Colour

Outline

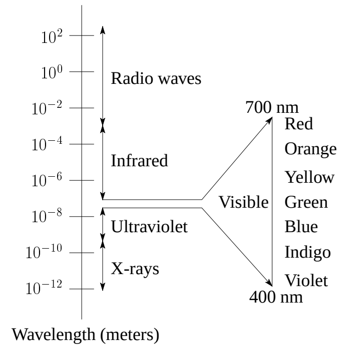
- Spectrum and colour
- Measuring colour
- The CIE XYZ colour space
- Colour spaces for computer graphics

What is Light?

- When light flies through space and interacts with itself, it behaves as a *wave*.
- When light interacts with matter, it behaves as a *particle*.
- The truth is more complicated than both of these!

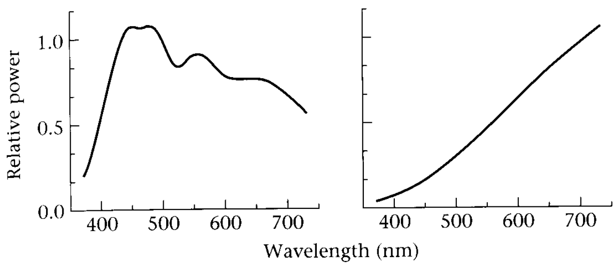
Light as Waves

- Maxwell described the *electromagnetic spectrum* and showed that visible light was just part of the spectrum.



Light as Particles

- At any given moment, a light source emits some relative amount of photons at each frequency.
- We can plot the *emission spectrum* of a light source as power vs. wavelength.



Emission spectra for daylight and a tungsten bulb (Wandell 4.4)

- A light source is characterized by its emission spectrum.

What We Do With Light

The eyes and brain turn an incoming emission spectrum into a discrete set of values.

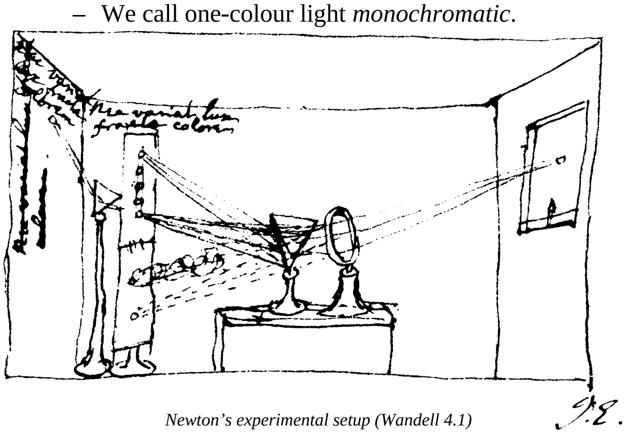
Mathematically, this is accomplished by integrating the product of emission spectrum with each of the three cone response curves.

The signal sent to our brain is somehow interpreted as *colour*.

Newton's Experiments

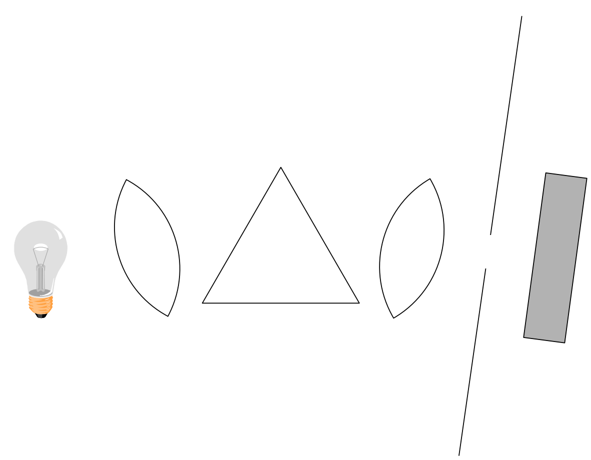
Newton showed that a prism spreads apart a light source's emission spectrum in space (why?).

- Light emerging from the prism cannot be further decomposed.
- Newton called the colours of these "atomic" lights *primaries*.
- We call one-colour light *monochromatic*.



