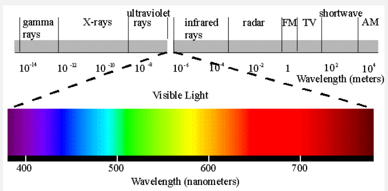
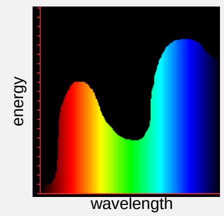
Light and Color

any particular beam of light is characterized by its spectral distribution

spectral distribution = distribution of energy at various wavelengths

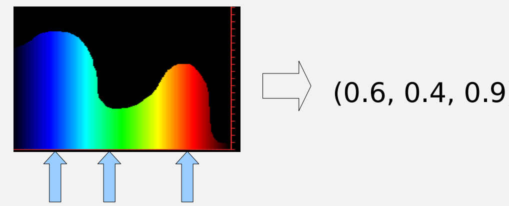




visible light consists of wavelengths ~400-700 nm

Color Description

- exactly describing a full spectral distribution is cumbersome and lengthy
- RGB color corresponds to sampling a spectral distribution at three points



The Human Eye

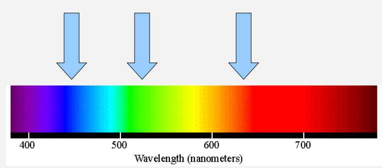
retina has two kinds of receptor cells

cones are color-sensitive

rods are very sensitive to low light, and are not color-sensitive

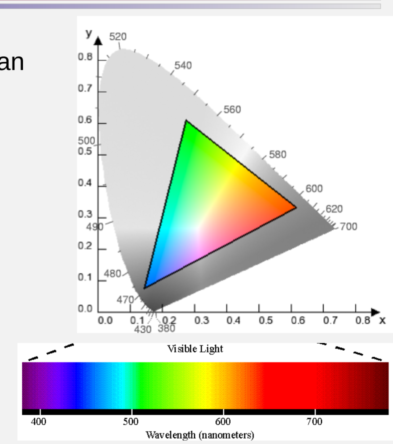
people are most sensitive to three wavelengths

630nm, 520nm, 450nm



RGB Color Gamut

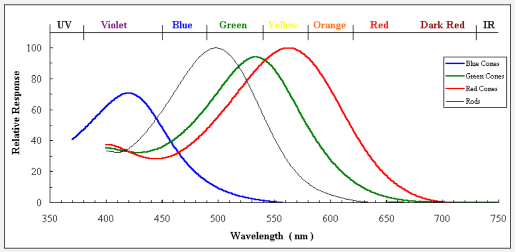
- not all possible colors can be realized with RGB color
  - gap around 500nm
- varies from screen to screen
  - exact chromaticities of red, green, blue vary



Cone Response Curves

furthermore, not all perceivable colors can be represented with RGB

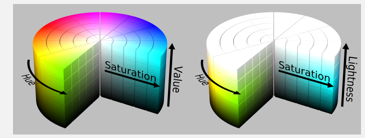
cones have peak sensitivities at red, green, blue but actually respond in varying degrees to a range of wavelengths

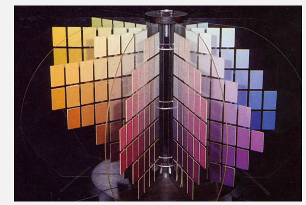


http://homepages.wmich.edu/~korista/web-images/human_cone_action_spectra.gif

Color Spaces

- RGB is not the only possible color model
  - e.g. HSV, HSL – hue, saturation, value/lightness
  - e.g. CIE XYZ – captures all perceivable colors
  - e.g. Munsell – perceptually uniform color space

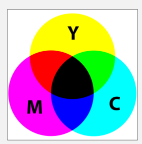




https://en.wikipedia.org/wiki/HSL_and_HSV#/media/File:HSL_color_solid_cylinder_saturation_gray.png
https://commons.wikimedia.org/wiki/File:HSV_color_solid_cylinder_saturation_gray.png
http://home.uchicago.edu/~eye1/images/Munselltree.jpg

