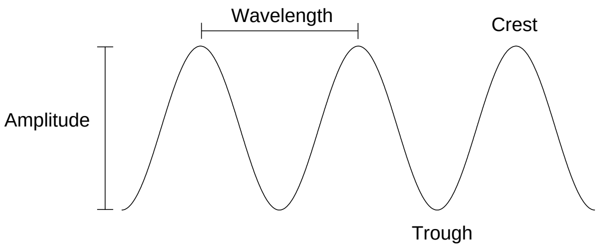
Statistics 120
Light and Color

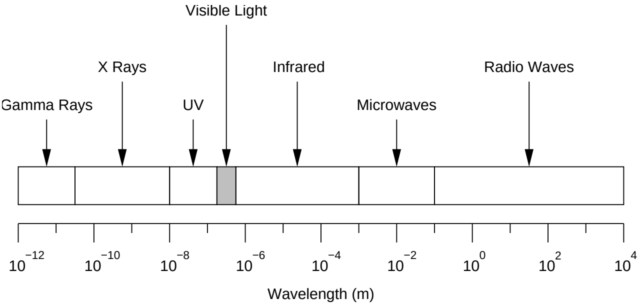
Light

- Light is a form of electromagnetic radiation.
- Electromagnetic radiation can be regarded as a wave-like phenomenon.
- There are different kinds of em-radiation, each characterised by its wavelength.



The Electromagnetic Spectrum

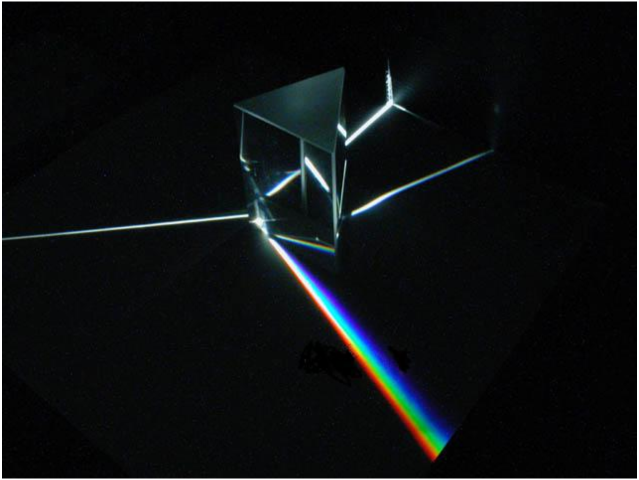
- Visible light has wavelengths in a narrow band centred on 600 nanometers (1 nanometre = 10^{-9} metres).
- Radio waves and microwaves have longer wavelengths than visible light; UV radiation, X and Gamma rays have shorter wavelengths.



Newton and Light

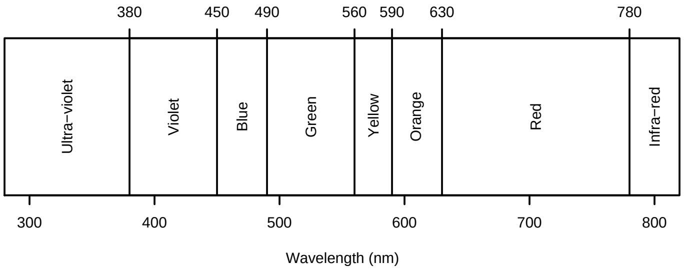
- Isaac Newton showed that white light could be decomposed into a spectrum of colours.
- Newton also showed that these colours could not be decomposed further and that they could be recombined to form white.
- We now know that colours correspond to different light wavelengths.

Isaac Newton's Prism Experiment



Wavelength and Colour

The wavelength of light corresponds directly to the colour sensation it produces.



