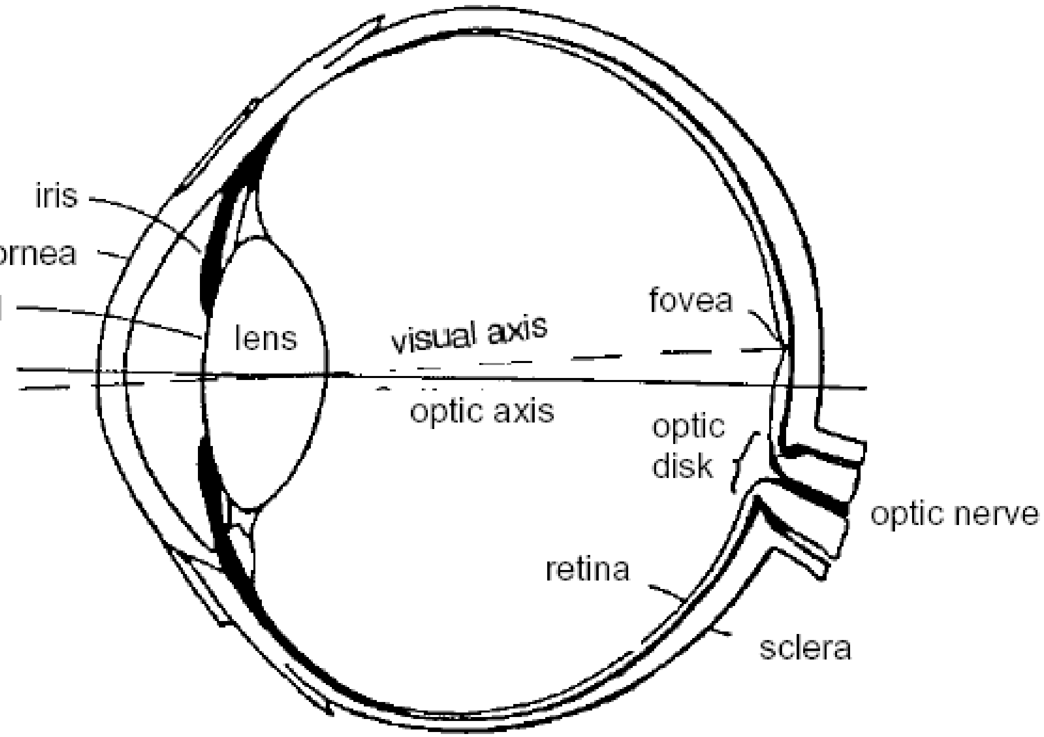
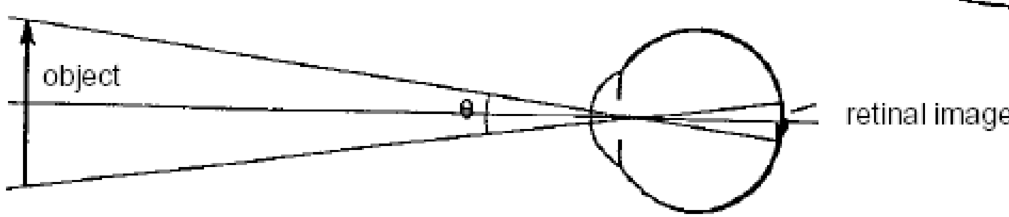
9 Visual Perception and Color

9.1 Anatomy of the Human Eye





Cell Types in the Human Retina

Signal propagation in the retina:

800,000 optic nerves

↑

ganglion cells

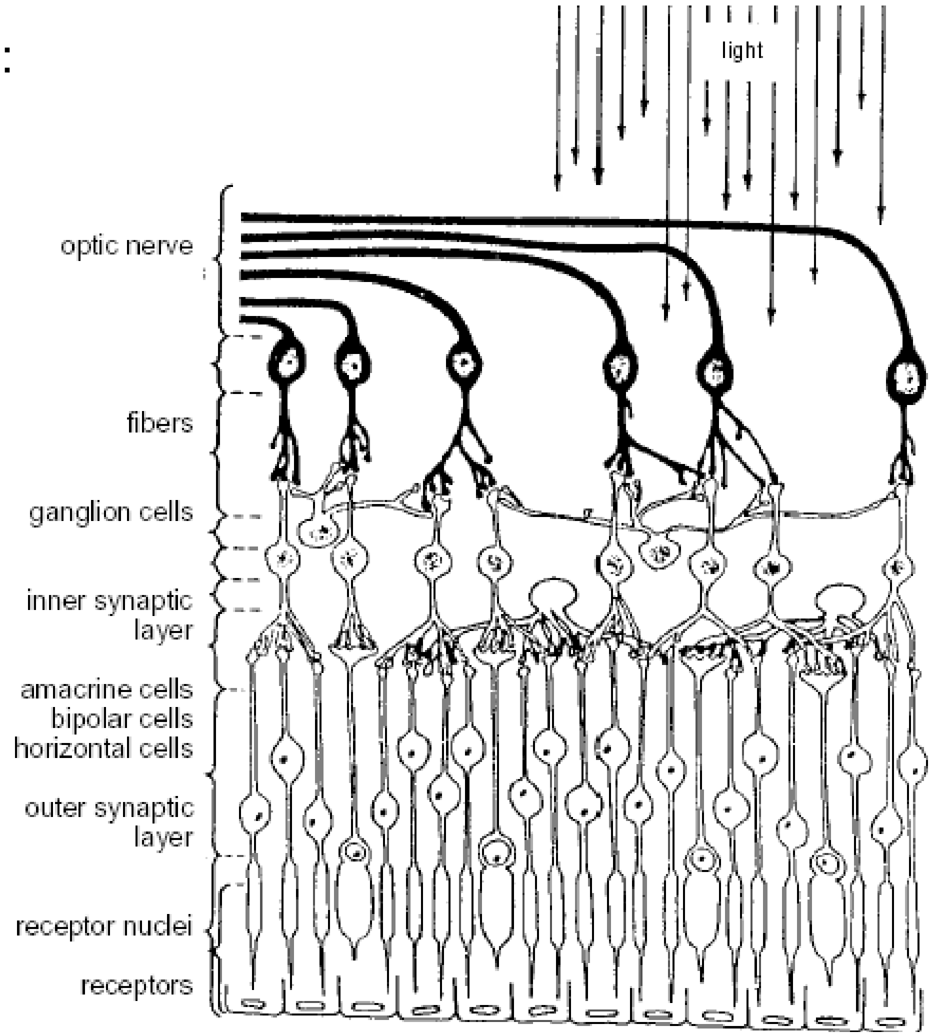
↑

“Differential” threshold analysis

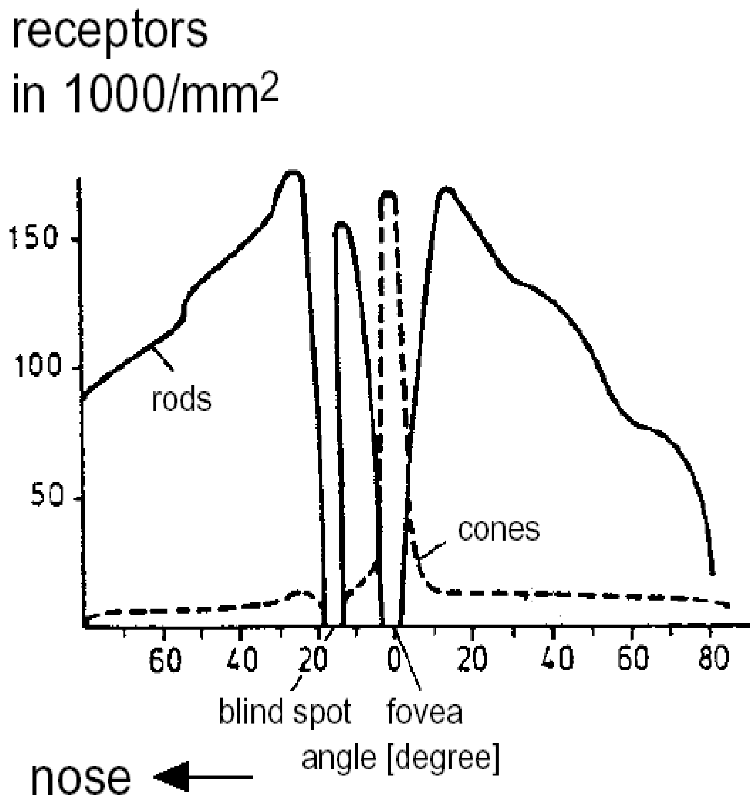
bipolar cells

↑

126 million receptors



Characteristics of Rods and Cones



Rods (*Stäbchen*)	**Cones** (*Zapfen*)
120 million	6 million
high sensitivity	low sensitivity
monochrome	color
low light vision	day light vision
“scotopic” vision	“photopic” vision

