Fundamentals of Radiometry & Photometry

Optical Engineering

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# Radiometric and Photometric Quantities

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<td>$I = \frac{d\Phi}{d\Omega}$</td>
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</tr>
<tr>
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<td>$I_e$</td>
<td>Watt/sr</td>
<td>$L = \frac{d^2\Phi}{d\Omega dA_{s\perp}}$</td>
<td>Luminous Intensity</td>
<td>$I_v$</td>
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</tr>
<tr>
<td>Radiance</td>
<td>$L_e$</td>
<td>Watt/m²sr</td>
<td>$E = \frac{d\Phi}{dA}$</td>
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<td>$L_v$</td>
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<td>$E_v$</td>
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</tr>
<tr>
<td>Radiant Exitance</td>
<td>$M_e$</td>
<td>Watt/m²</td>
<td>$M_v$</td>
<td>Luminous Exitance</td>
<td>$M_v$</td>
<td>Lumen/m²</td>
</tr>
</tbody>
</table>

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The intensity $I$ of a point source is constant!

\[ I = \frac{d\Phi}{d\Omega} \]

\[ d\Omega = \frac{dA}{R^2} \]
Point Source (continue)

\[ E = \frac{d\Phi}{dA} = \frac{Id\Omega}{dA} = \frac{I}{R^2} \]

\[ dA' = \frac{dA}{\cos \theta} \]

\[ R' = \frac{R}{\cos \theta}, \quad d\Omega' = \frac{dA}{R'^2} \]

\[ E' = \frac{d\Phi'}{dA'} = \frac{Id\Omega'}{dA'/\cos \theta} = \frac{I \cos \theta}{R'^2} = \frac{I}{R^2} \cos^3 \theta \]
Radiance and Luminance

From “Introduction of Radiometry and Photometry”, McCluney Artech House 1994

\[ L = \frac{d^2 \Phi}{dA_s \cos \theta d\Omega} = \frac{d^2 \Phi}{dA_s d\Omega} \]
Lambertian Source

Extended Source

Lambert’s Law

\[ L(\theta) = L_0 \]

\[ I(\theta) = I_0 \cos \theta \]
Extended Source (Lambertian)

Cosine-to-the-fourth Irradiance Falloff

\[ E(\theta) = E(0) \cos^4 \theta = L\Omega \cos^4 \theta \]
Radiance/Luminance Conservation

\[
d^2 \Phi_1 = L_1 dA_1 \cos \theta_1 d\Omega_1 = L_1 dA_1 \cos \theta_1 \left( \frac{dA_2 \cos \theta_2}{R^2} \right) = L_1 \frac{dA_1 dA_2 \cos \theta_1 \cos \theta_2}{R^2}
\]

\[
d^2 \Phi_2 = L_2 dA_2 \cos \theta_2 d\Omega_2 = L_2 dA_2 \cos \theta_2 \left( \frac{dA_1 \cos \theta_1}{R^2} \right) = L_2 \frac{dA_2 dA_1 \cos \theta_2 \cos \theta_1}{R^2}
\]

\[
d^2 \Phi_1 = d^2 \Phi_2 \implies L_1 = L_2
\]
Radiance/Luminance Conservation

\[ d^2\Phi_1 = L_1 dA \cos \theta_1 d\Omega_1 = L_1 dA \cos \theta_1 \sin \theta_1 d\theta_1 d\phi \]

\[ d^2\Phi_2 = L_2 dA \cos \theta_2 d\Omega_2 = L_2 dA \cos \theta_2 \sin \theta_2 d\theta_2 d\phi \]

\[ d^2\Phi_1 = L_1 \cos \theta_1 dA \sin \theta_1 d\theta_1 d\phi = d^2\Phi_2 = L_2 \cos \theta_2 dA \sin \theta_2 d\theta_2 d\phi \implies \]

\[ L_1 = L_2 \frac{\cos \theta_2 d\theta_2}{\cos \theta_1 d\theta_1} \frac{\sin \theta_2}{\sin \theta_1} = L_2 \frac{n_1^2}{n_2^2} \implies \]

