Interactive Computer Graphics

Lecture 7: Colour

Ways of looking at colour

1. Physics

2. Human visual receptors

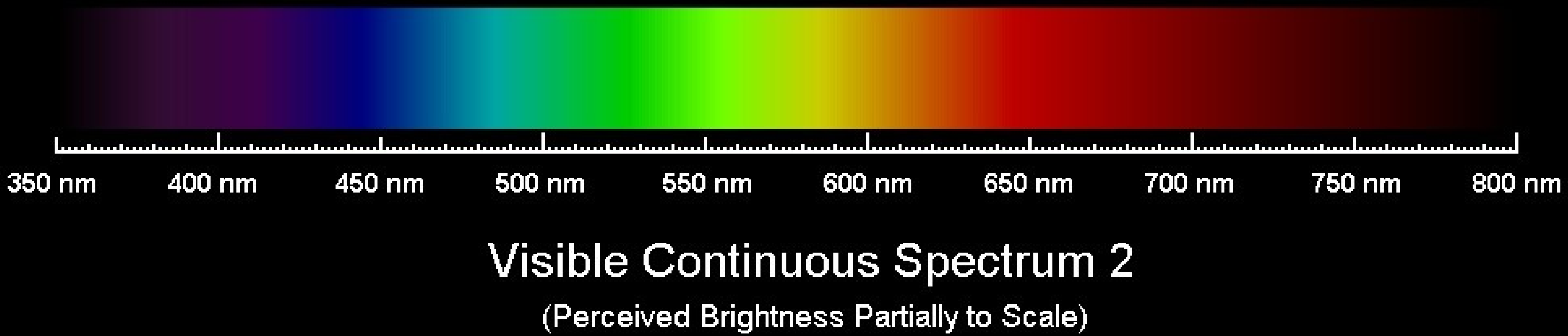
3. Subjective assessment

The physics of colour

A pure colour is a wave with:

Wavelength (λ)

Amplitude (intensity or energy) (I)

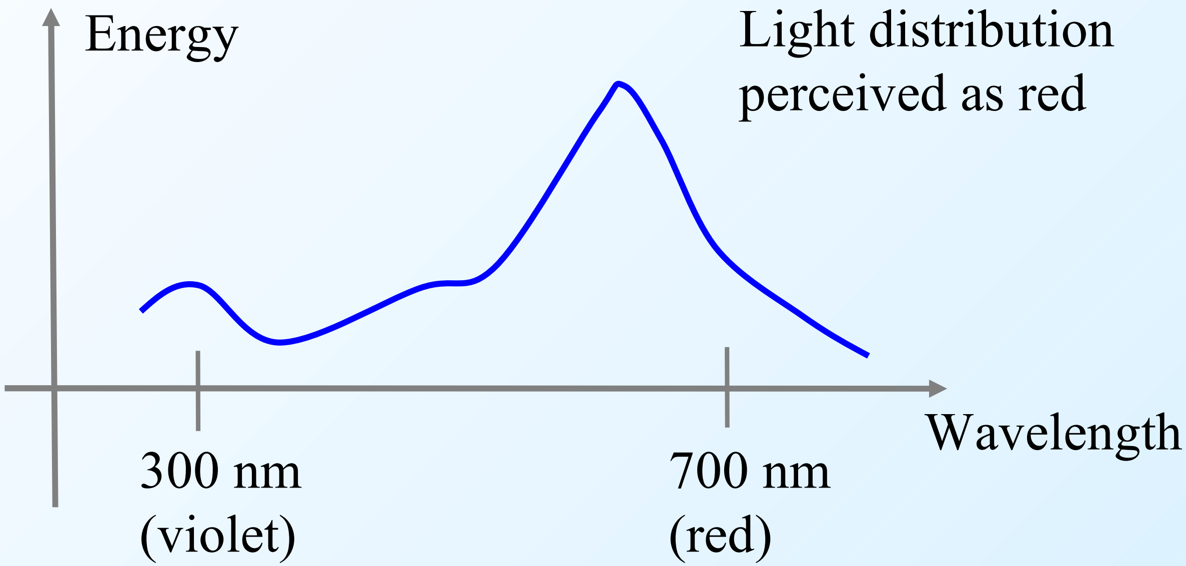

350 nm
400 nm
450 nm
500 nm
550 nm
600 nm
650 nm
700 nm
750 nm
800 nm
Visible Continuous Spectrum 2
(Perceived Brightness Partially to Scale)

Colours are energy distributions

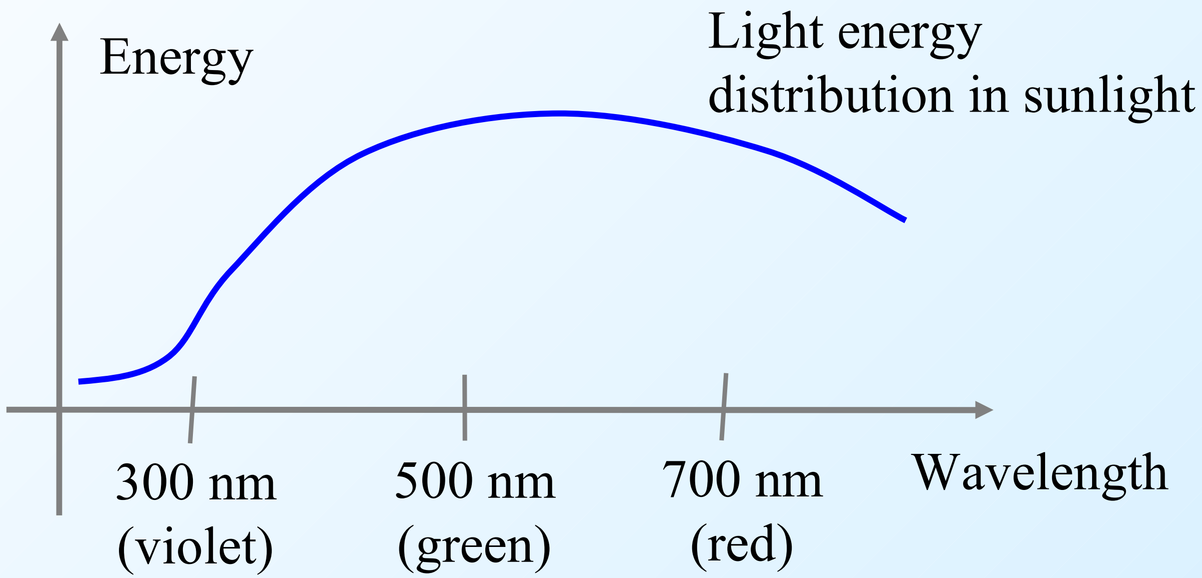
Lasers are light sources that contain a single wavelength (or a very narrow band of wavelengths)

