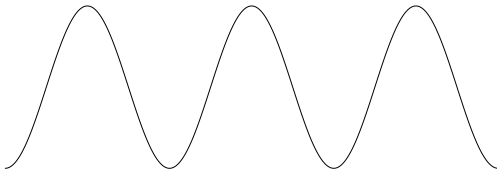


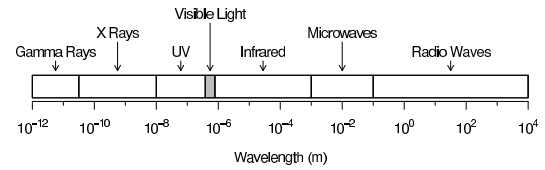
## Light

- 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

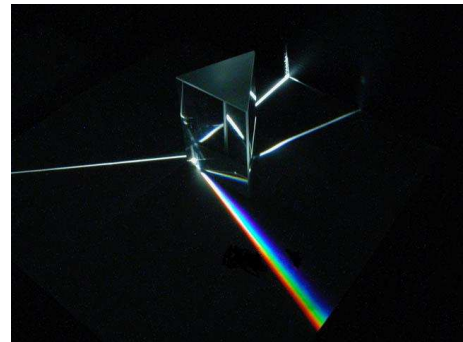
- Visible light has wavelengths in a narrow band centred on 600 nanometers (1 nanometre =  $10^{-9}$  metres).
- Radio waves and microwaves have longer wavelengths than visible light; UV radiation, X and Gamma rays have shorter wavelengths.



## Newton and Light

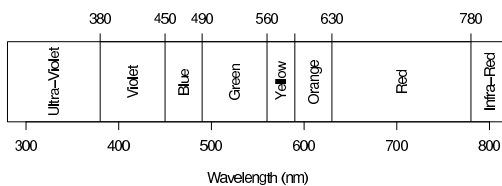
- Isaac Newton showed that white light could be decomposed into a spectrum of colours.
- Newton also showed that these colours could not be decomposed further and that they could be recombined to form white.
- We now know that colours correspond to different light wavelengths.

## Isaac Newton's Prism Experiment



## Wavelength and Colour

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



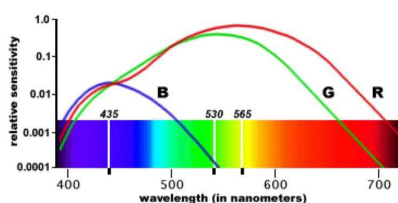
(Colours blend into one another so it is hard to draw precise boundaries between them.)

## Young-Helmholtz 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 Helmholtz 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 original 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 sometimes as  $\rho$ ,  $\gamma$  and  $\beta$ ).
- 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

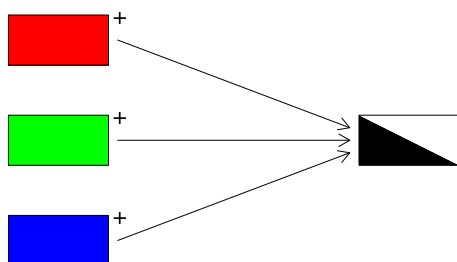
The image below shows an image as it would appear to a primate with a red/green/blue based vision system.



## Transforming RGB To Opponent Colours

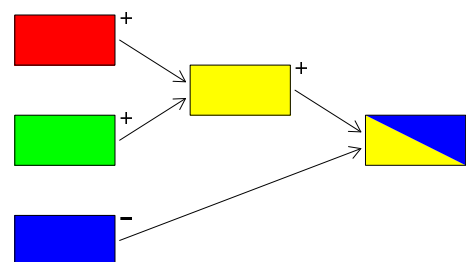
- The transformation of the signals from the R, G and B cones into opponent colour signals can be performed by very simple wiring.
- There are three different wiring diagrams. One for each of the Brightness, Red/Green and Yellow/Blue channels.

## Cone Wiring: Brightness Channel



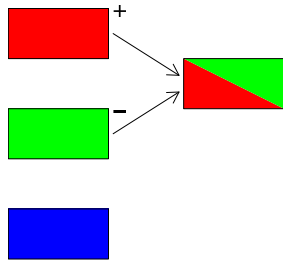
The ancient vision system: reveals form and structure.

