Part 1: 2D/3D Geometry, Colour, Illumination

Colours

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COMPSCI 373 Computer Graphics and Image Processing

http://socks-studio.com/2013/... http://www.mutluduvar.com/...

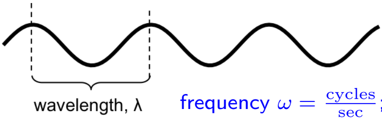
Colours in Real and Graphical World

Colours in Real and Graphical World

Electromagnetic Radiation: Waves

Theories of light:

1. Waves (classical physics)
2. Particles (quantum physics)



frequency $\omega = \frac{\text{cycles}}{\text{sec}}$; $\lambda \cdot \omega = c$;
$c = 3 \cdot 10^8 \frac{m}{sec}$ – speed of light.

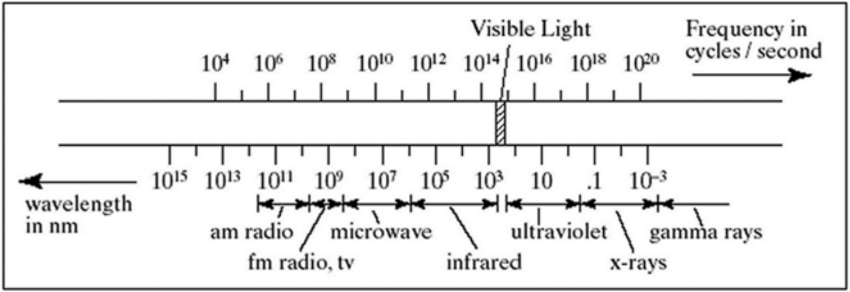
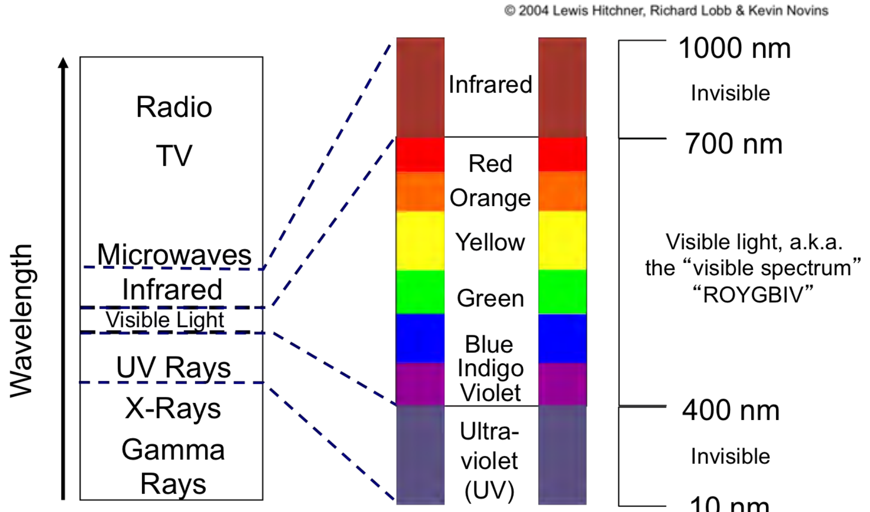


FIGURE 12.1 Electromagnetic spectrum.

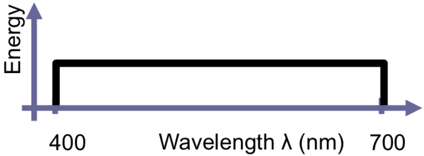
Neighbours of Visible Light



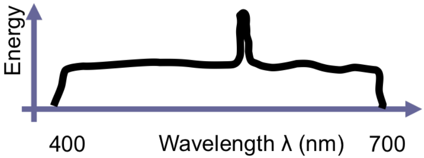
Spectral Density Function (SDF): $S(\lambda)$

$$S(\lambda) = \text{power} \; / \; \text{unit wavelength} = \text{energy}$$

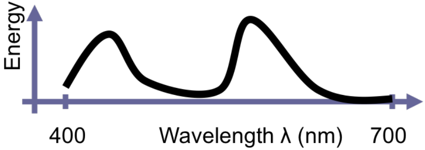
spike or “single” wavelength
= “<u>spectral colour</u>”



uniform white/gray light



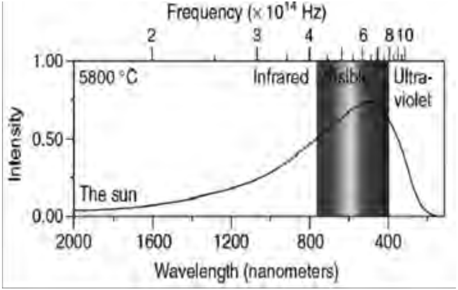
white light plus a dominant wavelength

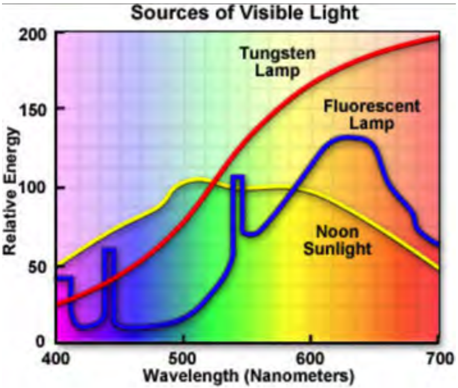


arbitrary SDF: blue plus orange/yellow

SDFs for Different Light Sources

Some other light spectra: sunlight, tungsten lamp, fluorescent lamp

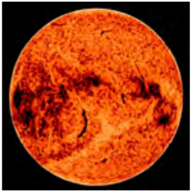




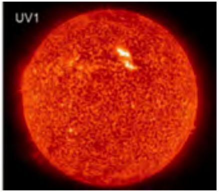
http://www.micro.magnet.fsu.edu/optics/lightandcolor/sources.html