\[ \frac{L_1}{n_1^2} = \frac{L_2}{n_2^2} = L_0 \quad \iff \quad \frac{M_1}{n_1^2} = \frac{M_2}{n_2^2} = M_0, \]
Radiance/Luminance Conservation

\[ d^2 \Phi_2 = (1 - \rho) d^2 \Phi_1 \implies \]

\[ L_2 dA \cos \theta_2 \sin \theta_2 d\theta_2 d\phi = (1 - \rho) L_1 dA \cos \theta_1 \sin \theta_1 d\theta_1 d\phi \implies \]

\[ L_2 \cos \theta_2 \sin \theta_2 d\theta_2 = (1 - \rho) L_1 \cos \theta_1 \sin \theta_1 d\theta_1. \]

\[ \frac{L_2}{n_2^2} = (1 - \rho) \frac{L_1}{n_1^2} \]

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Human Eye – Cones and Rods Photoreceptors

http://webvision.med.utah.edu/imageswv/Ostergr.jpeg


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Human Eye – Cones and Rods Photoreceptors

https://askabiologist.asu.edu/sites/default/files/resources/articles/seecolor/Light-through-eye-big.png
Fig. 16.1. (a) Cross section through a human eye. (b) Schematic view of the retina including rod and cone light receptors (adapted from Encyclopedia Britannica, 1994).

- **Cones**: Provide color sensitivity
- **Rods**: Color-insensitive
- Color perception depends on light level
- **Scotopic vision regime**: Low-light-level-vision regime
- **Photopic vision regime**: High-light-level-vision regime
Human Eye – Cones and Rods Photoreceptors

Rod and Cone photoreceptors in mammalian retina. A) A human retinal section showing three neuronal cell layers: outer nuclear layer (ONL) containing the nucleus of rods and cones; inner nuclear layer (INL) containing the nucleus of bipolar, horizontal and amacrine and Muller glial cells; gonglion cell layer (GCL). B) Diagram of rod and cone structure. C) Scan EM showing the outer segments

http://vrcore.wustl.edu/portals/chen_shiming/Chen_S_Photo4.jpg
Detection of the Blind Spot

Because no neuroepithelial cell is present in the portion of the retina where the optic nerve penetrates, this portion cannot sense light and is called the blind spot. The blind spot is located at an angle of 15° from the line of sight (optical axis) and is about 5° wide. This can be confirmed readily by a visual experiment using the above figure. If the observer fixates his/her right eye on the cross while closing his/her left eye and adjusting the distance between the eye and the cross to about 20 cm, the solid circle disappears from sight. This occurs because the solid circle is imaged on the blind spot.

N. Ohta and A. R. Robertson, “Colorimetry”, J. Wiley & Sons, 2005
The Color-Sensitive Cones

In 1965 came experimental confirmation that there are three types of color-sensitive cones in the retina of the human eye, corresponding roughly to red, green, and blue sensitive detectors. The "green" and "red" cones are mostly packed into the fovea centralis. By population, about 64% of the cones are red-sensitive, about 32% green sensitive, and about 2% are blue sensitive. The "blue" cones have the highest sensitivity and are mostly found outside the fovea. The shapes of the curves are obtained by measurement of the absorption by the cones, but the relative heights for the three types are set equal for lack of detailed data.

The Color-Sensitivity of Cones and Rods of Human Eye

Number of Cones: 6-7 millions, 12:6:1 to 40:20:1/R-G-B
Number of Rods: 120 millions

Scotopic Vision Regime < 0.003 cd/m²
0.003 cd/m² < Mesopic Vision Regime < 3 cd/m²
3 cd/m² < Photopic Vision Regime


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Luminous Efficiency Curve of Human Eye
CIE standard curve - 1931

Data from: http://www.cvrl.org
Flickering Photometry Measurements

Alternate between the source light and the reference light 17 times per second (17 Hz). A flicker will be noticeable unless the two lights have the same perceived “brightness”.

History of Photometric Units

• First definition (now obsolete): The luminous intensity of a standardized candle is 1 cd.

