Operation and performance of a color image sensor with layered photodiodes

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AeroSense 2003
5074-35

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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

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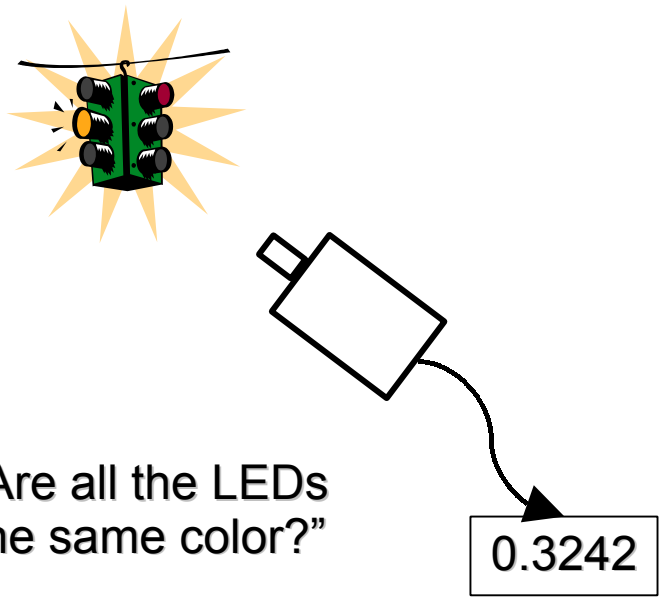
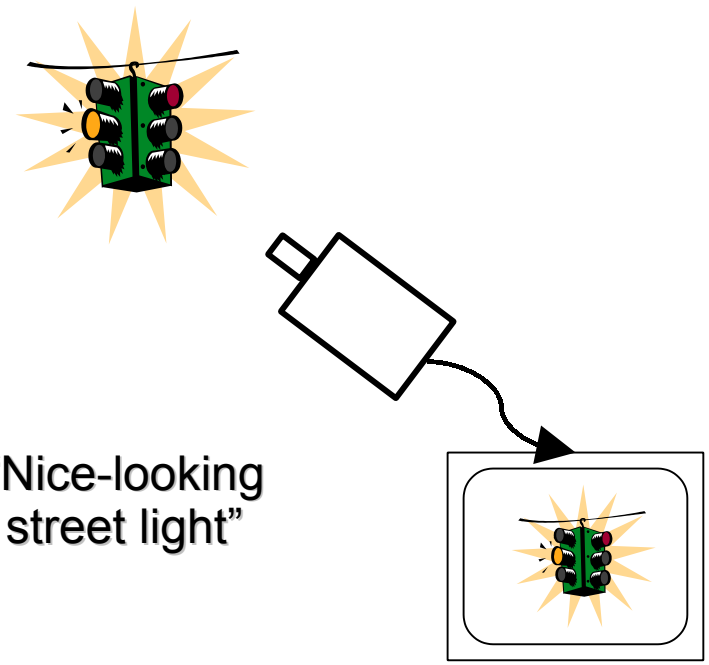
What is color imaging?

- Imaging for measurement



Not Perceptual

- Imaging for reproduction



Perceptual

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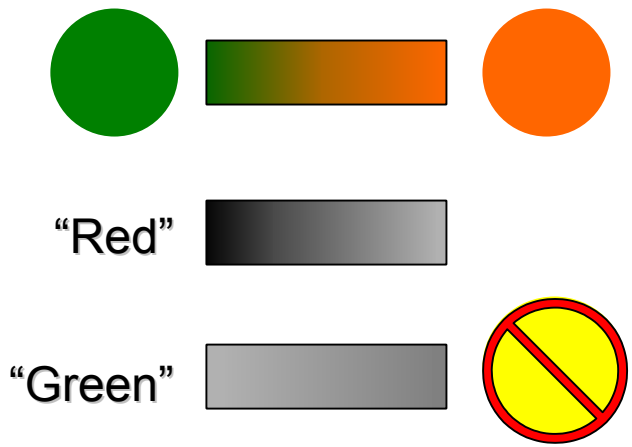
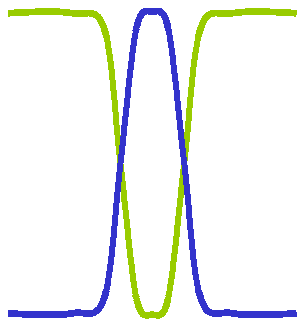
Imaging for color measurement

- 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"?

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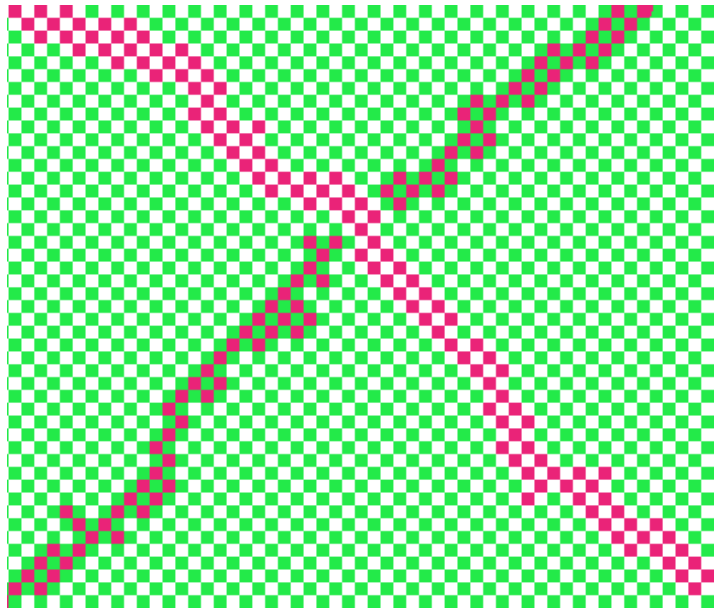
Imaging for color reproduction

