SCHOOL of ELECTRICAL ENGINEERING & COMPUTING
FACULTY of ENGINEERING & BUILT ENVIRONMENT
The UNIVERSITY of NEWCASTLE

Comp3320/6370 Computer Graphics

Semester 2, 2018

Lecture 10: Colour and Vision

Based on lectures by Naomi Henderson, Steven Nicklin

and the books of Shirley, Foley et al and Gonzalez & Woods

Colour and Vision: Overview

- **Vision Science**
  - **Characteristics of human vision**
  - **Spatial Vision**
- Light
  - Electromagnetic Spectrum
  - Radiometry
  - Photometry
- Introduction to Vision
  - Human Vision System
- Colour
  - Achromatic Light
  - Chromatic Light
  - Tristmulus Colour Theory
  - Colour Models
    - RGB, CMY, YUV, YIQ, HSV, CIE
    - Conversion Transforms
- Texture Mapping
  - Bump mapping
  - Displacement mapping
  - Environment mapping
  - Shadow mapping
- Anti Aliasing
  - Sampling
  - Reconstruction
  - Mipmapping

References

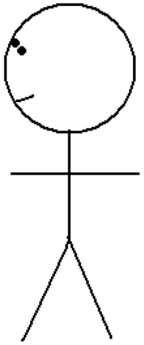
- The primary source for the concepts of these lecture slides are from:
  - [Shirley, 200x], and
  - [Foley et al., 1997]
  - [Gonzalez and Woods, 2002]
- Most images are resourced from:
  - Wikipedia, www.wikipedia.org/topic/ , or
  - Textbook website: http://www.cs.utah.edu/~shirley/fcg/
- With additional information from:
  - [Möller and Haines, 1999]
  - [Akenine-Möller and Haines, 2002]
  - [Foley et al., 1994]
  - [Hill, 2001]

More details are in the literature list on blackboard.

Vision Science

- Vision is the strongest sense that describes the environment
- Vision Science is the study of visual perception that includes the following fields:
  - Perceptual Psychology
  - Neuroscience
  - Computational Analysis

Vision includes two major processes:
1. The external world is mapped on the retina.
2. The retinal image is converted into a brain process.

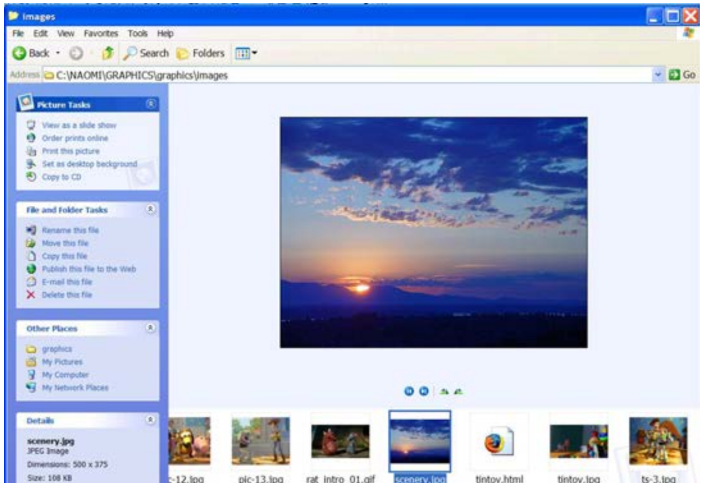


Vision Science

- The purpose of vision is to get information about objects, locations and events.
- Light travels in straight lines hence we can get information from distant locations
- The way things look depend on lighting, surface shape and reflectivity of a material.

Visual Sensitivity

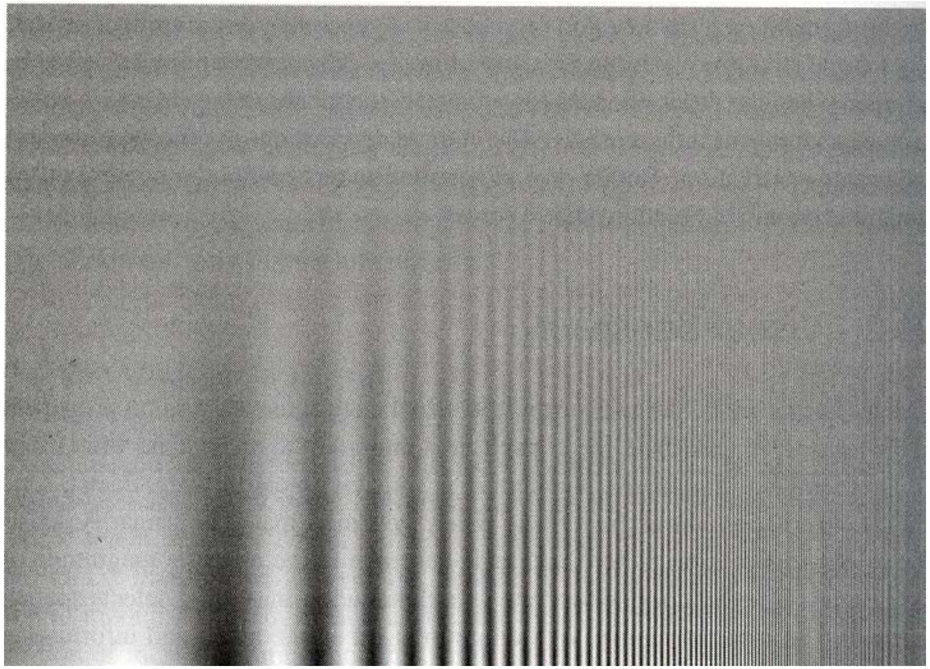
- Descriptions of the environment are based on incident illumination
- It is important to understand what properties of incident illumination can be detected by humans.
- Humans are sensitive to patterns of light rather than the magnitude of energy of the light.
- Spatial, temporal and spectral patterns are detected from an image.
- The pictures on the right indicate that a picture on a monitor can be recognised as a real life image, (pretending that the real image isn't also being displayed on a monitor!)



Brightness and Contrast

Example:

- Contrast increases from top to bottom, frequency increases from left to right.
- Threshold of visibility varies with frequency.



Spatial Vision

- The vision system estimates geometric properties of the visible environment (objects, locations and events).

- Determining *surface layout* is thought to be a key step in vision

- *Visual cues* describe a particular visual pattern which is used to infer properties of the surface layout. There are typically 4 categories:
  1. *Oculomotor cues:* information about the position and focus of the eye
  2. *Disparity cues:* accounts for two eyes focusing on one point
  3. *Motion cues:* information about movement of viewer and/or objects relative to each other.
  4. *Pictorial cues* : information about 3D shapes' light patterns projected onto a 2D surface

[This slide is additional information and will not be examined.]

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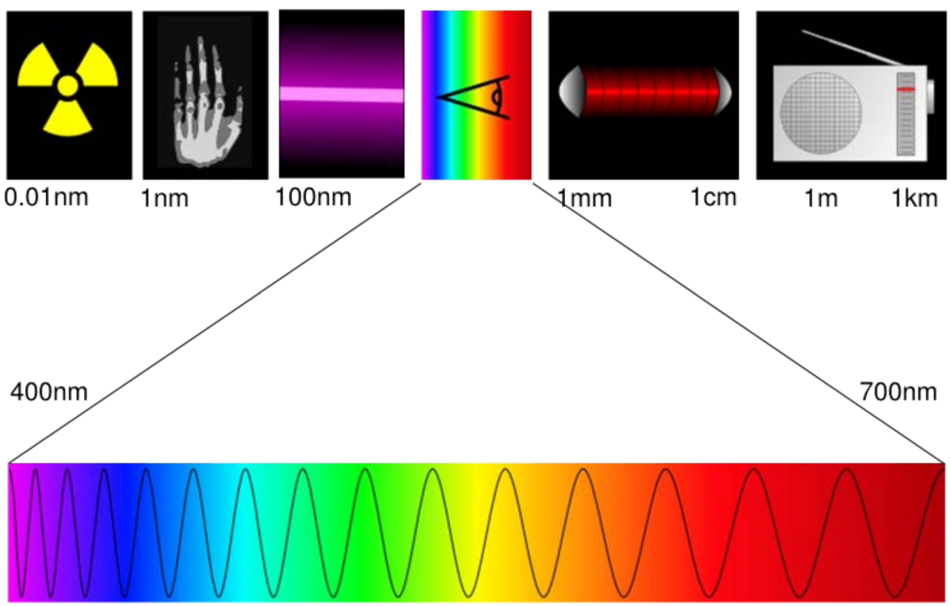
Light and the Electromagnetic Spectrum

Light is electromagnetic energy with wavelengths visible to the human eye. These wavelengths are between 380nm and 700nm.

The Electromagnetic Spectrum:

- Gamma rays
- X-rays
- Ultraviolet light
- **Visible light**
- Infrared radiation
- Radio waves



Violet blue cyan green yellow red

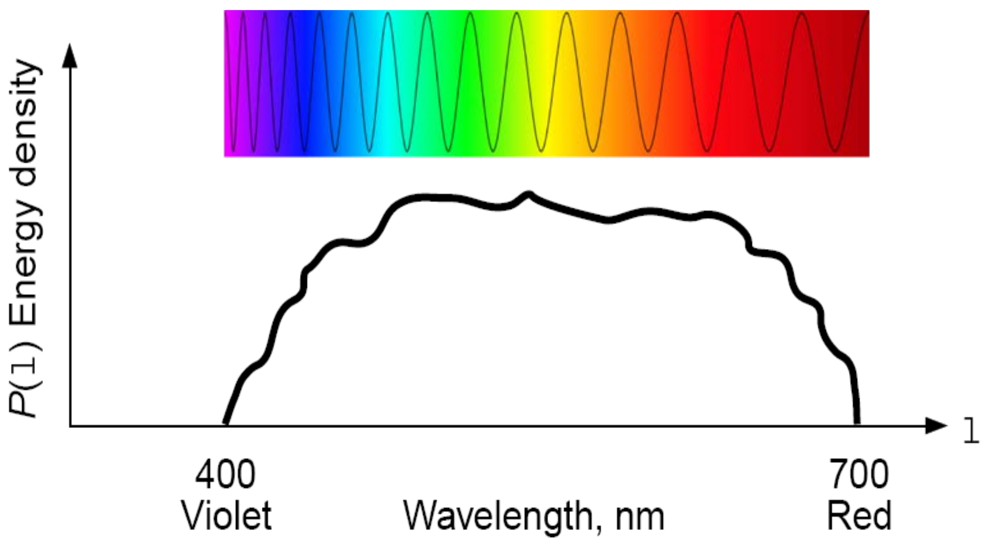
Light

- **Radiometry** is the science of measuring light. It uses SI units.
- **Photometry** uses radiometric quantities and scales them to quantities more useful to human perception.
- Radiometry includes the entire optical radiation spectrum, whilst photometry is bounded to the visible spectrum as defined by the response of the human eye

Spectral Energy

- The amount of energy present at each wavelength is represented by a spectral energy distribution.
- The total energy Q of a wavelength interval can be calculated by looking at the population density and summing the energy of each photon.

$$Q = \frac{\Delta q}{\Delta \lambda}$$

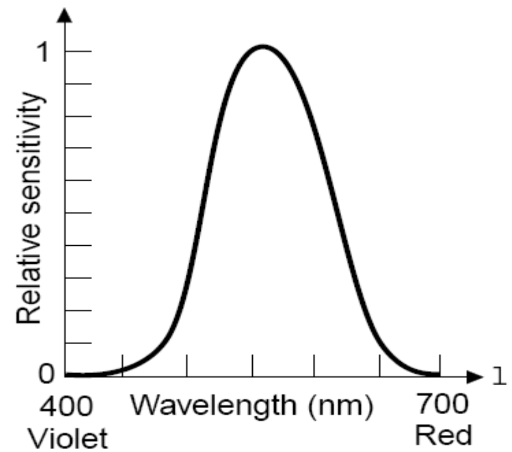


Photometry

- For every radiometric quantity there is a photometric quantity that measures light relative to human perception.
- For a spectral radiometric quantity $f_r()$ at constant luminance, the related photometric quantity f_p is

$$f_p = 683 \frac{lm}{W} \int_{\lambda=380nm}^{800nm} \overline{y}(\lambda) f_r(\lambda) d\lambda$$

- y (with bar) is the luminous efficiency function of the human visual system. The peak sensitivity is to pure green light of wavelength of approx 555nm.
- The function is 0 outside of the integral as λ=380nm and 800nm are the lower and upper limits of the human vision system.



The luminous efficiency function vs. wavelength (nm)

[This slide is additional information and will not be examined.]

Luminance

- The most commonly used photometric quantity used in computer graphics is luminance, from the radiometric quantity radiance. It describes how bright something is.

$$Y = 683 \frac{lm}{W} \int_{\lambda=380nm}^{800nm} \overline{y}(\lambda) L(\lambda) d\lambda$$

[This slide is additional information and will not be examined.]

Why do we only see this range?

The human eye has four kinds of light sensitive cells in the eye that each respond to certain wavelengths and different levels of illumination. These wavelengths are between 400nm and 700nm.

Cone Cells are colour sensors that respond at **mid to high** levels of illumination there are three types:

•Short (blue) cones

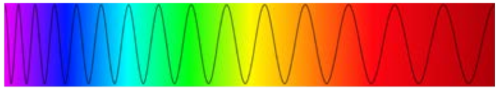
•Middle (green) cones

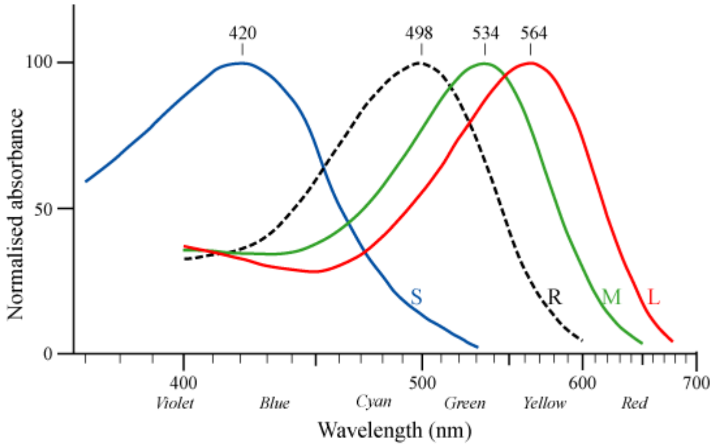
•Long (red) cones

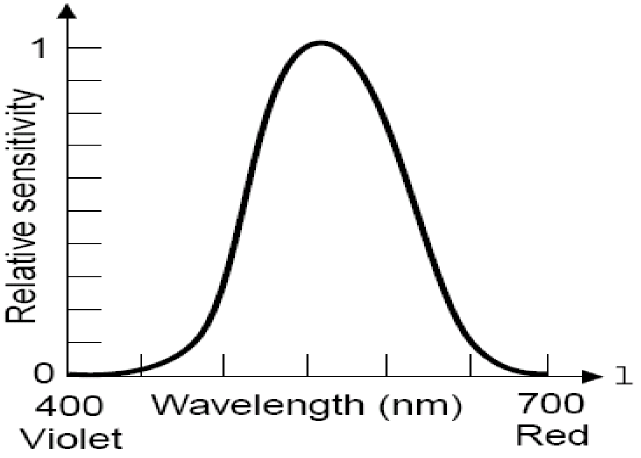
Rods are photoreceptor cells that respond at **low to mid** levels of illumination. Wavelength response is between the short and middle cones.