• Second definition (now obsolete): 1 cm\textsuperscript{2} of platinum (Pt) at 2042\textdegree K (temperature of solidification) has a luminous intensity of 20.17 cd.

• Third definition (current): A monochromatic light source emitting an optical power of \(\frac{1}{683}\) Watt at 555 nm into the solid angle of 1 steradian (sr) has a luminous intensity of 1 cd.

E. F. Schubert, Light Emitting Diodes, 2\textsuperscript{nd} Ed., Cambridge University Press, 2006
Luminous and Radiant Powers

Luminous and Radiant Power Relation

\[ \Phi_v = K \Phi_e \]

Efficacies

**Photopic Vision**

\[ K(\lambda_0) = K_m V(\lambda_0), \]

**Scotopic Vision**

\[ K'(\lambda_0) = K'_m V'(\lambda_0), \]

\[
\Phi_v = 683 (lm/W) \int_{\lambda_0} \Phi_e(\lambda_0)V(\lambda_0) d\lambda_0, \quad \text{Photopic Vision,}
\]

\[
\Phi_v = 1700 (lm/W) \int_{\lambda_0} \Phi_e(\lambda_0)V'(\lambda_0) d\lambda_0, \quad \text{Scotopic Vision,}
\]
Luminous Flux and Efficiency

\[ \Phi_{\text{lum}} = 683 \frac{\text{lm}}{\text{W}} \int_{\lambda} V(\lambda) P(\lambda) \, d\lambda \]

**Luminous efficacy of radiation** (Unit: lm / W)

Luminous efficacy = \( \Phi_{\text{lum}} / P = \left( 683 \frac{\text{lm}}{\text{W}} \int_{\lambda} V(\lambda) P(\lambda) \, d\lambda \right) \bigg/ \left( \int_{\lambda} P(\lambda) \, d\lambda \right) \)

**Luminous efficacy of the source** (Unit: lm / W)

Luminous efficiency = \( \Phi_{\text{lum}} / (IV) \)

