Color

- Color Science
- Color Models
- Further Exploration

Color Science

- **Light and Spectra**
  - 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.
  - Human cannot detect all light, just contributions that fall in the "visible wavelengths".
  - Short wavelengths produce a blue sensation, long wavelengths produce a red one.

Color Science

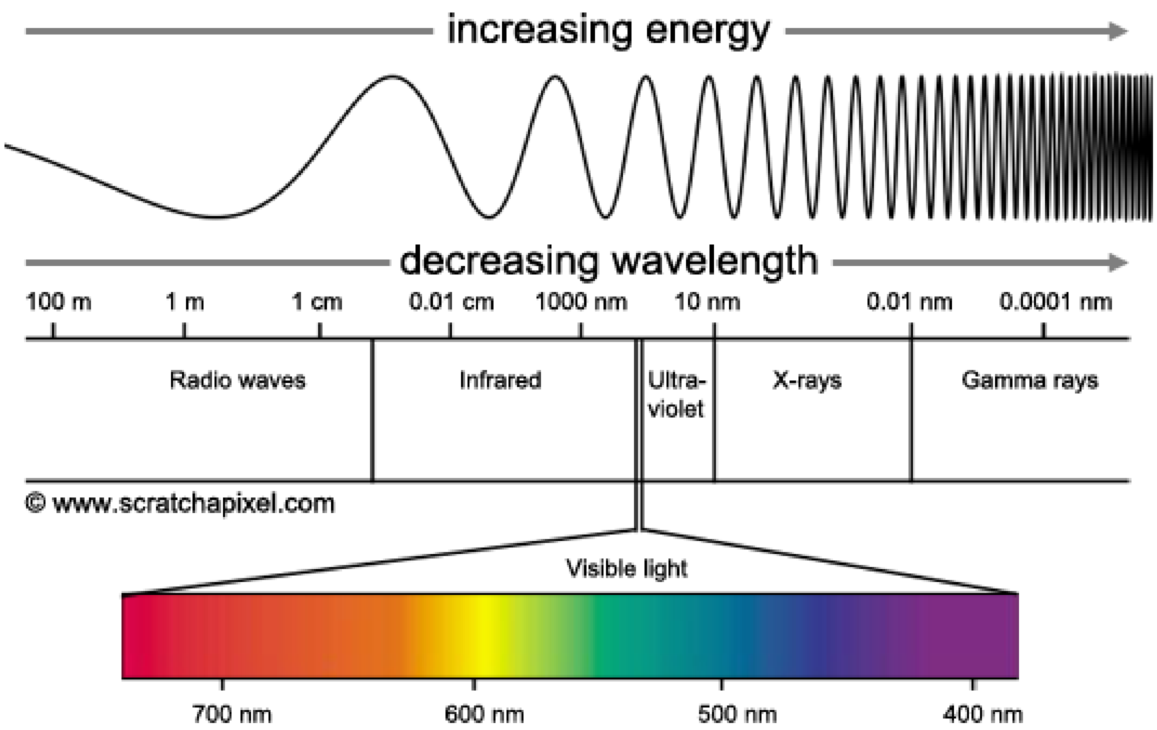


Fig. 3.1: the spectra

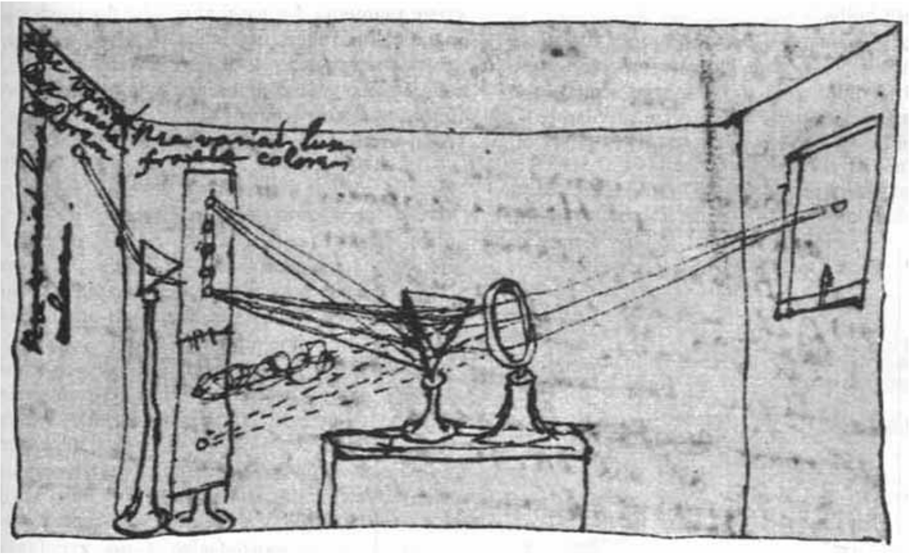


Fig. 3.2: Sir Isaac Newton's experiments.

- Visible light is an electromagnetic wave in the range *400 nm* to *700 nm* (where nm stands for nanometer, 10^{-9} meters).

- Spectrophotometer: a device used to measure visible light, by reflecting light from a diffraction grating (a ruled surface) that spreads out the different wavelengths.
- Figure 3.3 shows the phenomenon that white light contains all the colors of a rainbow and how spectrophotometer works.

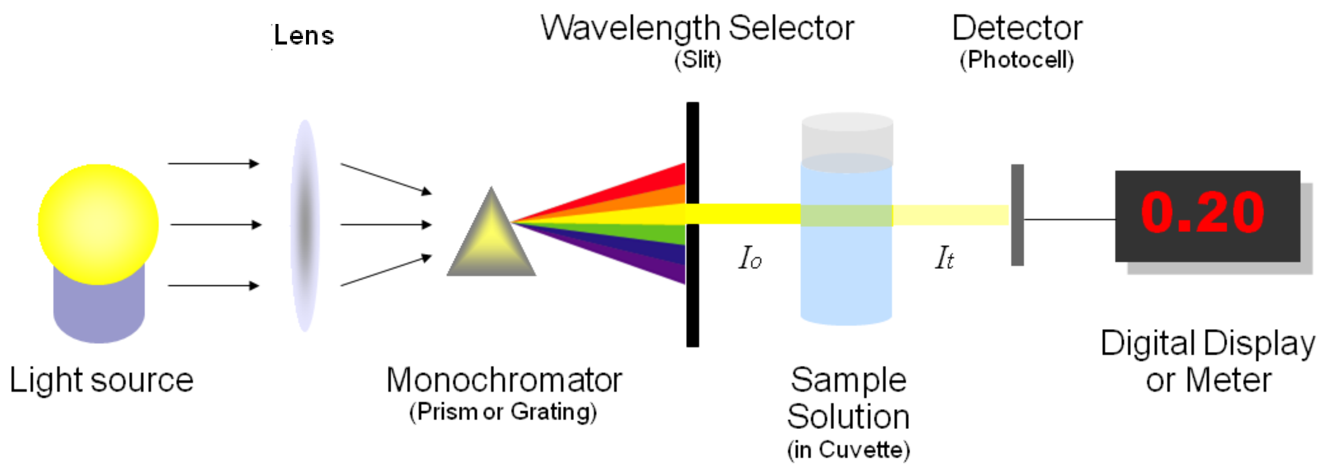


Fig. 3.3: how spectrophotometer works

- Fig. 3.4 shows the relative power in each wavelength interval for typical outdoor light on a sunny day. This type of curve is called a **Spectral Power Distribution** (**SPD**) or a **spectrum**.
- The symbol for wavelength is λ. This curve is called $E(\lambda)$.

