History and Future of Electronic Color Photography:

Where Vision and Silicon Meet

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UC Berkeley Photography class

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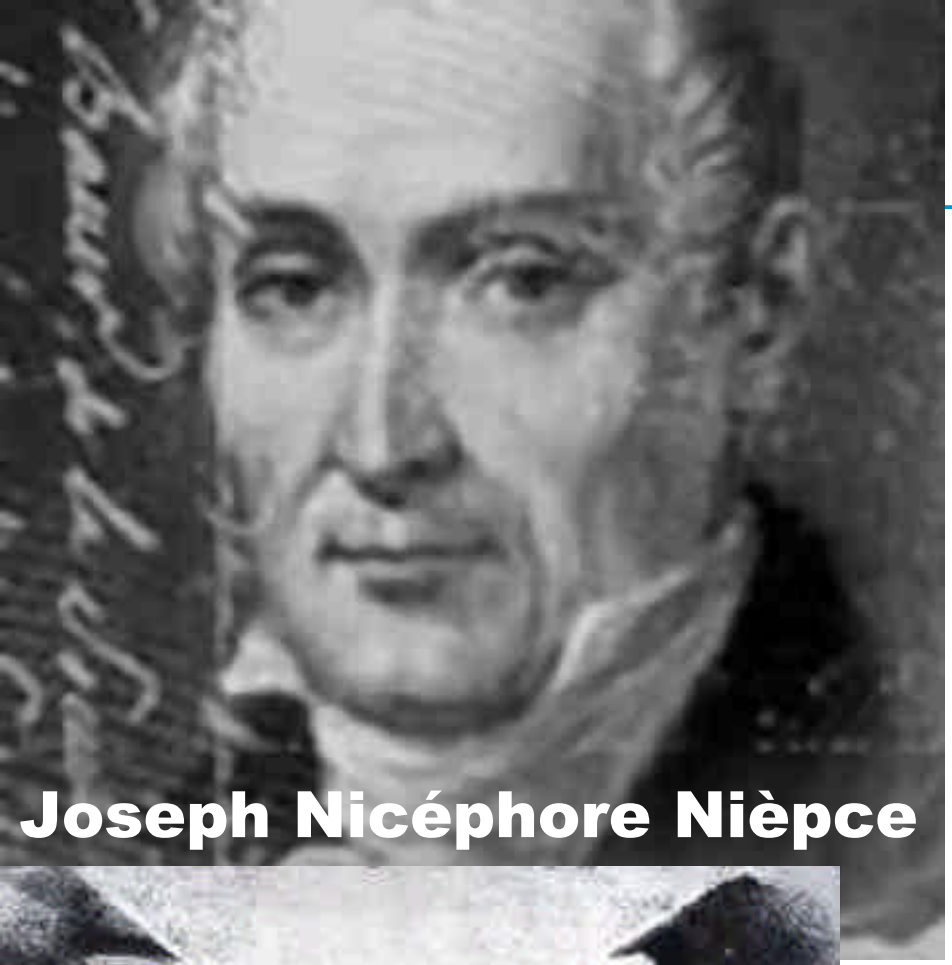
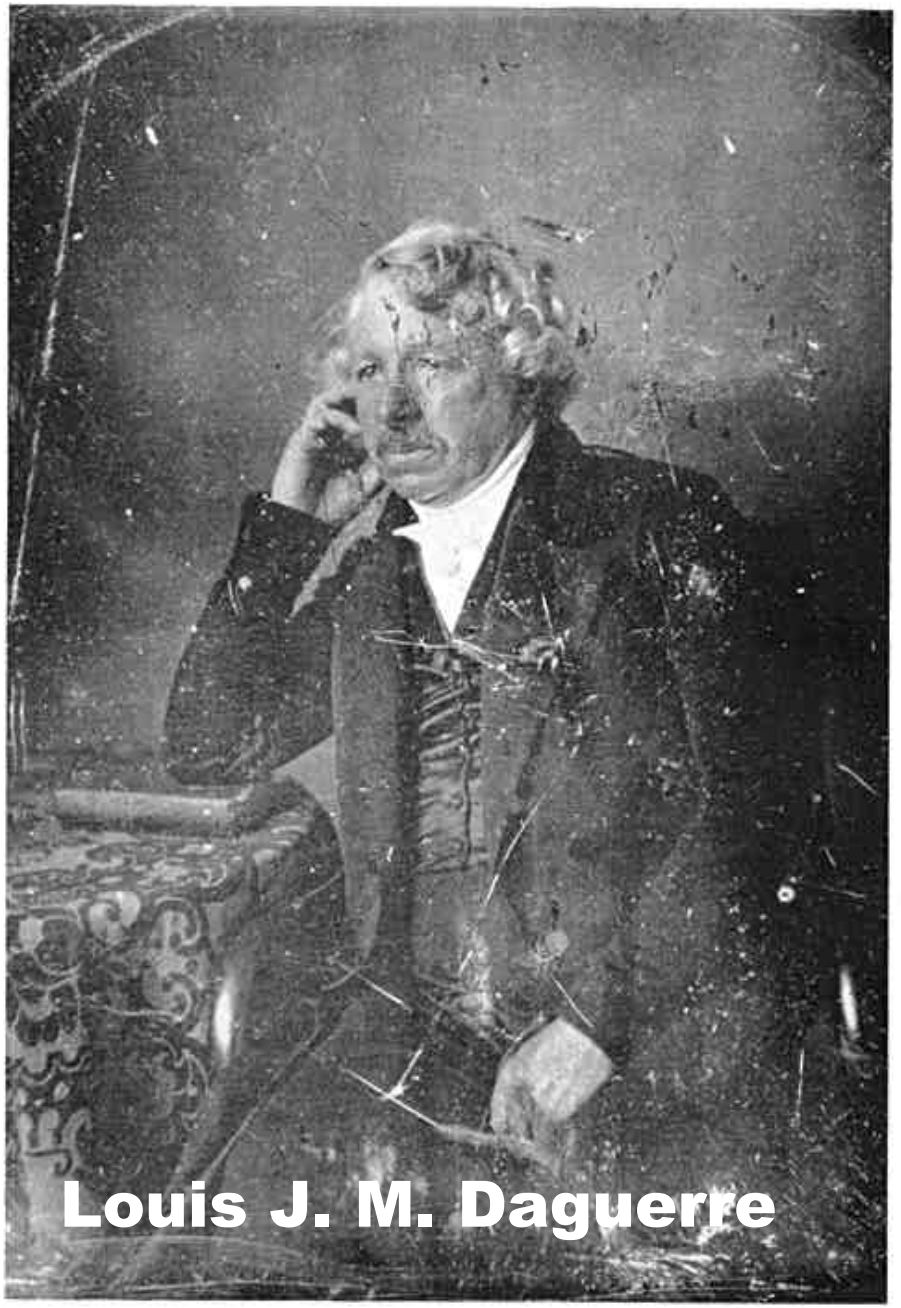
Color Photographic History
– in a nutshell –

