AMME4710: COMPUTER VISION AND IMAGE PROCESSING WEEK 2

Dr. Mitch Bryson

School of Aerospace, Mechanical and Mechatronic Engineering, University of Sydney

Last Week

- Introduction to the course

- Introduction to Image Processing:
  - MATLAB Image Processing Toolbox
  - Histogram Equalisation
  - Thresholding and Otsu's Method

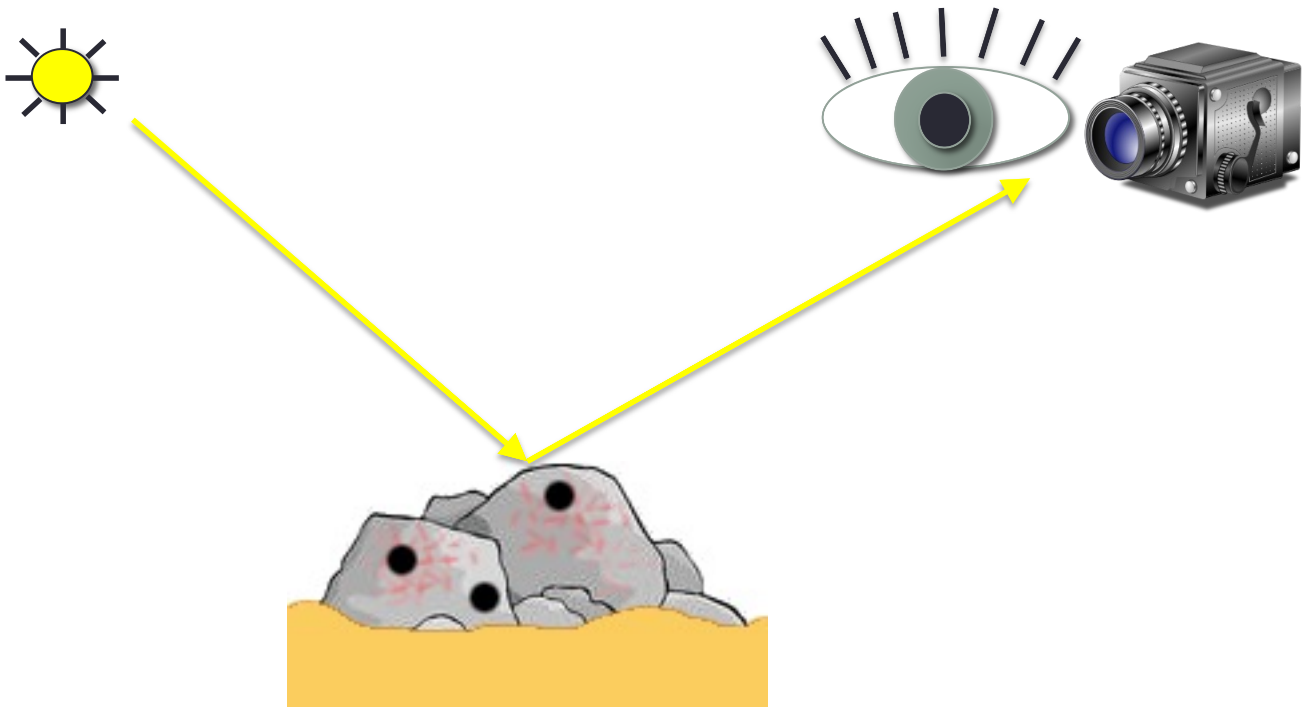
This Week's Lecture

- Radiometry, Light and Shading
- Colour and Colour Image Processing

- Learning Objectives:
  - To understand the fundamentals of how light interacts with objects in the world to produce image brightness and colour
  - To examine some basic applications of brightness and colour in computer vision

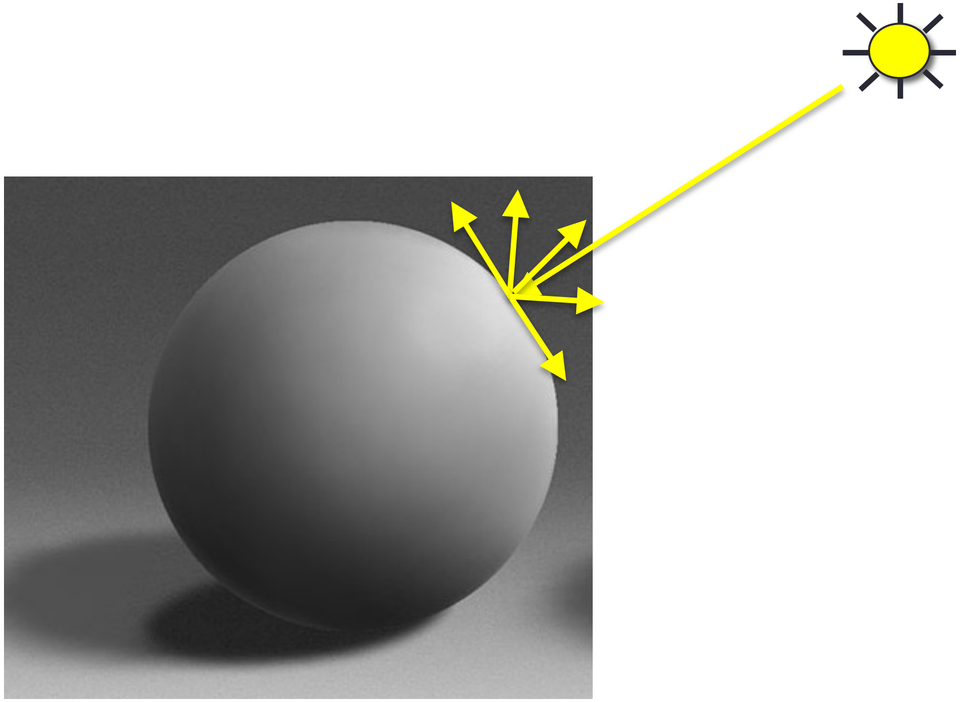
Light

- How we see:
  - Light emitted from source, interacts with the environment
  - Resulting light received by eye/camera
- Types of interaction:
  - Reflection: diffuse/specular, refractions, attenuation, fluorescence, etc.



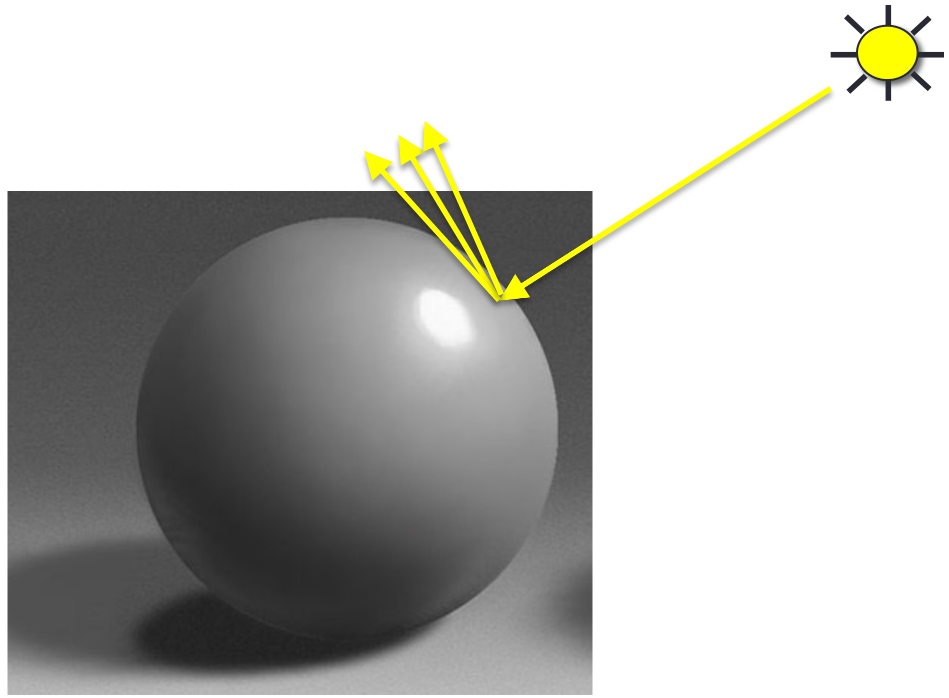
Light

- How we see:
  - Light emitted from source, interacts with the environment
  - Resulting light received by eye/camera
- Types of interaction:
  - Reflection: diffuse/specular, refractions, attenuation, fluorescence, etc.



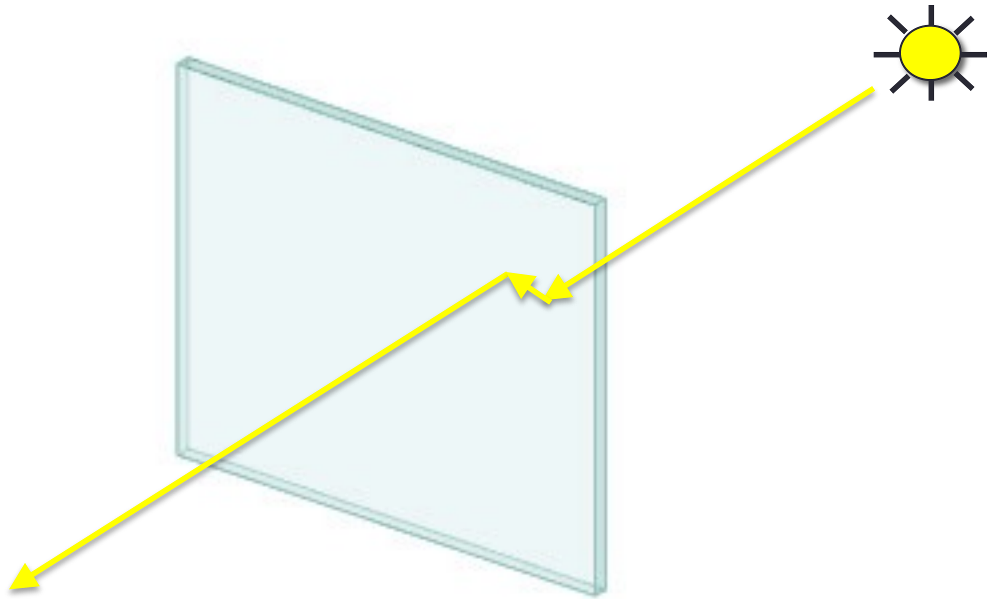
Light

- How we see:
  - Light emitted from source, interacts with the environment
  - Resulting light received by eye/camera
- Types of interaction:
  - Reflection: diffuse/**specular**, refractions, attenuation, fluorescence, etc.



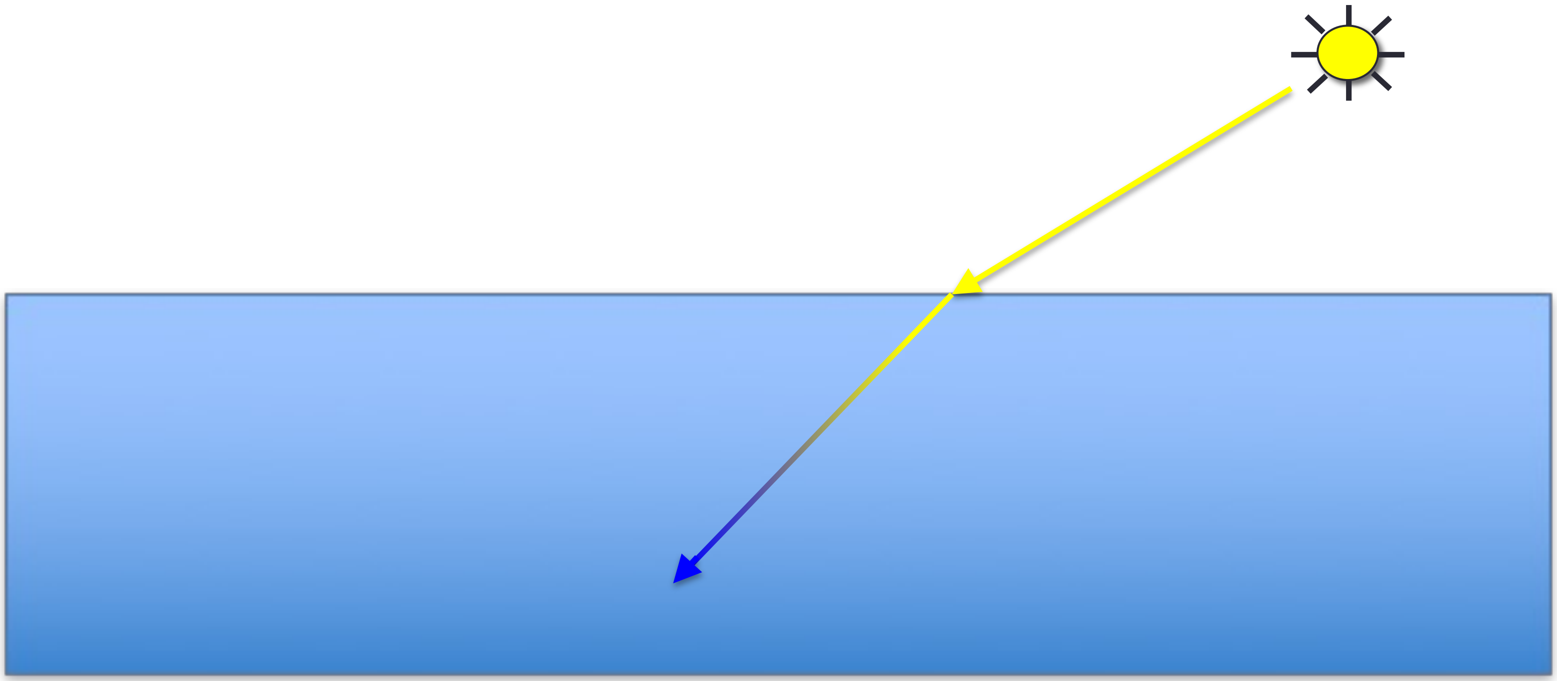
Light

- How we see:
  - Light emitted from source, interacts with the environment
  - Resulting light received by eye/camera
- Types of interaction:
  - Reflection: diffuse/specular, refractions, attenuation, fluorescence, etc.



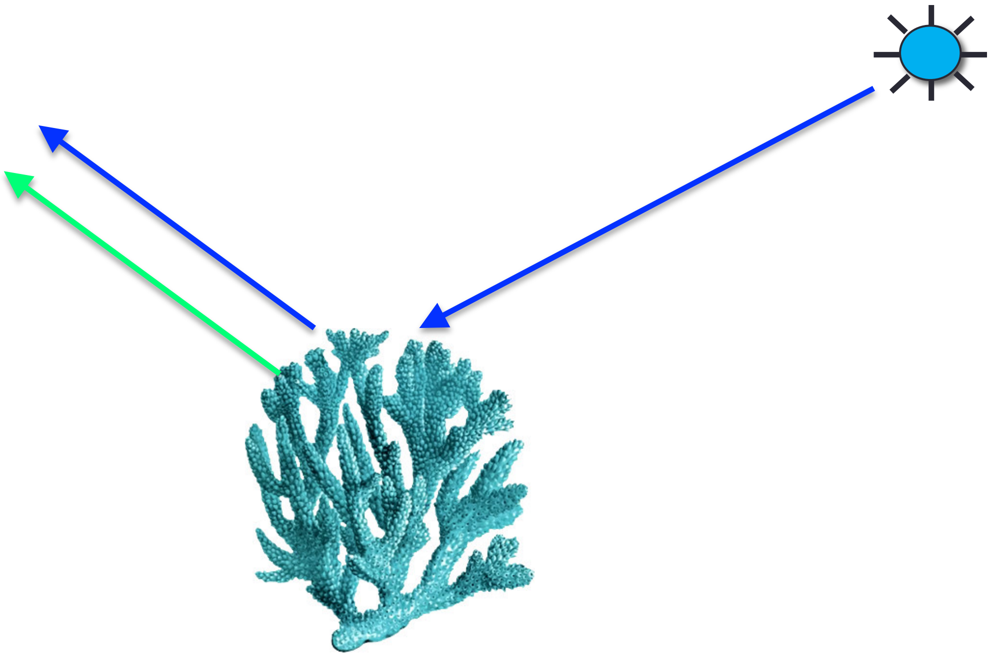
Light

- How we see:
  - Light emitted from source, interacts with the environment
  - Resulting light received by eye/camera
- Types of interaction:
  - Reflection: diffuse/specular, refractions, attenuation, fluorescence, etc.

