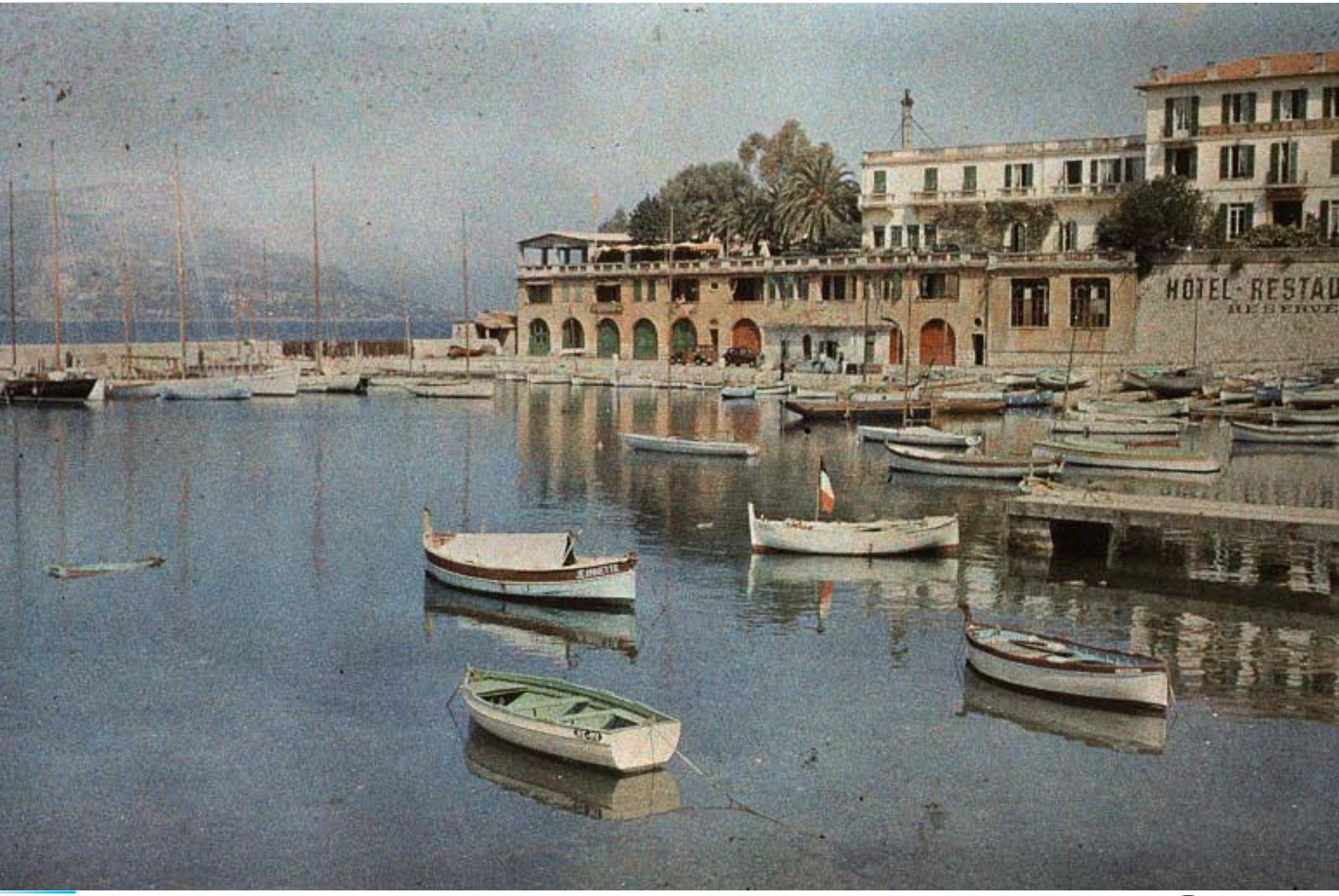
The Lumiéres dusted a plate with millions of grains of potato starch that they had dyed orange, green, and violet.

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

FOVEON

Autochrome



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

FOVEON

Three-shot color

1908–1915

Photographer to the Tsar: Sergei Mikhailovich Prokudin-Gorskii

Austro-Hungarian Prisoners of World War I

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

Color one-shot still camera

Devin Tri-Color has three plates with RGB filters and beam-splitting pellicles.

FOVEON

The Silver Solution: Kodachrome

Separates colors in three layers

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

Electrical/Electronic Roots

- Telegraphy and Wireless Telegraphy: Discrete Symbols Communicated by Electromagnetic Waves
- Electronic Image Communication: Facsimile
- Pulse Code Modulation: Going digital
- Television: Electronic images everywhere
- Transistors: Quantum electronic devices
- DSP: Digital Signal/Image Processing
- CCD and MOS Sensors
- Moore’s Law: Complexity, VLSI Design Methods, CPU Performance, and Megapixels

Telegraphy and Wireless Telegraphy

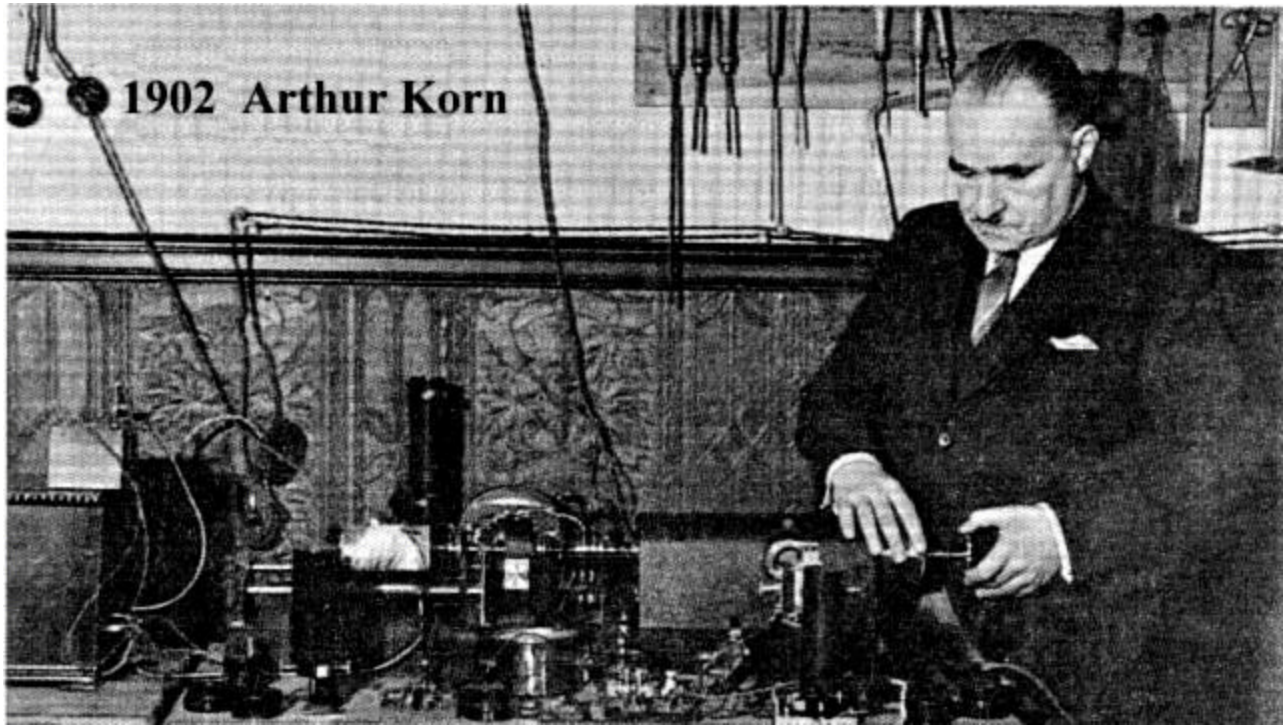
Discrete Symbols Communicated by Electromagnetic Waves

- Samuel F. B. Morse
- James Clerk Maxwell
- Sir Charles Wheatstone
- Heinrich Hertz
- Oliver Heaviside
- Guglielmo Marconi
- Nicola Tesla
- Albert Einstein

