# Opponent Color Spaces

- Perception of color is usually not best represented in RGB.

- A better model of HVS is the so-call opponent color model

- Opponent color space has three components:

  - $O_1$ is luminance component
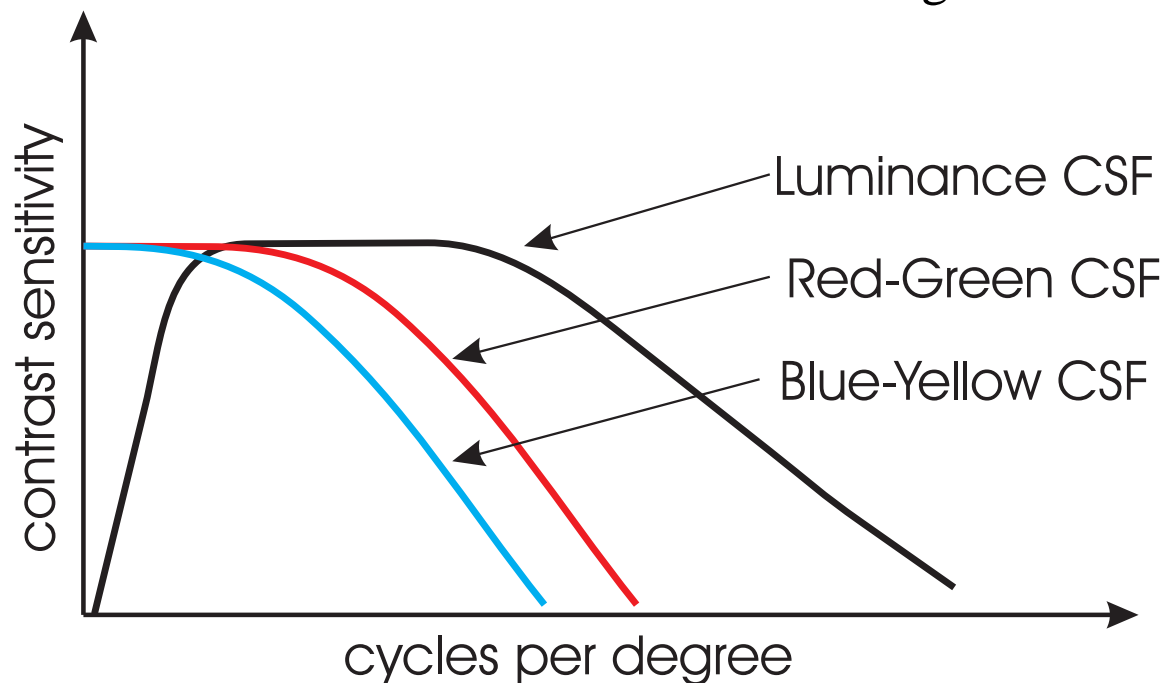  - $O_2$ is the red-green channel

$$O_2 = G - R$$

  - $O_3$ is the blue-yellow channel

$$O_3 = B - Y = B - (R + G)$$

- Comments:

  - People don't perceive redish-greens, or bluish-yellows.
  - As we discussed, $O_1$ has a bandpass CSF.
  - $O_2$ and $O_3$ have low pass CSF's with lower frequency cut-off.

# Opponent Channel Contrast Sensitivity Functions (CSF)

- Typical CSF functions looks like the following.

# Consequences of Opponent Channel CSF

- Luminance channel is

  – Bandpass function

  – Wide band width $\Rightarrow$ high spatial resolution.

  – Low frequency cut-off $\Rightarrow$ insensitive to average luminance level.

- Chrominance channels are

  – Lowpass function

  – Lower band width $\Rightarrow$ low spatial resolution.

  – Low pass $\Rightarrow$ sensitive to absolute chromaticity (hue and saturation).

# Some Practical Consequences of Opponent Color Spaces

- Analog video has less bandwidth in $I$ and $Q$ channels.

- Chrominance components are typically subsampled 2-to-1 in image compression applications.

- Black text on white paper is easy to read. (couples to $O_1$)

- Yellow text on white paper is difficult to read. (couples to $O_3$)

- Blue text on black background is difficult to read. (couples to $O_3$)

- Color variations that do not change $O_1$ are called "isoluminant".

- Hue refers to angle of color vector in $(O_2, O_3)$ space.

- Saturation refers to magnitude of color vector in $(O_2, O_3)$ space.