**Caution:** Luminous “efficacy” and “efficiency” is being used in literature

<table>
<thead>
<tr>
<th>Category</th>
<th>Type</th>
<th>Overall luminous efficacy (lm/W)</th>
<th>Overall luminous efficiency</th>
</tr>
</thead>
<tbody>
<tr>
<td>Combustion</td>
<td>candle</td>
<td>0.3</td>
<td>0.04%</td>
</tr>
<tr>
<td></td>
<td>gas mantle</td>
<td>1–2</td>
<td>0.15–0.3%</td>
</tr>
<tr>
<td>Incandescent</td>
<td>100–200 W tungsten incandescent (220 V)</td>
<td>13.8–15.2</td>
<td>2.0–2.2%</td>
</tr>
<tr>
<td></td>
<td>100–200–500 W tungsten glass halogen (220 V)</td>
<td>16.7 – 17.6 –19.8</td>
<td>2.4–2.6–2.9%</td>
</tr>
<tr>
<td></td>
<td>5–40–100 W tungsten incandescent (120 V)</td>
<td>5–12.6–17.5</td>
<td>0.7–1.8–2.6%</td>
</tr>
<tr>
<td></td>
<td>2.6 W tungsten glass halogen (5.2 V)</td>
<td>19.2</td>
<td>2.8%</td>
</tr>
<tr>
<td></td>
<td>tungsten quartz halogen (12–24 V)</td>
<td>24</td>
<td>3.5%</td>
</tr>
<tr>
<td></td>
<td>photographic and projection lamps</td>
<td>35</td>
<td>5.1%</td>
</tr>
<tr>
<td>Light-emitting diode</td>
<td>white LED (raw, without power supply)</td>
<td>4.5–150</td>
<td>0.66–22.0%</td>
</tr>
<tr>
<td></td>
<td>4.1 W LED screw base lamp (120 V)</td>
<td>58.5–82.9</td>
<td>8.6–12.1%</td>
</tr>
<tr>
<td></td>
<td>6.9 W LED screw base lamp (120 V)</td>
<td>55.1–81.9</td>
<td>8.1–12.0%</td>
</tr>
<tr>
<td></td>
<td>7 W LED PAR20 (120 V)</td>
<td>28.6</td>
<td>4.2%</td>
</tr>
<tr>
<td></td>
<td>8.7 W LED screw base lamp (120 V)</td>
<td>69.0–93.1</td>
<td>10.1–13.6%</td>
</tr>
<tr>
<td>Arc lamp</td>
<td>xenon arc lamp</td>
<td>30–50</td>
<td>4.4–7.3%</td>
</tr>
<tr>
<td></td>
<td>mercury-xenon arc lamp</td>
<td>50–55</td>
<td>7.3–8.0%</td>
</tr>
<tr>
<td>Fluorescent</td>
<td>T12 tube with magnetic ballast</td>
<td>60</td>
<td>9%</td>
</tr>
<tr>
<td></td>
<td>9–32 W compact fluorescent</td>
<td>46–75</td>
<td>8–11.45%</td>
</tr>
<tr>
<td></td>
<td>T8 tube with electronic ballast</td>
<td>80–100</td>
<td>12–15%</td>
</tr>
<tr>
<td></td>
<td>T5 tube</td>
<td>70–104.2</td>
<td>10–15.63%</td>
</tr>
<tr>
<td>Gas discharge</td>
<td>1400 W sulfur lamp</td>
<td>100</td>
<td>15%</td>
</tr>
<tr>
<td></td>
<td>metal halide lamp</td>
<td>65–115</td>
<td>9.5–17%</td>
</tr>
<tr>
<td></td>
<td>high pressure sodium lamp</td>
<td>85–150</td>
<td>12–22%</td>
</tr>
<tr>
<td></td>
<td>low pressure sodium lamp</td>
<td>100–200</td>
<td>15–29%</td>
</tr>
<tr>
<td>Ideal sources</td>
<td>Truncated 5800 K blackbody</td>
<td>251</td>
<td>37%</td>
</tr>
<tr>
<td></td>
<td>Green light at 555 nm (maximum possible LER)</td>
<td>683.002</td>
<td>100%</td>
</tr>
</tbody>
</table>
Mesopic Vision

\[ M(m)V_{mes,m}(\lambda_0) = mV(\lambda_0) + (1 - m)V'(\lambda_0) \]

\( m = \) adaptation coefficient
Mesopic Vision

\[ M(m) V_{mes,m}(\lambda_0) = m V(\lambda_0) + (1 - m) V'(\lambda_0) \]

\[ K_{mes,m} = \frac{683}{V_{mes,m}(\lambda_0 = \lambda_{0,p})}, \quad \text{lm/W,} \]

\[ \lambda_{0,p} = 555 \text{ nm} \]
Luminous Efficacy/Efficiency of a Blackbody

\[
M_{\lambda_0}(\lambda_0) = \frac{2\pi n^2 c}{\lambda_0^4} \frac{hc/\lambda_0}{\exp(hc/\lambda_0 k_B T) - 1}
\]

\[
\frac{\Phi_v}{\Phi_e} = \frac{683 \int_{0}^{\infty} M_{\lambda_0}(\lambda_0)V(\lambda_0)d\lambda_0}{\int_{0}^{\infty} M_{\lambda_0}(\lambda_0)d\lambda_0} \left( \frac{lm}{W} \right)
\]
**ILLUMINATION VALUES**
(from I.E.S. Lighting Hndbook)

<table>
<thead>
<tr>
<th>ILLUMINANCE (footcandles)</th>
<th>ILLUMINATION SITUATION</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.02</td>
<td>Full moonlight</td>
</tr>
<tr>
<td>50</td>
<td>Artificial Illuminated Interiors</td>
</tr>
<tr>
<td>100</td>
<td>Sunlight (dull day)</td>
</tr>
<tr>
<td>5000-10000</td>
<td>Sunlight (bright day)</td>
</tr>
</tbody>
</table>