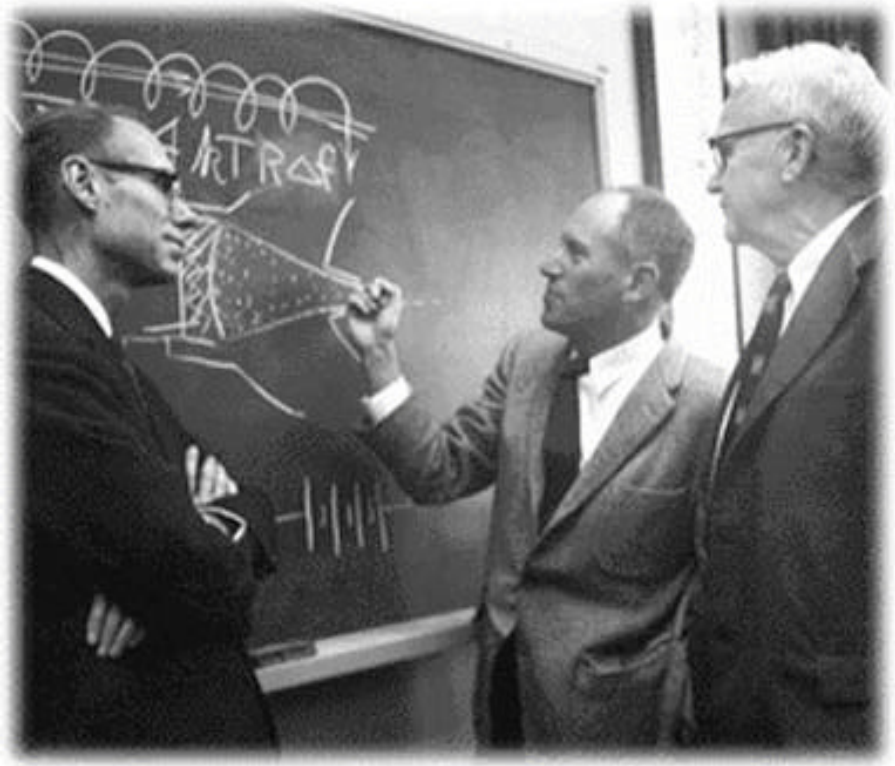
Electronic Image Communication

1888: Telautograph,
Elisha Gray

1902: Telephotography
(photoelectric fax), Arthur Korn



Nyquist and Telephotography

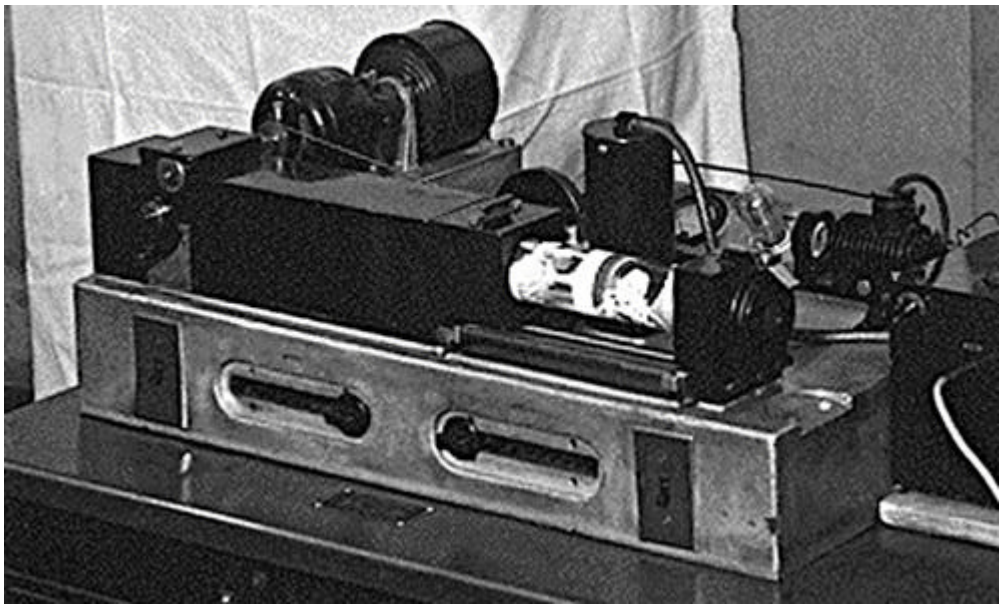


http://lucent.netlabs.net/minds/gallery/1944trw.html

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

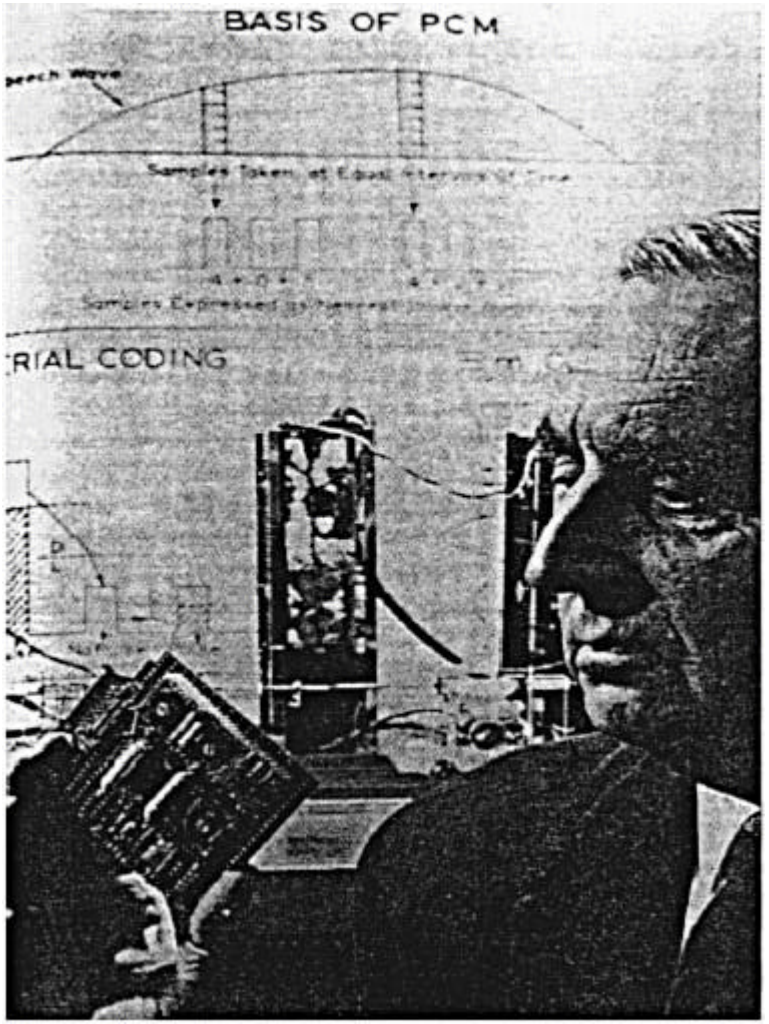
- 1924: Telephotography (Fax)
- 1925: AT&T Wirephoto System
- 1926: Sampling Theorem

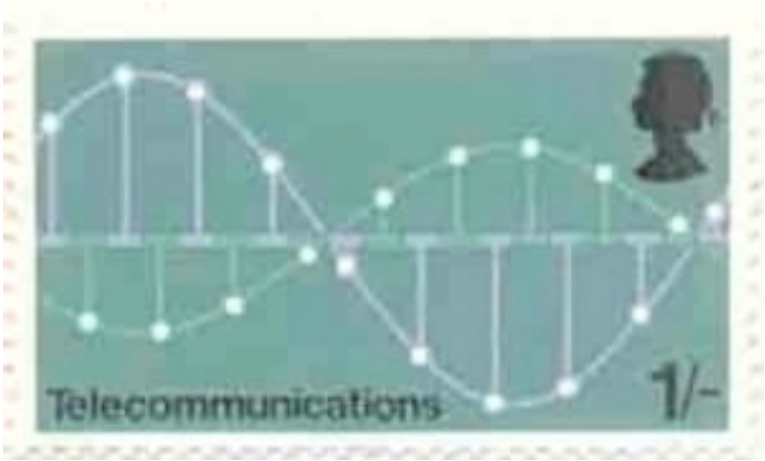
Nyquist's fax machine



Pulse Code Modulation (PCM)

