Color

CS 554 – Computer Vision

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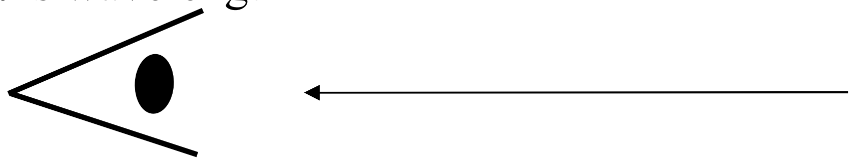
What is light?

- Electromagnetic radiation (EMR) moving along rays in space
  - R(λ) is EMR, measured in units of power (watts)
    - λ is wavelength

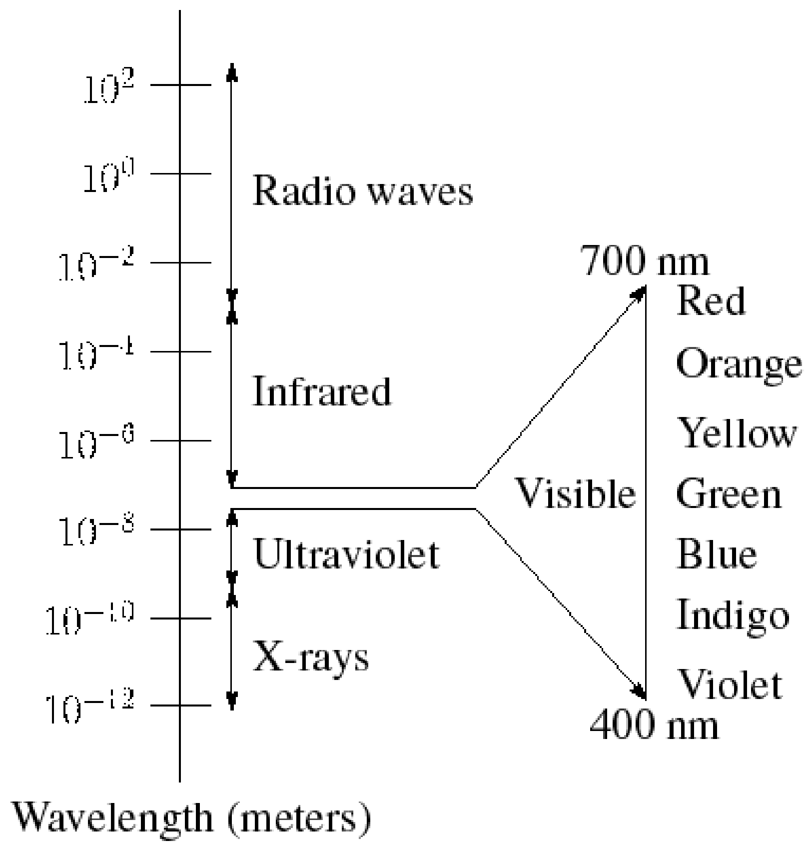


- Perceiving light
  - How do we convert radiation into “color”?
  - What part of the spectrum do we see?

Adapted from Seitz

The visible light spectrum

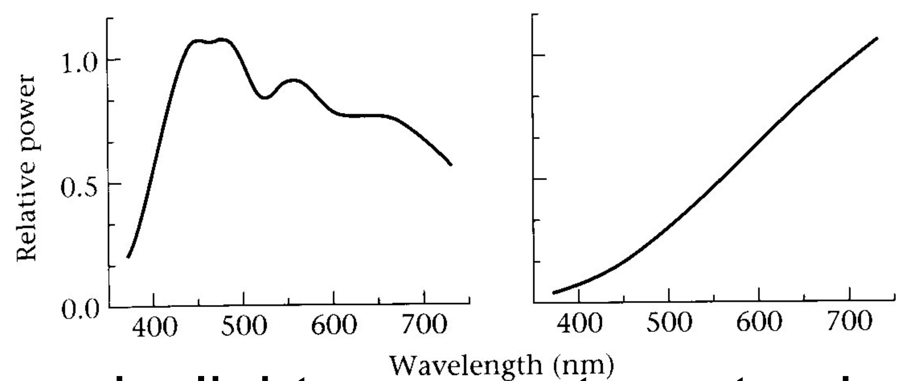
- We “see” electromagnetic radiation in a range of wavelengths



Adapted from Seitz

Light spectrum

- The appearance of light depends on its power **spectrum**
  - How much power (or energy) at each wavelength

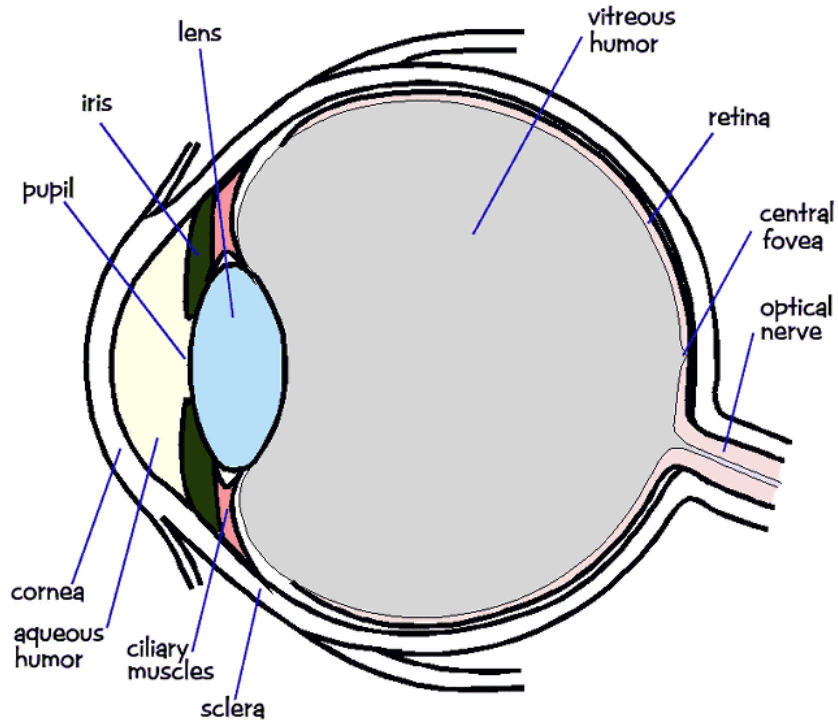


daylight tungsten bulb

- Our visual system converts a light spectrum into "color"
  - This is a rather complex transformation

Adapted from Seitz

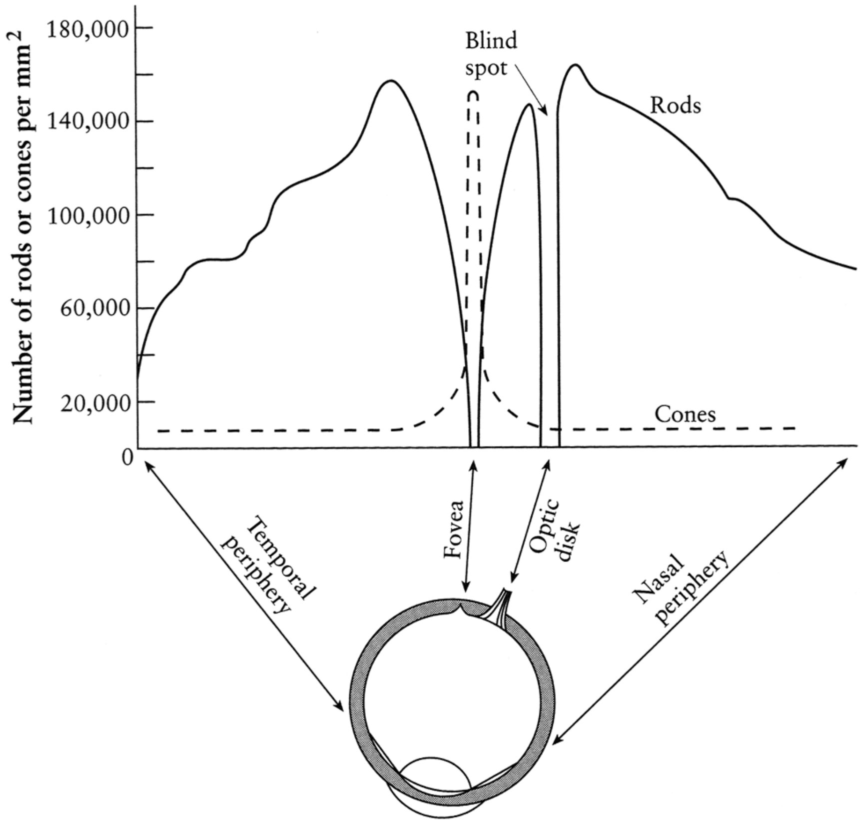
The human visual system



- Color perception
  - Light hits the retina, which contains photosensitive cells
    - rods and cones
  - These cells convert the spectrum into a few discrete values

Adapted from Seitz

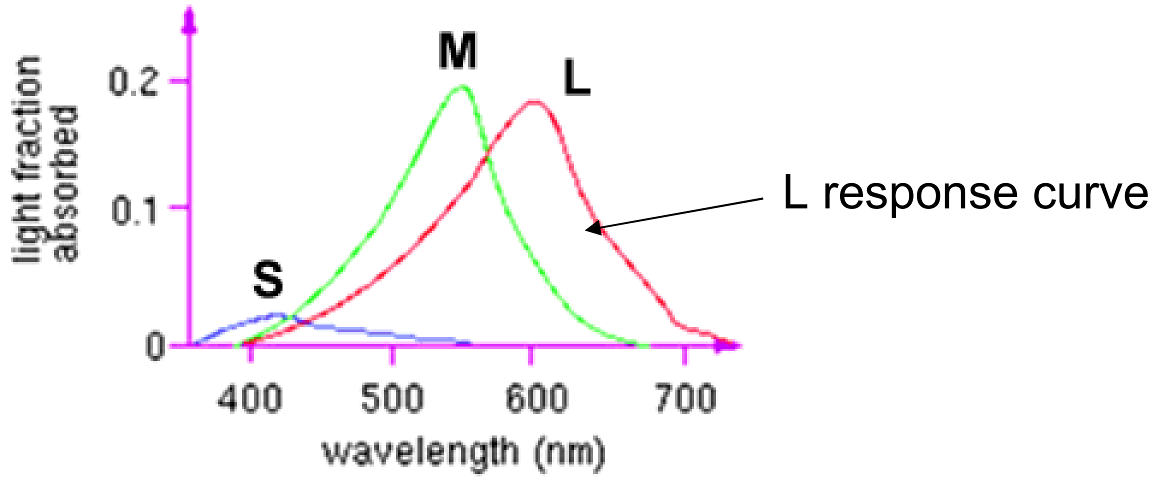
Density of rods and cones



- Rods and cones are *non-uniformly* distributed on the retina
  - Rods responsible for intensity, cones responsible for color
  - **Fovea** - Small region (1 or 2°) at the center of the visual field containing the highest density of cones (and no rods).
  - Less visual acuity in the periphery—many rods wired to the same neuron

Adapted from Seitz

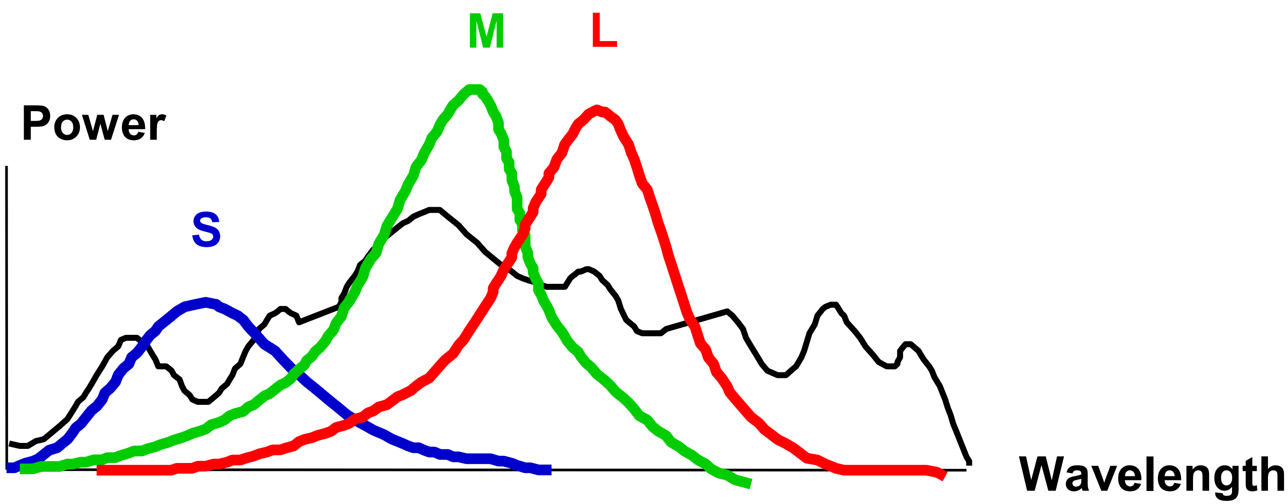
Color perception



- Three types of cones
  - Each is sensitive in a different region of the spectrum
    - but regions overlap
    - Short (S) corresponds to blue
    - Medium (M) corresponds to green
    - Long (L) corresponds to red
  - Different sensitivities: we are more sensitive to green than red
    - varies from person to person (and with age)
  - Colorblindness—deficiency in at least one type of cone

Adapted from Seitz

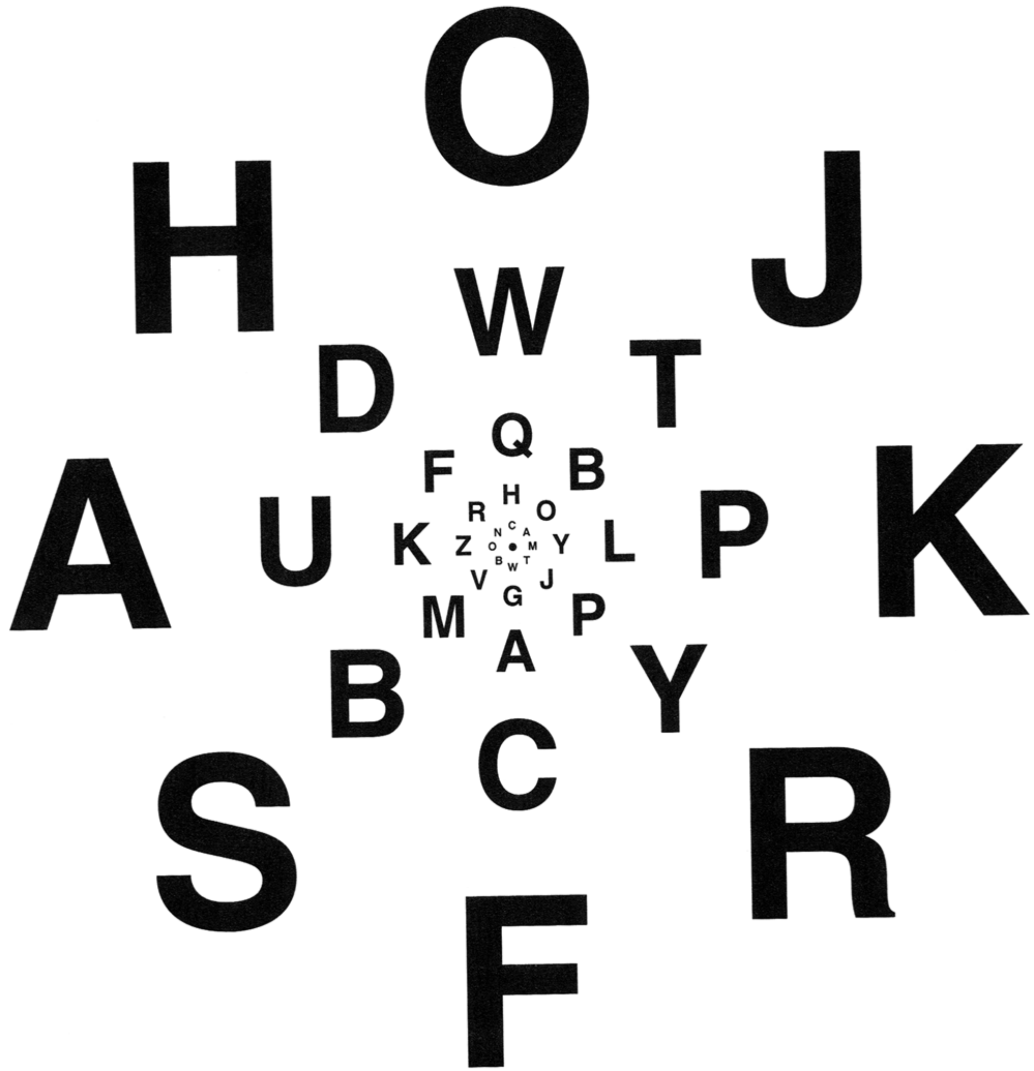
Color perception



- Rods and cones act as filters on the spectrum
  - To get the output of a filter, multiply its response curve by the spectrum, integrate over all wavelengths
    - Each cone yields one number

Adapted from Seitz

Demonstrations of visual acuity



•*With one eye shut, at the right distance, all of these letters should appear equally legible (Glassner, 1.7).*

Adapted from Seitz

Demonstrations of visual acuity

•*With left eye shut, look at the cross on the left. At the right distance, the circle on the right should disappear (Glassner, 1.8).*

Adapted from Seitz

Brightness contrast and constancy

- The apparent brightness depends on the surrounding region
  - **brightness contrast**: a constant colored region seem lighter or darker depending on the surround:

- http://www.sandlotscience.com/Contrast/CheckerBoard_illusion.htm

  - **brightness constancy**: a surface looks the same under widely varying lighting conditions.

Adapted from Seitz

Light response is nonlinear

- Our visual system has a large *dynamic range*
  - We can resolve both light and dark things at the same time
  - One mechanism for achieving this is that we sense light intensity on a *logarithmic scale*
    - an exponential intensity ramp will be seen as a linear ramp
  - Another mechanism is *adaptation*
    - rods and cones adapt to be more sensitive in low light, less sensitive in bright light.

Adapted from Seitz

Light response is nonlinear

Background	Luminance (candelas per square meter)
Horizon sky	
Moonless overcast night	0.00003
Moonless clear night	0.0003
Moonlit overcast night	0.003
Moonlit clear night	0.03
Deep twilight	0.3
Twilight	3
Very dark day	30
Overcast day	300
Clear day	3,000
Day with sunlit clouds	30,000
Daylight fog	
Dull	300–1,000
Typical	1,000–3,000
Bright	3,000–16,000
Ground	
Overcast day	30–100
Sunny day	300
Snow in full sunlight	16,000

FIGURE 1.13
Luminance of everyday backgrounds. *Source:* Data from Rea, ed., *Lighting Handbook 1984 Reference and Application*, fig. 3-44, p. 3-24.