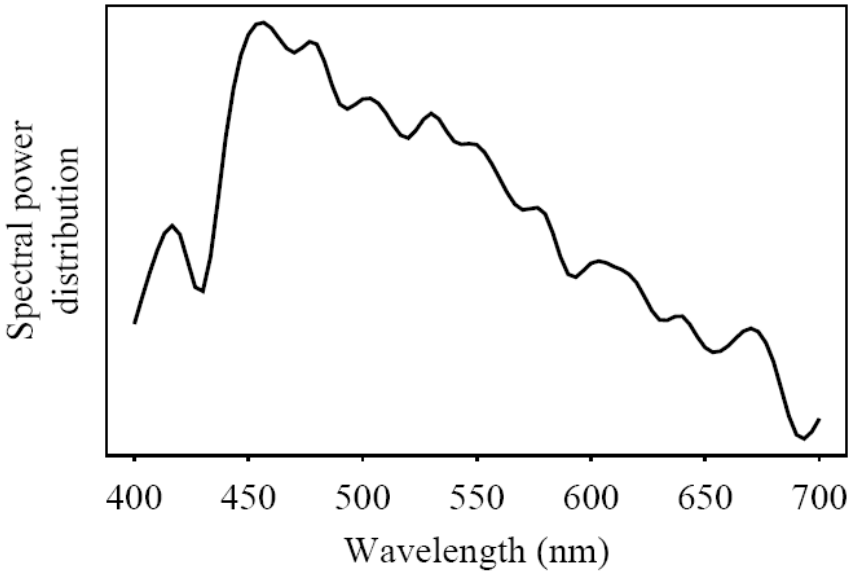


Fig. 3.4: Spectral power distribution of daylight.

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*.

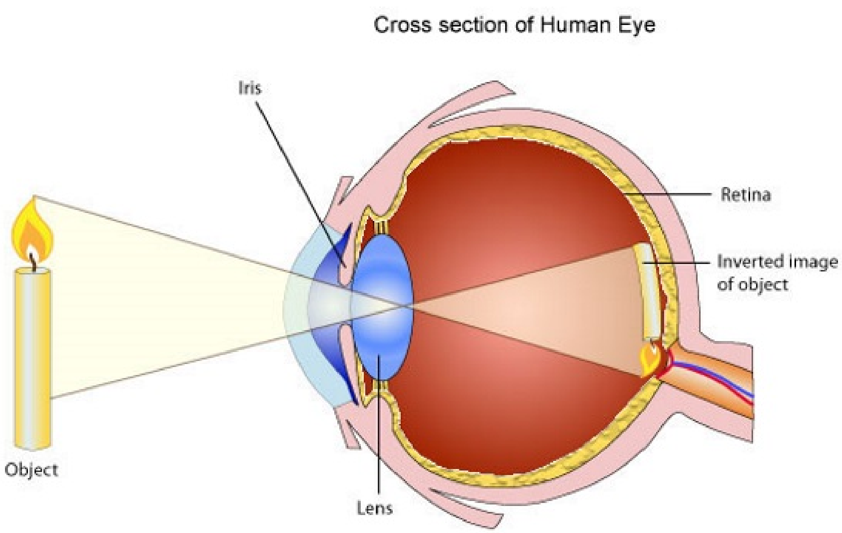


Fig. 3.4: Cross section of human eye

Human Vision

- The rods come into play when light levels are low and produce a 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.

- 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 image.

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 (Fig. 3.5 below).
- The Blue receptor sensitivity is not shown to scale because it is much smaller than the curves for Red or Green — Blue is a late addition, in evolution.
  - Statistically, Blue is the favorite color of humans, regardless of nationality — perhaps for this reason: Blue is a latecomer.
- Fig. 3.5 shows the overall sensitivity 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.

- The rod sensitivity curve looks like the luminous-efficiency function V (λ).

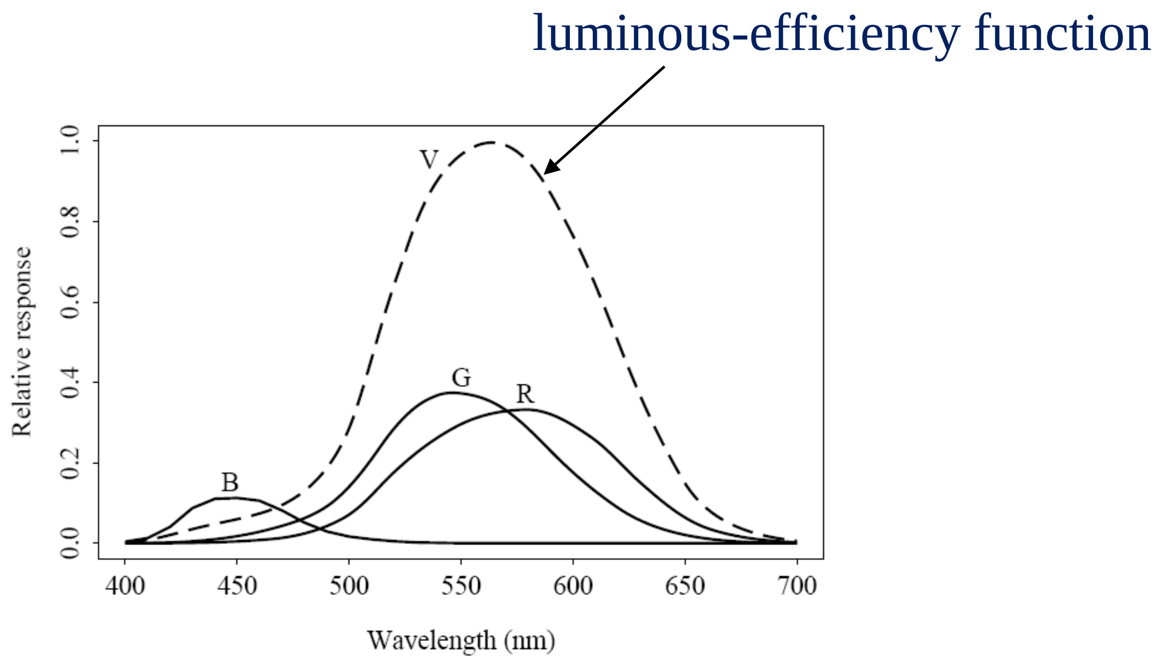


Fig. 3.5: Cone sensitivities: R, G and B cones, and Luminous Efficiency curve V(λ).

- These **spectral sensitivity functions** are usually denoted by letters other than "*R,G,B*"; here let's use a vector function $q(\lambda)$, with components

$$q(\lambda) = (q_R(\lambda), q_G(\lambda), q_B(\lambda))^T \qquad (3.1)$$

- 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 is a combination of single-frequency lights (like "lasers"), so we add up the light power for all wavelengths, weighted by the eye's relative response at that wavelength.

- We can succinctly write down this idea in the form of an integral
- Applied only when we view *self-luminous* objects

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

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

$$B = \int E(\lambda)\, q_B(\lambda)\, d\lambda \qquad (3.2)$$

SPD: Energy of light with wavelength Lamda

B cone sensitivity of light with wavelength Lamda

Image Formation

- Surfaces reflect different amounts of light at different wavelengths, and dark surfaces reflect less energy than light surfaces.

- Fig. 3.4 shows the surface spectral reflectance from (1) orange sneakers and (2) faded blue jeans. The reflectance function is denoted $S(\lambda)$.