- 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



www.optillusions.com

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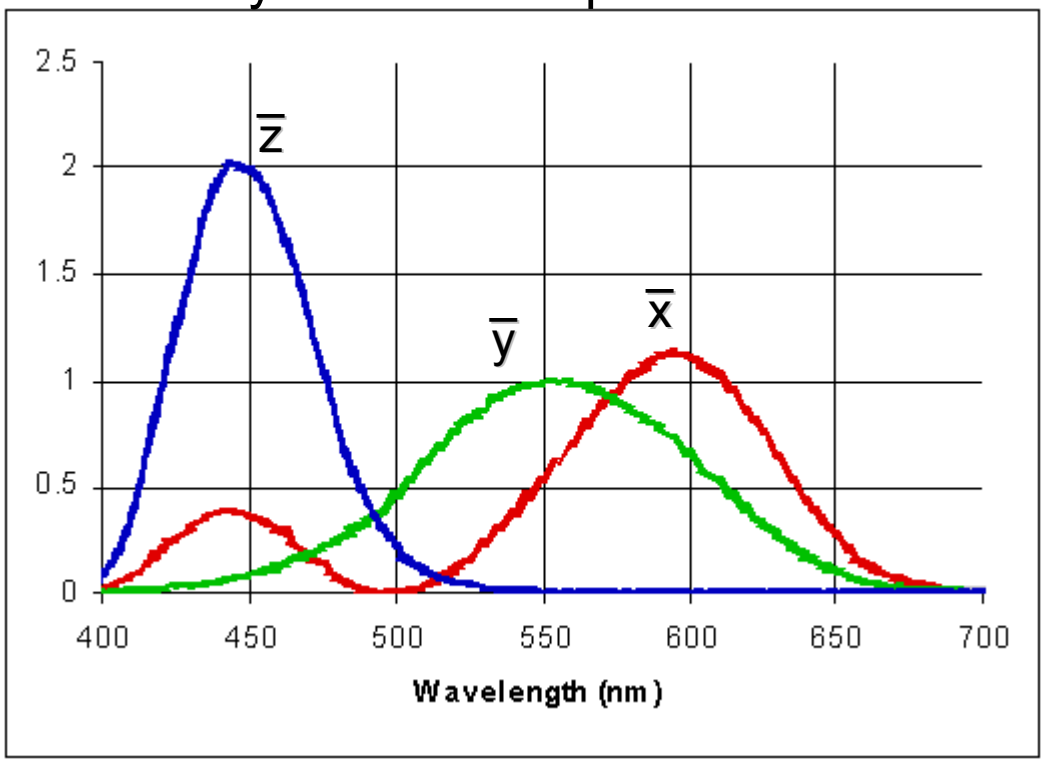
The Standard

- 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

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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:

$$x = \frac{X}{X + Y + Z}$$

$$y = \frac{Y}{X + Y + Z}$$

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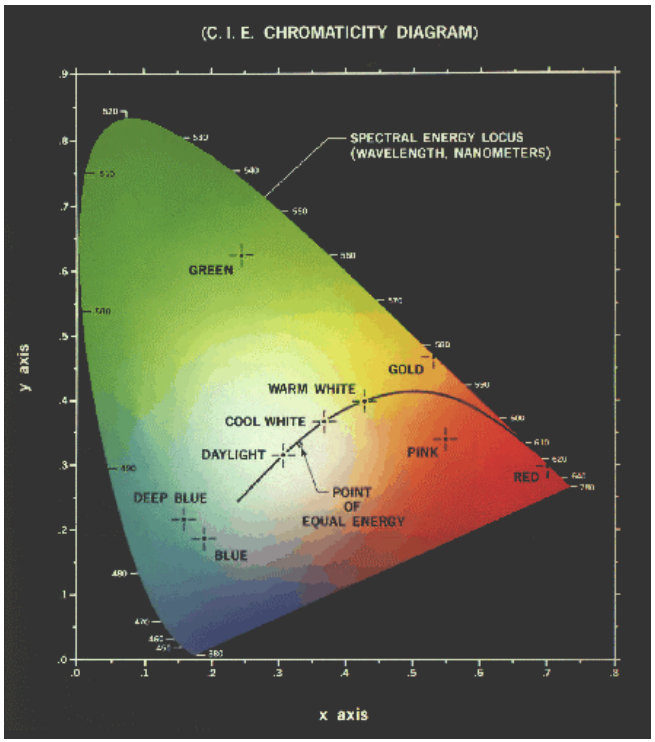
Chromaticity Diagram

- 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.

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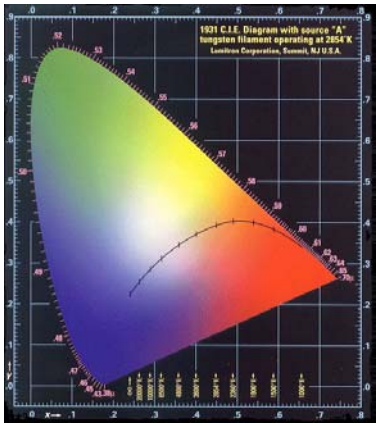
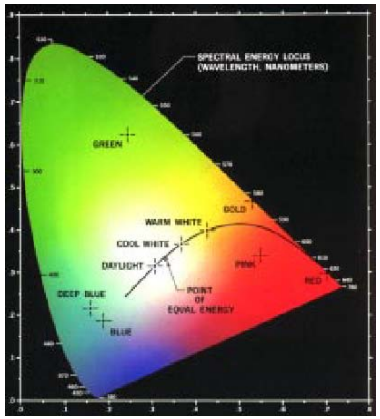
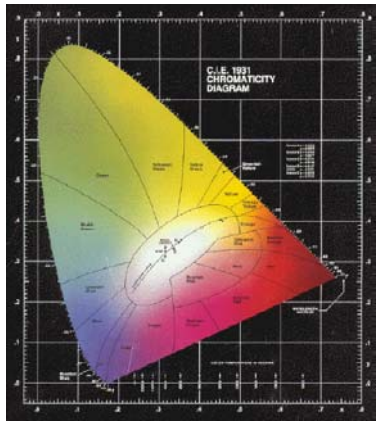
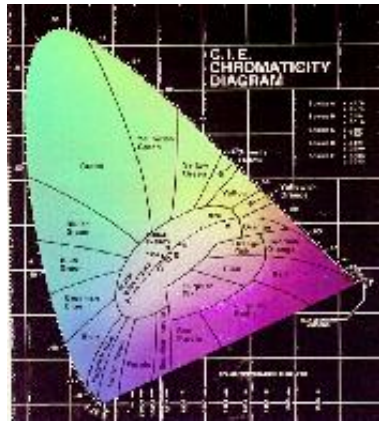
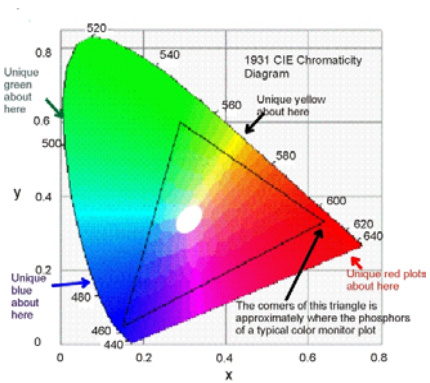
“Standard” chromaticity diagram