Newton's experimental setup (Wandell 4.1)

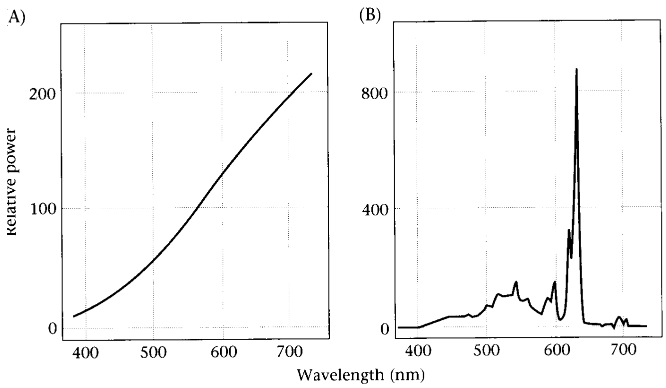
Measuring the Emission Spectrum



A spectroradiometer

Emission Spectrum is not Colour

- Recall how much averaging the eye does. Light is infinite dimensional!
- Different light sources can evoke exactly the same colours. Such lights are called "metamers".



A dim tungsten bulb and an RGB monitor set up to emit a metameric spectrum (Wandell 4.11)

Colour Matching

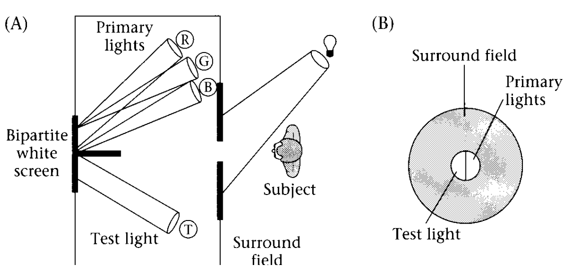
Conjecture: every colour can be uniquely expressed as a mixing of a small number of *primaries*. (Why is this plausible?)

If true, this gives us a meaningful definition of colour as a set of primaries and the range of possible combinations between them.

Given a choice of primaries, how can we verify the conjecture?

The Colour Matching Experiment

Subject attempts to match a combination of primaries with a test light.



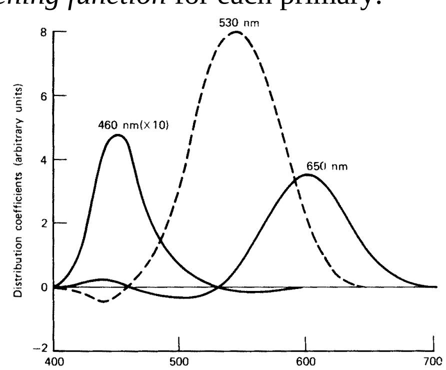
Experimental setup for colour matching (Wandell 4.10)

It turns out that three primaries suffice to produce all perceivable colours.

The experiment tells us a lot more about colour perception…

Colour Matching Functions

A colour matching experiment yields a *colour matching function* for each primary.

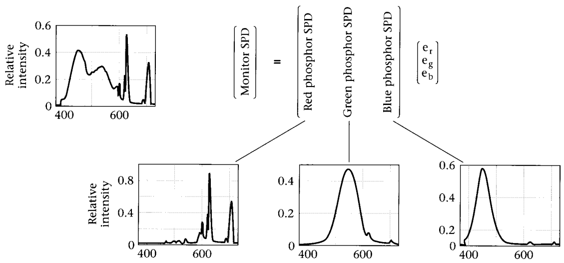


Colour matching functions for primaries at 460, 530 and 650 nm (Wasserman 3.3)

How can we use the matching functions to match an arbitrary monochromatic light?

What about an arbitrary light?

Choosing Primaries



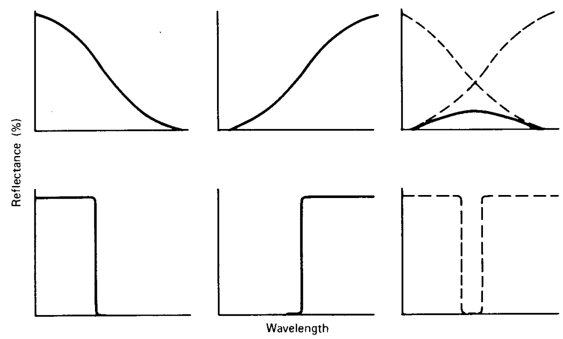
Emission spectra for RGB monitor phosphors (Wandell B.3)

Primaries don't have to be monochromatic.
You can still derive colour matching functions.

