

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

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UC Berkeley Photography class  
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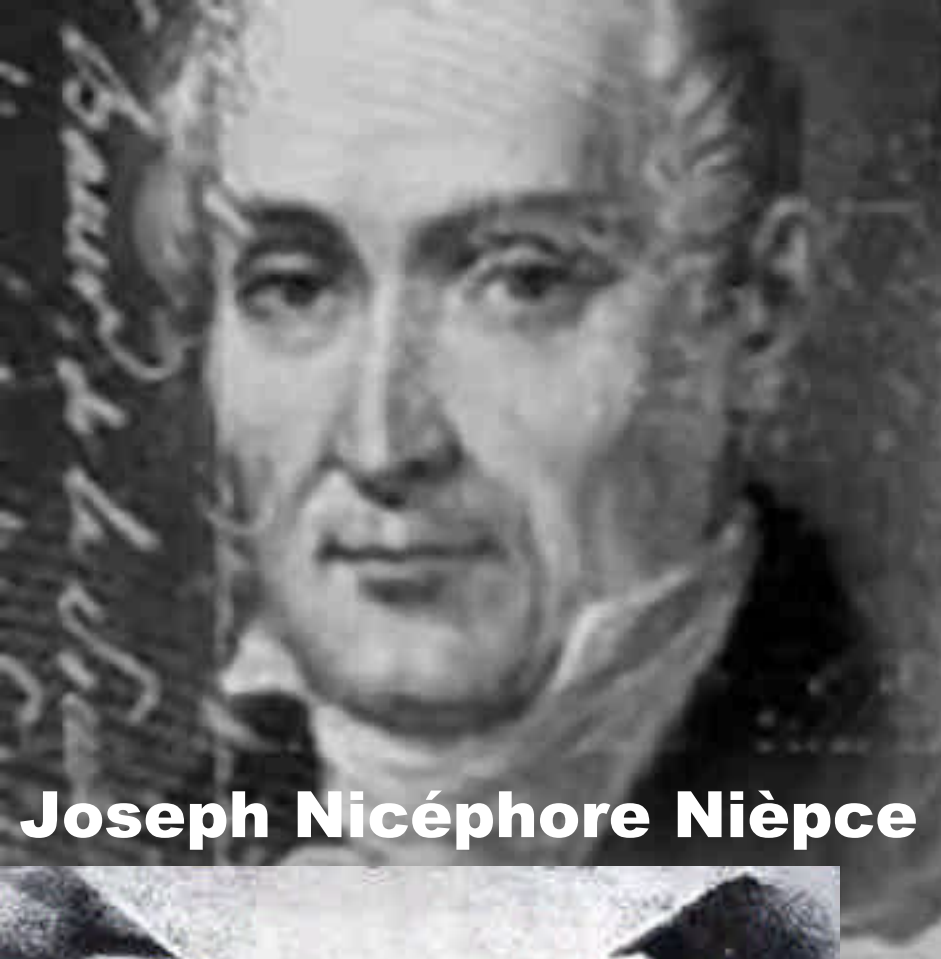
FOVEON

# Color Photographic History

– in a nutshell –

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- **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



