Colour, RGB, HSI[1]

Lecture 03

See Section 1.3 in
Reinhard Klette: Concise Computer Vision
Springer-Verlag, London, 2014

`ccv.wordpress.fos.auckland.ac.nz`

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[1] See last slide for copyright information.

Agenda

1. Color Definitions
2. Color Perception
3. Gray Levels
4. Color Representations

Perceived Color

Not objectively defined

Varies for people

Depends on lighting:

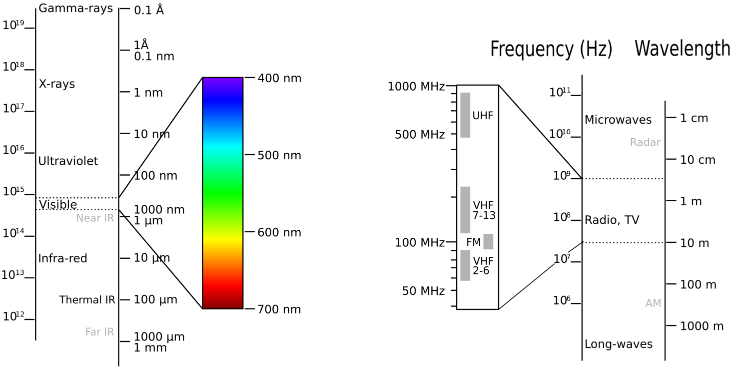
- Why is the sky blue or orange, but never green?
- There are good explanations on the net.

No light then there is no color (e.g inside of a body)

Human vision can discriminate a few dozens of gray-levels but hundreds to thousands of different colors

Electromagnetic Spectrum

The *visible Spectrum* is only a very small interval in the *electromagnetic spectrum* of frequencies or wavelengths of electromagnetic radiation



(Figure by Victor Blacus, in the public domain)

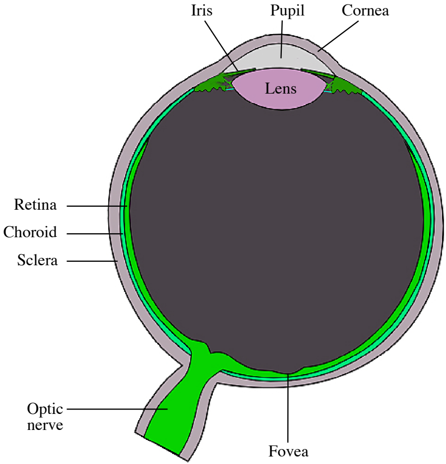
Color Definitions in Visible Spectrum

1 nm = 1 nanometer = 10^{-9} m

1. Red (about 625 to 780 nm), Orange (about 590 to 625 nm), invisible spectrum continues with Infrared (IR)
2. Yellow (about 565 to 590 nm), Green (about 500 to 565 nm), Cyan (about 485 to 500 nm)
3. Blue (about 440 to 485 nm)
4. Violet (about 380 to 440 nm), invisible spectrum continues with Ultraviolet (UV)

Retina of the Human Eye

Photoreceptors: some 120 million rods for luminosity response, and some 6 to 7 million cones, concentrated towards the fovea



Tristimulus Values and CIE

Experimental evidence: three types of color-sensitive cones, Red (about 64%), Green (about 32%), Blue (about 2%)

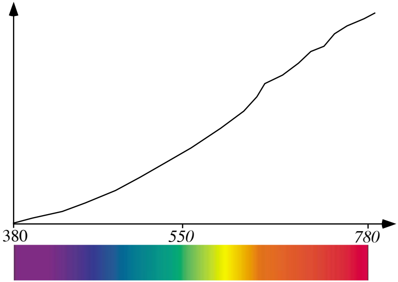
Visible color modeled by *tristimulus values*

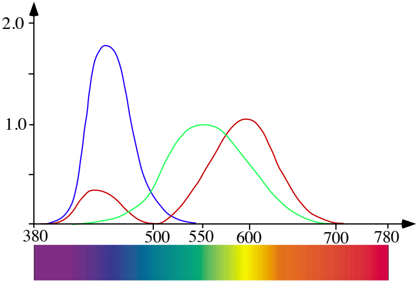
CIE (*Commission Internationale de l'Eclairage* = *International Commission on Illumination*) defines color standards since the 1930*s*