In practice light is made up of a mixture of many wavelengths with an energy distribution.

Light distribution for red



Sunlight

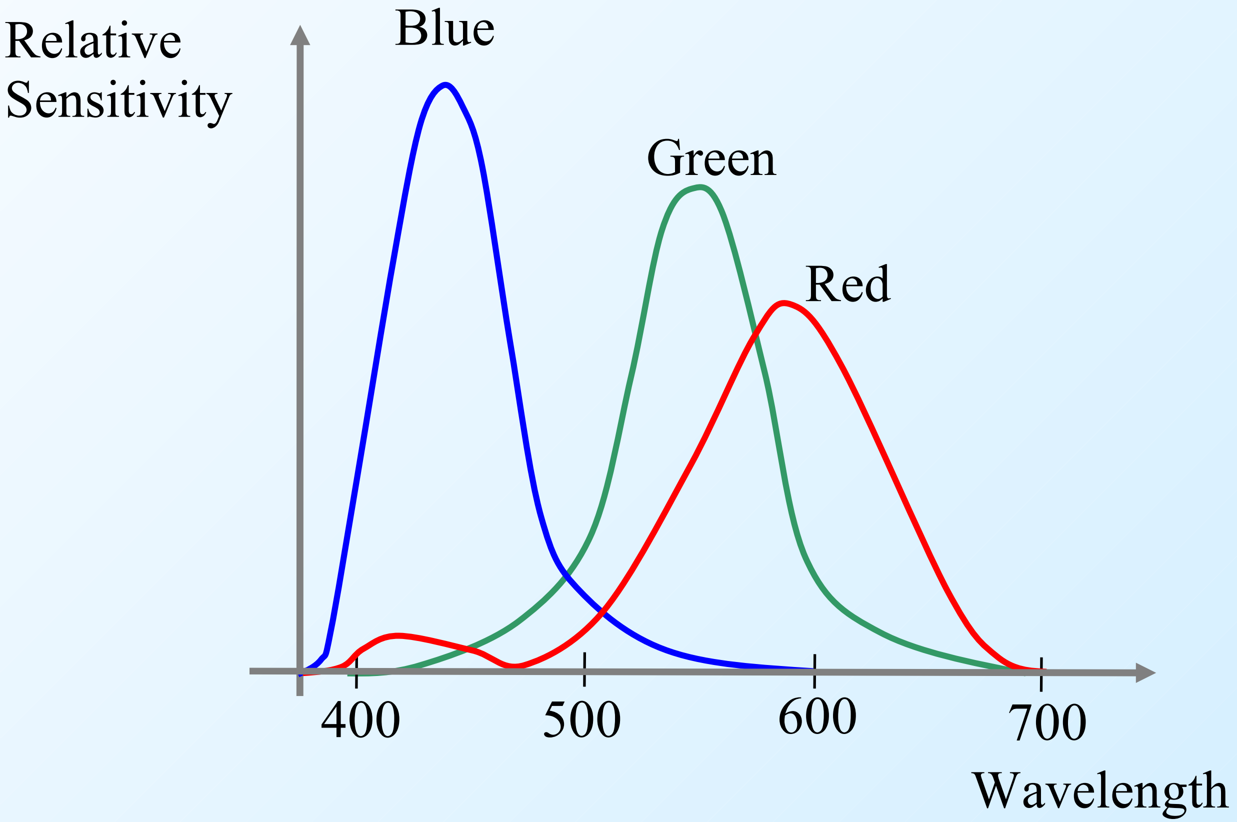

Energy
Light energy
distribution in sunlight
300 nm
(violet)
500 nm
(green)
700 nm
(red)
Wavelength

Human Colour Vision

Human colour vision is based on three ‘cone’ cell types which respond to light energy in different bands of wavelength.

The bands overlap in a curious manner.

Human receptor response



Tri-Stimulus Colour theory

The receptor performance implies that colours do not have a unique energy distribution.

and more importantly

Colours which are a distribution over all wavelengths can be matched by mixing three.

R G B

Colour Matching

Given any colour light source, regardless of the distribution of wavelengths that it contains, we can try to match it with a mixture of three light sources

$$X = r\,R + g\,G + b\,B$$

where R, G and B are pure light sources and r, g and b their intensities

For simplicity we can drop the R G B.

Subtractive matching

Not all colours can be matched with a given set of light sources (we shall see why later)

However, we can add light to the colour we are trying to match:

$$X + r = g + b$$

With this technique all colours can be matched.

The CIE diagram

The CIE diagram was devised as a standard normalised representation of colour.

As we noted, given three light sources we can mix them to match any given colour, providing we allow ourselves subtractive matching.

Suppose we normalise the ranges found to [0..1] to avoid the negative signs.