- **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

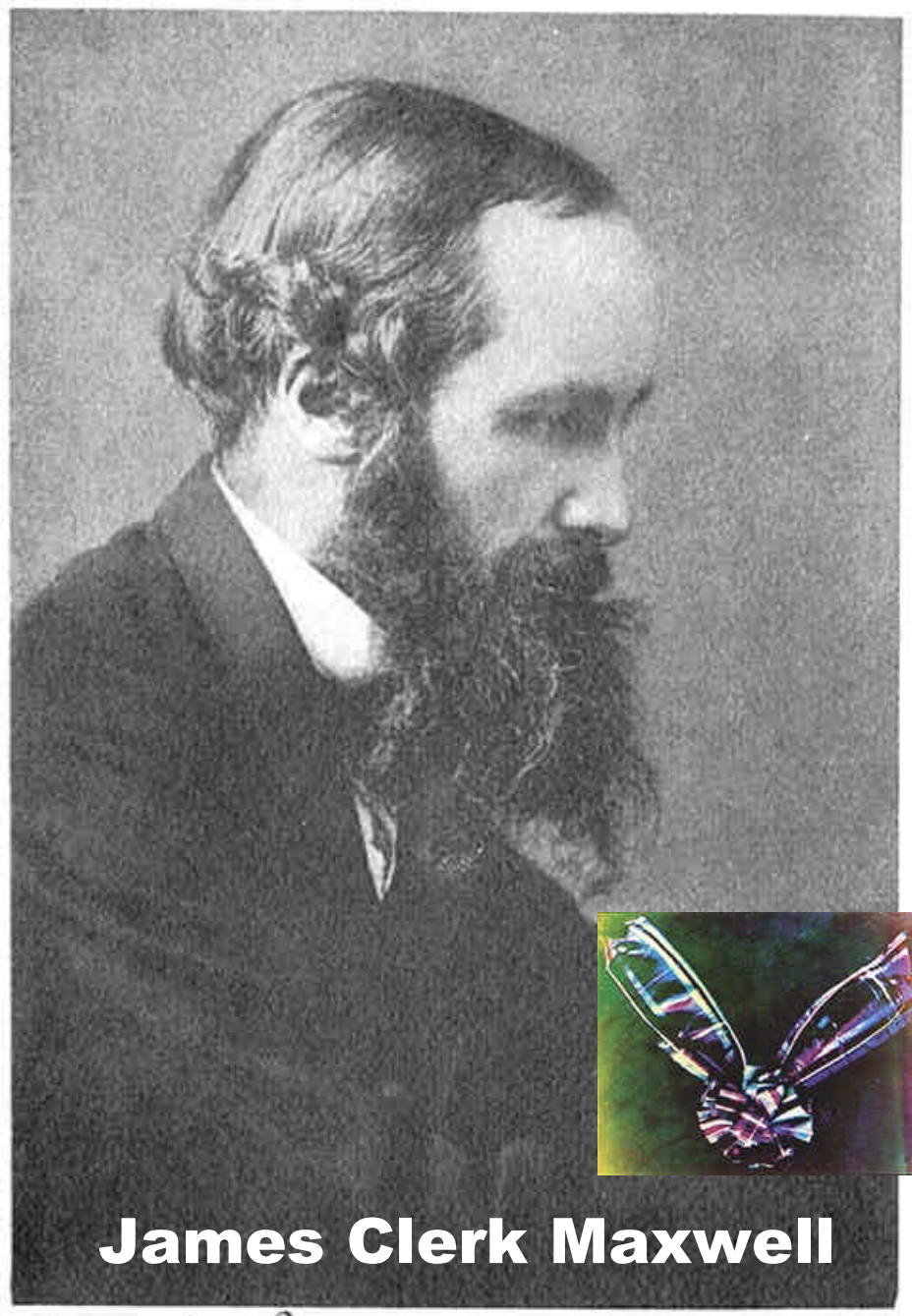


Joseph Nicéphore Nièpce



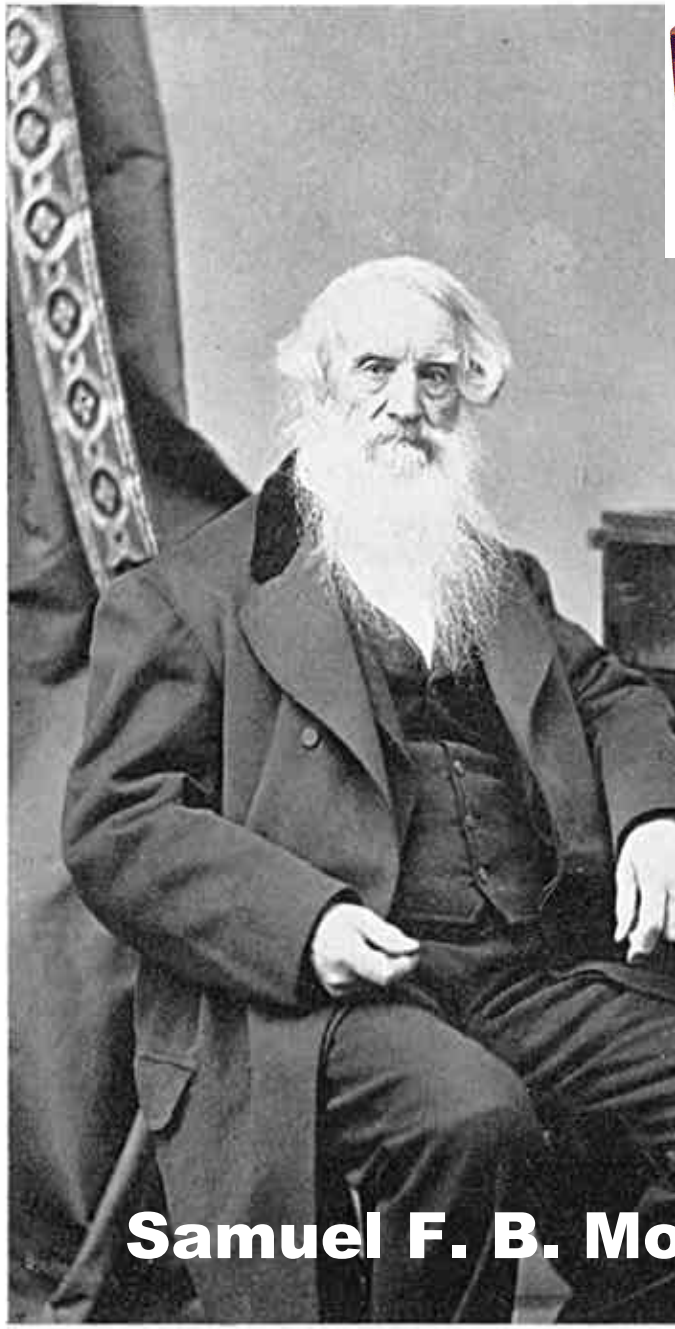
Louis J. M. Daguerre

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.



James Clerk Maxwell

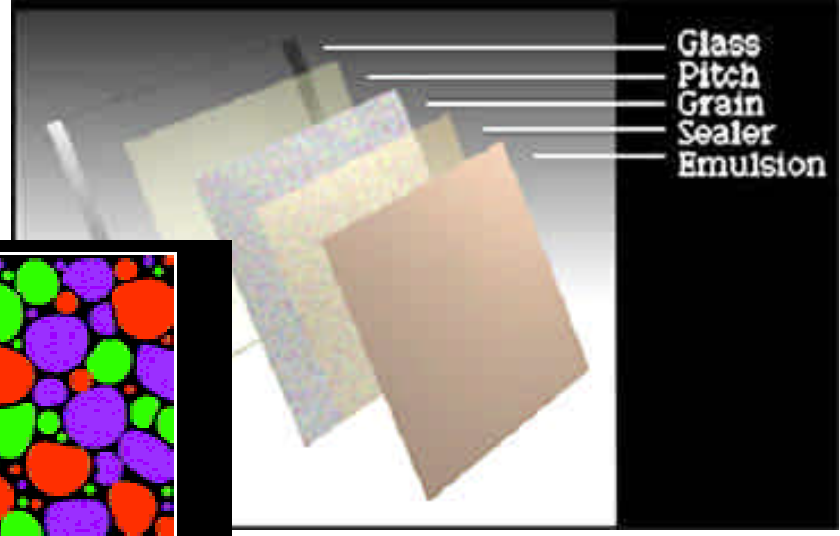
J. Clerk Maxwell

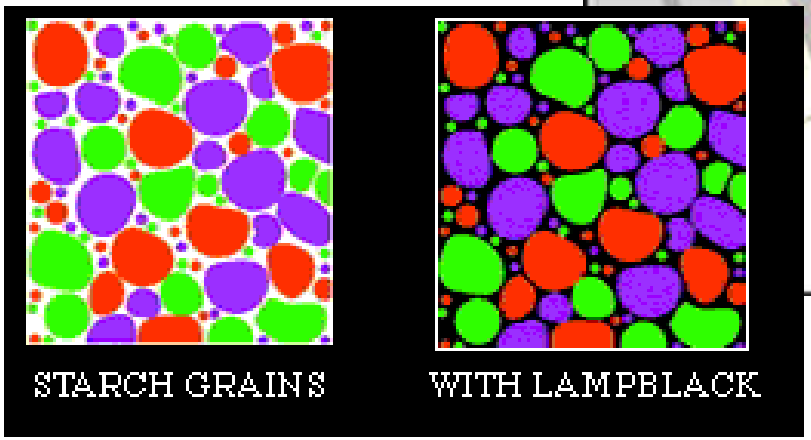


Samuel F. B. Morse

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.)

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**.