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

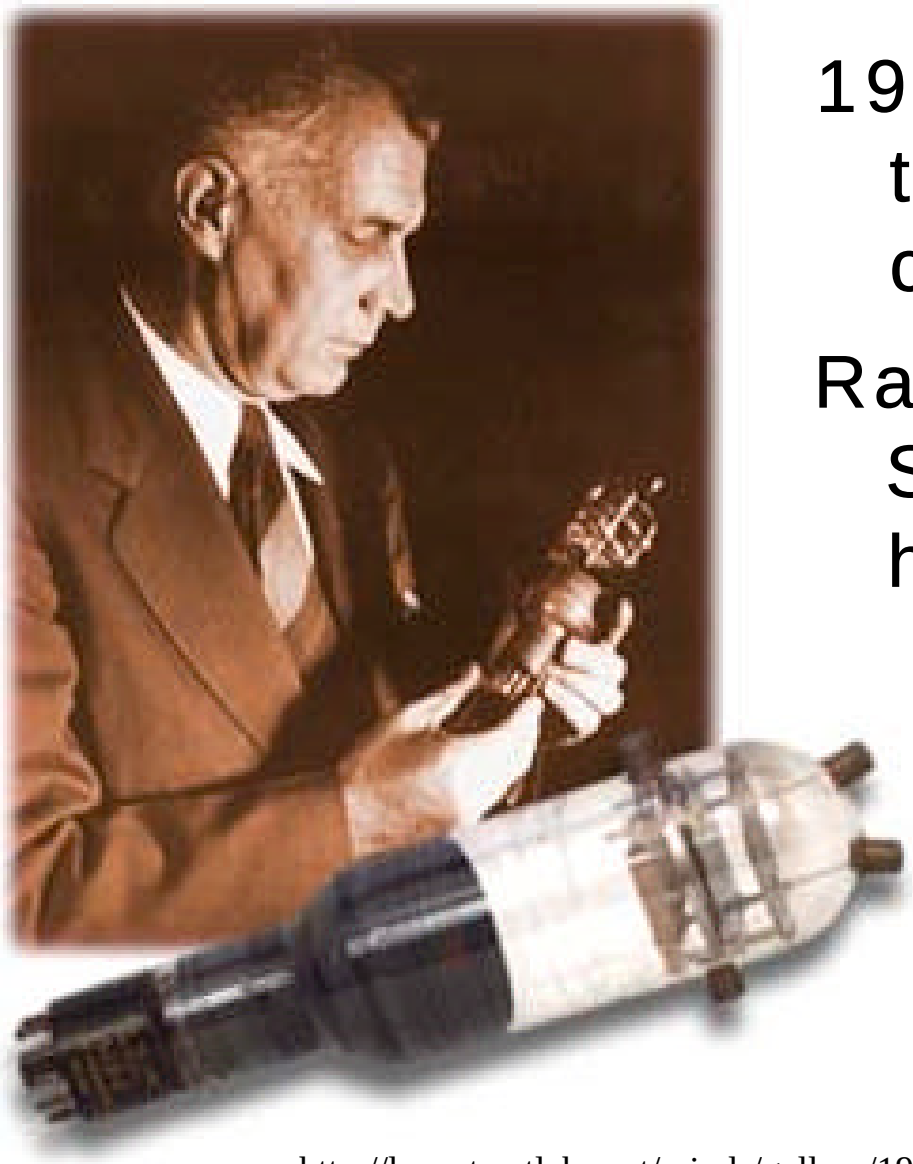




http://www.derivaz.fsnet.co.uk/ahr/pcm.htm

FOVEON

PCM Tube



- 1948 – Vacuum-tube A-to-D converter
- Raymond W. Sears holding his invention

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

Transistor

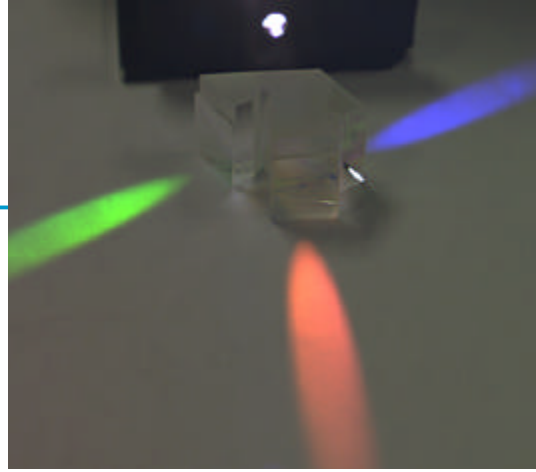
- 1947 – Bipolar Junction Transistor of John Bardeen, Walter Brattain, and William Shockley, at Bell Labs

http://lucent.netlabs.net/minds/gallery/1947trn.html

Television

- Paul Nipkow, Charles F. Jenkins, John L. Baird
- Philo T. Farnsworth: image dissector
- Vladimir K. Zworykin: iconoscope
- Albert Rose: orthiconoscope & image orthicon; figures of merit for TV pickups, film, and the human eye based on detective quantum efficiency; solid-state photoconductivity, electron tunneling, and electron-phonon interactions; "picture element"
- P. K. Weimer: vidicon (photoconductive instead of photoemissive); 1966 thin-film CMOS sensor
- E. I. DeHann: plumbicon (modern TV tube)

Late Twentieth Century:



Steps Toward Electronic Photography

1960: Color-separation beam-splitter prism for television cameras, Philips

1967: MOS image sensor, Peter Noble (Plessey), William List (Westinghouse), P. Weimer et al. (RCA), Gene Weckler, others

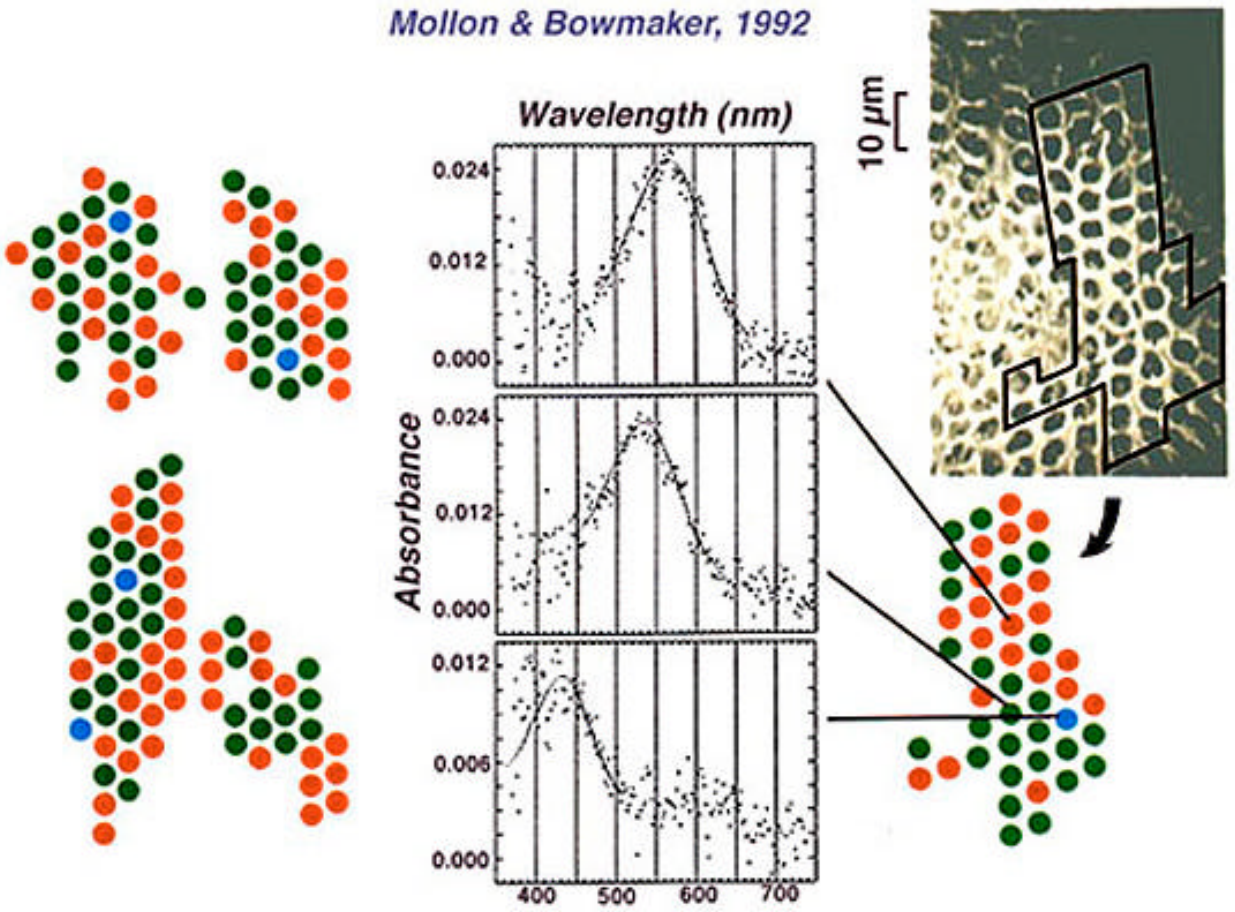
1970: CCD image sensor, Philips, Bell Labs, and Caltech

1975: Bayer pattern for single-chip sensor, Bryce Bayer of Eastman Kodak

1999: Foveon 3-CMOS prism camera

How do Humans See Color?

