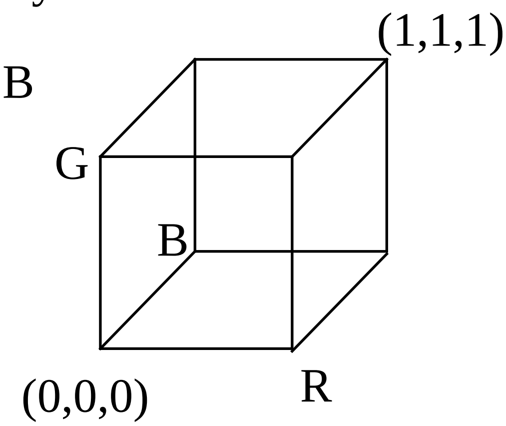
Color

Color

How to represent color images?

How display?

R G B



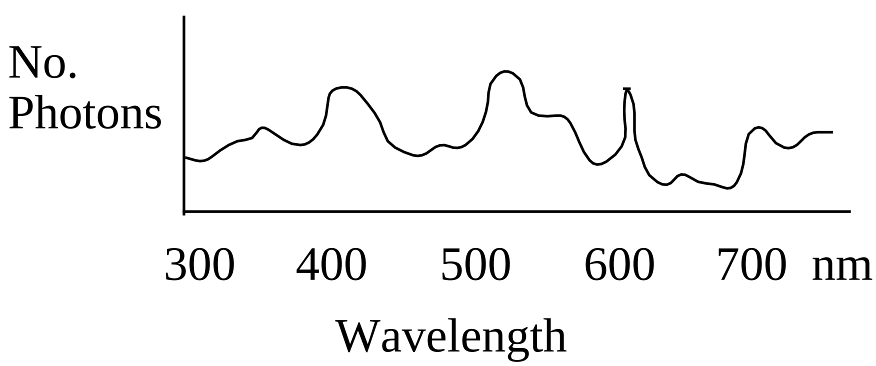
Normalized
RGB
Color
Space

Contains all displayable colors

Where are the grays?

Hard to use to conceptualize colors

What are the physical correlates of color?

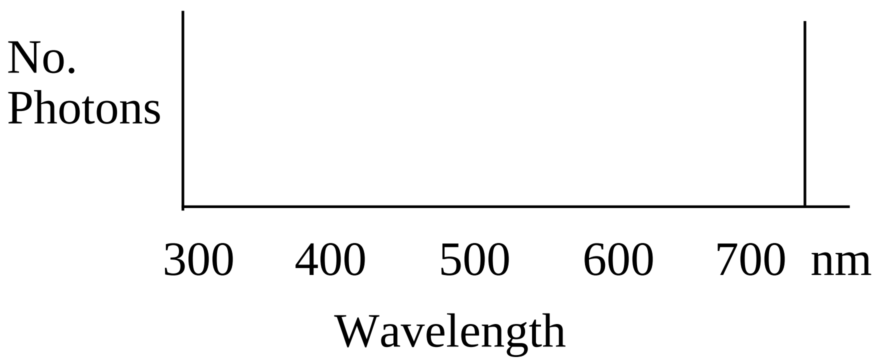


Monochromatic Light

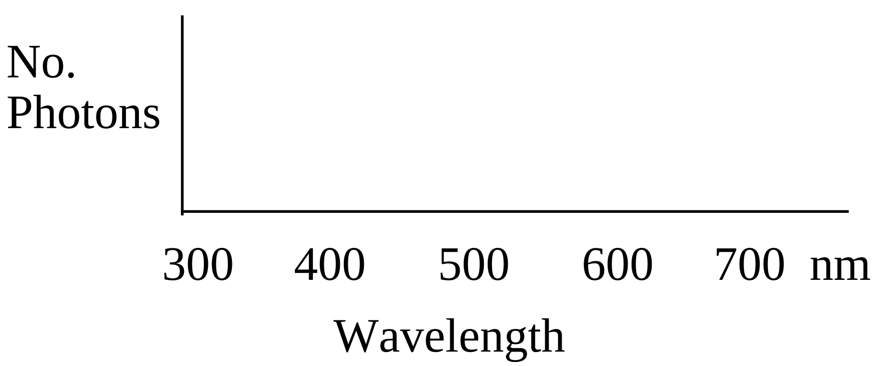
Simple correlation between wavelength and color