The wavelength sensitivity of these sensors can be seen in figure to the right.

Humans can distinguish between approximately 10 million different colours.







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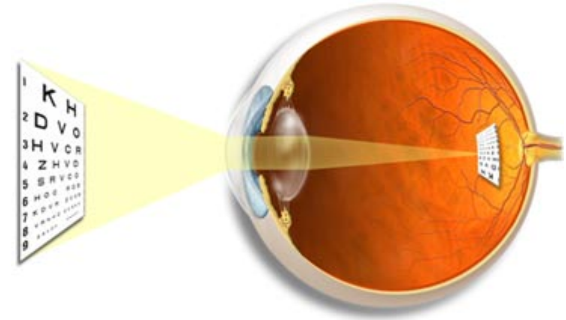
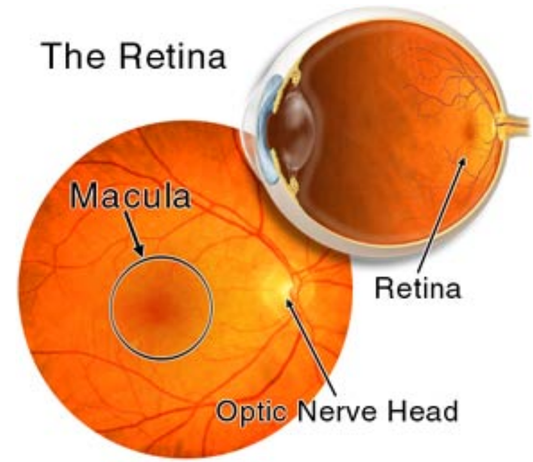
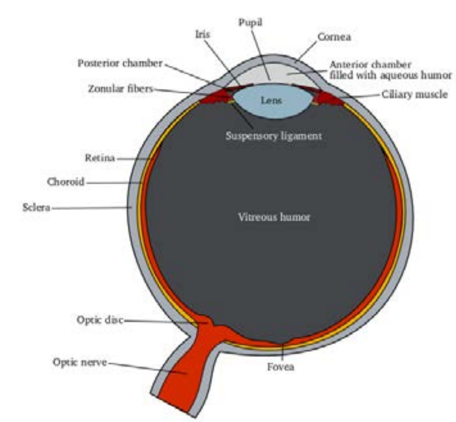
Human Vision



- Lens
  - The lens system projects images upside down onto the retina. It absorbs approx 8% of the visible spectrum with a higher ratio of shorter wavelength, it also absorbs UV and IR light.
- Retina
  - Located on the back of the eyeball is a thin layer of neural cells, including photoreceptor cells, and a series of nerves that stem from the optic nerve and information to the brain.
- Macula
  - Area of the retina approx 1.5 mm in diameter.
  - Designed for acuity vision, the ability to resolve fine image details.
- Fovea
  - Is the sharp central focus area of an image, it is approx 0.2mm in diameter in the centre of the macula. Compared to the rest of the retina it has smaller and a high density of colour sensitive cones but almost no rods.
  - This is the area that scans as you read, drive, etc.
  - Because there are no rods the focus area is not sensitive to dim lights, e.g. to look at a dim star it is better to use your peripheral vision and look out the side of your eye.
- Optic Nerve
  - There are no light sensors so it becomes a “blind spot”. Instead of seeing a black spot your brain fills in/ adapts this for you.

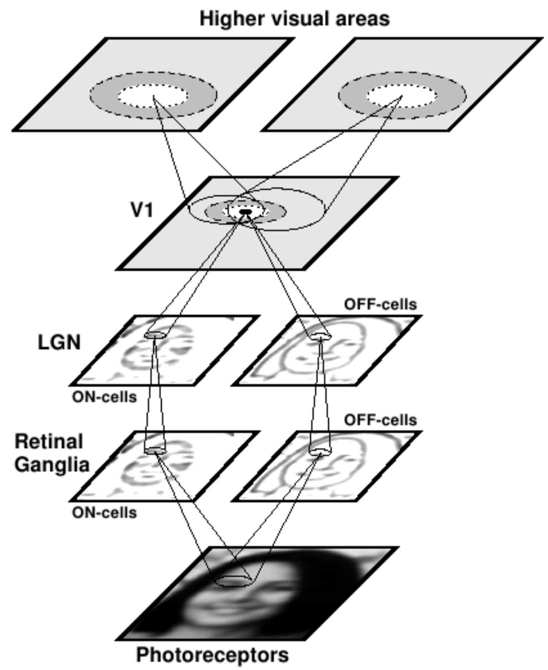




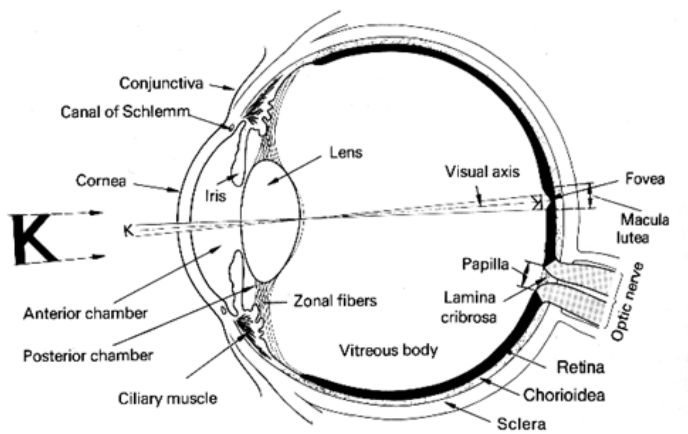
Human Vision

How it works together:

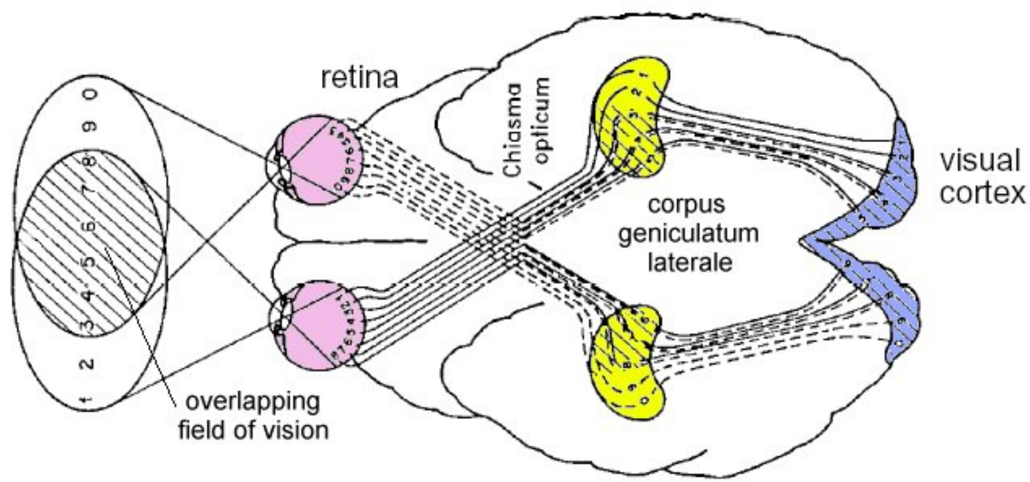
- The light of an image is projected onto the retina where a series of photoreceptor cells (cones and rods) detect the pattern.
- The 6-7 million colour receptors (cones) are mainly in the central vision area (fovea and macula) and allow for high resolution of fine detail. Each cone is attached to its own nerve end thus allowing for high sensitivity. Cones react in mid to high levels of lighting thus are “bright light vision”.
- There are 75 to 150 million rods distributed over the retina (besides the fovea). Rods are less sensitive than cones because several are attached to a single nerve and they do not detect colour. They are sensitive in low to mid levels of illumination and give an “overall” image, it forms the images you see in the night and is known as “dim-light vision”.
- Muscles control the eyeball to center an image into the focus area (macula region). The main focus e.g. the scanning area when reading, is then centered on the fovea region.



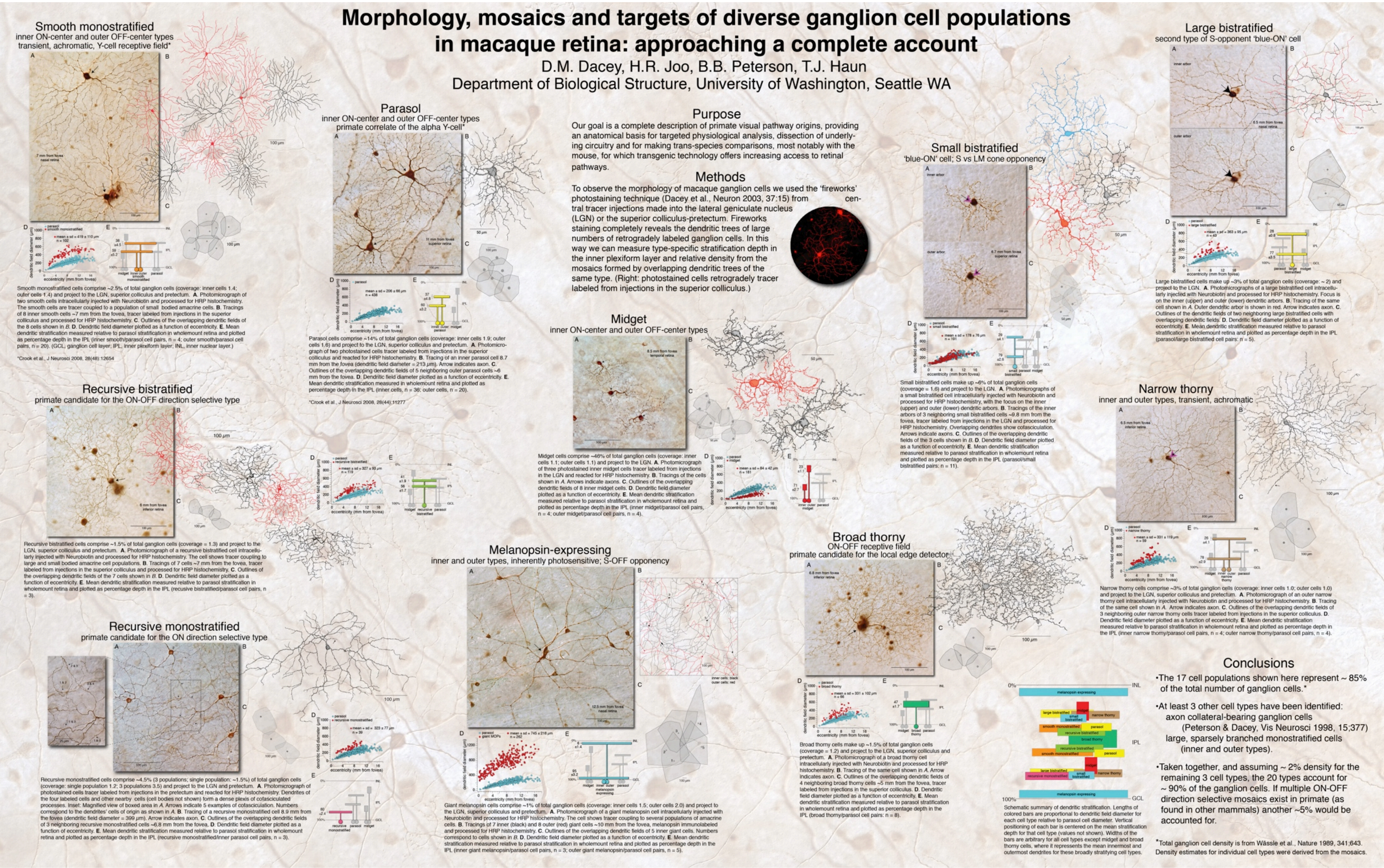
Higher visual areas
V1
LGN
OFF-cells
ON-cells
Retinal
Ganglia
OFF-cells
ON-cells
Photoreceptors

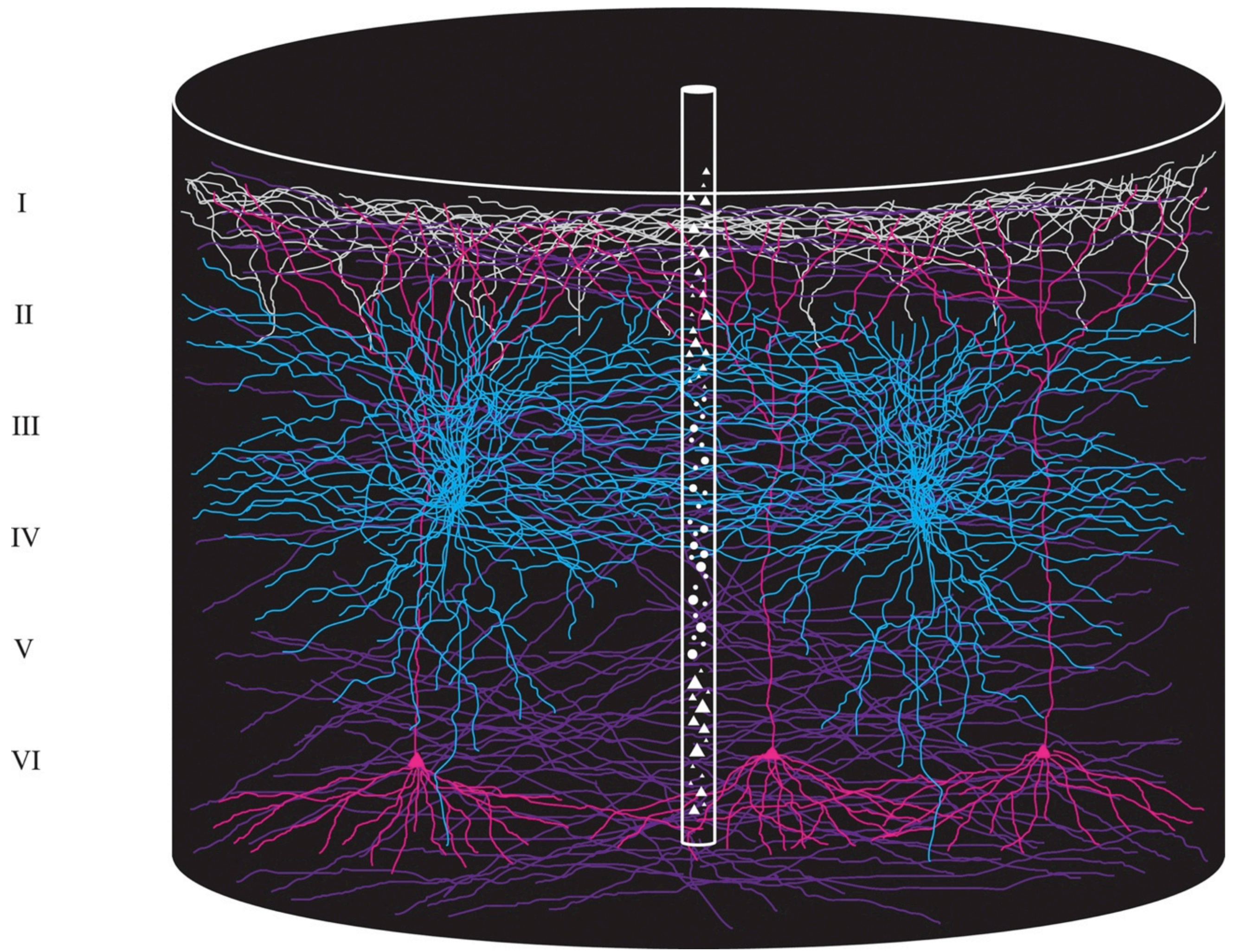


Conjunctiva
Canal of Schlemm
Cornea
Iris
Lens
Visual axis
Fovea
Macula
lutea
K
Papilla
Lamina
cribrosa
Optic nerve
Anterior chamber
Zonal fibers
Posterior chamber
Vitreous body
Retina
Ciliary muscle
Chorioidea
Sclera

