Operation and performance of a color image sensor with layered photodiodes

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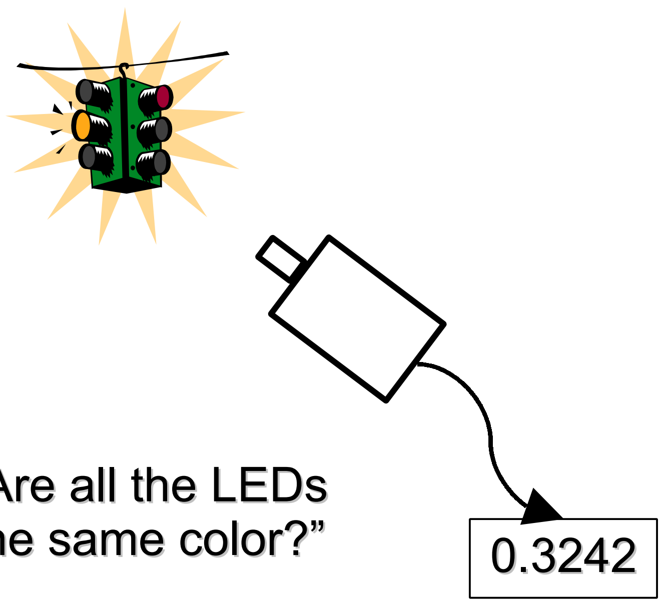
Summary

- Review of color imaging
- Color imaging technologies
- Color sensing with layered photodiodes
- An example device
- Image characteristics
- Applications
- Paths for development

What is color imaging?

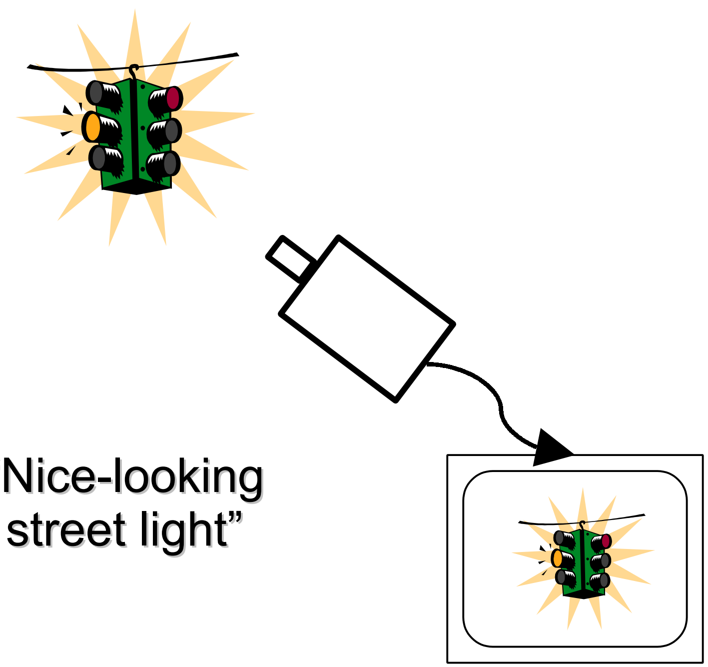
- Imaging for measurement



"Are all the LEDs the same color?"

<u>Not Perceptual</u>

- Imaging for reproduction



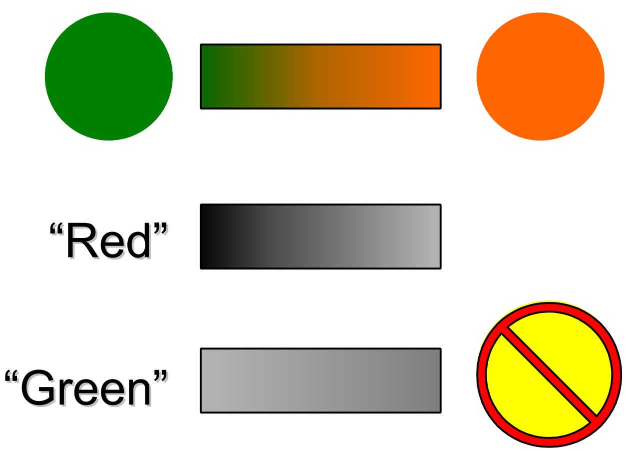
"Nice-looking street light"

<u>Perceptual</u>

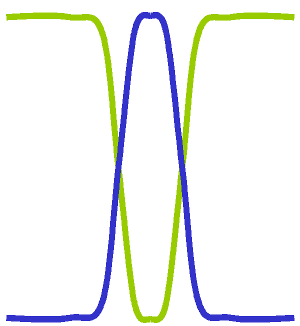
Imaging for color measurement

- Could use any collection of spectral measurements as long as these discriminate required differences
- Two measurements can measure color, three are required for brightness as well

Two endpoints coded to gray-scale



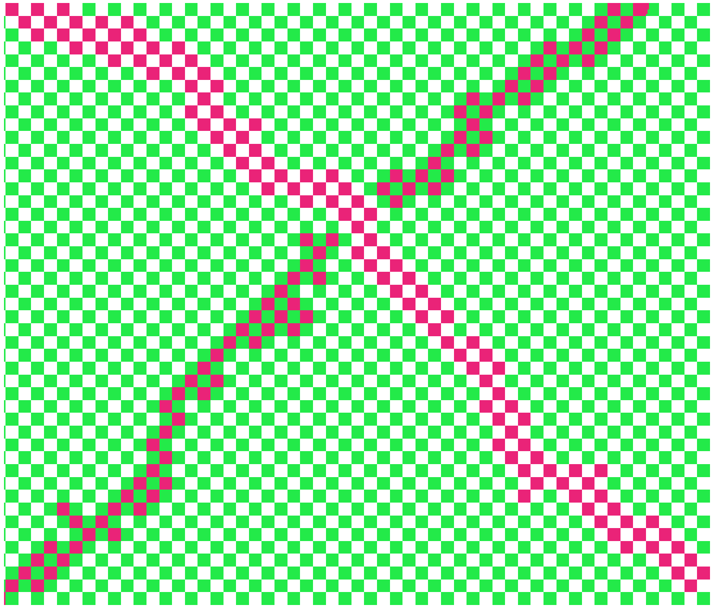
In band : Out of band



What “Blue”?