Blue - 360 nm

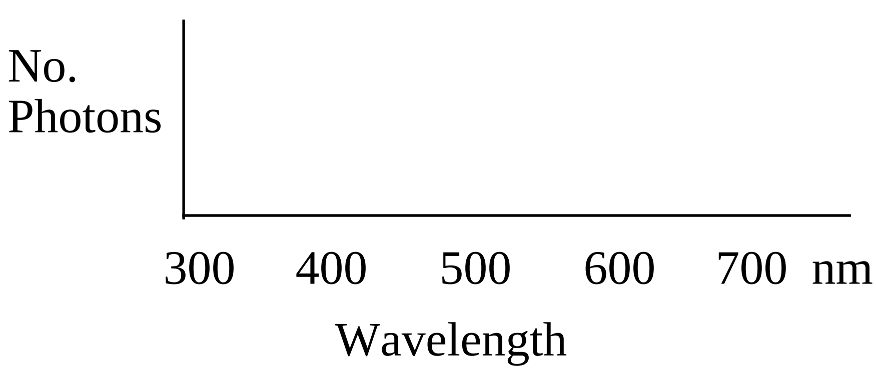
Red - 780 nm



Black ?



White ?



Colors are cognitive concepts

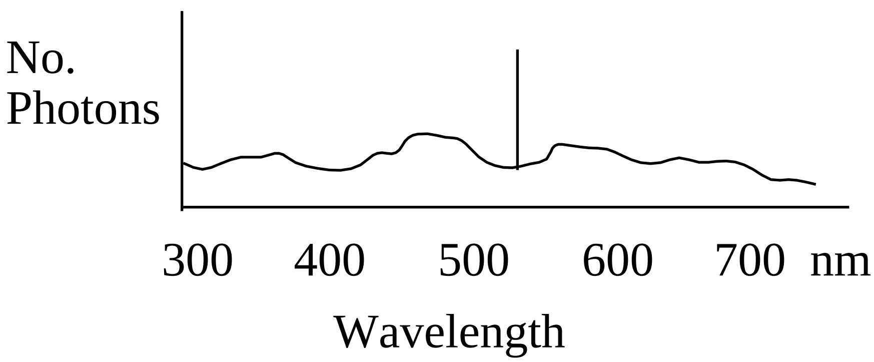
By definition we must look at human perception to understand color

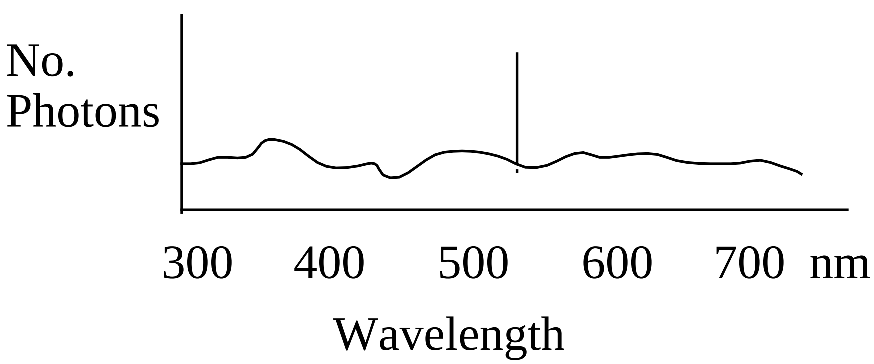
Is there a unique perception for each unique spectral signal?