## Cone Wiring: Yellow/Blue Channel



Pre-Mammalian Colour: reveals blue/yellow differences.

## Cone Wiring: Red/Green Channel



Primate Colour: reveals red/green differences.

## 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

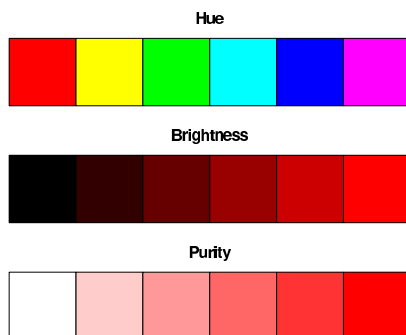
- The RGB description of light corresponds to the stimulation of the receptors in our eyes. It is one that we can examine by applying external stimuli.
- The opponent description is an internal one, and is less subject to experimentation.
- Although the RGB and Opponent models provide a full description 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.

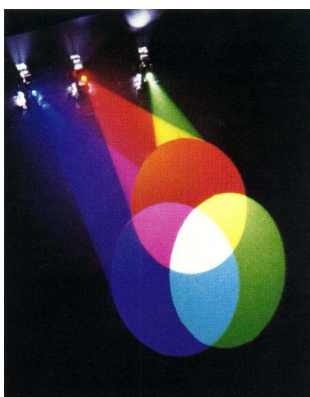
## Perceptually Based Colour Parameters



## 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:  
$$R \approx 610 \text{ nm}, \quad G \approx 540 \text{ nm}, \quad B \approx 475 \text{ nm}.$$
- Although there are only three spectral wavelength present, it still possible to generate a wide variety of colour sensations.

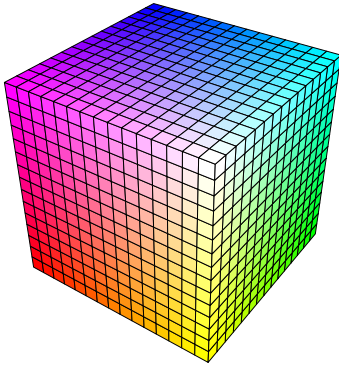
## Combination of Color Primaries



## Numerical RGB Specificaton

- Colours can be specified by giving the amount of red, green and blue they contain.
- Often these specifications are given as values in the range  $[0, 1]$ , with 0 indicating none of the given primary and 1 the maximum amount.
- A colour can thus be thought of as a point in the unit cube  $[0, 1]^3$ .
- Some graphics systems use an integer value in the range  $[0, 255]$  to specify primary amounts. The corresponding value in the  $[0, 1]$  range is obtained by dividing by 255.

## 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"`.

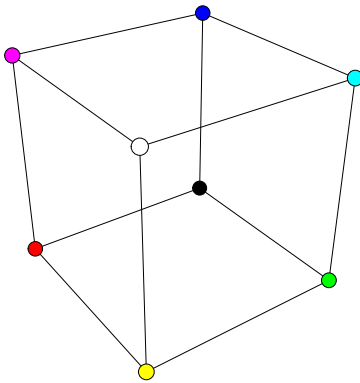
```
"#FF0000" = Red
```

```
"#FFFF00" = Yellow
```

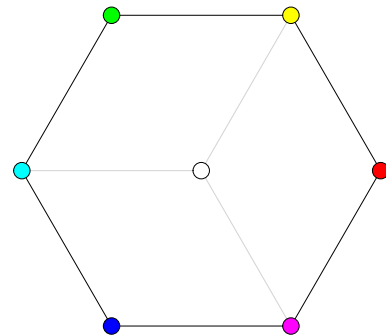
```
"#00FF00" = Green
```

Using RGB in this way is quite unintuitive.