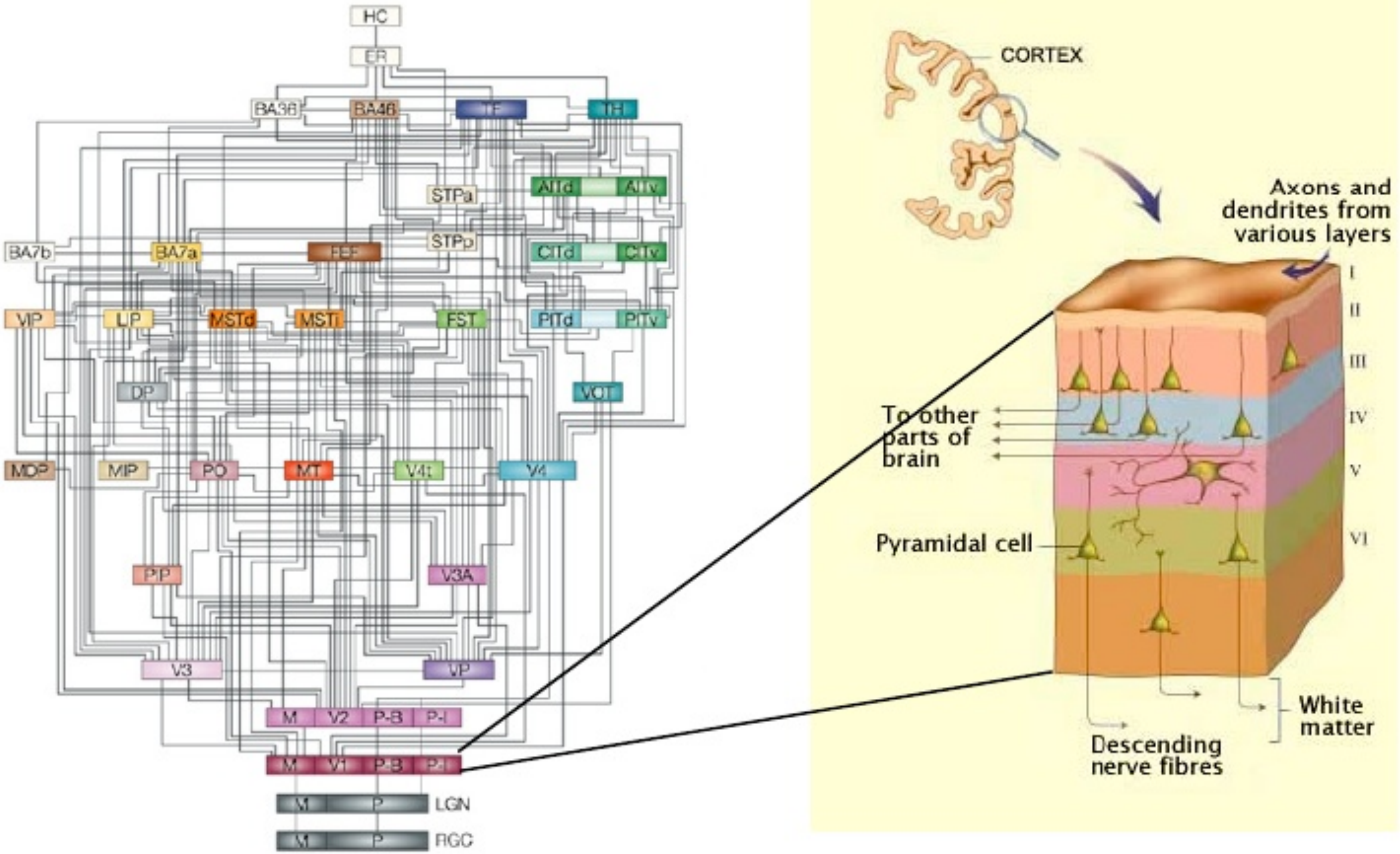


retina
Chiasma
opticum
visual
cortex
corpus
geniculatum
laterale
overlapping
field of vision


Morphology, mosaics and targets of diverse ganglion cell populations in macaque retina: approaching a complete account
D.M. Dacey, H.R. Joo, B.B. Peterson, T.J. Haun
Department of Biological Structure, University of Washington, Seattle WA
Purpose
Our goal is a complete description of primate visual pathway origins, providing an anatomical basis for targeted physiological analysis, dissection of underlying circuitry and for making trans-species comparisons, most notably with the mouse, for which transgenic technology offers increasing access to retinal pathways.
Methods
To observe the morphology of macaque ganglion cells we used the 'fireworks' photostaining technique (Dacey et al., Neuron 2003, 37:15) from central tracer injections made into the lateral geniculate nucleus (LGN) or the superior colliculus-pretectum. Fireworks staining completely reveals the dendritic trees of large numbers of retrogradely labeled ganglion cells. In this way we can measure type-specific stratification depth in the inner plexiform layer and relative density from the mosaics formed by overlapping dendritic trees of the same type. (Right: photostained cells retrogradely tracer labeled from injections in the superior colliculus.)
Smooth monostratified
inner ON-center and outer OFF-center types
transient, achromatic, Y-cell receptive field*
Parasol
inner ON-center and outer OFF-center types
primate correlate of the alpha Y-cell*
Midget
inner ON-center and outer OFF-center types
Small bistratified
'blue-ON' cell; S vs LM cone opponency
Large bistratified
second type of S-opponent 'blue-ON' cell
Recursive bistratified
primate candidate for the ON-OFF direction selective type
Narrow thorny
inner and outer types, transient, achromatic
Broad thorny
ON-OFF receptive field
primate candidate for the local edge detector
Melanopsin-expressing
inner and outer types, inherently photosensitive; S-OFF opponency
Recursive monostratified
primate candidate for the ON direction selective type
Conclusions
•The 17 cell populations shown here represent ~ 85% of the total number of ganglion cells.*
•At least 3 other cell types have been identified:
axon collateral-bearing ganglion cells (Peterson & Dacey, Vis Neurosci 1998, 15;377)
large, sparsely branched monostratified cells (inner and outer types).
•Taken together, and assuming ~ 2% density for the remaining 3 cell types, the 20 types account for ~ 90% of the ganglion cells. If multiple ON-OFF direction selective mosaics exist in primate (as found in other mammals) another ~5% would be accounted for.
*Total ganglion cell density is from Wässle et al., Nature 1989, 341;643. Density estimates for individual cell types were derived from the mosaics.

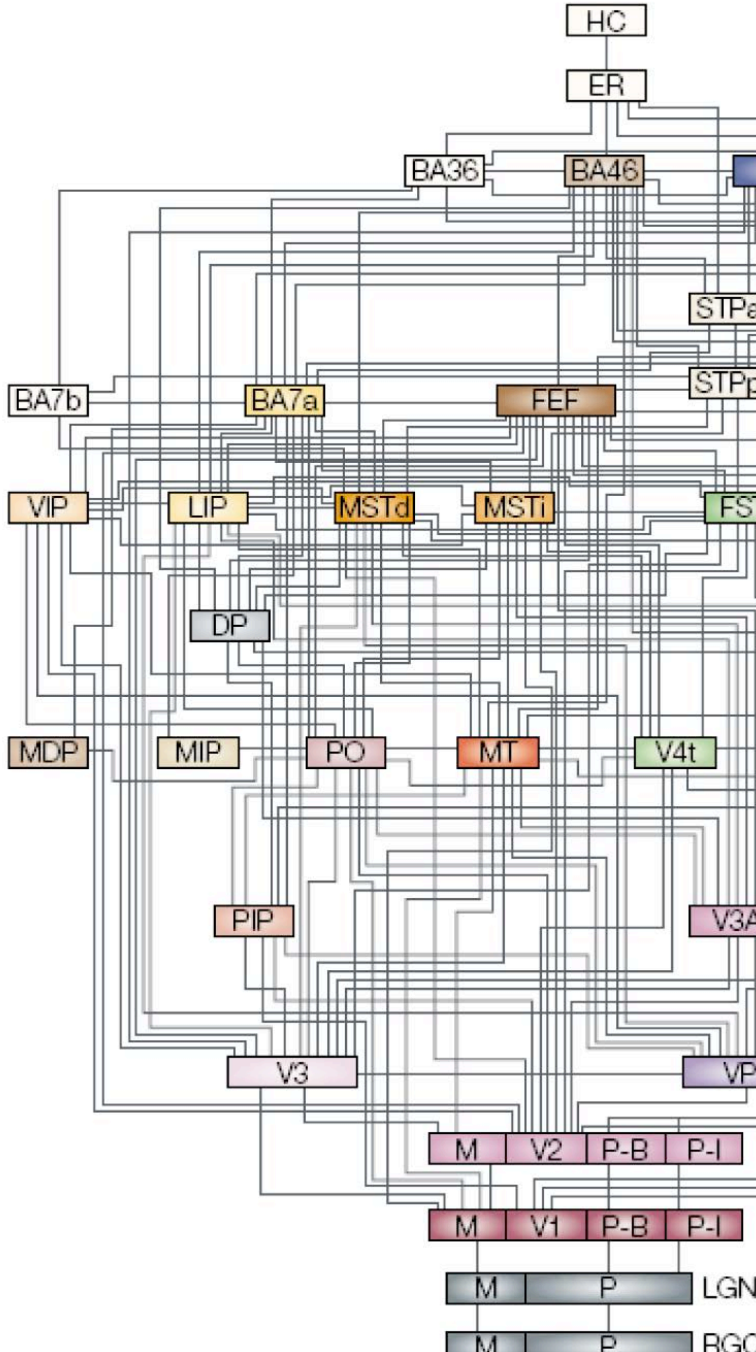


Per E. Roland. Six Principles of visual cortical dynamics.
Front. Syst. Neurosci., 02 July 2010 | http://dx.doi.org/10.3389/fnsys.2010.00028