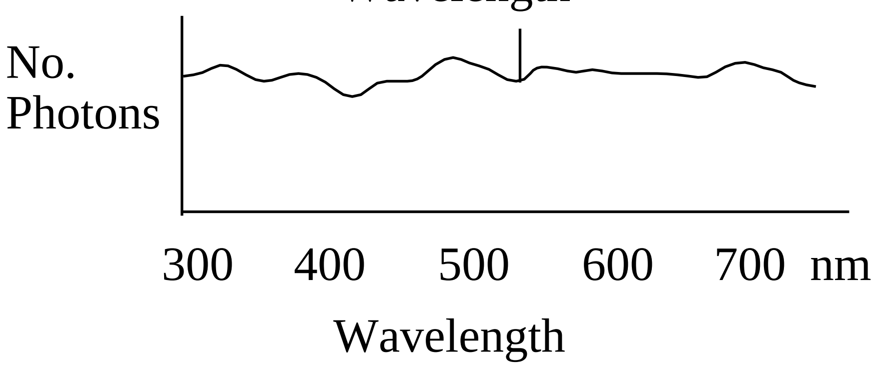
No

Metemers are different spectral signals that are perceived as being identical by humans

Generally a spectral signal containing a single large spike is perceived as having the hue associated with the wavelength of the spike







Achromatic Light

Black and white, grey-scale

How select intensities

Use scale of 0 to 1 to represent black to white

If can only represent (n +1) intensities
e.g. 8 intensities (3 bits/pixel in frame buffer)

How select which 8 intensities?

a) regularly spaced from 0 to 1?

No - human brightness perception is on a log scale

The difference in perceived brightness of two patches:
0.8 versus 0.4 = 0.4 versus 0.2

b) logarithmic spacing
let I_0 be the lowest possible intensity

let r be the multiplicative factor for each intensity step
$I_1 = r I_0$, $I_2 = r I_1$, etc.

for $0 <= j < 2^k$, where k = number of bits/pixel

$m = 2^k - 1$

$I_j = r^j I_0$

$r = (1/I_0)^{1/m}$

Ratio between minimum and maximum intensity
is the dynamic range

Problems with nonlinearities in CRT and in film
overcome with gamma corrections in the LUT

How many intensities are enough?

What value of n?

Depends on dynamic range of display device

Depends on dynamic range of eye

Depends on how small a step in intensity the eye can "see"
if r = 1.01 or less, then at the eye's maximum sensitivity

$1/I_0$ is the dynamic range of a device

$n = \log_{1.01}(1/I_0)$

e.g. CRT dynamic ranges of 50 to 200
gives values on n of 400-530

photographic slides - 1000
gives n of 700

B/W newsprint - 10
gives n of 234

Halftoning

Increase the dynamic range of a media, at the price of spatial resolution

Print dot for each pixel

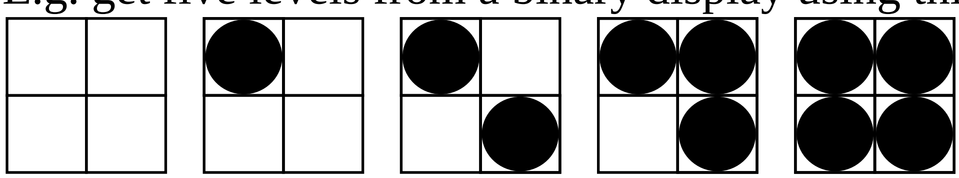
size of dot is function of pixel's intensity

(see figure)

Approximate halftoning

Use a set of display pixels for each image pixel

E.g. get five levels from a binary display using this:



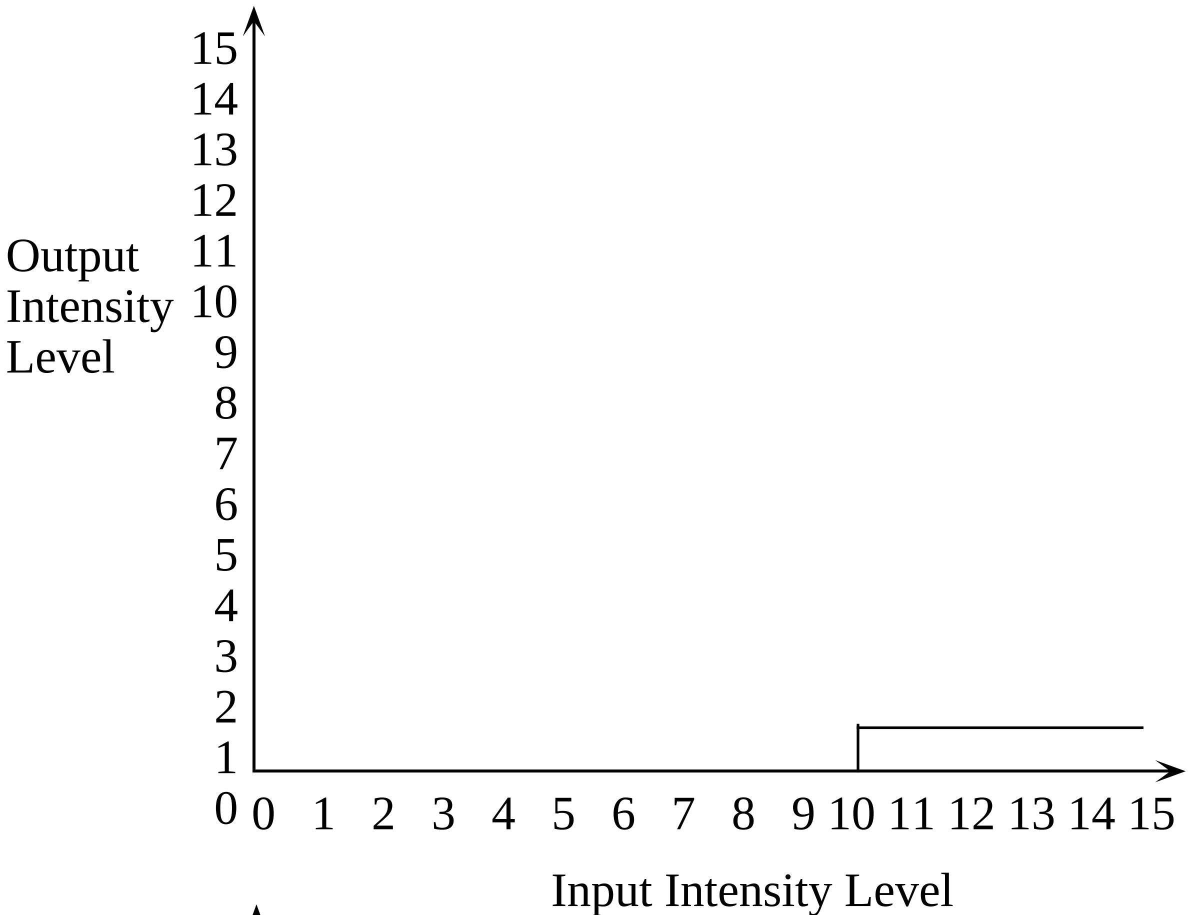
For an n by n group of display pixels,
how many intensity levels are possible?