Color resolution much lower than brightness resolution

9.2 Sensitivity of the Human Eye

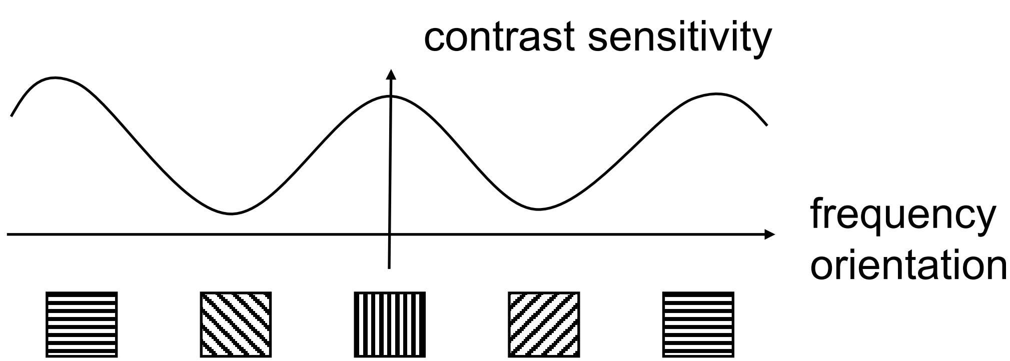
Brightness sensitivity of human visual system follows Weber's Law

$$\frac{\Delta L}{L} = \text{const.} \approx 0.01 \ldots 0.02$$

L absolute brightness
ΔL change in brightness

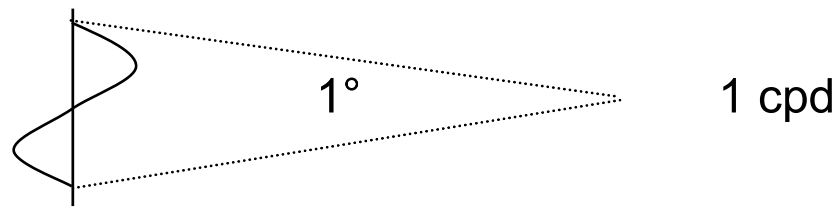
Directional sensitivity

- Preference for horizontal and vertical frequencies
- Diagonal structures are recognized with lower resolution



Contrast Sensitivity

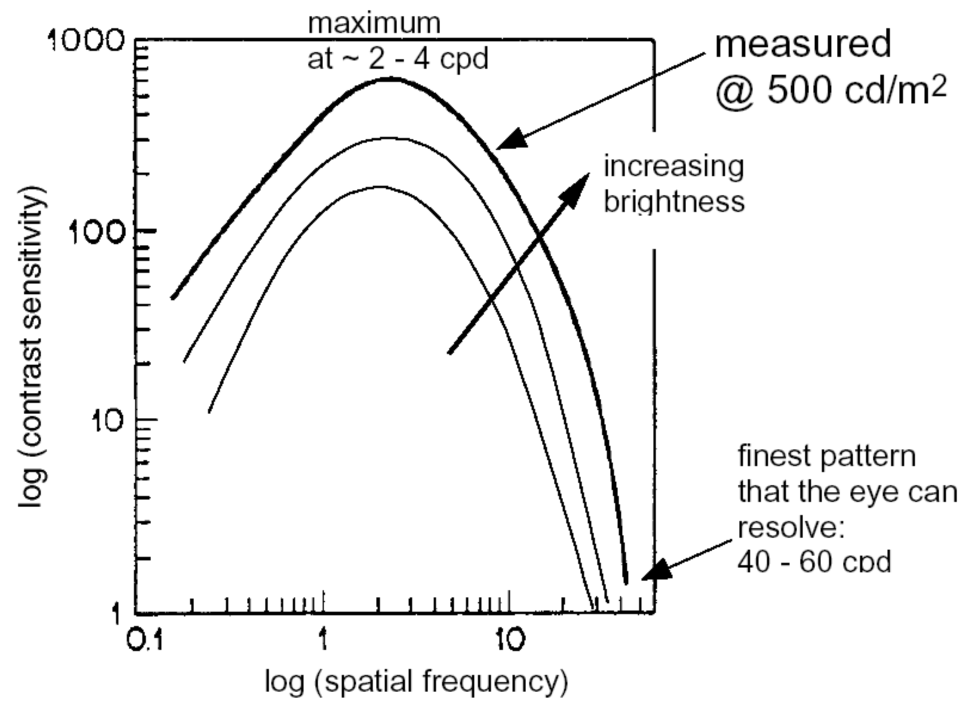
Spatial frequency in cycles / degree [cpd]



