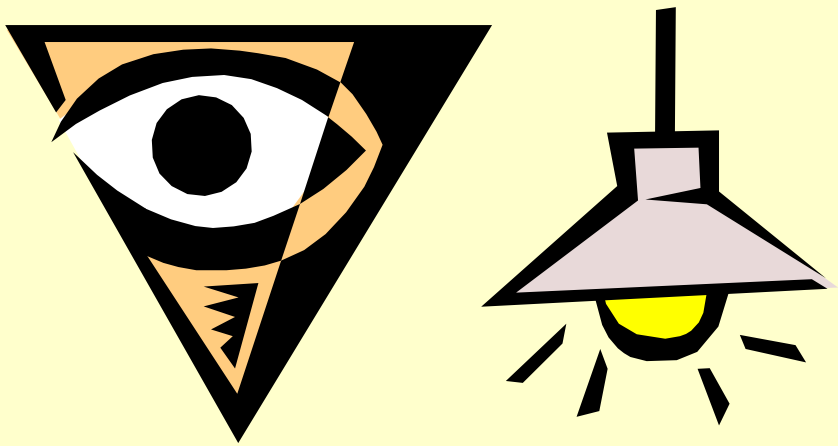
MECH3422 Building Services Engineering I

http://me.hku.hk/bse/MECH3422/



Lighting Systems – Basic Concepts

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Contents

- Purpose of Lighting
- Terminology
- Lighting Systems
- Human Eye
- Vision
- Colour

Nowadays, An Exciting Time for Lighting…

☼ Energy efficient lighting, LED, daylight harvesting, digital controls, wireless controls, smart luminaires, integrated lighting…

Purpose of Lighting

- Who are involved in Lighting Design?*
  - Architects
  - Engineers
    - ***Building Services Engineers***
    - Electrical Engineers
    - Lighting Engineers
  - Interior Designers
  - Lighting Designers (specialist)

(* See also http://en.wikipedia.org/wiki/Architectural_lighting_design)

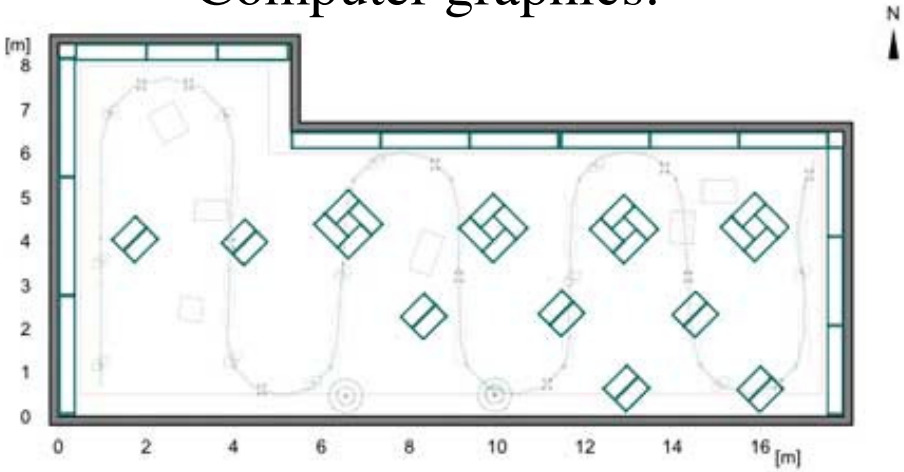
Purpose of Lighting

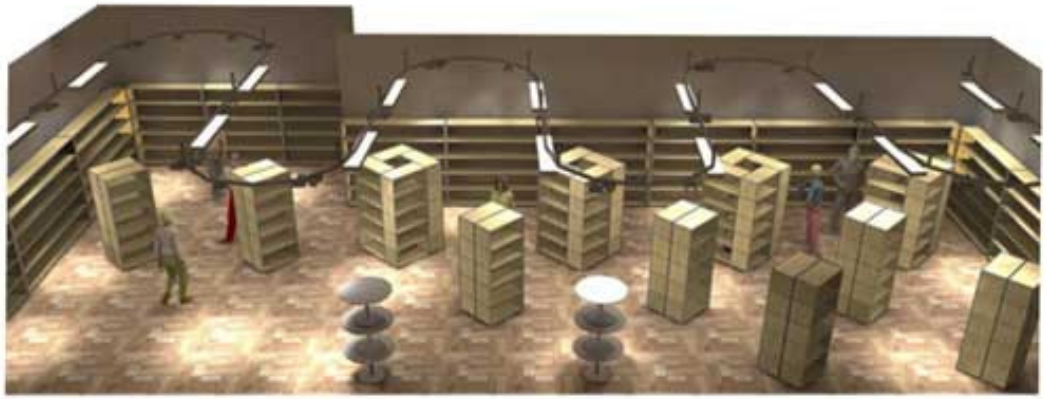
- Two main concerns of lighting design:
  - Provide *illumination* for people to use a space and to see well enough to FUNCTION at their designated tasks
  - Create *perception* of the space(s) or form(s) so that the designer's CONCEPT is communicated and/or felt
- Effect of lighting
  - On architecture (defines space & shows form)
  - On interior design (reveals texture & colour)

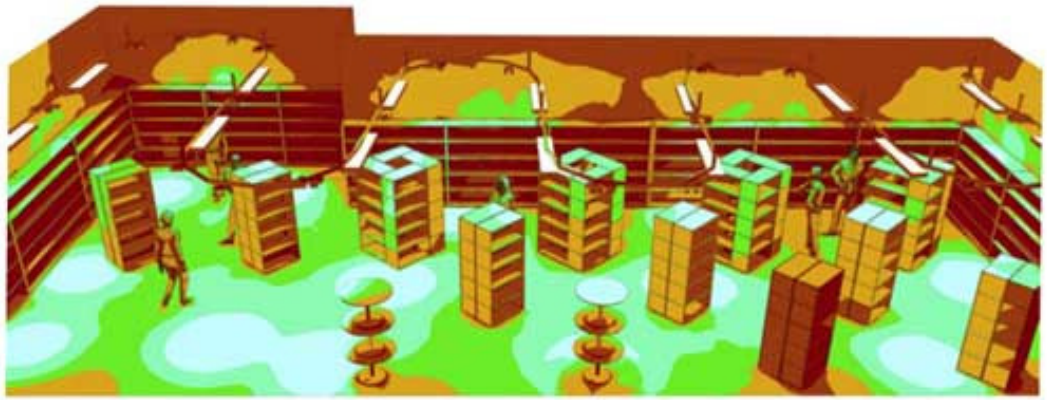
Real pictures:

Student union rotunda with view of campus courtyard.

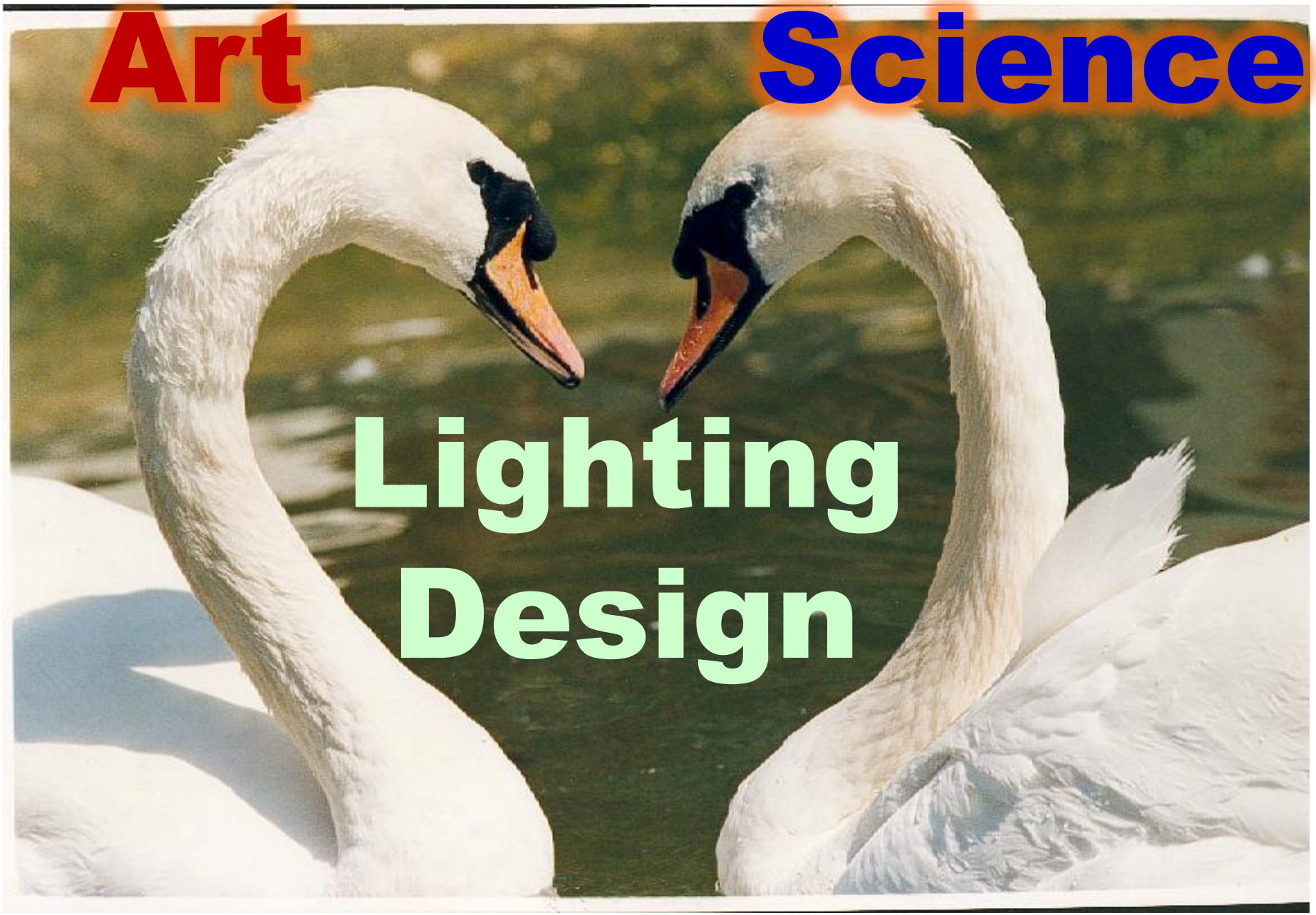
Computer graphics:





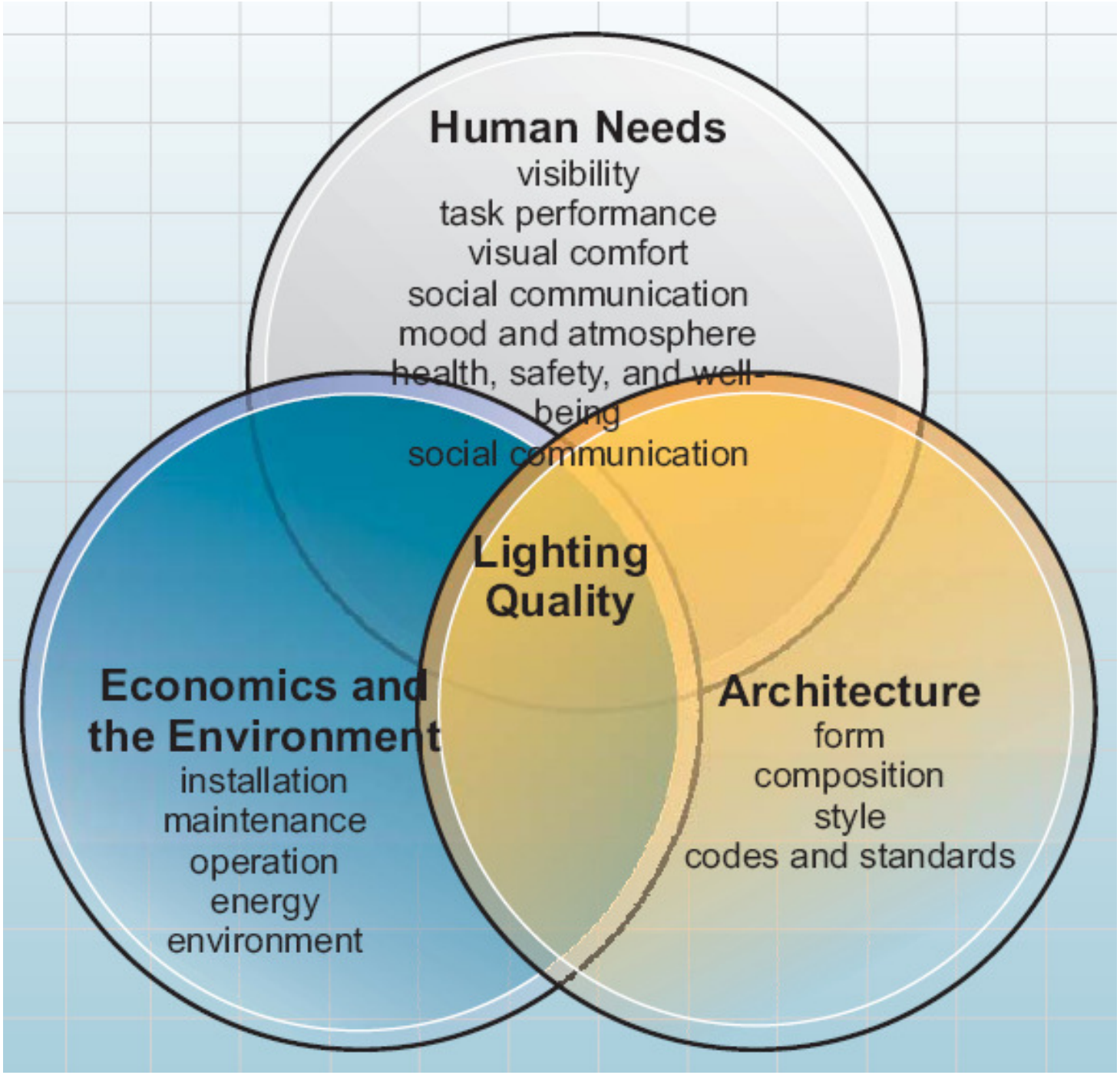


Examples of lighting design


Art
Science
Lighting
Design

Purpose of Lighting

- As a **SCIENCE**
  - The amounts of illumination needed and certain aspects of the quality of light are quantified
- As an **ART**
  - Attaching numbers is meaningless because light is an experience of the SENSES
    - Lighting can motivate people to be active, relaxed, productive, lively or depressed
    - Create an atmosphere pleasing to the occupants
    - Provide visibility, character, and mood as well as relate harmoniously to the space in which it is used



Overlapping lighting issues

(Source: IESNA Lighting Handbook, 9th ed.)