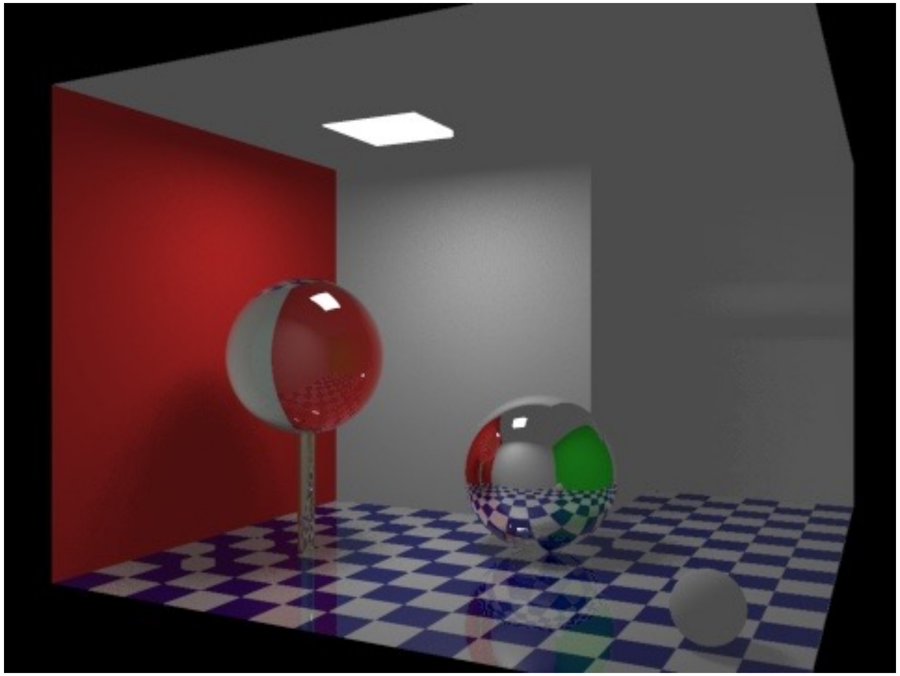


Light

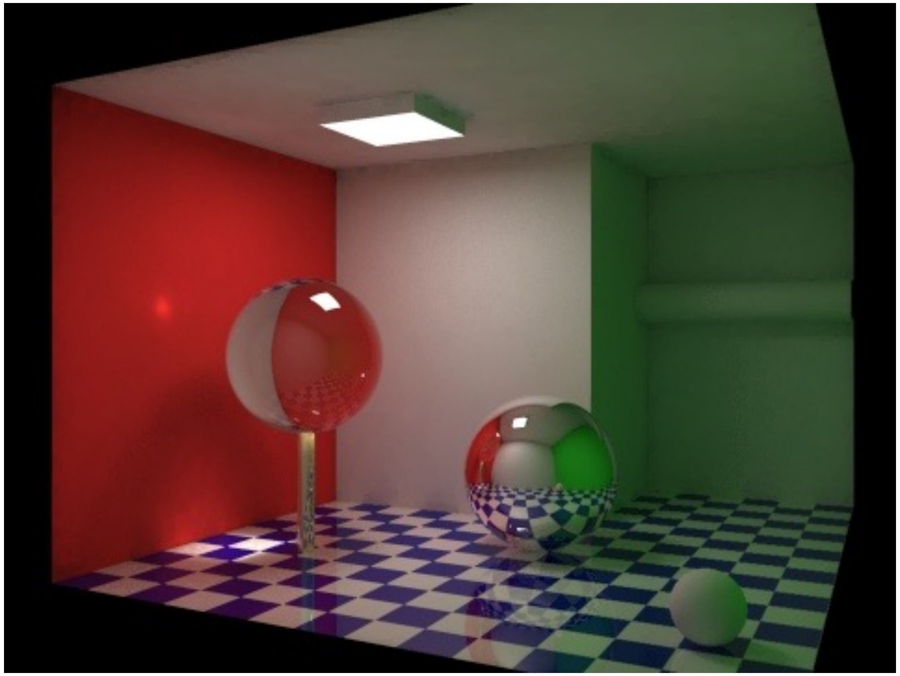
- How we see:
  - Light emitted from source, interacts with the environment
  - Resulting light received by eye/camera
- Types of interaction:
  - Reflection: diffuse/specular, refractions, attenuation, fluorescence, etc.



Light and it's interactions



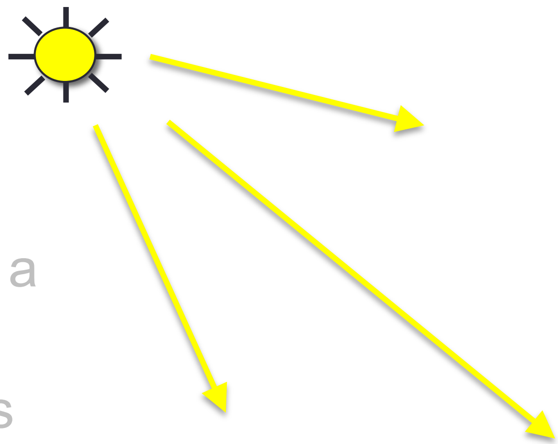
Local illumination



Global illumination

Light and Reflection

- Light is measured at a point in space and travelling in a particular direction
- Light arrives at a surface and reflects from the surface in a hemi-sphere about the normal vector to the surface

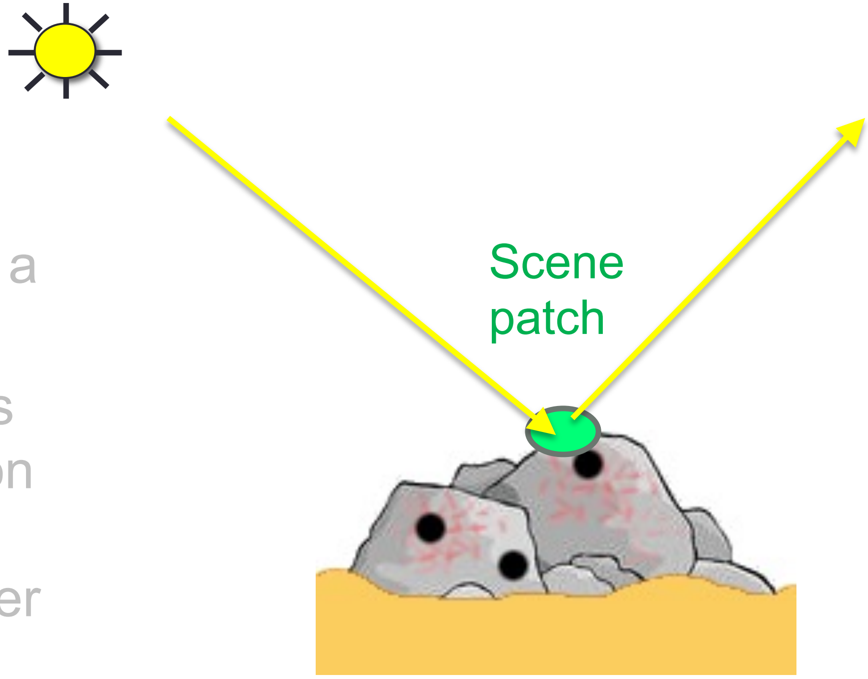


- The amount of light reflected and in what direction depends on the material and is generally a function of (θ_i, φ_i, θ_o, φ_o)
- The perceived brightness corresponds to the portion of reflected light points back towards the observer and passes through the aperture

Light and Reflection

- Light is measured at a point in space and travelling in a particular direction
- Light arrives at a surface and reflects from the surface in a hemi-sphere about the normal vector to the surface

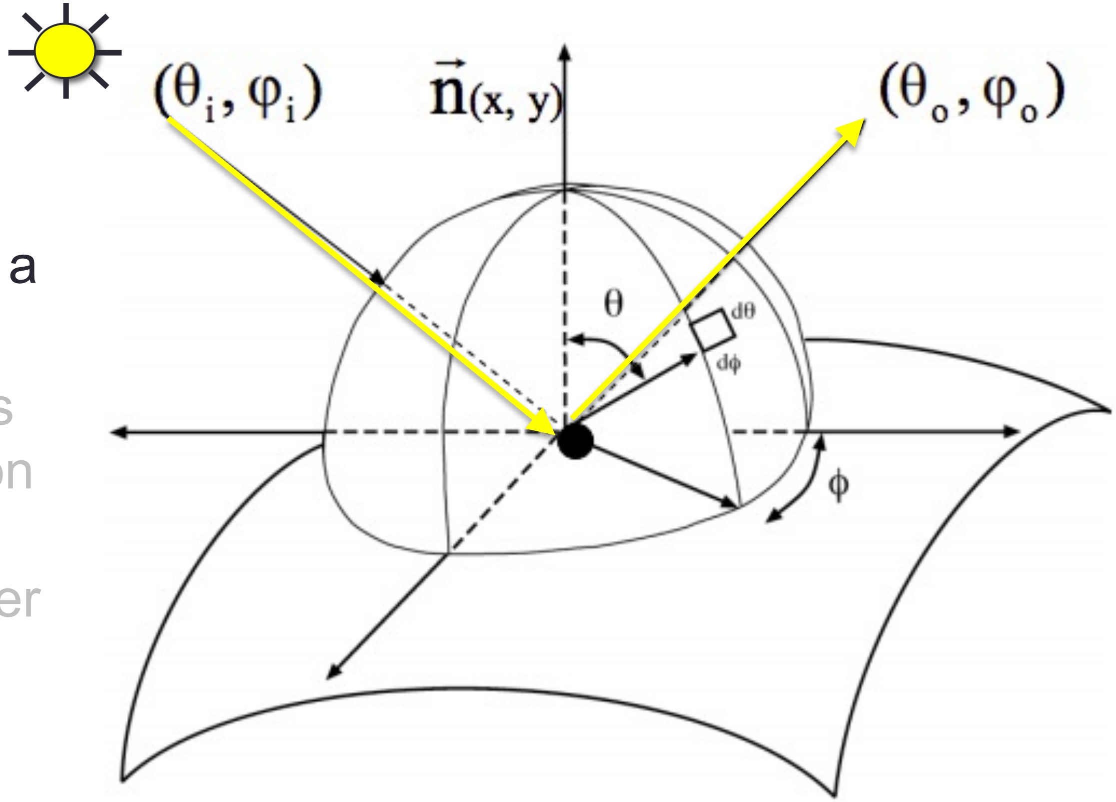
- The amount of light reflected and in what direction depends on the material and is generally a function of (θ_i, φ_i, θ_o, φ_o)
- The perceived brightness corresponds to the portion of reflected light points back towards the observer and passes through the aperture



Light and Reflection

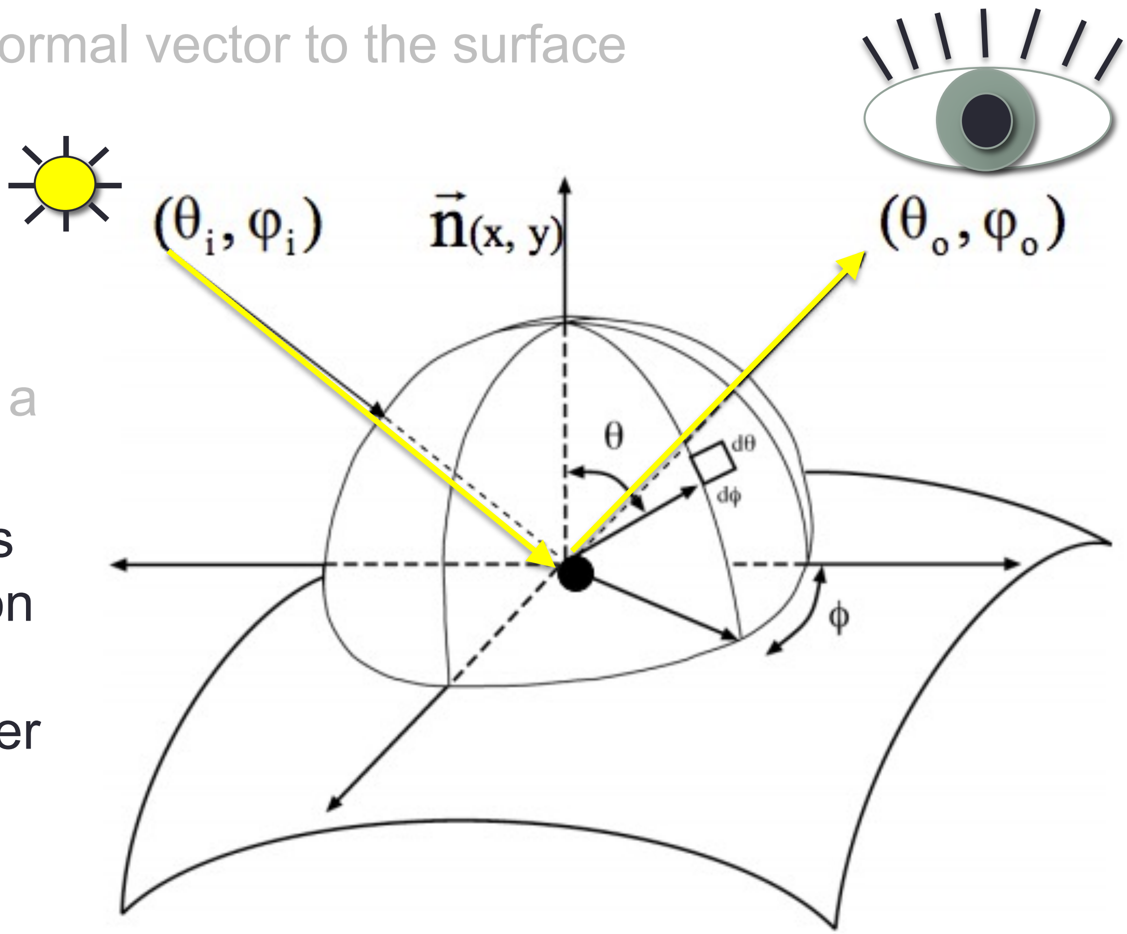
- Light is measured at a point in space and travelling in a particular direction
- Light arrives at a surface and reflects from the surface in a hemi-sphere about the normal vector to the surface

- The amount of light reflected and in what direction depends on the material and is generally a function of (θ_i, φ_i, θ_o, φ_o)
- The perceived brightness corresponds to the portion of reflected light points back towards the observer and passes through the aperture



Light and Reflection

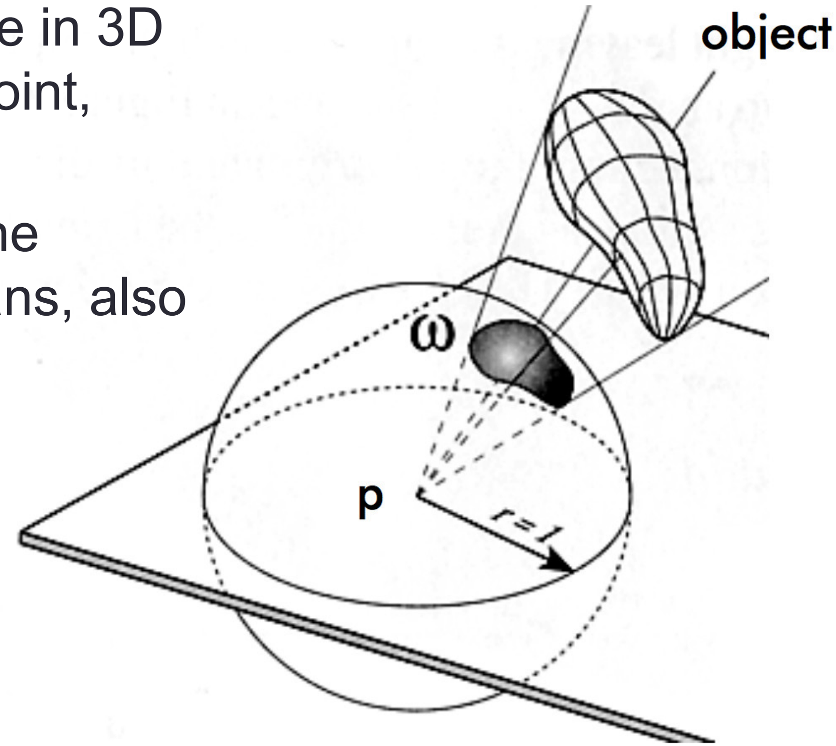
- Light is measured at a point in space and travelling in a particular direction
- Light arrives at a surface and reflects from the surface in a hemi-sphere about the normal vector to the surface

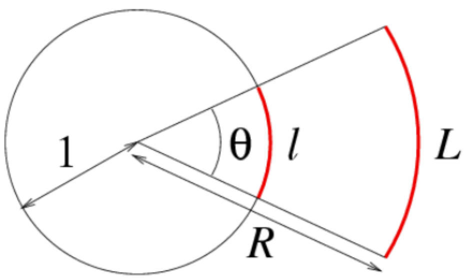


- The amount of light reflected and in what direction depends on the material and is generally a function of (θ_i, φ_i, θ_o, φ_o)
- The perceived brightness corresponds to the portion of reflected light points back towards the observer and passes through the aperture

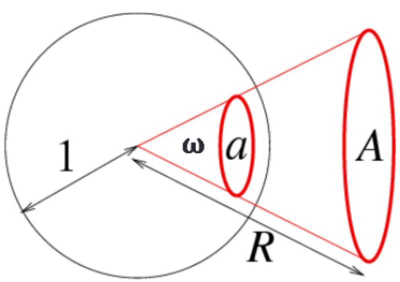
Geometric Preliminaries: Solid Angles

- **Solid angle**: a two-dimensional angle in 3D space that an object subtends at a point, denoted by $\boldsymbol{\omega}$
- The standard unit for solid angle is the ***steradian*** (sr), a 2D analogy to radians, also dimensionless