Imaging for color reproduction

- Does it look right?
  - Purely psychophysical
  - Very sensitive to
    - Illumination context
    - Object brightness
    - Observation cone angle
    - Genetic factors
  - People have odd expectations
  - Display is always subject to compromise



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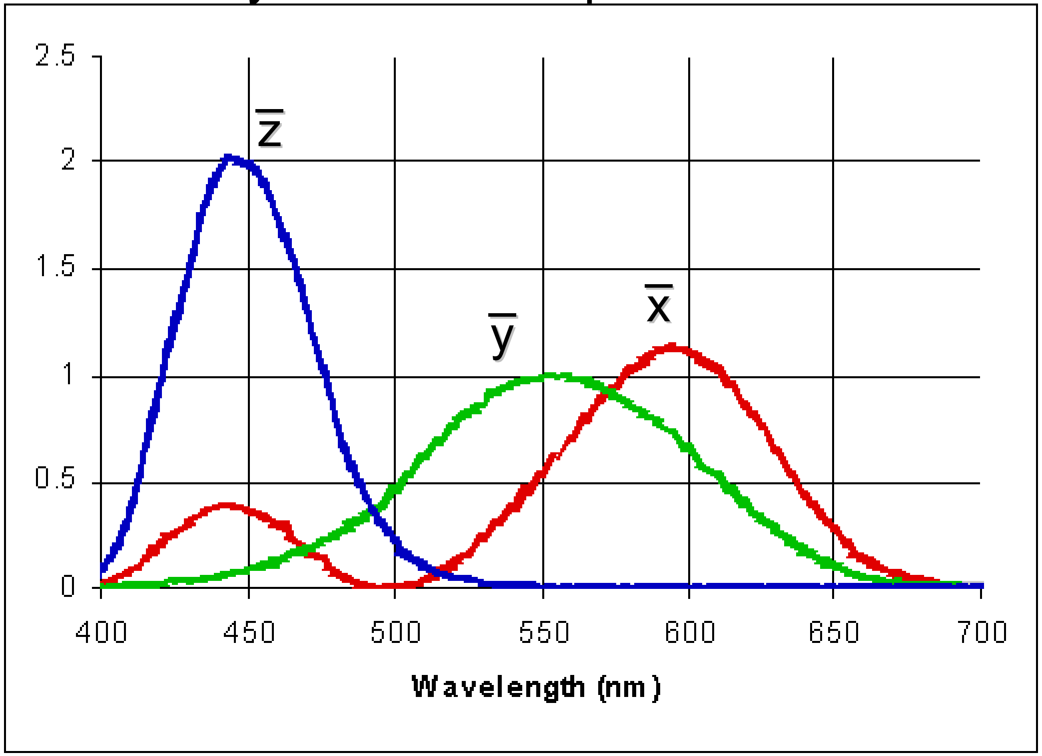
The Standard

- For comparability, a standard has been adopted – the Color Matching Functions
- These are the amount of imaginary primaries that need to be mixed linearly to form the spectral colors



$\bar{y}$ is was defined to match the luminous efficacy function

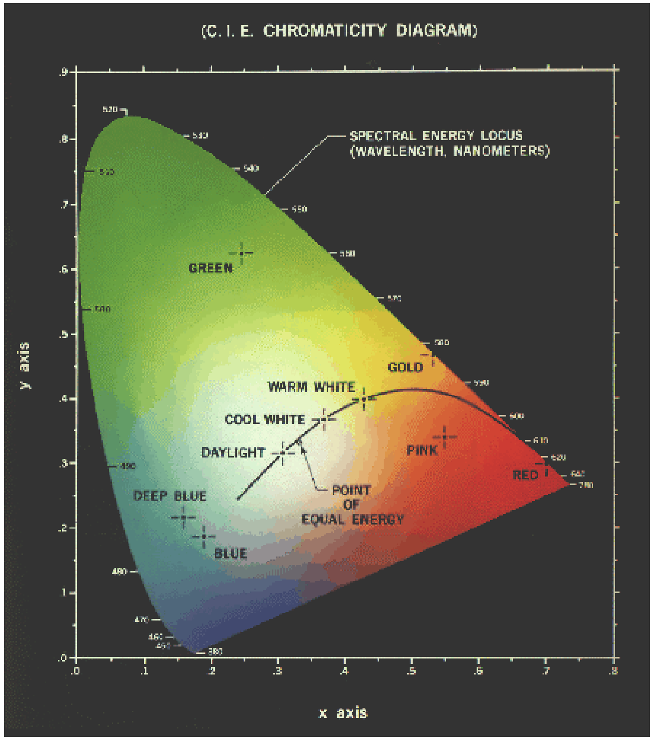
CIE, 10º, 1964

Tristimulus values

- Integrating the product of the spectral content of a real source with the color matching function over the visible band gives the tristimulus values X, Y and Z
- These fully specify:
  - Hue – the dominant spectral color
  - Saturation – level of mixing with white (equal energy)
  - Brightness – total energy
- We can plot the hue and saturation on a plane using only two numbers:
  - $x = \dfrac{X}{X + Y + Z}$
  - $y = \dfrac{Y}{X + Y + Z}$

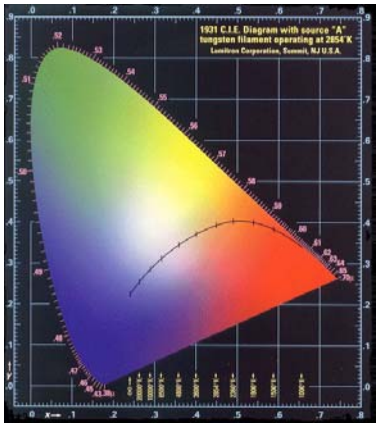
Chromaticity Diagram

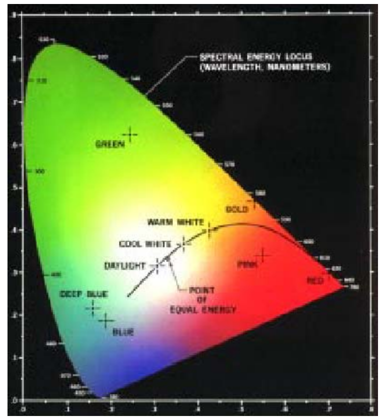
- These two values (x, y) are the chromaticity coordinates

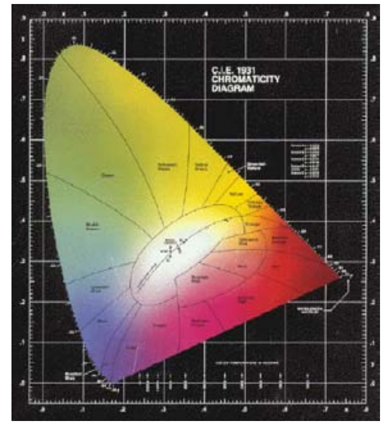


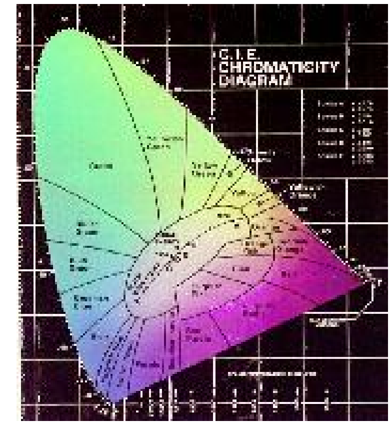
The chromaticity diagram shows all visible colors but it is limited by the medium in which it is reproduced.