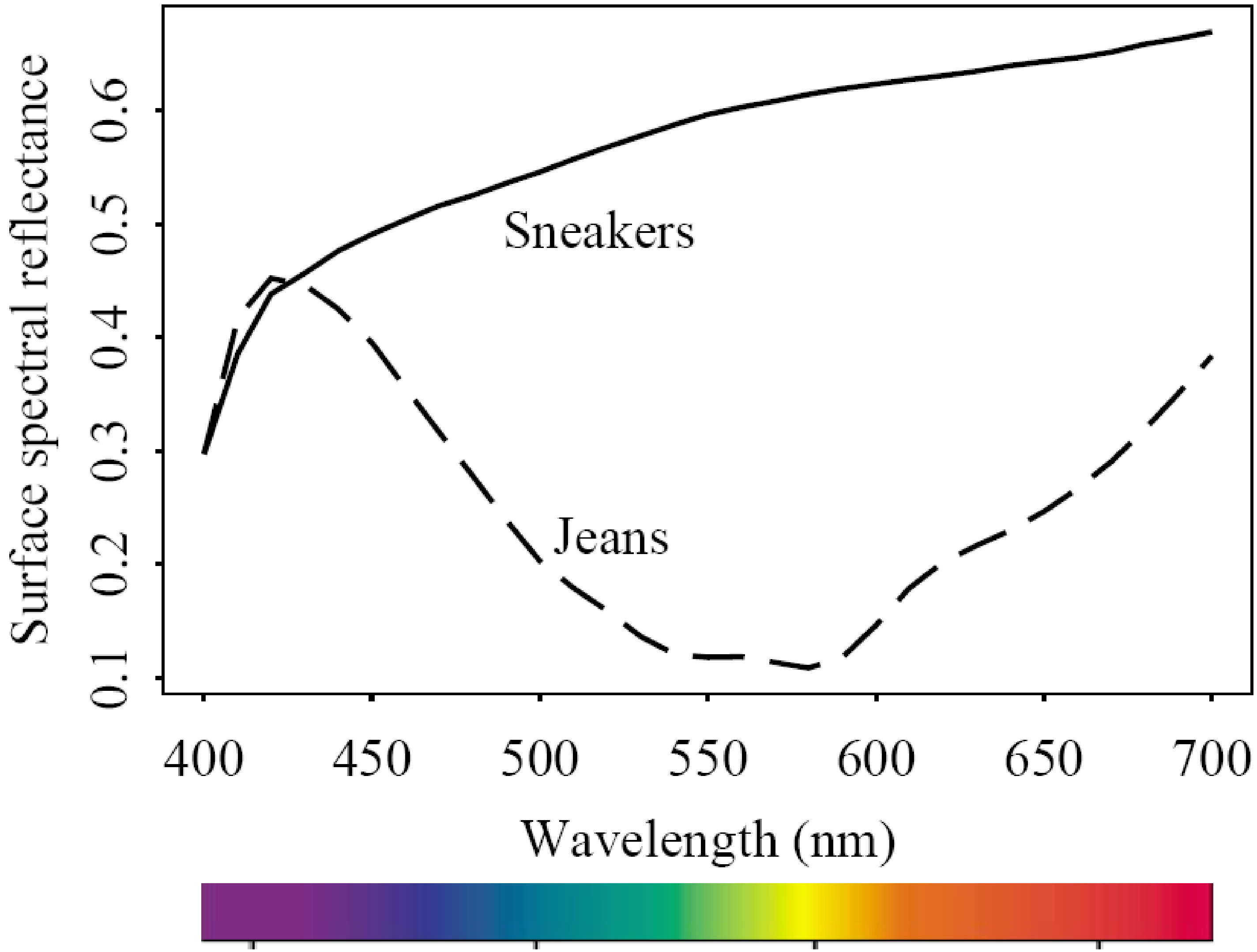


Fig. 3.6: Surface spectral reflectance functions S(λ) for objects.

- Image formation is thus:
  - Light from the illuminant with SPD $E(\lambda)$ impinges on a surface, with surface spectral reflectance function $S(\lambda)$, is reflected, and then is filtered by the eye's cone functions $q\ (\lambda)$.
  - Reflection is shown in Fig. 3.7 below.
  - The function $C(\lambda)$ is called the color signal and consists of the product of $E(\lambda)$, the illuminant, times $S(\lambda)$, the reflectance:

$$C(\lambda) = E(\lambda)\ S(\lambda).$$

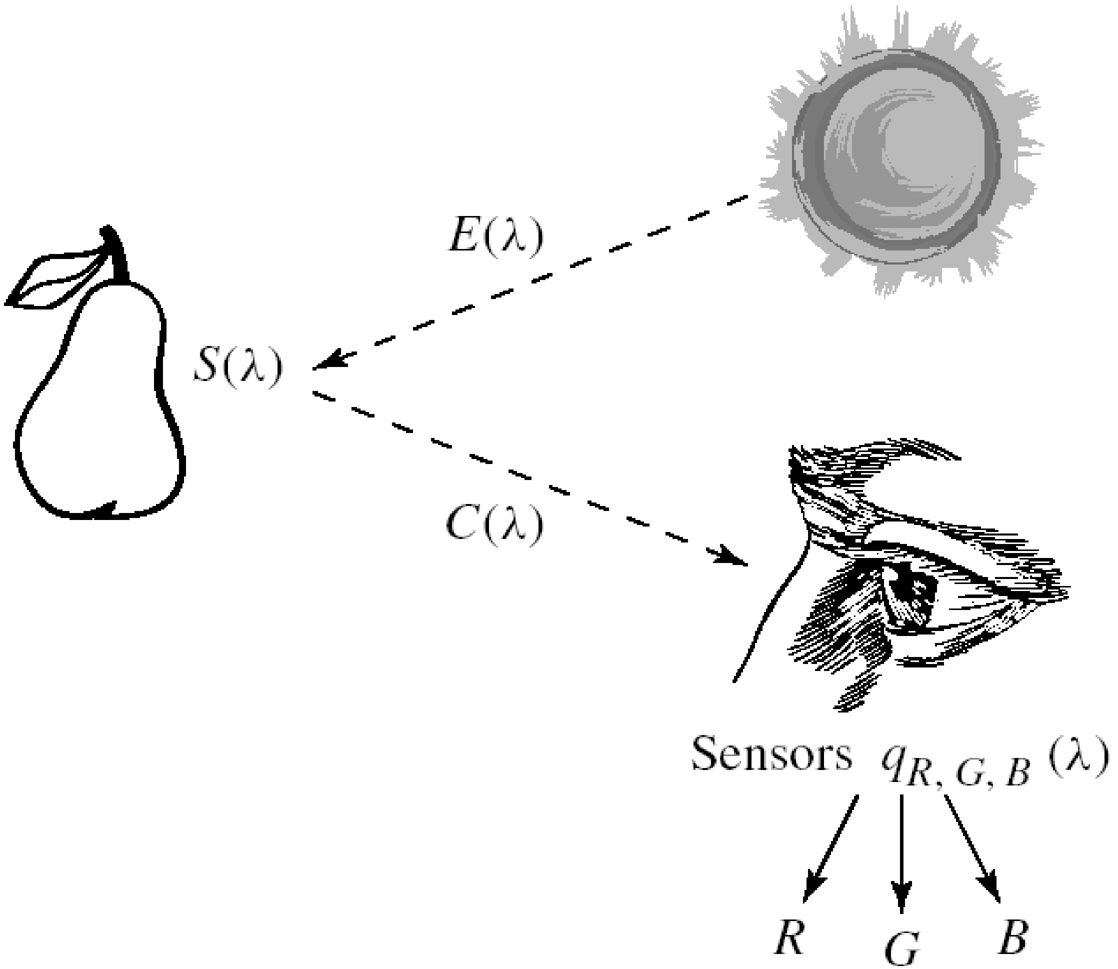


Fig. 3.7: Image formation model.

- The equations that take into account the image formation model are:

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

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

$$B = \int E(\lambda)\, S(\lambda)\, q_B(\lambda)\, d\lambda \qquad (3.3)$$

Color Models

- Color Space
  - A way of representing colors, usually three dimensional.
  - Examples: RGB, CMYK, HSB, HSL
- Color Models
  - A way of defining colors mathematically.
  - Examples: RGB, CMYK
- Color Gamut
  - A certain complete subset of colors.
  - Entire range of colors available for a particular devices

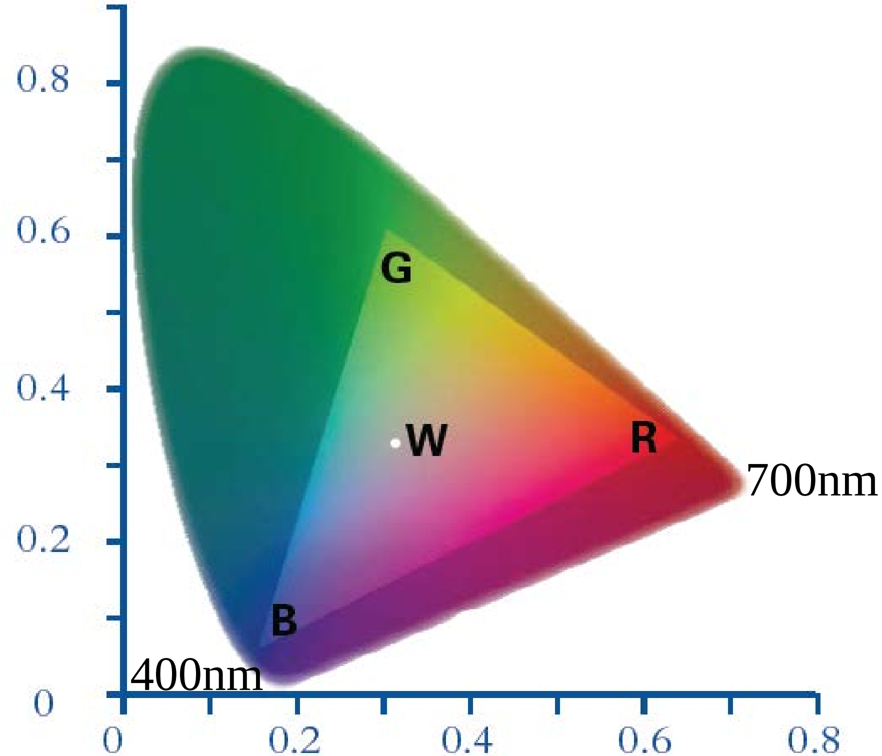
Two Major Types of Color Models

- Additive Color (adding light)
  - Describes the situation where color is created by mixing the visible light emitted from differently colored light sources.
  - Computer monitors and televisions are the most common form of additive light.