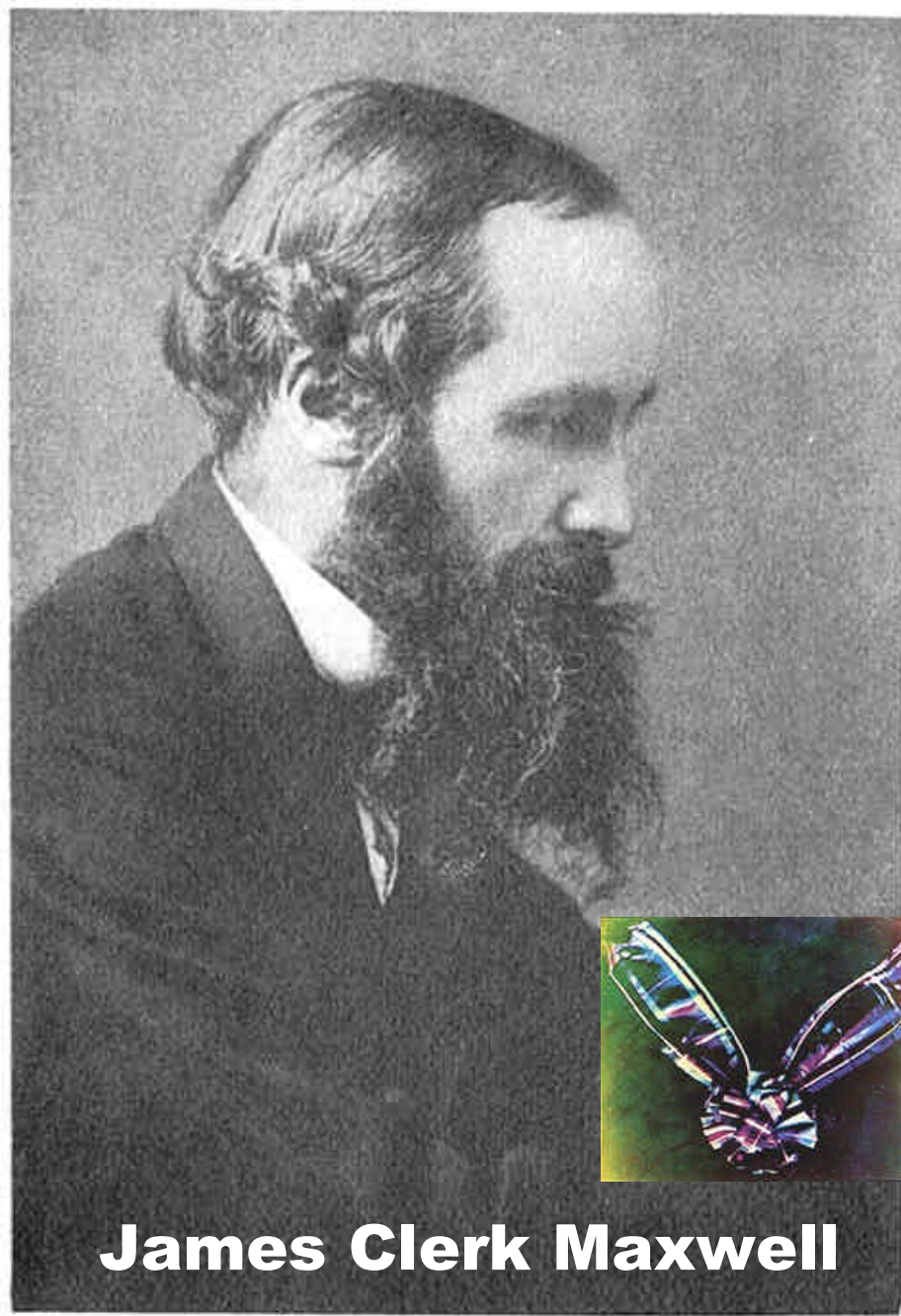
**Joseph Nicéphore Niépce**



**Louis J. M. Daguerre**

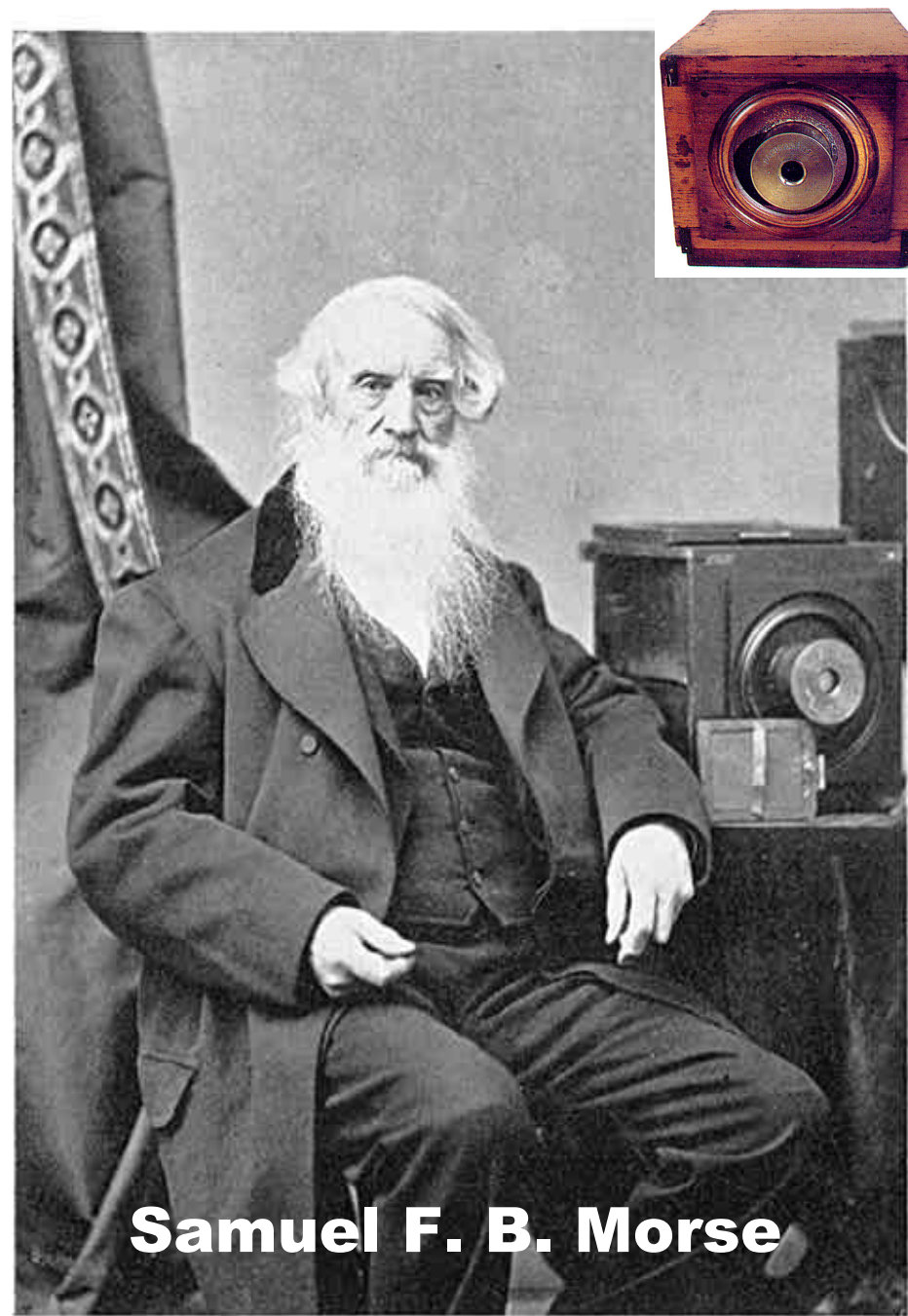
E. J. M. Daguerre: A photographic copy (1935) of an original daguerreotype made by Charles R. Meade of New York in 1848. The daguerreotype is now in the possession of the United States National Museum, through whose courtesy the copy is reproduced.





**James Clerk Maxwell**

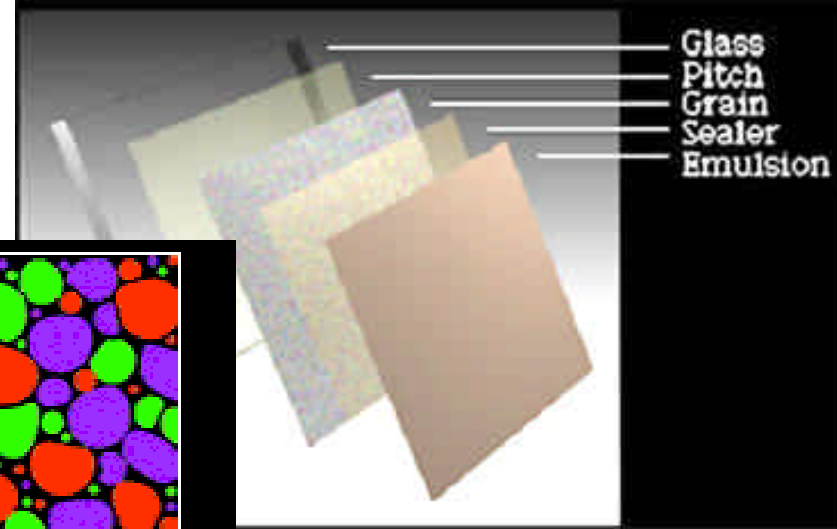
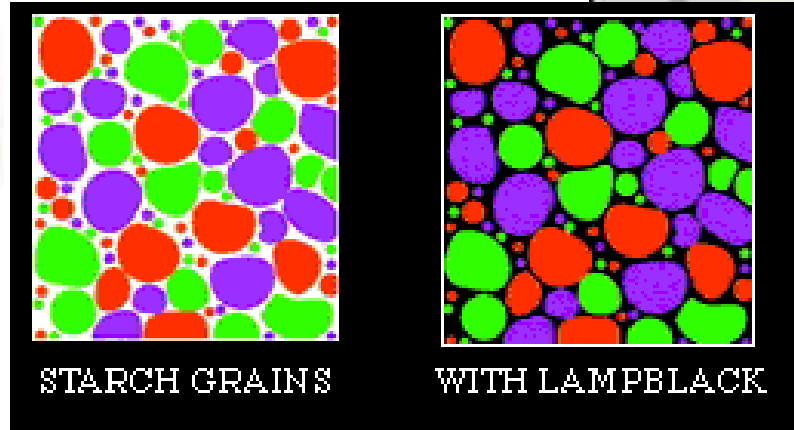
*J. Clerk Maxwell* Emery Walker p.c.



**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



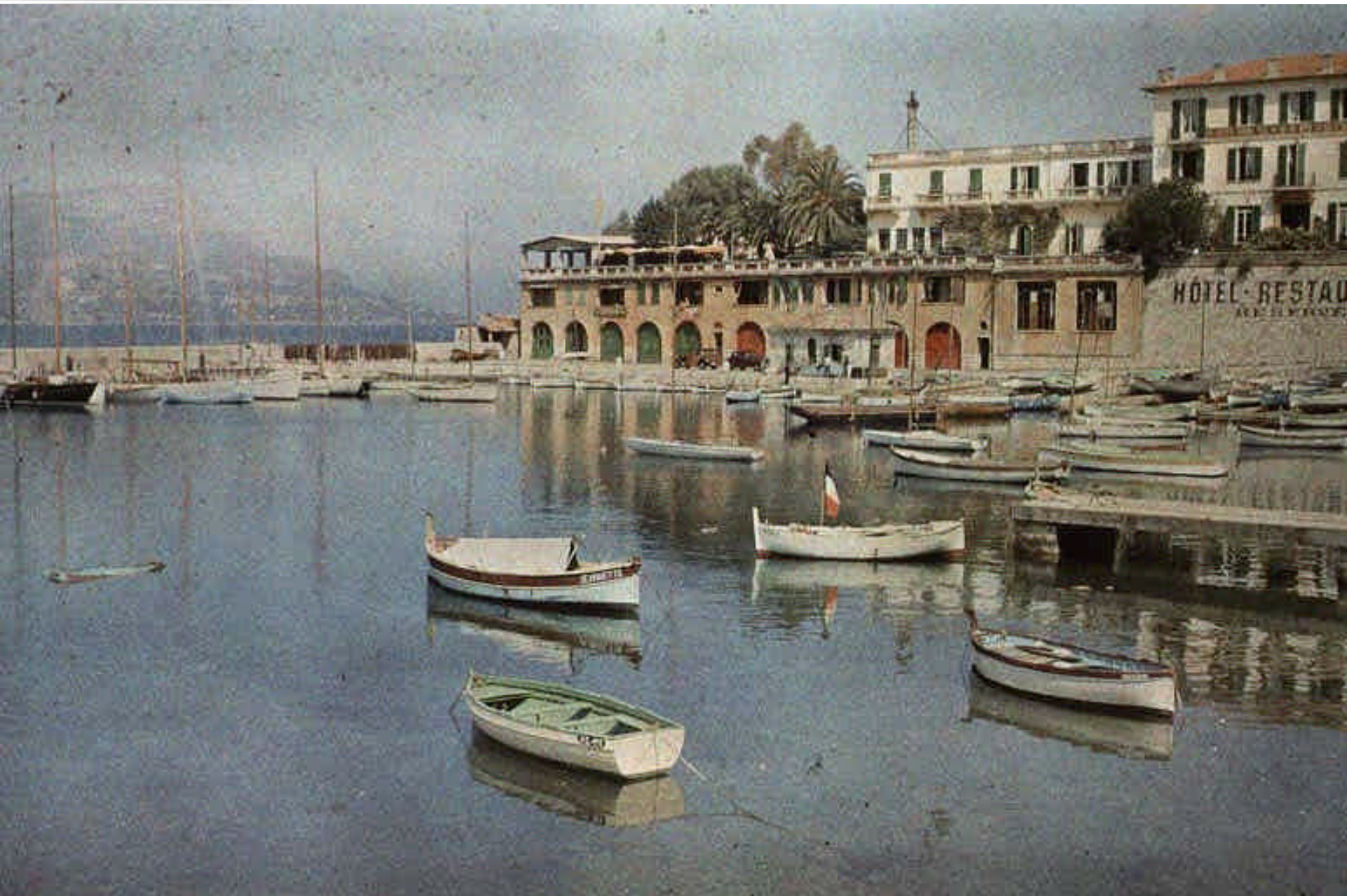
**1906: Autochrome**, a photographic transparency plate patented by the Lumière brothers of Lyons, France.

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.



