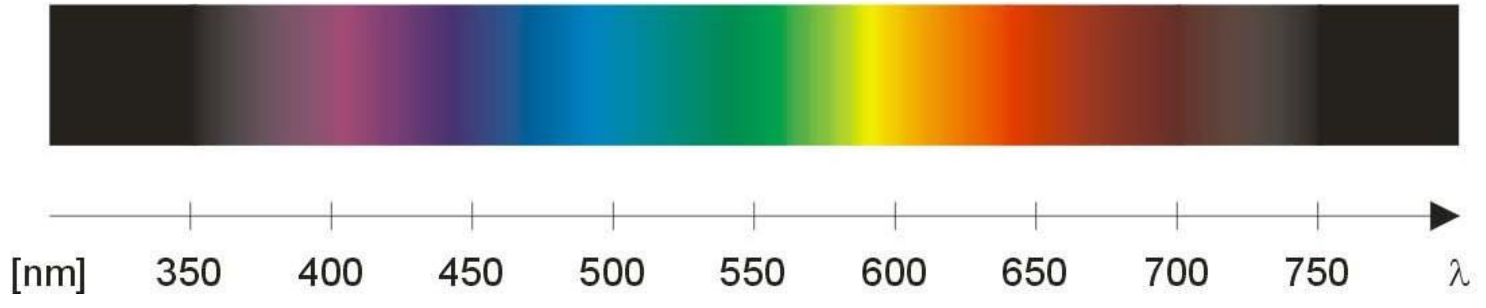
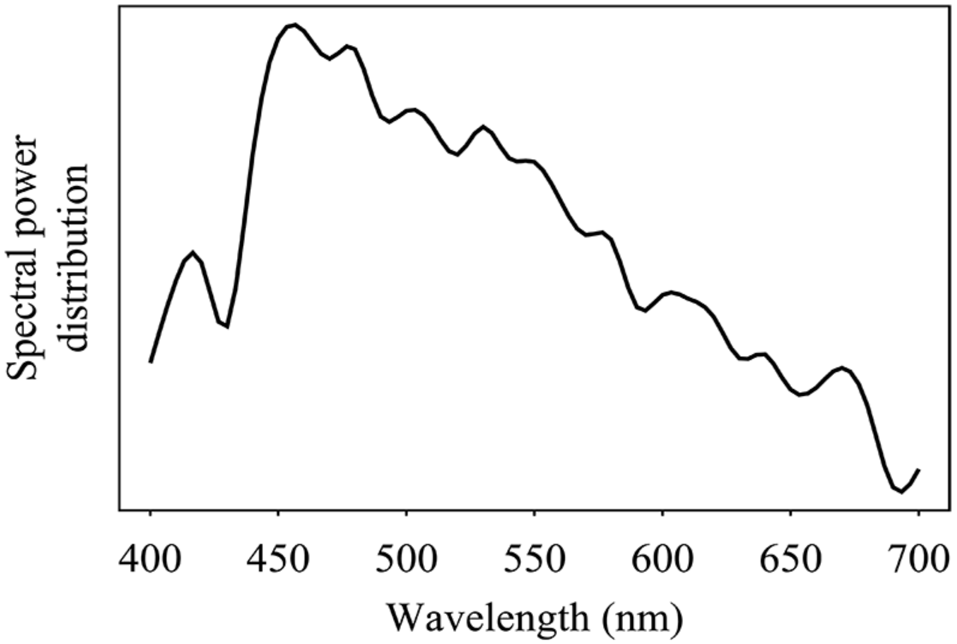
Colour Science

- Light is an electromagnetic wave. Its color is characterized by the wavelength content of the light.
  - Laser light consists of a single wavelength: e.g., a ruby laser produces a bright, scarlet-red beam
  - Most light sources produce contributions over many wavelengths
  - Humans cannot detect all light, just contributions that fall in the “visible wavelengths” (λ ~ 400 to 700 nm)



Colour Science (cont'd)

- Characterize a particular source of light by *spectral power distribution*, or simply *spectrum*, $E(\lambda)$
  - Relative power of different wavelength components
- Daylight (sun) contains contributions from all visible wavelengths

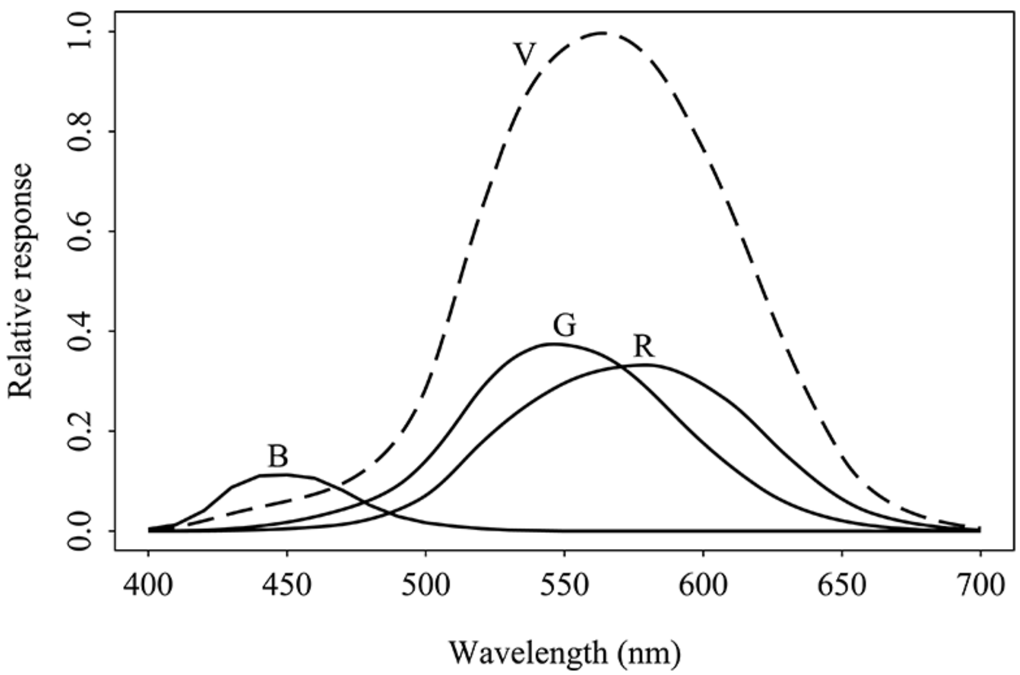


Colour Science (cont'd)