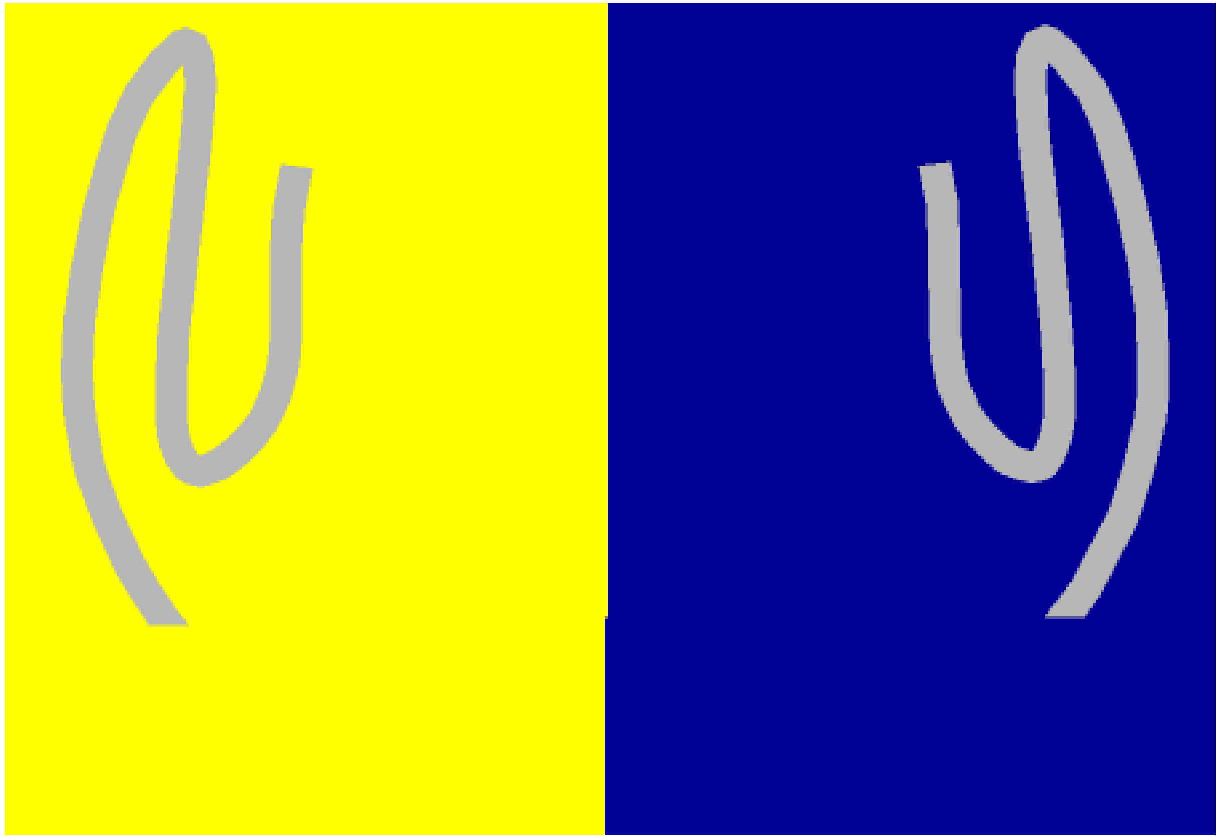
Adapted from Seitz

Adaptation phenomena

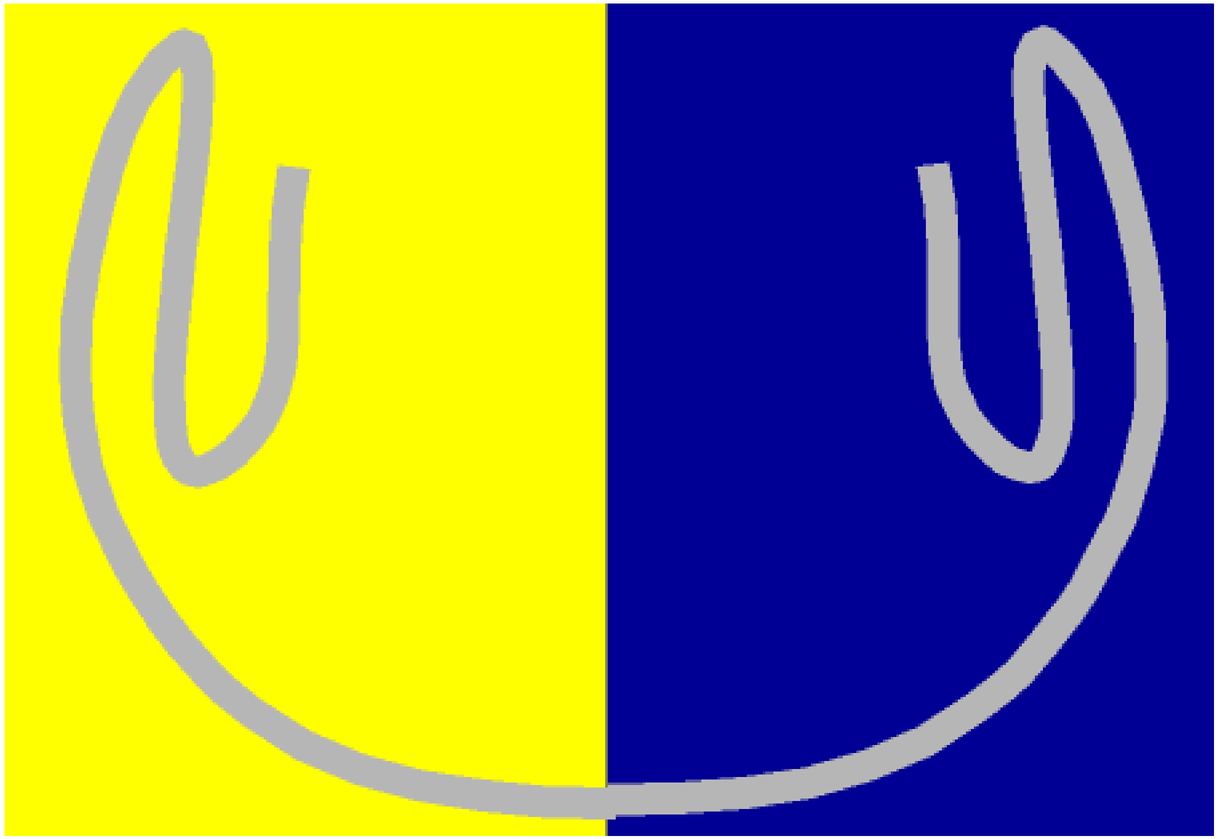
- The response of your color system depends both on spatial contrast and what it has seen before (adaptation)
- This seems to be a result of coding constraints --- receptors appear to have an operating point that varies slowly over time, and to signal some sort of offset. One form of adaptation involves changing this operating point.

- Common example: walk inside from a bright day; everything looks dark for a bit, then takes its conventional brightness.

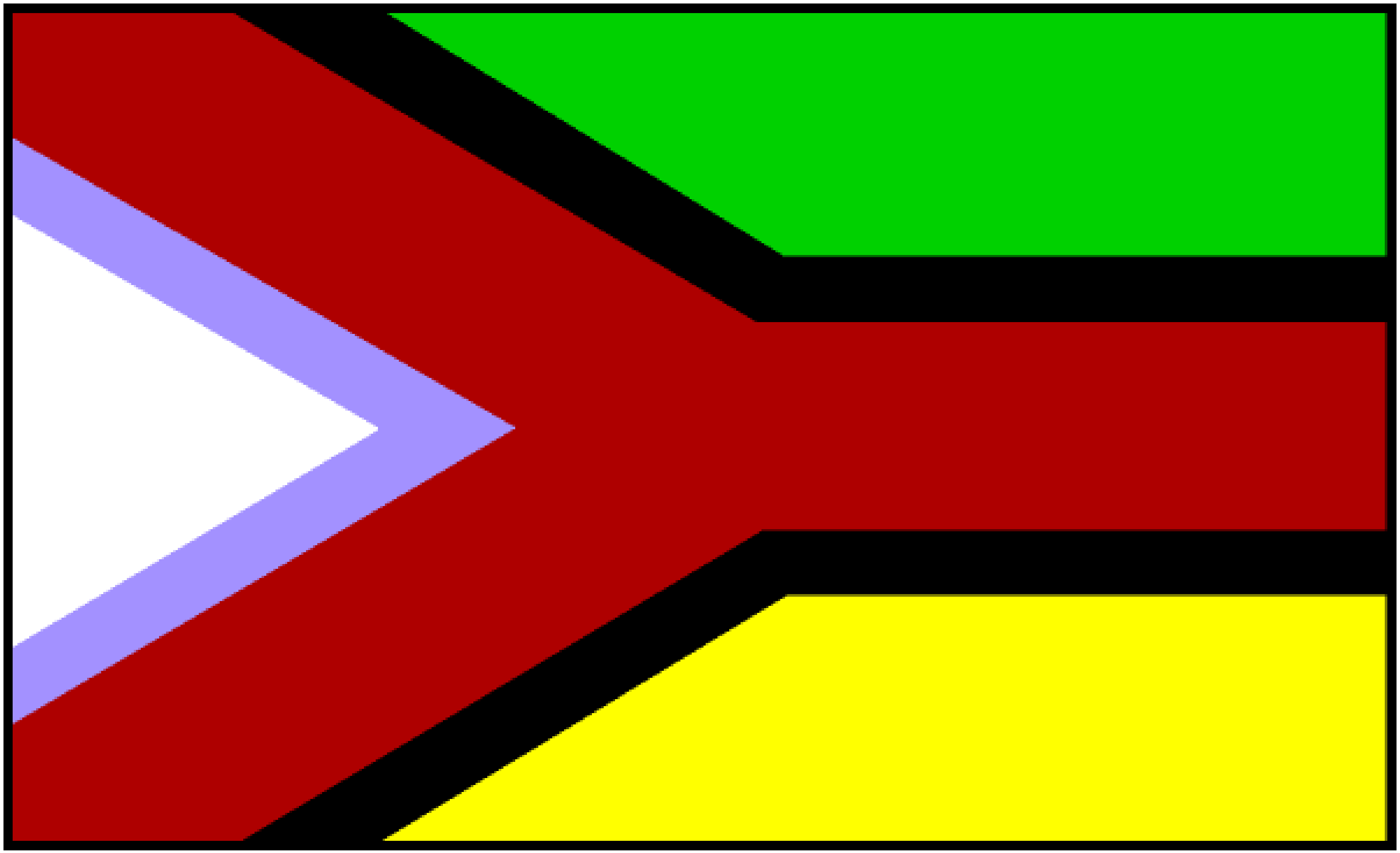
Adapted from David Forsyth, UC Berkeley



Adapted from David Forsyth, UC Berkeley



Adapted from David Forsyth, UC Berkeley



Adapted from David Forsyth, UC Berkeley

you should see an image of opponent colors

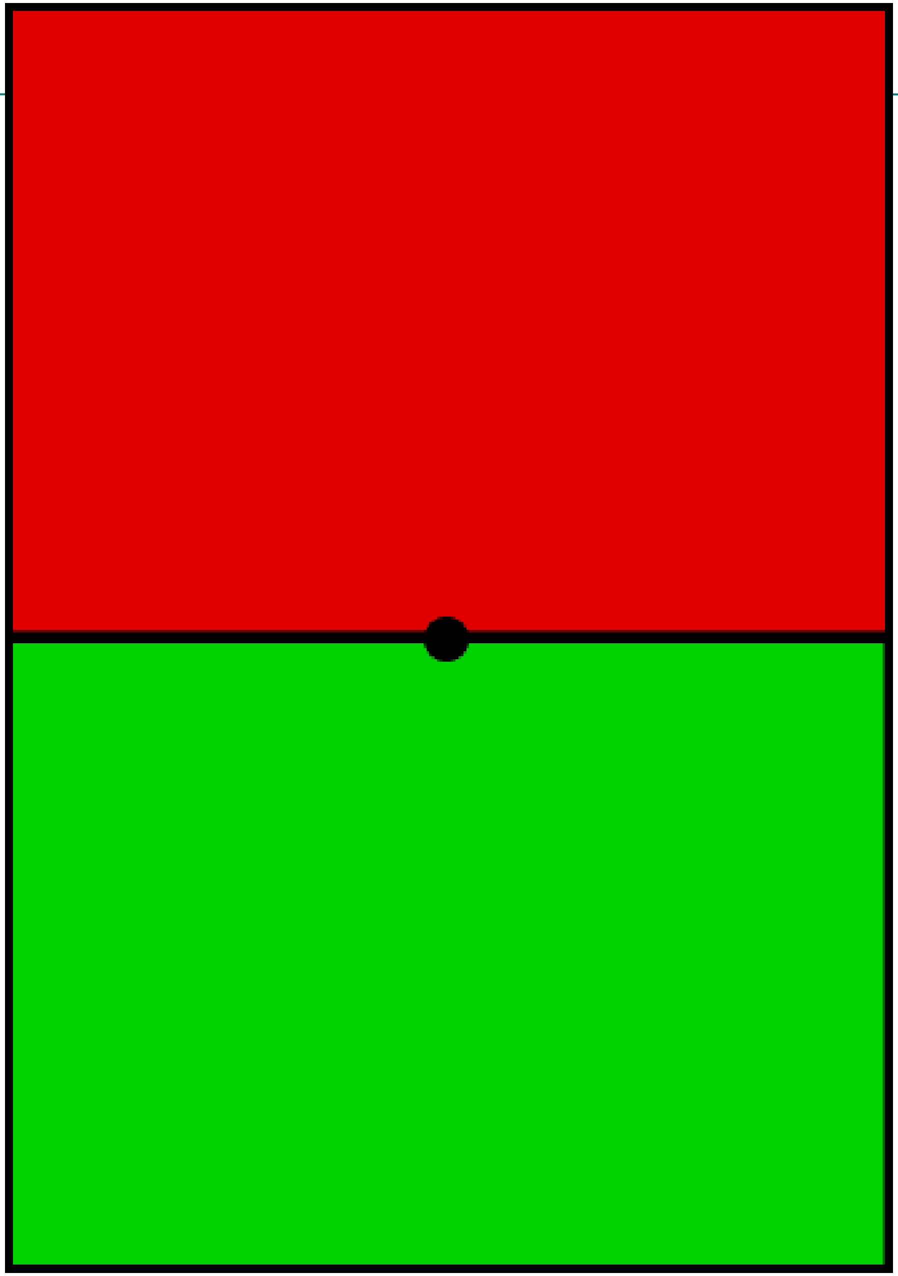
(blue->yellow, red->green, etc.)

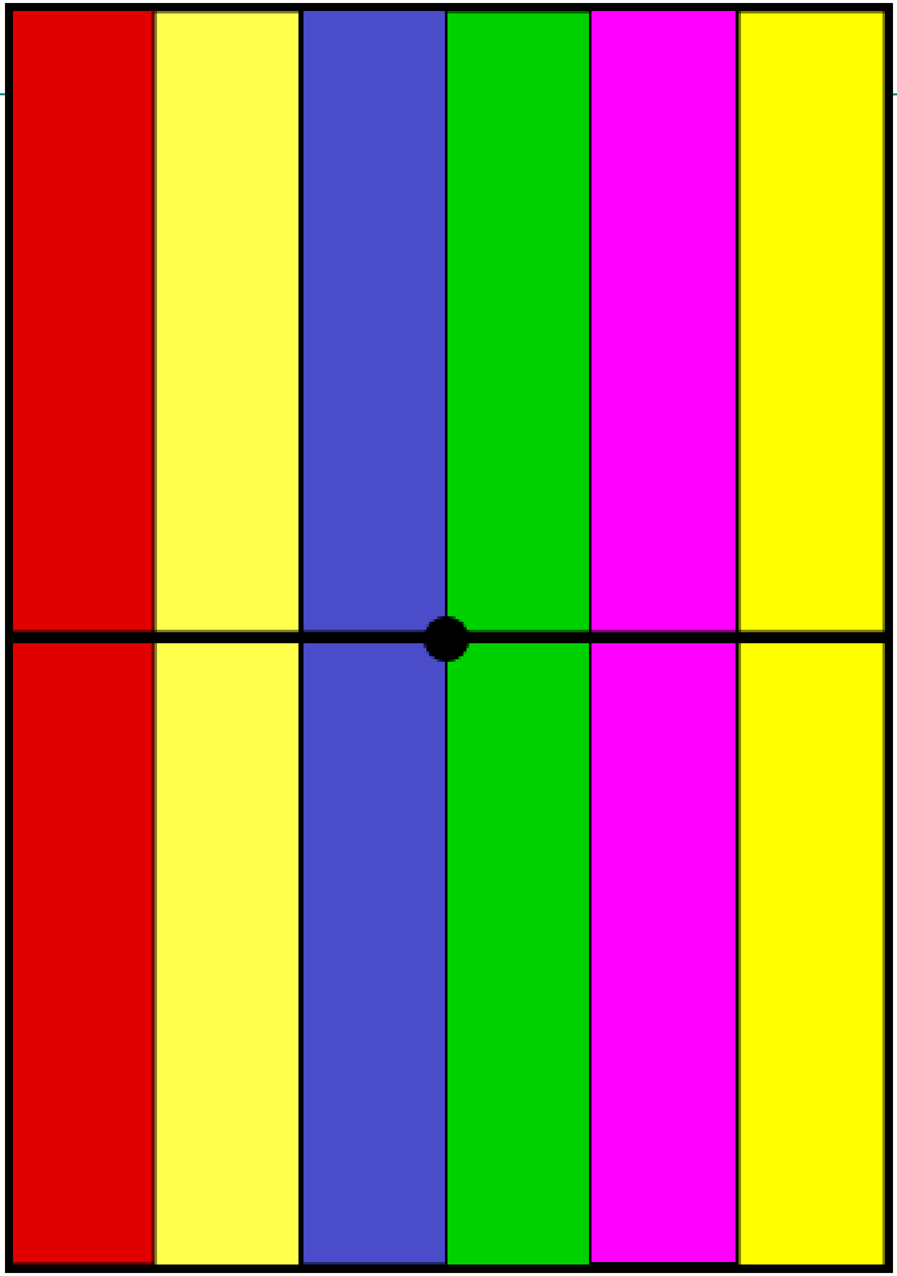
This is a color afterimage.