# Autochrome – Color Filter Mosaic





# Three-shot color



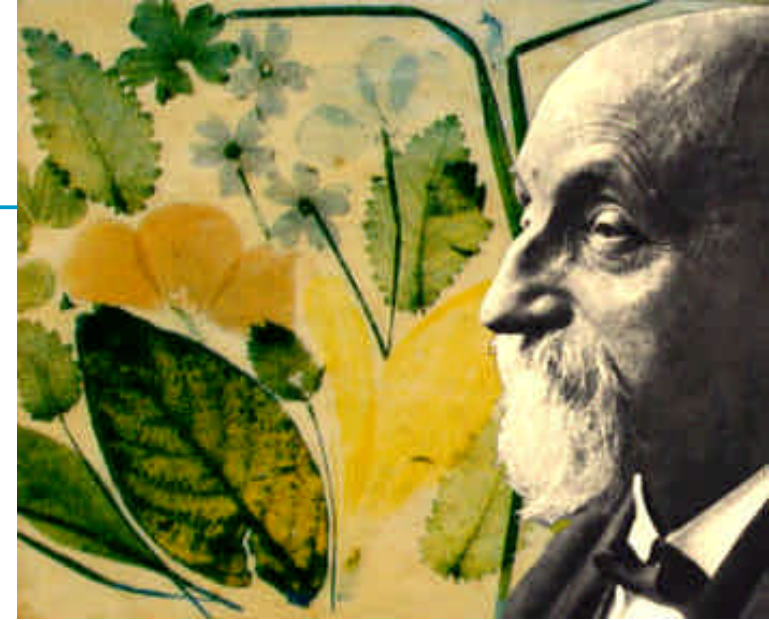
Sergei  
Mikhailovich  
Prokudin-  
Gorskii:  
Photographer  
to the Tsar  
1908–1915

Austro-  
Hungarian  
Prisoners of  
World War I



# Color one-shot still cameras

1932  
Devin Tri-Color



Louis Ducos du Hauron  
1873

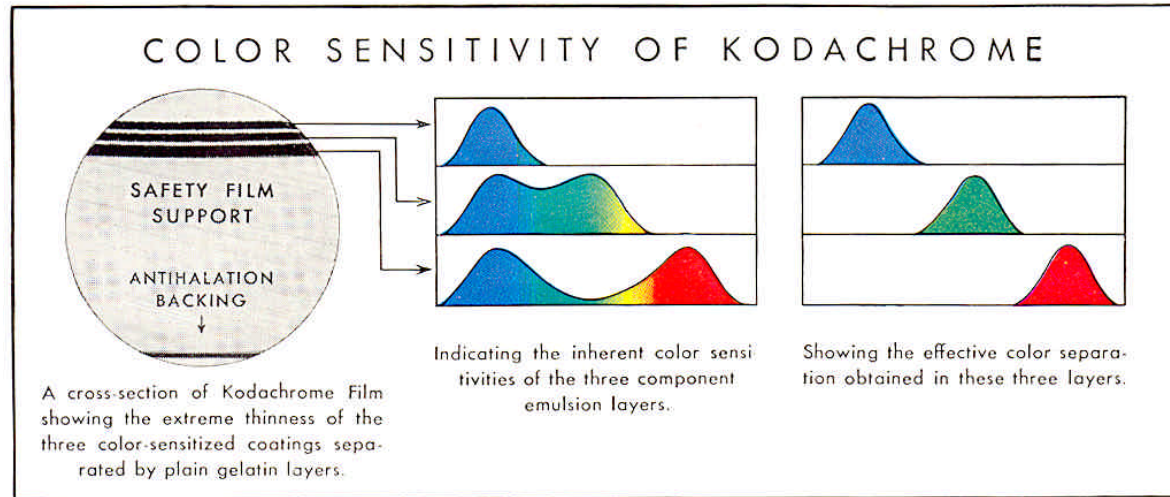




# The Silver Solution: Kodachrome



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



## Senses colors in layers

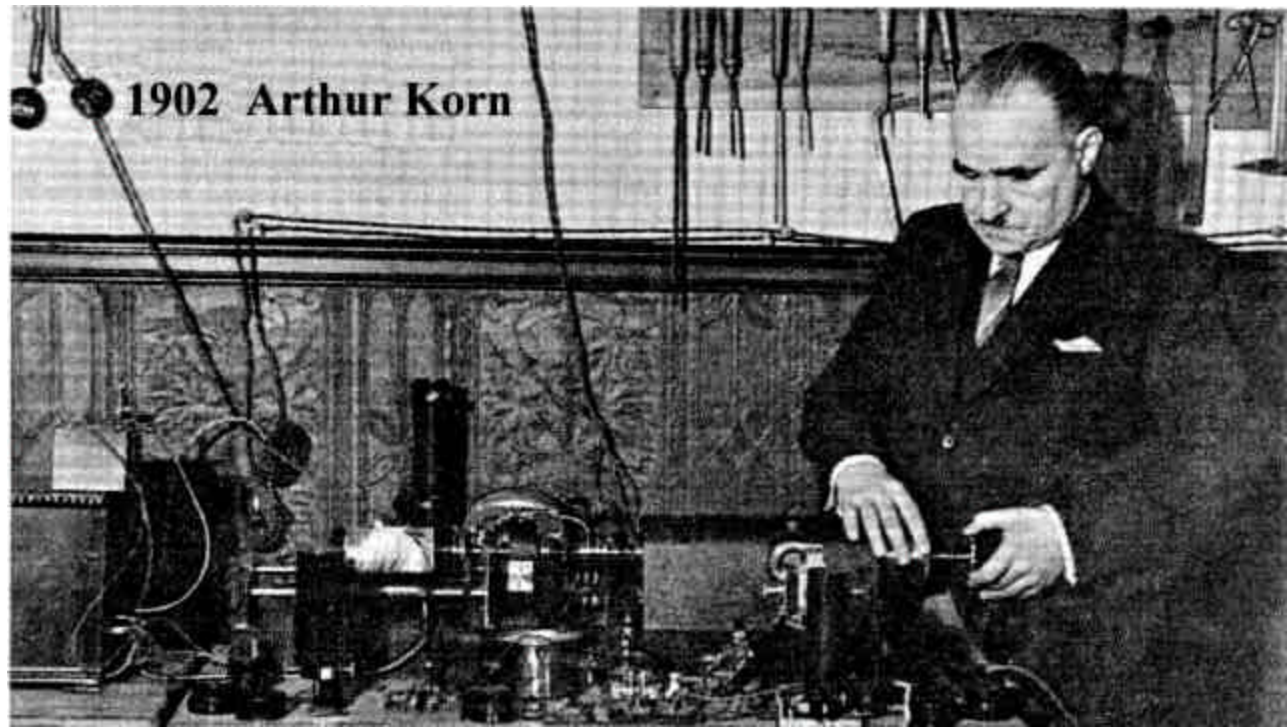
- one shot
  - no motion problems
- all colors at all locations
  - no sampling artifacts
- one piece of film
  - no registration problem