**RECOMMENDED VALUES OF ILLUMINANCE**

<table>
<thead>
<tr>
<th>ILLUMINANCE (footcandles)</th>
<th>ILLUMINATION SITUATION</th>
</tr>
</thead>
<tbody>
<tr>
<td>5-10</td>
<td>Halls, aisles, auto parking areas</td>
</tr>
<tr>
<td>10-20</td>
<td>Stairways, storage rooms, dining rooms, bedrooms, auditoriums</td>
</tr>
<tr>
<td>20-50</td>
<td>Rough assembly, materials wrapping, average workshop, reading usual prints</td>
</tr>
<tr>
<td>50-100</td>
<td>Medium assembly work, kitchens, reading fine print, sewing, writing, workbench, barber shops</td>
</tr>
<tr>
<td>100-200</td>
<td>Drafting rooms, severe visual work, extra fine grading and sorting, difficult inspection</td>
</tr>
<tr>
<td>200-500</td>
<td>Fine bench and machine work, very difficult inspection</td>
</tr>
</tbody>
</table>

1 footcandle = 1 lumen/ft² = 10.7639 lumen/m² = 10.7639 lux

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# Other Luminance (non SI) Units

<table>
<thead>
<tr>
<th>Name</th>
<th>Symbol</th>
<th>Conversion to SI</th>
</tr>
</thead>
<tbody>
<tr>
<td>Apostilb</td>
<td>asb</td>
<td>$1 \text{ asb} = \frac{1}{\pi} \text{ cd/m}^2$</td>
</tr>
<tr>
<td>Blondel</td>
<td>blondel</td>
<td>$1 \text{ blondel} = \frac{1}{\pi} \text{ cd/m}^2$</td>
</tr>
<tr>
<td>Candela per square foot</td>
<td>cd/ft²</td>
<td>$1 \text{ cd/ft}^2 = 10.764 \text{ cd/m}^2$</td>
</tr>
<tr>
<td>Candela per square inch</td>
<td>cd/in²</td>
<td>$1 \text{ cd/in}^2 = 1550 \text{ cd/m}^2$</td>
</tr>
<tr>
<td>Footlambert</td>
<td>fL</td>
<td>$1 \text{ fL} = 3.426 \text{ cd/m}^2$</td>
</tr>
<tr>
<td>Lambert</td>
<td>L</td>
<td>$1 \text{ L} = \frac{10^4}{\pi} \text{ cd/m}^2$</td>
</tr>
<tr>
<td>Nit</td>
<td>nit</td>
<td>$1 \text{ nit} = 1 \text{ cd/m}^2$</td>
</tr>
<tr>
<td>Skot</td>
<td>skot</td>
<td>$1 \text{ skot} = \frac{10^{-3}}{\pi} \text{ cd/m}^2$</td>
</tr>
<tr>
<td>Stilb</td>
<td>sb</td>
<td>$1 \text{ sb} = 10000 \text{ cd/m}^2$</td>
</tr>
</tbody>
</table>
Colorimetry Fundamentals

Colorimetry is the field of science and technology that deals with the assessment, quantification and measurement of color as it is perceived by the human eye.

Trichromatic Theory of Color
Every visible color can be reproduced by appropriate mixing of three basic colors: (red, R), (green, G) and (blue, B).

CIE Color Matching Functions

\[ \lambda_R = 700.0 \text{ nm} \quad (\text{red, R}) \]
\[ \lambda_G = 546.1 \text{ nm} \quad (\text{green, G}) \]
\[ \lambda_B = 435.8 \text{ nm} \quad (\text{blue, B}) \]

Color Space

\[ [F(\lambda_0)] = \bar{r}(\lambda_0)[R] + \bar{g}(\lambda_0)[G] + \bar{b}(\lambda_0)[B] \]
Color Matching Functions Experiment

Primaries Used (1931)
Red: 700nm
Green: 546.1nm
Blue: 435.8nm
(Mercury discharge lamp)

\[ F(\lambda_0) = \tilde{r}(\lambda_0)[R] + \tilde{g}(\lambda_0)[G] + \tilde{b}(\lambda_0)[B] \]