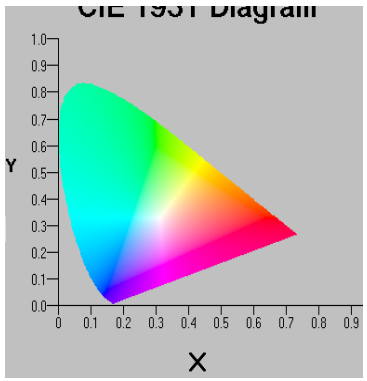


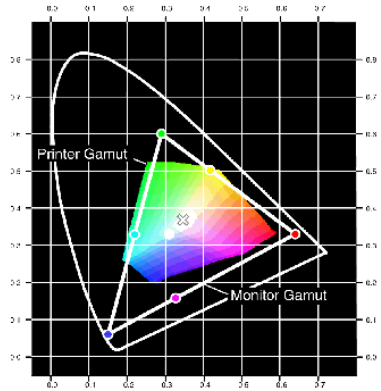


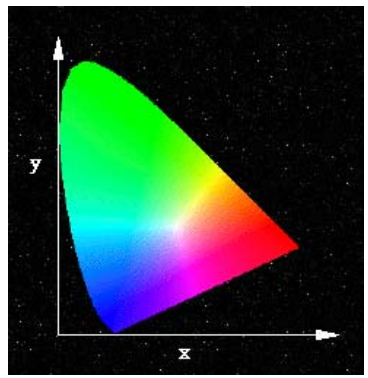












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Color spaces

- 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

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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

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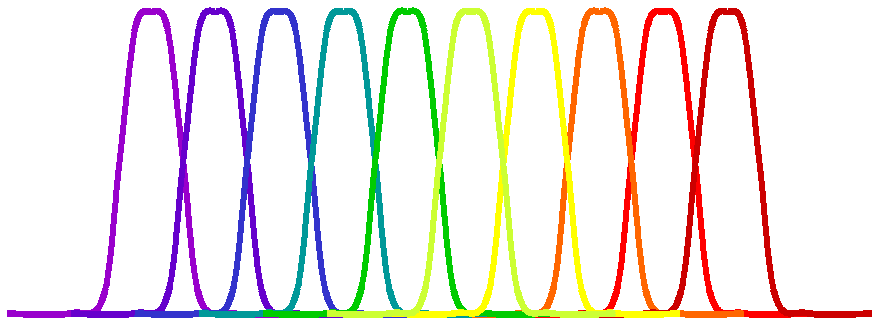
Spectral measurement

- 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

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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

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Three-channel color technologies

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

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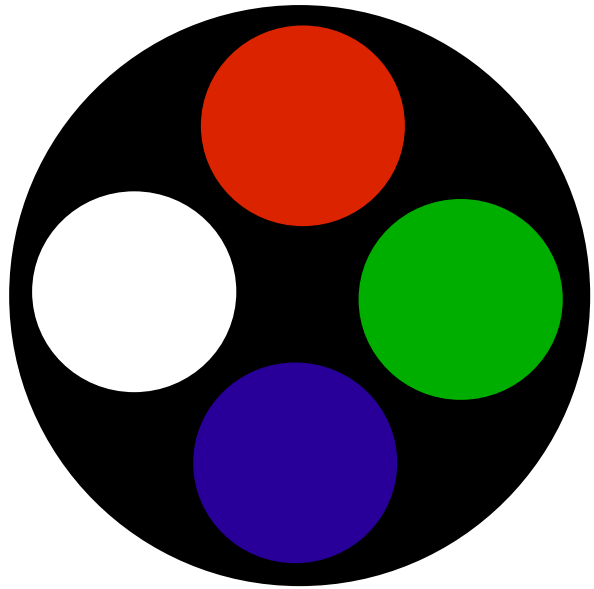
Sequential filtering

- 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



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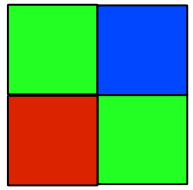
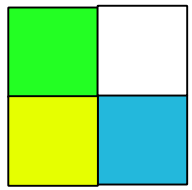
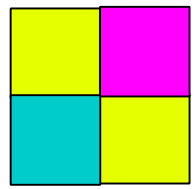
Simultaneous filtering

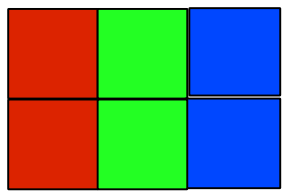
- Good
  - Only one sensor
  - Fixed intercolor alignment
  - Simple optics
  - Several filter options
- Bad
  - Colors geometrically separated
  - Color fill requires interpolation
  - Filters can age
  - Substantial light loss



Bayer







Stripe

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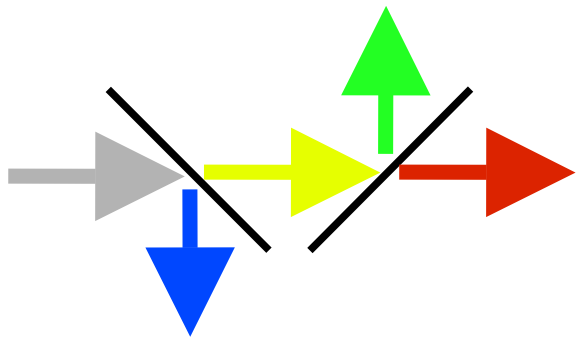
Three monochrome sensors