Purpose of Lighting

- Three main functions of lighting:
  - Ensure the safety of people
  - Facilitate the performance of visual tasks
  - Aid the creation of an appropriate visual environment

Purpose of Lighting

- Two sources of light:
  - Natural sources of light (daylight)
    - People prefer daylight to “windowless” rooms
    - Windows provide a view & connection to outdoor
  - Artificial or man-made (electric light)
- Electric lighting and the daylighting should be complementary to ensure
  - Efficient use of energy
  - High quality lighting

Terminology

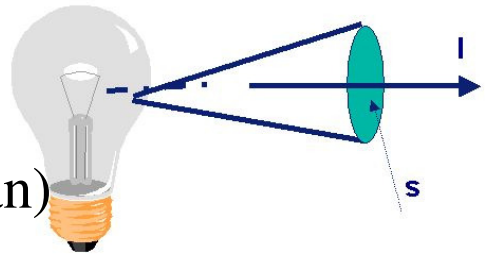
- Lighting terminology
  - Luminous flux 光通量 (lumen, lm), Φ

Radiation value

  - Light power emitted by a source or received by a surface (radiant flux according to the spectral sensitivity of the human eye)
  - A candle flame generates about 12 lumens
  - Fluorescent lamp 32W = 3,300 lumens
  - Luminous intensity 光強 (candela, cd), *I*

Sender-side value

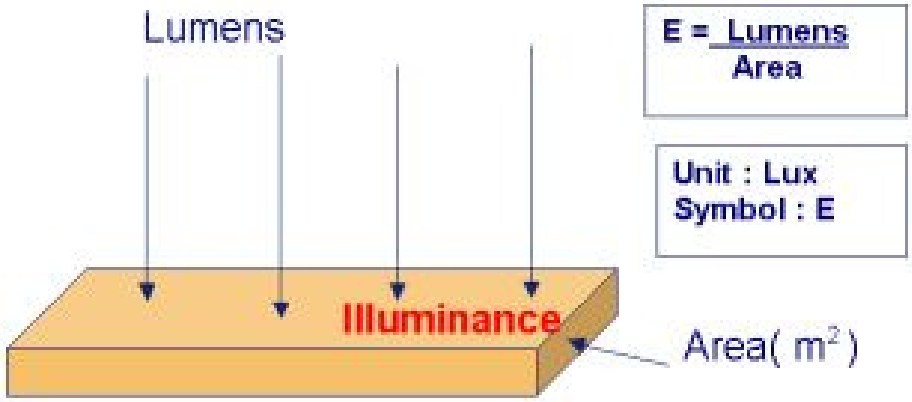
  - Luminous flux per unit solid angle in the direction in question, $I = d\Phi / d\omega$ (ω = solid angle, in steradian)



  - Illuminance 照明度 (lm/m^2, or lux), *E*

Recipient-side value

  - Light energy arriving at a real surface, $E = d\Phi / dA$ (*A* = receiving surface area) (“lumen per unit area”)



Summer, at noon, under a cloudiness sky	100 000 lux
Ditto, but in the shade	10 000 lux
In the open under a heavily-overcast sky	5000 lux
Artificial light, in a well-lit office	1000 lux
Artificial light, average living-room	100lux
Street lighting	5-30 lux
Full moon, on a clear night	0,25 lux

Practical examples of illuminance

(Source: Philips Lighting, http://www.lighting.philips.co.in)

Terminology

- Lighting terminology*
  - Luminance 亮度 (cd/m^2), L

Sender-side value

- Luminous flux density (I) leaving a projected surface in a particular direction (often called "brightness")
- $L = I / dA.\cos\theta = (d\Phi/d\omega) / dA.\cos\theta$
  - $d\omega$ = solid angle containing the given direction
  - dA = area of a section of that beam (the source side) containing the given point
  - θ = the angle between the normal to that section and the direction of the beam

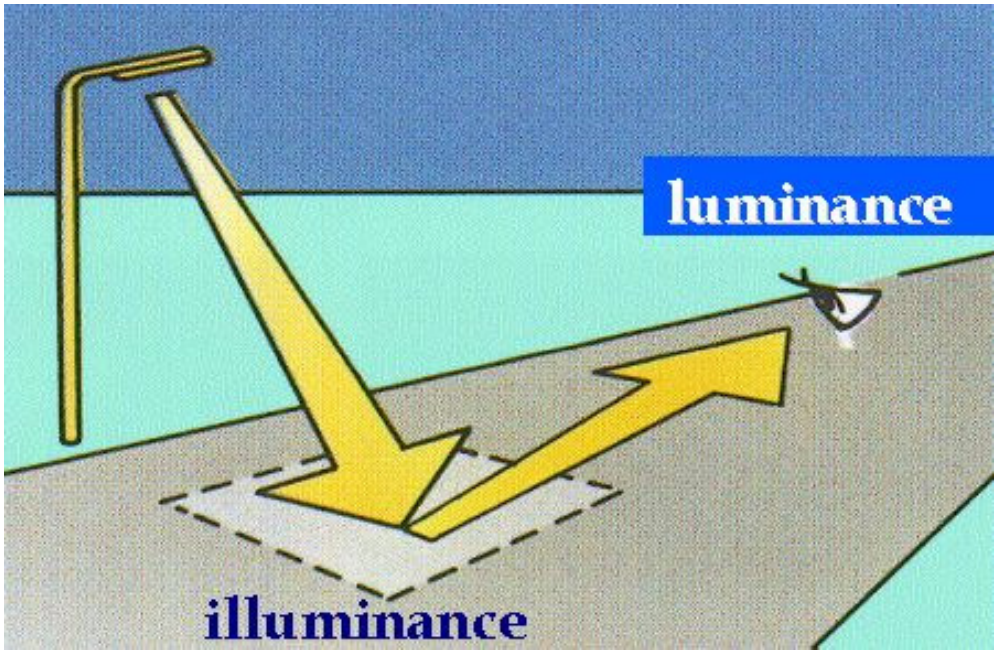
(* See also http://hyperphysics.phy-astr.gsu.edu/hbase/vision/photomcon.html)

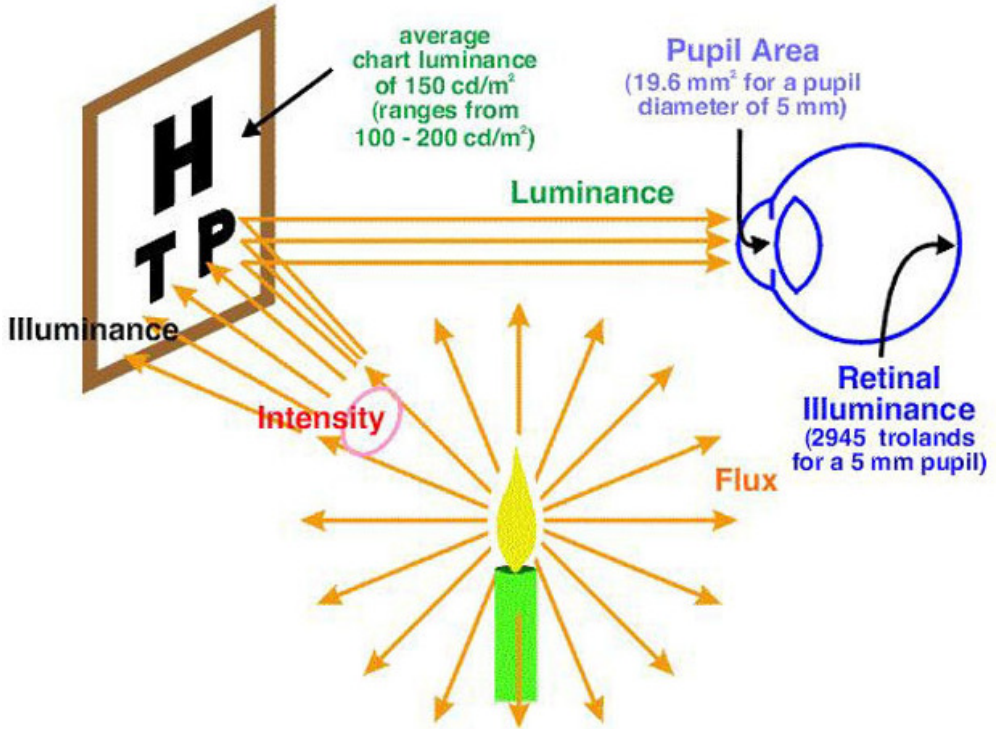
Surface of the sun	1 650 000 000 cd/m^2
Filament of a clear incandescent lamp	7 000 000 cd/m^2
Bulb of an 'Argenta' incandescent lamp	200 000 cd/m^2
Fluorescent lamp	5000 -15 000 cd/m^2
Surface of the full moon	2500 cd/m^2
Sun-lit beach	15 000 cd/m^2
White paper (reflectance 0,8) under 400 lux	100 cd/m^2
Grey paper (reflectance 0,4) under 400 lux	50 cd/m^2
Black paper (reflectance 0,04) under 400 lux	5 cd/m^2
Road surface under artificial lighting	0,5 - 2 cd/m^2

Practical examples of luminance

(Source: Philips Lighting, http://www.lighting.philips.co.in)

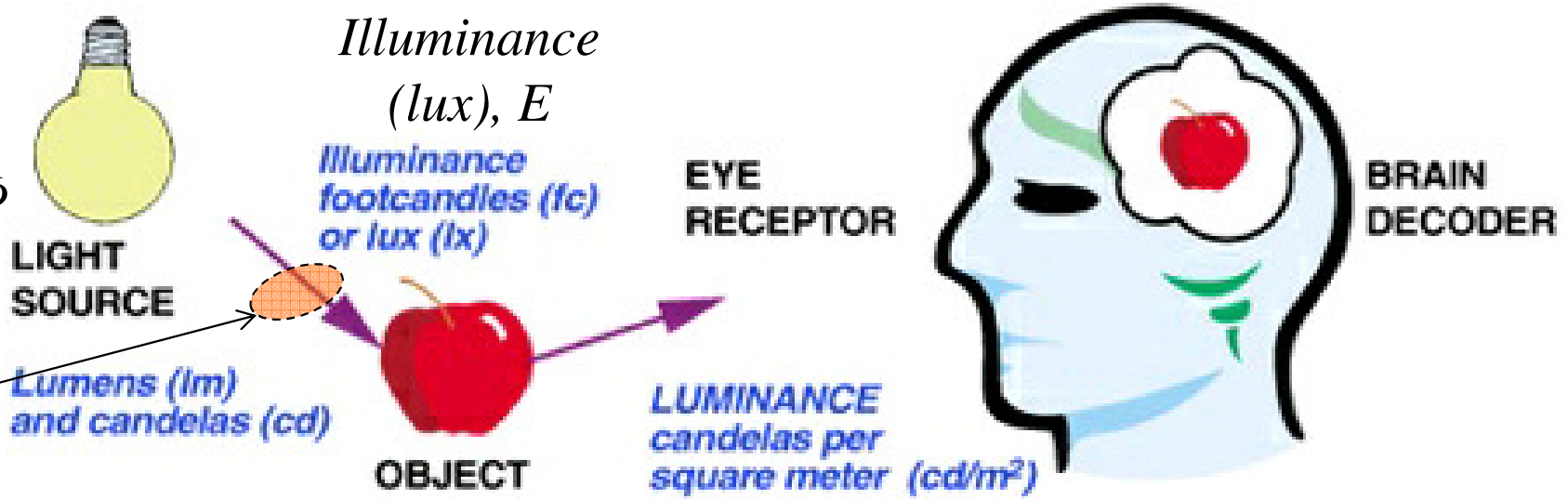
Illuminance and luminance (Source: Lessons in Lighting, http://www.lightolier.com)





Luminous flux (lm), Φ

Luminous intensity (cd), I



Illuminance (lux), E

Luminance (cd/m^2), L

Terminology

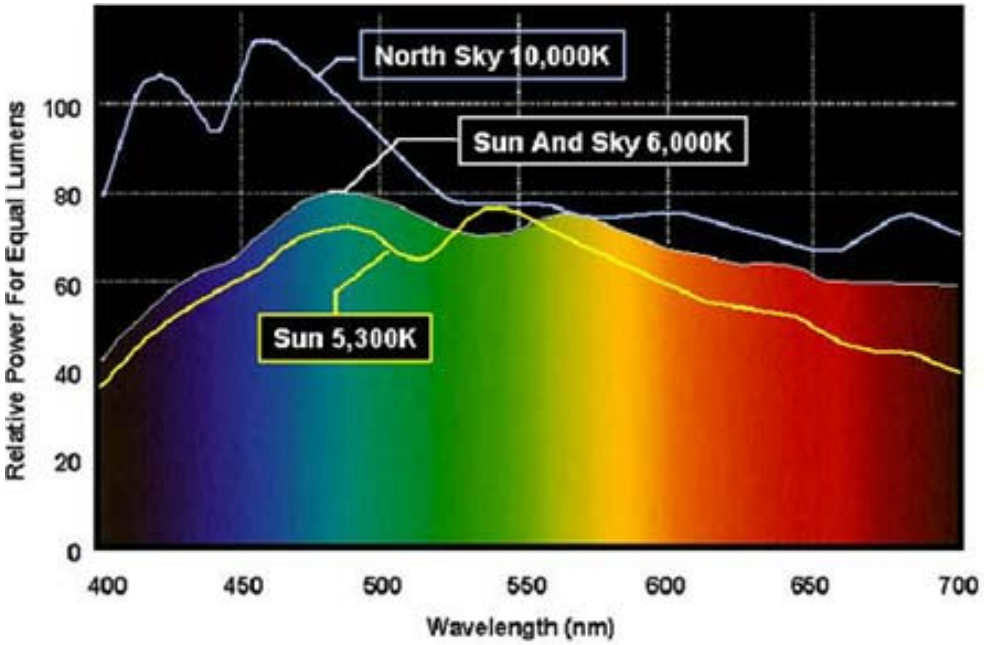
- Lighting terminology
  - Luminous efficacy of a source (lm/W), η
    - Ratio between the luminous flux emitted and the power consumed by the source *
  - Spectral power distribution (SPD) curves**
    - Curves to show the visual profile and colour characteristics of a light source
    - Plot of relative power emitted in the different regions of the spectrum

(* See also http://en.wikipedia.org/wiki/Luminous_efficacy)

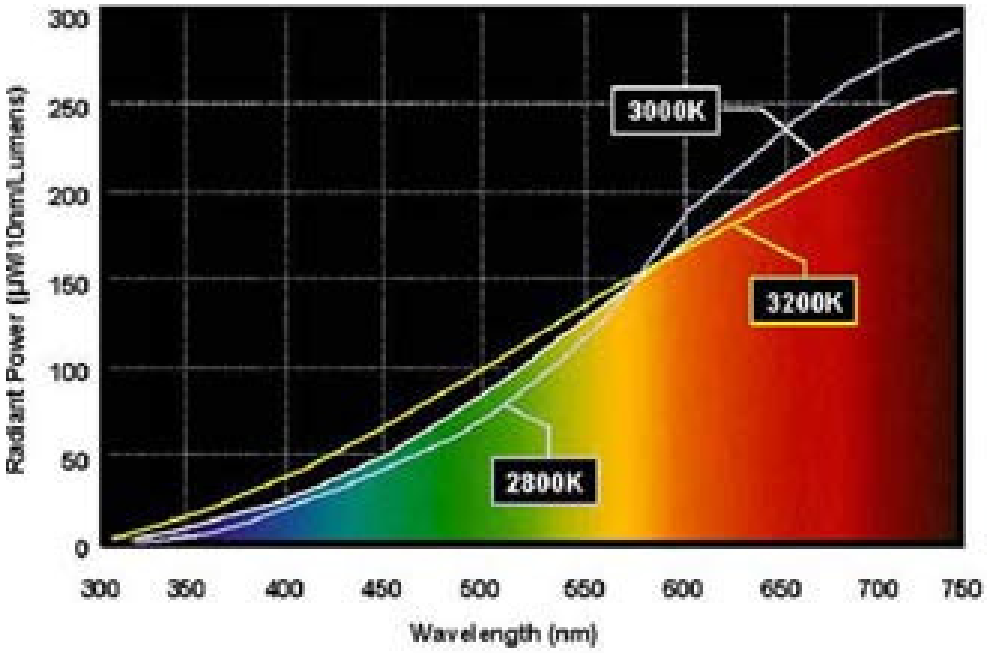
(**See http://www.gelighting.com/na/business_lighting/spectral_power_distribution_curves/)

Spectral power distribution (SPD) (Source: GE Lighting, http://www.gelighting.com)