The Sun (across the electromagnetic spectrum)


Low frequency

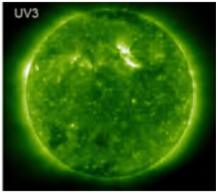

IR (infrared)

Visible light

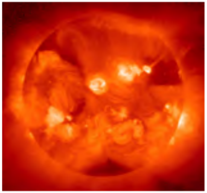


UV_1 (ultraviolet)

UV_2

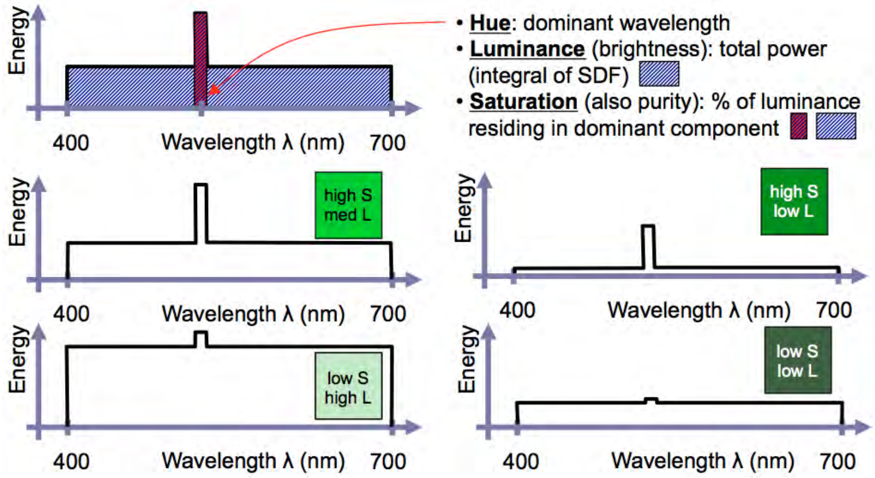


UV_3


X-ray


Gamma-ray

Describing Colors using the SDF



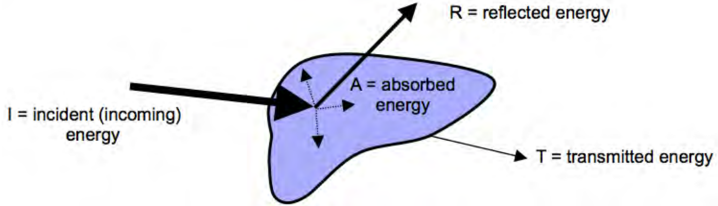
Interaction of Light with Materials

Interaction of Light with Materials

Light ⇒ surface of some "body": 3 possible results:

1. **Absorption** – energy of selected wavelengths retains in the body.
2. **Transmission** – energy of selected wavelengths travels through and exits the body; *refraction* of light occurs at boundaries.
3. **Reflection** – an energy of selected wavelengths bounces off the surface: angle of reflection = angle of incidence.

+ combinations of 1–3, such as "internal reflection" when light enters a semi-translucent body, scatters, and some light reflects back out: human or Shreks skin. . .



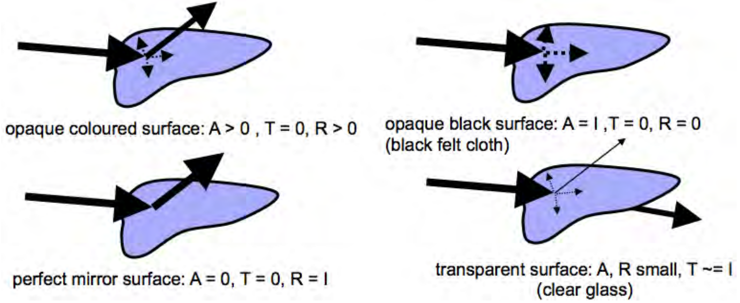
Interaction of Light with Materials

Incident (incoming) light energy:

= **A**bsorbed energy + **T**ransmitted energy + **R**eflected energy

= retained + passed through + bounced off

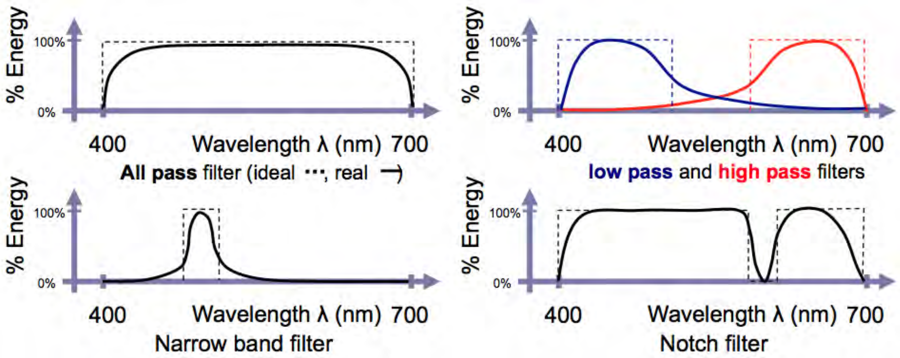
Chemical properties of the body determine the % of each.