Tired photoreceptors

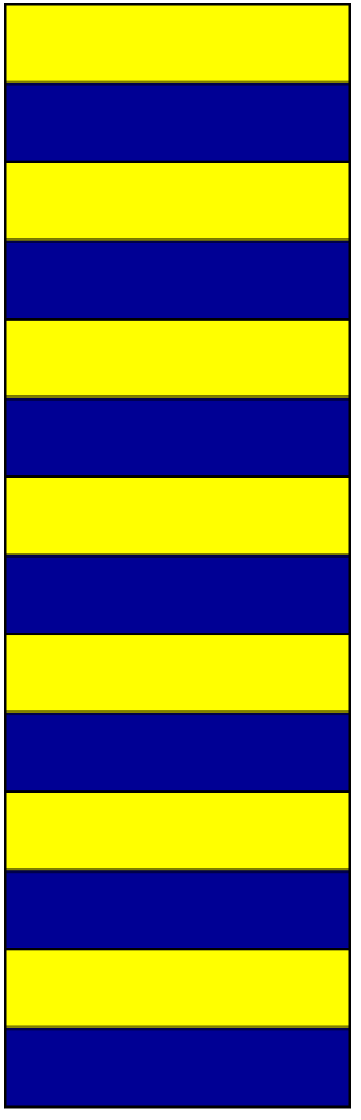
- Send out negative response after a strong stimulus

Adapted from David Forsyth, UC Berkeley

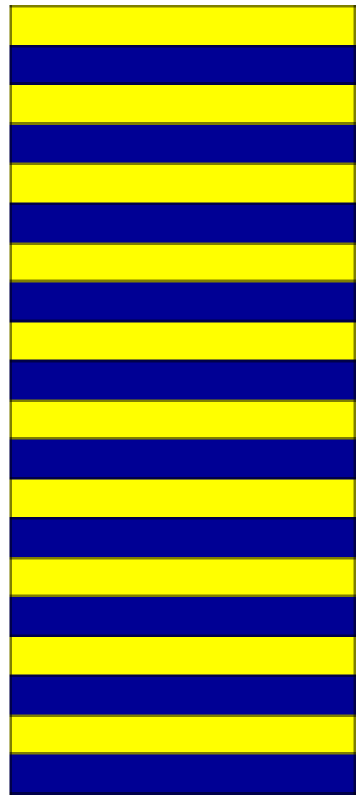




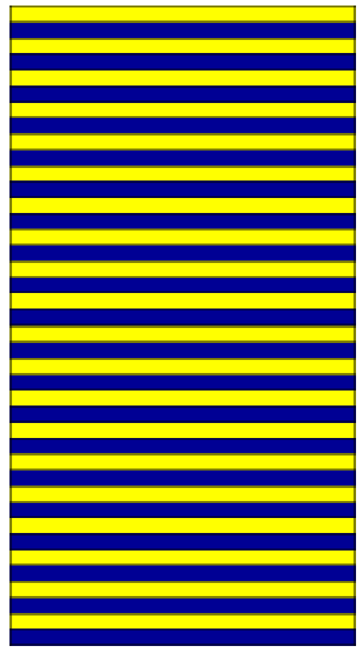
Are the colors on top and bottom the same?



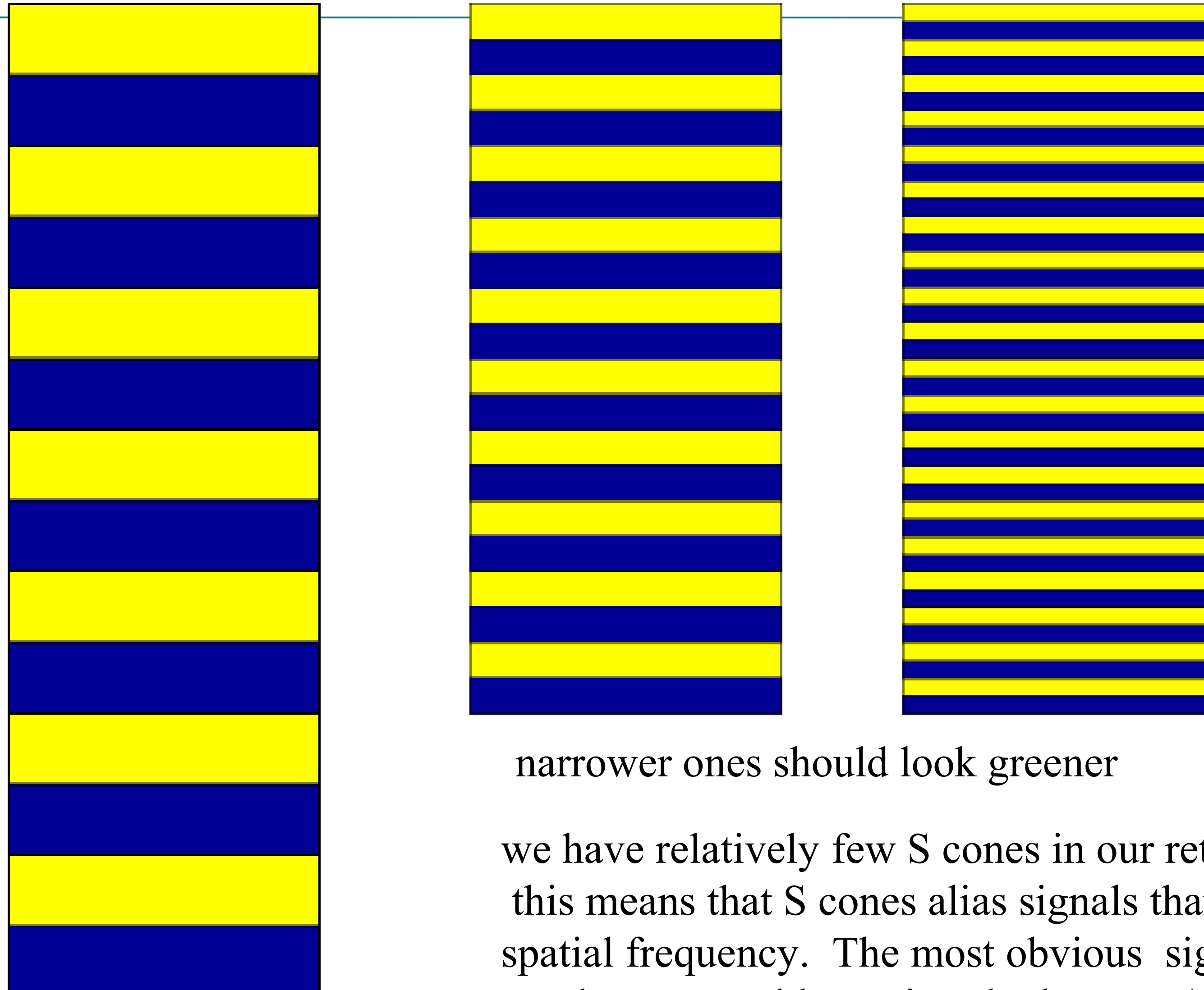
Adapted from David Forsyth, UC Berkeley



Adapted from David Forsyth, UC Berkeley



Adapted from David Forsyth, UC Berkeley



narrower ones should look greener

we have relatively few S cones in our retina. In turn, this means that S cones alias signals that have high spatial frequency. The most obvious signs of this are that narrow blue stripes look green (and blue text is notoriously hard to read).

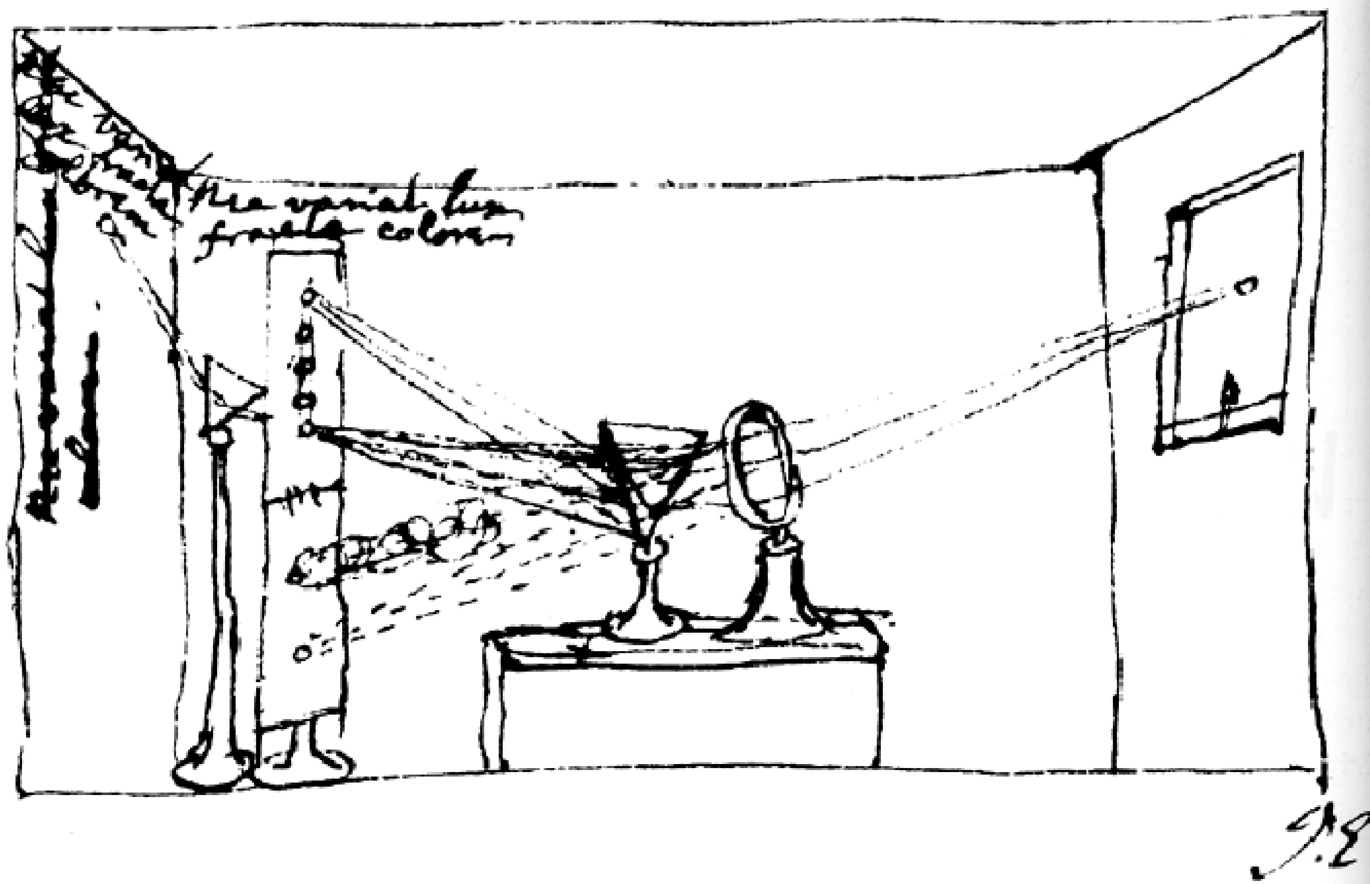
Adapted from David Forsyth, UC Berkeley

XXXXXX	GREEN	GREEN
XXXXXX	BLUE	BLUE
XXXXXX	YELLOW	YELLOW
XXXXXX	PURPLE	PURPLE
XXXXXX	ORANGE	ORANGE
XXXXXX	RED	RED
XXXXXX	WHITE	WHITE
XXXXXX	PURPLE	PURPLE
XXXXXX	ORANGE	ORANGE
XXXXXX	BLUE	BLUE
XXXXXX	RED	RED
XXXXXX	GREEN	GREEN
XXXXXX	WHITE	WHITE
XXXXXX	YELLOW	YELLOW
XXXXXX	PURPLE	PURPLE
XXXXXX	RED	RED
XXXXXX	GREEN	GREEN
XXXXXX	BLUE	BLUE

your ability to name the colors is being interfered with by some input from reading. There is no reason to describe what; this is a clear demonstration that color naming is affected by more than just physics.

Adapted from David Forsyth, UC Berkeley

Color



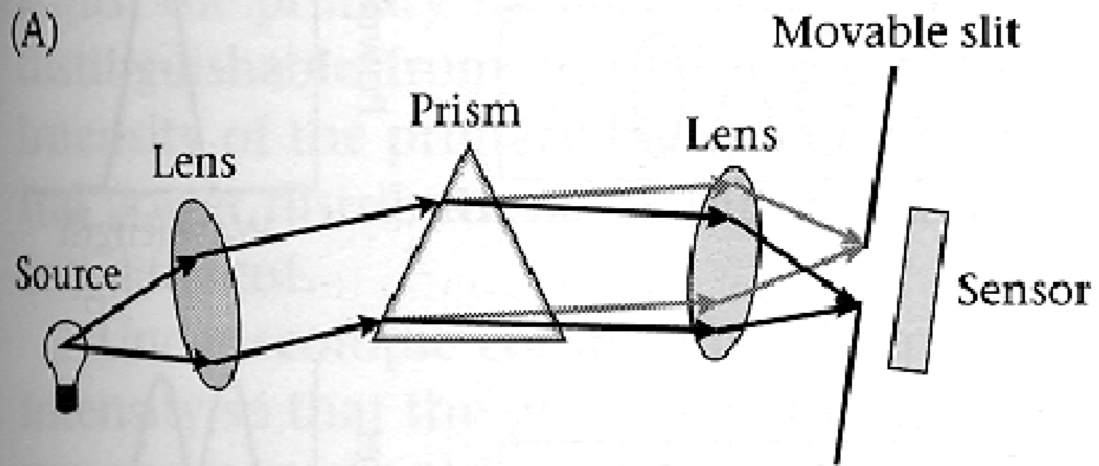
4.1 **NEWTON'S SUMMARY DRAWING** of his experiments with light. Using a point source of light and a prism, Newton separated sunlight into its fundamental components. By reconverging the rays, he also showed that the decomposition is reversible.

From Foundations of Vision, by Brian Wandell, Sinauer Assoc., 1995

Adapted from Freeman and Darrell, MIT

Spectrophotometer

(A)



(B)

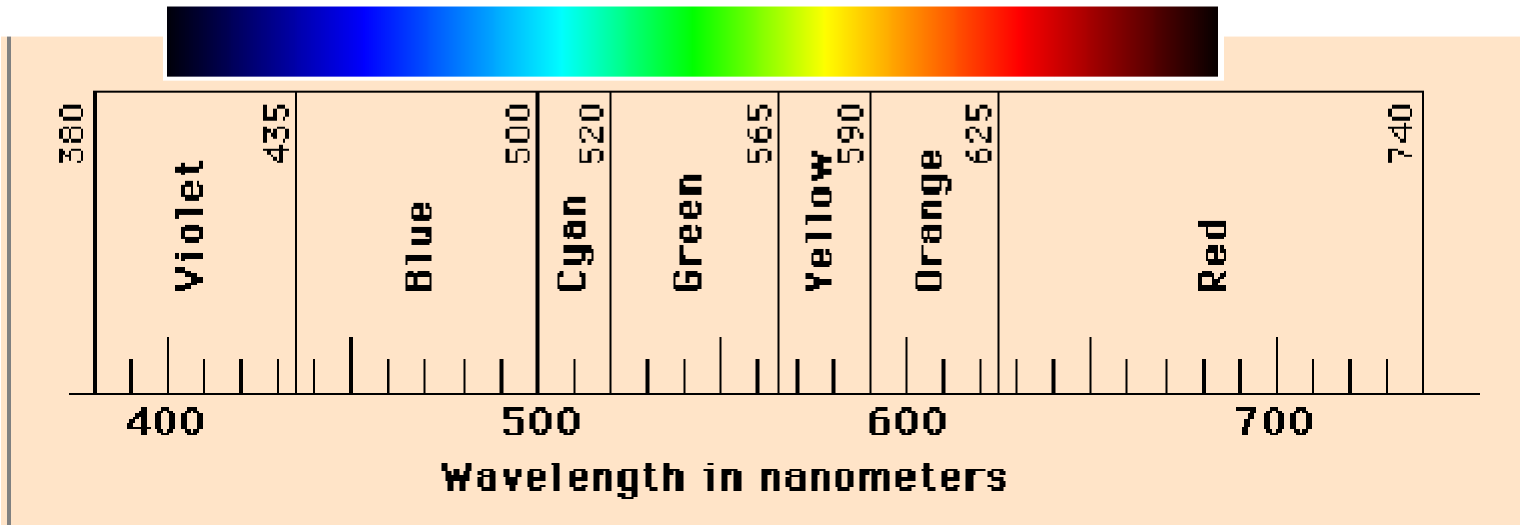
Wavelength (nm)	Color (viewed in isolation)
700	Red
610	Orange
580	Yellow
540	Green
480	Blue
400	Violet

4.2 **A SPECTRORADIOMETER** is used to measure the spectral power distribution of light. (A) A schematic design of a spectroradiometer includes a means for separating the input light into its different wavelengths and a detector for measuring the energy at each of the separate wavelengths. (B) The color names associated with the appearance of lights at a variety of wavelengths are shown. After Wyszecki and Stiles, 1982.