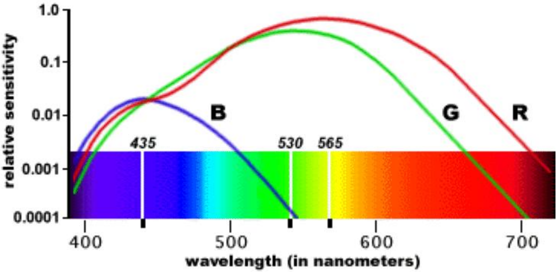
(Colours blend into one another so it is hard to draw precise boundaries between them.)

Young-Helmhotz Theory

- In the 19th century, Young suggested that human colour vision could be explained by the existence of separate Red, Green and Blue colour receptors.
- The theory was popularised by Helmholz and is now known as the Young-Helmholtz theory.
- We now know that there really are three kinds of colour receptors in the eye.

Colour and Cone Cells

- It has been shown that the cone cells in the retina are not identical in their spectral response to light.
- There are three different types of cone cell, which have the relative sensitivities shown below.



Names for the Cone Cells

- Young's orginal theory was based on Red, Green and Blue receptors. As a result the three kinds of cones in the eye have been labelled as R, G and B (or ρ, γ and β).
- The peak sensitivity for the "Red" cones occurs in the yellow region of the spectrum and the modern naming convention is L, M and S for long, medium and short wavelength.
- Both conventions are still used.

Cone Numbers

- The *R*, *G* and *B* cones are not found in the eye in equal numbers.
- The relative abundances are:

Cone Type	*Relative Abundance*
R	40
G	20
B	1

Opponent Colour Theory

- Predates the Young-Helmholz theory. Dates as far back as Leonardo da Vinci.
- The colour pairs *red/green* and *yellow/blue* are *in opposition*.
- No colour can simultaneously exhibit both redness and greenness or blueness and yellowness.
- A colour can be described by three parameters:

  1. Where it lies on a light/dark scale,
  2. Where it lies on a red/green scale,
  3. Where it lies on a yellow/blue scale.

The Evolution of Colour Vision

- The human colour vision system appears to have evolved in steps.
- Initially our (very remote) ancestors had a single class of light sensitive cells.
- At a point predating the evolution of the mammals this single class of cells differentiated into separate yellow and blue classes.
- Much later, in primates, the class of yellow sensitive cells differentiated into separate red and green sensitive classes.

Primitive Colour

The image below shows an image as it would appear to an animal with just a yellow/blue based vision system.

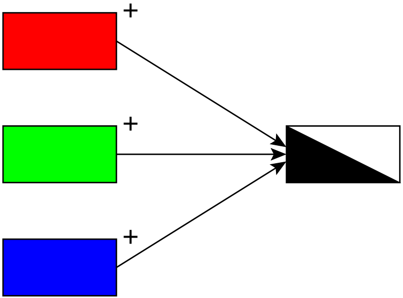
Primate Colour

The image below shows an image as it would appear to a primate with a red/green/blue based vision system.

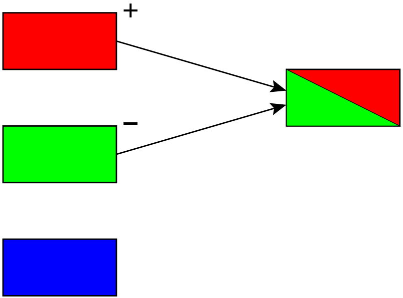
Tranforming RGB To Opponent Colours

- The transformation of the signals from the R, G and B cones into oponent colour signals can be performed by very simple wiring.
- There are three different wiring diagrams. One for each of the Brightness, Red/Green and Yellow/Blue channels.