Hierarchical architecture: Anatomy

Rockland & Pandya '79;
Maunsell & Van Essen '83;
Felleman & Van Essen '91


HC
ER
BA36
BA46
TF
TH
STPa
AITd
AITv
STPp
BA7b
BA7a
FEF
CITd
CITv
VIP
LIP
MSTd
MSTi
FST
PITd
PITv
DP
VOT
MDP
MIP
PO
MT
V4t
V4
PIP
V3A
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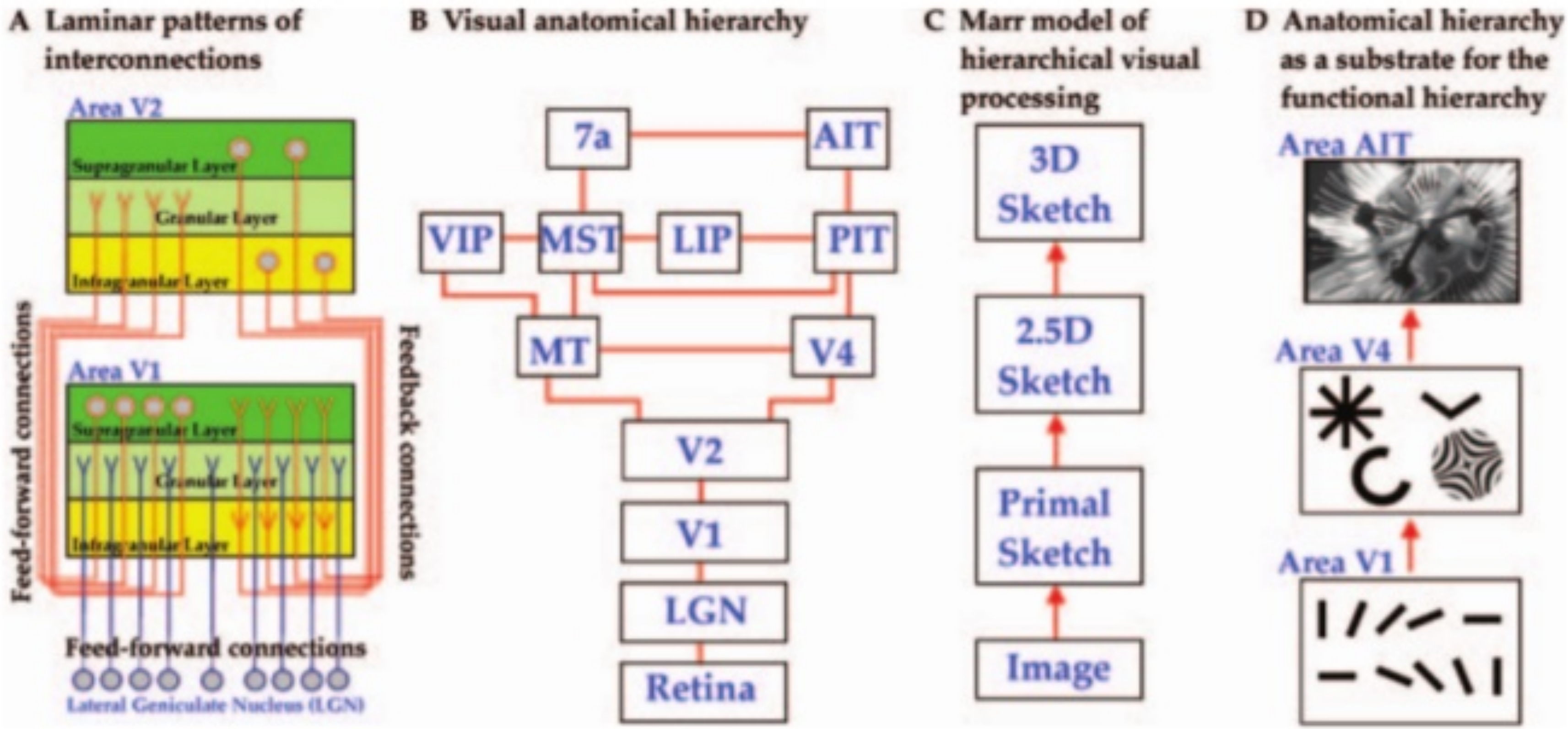
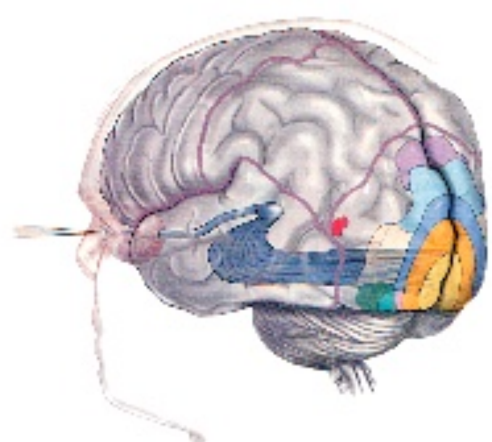
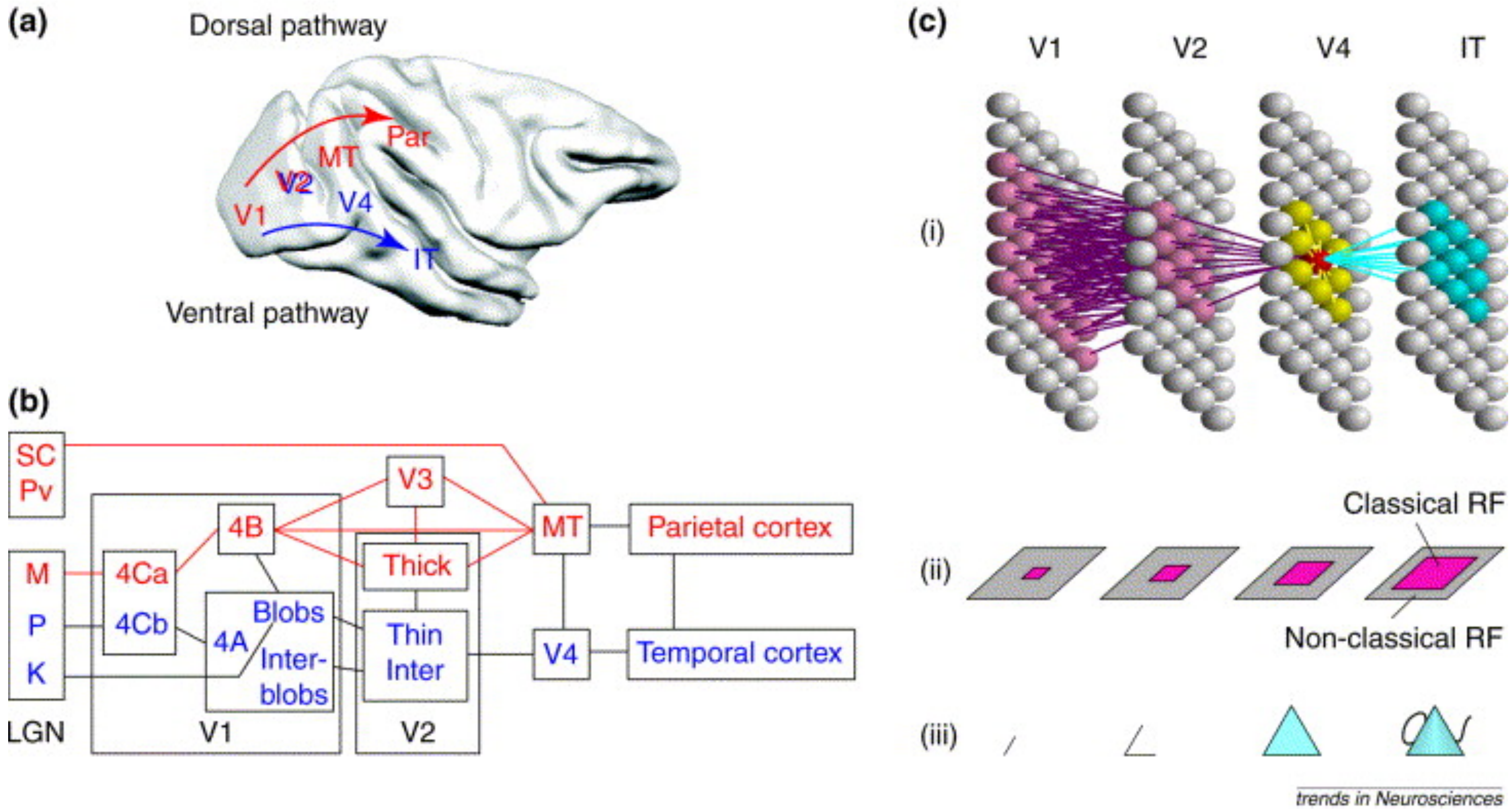
P
LGN
M
P
RGC



from Hedgé and Felleman, 2007





Anatomical connections and receptive fields. Anatomical connections are shown at three different levels of detail. (a) The two cortical streams are shown in an MRI image of monkey cortex rendered with BrainVoyager© software

(b) Dorsal pathway, parietal lobe: spatial location and action
Ventral pathway, temporal lobe: characteristics of objects

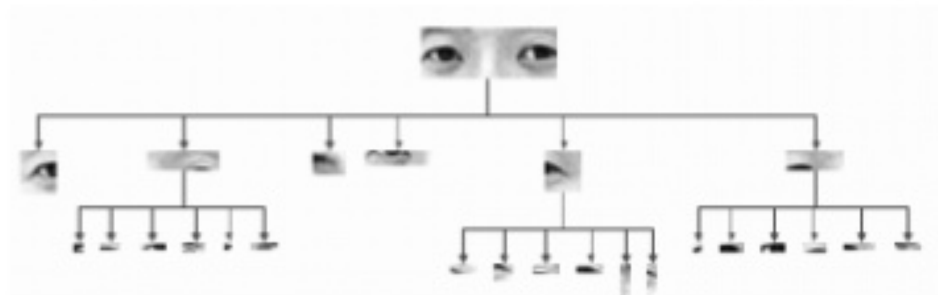
Victor A.F. Lamme, Pieter R. Roelfsema

The distinct modes of vision offered by feedforward and recurrent processing

null, Volume 23, Issue 11, 2000, 571–579

http://dx.doi.org/10.1016/S0166-2236(00)01657-X

Hierarchies vs. holistic features



Feature hierarchies are often inspired by the structure of the primate visual system, which has been shown to use a hierarchy of features of increasing complexity, from simple local features in the primary visual cortex, to complex shapes and object views in higher cortical areas.

S. Ullman et al.

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Achromatic Light

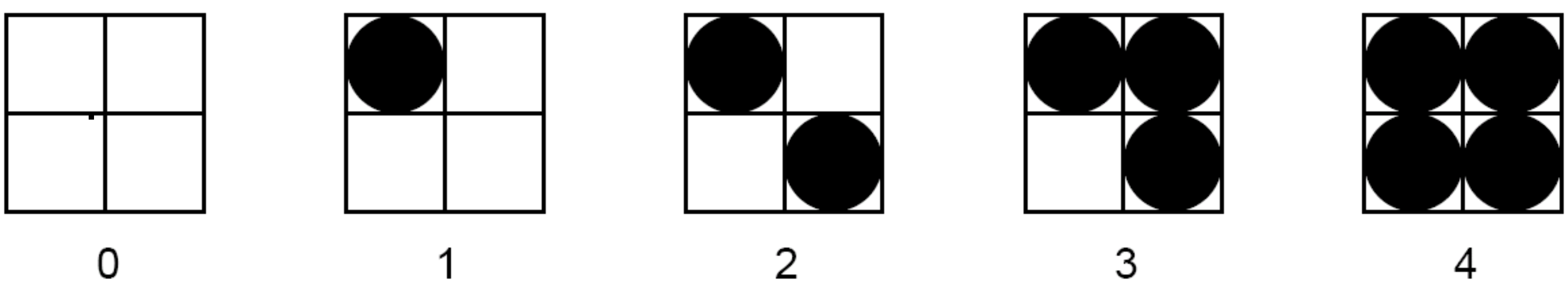
- Achromatic means the absence of colour
- Only one light property, **intensity,** the amount of light.

    Physics is intensity, luminance

    Psychology is brightness.
- Halftoning or clustered-dot ordered dither

    Makes use of the spatial integration that our eyes perform.

    A 2 × 2 pixel area of a bi-level display can be used to produce five different intensity levels (see figure below).
- Used for greyscale i.e. black, grey, white.
- Used for B/W television.



Chromatic Light

Chromatic light are the wavelengths between 400nm and 700nm of the electromagnetic spectrum. The three quantities used to describe chromatic light are:

- **Radiance** (W): Total energy from the light source
- **Luminance** (lm): Perceived energy from light source
- **Brightness**: Achromatic notion of intensity.

Chromatic Colour

Visual sensations caused by coloured light are much richer than those caused by achromatic light. There are generally three characteristics used to distinguish colours:

- **Hue:** distinguishes between colours such as red, green, purple and yellow.
- **Saturation:** refers to how far a colour is from a grey of equal intensity (eg. red – pink, royal blue – sky blue). Unsaturated colours such as pastel colours include more white light than do the saturated colours.
- **Brightness:** refers to the perceived intensity of a self-luminous object.

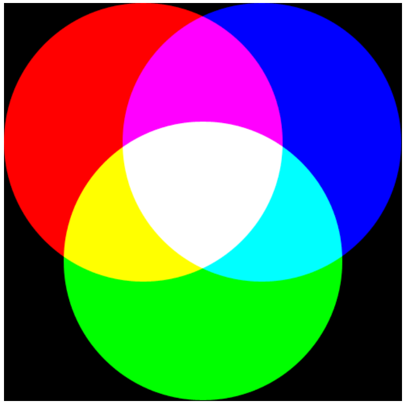
Colour Models

A colour model is a specification for a 3D colour coordinate system and a visible subset in the coordinate system within which all colours in a particular colour gamut lie. We look at the following colour models:

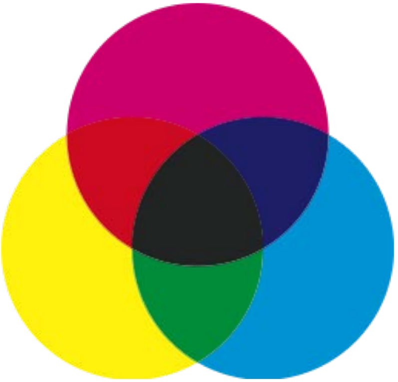
- **RGB**: used with computer monitors
- **YIQ**: the broadcast TV colour system
- **CMY** (cyan, magenta, yellow): colour printing devices
- **HSB** or **HSV**: in contrast to the above three systems the goal is ease of use.

Models can be additive or subtractive.

We also need to know conversion algorithms between the different colour models.



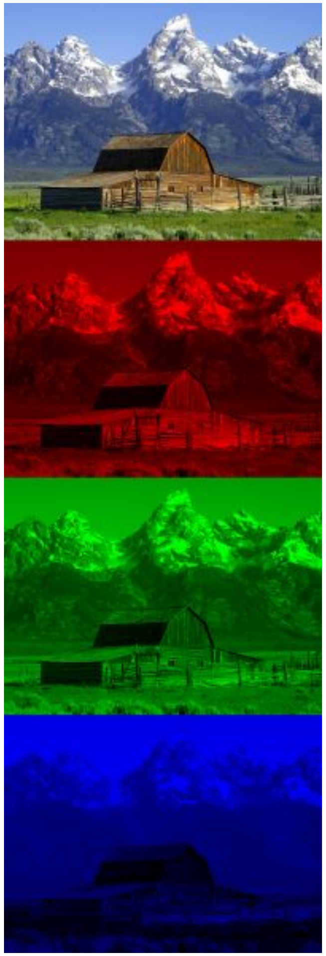
Additive colour model : RGB



Subtractive colour model : CMY

RGB Colour Model

- RGB (red, green, blue)
- Uses light principals.
- Used for computer monitors (CRT) and colour raster graphics.
- Additive colour model.
- Employs a cartesian coordinate system.
- Black = (0,0,0), white = (1,1,1) and the greys are on the main diagonal (equal amount of each primitive).
- The colour gamut defined by the RGB model is defined by the chromaticities of a CRT’s phosphors.

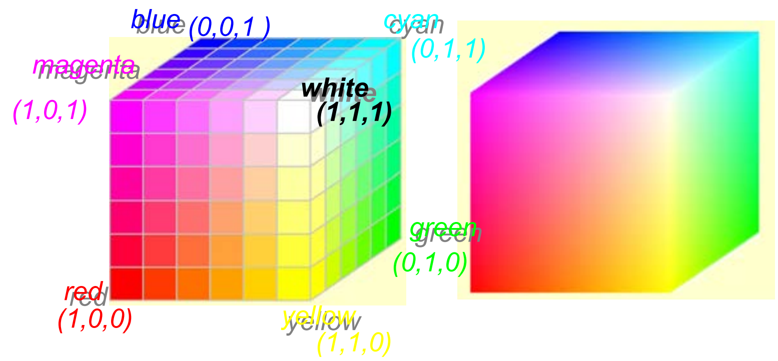


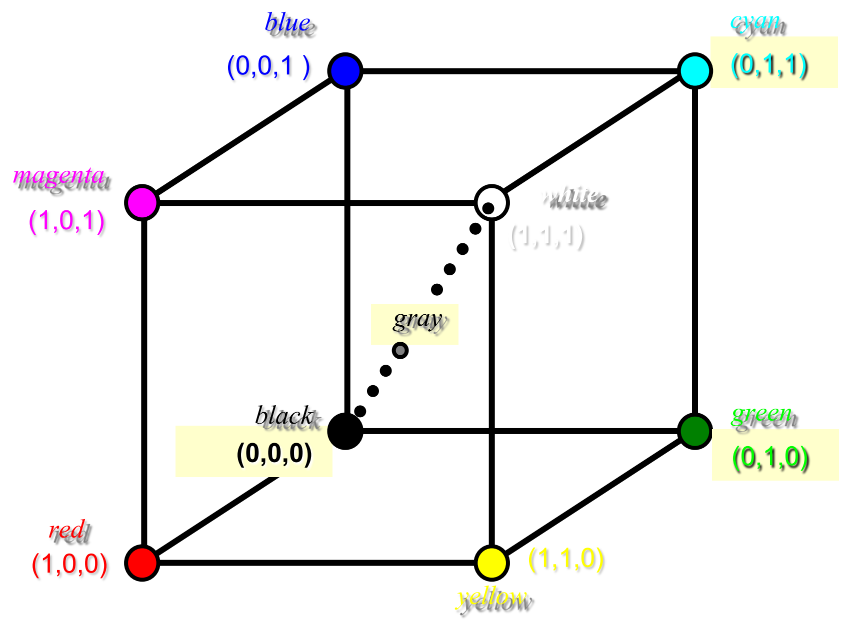
RGB Cube

(R,G,B) Cube has 8 vertices:

- Red= (1,0,0)
- Green=(0,1,0)
- Blue=(0,0,1)
- Magenta= Red + Blue= (1,0,1)
- Cyan= Green + Blue= (0,1,1)
- Yellow= Red + Green= (1,1,0)
- Black= (0,0,0)
- White= (1,1,1)
- The diagonal between black and white are the greys.