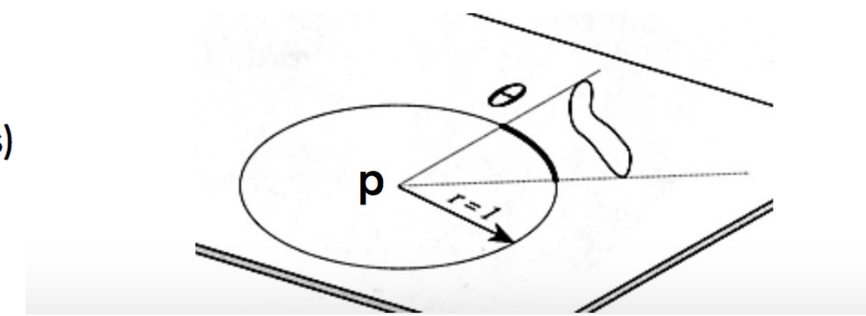




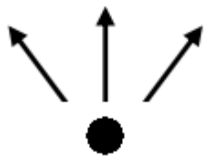
$$\boxed{\theta = l = \frac{L}{R}}$$ (radians)



$$\boxed{\omega = a = \frac{A}{R^2}}$$ (steradians)



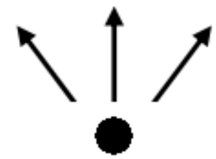
Light and Observed Brightness



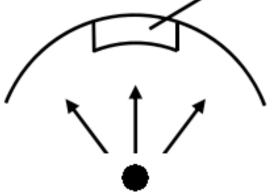
- **Light power or flux** (Φ): energy per unit time of light, measured in W
- **Intensity** ($I = d\Phi/d\omega$): power per unit solid angle, usually associated with light leaving a point source, measured in $W.sr^{-1}$
- **Irradiance** ($E = d\Phi/dA$): power per unit area arriving at or leaving a surface, measured in $W.m^{-2}$
- **Radiance** ($L = d^2\Phi/d\omega dA$): power per unit area per unit solid angle ($W.m^{-2}sr^{-1}$)
  - Can be thought of as either intensity per area, or irradiance per solid angle

Light and Observed Brightness

- **Light power or flux** (Φ): energy per unit time of light, measured in W



- **Intensity** ($I = d\Phi/d\omega$): power per unit solid angle, usually associated with light leaving a point source, measured in $W.sr^{-1}$

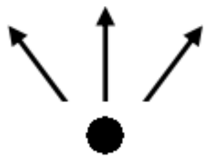


- **Irradiance** ($E = d\Phi/dA$): power per unit area arriving at or leaving a surface, measured in $W.m^{-2}$

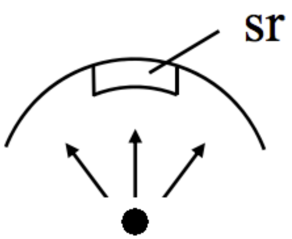
- **Radiance** ($L = d^2\Phi/d\omega dA$): power per unit area per unit solid angle ($W.m^{-2}sr^{-1}$)
  - Can be thought of as either intensity per area, or irradiance per solid angle

Light and Observed Brightness

- **Light power or flux** (Φ): energy per unit time of light, measured in W



- **Intensity** ($I = d\Phi/d\omega$): power per unit solid angle, usually associated with light leaving a point source, measured in $W.sr^{-1}$

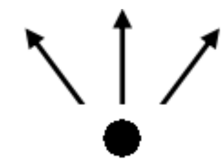


- **Irradiance** ($E = d\Phi/dA$): power per unit area arriving at or leaving a surface, measured in $W.m^{-2}$

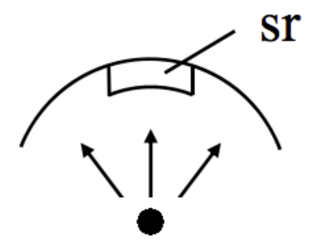
- **Radiance** ($L = d^2\Phi/d\omega dA$): power per unit area per unit solid angle ($W.m^{-2}sr^{-1}$)
  - Can be thought of as either intensity per area, or irradiance per solid angle

Light and Observed Brightness

- **Light power or flux** (**Φ**): energy per unit time of light, measured in W

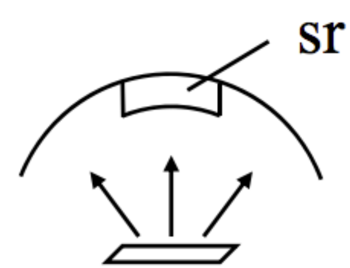


- **Intensity** ($I = d\Phi/d\omega$): power per unit solid angle, usually associated with light leaving a point source, measured in $W.sr^{-1}$



- **Irradiance** ($E = d\Phi/dA$): power per unit area arriving at or leaving a surface, measured in $W.m^{-2}$

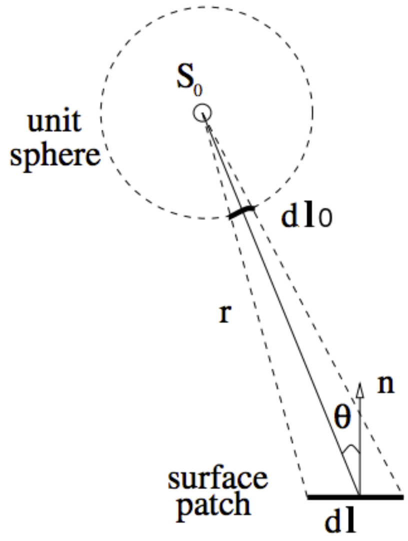
- **Radiance** ($L = d^2\Phi/d\omega dA$): power per unit area per unit solid angle ($W.m^{-2}sr^{-1}$)
  - Can be thought of as either intensity per area, or irradiance per solid angle



Projected Light and Foreshortening

- The amount of light reaching a surface patch depends on the source intensity and patch orientation to the source

- Firstly, consider the geometry in 2D:

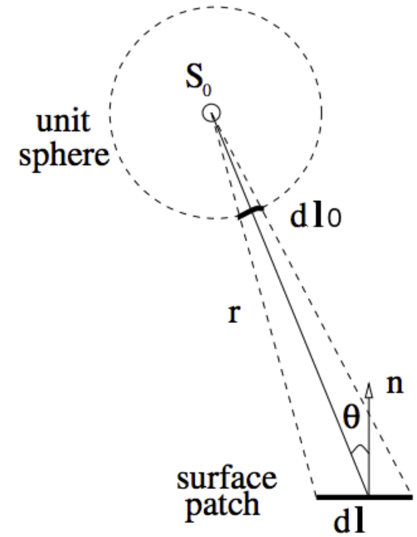


$$d\phi = dl_0 = \frac{dl \cos\theta}{r}$$

Projected Light and Foreshortening

- The amount of light reaching a surface patch depends on the source intensity and patch orientation to the source

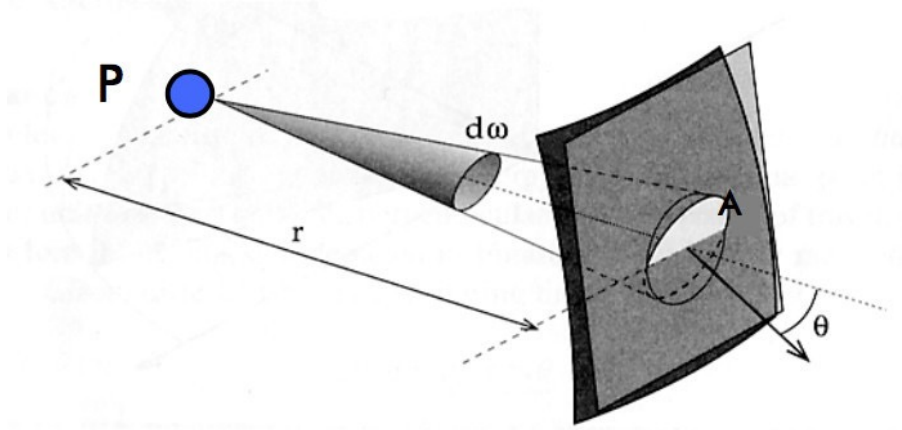
- Firstly, consider the geometry in 2D:



$$d\phi = dl_0 = \frac{dl \cos\theta}{r}$$

- Generalising to 3D with solid angle **ω**:

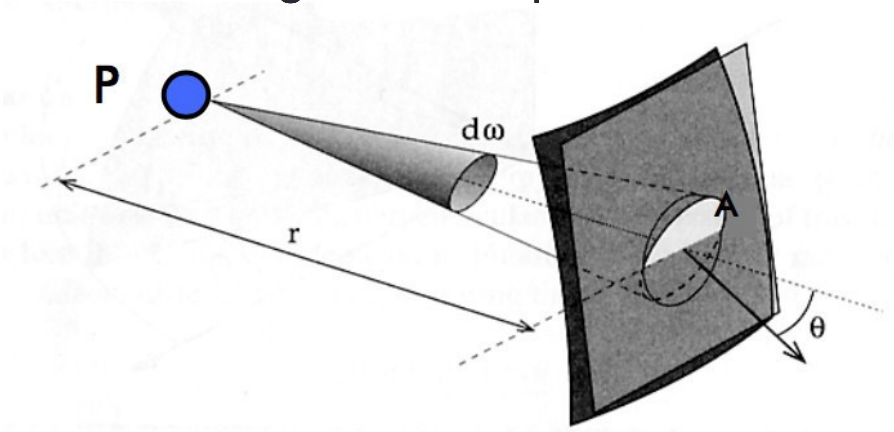
$$d\omega = dA_0 = \frac{dA \cos\theta}{r^2}$$



Projected Light and Foreshortening

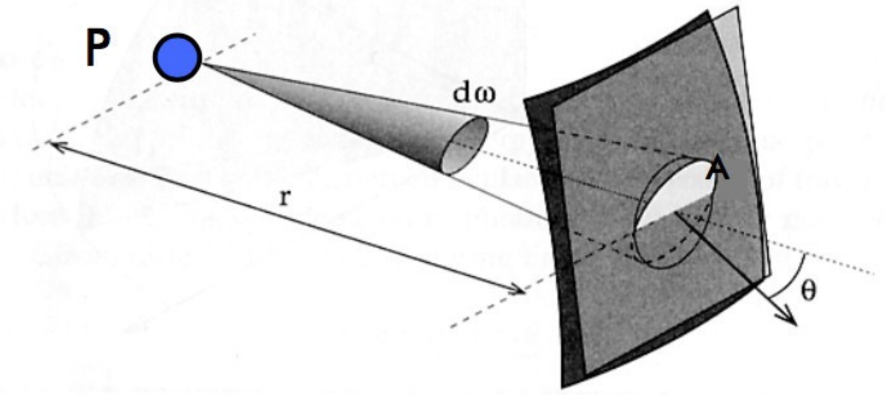
- Consider now the light power per unit area arriving at the surface patch (irradiance E) based on power emanating from the point source per unit solid angle (intensity I):

$$I = \frac{d\phi}{d\omega}$$



Projected Light and Foreshortening

- Consider now the light power per unit area arriving at the surface patch (irradiance E) based on power emanating from the point source per unit solid angle (intensity I):



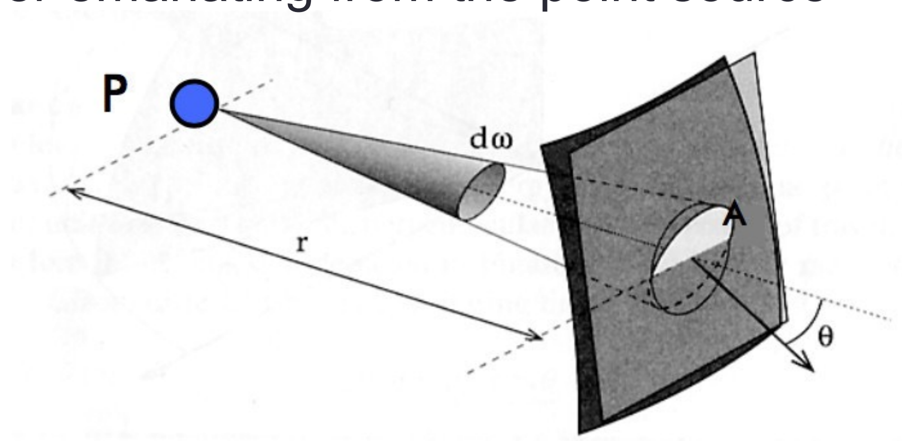
$$I = \frac{d\phi}{d\omega}$$

$$d\phi = I d\omega$$

Projected Light and Foreshortening

- Consider now the light power per unit area arriving at the surface patch (irradiance E) based on power emanating from the point source per unit solid angle (intensity I):

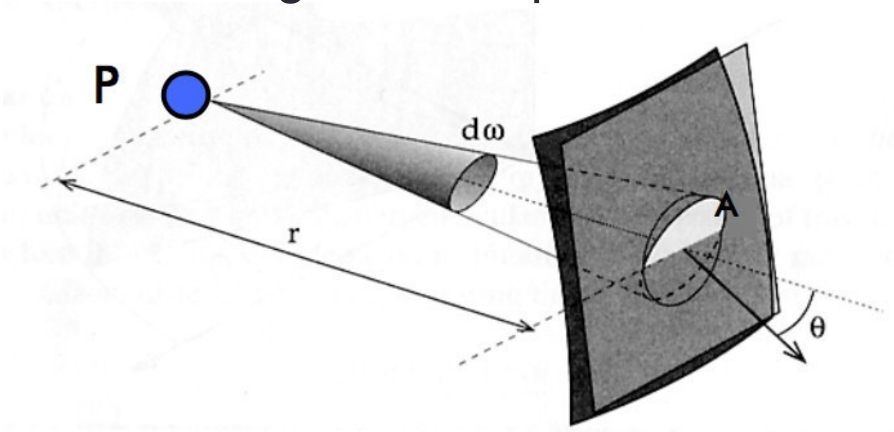
$$I = \frac{d\phi}{d\omega} \qquad d\omega = \frac{dA\cos\theta}{r^2}$$



$$d\phi = I d\omega$$

Projected Light and Foreshortening

- Consider now the light power per unit area arriving at the surface patch (irradiance E) based on power emanating from the point source per unit solid angle (intensity I):

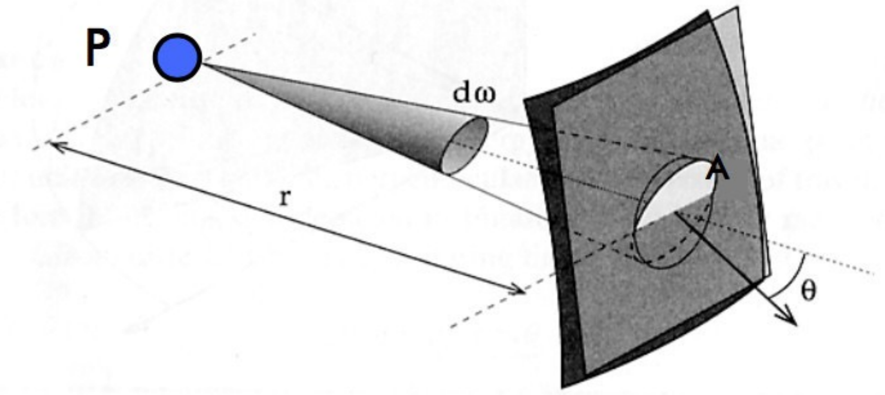


$$I = \frac{d\phi}{d\omega} \qquad d\omega = \frac{dA\cos\theta}{r^2}$$

$$d\phi = I\,d\omega \qquad d\phi = \frac{I\cos\theta}{r^2}dA$$

Projected Light and Foreshortening

- Consider now the light power per unit area arriving at the surface patch (irradiance E) based on power emanating from the point source per unit solid angle (intensity I):



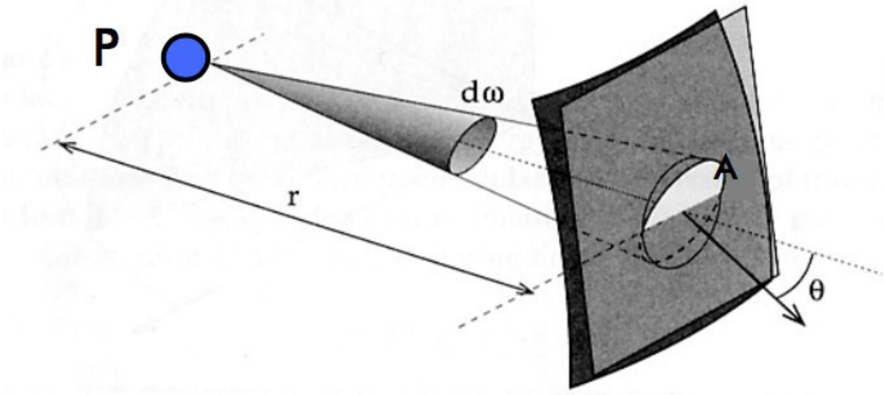
$$I = \frac{d\phi}{d\omega} \qquad d\omega = \frac{dA\cos\theta}{r^2}$$

$$d\phi = I\,d\omega \qquad d\phi = \frac{I\cos\theta}{r^2}dA$$

$$E = \frac{d\phi}{dA}$$

Projected Light and Foreshortening

- Consider now the light power per unit area arriving at the surface patch (irradiance E) based on power emanating from the point source per unit solid angle (intensity I):