- 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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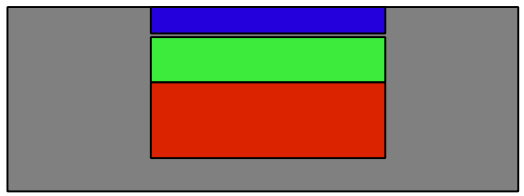
One layered color sensor

- 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

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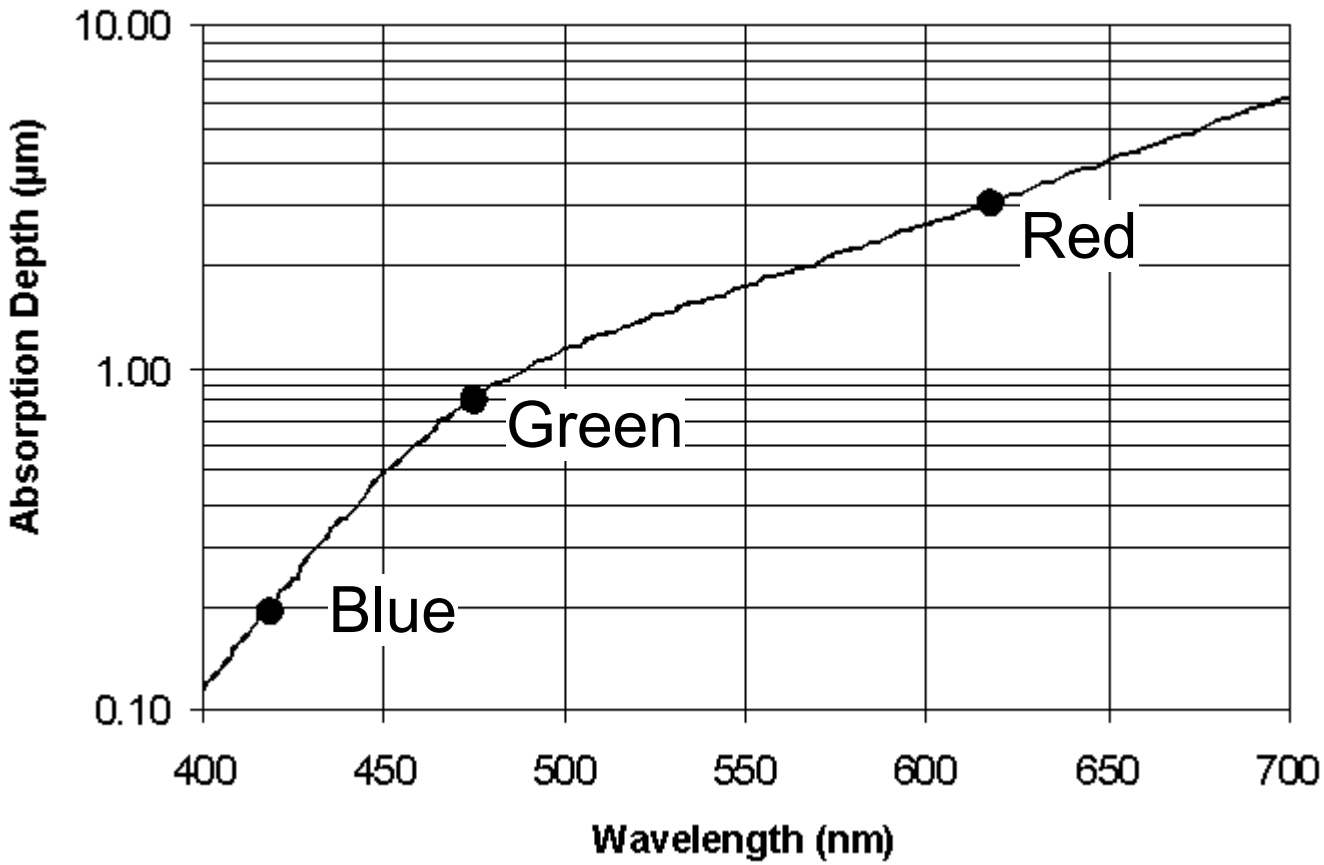
Where to put the diodes



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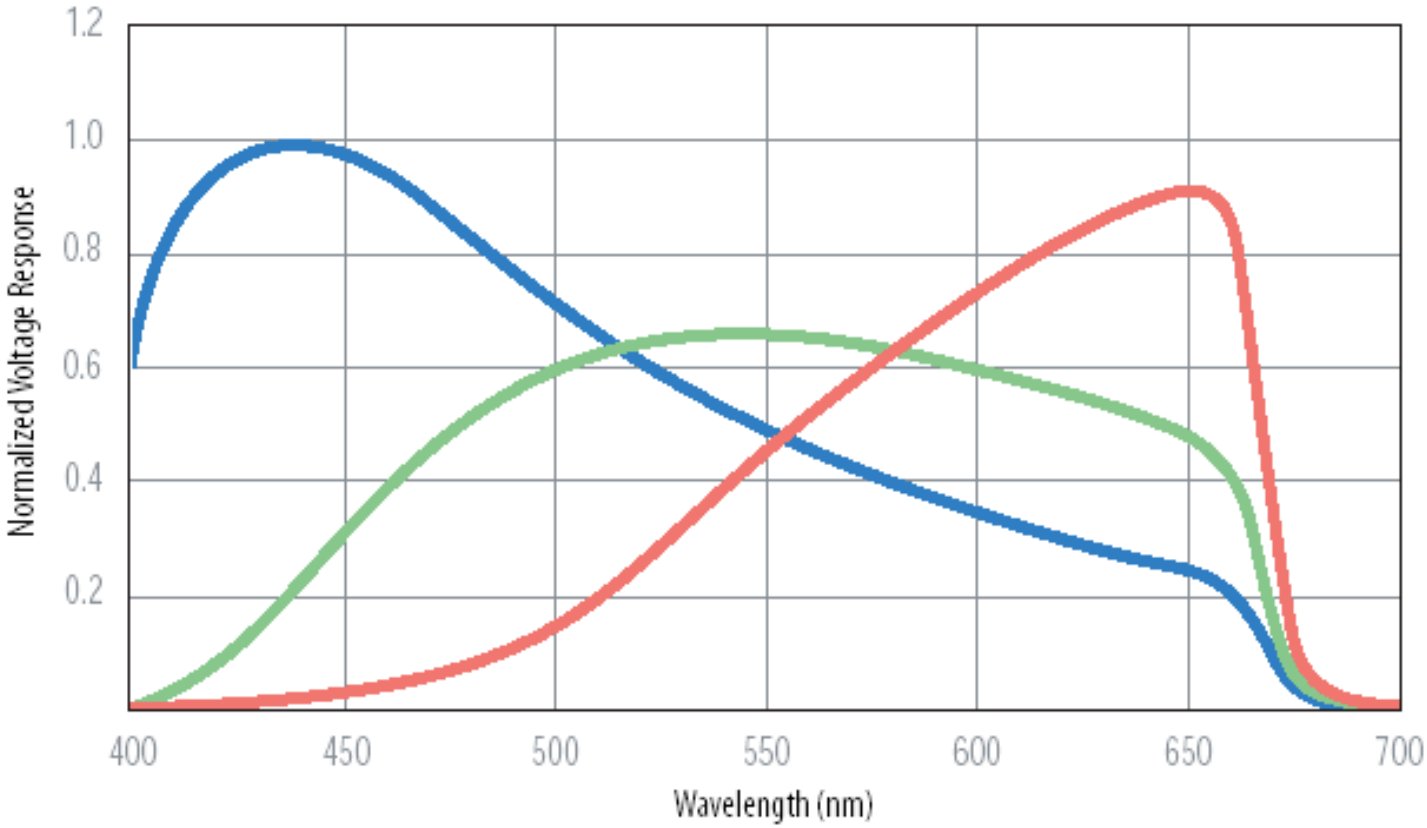
Spectral Characteristics