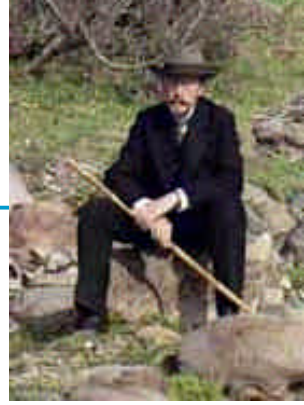
This screen of grains worked as a **filter mosaic**, exposing a panchromatic emulsion. The exposed plate was then reversal processed resulting in a transparency, and was viewed through the same filter grains.

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

Autochrome – Color Filter Mosaic

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

Three-shot color



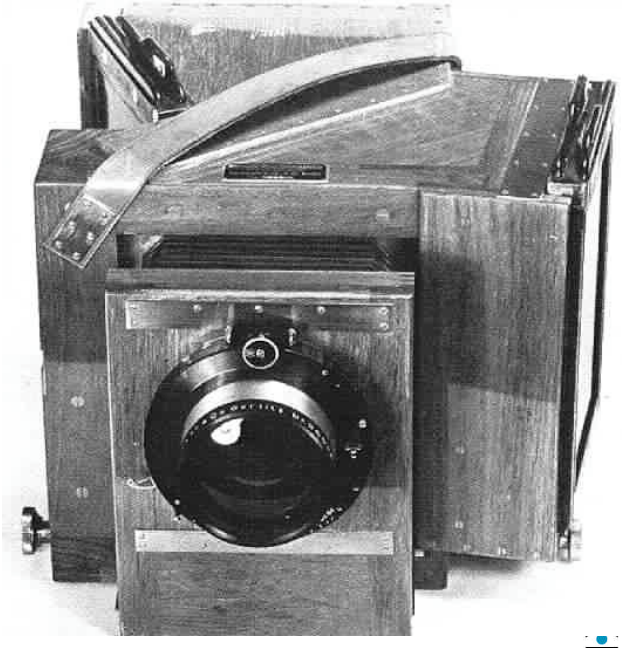
Sergei Mikhailovich Prokudin-Gorskii: Photographer to the Tsar 1908–1915

Austro-Hungarian Prisoners of World War I

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

Color one-shot still cameras

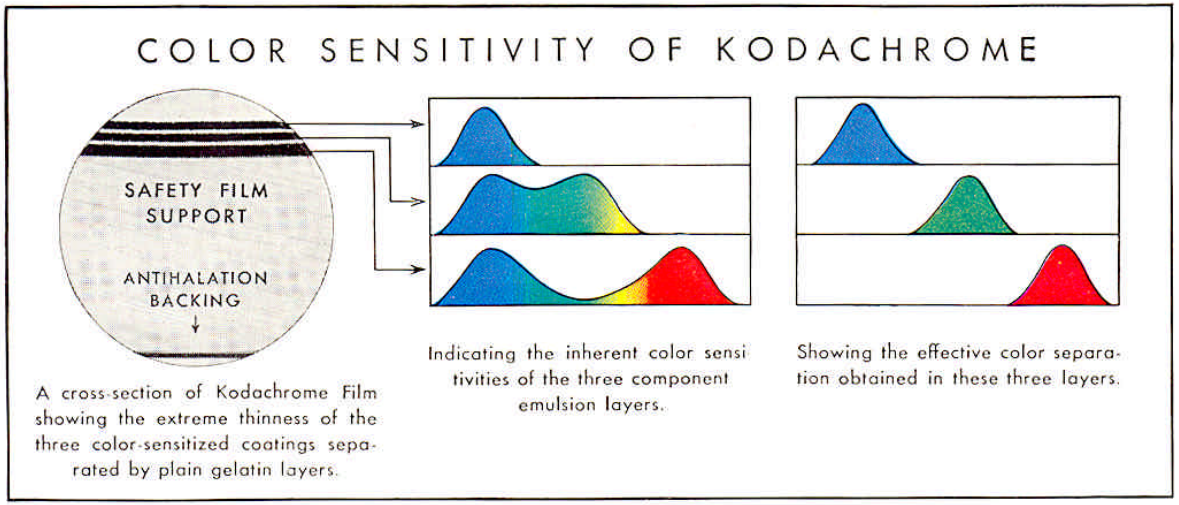
Louis Ducos du Hauron
1873



1932
Devin Tri-Color

The Silver Solution: Kodachrome

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



Senses colors in layers

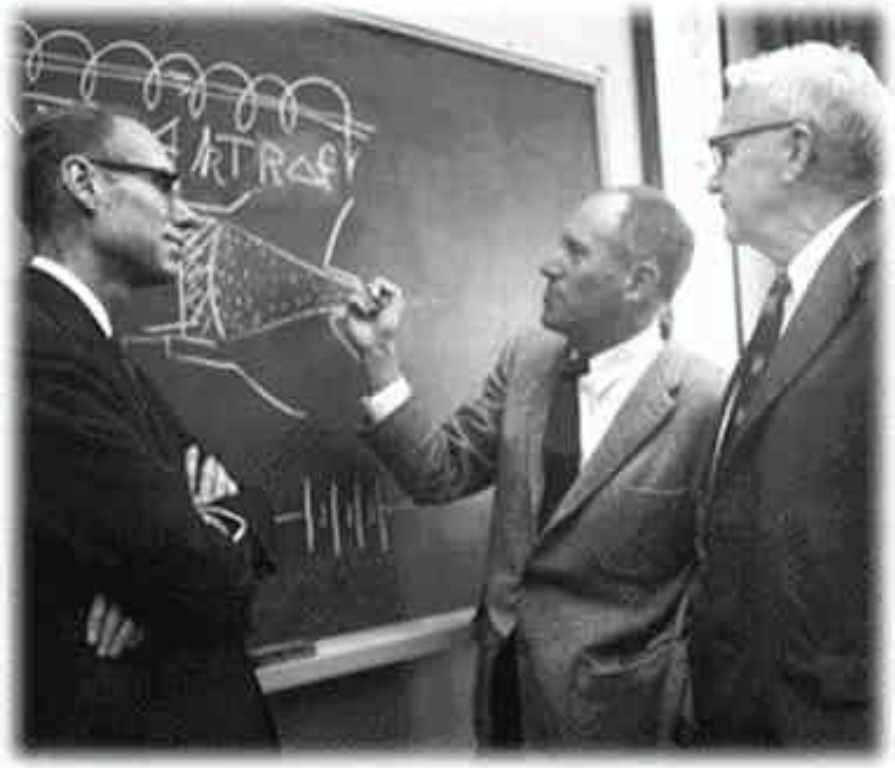
- one shot
  - no motion problems
- all colors at all locations
  - no sampling artifacts
- one piece of film
  - no registration problem