# Electronic Image Communication



**1888: Telautograph,**  
Elisha Gray

**1902: Telephotography**  
(photoelectric fax), Arthur Korn

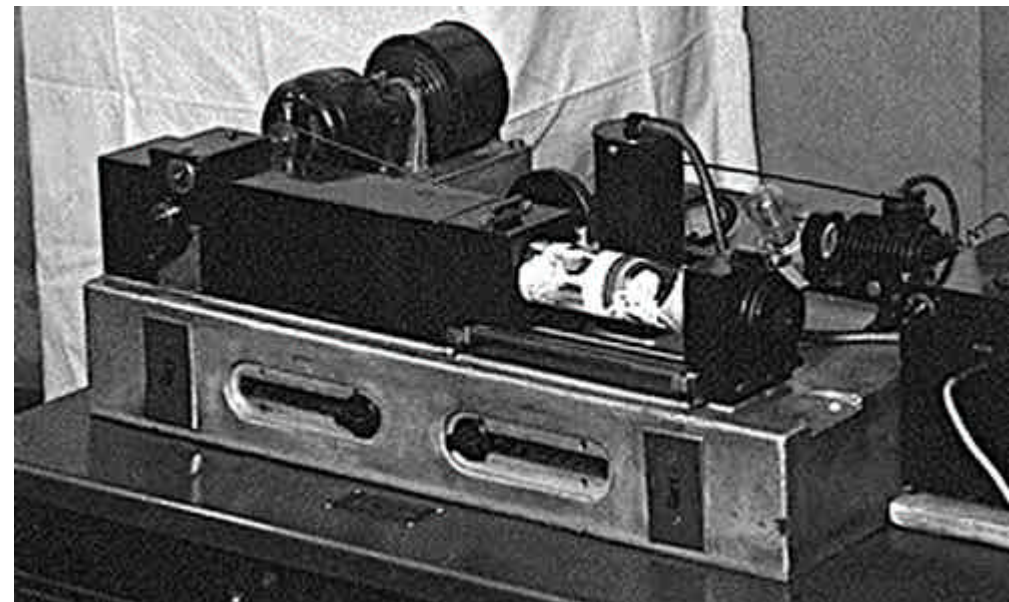
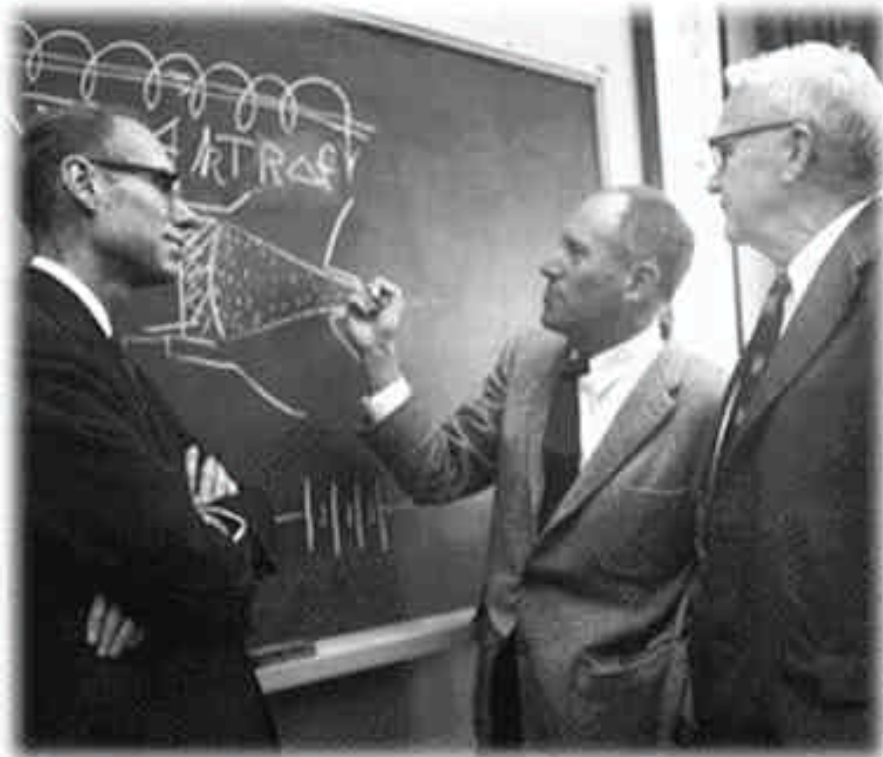




# Nyquist and Telephotography

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

Nyquist's fax machine

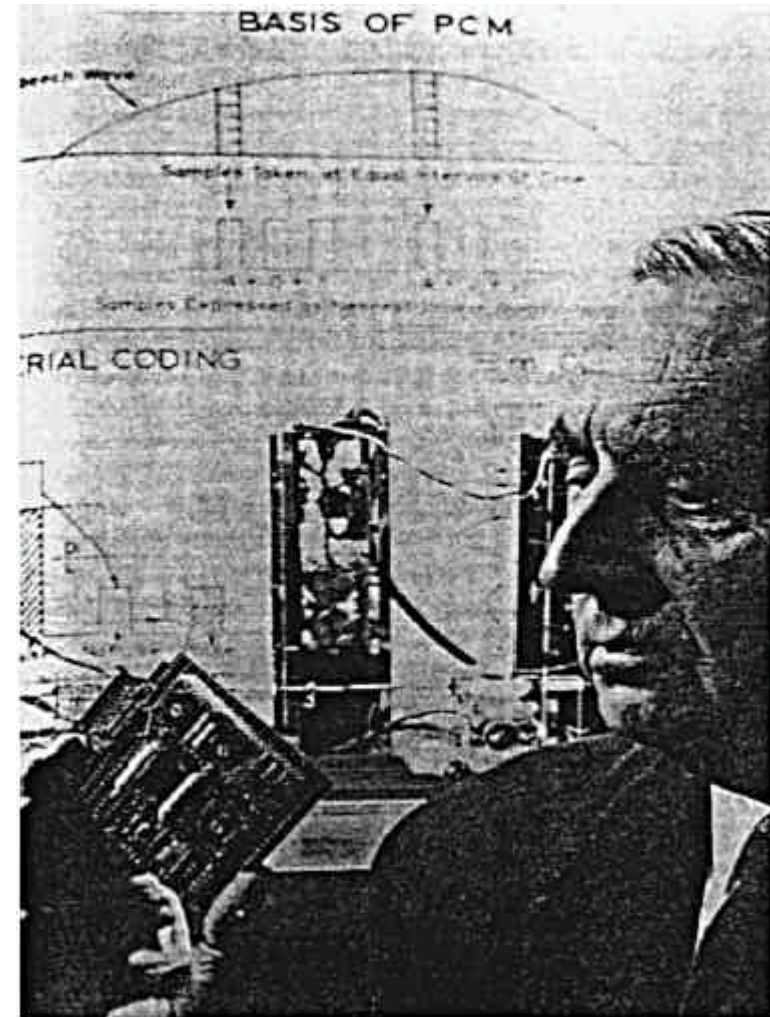
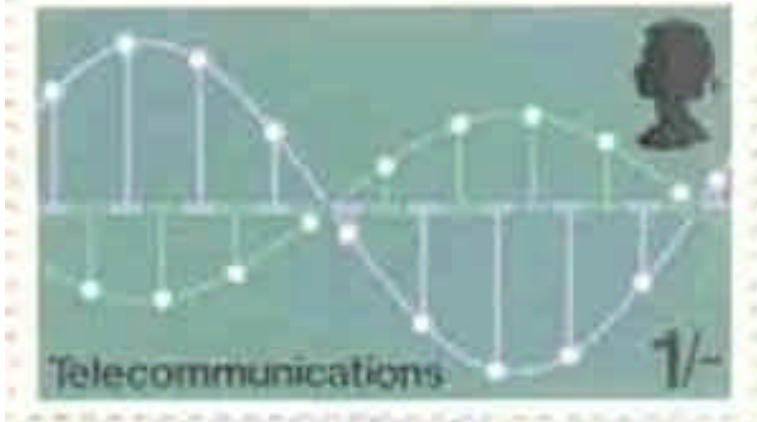


<http://lucent.netlabs.net/minds/gallery/1944trw.html>

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

# Pulse Code Modulation (PCM)

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





# PCM Tube



**1948 – Vacuum-tube A-to-D converter**

**Raymond W. Sears holding his invention**

# "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

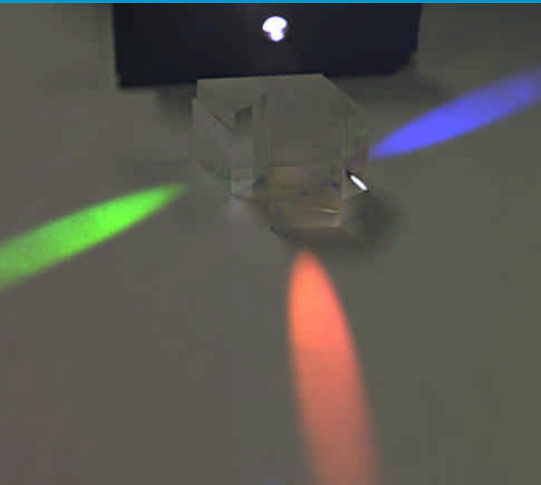


## Surveyor 1 – 1966

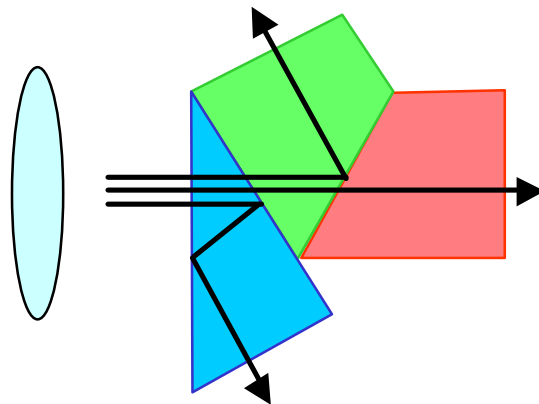
<http://history.nasa.gov/SP-168/section2b.htm>

