Colour Image Analysis

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Why is it important?

- Image understanding is one of the main research areas of computer vision.
- One of its aims to to improve image search engines.

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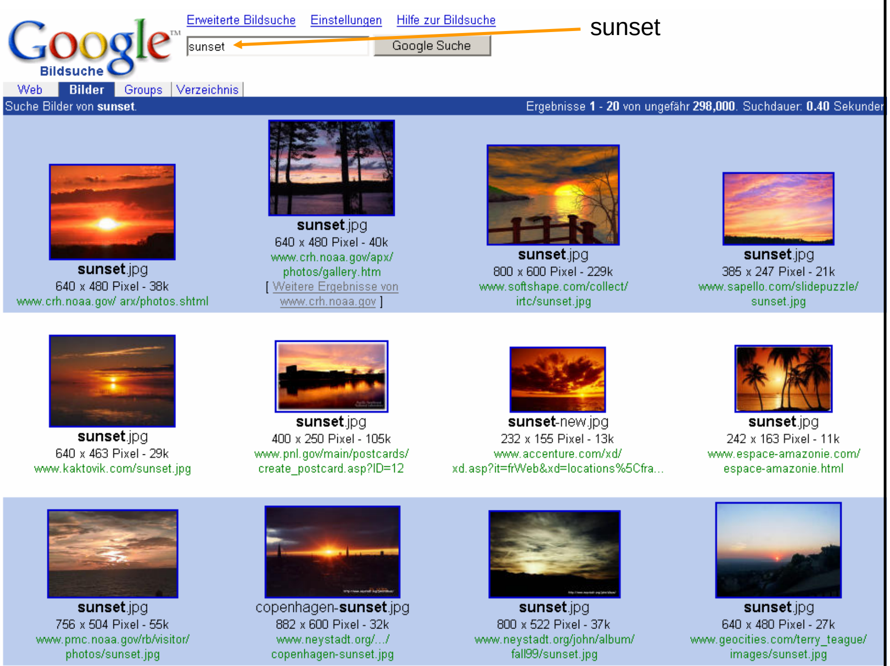
Simple search term

sunset




A more difficult search
otto wagner
Google Bildsuche
Erweiterte Bildsuche Einstellungen Hilfe zur Bildsuche
otto wagner
Google Suche
Web Bilder Groups Verzeichnis
Suche Bilder von otto wagner.
Ergebnisse 1 - 20 von ungefähr 431. Suchdauer: 0.38 Sekunden.
wagner.jpg
142 x 200 Pixel - 15k
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postsparkasse.jpg
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owkirch.jpg
432 x 293 Pixel - 30k
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karlspl4.jpg
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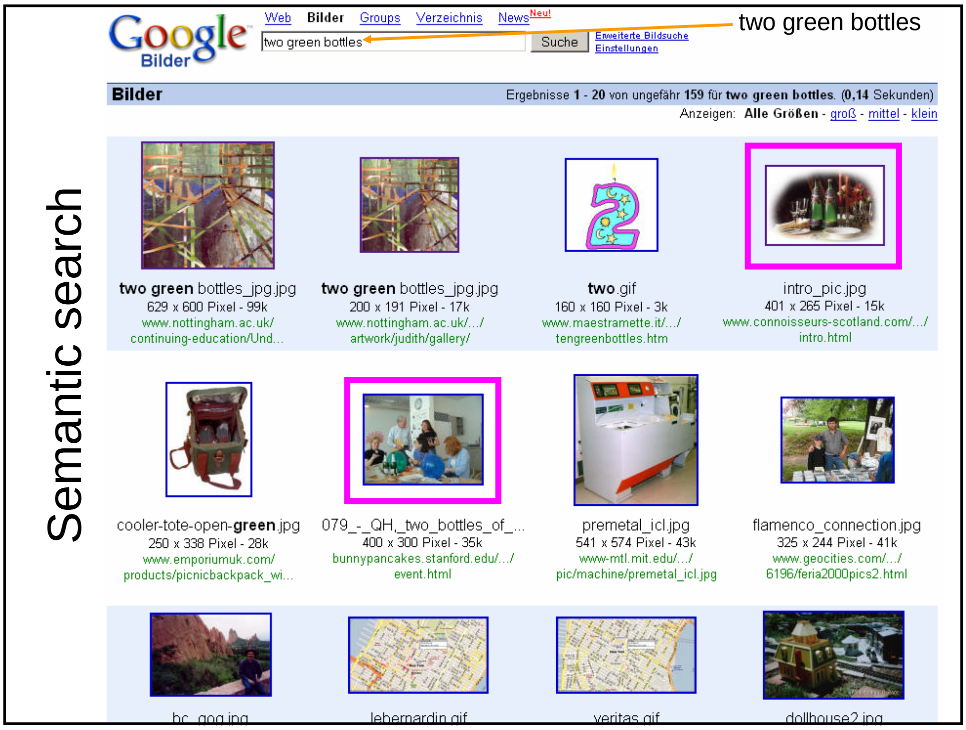
Semantic search
two green bottles
Google Bilder
Web Bilder Groups Verzeichnis News Neu!
two green bottles
Suche
Erweiterte Bildsuche
Einstellungen
Bilder
Ergebnisse 1 - 20 von ungefähr 159 für two green bottles. (0,14 Sekunden)
Anzeigen: Alle Größen - groß - mittel - klein
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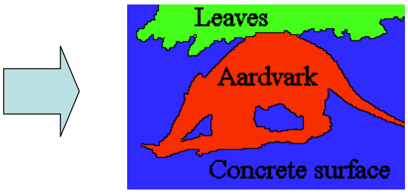
325 x 244 Pixel - 41k
www.geocities.com/.../6196/feria2000pics2.html
bc_gog.jpg
lebernardin.gif
veritas.gif
dollhouse2.jpg

- A general image understanding algorithm would improve this image search immensely.
- Given any image, this algorithm should describe the contents and possibly the relations between them.



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- This is difficult for many reasons…

From the Graz Object Recognition Database (Opelt and Pinz)

- To assist in developing image understanding algorithms, it helps to know:
  - How the world works
  - How our brains work

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Contents

- Visible spectrum
- Colour and the human brain
- Colour image formation
- Colourimetry
- Colour appearance
- Computational colour constancy
- Colour appearance models

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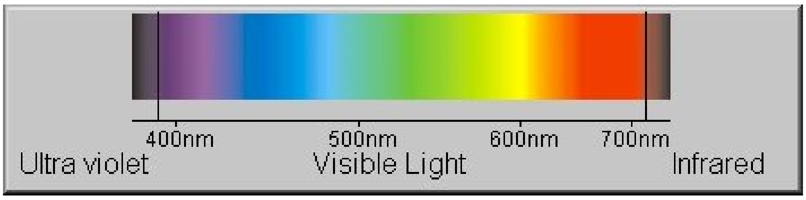
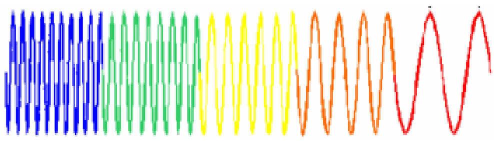
Visible spectrum

- The human eye is sensitive to wavelengths of electromagnetic radiation between approximately 400nm and 700nm:



Blue  Red

Short wavelength | Long wavelength

High frequency | Low frequency

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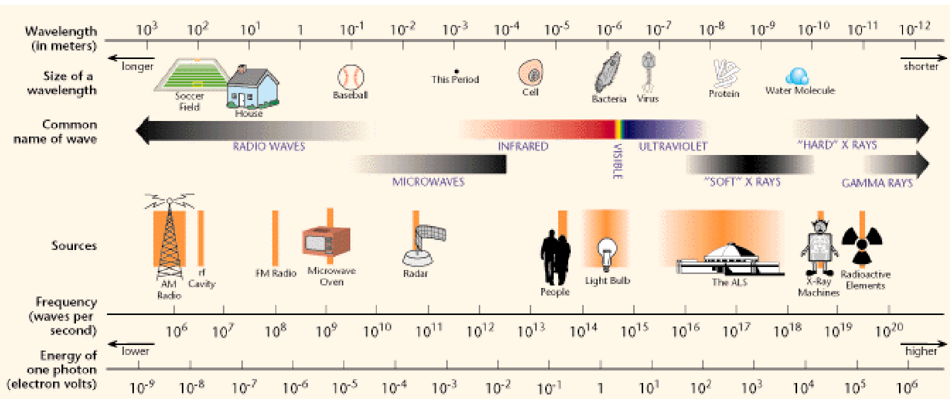
Electromagnetic spectrum

- The term electromagnetic spectrum refers to the collection of possible wavelengths of electromagnetic radiation.



$1\ \text{eV} \approx 1.6 \times 10^{-19}\ \text{J}$

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Spectrum

- A spectrum is a description of the amount of light (intensity) broken up by wavelength.