Foundations of Vision, by Brian Wandell, Sinauer Assoc., 1995

Adapted from Freeman and Darrell, MIT

Spectral Colors



http://hyperphysics.phy-astr.gsu.edu/hbase/vision/specol.html#c2

Adapted from Freeman and Darrell, MIT

Color of sources

- Building a light source usually involves heating something until it glows.
- Construct a black body – a body that reflects no light
  - Easiest way to do this is to build a hollow metal object with a tiny hole in it, and look at the hole.
- The spectral power distribution of light leaving this object is a simple function of temperature
- At relatively low temperatures black bodies are red, passing through orange to yellow and then white

Adapted from David Forsyth, UC Berkeley

Color of sources

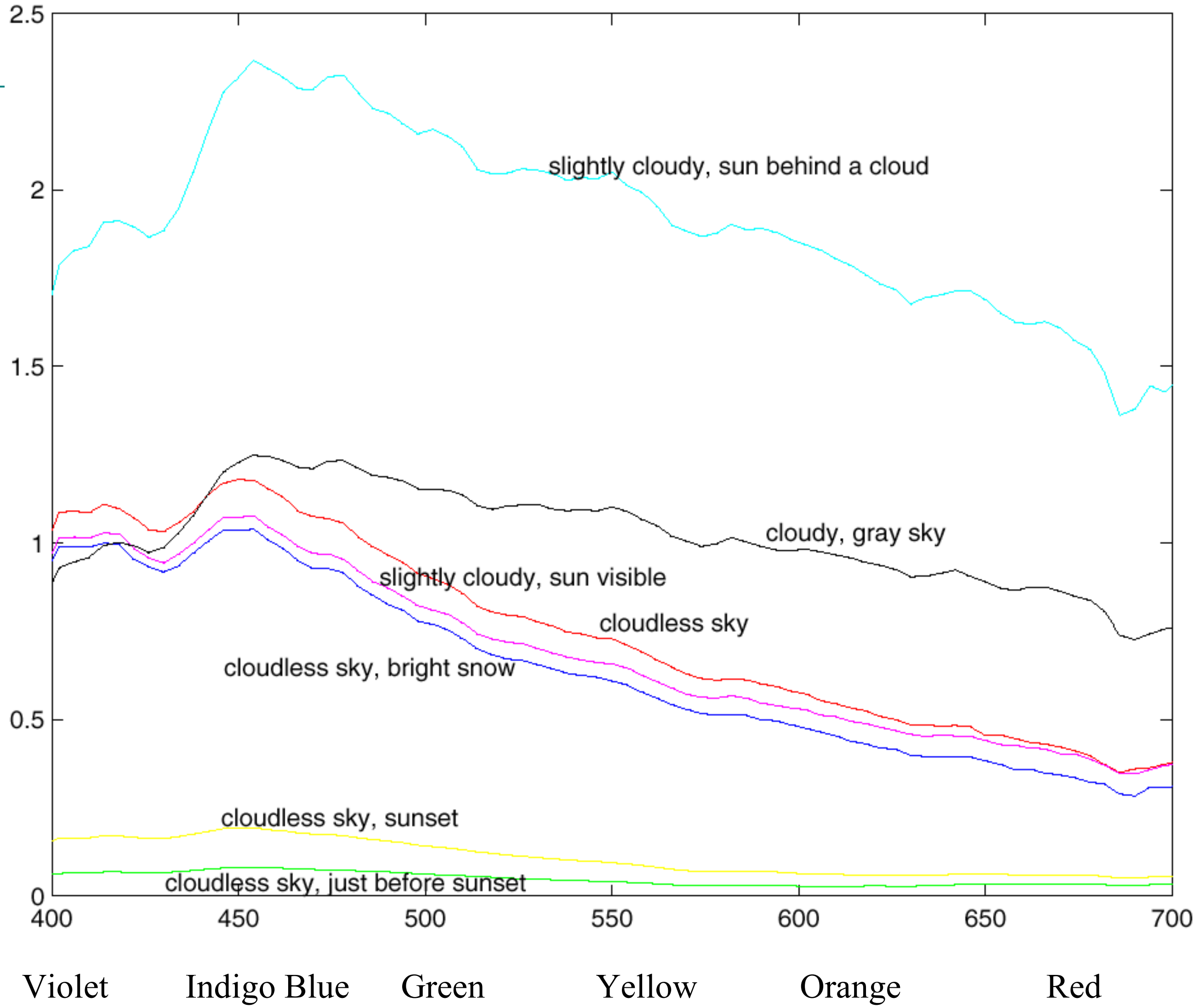
- The most important natural light source is the sun
- Light from the sun is scattered by the air
  - Sky is also an important light source
- A patch of surface outdoors is illuminated by
  - Sun light
  - Skylight
- The presence of snow or clouds is also important
- The color of daylight varies by time of the day and by time of the year

Color of sources

- Light of a long wavelength can travel much farther before being scattered than light of a short wavelength
- i.e. when the sun is high on the sky blue light is scattered out of the ray from the sun to the earth – meaning that sun looks yellow – and can scatter from the sky to the eye – meaning that the sky is blue
- There are standard models of the spectral radiance of the sky at different times of day

Color of sources

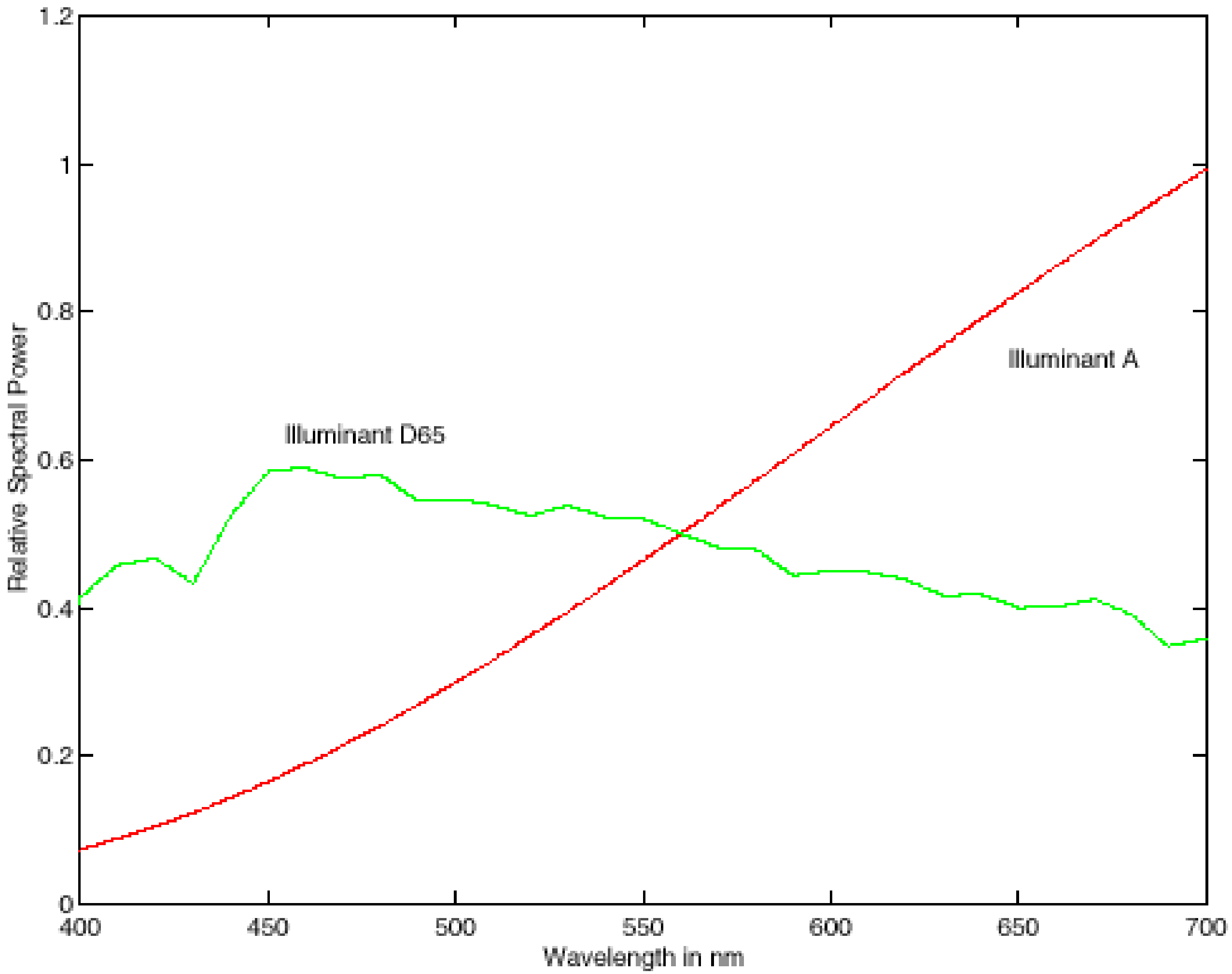
- Artificial illumination
  - Incandescent light - metal filament that is heated to a high temperature (reddish)
  - Fluorescent light – high speed electrons that strike gas within the bulb, releasing ultraviolet radiation (bluish)



Measurements of relative spectral power of sunlight

Relative spectral power is plotted against wavelength in nm. The visible range is about 400nm to 700nm. The color names on the horizontal axis give the color names used for monochromatic light of the corresponding wavelength --- the "colors of the rainbow".

Adapted from David Forsyth, UC Berkeley



Violet Indigo Blue Green Yellow Orange Red

Relative spectral power of two standard illuminant models

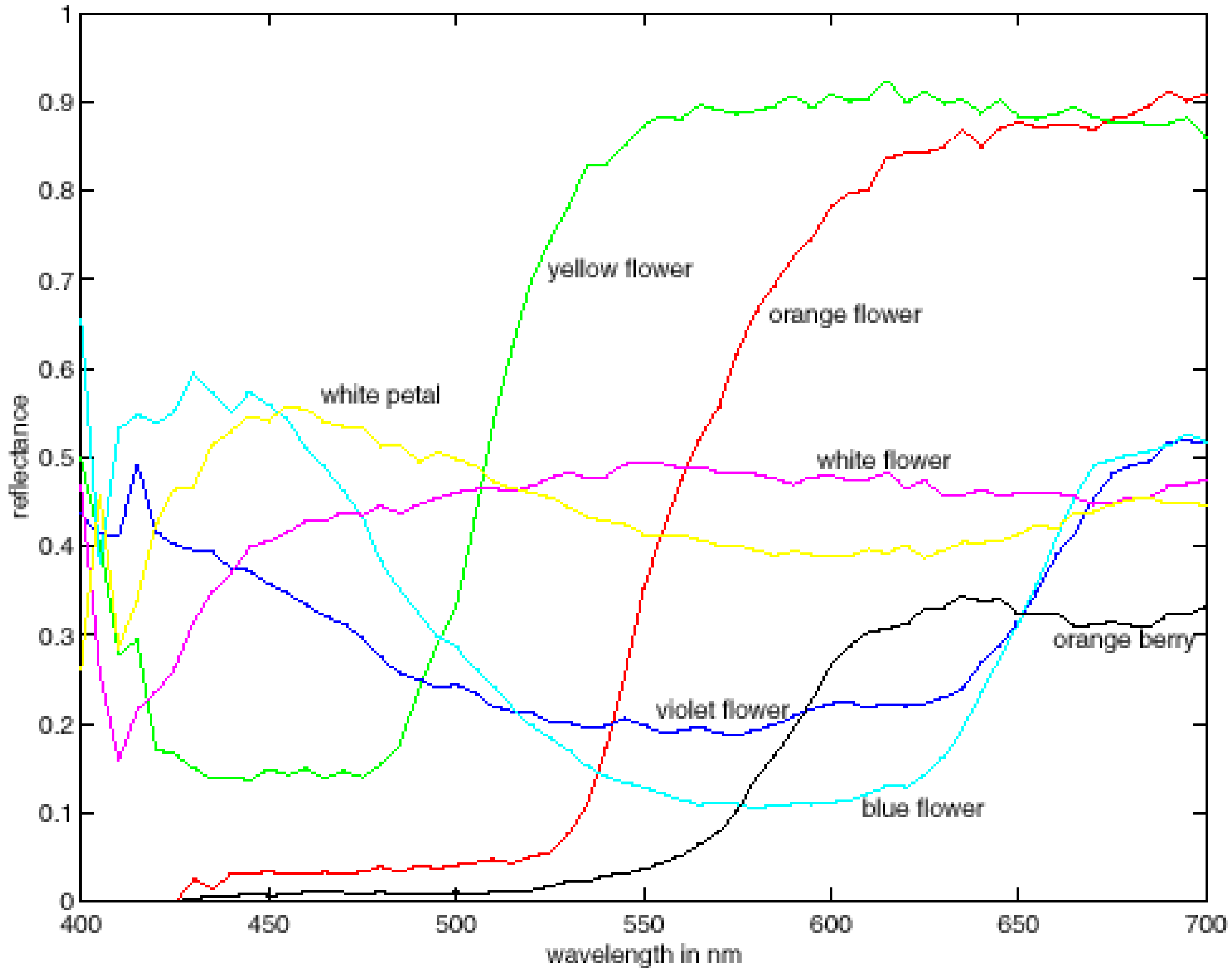
D65 models sunlight

illuminant A models incandescent lamps.

Adapted from David Forsyth, UC Berkeley

Color of surfaces

- It is a result of absorption at different wavelengths, refraction, diffraction and scattering



Spectral reflectances for several different leaves, with color names attached. Notice that different colours typically have different spectral albedo, but that different spectral albedoes may result in the same perceived color (compare the two whites). Spectral albedoes are typically quite smooth functions. Measurements by E.Koivisto.

Adapted from David Forsyth, UC Berkeley

Causes of color

- The sensation of color is caused by the brain.
- Some ways to get this sensation include:
  - Pressure on the eyelids
  - Dreaming, hallucinations, etc.
- Main way to get it is the response of the visual system to the presence/absence of light at various wavelengths.

- Light could be produced in different amounts at different wavelengths (compare the sun and a fluorescent light bulb).
- Light could be differentially reflected (e.g. some pigments).
- It could be differentially refracted - (e.g. Newton's prism)
- Wavelength dependent specular reflection - e.g. shiny copper penny (actually most metals).
- Flourescence - light at invisible wavelengths is absorbed and reemitted at visible wavelengths.

Adapted from David Forsyth, UC Berkeley

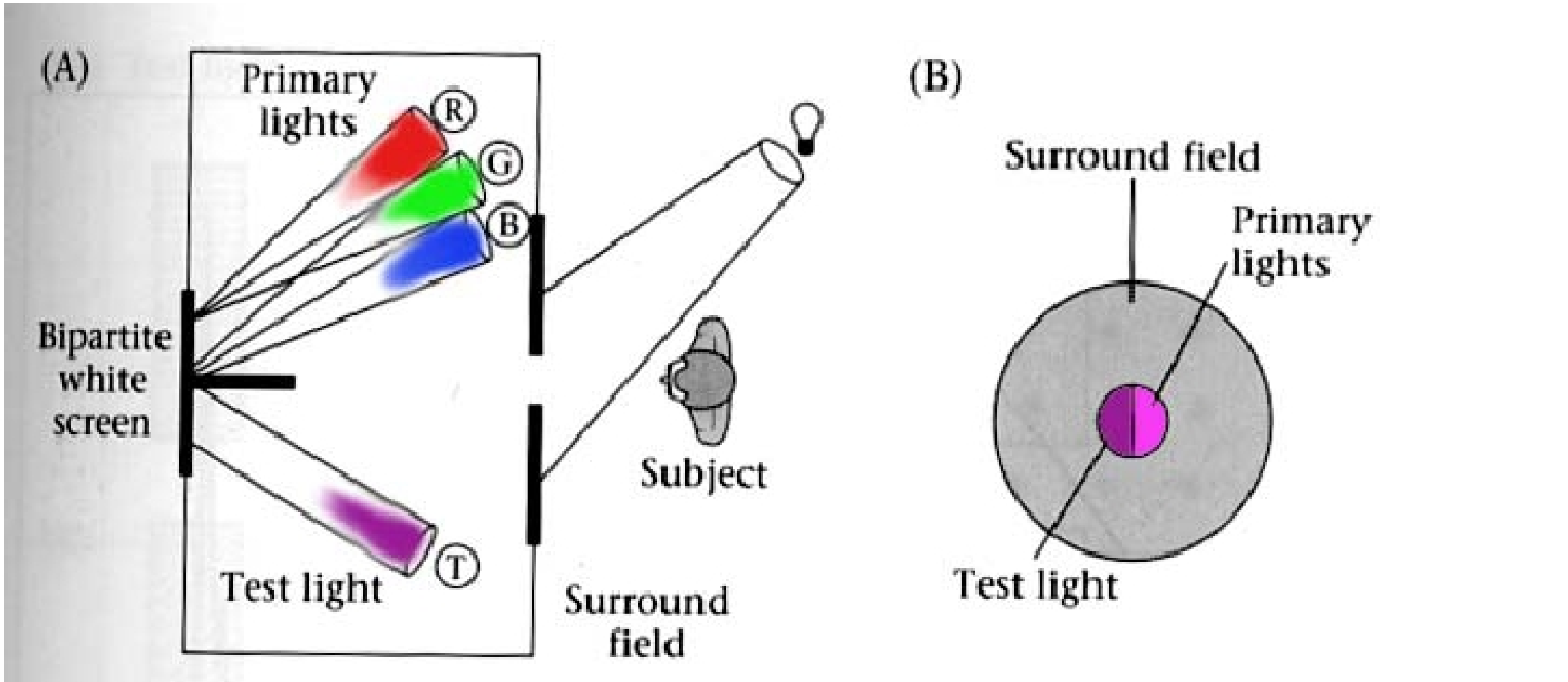
Why does a visual system need color?

- To tell what food is edible.
- To distinguish material changes from shading changes.
- To group parts of one object together in a scene.
- To find people's skin.
- Check whether someone's appearance looks normal/healthy.
- To compress images

Color is intuitively an important cue for understanding images. In particular, objects that look similar in black/white images can be discriminated more easily in color images.

Adapted from Freeman and Darrell, MIT

Color matching experiment

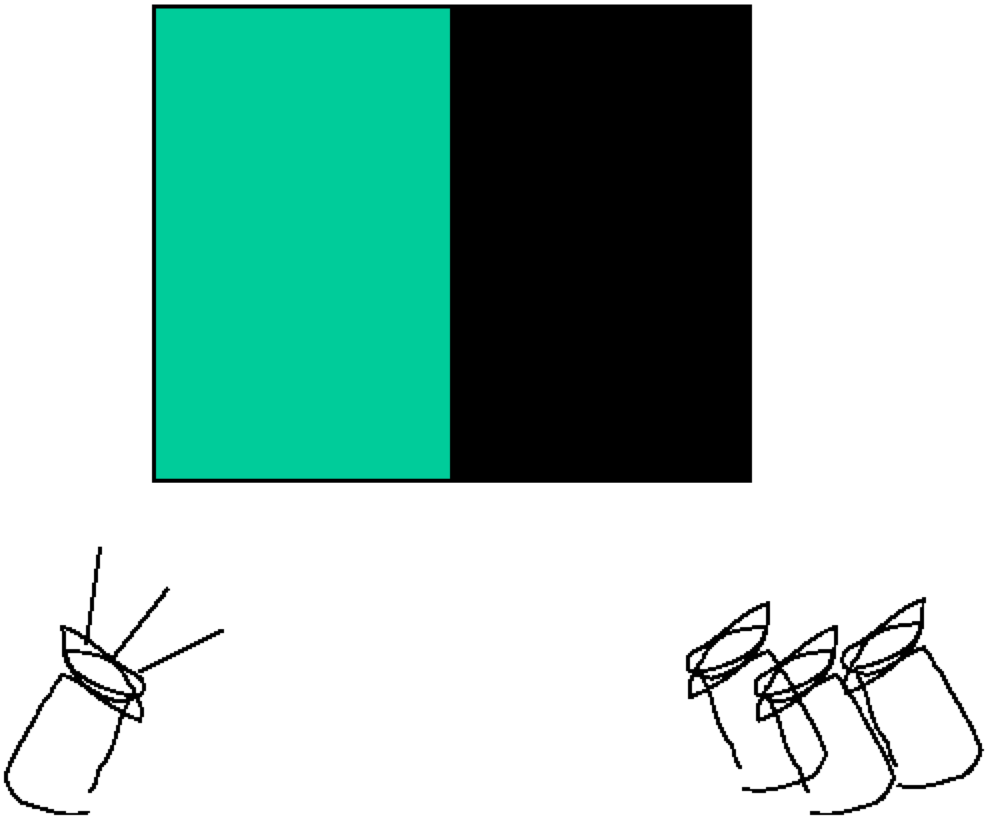


4.10 THE COLOR-MATCHING EXPERIMENT. The observer views a bipartite field and adjusts the intensities of the three primary lights to match the appearance of the test light. (A) A top view of the experimental apparatus. (B) The appearance of the stimuli to the observer. After Judd and Wyszecki, 1975.