<http://nssdc.gsfc.nasa.gov/database/MasterCatalog?sc=1966-045A&ex=1>

# Prism-based Color Camera



2000 – Foveon II



100% green

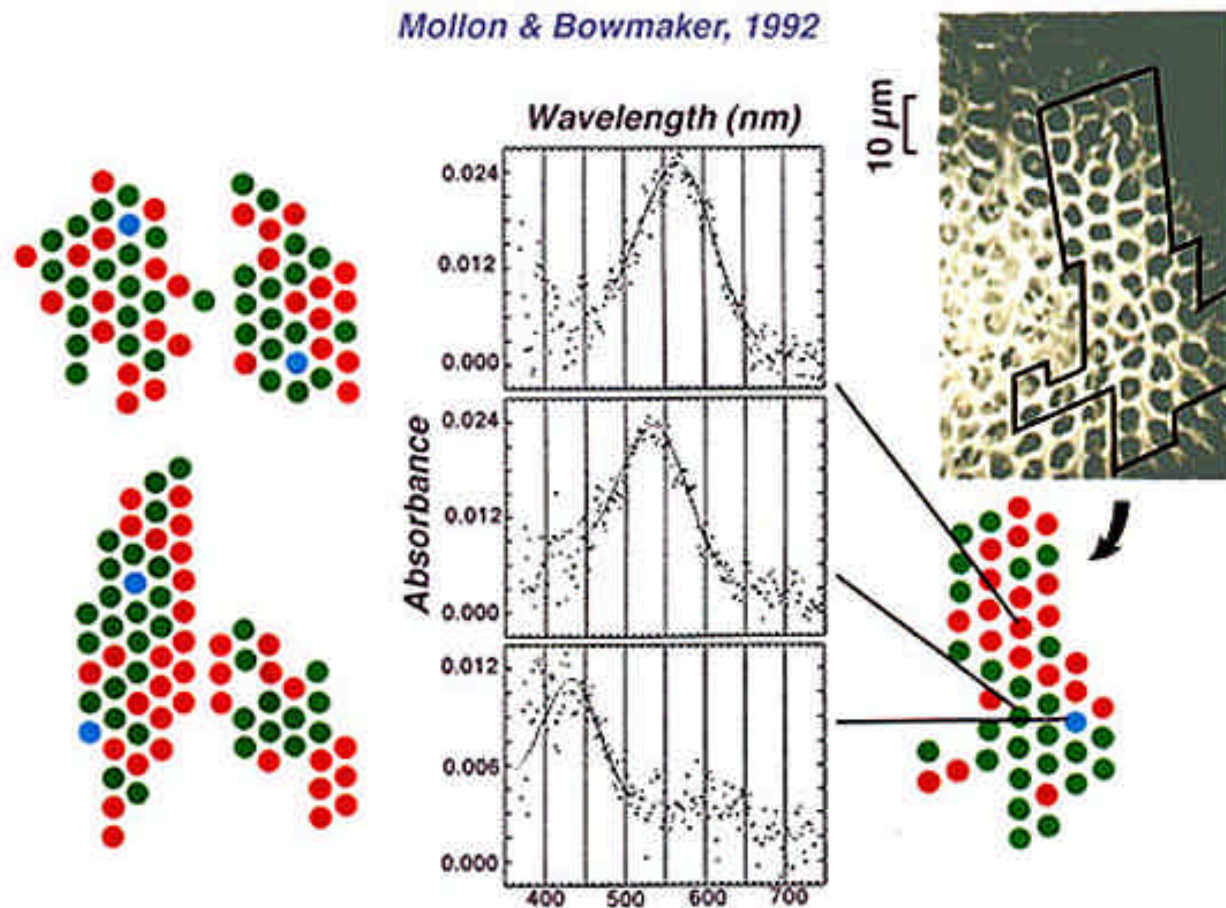
100% red

100% blue

No guessing!

# How do Humans See Color?

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





[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.<sup>2</sup> ..... 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]

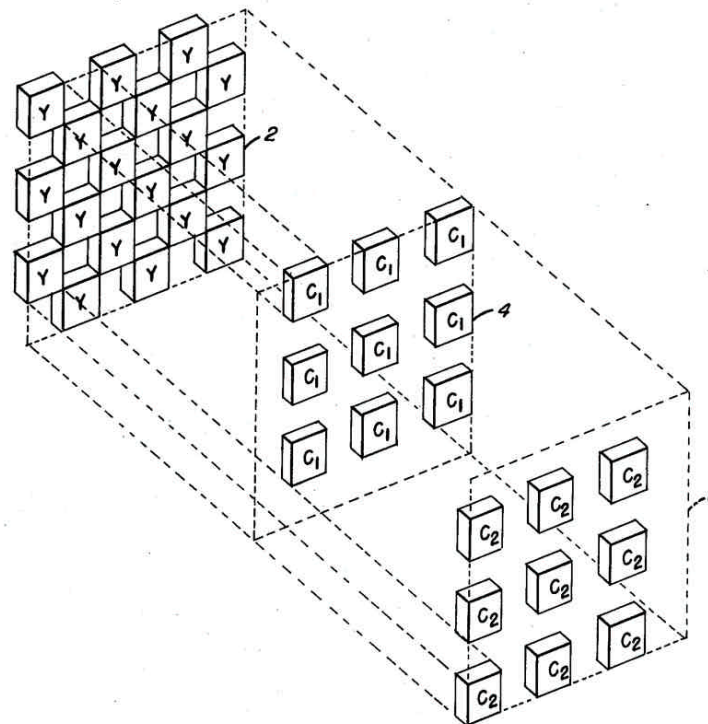
ABSTRACT

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

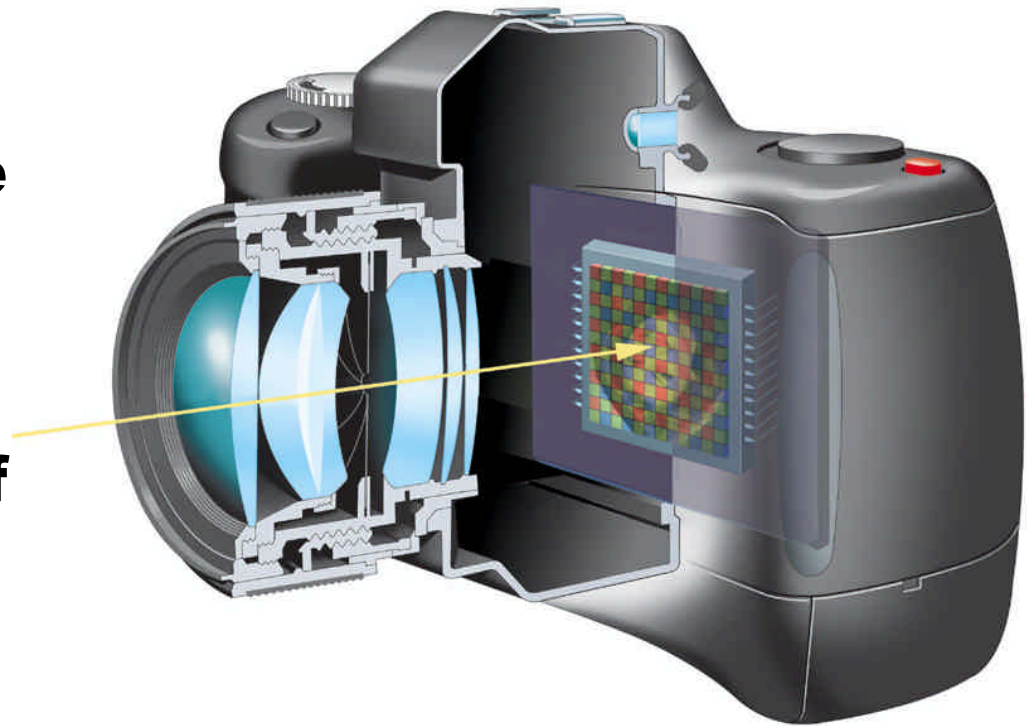
# Bryce Bayer's US Patent #3,971,065



# Digital Camera Image Sensors

## – A Return to Screen Plates

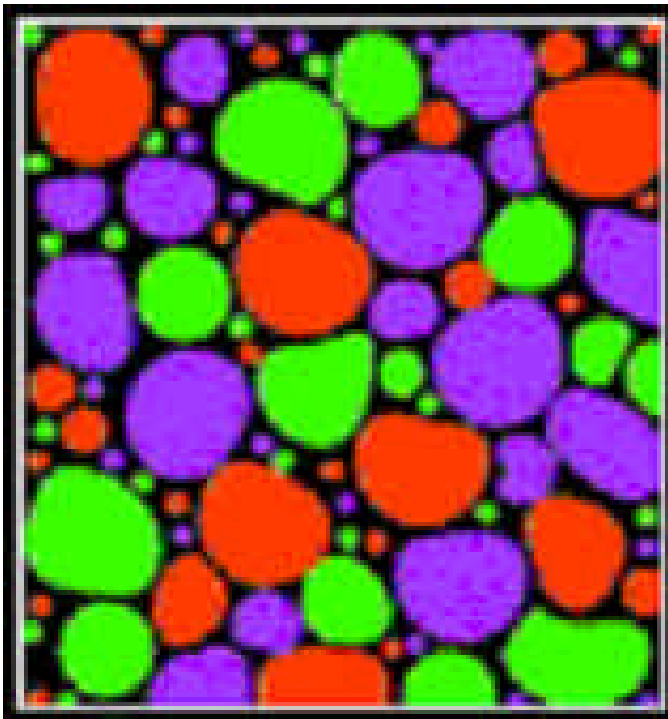
- **Light goes through lens and hits image sensor plane.**
- **Image sensor sees a mosaic pattern of color.**
- **Camera estimates image color from mosaic pattern.**