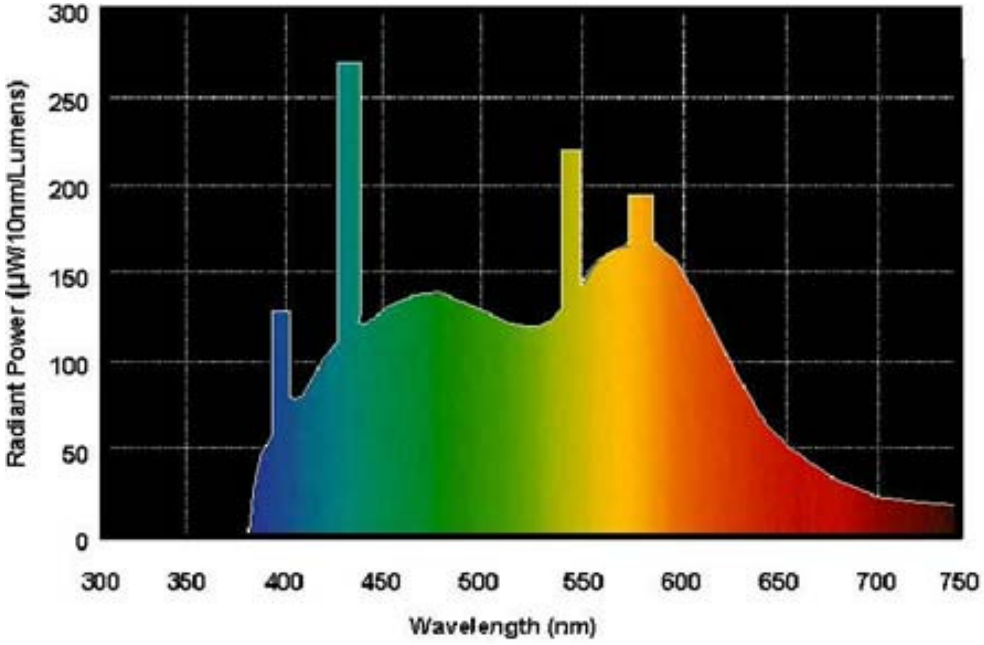
Outdoor daylight



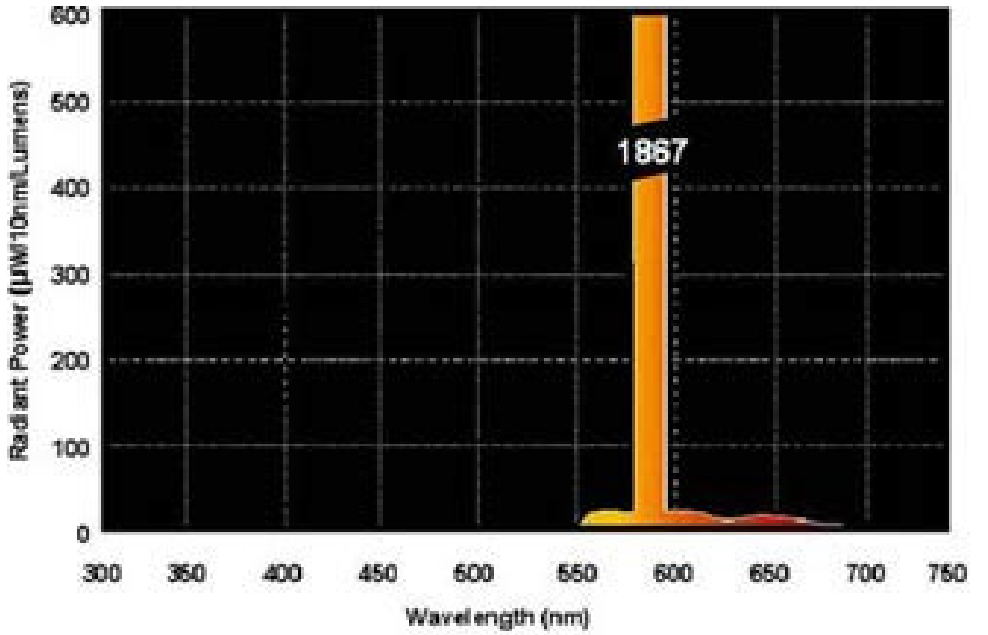
Incandescent



Fluorescent lamp (Daylight)

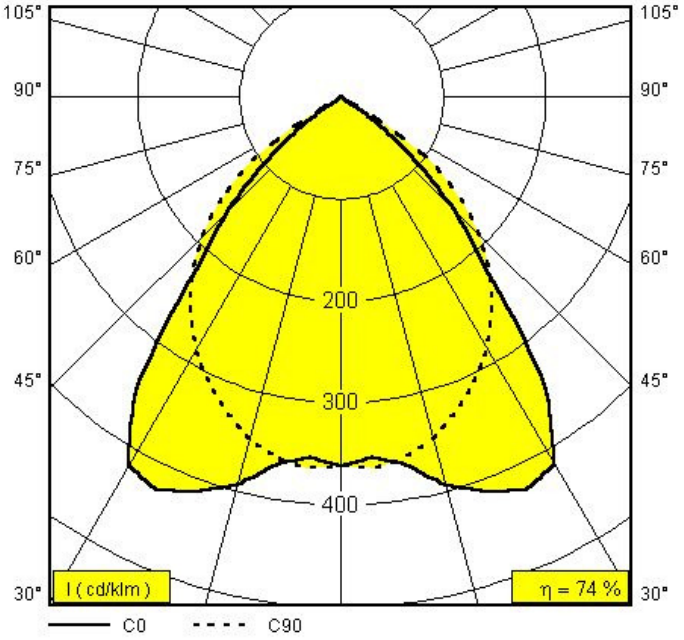


Low pressure sodium (LPS)



Terminology

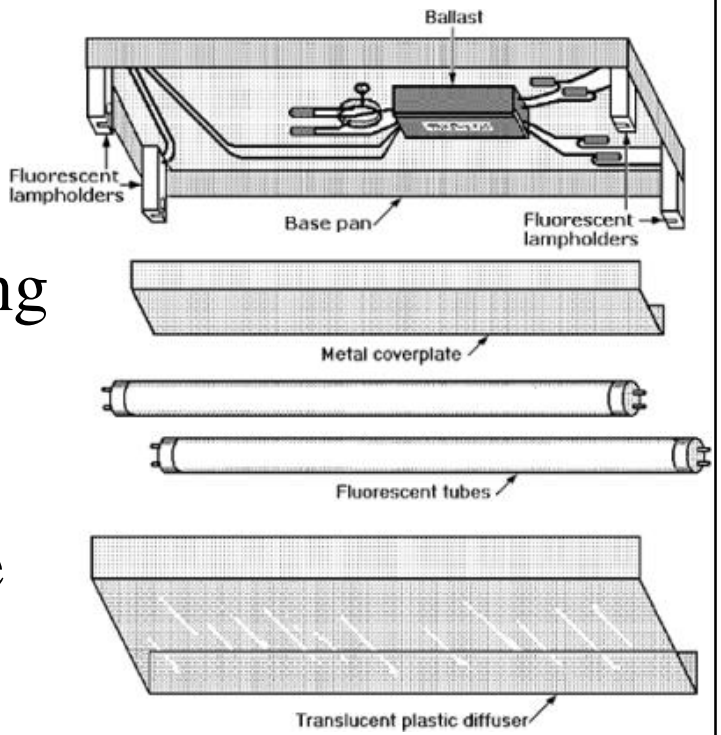
- Lighting terminology
  - Photometric data
    - Indicate how a particular lamp or luminaire “sends out” light – light distribution in terms of intensity and direction
  - Glare
    - Visual discomfort/disability caused by excessive brightness or extreme contrast *
    - Glare index or limiting glare rating



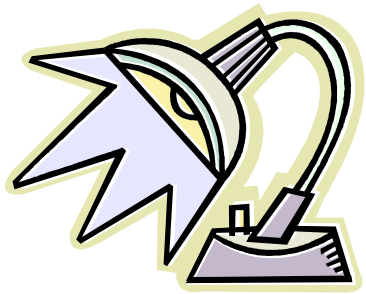
(* See also http://en.wikipedia.org/wiki/Glare_(vision))

Lighting Systems

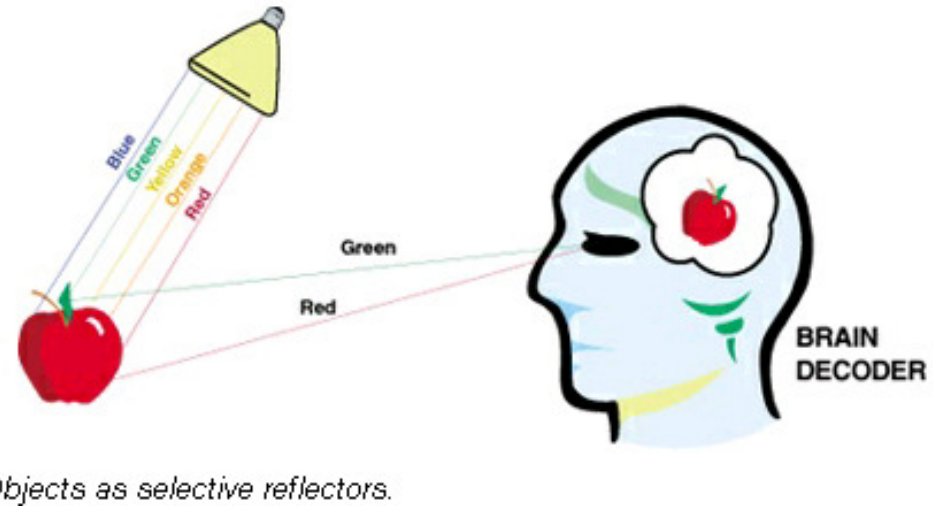
- Anatomy of a “lighting system”
  - Lighting components
    - Power source
    - Power controller: switching/dimming
    - Power regulators: ballasts
    - Light source: lamp
    - Optical control: luminaire or fixture
  - Environmental components
    - Room finishes: reflectances and texture
    - Spatial envelope: room boundaries
    - Fenestrations: windows and skylights



Lighting Systems

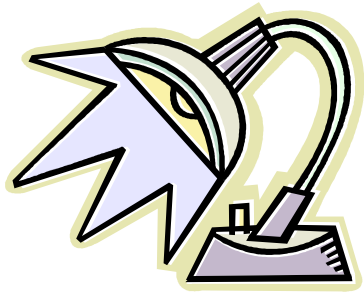


- Anatomy of a "lighting system" (cont'd)
  - Human components
    - Visual receiver: Eye
    - Visual acuity: Vision
    - Visual decoder: Brain
  - Task components
    - Task finishes: texture, colour, reflectance, specularity
    - Task size: object size
    - Task brightness: luminance
    - Contrast: brightness ratios
    - Speed and accuracy: time

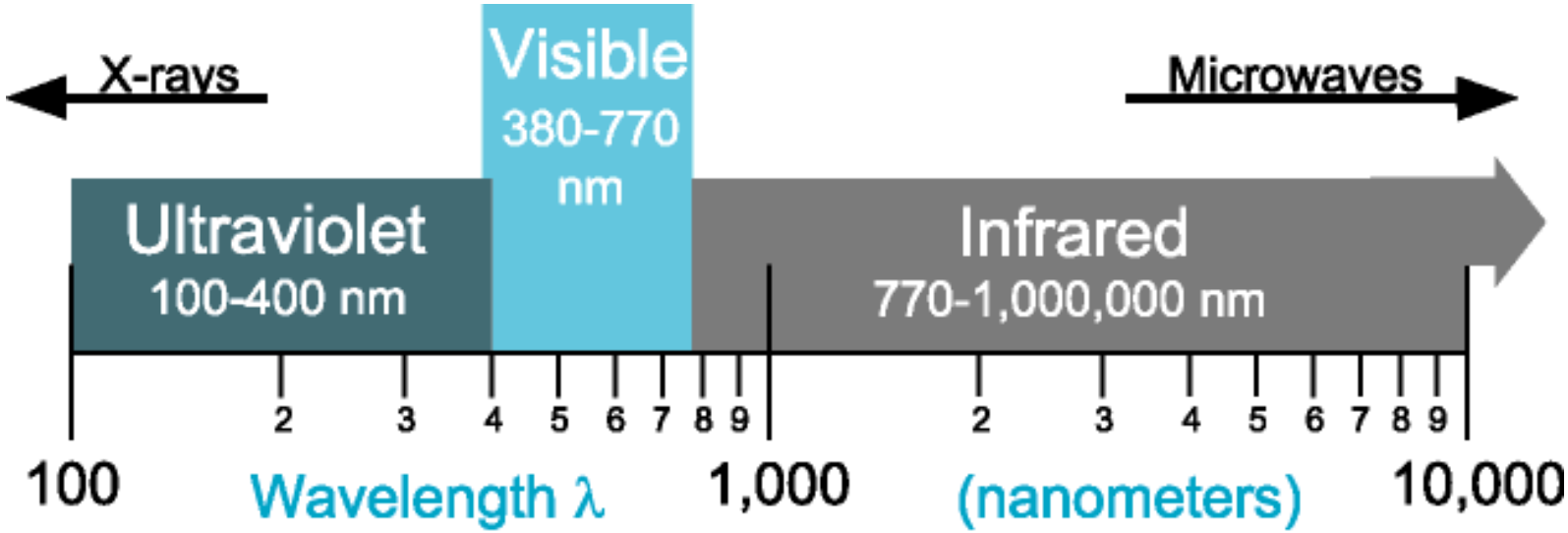


Objects as selective reflectors.

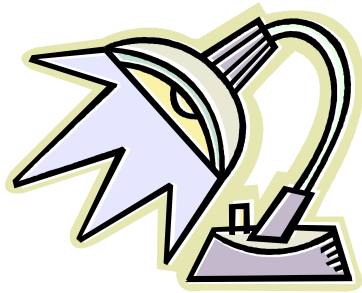
Lighting Systems



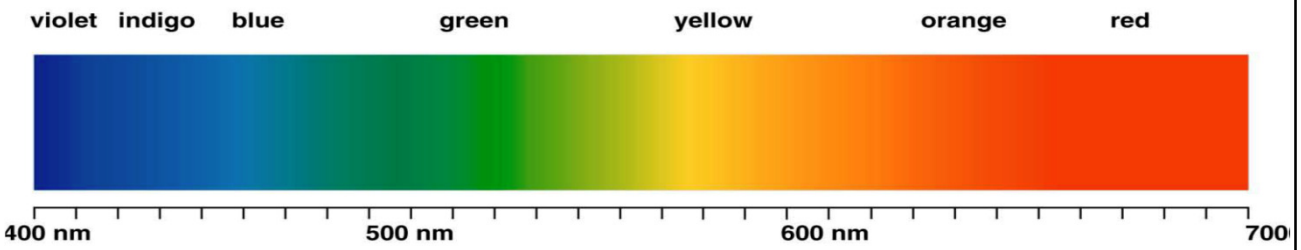
- What is *Light*?
  - Light is a form of electromagnetic radiation and is a major medium through which we discover the world around us



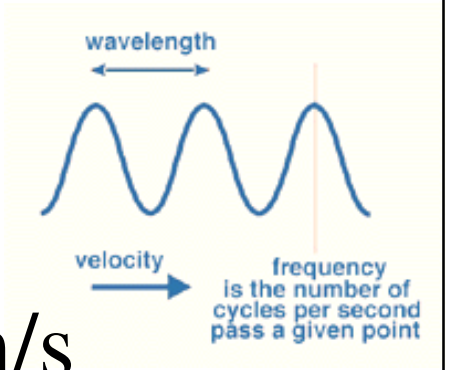
Lighting Systems



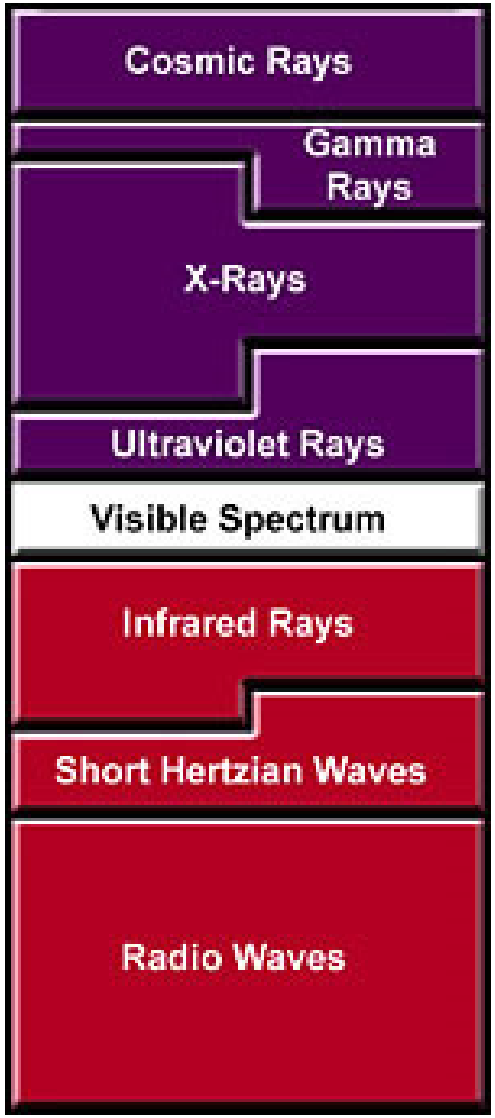
- Electromagnetic spectrum
  - Visible light (380 to 760 nm)
    - Mr. ROY G. BIV (Red, Orange, Yellow, Green, Blue, Indigo, Violet)