- **Human vision:**
  - The eye works like a camera, with the lens focusing an image onto the retina (upside-down and left-right reversed)
  - The retina consists of an array of rods and three kinds of cones
  - The rods come into play when light levels are low and produce an image in shades of gray
  - For higher light levels, the cones each produce a signal. Because of their differing pigments, the three kinds of cones are most sensitive to red (R), green (G), and blue (B) light
  - It is believed that the brain makes use of differences R-G, G-B, and B-R, as well as combining all of R, G, and B into a high- light-level achromatic channel

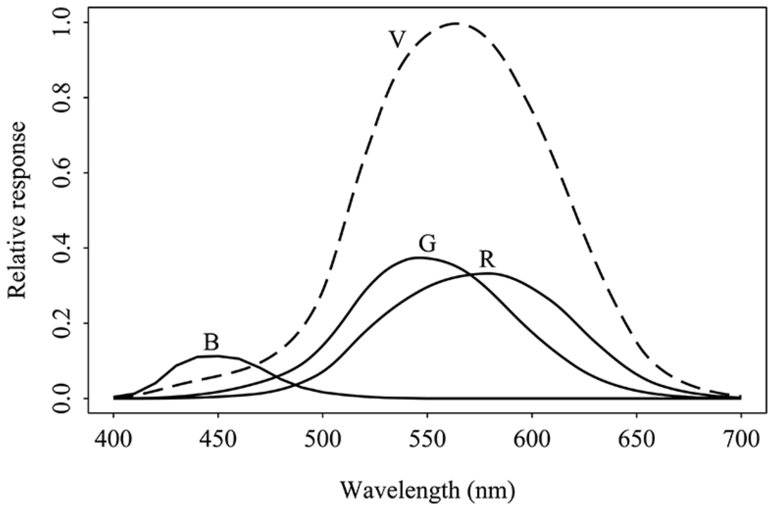
Colour Science (cont'd)

- **Spectral Sensitivity of the Eye:**
  - The eye is most sensitive to light in the middle of the visible spectrum.
  - The sensitivity of our receptors is also a function of wavelength



Colour Science (cont’d)

- **Spectral Sensitivity of the Eye (cont’d):**



  - The Blue receptor sensitivity is not shown to scale because it is much smaller than the curves for Red or Green
  - Overall sensitivity shown as a dashed line – this important curve is called the luminous-efficiency function
    - It is usually denoted $V(\lambda)$ and is formed as the sum of the response curves for Red, Green, and Blue

Colour Science (cont'd)

- **Spectral Sensitivity of the Eye (cont'd):**
  - Spectral sensitivity functions can be combined into a vector function
    - $\boldsymbol{q}(\lambda) = [q_R(\lambda), q_G(\lambda), q_B(\lambda)]^T$
  - The response in each color channel in the eye is proportional to the number of neurons firing
  - A laser light at wavelength λ would result in a certain number of neurons firing. An SPD can be viewed as a combination of single-frequency lights (like "lasers"), so we add up the cone responses for all wavelengths, weighted by the eye's relative response at that wavelength.

Colour Science (cont'd)

- **Spectral Sensitivity of the Eye (cont'd):**
  - Response of each cone type is calculated as follows:

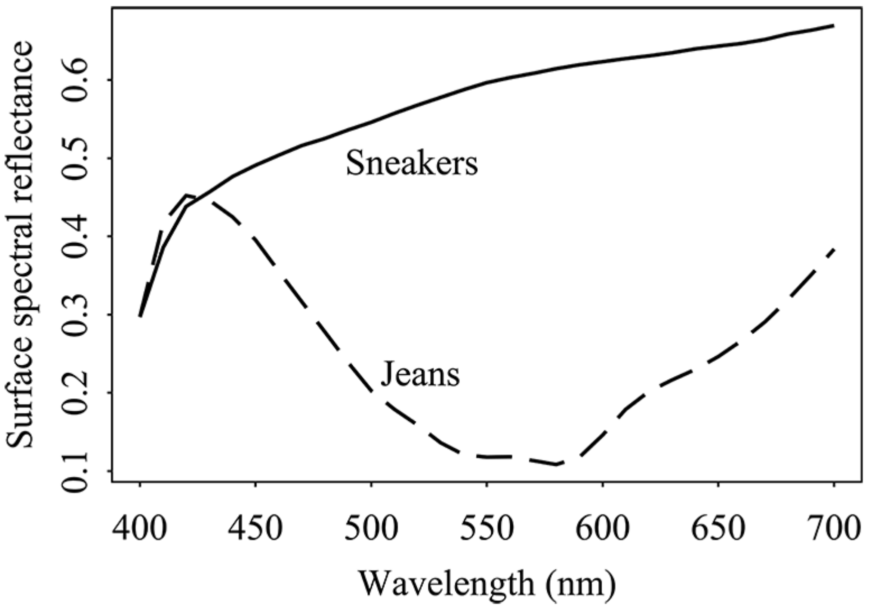
$$R = \int E(\lambda)\, q_R(\lambda)\, d\lambda$$

$$G = \int E(\lambda)\, q_G(\lambda)\, d\lambda$$

$$B = \int E(\lambda)\, q_B(\lambda)\, d\lambda$$

Colour Science (cont'd)