The RGB values are scaled depending on the number of bits used to describe the colour.





CMY Colour Model

- CMY (Cyan, Magenta, Yellow)
- Used in photographic and printing devices.
- Employs a cartesian coordinate system similar as the RGB system. The difference is that white light is at the origin and not black.
- Subtractive primitives: used as filters to subtract colour from white light. E.g. when a surface is coated with cyan ink no red light is reflected from the surface.
- Cyan, magenta, and yellow are the complements of red, green, and blue, respectively.
  - Red = black - cyan
  - Green = black - magenta
  - Blue = black – yellow
  - White= black-cyan-magenta-yellow
- A surface coated with cyan and yellow absorbs red and blue, leaving only green to be reflected.
- Also, CMYK, K (black) used for print technology.

CMY

CMYK

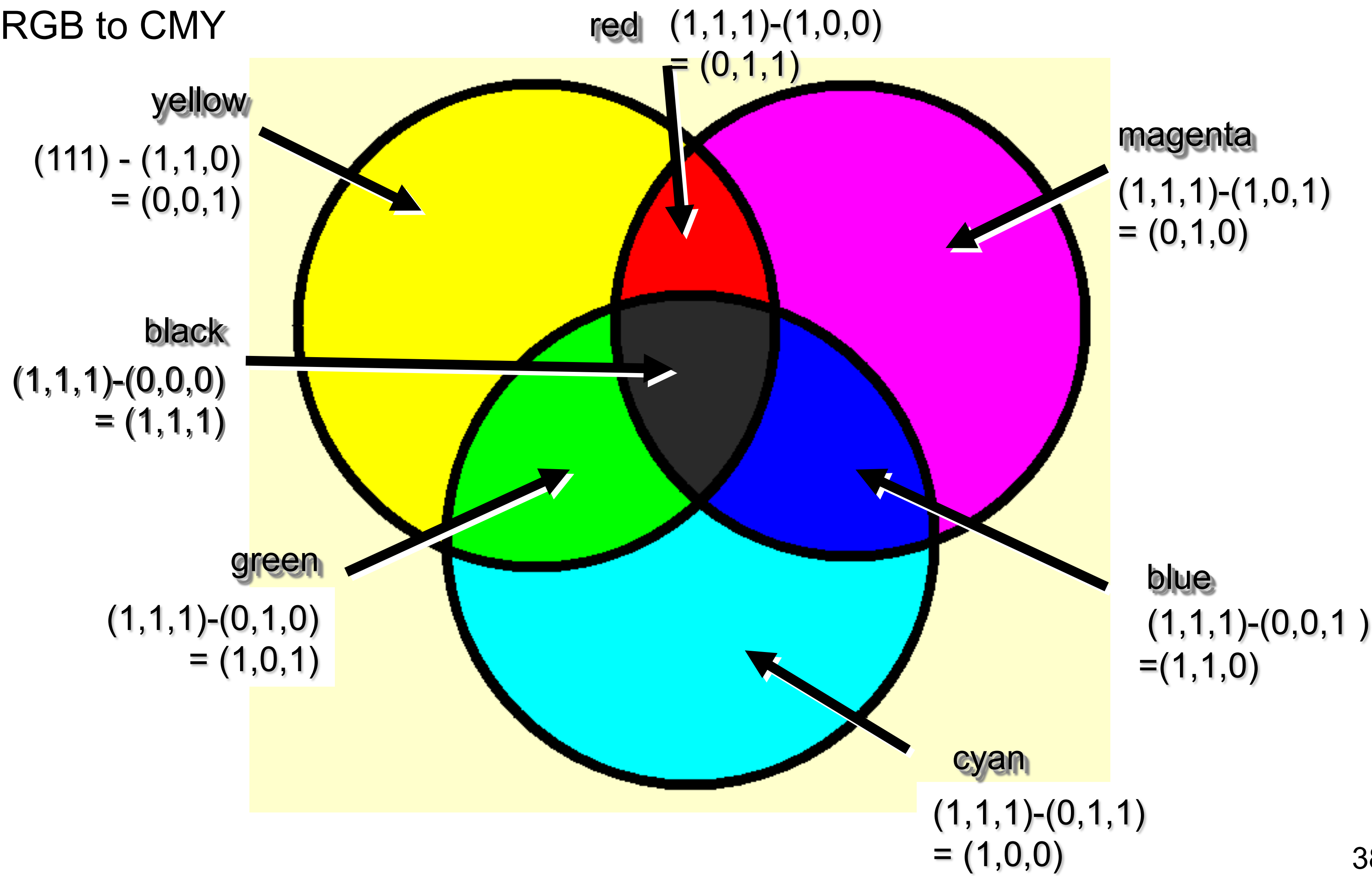
Colour Space Transforms

- RGB to CMY

$$\begin{bmatrix} C \\ M \\ Y \end{bmatrix} = \begin{bmatrix} 1 \\ 1 \\ 1 \end{bmatrix} - \begin{bmatrix} R \\ G \\ B \end{bmatrix}$$

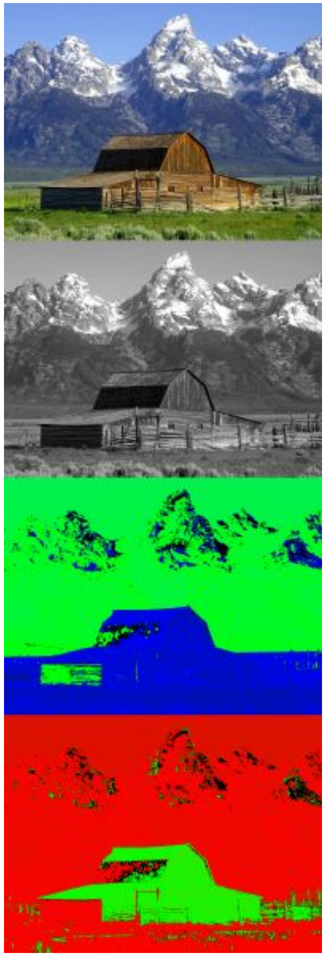
Subtractive Properties CMY

RGB to CMY



YUV Colour Model

- Y is luminance
- U and V are blue green and red green chrominance components respectively.
- Models human perception of colour.
- There are other models derived from YUV e.g. YIQ, YCbCr, YPbPr that use a different scale but use the same principal.
- Used in PAL and NTSC television



Colour Space Transforms

- RGB to YUV

$$\begin{bmatrix} Y \\ U \\ V \end{bmatrix} = \begin{bmatrix} 0.299 & 0.587 & 0.114 \\ -0.147 & -0.289 & 0.436 \\ 0.615 & -0.515 & -0.100 \end{bmatrix} \begin{bmatrix} R \\ G \\ B \end{bmatrix}$$

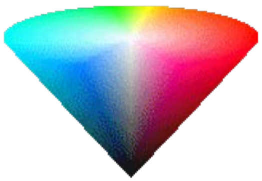
- YUV to RGB

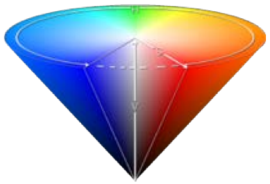
$$\begin{bmatrix} R \\ G \\ B \end{bmatrix} = \begin{bmatrix} 1 & -0.000039457070707 & 1.139827967171717 \\ 1 & -0.394610164141414 & -0.580500315656566 \\ 1 & 2.031999684343434 & -0.000481376262626 \end{bmatrix} \begin{bmatrix} Y \\ U \\ V \end{bmatrix}$$

- These matrix values model the relationship between intensity, blue and red chrominance as they vary with the ratio of R, G and B

[This slide is additional information and will not be examined.]

HSV Colour Model



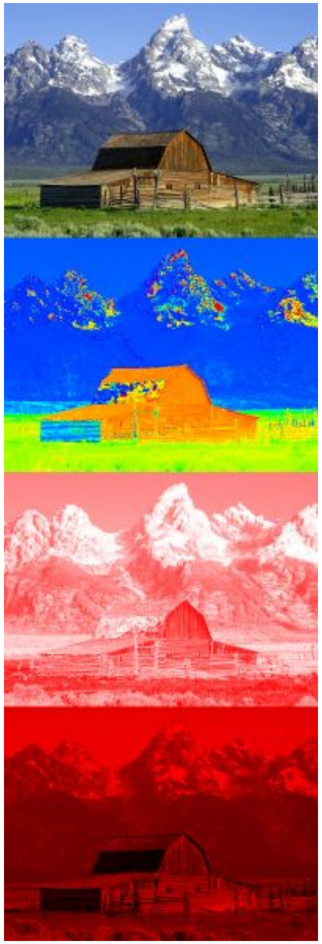


HSV (hue, saturation, value) also known as HSB (hue, saturation, brightness) or HSI (hue, saturation, intensity)

- **Hue** is the colour with value between 0 and 360 (circle in diagram).
- **Saturation** describes vibrancy, how much colour there is. It is the distance from the centre axis (grays)
- **Value** is the brightness, the centre axis that varies from 0 (black) to 1 (white).

The coordinate system is cylindrical. The subset within which the model is defined is a six-sided pyramid and is called a *hexcone*.

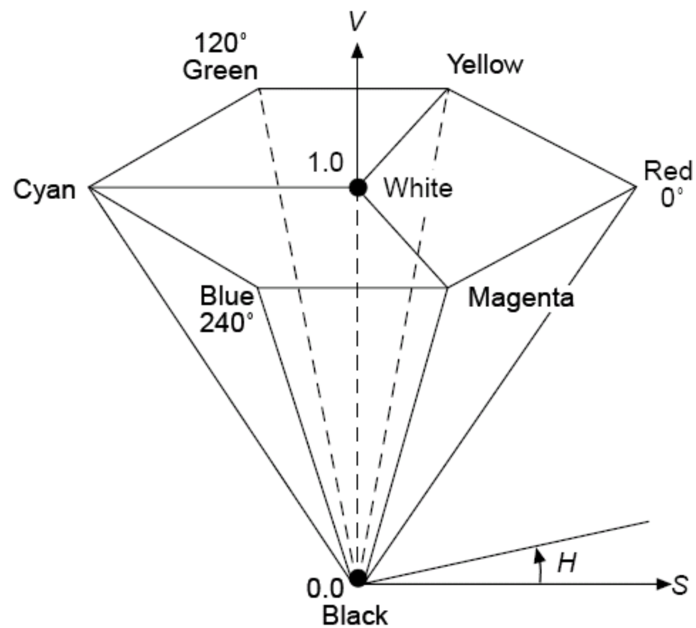
The top of the pyramid corresponds to V=1. Not all colours of the V=1 plane are of the same brightness.

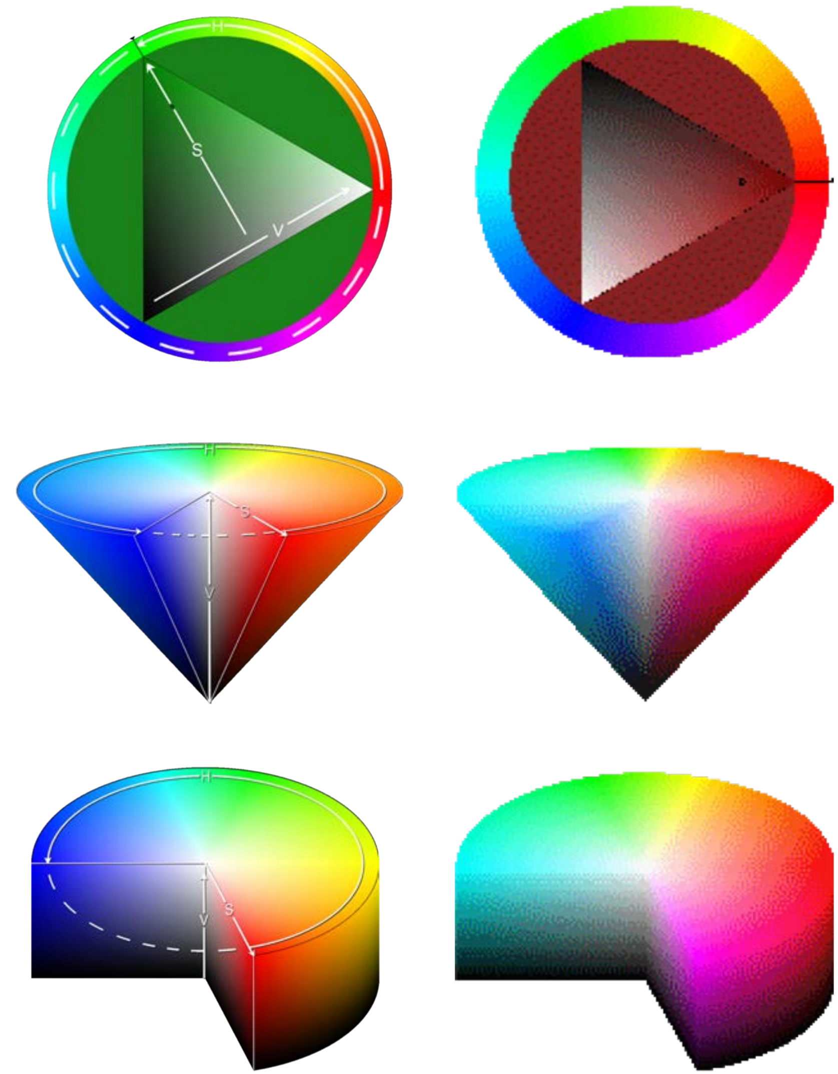


HSV Colour Model

Hue (H) is measured by the angle around the vertical axis.

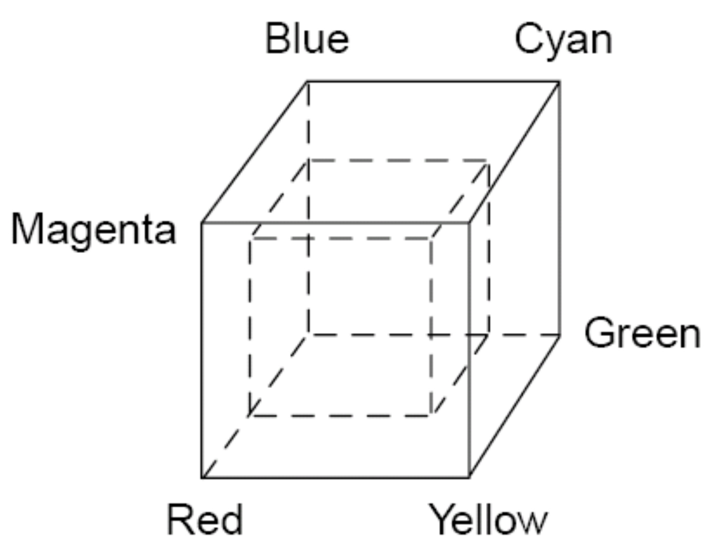
- Complementary colours are opposite.
- At the apex V=0 S and H are irrelevant.
- S = 0 are the greys.
- Corresponds to an artist’s colour system.