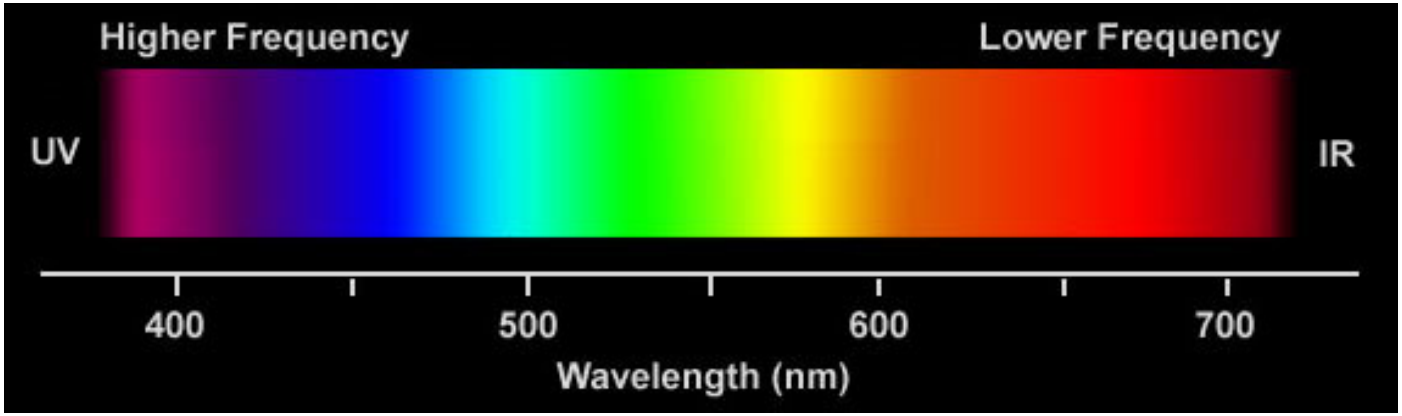


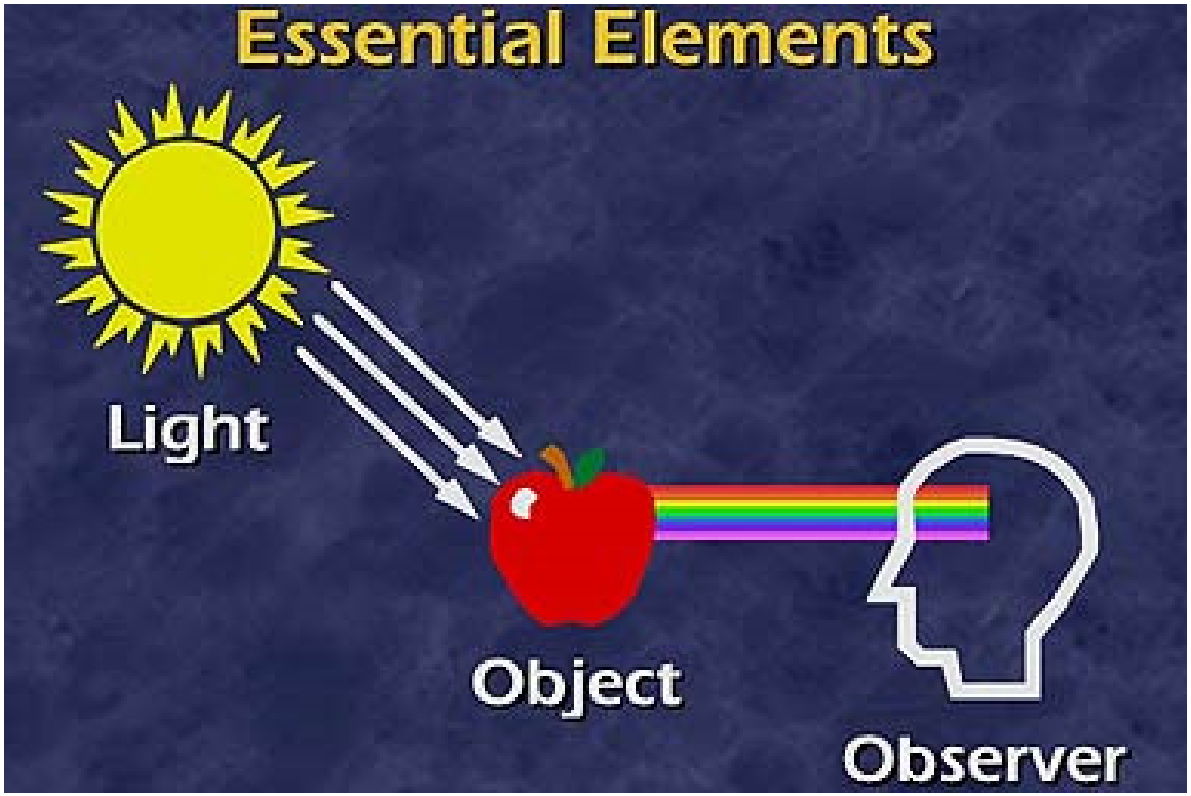
  - Ultraviolet (100 to 380 nm)
  - Infrared (760 to 1,000,000 nm)



- Speed of light (in air) = 299 702 547 m/s
  - = (wavelength, metres) x (frequency, Hertz)

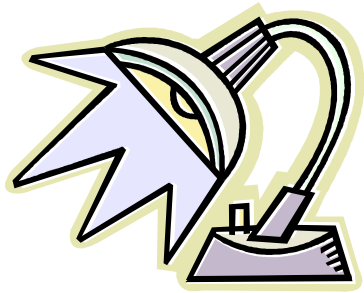






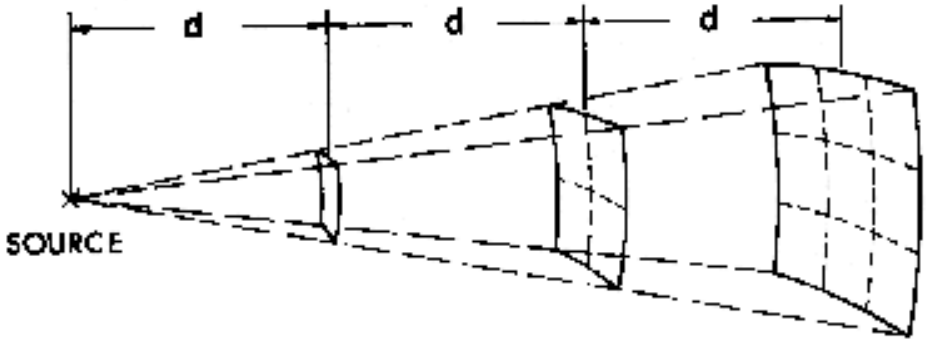
[Color Science, Texas A&M University, http://www.isc.tamu.edu/%7Eastro/color.html]

Lighting Systems

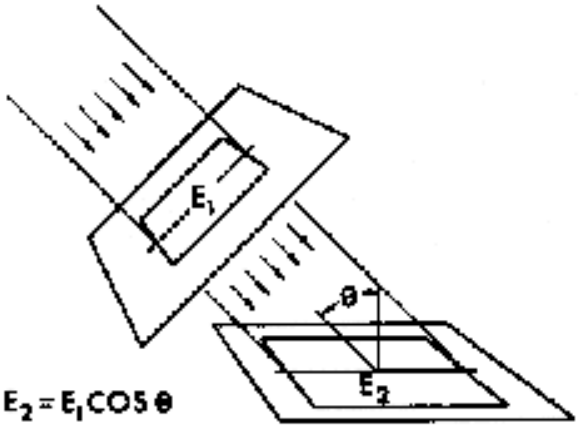


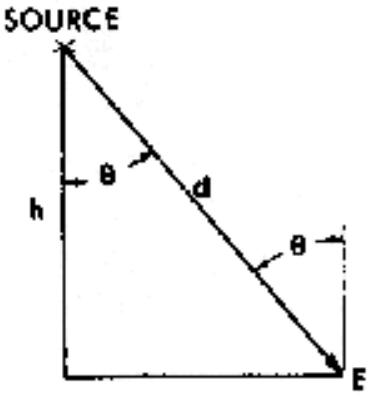
- The behaviour of light
  - Inverse square law $E = I / d^2$
  - Cosine law - the irradiance falling on any surface varies with the cosine of the incident angle
    - $E_\theta = E \cos \theta = (I / d^2) \cos \theta$
  - Optical properties
    - Reflection (specular, diffuse, spread, mixed, scattered)
    - Transmission and absorption
    - Refraction
    - Diffraction
    - Scattering and polarization

Inverse square law



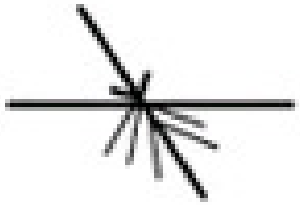
Cosine law



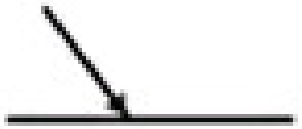


TYPES OF LIGHT MODIFICATION

TRANSMISSION
(Diffuser)
Opal Glass
or Plastic

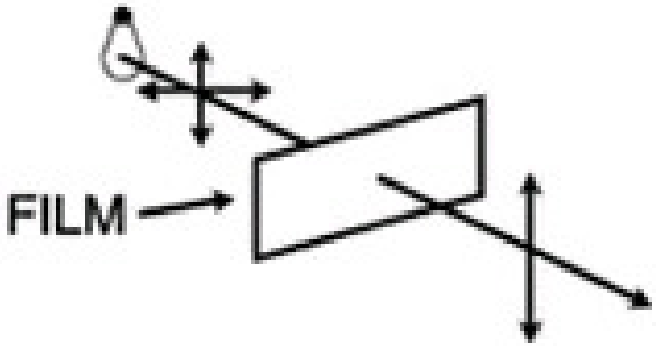


ABSORPTION
Matte Black
Paint

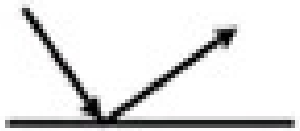


REFRACTION
Clear Glass

POLARIZATION



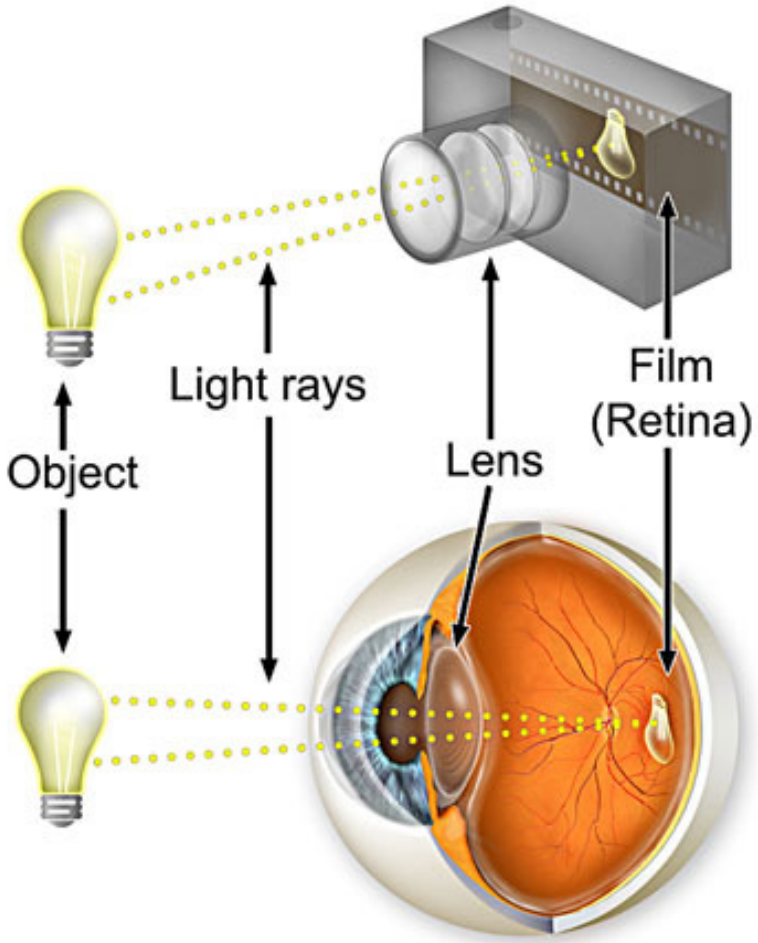
REFLECTION
Polished
Metal



Human Eye

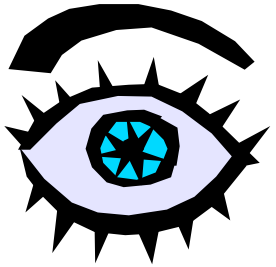
- The camera and the eye

- Structure of human eye
  - 1. Optical elements
  - 2. The retina
  - 3. Photoreceptors



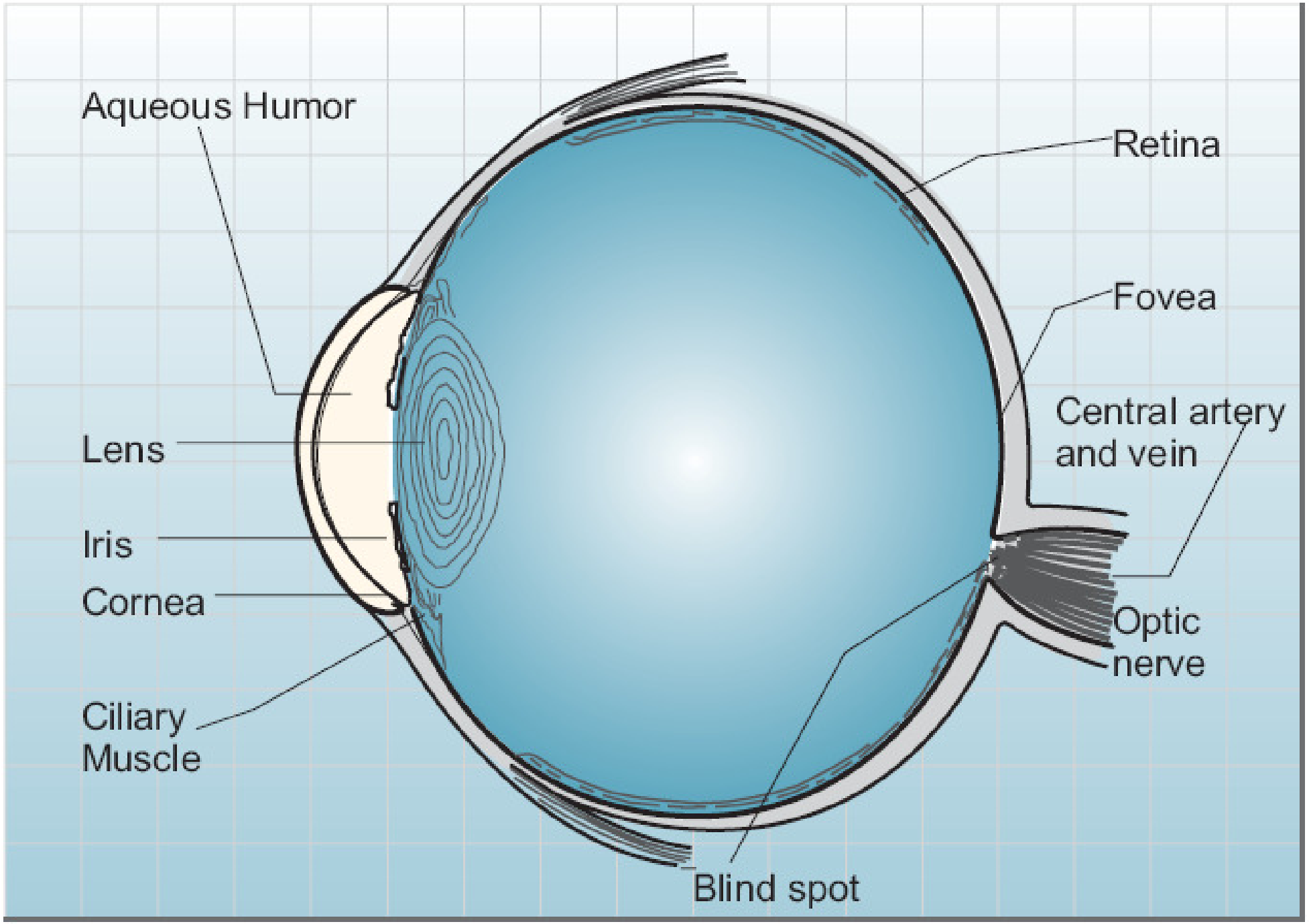
(Video: A Journey Through the Human Eye: How We See (YouTube 2:39), http://www.youtube.com/watch?v=gvozcv8pS3c)