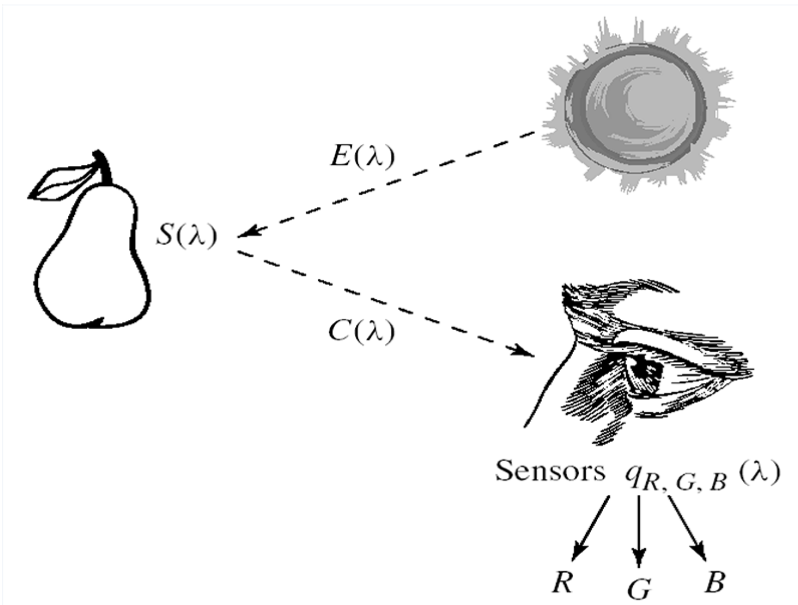
- **Image Formation:**
  - Surfaces reflect different amounts of light at different wavelengths, and dark surfaces reflect less energy than light surfaces



  - Figure shows the surface spectral reflectance from: (1) orange sneakers; and (2) faded blue jeans. The reflectance function is denoted $S(\lambda)$

Colour Science (cont'd)

- **Image Formation (cont'd):**
  - Light from the illuminant with SPD $E(\lambda)$ hits a surface, with surface spectral reflectance function $S(\lambda)$, is reflected, and then is filtered by the eye's cone functions $q(\lambda)$.
  - The function $C(\lambda)$ is called the color signal and consists of the product of $E(\lambda)$, the illuminant, times $S(\lambda)$, the reflectance: $C(\lambda) = E(\lambda)\, S(\lambda)$



Colour Science (cont'd)

- **Image Formation (cont'd):**
  - Restate the cone response calculations for reflected light:

$$R = \int E(\lambda)\, S(\lambda)\, q_R(\lambda)\, d\lambda$$

$$G = \int E(\lambda)\, S(\lambda)\, q_G(\lambda)\, d\lambda$$

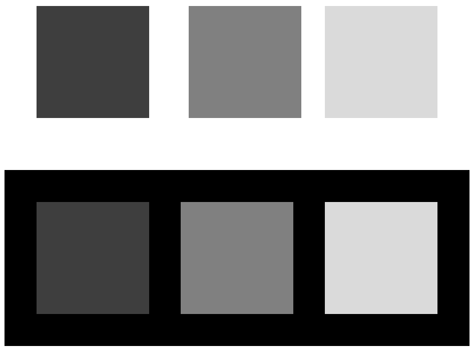
$$B = \int E(\lambda)\, S(\lambda)\, q_B(\lambda)\, d\lambda$$

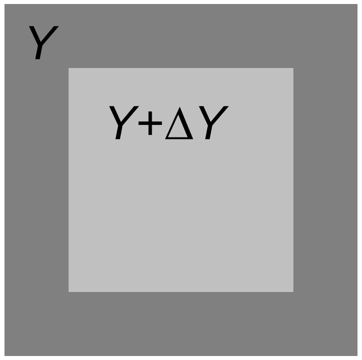
Colour Science (cont'd)

- **Light and Vision Concepts:**
  - **Intensity:** rate at which radiant energy is transferred per unit area (W/m^2)
  - **Luminance:** radiant power weighted by spectral sensitivity function characteristic of vision (luminous- efficiency function, $V(\lambda)$)
    $Y = \int E(\lambda)\ V(\lambda)\ d\lambda$ (cd/m^2 – cd = candela)
  - **Brightness:** "perceived luminance" – subjective attribute affected by human perception
    - Humans sensitive to luminance contrast (differences) rather than absolute luminance

Colour Science (cont'd)

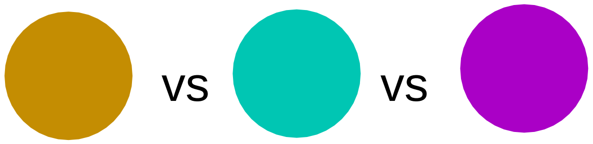
- **Light and Vision Concepts (cont'd):**
  - **Surround Effect:** set of 3 gray squares is identical, but appear as different shades due to contrast with background
  - **Weber's Law**
    - $\Delta Y \rightarrow 0$: two regions indistinguishable
    - $\Delta Y = \Delta Y_N$: just noticeable difference between regions
    - $\Delta Y_N \, / \, Y \approx k$ (a constant)



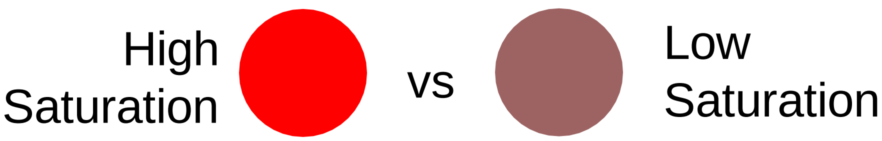


Colour Science (cont'd)

- **Light and Vision Concepts (cont'd):**
  - **Hue:** colour attribute associated with dominant wavelength in a mixture of lightwaves



  - **Saturation:** relative purity or the amount of white light mixed with hue

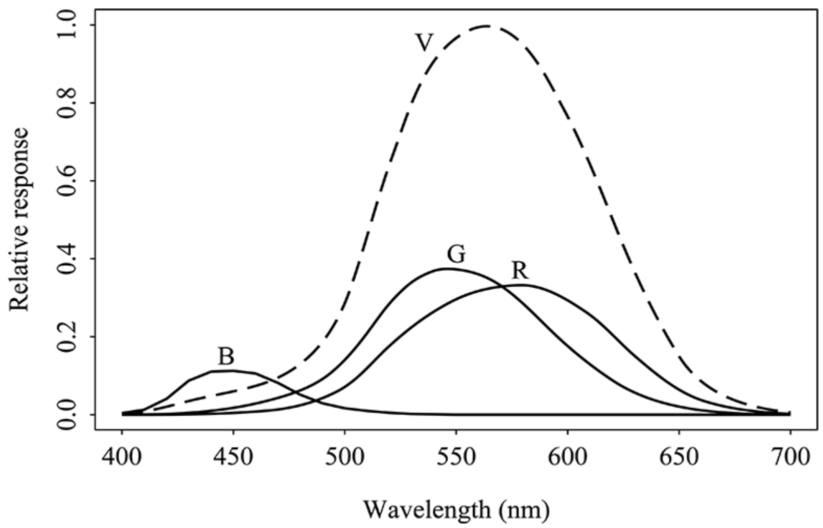


  - **Hue and Saturation determine "Chrominance"**
  - **Luminance and Chrominance determine overall colour perception**