Includes effect of 400-660 nm pass filter

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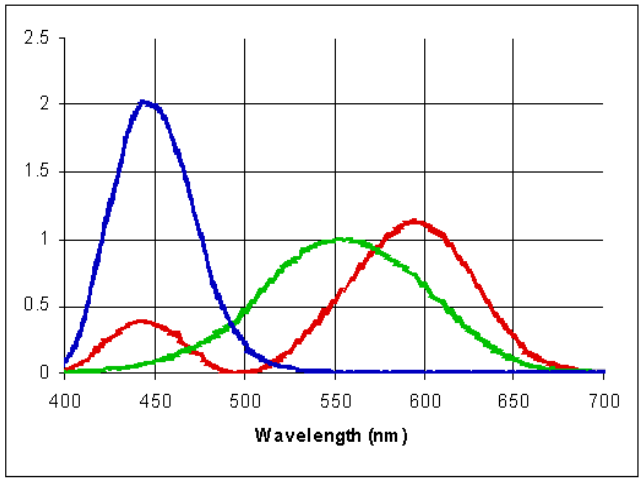
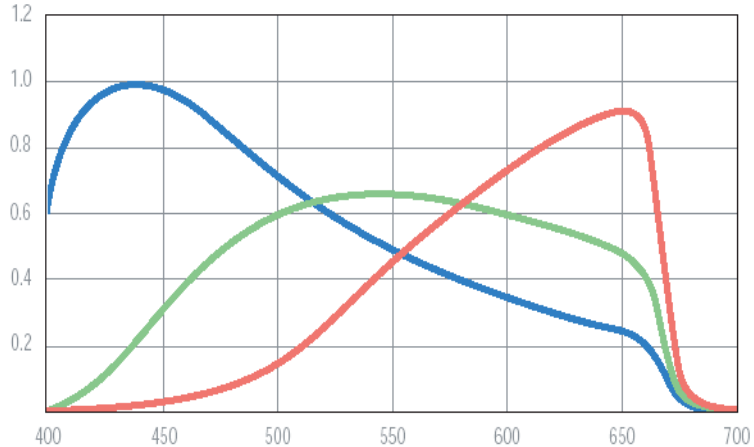
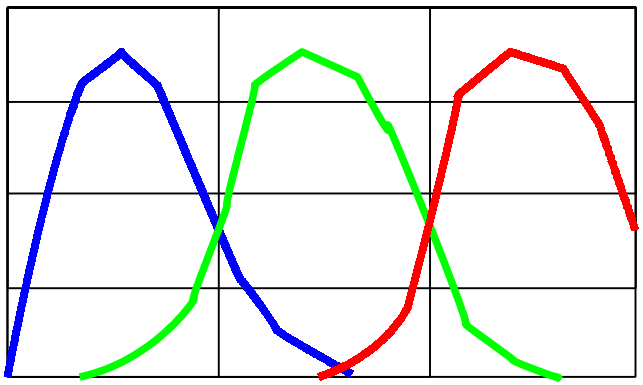
Color channel comparison

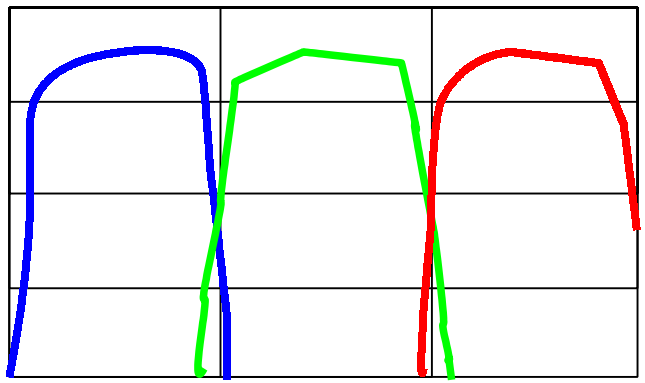




Layered



One-chip



Three-chip

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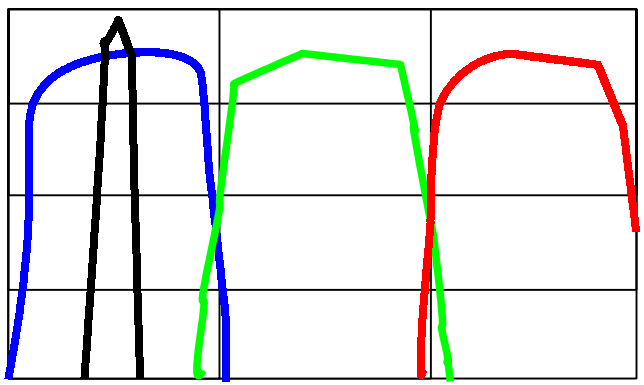
Real channels to tristimulus data