Tristimulus values defined by weighting functions $\overline{x}$ $\overline{y}$, and $\overline{z}$

Energy Distributions: A Lamp and a Model

Monochromatic energy distributions $L(\lambda)$, $380 \leq \lambda \leq 780$
Chromatic is $L_R(\lambda)$, $L_G(\lambda)$, and $L_B(\lambda)$





Sketch for an incandescent house lamp

CIE energy distribution functions $\overline{x}(\lambda)$ (blue), $\overline{y}(\lambda)$ (green), and $\overline{z}(\lambda)$ (red) for defining tristimulus values X, Y, and Z

Weighting Functions

Cut-offs at both ends of functions $\overline{x}(\lambda)$ (blue), $\overline{y}(\lambda)$ (green), and $\overline{z}(\lambda)$ (red) do not correspond exactly to human-eye abilities to perceive shorter (down to 380 nm) or larger (up to 810 nm) wavelengths

Curves have also been scaled:

$$\int_{400}^{700} \overline{x}(\lambda)\,\mathrm{d}\lambda = \int_{400}^{700} \overline{y}(\lambda)\,\mathrm{d}\lambda = \int_{400}^{700} \overline{z}(\lambda)\,\mathrm{d}\lambda$$

Example: Curve $\overline{y}$ models the luminosity response of an “average human eye”

Tristimulus Values

Values X, Y, and Z by integrating a given energy function L

$$
\begin{aligned}
X &= \int_{400}^{700} L(\lambda)\overline{x}(\lambda)\,\mathrm{d}\lambda \\
Y &= \int_{400}^{700} L(\lambda)\overline{y}(\lambda)\,\mathrm{d}\lambda \\
Z &= \int_{400}^{700} L(\lambda)\overline{z}(\lambda)\,\mathrm{d}\lambda
\end{aligned}
$$

Example: Y models brightness (= intensity) or, approximately, the green component of given L

Normalized CIE *xy*-Parameters

$$x = \frac{X}{X+Y+Z} \quad \text{and} \quad y = \frac{Y}{X+Y+Z}$$

Assume: Y is given. Can derive X and Z from x and y

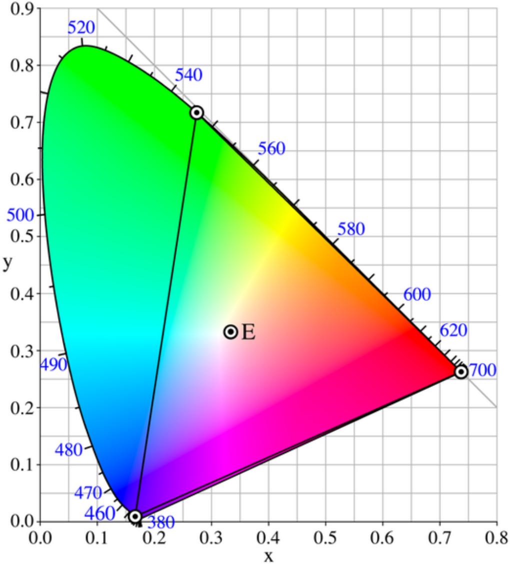
With $z = Z/(X+Y+Z)$ it is $x+y+z=1$

The xy Color Space of the CIE.

Represents colors, not brightness

xy color space represented by a chromaticity diagram for $0 \leq x, y \leq 1$

Chromaticity Diagram: The *xy* CIE Color Space



Gamut of Human Vision

Shows the *gamut* of human vision

Colors which are visible to the average person; white parts already in the invisible spectrum

Convex outer curve: contains monochromatic colors (pure spectral colors)

Straight edge at the bottom (i.e. the purple line): contains colors which are not monochromatic

In the interior: less saturated colors, with White at $E = (0.33, 0.33)$

Triangle: gamut of *RGB primaries* defined by CIE

700 nm for Red, 546.1 nm for Green, and 435.8 nm for Blue

Different Gamuts of Media

Gamut: available color range (such as “perceivable”, “printable”, or “displayable”)

Depends on used medium

Example: warning of image-editing system:

Warning: out of gamut for printing

Rule of thumb: transparent media have potentially larger gamut than printed material

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Red-Green Color Blindness

Different energy distributions $L_1(\lambda)$ and $L_2(\lambda)$ for visible spectrum, human H may perceive both as identical colors

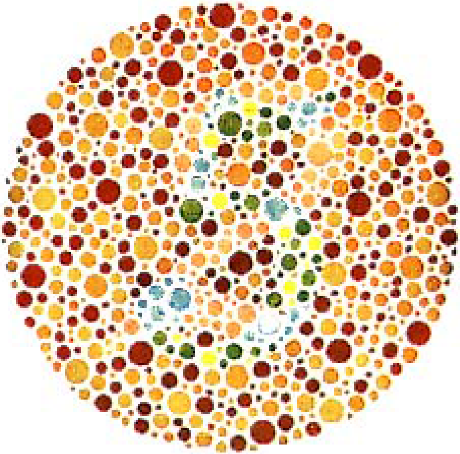
$$L_1 \overset{H}{=} L_2$$

Color blindness: some colors cannot be distinguished

About 99% of cases: red-green color blindness

For people of European origin: about 8% - 12% males, about 0.5% females

Ishihara Color Test



Dot pattern: a 5 for most of the people, but for some it is a 2

Two Comments on Colour Presentations

A Rule for Graphics Design

When using red-green colors in a presentation then some of your audience (e.g. the above-mentioned percentage with European origin) might not see what you are intending to show.

Red-blue or red-yellow works in general for a larger audience.

Gamma Correction

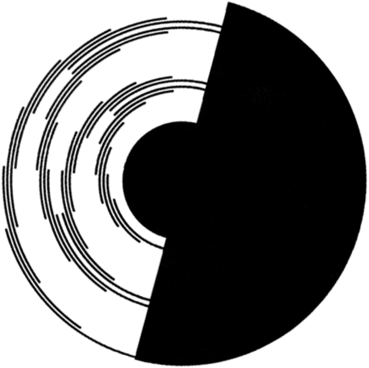
For a computer screen, for $\gamma > 0$:

Color value $u = k/2^a$ (one channel) presented as u^γ

$\gamma < 1$ defines *gamma compression*; $\gamma > 1$ defines *gamma expansion*

Color as a Purely Visual Sensation

Benham Disk: Benham was a nineteenth-century toymaker



Spinn under bright incandescent light or sunlight

Three types of cones in the eye, each type has a different latency time .. (full explanation is more complicated)

Four Primary Colors

There appears to be agreement that Yellow, Red, Green, and Blue define the four *primary color perceptions*

For avoiding green-red misperceptions, option is to use yellow, red, and blue as base colors in presentations

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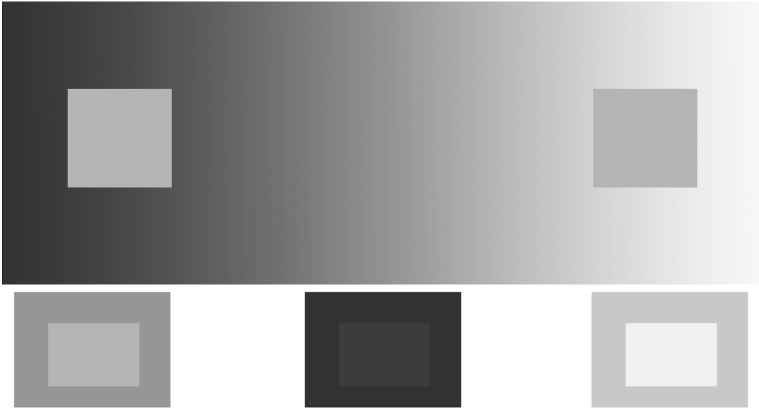
Specific Perceptions



Two squares of identical intensity
Three examples for gray-level ratios of 5 to 6

Gray-Levels

Gray-levels are not colors

Described by *luminance* (the physical intensity) or *brightness* (the perceived intensity)