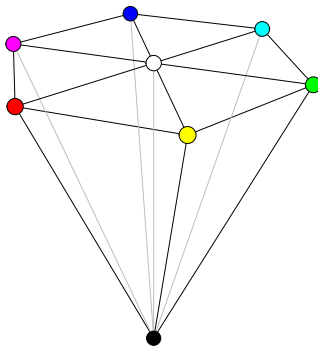
## The RGB Colour Cube



## A Colour Hexagon



## The HSV Hexcone



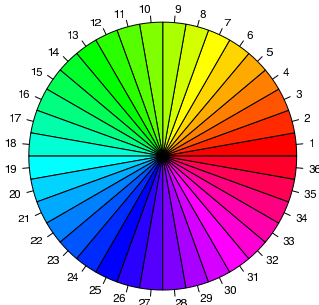
## HSV Colour Specification

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.

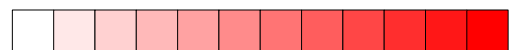
## Example: A Simple Colour Wheel

```
> 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)))
```



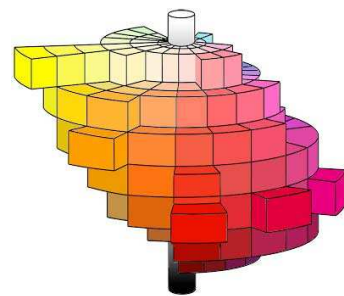
### Perceptual Uniformity

- There is a problem associated with choosing colours in RGB or HSV spaces.
- The way that colours are spaced in these spaces is not in accordance with our perception of how similar or different the colours appear to be.
- A number of alternative spaces have been developed which give more agreement between the positions of colours with the space and our perception of how similar or different the colours are.

### The Munsell Colour Space

- Albert Munsell was an art teacher and painter who lived and taught in Boston at the start of the 20th century.
- In the course of teaching Munsell created a colour description system which is still in widespread use today.
- The Munsell system seeks to arrange the colours in a three dimensional space so that distances in the space reflect the perceived similarity of the colours.
- the space resembles a distorted version of the HSV colour space.

### The Munsell Space



### Munsell Details

- The vertical position of a colour in the space gives the apparent lightness of the colour — black is at the bottom and white is at the top.
- The hues of the spectrum are arranged around the circular gray axis.
- The distance outwards from the central axis is proportional to the colourfulness of the colour.
- The Munsell system is proprietary and expensive to get access to.
- The space is not completely perceptually uniform.

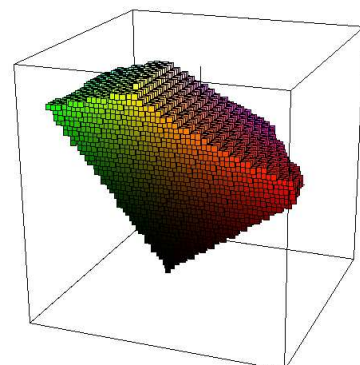
### CIE Uniform Colour Spaces

- The CIE (the *Commission Internationale de l'Éclairage*) is the major standards organisation for colour measurement and description.
- The CIE has developed a number of approximately perceptually uniform colour spaces for describing colour — notably the CIE Luv and CIE Lab spaces.
- These also appear to be slightly distorted versions of the HSV hexcone.
- The CIE standards are open and provide good alternatives to the Munsell system.

### CIELUV and the HCL Space

- The CIELUV space arranges the colours around a central gray (*z*) axis with black at height 0 and white at height 100.
- The hues of the spectrum are arranged in a circle around this central gray axis with their height proportional to the apparent lightness of the colour.
- The horizontal distance from the gray axis to a colour is proportional to its colourfulness or chroma.
- The HCL space reparameterizes the horizontal planes of the LUV space in polar coordinates, with angle corresponding to hue and radius corresponding to colourfulness or chroma.