Computer graphics: **reflected** (and refracted), **transmitted light**.

Spectral Response Function (SRF)

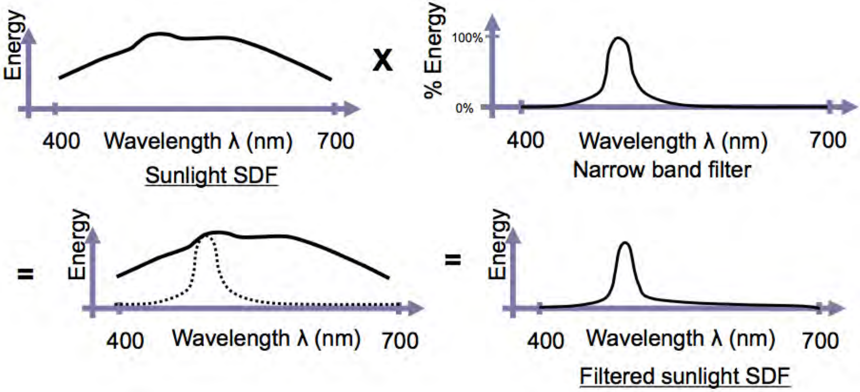
- Molecular structure of a body determines which wavelengths of light and what amount are absorbed, transmitted, or reflected.
- Can be measured with a **spectral response function** (**SRF**), or *filter function*.



$\text{SDF}_{\text{light source}} \times \text{SRF} = \text{SDF}_{\text{result}}$

SDF of result = product of the SRF and the light-source's SDF:

Multiply at each wavelength λ – the SRF % times the source energy.

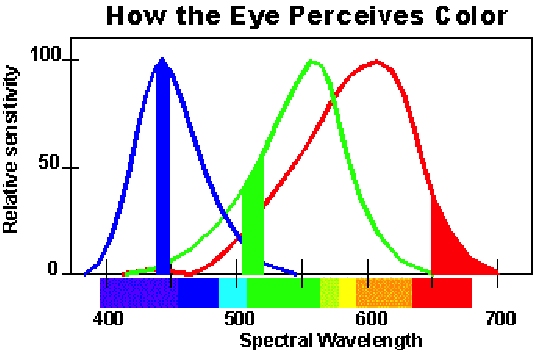


$\text{SDF} \times \text{SRF} = \text{SDF}_{\text{result}}$

Why is this relevant for computer graphics?

1. All light sources can be defined by their SDF.
   - Natural light source: sun, fire.
   - Artificial light source: light bulb, laser, LED, computer display.
2. All light absorbers, transmitters, or reflectors can be defined by their SRF.
   - Sensing devices: an **absorbed light SRF**.
   - Camera (digital photocell, film).
   - Human eye (retina).
     - Definition of “colour” = integral of ($\text{SDF}_{\text{light source}} \times \text{SRF}_{\text{sensor}}$).
   - Glass, still water, cellophane: a **transmitted light SRF**.
   - Surface material of an object: a **reflected light SRF**.

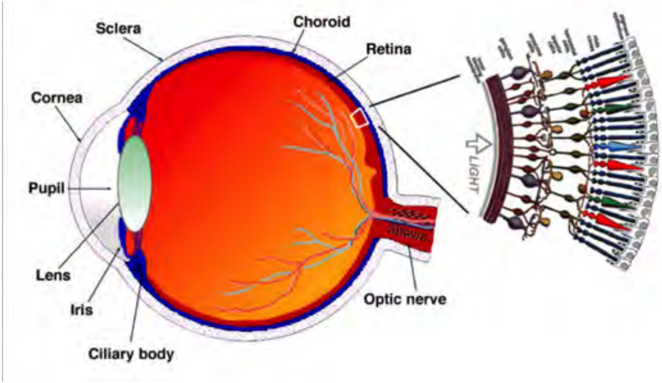
Human Perception of Light



pixshark.com
www.colorcube.com

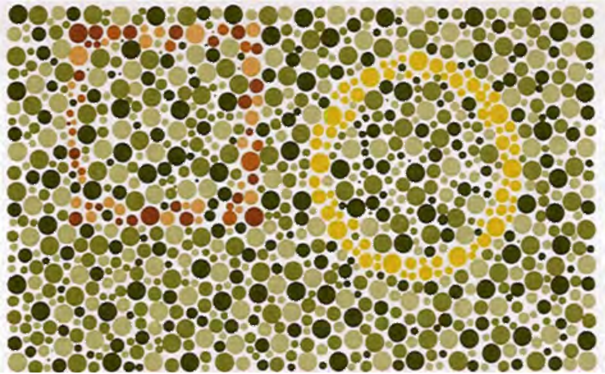
The Eye

Four types of receptors (sensors):
R/G/B cones + rods, each having the unique SRF.



http://webvision.med.utah.edu/imageswv/fovmoswv.jpeg
http://webvision.med.utah.edu/imageswv/Sagschem.jpeg

Colour “Blindness”