Foundations of Vision, by Brian Wandell, Sinauer Assoc., 1995

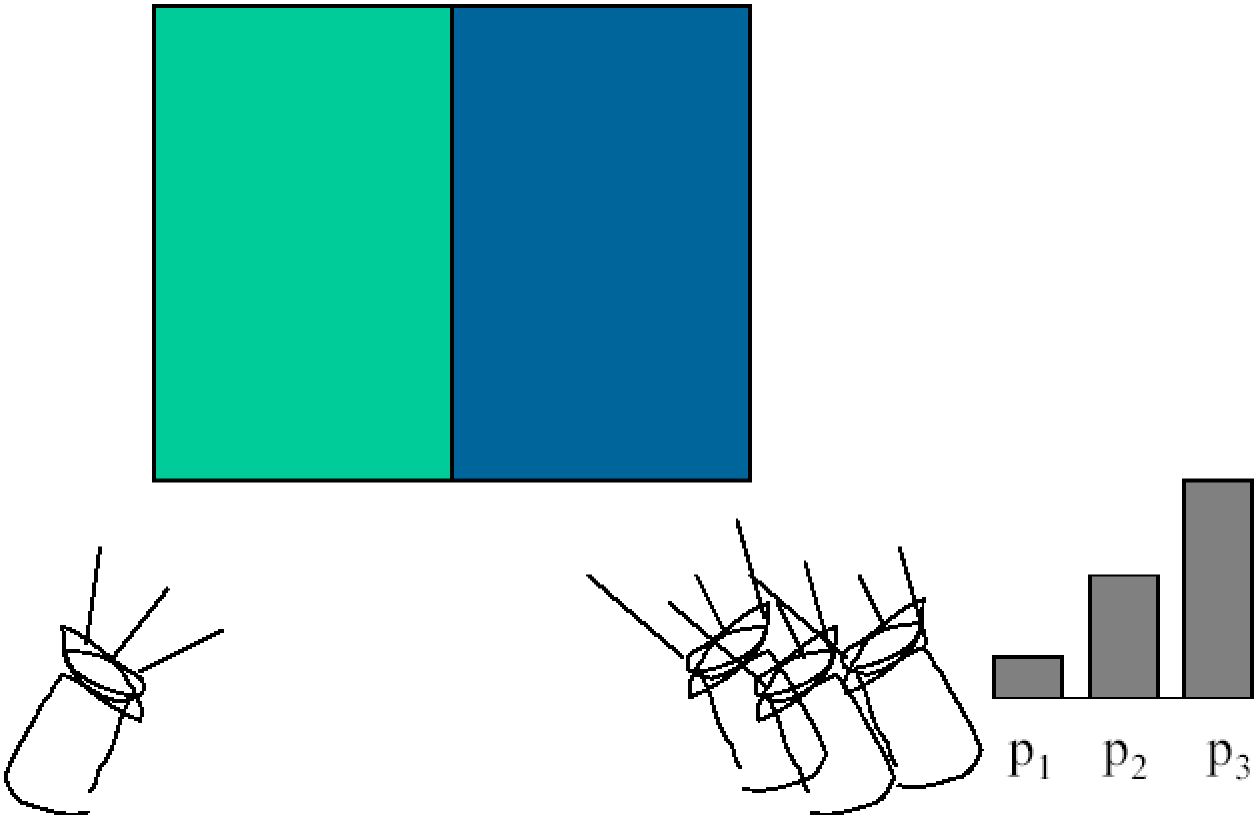
Adapted from Freeman and Darrell, MIT

Color matching experiment



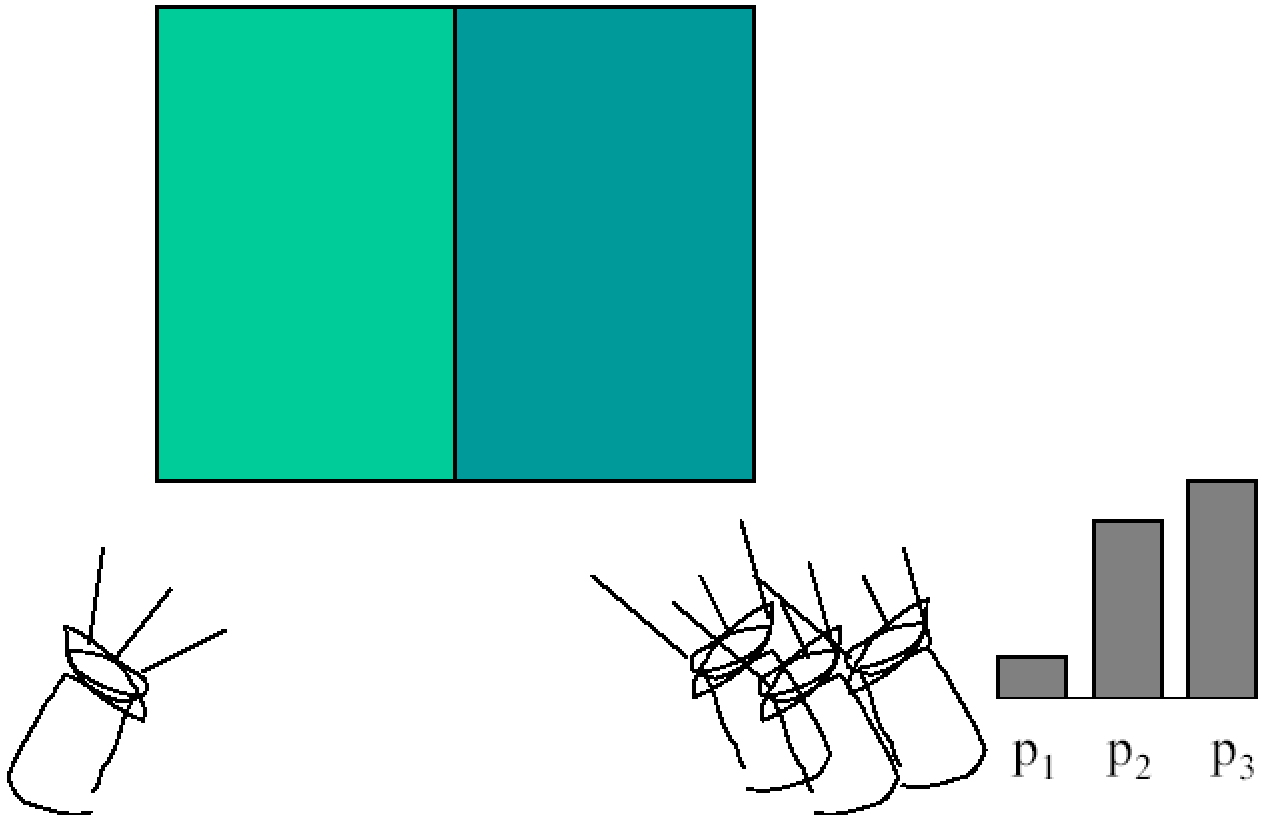
Adapted from Freeman and Darrell, MIT

Color matching experiment



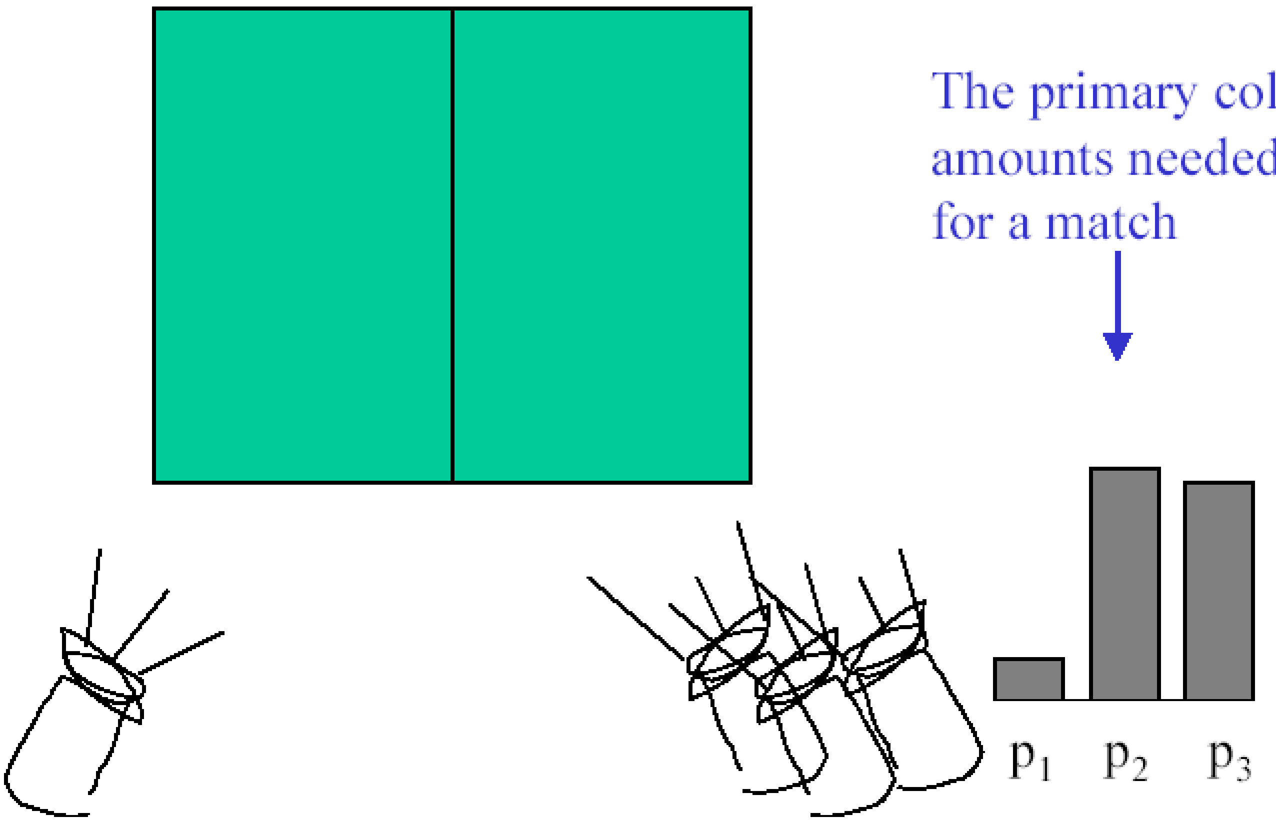
Adapted from Freeman and Darrell, MIT

Color matching experiment



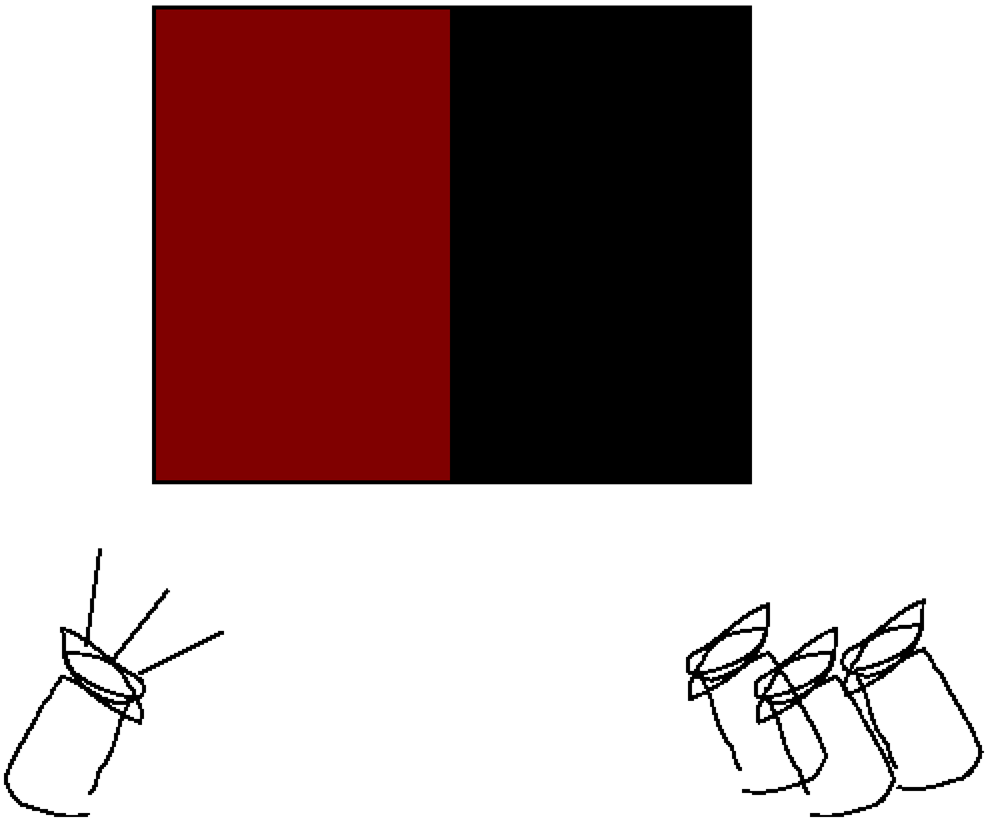
Adapted from Freeman and Darrell, MIT

Color matching experiment



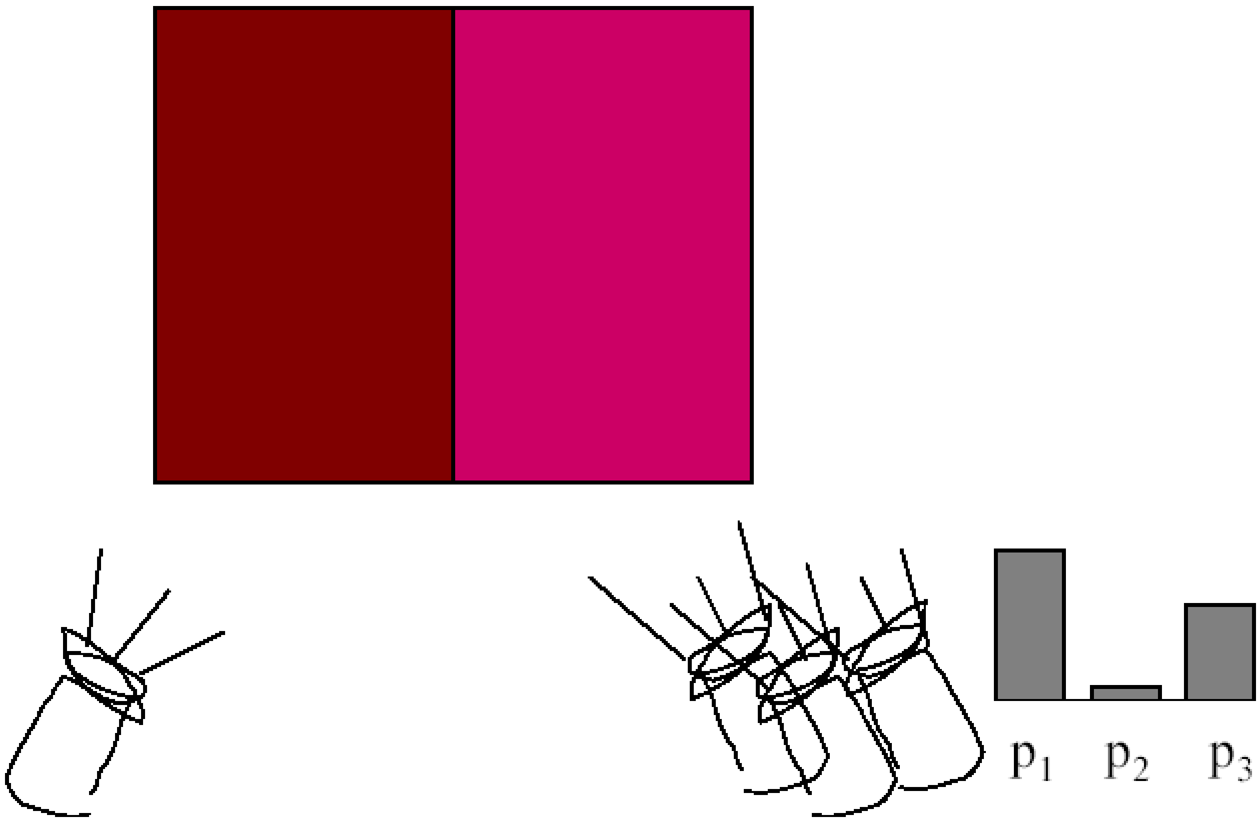
Adapted from Freeman and Darrell, MIT

Color matching experiment



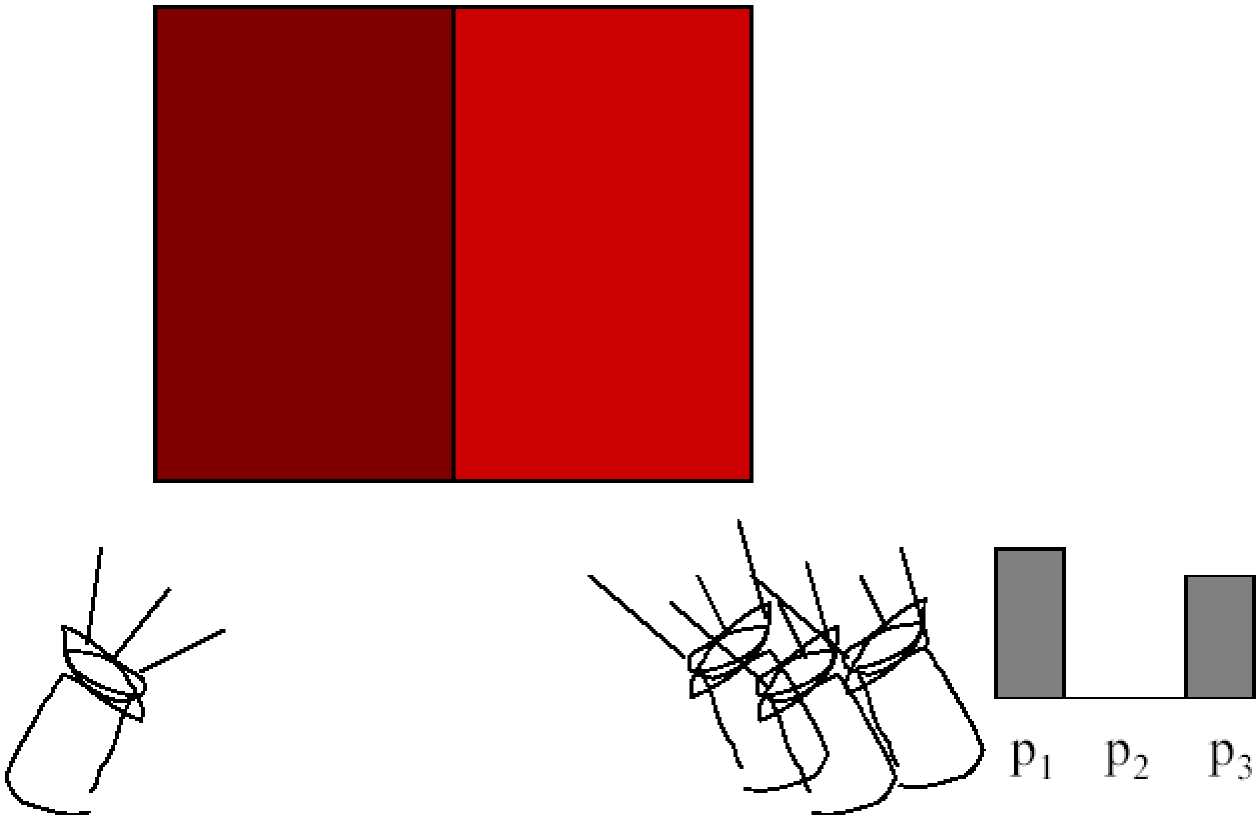
Adapted from Freeman and Darrell, MIT

Color matching experiment



Adapted from Freeman and Darrell, MIT

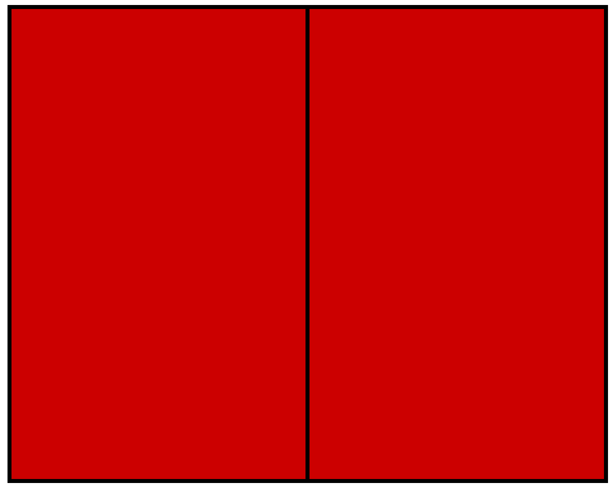
Color matching experiment



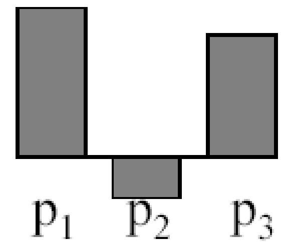
Adapted from Freeman and Darrell, MIT

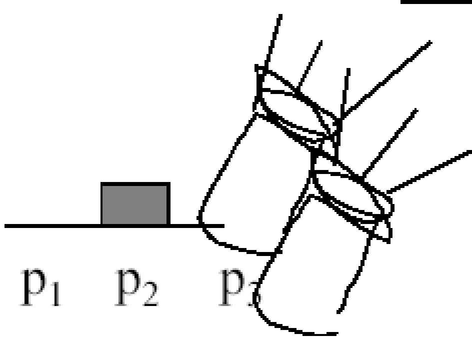
Color matching experiment

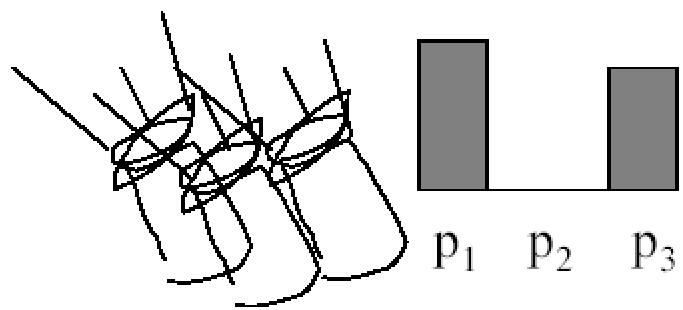
We say a “negative” amount of p_2 was needed to make the match, because we added it to the test color’s side.



The primary color amounts needed for a match:

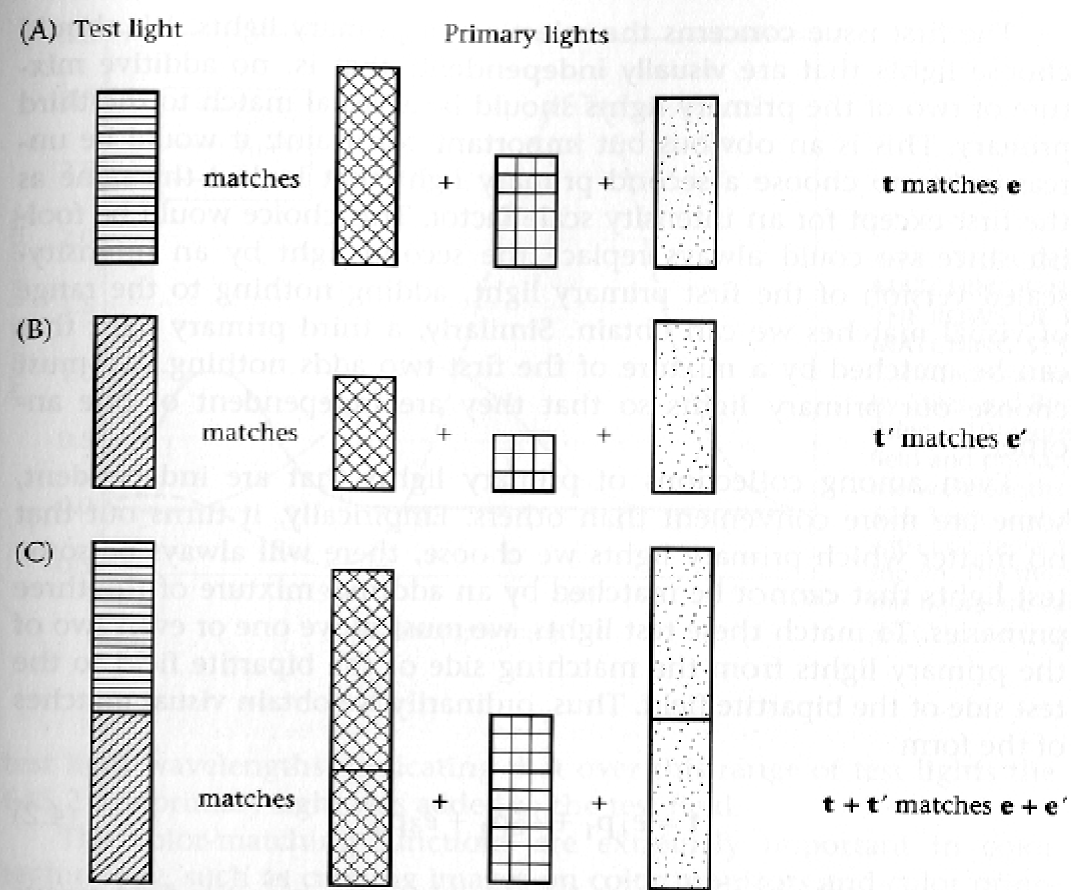






Adapted from Freeman and Darrell, MIT

Color matching experiment



4.12 THE COLOR-MATCHING EXPERIMENT SATISFIES THE PRINCIPLE OF SUPERPOSITION. In parts (A) and (B), test lights are matched by a mixture of three primary lights. In part (C) the sum of the test lights is matched by the additive mixture of the primaries, demonstrating superposition.

Foundations of Vision, by Brian Wandell, Sinauer Assoc., 1995

Adapted from Freeman and Darrell, MIT

Color matching experiments

- Many colors can be represented as a mixture of A, B, C
- write

  $$M = a\ A + b\ B + c\ C$$

  where the = sign should be read as "matches"
- This is **additive** matching.
- Gives a color description system - two people who agree on A, B, C need only supply (a, b, c) to describe a color.

Adapted from David Forsyth, UC Berkeley

Subtractive matching

- Some colors can’t be matched like this: instead, must write

$$M+a\ A = b\ B+c\ C$$

- This is **subtractive** matching.
- Interpret this as (-a, b, c)

Adapted from David Forsyth, UC Berkeley

Trichromacy

By experience, it is possible to match almost all colors, using only three primary sources - the principle of **trichromacy**

The primaries must be independent – no mixture of two of the primaries may match a third

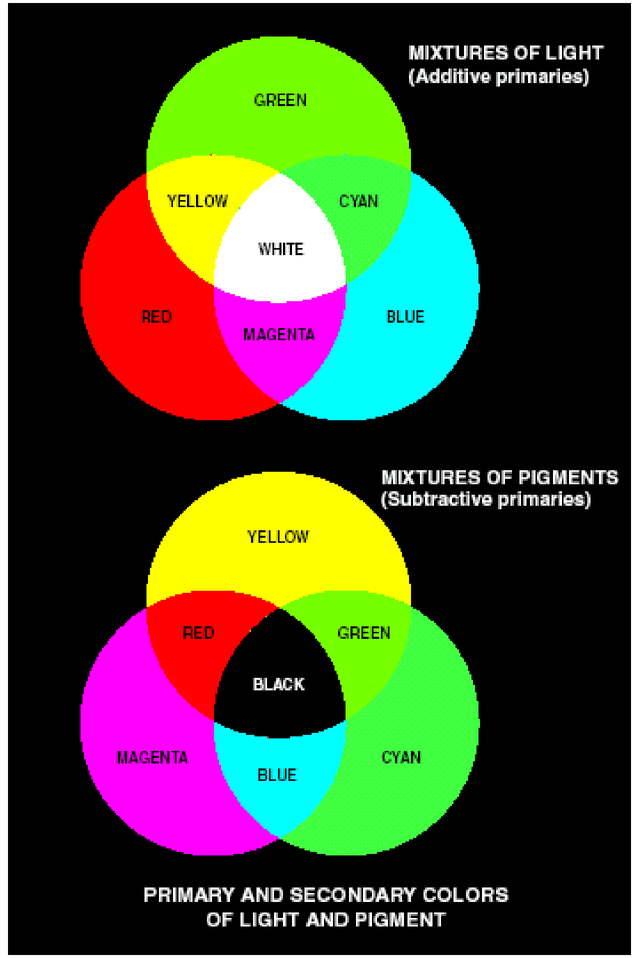
Adapted from David Forsyth, UC Berkeley

The principle of trichromacy

- Experimental facts:
  - Three primaries will work for most people if we allow subtractive matching