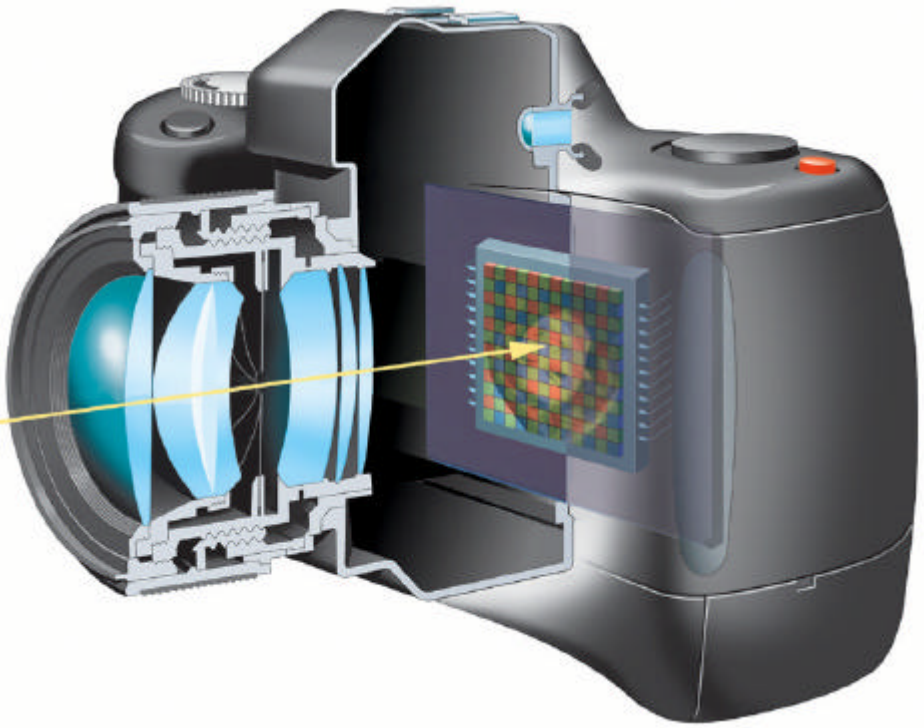
- Packed mosaic of cones in the *fovea centralis* (few blue cones)



Digital Camera Image Sensors

– A Return to Screen Plates

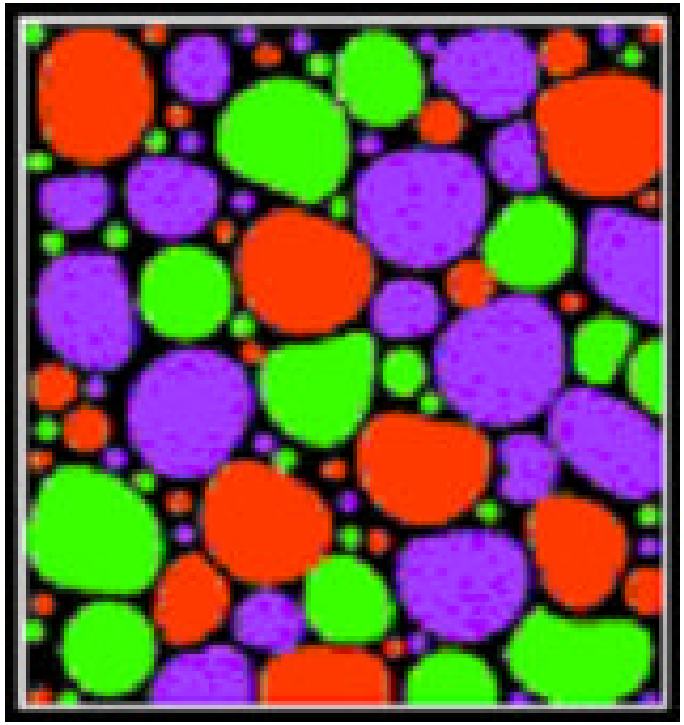
- Light goes through lens and hits image sensor plane.
- Image sensor sees a mosaic pattern of color.
- Camera estimates image color from mosaic pattern.



FOVEON

Tried and True?

1906
Potato starch
on glass plates

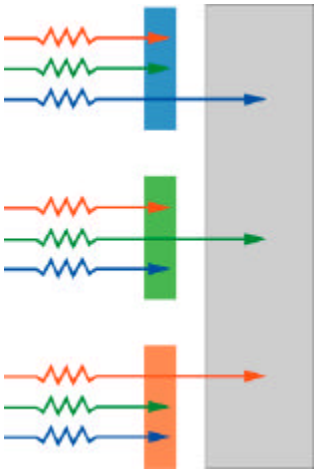


1975
Bayer pattern
on Silicon

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

Mosaic Sampling Artifacts

Mosaic Summary



Throw Away 2/3 of the Light

\+

Throw Away 2/3 of the Information

= Low Quality

			-4	-1	2			
	4	-4	14	-2	9	-14	3	
	-2	-6	-52	-35	-5	9	1	
-6	16	-55	127	161	-35	-1	-1	-4
0	-6	-18	145	127	-51	13	-6	4
	8	-9	-18	-55	-6	-4	1	
	-10	7	-5	16	-3	4	-4	
			1	-7	1			