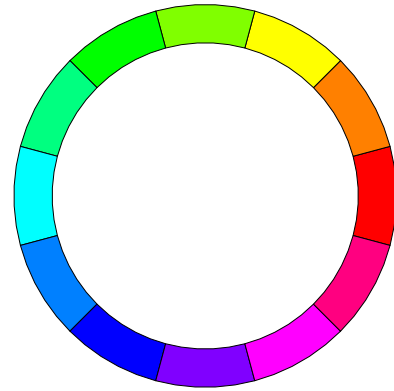
### The RGB “Cube” in LUV Space



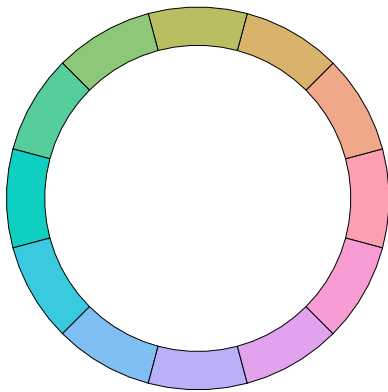
## The R “hcl” Function

- The hcl function in R creates colours from their HCL description.
- Hue is described by an angle in the interval  $[0, 360]$ .
- Chroma gives the horizontal distance from the gray axis to the colour.
- Lightness is the vertical distance from black to the colour. Lightness lies in the interval  $[0, 100]$ .
- Note that the maximum possible chroma for a given hue depends on what the hue is.

## An HSV Colour Wheel



## An HCL Colour Wheel



## Some Colour Terms

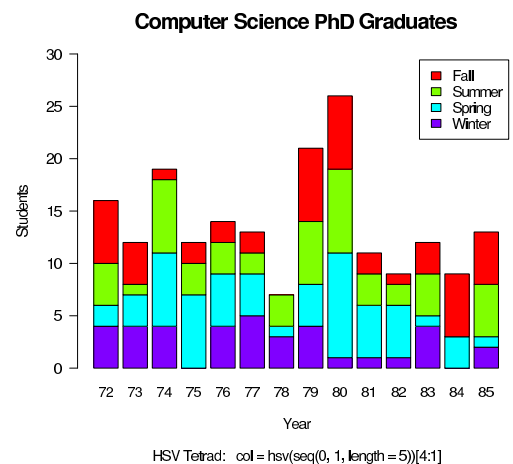
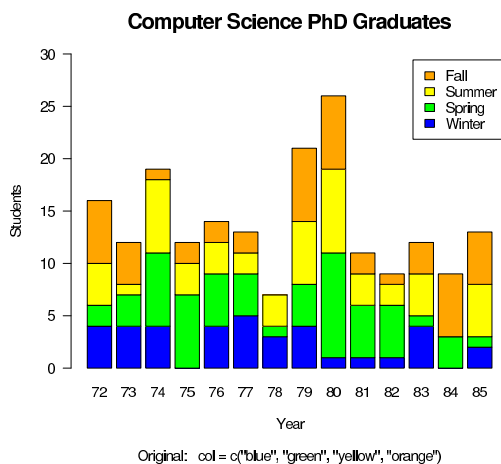
- **Analogous Colours:** Colours chosen from the same region of the colour circle.
- **Complementary Colours:** A pair of colours diametrically opposite each other on the colour wheel.
- **A Colour Triad:** Three colours equally spaced around the colour wheel.
- **A Colour Tetrad:** Four colours equally spaced around the colour wheel.
- **Warm Colours:** Colours close to yellow.
- **Cool Colours:** Colours close to blue.

## Equal Impact Colours

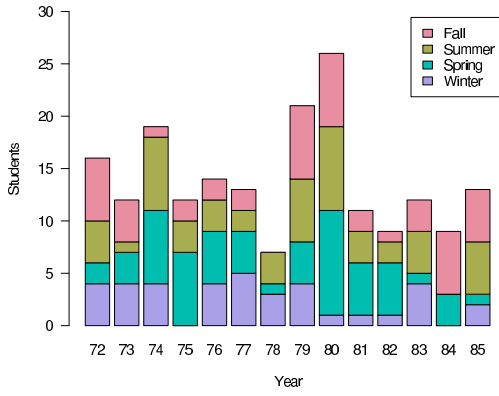
- HCL colours with equal chroma and lightness make a good choice for areas in graphs.
- The use of equal luminance means that areas can be compared because there is no irradiation illusion (which depends on differences in luminance).
- The use of equal chroma means that the eye is not drawn to (or repelled by) especially colourful parts of the graph.
- Such colours can be regarded as having equal visual impact.
- They also appear to work harmoniously together.