Normalised colours

Having normalised the range over which the matching is done we can now normalise the colours such that the three components sum to 1.

thus

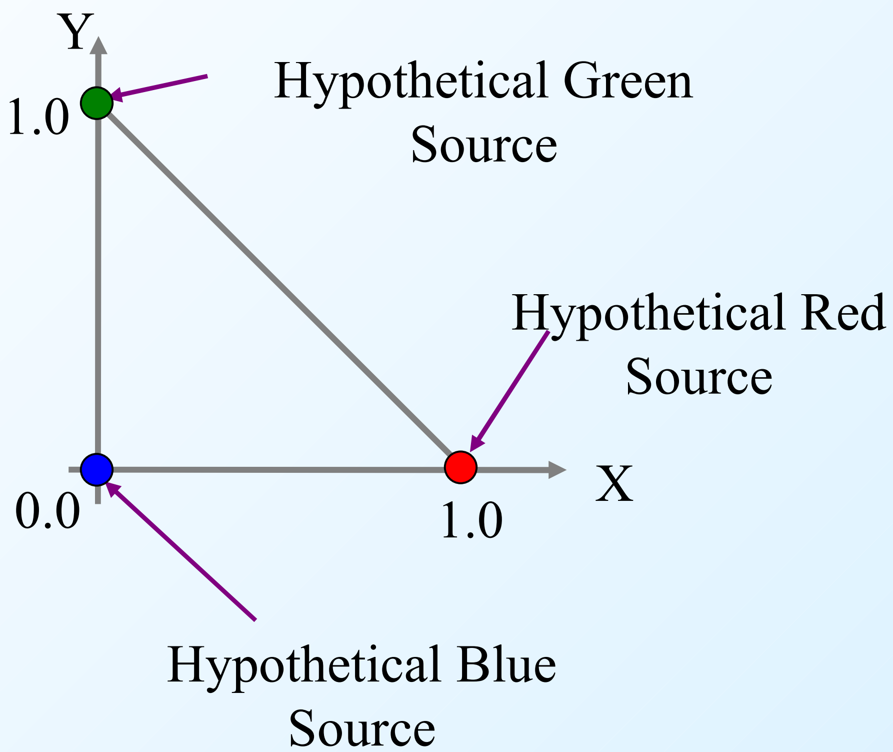
$$x = r/(r+g+b)$$

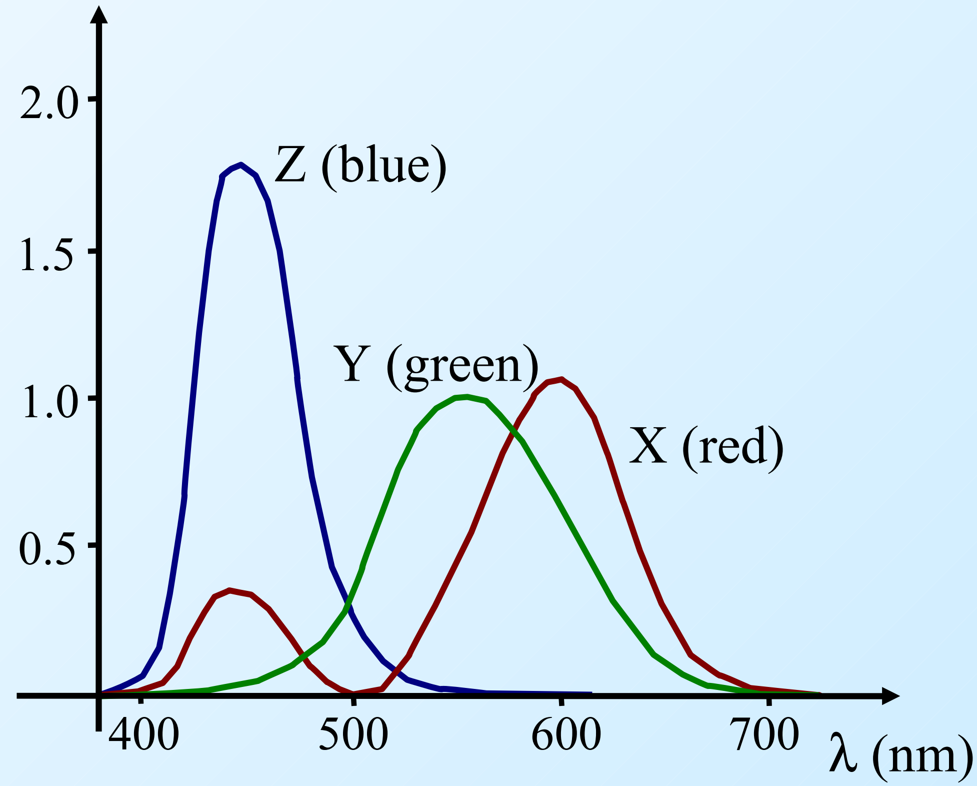
$$y = g/(r+g+b)$$

$$z = b/(r+g+b) = 1 - x - y$$

We can now represent all our colours in a 2D space.

