Light and Color

CS 148, Summer 2012
Introduction to Computer Graphics and Imaging
What is Light?

Visible electromagnetic radiation

What is Light?

Visible electromagnetic radiation


Electric field

Magnetic field


Visible electromagnetic radiation
What is Light?

Visible electromagnetic radiation

Important Facts

\[ c = 299,792,458 \text{ m/s} \text{ in a vacuum} \]

<table>
<thead>
<tr>
<th>Material</th>
<th>Speed (multiple of c)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Air</td>
<td>0.9997</td>
</tr>
<tr>
<td>Water</td>
<td>0.75</td>
</tr>
<tr>
<td>Fused quartz</td>
<td>0.686</td>
</tr>
<tr>
<td>Crown glass</td>
<td>0.658</td>
</tr>
<tr>
<td>Dense flint glass</td>
<td>0.60</td>
</tr>
<tr>
<td>Diamond</td>
<td>0.41</td>
</tr>
</tbody>
</table>

http://wiki.answers.com/Q/What_is_the_velocity_of_light_in_space_and_in_different_materials
"Both" wave and particle

http://en.wikipedia.org/wiki/Wave%E2%80%93particle_duality
Photon [foh-ton]:
A quantum of light that has a position, a direction of propagation, and a wavelength.
Radiometry
[rey-dee-om-i-tree]: Techniques for the measurement of light.
Energy Carried by a Photon

Planck’s constant

\[ q = hf = \frac{hc}{\lambda} \]

- Frequency
- Wavelength
Radiant Flux (Power)

$$\Phi \propto \text{energy/time}$$

Photon energy released by a light source
Spectral Power Distribution

- Tungsten Incandescent
- Daylight (D65)
- Mercury Fluorescent (MBF)
- Low Pressure Sodium (SOX)
- High Pressure Sodium (SON)
- Metal Halide 3000K (MBI)

\[
\frac{d\Phi}{d\lambda}
\]
More Radiometric Vocabulary

- **Radiance**: flux per solid angle (directional quantity)
- **Irradiance**: incident flux per area of surface
Radiance

Measures amount of radiation through a given direction/area

http://www.scratchapixel.com/assets/Uploads/Lighting%20Pipeline/lp-solidangle.png
Photometry

[foh-tom-i-tree]: Measurement of light in terms of its perceived brightness to humans.
Types of Cones

Recall!
Measuring Light Perception

Sensitivity

“This cone sees green light”
“This cone sees green light”

“This light is orange.”

Measuring Light Perception

Sensitivity

Power distribution
Measuring Light Perception

\[ \int \text{Multiply and integrate} \]
Measuring Light Perception

Multiply and integrate

Measures how much they overlap
Cone Responses

\[
L = \int_{\lambda} \Phi(\lambda) L(\lambda) \, d\lambda
\]

\[
M = \int_{\lambda} \Phi(\lambda) M(\lambda) \, d\lambda
\]

\[
S = \int_{\lambda} \Phi(\lambda) S(\lambda) \, d\lambda
\]

Tristimulus Values

Sensitivity
Cone Responses

Power distribution

\[ L = \int \Phi(\lambda) L(\lambda) \, d\lambda \]

\[ M = \int \Phi(\lambda) M(\lambda) \, d\lambda \]

\[ S = \int \Phi(\lambda) S(\lambda) \, d\lambda \]

Tristimulus Values
There is an infinite number of wavelengths, but we only see three integral values.
Cones are not single-wavelength detectors!

There is an infinite number of wavelengths, but we only see three integral values.
There is an infinite number of wavelengths, but we only see three integral values.

Tristimulus values
Metamers

[met-uh-mers]:
Spectral compositions that create the same tristimulus values.
We can simulate visual effects of any wavelength by stimulating cones independently.
Chromatic sensation is linear
CIE Primaries

- **Red**: 700 nm
- **Green**: 546.1 nm
- **Blue**: 435.8 nm

Reproduce all visible wavelengths when combined.
Specifying a Color

Linear combination of primaries

\[(R, G, B) \in \mathbb{R}^3\]
Color Matching Experiments

“Match this color.”
One wavelength
How to combine primaries to mimic each visible wavelength
How to combine primaries to mimic each visible wavelength

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

- **Red**: 700 nm
- **Green**: 546.1 nm
- **Blue**: 435.8 nm

This problem cannot be solved by changing ‘‘real’’ primaries.
Map rgb to xyz values, which are positive for visible wavelengths.
Map rgb to xyz values, which are positive for visible wavelengths.

No longer corresponds to a single wavelength.
Map rgb to xyz values, which are positive for visible wavelengths
Chromaticity Diagram

\[ x = \frac{X}{X + Y + Z} \]
\[ y = \frac{Y}{X + Y + Z} \]

Divide out luminance
RGB are vertices; can achieve colors inside the triangle by combining them.
CIE Primaries

RGB are vertices; can achieve colors inside the triangle by combining them.
Gamut [gam-\textit{uht}]::
The set of colors representable using a particular display device or color space.
Describing a Display

Vertices are primaries, possibilities are inside triangle
So far we have:

- **CIE RGB**
  Can have negative numbers

- **CIE XYZ**
  Nonnegative, no physical realization

- **Display-dependent RGB**
  Values saying how much to light each pixel
Alternative Color Spaces

Designed to be more intuitive

HSV (HSL):
Hue, Saturation, Value (Luminance)

http://upload.wikimedia.org/wikipedia/commons/a/a0/Hsl-hsv_models.svg
Subtractive Color

What matters is the color of a pigment does *not* absorb!

CMYK:
Cyan, Magenta, Yellow, Black

CMYK is Nonunique

Four primaries!

No black

Max black

Both wave and particle

http://en.wikipedia.org/wiki/Wave%E2%80%93particle_duality
"Both" wave and particle

http://en.wikipedia.org/wiki/Wave%E2%80%93particle_duality
Fermat’s Principle

The path taken between two points by a ray of light is the path that can be traversed in least time.
In uniform material, light travels in a straight line!

http://www.nidokidos.org/userpix/38570_3__Ibn_alHaytham_proved_that_light_travels_in_straight_lines_using_the_scientific_method_in_his_Book_of_Optics__1.jpg
Ray Tracing Optics

Optics as tracing paths of light

http://www.physics.rutgers.edu/~croft/divconvprism.jpg
Ways to Modify Path

Reflection

http://upload.wikimedia.org/wikipedia/commons/e/e3/F%C3%A9nyvisszaver%C5%91d%C3%A9s.jpg
Ways to Modify Path

Refraction
Ways to Modify Path

Index of refraction (property of material)

Refraction
Lens: Application of Refraction
Total Internal Reflection

Refraction becomes reflection
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