Colour Science (cont'd)

- **Recap:**
  - Human colour perception determined by spectral response of 3 types of cones in the retina

$$\boldsymbol{q}(\lambda) = [q_R(\lambda), q_G(\lambda), q_B(\lambda)]^T$$



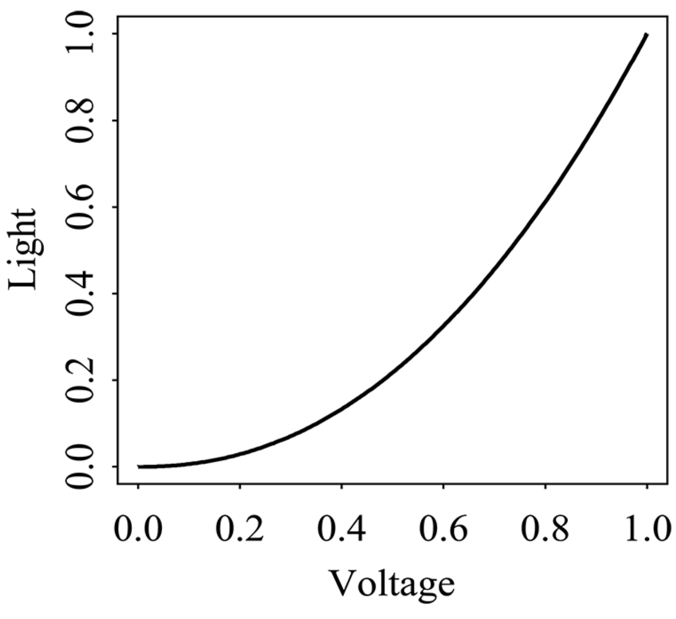
- $R = \int E(\lambda)\, q_R(\lambda)\, d\lambda$
  $G = \int E(\lambda)\, q_G(\lambda)\, d\lambda$
  $B = \int E(\lambda)\, q_B(\lambda)\, d\lambda$

- Reflected light:
  $R = \int E(\lambda)\, S(\lambda)\, q_R(\lambda)\, d\lambda$
  $G = \int E(\lambda)\, S(\lambda)\, q_G(\lambda)\, d\lambda$
  $B = \int E(\lambda)\, S(\lambda)\, q_B(\lambda)\, d\lambda$

- Concepts: intensity, luminance, brightness, hue, saturation, surround effect, Weber's law

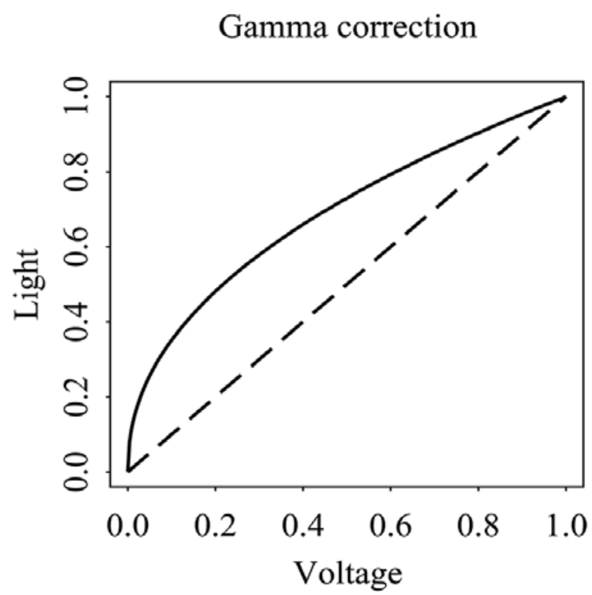
Colour Coding and Models (cont'd)

- **Gamma:**
  - Traditional CRT monitors emit light roughly proportional to the input voltage *raised to a power*, called gamma (γ)
    - Value typically $\gamma \approx 2.2$
    - Note the assumed data range (0,1)!
    - Data coded with linear intensity will result in "dark images" being displayed



Colour Coding and Models (cont'd)

- **Gamma (cont'd):**
  - Example: with red channel file value R, monitor emits light proportional to R^{γ}
  - To compensate for this, we store **gamma-corrected** values
    - $R \to R' = R^{1/\gamma} \quad \Rightarrow \quad (R')^{\gamma} \to R$
    - Gamma-corrected values often denoted with "prime" symbol
    - In practice, "gamma" is a more complicated piecewise function



Colour Coding and Models (cont'd)

- **YUV Colour Space:**
  - Used in analog video (PAL in Europe)
  - $U = B' - Y'$; $V = R' - Y'$;
  - Matrix multiplication: $[Y', U, V]^T = \mathbf{A}\,[R', G', B']^T$

$$\mathbf{A} = \begin{bmatrix} 0.299 & 0.587 & 0.114 \\ -0.299 & -0.587 & 0.886 \\ 0.701 & -0.587 & -0.114 \end{bmatrix}$$

    - Note: Y' is called *luma*, but is often referred to as luminance for convenience
  - This representation is very convenient because the grayscale image can be displayed by simply ignoring the U and V channels
  - Furthermore, the B' and R' channels are reconstructed by simply calculating $Y' + U$ or $Y' + V$ – very easily implemented in analog circuits
  - U and V represent *chrominance* information

Colour Coding and Models (cont'd)

- **YIQ Colour Space:**
  - Used in analog video (NTSC in North America)
  - Better matched to human perception than YUV, but more complicated to implement
  - $I = 0.877283(R' - Y')\cos 33° - 0.492111(B' - Y')\sin 33°$
    $Q = 0.877283(R' - Y')\sin 33° - 0.492111(B' - Y')\cos 33°$
  - Matrix multiplication: $[Y', I, Q]^T = \mathbf{A}\,[R', G', B']^T$

$$\mathbf{A} = \begin{bmatrix} 0.299 & 0.587 & 0.114 \\ 0.595879 & -0.274133 & 0.321746 \\ 0.211205 & -0.523083 & -0.311878 \end{bmatrix}$$