- 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



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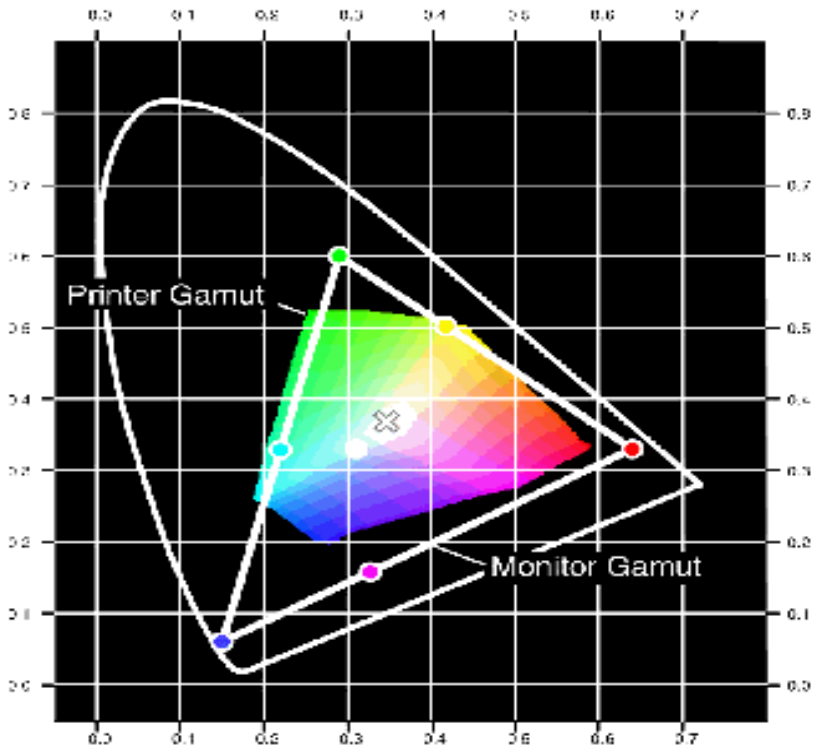
Does it matter?

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



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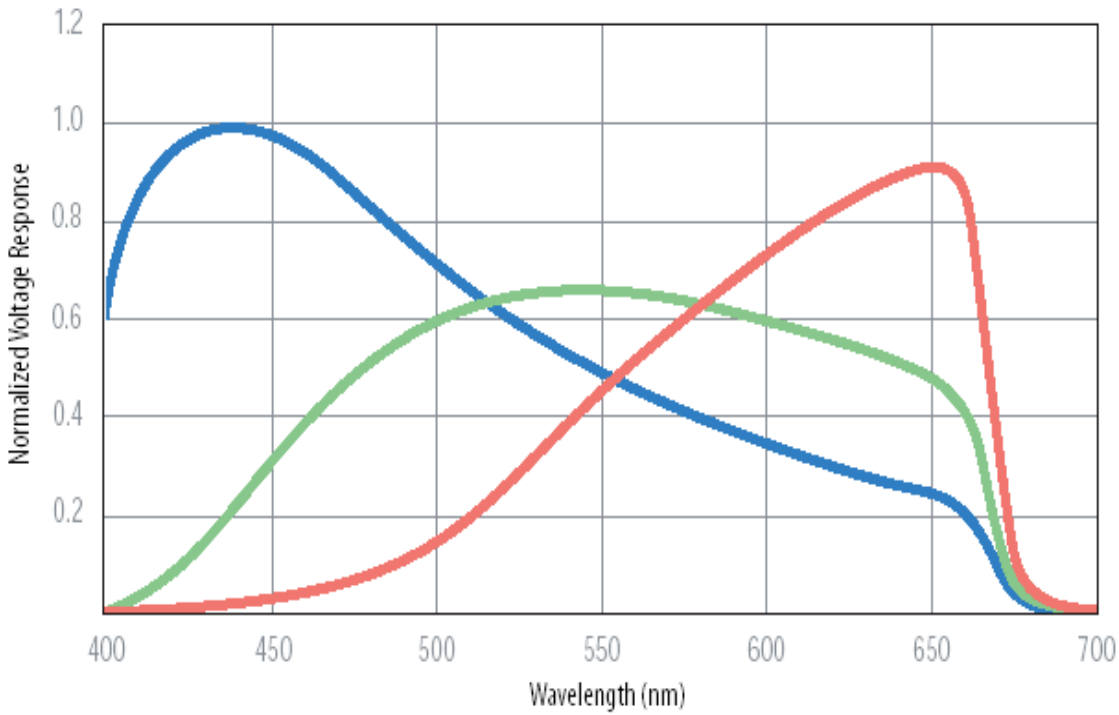
Does overlapping help?

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



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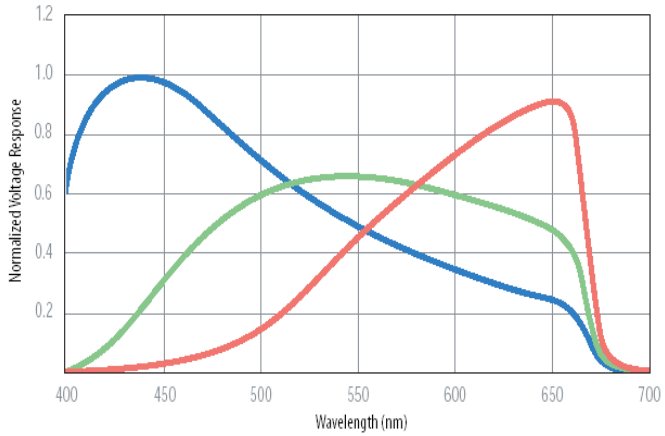
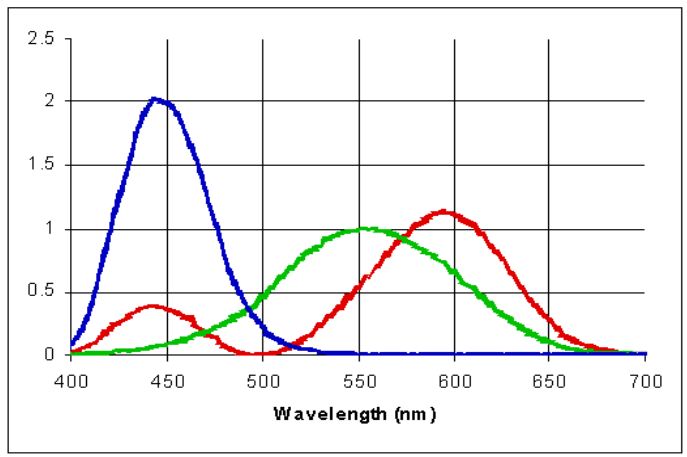
Overlaps require strong matrices