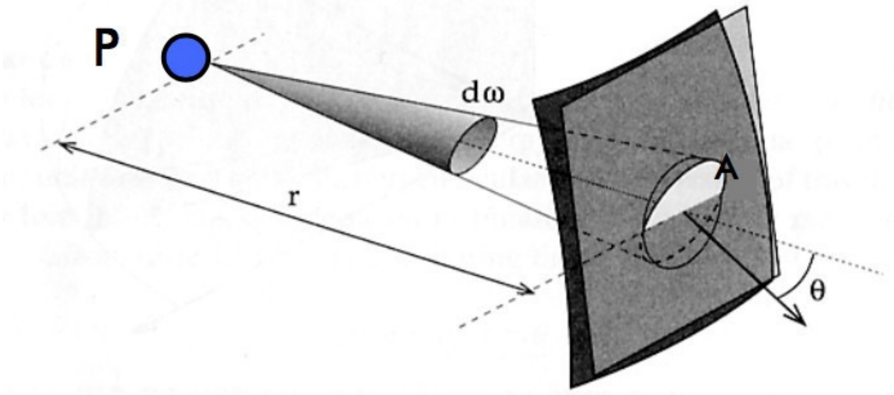
$$I = \frac{d\phi}{d\omega} \qquad d\omega = \frac{dA\cos\theta}{r^2}$$

$$d\phi = I d\omega \qquad d\phi = \frac{I\cos\theta}{r^2}dA$$

$$E = \frac{d\phi}{dA} \qquad \boxed{E = \frac{I\cos\theta}{r^2}}$$

Projected Light and Foreshortening

- Consider now the light power per unit area arriving at the surface patch (irradiance E) based on power emanating from the point source per unit solid angle (intensity I):



$$I = \frac{d\phi}{d\omega} \qquad d\omega = \frac{dA\cos\theta}{r^2}$$

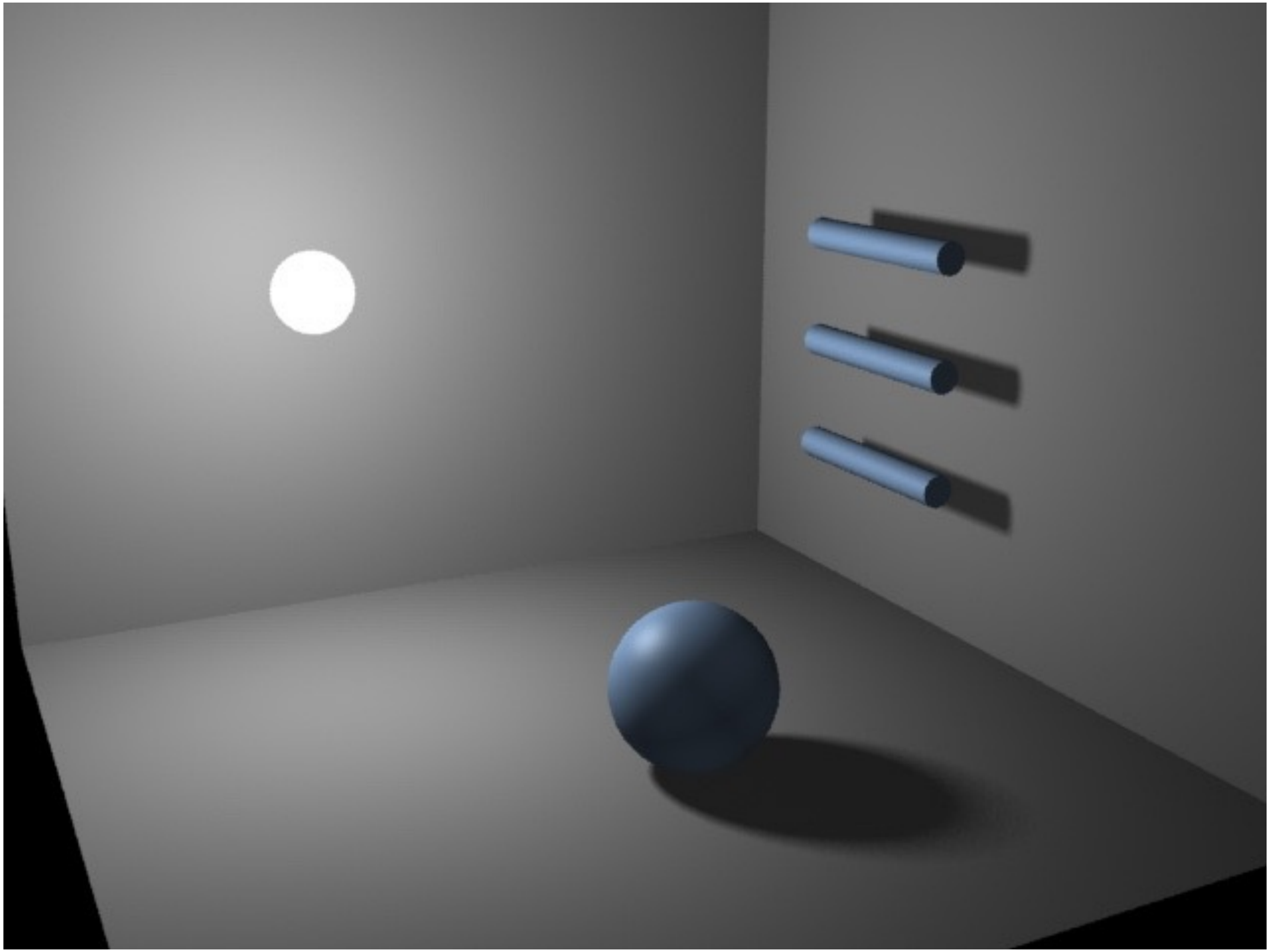
$$d\phi = I\,d\omega \qquad d\phi = \frac{I\cos\theta}{r^2}dA$$

- This effect is known as **radiometric foreshortening**: if we measured the light arriving at the surface (say indirectly by observing reflected light) then:

$$E = \frac{d\phi}{dA} \qquad \boxed{E = \frac{I\cos\theta}{r^2}}$$

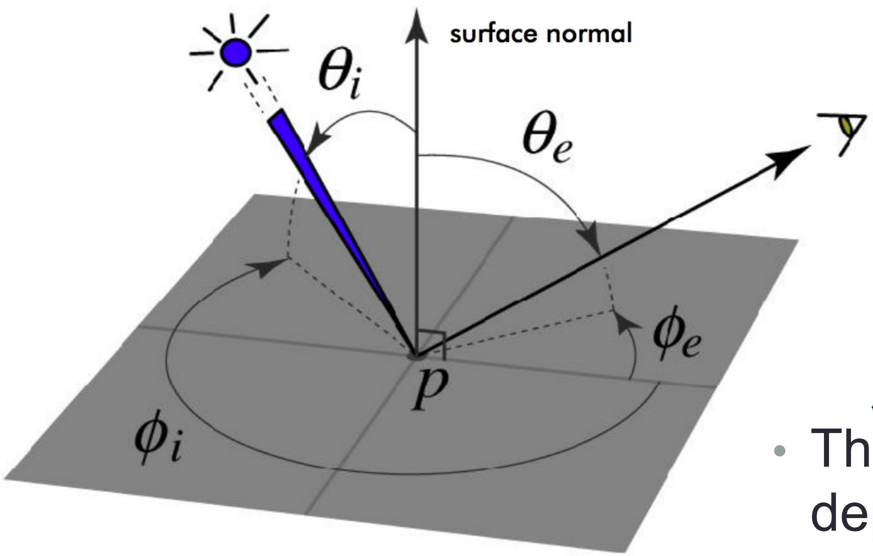
- Drop-off in brightness with distance from source ($\sim r^{-2}$)
- Drop-off in brightness with increase projected angle to source ($\sim \cos\theta$)

Projected Light and Foreshortening



The Bidirectional Reflectance Distribution Function (BRDF)

- Once light arrives at a surface how much is reflected back, and in what direction is controlled by the BRDF $\rho_{bd}(\theta_i, \phi_i, \theta_o, \phi_o)$
- The BRDF determines the ratio of out-going light radiance to the irradiance arriving at the surface, typically as a function of the in-going and out-going light directions:

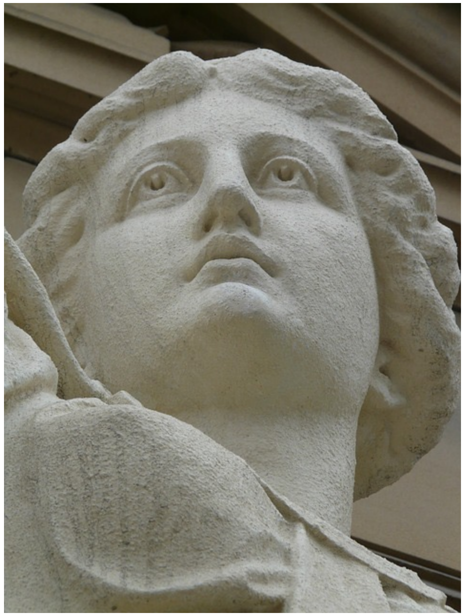


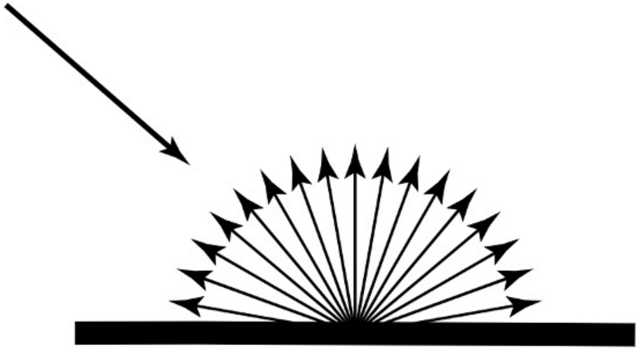
$$\rho_{bd}(\theta_i, \phi_i, \theta_o, \phi_o) = \frac{L(\theta_o, \phi_o)}{E(\theta_i, \phi_i)}$$

- The BRDF in general can also be dependent on light wavelength (hence colour, see second half of lecture)

Types of Reflection

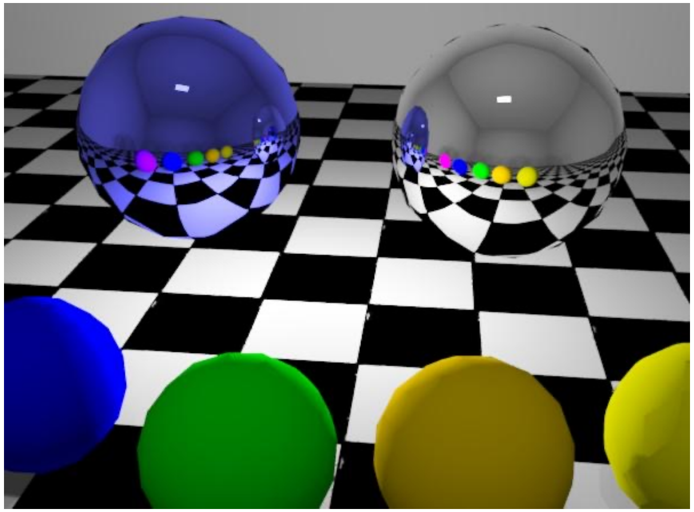
- **Lambertian or Diffuse Reflection**: rough surfaces that scatter light, BRDF independent of ingoing/outgoing angle (ρ_{bd} is constant)
- **Mirrored/Specular Surface Reflection:** Perfectly reflects all light back along angle equal to ingoing light
- **Mixed Reflection:** A combination of mirror and Lambertian effects, exhibits flat shading and highlights

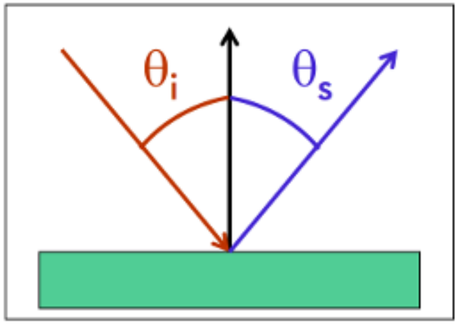




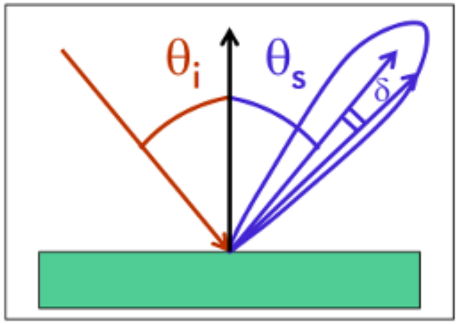
Types of Reflection

- **Lambertian or Diffuse Reflection**: rough surfaces that scatter light, BRDF independent of ingoing/outgoing angle (ρ_{bd} is constant)
- **Mirrored/Specular Surface Reflection:** Perfectly reflects all light back along angle equal to ingoing light
- **Mixed Reflection:** A combination of mirror and Lambertian effects, exhibits flat shading and highlights





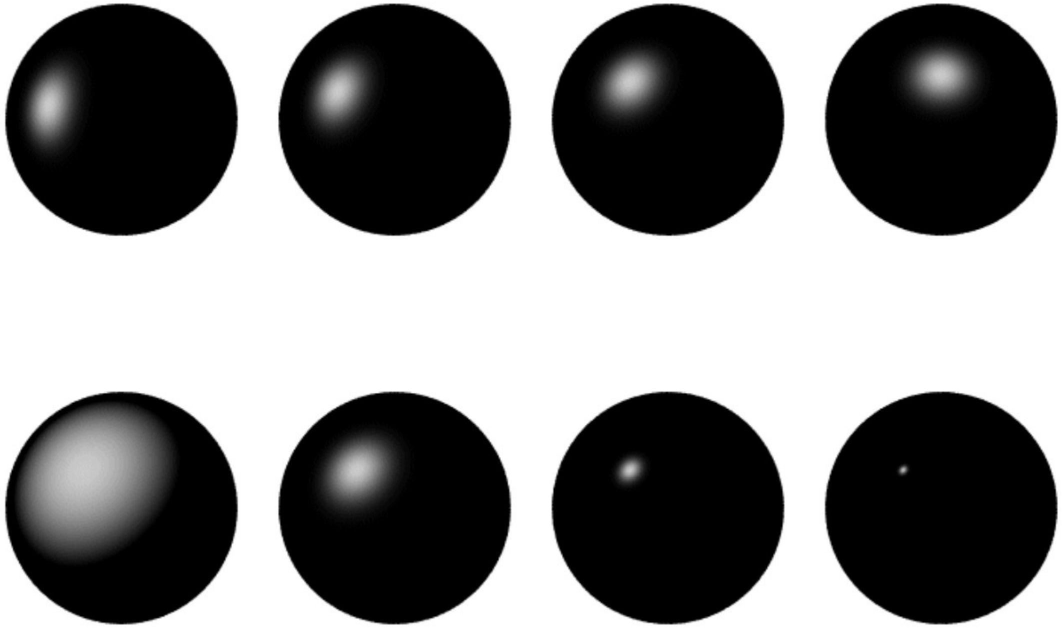
Perfect mirror

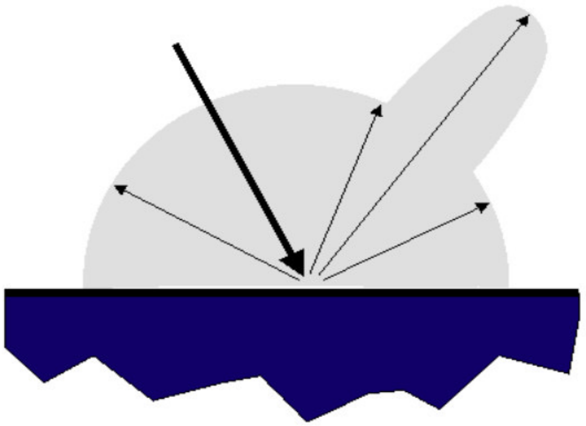


Rough mirror

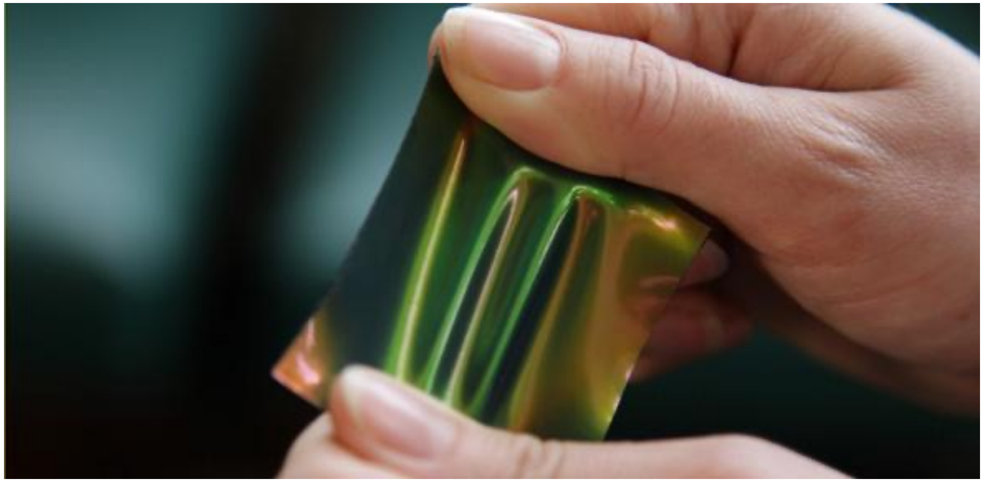
Types of Reflection

- **Lambertian or Diffuse Reflection**: rough surfaces that scatter light, BRDF independent of ingoing/outgoing angle (ρ_{bd} is constant)
- **Mirrored/Specular Surface Reflection:** Perfectly reflects all light back along angle equal to ingoing light
- **Mixed Reflection:** A combination of mirror and Lambertian effects, exhibits flat shading and highlights





The Bidirectional Reflectance Distribution Function (BRDF)