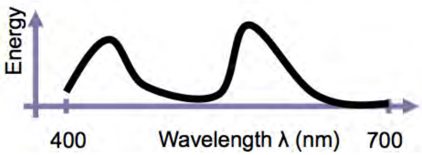


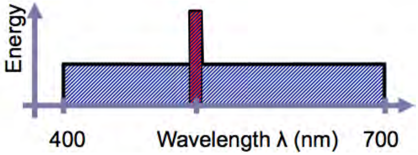
http://members.aol.com/protanope/card2.html

If you didnt see both a yellow circle and a faint brown square, you are somewhat colour blind (in the USA 5.0% of males, 0.5% of females). To find out more, visit: http://www.kcl.ac.uk/teares/gktvc/vc/lt/colourblindness/cblind.htm

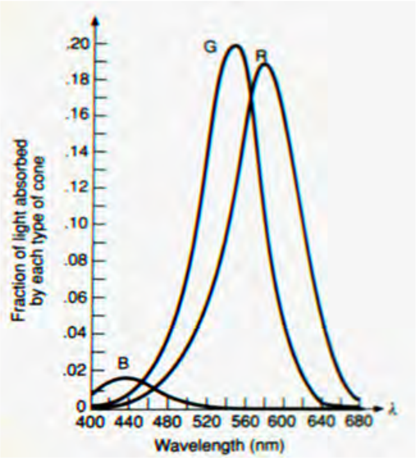
Colours and the SDF

- Many different SDFs are perceived by us as the same color!
- When describing a colour (as seen by the eye) exactly, we do not need to know the full SDF.
- Three parameters are enough.
- For example: just use hue, luminance and saturation.

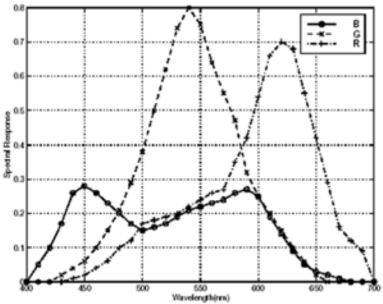




SRFs for the Eye and a Camera



RGB spectral responses for a Kodak digital camera



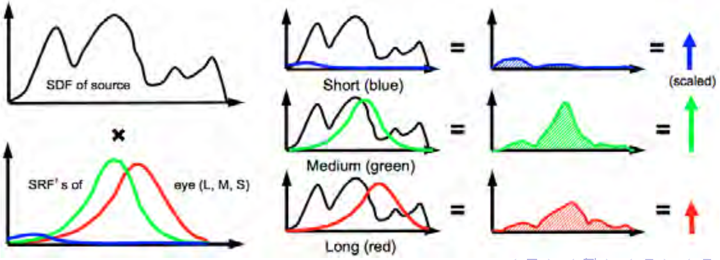
http://www.ecs.csun.edu/~dsalomon/DC2advertis/AppendH.pdf http://www.stanford.edu/class/ee392b/handouts/color.pdf

Seeing Red, Green and Blue

- A cone cell in the retina measures amount of red, green, or blue wavelength energy (3 SRF's). Responds only in bright light.
- The SRF of a **rod** cell covers all wavelengths (measures grey level, or intensity). Responds in low light, but not in bright light.
- Integral of R, G, or B cone response produces a single value.

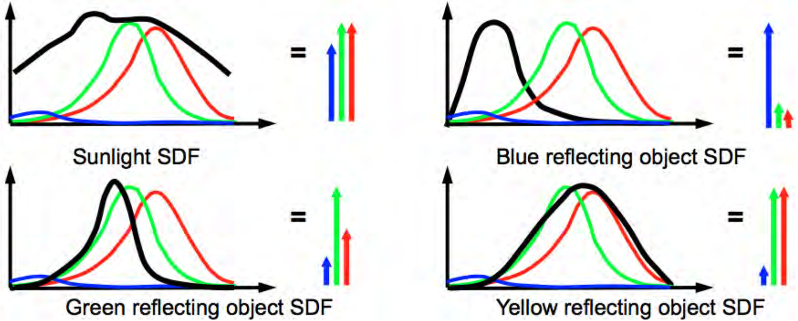
  Note: SRFs are really L, M, S (long, medium, short) wave responses, not R, G, B.

  Note: Low short (blue) response is scaled up by vision system (after retina).



Seeing Red, Green and Blue

- Example L, M, S responses for various SDFs.



- Resulting L, M, and S SRF responses are independent values.
- The three SRF response values are interpreted as hues by our brain, e.g.,

red + green = yellow , red + green + blue = white

Summary 1

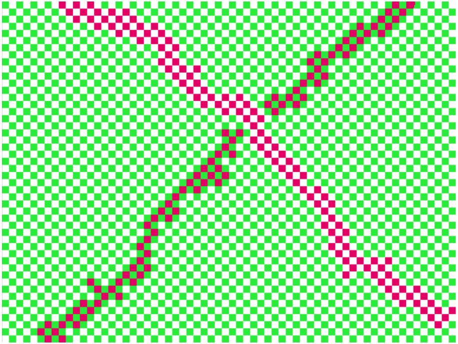
1. **Spectral Density Function (SDF)**: describes the wave composition of light with power for each wave length segment.
2. **Spectral Response Function (SRF)**: can be used to specify how much % of each wave length are absorbed or reflected or transmitted.
3. Light with the different SDFs can have the same colour for our eye.