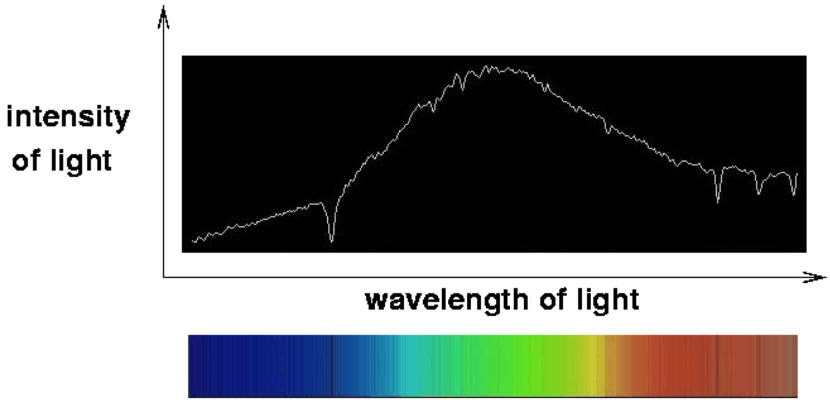

Image and spectrum copyright [Maurice Gavin]

Colour and the human brain

- How does the brain "see" and analyse colours in the external world?
- Is colour a property of the brain or the world outside?
- Are the same colours seen by everybody?

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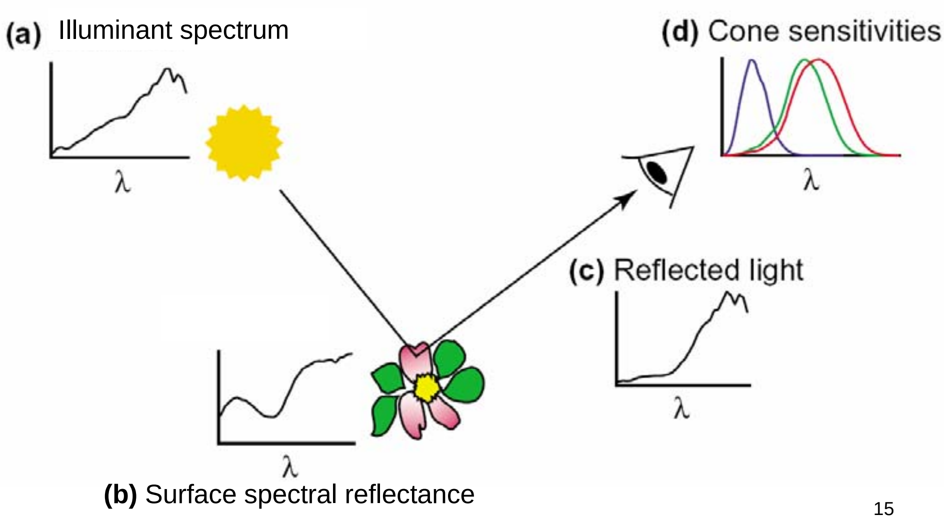
What reaches the brain?



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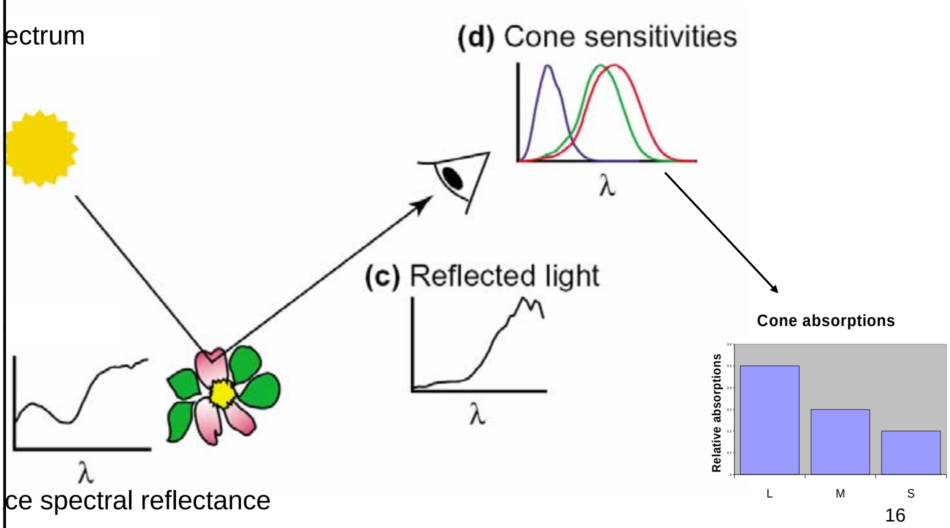
From Foster, “Does colour constancy exist?”, Trends in Cognitive Neurosciences

What reaches the brain?



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From Foster, “Does colour constancy exist?”, Trends in Cognitive Neurosciences

What reaches the brain?

- Values from three types of cones, the L-, M- and S-cones.
  - Refer to Long, Medium and Short wavelength sensitivities.
- The values of L, M and S depend on:
  - Light sources and illuminants
  - Coloured materials
  - Visual response functions (cone sensitivities)

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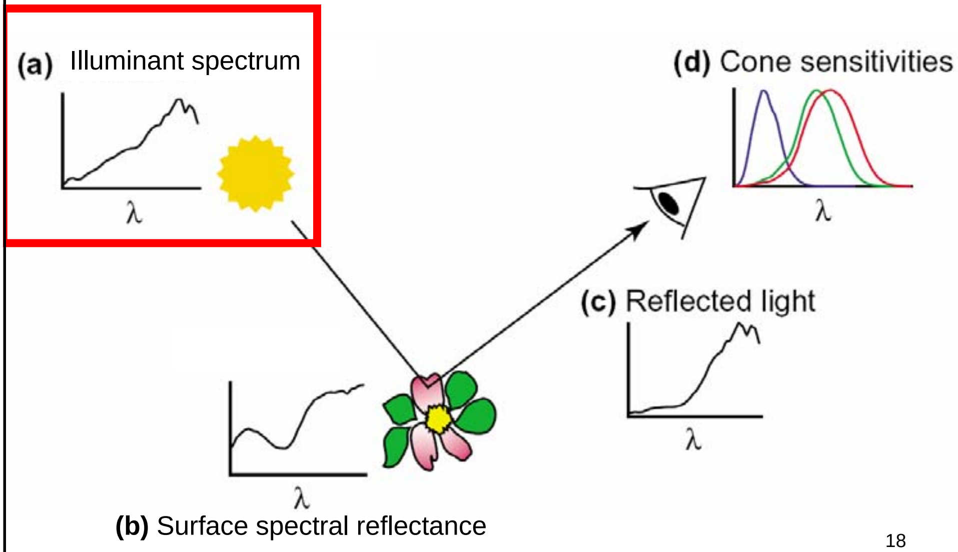
Illuminant Spectrum



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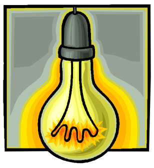
Light sources and illuminants

- A light source is an actual physical emitter of visible energy.

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Light sources and illuminants (2)

- An illuminant is a standardised table of values that represent a spectral power distribution typical of some particular light source.
- CIE illuminants A, D65 and F2 are standardised representations of typical incandescent, daylight and fluorescent light sources, respectively.
- Some illuminants have corresponding light sources, others such as D65 (average daylight illuminant) do not.

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Definitions from Mark D. Fairchild, “Color Appearance Models”, Addison-Wesley, 1998

Light sources and illuminants (3)

- Black body radiators:
  - Theoretical light source.
  - Emits energy only due to thermal excitation and is a perfect emitter of energy.
  - Energy emitted and wavelength distribution depends only on its temperature, called the colour temperature.
  - Correlated Colour Temperature (CCT) of a light source is the colour temperature of a blackbody radiator that has almost the same colour as the light source.

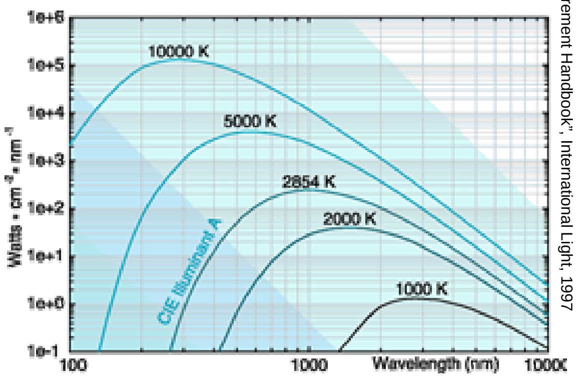

Fig. 5.1 Blackbody radiation at several color temperatures

From Alex Ryer, "Light Measurement Handbook", International Light, 1997

- Example light sources and illuminants:

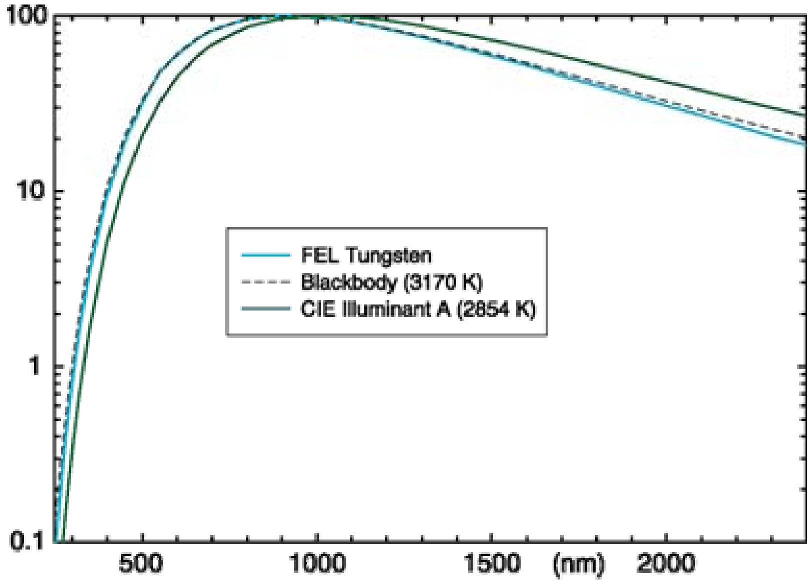

Fig. 5.3 Incandescent sources

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From Alex Ryer, "Light Measurement Handbook", International Light, 1997