## An Example

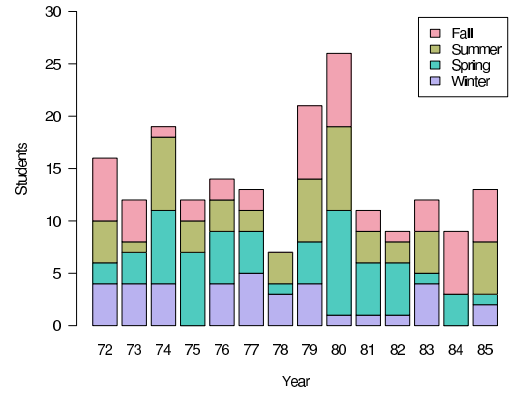
To illustrate how HCL (and other) colours work let's look at a barplot example. The example is taken from a famous book on computer graphics — Foley, van Dam, Feiner and Hughes Foley, van Dam, Feiner and Hughes *Computer Graphics: Principles and Practice* — and shows the number of graduating PhDs in computer science from Brown University during the 1970s and 1980s.



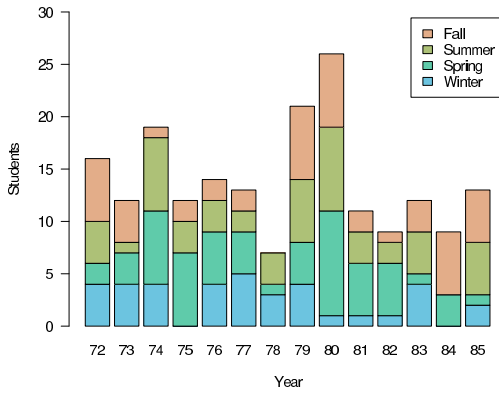
Computer Science PhD Graduates



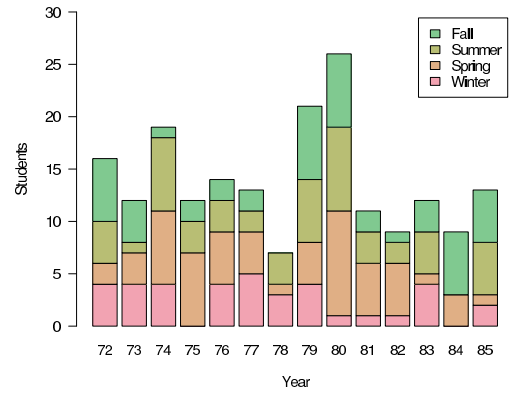
Computer Science PhD Graduates



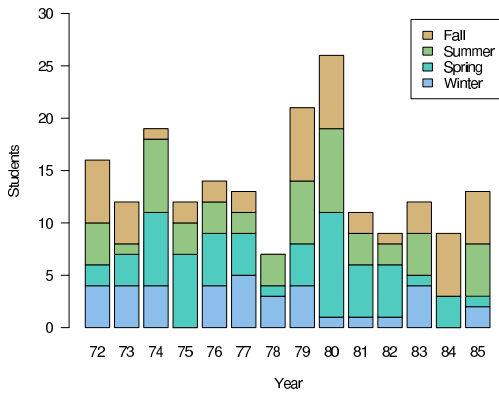
Computer Science PhD Graduates



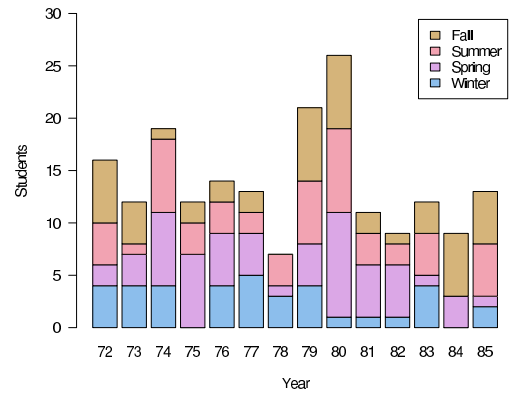
Computer Science PhD Graduates



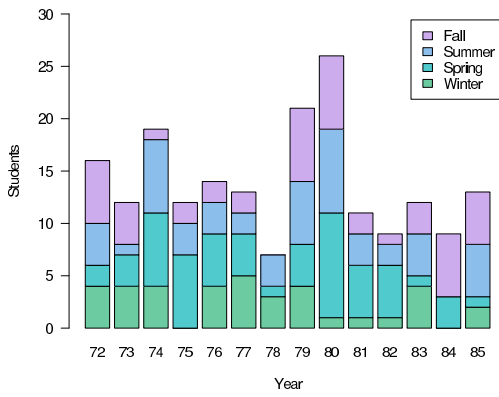
Computer Science PhD Graduates



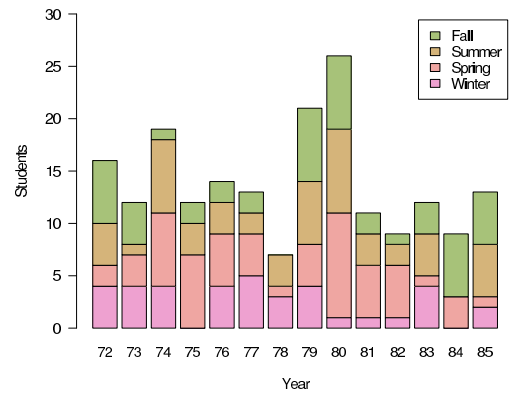
Computer Science PhD Graduates



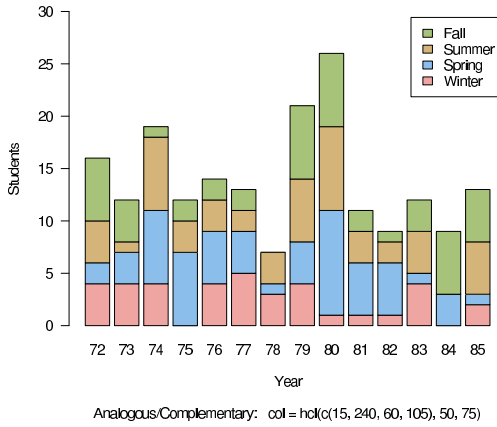
Computer Science PhD Graduates



Computer Science PhD Graduates



### Computer Science PhD Graduates



### Colour Harmony

- Much of Albert Munsell’s work was concerned with “colour harmony.”