- Subtractive Color (subtracting light)
  - Light is removed from various part of the visible spectrum to create colors.
  - Used in paints and pigments and color filters.
    - Example: Subtracts blue from white illumination will reflects red and green, which is yellow.

RGB Color Model

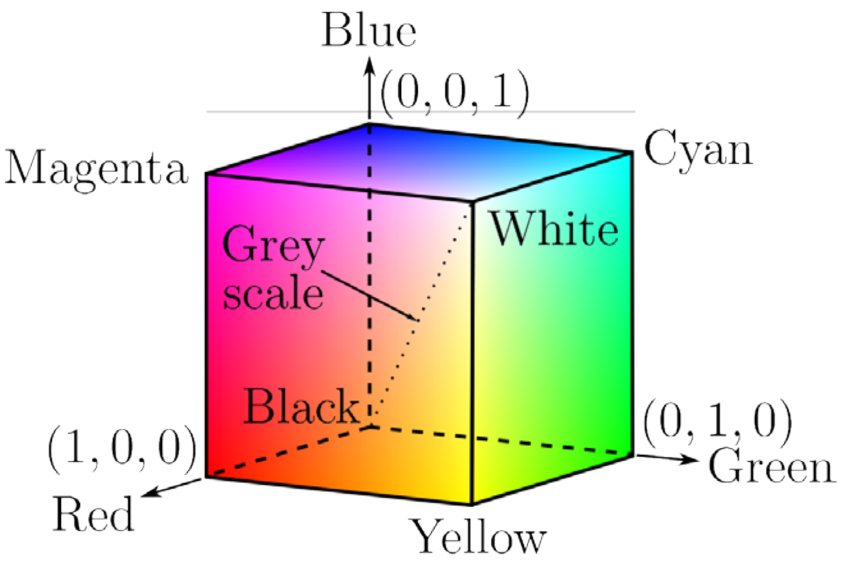
- The RGB color model is an additive primaries in which red, green, and blue light is added together in various ways to reproduce a broad array of colors.
- In RGB color, the three primaries are standard shades of red, green and blue.
- Only colors in the RGB gamut can be represented in this way.



The RGB colour gamut

RGB Color Model

- Any color is specified as three values (*R*, *G*, *B*) *giving the relative proportions of the three* primaries.
- This is often written as a 6-digit hexadecimal number, with *R*, *G and B each* being between 0 and 255, so a color value occupies 24 bits.



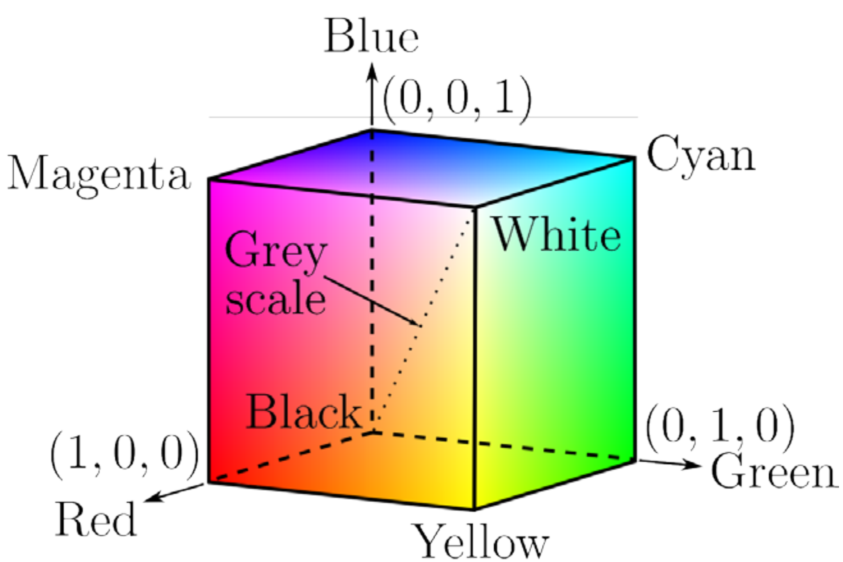
The RGB color space

- Each color is a triplet corresponding to R, G and B component.
- The color representation: (R,G,B)

e.g. Cyan (0,1,1)

- If R=G=B for all pixels in an image, it is a greyscale image.
- The RGB color space can be represented as a color cube.

Vertices are the primary (RGB) and secondary colours (CMY) plus black and white.



The RGB color space

RGB Color Model

- The number of bits used to store a color value – **the color depth** – determines how many different colors can be represented.
- The use of lower color depths leads to posterization and loss of image detail, but reduces file size.

A photograph in 24, 8 (top), 4 and 1 (bottom) bit colour

Detail of photograph in 24-bit (left) and 8-bit (right) colour

RGB Color Model

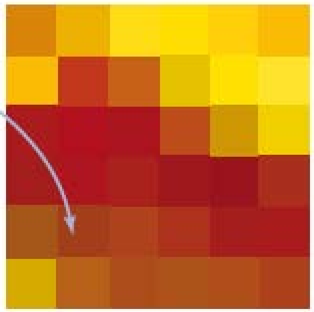
- In indexed color, instead of storing a 24-bit color value for each pixel, we use an 8-bit value which serves as an index into a color table.
- The color table contains the palette of colors used in the image.

1A	1C	20	21	1F	1E
0D	16	17	1B	22	23
0A	13	09	15	18	1D
03	10	08	01	00	07
05	02	11	0E	04	06
10	14	0B	0C	12	09

stored values

00	99141B
01	A0191C
02	A23E1A
03	A51B1C
04	A51D1C
05	A65619
06	A9191C
07	A92E1C
08	AB201C
09	AC111C
0A	AC191D
0B	AC4C1A
0C	AC5219
0D	AD111D
0E	AD331C
0F	AD401B
etc	

Colour Lookup Table

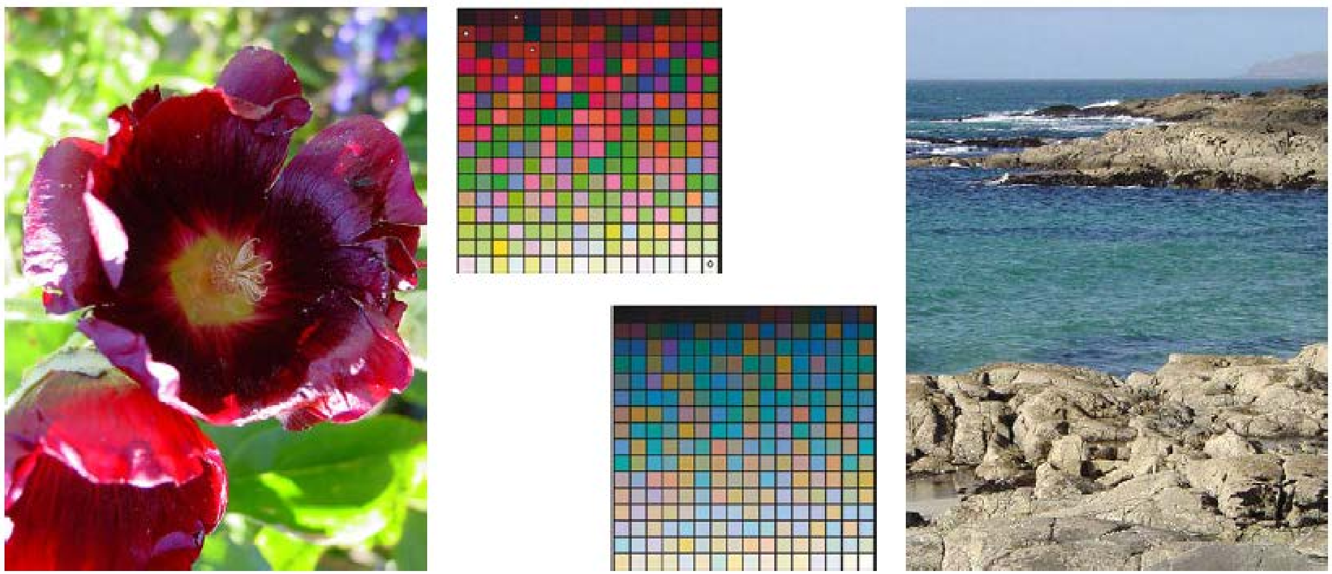


displayed pixels

Using a colour table

Indexed color in RGB model

- In indexed color, instead of storing a 24-bit color value for each pixel, we use an 8-bit value which serves as an index into a color table. The color table contains the palette of colors used in the image.