HSV Hexcone-RGB Cube Relationship

- Top of the hexcone = projection of the RGB cube along the principal diagonal from white to black.
- Each different value of V plane in the HSV model corresponds to a sub-cube of the RGB model (a cross section of the HSV cone is a sub cube of the RGB cube)
- V=1 corresponds to the vertices of the RGB cube



Colour Space Transforms

- RGB to HSI

$$H = \begin{cases} \theta \ \ if \ \ B \le G \\ 360 - \theta \ \ if \ \ B > G \end{cases}$$

$$\theta = cos^{-1} \left\{ \frac{1/2\left[(R-G)+(R-B)\right]}{\left[(R-G)^2+(R-B)(G-B)\right]^{1/2}} \right\}$$

$$S = 1 - \frac{3}{(R+G+B)}\left(min(R,G,B)\right)$$

$$I = \frac{1}{3}(R+G+B)$$

[This slide is additional information and will not be examined.]

Colour Space Transforms

- HSI to RGB

  The transformation formula depends on the hue value

$$RG\,sector \qquad \left(0^\circ \le H < 120^\circ\right)$$
$$B = I(1 - S)$$
$$R = I\left[1 + \frac{S\cos H}{\cos(60^\circ - H)}\right]$$
$$G = 3I - (R + B)$$

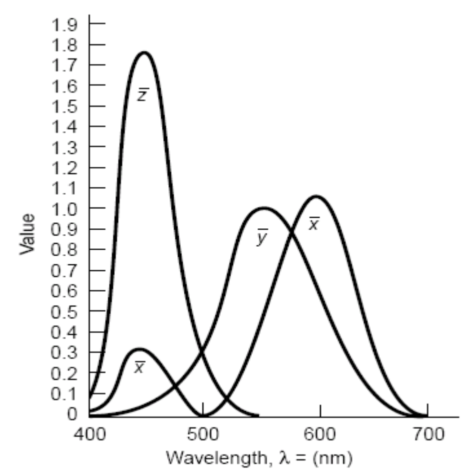
$$GB\,sector \qquad \left(120^\circ \le H < 240^\circ\right)$$
$$H = H - 120^\circ$$
$$R = I(1 - S)$$
$$G = I\left[1 + \frac{S\cos H}{\cos(60^\circ - H)}\right]$$
$$B = 3I - (R + G)$$

$$BR\,sector \qquad \left(240^\circ \le H < 360^\circ\right)$$
$$H = H - 240^\circ$$
$$G = I(1 - S)$$
$$B = I\left[1 + \frac{S\cos H}{\cos(60^\circ - H)}\right]$$
$$R = 3I - (B + G)$$

[This slide is additional information and will not be examined.]

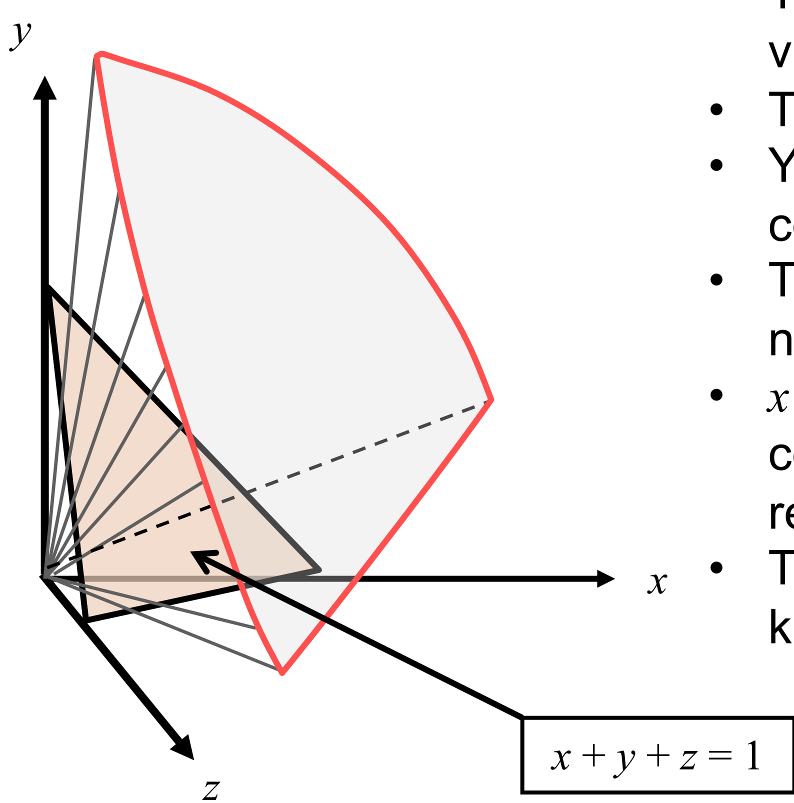
CIE Tristmulus Theory

- In 1931 the Comission Internationale de l'Eclairage (CIE)defined three standard primary colours, called X, Y and Z, to replace red, green and blue. These primaries can be used to match, with positive weights only, all the colours we can see. The colour matching functions on the right can be used to compute how much of X, Y and Z should be mixed together to generate any visible colour.
- The definition of a colour with red green and blues can be converted into CIE and vice versa.
- Amounts of X, Y, Z needed to match a colour with a spectral energy distribution P():
  - $X = k \int P(\lambda)\bar{x}_\lambda d\lambda$
  - $Y = k \int P(\lambda)\bar{y}_\lambda d\lambda$
  - $Z = k \int P(\lambda)\bar{z}_\lambda d\lambda$
- For self-luminous objects k is 680 lumens/watt
- The wavelength, xbar, ybar and zbar relationship can be obtained from the CIE sensitivity curve diagram.



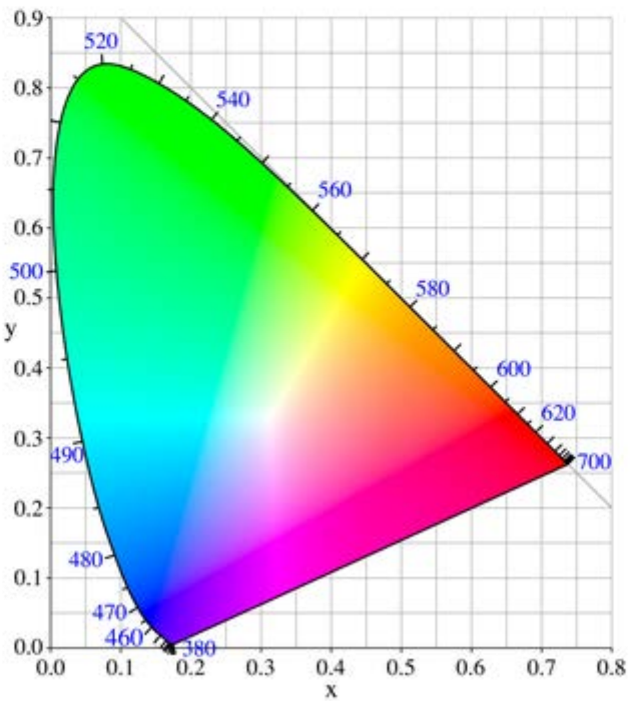
Cone of Visible Colours in CIE Space

$$x = \boldsymbol{X} / (\boldsymbol{X} + \boldsymbol{Y} + \boldsymbol{Z})$$
$$y = \boldsymbol{Y} / (\boldsymbol{X} + \boldsymbol{Y} + \boldsymbol{Z})$$
$$z = \boldsymbol{Z} / (\boldsymbol{X} + \boldsymbol{Y} + \boldsymbol{Z}) = 1\text{-}x\text{-}y$$



- X, Y, Z are the components of the CIE model
- Every colour can be represented by a set of three tristimulus values (X,Y,Z)
- The volume of XYZ – space that contains visible colours is cone shaped.
- The graph shows the X+Y+Z=1 plane.
- Y measures brightness (or luminance) of a colour.
- The chromaticity is described by the normalised parameters x and y.
- x and y are projective coordinates and the colors of the chromaticity diagram occupy a region of the real projective plane.
- The color space specified by x, y, and Y is known as the **CIE xyY** color space.

CIE Chromaticity Diagram



- All chromaticities that are visible to the human eye, known as the ***gamut*** of human vision, occur in the x, y plane.
- The curved edge of the gamut is the ***spectral locus*** that corresponds to the wavelength of the light spectrum.
- The edge corresponds to fully saturated hues and at the centre (white) there is no saturation.
- All the colors that lie in a straight line between two points in the diagram can be formed by mixing these two colors.

Colour Space Transforms

- RGB to XYZ and XYZ to RGB

$$\begin{bmatrix} X \\ Y \\ Z \end{bmatrix} = \begin{bmatrix} 0.5149 & 0.3244 & 0.1607 \\ 0.2654 & 0.6704 & 0.0642 \\ 0.0248 & 0.1248 & 0.8504 \end{bmatrix} \begin{bmatrix} R \\ G \\ B \end{bmatrix}$$

This is just the XYZ response from slide 36 put into matrix form

$$\begin{bmatrix} R \\ G \\ B \end{bmatrix} = \begin{bmatrix} 2.5623 & -1.1661 & -0.3962 \\ -1.0215 & 1.9778 & 0.0437 \\ 0.0752 & -0.2562 & 1.1810 \end{bmatrix} \begin{bmatrix} X \\ Y \\ Z \end{bmatrix}$$

- RGB to XYZ in equation form for coding

$$X = 0.5149R + 0.3244G + 0.1607B$$

$$Y = 0.2654R + 0.6704G + 0.0642B$$

$$Z = 0.0248R + 0.1248G + 0.8504B$$

[This slide is additional information and will not be examined.]

Colour and Vision: Overview

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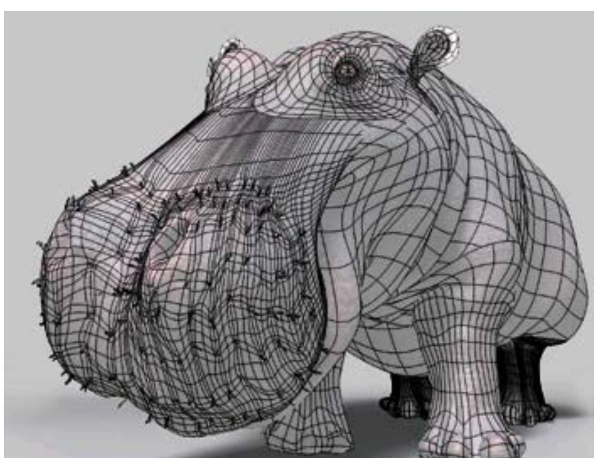
  - Bump mapping
  - Displacement mapping
  - Environment mapping
  - Shadow mapping
- Anti Aliasing
  - Sampling
  - Reconstruction
  - Mipmapping

Texture Mapping

- What for…?
- At what point do things start to look real?
- How does it compare?

Model



Model with shading

Model with shading and texture

Images from www.3drender.com

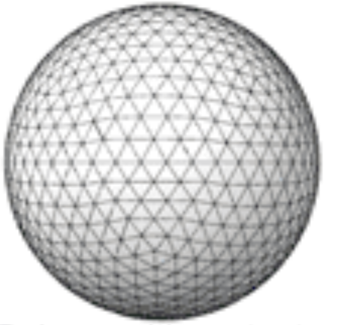
Texture Mapping

Texture Mapping

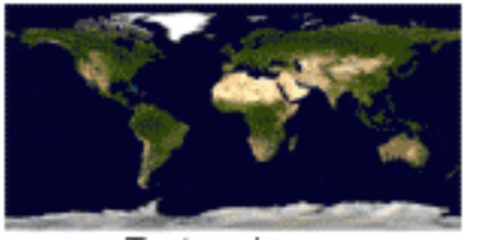
- Common technique to handle variations in reflectance is to store the reflectance as a function or pixel based image and *map* it to a surface.
  - The function or image is called a *texture map*
  - The process of controlling the reflectance properties is called *texture mapping.*
- Texture mapping can be defined by different properties:
  - Dimensionality of texture function
  - Correspondences defined between points on the surface and points in the texture function
  - Whether the texture function is primarily procedural or table look up.
- We look at 3D textures (known as *solid* or *volume* textures) and 2D textures (known as *image* textures)

2D Texture Mapping

- We use *u,v* coordinates to create reflectance R(u,v)
- Idea is to take an image and associate a (u,v) coordinate system with a 3D surface.
- E.g. latitude and longitude associated to polar coordinates of a sphere. A Miller cylindrical projection map and its placement on a sphere. The distortions e.g. Antarctica being so large corresponds to the shrinking that occurs when it is placed on the sphere.



Sphere with no texture



Texture image

Sphere with texture

2D Texture Mapping

- Example: mapping world map to sphere.

The coordinate system on the image is set to the unit square $(u,v) \in [0,1]^2$

The image is wider than it is tall so there is a non uniform aspect ratio in the (u,v) space.

To map the $(u,v) \in [0,1]^2$ image to a sphere of radius R and centre (c_x, c_y, c_z)

The parametric equation is:

$$x = x_c + R\cos\phi\sin\theta,$$

$$y = y_c + R\sin\phi\sin\theta,$$

$$z = z_c + R\cos\theta$$

We can find (θ,ϕ):

$$\theta = \arccos\left(\frac{z - z_c}{R}\right)$$

$$\phi = \arctan 2(y - y_c, x - x_c)$$

where arctan2(a,b) is the arctan2 of most libraries and returns the arctanget of a/b.

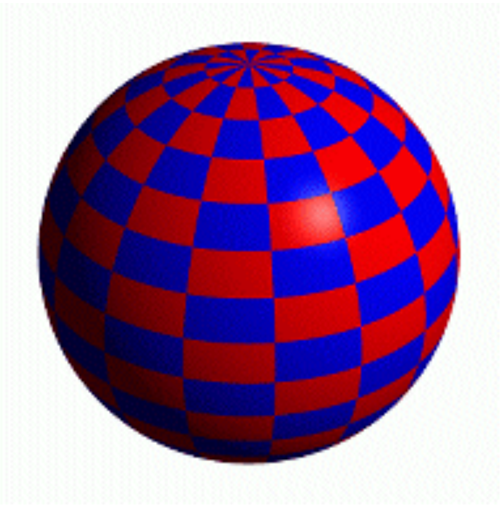
$(\theta,\phi) \in [0,\pi] \times [-\pi,\pi]$ we convert (u,v) by adding 2π to ϕ if negative

$$u = \frac{\phi}{2\pi},$$

$$v = \frac{\pi - \theta}{\pi}$$

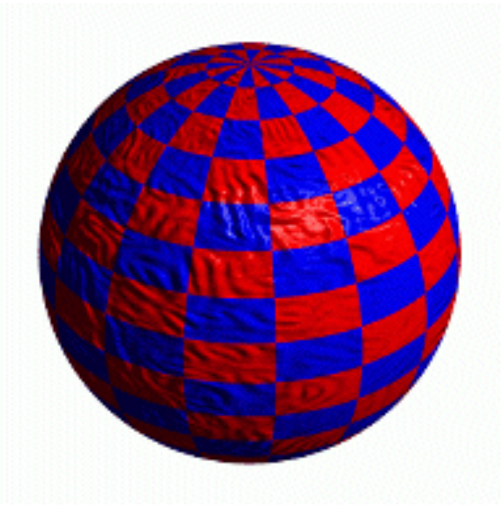
Bump Textures

- A *bump map* can be used to alter the surface normal of an object.
- This does not change the actual shape of the surface, we are only shading it as if it were a different shape!
- The texture map is treated as a single-valued height function.
- The partial derivatives of the texture tell us how to alter the true surface normal at each point to make the object appear as if it were deformed by the height function.