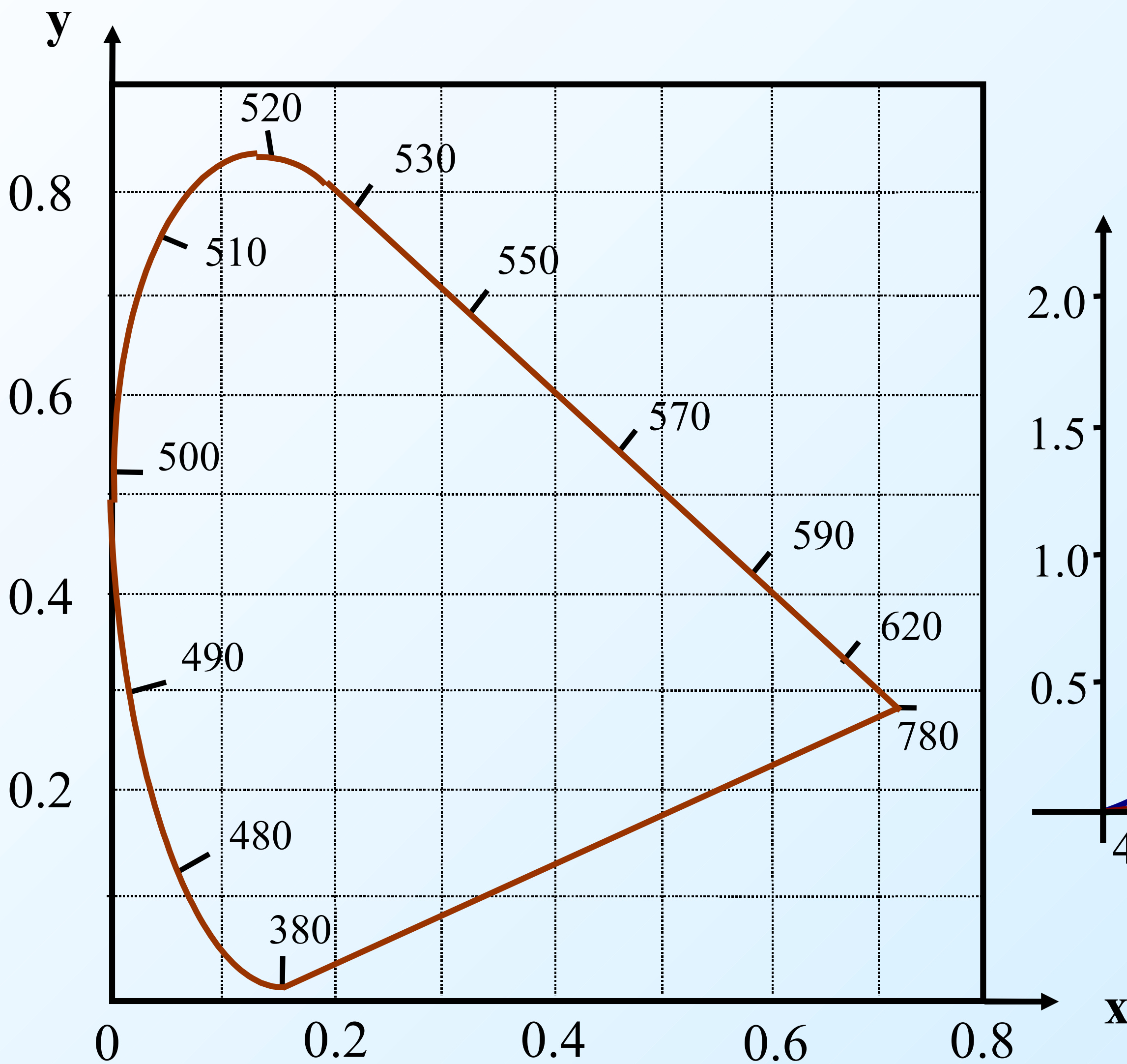
Defining the normalised CIE diagram

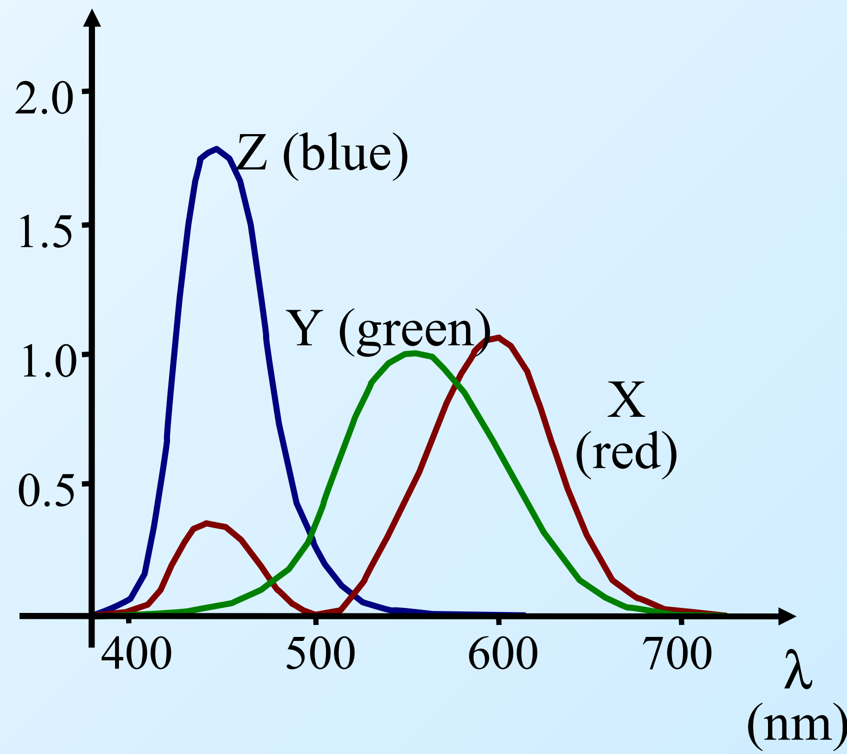




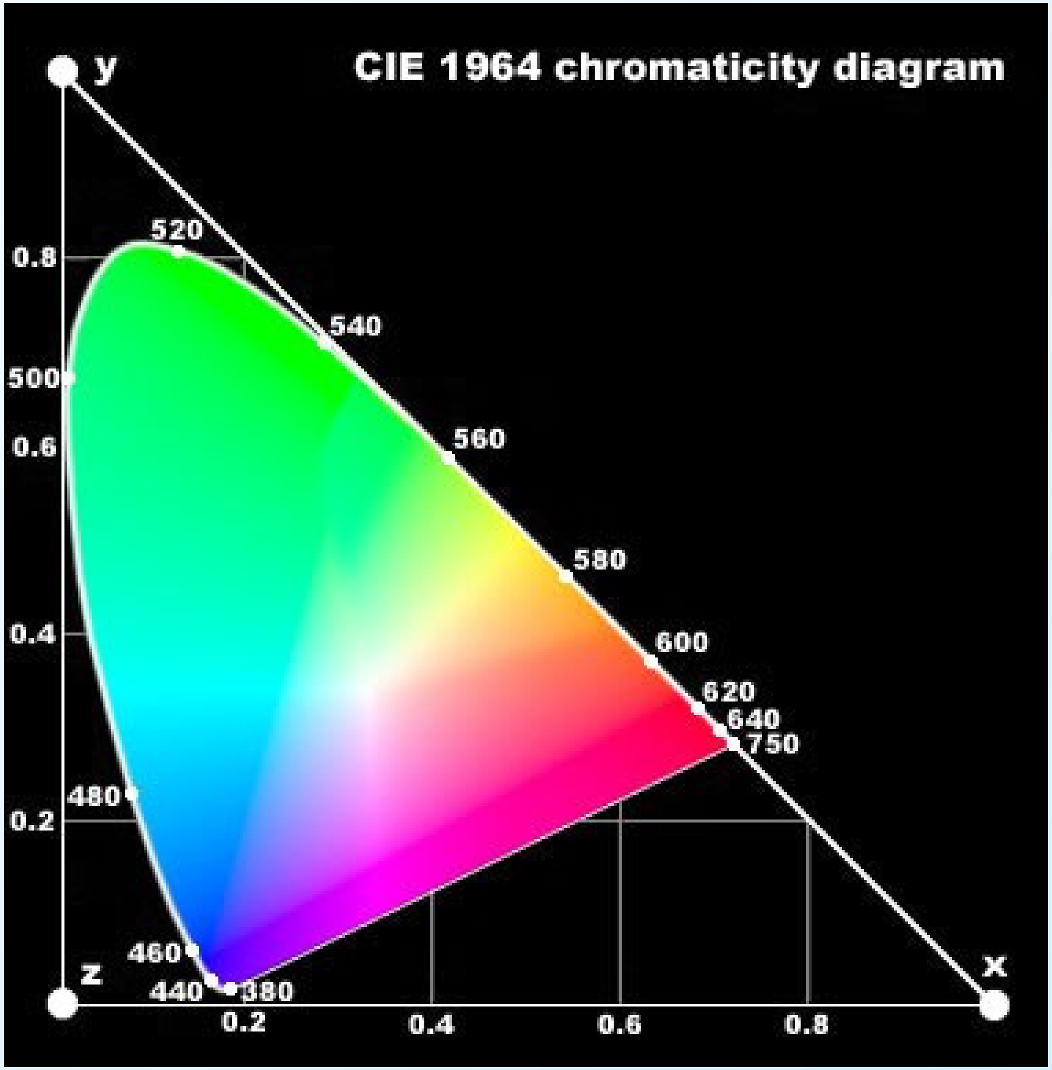
Standard observer response accounting for the cone cell densities in a solid angle

Actual Visible Colours





The CIE Diagram 1964 standard



Convex Shape

Notice that the pure colours (coherent λ) are round the edge of the CIE diagram.

The shape must be convex, since any blend (interpolation) of pure colours should create a colour in the visible region.

The line joining purple and red has no pure equivalent. The colours can only be created by blending.