Organic Filter Processing

\+

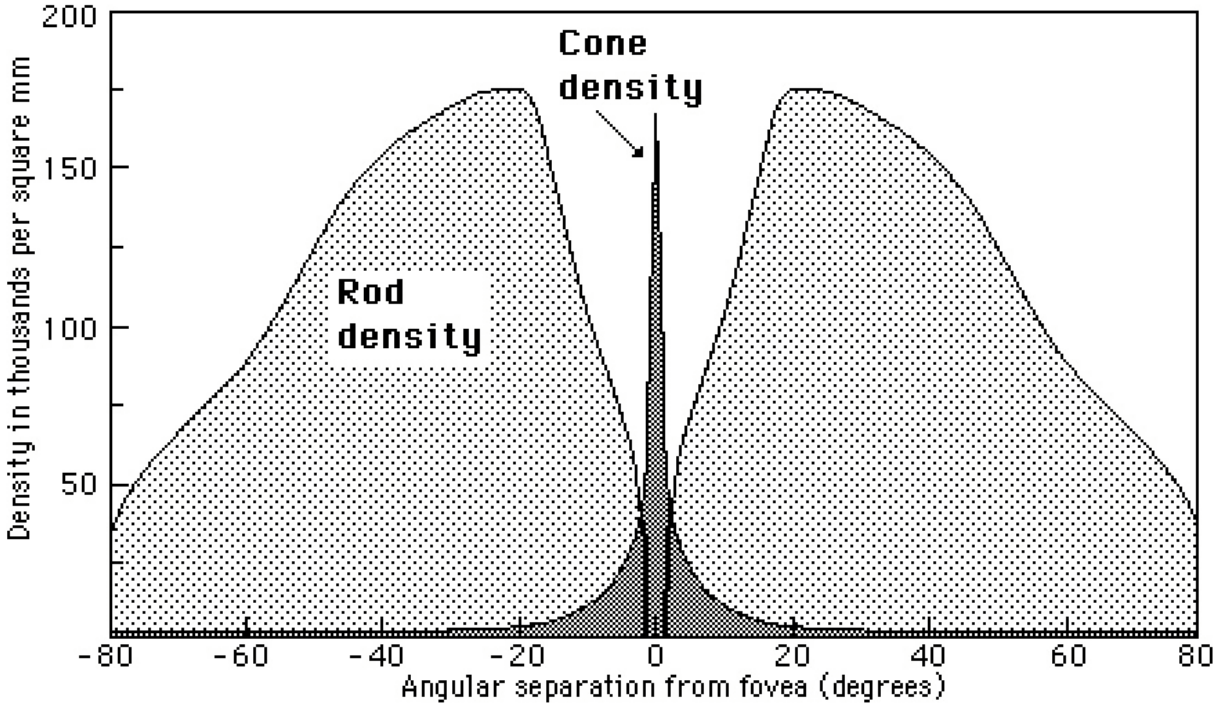
Complex Data Processing

= Expensive

FOVEON

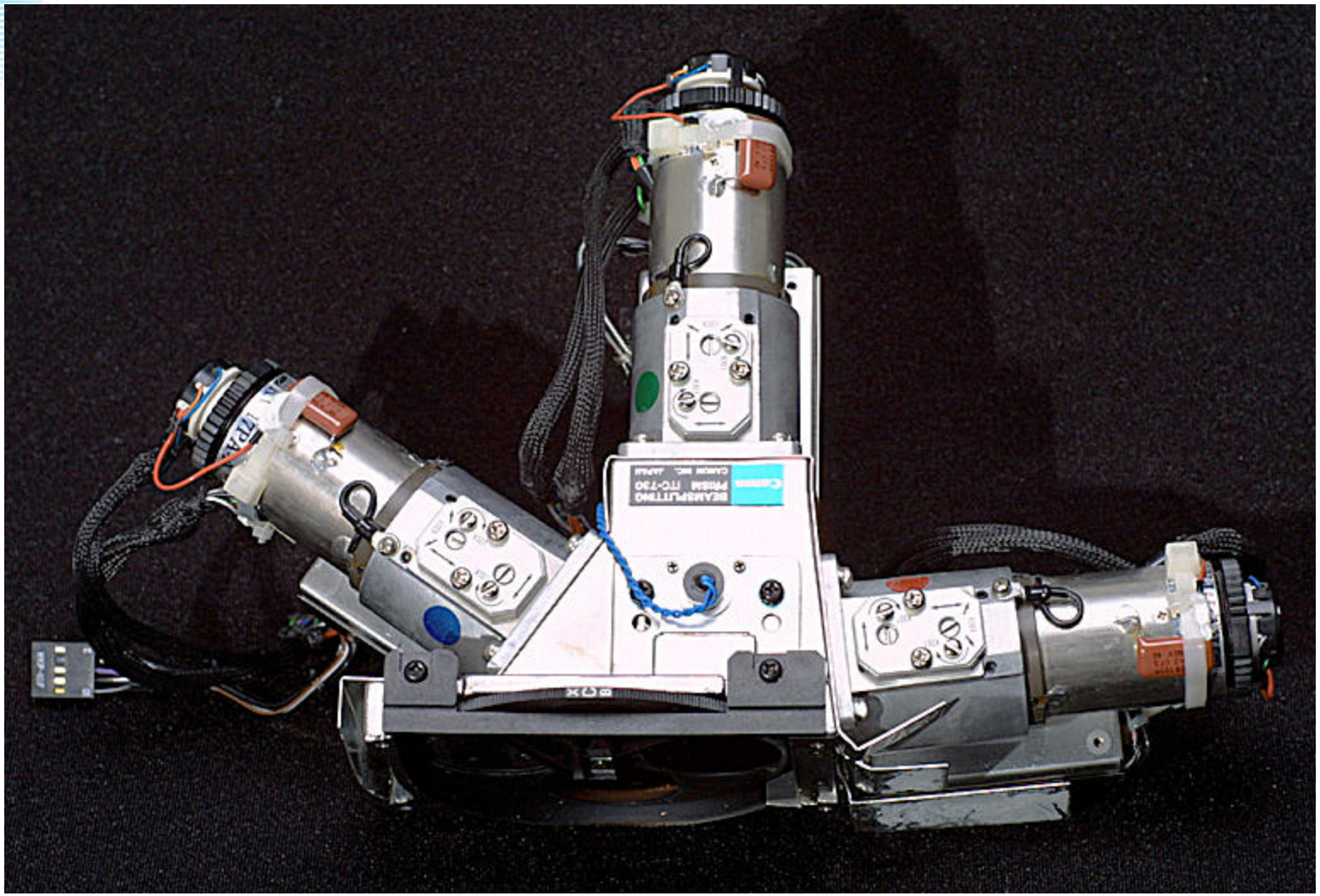
The Fovea, or *Fovea Centralis*

- The central part of the retina, dedicated to high-resolution color imaging – very small area:



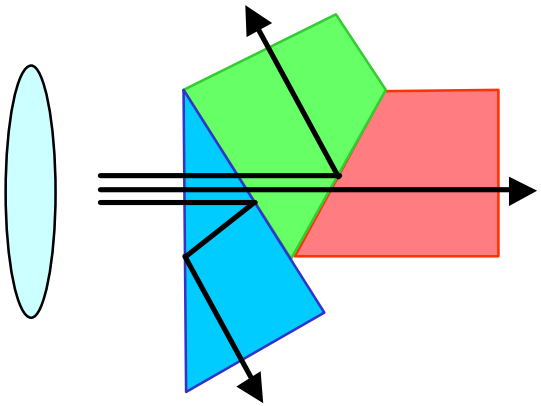
Thanks to: Grade 4 students in Mr. Symington's class and Ms. Phillips's class Briargreen Public School, Spring 2002

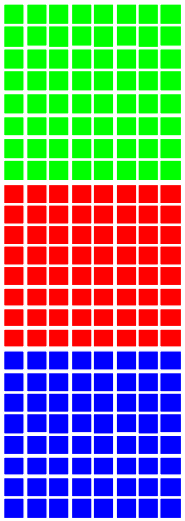
Color Television Camera Tube and Prism Assembly



FOVEON

Prism-based Color Camera





100% green

100% red

100% blue

No guessing!

FOVEON

Recycled Color Techniques

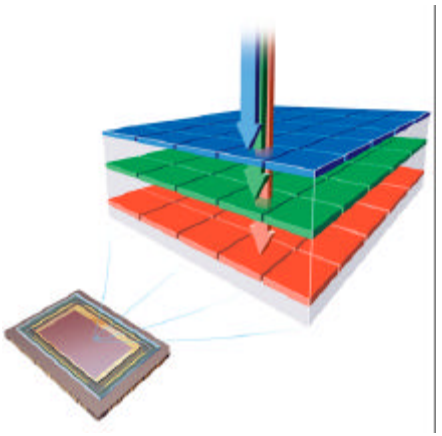
- Mosaics (in common use)
- Three-shot (e.g. Megavision)
- Prism (e.g. Foveon II)

What's left?

Can we copy multi-layered film?