Sphere w/Diffuse Texture

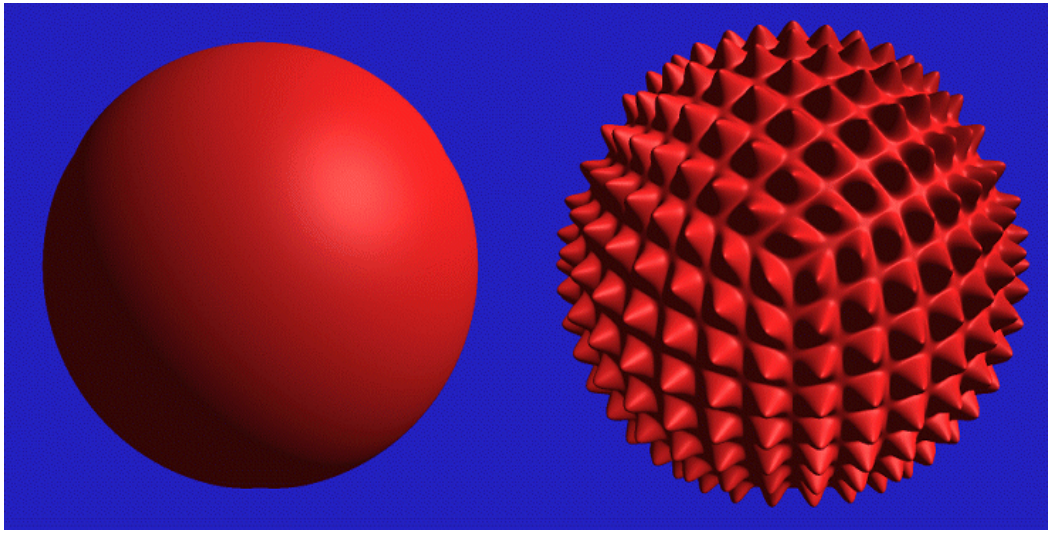
Swirly Bump Map



Sphere w/Diffuse Texture & Bump Map

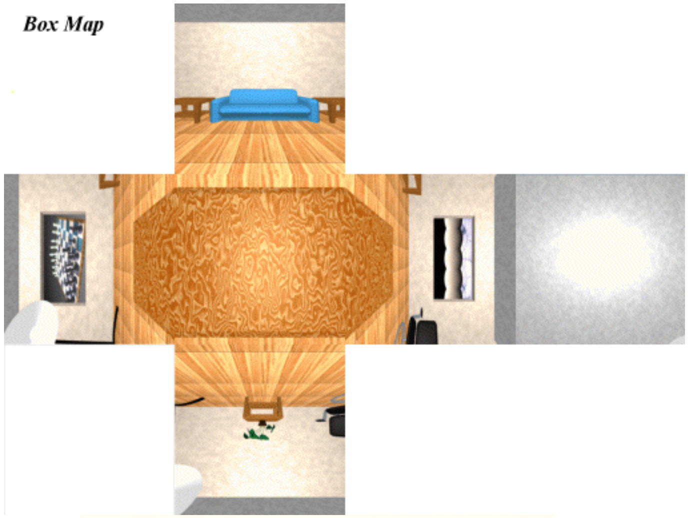
Displacement Mapping

- Bump mapping doesn't really change the geometry of the shape. The silhouette is not changed and no shadows are cast.
- For more realism we can use a *displacement map* that changes the geometry using a texture
- This can be done using a tessellated object, each vertex can be displaced in the direction of the normal vector.



Environment Maps

- Objects often require reflections of a texture mapped background. This can be done using an *environment map*.
- An environment map takes in a viewing direction **b** and returns an RGB value from a texture map. The environment can be mapped in a number of ways a sphere or cube are two examples.



Shadow Maps

- If you looked at a scene from the perspective of the light source everything would be lit and anything shadowed would be out of view. Usually, however, the observer is at a different angle and can see shadowing.
- Shadow mapping involves producing the scene from the view of the light source, this creates the information about what area will be shadowed (i.e. what isn't shadowed). This function of (x,y,z) can be mapped to the image from the view point and anything not in this image is shadowed with a certain depth.

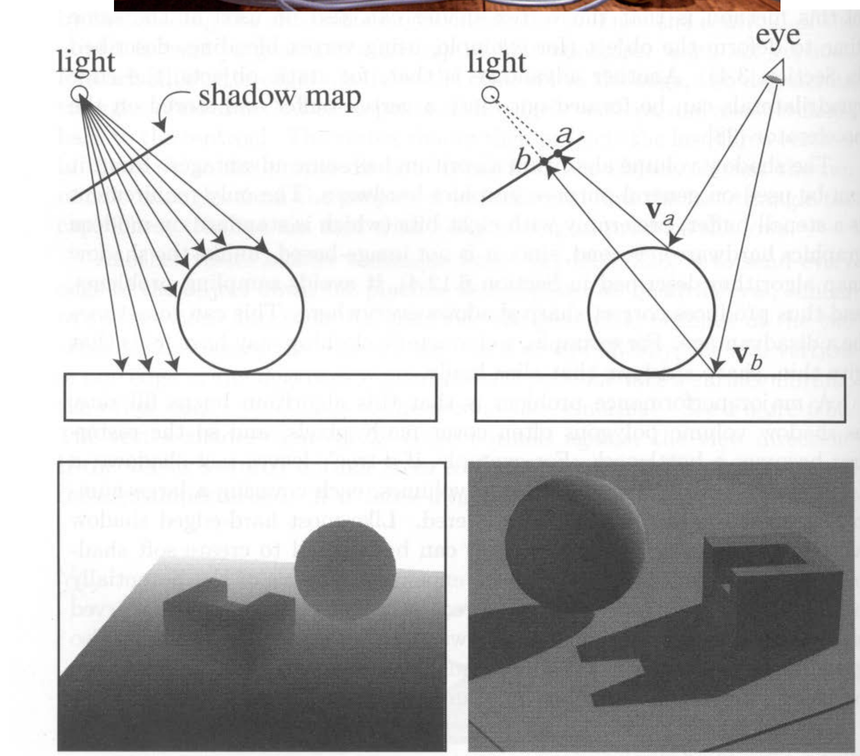


Figure from Foley et al. "Computer Graphics Principles and Practice"

Shadow Maps

- This is a good conceptual example…

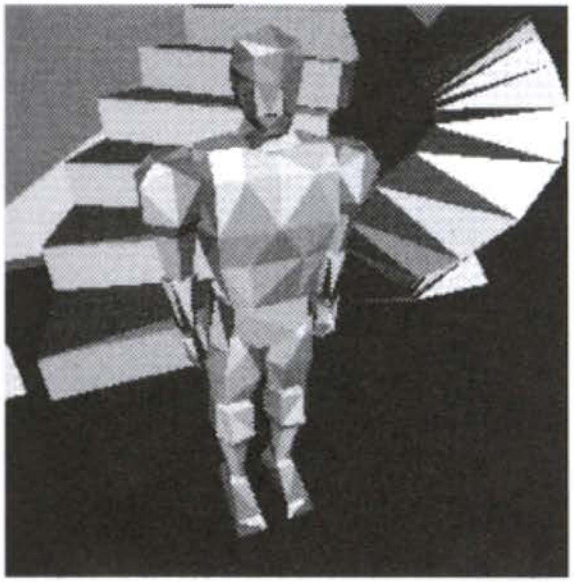
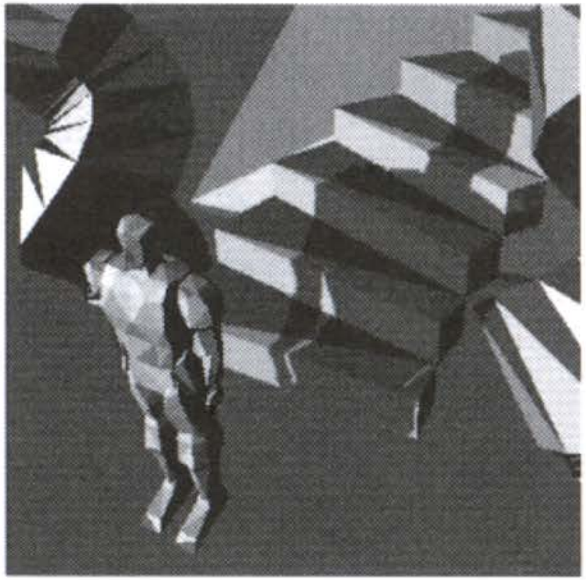


Image from light source viewpoint

BW image of obstacle for shadow information



Final image from different viewpoint mapping shadow information to the different angle

Figure from Moller & Haines "Real Time Rendering"

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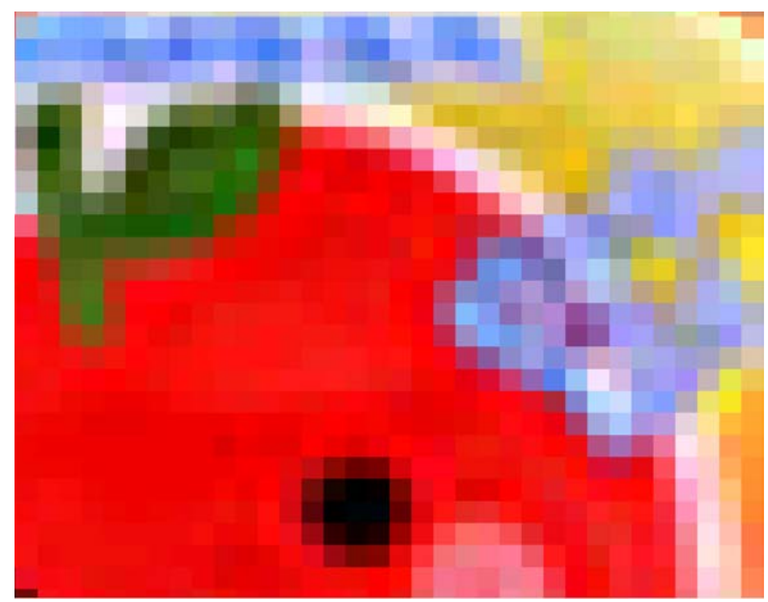
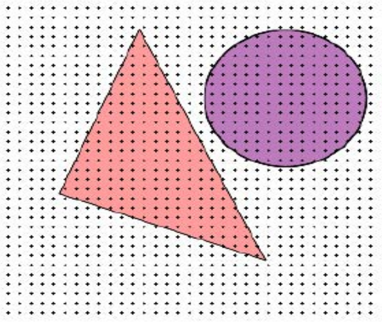
Pixels

- *Pixel* is short for picture element.
- An image is just samples of points in continuous space. These points are represented by pixels.
- A pixel is a point
  - it has no dimension
  - it occupies no area
  - it cannot be seen
  - it can have a coordinate
- If enough information exists pixels in an image can be reproduced at any size without being able to see dots or squares. When detail is not fine enough pixels are reproduced as dots or squares.

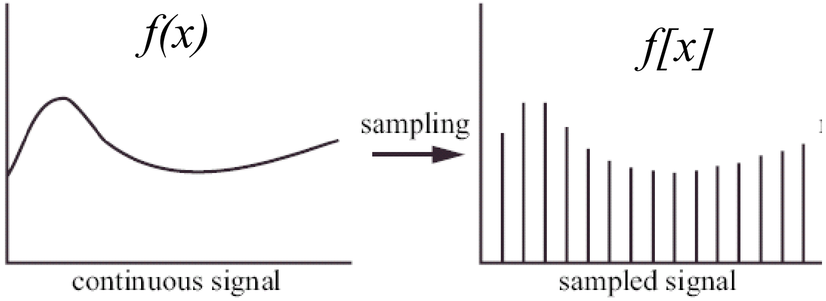


Sampling and Quantisation

- The real world is *continuous* however the computer world is *discrete*
- The process of mapping a continuous function to a discrete function is called *sampling*
- The process of mapping a continuous variable to a discrete value is called *quantisation.*
- To represent or render an image using a computer, we must both sample and quantise.
- f(x) is the continuous function and f[x] is the discrete function.
- f(x) is continuous so can be of any value, however there are limitations to the values f[x] can be, so samples are quantised to only possible discrete values.

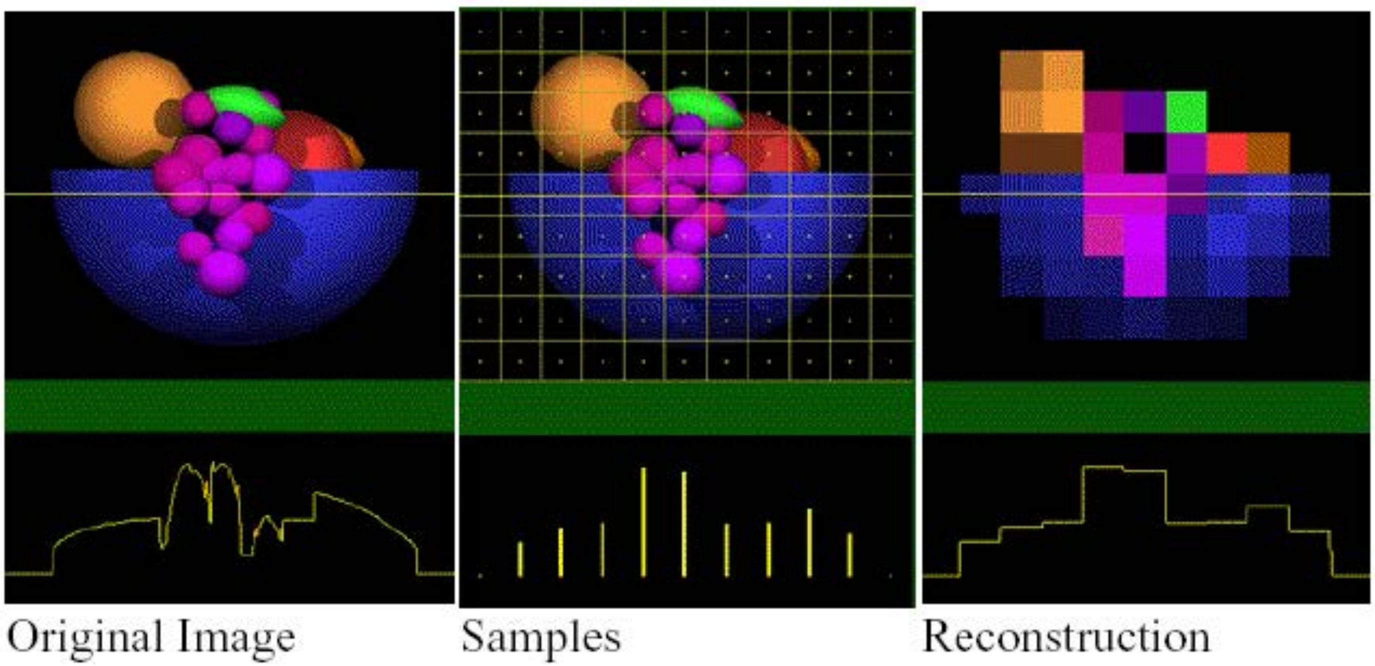


Sampling Grid



Aliasing and Antialiasing

- Aliasing occurs when a signal is **under sampled**
- Due to the sensitivity of the human eye it is very noticeable in computer graphics….