Intensities

Since the colours are all normalised there is no representation of intensity.

By changing the intensity perceptually different colours can be seen.

White Point

When the three colour components are equal, the colour is white:

$x = 0.33$

$y = 0.33$

This point is clearly visible on the CIE diagram

Saturation

Pure colours are called fully saturated.

These correspond to the colours around the edge of the horseshoe.

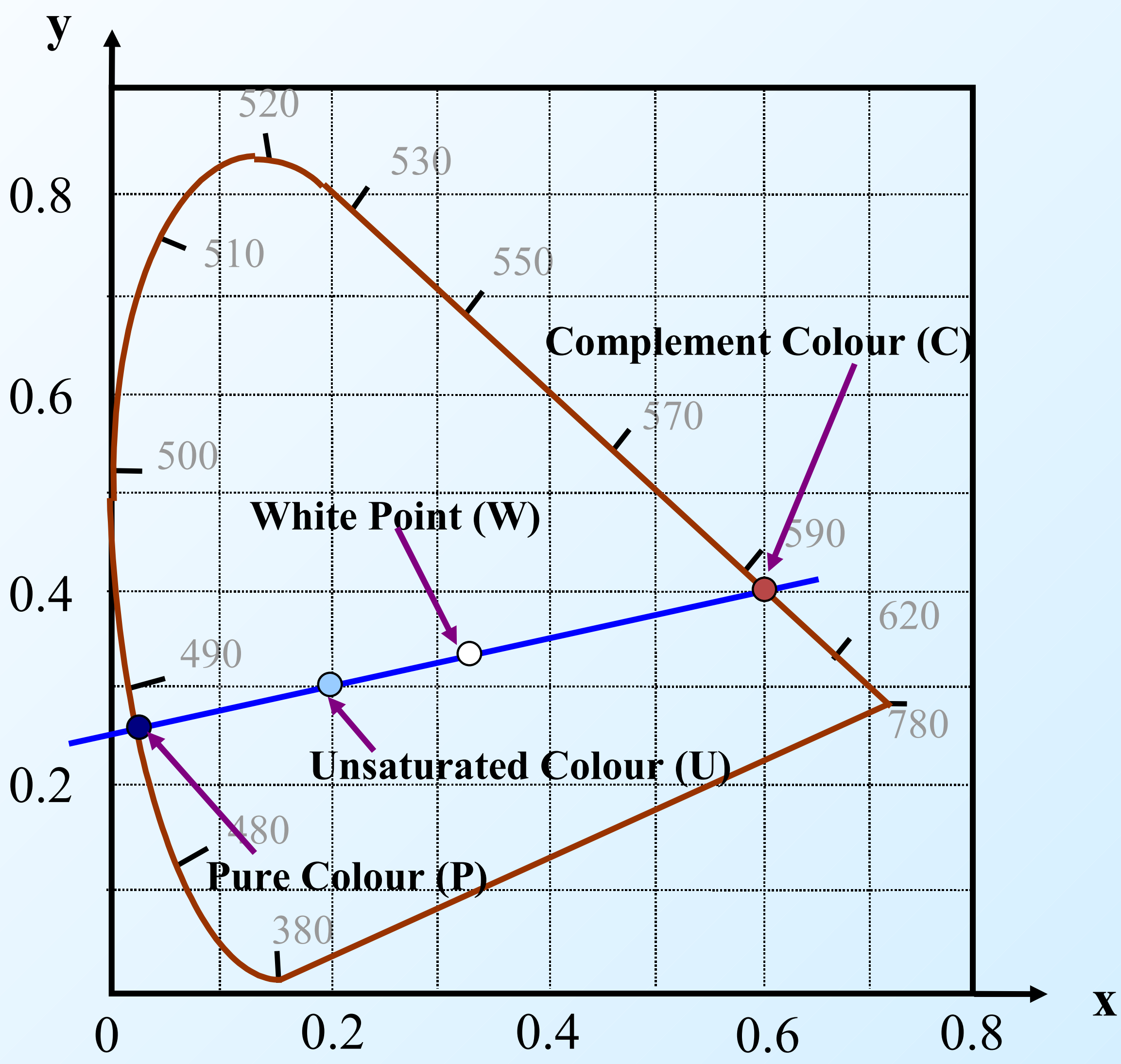
Saturation of a arbitrary point is the ratio of its distance to the white point over the distance of the white point to the edge.