  - Again, this representation is very convenient because the grayscale image can be displayed by simply ignoring the *I* and *Q* channels
  - Again, *I* and *Q* represent *chrominance* information

Colour Coding and Models (cont'd)

- **YCbCr Colour Space:**
  - Used in digital images and video (including JPEG, MPEG, etc.)
  - Defined in "Recommendation ITU-R BT.601-4" or just "Rec. 601"
  - Provides data range appropriate for digital coding
    - $Cb = ((B' - Y')/1.772) + 0.5$
      $Cr = ((R' - Y')/1.402) + 0.5$
  - Matrix multiplication: $[Y', Cb, Cr]^T = \mathbf{A}\,[R', G', B']^T + [0, 0.5, 0.5]^T$

$$\mathbf{A} = \begin{bmatrix} 0.299 & 0.587 & 0.114 \\ -1.68736 & -0.331264 & 0.5 \\ 0.5 & -0.418688 & -0.081312 \end{bmatrix}$$

  - Again, this representation is very convenient because the grayscale image can be displayed by simply ignoring the *Cb* and *Cr* channels
  - Again, *Cb* and *Cr* represent *chrominance* information

Colour Coding and Models (cont'd)

YCbCr Colour Space (cont'd):

- In practice, based on Rec. 601:
  - $[Y',Cb,Cr]^T = \mathbf{A}\,[R',G',B']^T + [16,128,128]^T$,
  - [Assumes (R,G,B) in the (0,1) range]

$$\mathbf{A} = \begin{bmatrix} 65.481 & 128.553 & 24.966 \\ -37.797 & -74.203 & 112 \\ 112 & -93.786 & -18.214 \end{bmatrix}$$

- **Example:**


"Monarch" colour image

=


R Channel

+


G Channel

+


B Channel

=


Y Channel

+

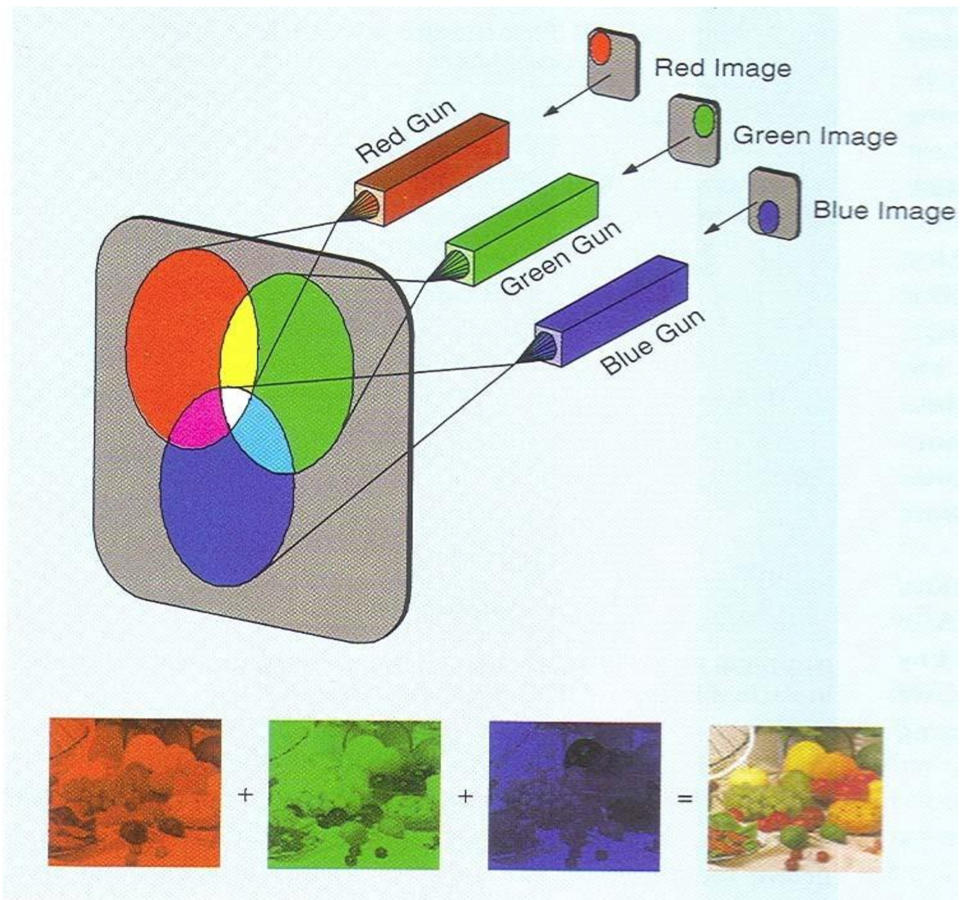

Cb Channel

+


Cr Channel

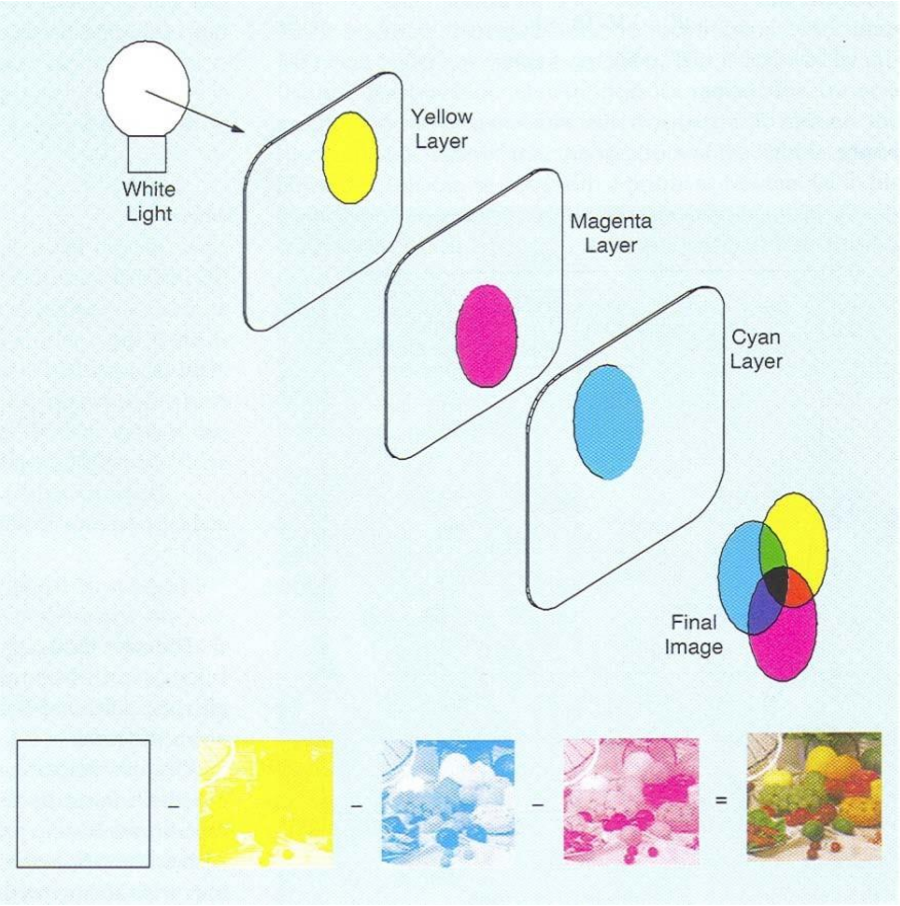
Colour Coding and Models (cont'd)