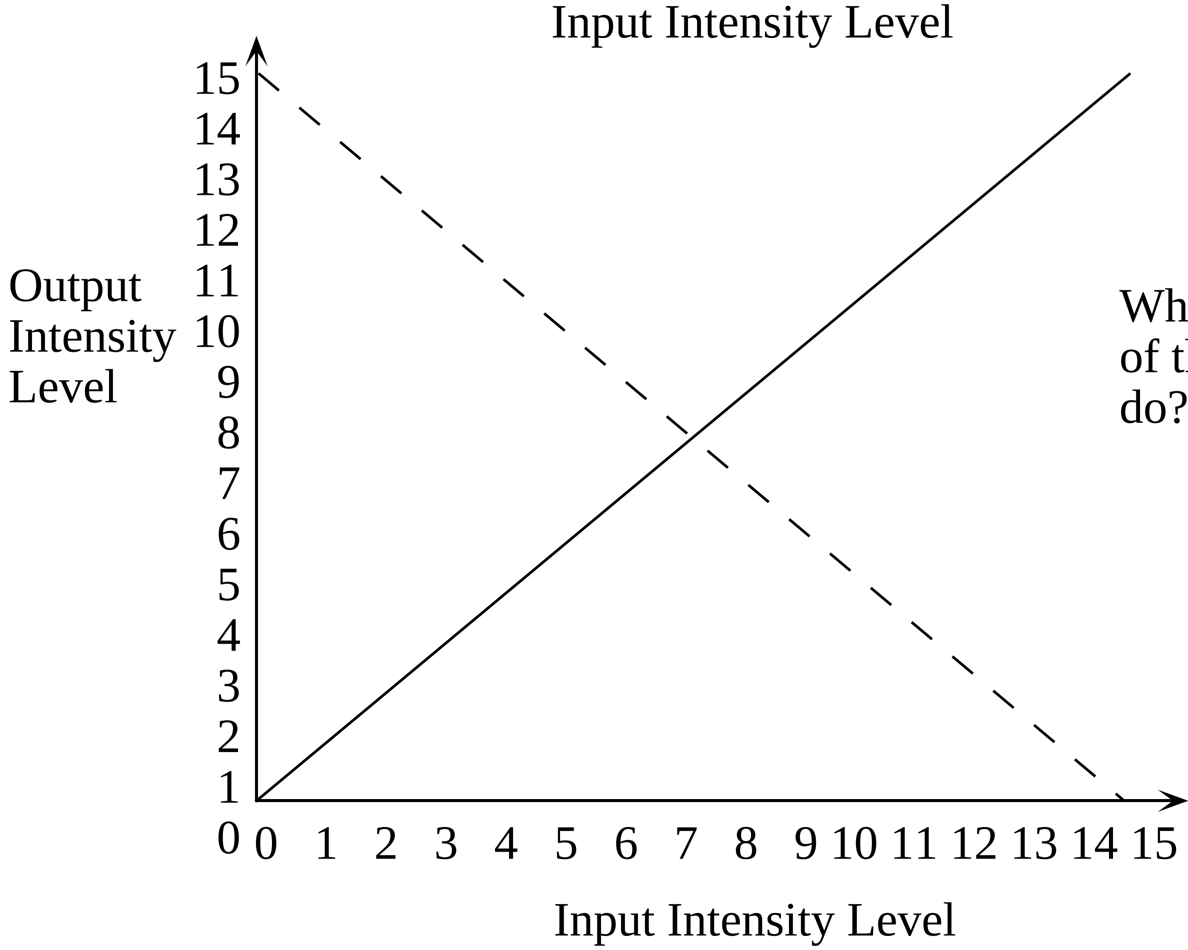
$n^2 + 1$

Can extend to multilevel displays to increase their intensity resolution

Must have more output pixels than image pixels for this technique

Look-up Tables (LUT)





What do each of these LUT's do?

Achromatic perception is scene dependent

Experiments

Land set up scene with varying luminance, varying reflectances

Dark grey card in brightest spot
Light grey card in darkest spot
Medium grey card in middle illumination

Carefully set up so that brightness from each card the same

Question: How would observers perceive the reflectances?

Related experiment by Mach

white card folded and illuminated from the side

perceived as being white and folded if viewed binocularly

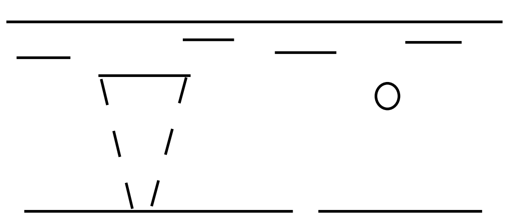
can make grey and white flat figure be perceived as white
when viewed monocularly through a peephole

Related experiment

room illuminated by one visible dim light bulb
viewed monocularly through a peephole

black circle illuminated by a bright hidden spotlight

circle perceived as white



Conclusion?

Chromatic Color

How get the same colors on different output devices?