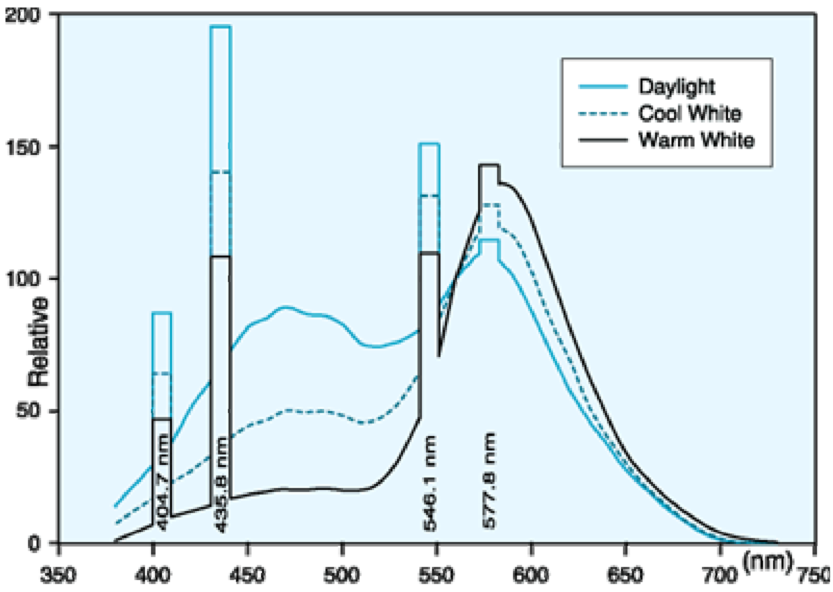

Fig. 5.6 Typical fluorescent sources.

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From Alex Ryer, “Light Measurement Handbook”, International Light, 1997

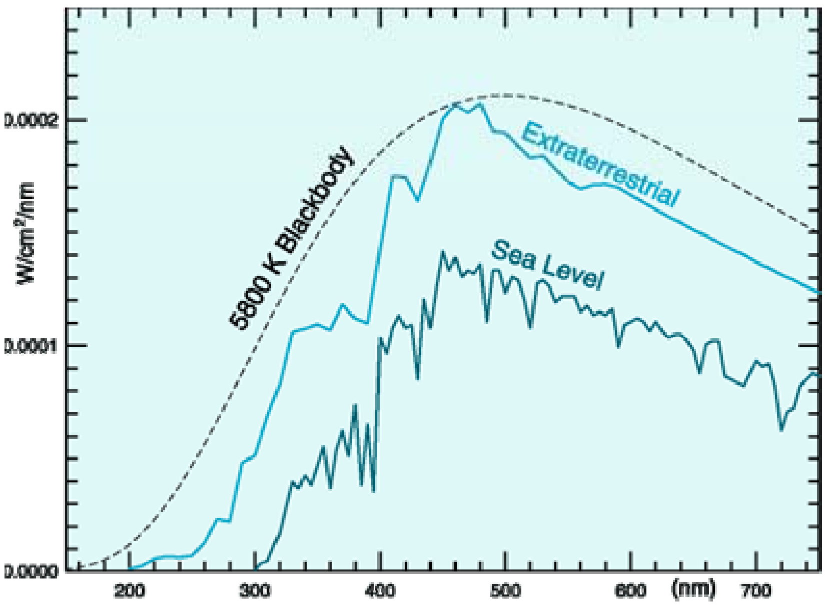

Fig. 5.8 Solar irradiance at sea level.

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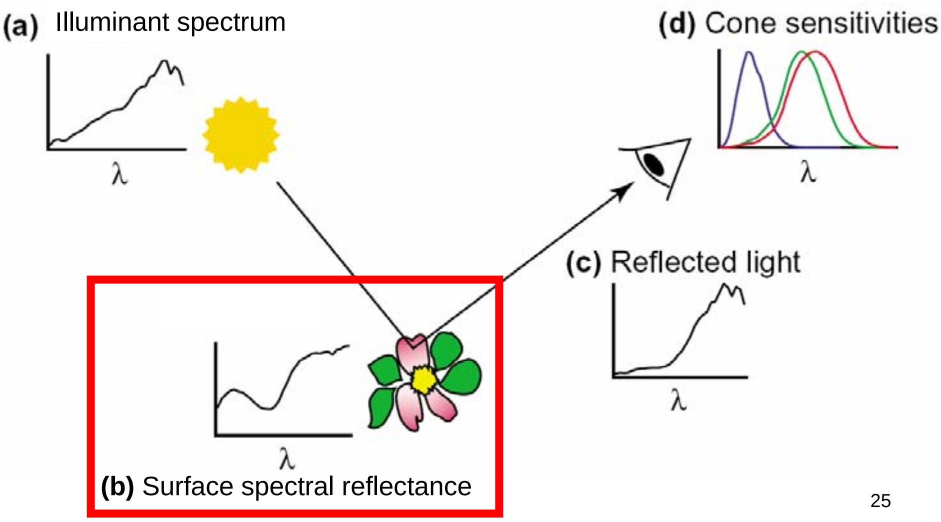
From Alex Ryer, “Light Measurement Handbook”, International Light, 1997

Surface spectral reflection



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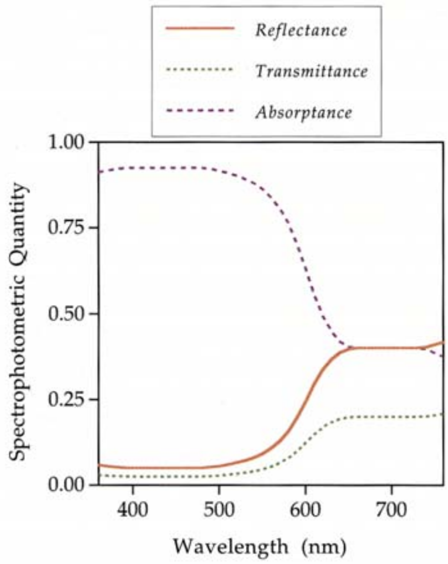
Coloured Materials

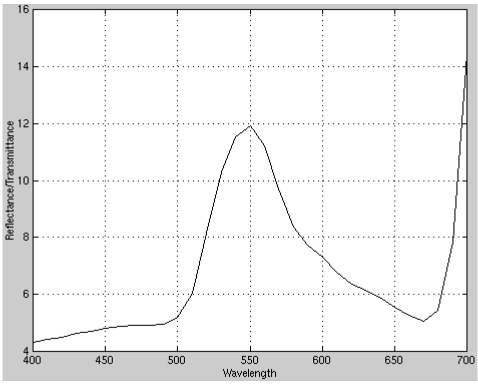
- A surface can be described by a curve giving the percentage of transmittance, reflectance and absorbtance of light as a function of wavelength.
- Remember conservation of energy, it is not necessary to measure all three!



From Fairchild

Examples of reflectance/transmission spectra

- Green leaves:



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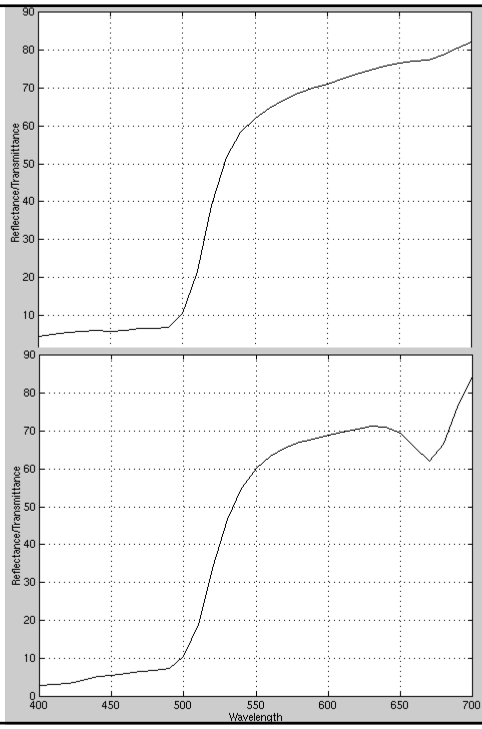
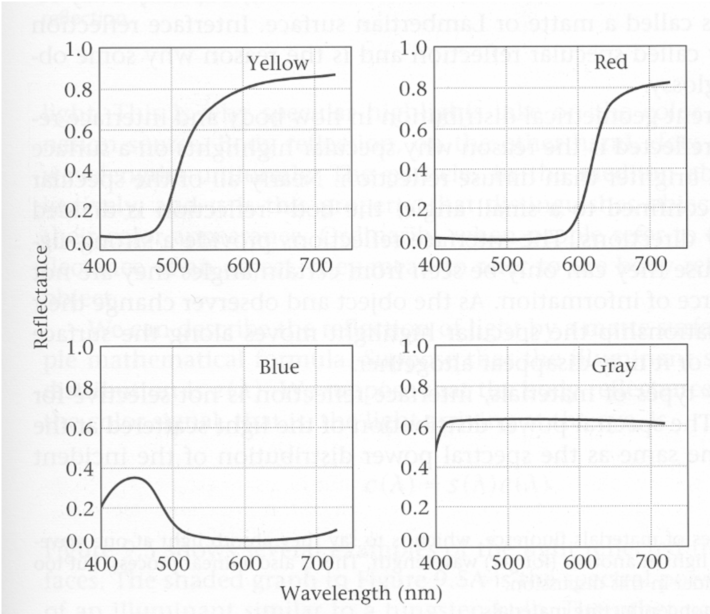
From http://spectral.joensuu.fi/databases/autumn/index.html