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RGB Color Matching Functions

Tristimulus Values

\[ R = k \int_{\lambda_0} \tilde{r}(\lambda_0) P(\lambda_0) \, d\lambda_0, \]
\[ G = k \int_{\lambda_0} \tilde{g}(\lambda_0) P(\lambda_0) \, d\lambda_0, \]
\[ B = k \int_{\lambda_0} \tilde{b}(\lambda_0) P(\lambda_0) \, d\lambda_0, \]

Chromaticity Coordinates

\[ r = \frac{R}{R + G + B}, \]
\[ g = \frac{G}{R + G + B}, \]
\[ b = \frac{B}{R + G + B}, \]

RGB color matching functions

Stiles-Burch 10° color matching functions averaged across 37 observers (adapted from Wyszecki & Stiles, 1982)
Fig. 17.1. CIE (1931) and CIE (1978) $\bar{x}\bar{y}\bar{z}$ color matching functions (CMFs). The $\bar{y}$ CMF is identical to the eye sensitivity function $V(\lambda)$. Note that the CIE 1931 CMF is the currently valid official standard.
Color Matching Functions and Chromaticity

**X, Y, Z Tristimulus Values**

\[
X = k \int_{\lambda_0} \bar{x}(\lambda_0) P(\lambda_0) d\lambda_0, \\
Y = k \int_{\lambda_0} \bar{y}(\lambda_0) P(\lambda_0) d\lambda_0, \\
Z = k \int_{\lambda_0} \bar{z}(\lambda_0) P(\lambda_0) d\lambda_0,
\]

**X, Y, Z Tristimulus Values**

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

Chromaticity Coordinates \(x\) and \(y\) are only needed since:

\[
x + y + z = 1
\]

**Transformation between XYZ and RGB**

\[
\begin{pmatrix}
X \\
Y \\
Z
\end{pmatrix} = \begin{pmatrix}
2.7689 & 1.7517 & 1.1302 \\
1.0000 & 4.5907 & 0.0601 \\
0.0000 & 0.0565 & 5.5943
\end{pmatrix} \begin{pmatrix}
R \\
G \\
B
\end{pmatrix}
\]

\[
x = (0.490000 r + 0.310000 g + 0.200000 b) / (0.66697 r + 1.13240 g + 1.20063 b) \\
y = (0.17697 r + 0.81240 g + 0.01063 b) / (0.66697 r + 1.13240 g + 1.20063 b) \\
z = (0.00000 r + 0.01000 g + 0.99000 b) / (0.66697 r + 1.13240 g + 1.20063 b)
\]

CIE 1931 – r, g Chromaticity Diagram

R = G = B = 1/3

R = G = B = 1
CIE 1931 – x, y Chromaticity Diagram

Fig. 17.2. CIE 1931 (x, y) chromaticity diagram. Monochromatic colors are located on the perimeter and white light is located in the center of the diagram.
CIE 1931 – x,y Chromaticity Diagram

Fig. 17.4. CIE 1931 (x, y) chromaticity diagram. Monochromatic colors are located on the perimeter. Color saturation decreases towards the center of the diagram. White light is located in the center. Also shown are the regions of distinct colors. The equal-energy point is located at the center and has the coordinates \((x, y) = (1/3, 1/3)\).
CIE 1931 – x,y Chromaticity Diagram (created with MatLab)
CIE 1931 – x,y Chromaticity Diagram

Color Mixing

Fig. 19.1. (a) Schematic of additive color mixing of three primary colors. (b) Additive color mixing using LEDs.

Object’s Apparent Color

Incandescent Lamp Spectrum, $S(\lambda)$

Reflected Spectrum, $S(\lambda) \times R(\lambda)$

Object’s reflectance, $R(\lambda)$

Human eye

Detector

From: Toni Litorja’s presentation, National Institute of Standards and Technology

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Additive Colors and Color Mixing
Colored lights are mixed using additive color properties. Light colors are combining two or more additive colors together which creates a lighter color that is closer to white. Examples of additive color sources include computers and televisions.