Color Spaces

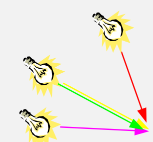
- RGB is not the only possible color model
  - e.g. CMYK
    - inks are subtractive rather than additive
    - CMY are the complements of RGB

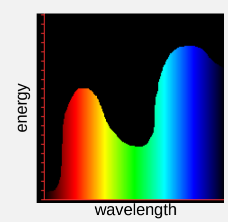


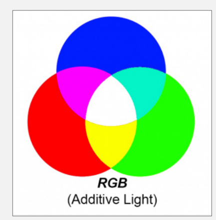
https://commons.wikimedia.org/wiki/File:CMYK_subtractive_color_mixing.svg

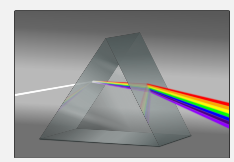
Color Mixing

- combining lights results in *additive* color mixing
  - the result of combining two lights is the sum of the spectral distributions of each
  - white light contains all wavelengths





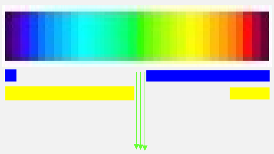




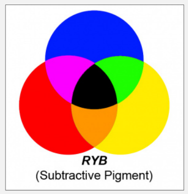
https://www.sparkfun.com/news/2844
https://commons.wikimedia.org/wiki/File:Dispersion_prism-svg.svg

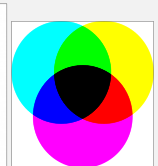
Color Mixing

- combining pigments results in *subtractive* color mixing
  - the color of a pigment is what it reflects
    - all other wavelengths are absorbed
  - the result of combining two pigments is what is reflected by both / absorbed by neither
    - each pigment subtracts wavelengths from the light hitting it
  - if all wavelengths are absorbed, the pigment appears black



blue(ish) pigment reflects blue and absorbs all other colors
yellow(ish) pigment reflects yellow and absorbs all others
→ only light not absorbed by one of the pigments is reflected, so a combination of blue(ish) and yellow(ish) pigments appears green

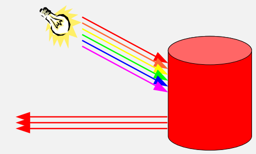




https://www.sparkfun.com/news/2844

Incorporating Color

- when light hits an object…
  - some energy is absorbed
  - some energy is reflected
  - some energy is transmitted



- amounts are different for different wavelengths

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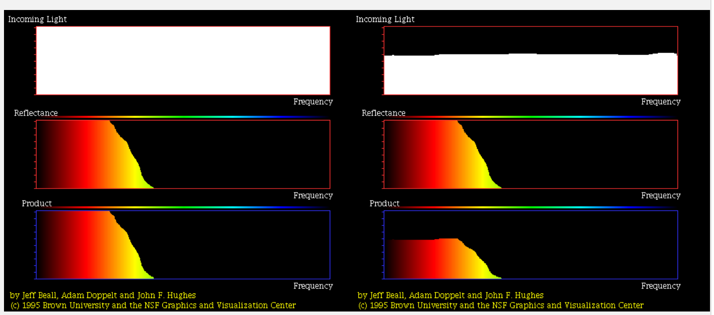
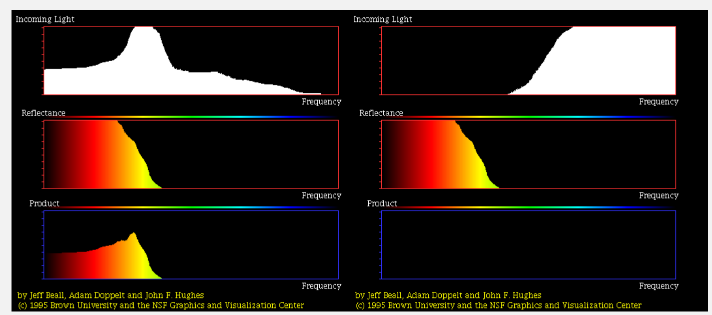
color we see =

spectral distribution of the incoming light
×
reflectance of the object at each wavelength