- 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

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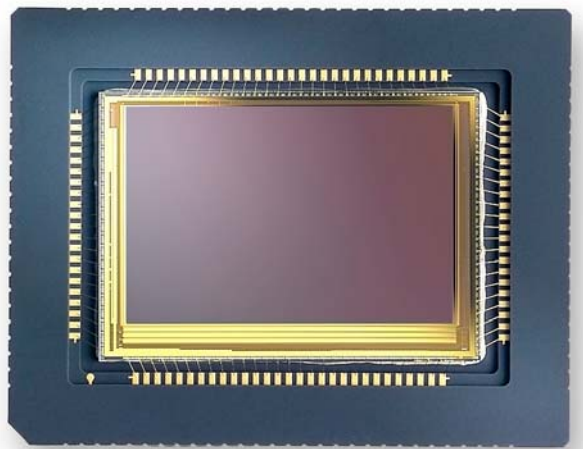
The first commercial sensor

- 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



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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

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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)

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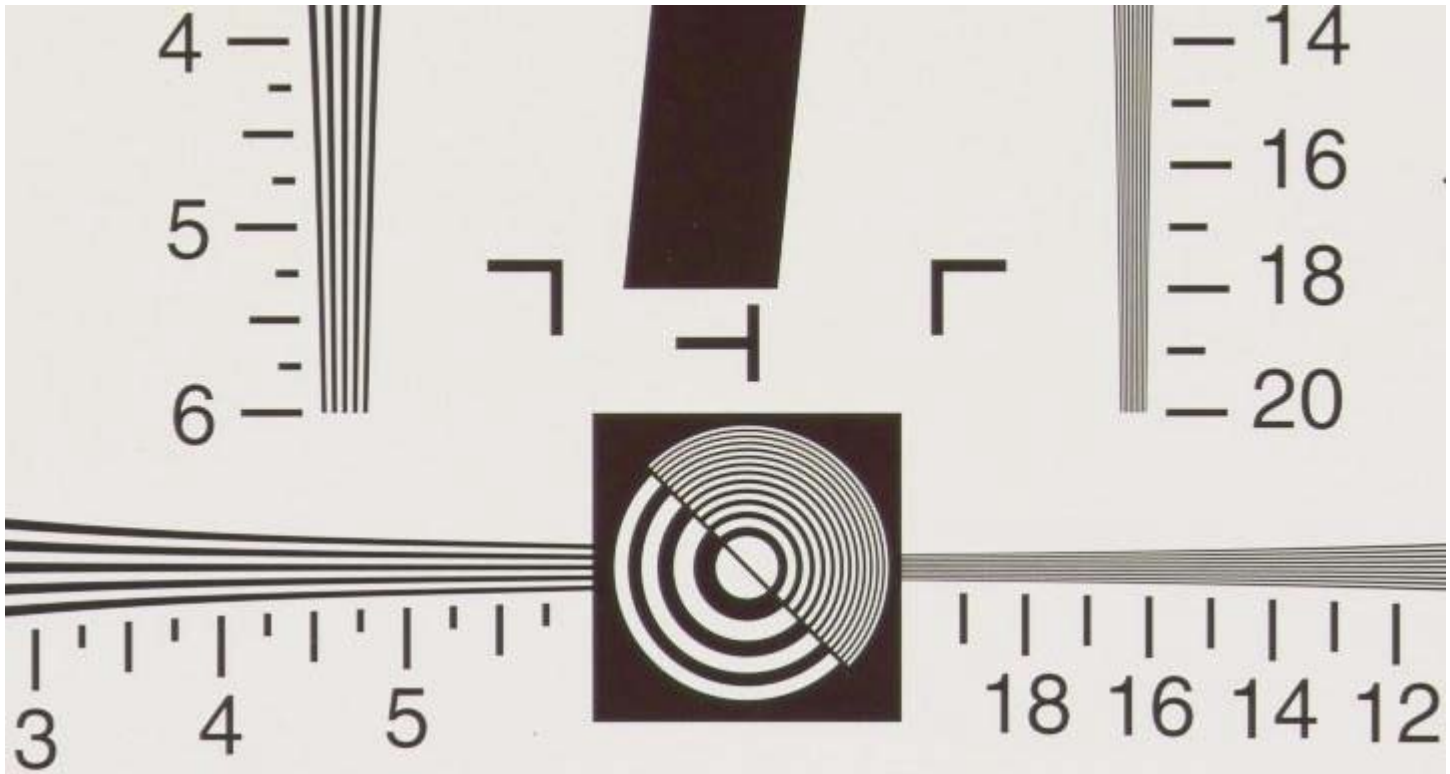
No color aliasing



This is a color image

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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