# Tried and True?

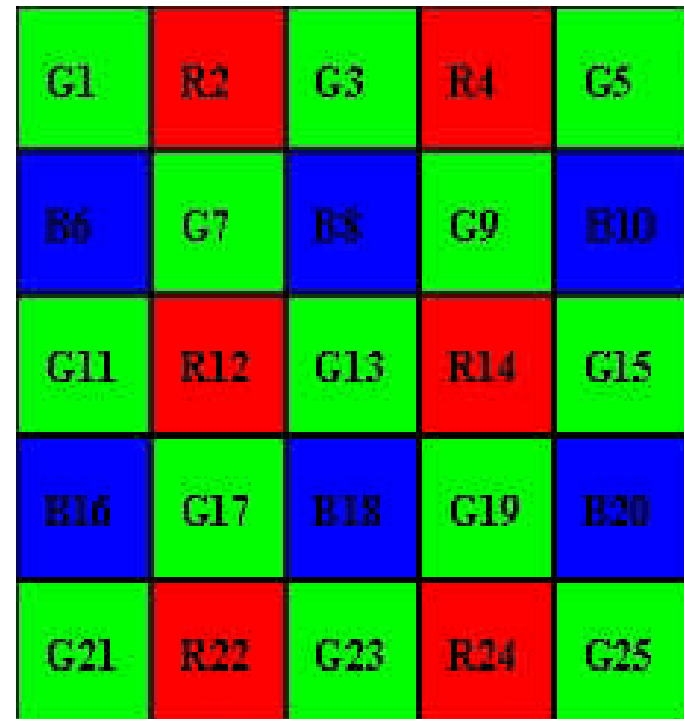
**1906**

**Potato starch  
on glass plates**



**1975**

**Bayer pattern  
on Silicon**





# Mosaic Sampling Artifacts



# Recycled Color Techniques in Electronic Cameras

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

## What's left?

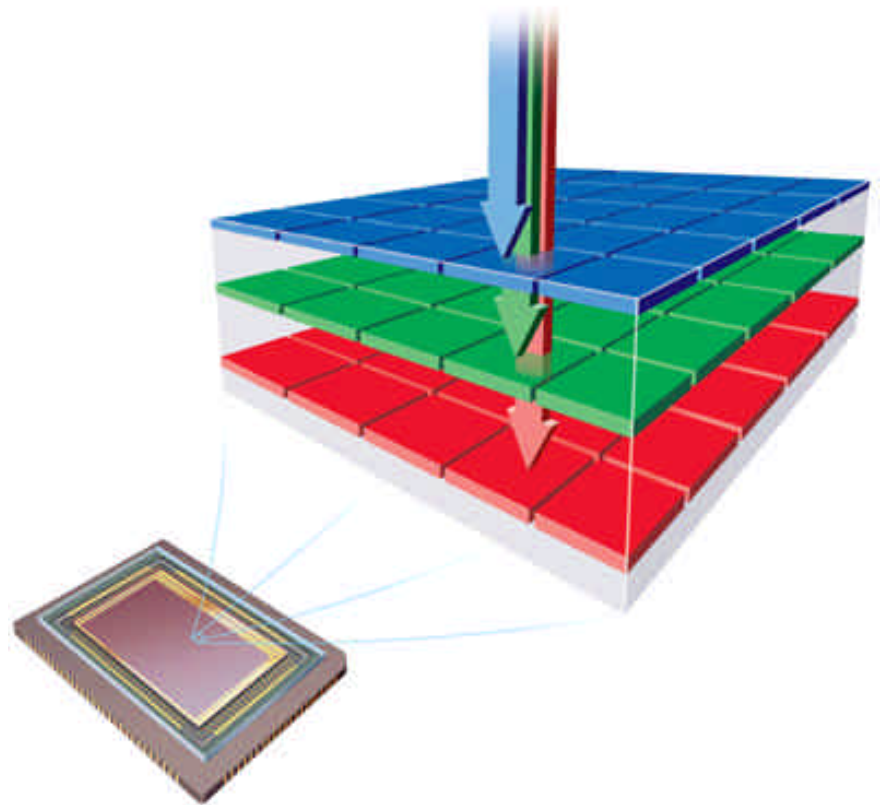
Can we copy multi-layered film?