- Yellow leaves:



From http://spectral.joensuu.fi/databases/autumn/index.html

- Reflection spectra of four coloured papers:



From Wandell

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But it can be more complicated…

- The reflectance or transmittance is also a function of illumination and viewing geometry.
- Examples:
  - Matte, gloss and semi-gloss photographic paper
  - BTFs (Bidirectional texture functions)
    - Textures are imaged from a large number of viewing directions using different illumination directions.
    - Typically a few hundred to a few thousand images per texture.

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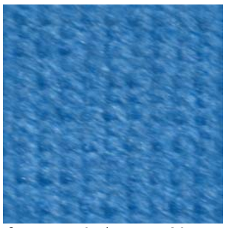
- Wool BTF from the University of Bonn database.
  - 81 view directions and 81 light directions = 6561 images

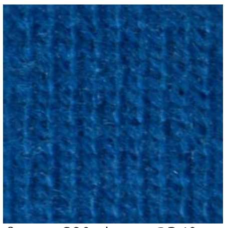
θ_{light}= 0°, ϕ_{light}= 0°
θ_{view}= 30°, ϕ_{view}= 30°

θ_{light}= 30°, ϕ_{light}= 300°
θ_{view}= 45°, ϕ_{view}= 220°

θ_{light}= 45°, ϕ_{light}= 0°
θ_{view}= 0°, ϕ_{view}= 0°



θ_{light}= 45°, ϕ_{light}= 40°
θ_{view}= 75°, ϕ_{view}= 345°



θ_{light}= 60°, ϕ_{light}= 234°
θ_{view}= 60°, ϕ_{view}= 324°

θ_{light}= 75°, ϕ_{light}= 270°
θ_{view}= 60°, ϕ_{view}= 306°

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http://btf.cs.uni-bonn.de/

- Huge amount of information.
- These textures are difficult to model.
- Important applications in the automobile industry – modelling how the car looks in different lighting conditions.
- Example from the RealReflect EU project:

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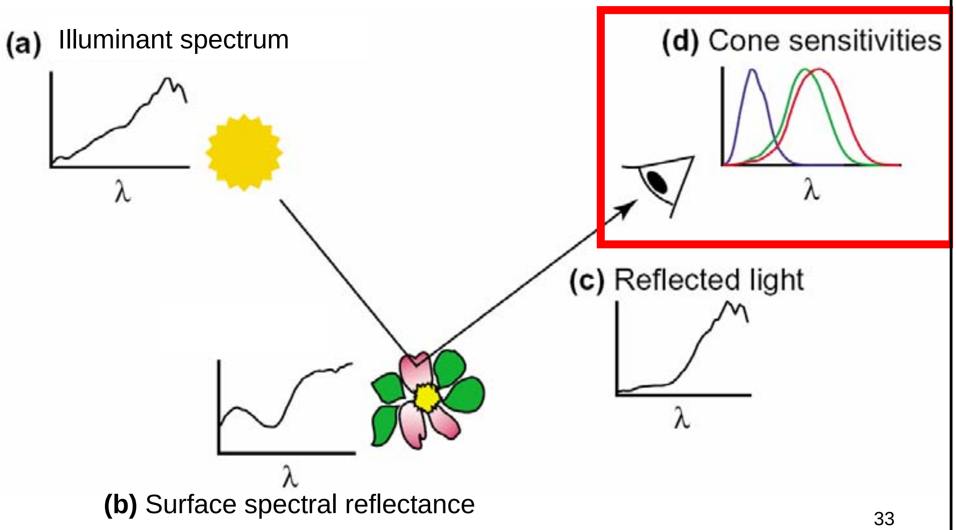
http://www.realreflect.org/

Cone sensitivities



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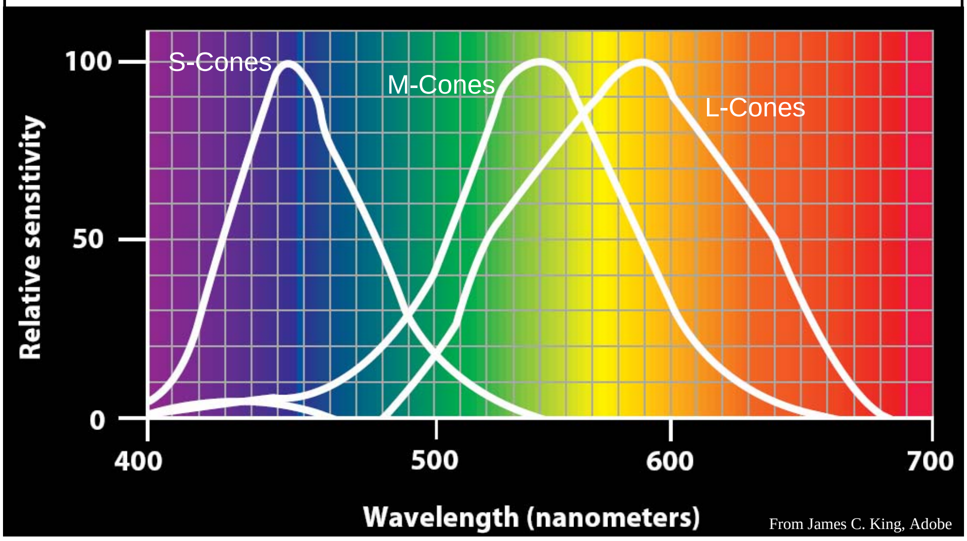
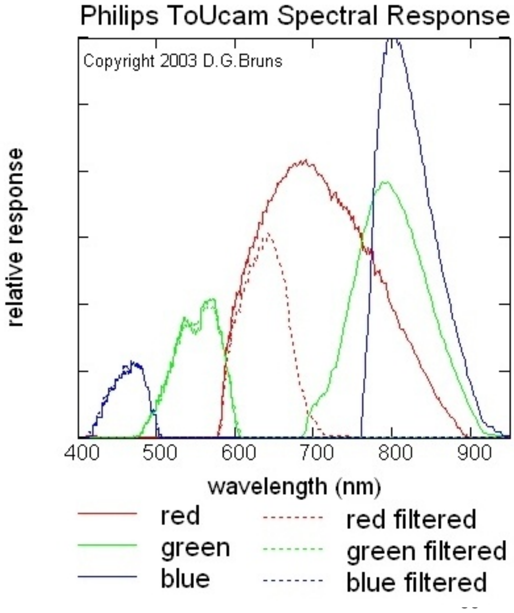
Response functions

- Cone sensitivities



From James C. King, Adobe

- CCD Camera
  - Colour CCD cameras usually also have three types of receptor with corresponding sensitivities, usually labelled Red, Green and Blue.
  - These vary from camera to camera!
  - Different to human eye sensitivities…



From http://www.stellarproducts.com/imageall/ToUcam/ToUcam%20spectral%20response.jpg

Result of the process

- The result is three values (tristimulus values):
  - L, M and S for the human eye response functions.
  - R, G and B for the CCD response functions.
- Calculating these values:
  - The spectral response functions of the three cone types as a function of wavelength are $L(\lambda)$, $M(\lambda)$ and $S(\lambda)$.
  - A stimulus is denoted by its spectral power distribution $\Phi(\lambda)$.
  - The resulting values are:

$$L = \int_{\lambda} \Phi(\lambda) L(\lambda) d\lambda \qquad M = \int_{\lambda} \Phi(\lambda) M(\lambda) d\lambda$$

$$S = \int_{\lambda} \Phi(\lambda) S(\lambda) d\lambda$$

  - For cameras, replace the spectral response functions.