Human Eye



- 1. Optical elements
  - Cornea 角膜 – first “lens”, 70% of optical power
  - Sclera 鞏膜 – whites of the eye
  - Aqueous humour – liquid between cornea & iris
  - Iris 虹膜 – coloured muscular ring around pupil
  - Pupil 瞳孔 – hole into which light enters eye
  - Crystalline lens – 2nd lens, 30% of optical power
  - Vitreous humour – fluid filling the eye

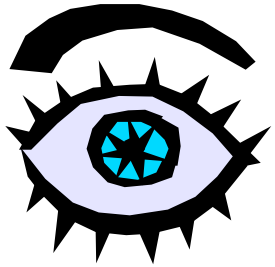
(* See also http://hyperphysics.phy-astr.gsu.edu/hbase/vision/eye.html and http://en.wikipedia.org/wiki/Human_eye)



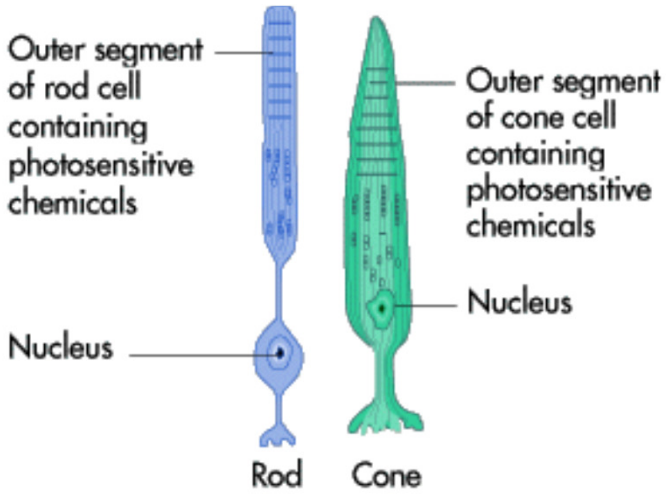
The Human Eye

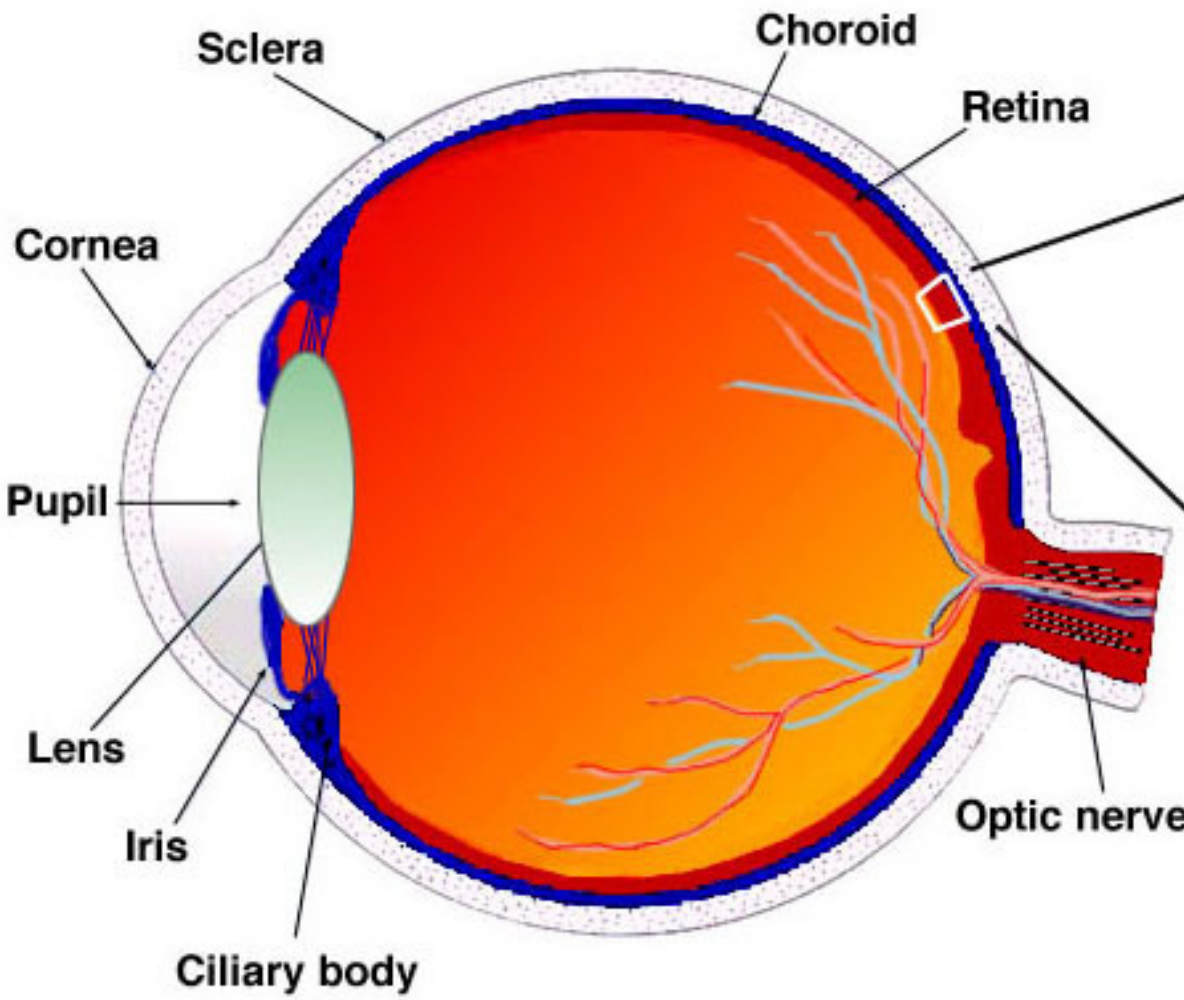
(Source: Advanced Lighting Guidelines 2001, adapted from IESNA Lighting Handbook, 9th ed.)

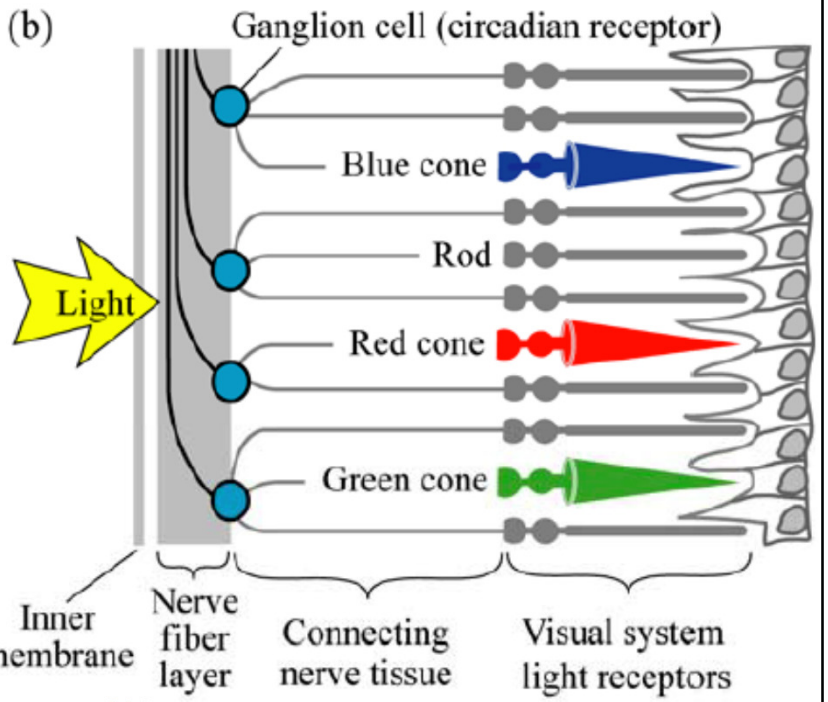
Human Eye



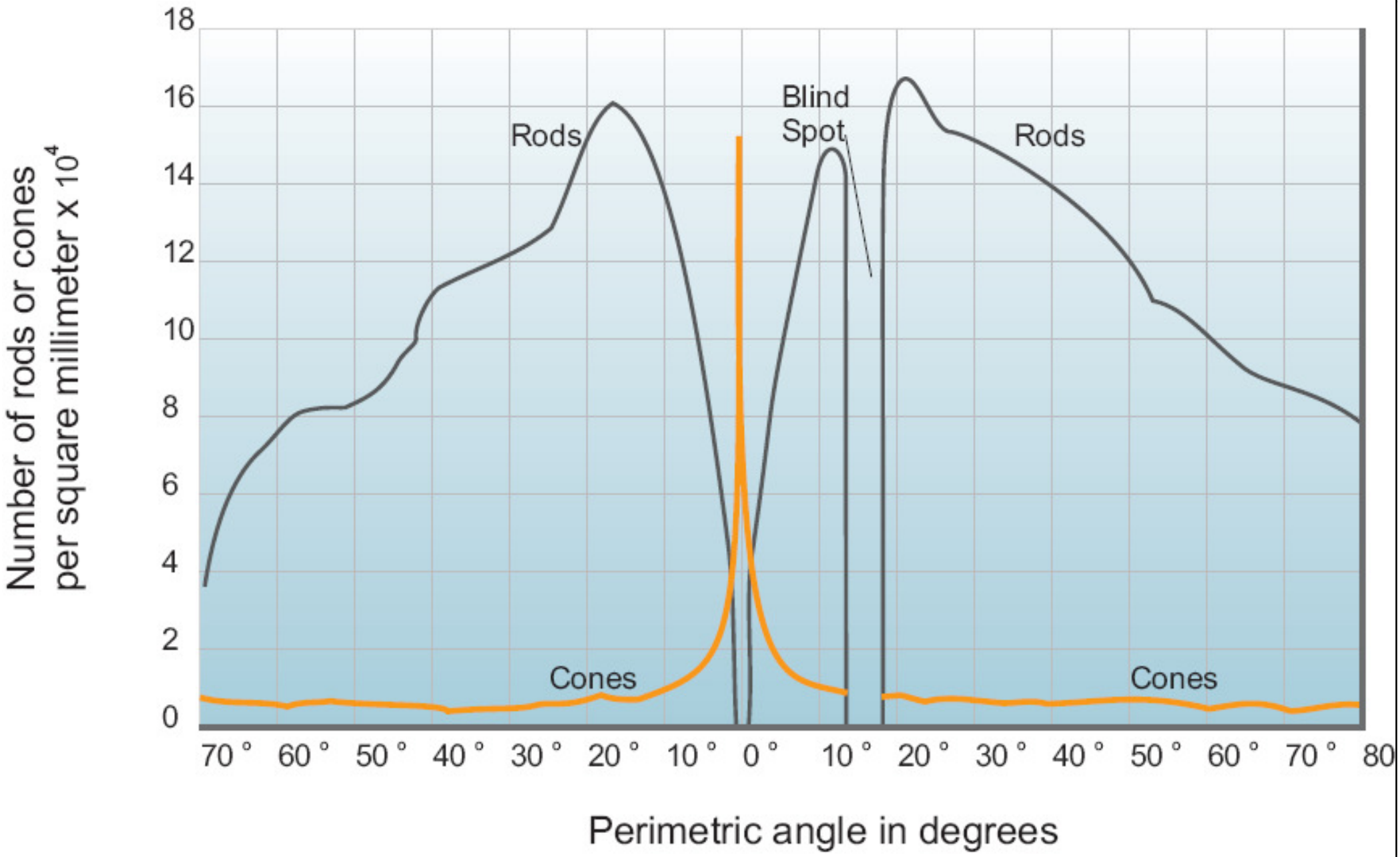
- 2. The retina 視網膜
  - Photoreceptors
  - Fovea – highly concentrated 2 degree field allowing colour and fine detail vision
  - Optic disk – "blind spot" pathway to end of the optic nerve (deficient in receptors)
- 3. Photoreceptors
  - Rods – 120 millions per eye
  - Cones – 8 millions per eye







(* See also http://en.wikipedia.org/wiki/Photoreceptor_cell)

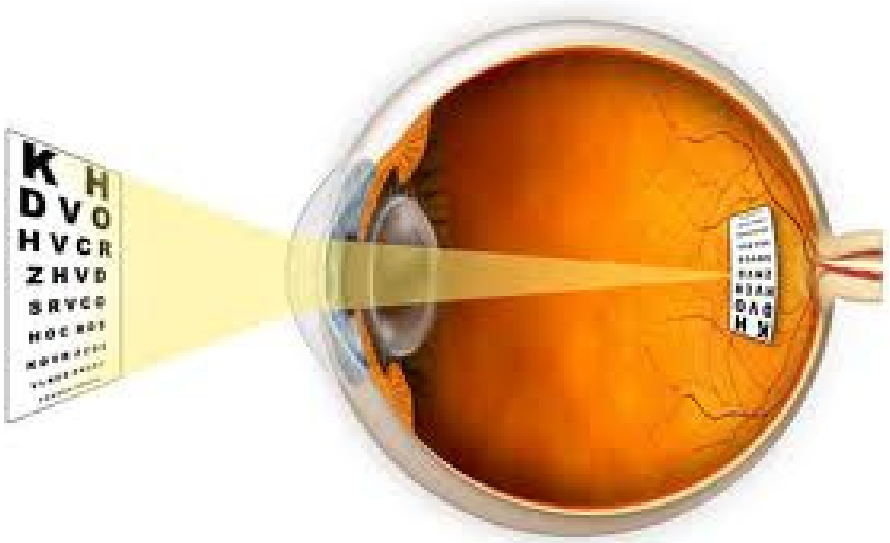


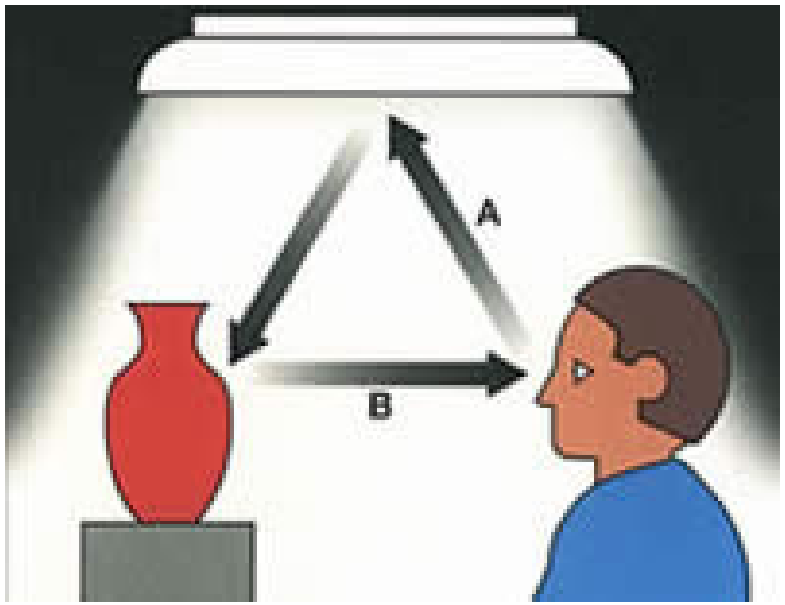
Distribution of rods and cones in the retina

(Source: Advanced Lighting Guidelines 2001, adapted from IESNA Lighting Handbook, 9th ed.)