Electronic Image Communication

1888: Telautograph,
Elisha Gray

1902: Telephotography
(photoelectric fax), Arthur Korn

Nyquist and Telephotography

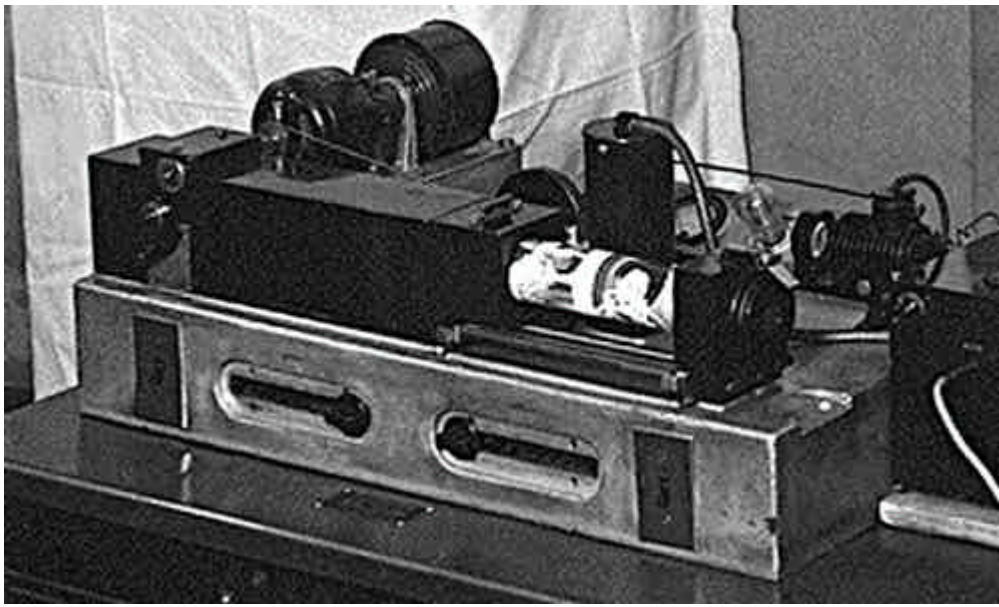


http://lucent.netlabs.net/minds/gallery/1944trw.html

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

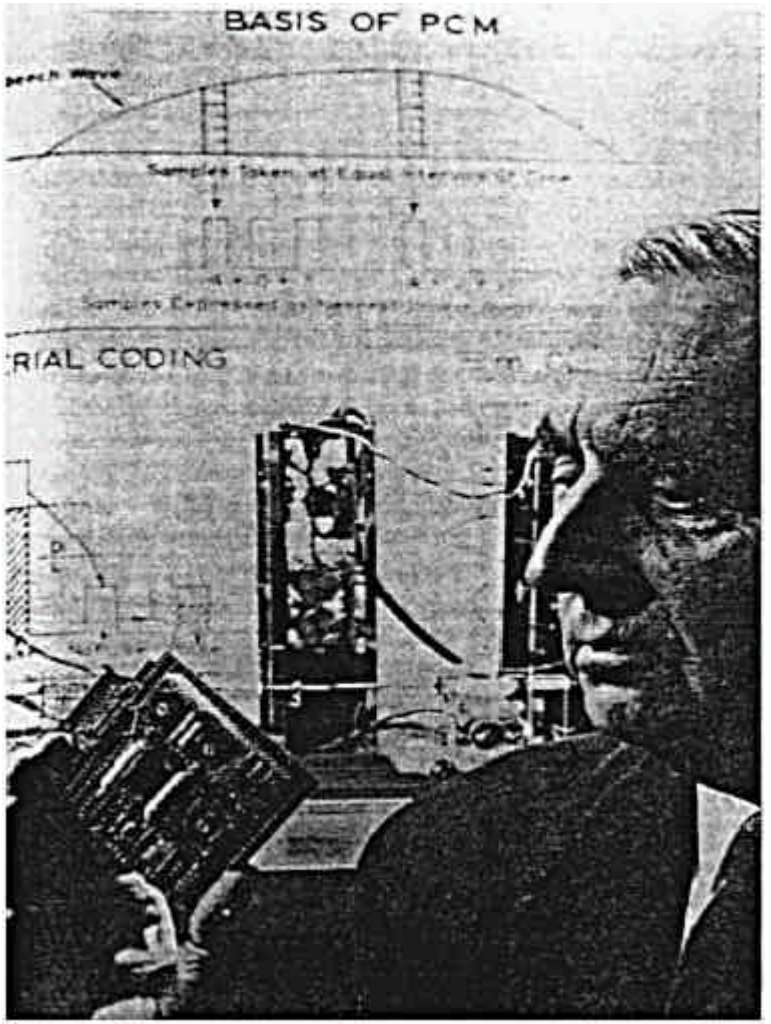
- 1924: Telephotography (Fax)
- 1925: AT&T Wirephoto System
- 1926: Sampling Theorem

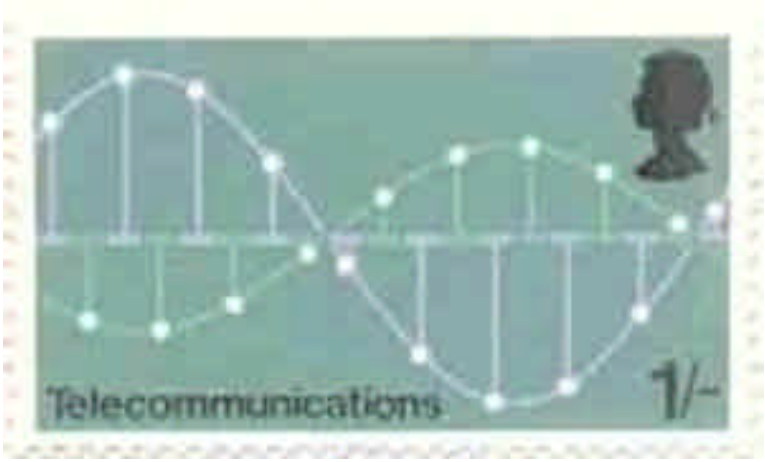
Nyquist's fax machine



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

"The Philosophy of PCM"

John R. Pierce
1910–2002
with TWTA

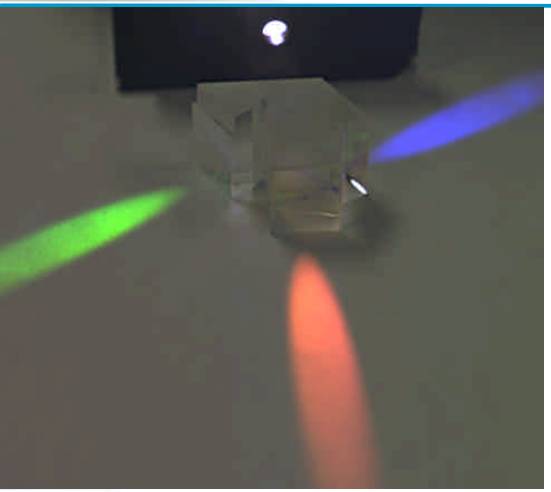
- 1948: **The Philosophy of PCM**, by John Pierce, Claude Shannon, and Barney Oliver (Proc. IRE) led the way to media going digital, starting with the Bell System's voice transmission network
- 1951: Digital image coding kicked off by W. M. Goodall, **Television by Pulse Code Modulation**, BSTJ(30) 1951

Three-Shot Color Photography with Vidicon TV Tube

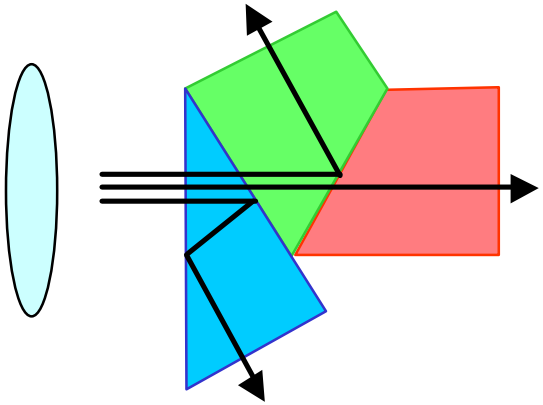
Surveyor 1 – 1966

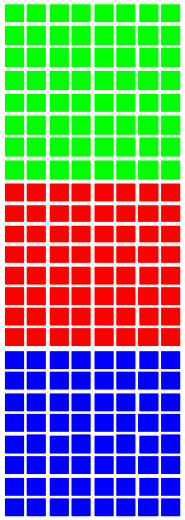
http://history.nasa.gov/SP-168/section2b.htm
http://nssdc.gsfc.nasa.gov/database/MasterCatalog?sc=1966-045A&ex=1