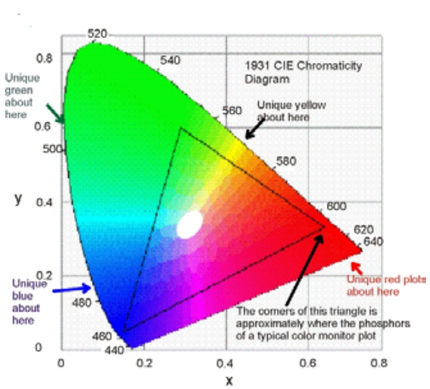
“Standard” chromaticity diagram

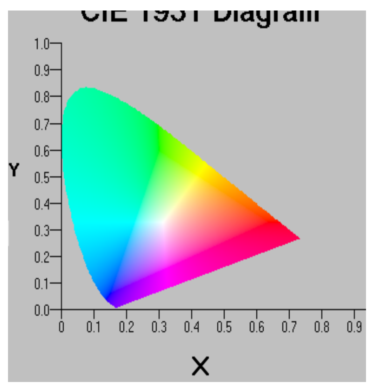


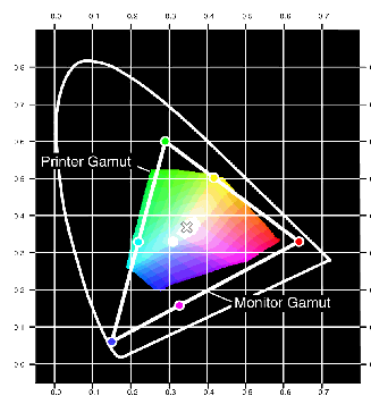


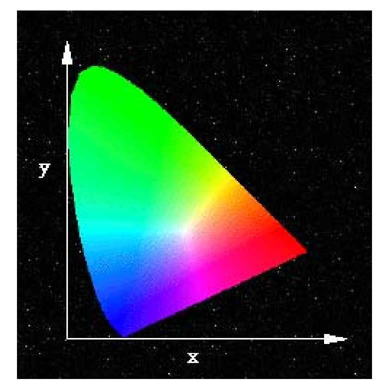












Color spaces

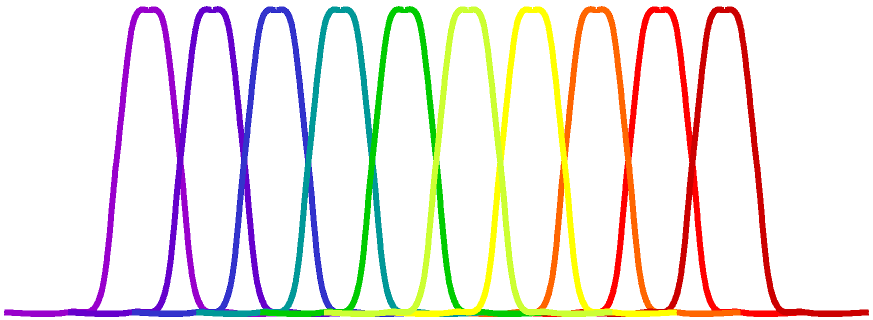
- Numerical representations of all of the visible colors
- XYZ is called the tristimulus color space
- Some others:
  - sRGB – the common computer color display space
  - CMYK – the common color space for 4-color printing
  - CIELAB – A color space with more uniform color difference values
- Color space conversion uses three simultaneous equations usually expressed as a matrix

Color separation techniques

- The goal is to generate three signals that can represent accurately all of the values on the chromaticity chart
- The requirement is to use a detection scheme that
  - Provides at least three reasonably independent measurements of spectral content
  - Includes all wavelengths in the visible spectrum
  - Provides sufficient signal-to-noise ratio to allow discrimination among closely-spaced colors
  - Has sufficient dynamic range to allow computation of coordinates for nearly saturated colors over a reasonable brightness range
- Additionally, the scheme should
  - Maintain repeatability over time
  - Provide sufficient speed and resolution
  - Not suffer too greatly from the limits of sampling theory

Spectral measurement

- Take 20-50 images with narrowband filters



- Do the integrations directly
- Big penalties in data rates and data processing
- But - three channels should be sufficient

Three-channel separation methods

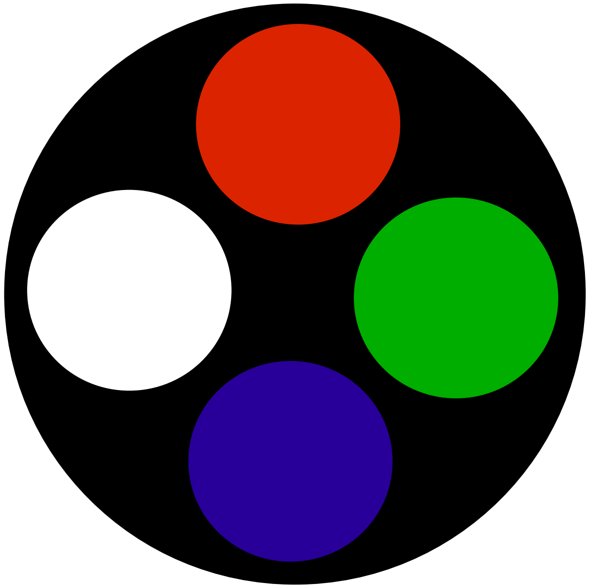
- Match 3 sensors to the spectral response of the eye
  - Hard to do accurately
  - Noise problems in the blue channel
  - No mathematical convenience
- Match 3 sensors to the shape of the color matching curves
  - Hard to do accurately
  - Very hard to do inexpensively
  - Unlikely to do repeatedly in volume production
- Match 3 sensors to a linear combination of the color matching curves
  - Need to figure out the color space transformation matrix
  - Probably not entirely accurate, ever
  - Arithmetic reduces signal-to-noise ratio
- Use arbitrary channels and a big lookup table (color profiling)
  - Highly variable accuracy due to extreme non-linearities

Three-channel color technologies

- One monochrome sensor
  - Sequential filtering
  - Simultaneous filtering
- Three monochrome sensors
- One layered color sensor

Sequential filtering

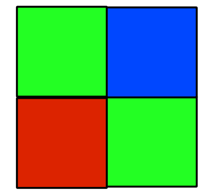
- Good
  - Perfect color registration
  - Easy to change filter set
  - Very repeatable
  - Excellent illumination control
  - Requires only one sensor