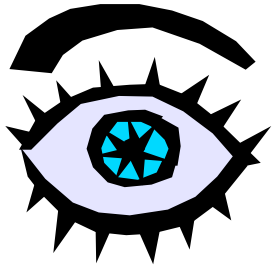
Human Eye

- Functions performed by the eye
  - 1. Adaptation
  - 2. Accommodation
  - 3. Eye movements



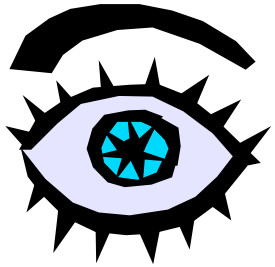


Human Eye

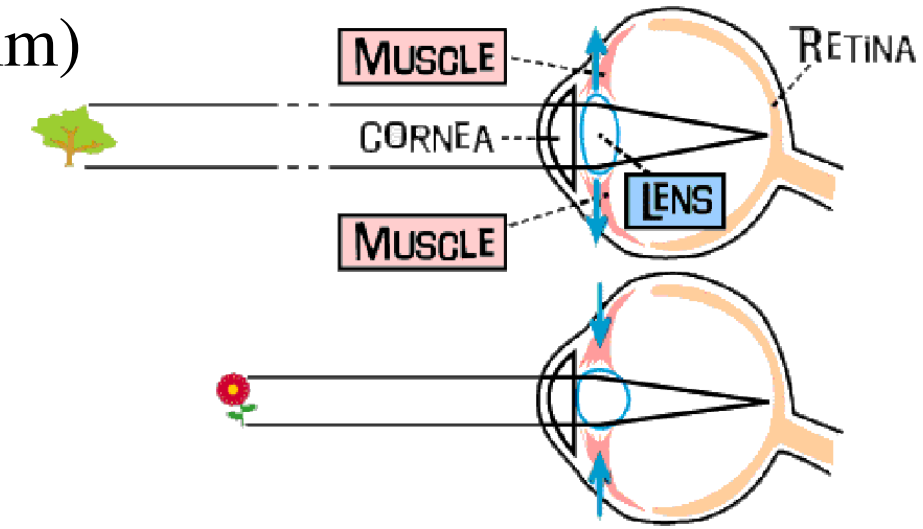


- 1. Adaptation
  - The process through which the eye changes its sensitivity to *respond* to different levels of light stimulation
    - Such as from dim “moonlight” to clear sky “daylight”
    - May take > 60 minutes for complete dark adaptation
  - Pupil size – 64 distinct magnitudes of control
    - Accounts for quantity of light entering eye and depth of field
  - Photochemical adaptation – over 1,000 levels

Human Eye

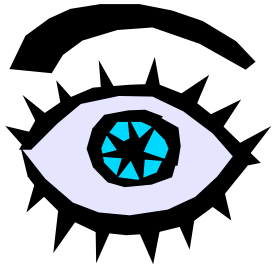


- 2. Accommodation
  - A process to focus images onto the retina by adjusting the curvature of the lens (by tightening the ciliary muscles)
    - *Near point* - closest distance at which objects can be focused (about 100-750 mm)



(* See also http://hyperphysics.phy-astr.gsu.edu/hbase/vision/accom.html)

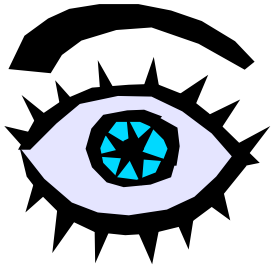
Human Eye



- Common refractive errors in accommodation:
  - Myopia (near-sightedness) 近視– cannot focus on far objects [Image forms in front of the retina]
  - Hyperopia (far-sightedness) 遠視 – cannot focus on near objects [Image forms behind the retina]
  - Astigmatism 散光 – a difference in horizontal vs. vertical focus die to asymmetric cornea shape [Multiple foci are formed]
  - Presbyopia 老花 – cannot focus on near objects due to loss of lens elasticity in the elderly [Near objects focus behind the retina]

(* See also http://hyperphysics.phy-astr.gsu.edu/hbase/vision/eyedef.html)

Human Eye

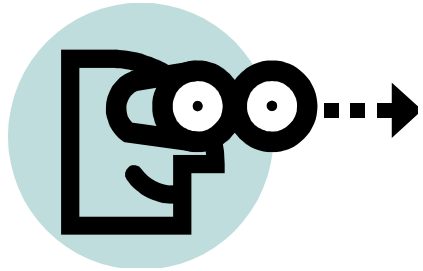


- 3. Eye movements
  - Smooth pursuit movement – binocular
  - Saccadic movement – "jumping" focus when scanning areas
  - Disjunctive eye movements – opposing eye movements for different distances

Vision

- Principle of VISION
  - Light energy → retina (photo-chemical) → optic nerve (electrical signal) → brain (sight centre)
  - Initial information: brightness + colour
  - *Stereoscopic effect* of two eyes (size & position)
  - The brain selects items in the *field of view*
  - The *sense of vision* depends on interpretations from previous experience

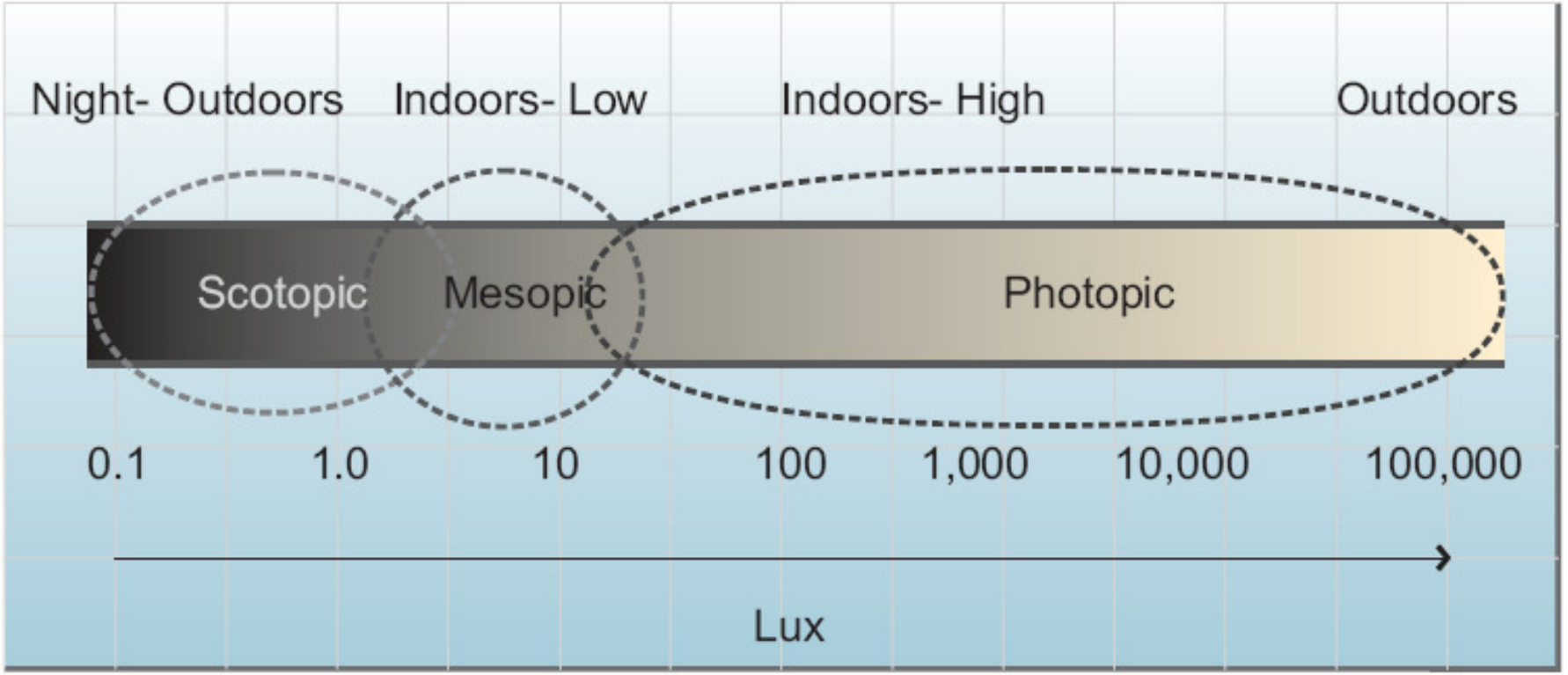
Vision

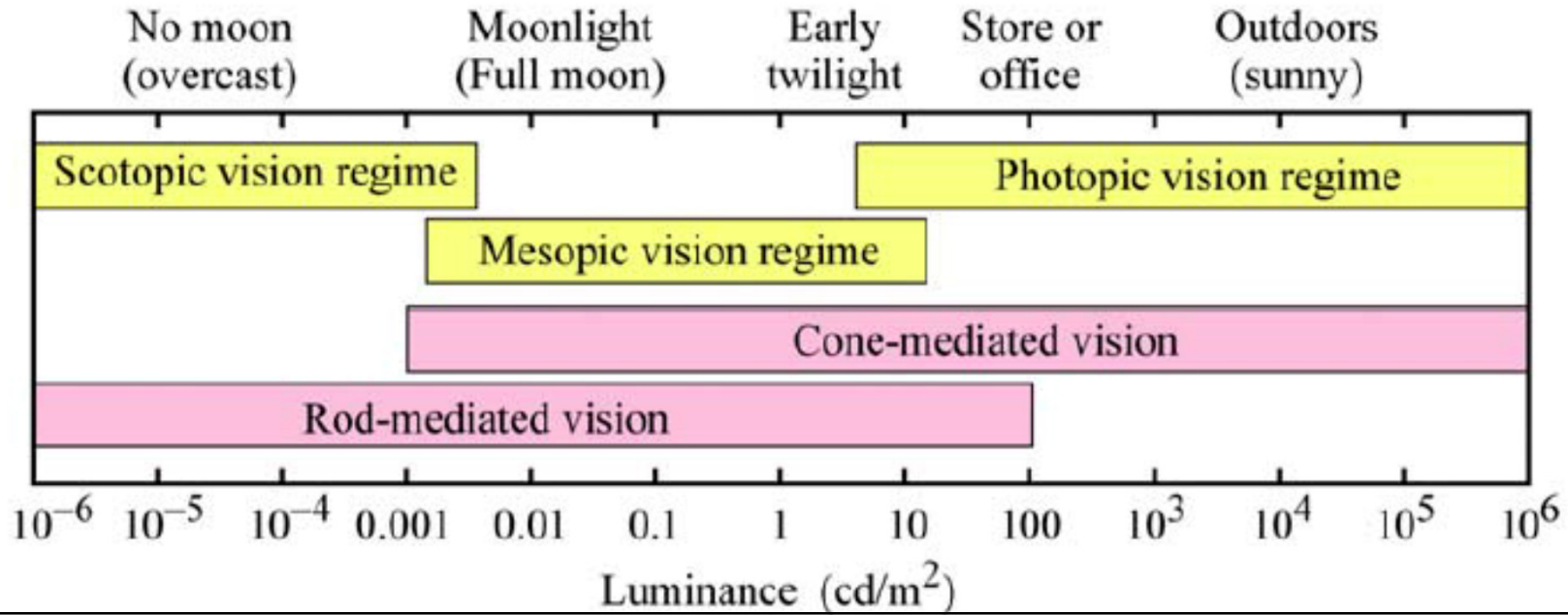


- Characteristics/Regimes of VISION
  - *Scotopic vision* 暗視 - in the dark by the rods
    - Luminance 10^{-6} to 10^{-2} cd/m^2 (dark adapted, by rods)
    - Low ambient light; only see in shades of grey
  - *Mesopic vision* 暮視 - between 10^{-2} and 10 cd/m^2
    - Sense of brightness & colour; foval detection
  - *Photopic vision* 適光 - above 10^{-2} cd/m^2
    - By cone mechanism (light adapted); in colour
    - High ambient light; enables details to be seen

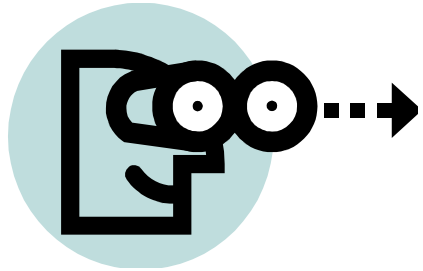
Ranges of scotopic, mesopic and photopic visions

(Source: Advanced Lighting Guidelines 2001 and www.ecse.rpi.edu)



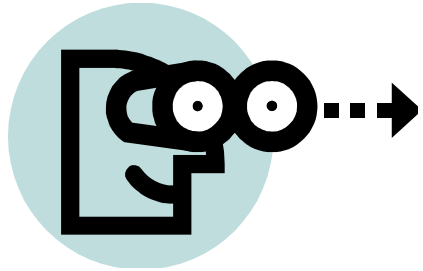


Vision



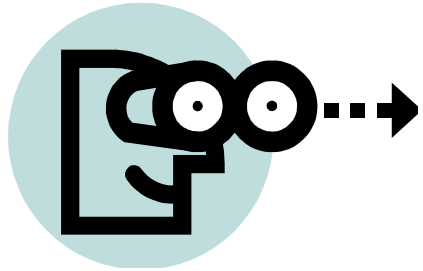
- Purpose of vision
  - The primary goal of any lighting system is to provide a proper stimulus for the human visual system
- Processing of visual information
  - 1. Depth perception
  - 2. Motion detection
  - 3. Brightness perception
  - 4. Colour deficiencies in the visual system

Vision



- 1. Depth perception
  - Pictorial cues
    - Relative image size due to distance or scale of known objects
    - Interposition or layering
    - Shadowing, perspective, or surface texture
    - Motion parallax – relative movement between any two objects at different distances
  - Binocular cues
    - Eye convergence – “cross-eyedness”
    - Binocular disparity or parallax – “stereo” vision