References:

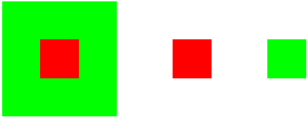
- Light and colours: Hill, Chapter 11.1
- Dominant wave length: Hill, Chapter 11.2.1

Quiz

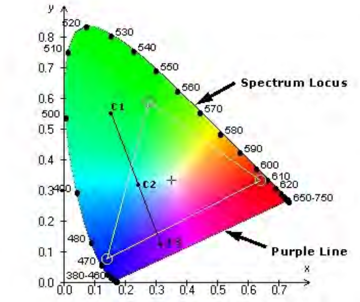
1. What is a spectral density function (SDF)?
2. In what ways can light interact with a material?
3. How can we describe this interaction?
4. What are hue, luminance and saturation?



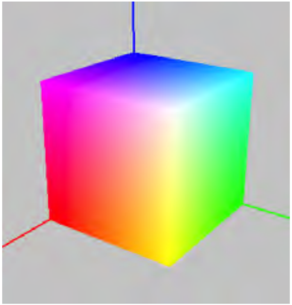
⇐How many different colors?



Colour Spaces



CIE XYZ



RGB

HLS

http://www.hf.faa.gov/webtraining/visualdisplays/HumanVisSys2c5.htm

Colour Coordinate Space

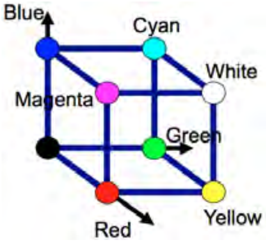
- Defines 3 SRFs (**colour matching functions**) for some sensor.
- One dimension for each SRF ($\rightarrow$ **tristimulus colour space**).
  - Each dimension represents a **primary color P**.
  - Coordinate value = resulting SDF integral normalised to $(0, 1)$.
- Colour triple: a 3D point defined by **chromaticity values** (c_0, c_1, c_2)
- Example: the RGB colour space (Red, Green, Blue primaries).

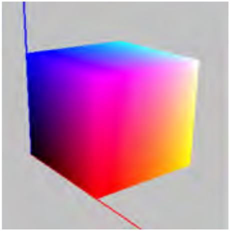
Basis vectors:

$\mathbf{R} = [1, 0, 0]^\mathsf{T}$

$\mathbf{G} = [0, 1, 0]^\mathsf{T}$

$\mathbf{B} = [0, 0, 1]^\mathsf{T}$



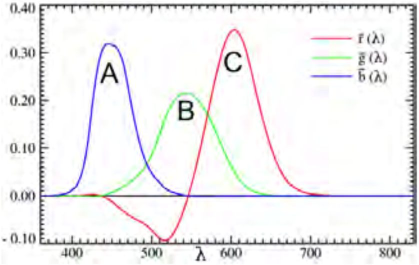


Chromaticity values: $[r, g, b]^\mathsf{T} = r\mathbf{R} + g\mathbf{G} + b\mathbf{B}$

Finding Color Matching Functions

- **Given** 3 primaries A, B, C, **find** 3 SRFs, one for each primary.
- **An idea**:
  1. Show light L with pure color of wavelength λ and brightness 1 to test persons.
  2. Let them adjust another light P using chromaticity values a, b, c until L and P match.
  3. Do this with the whole range of wavelengths λ and note down the a, b, c values for each λ.

Problem: when using normal, visible colours as primaries, some wavelengths λ need negative chromaticity values because adding colours decreases saturation.

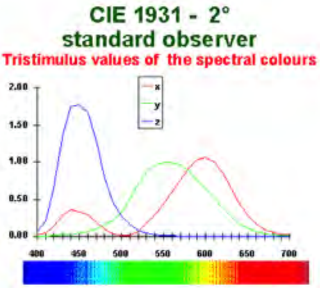


CIE XYZ Colour Space (1931)

International Commission on Illumination (Commission internationale de l'éclairage)

Normalised standard space designed according to requirements:

- Standard primaries "R", "G", "B".
- Only positive chromaticities.
- Equal chromaticities are greys.
- Easy conversion to brightness.

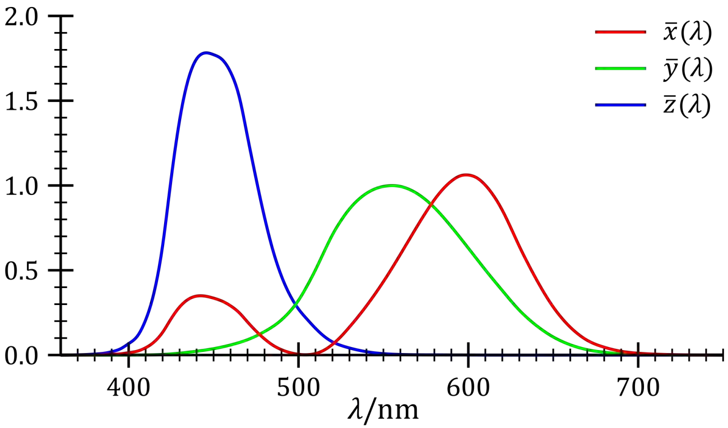


Three primaries: X, Y, Z

- All are imaginary (not real colours).
- The SRFs were designed by engineers to meet above requirements.
- Y corresponds to brightness
- Conversion to RGB by matrix multiplication (linear combination of X,Y,Z = R,G,B and vice versa).