Prism-based Color Camera



2000 – Foveon II





100% green

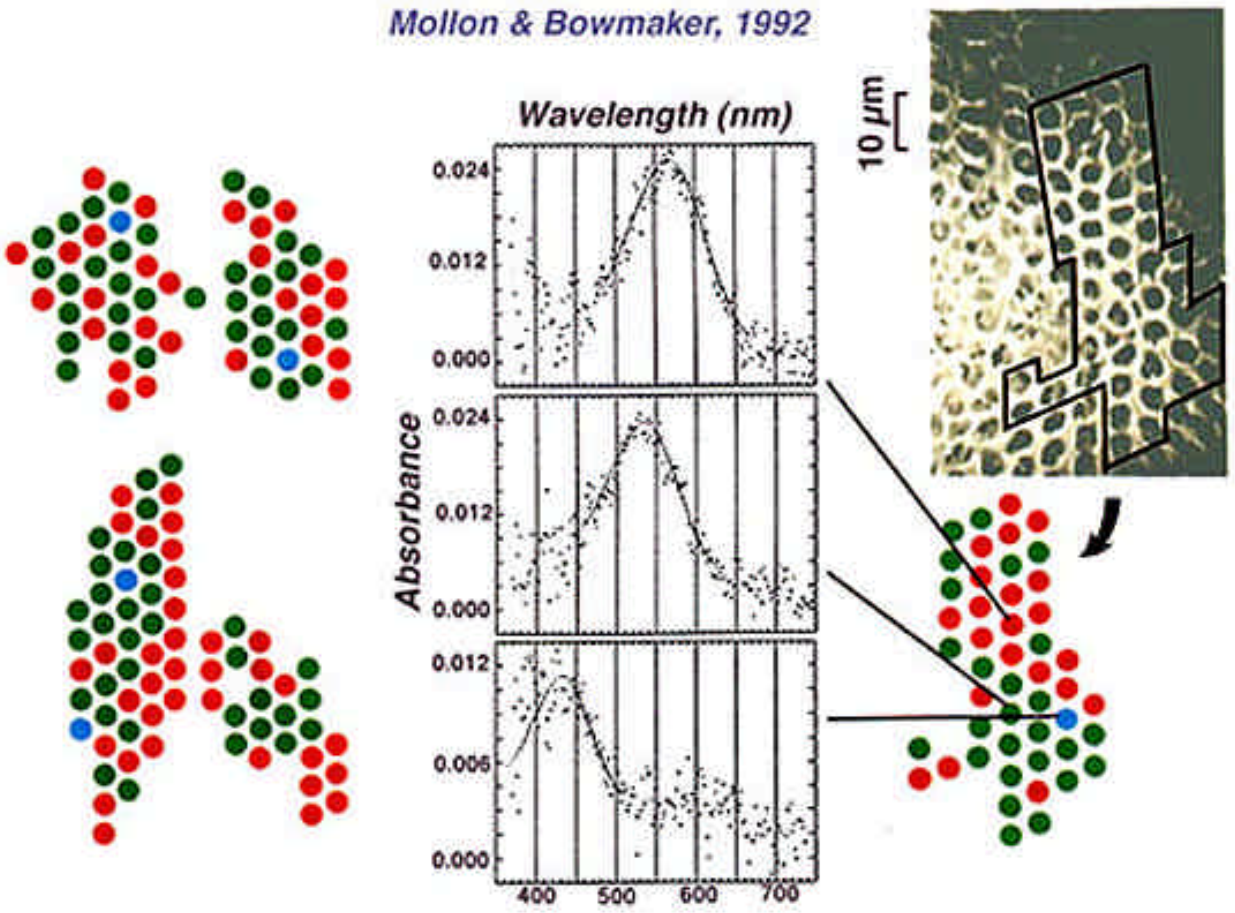
100% red

100% blue

No guessing!

How do Humans See Color?

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



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

United States Patent [19]

Bayer

[11] **3,971,065**

[45] **July 20, 1976**

[54] **COLOR IMAGING ARRAY**

[75] Inventor: **Bryce E. Bayer,** Rochester, N.Y.

[73] Assignee: **Eastman Kodak Company,** Rochester, N.Y.

[22] Filed: **Mar. 5, 1975**

[21] Appl. No.: **555,477**

[52] **U.S. Cl.** ..... **358/41;** 350/162 SF; 350/317; 358/44

[51] **Int. Cl.**[2] **H04N 9/24**

[58] **Field of Search** ..... 358/44, 45, 46, 47, 358/48; 350/317, 162 SF; 315/169 TV

[56] **References Cited**

UNITED STATES PATENTS

2,446,791	8/1948	Schroeder	358/44
2,508,267	5/1950	Kasperowicz	358/44
2,884,483	4/1959	Ehrenhaft et al.	358/44
3,725,572	4/1973	Kurokawa et al.	358/46

Primary Examiner—George H. Libman

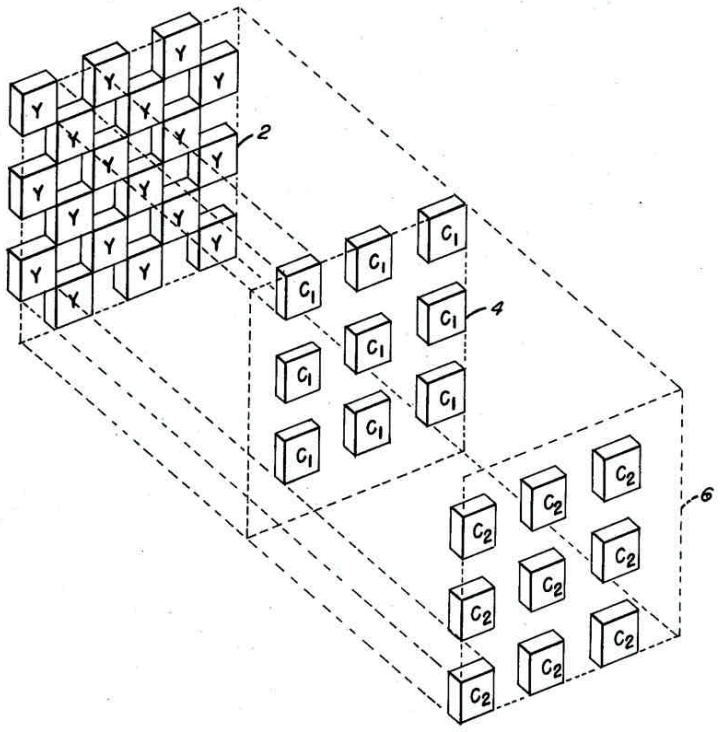
Attorney, Agent, or Firm—George E. Grosser

[57] **ABSTRACT**

A sensing array for color imaging includes individual luminance- and chrominance-sensitive elements that are so intermixed that each type of element (i.e., according to sensitivity characteristics) occurs in a repeated pattern with luminance elements dominating the array. Preferably, luminance elements occur at every other element position to provide a relatively high frequency sampling pattern which is uniform in two perpendicular directions (e.g., horizontal and vertical). The chrominance patterns are interlaid therewith and fill the remaining element positions to provide relatively lower frequencies of sampling.

In a presently preferred implementation, a mosaic of selectively transmissive filters is superposed in registration with a solid state imaging array having a broad range of light sensitivity, the distribution of filter types in the mosaic being in accordance with the above-described patterns.

11 Claims, 10 Drawing Figures



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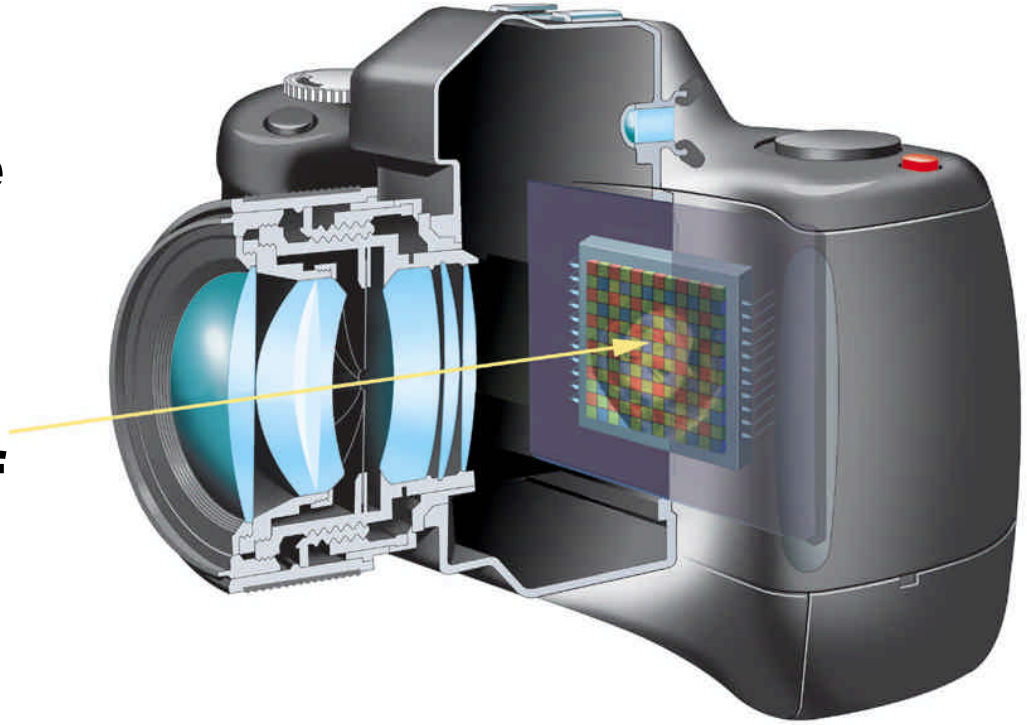
Digital Camera Image Sensors