It turns out that colour matching functions are always linearly related! Why?

Coloured Surfaces

So far, we've discussed the colours of lights.
How do **surfaces** acquire colour?

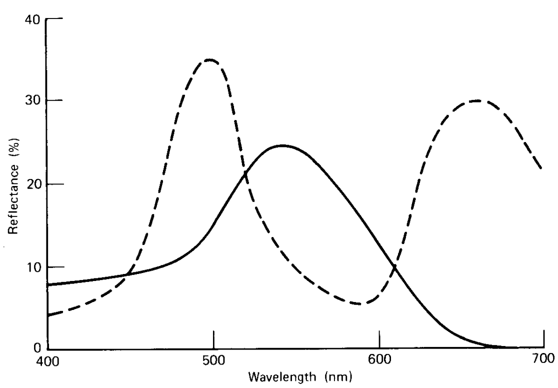


Subtractive colour mixing (Wasserman 2.2)

A surface's *reflectance* is its tendency to reflect incoming light across the spectrum.

Reflectance is combined *subtractively* with incoming light.

Subtractive Metamers

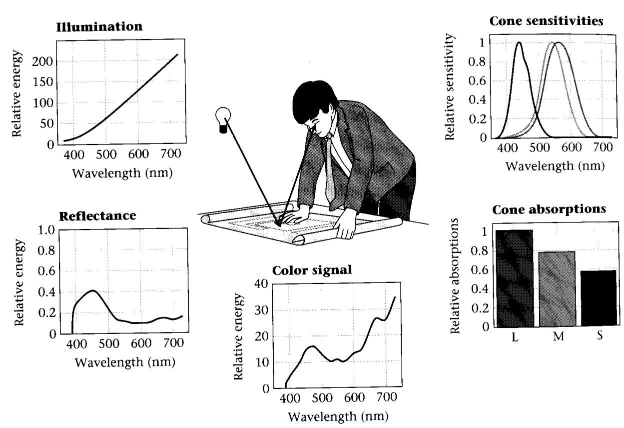


Surfaces that are metamers under only some lighting conditions (Wasserman 3.9)

Reflectance adds a whole new dimension of complexity to colour perception.

The solid curve appears green indoors and out.
The dashed curve looks green outdoors, but brown under incandescent light.

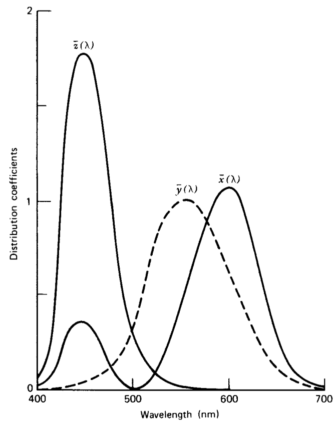
Illustration of Colour Appearance



How light and reflectance become cone responses (Wandell, 9.2)

The CIE *XYZ* System

A standard created in 1931 by CIE, defined in terms of three colour matching functions.



The XYZ colour matching functions (Wasserman 3.8)

What are the primaries?

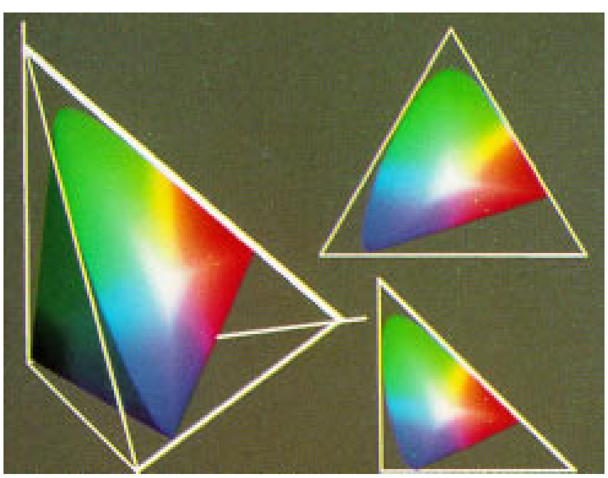
Why were these colour matching functions chosen?