- Up to this point, only discussing additive colour models



Colour Coding and Models (cont'd)

- Also subtractive colour system:



Colour Coding and Models (cont'd)

- **Subtractive Color Models:**
  - Used in printing where ink only reflects part of the spectrum (based on S(λ)), effectively removing or attenuating regions of the visible spectrum
  - Cyan, Magenta, Yellow model:

$$\begin{bmatrix} C \\ M \\ Y \end{bmatrix} = \begin{bmatrix} 1 \\ 1 \\ 1 \end{bmatrix} - \begin{bmatrix} R \\ G \\ B \end{bmatrix}$$

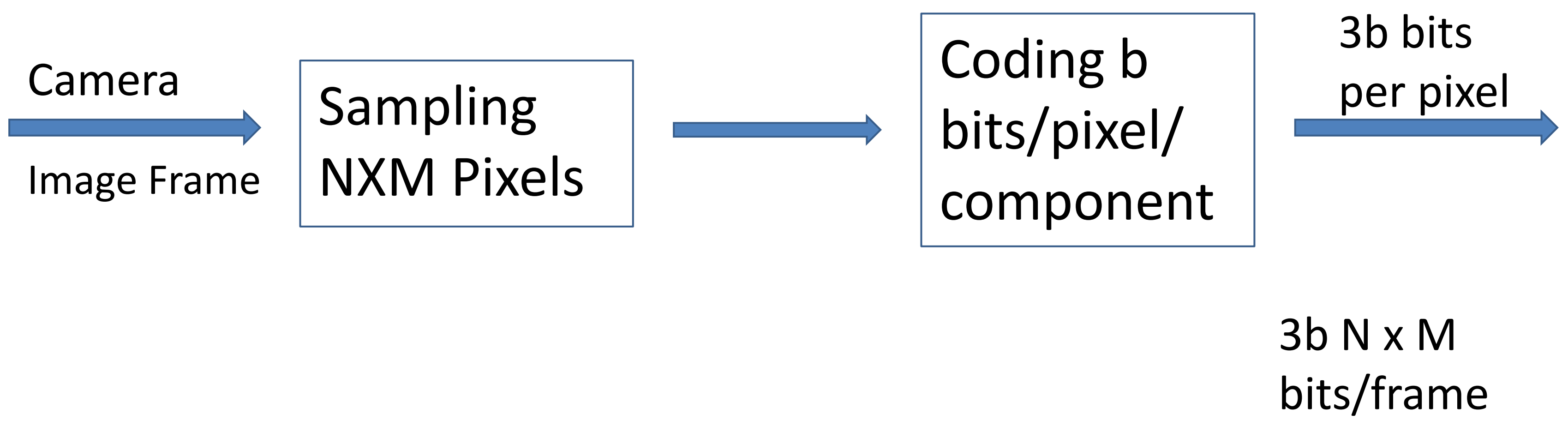
  - In practice, black (*K*) cannot be easily produced via combination of CMY – therefore, use black ink:

$$K \equiv \min\{C, M, Y\}$$

$$\begin{bmatrix} C \\ M \\ Y \end{bmatrix} \Rightarrow \begin{bmatrix} C-K \\ M-K \\ Y-K \end{bmatrix}$$

  - Note: Y is "yellow" here, not luminance!

Color Coding



- **True Color:** Provision of three separate components for additive RGB
  8 bits/component → 24 bits
- Hi color: 5(R), 6(G), 5(B) → 16 bits

Question: How many different colors can I obtain with true color coding?

Answer: Each of the RGB components is represented by 8 bits that is can take
256 different values.

Therefore, the number of different colors that we can obtain is
256x256x256=…

Question: How many bits (greyscale levels) do I need to smoothly shade from black to white?

Assume that human vision responds to 100:1 contrast ration from white to black

Answer: Consider a range from 1 to 100 between black and white.

With non-linear coding a 100:1 contrast ratio, vision can detect that two intensities are different if the ratio between them exceeds about 1.01. (1% contrast sensitivity)

Thus, 1.01**k=100 and therefore approximately k=460 coding (or greyscale) levels are needed or about 9 bits per level. (obviously in this case the greyscale levels are not equally spaced)

what happens with linear coding (i.e. equally spaced greyscale levels?)

Question: (Problem 4.10 from text)

A sample definition of "Hue" can be given as set of ratios R:G:B. Suppose a color is divided by 2 so that the RGB triple now has values 0.5 smaller

a) If gamma correction is applied after the division by 2 does the hue remains same on CRT display?
b) What happened if gamma correction is not applied?