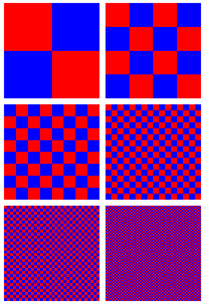


Images and their palettes

Indexed color in RGB model

Two approaches of displaying image with a reduced palette

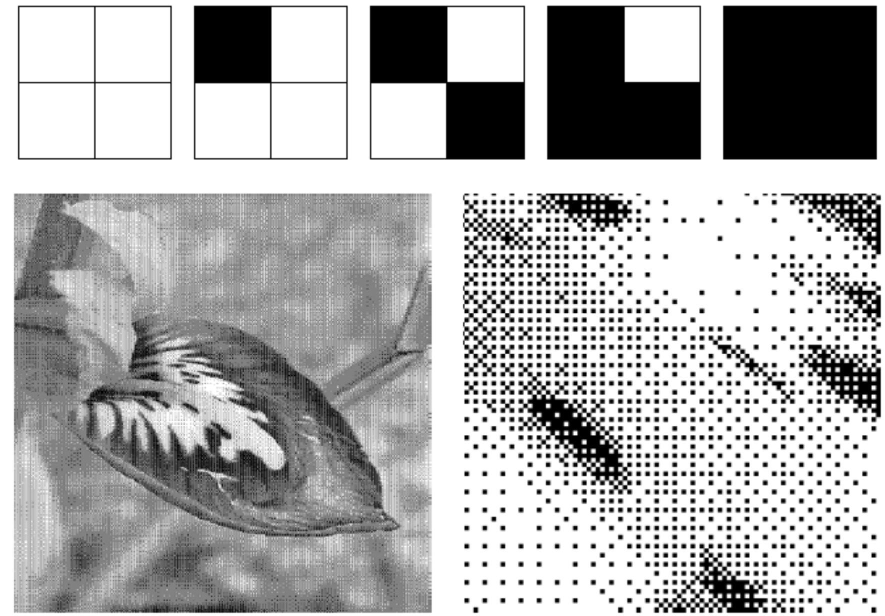
- Replace the colour value of each individual pixel with the color from the palette which is closest to it.
  - Can cause posterization
- Colour dithering
  - Areas of a single colour are replaced by a pattern of dots of several different colours, with the intention that optical mixing in the eye will produce the effect of a colour which is not really present.



RGB Color Model

- Some colors from the original image may be missing from the palette.

- Dithering can be used to reduce the resulting posterization.



Dithering in black and white

RGB Color Model

- Some colors from the original image may be missing from the palette. Dithering can be used to reduce the resulting posterization.

Dithering and posterization

Grayscale

- A grayscale image is an image in which the value of each pixel is a single sample, that is, it carries only intensity information. Images of this sort, are composed exclusively of shades of gray, varying from black at the weakest intensity to white at the strongest.
- Grayscale images are distinct from one-bit black-and-white images, which are images with only the two colors, black, and white. Grayscale images have many shades of gray in between.

Grayscale - Representation

- Grayscale images are often the result of measuring the intensity of light at each pixel in a single band of the electromagnetic spectrum (e.g. infrared, visible light, ultraviolet, etc.), and in such cases they are monochromatic proper when only a given frequency is captured. But also they can be synthesized from a full color image.

- The intensity of a pixel is expressed within a given range between a minimum and a maximum, inclusive. This range is represented in an abstract way as a range from 0 (total absence, black) and 1 (total presence, white), with any fractional values in between.

Grayscale - Representation

- Another convention is to employ percentages, so the scale is then from *0% to 100%*. This is used for a more intuitive approach, but if only integer values are used, the range encompasses a total of only *101* intensities, which are insufficient to represent a broad gradient of grays.

- In computing, although the grayscale can be computed through rational numbers, image pixels are stored in binary form. Today grayscale images intended for visual display are commonly stored with *8 bits per sampled pixel,* which allows 256 different intensities to be recorded, typically on a non-linear scale. The precision provided by this format is barely sufficient to avoid visible banding artifacts, but very convenient for programming due to a single pixel occupies a single byte.

Grayscale - Representation

- Technical uses often require more levels, to make full use of the sensor accuracy (typically *10 or 12 bits* per sample) and to guard against round-off errors in computations. Sixteen bits per sample (65,536 levels) is a convenient choice for such uses, as computers manage 16-bit words efficiently.

- The TIFF and the PNG (among other) image file formats supports 16-bit grayscale natively, although browsers and many imaging programs tend to ignore the low order 8 bits of each pixel.

- No matter what pixel depth is used, the binary representations assume that 0 is black and the maximum value (255 at 8 bit, 65,535 at 16 bit, etc.) is white, if not otherwise noted.

Grayscale - Conversion

- Conversion of a color image to grayscale is not unique.
- Different weighting of the color channels effectively represent the effect of shooting black-and-white film with different-colored photographic filters on the cameras.
- A common strategy is **to match the luminance of the grayscale image to the luminance of the color image**.
- To convert color image to a grayscale representation of its luminance
  - Step 1: Obtain the values of its red, green, and blue (RGB) primaries in linear intensity encoding.
  - Step 2:

$$30\%*R+59\%*G+11\%*B$$

Note: these weights depend on the exact choice of the RGB primaries, but are typical.

Or

$$(11*R + 16*G + 5*B) /32$$

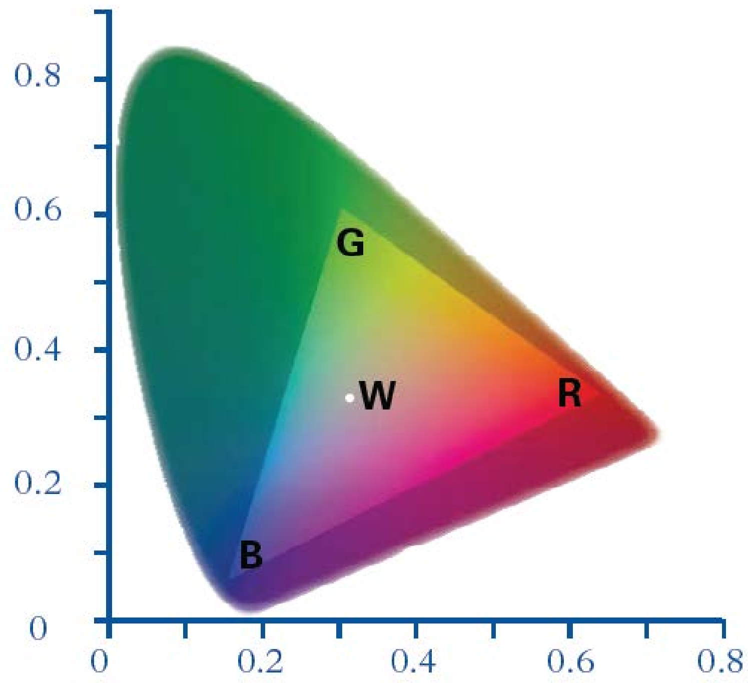
Note: The formula is also popular since it can be efficiently implemented using only integer operations.

Questions

1. Is it true that any colour can be produced by mixing red, green and blue light in variable proportions?
2. What are the colours correspond to the eight corners of the RGB colour space cube?
3. Explain the process of how the image of a non-luminous object is formed in the human eyes and what factors will influence the image formation process?