Linear scale of *gray-levels* or *intensities* is common:

$$u_k = k/2^a, \quad \text{for } 0 \leq k < 2^a$$

Human vision perceives the ratio of intensities

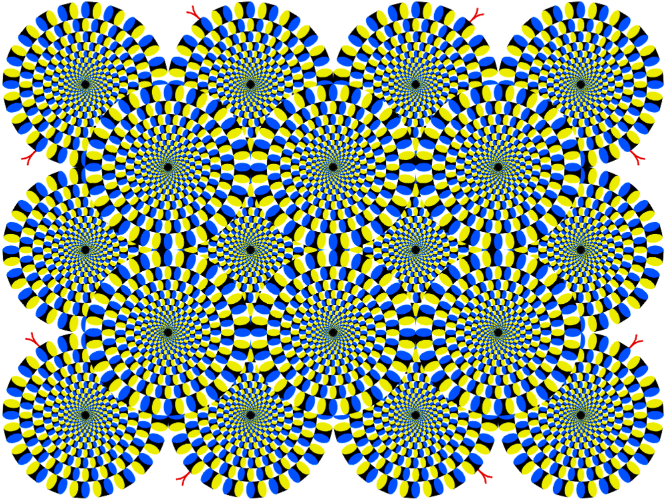
Visually difficult to discriminate between slightly different very dark gray-levels

Human eye: better for noticing different bright gray-levels

See: build-in non-linear correction in digital cameras

Visual Illusions: Rotating Snake by A. Kitaoka

From motion, luminance or contrast, geometry, 3D space, cognitive effects, specialized imaginations, or from color



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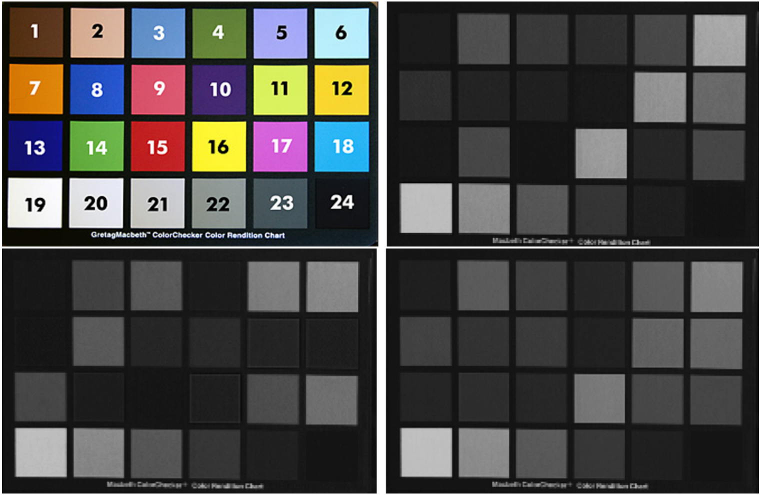
Color Checker by Macbeth^{TM} and Scalar Channels



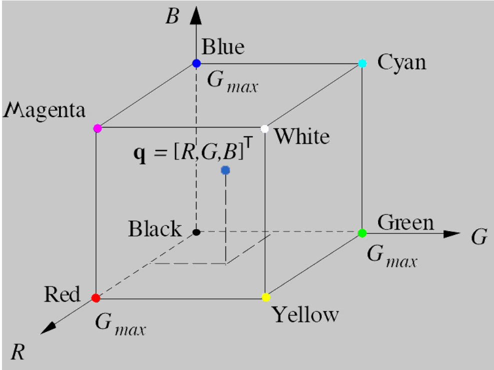
Top: RGB image and channel for Green
Bottom: Channel for Blue and intensity channel

RGB

RGB color representation model is *additive*: adding to a color contributes to going towards White

Color models used for printing are *subtractive*: adding to a color contributes to going towards Black

The RGB Space



RGB Comments

$0 \leq R, G, B \leq G_{max}$, image I with pixel values $\mathbf{u} = (R, G, B)$

If $G_{max} = 255$ then 16,777,216 different colors

$\mathbf{u} = (255, 0, 0)$ for Red, $\mathbf{u} = (255, 255, 0)$ for Yellow, and so forth