– 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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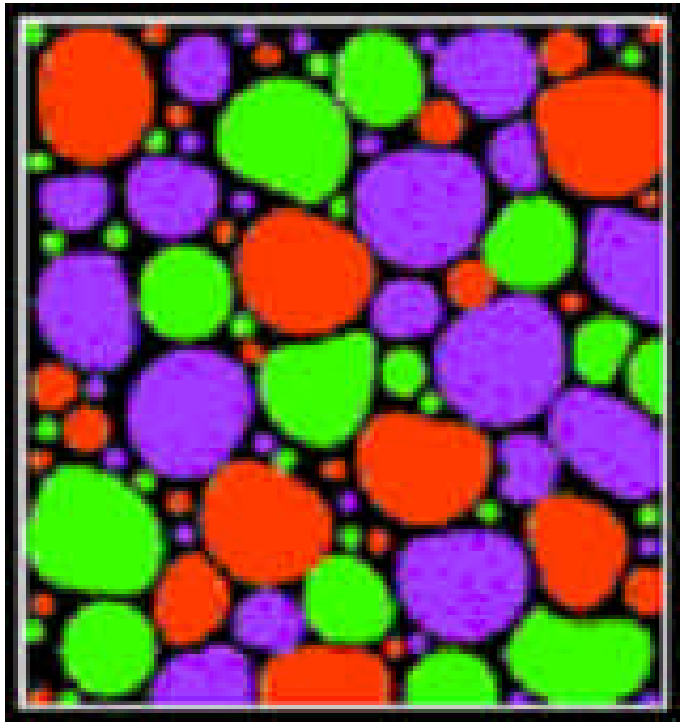
Tried and True?

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

Mosaic Sampling Artifacts

Recycled Color Techniques
in Electronic Cameras

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

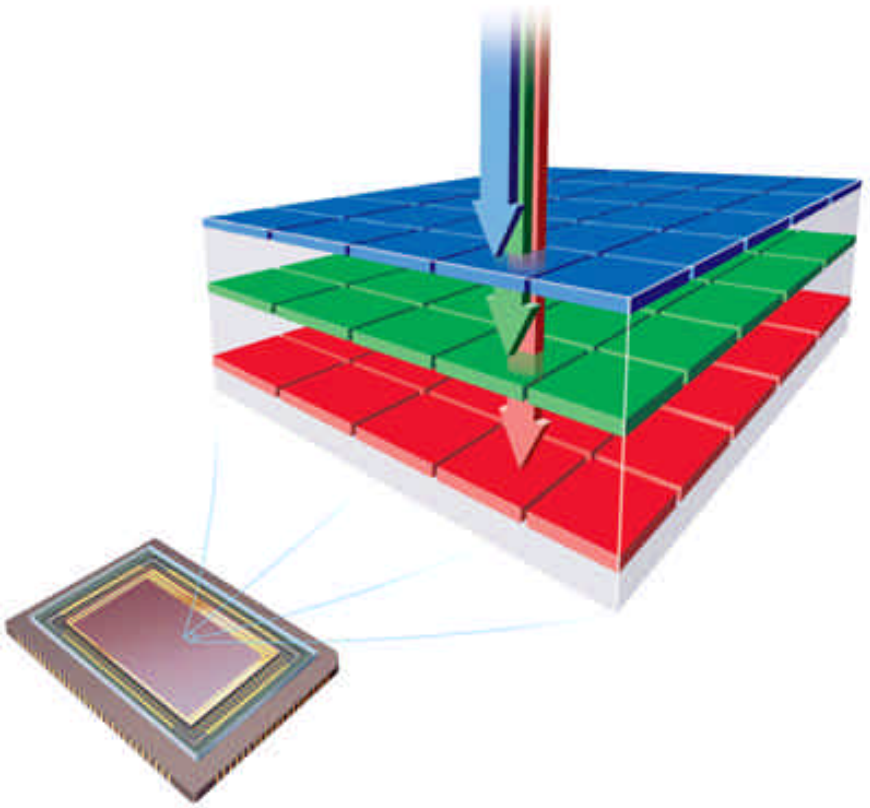
What's left?

Can we copy multi-layered film?

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

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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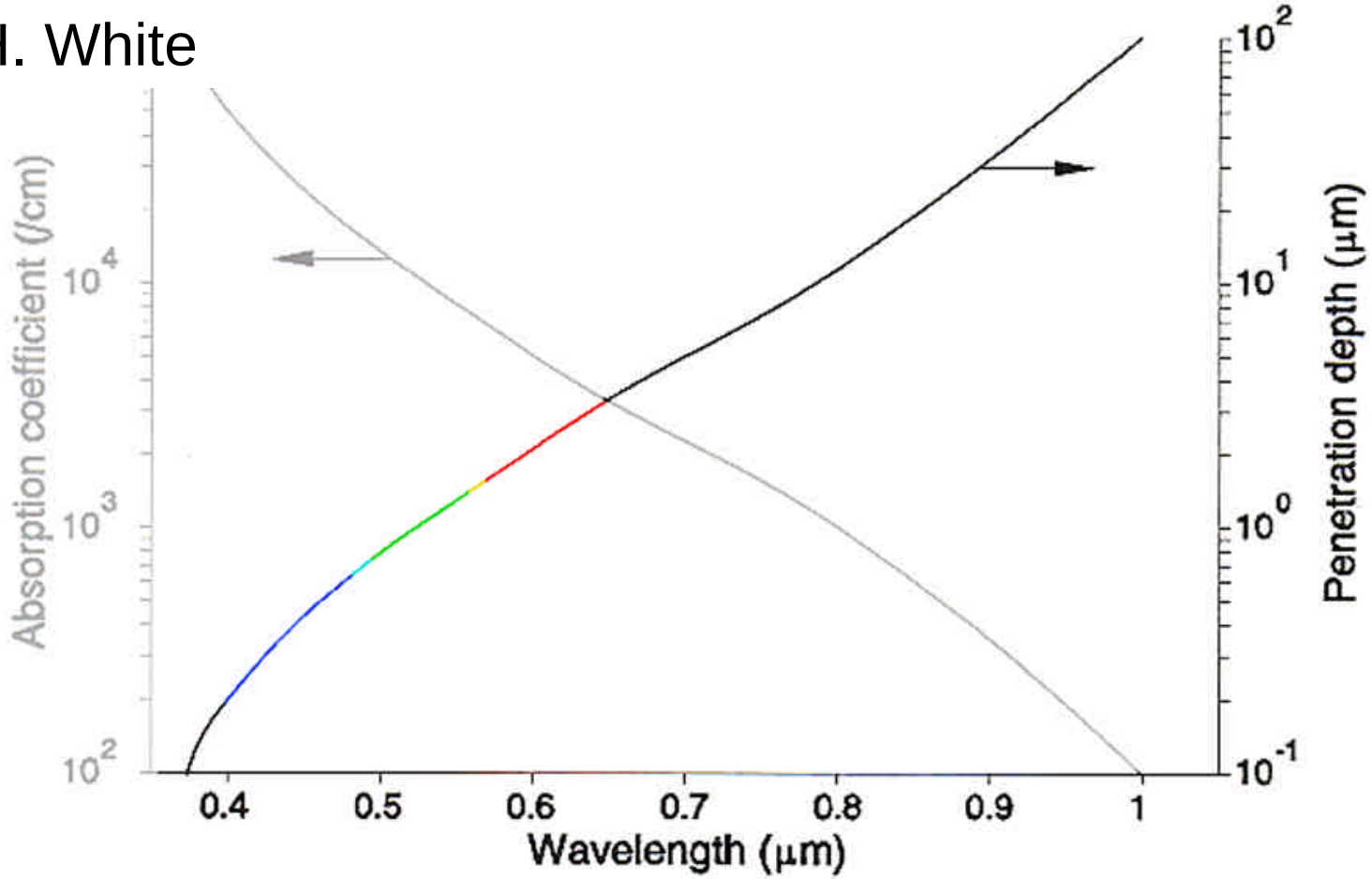
Silicon as a Color Filter