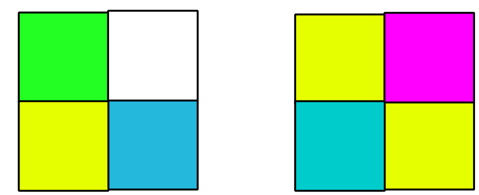
- Bad
  - Slow
  - Requires mechanical elements
  - Substantial light loss

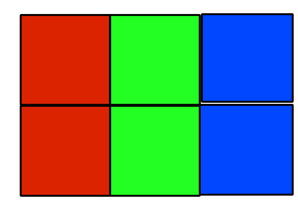
Simultaneous filtering

- Good
  - Only one sensor
  - Fixed intercolor alignment
  - Simple optics
  - Several filter options
- Bad
  - Colors geometrically separated
  - Color fill requires interpolation
  - Filters can age
  - Substantial light loss



Bayer

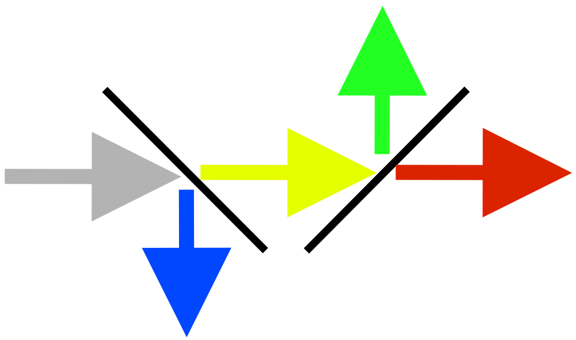




Stripe

Three monochrome sensors

- Good
  - Can get accurate registration
  - Uses light efficiently
  - Large sensor selection
- Bad
  - Several elements behind lens
  - Limited filter selection
  - Requires three sensors
  - Large volume



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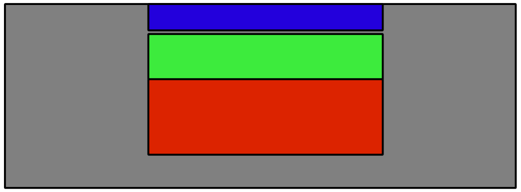
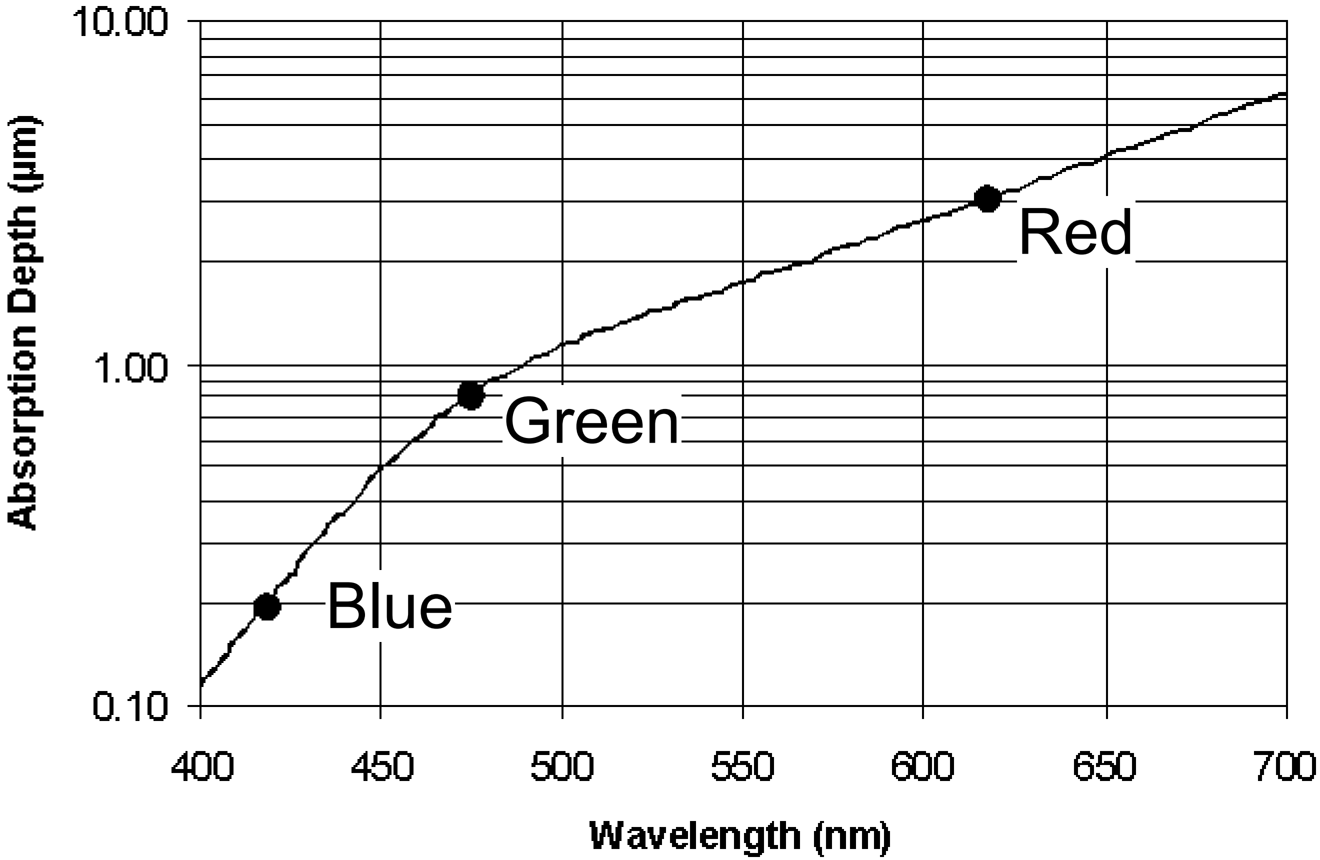
One layered color sensor