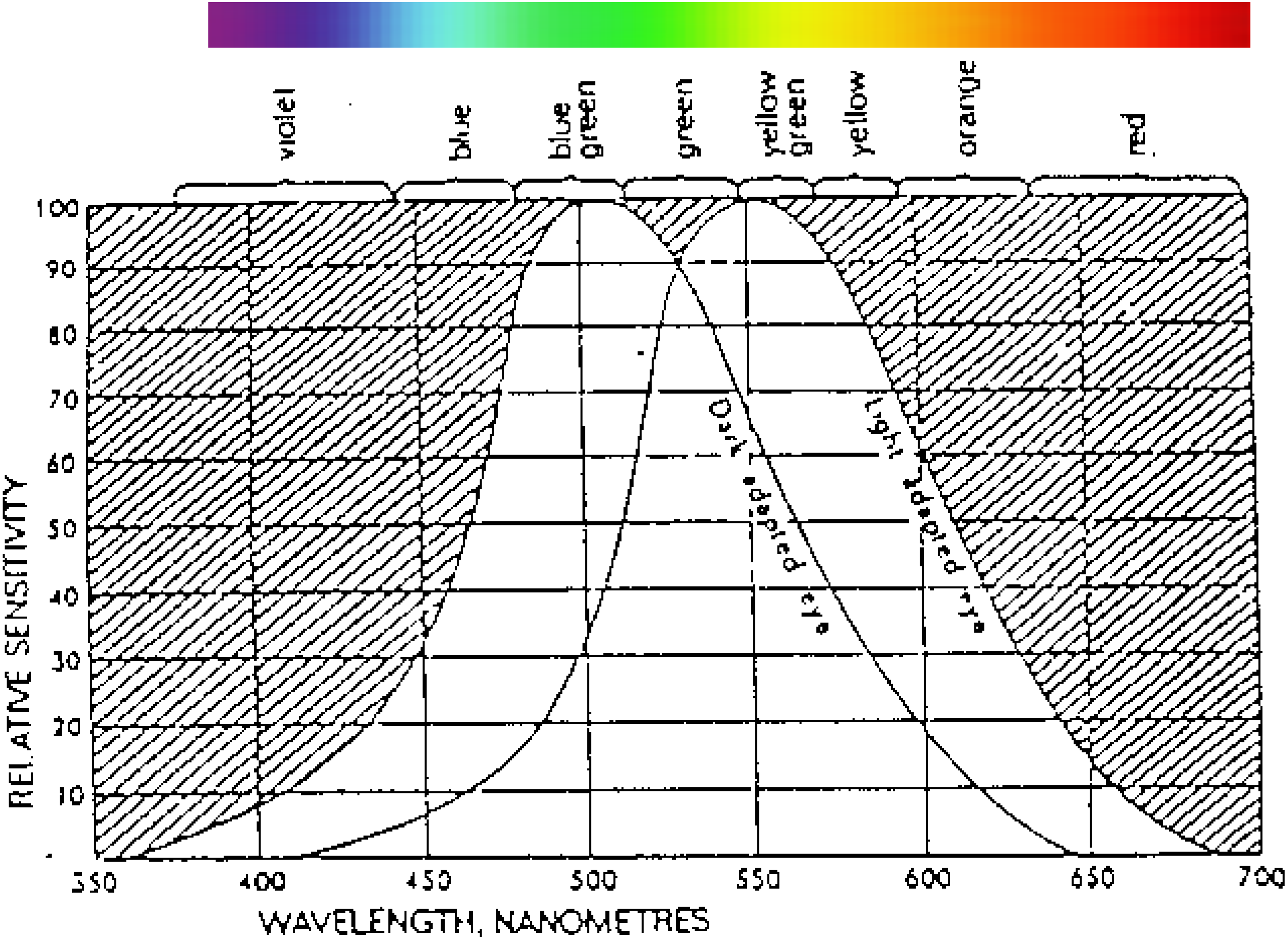
Vision

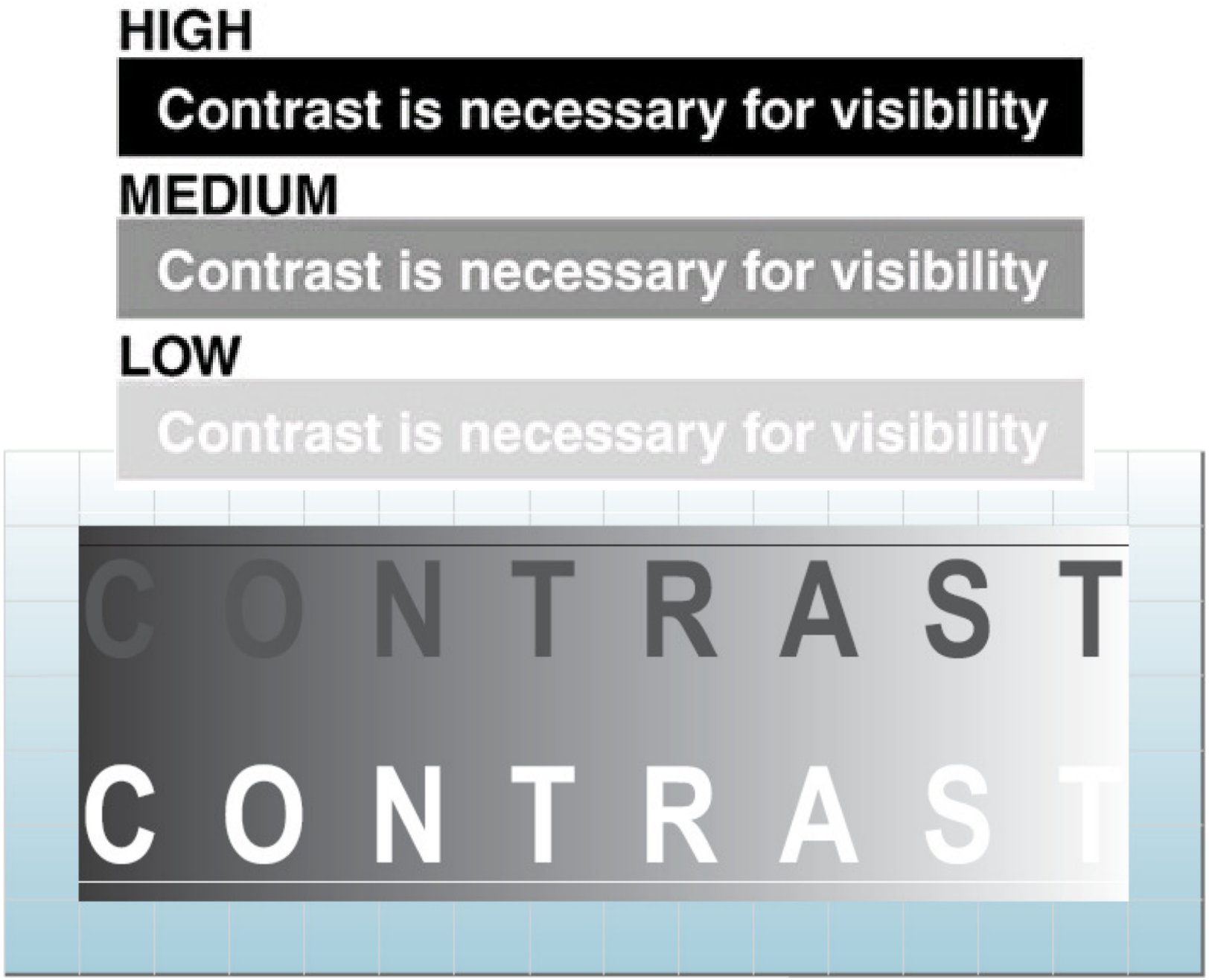


- 2. Motion detection
  - Stroboscopic integration – perceived motion from stills
- 3. Brightness perception*
  - Luminance is measurable quantity of light reflected from objects
  - Brightness is the perceived difference in light reflected from objects
  - Simultaneous contrast – the perceived difference in brightness of two objects of the same luminance when viewed against different backgrounds

(* See also http://hyperphysics.phy-astr.gsu.edu/hbase/vision/bright.html)

The eye's response to equal energy of radiation

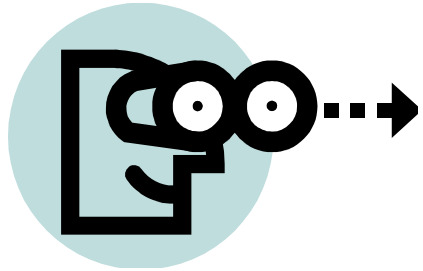




Visual contrast – lack of contrast can reduce visibility

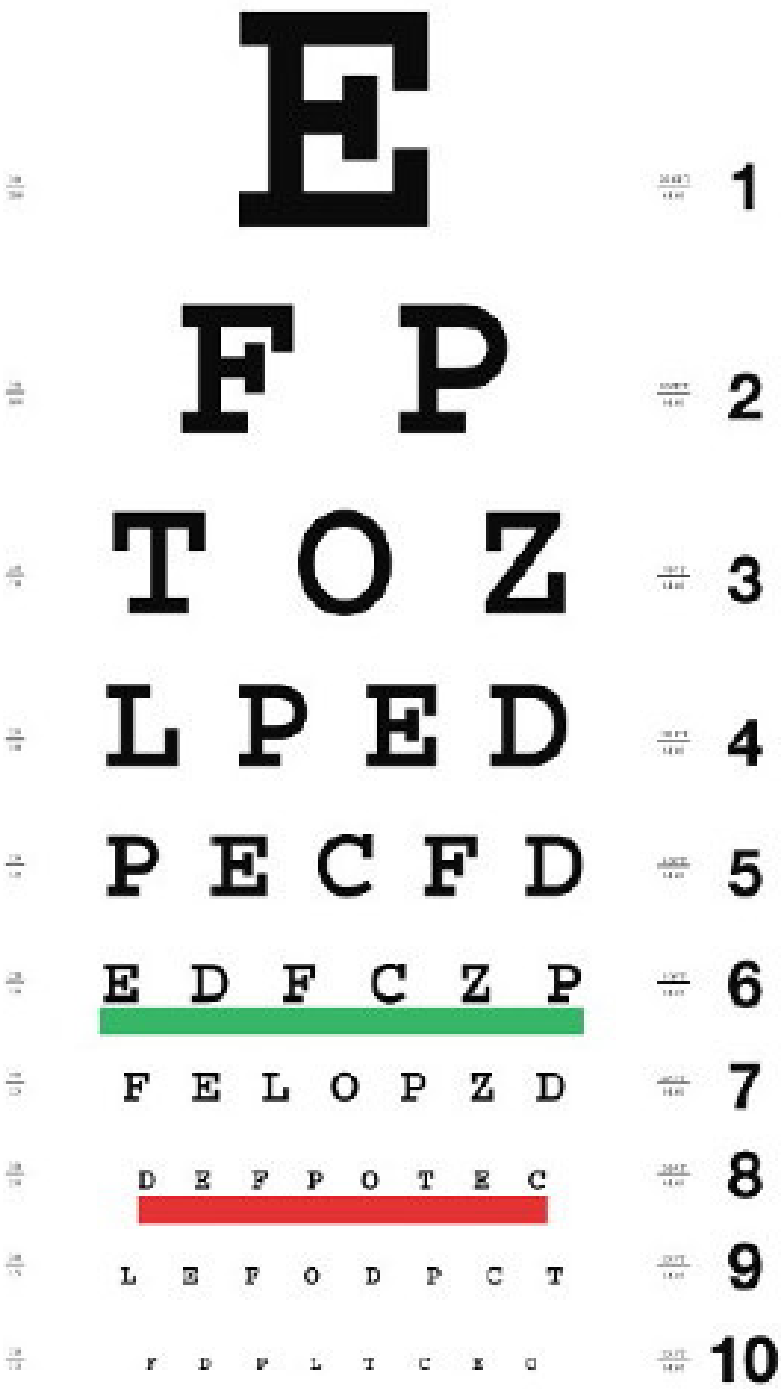
(Source: Advanced Lighting Guidelines 2001)

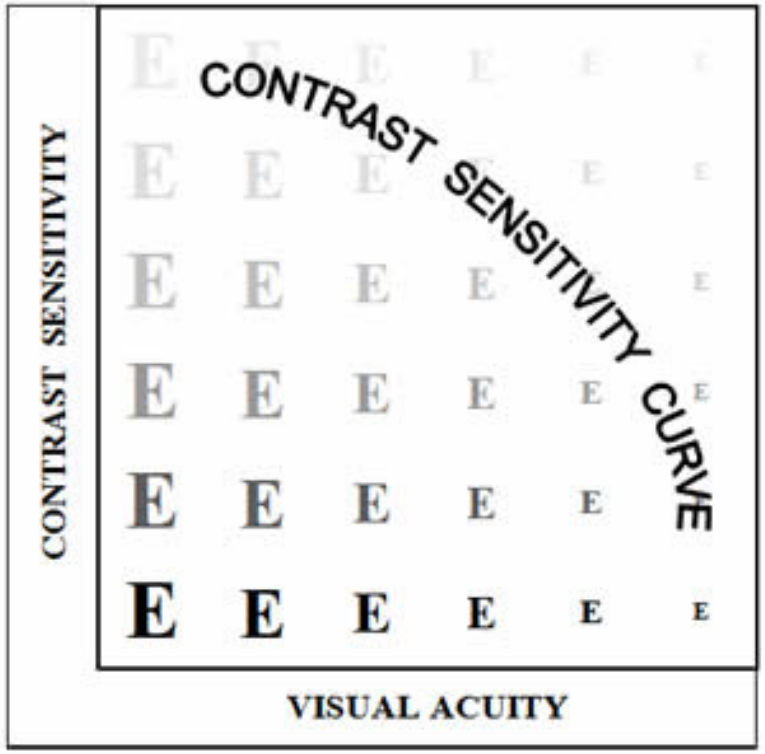
Vision

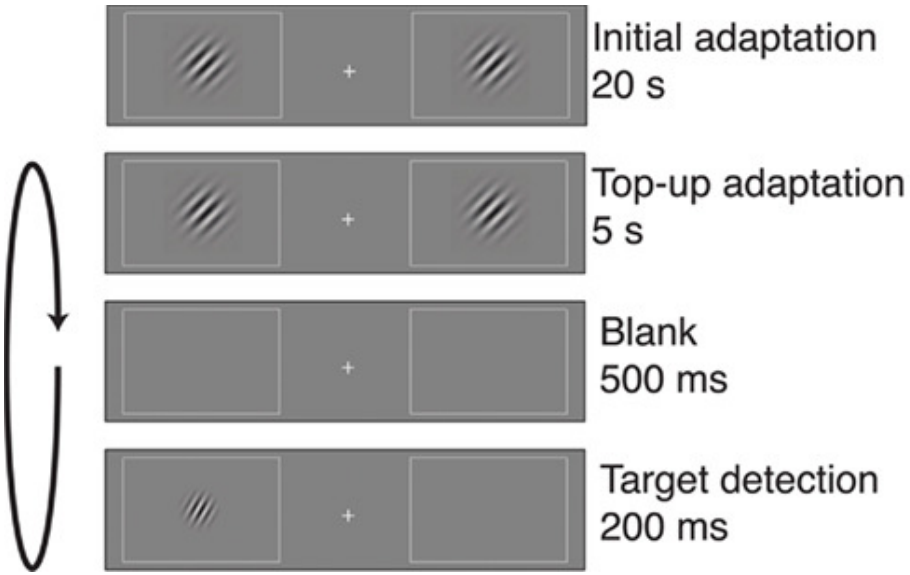


- 4. Colour deficiencies in the visual system
  - Colour-blindness – deficiencies in or lack of cone sensitivity
    - 8% of males
    - 0.5% of females
- Measuring vision
  - Visual acuity – measure of the smallest detail a person's visual system can resolve
  - Contrast sensitivity – the ability to detect the presence of luminance differences
  - Contrast detection – the contrast at which an object is just visible

Measuring vision



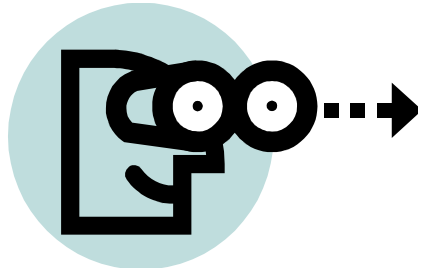




Vision

- Effects of aging
  - Increased lens opacity – light scattering within the eye flare
  - Crystalline lens yellowing – reduced blue vision
  - Presbyopia – loss of lens elasticity and near vision
  - Reduced pupil size – less light reaching retina – more light required
  - Increased visual processing and adaptation time – reduced performance
  - Decreased acuity and contrast sensitivity – due to decreased nerve function

Vision



- Task parameters affecting performance
  - Contrast (C) – relationship between object and background luminances (L)
    - $C = (L_{task} - L_{background}) / L_{background}$
  - Size – visual angle subtended by an object from an observer
  - Luminance – quantity and quality of light reflected from an object
  - Time – viewing time necessary to process vision

Vision

- Building design considerations
  - Discomfort glare
    - Luminance which causes visual discomfort
      - Source luminance, position, size, number of sources, field luminance
  - Disability glare
    - Luminance which adversely affects visual performance
  - Veiling reflections
    - Reflected luminance which prevents visual performance
      - Tasks viewed at a mirror angle to a source