Solutions

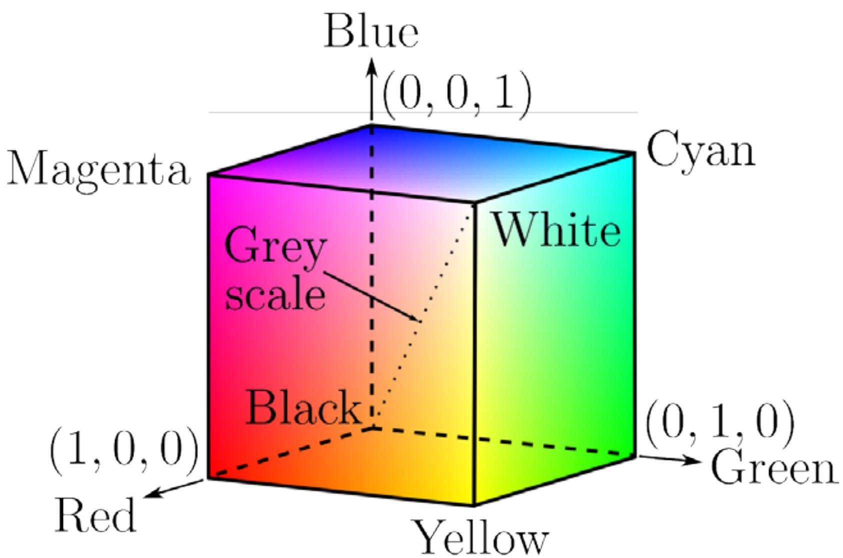
1. No, not all the colors can be represented by mixing Red, Green and Blue. There are colours outside the RGB gamut.



The RGB colour gamut

Solutions

2. Red, green and blue, where the cube intersects the R, G and B axes, respectively. Cyan, magenta and yellow at the corners opposite their respective complements. Black at the origin and white at the remaining corner.



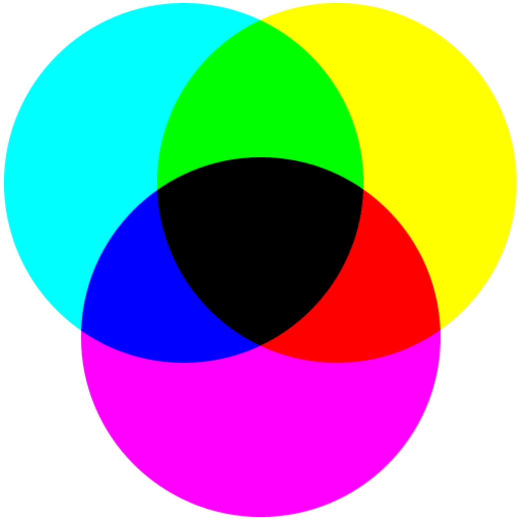
Solutions

3. The process:
   1. Light from a light source with SPD $\mathrm{E}(\lambda)$impinges on a surface of a object. SPD describes the power carried by each wavelength.
   2. The surface reflects different amounts of light at different wavelengths which is described by the surface spectral reflectance $\mathrm{S}(\lambda)$
   3. The reflected light goes into the human eyes and is filtered by the eyes' cone function $\boldsymbol{q}(\lambda) = [q_R(\lambda), q_G(\lambda), q_B(\lambda)]$.
   - The influence factors are: $\mathrm{E}(\lambda)$, $\mathrm{S}(\lambda)$, $\boldsymbol{q}(\lambda)$.

CMYK Color Model

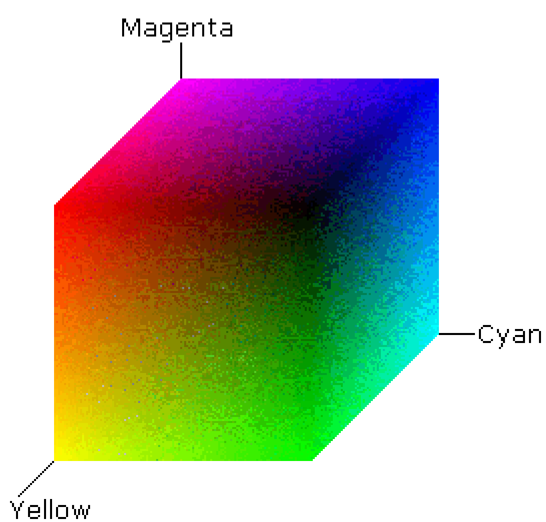
- A **subtractive** color model, used in color printing.
- Cyan, Magenta and Yellow are the subtractive primaries.
- CMYK refers to the four inks used in some color printing:

  cyan, magenta, yellow, and key (black).



CMYK Color Model

- The "K" in CMYK stands for *key* since in four-color printing cyan, magenta, and yellow printing plates are carefully keyed or aligned with the black key plate.
- The CMYK color space is related to the RGB color space by being the inverse of it.
  - White(0,0,0) and Black (1,1,1) and the primary axes of the coordinate system are cyan, yellow, and magenta.



The CMYK color space

CMYK Color Model

Since in this color space:

C =G+B=W-R

M=R+B=W-G

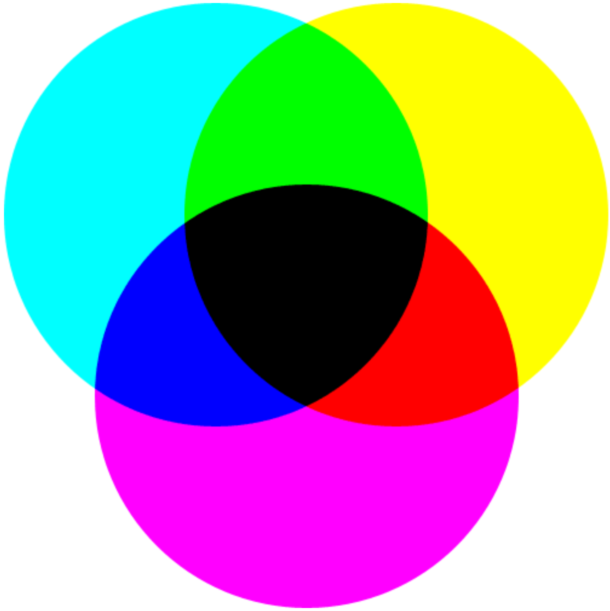
Y =R+G=W-B

+ means additive mixing of light

- subtraction of light

The complementary colors are:

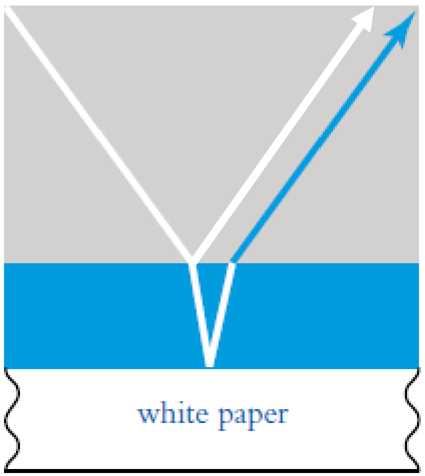
C	<->	R
M	<->	G
Y	<->	B



CMYK Color Model

Two situations when light shine out on a colored surface:

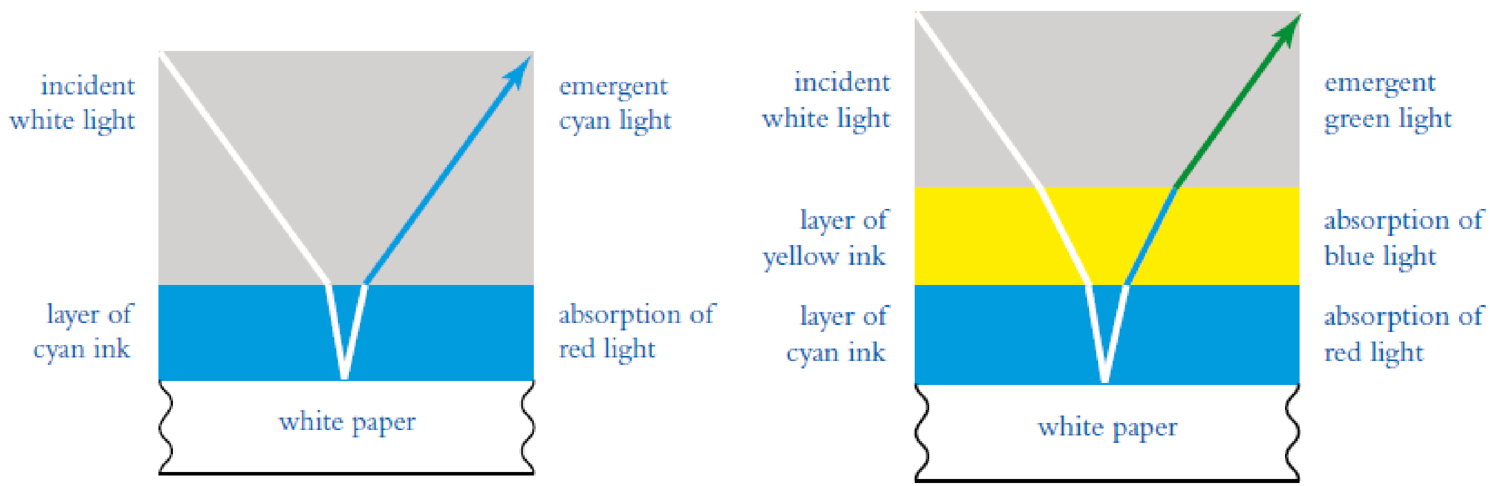
1. The light that is reflected from a colored surface is not changed in color.
2. The light that penetrates through a colored surface will be reflected or scattered back from beneath it. During the light's journey through the particles of dye, ink or paint, the pigments absorb light at some frequencies. The light that emerges thus appears to be colored.