- Good
  - Perfect alignment
  - No filters
  - Efficient use of light

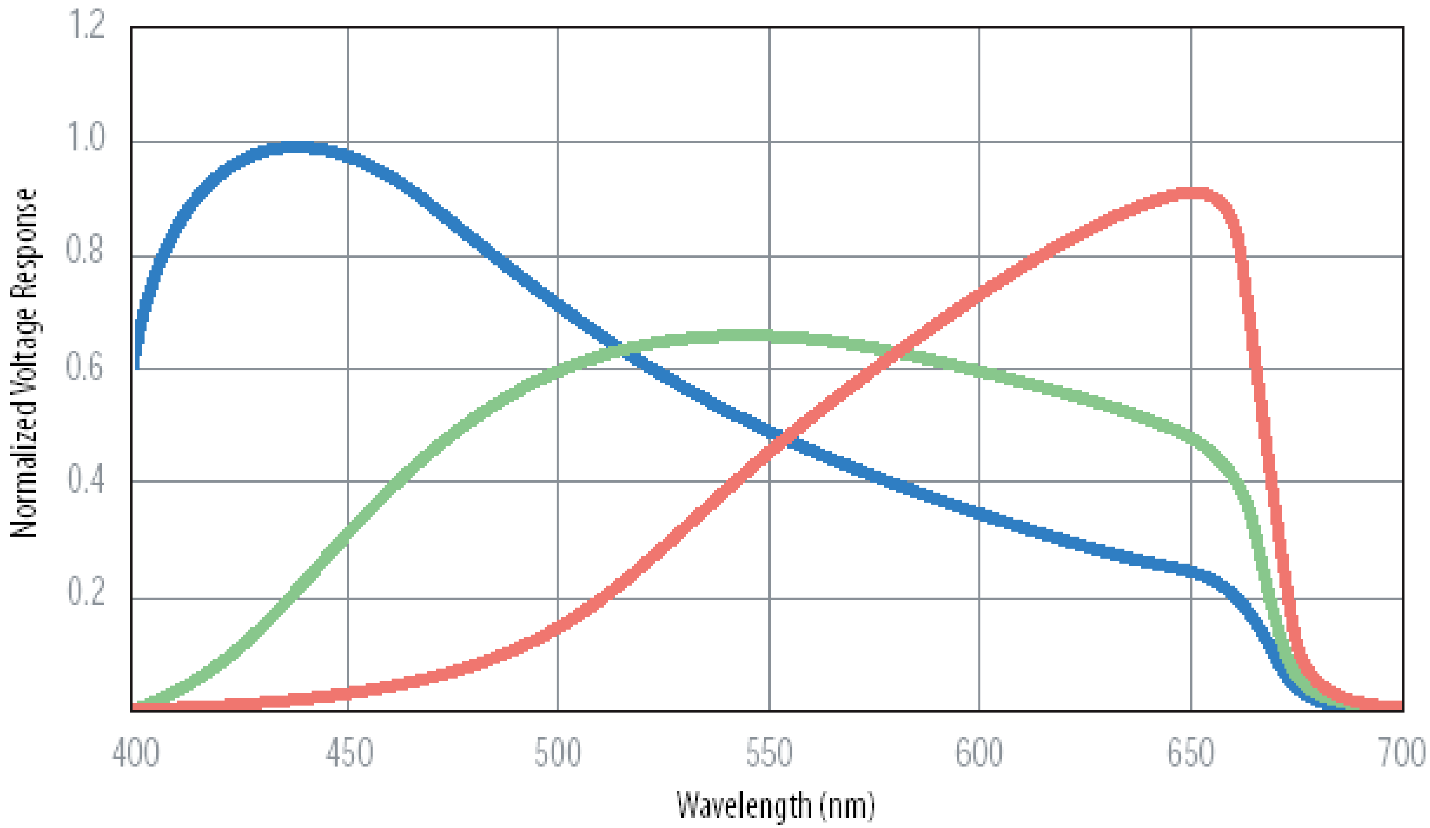


- Bad
  - Limited range of filter shapes
  - Must be designed into sensor
  - Depends on silicon absorption profile

Where to put the diodes

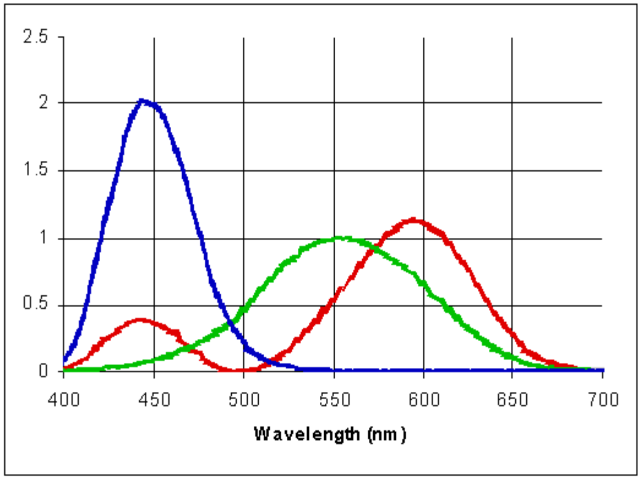


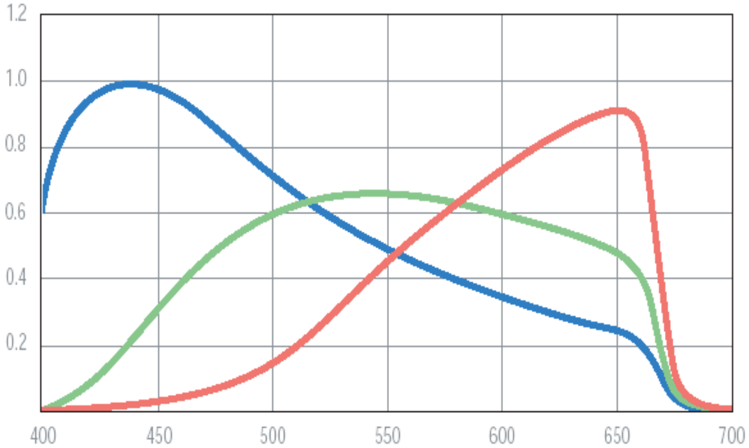
Spectral Characteristics



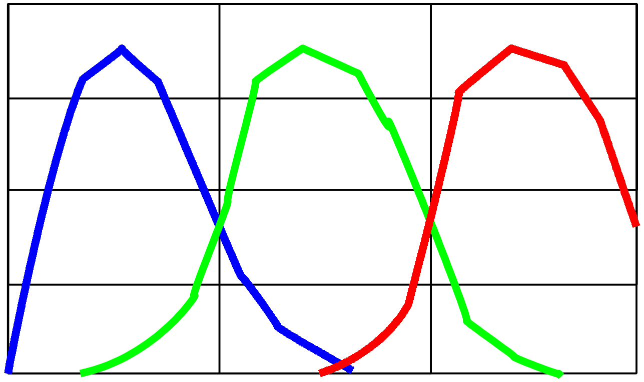
Includes effect of 400-660 nm pass filter