    - Exceptional people can match with two or only one primary.
    - This could be caused by a variety of deficiencies.
  - Most people make the same matches.
    - There are some anomalous trichromats, who use three primaries but make different combinations to match.

Adapted from David Forsyth, UC Berkeley

Additive and subtractive color matching



a
b

FIGURE 6.4 Primary and secondary colors of light and pigments. (Courtesy of the General Electric Co., Lamp Business Division.)

Adapted from Alyosha Efros, CMU

Color receptors and color deficiency

- Trichromacy is justified - in color normal people, there are three types of color receptor, called **cones**, which vary in their sensitivity to light at different wavelengths (shown by molecular biologists).
- Deficiency can be caused by CNS, by optical problems in the eye, or by absent receptor types
  - Usually a result of absent genes.
- Some people have fewer than three types of receptor; most common deficiency is red-green color blindness in men.
- Color deficiency is less common in women; red and green receptor genes are carried on the X chromosome, and these are the ones that typically go wrong. Women need two bad X chromosomes to have a deficiency, and this is less likely.

Adapted from David Forsyth, UC Berkeley

Representing Color

Since we can define colors using almost any set of primary colors, let's agree on a set of primaries and color matching functions for the world to use…

Adapted from Freeman and Darrell, MIT

Representing Color - Why specify color numerically?

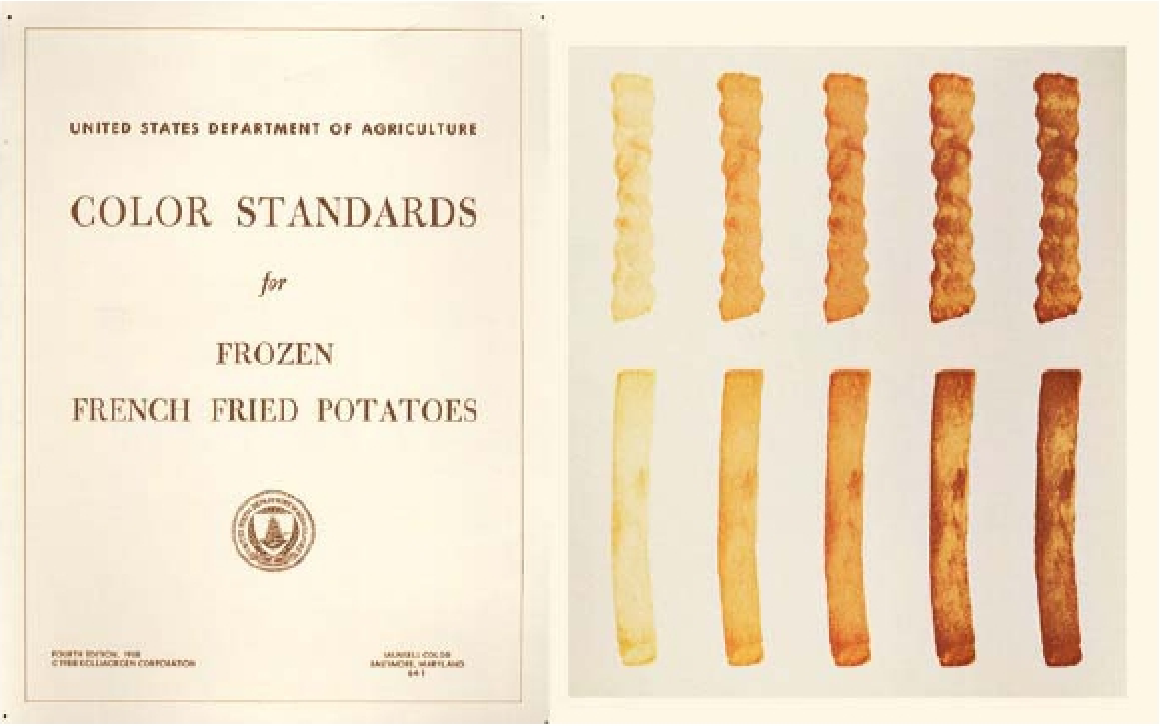
- Accurate color reproduction is commercially valuable
  - Many products are identified by color ("golden" arches;
- Few color names are widely recognized by English speakers -
  - About 10; other languages have fewer/more, but not many more.
  - It's common to disagree on appropriate color names.
- Color reproduction problems increased by prevalence of digital imaging - eg. digital libraries of art.
  - How do we ensure that everyone sees the same color?

Adapted from David Forsyth, UC Berkeley

Color standards are important in industry

Adapted from Freeman and Darrell, MIT

Color standards are important in industry



Adapted from Freeman and Darrell, MIT

Linear color spaces

- A choice of primaries yields a linear color space --- the coordinates of a color are given by the weights of the primaries used to match it.
- Choice of primaries is equivalent to choice of color space.

Adapted from David Forsyth, UC Berkeley

RGB Color space

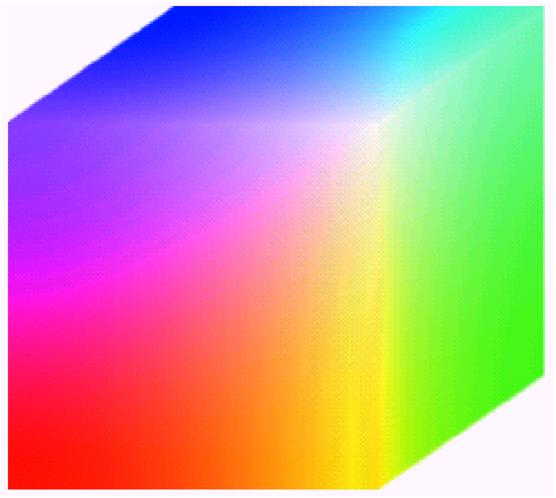
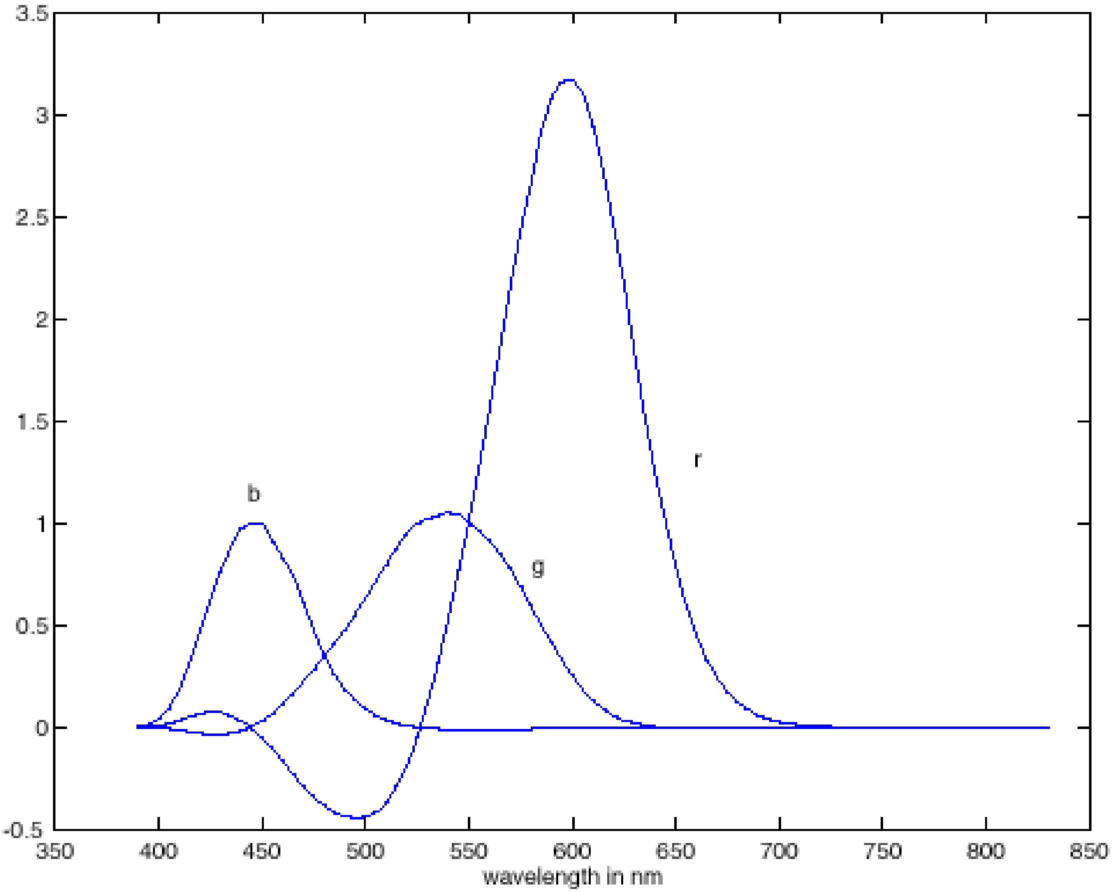


FIGURE 6.8 RGB 24-bit color cube.