# Opponent Color Space of Wandell

- First define the LMS color system which is approximately given by

$$
\begin{bmatrix} L \\ M \\ S \end{bmatrix} = \begin{bmatrix} 0.2430 & 0.8560 & -0.0440 \\ -0.3910 & 1.1650 & 0.0870 \\ 0.0100 & -0.0080 & 0.5630 \end{bmatrix} \begin{bmatrix} X \\ Y \\ Z \end{bmatrix}
$$

- The opponent color space transform is then[1]

$$
\begin{bmatrix} O_1 \\ O_2 \\ O_3 \end{bmatrix} = \begin{bmatrix} 1 & 0 & 0 \\ -0.59 & 0.80 & -0.12 \\ -0.34 & -0.11 & 0.93 \end{bmatrix} \begin{bmatrix} L \\ M \\ S \end{bmatrix}
$$

- We many use these two transforms together with the transform from sRGB to XYZ to compute the following transform.

$$
\begin{bmatrix} O_1 \\ O_2 \\ O_3 \end{bmatrix} = \begin{bmatrix} 0.2814 & 0.6938 & 0.0638 \\ -0.0971 & 0.1458 & -0.0250 \\ -0.0930 & -0.2529 & 0.4665 \end{bmatrix} \begin{bmatrix} sR \\ sG \\ sB \end{bmatrix}
$$

- Comments:
  - $O_1$ is luminance component
  - $O_2$ is referred to as the red-green channel (G-R)
  - $O_3$ is referred to as the blue-yellow channel (B-Y)
  - Also see the work of Mullen '85[2] and associated color transforms.[3]

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[1] B. A. Wandell, *Foundations of Vision*, Sinauer Associates, Inc., Sunderland MA, 1995.

[2] K. T. Mullen, "The contrast sensitivity of human color vision to red-green and blue-yellow chromatic gratings," *J. Physiol.*, vol. 359, pp. 381-400, 1985.

[3] B. W. Kolpatzik and C. A. Bouman, "Optimized Error Diffusion for Image Display," *Journal of Electronic Imaging,* vol. 1, no. 3, pp. 277-292, July 1992.

# Paradox?

- Why is blue text on yellow paper easy to read??

- Shouldn't this be hard to read since it stimulates the yellow-blue color channel?

# Better Understanding Opponent Color Spaces

- The XYZ to opponent color transformation is:

$$
\begin{bmatrix} O_1 \\ O_2 \\ O_3 \end{bmatrix} = \begin{bmatrix} 0.2430 & 0.8560 & -0.0440 \\ -0.4574 & 0.4279 & 0.0280 \\ -0.0303 & -0.4266 & 0.5290 \end{bmatrix} \begin{bmatrix} X \\ Y \\ Z \end{bmatrix}
$$

$$
= \begin{bmatrix} v_y \\ v_{gr} \\ v_{by} \end{bmatrix} \begin{bmatrix} X \\ Y \\ Z \end{bmatrix}
$$

- What are $v_y$, $v_{gr}$, and $v_{by}$?

  – They are row vectors in the XYZ color space.

  – $v_{gr}$ is a vector point from red to green

  – $v_{by}$ is a vector point from yellow to blue

  – They are not orthogonal!