Twenty-First Century

FOVEON



2002 – Foveon X3™

Single-Chip

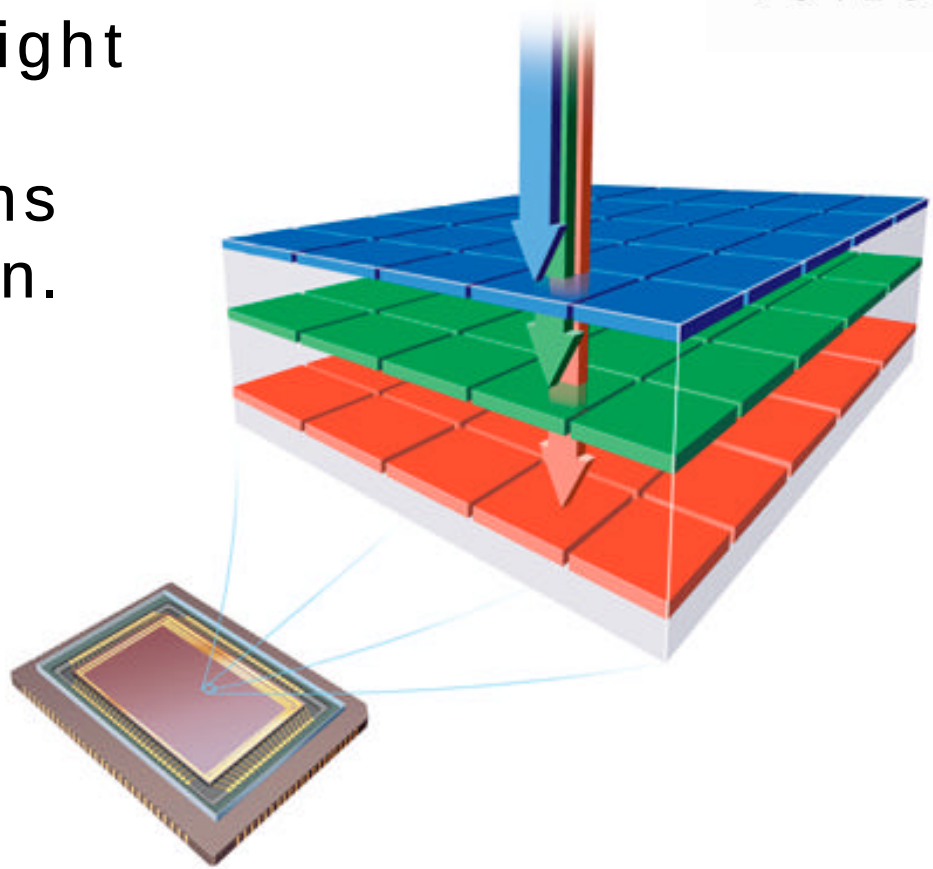
Full-Measured-Color

Image Sensor

Each Location – All 3 Colors

FOVEON

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



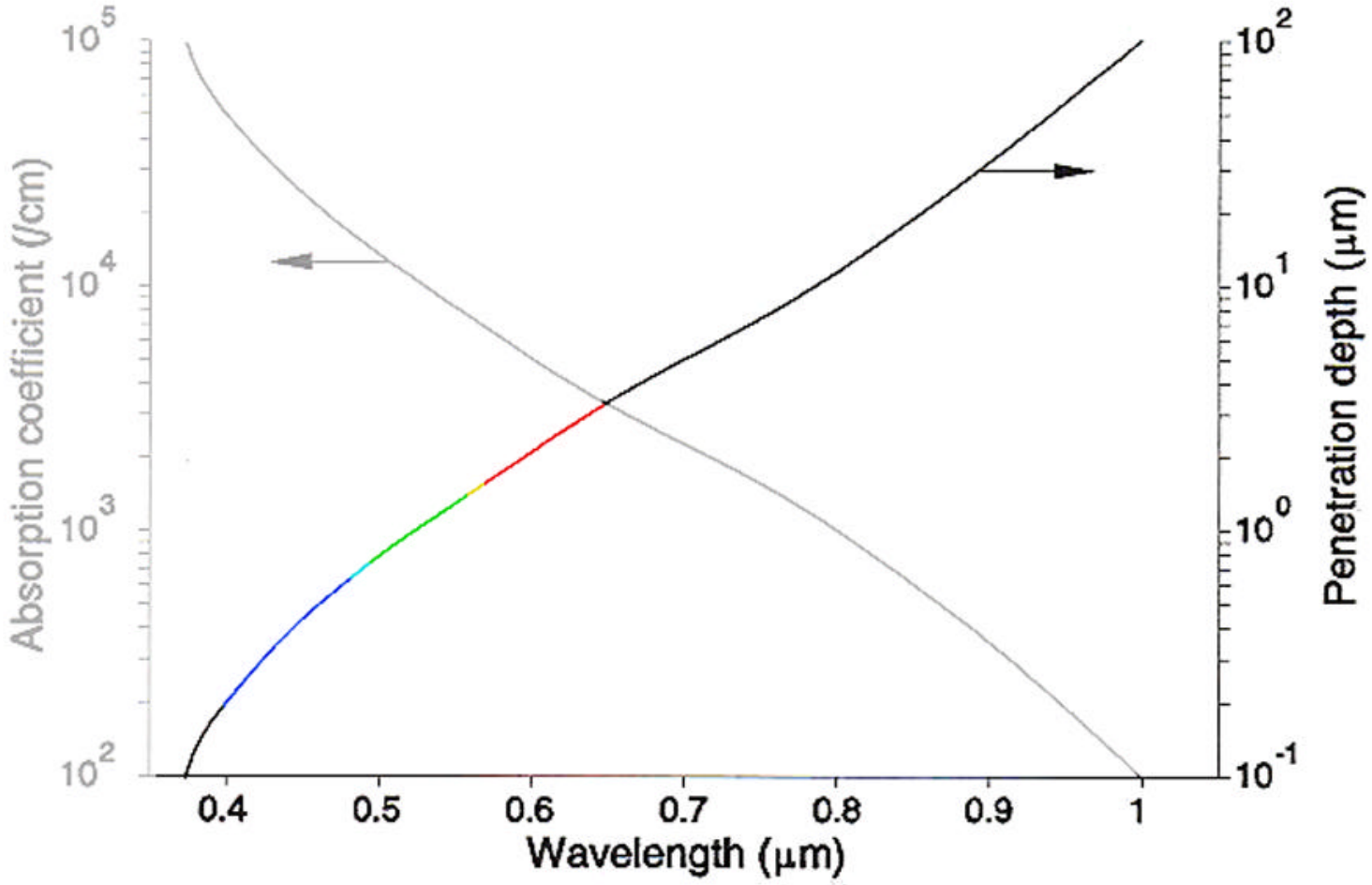
Uses ALL of the Photons

Captures ALL of the Image Information

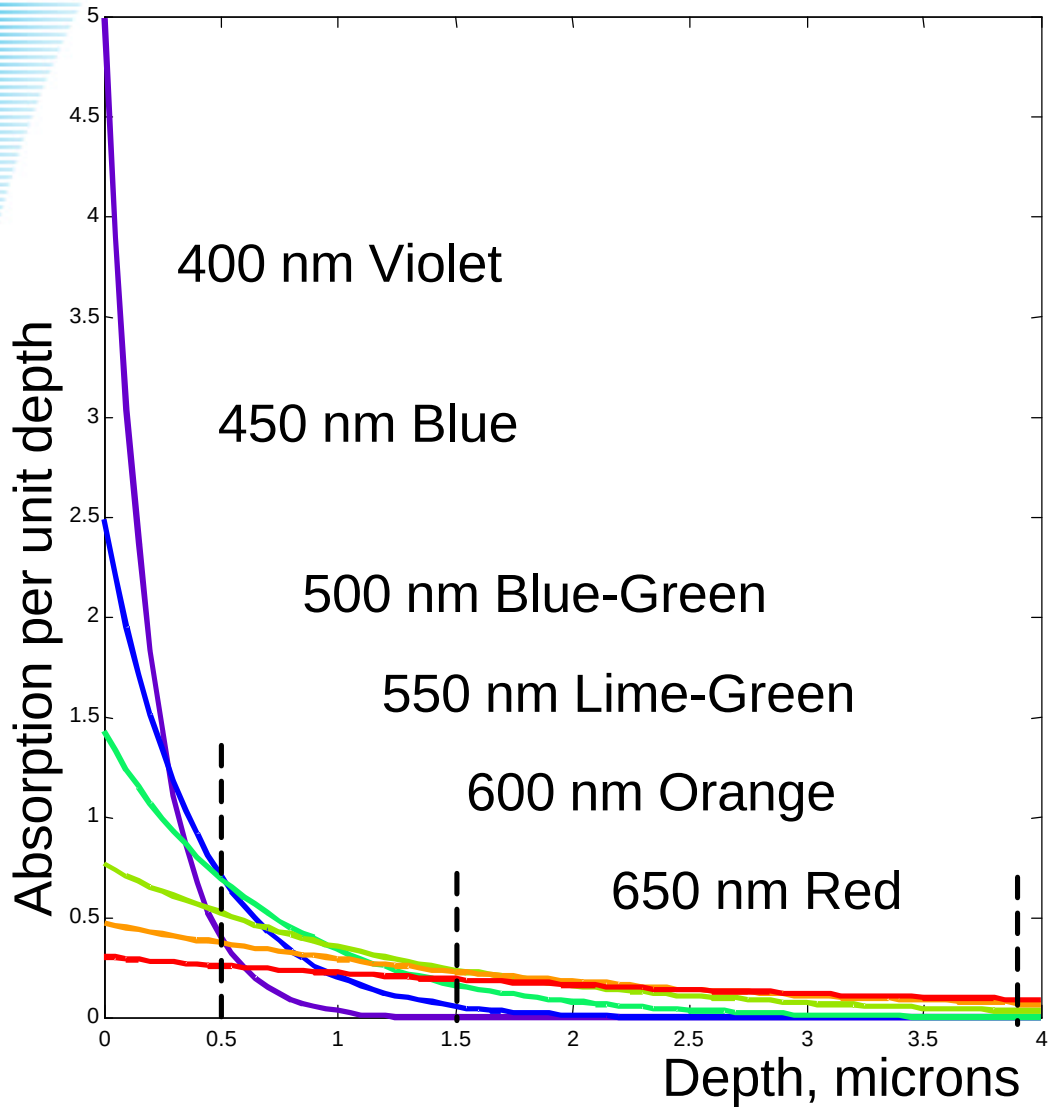
Silicon as a Color Filter

Absorption Coefficient and Penetration Depth in Silicon, vs. Wavelength

from Theuwissen, based on M. H. White 1976



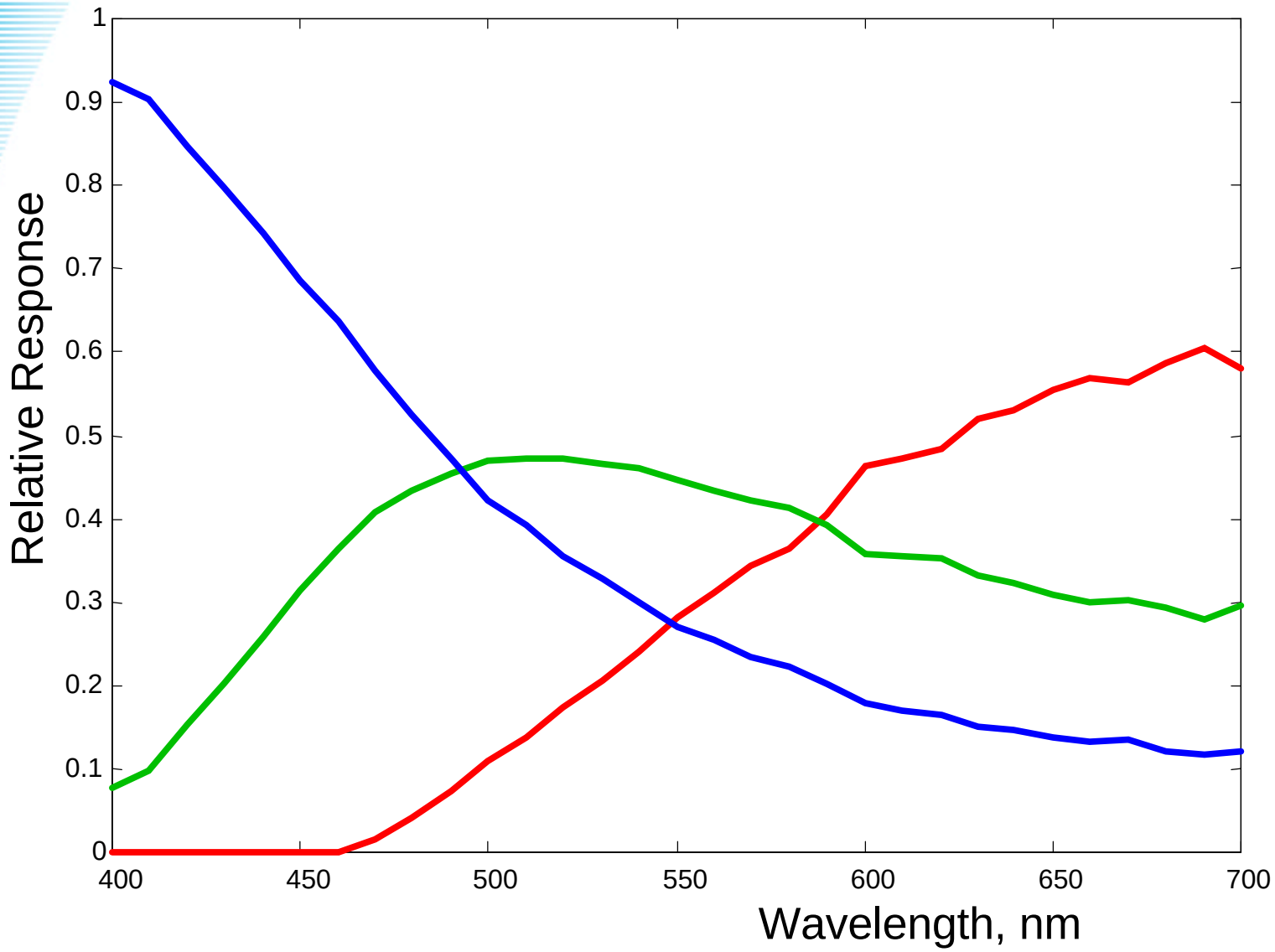
Silicon Color Separation



- Silicon's indirect band-gap makes it semi-transparent
- Absorption is an exponential function of depth for any wavelength
- Higher-energy photons interact more strongly, so have a smaller space constant