Reflected Color



Reflected Color



Incorporating Color

- I, ma, md, ms are intensities and reflectances for particular wavelengths
- compute equation three times (R, G, B)

$$I_r = ma\,I_{ar} + \sum_{all\,lights}\left[md_r I_{sr} max(0,(N\cdot L)) + ms_r I_{sr} max(0,(R\cdot V))^{mh}\right]$$
$$I_g = ma\,I_{ag} + \sum_{all\,lights}\left[md_g I_{sg} max(0,(N\cdot L)) + ms_g I_{sg} max(0,(R\cdot V))^{mh}\right]$$
$$I_b = ma\,I_{ab} + \sum_{all\,lights}\left[md_b I_{sb} max(0,(N\cdot L)) + ms_b I_{sb} max(0,(R\cdot V))^{mh}\right]$$

Incorporating Color

$$I_r = ma\,I_{ar} + \sum_{all\,lights}\left[md_r I_{sr} max(0,(N\cdot L)) + ms_r I_{sr} max(0,(R\cdot V))^{mh}\right]$$
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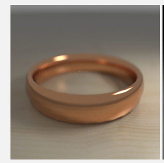
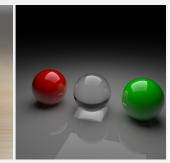
$$I_b = ma\,I_{ab} + \sum_{all\,lights}\left[md_b I_{sb} max(0,(N\cdot L)) + ms_b I_{sb} max(0,(R\cdot V))^{mh}\right]$$

- ambient, diffuse coefficients are the color of the surface (in white light)
- color of specular highlights depends on the material
  - for plastics, highlights take on the color of the light
    - choose equal values for ms_R, ms_G, ms_B
  - for metal, highlights are often closer to the color of the material


metal


glass


metal


plastic

http://homepages.paradise.net.nz/nickamy/

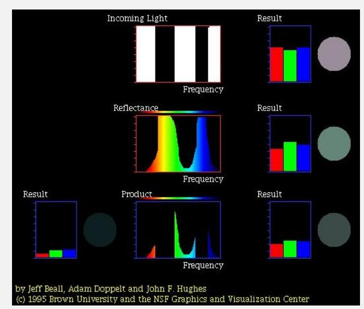
Material	Ambient: $\rho_{ar}, \rho_{ag}, \rho_{ab}$	Diffuse: $\rho_{dr}, \rho_{dg}, \rho_{db}$	Specular: $\rho_{sr}, \rho_{sg}, \rho_{sb}$	(shininess) Exponent: f
Black Plastic	0.0 0.0 0.0	0.01 0.01 0.01	0.50 0.50 0.50	32
Brass	0.329412 0.223529 0.027451	0.780392 0.568627 0.113725	0.992157 0.941176 0.807843	27.8974
Bronze	0.2125 0.1275 0.054	0.714 0.4284 0.18144	0.393548 0.271906 0.166721	25.6
Chrome	0.25 0.25 0.25	0.4 0.4 0.4	0.774597 0.774597 0.774597	76.8
Copper	0.19125 0.0735 0.0225	0.7038 0.27048 0.0828	0.256777 0.137622 0.086014	12.8
Gold	0.24725 0.1995 0.0745	0.75164 0.60648 0.22648	0.628281 0.555802 0.366065	51.2
Pewter	0.10588 0.058824 0.113725	0.427451 0.470588 0.541176	0.3333 0.3333 0.521569	9.84615
Silver	0.19225 0.19225 0.19225	0.50754 0.50754 0.50754	0.508273 0.508273 0.508273	51.2
Polished silver	0.23125 0.23125 0.23125	0.2775 0.2775 0.2775	0.773911 0.773911 0.773911	89.6

Hill, Kelley, *Computer Graphics Using OpenGL*, 3rd ed.