Answer:

a) (R:G:B)=(R/2:G/2:B/2)

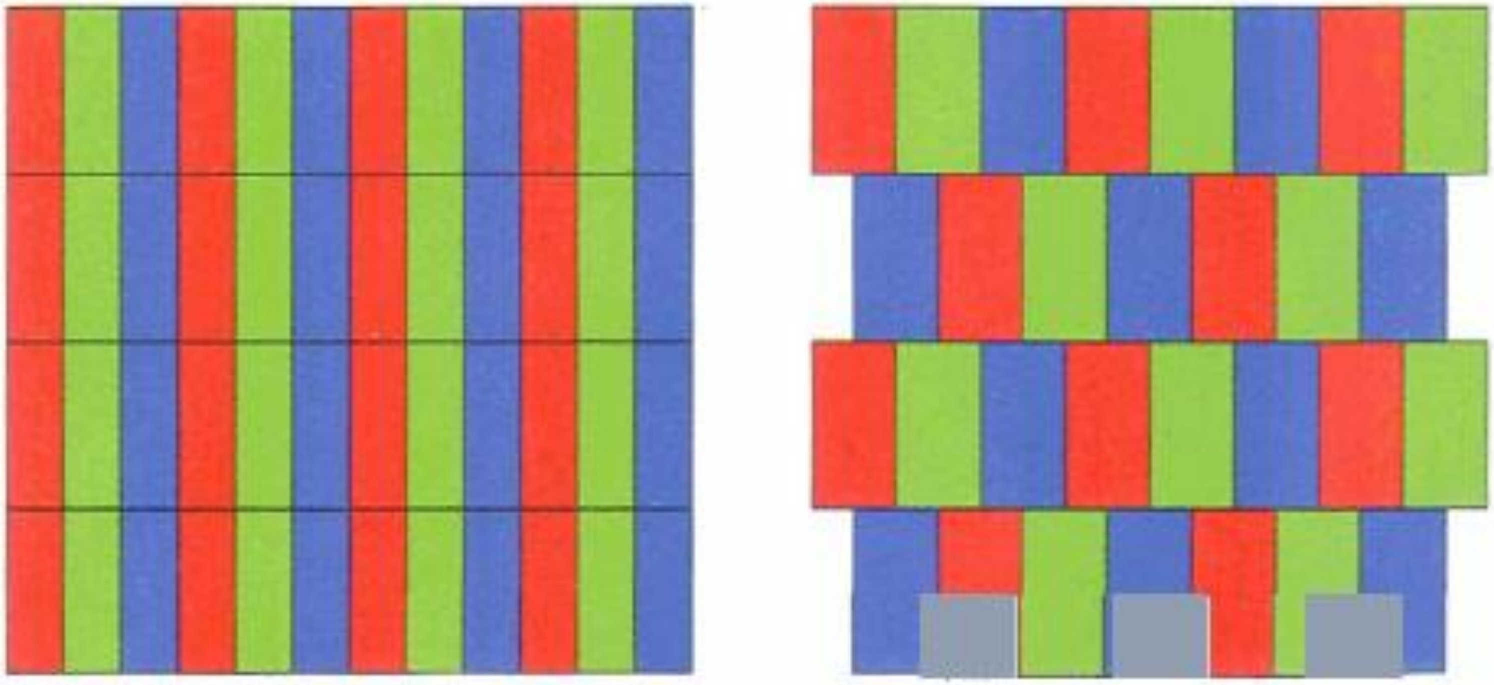
Gamma correction: (R/2)->(R/2)'
CRT display:(R/2)'->(R/2)

Thus since the ratio is preserved the hue remains the same.

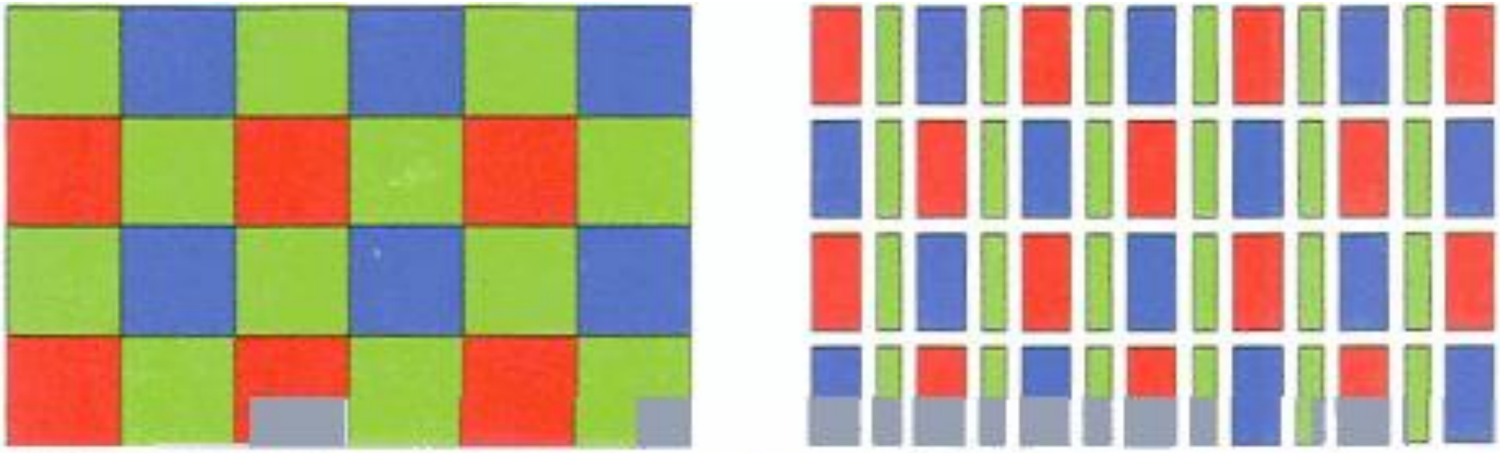
b) Hue will not remain the same.