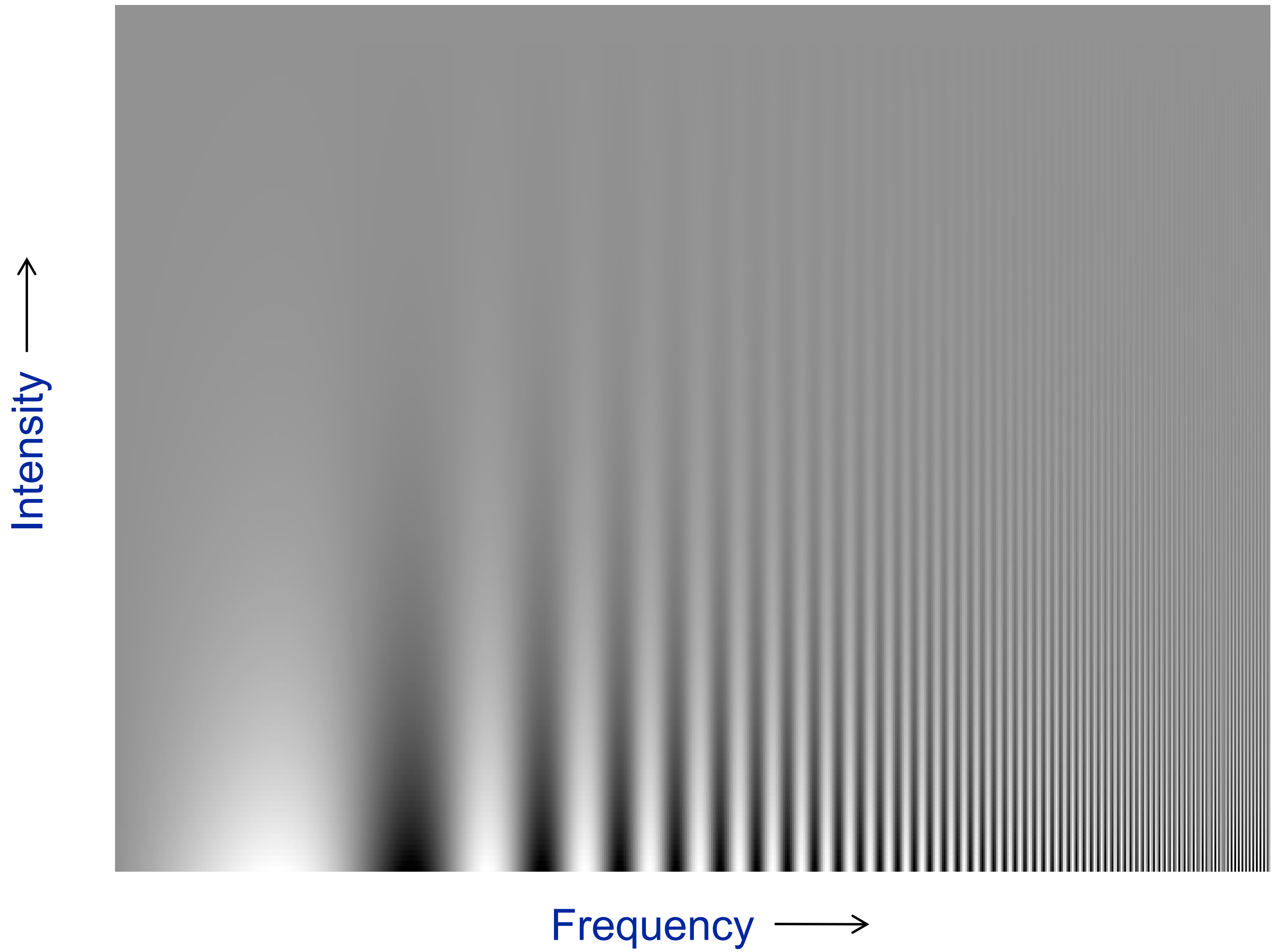
Contrast sensitivity given as ratio

$$\frac{\text{background luminance}}{\text{just noticeable amplitude of sinusoid}}$$