Color channel comparison

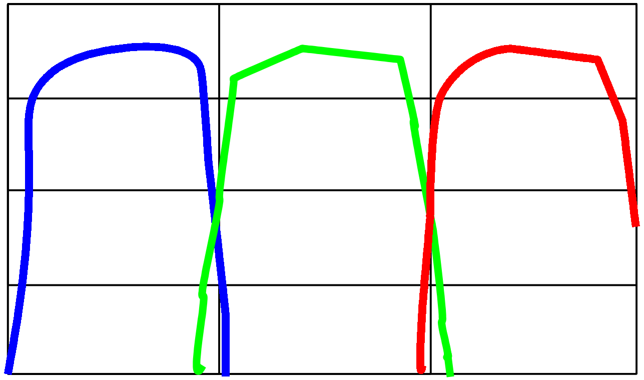




Layered



One-chip



Three-chip

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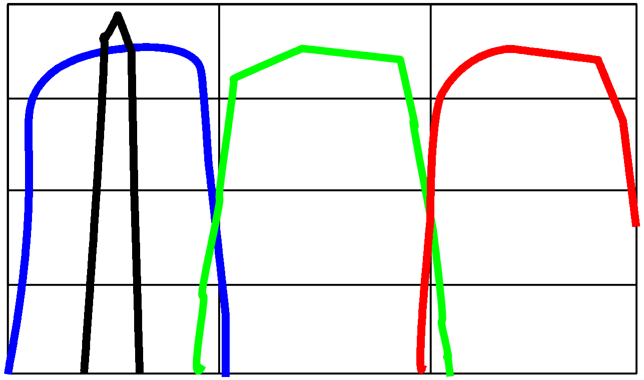
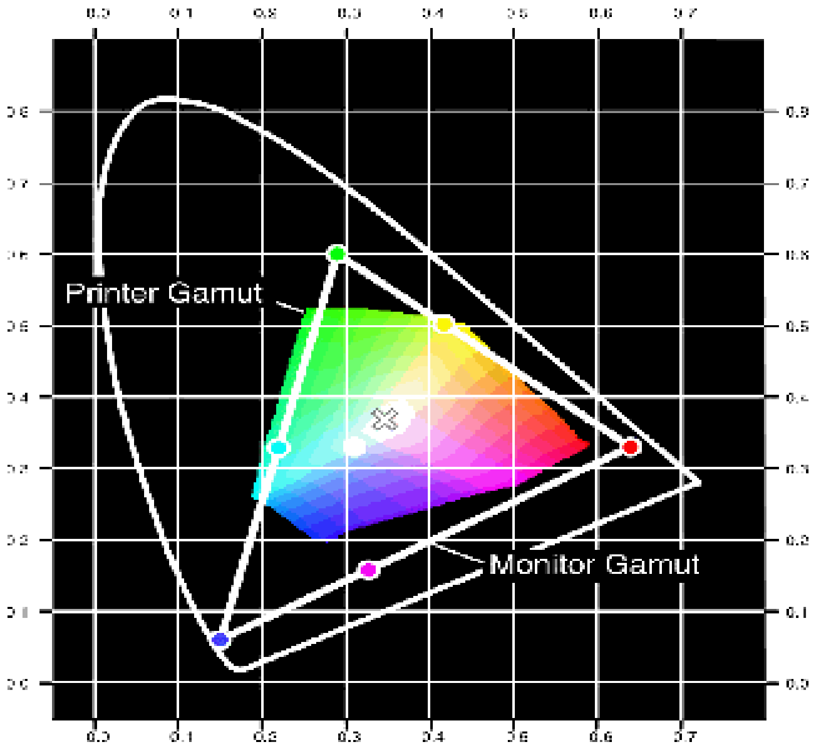
Real channels to tristimulus data

- Most channel shapes work reasonably well with broadband inputs (unsaturated colors)
- As channels sharpen, discrimination of narrowband inputs worsens
- Sharp-edged channels cannot discriminate wavelength changes in narrowband sources



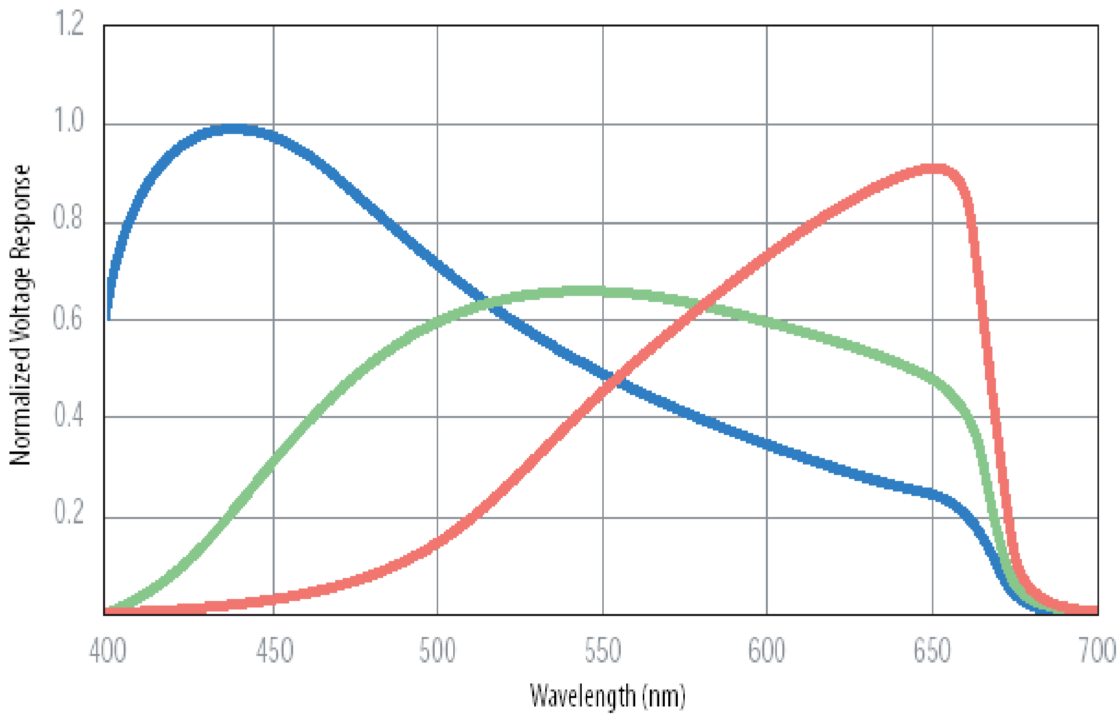
Does it matter?

- Most displays cannot reproduce saturated colors so the effects only appear at spectral extremes.



Does overlapping help?