CMYK Color Model

- Thin layers of ink absorb some components of the incident light, so overlaying ink, as in printing processes, mixes colors subtractively.
- Cyan ink absorbs red from incident white light but reflects blue and green which becomes Cyan.

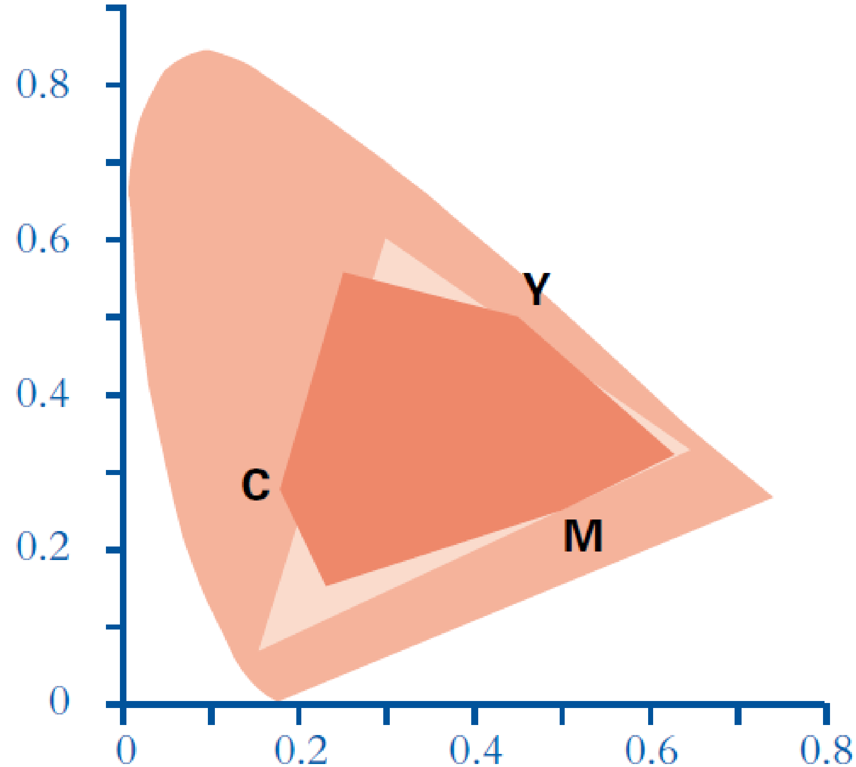
Cyan + Yellow → Green   Magenta + Cyan → Blue   Yellow + Magenta → Red



Coloured inks

CMYK Color Model

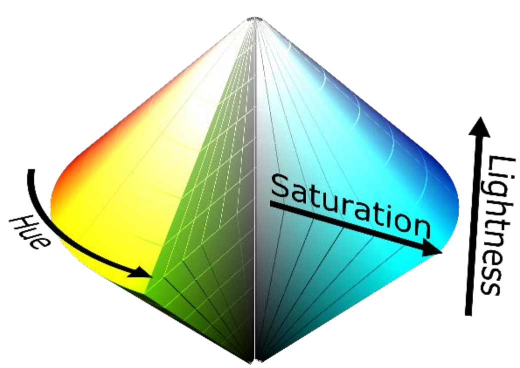
- The CMYK color gamut, corresponding to easily printable colors, is smaller than the RGB gamut, but some CMYK colors lie outside the RGB gamut.

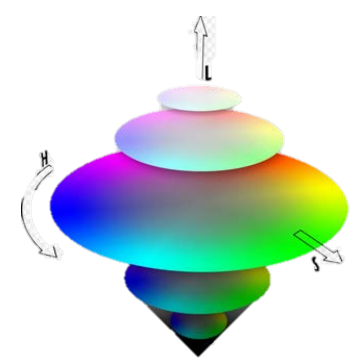


The CMYK gamut

HSL Color Space

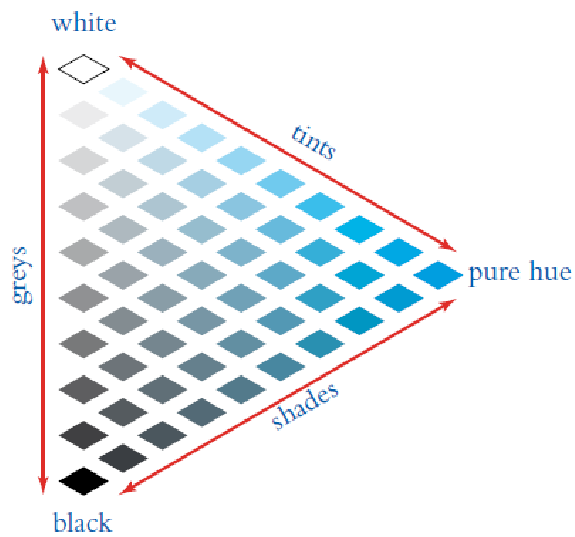
- A color can be identified by its hue, saturation and lightness (H,S and L).
- Hue is the particular wavelength at which the energy of the light is concentrated. (Hue is the pure color of light).
- Saturation describes the purity of the hue.
- Lightness describes how much light is put into the Hue.



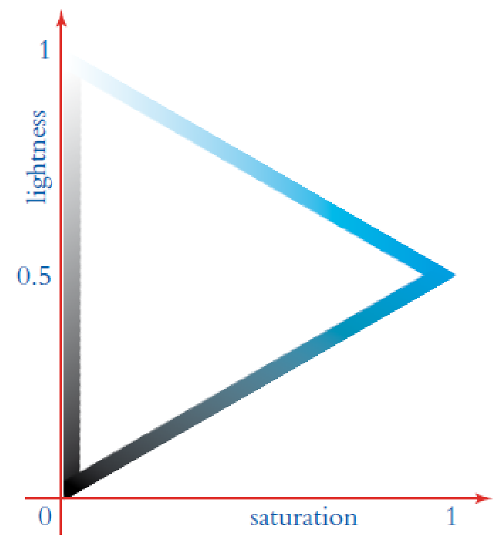


HSL Color Space

- Tones of a single hue can be arranged two-dimensionally, with lightness increasing upwards, and saturation increasing from left to right.