# Plots of $v_y$, $v_{gr}$, and $v_{by}$

Opponent Color Directions of Color Matching Functions
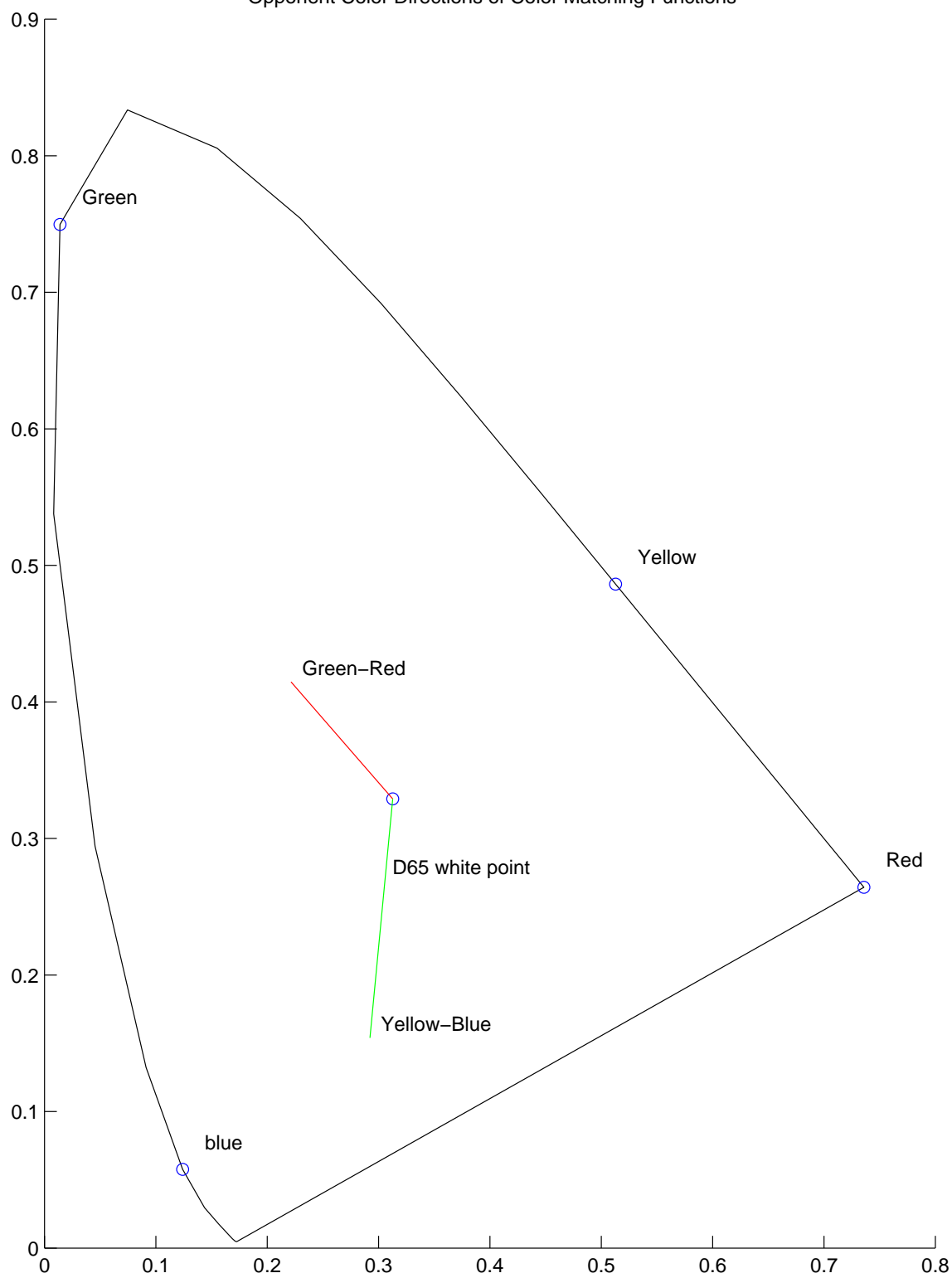
# Answer to Paradox

- Since $v_y$, $v_{gr}$, and $v_{by}$ are not orthogonal

$$\begin{bmatrix} v_y \\ v_{gr} \\ v_{by} \end{bmatrix} \begin{bmatrix} v_y^t \ v_{gr}^t \ v_{by}^t \end{bmatrix} \neq \text{identity matrix}$$

- Blue text on yellow background produces and stimulus in the $v_{by}$ space.

$$\begin{bmatrix} O_1 \\ O_2 \\ O_3 \end{bmatrix} = \begin{bmatrix} v_y \\ v_{gr} \\ v_{by} \end{bmatrix} v_{by}^t = \begin{bmatrix} -0.3958 \\ -0.1539 \\ 0.4627 \end{bmatrix}$$

- This stimulus is not isoluminant!

- Blue is much darker than yellow.

# Basis Vectors for Opponent Color Spaces

- The transformation from opponent color space to XYZ is:

$$\begin{bmatrix} X \\ Y \\ Z \end{bmatrix} = \begin{bmatrix} 0.9341 & -1.7013 & 0.1677 \\ 0.9450 & 0.4986 & 0.0522 \\ 0.8157 & 0.3047 & 1.9422 \end{bmatrix} \begin{bmatrix} O_1 \\ O_2 \\ O_3 \end{bmatrix}$$

$$= \begin{bmatrix} c_y & c_{gr} & c_{by} \end{bmatrix} \begin{bmatrix} O_1 \\ O_2 \\ O_3 \end{bmatrix}$$

- What are $c_y$, $c_{gr}$, and $c_{by}$?

  - They are column vectors in XYZ space.
  - $c_{gr}$ is a vector which has no luminance component.
  - $c_{by}$ is a vector which has no luminance component.
  - They are orthogonal to the vectors $v_y$, $v_{gr}$, and $v_{by}$.