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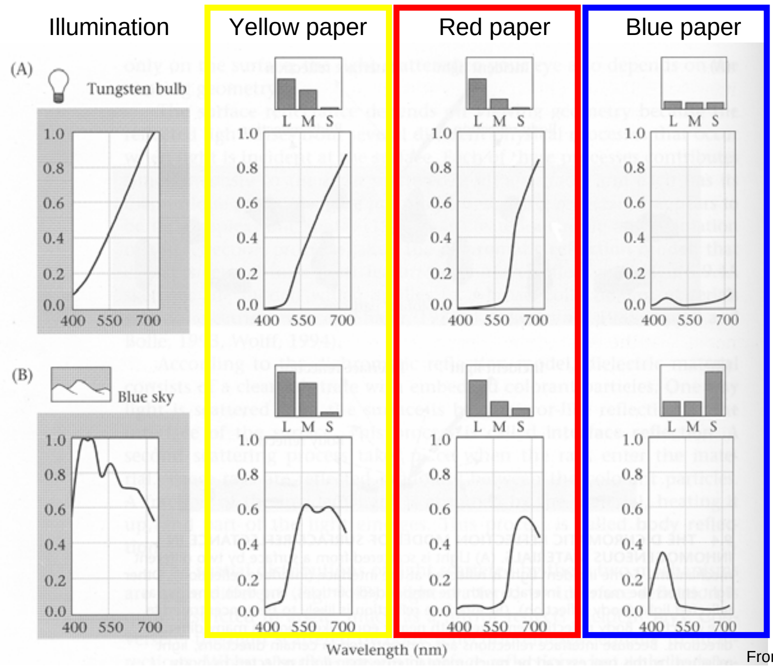
• These values depend heavily on the illumination:



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From Wandell

• The illumination conditions of the scene have a large effect on the colours recorded.

Image taken lit by a flash.

Image taken lit by a tungsten lamp.

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Fluorescent light   Daylight   Tungsten light

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From http://cs.joensuu.fi/spectral/colorlab_brief.htm

Gamma correction

- Gamma correction plays a role in the formation of colour images.
- In general, video display devices have a non-linear brightness response to the input voltage, of the form
$$L = \alpha V^{\gamma}$$
where L is the brightness, V is the input voltage and α and γ are controlled by the brightness and contrast settings.
- To take this non-linearity into account, the outputs of the majority of video cameras are corrected as follows
$$V_{out} = I^{1/\gamma}$$
where I is the light intensity recorded by the camera.

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Transmitting tristimulus values to the brain

- Trichromatic theory
  - Developed in the latter half of the 19th century.
  - States that the *L*, *M* and *S* values are transmitted directly to the brain.
- Opponent colours theory
  - Imagine a greenish-blue colour.
  - Now imagine a greenish-red colour, then a yellowish-blue.
  - This, along with other visual phenomena, suggests that there is something fundamental about red-green and yellow-blue pairs that cause them to oppose each other.

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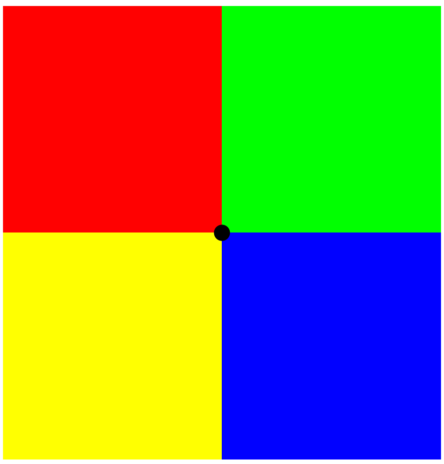
- Demonstration:
  - Fixate upon the black spot in the centre of the squares for about 30 seconds…



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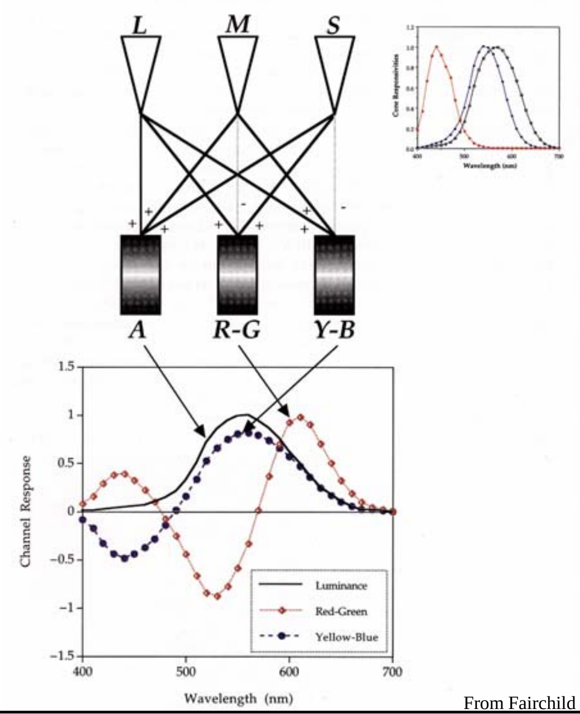
- Experiments have shown that the neurons of the retina encode the colour into opponent signals.
- This serves to decorrelate the colour information, allowing efficient signal transmission and reducing difficulties with noise.



From Fairchild

Using tristimulus values

- Colourimetry:
  - Tristimulus values measured depend on the device used.
  - Colourimetry aims at specifying a colour in a standard way (using a standard observer), such that:
    - Colours having the same standard specification viewed under the same observing conditions look alike.
    - Colours which look alike have the same specification.
- Colour appearance:
  - The human brain does some extra processing to colour, to take the illuminant into account, for example.
  - This means that colours which are colorimetrically different may appear the same to a human.
  - Can one model this?

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Colourimetry

- Focuses on the earliest level of vision – absorption of energy in the cones.
- Allows the prediction of when two colour stimuli match for an average observer.
- The spectrum of the light is not taken into account, because once the energy is absorbed by the cones, the spectral information is lost.

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Colour matching

- Two stimuli are given by their spectral power distributions $\Phi_1(\lambda)$ and $\Phi_2(\lambda)$.
- Two colour stimuli match if the following hold:

$$\int_\lambda \Phi_1(\lambda) L(\lambda)\, d\lambda = \int_\lambda \Phi_2(\lambda) L(\lambda)\, d\lambda$$

$$\int_\lambda \Phi_1(\lambda) M(\lambda)\, d\lambda = \int_\lambda \Phi_2(\lambda) M(\lambda)\, d\lambda$$

$$\int_\lambda \Phi_1(\lambda) S(\lambda)\, d\lambda = \int_\lambda \Phi_2(\lambda) S(\lambda)\, d\lambda$$

- These equations illustrate the definition of metamerism.
  - Since only these three integrals need to be equal for a colour match, it is possible that two colours with different spectra can match.

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- Colour matching is easy when one knows the cone response functions.
- However, in the 1920s these were not known.
- A system of colourimetry was therefore developed based on the trichromatic generalisation:
  - “This states that over a wide range of conditions of observation, many colour stimuli can be matched in colour completely by additive mixtures of three fixed primary stimuli whose radiant powers have been suitably adjusted.” (Wyszecki and Stiles)

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- This can be written as follows:

$$C \equiv R(\mathcal{R}) + G(\mathcal{G}) + B(\mathcal{B})$$

  A colour C is matched by R units of the $\mathcal{R}$ primary, G units of the $\mathcal{G}$ primary and B units of the $\mathcal{B}$ primary.
- $\mathcal{RGB}$ define the particular set of primaries used.
- For different sets of primaries, different amounts of each primary need to be used to make a match.
- *RGB* are the tristimulus values.
- Therefore, to specify a colour, one needs
  - A specification of the primaries
  - The tristimulus values.

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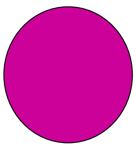
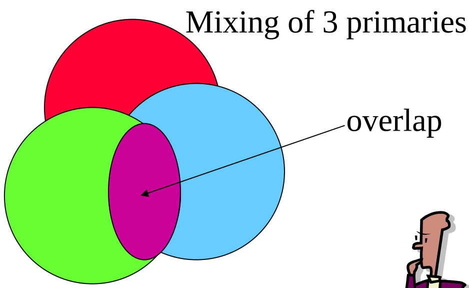
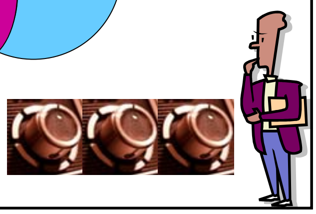
- The tristimulus values for a given primary are obtained by colour matching experiments.
  - A series of colours corresponding to each wavelength are shown (with unit power at each wavelength).
  - A person has to adjust the power of each of the three primaries so that the resulting colour matches.