- His fundamental conclusion was that systematic choice of colours from perceptually uniform colour spaces lead to harmonious results.
- Munsell particularly favoured sets of colours with equal lightness and chroma, or sets of colours which differ from this in a systematic way.
- The equal-impact colour palette gives a good way of choosing colours leads by design to pleasant or harmonious colour combinations.

### Equal Luminance and Chroma



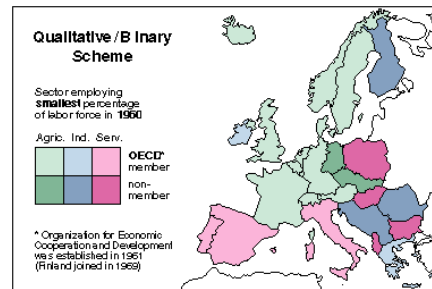
### Harmonious Adjustment



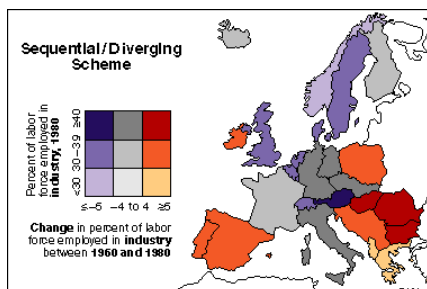
### Cynthia Brewer’s Colour Palettes

- Cynthia Brewer is a geographer who specialises in colour design for maps.
- The choices she recommends are made systematically in a perceptually uniform space (probably Munsell).
- The colour palettes are beautiful, but beware that Brewer does not consider the effects of irradiation illusions.

### Cyndia Brewer – Example 1



### Cyndia Brewer – Example 2



### Cyndia Brewer – Example 3