⇨ Bandpass characteristic of HVS

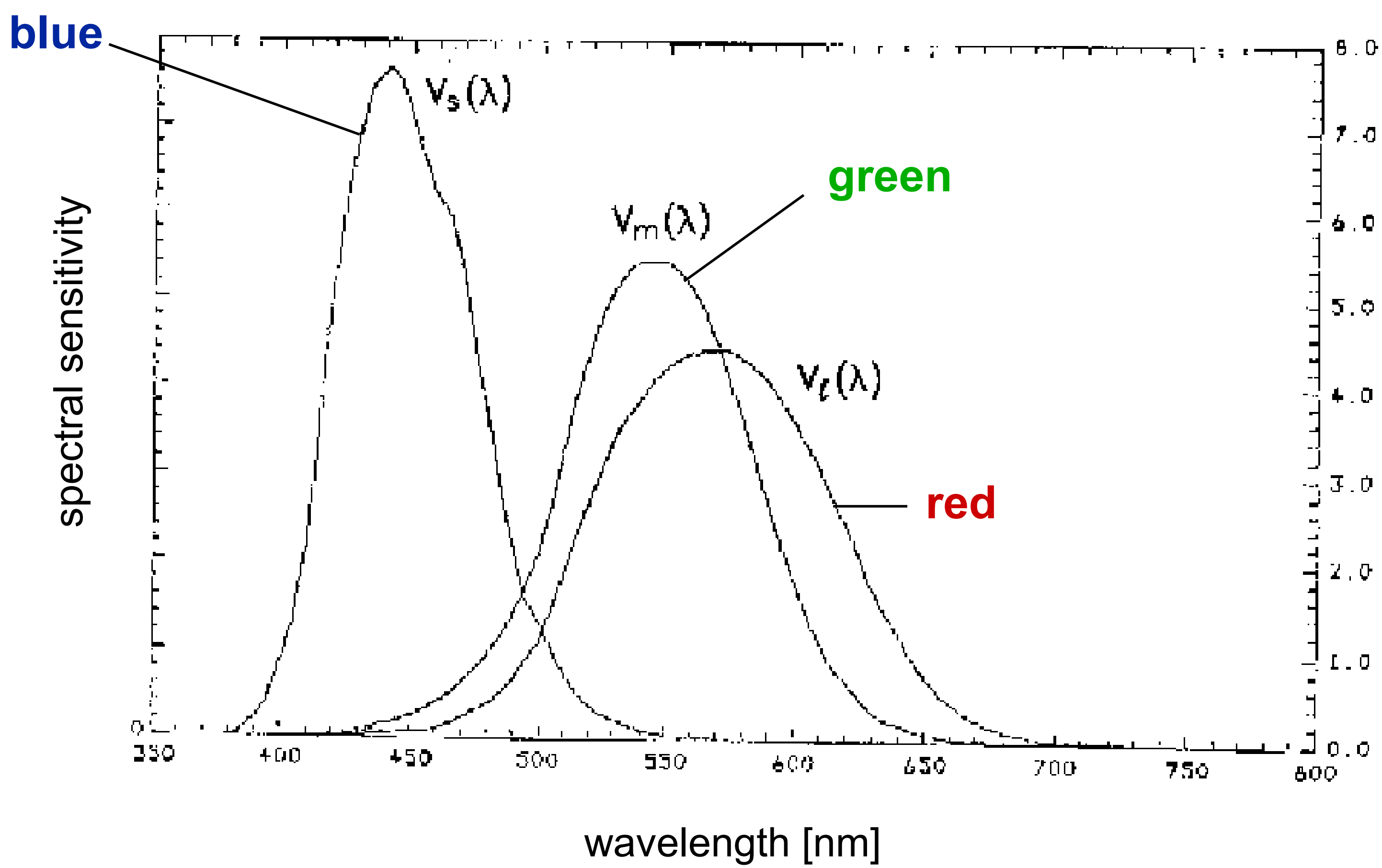


Bandpass Characteristic of HVS



Color Perception

Normalized absorption spectra of cones



Other Characteristics of Human Visual System

Mach effect: Contrast recognition at edges

- Human eye is especially sensible to edges
- Contrast changes at edges are enhanced by the human brain

Masking effect

- Image details are not recognized in highly structured image areas
- Only valid in still image regions

Resolution of moving objects

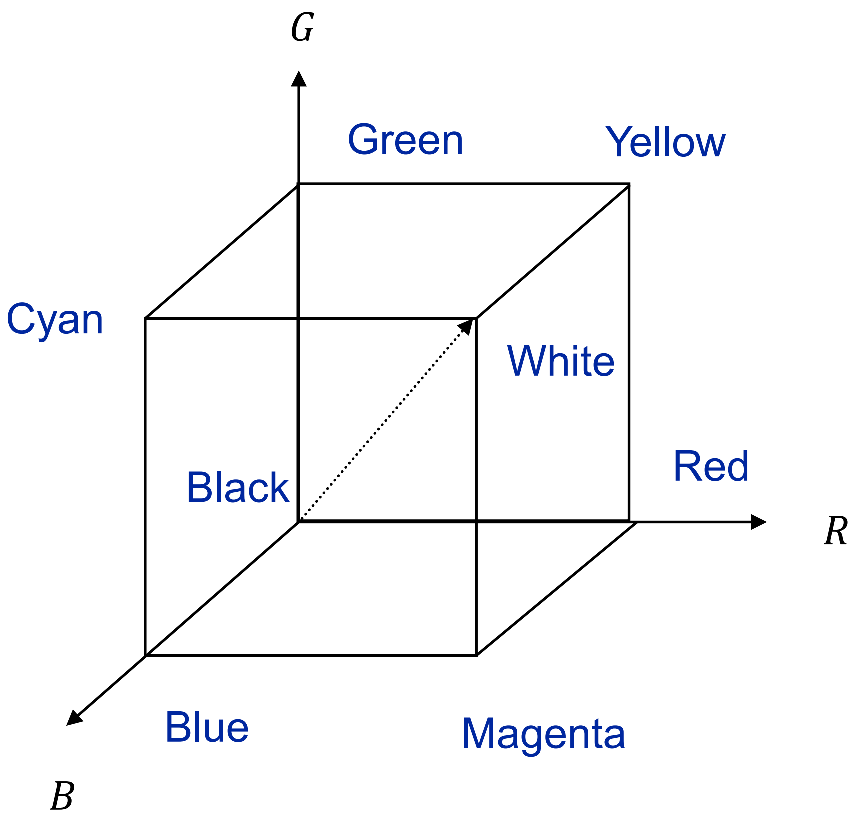
- Still objects are recognized much sharper than moving objects

Motion resolution

- Slow motion can be shown with low temporal resolution
- Fast motion needs better temporal resolution

9.3 Color Spaces

RGB color space using primary red (R), green (G), and blue (B) components:



Red, green, and blue are

- three primary additive colors
- used as phosphors by CRTs
- basic color for computer graphics and frame buffers

Disadvantages

- Bandwidth requirements
- Luminance / chrominance sensitivity of human eye

YUV Color Coordinates

Basic color format for analog PAL TV standards in Europe

- Separates color into luminance Y and two chrominance components U and V

$$\begin{bmatrix} Y \\ U \\ V \end{bmatrix} = \begin{bmatrix} 0.299 & 0.587 & 0.114 \\ -0.147 & -0.289 & 0.436 \\ 0.615 & -0.515 & -0.100 \end{bmatrix} \cdot \begin{bmatrix} R \\ G \\ B \end{bmatrix}$$

- Luminance Y represents the black and white component
- Chrominance U and V correspond to color difference components

$$\begin{bmatrix} U \\ V \end{bmatrix} = \begin{bmatrix} 0.493 \cdot (B - Y) \\ 0.877 \cdot (R - Y) \end{bmatrix}$$