Target colour





Color Matching Experiment 1

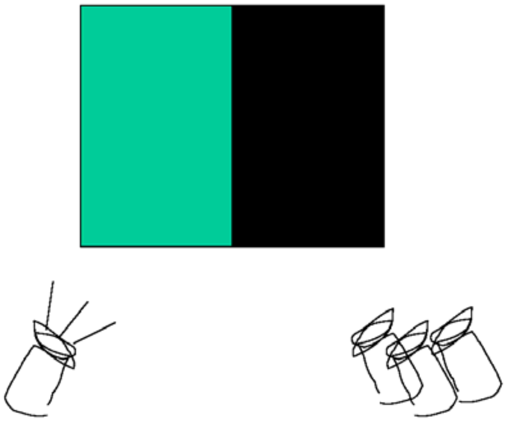


Image by Bill Freeman

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Color Matching Experiment 1

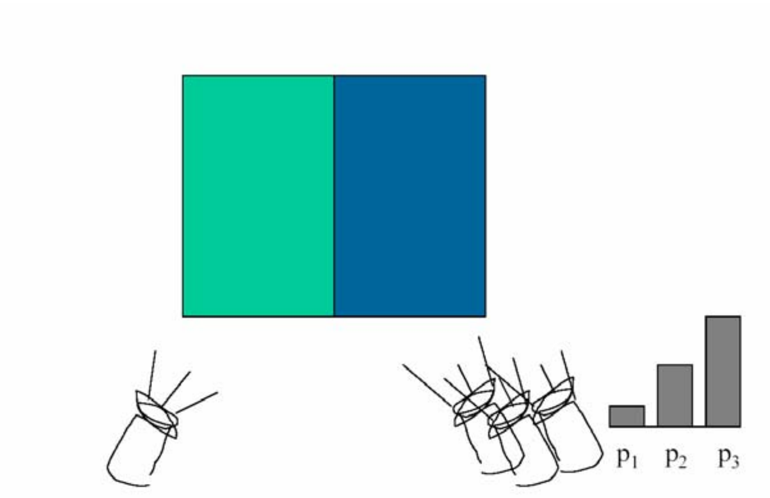

Image by Bill Freeman

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Color Matching Experiment 1

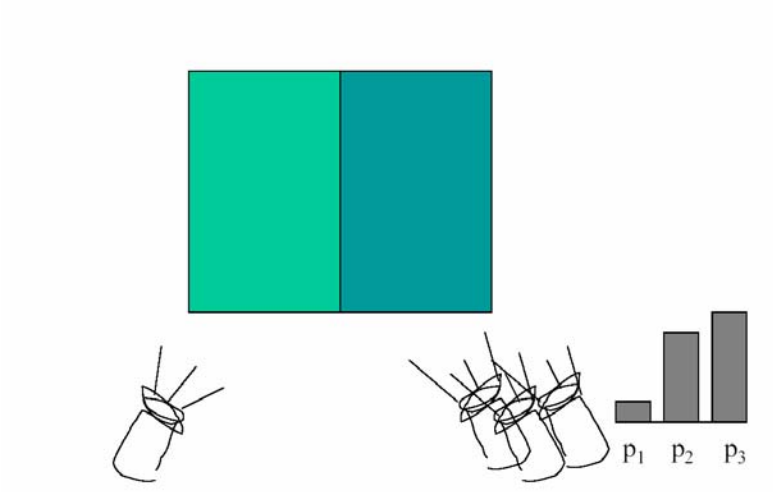

Image by Bill Freeman

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Color Matching Experiment 1

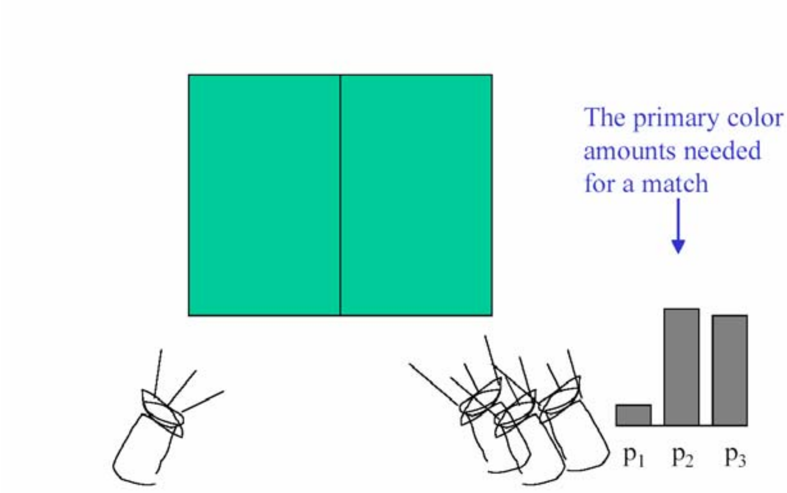

Image by Bill Freeman

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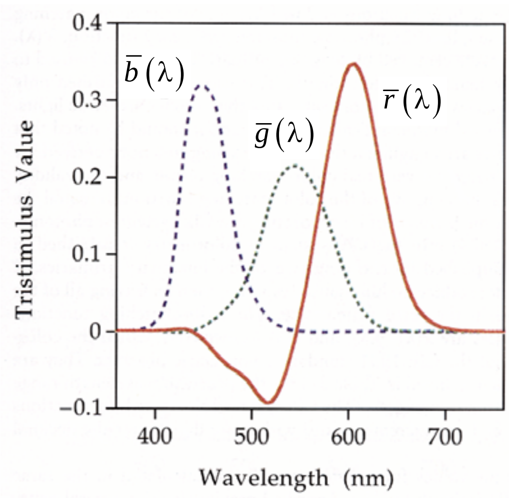
Results of the experiment

- For monochromatic primaries at 435.8 nm ($\mathcal{R}$), 546.1 nm ($\mathcal{G}$) and 700.0 nm ($\mathcal{B}$).
- The tristimulus values for all visible wavelengths are shown on the right.
- These are also called colour-matching functions.
- What about the negative part in the *R*-function?



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From Fairchild

Color Matching Experiment 2

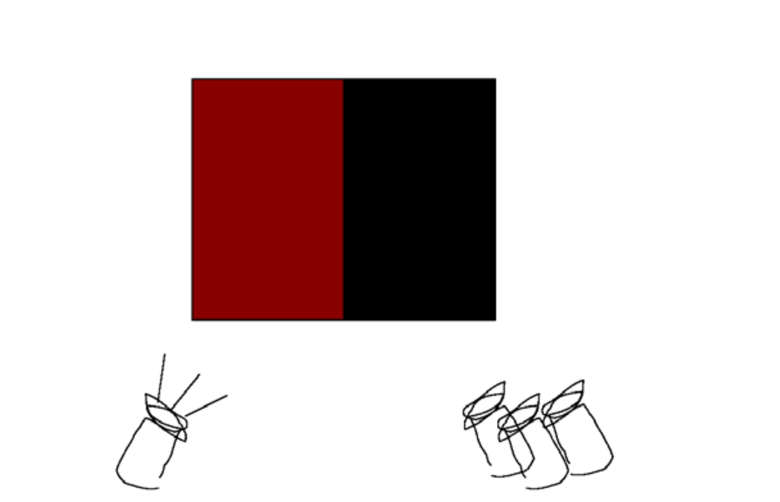

Image by Bill Freeman

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Color Matching Experiment 2

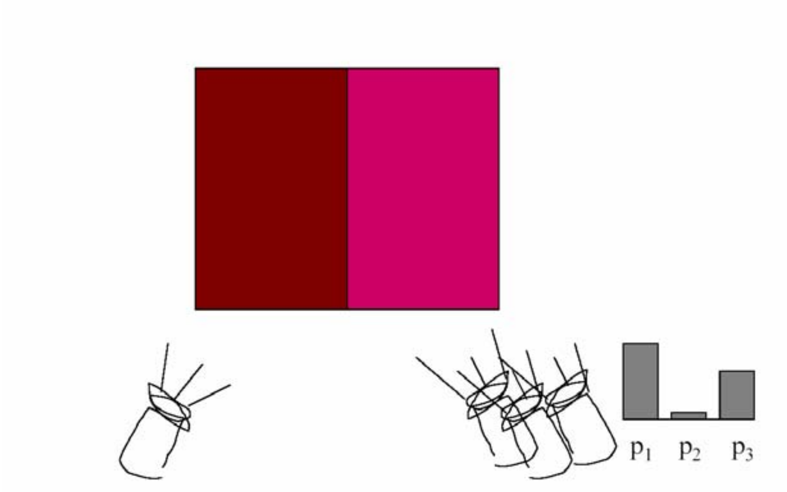

Image by Bill Freeman

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Color Matching Experiment 2

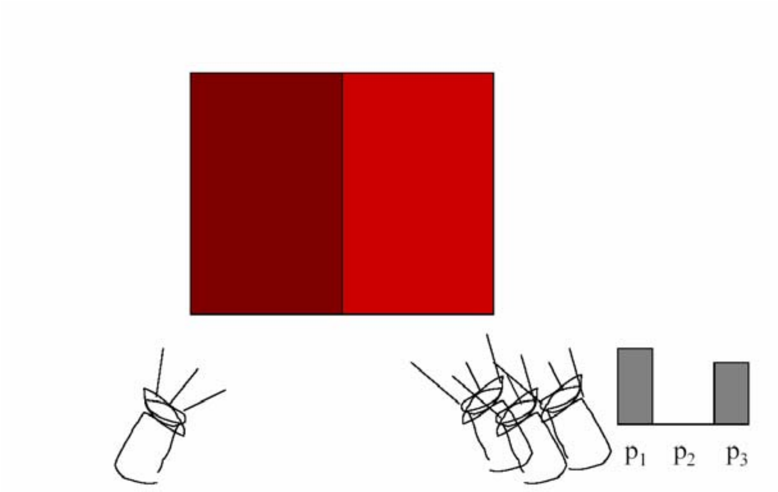

Image by Bill Freeman

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Color Matching Experiment 2

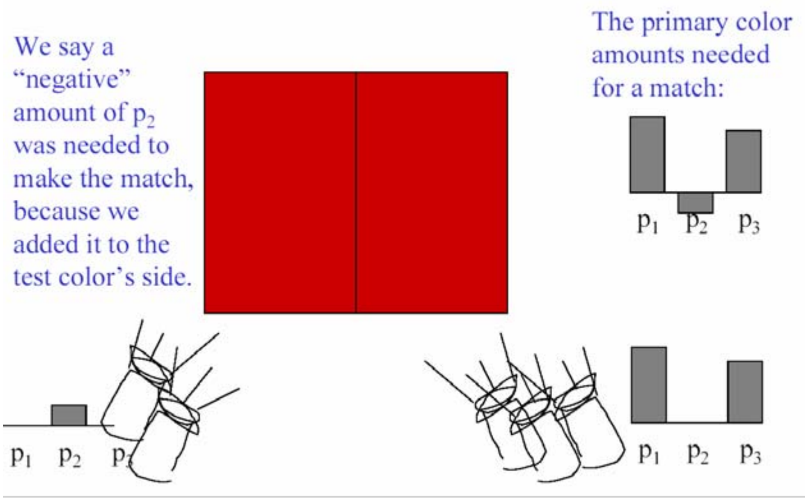

Image by Bill Freeman

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- For a stimulus with spectral power distribution $\Phi(\lambda)$, the tristimulus values are calculated as:

$$R = \int_{\lambda} \Phi(\lambda)\bar{r}(\lambda)\,d\lambda \qquad G = \int_{\lambda} \Phi(\lambda)\bar{g}(\lambda)\,d\lambda$$

$$B = \int_{\lambda} \Phi(\lambda)\bar{b}(\lambda)\,d\lambda$$

- Colour matching functions differ between people.
- The CIE therefore defined a standard set of colour matching functions based on the average of a number of observers (15 – 20 people).
- This is based on the *RGB* primaries mentioned before.

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XYZ primaries

- The CIE also defined another set of primaries, the *XYZ* primaries, to:
  - Eliminate the negative parts of the colour matching functions.
    - There are no real primaries which can do this.
    - The *XYZ* primaries are virtual primaries, they cannot be physically realised.
    - They still produce perfectly usable colour matching functions.
  - Match one of the functions to the human perception of luminance.
    - The *Y* primary responds only to luminance, the *X* and *Z* primaries to chrominance.

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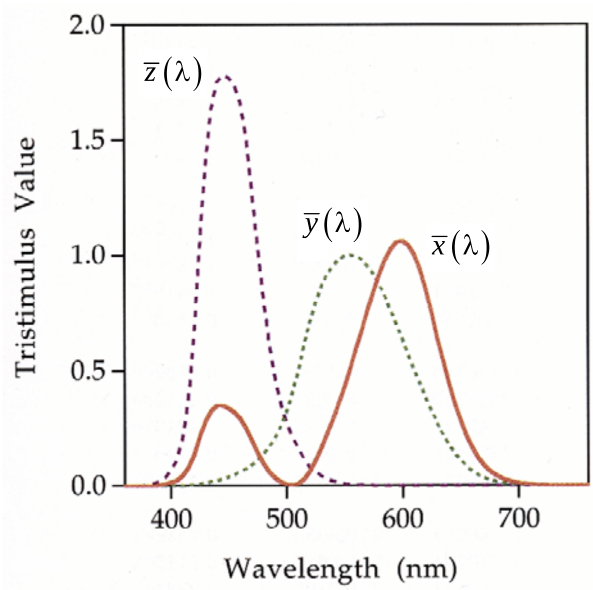
- The resulting colour-matching functions are:



From Fairchild

- The tristimulus values are calculated as before.

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Converting between primaries

- One set of primaries can always be expressed in terms of the tristimulus values for another set of primaries.
- It is therefore possible to derive a linear transform (3 × 3 matrix transformation) to convert tristimulus values from one set of primaries to another.
- It also applies to the colour matching functions, as they are tristimulus values.
- Example:

$$\begin{pmatrix} L \\ M \\ S \end{pmatrix} = \begin{pmatrix} 0.400 & 0.708 & -0.081 \\ -0.226 & 1.165 & 0.046 \\ 0.000 & 0.000 & 0.918 \end{pmatrix} \begin{pmatrix} X \\ Y \\ Z \end{pmatrix}$$

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Chromaticity diagrams

- Developed to provide a convenient 2-dimensional representation of colours.
- Accomplished through a normalisation which removes luminance information:

$$x = \frac{X}{X+Y+Z} \qquad y = \frac{Y}{X+Y+Z} \qquad z = \frac{Z}{X+Y+Z}$$

- The third chromaticity coordinate can always be calculated from the other two:

$$z = 1.0 - x - y$$

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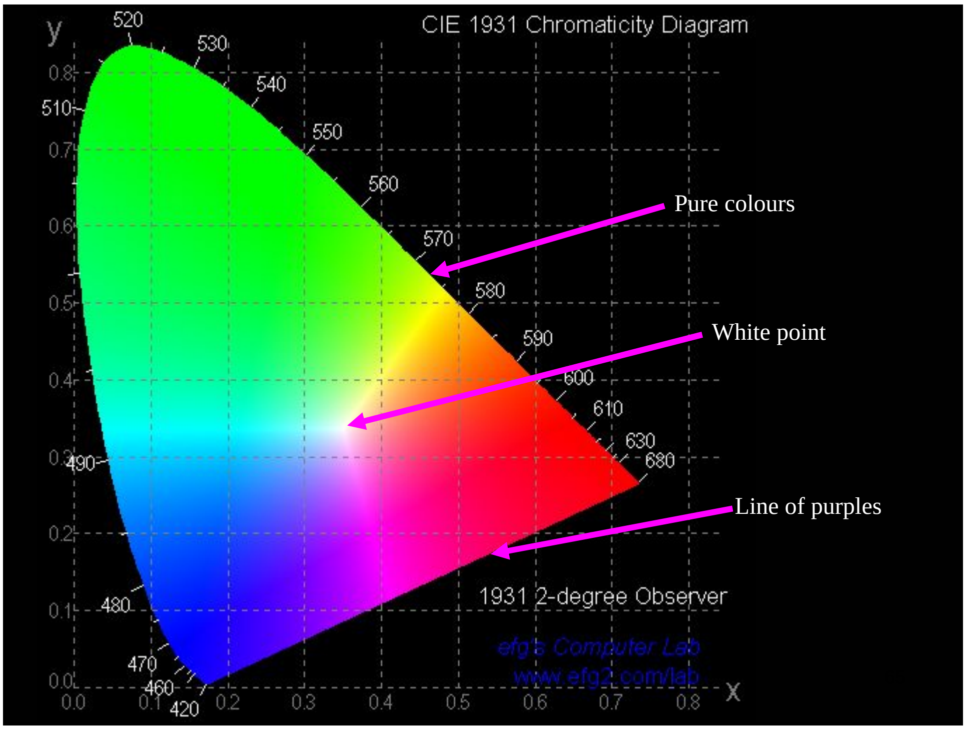
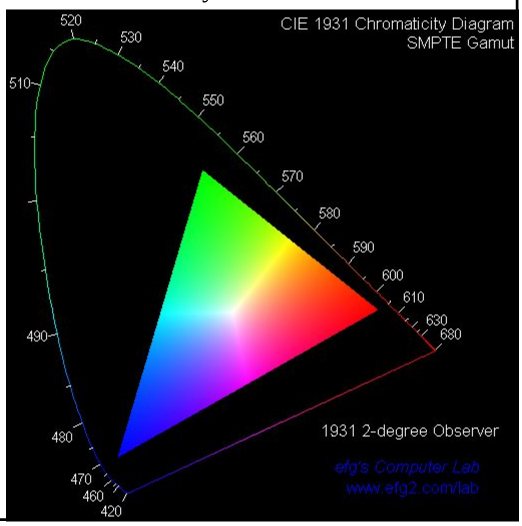
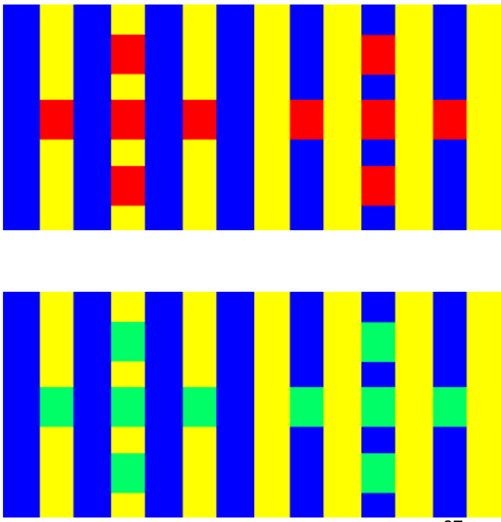


- Comments on the chromaticity diagram:
  - Use with care – they represent a 3-dimensional phenomenon in just 2 dimensions.
    - To fully specify a colour, one must give one of the tristimulus values (usually *Y*) in addition to two chromaticity coordinates.
  - It is almost always impossible to see all the possible colours on any reproduction device.
    - For a CRT monitor, the gamut of displayable colours is given by the triangle lying between the coordinates of the RGB primaries used.