# Plots of $c_y$, $c_{gr}$, and $c_{by}$



Opponent Color Directions of Color Matching Functions
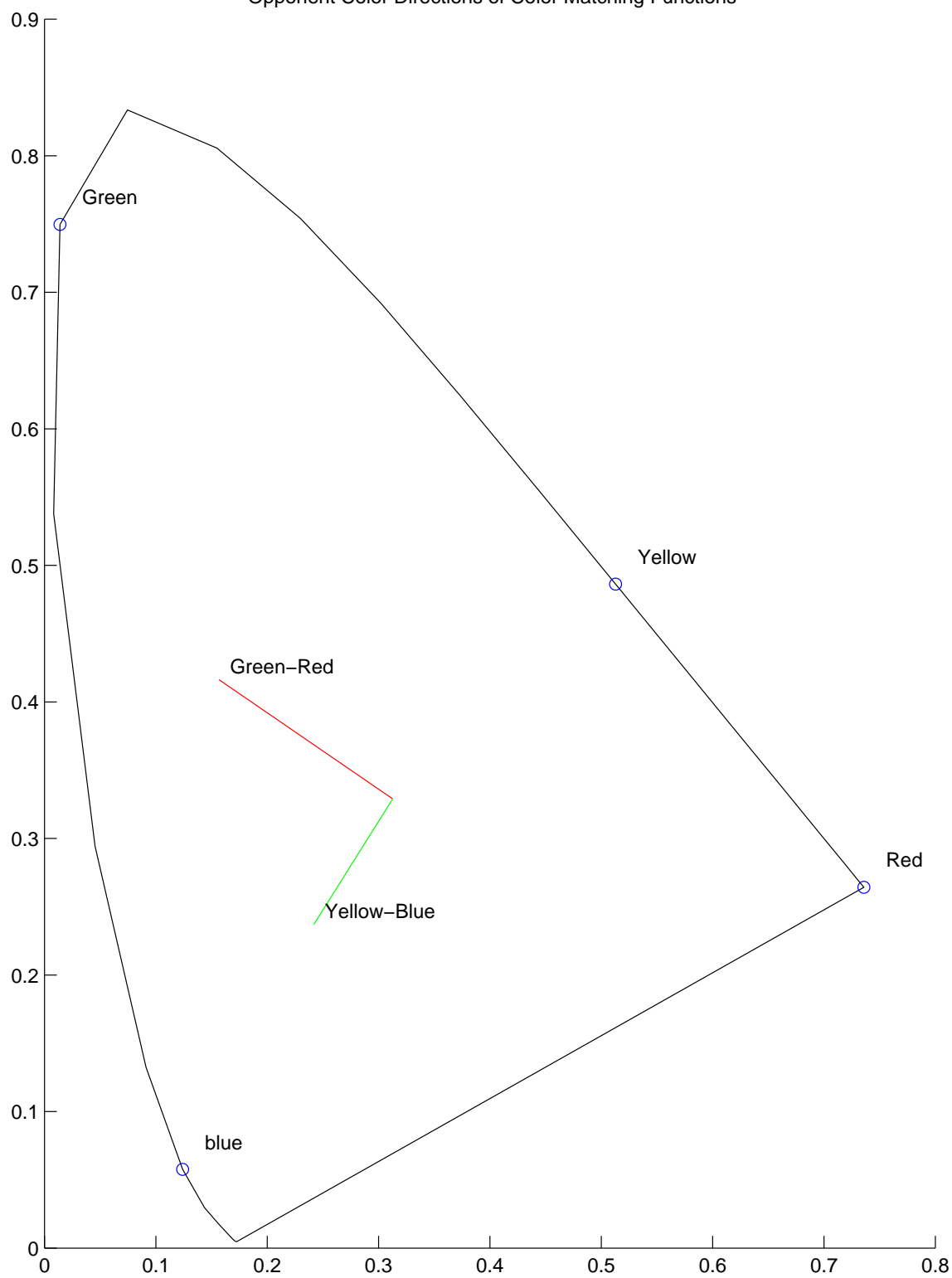
# Interpretation of Basis Vectors

- Since $c_y$, $c_{gr}$, and $c_{by}$ are orthogonal to $v_y$, $v_{gr}$, and $v_{by}$, we have

$$\begin{bmatrix} v_y \\ v_{gr} \\ v_{by} \end{bmatrix} [c_y \; c_{gr} \; c_{by}] = \begin{bmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{bmatrix}$$

- Therefore, we have that

$$\begin{bmatrix} O_1 \\ O_2 \\ O_3 \end{bmatrix} = \begin{bmatrix} v_y \\ v_{gr} \\ v_{by} \end{bmatrix} c_{by}$$

$$= \begin{bmatrix} 0.2430 & 0.8560 & -0.0440 \\ -0.4574 & 0.4279 & 0.0280 \\ -0.0303 & -0.4266 & 0.5290 \end{bmatrix} \begin{bmatrix} 0.1677 \\ 0.0522 \\ 1.9422 \end{bmatrix}$$

$$= \begin{bmatrix} 0 \\ 0 \\ 1 \end{bmatrix}$$

- So, $c_{by}$ is an isoluminant color variation.

- Something like a bright saturated blue on a dark red.

# Solution to Paradox

- Why is blue text on yellow paper is easy to read??

- Solution:

  – The blue-yellow combination generates the input $v_{by}$.

  – This input vector stimulates all three opponent channels because it is not orthogonal to $c_y$, $c_{gr}$, and $c_{by}$.

  – In particular, it strongly stimulates $c_y$ because it is **not** iso-luminant.