Complement Colour

The complement of a fully saturated colour is the point diametrically opposite through the white point.

A colour added to its complement gives us white.

Actual Visible Colours



Subtractive Primaries

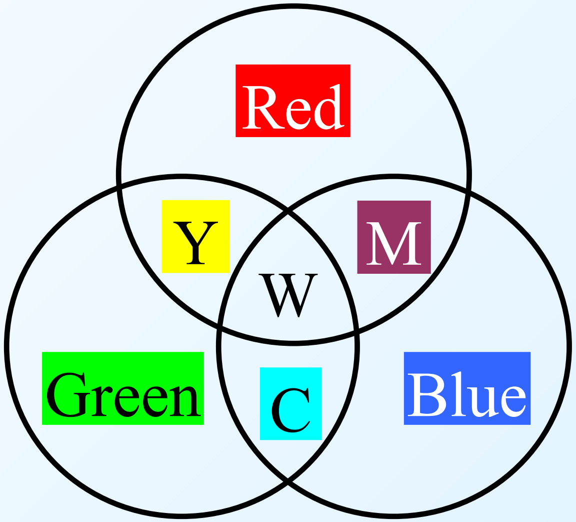
When printing colour we use a subtractive representation.

Inks absorb wavelengths from the incident light, hence they subtract components to create the colour.

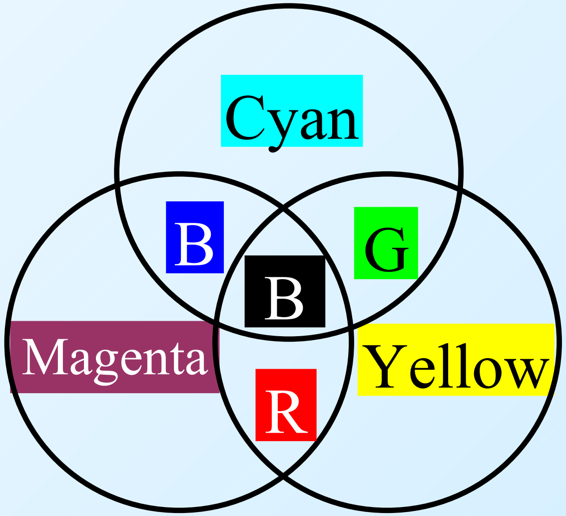
The subtractive primaries are

- Magenta (purple)
- Cyan (light Blue)
- Yellow

Additive and Subtractive Primaries



Additive Primaries



Subtractive Primaries

Additive vs Subtractive Colour representation

Surprisingly, the subtractive representation is capable of representing far more of the colour space than the additive.

We will see why this is so shortly.

Colour Perception

Perceptual tests suggest that humans can distinguish:

128 different hues

For each hue around 30 different saturation.

60 and 100 different brightness levels.

If we multiply these three numbers, we get approximately 350,000 different colours.

Colour Perception

These figures must be treated with caution since there seems to be a much greater sensitivity to differentials in colour.

Never the less, a representation with 24 bits (8 bits for red, 8 bits for green and 8 bits for blue does provide satisfactory results.