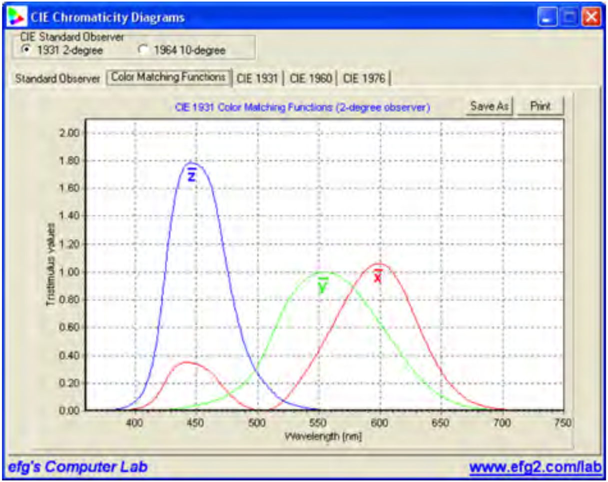
CIE 1931 - 2° Standard Observer Colour Matching Functions

Tristimulus values of the spectral colours:



http://en.wikipedia.org/wiki/CIE_1931_color_space

CIE XYZ Colour Matching Functions



(X, Y, Z)-coordinates of any input SDF are found by multiplying and integrating, thus defining the (X, Y, Z) colour of the SDF.

CIE Chromaticity Diagram: 2D Chromaticity Space

Projection of the 3D XYZ space onto the 2D plane

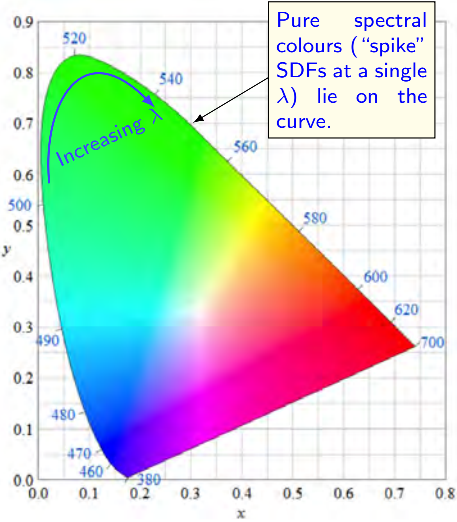
$$x + y + Z = 1:$$

- Looking only at colours with brightness 1.
- 2D coordinates (x, y):

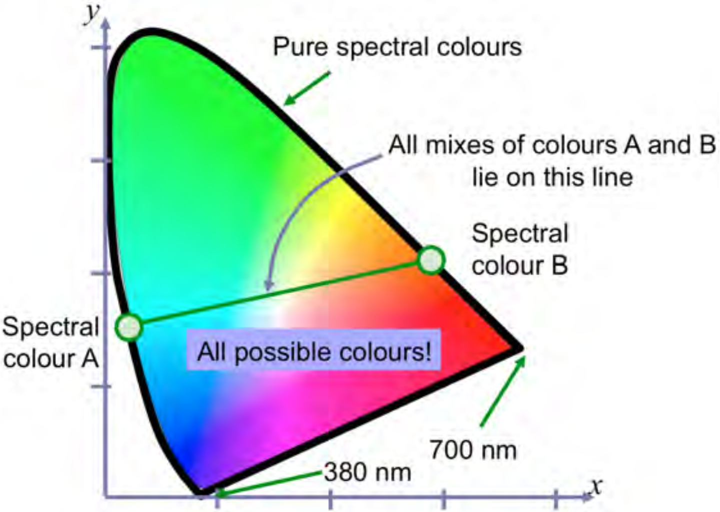
$$x = \frac{X}{X+Y+Z}$$

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

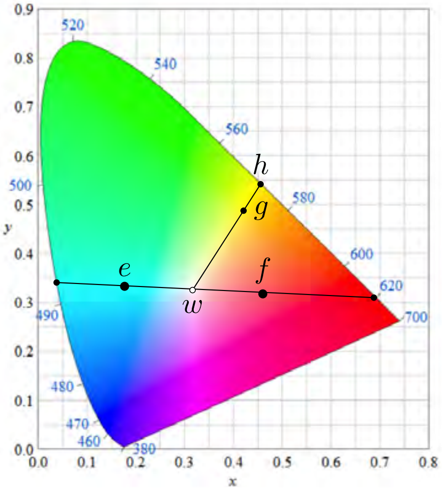
(x, y) is the chromaticity of the colour.



CIE Chromaticity Diagram



Using the CIE Chromaticity Diagram

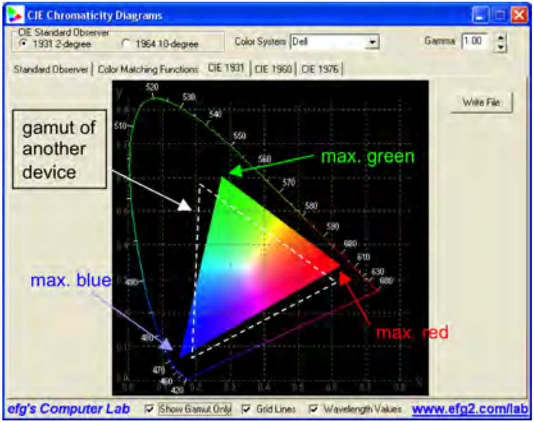


- w – white.
- e and f – complementary colours $(\frac{x_e+x_f}{2} = x_w;\ \frac{y_e+y_f}{2} = y_w)$.
  - Can be combined to white.
- h – the dominant wavelength of chromaticity g.
- $\frac{(wg)}{(wh)}$ – the saturation of g.
  - How close (in %) the chromaticity g is to its pure colour h.