Primary Colors

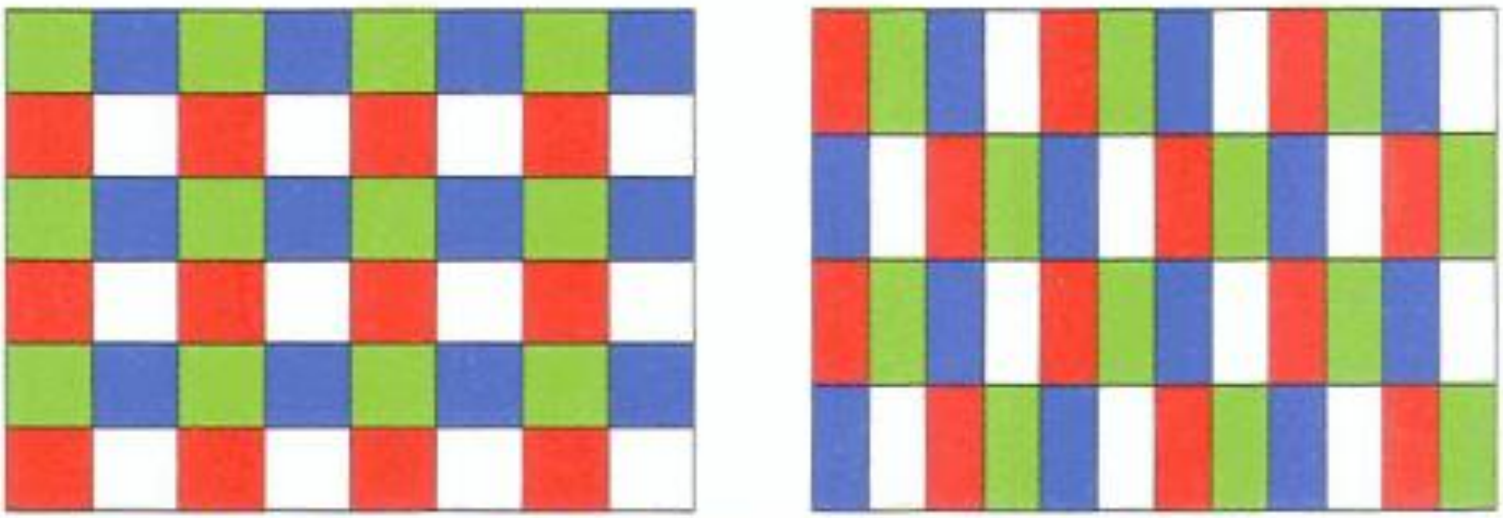
High-resolution color displays add to the media-rich features in next-generation cellphones, driving power consumption way up and operating life way down.



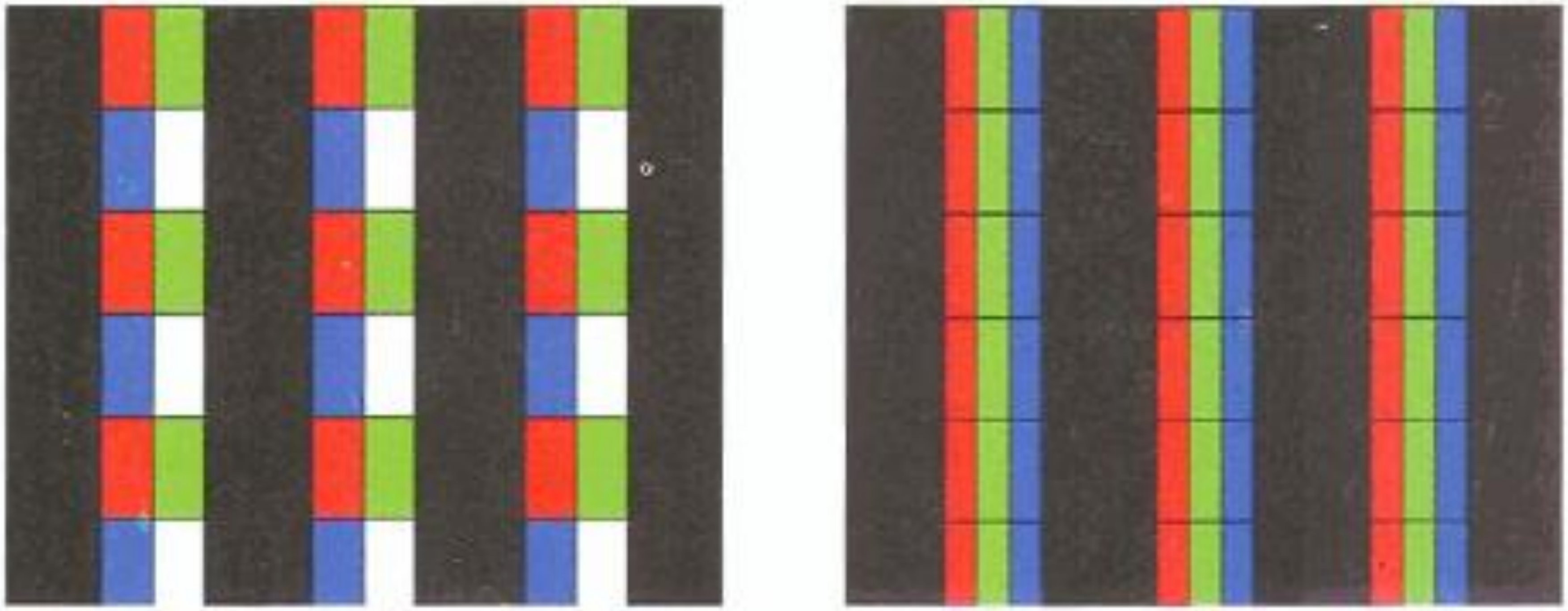
TRADEOFFS: Most flat-panel displays today, with their 1:1:1 ratio of red, green, and blue elements, compromise on power consumption and resolution. These elements, or subpixels, are arranged in either a conventional stripe pattern [left] or a delta pattern [right]. Because light from the blue subpixels does little to help the eye resolve images, most of it goes to waste.



EASY ON THE EYES: The Bayer pattern [left] saves power by including extra subpixels in the color green, which the human visual system resolves with particular efficiency. The PenTile Matrix [right] yields even better results by changing the size and arrangement of the pixels.



WHITE MAKES BRIGHT: Replacing one of the extra green subpixels of a Bayer pattern with a white subpixel [left] provides better color balance and improves brightness. A further modification in the PenTile pattern [right] pushes performance up another rung.



TWO DO THE JOB OF THREE: A PenTile red-green-blue-white pattern [left] requires fewer columns than a red-green-blue stripe pattern [right], providing both economic and performance advantages.

Dis
A Dif
S

NEW IM
TECHNI
FOR HA
THE BR
RICH G

Today's fl
vivid imag
it. It's a tr
watched n
anything
power cor
today, wh
data on th
players lik
is now, it
engineer
mation o
be displa
Fortu
as 50 per
the displ
eye can
is called
a living
Biom