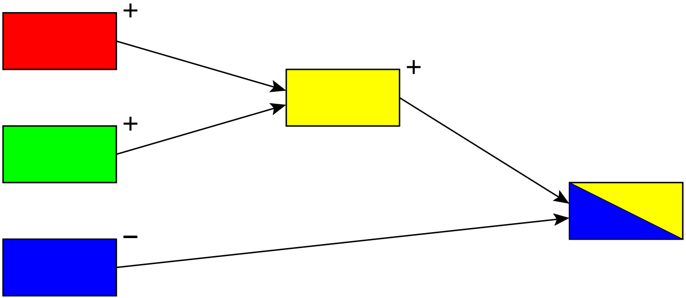
Cone Wiring: Brightness Channel



Cone Wiring: Red/Green Channel



Cone Wiring: Yellow/Blue Channel



Opponent Colours and Television

- In prehistoric times, television was only available in black and white.
- When the technology became available to make colour television, engineers faced the problem of how to transmit the colour information but still remain compatible with all the existing black and white sets.
- They chose to add the colour information by adding two additional colour signals.
- The two signals were the colour positions on the opponent red/green and yellow/blue scales.

RGB and Opponent Colour Compared

- The RGB description of light corresponds to the stimulation of the receptors in our eyes. It is one that we can examine by applying external stimuli.
- The opponent description is an internal one, and is less subject to experimentation.
- Although the RGB and Opponent models provide a full description of colour, they do not provide a natural way to think about colour.

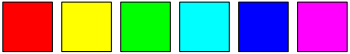
Perceptually Based Colour Parameters

We most naturally think about colour in terms of three parameters.

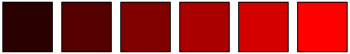
- *Hue* – the property of colour corresponding to wavelength.
- *Brightness* – the same hue can exist in brighter or dimmer forms.
- *Purity* – colours can be pure (the hues found in the spectrum), or they can be a mixture of hues. For example, pink is a mix of red and white.

Perceptually Based Colour Parameters

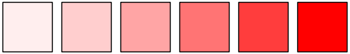
Hue:



Brightness:



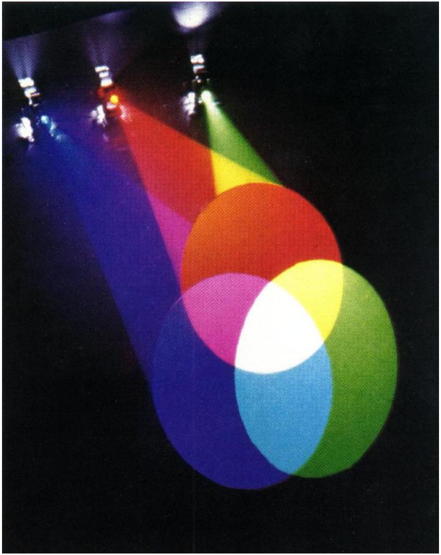
Purity:



Device Based Colour Specification

- Our eyes are based on three colour receptors — R, G and B.
- We can use variable amounts of three primary colours to stimulate these receptors differentially. A typical choice of primaries is:
  - $R \approx 610$ nm.
  - $G \approx 540$ nm.
  - $B \approx 475$ nm.
- Although there are only three spectral wavelength present, it still possible to generate a wide variety of colour sensations.

Combination of Color Primaries



RGB Colour

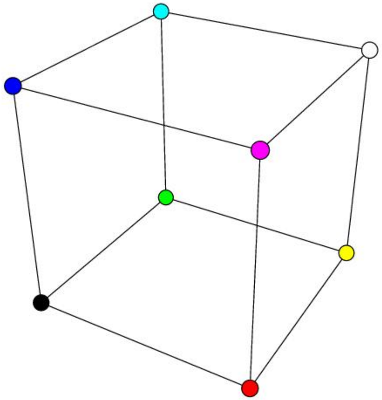
- Computer displays use combinations of red, green and blue primary colours to generate a range of on-screen colours.

- Each generated colour can be described by the amount of red, green and blue it contains.

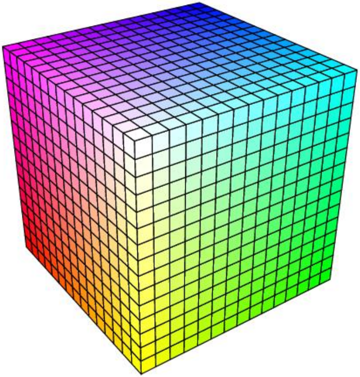
- The amounts of R, G and B are usually normalised to the range $[0,1]$ (or possibly $[0,255]$).