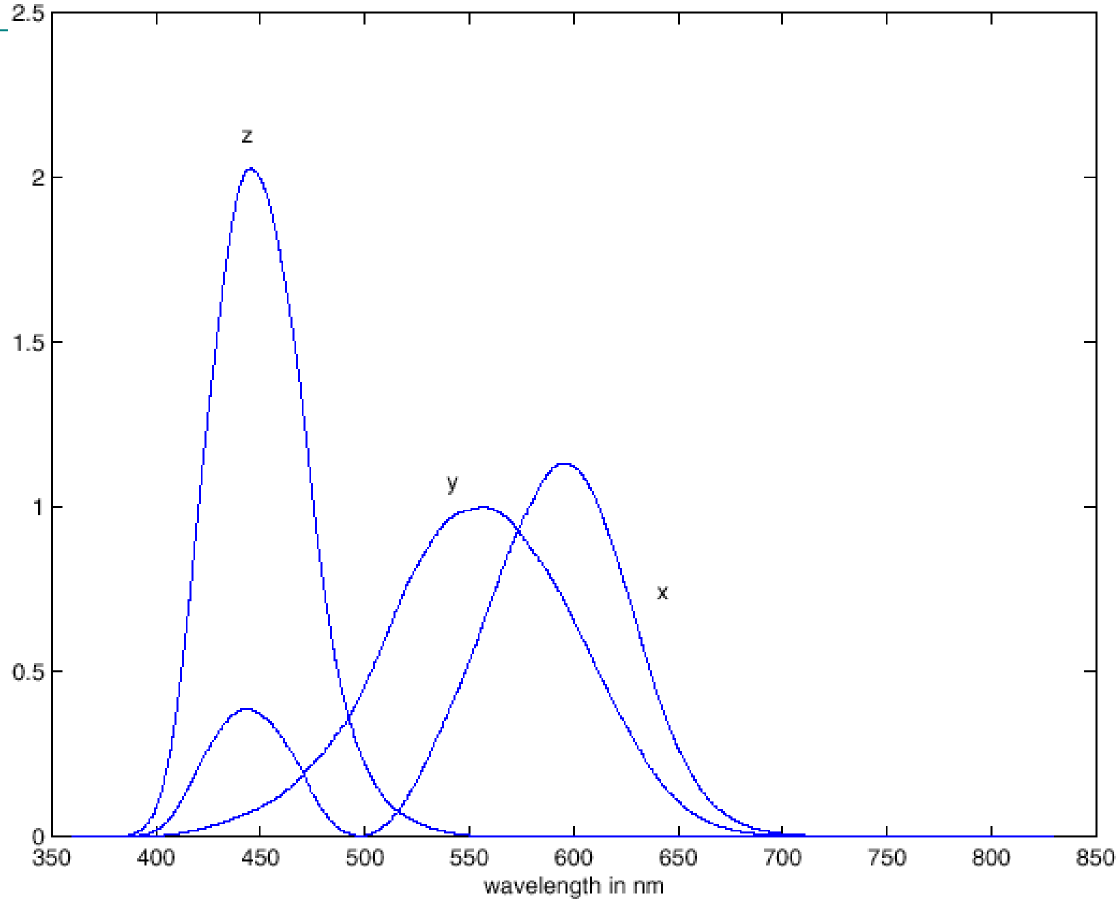
Adapted from Alyosha Efros, CMU



RGB: primaries

Color matching functions have negative parts -> some colors can be matched only subtractively.

Adapted from David Forsyth, UC Berkeley

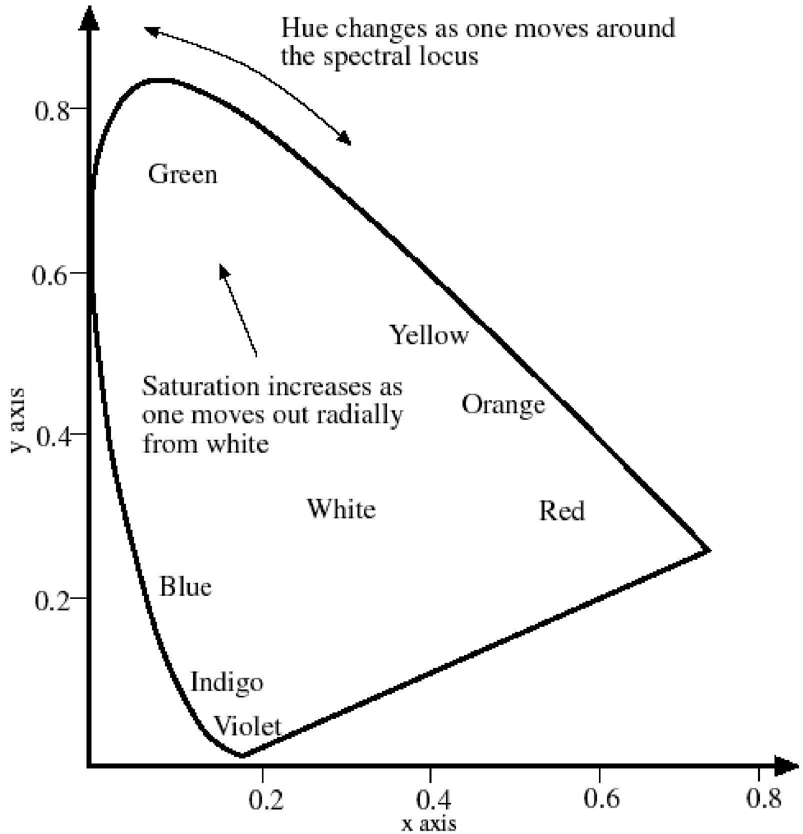


CIE XYZ: Color matching functions are positive everywhere, but primaries are imaginary. Usually draw x, y, where

$x=X/(X+Y+Z)$

$y=Y/(X+Y+Z)$

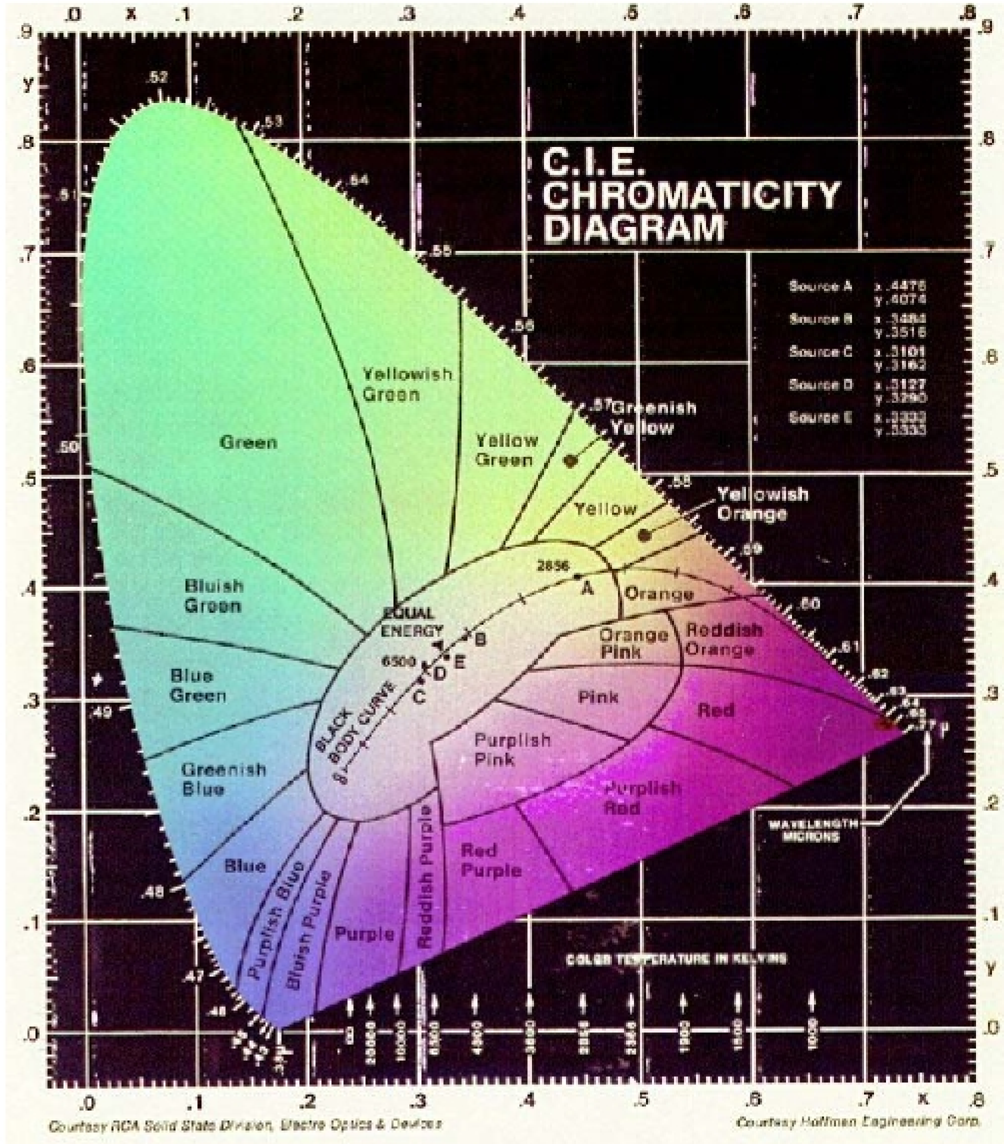
Adapted from David Forsyth, UC Berkeley



A qualitative rendering of the CIE (x,y) space. The blobby region represents visible colors. There are sets of (x, y) coordinates that don't represent real colors, because the primaries are not real lights (so that the color matching functions could be positive everywhere).

hue is a "pure" colour, i.e. one with no black or white in it.

Adapted from David Forsyth, UC Berkeley

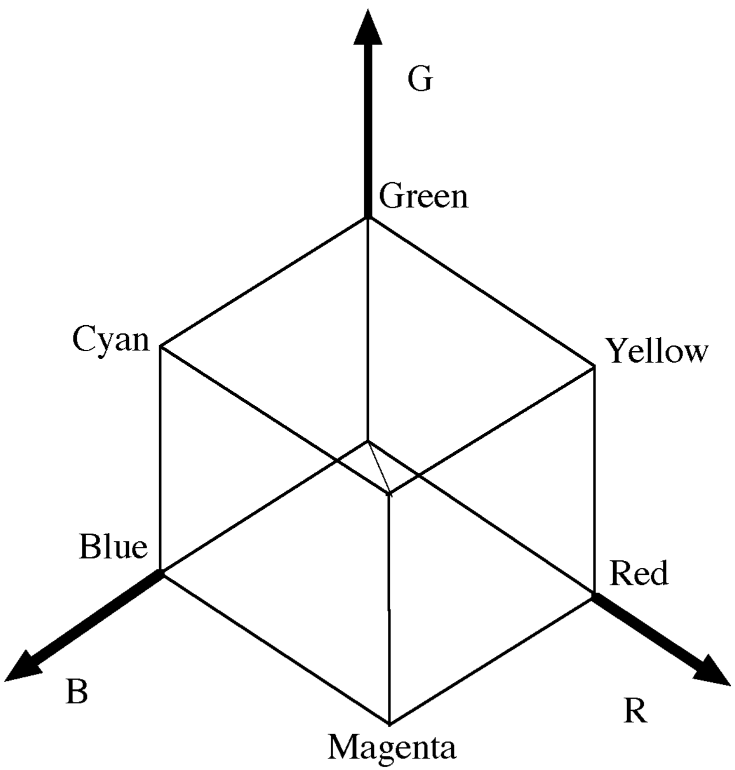

C.I.E.
CHROMATICITY
DIAGRAM
Source A x .4476 y .4074
Source B x .3484 y .3516
Source C x .3101 y .3162
Source D x .3127 y .3290
Source E x .3333 y .3333
Green
Yellowish Green
Yellow Green
Greenish Yellow
Yellow
Yellowish Orange
Orange
Orange Pink
Reddish Orange
Pink
Red
Purplish Pink
Purplish Red
Red Purple
Reddish Purple
Purple
Bluish Purple
Purplish Blue
Blue
Greenish Blue
Blue Green
Bluish Green
EQUAL ENERGY
BLACK BODY CURVE
WAVELENGTH MICRONS
COLOR TEMPERATURE IN KELVINS
Courtesy RCA Solid State Division, Electro Optics & Devices
Courtesy Hoffman Engineering Corp.

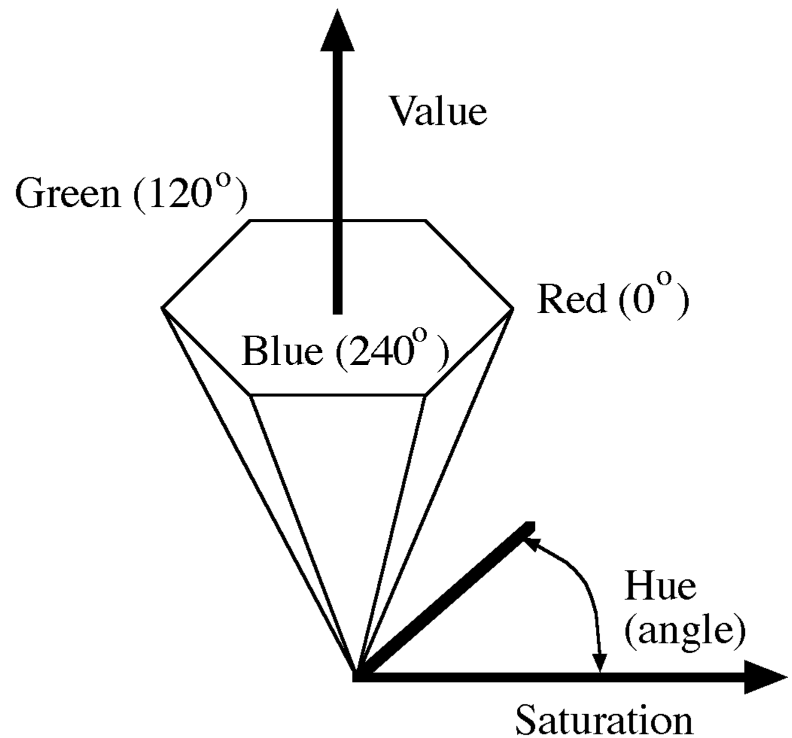
Non-linear colour spaces

- HSV: Hue, Saturation, Value are non-linear functions of XYZ.
  - because hue relations are naturally expressed in a circle
- Uniform: equal (small!) steps give the same perceived color changes.
- Munsell: describes surfaces, rather than lights - less relevant for graphics. Surfaces must be viewed under fixed comparison light

Adapted from David Forsyth, UC Berkeley

HSV hexcone



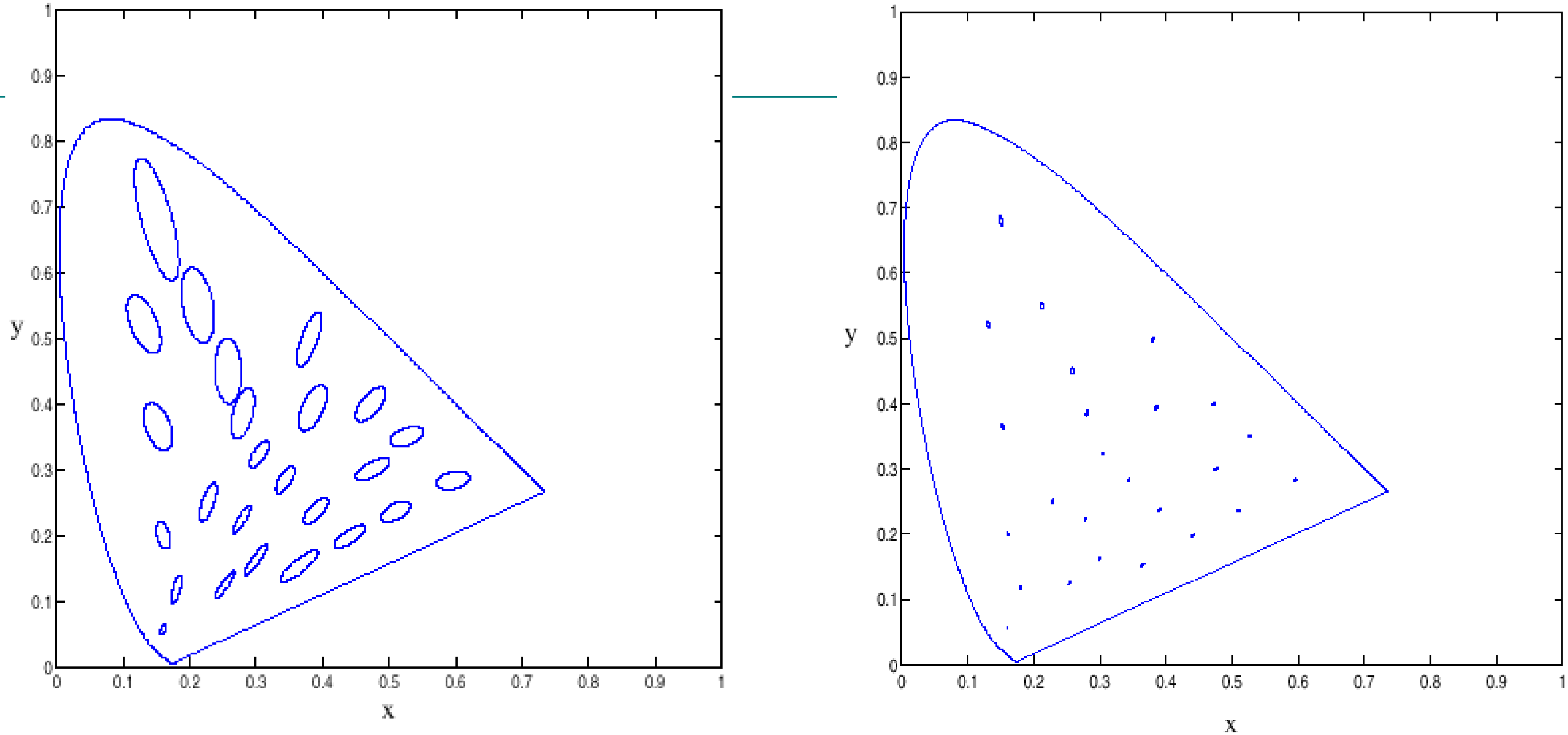


Adapted from David Forsyth, UC Berkeley

Uniform color spaces

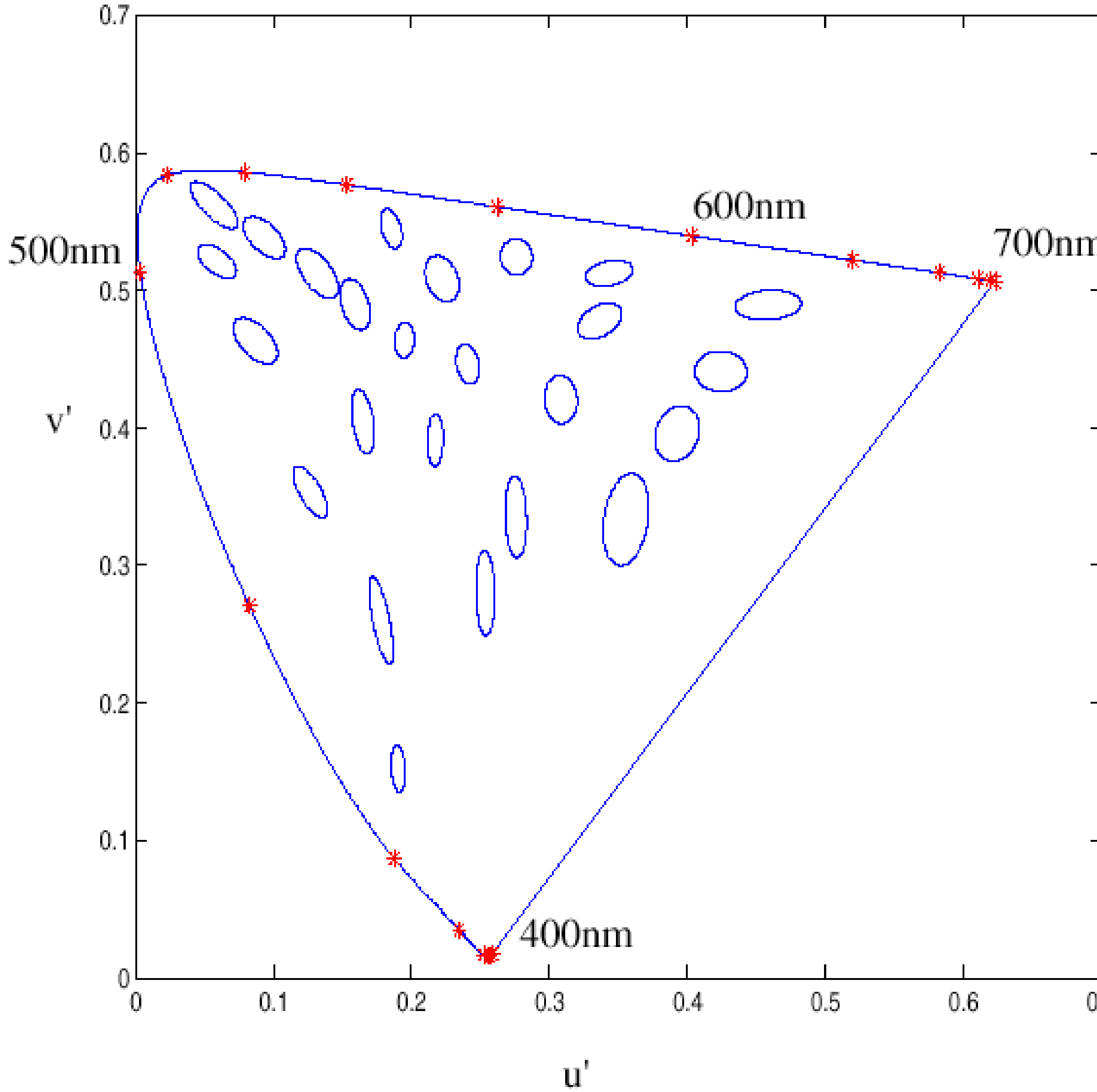
- McAdam ellipses (next slide) demonstrate that differences in x,y are a poor guide to differences in color
- Construct color spaces so that differences in coordinates are a good guide to differences in color.