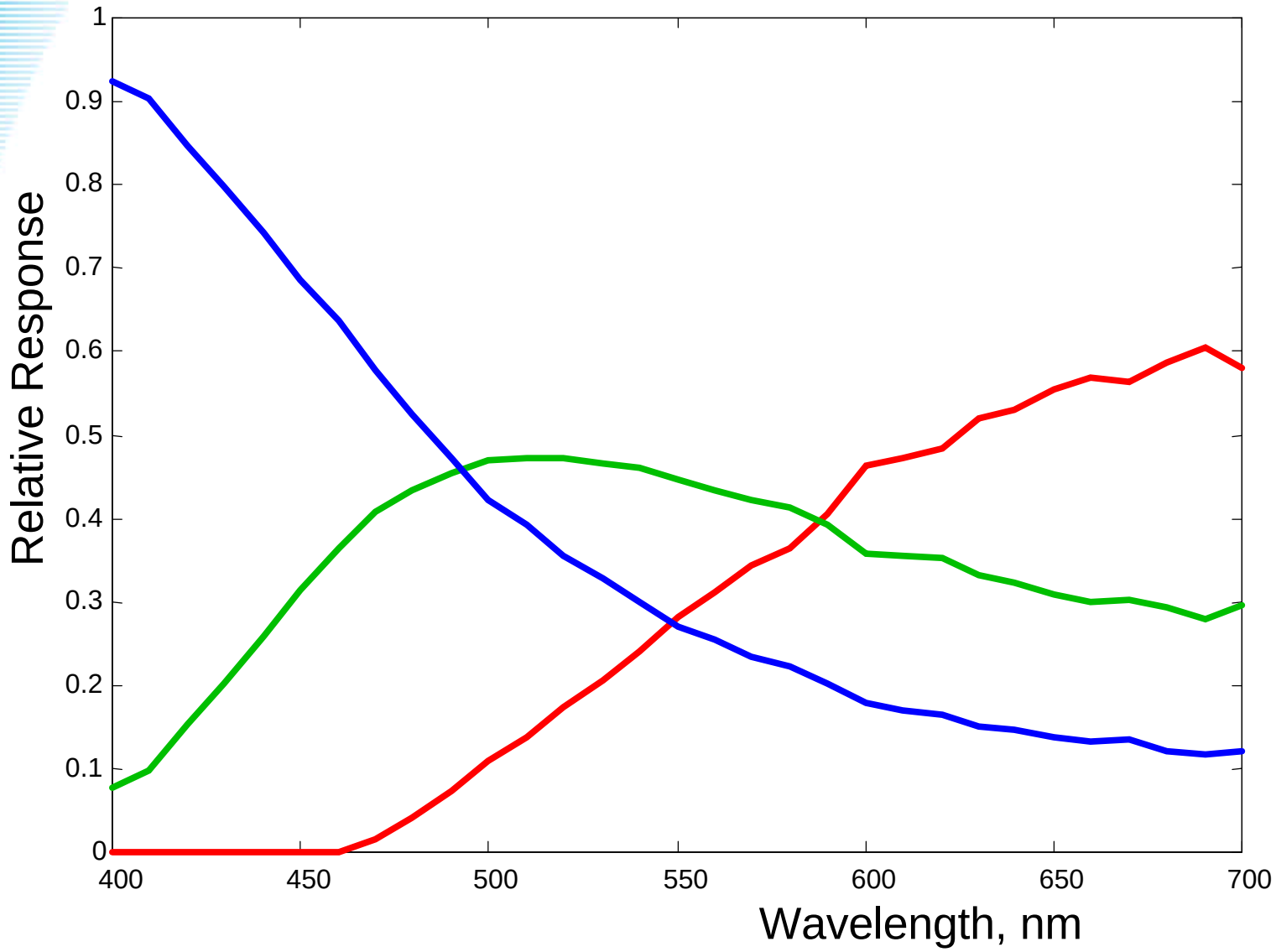
Marvin H. White

Absorption Coefficient and Penetration Depth in Silicon, vs. Wavelength

from Theuwissen, based on M. H. White 1976



Spectral Response Curves



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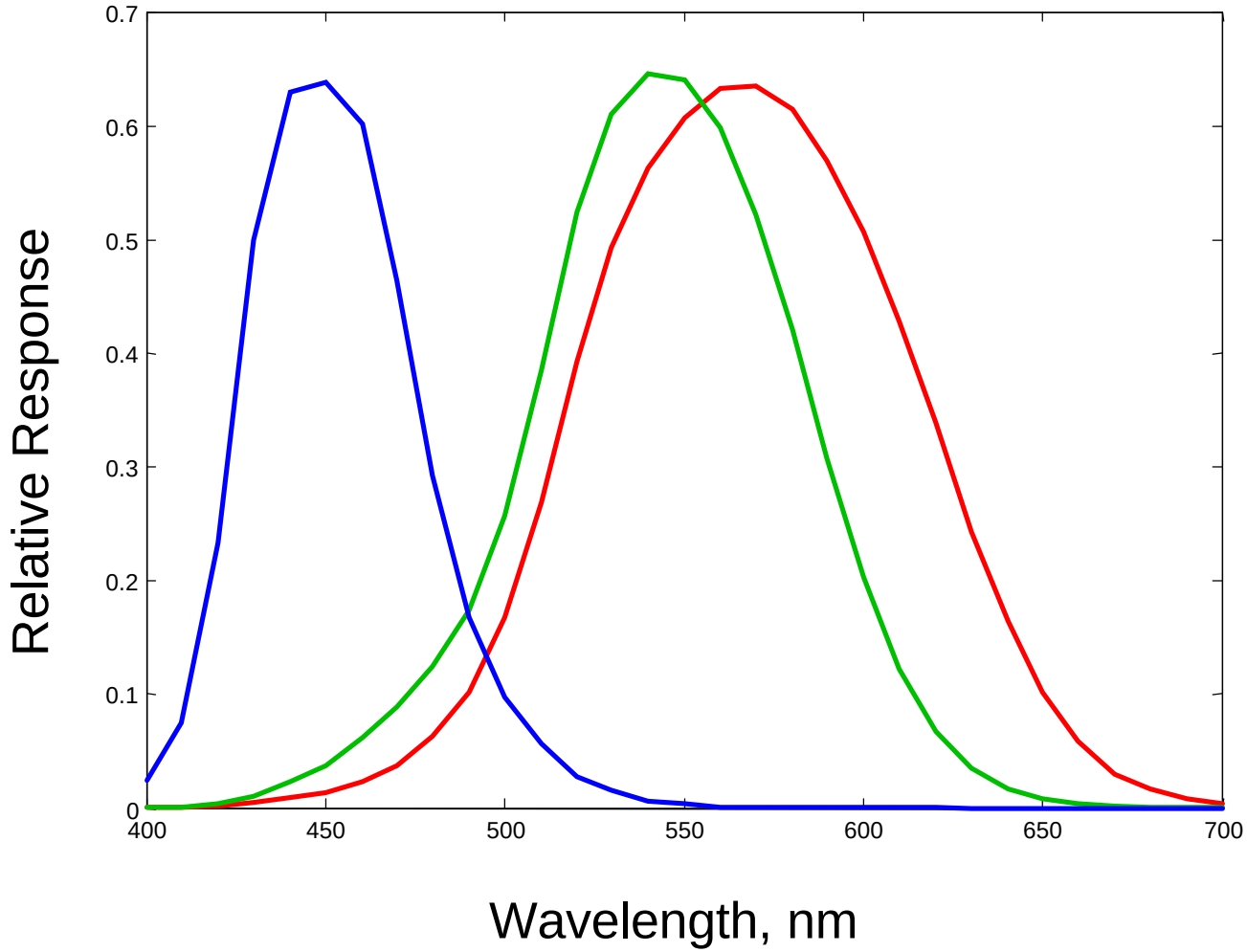
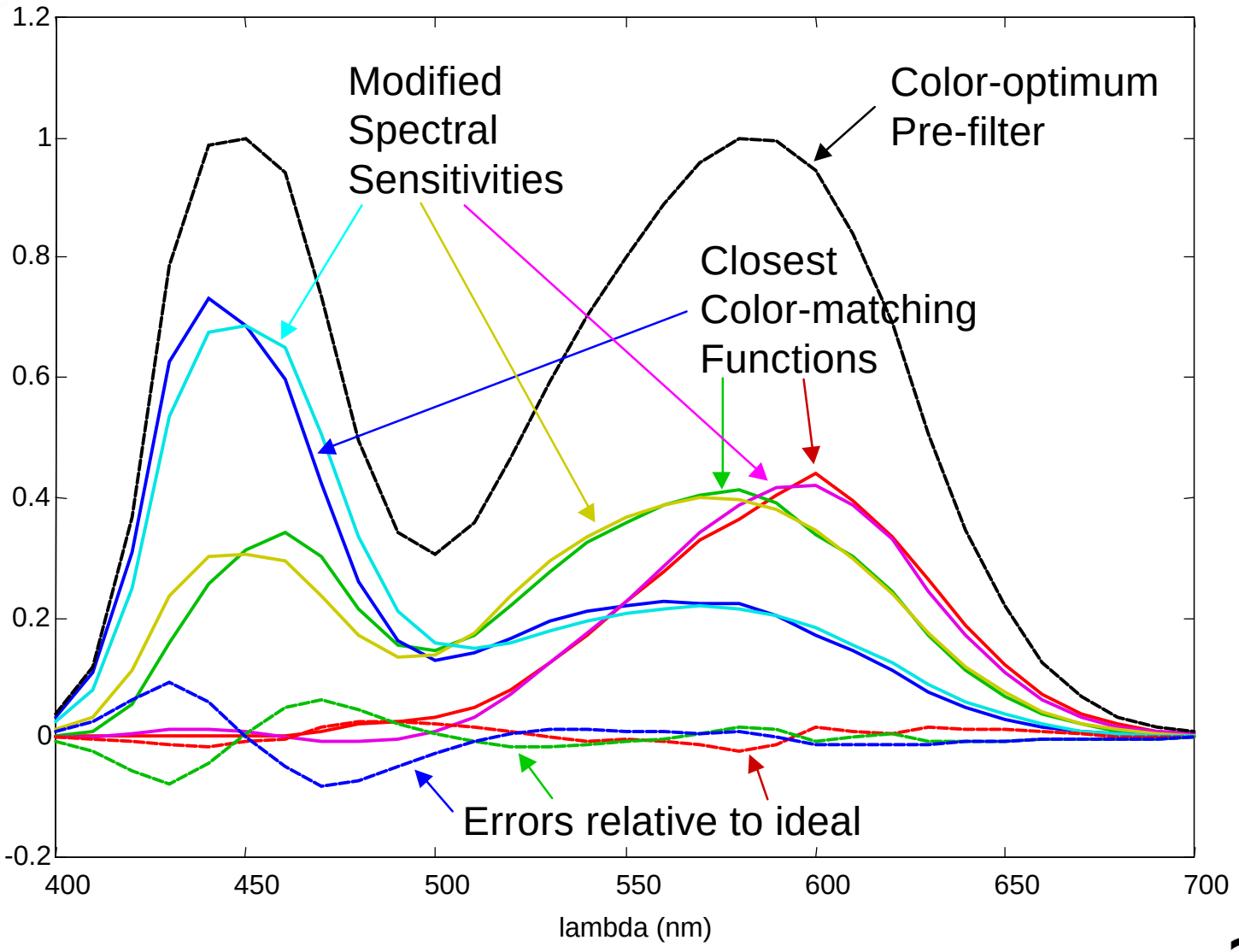
Human Cone Spectral Responses