- This is why we need antialiasing!

Aliasing and Antialiasing

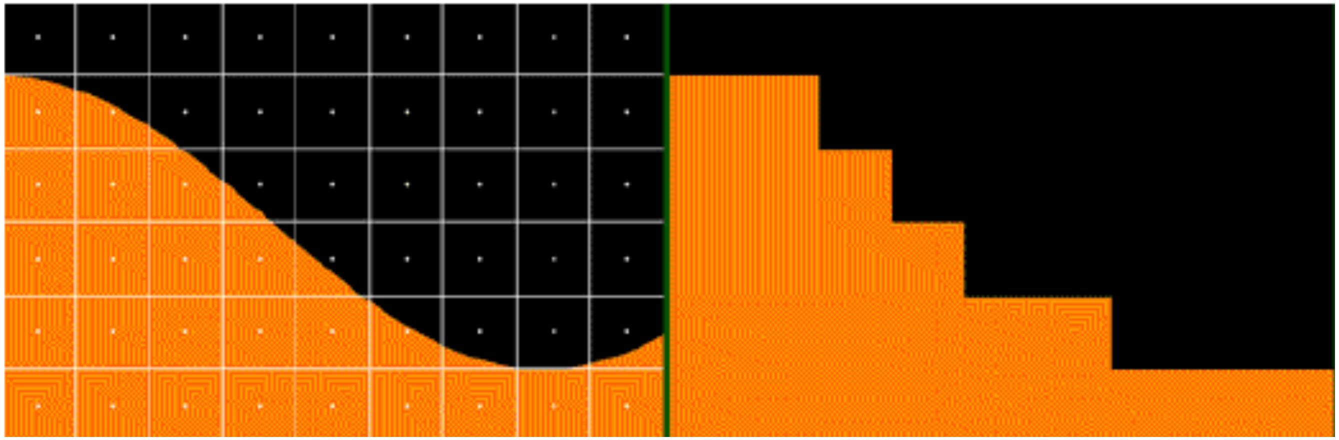
Aliasing characteristics can occur …

- because a pixel is either “on” or “off”;
- consequently edges and lines can have “jaggies” or “staircase effect”
- animated “jaggies” can turn into “crawlies”.
- Aliasing can occur when a signal is being sampled at a too low a frequency.
- It can appear at edges of polygons, shadow boundaries, rapid changes of colour.

Antialiasing is about avoiding or minimising aliasing effects. All algorithms are “screen-based” (i.e. no knowledge of the object to be rendered.)

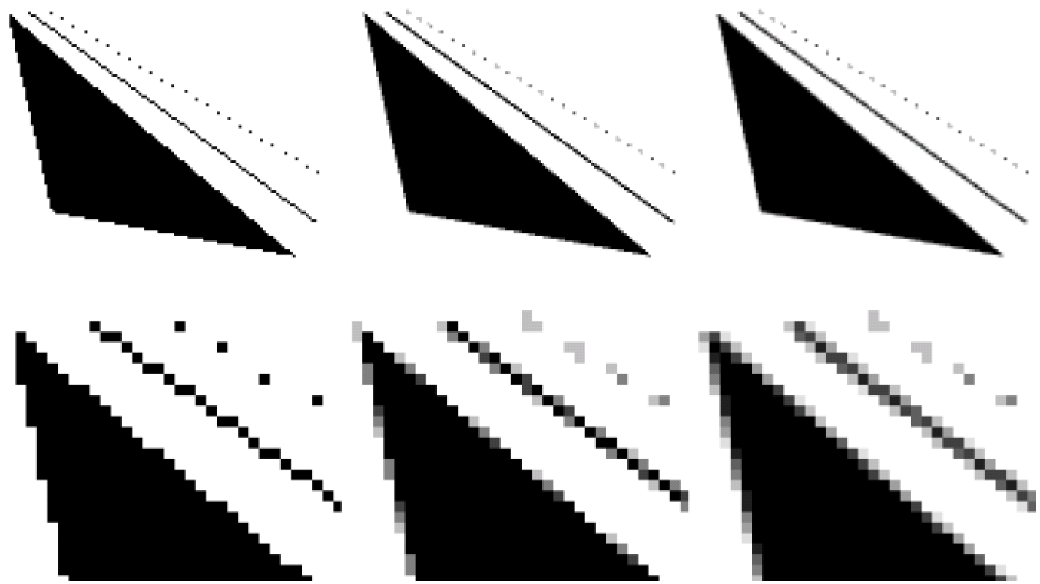
Examples of Aliasing

- Jagged edges/ staircase effect



Examples of Different Levels of Anti Aliasing

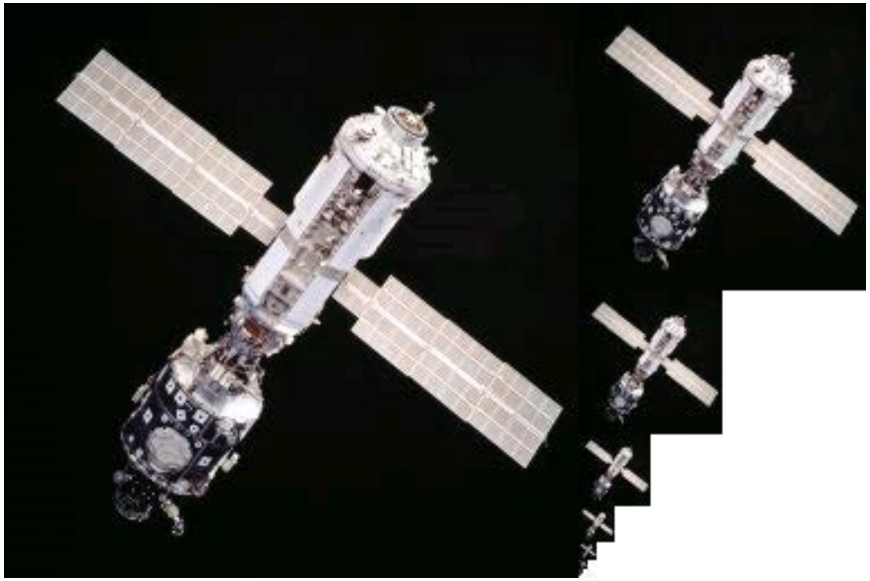
- The higher the samples per pixel the smoother the image



1 sample per pixel; 4 samples per pixel; 8 samples per pixel

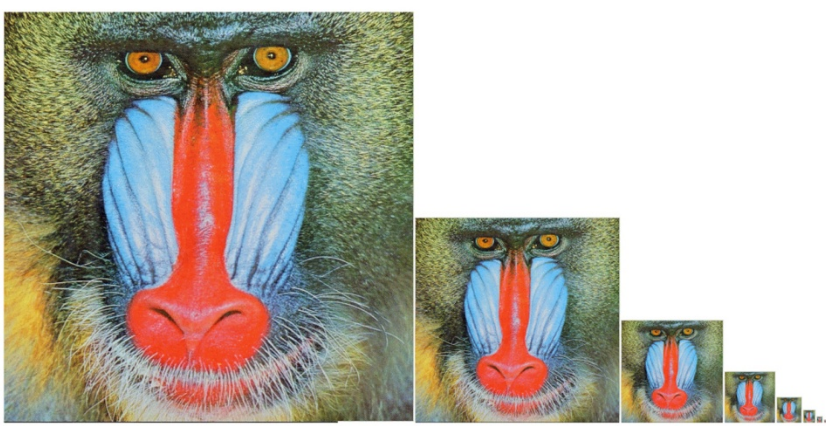
Mipmap

- Mipmap is a way of dynamically choosing texture resolution based on viewing conditions. It is a set of optimised pre defined; pre- filtered re-sampled images at 0.5, 0.25,0.125 etc times the original image sampling.
- During rasterization we compute the index of the decimated image that is sampled at a rate closest to the density of our desired sampling rate
- MIP stands for *multium in parvo* which means *many in a small place*

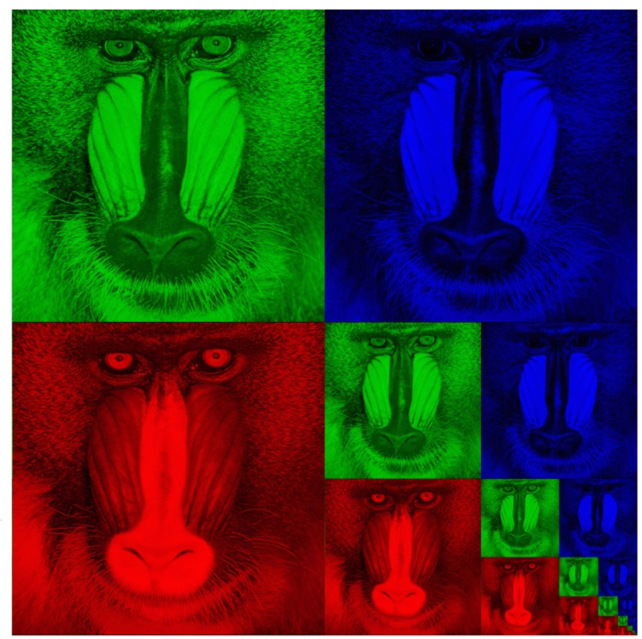


Mipmapping

- It would seem like this is a lot of additional memory but it can be stored compactly
- It can be seen that there is only 1/3 additional overhead due to MIP mapping.

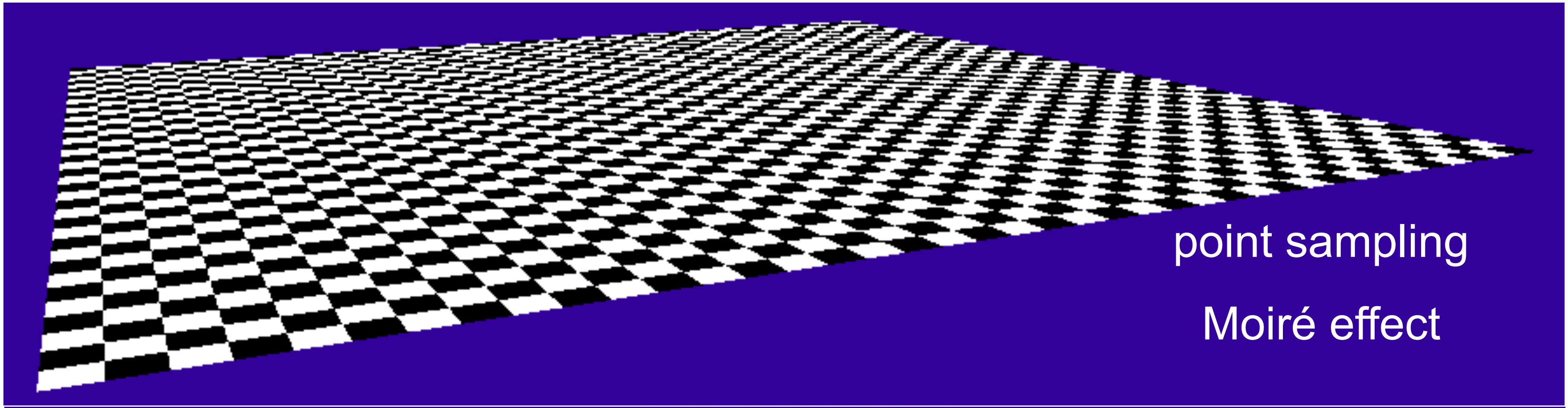


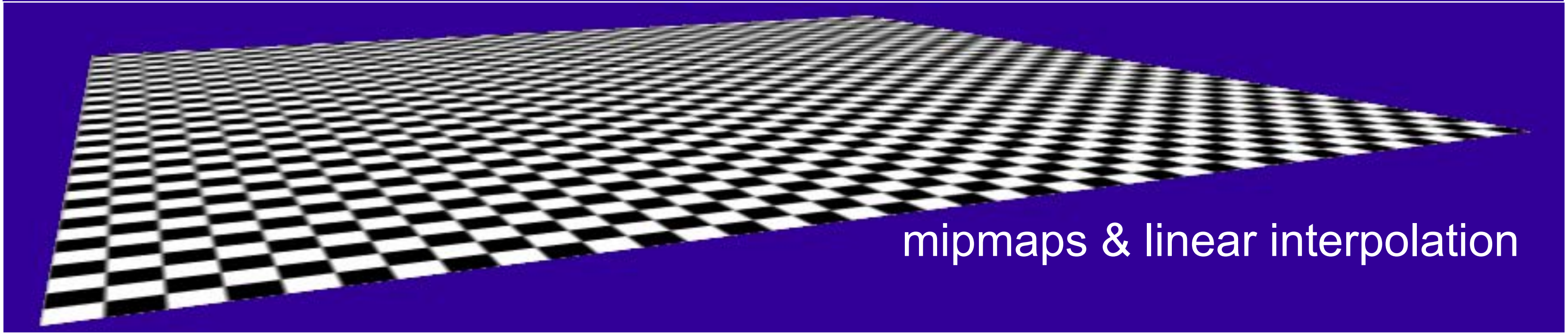
10-level mip map



Memory format of a mip map

Mipmapping and Anti Aliasing





Mipmapping and Antialiasing

- Pixels between two images are interpolated and used to create smoothness and avoid aliasing effects.
- *Texels* is the name for texture pixels
- Rendering speed increases because the number of texels being processed is lower with simple textures.
- Artifacts are reduced because the mip map images are effectively anti aliased.
- Scaling up and down is more efficient.

Examples..

Dramatic improvements have been made in lighting, texturing, shadow mapping etc. all these things add to realism. The first 3 images are from short films made by Pixar in the 80’s, the other is Toy Story released in 1995. The advancement is notable over each decade, even from Toy Story to Cars the advances are dramatic.

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  - Mipmapping

Exercises

Please see the Exercise IV sheet for this lecture's exercises.