- More complex effects

Image Formation Model for Lambertian Surfaces

- For Lambertian/diffuse surfaces, we can represent the reflectance on a surface based on it's albedo (ρ):

$$\rho = \int \rho_{bd}(\theta_i, \phi_i, \theta_o, \phi_o) \cos\theta_o d\omega_o$$

- Albedo is measured between 0 (totally dark/black) to 1 (totally bright/white), and represents the total fraction of light energy reflected back per irradiance

- Consider a Lambertian scene path illuminated by a point source: the total observed radiance L becomes:

$$L = \rho \frac{I \cos\theta}{r^2}$$

Image Formation Model for Lambertian Surfaces

- Image brightness (B) observed by a human or camera is proportional to the radiance of light entering the aperture/pupil, hence:

$$B \propto \rho \frac{\cos\theta}{r^2}$$

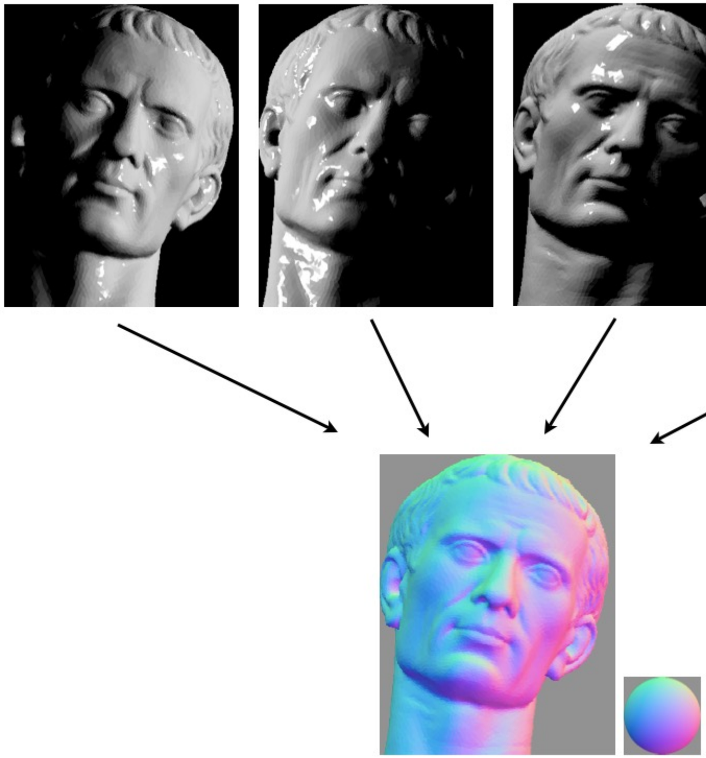
- For distant point sources, where differences in r are small relative to r, we can further approximate to:

$$B \propto \rho \cos\theta = \rho \mathbf{N} \cdot \mathbf{S}$$

- Where B is brightness, ρ is albedo, **N** is the normal vector of the surface and **S** is the vector from the patch to the light source (cos θ = **N.S**)

Application: Photometric stereo

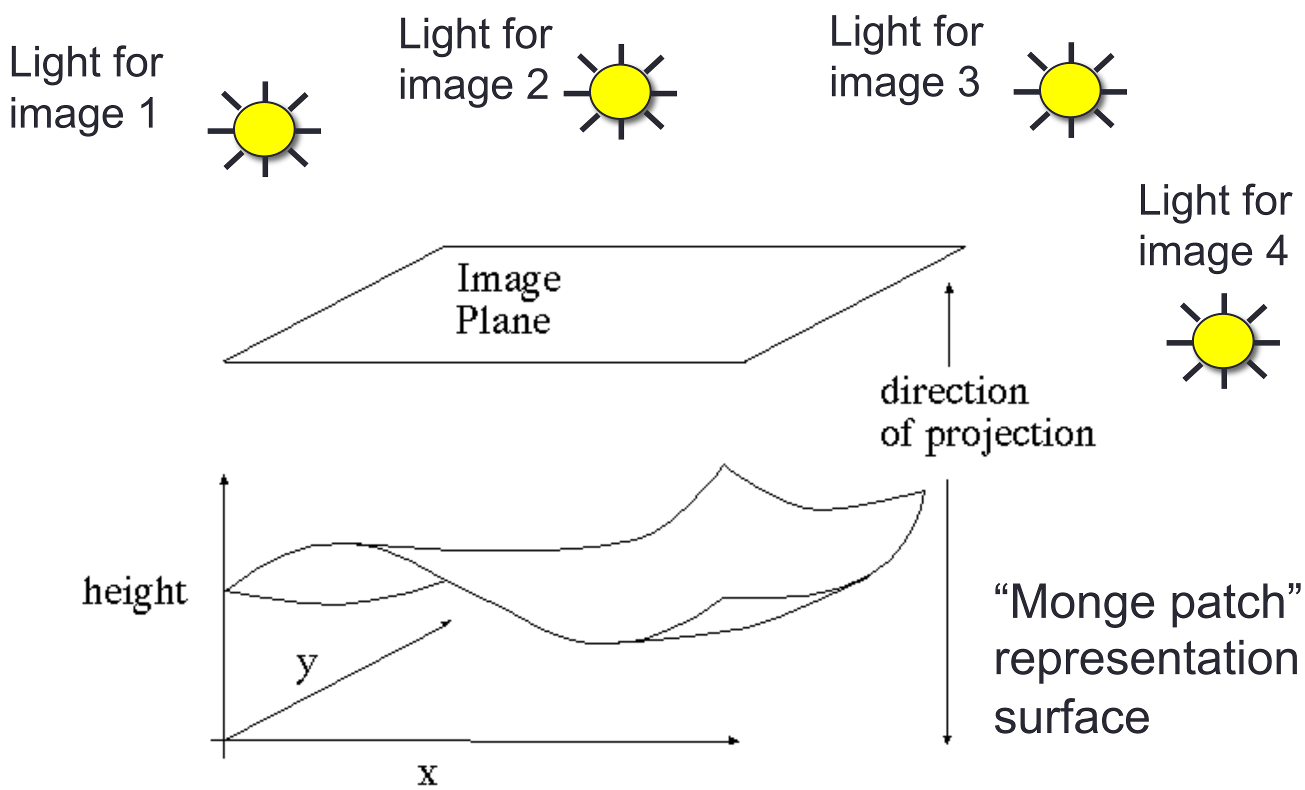
- Photometric stereo is the process of recovering the 3D shape of an imaged object from multiple images, taken from a single view, but with varying light source direction



- Use knowledge of the lighting directions to estimate surface normal vectors and surface albedo, through rearranging an image formation model

Application: Photometric stereo

- Assumptions:
  - Object with predominantly Lambertian surface reflection
  - A set of know source light directions (and lights are distant from object)
  - Local shading only: minimal inter-reflectance between adjacent surfaces
  - Multiple images are spatially aligned (i.e camera and subject don't move)



"Monge patch" representation of the surface

Application: Photometric stereo

- Assume the response function of the camera is linear, and hence k represents a scale factor that encompasses the scaling between image pixel brightness and source light intensity:

$$
\begin{aligned}
B_j(x,y) or I_j(x,y) &= k\rho(x,y)(\mathbf{N}(x,y)\cdot\mathbf{S}_j) \\
&= (k\rho(x,y)\mathbf{N}(x,y))\cdot\mathbf{S}_j \\
&= \mathbf{g}(x,y)\cdot\mathbf{S}_j
\end{aligned}
$$

  - Where (x,y) corresponds to a position in the image plane (pixel location) and j is the image/light source number

  - Combining over multiple images/lights:

$$
\begin{bmatrix} I_1(x,y) \\ I_2(x,y) \\ \vdots \\ I_n(x,y) \end{bmatrix} = \begin{bmatrix} \mathbf{s}_1^T \\ \mathbf{s}_2^T \\ \vdots \\ \mathbf{s}_n^T \end{bmatrix} \mathbf{g}(x,y)
$$

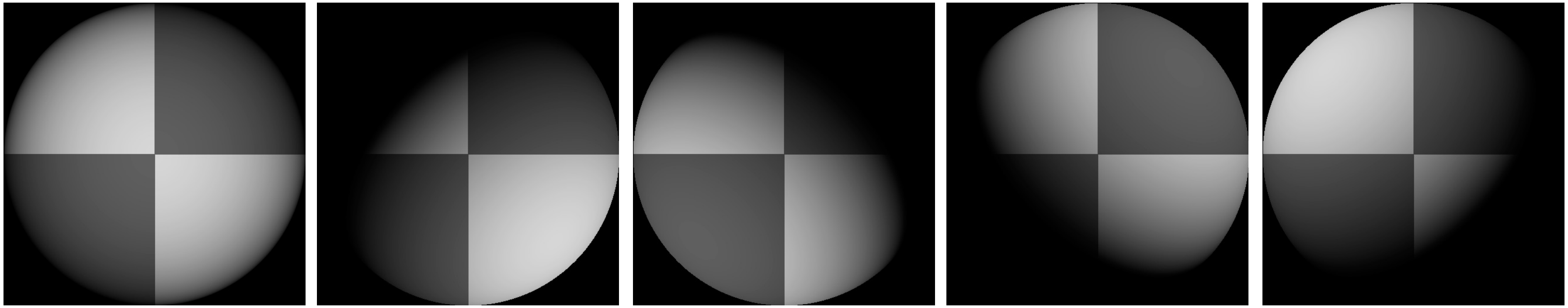
Application: Photometric stereo

- The vector g(x,y) for each pixel in the scene can be solved for when at least three different lightings are available, and a least-squares estimate can be computed when more than three are available:

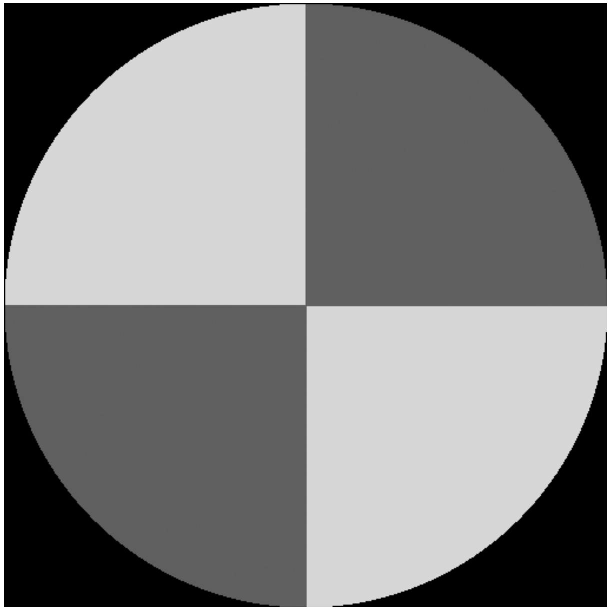
$$\underbrace{\begin{bmatrix} I_1(x,y) \\ I_2(x,y) \\ \vdots \\ I_n(x,y) \end{bmatrix}}_{\substack{(n \times 1) \\ \text{known}}} = \underbrace{\begin{bmatrix} \mathbf{s}_1^T \\ \mathbf{s}_2^T \\ \vdots \\ \mathbf{s}_n^T \end{bmatrix}}_{\substack{(n \times 3) \\ \text{known}}} \underbrace{\mathbf{g}(x,y)}_{\substack{(3 \times 1) \\ \text{unknown}}}$$

- Once g(x,y) is known, the magnitude of the vector is equal to the albedo of point (x,y) (assuming k = 1) and the vector direction is the normal vector **N**

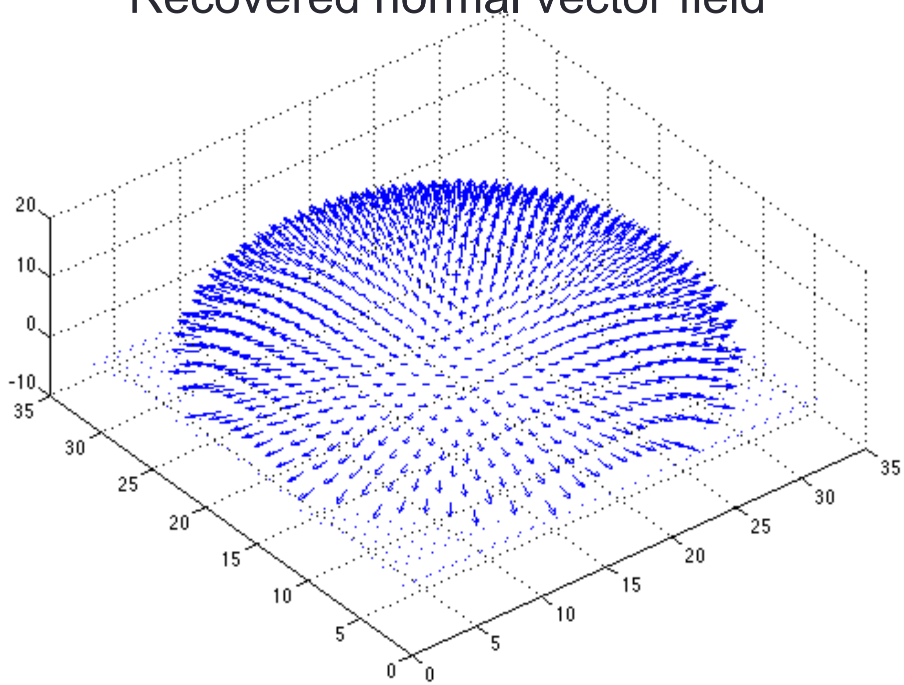
Application: Photometric stereo



Recovered albedo



Recovered normal vector field



“Computer Vision: A Modern Approach”, Forsyth and Ponce

Application: Photometric stereo

- The 3D structure of the surface h = f(x,y) can be recovered by integration over the normal vectors, setting the height of one pixel at the start of the integration path to be an arbitrary height value
- The partial derivatives of the surface f(x,y) are:

$$\delta_x f(x,y) = \frac{g_x(x,y)}{g_z(x,y)} \qquad \delta_y f(x,y) = \frac{g_y(x,y)}{g_z(x,y)}$$

- The value of f(x,y) can be recovered by integrating along any path from the starting location (i.e. (0,0)):

$$f(u,v) = \int_0^u \delta_x f(x,0)dx + \int_0^v \delta_y f(u,y)dy$$

Application: Photometric stereo

- The 3D structure of the surface h = f(x,y) can be recovered by integration over the normal vectors, setting the height of one pixel at the start of the integration path to be an arbitrary height value
- The partial derivatives of the surface f(x,y) are:

$$\delta_x f(x,y) = \frac{g_x(x,y)}{g_z(x,y)} \qquad \delta_y f(x,y) = \frac{g_y(x,y)}{g_z(x,y)}$$

- The value of f(x,y) can be recovered by integrating along any path from the starting location (i.e. (0,0)):

$$f(u,v) = \int_0^u \delta_x f(x,0)dx + \int_0^v \delta_y f(u,y)dy$$

Example: integrate first along the top row of the image from (0,0) to (u,0)

Application: Photometric stereo

- The 3D structure of the surface h = f(x,y) can be recovered by integration over the normal vectors, setting the height of one pixel at the start of the integration path to be an arbitrary height value
- The partial derivatives of the surface f(x,y) are:

$$\delta_x f(x,y) = \frac{g_x(x,y)}{g_z(x,y)} \qquad \delta_y f(x,y) = \frac{g_y(x,y)}{g_z(x,y)}$$

- The value of f(x,y) can be recovered by integrating along any path from the starting location (i.e. (0,0)):

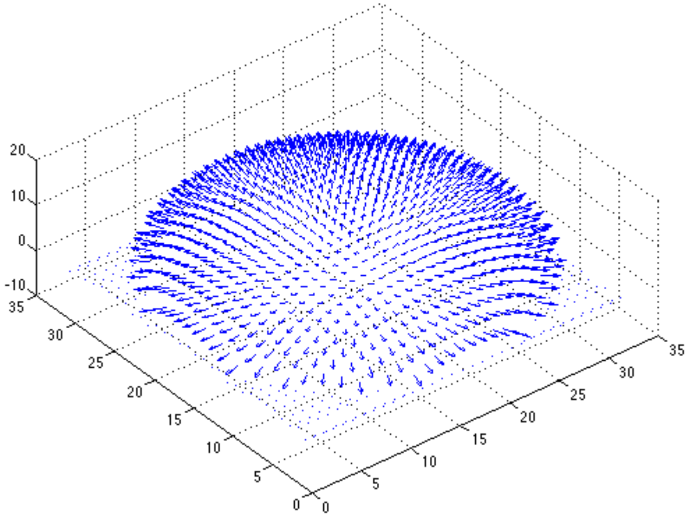
$$f(u,v) = \int_0^u \delta_x f(x,0)dx + \int_0^v \delta_y f(u,y)dy$$

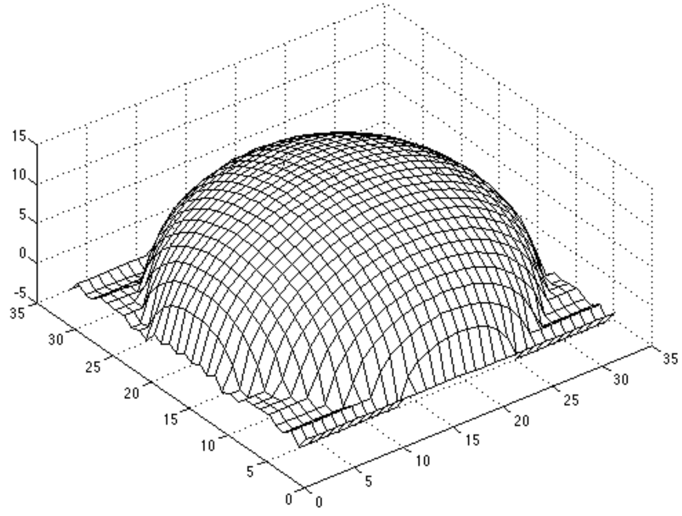
Then integrate down column from (u,0) to (u,v)