- Backwards compatible to black-and-white receiver

YIQ Color Coordinates

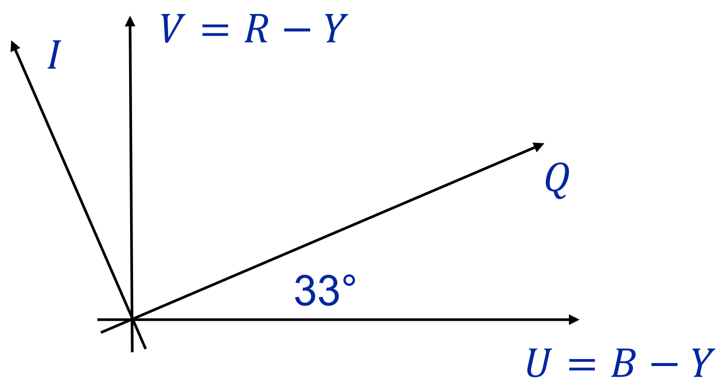
Color format for analog NTSC TV standard in US and Japan

- Modified color transform into luminance and chrominance

$$\begin{bmatrix} Y \\ I \\ Q \end{bmatrix} = \begin{bmatrix} 0.299 & 0.587 & 0.114 \\ 0.596 & -0.275 & -0.321 \\ 0.212 & -0.523 & 0.311 \end{bmatrix} \cdot \begin{bmatrix} R \\ G \\ B \end{bmatrix}$$

- Same luminance Y representing black and white component
- Chrominance components I, Q are rotated by 33° compared to U, V

$$\begin{bmatrix} Q \\ I \end{bmatrix} = \begin{bmatrix} \cos(33°) & \sin(33°) \\ -\sin(33°) & \cos(33°) \end{bmatrix} \cdot \begin{bmatrix} U \\ V \end{bmatrix}$$



YCbCr Color Coordinates

Part of ITU-R 601 Recommendation for digital TV representation

- Commonly used in JPEG and MPEG coding standards, R, G, B from $[0,...,255]$

$$\begin{bmatrix} Y \\ C_\mathrm{b} \\ C_\mathrm{r} \end{bmatrix} = \begin{bmatrix} 0.257 & 0.504 & 0.098 \\ -0.148 & -0.291 & 0.439 \\ 0.439 & -0.368 & -0.071 \end{bmatrix} \cdot \begin{bmatrix} R \\ G \\ B \end{bmatrix} + \begin{pmatrix} 16 \\ 128 \\ 128 \end{pmatrix}$$

- Derived from Y, U, V by scaling, C_b “chrominance blue”, C_r “chrominance red”
- Luminance Y limited to $[16,...,235]$
- C_b and C_r limited to $[16,...,240]$ with 128 corresponding to zero level

Inverse transform to convert back to R, G, B:

$$\begin{bmatrix} R \\ G \\ B \end{bmatrix} = \begin{bmatrix} 1.164 & 0.000 & 1.596 \\ 1.164 & -0.392 & -0.813 \\ 1.164 & 2.017 & 0.000 \end{bmatrix} \cdot \begin{bmatrix} Y - 16 \\ C_\mathrm{b} - 128 \\ C_\mathrm{r} - 128 \end{bmatrix}$$

Reversible YUVr Color Transform

Disadvantage of previous color transforms: require floating point operation if color transforms have to be invertible without loss

Goal: reversible color transform (without loss) using only integer arithmetic

- Achieved e.g. by YUVr transform used in JPEG2000 standard

$$Y_\mathrm{r} = \left\lfloor \frac{R + 2G + B}{4} \right\rfloor \qquad\qquad G = Y_\mathrm{r} - \left\lfloor \frac{U_\mathrm{r} + V_\mathrm{r}}{4} \right\rfloor$$
$$U_\mathrm{r} = R - G \qquad\qquad R = U_\mathrm{r} + G$$
$$V_\mathrm{r} = B - G \qquad\qquad B = V_\mathrm{r} + G$$