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Future Directions

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

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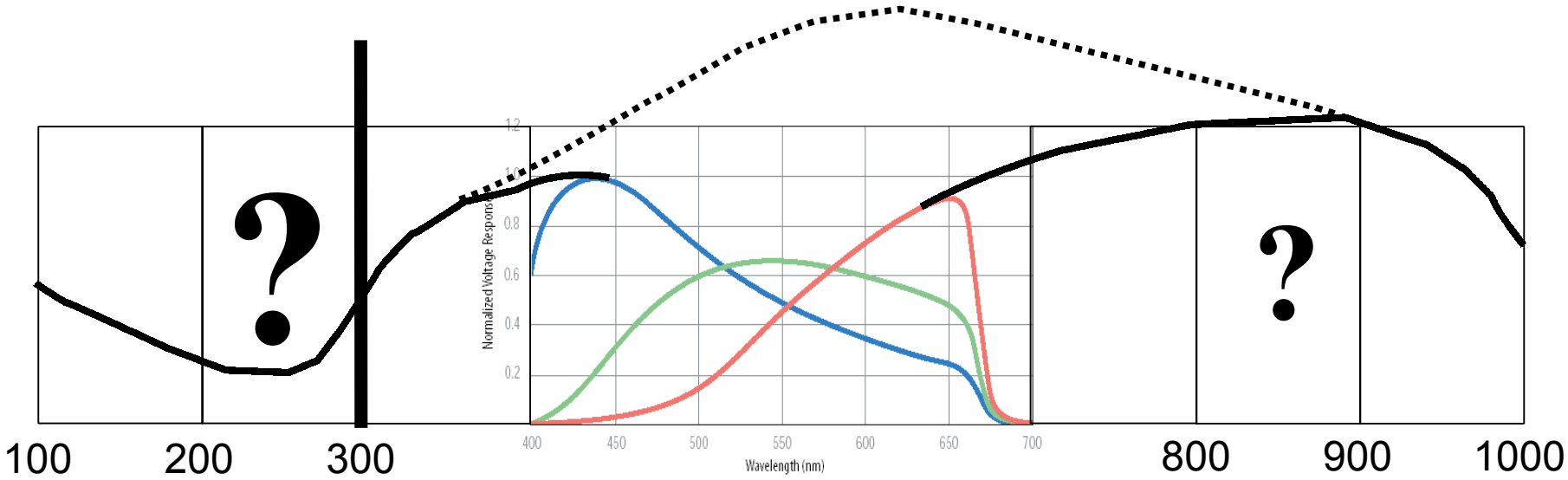
Non-color imaging

Monochrome response



Naked diode at the surface

Depletion into the substrate

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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

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Some images – Moon Shot

London

Askey

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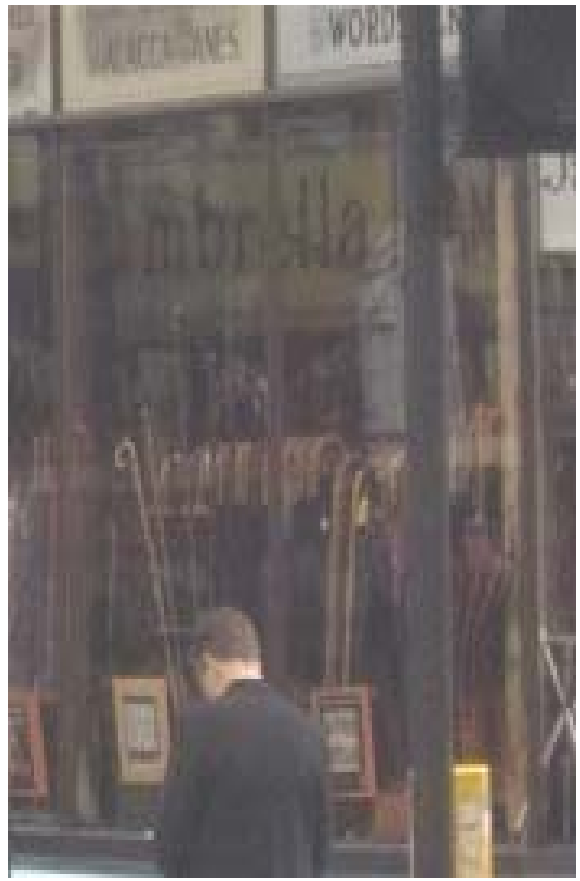
Umbrella



Askey

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Suit

Fritz

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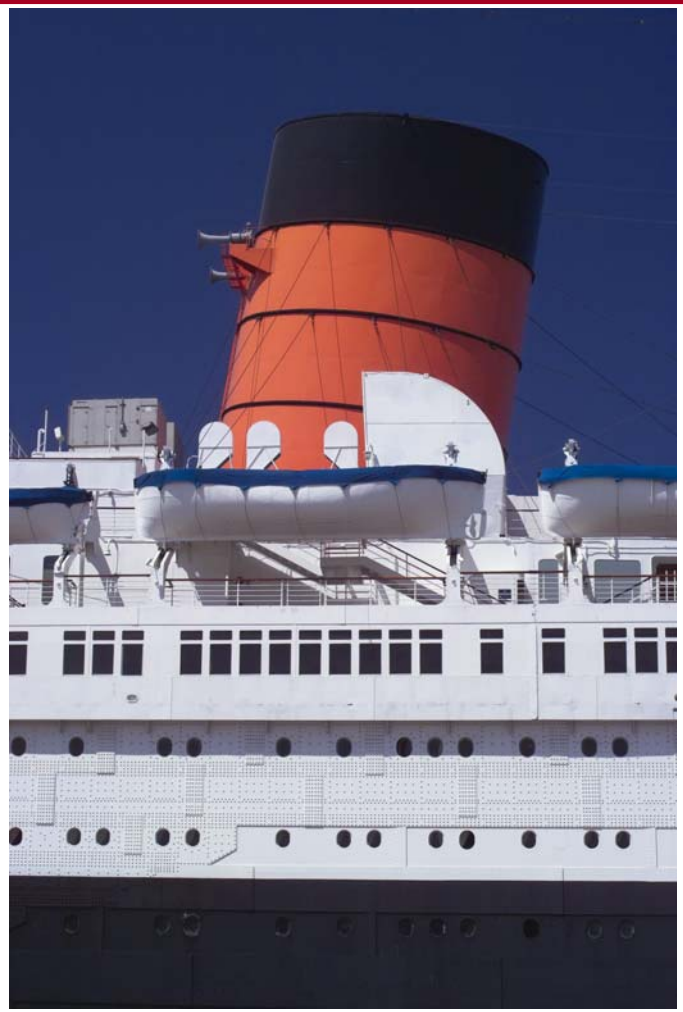
Hinasama

Alternative Vision

Queen Mary



Sphomphanh

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Tiles

Sphomphanh

Alternative Vision

Mountains & Lake

Toth

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