- The set of possible colours thus corresponds to points (R,G,B) lying in a cube.

The RGB Colour Cube



The RGB Colour Cube



RGB Color in R

It is possible to specify an RGB colour specification in R using the `rgb` function.

```
rgb(r, g, b)
```

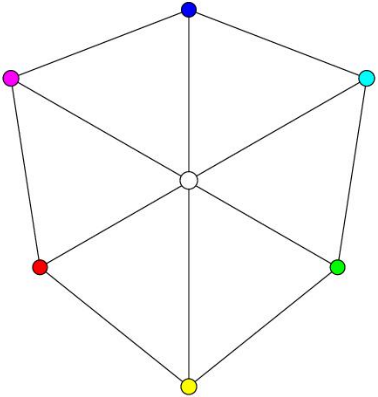
where `r`, `g` and `b` are vectors of values between 0 and 1.

It is also possible to specify colour as a string of two digit hexadecimal digits of the form `"#RRGGBB"`.

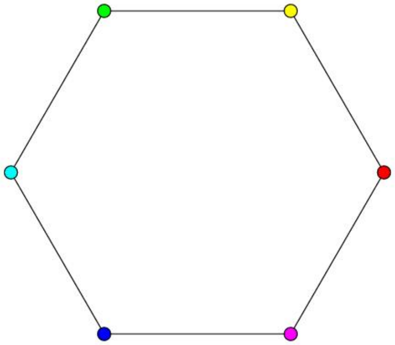
`"#FF0000"` = Red
`"#FFFF00"` = Yellow
`"#00FF00"` = Green

Using RGB in this way is quite unintuitive.

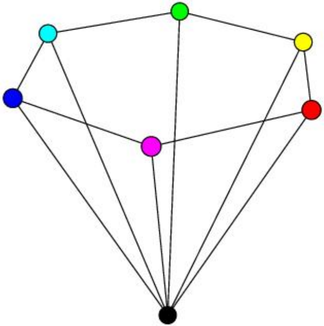
The RGB Colour Cube



A Colour Hexagon



The HSV Hexcone

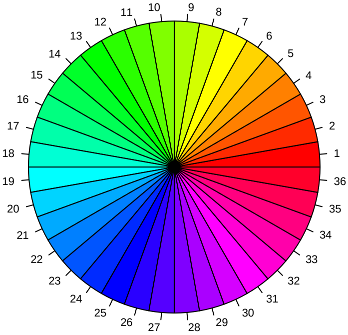


HSV Colour Specification

An HSV colour specification gives a location within the colour hexcone.

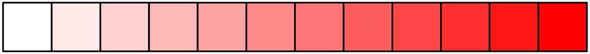
- Hue is the “angle” around the colour hexagon to the colour. This is often in degrees or radians. In R it is a value in $[0, 1]$.
- Saturation is distance from the central axis of the hexcone to the colour as a fraction of the horizontal distance from the central axis to the boundary.
- Value is the fraction of the distance from the base of the hexcone to the colour.

Example: A Simple Colour Wheel



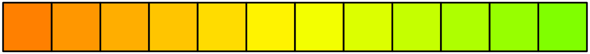

```
> pie(rep(1, 36), col = hsv(h=0:35/36))
```

Example: A Saturation Ramp



```
> plot.new()
> plot.window(xlim=c(0, 12), ylim=c(0,1), asp=1)
> rect(0:11, 0, 1:12, 1, col = hsv(s = 0:11/11))
```

Example: A Hue Ramp



```
> plot.new()
> plot.window(xlim=c(0, 12), ylim=c(0,1), asp=1)
> rect(0:11, 0, 1:12, 1,
col = hsv(h = seq(1/12, 3/12, length=12)))
```