The additive primary colors are red, green and blue (RGB). Combining one of these additive primary colors with equal amounts of another one results in the additive secondary colors of cyan, magenta and yellow. Combining all three additive primary colors in equal amounts will produce the color white. Remember combing additive colors creates lighter colors, so adding all three primary colors results in a color so "light" it's actually seen as white. Although that may seem strange, if you think of the absence of all light equaling black, it begins to make sense that adding different colors creates white.

<table>
<thead>
<tr>
<th>Additive Colors Combined in Equal Parts</th>
</tr>
</thead>
<tbody>
<tr>
<td>Blue + Green = Cyan</td>
</tr>
<tr>
<td>Red + Blue = Magenta</td>
</tr>
<tr>
<td>Green + Red = Yellow</td>
</tr>
<tr>
<td>Red + Green + Blue = White</td>
</tr>
</tbody>
</table>

http://www.colorbasics.com/AdditiveSubtractiveColors/
### Additive Color Mixing

#### Additive Colors
Combined in Unequal Parts

<table>
<thead>
<tr>
<th></th>
<th>=</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>1 Green + 2 Red</td>
<td></td>
<td>Orange</td>
</tr>
<tr>
<td>1 Red + 2 Green</td>
<td></td>
<td>Lime</td>
</tr>
<tr>
<td>2 Green + 1 Blue + 3 Red</td>
<td></td>
<td>Brown</td>
</tr>
</tbody>
</table>

**Subtractive Color Mixing**

Before TVs and computer monitors, printers and publishers wondered if they could print color pictures using just three colors of ink. Yes, it is possible, but you have to work in reverse of the process of mixing light colors! We see light colors by the process of **emission** from the source. We see pigment colors by the process of **reflection** (light reflected off an object). The colors which are not reflected are absorbed (subtracted).

The subtractive primary colors are **cyan**, **magenta** and **yellow** (CMY). These are the three colors used in printer ink cartridges.

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<table>
<thead>
<tr>
<th>Reflects</th>
<th>Absorbs</th>
<th>Creates</th>
</tr>
</thead>
<tbody>
<tr>
<td>Blue + Green</td>
<td>Red</td>
<td>Cyan</td>
</tr>
<tr>
<td>Red + Blue</td>
<td>Green</td>
<td>Magenta</td>
</tr>
<tr>
<td>Green + Red</td>
<td>Blue</td>
<td>Yellow</td>
</tr>
</tbody>
</table>

http://www.colorbasics.com/AdditiveSubtractiveColors/
**Subtractive Color Mixing**

<table>
<thead>
<tr>
<th>Combine</th>
<th>Absorbs</th>
<th>Leaves</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cyan + Magenta</td>
<td>Red + Green</td>
<td>Blue</td>
</tr>
<tr>
<td>Cyan + Yellow</td>
<td>Red + Blue</td>
<td>Green</td>
</tr>
<tr>
<td>Magenta + Yellow</td>
<td>Green + Blue</td>
<td>Red</td>
</tr>
<tr>
<td>Cyan + Magenta + Yellow</td>
<td>Red + Green + Blue</td>
<td>Black</td>
</tr>
</tbody>
</table>
Transform a Visible Wavelength in RGB values

http://www.physics.sfasu.edu/astro/color/spectra.html
Some Simple Photometry Examples

A 50mW He-Ne Laser at 633 nm (red light): what is its luminous power?

<table>
<thead>
<tr>
<th>$\lambda_0$ (nm)</th>
<th>$V(\lambda_0)$</th>
</tr>
</thead>
<tbody>
<tr>
<td>628</td>
<td>0.2865936</td>
</tr>
<tr>
<td>629</td>
<td>0.2756245</td>
</tr>
<tr>
<td>630</td>
<td>0.265</td>
</tr>
<tr>
<td>631</td>
<td>0.2547632</td>
</tr>
<tr>
<td>632</td>
<td>0.2448896</td>
</tr>
<tr>
<td>633</td>
<td>0.2353344</td>
</tr>
<tr>
<td>634</td>
<td>0.2260528</td>
</tr>
<tr>
<td>635</td>
<td>0.217</td>
</tr>
<tr>
<td>636</td>
<td>0.2081616</td>
</tr>
<tr>
<td>637</td>
<td>0.1995488</td>
</tr>
</tbody>
</table>