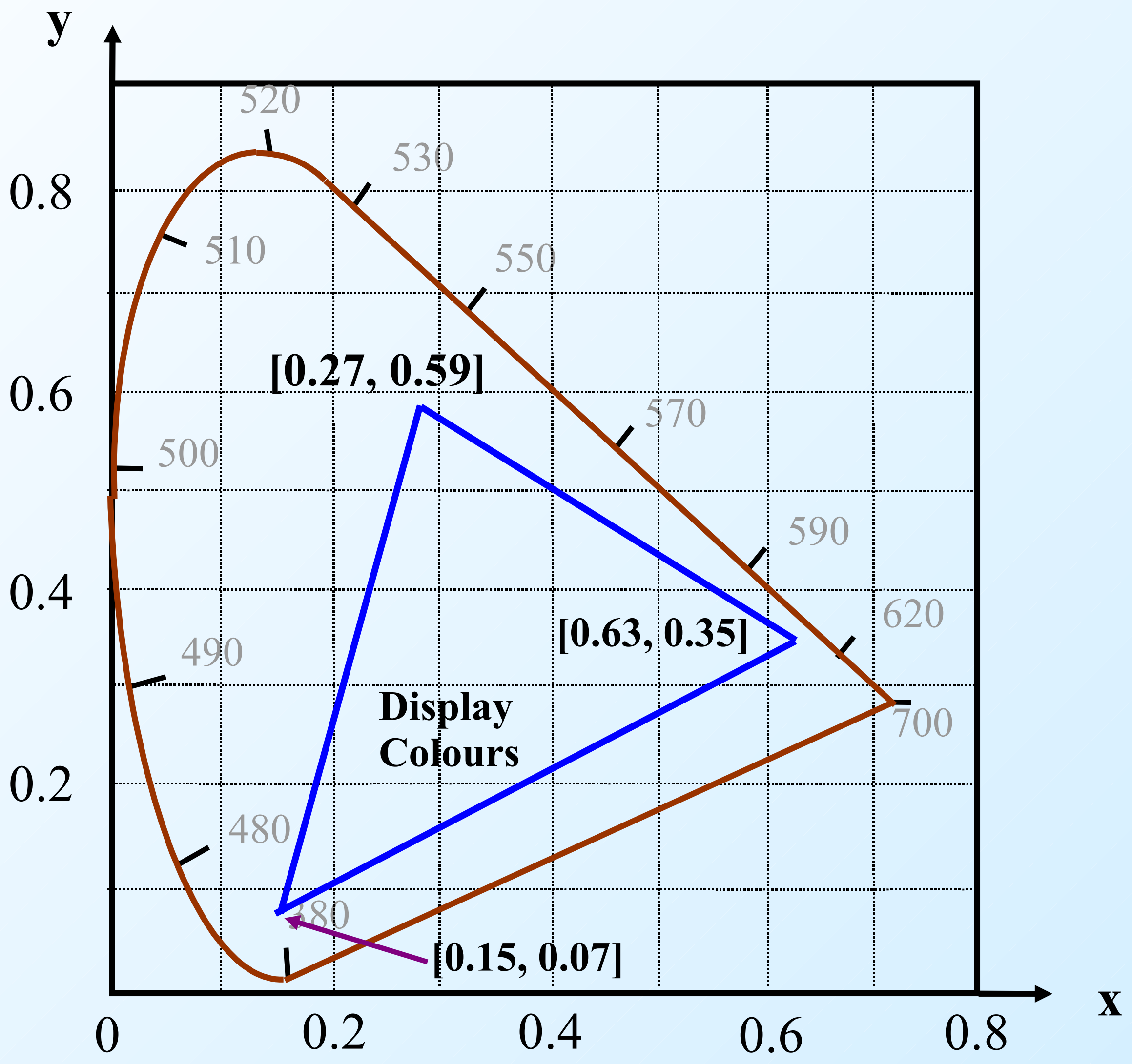
Reproducible colours

Colour monitors are based on adding three the output of three different light emitting phosphors or diodes.

The nominal position of these on the CIE diagram is given by:

	x	y	z
Red	0.628	0.346	0.026
Green	0.268	0.588	0.144
Blue	0.150	0.07	0.780

Actual Visible Colours



RGB to CIE

The monitor RGB representation is related to the CIE colours by the equation:

$$(x, y, z) = \begin{pmatrix} 0.628 & 0.268 & 0.15 \\ 0.346 & 0.588 & 0.07 \\ 0.026 & 0.144 & 0.78 \end{pmatrix} \begin{pmatrix} R \\ G \\ B \end{pmatrix}$$