Diagonal in cube from
White at $(255, 255, 255)$ to Black at $(0, 0, 0)$

Gray-levels (u, u, u) are not colors

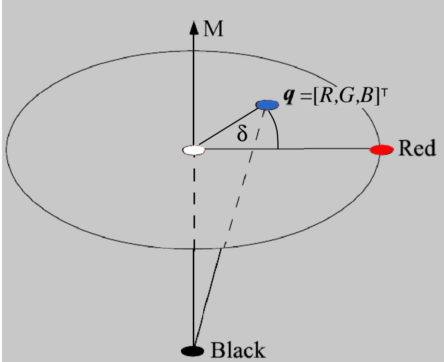
$\mathbf{q} = (R, G, B)$ in RGB cube defines a color or a gray-level

Intensity given by the mean

$$M = \frac{R + G + B}{3}$$

HSI

Assume: plane cuts RGB cube orthogonal to gray-level diagonal



$\mathbf{q} = (R, G, B)$ incident with plane but not on diagonal

Disc is an abstract representation of actually resulting polygons

Hue, Saturation, Intensity

The intensity axis: along the gray-level diagonal in the RGB cube

Identify one color (here, Red) as reference color

Describe **q** by *intensity*, *hue* (angle with respect to reference color), and *saturation* (distance to the intensity axis)

Formal HSI Definition

One of many options

$$H = \begin{cases} \delta, & \text{if } B \leq G \\ 2\pi - \delta, & \text{if } B > G \end{cases} \quad \text{with}$$

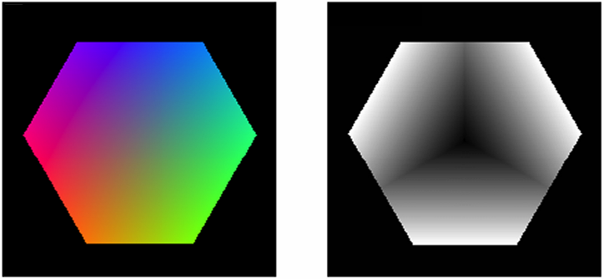
$$\delta = \text{arcos} \frac{(R-G)+(R-B)}{2\sqrt{(R-G)^2+(R-B)(G-B)}} \ \text{ in } \ [0, \pi)$$

$$S = 1 - 3 \cdot \frac{\min\{R, G, B\}}{R+G+B}$$

Intensity defined by the mean M (note: symbol I used for an image in this lecture)

This defines an *HSI color model*; more options possible

Actual Cuts Through the RGB Cube



Cuts through the RGB cube at $u = 131$
RGB image I_{131} of the cut
Saturation values for this cut
How do the hue values look like if shown as gray-level image?

RGB and HSI Examples

Gray-level (u, u, u) with $u \neq 0$:
$M =$??, $S =$??, and H undefined

Black $(0, 0, 0)$:
$M =$??; saturation and hue undefined

Transformation of other RGB values into HSI values is one-one

Red $(G_{max}, 0, 0)$:
$M =$??, $H =$??, and $S =$??

Green $(0, G_{max}, 0)$:
$M =$??, $S =$??, $\delta =$??, $H =$??

Blue $(0, 0, G_{max})$:
$\delta =$??, $H =$??

A Visualization Effect

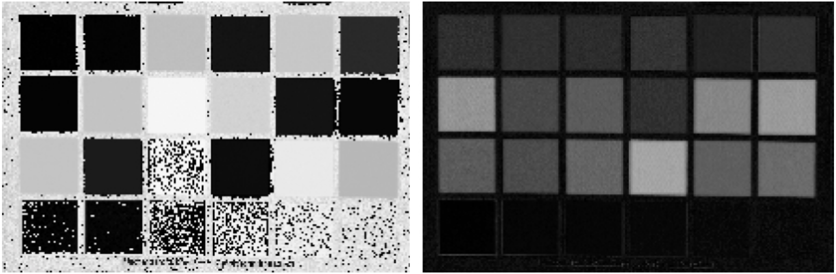
Map S and H linearly into $\{0, 1, \ldots, G_{max}\}$

Visualize resulting images

Then: hue value of $(G_{max}, \varepsilon_1, \varepsilon_2)$ either black or white, just for minor changes in small reals ε_1 and ε_2

Why?

Color Checker Again



Visualizing hue and saturation values by means of gray-levels

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