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**



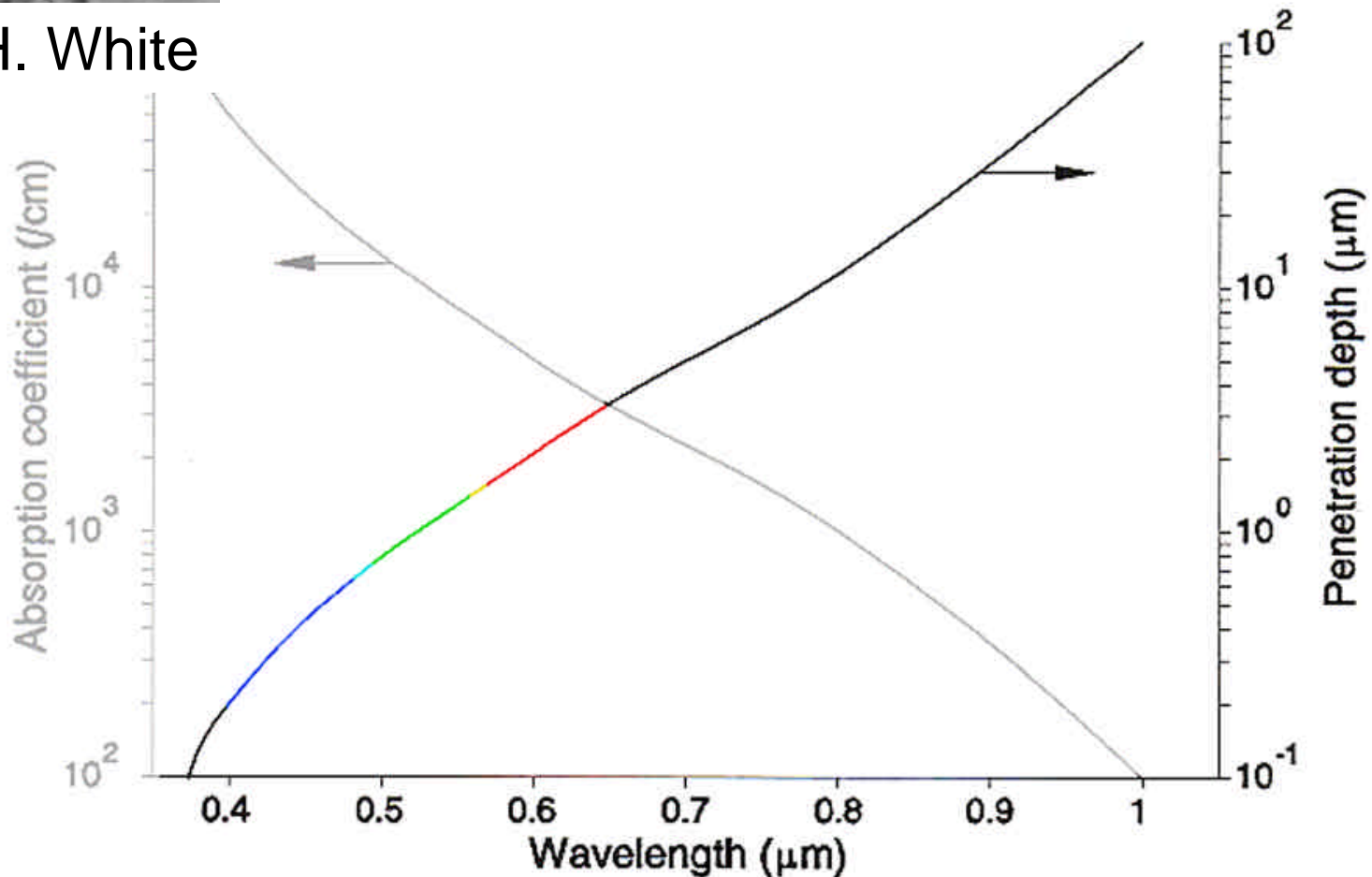
# Silicon as a Color Filter



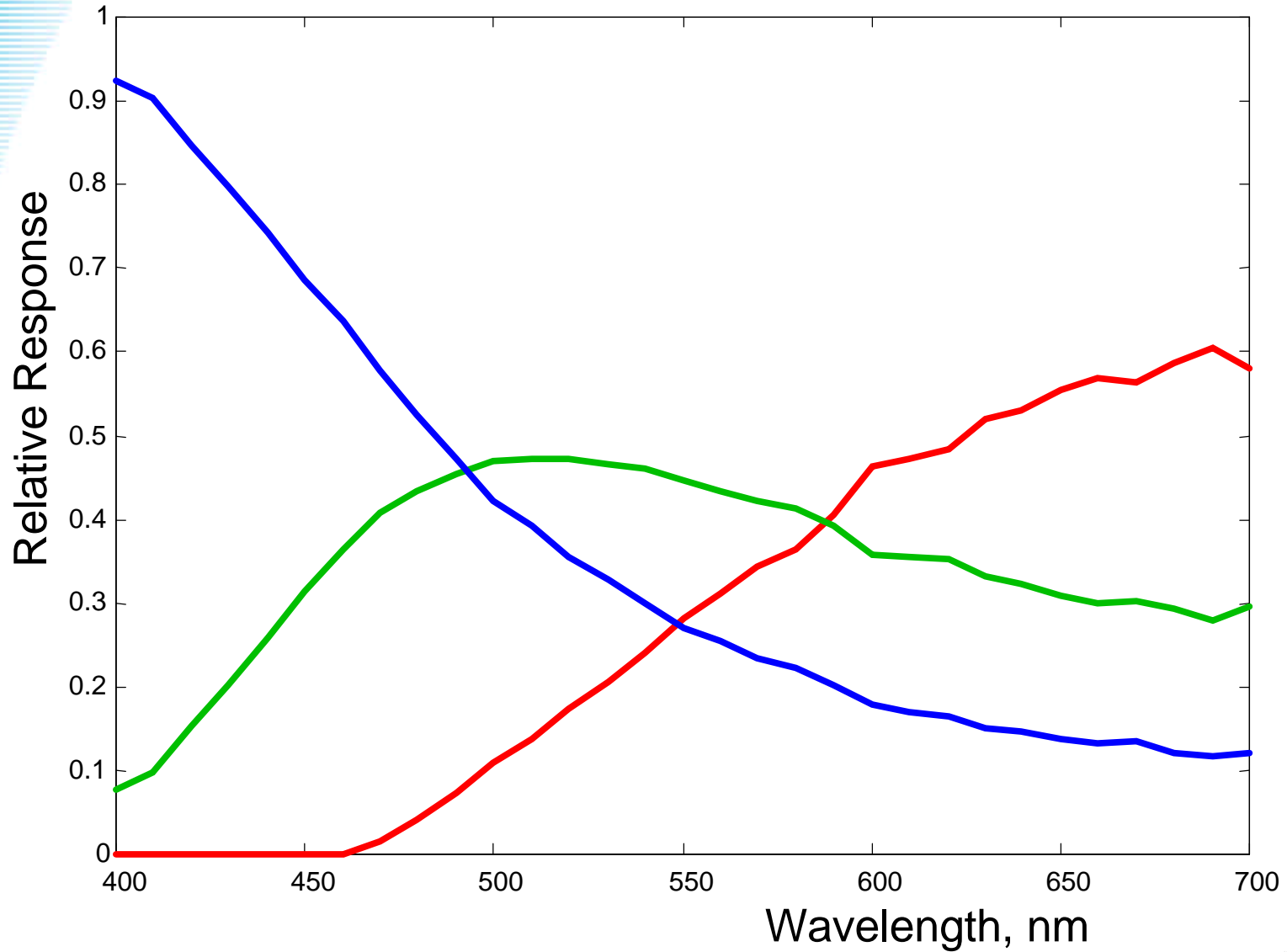
## Absorption Coefficient and Penetration Depth in Silicon, vs. Wavelength