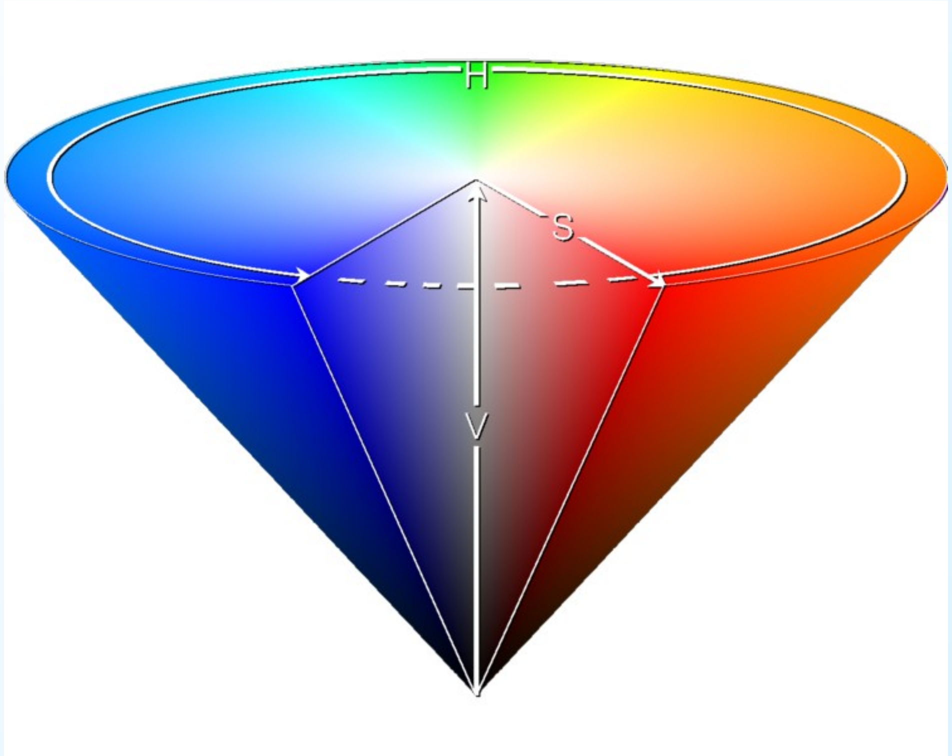
HSV Colour representation

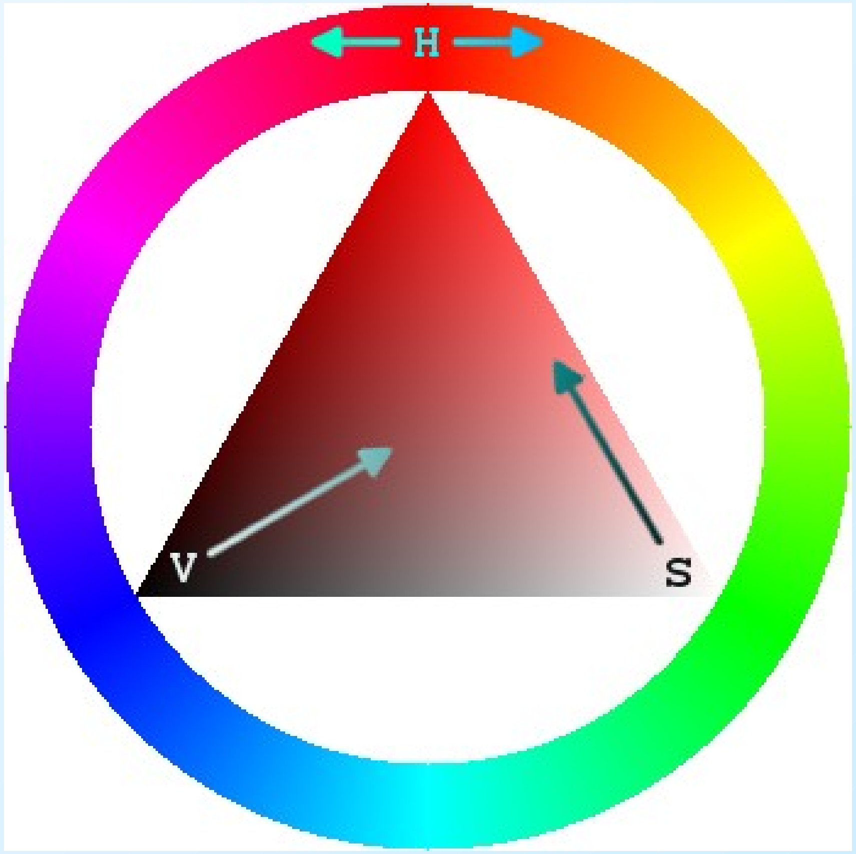
The RGB and CIE systems are practical representations, but do not relate to the way we perceive colours.

For interactive image manipulation it is preferable to use the HSV (or HSI) representation. HSV has three values per colour:

Hue - corresponds notionally to pure colour.
Saturation - The proportion of pure colour
Value - the brightness (Sometimes called Intensity (I))

Visualising the Perceptual Colour Space





Conversion between RGB and HSV

$V = \max(r,g,b)$

$S = (\max(r,g,b) - \min(r,g,b)) / \max(r,g,b)$

Hue (which is an angle between 0 and 360^{o}) is best described procedurally

Calculating hue

if (r=g=b) Hue is undefined, the colour is black, white or grey.

if (r>b) and (g>b) Hue = 120*(g-b)/((r-b)+(g-b))

if (g>r) and (b>r) Hue = 120 + 120*(b-r)/((g-r)+(b-r))

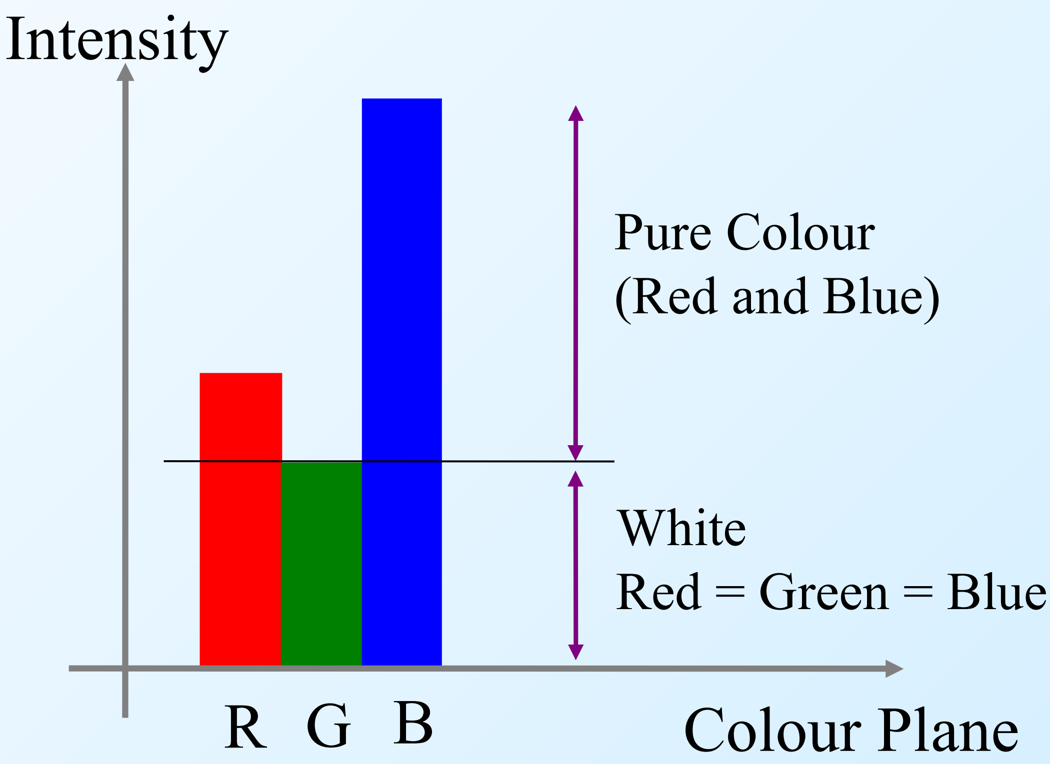
if (r>g) and (b>g) Hue = 240 +120*(r-g)/((r-g)+(b-g))

Saturation in the RGB system

In the RGB system we can treat each point as a mixture of pure colour and white.

Note however that the so called pure colours are not coherent wavelengths as in the CIE diagram

The composition of a tri-stimulus colour



Alpha Channels

Colour representations in computer systems sometimes use four components - r g b α.

The fourth is simply an attenuation of the intensity which:

allows greater flexibility in representing colours.
avoids truncation errors at low intensity
allows convenient masking certain parts of an image.