Application: Photometric stereo

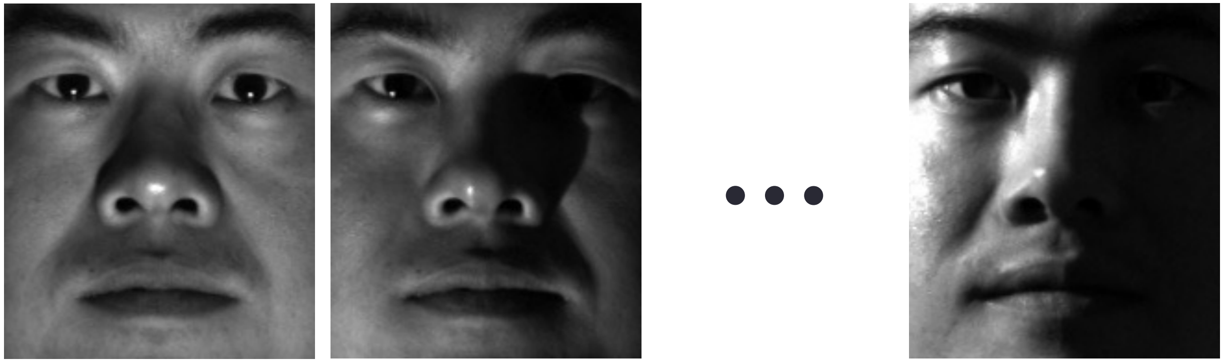
$$f(u,v) = \int_0^u \delta_x f(x,0)dx + \int_0^v \delta_y f(u,y)dy$$

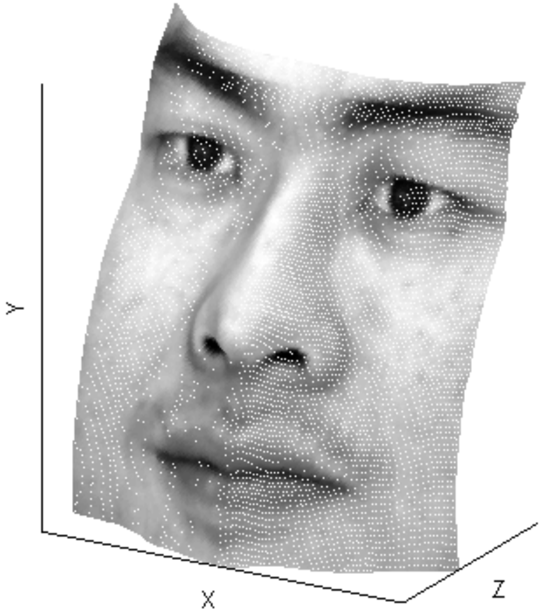
- For a discrete image, this integration is performed numerically by taking a cumulative sum of the partial derivative values in either the horizontal (x) or vertical (y) directions
- In practice (due to errors in the computed normals) its best to average the height values computed by integrating over multiple paths

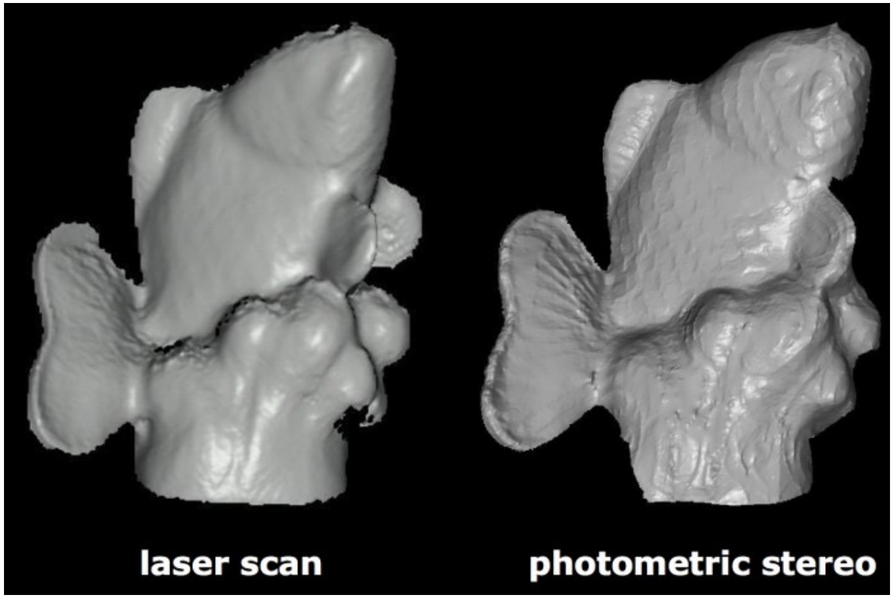




Photometric stereo: Results

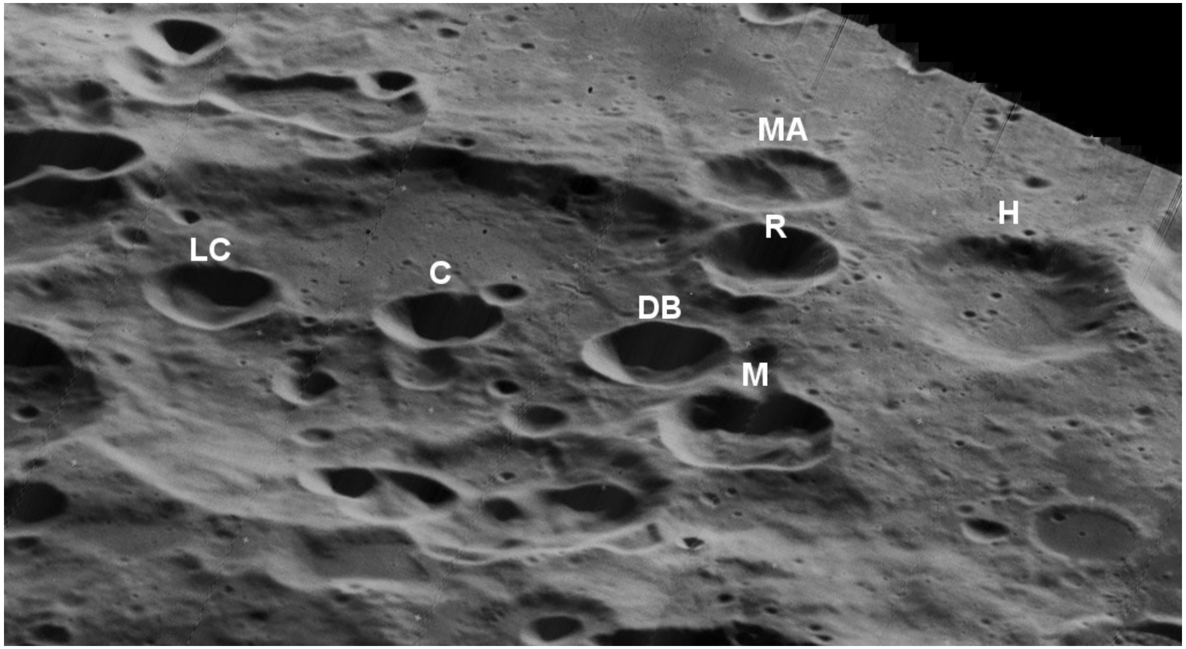


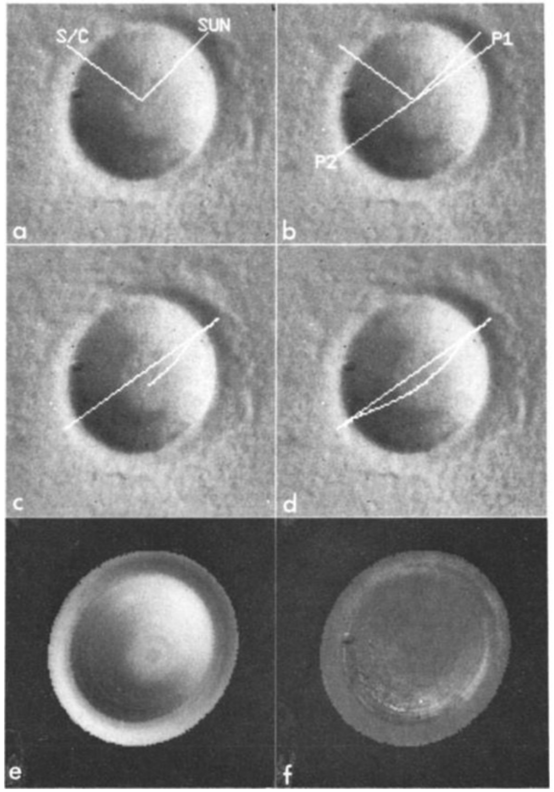




Other applications: Photoclinometry

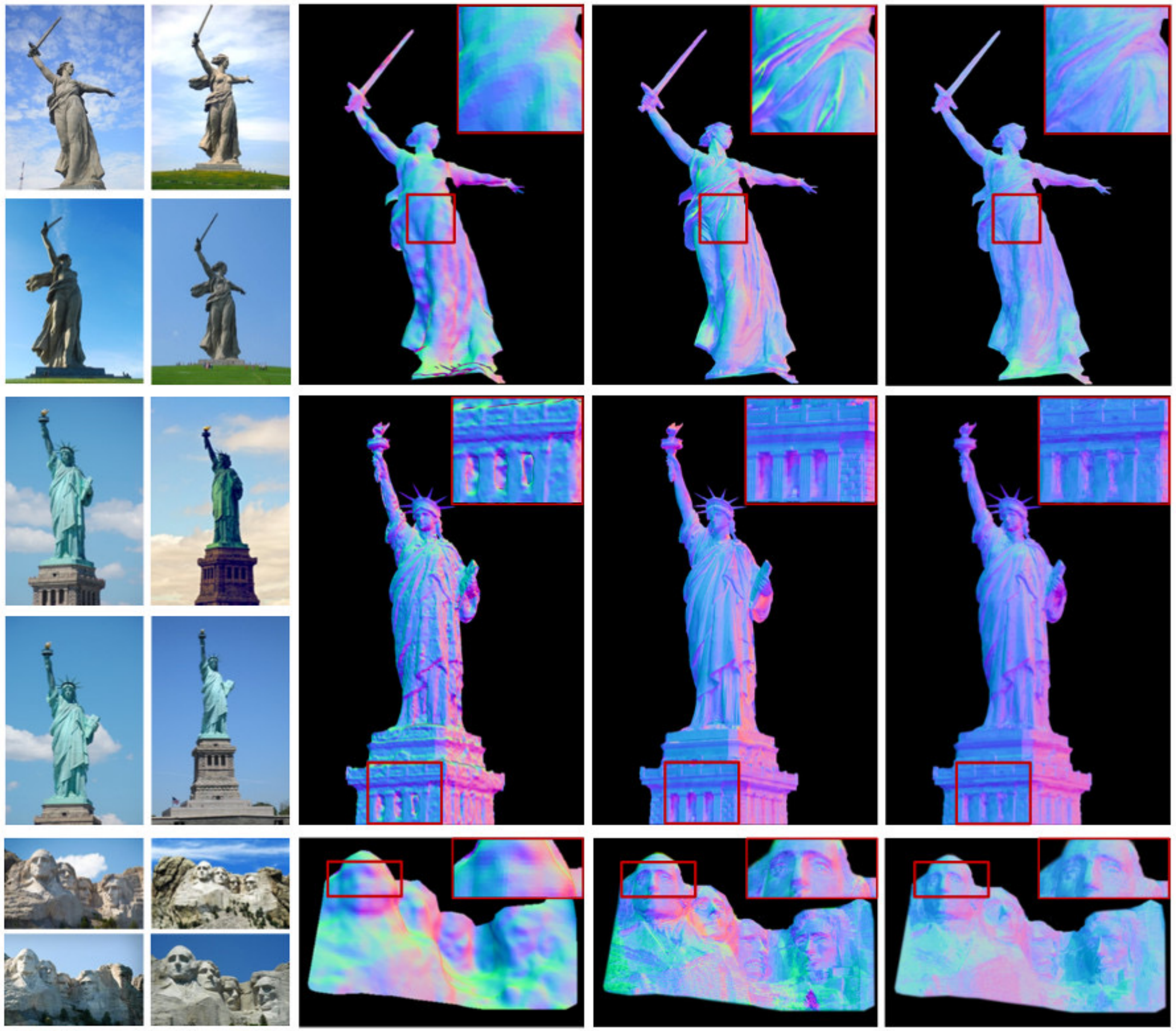
- Photoclinometry/shape-from-shading: more general use of shading in imagery to recover structure and measure surface heights
- Recovery of high-resolution topographic information from planetary images





P.A. Davis, "Modeling crater topography and albedo from monoscopic Viking Orbiter images", Journal of Geophysical Research, 1984

Other applications: photometric stereo using internet images



B. Shi et. al., Photometric Stereo using Internet Images, International Conference on 3D Vision (3DV), 2014

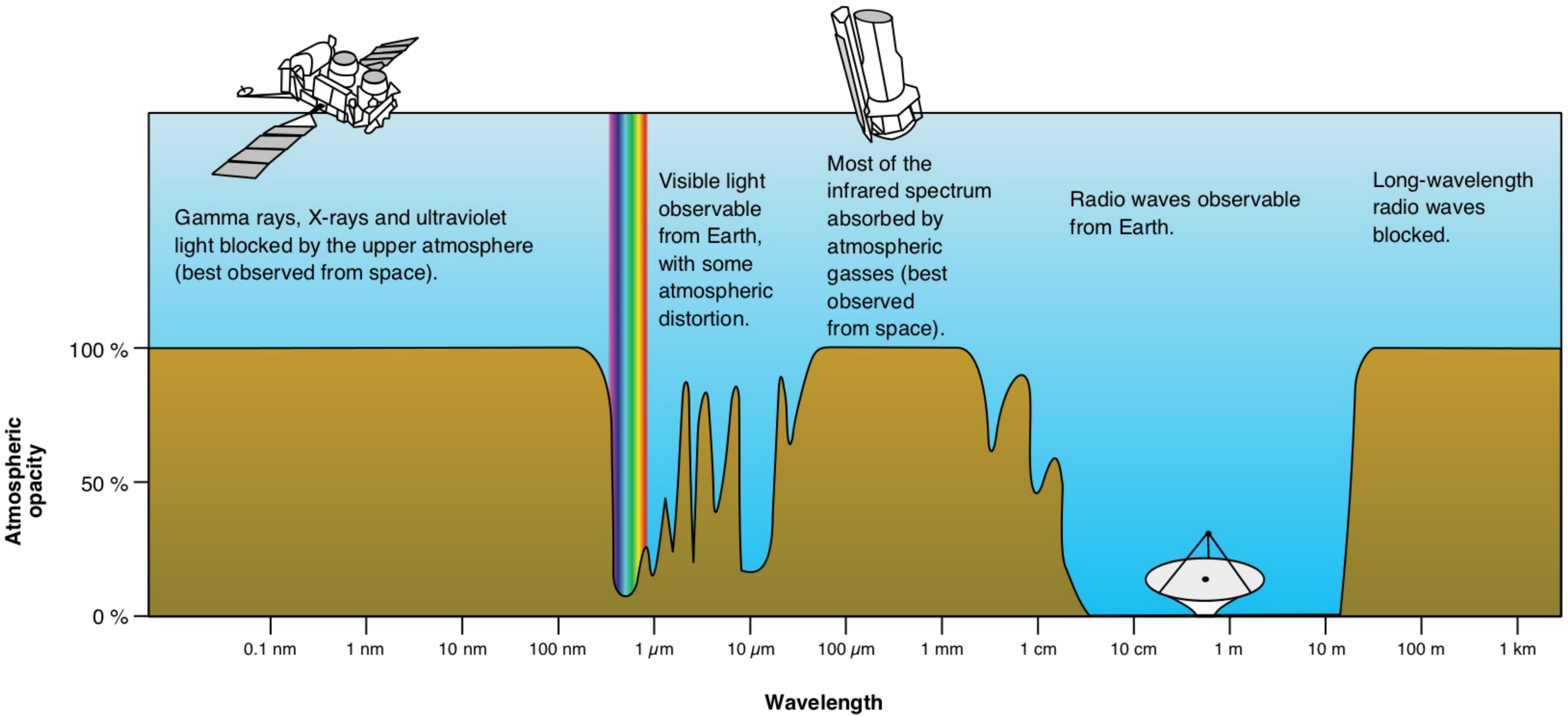
Other applications: Exposing forgeries by detecting lighting inconsistency