RGB Insufficiency

- RGB version of product of spectral distributions ≠ product of RGB versions

RGB approximation of product



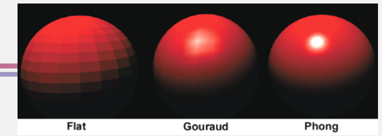
product of RGB approximations

from Brown exploratories, http://www.cs.brown.edu/exploratories/

Shading Models

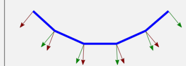
- a *lighting model* specifies how to determine the color (illumination) of a point in the scene
- a *shading model* defines the interpolation technique for determining the colors of pixels across a polygon

Shading Models

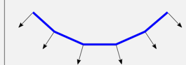


- flat shading
  - lighting equation is computed for each vertex using polygon normals
  - pixel colors are interpolated from vertex colors
- smooth shading – Gouraud
  - lighting equation is computed for each vertex using vertex normals
  - pixel colors are interpolated from vertex colors
- smooth shading – Phong
  - lighting equation is computed for each pixel using pixel normals
  - pixel normals are interpolated from vertex normals

polygon normals



vertex normals – average of normals for the adjacent polygons



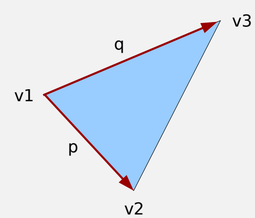
https://commons.wikimedia.org/wiki/File:SHADING.GIF

Obtaining Surface Normals

- appropriate normals for each vertex are often provided as part of the model
  - polygon normals for polyhedra, vertex normals for polymeshes

Math – Surface Normals

- computing the surface normal for a polygon



vertices v1, v2, v3 are in CCW order when viewed from the front of the polygon

let p = v2-v1 and q = v3-v1
then n = p × q

p × q is the *cross product*

$$n = p \times q = \begin{pmatrix} p_y q_z - p_z q_y \\ p_z q_x - p_x q_z \\ p_x q_y - p_y q_x \end{pmatrix}$$

Math – Surface Normals

- the surface normal for an implicit surface is given by the normalized gradient

The normal $\vec{n}$ at a position $\mathbf{p}(x, y, z) \in \mathbb{R}^3$ of a distance field $f : \mathbb{R}^3 \to \mathbb{R}$ is computed with the gradient $\nabla f \in \mathbb{R}^3$:

$$\vec{n}(\mathbf{p}) = \frac{\nabla f(x, y, z)}{\|\nabla f(x, y, z)\|}$$

The gradient is a vector of the partial derivatives of f in x, y and z:

$$\nabla f(x, y, z) = \left[\frac{\partial f(x, y, z)}{\partial x}, \frac{\partial f(x, y, z)}{\partial y}, \frac{\partial f(x, y, z)}{\partial z} \right] = \left[f_x(x, y, z), f_y(x, y, z), f_z(x, y, z) \right]$$

example:
sphere with center *c*
and radius *r*

the normal vector of a sphere of center $\mathbf{c} \in \mathbb{R}^3$ and radius r:

$$\begin{aligned} f(\mathbf{p}(x, y, z)) &= (\|\mathbf{p} - \mathbf{c}\| - r)^2 \\ &= \|\mathbf{p} - \mathbf{c}\|^2 - r^2 \\ &= ((x - c_x)^2 + (y - c_y)^2 + (z - c_z)^2) - r^2 \end{aligned}$$

Then you need to compute $\nabla f = (f_x, f_y, f_z)$:

$$\begin{aligned} f_x(x, y, z) &= (2).(1).(x - c_x)^{(2-1)} + 0 + 0 - 0 = 2(x - c_x) \\ f_y(x, y, z) &= 2(y - c_y) \\ f_z(x, y, z) &= 2(z - c_z) \end{aligned}$$

https://mobile.rodolphe-vaillant.fr/entry/87/normal-to-an-implicit-surface