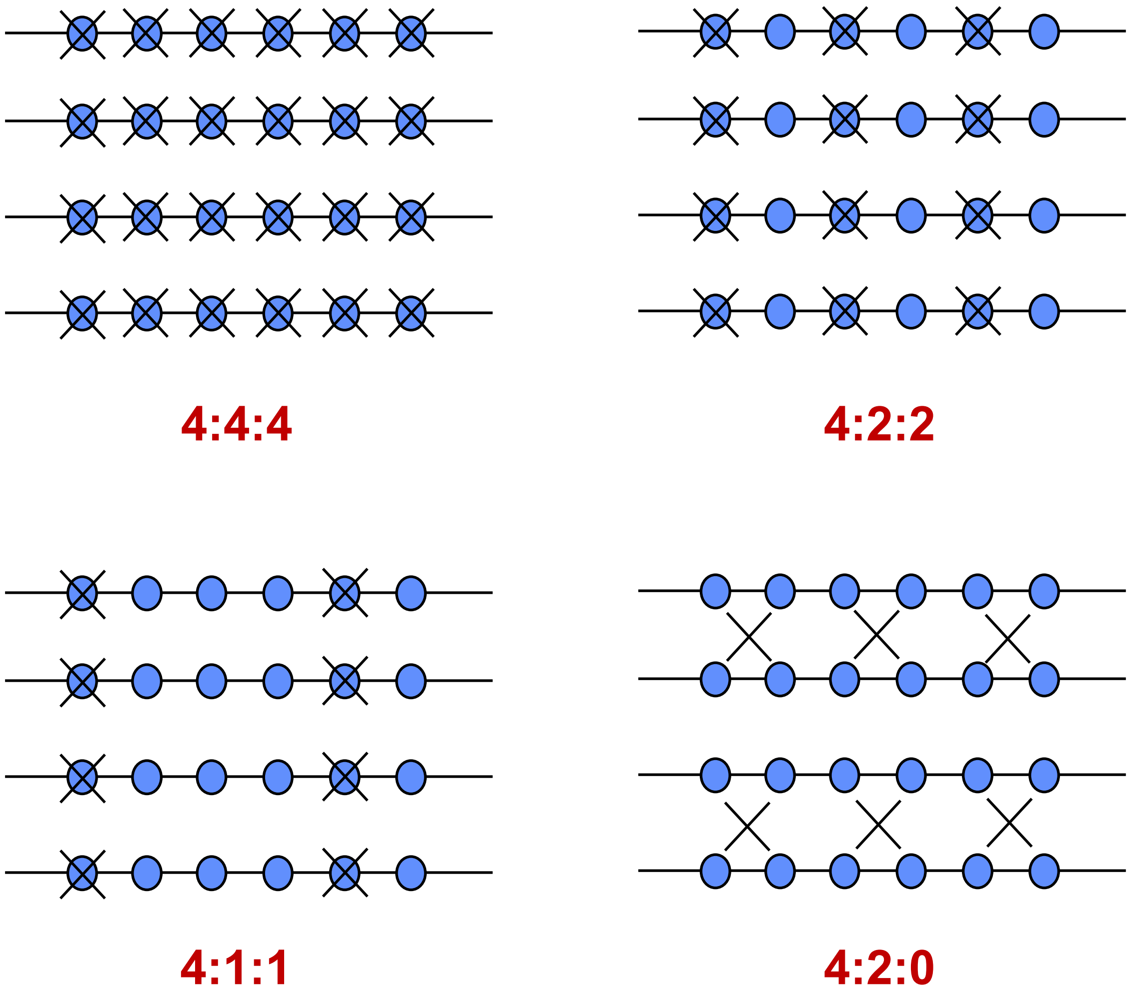
- Range of values given by

$$0 \le Y_\mathrm{r} \le 255, \qquad -255 \le U_\mathrm{r} \le 255, \qquad -255 \le V_\mathrm{r} \le 255,$$

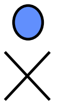
Low complexity: transform requires only 4 additions and 2 bit shift operations

Demo 9 „Color Spaces“

9.4 Color Sampling Formats



Color Format	Bits per Sample
4:4:4	24
4:2:2	16
4:1:1	12
4:2:0	12



Visual Perception and Color - Summary

- Brightness sensitivity – Weber's law
- Directional sensitivity of human eye
- Low chrominance vs. luminance resolution
- Suitable color spaces decorrelate RGB