- As long as two channels are changing, wavelength can be discriminated



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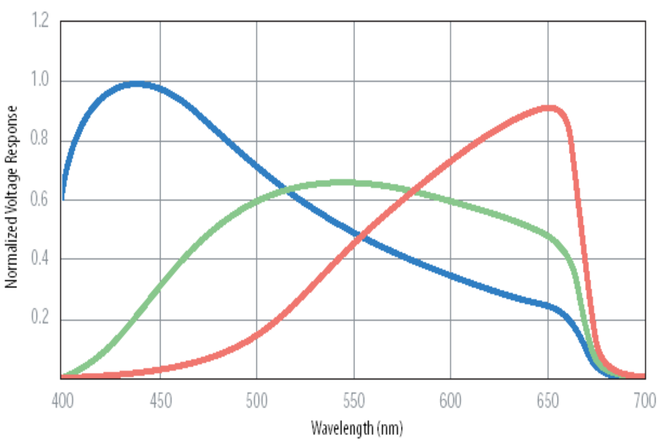
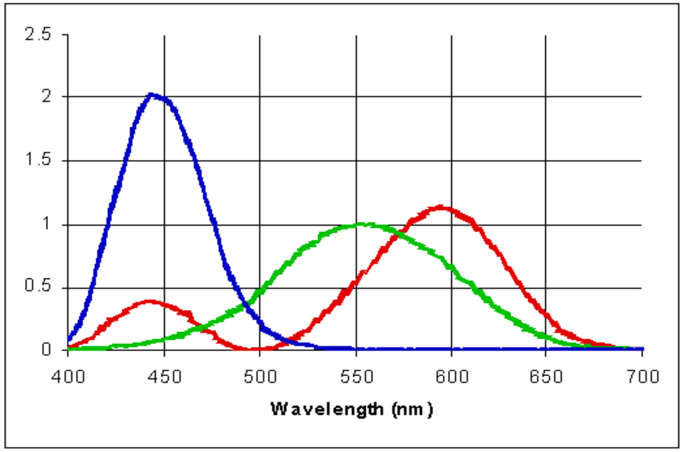
Overlaps require strong matrices

- Sharpening requires large off-axis factors to convert to tristimulus space



Sensor Inputs

	R	G	B
X	0.381	0.597	-0.03
Y	-1.18	3.472	-1.3
Z	0.887	-3.91	4.112



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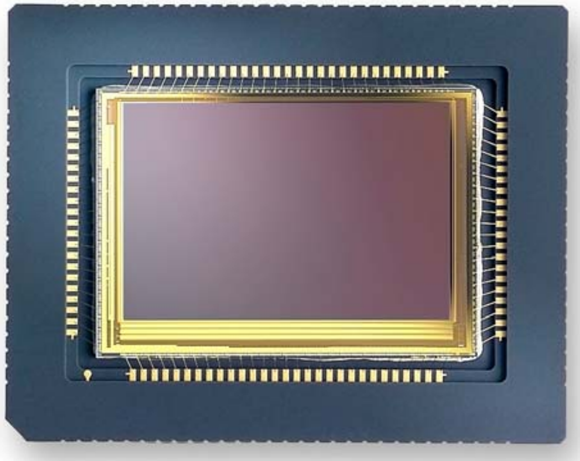
How good are the results?

- The usual measurement involves measuring color errors in La*b* space
- The measurement is ΔE, the rms error between the true color coordinates and the sensor measure
- The overlapped bands give a lower average error, more very small errors and no more large errors than the best filter systems
- Overlapped bands produce slightly more chroma noise but better average chroma values
- Sensors with overlapped bands have no interpolation noise

The first commercial sensor

- 2268 x 1512 active pixel locations
- 3 photodiodes per pixel location
- ~54% fill factor
- 9.12 x 9.12 µm pitch
- Black matrix mask
- 0.18 µm, 3.3 V CMOS
- 400 – 660 nm window
- 100-pin CLCC package

FOVEON



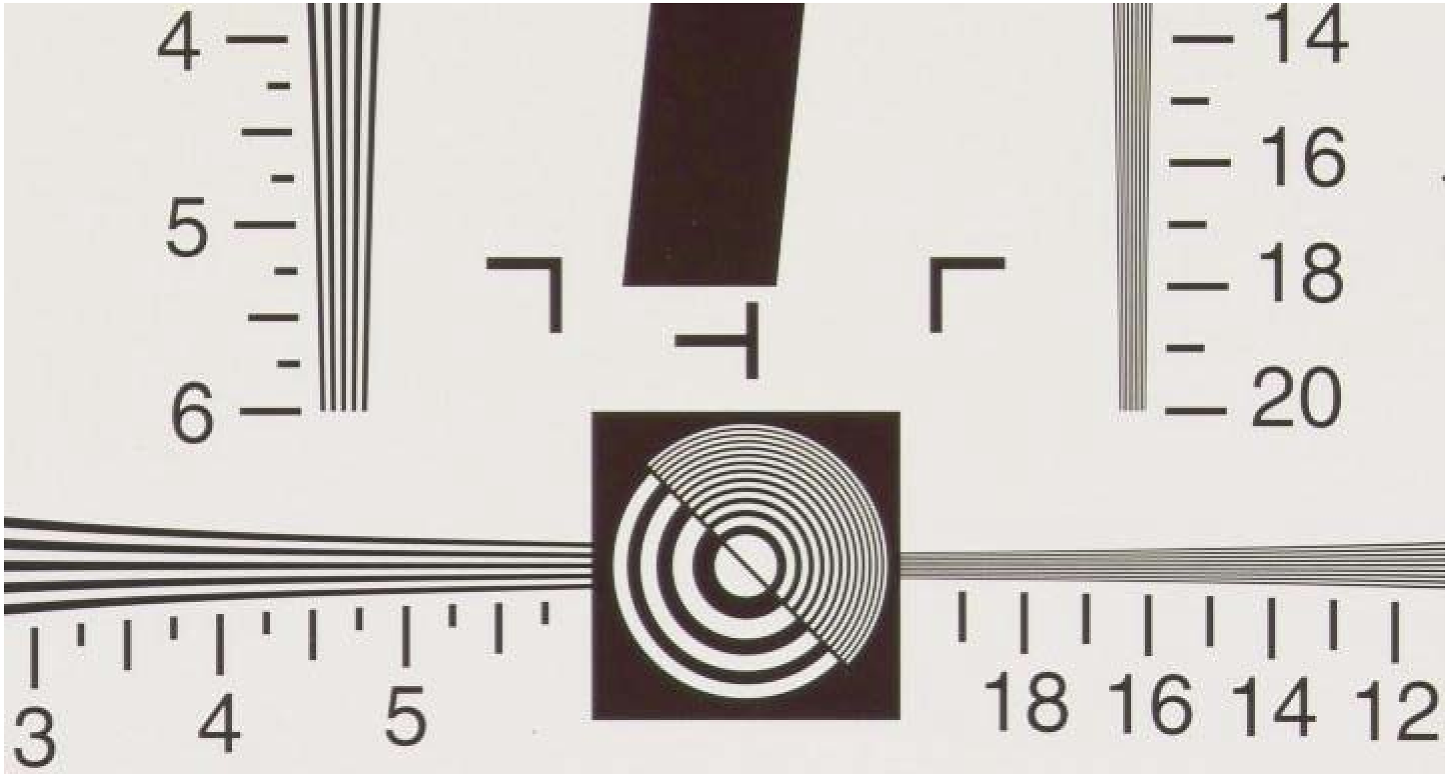
Special Features

- Extensive scan control
  - Select any rectangular regoion of interest
  - Bin H and V independently
  - Skip every n lines or columns
- Adjustable analog voltages
  - Output levels
  - Anti-blooming level
- Three exposure control modes
  - Synchronized external shutter – still shot
  - Full-frame with no shutter
  - Rolling shutter down to one line interval