from Theuwissen, based on M. H. White 1976

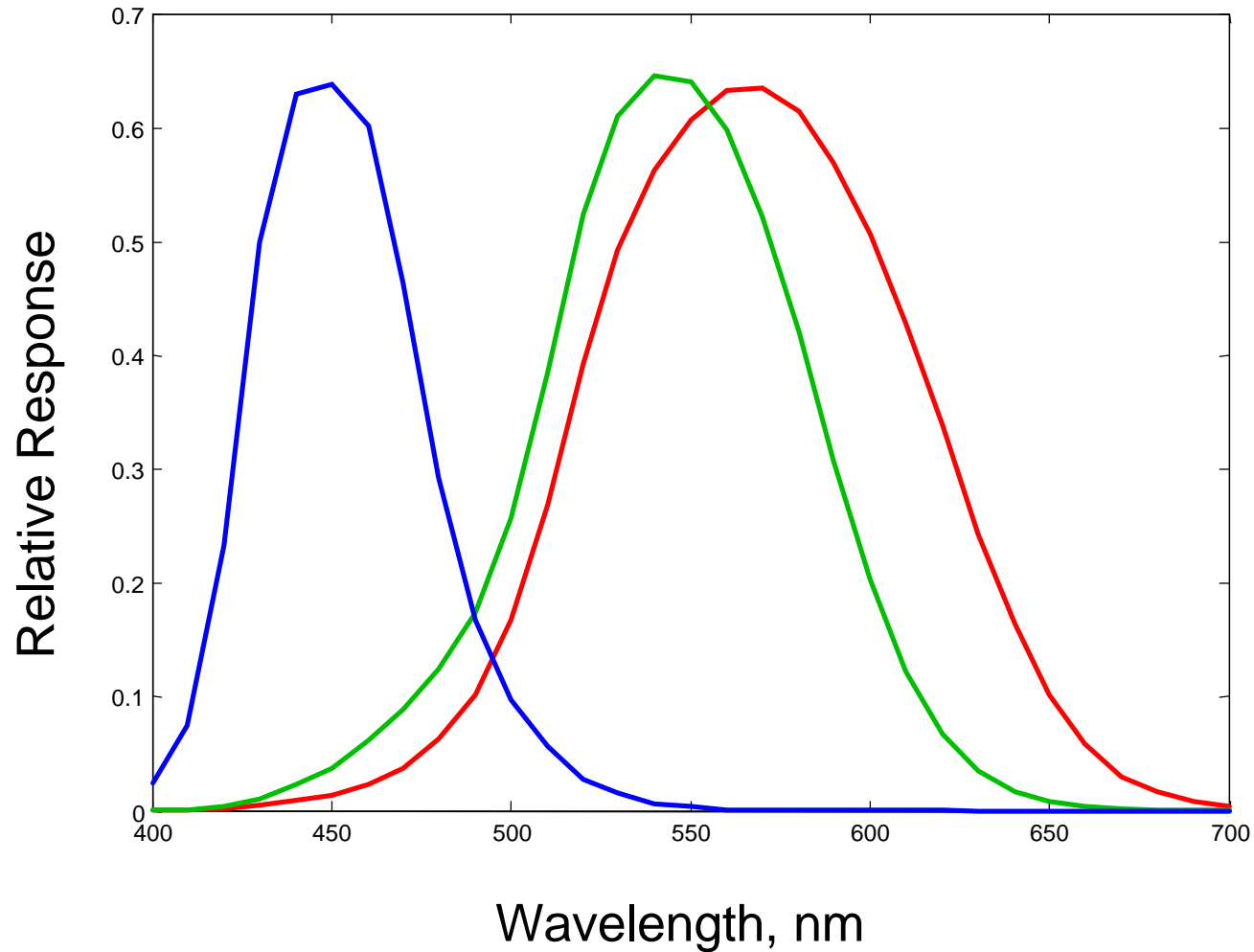
Marvin H. White



# Spectral Response Curves

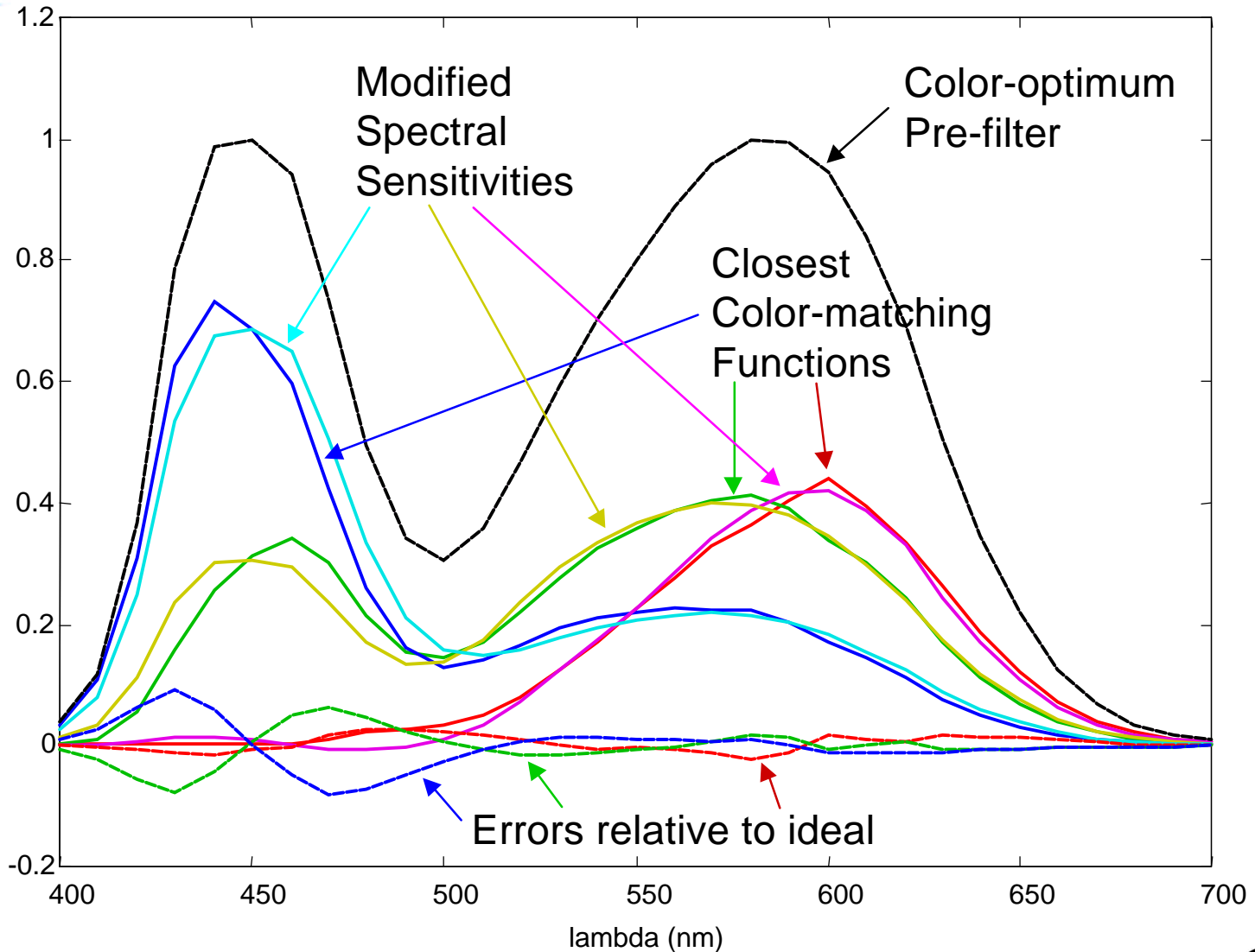


# Human Cone Spectral Responses





# Color-Matching Functions

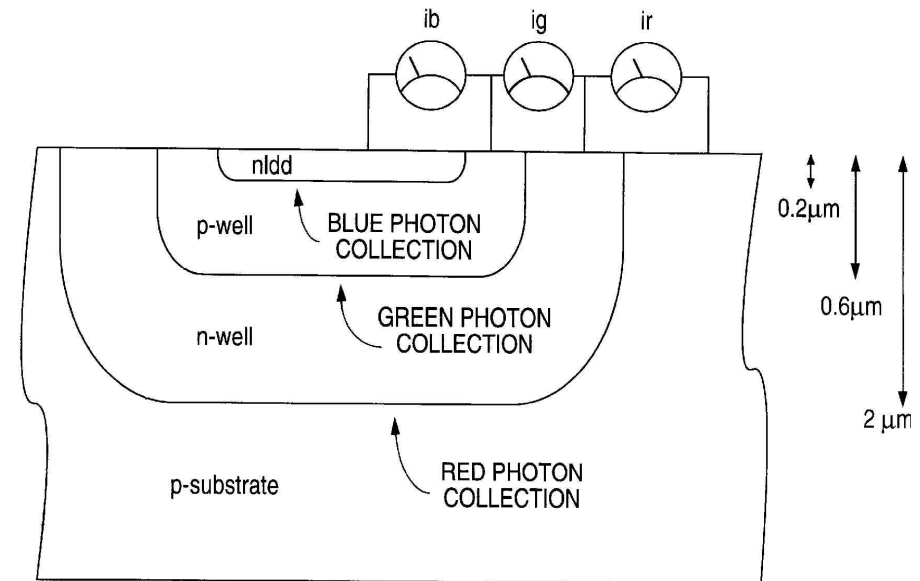
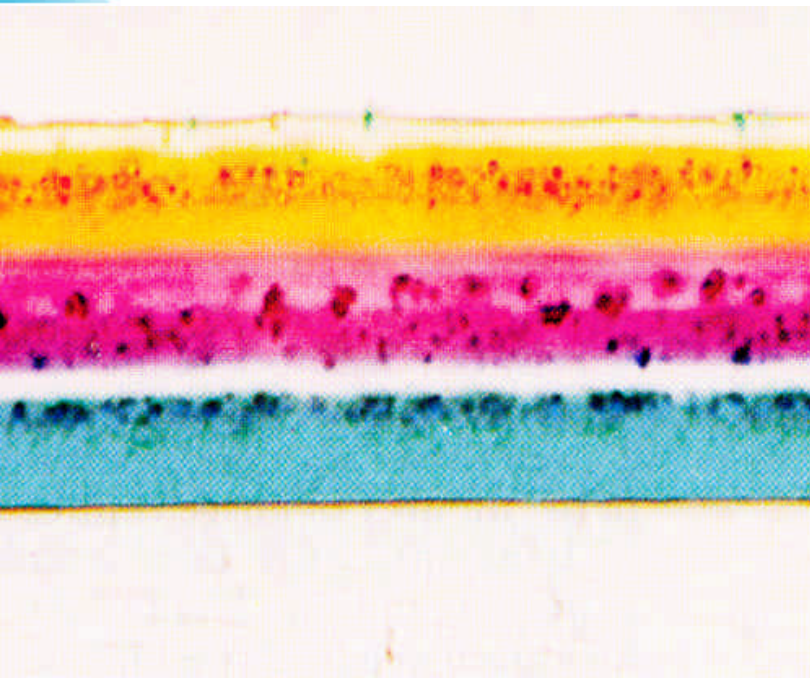


# Film versus Direct VCF

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

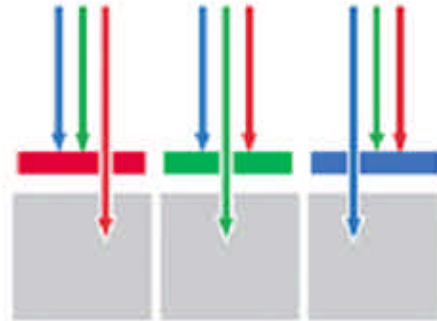
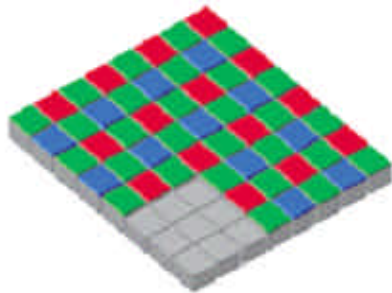


Dick Merrill



# Mosaic vs. Direct VCF

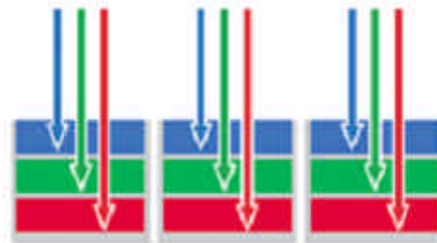
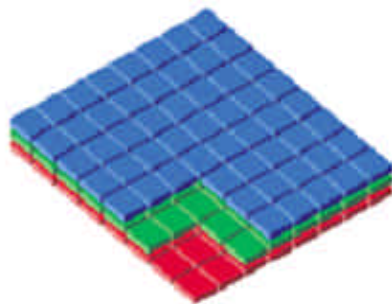
Mosaic Capture



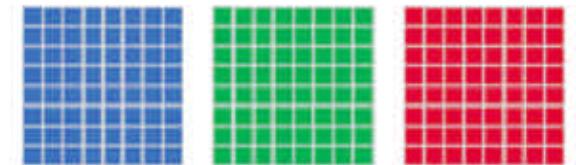
**sampling element  
is 2x2 'pixels'**



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**



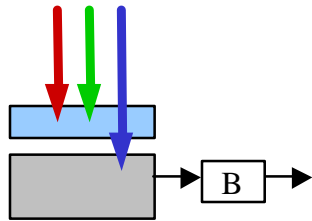
# What's in a Megapixel?

Accepted definitions:

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

Each 20th-century cell

**1 pixel sensor**  
**1/3 picture element**

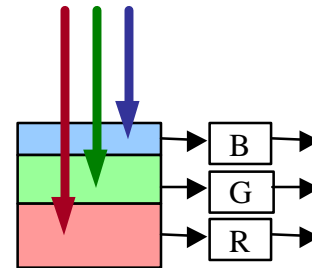


1/3 pixel?

1 pixel?

Each Foveon X3 cell

**3 pixel sensors**  
**1 picture element**



1 pixel?

3 pixels?

# Products with X3 Imagers

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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?

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- 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



FOVEON

# **Photography for the Twenty-First Century**