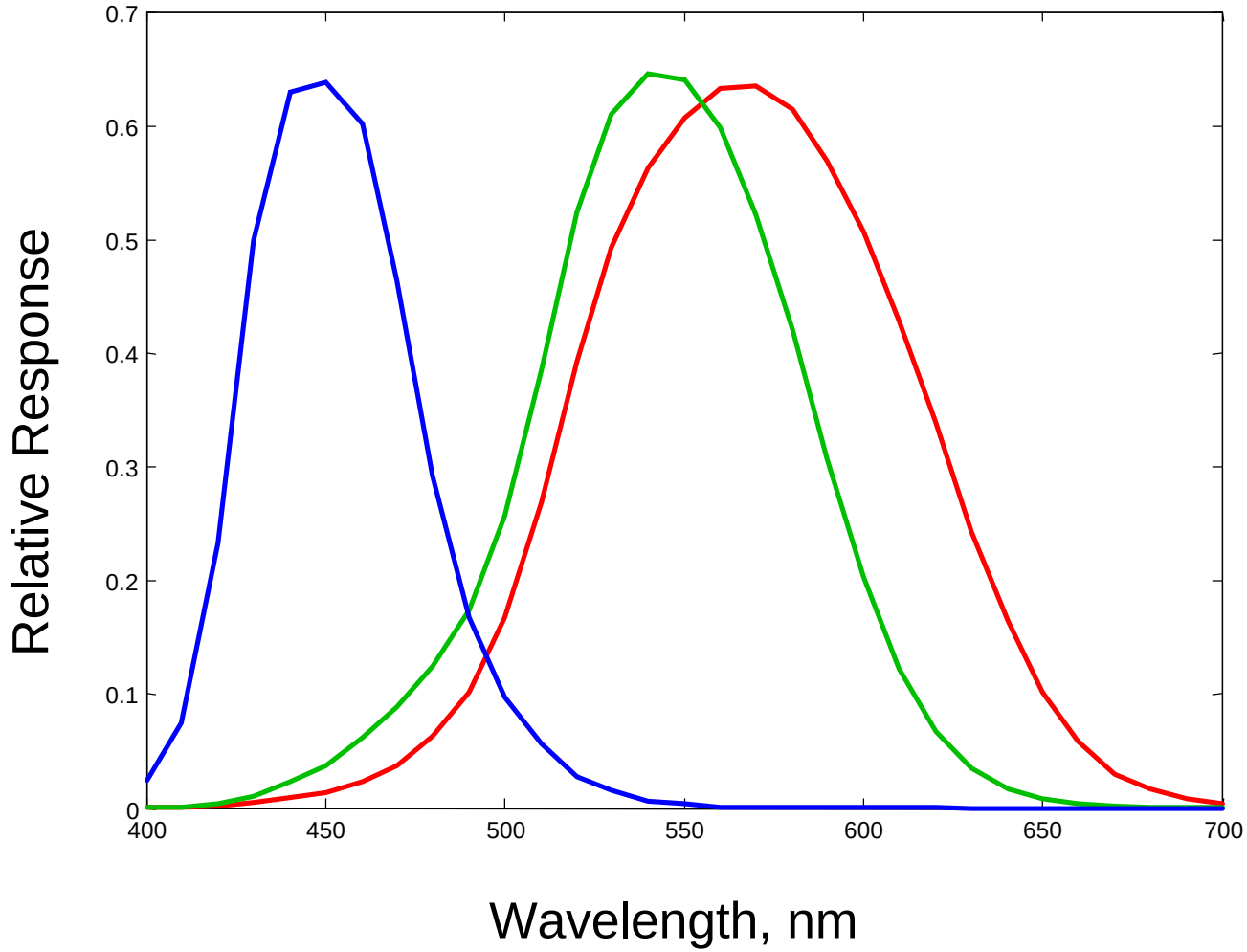
FOVEON

X3 Spectral Response Curves



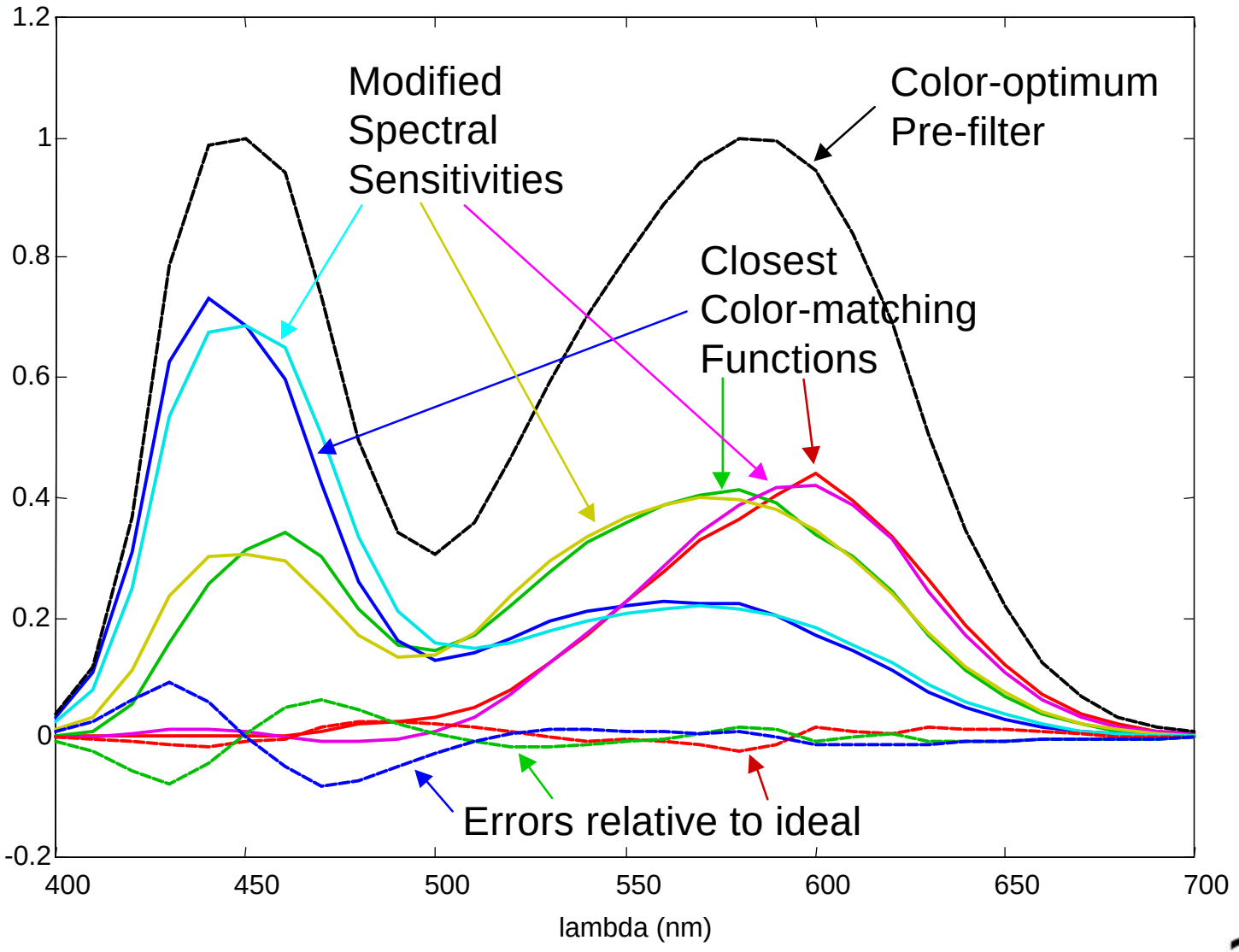
FOVEON

Human Cone Spectral Responses



FOVEON

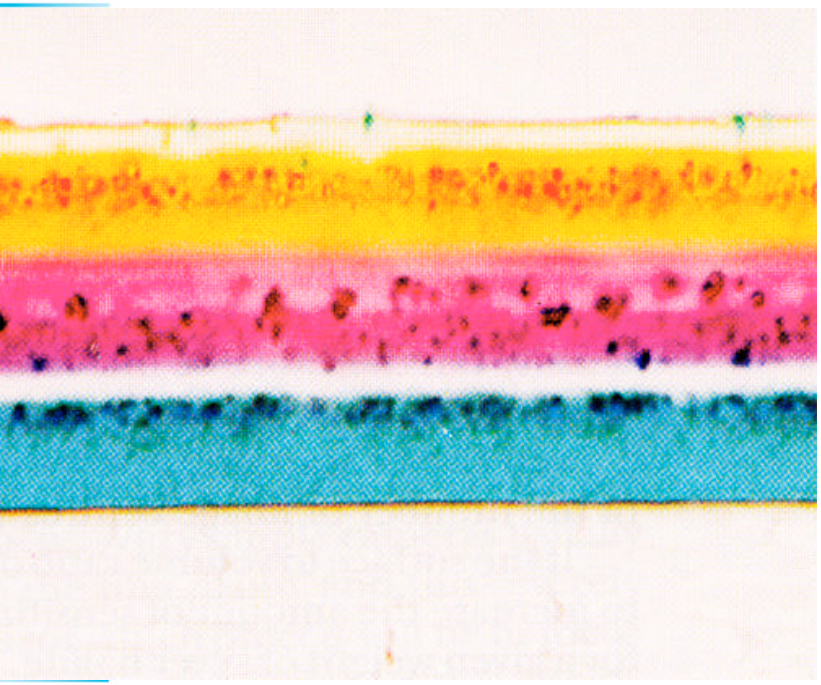
Color-Matching Functions

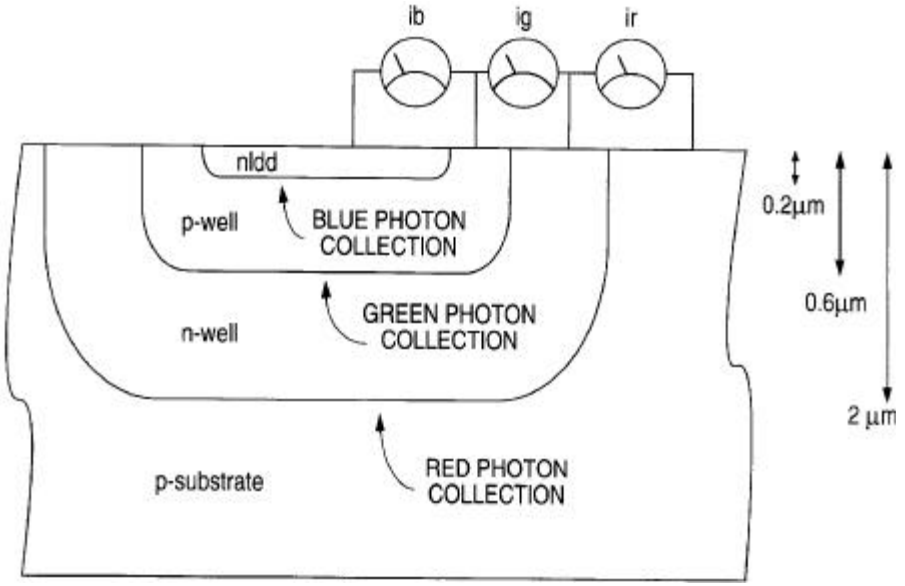


FOVEON

Film versus X3

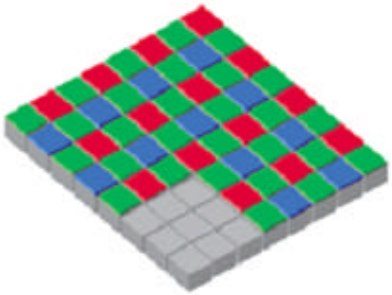
- Kodachrome (left) versus a *vertical-color-filter* detector group in triple-well CMOS (right)

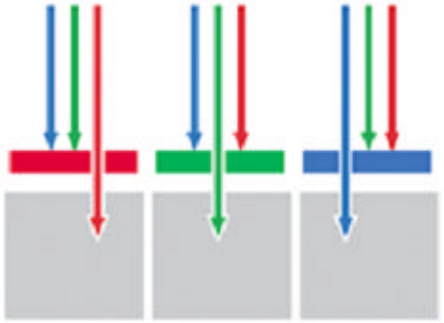




Mosaic Filter vs. Foveon X3

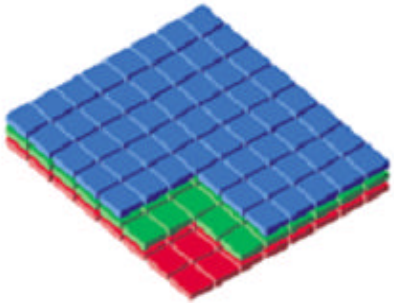
Mosaic Capture

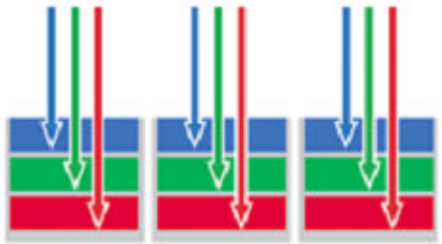




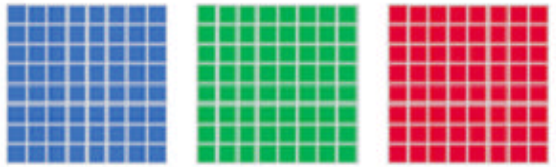
sampling element
is 2x2 'pixels'

Foveon® X3 Capture





sampling element
is 1 'pixel'



works like color film

FOVEON

Fabric with Loops

Mosaic Sensor

Foveon X3

FOVEON

Cereal Box

Mosaic Sensor

Foveon X3

FOVEON

Moiré patterns in cloth

Mosaic Sensor

Foveon X3

FOVEON

The Silicon Solution: Foveon X3

Single-Chip Full-Measured-Color Image Sensor

- Has 3x the color information
  - About 1.7x the spatial resolution
- 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

FOVEON

Sigma SD9 SLR Camera

2268 x 1512 x 3 =

3.4 Million x 3 =

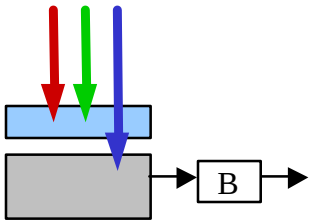
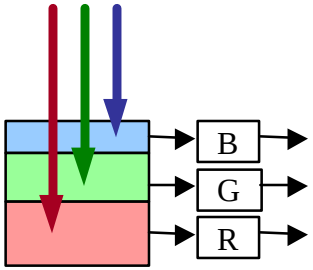
10.2 Million Pixel Sensors (Photodetectors)

FOVEON

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?

Do Vision and Silicon Meet?

- Photodetector mosaic in the human fovea for vision does not mean that a mosaic on silicon is good for photography
- 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

Photography
for the Twenty-First Century