Performance

- 49% QE at 625 nm
- 61 db dynamic range
- Dark current ~1na/cm^2 at 25C
- PRNU < ±1%
- 80 mW maximum power
- 24 MHz clock – 4 fps for full sensor
- 7.14 µV/electron sensitivity
- Noise = 70 electrons rms (mostly kTC)

No color aliasing



This is a color image

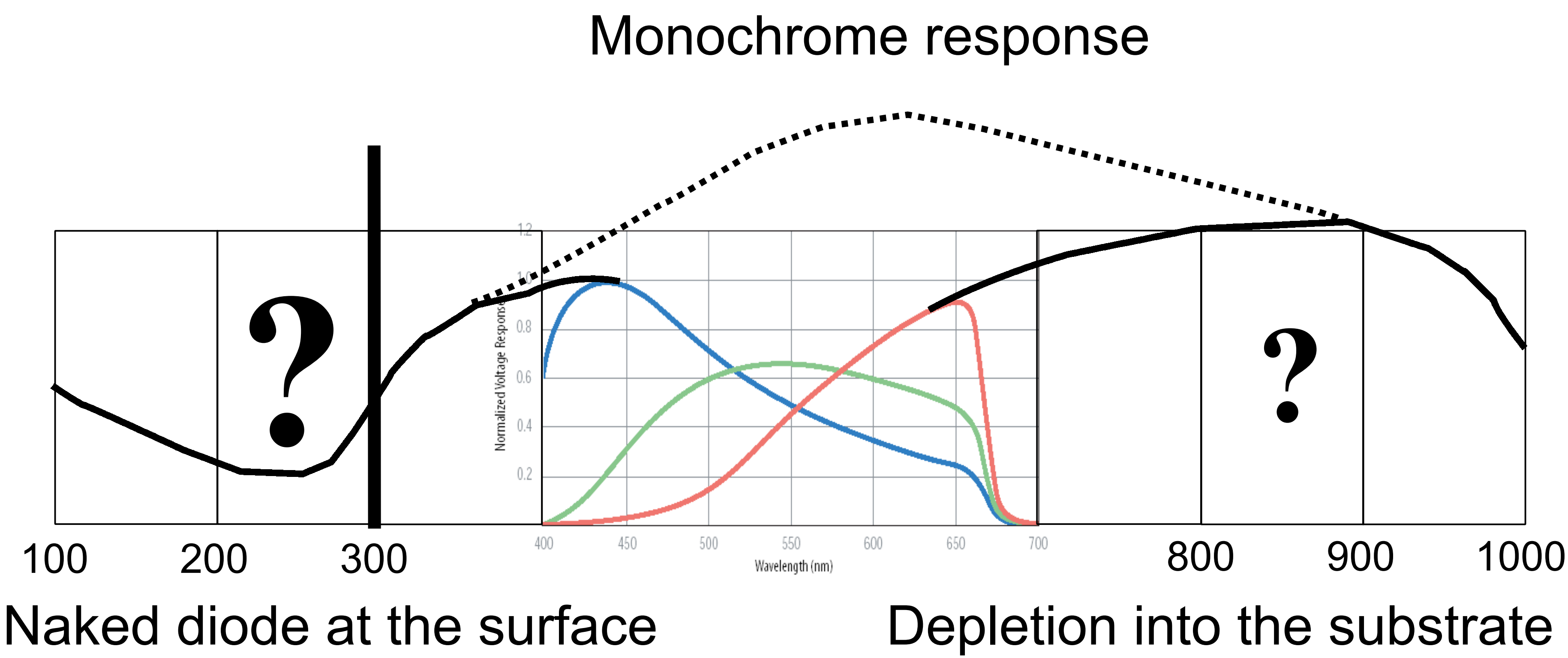
Processing requirements

- Four necessary steps
  - Column filter – FIR, noise reduction
  - Linearization – static lookup table
  - Dark field subtraction – long exposures
  - Color transformation – for display
- Other useful options
  - Red sharpening
  - White balance
  - Highlight neutralization

Future Directions

- Smaller pixels, larger pixels
- Bigger arrays, smaller arrays
- More integration
  - Control
  - Processing
- Microlenses
- Other spectral bands?

Non-color imaging



Very accurate color imaging

- Six bands is sufficient for 95th percentile spectral estimation
- Requirement is reasonable independence
- Method:
  - Take two images with a 3-channel sensor
  - Each exposure has a shaping filter
- Result should be $\Delta E < 1.0$ over 95% of the chromaticity chart
- Supports 6-channel displays

Some images – Moon Shot

London

Askey

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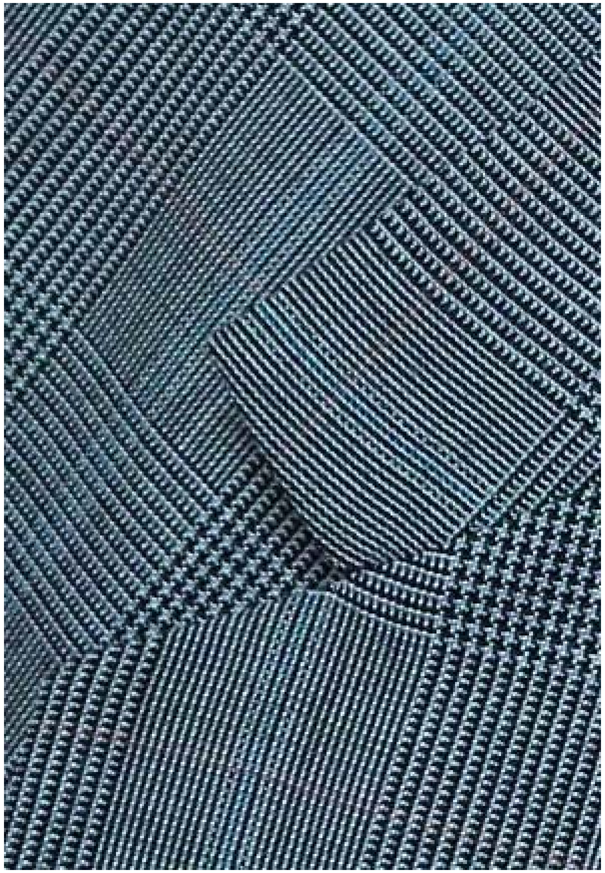
Umbrella

Suit



Fritz

Alternative Vision

Hinasama

Queen Mary

Sphomphanh

Alternative Vision

Tiles

Sphomphanh

Mountains & Lake

Toth