CIE Coordinates

Given an emission spectrum, we can use the CIE matching functions to obtain the *X*, *Y* and *Z* coordinates.

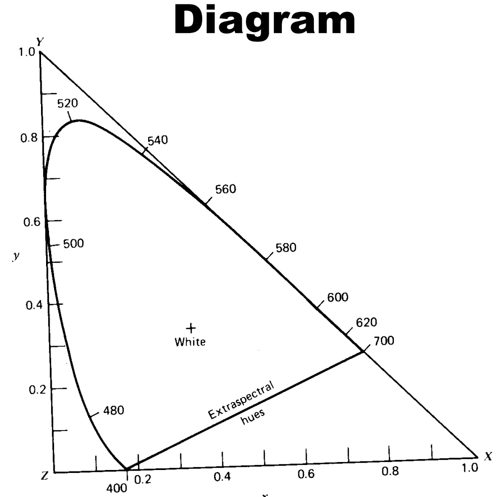
Then we can compute *chromaticity coordinates*. This gives a brightness independent notion of colour.

The CIE Colour Blob



Different views of the CIE colour space (Foley II.1)

The CIE Chromaticity Diagram



The chromaticity diagram (Wasserman 3.7)

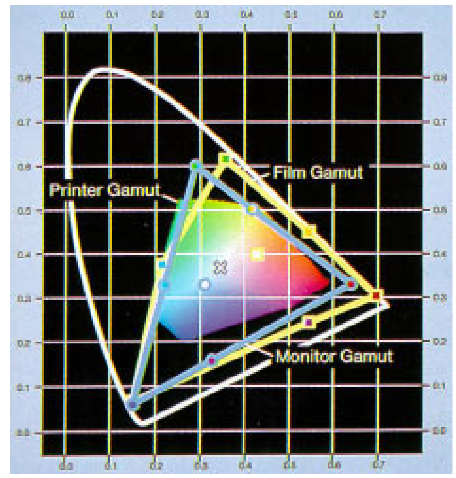
- A projection of the plane $X+Y+Z=1$.
- Each point is a *chromaticity* value, which depends on *dominant wavelength*, or *hue*, and *excitation purity*, or *saturation*.

More About Chromaticity

- Dominant wavelengths go around the perimeter of the chromaticity blob.
  - A colour's dominant wavelength is where a line from white through that colour intersects the perimeter.
  - Some colours, called *nonspectral* colours, don't have a dominant wavelength.
- Excitation purity is measured in terms of a colour's position on the line to its dominant wavelength.
- Complementary colours lie on opposite sides of white, and can be mixed to get white.

Gamuts

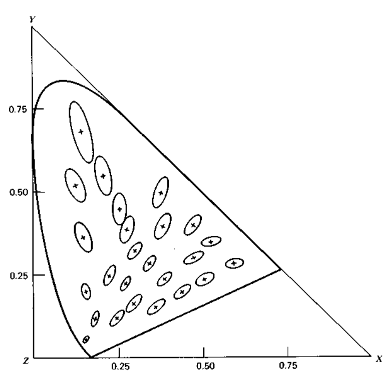
Not every output device can reproduce every colour. A device's range of reproducible colours is called its *gamut*.



Gamuts of a few common output devices in CIE space (Foley, II.2)