Colour Gamut: A Subset of Colours A Device Can Represent

The CIE colour space can be used to describe the colour gamut.

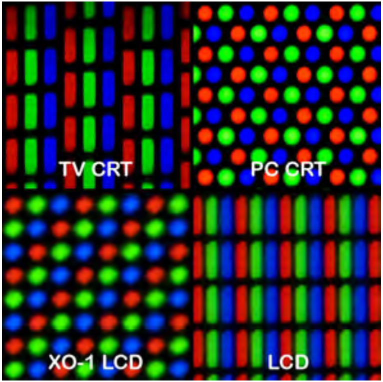
1. Measure maximum intensity of each **device primary** in CIE (use filters with SRFs =CIE SRFs).
2. Convert to the (x, y) chromaticity.
3. The 2D triangle defines possible device colours (i.e., the colour gamut).



Different devices have different gamuts (colour conversion problems).

Additive Colour Systems

- Colours are mixed by adding up appropriate amounts of primaries (adding SDF spikes to black).
- Widely used in screens with subpixels emitting R,G,B.
- Cones in retina respond to light emitted by each subpixel.
- Brain adds the individual cone responses to produce perception of hue, luminance, and saturation.



http://www.csfieldguide.org.nz/DataRepresentation.html

⇒ **Demo program**: ColorMix.exe

http://www.efg2.com/Lab/Graphics/Colors/ColorMix.htm

Subtractive Colour Systems

- Colours are mixed by subtracting appropriate amounts of colours from white (like using notch SRFs on white).
- White light is reflected or transmitted, and some wavelengths are absorbed (subtracted), e.g., coloured glass, printed images.

The colours to subtract are the complements of the primaries, e.g., **cyan magenta yellow** (CMY).

- Cyan absorbs red.
- Magenta absorbs green.
- Yellow absorbs blue.

$$\begin{bmatrix} r \\ g \\ b \end{bmatrix} = \begin{bmatrix} 1 \\ 1 \\ 1 \end{bmatrix} - \begin{bmatrix} c \\ m \\ y \end{bmatrix}$$

CMYK (K = blacK) is often used for four-colour printers.

Troubles with RGB

Difficult to use for colour design as selecting a hue is sometimes non-intuitive.

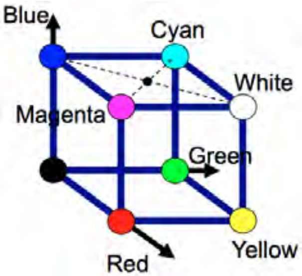
- E.g., what RGB combination would you use to make brown?
- $[128, 80, 50]$ is a good choice. Could you figure that out?

Not a good colour space for interpolating between colours. For example:

$\frac{1}{2}$ blue ■ $+$ $\frac{1}{2}$ white □ $=$ ■

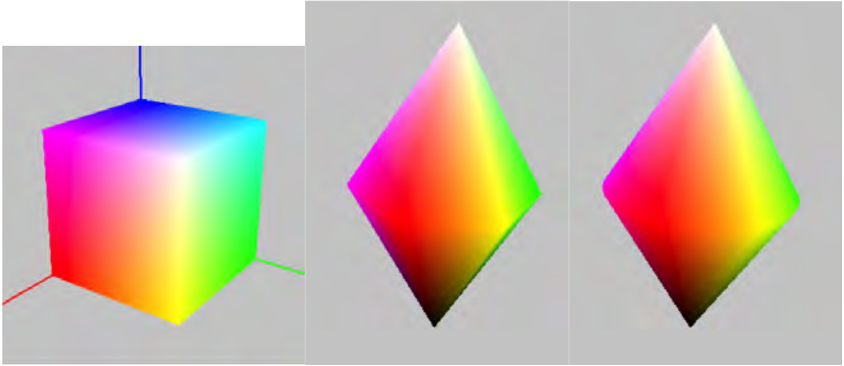
$\frac{1}{2}$ magenta ■ $+$ $\frac{1}{2}$ cyan ■ $=$ ■

Linear interpolation between (r, g, b) chromaticities does not linearly interpolate the saturation or the luminance.