Tints, shades and tones



Saturation and lightness

HSL Color Space

- Hues can be arranged around the rim of a color wheel, with complementary colors opposite each other. A hue's value is the angle between its position on the wheel and the position of red.
- Saturation can be added to the model by filling in the circle, putting 50% grey at the centre of the circle, and then showing a gradation of tints from the saturated hues on the perimeter to the neutral grey at the centre

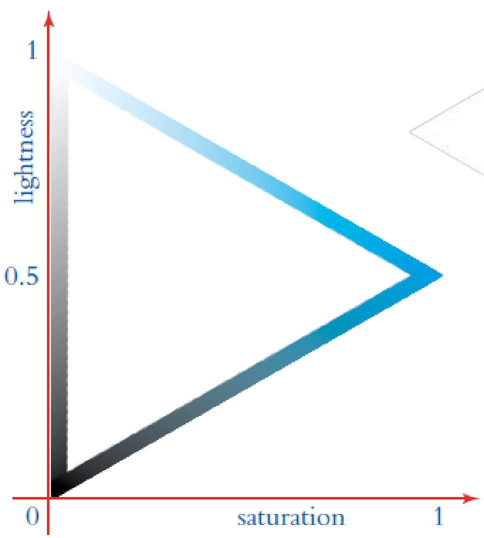
A colour wheel

Hue only


Filling the colour wheel

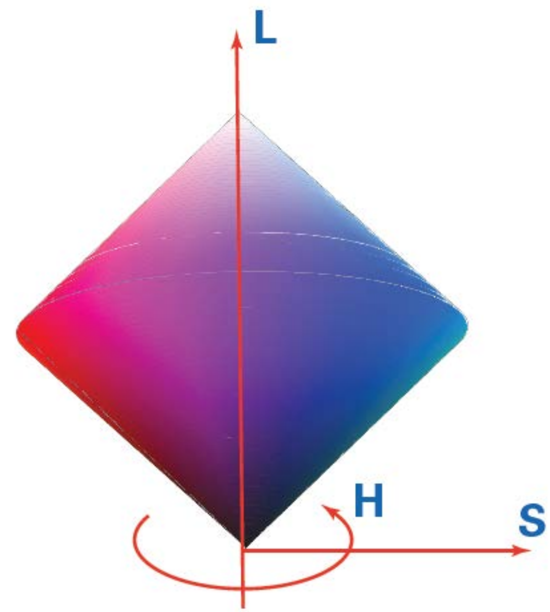
Hue+Saturation

HSL Color Space



Lightness + Saturation

Hue + Saturation

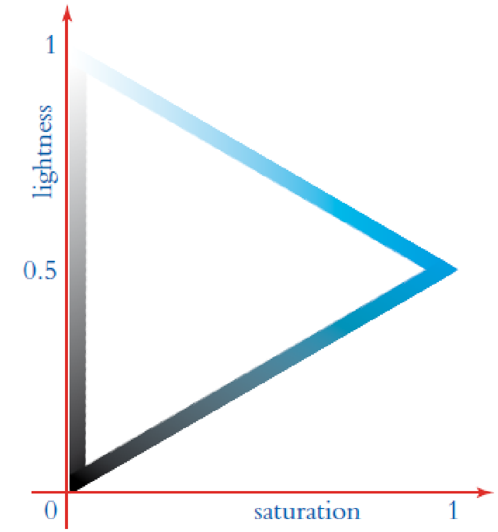


The HSL colour solid

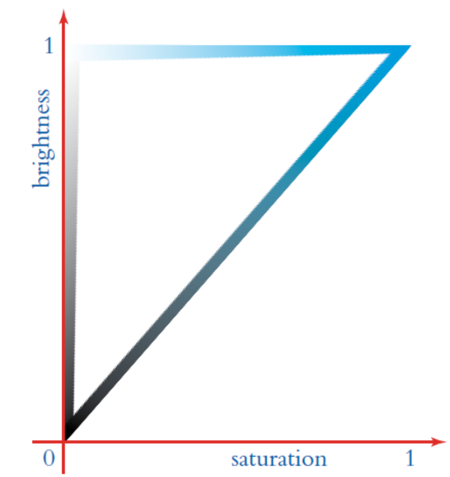
Hue + Saturation + Lightness

HSL Color Space

- Hue, saturation and lightness can be combined into a three-dimensional double cone. Any components color can be specified by its H, S and L.
- HSB is a variant of HSL, where the tones are arranged differently.
  - HSB is equivalent to HSV (brightness is called value sometimes)
  - Different from HSL assigning a lightness of 0.5 to pure hues, HSB gives pure hues a brightness value of 1.
  - Its shape is an inverted cone.



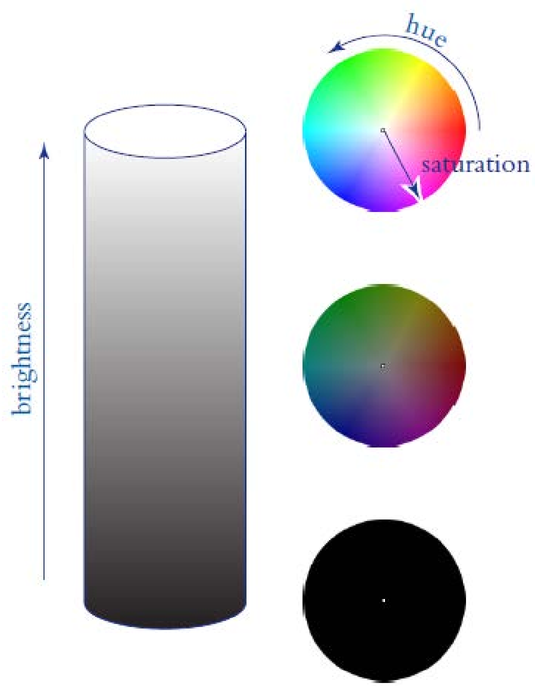
Saturation and lightness



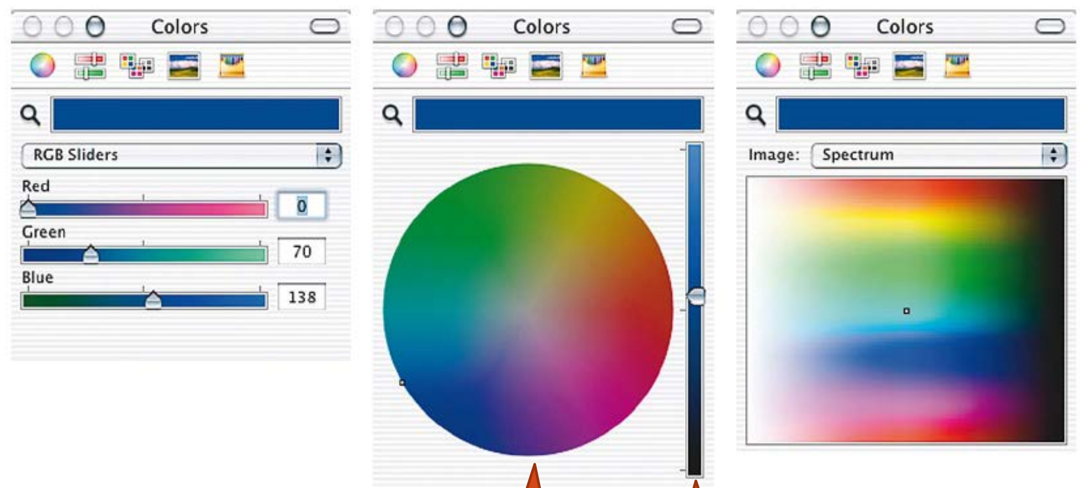
Saturation and brightness

HSL Color Space

- Both HSL and HSB are normally distorted into a cylindrical shape, so that they can be presented as color pickers.



The HSB cylinder



Colour pickers

Corresponding slice through the cylinder

Brightness

Models – Device Independence

- Different monitors provide different red, green and blue.
- Most color models suffers from not being *perceptually uniform*.
- Perceptually uniform:
  - The same change in one of the RGB values produce the same change in appearance, no matter what the original value is.
  - Difference between two colors (as perceived by the human eye) is proportional to the Euclidian distance within the given color space.
- CIE L*a*b* and L*u*v* color spaces are perceptually uniform and serve as device-independent reference models.

- Far away from mature!!!

Channels and Color Corrections

- The R, G and B components of each pixel can be stored as separate values.
- The three arrays of values can be treated as grayscale images, called channels.

An RGB colour image and its red, green and blue channels

The lightness represents the intensity of the corresponding color on a channel.

Red cherry appears white in Red channel and appears black in Green and Blue channels.

Channels and Color Corrections

- Each channel can be manipulated separately.

  In particular, levels and curves can be used to alter the brightness and contrast of each channel independently.

Correcting and over-correcting a colour cast

Channels and Color Corrections

Hue and saturation adjustments

- Adjustments to hue and saturation alters the colors of the image.

Channels and Color Corrections

- The color balance, hue and saturation and color replacement adjustments change the color of the image as a whole.
- Figure shows a repainted house door using the color replacement setting.

Colour replacement

Further Exploration

"Further Exploration" directory on http://www.cs.sfu.ca/mmbook/ include:

– More details on gamma correction

– The full specification of the new sRGB standard color space for WWW applications.

– A link to an excellent review of color transforms.

– A Matlab script to exercise (and expand upon) the color transform functions that are part of the Image Toolbox in Matlab: the standard 'Lena' image is transformed to YIQ and to YCbCr.

– The new MPEG standard, MPEG-7, includes six color spaces.