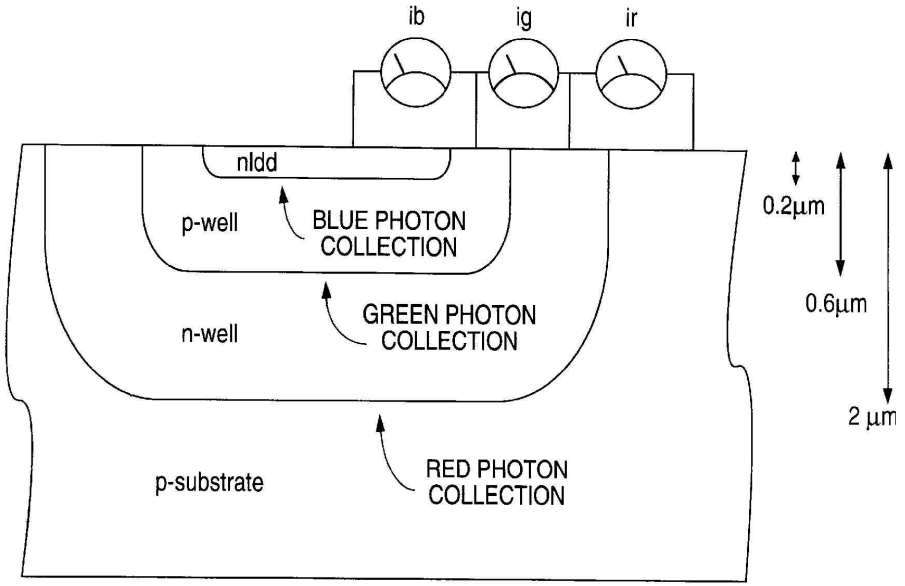
Color-Matching Functions



Film versus Direct VCF

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

Dick Merrill



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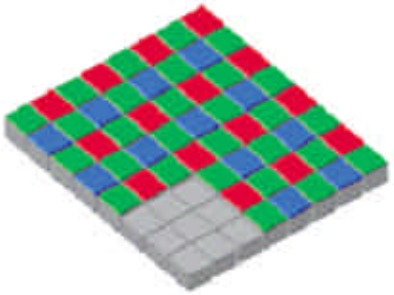
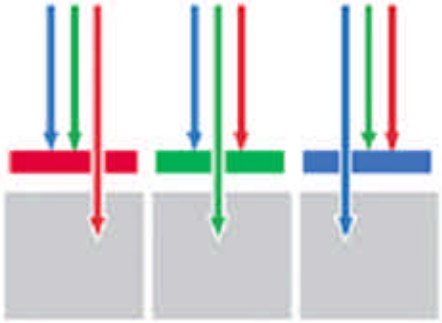
Mosaic vs. Direct VCF

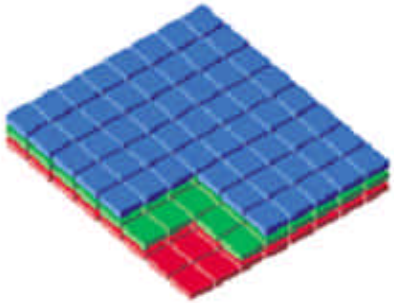
Mosaic Capture

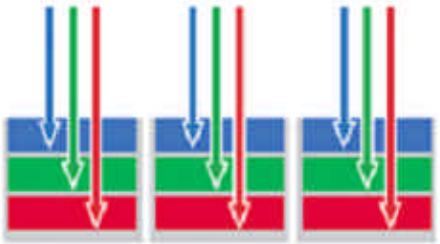




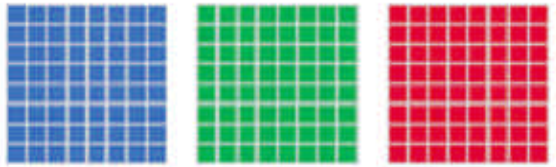
sampling element is 2x2 'pixels'

Foveon® X3 Capture





sampling element is 1 'pixel'



works like color film

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Moiré patterns

Mosaic Sensor

VCF (Foveon X3)

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Chroma Resolution

Mosaic Sensor

Direct Sensor (Foveon X3)

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The Silicon Solution: Direct Sensor using VCF

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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

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

What's in a Megapixel?

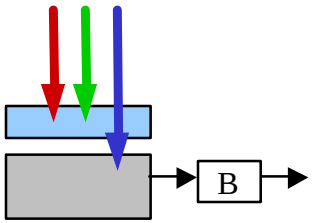
Accepted definitions:

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

Each 20th-century cell

1 pixel sensor

1/3 picture element



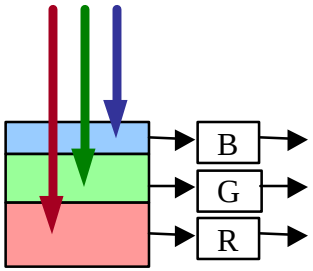
1/3 pixel?

1 pixel?

Each Foveon X3 cell

3 pixel sensors

1 picture element



1 pixel?

3 pixels?

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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

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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

Photography for the Twenty-First Century