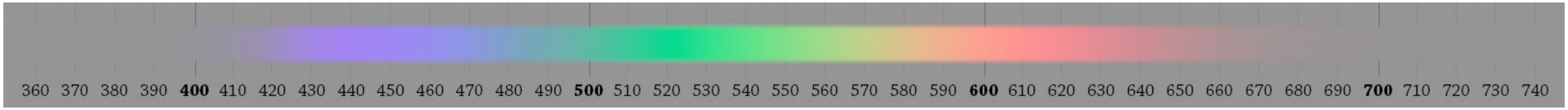
- Detect whether images are forged/doctored images based on inconsistencies in detected lighting directions, inferred from local shading pattern

http://www.cs.dartmouth.edu/farid/downloads/publications/acm05.pdf

5 minute break

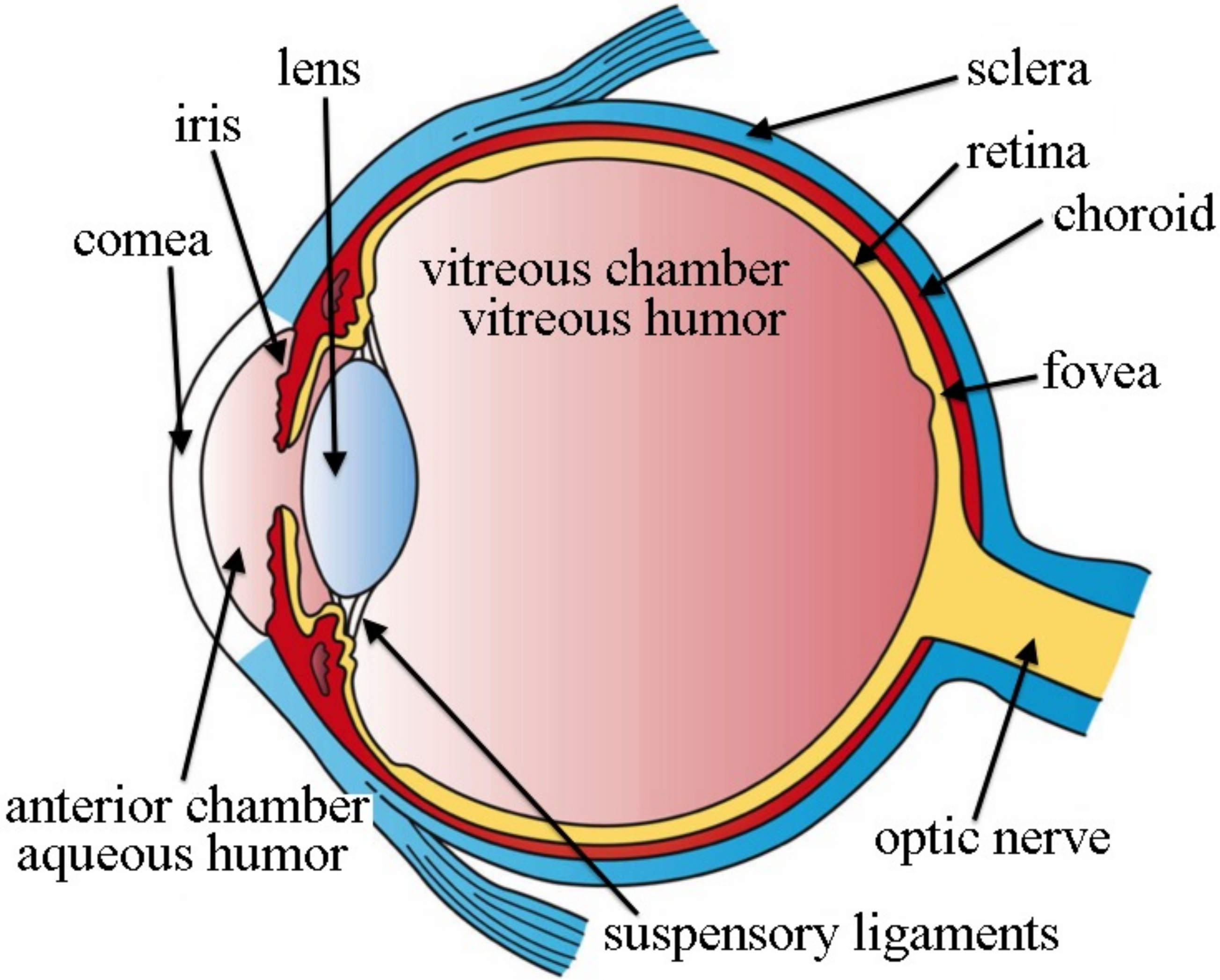
Light spectrum and colour





http://en.wikipedia.org/wiki/File:Rendered_Spectrum.png

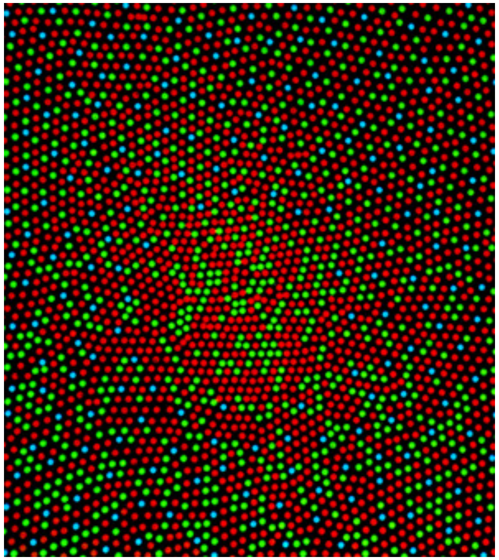
Human Eye



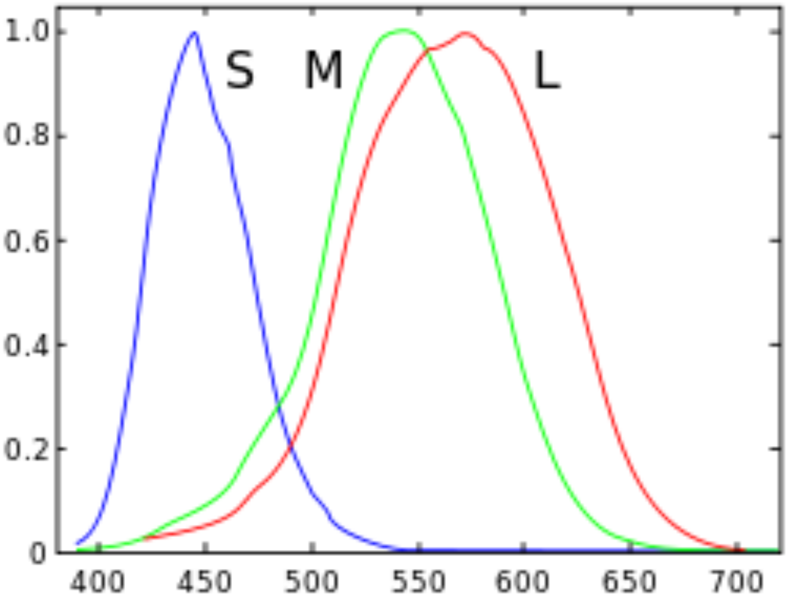
Courtesy: Holly Fischer (http://open.umich.edu/education/med/resources/second-look-series/materials)

Human Eye and Colour

- Human eye contains two types of photosensitive cells on the retina:
  - *Rods:* high light sensitivity, monochromatic
  - *Cones:* three types of cells with varying sensitivities to wavelength, combination of signals creates trichromatic vision



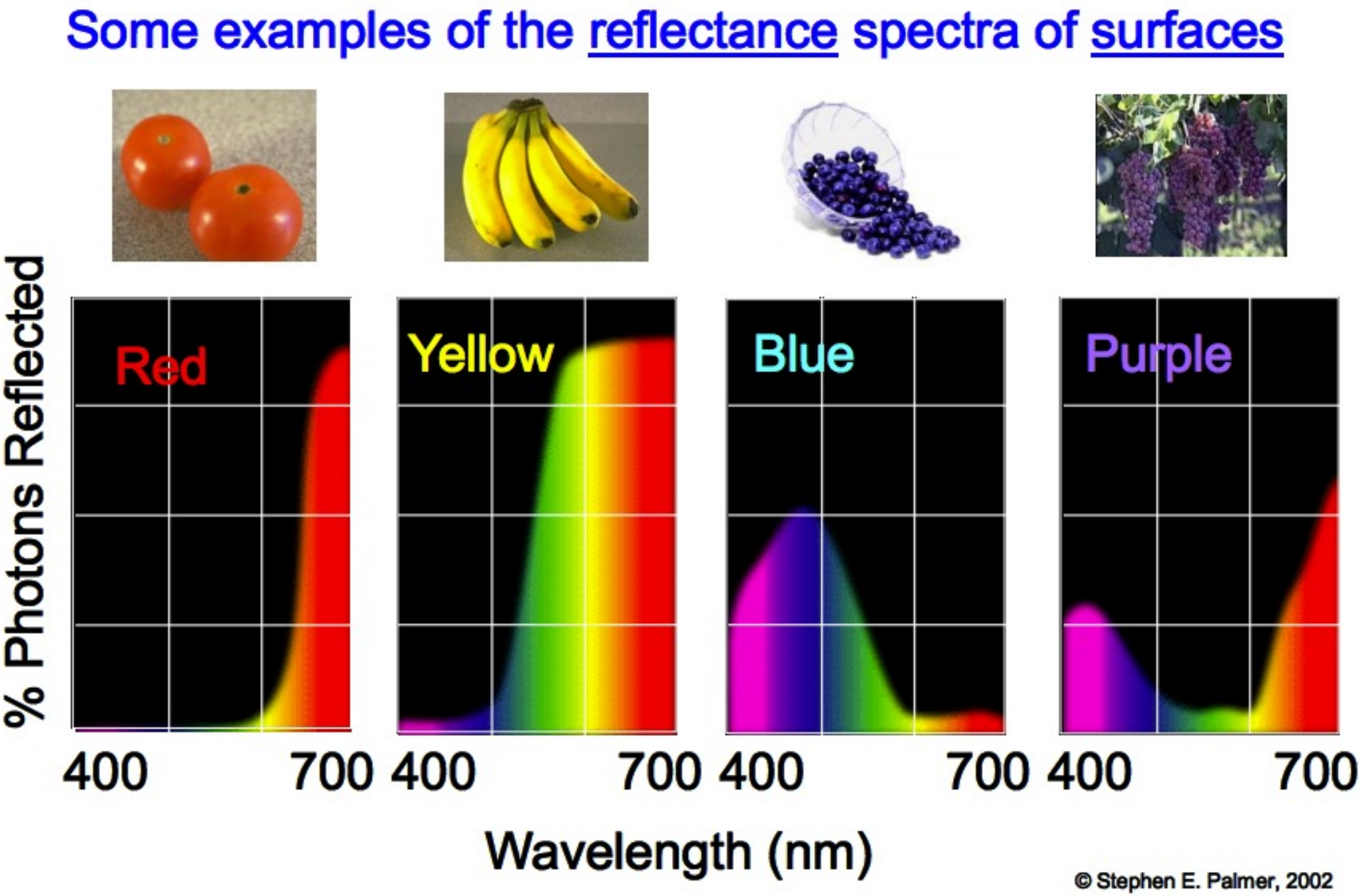
Microscopic image of mosaic of human cone cells in retina



Normalised spectral response functions of human cone cells (S,M,L)

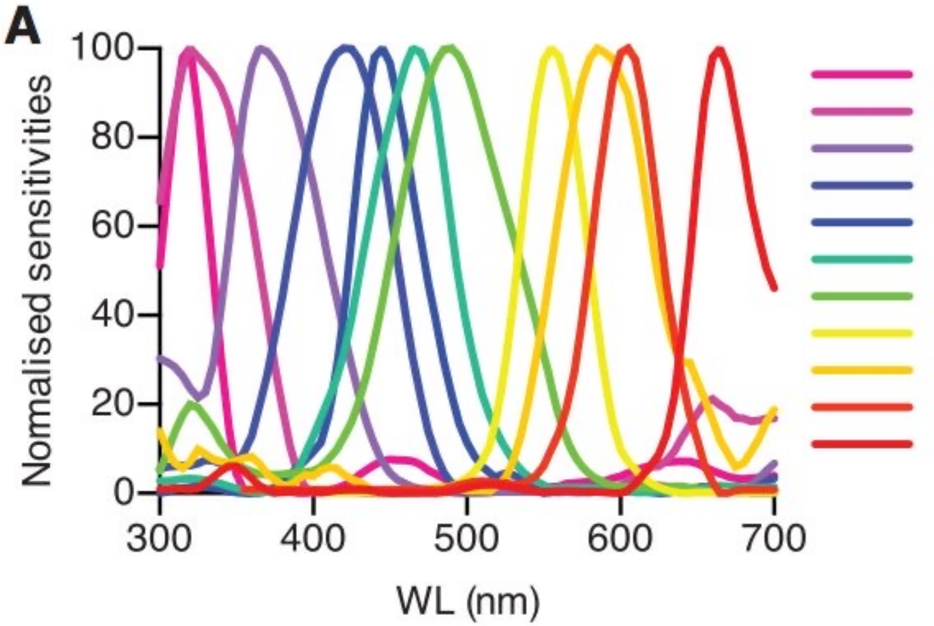
Courtesy: Mark Fairchild (http://rit-mcsl.org/fairchild/WhyIsColor/images/ConeMosaics.jpg)

Spectrum and colour



Tetrachromacity and Animal Colour Vision

- A large number of animals (fish, reptiles birds) can perceive 4 colours (tetrachromatic vision)
- The Mantis Shrimp has 12 difference types of photo-receptors in it's eye:
  - uses sophisticated neurological processes for quickly recognising objects based on colour

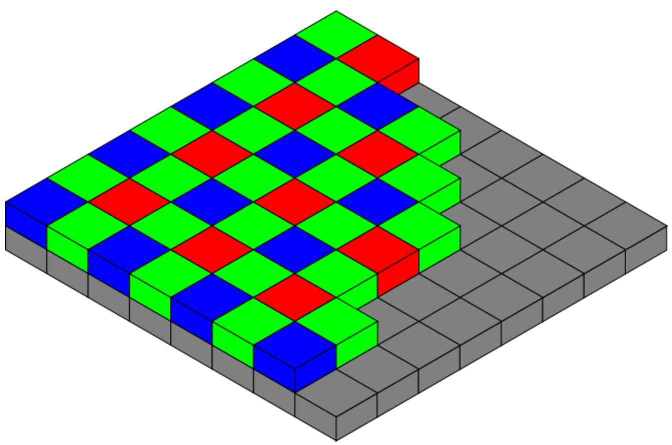


http://science.sciencemag.org/content/343/6169/411

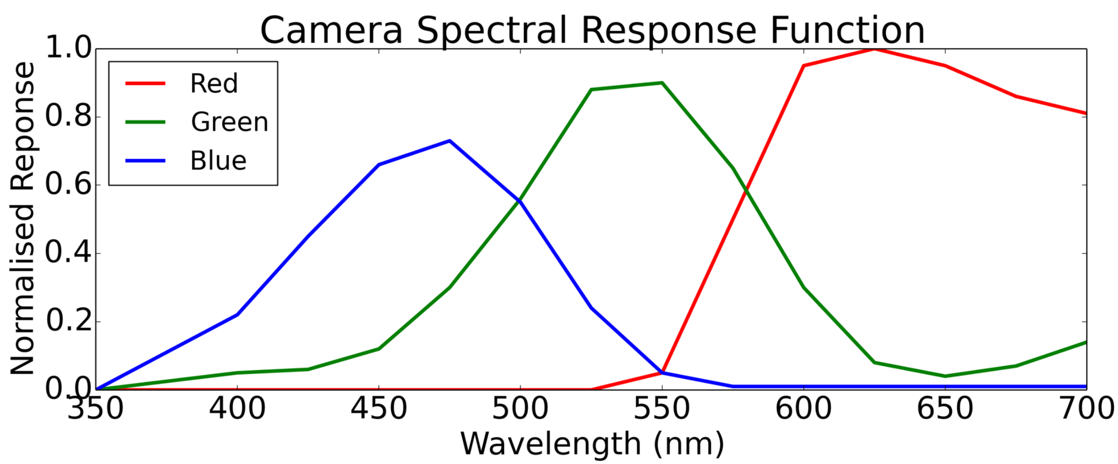
Cameras and Colour

- Most cameras use an image sensor (CCD/CMOS), monochromatic (colour/NIR)
- Colour through bandpass filters:
  - **3-CCD Cameras** use three separate sensors, one for each of Red, Green and Blue
  - **Bayer cameras** use a "mosaic" of per-pixel filters

CCD sensor
(http://www.teledynedalsa.com/corp/)



Bayer Mosaic
(http://en.wikipedia.org/wiki/File:Bayer_pattern_on_sensor.svg)



Typical bayer camera spectral response functions (Sony/Prosilica 12B CCD)