Adapted from David Forsyth, UC Berkeley



Variations in color matches on a CIE x, y space. At the center of the ellipse is the color of a test light; the size of the ellipse represents the scatter of lights that the human observers tested would match to the test color; the boundary shows where the just noticeable difference is. The ellipses on the left have been magnified 10x for clarity; on the right they are plotted to scale. The ellipses are known as MacAdam ellipses after their inventor. The ellipses at the top are larger than those at the bottom of the figure, and that they rotate as they move up. This means that the magnitude of the difference in x, y coordinates is a poor guide to the difference in color.

CIE u'v' which is a projective transform of x, y. We transform x,y so that ellipses are most like one another. Figure shows the transformed ellipses.



Adapted from David Forsyth, UC Berkeley

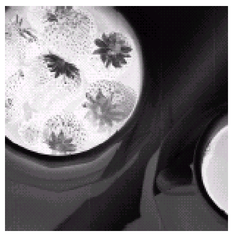
Color Space Transformations

- Why
  - To print (RGB → CMYK or Greyscale)
  - To compress images (RGB → YUV)
    - Color information (U,V) can be compressed 4 times without significant degradation in perceptual quality)
  - To compare images (RGB → CIELAB)
    - CIELAB space is more perceptually uniform
    - Euclidean distance in LAB space hence meaningful
    - e.g. Photoshop operations

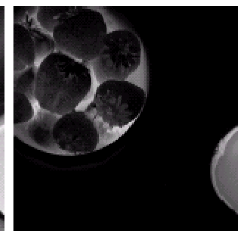
Color Channels


Full color


Cyan


Magenta

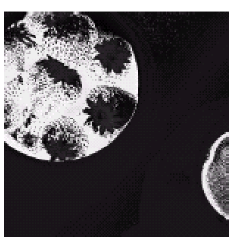

Yellow


Black


Red


Green


Blue


Hue


Saturation


Intensity

Color Constancy

If you observe an object, say a red object, on a bright sunny day and later on a cloudy day, you would not perceive any difference in the color, the object still appears red. However, looking at the spectrum of natural ambient lights under different conditions, we see that the illuminant color is very different depending on the conditions. This implies that the cones in the eye must have measured very different "observed color". In fact, if we measure the spectral distribution of the reflected light under different conditions, it clearly varies a lot, yet the human visual system seems to report a constant color, the surface color.

Again, the perceived color is unaffected by the illuminant and is the surface color. The basic phenomenon is that the visual system normalizes for the color of the illuminant.

Adapted from Martial Hebert, CMU

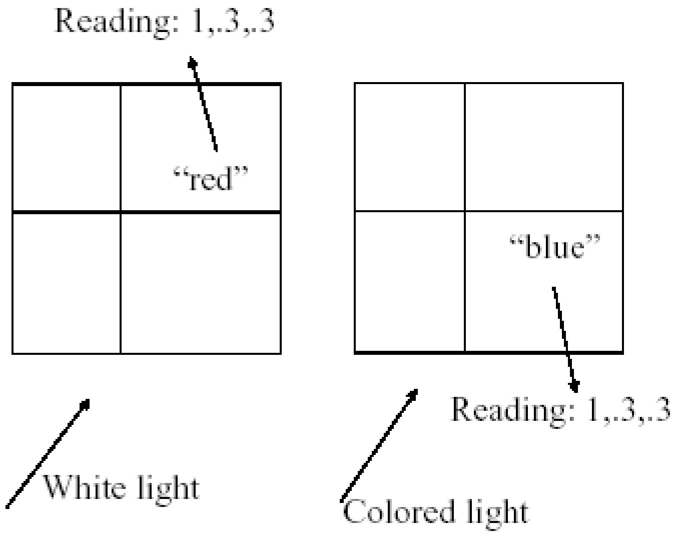
Color Constancy

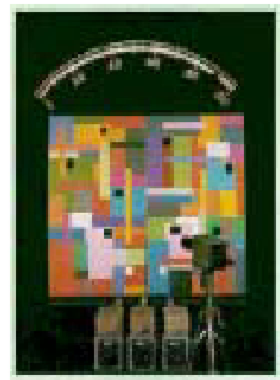
Adapted from Martial Hebert, CMU

Color Constancy

Adapted from Martial Hebert, CMU

Color Constancy

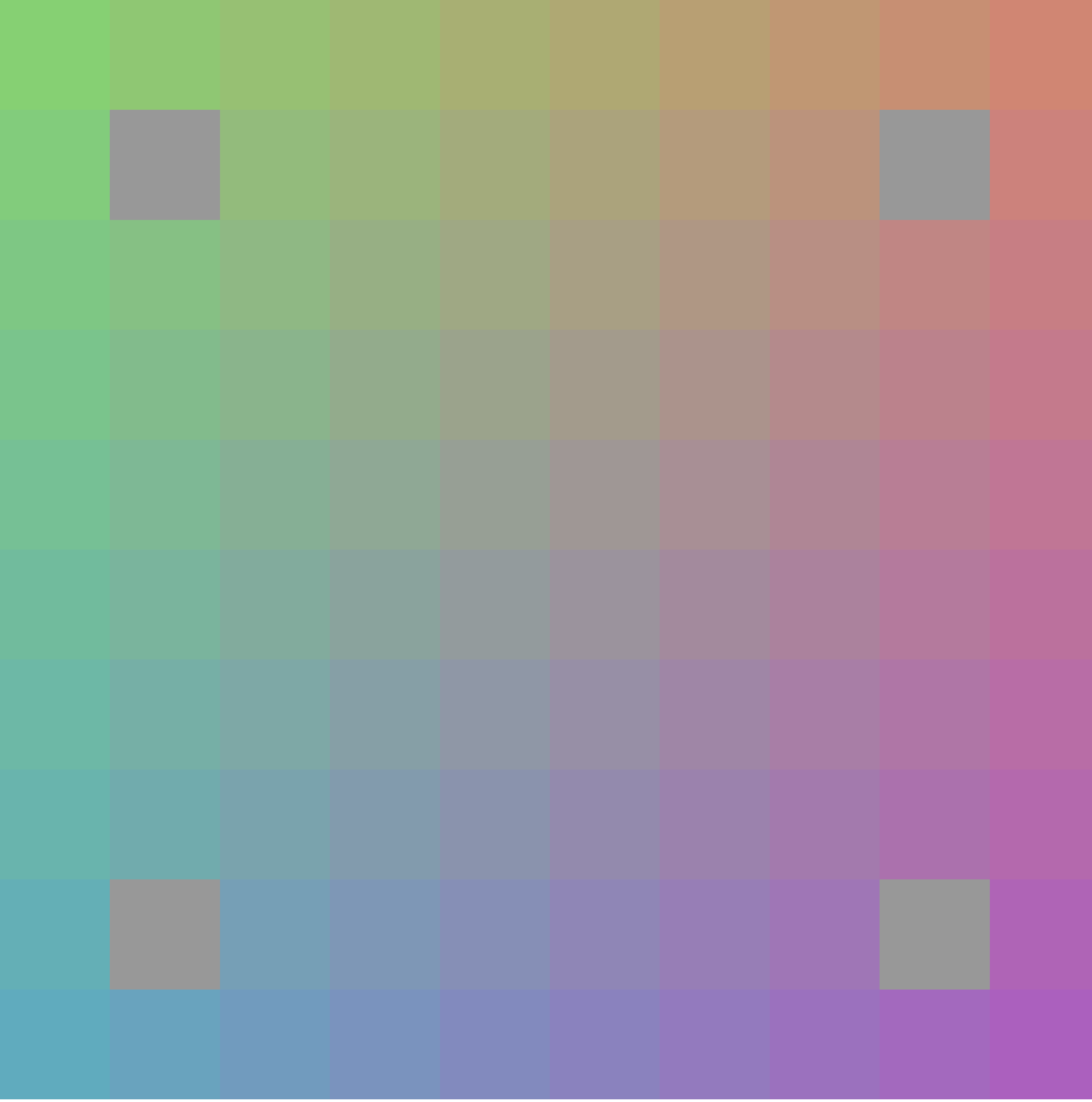




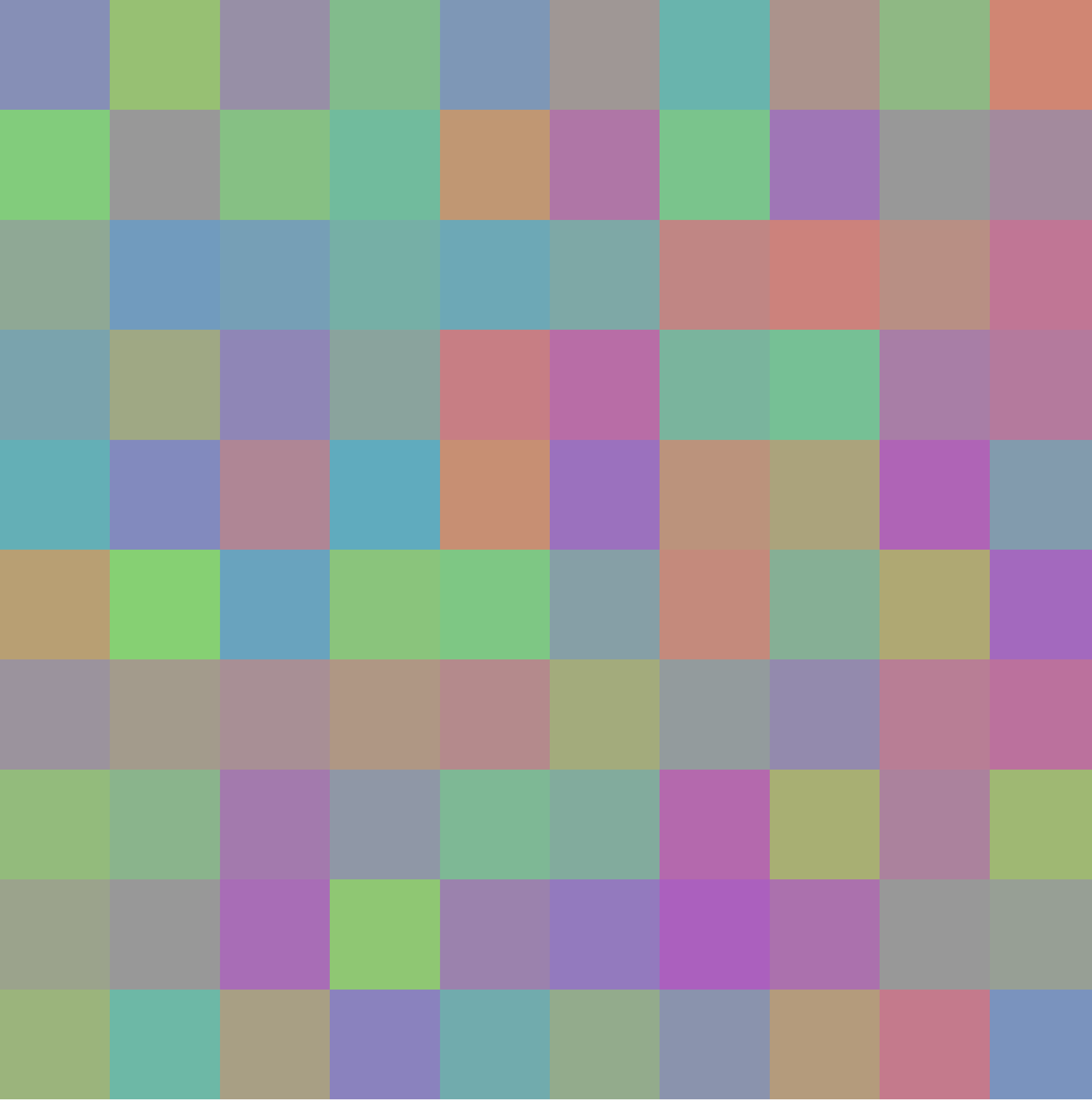
Land's experiments

The color constancy phenomenon was confirm by Edwin Land's experiments in which subjects are presented with flat patterns of colored rectangles under different lights. In all experiments, subjects would name the correct color irrespective of the illuminant color. For example, a red square illuminated with white light would elicit the correct response "red", but a blue square illuminated with colored light would also get the correct answer "blue", even though the actual reflected light is the same in both cases. In that case, the human visual system seems to be able to distinguish between two colors even though the light radiating to the eye has the same spectrum!

Adapted from Martial Hebert, CMU



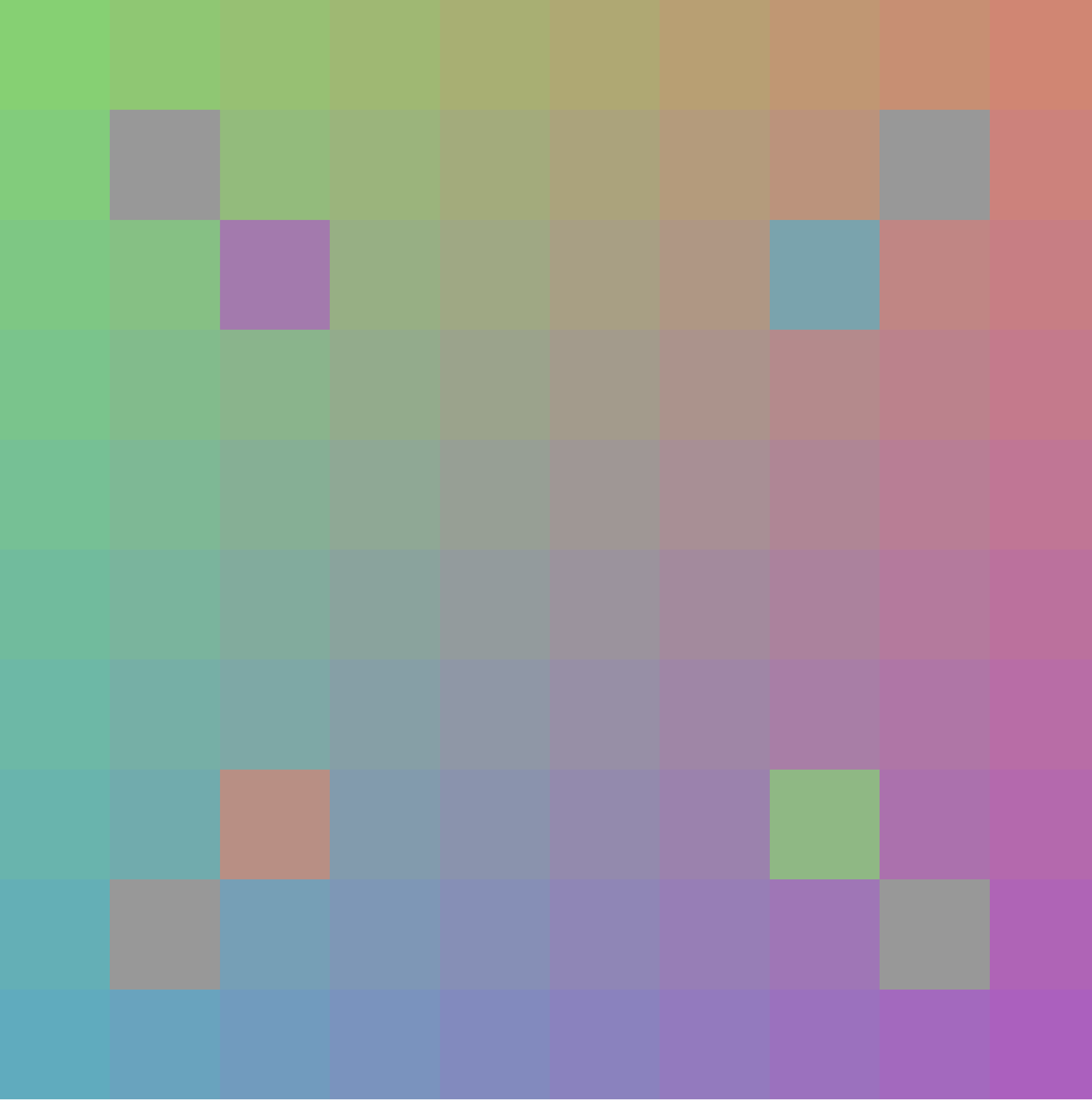
Adapted from David Forsyth, UC Berkeley



same set of tiles, but they've been rearranged, though the four grey tiles have been fixed.

Notice how they now appear to have the same hue.

Adapted from David Forsyth, UC Berkeley



just rearranging four of the tiles makes the grey tiles look as though they have the same hue and increases the range of apparent colors what is next to a tile has a strong effect on its perceived color.

Adapted from David Forsyth, UC Berkeley