Perceptual (non-)Uniformity

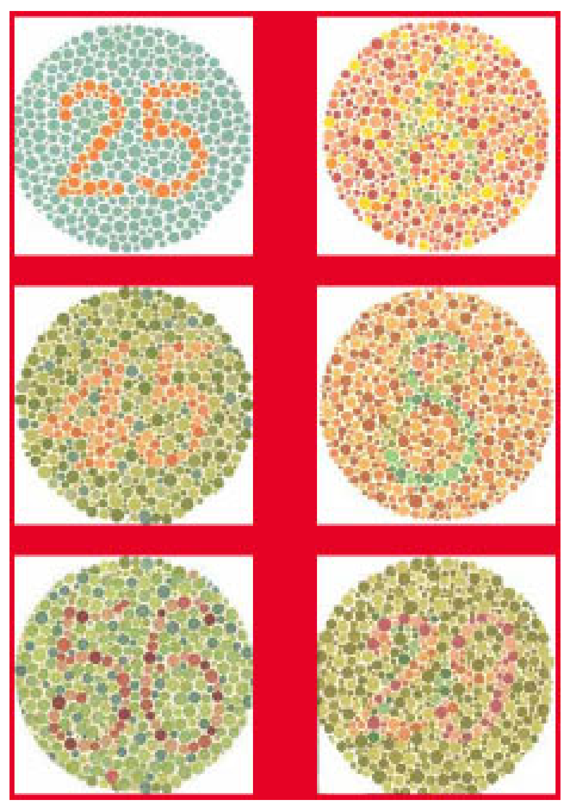
The *XYZ* colour space is not perceptually uniform!



Enlarged ellipses of constant colour in XYZ space (Wasserman 3.10)

Some modified spaces attempt to fix this:

•*L*u*v**
•*L*a*b**



Colour Spaces for Computer Graphics

In practice, there's a set of more commonly-used colour spaces in computer graphics:

- RGB for display
- HSV for user selection
- CMY (or CMYK) for hardcopy
- YIQ for television broadcast

RGB

Perhaps the most familiar colour space, and the most convenient for display on a CRT (why?)

What does the RGB colour space look like?

HSV

More natural for user interaction, corresponds to the artistic concepts of tint, shade and tone.

The HSV space looks like a "hexcone":

CMY

A subtractive colour space used for printing.

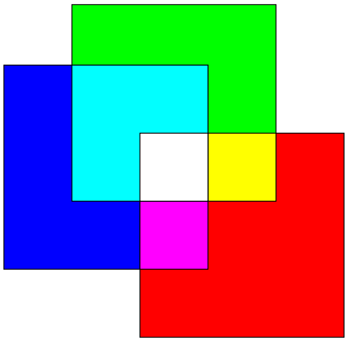
Involves three subtractive primaries:

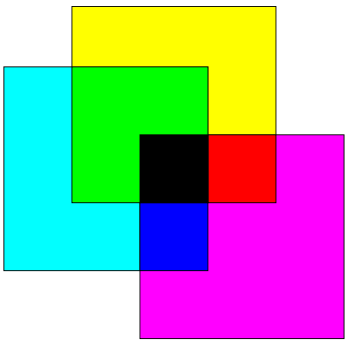
- Cyan - subtracts red
- Magenta - subtracts green
- Yellow - subtracts blue

Mixing two pigments subtracts their opposites from white.

CMYK adds blacK ink rather than using equal amounts of all three.

RGB vs. CMY





YIQ

Used in TV broadcasting, YIQ exploits useful properties of the visual system.

- Y - luminance (taken from CIE)
- I - major axis of remaining colour space
- Q - remaining axis

YIQ is broadcast with relative bandwidth ratios 8:3:1

- We're best as distinguishing changes in luminance.
- Small objects can be compressed into a single colour dimension.

Why do we devote a channel to luminance?

Summary

Lights are characterized by emission spectra; surfaces have reflectance spectra.

Emission spectrum is not colour. Our visual systems integrate and average emission spectra into cone responses, which are interpreted as colour.

Many different spectra can have the same colour. Such spectra are called metamers.

The CIE *XYZ* system is a standardized colour space defined in terms of three matching functions. The chromaticity diagram, derived from the *XYZ* space, gives a useful interpretation of colour.

A gamut is the range of colours a device can reproduce.

There are several important colour spaces commonly used in computer graphics and broadcast.

Reading

Suggested:

- Angel, section 1.3
- Foley et al., sections 13.2 - 13.6
- Glassner, sections 1.7, 2.1, 2.2, 3.6

Further reading:

- Gerald S. Wasserman. *Color Vision: An Historical Introduction.* John Wiley & Sons, New York, 1978
- Brian Wandell. *Foundations of Vision.* Sinauer Associates, Sunderland, MA, 1995.