The colour “seen”

- The colour seen depends not only on the spectral power distribution, but on the spatial structure of the image as a whole.
- Colour appearance is influenced more by the local contrast of the cone absorptions than by the absolute levels of absorption.



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Colour appearance

- If you look at a patch of grass under a blue sky and then again at sunset, the colour of the grass seems unchanged.
- But the reflected light reaching the eye has a very different spectrum in the two situations: more blue during the day and more red in the evening.
- “Colour constancy refers to the constant appearance of object or surface colour despite changes in the colour of the illumination, and scene composition and configuration” (Maloney)

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From Fairchild


From Fairchild

But…

- Colour constancy:
  - "… color constancy does not exist in humans!" (Fairchild, 1998)
  - "Does colour constancy exist?" (title of paper by Foster, 2003)
- However computational colour constancy exists!
  - "The objective … is to take limited color information available in a typically trichromatic representation of a scene and produce color constant estimates of the objects. Essentially … an attempt to estimate signals that depend only on the spectral reflectances of objects and not on the illumination" (Fairchild, 1998)
  - "The goal of computational colour constancy is to account for the effect of the illuminant" (Barnard et al., 2002)

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Computational colour constancy

- Two approaches:
  1. Determining a description of the illuminant which can be used for subsequent colour correction of the image.
  2. Mapping the image to a standardised illuminant invariant representation.
- Important applications:
  - Object recognition
  - Scene understanding
  - Image reproduction and digital photography.

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Chromatic adaptation models

- Assume we have an image for which we know
  - The L, M and S values at every pixel.
  - The coordinates of the illuminant L_{white}, M_{white} and S_{white}
- Chromatic adaptation models allow one to:
  - Convert the image so that it is illuminated by some canonical illuminant.
  - Convert the image so that it is illuminated by an illuminant of any other colour.

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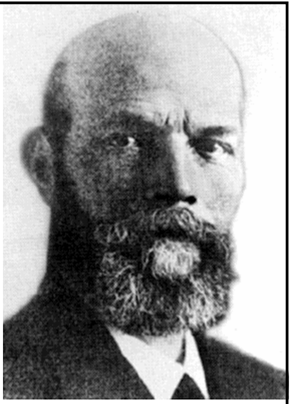
- Von Kries model:
  - "… the individual components present in the organ of vision are completely independent of one another and each is fatigued or adapted exclusively according to its own function." (von Kries, 1902)
  - In symbols: the post-adaptation cone signals L_a, M_a and S_a are calculated as:



$$L_a = k_L L$$
$$M_a = k_M M$$
$$S_a = k_S S$$

k_L, k_M and k_S are the "gain-control" coefficients.

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- How does one obtain k_L, k_M and k_S?
  - To convert to the canonical illuminant:

$$k_L = 1/L_{\text{white}} \qquad k_M = 1/M_{\text{white}} \qquad k_S = 1/S_{\text{white}}$$

  - To convert
    - from a scene illuminated by illuminant "white1" resulting in cone values L_1, M_1 and S_1
    - to a scene illuminated by illuminant "white2" having the cone values L_2, M_2 and S_2:

$$L_2 = \left(\frac{L_{\text{white2}}}{L_{\text{white1}}}\right) L_1$$
$$M_2 = \left(\frac{M_{\text{white2}}}{M_{\text{white1}}}\right) M_1$$
$$S_2 = \left(\frac{S_{\text{white2}}}{S_{\text{white1}}}\right) S_1$$

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- These transformations can easily be written in matrix form, for example:
  - Let M be that transformation matrix from XYZ to LMS coordinates.
  - Starting with an image under illuminant "white1" having coordinates X_1, Y_1 and Z_1, the coordinates X_2, Y_2 and Z_2 under the new illuminant "white2" are:

$$\begin{pmatrix} X_2 \\ Y_2 \\ Z_2 \end{pmatrix} = M^{-1} \begin{pmatrix} L_{\text{white2}} & 0 & 0 \\ 0 & M_{\text{white2}} & 0 \\ 0 & 0 & S_{\text{white2}} \end{pmatrix} \begin{pmatrix} 1/L_{\text{white1}} & 0 & 0 \\ 0 & 1/M_{\text{white1}} & 0 \\ 0 & 0 & 1/S_{\text{white1}} \end{pmatrix} M \begin{pmatrix} X_1 \\ Y_1 \\ Z_1 \end{pmatrix}$$

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Back to computational colour constancy

- To be able to apply the first approach, all we need is the colour of the illuminant.
- For most images, we don't have it $\Rightarrow$ estimate it!
- Various algorithms exist:
  - Grey-world algorithm
  - White patch algorithm
  - Colour-by-correlation (Finlayson et al.)
  - Neural network methods (Funt et al.)
  - Specular reflections

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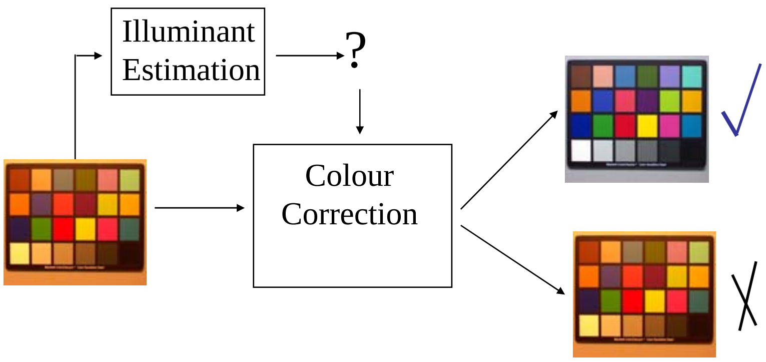
- Estimating the illuminant colour:



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From Moritz Störring

- The simplest illuminant estimation algorithms:
  - Grey-world algorithm:
    - Assume that the average reflectances of a typical scene is some pre-specified value – “grey”.
    - Grey has a number of interpretations. We can assume it means a surface which reflects 50% of the light falling on it.
    - The illuminant estimate is then twice this average value.
  - White patch algorithm:
    - Assumption: there is always a white patch present somewhere in the scene, which has the maximum tristimulus values.
    - The illuminant estimate is then the maximum response in each channel in the image.

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- Example of their use – images of the Macbeth colour chart:

A illumination (tungsten lamp)

TL84 illumination (fluorescent light)

D65 illumination – canonical illumination

Greyworld correction of the above two images

White patch correction of the above two images

From G. Finlayson and G. Schaefer, Proc. 7th Color Imaging Conference: Color Science, Systems, and Applications, pp. 106-113, Scottsdale, USA, 1999

Colour appearance models

- Chromatic adaptation models do not take other effects of the human visual system into account, e.g. the surround effect – the central squares are all the same grey.

- Colour appearance models are needed for this.

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- A number of colour appearance models of varying complexity exist:
  - Hunt model (most comprehensive)
  - RLAB model (developed for cross-media image reproduction)
  - CIECAM02 (latest suggestion by the CIE)
- The main applications are:
  - Image reproduction.
  - Colour measurement and specification.

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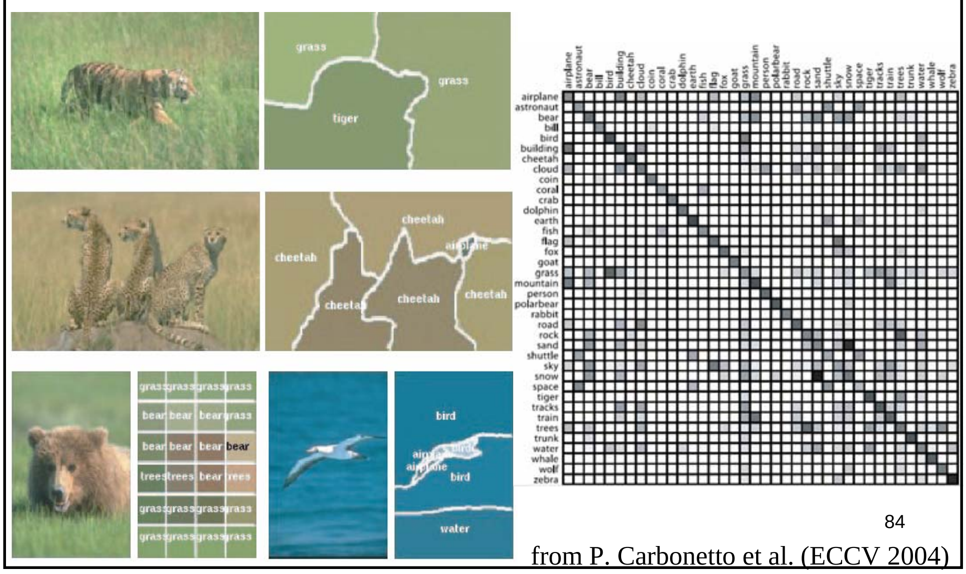
How good are current image understanding algorithms?



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from P. Carbonetto et al. (ECCV 2004)

Summary

- Colour appearance is not simple, as it depends on many factors.
- Chromatic adaptation models take the illumination into account
  - But they need to know the colour of the illumination to do this – usually not available, so an estimate is used.
- Further processing done by the brain is modelled by colour appearance models.

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