Compare patches of color

For reflected light - compare using standard lighting

Standards used:

Munsell color chips

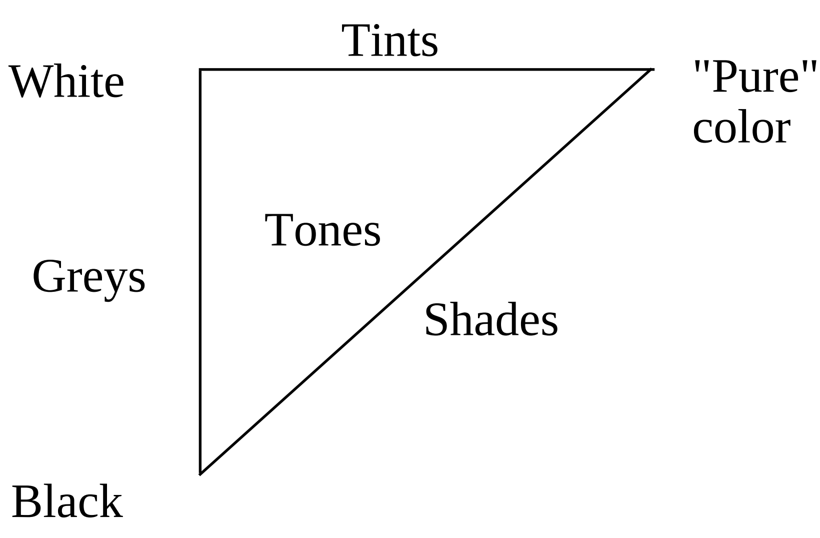
Hue, value, saturation space

named colors are equal perceived distances apart

PANTONE MATCHING SYSTEM

How specify colors?

Tints, shades and tones



Human color perception

Human psychophysics

Sensitivity of cones

- (see figure)
- Not really R, G, B
- Now say long, medium and short wavelength
- Tristimulus color theory
  - colors perceived based on sensitivity of the three cone types
  - get different colors by adding together different amounts of the three primaries

Luminous sensitivity

- (see figure)
- basically sum of the three cone sensitivity functions

Color matching functions

- How produce a given color by combining the three primaries
- (see figure)
- Note negative values of "red"
- By adding RGB can't get all perceivable colors

Color Spaces

Colors can be represented using any three linearly independent

primaries

Eg RGB, Hue Brightness and Saturation

How convert between spaces?

Matrix multiplication of the primaries (see table)

Can all spaces represent all colors?

No

For example, a color monitor cannot display all perceivable colors

Use chromaticity diagrams to understand this

P_k(lamda), k = 1, 2, 3, are the primary sources of light

$T_k(C) = b_k / w_k$, C is a color, w_k is the amount of the kth primary needed to produce white light, b_k is the amount of the kth primary needed to produce color C

$T_k(C)$ are called the tristimulus values of the color C

$t_k = (T_k) / (T_1 + T_2 + T_3)$, k = 1, 2, 3

t_k are the chromaticities of a color

$t_1 + t_2 + t_3 = 1$, thus only need to use two

use to take 3-D color space to a 2-D space

CIE Chromaticity Diagrams

- CIE defined three primaries that could be added to get all colors
  - (see figure)
  - X, Y, Z
- Color matching with X, Y, Z
  - (see figure)
- Y is defined to represent luminance
- Get 3-D X, Y, Z Color space
  - (see figure)
- 2-D Chromiticity Diagrams
  - (see figure)
  - only valid for one luminance
    - get different colors with different luminances
    - (e.g. brown only at low luminances)
  - "white" in center (approximates sunlight)
  - Hues around the perimeter of perceivable area
    - Line of purples - nonspectral colors
    - Dominant wavelength - line from white through color

Complementary colors

Along line on other side of white

Define dominant wavelength of nonspectral colors by the

wavelength of it's complement

Color Gamuts

Mix two colors and get colors lying on line between them

Mix three colors and get colors lying in triangle between them

See that can't mix visible red, blue and green to get all colors

When want to shade colored scenes

want to interpolate between two colors

result depends upon the color space being used

Use CIE Chromitity Diagrams to specify color ability of graphics devices

Perceptual Color Space

Uses dimensions which make sense to humans

Brightness
Perceptual luminance

Hue
"redness", "greeness", etc.
For monochromatic light, corresponds to wavelength
Dominant wavelength

Saturation
the aspect of perception that varies most strongly when white light is added to monochromatic light
Excitation purity