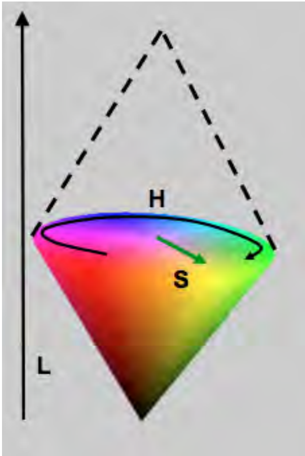


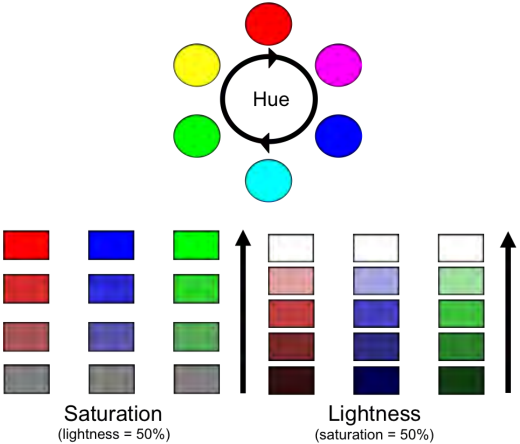
HSL Colour Space

- **H**ue, **S**aturation, **L**ightness.
- Based on transforming the RGB cube → double hexcone → double cone.



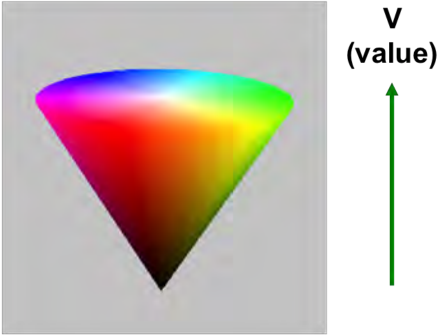
HSL Color Space





HSV Color Space

- **H**ue, **S**aturation, **V**alue (similar to Lightness).
- Only a single cone: at the top all colours are the brightest.



Colour interpolation: RGB vs. HSL

Linear interpolation between two RGB colours $C_0 = [r_0, g_0, b_0]$ and $C_1 = [r_1, g_1, b_1]$ in the RGB space:

$$\begin{aligned} r(t) &= r_0 + t \cdot (r_1 - r_0) \\ g(t) &= g_0 + t \cdot (g_1 - g_0); \\ b(t) &= b_0 + t \cdot (b_1 - b_0); \quad 0 \le t \le 1 \end{aligned}$$

Problem:

- Saturation and luminance are not linearly interpolated.
- Interpolation may correctly vary from one hue (H) to another, but the saturation (S) and luminance (L) may vary in strange ways!

Colour interpolation: RGB vs. HSL

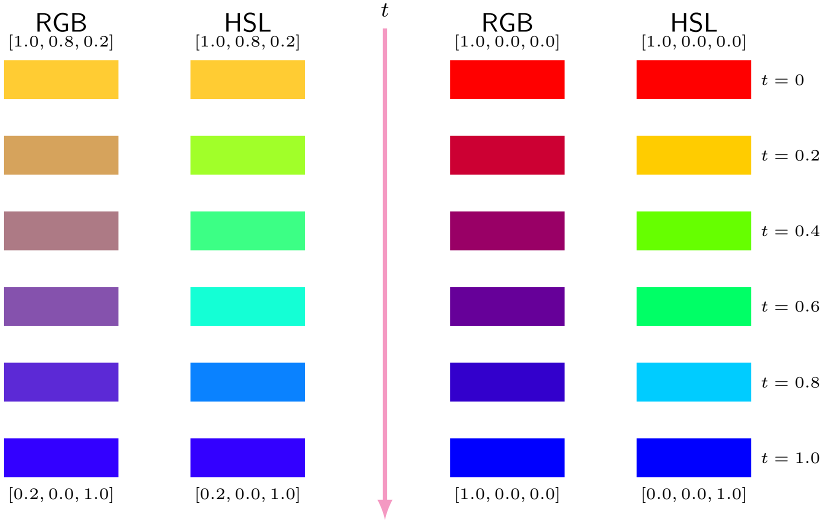
Linear interpolation between two HSL colours $C_0 = [h_0, s_0, l_0]$ and $C_1 = [h_1, s_1, l_1]$ in the HLS space:

$$\begin{aligned} h(t) &= h_0 + t(h_1 - h_0) \\ s(t) &= s_0 + t(s_1 - s_0); \\ l(t) &= l_0 + t(l_1 - l_0); \quad 0 \leq t \leq 1 \end{aligned}$$

All three components (HSL) are linearly interpolated.

- **Solution**: Convert C_0 and C_1 to HLS; interpolate in HSL, convert results back to RGB.

Colour interpolation: RGB vs. HSL



Summary

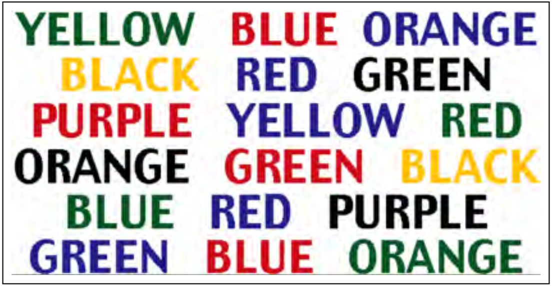
1. Colors can be represented using a 3D colour space.
2. RGB: is easy to use for additive colour mixing, but has limited gamut.
3. CIE XYZ: can represent all visible colours.
4. HSL: makes proper linear interpolation between hue, saturation and lightness.

References:

- Colour description: Hill, Chapter 11.2
- CIE colour Model: Hill, Chapter 11.3
- Other colour spaces: Hill, Chapter 11.4

Quiz

1. What is a colour coordinate space?
2. Name an advantage of the CIE XYZ colour model.
3. What is the disadvantage of the RGB colour model?



Say the colour of the word (not the word itself)