Colour Intensity and Image Formation

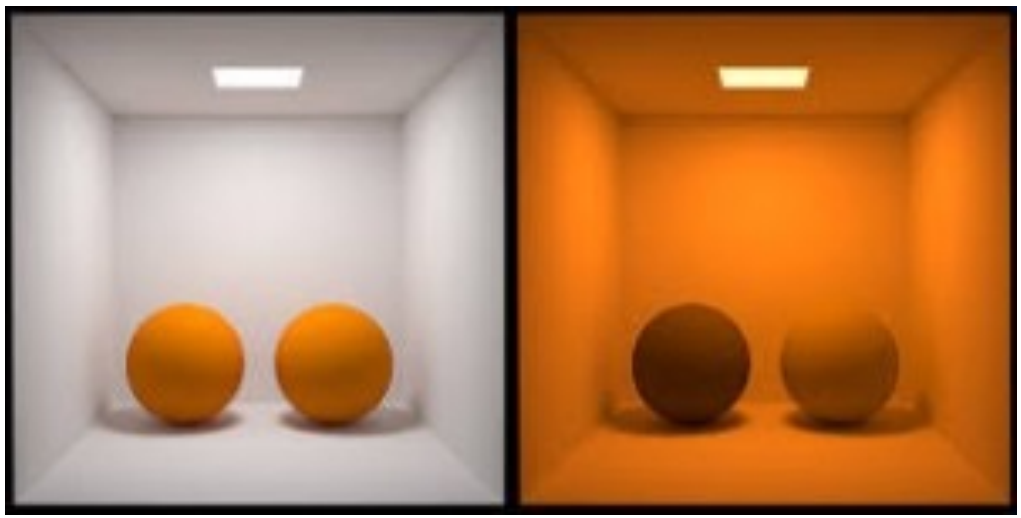
- The final brightness measured in each of the Red-Green-Blue (RGB) channels of a camera depends on three factors:
  - Emission spectra of illuminating light source: $E(\lambda)$
  - Reflectance spectra of the object viewed: $S(\lambda)$
  - Spectral response function of each colour channel k: $R_k(\lambda)$

$$\mathbf{I}_k = \int R(\lambda)E(\lambda)S(\lambda)d\lambda \qquad k \in \{R, G, B\}$$

Where I_k is the measured image intensity for channel k and λ is light wavelength

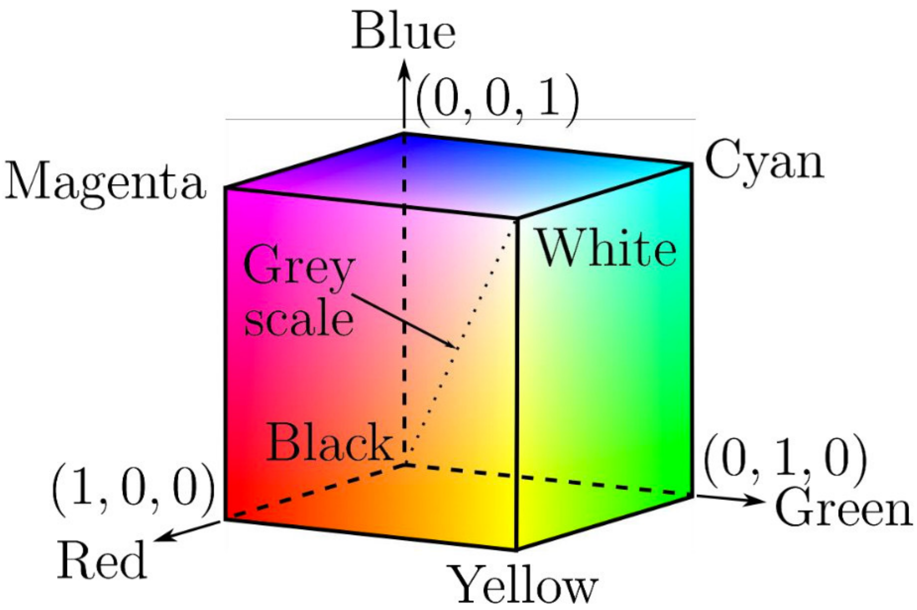
Metamerism

- Metamerism: colours appear to match under certain illumination conditions, but not others
- Reflectance spectra of objects do not actually match



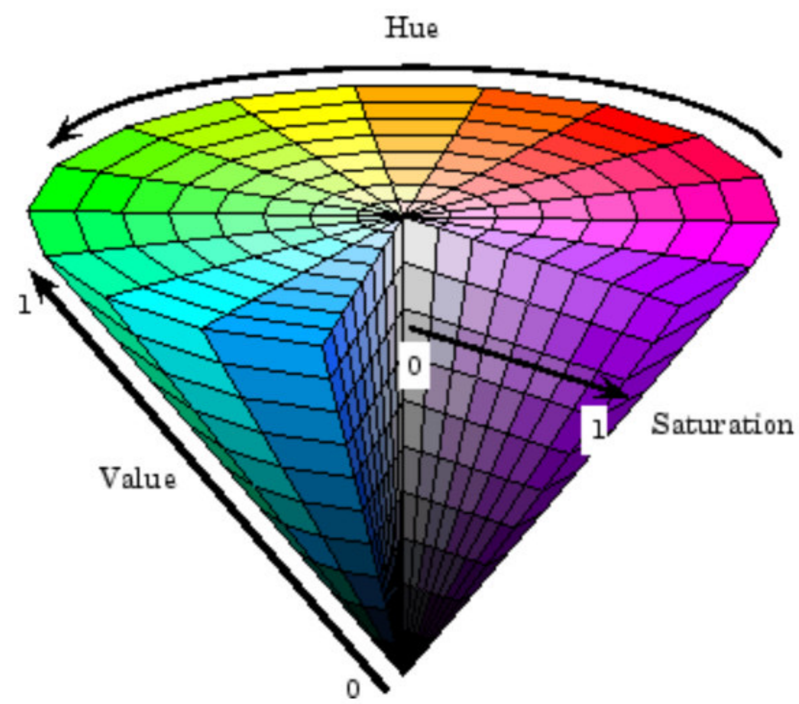
Colour Spaces and Representation

- A colour space is an organisation of (typically) trichromatic colours into a vector space: RGB is an example of a colour space
- Other colour spaces may be useful for:
  - Grouping colours that are perceptually similar (to humans) close to one another in a vector space (i.e. small distances between points)
  - Arranging different perceptual attributes of colour (i.e. hue, luminance etc.) along different axes of the vector space
- RGB Colour Space:
  - Colour space is represented by a cube with each axis representing the primary spectral components red, green and blue



Colour Spaces and Representation

- Hue-Saturation-Value (HSV): A colour space which is a non-linear transformation of RGB:
  - **Hue**: describes 'pure' colour (i.e. red to yellow to green)
  - **Saturation**: the degree to which the pure colour is diluted by white light
  - **Value**: overall brightness, distance along a line from black to white



- Variations to HSV include Hue-Saturation-Intensity (HSI) and Hue-Saturation-Lightness (HSL) which have altered definitions of saturation and Value/Lightness/Intensity

Colour Spaces and Representation

- Converting from RGB to HSV:

$$R' = R/255 \qquad Cmax = \max(R', G', B')$$

$$G' = G/255 \qquad Cmin = \min(R', G', B')$$

$$B' = B/255 \qquad \Delta = Cmax - Cmin$$

$$H = \begin{cases} 0^\circ & \Delta = 0 \\ 60^\circ \times \left(\frac{G'-B'}{\Delta} mod 6\right) & , C_{max} = R' \\ 60^\circ \times \left(\frac{B'-R'}{\Delta} + 2\right) & , C_{max} = G' \\ 60^\circ \times \left(\frac{R'-G'}{\Delta} + 4\right) & , C_{max} = B' \end{cases}$$

$$S = \begin{cases} 0 & , C_{max} = 0 \\ \frac{\Delta}{C_{max}} & , C_{max} \neq 0 \end{cases}$$

$$V = Cmax$$

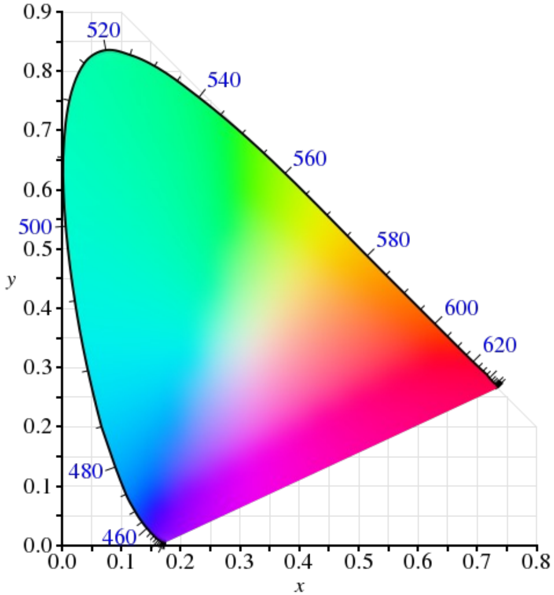
RGB to HSV color table

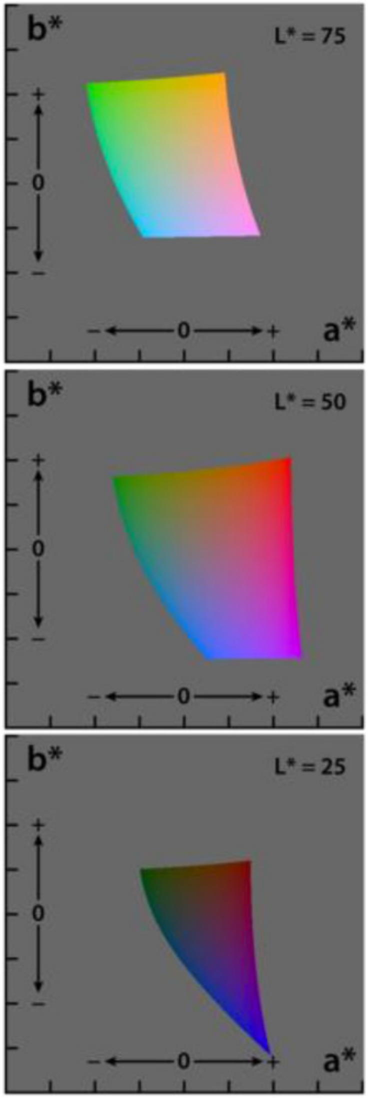
Color	Color name	Hex	(R,G,B)	(H,S,V)
	Black	#000000	(0,0,0)	(0°,0%,0%)
	White	#FFFFFF	(255,255,255)	(0°,0%,100%)
	Red	#FF0000	(255,0,0)	(0°,100%,100%)
	Lime	#00FF00	(0,255,0)	(120°,100%,100%)
	Blue	#0000FF	(0,0,255)	(240°,100%,100%)
	Yellow	#FFFF00	(255,255,0)	(60°,100%,100%)
	Cyan	#00FFFF	(0,255,255)	(180°,100%,100%)
	Magenta	#FF00FF	(255,0,255)	(300°,100%,100%)
	Silver	#C0C0C0	(192,192,192)	(0°,0%,75%)
	Gray	#808080	(128,128,128)	(0°,0%,50%)
	Maroon	#800000	(128,0,0)	(0°,100%,50%)
	Olive	#808000	(128,128,0)	(60°,100%,50%)
	Green	#008000	(0,128,0)	(120°,100%,50%)
	Purple	#800080	(128,0,128)	(300°,100%,50%)
	Teal	#008080	(0,128,128)	(180°,100%,50%)
	Navy	#000080	(0,0,128)	(240°,100%,50%)

http://www.rapidtables.com/convert/color/rgb-to-hsv.htm

Colour Spaces and Representation

- Experiments initially performed in the 1930s were used to develop colour models that represent colours in a way that captures the physiologically-perceived differences made by humans
  - Resulted in the development of the CIE (International Comission on Illumination) XYZ colour space
- In the 1970s, new data was used to generate the CIE L*a*b* colour space:
  - L*: measured luminance (brightness)
  - a*: red to green
  - b*: yellow to blue





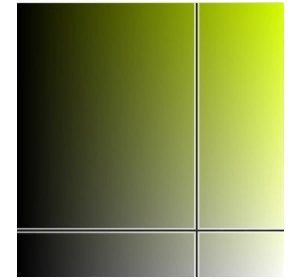
Issues with detecting objects based on colour

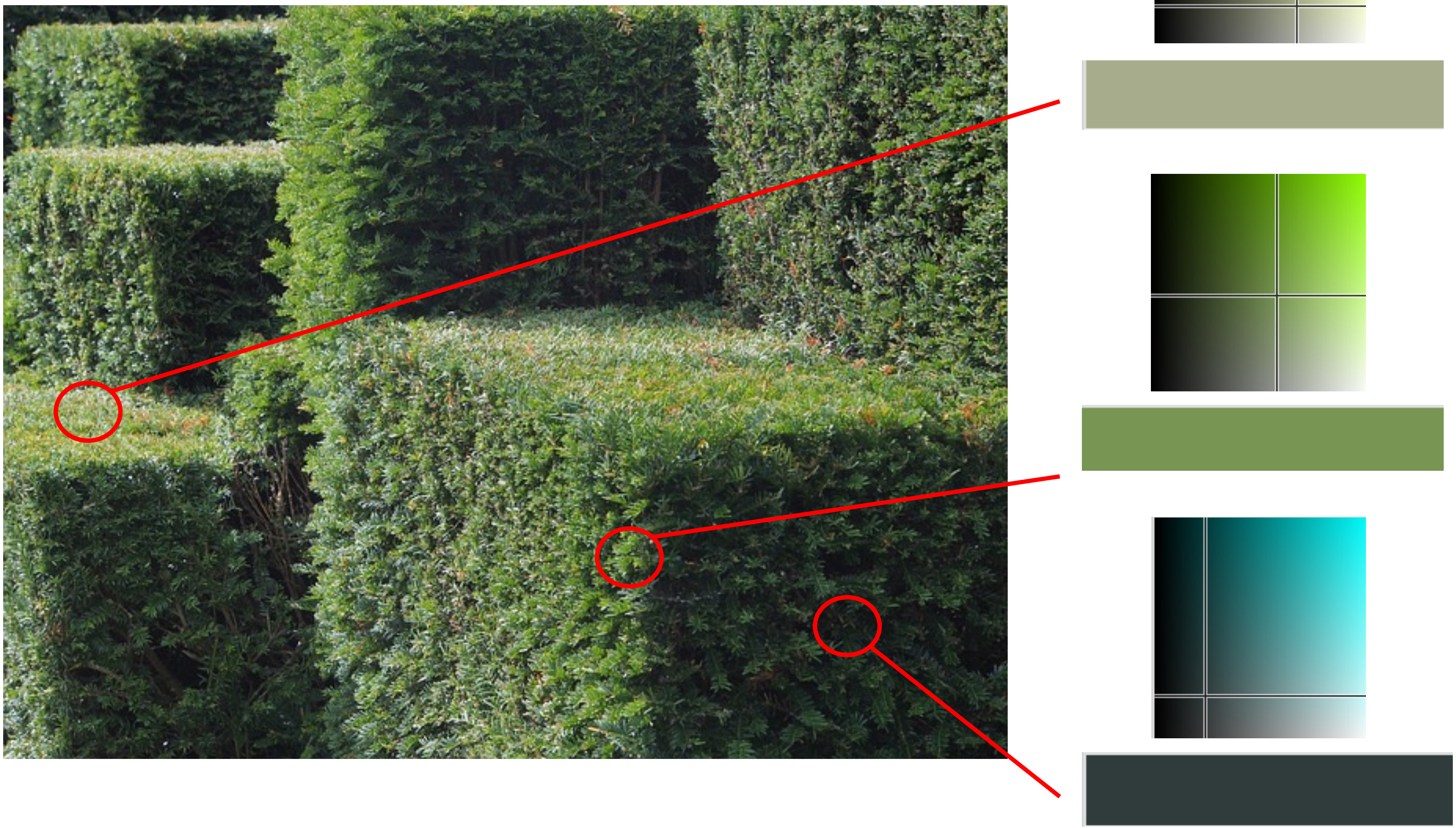
Issues with detecting objects based on colour

Issues with detecting objects based on colour

Issues with detecting objects based on colour

Issues with detecting objects based on colour





Illuminant Estimation and Correction

- Being able to detect or segment objects based on colour relies on being able to separate out the effects of illumination spectra vs. reflectance spectra
- If the illumination spectra is known in the RGB channels of the image, then an illumination-corrected (or sometimes white balanced) image can be produced by dividing by the white colour ($[E_R, E_G, E_B]$) and re-scaling the image:

$$I_R^* \propto \frac{I_R}{E_R} \qquad I_G^* \propto \frac{I_G}{E_G} \qquad I_B^* \propto \frac{I_B}{E_B}$$

- Since the illumination spectra is typically unknown, there are several methods used to approximate it based on the statistics of the image values themselves

Illuminant Estimation and Correction

- Grayworld: ($[E_R, E_G, E_B]$) is estimated by taking the mean of each channel: work on the assumption that the average colour of the scene is gray

$$E_k = \frac{1}{N}\sum_j I_{k,j}$$

- maxRGB: ($[E_R, E_G, E_B]$) is estimated by taking the maximum value of each channel: work on the assumption that something in the scene is white

$$E_k = max(I_{k,j})$$

- Grayworld and maxRGB are in-fact the p = 1 and p = ∞ Minowski norms of the vector of all image pixels: any general p-norm can be calculated as:

$$E_k = [\frac{1}{N}\sum_j I_{k,j}^p]^{\frac{1}{p}}$$

- It turns out that p = 4 or p = 5 works remarkably well across a wide variety of illuminated scenes*

*A. Gijsenij et al, "Computational Color Constancy: Survey and Experiments" IEEE Trans. on Image Processing, 20(9), 2475-2489, 2011.

Illuminant Estimation and Correction

original grayworld maxRGB Minowski (p=4)

Illuminant Estimation and Correction

original

grayworld

maxRGB

Minowski (p=4)

Further Reading and Next Week

- References:
  - D. A. Forsyth and J. Ponce, “Computer Vision - A Modern Approach”, Prentice Hall, 2002 (Section 2.5)

- Next Week:
  - Image filtering, edge detection, object detection and features