$$\Phi_v = 683 \left( \frac{lm}{W} \right) V(\lambda_0) \Phi_e(\lambda_0)$$

$$\Phi_v = 683 \left( \frac{lm}{W} \right) (0.2353344) \times (50 \times 10^{-3} W) = 8.0367 \text{ lm}$$

A 1W of white light equally distributed between 0.360\(\mu m\) ≤ $\lambda_0$ ≤ 0.750\(\mu m\): what is its luminous power?

$$\Phi_v = 683 \left( \frac{lm}{W} \right) \int_{\lambda_0} V(\lambda_0) \Phi_e(\lambda_0) d\lambda_0$$

$$\Phi_v \approx 683 \left( \frac{lm}{W} \right) \sum_i V(\lambda_{0,i}) \Phi_e(\lambda_{0,i}) \Delta \lambda_0$$

$$= 683 \left( \frac{lm}{W} \right) \sum_{i=1}^{N} \frac{V(\lambda_{0,i}) + V(\lambda_{0,i+1})}{2} \frac{1 W}{\lambda_{max} - \lambda_{min}} \left( \frac{1}{nm} \right) \Delta \lambda_0 (\text{nm})$$

$$= 243.1340 \text{ lm} \quad \text{for} \quad \Delta \lambda_0 = 1 \text{ nm}$$

Prof. Elias N. Glytsis, School of ECE, NTUA
Luminous efficacy of LED luminaires measured in DIAL’s accredited photometric laboratory

<table>
<thead>
<tr>
<th>Description</th>
<th>Spectrum</th>
<th>System power consumption, measured (W)</th>
<th>Lamp or module luminous flux, measured (lm)</th>
<th>System luminous efficacy (lm/W)</th>
<th>Energy conversion efficiency</th>
<th>Theoretical maximum luminous efficacy (lm/W)</th>
</tr>
</thead>
<tbody>
<tr>
<td>High voltage halogen, 120 W</td>
<td><img src="image1" alt="Spectrum" /></td>
<td>127.4</td>
<td>2,249</td>
<td>17.7</td>
<td>11.9</td>
<td>148.7</td>
</tr>
<tr>
<td>Low voltage halogen, 60 W</td>
<td><img src="image2" alt="Spectrum" /></td>
<td>59.9</td>
<td>1,535</td>
<td>25.6</td>
<td>15.4</td>
<td>166.3</td>
</tr>
<tr>
<td>Fluorescent lamp T-5, 54 W, 830</td>
<td><img src="image3" alt="Spectrum" /></td>
<td>53.3</td>
<td>4,184</td>
<td>83.6</td>
<td>23.7</td>
<td>344.4</td>
</tr>
<tr>
<td>Metal halide lamp, 70 W, 810</td>
<td><img src="image4" alt="Spectrum" /></td>
<td>79.8</td>
<td>7,912</td>
<td>92.2</td>
<td>31.5</td>
<td>314.5</td>
</tr>
<tr>
<td>LED, 35 W, 830</td>
<td><img src="image5" alt="Spectrum" /></td>
<td>34.2</td>
<td>4,739</td>
<td>138.6</td>
<td>42.3</td>
<td>329.6</td>
</tr>
<tr>
<td>LED, 35 W, 840</td>
<td><img src="image6" alt="Spectrum" /></td>
<td>34.5</td>
<td>4,806</td>
<td>139.3</td>
<td>43.7</td>
<td>318.8</td>
</tr>
<tr>
<td>LED, 16 W, 730</td>
<td><img src="image7" alt="Spectrum" /></td>
<td>16.2</td>
<td>2,426</td>
<td>150.5</td>
<td>58.7</td>
<td>309.0</td>
</tr>
</tbody>
</table>