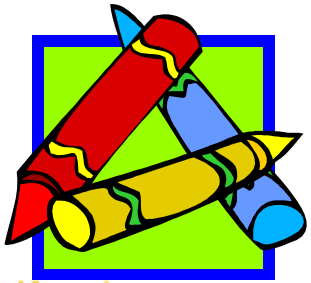
Glare = 眩目光

Bright light entering
from a window

Veiling reflection from
overhead light source

Examples of glare and veiling reflection

Colour



- White light
  - All wavelengths combined at approximately equal power levels

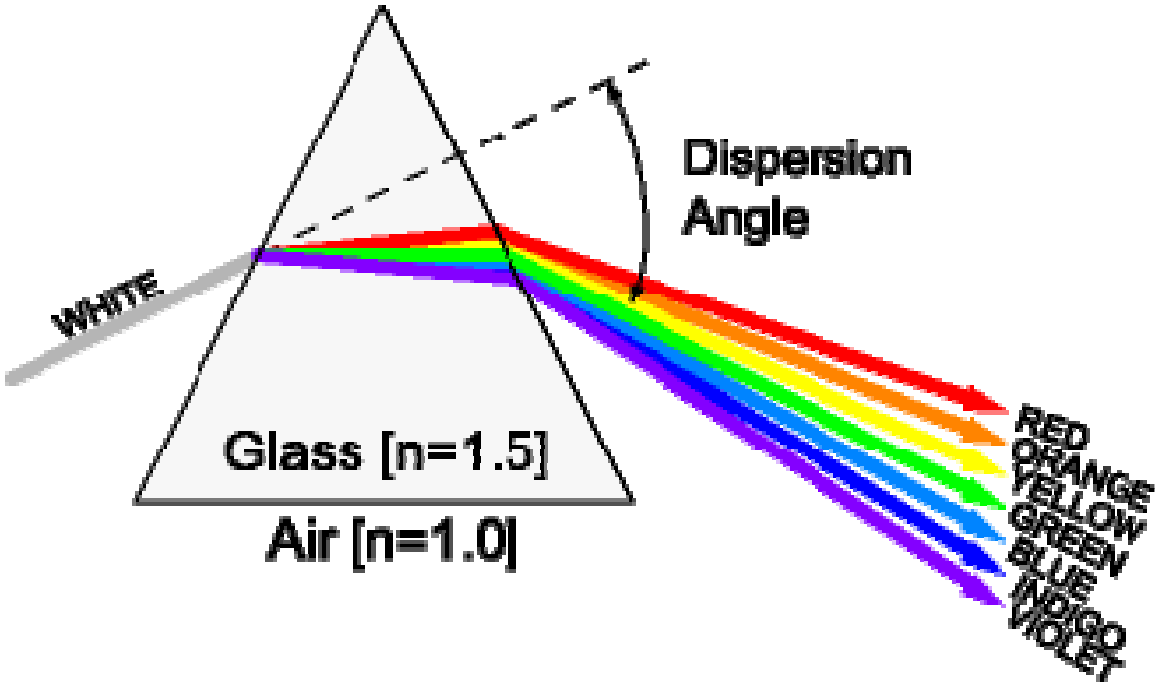
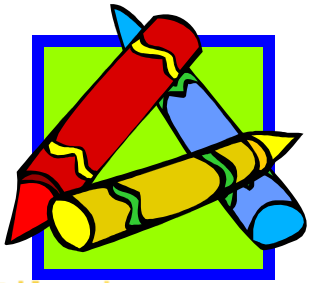


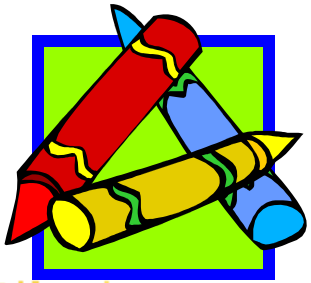
Fig. 4.8 Refraction through a prism.

Colour



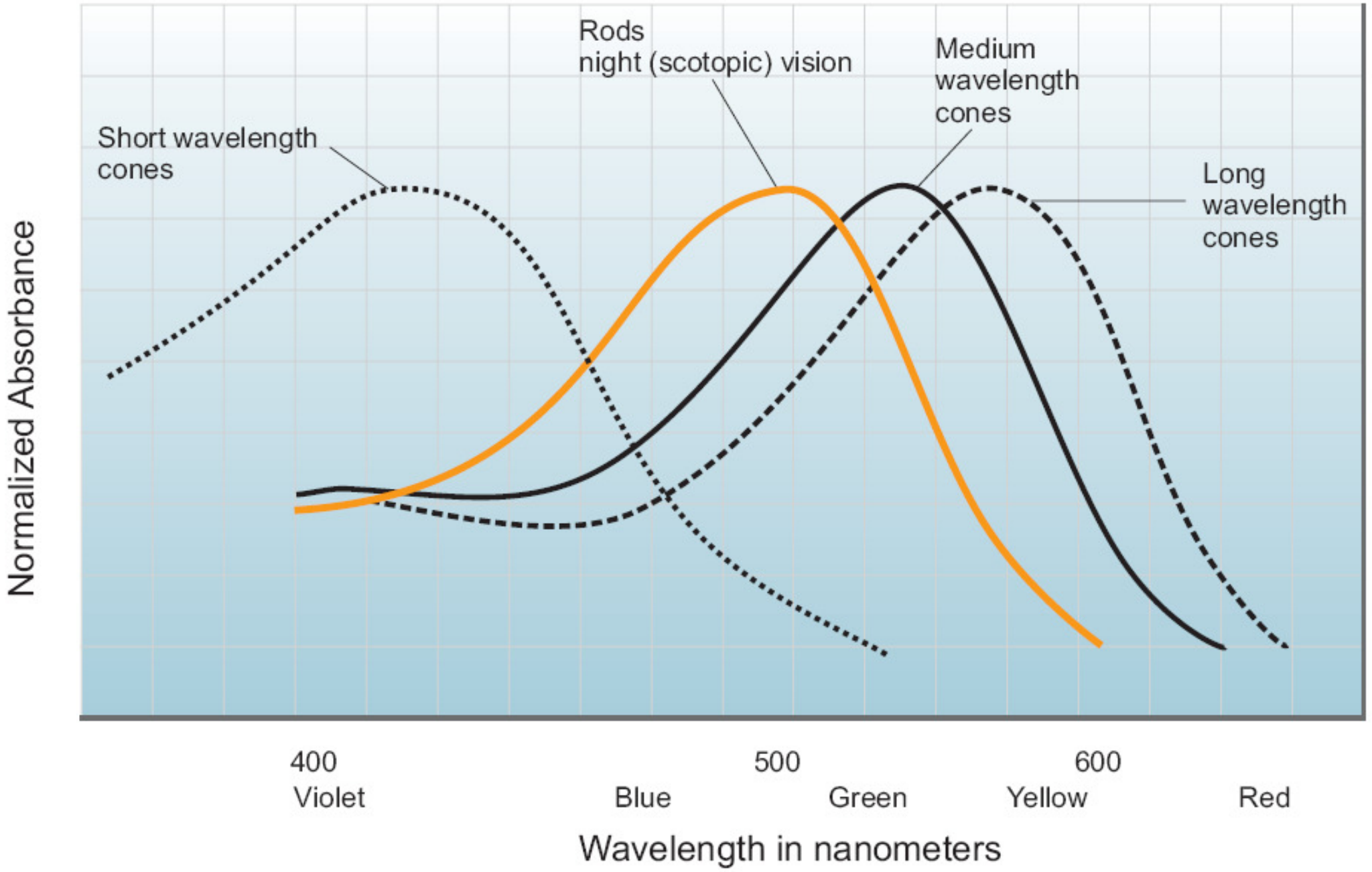
- The two types of receptor cells
  - Rods – *scotopic vision*
    - Night and peripheral vision
    - See very low luminance levels
    - Surfaces appear as shades of gray or blue/gray – difficult to distinguish between colours
  - Cones – *photopic vision*
    - Responsible for colour vision at normal interior and exterior lighting levels
    - Colour experience determined by relative strength of the signal from each of three types of cones (R, G, B)

Colour



- Photopic vs. scotopic sensitivity
  - Spectral luminous efficiency curve or the V-lambda curve
  - Peak sensitivity shifts to lower wavelengths under scotopic (rod) vision – Purkinje shift*
  - Surface colour that appears lighter under photopic vision may appear darker under scotopic

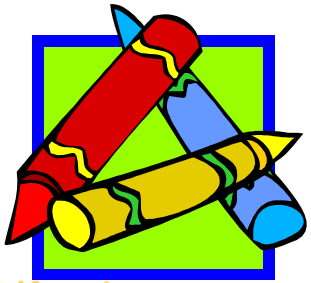
(* See also http://en.wikipedia.org/wiki/Purkinje_effect)



Spectral sensitivity of rods and cones

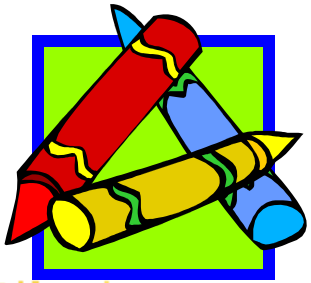
(Source: Advanced Lighting Guidelines 2001)

Colour



- Photopic curve
  - Used to determine the nos. of lumens present in a light source, given the spectral power distribution for a lamp
  - Trade-off between colour rendering and efficacy
- Mesopic vision
  - Rods and cones are nearly equal in sensitivity
  - Both photopic and scotopic systems contribute to response to object colour of different luminance
  - Luminance level is low so that rods and cones function at similar sensitivities, e.g. twilight

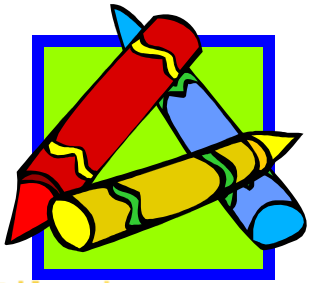
Colour



- Perceived object colour*
  - Visual experience
  - Based on relative proportions of different wavelengths of light reflected from a surface
  - Function of both surface characteristics and illuminant
  - Defined using three designations – Hue, Value and Chrome

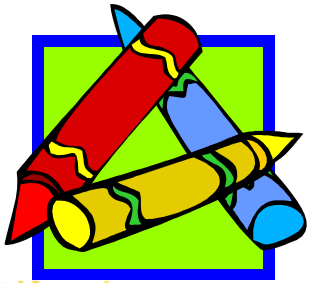
(* See also http://hyperphysics.phy-astr.gsu.edu/hbase/vision/colper.html)

Colour



- Hue
  - General description of the perceived colour of an object
  - Single colour name or combination of two adjacent colour names (red, yellow, green, blue)
- Value
  - Indicates the relative lightness or darkness of a colour – e.g. sky blue and navy blue
  - Value is related to gray scale – from black to white
  - The value of a particular colour is the value of the gray that is of the same relative lightness

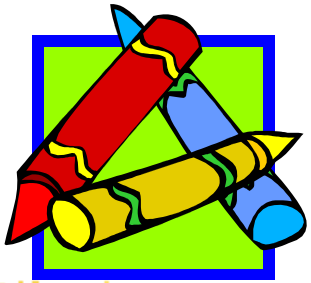
Colour



- Chroma
  - Indicates how saturated a colour appears
  - Two colours may be of the same hue and value, but one more rich in hue – e.g. a gray blue and a rich blue

- Metameric match
  - A condition where a different source/reflectance producing the same relative signal from the three types of cones will be perceived as being equal in colour
  - (Note that it is possible that two materials which appear to match under one illuminant will not match under a second)

Colour

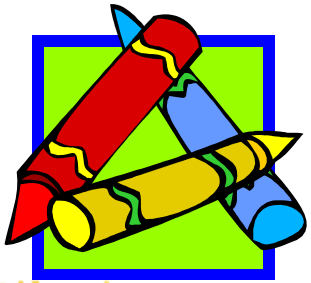


- Perceived colour of light source
  - Spectral content of emitted light determines source appearance
  - Two sources that appear to be the same colour may have different spectral compositions
  - Two sources that have the same colour appearance may have different colour rendering qualities

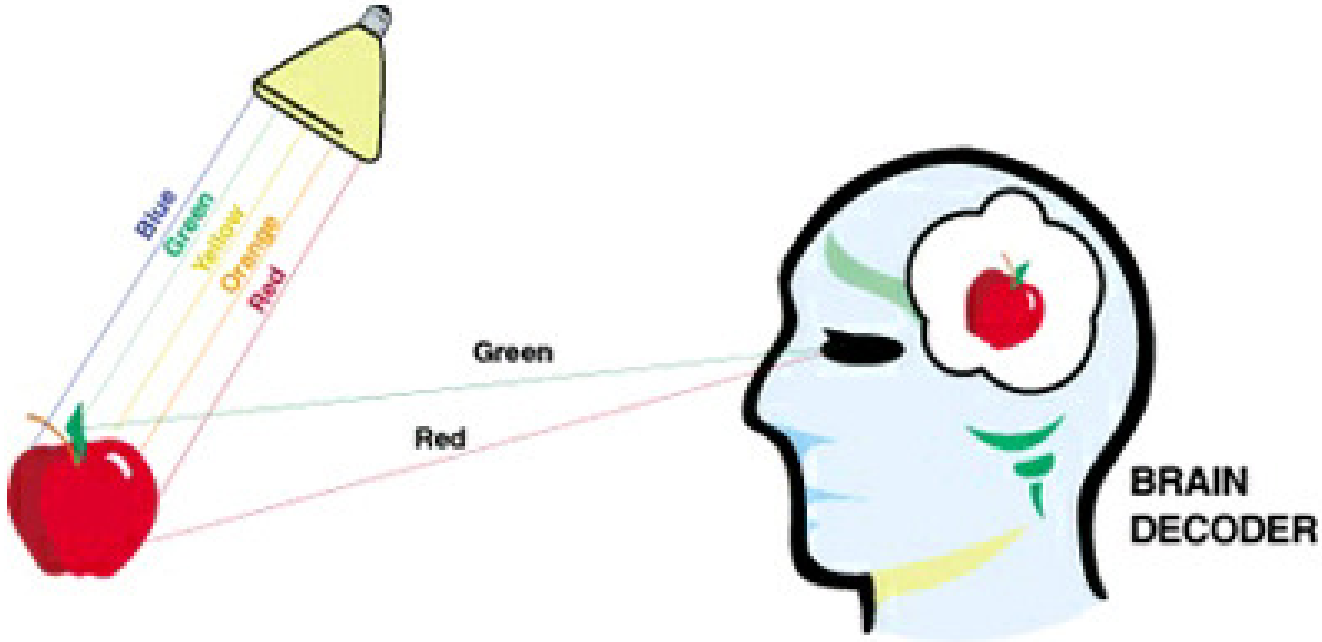
High CRI

Low CRI

Colour

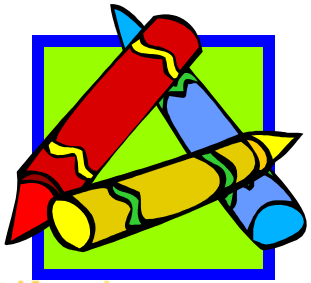


- Light source characteristics
  - Colour temperature
  - Colour rendering ability

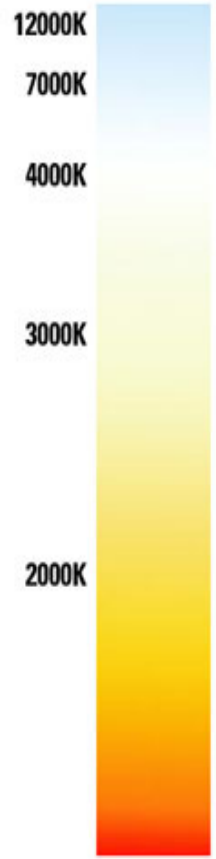


Objects as selective reflectors.

Colour

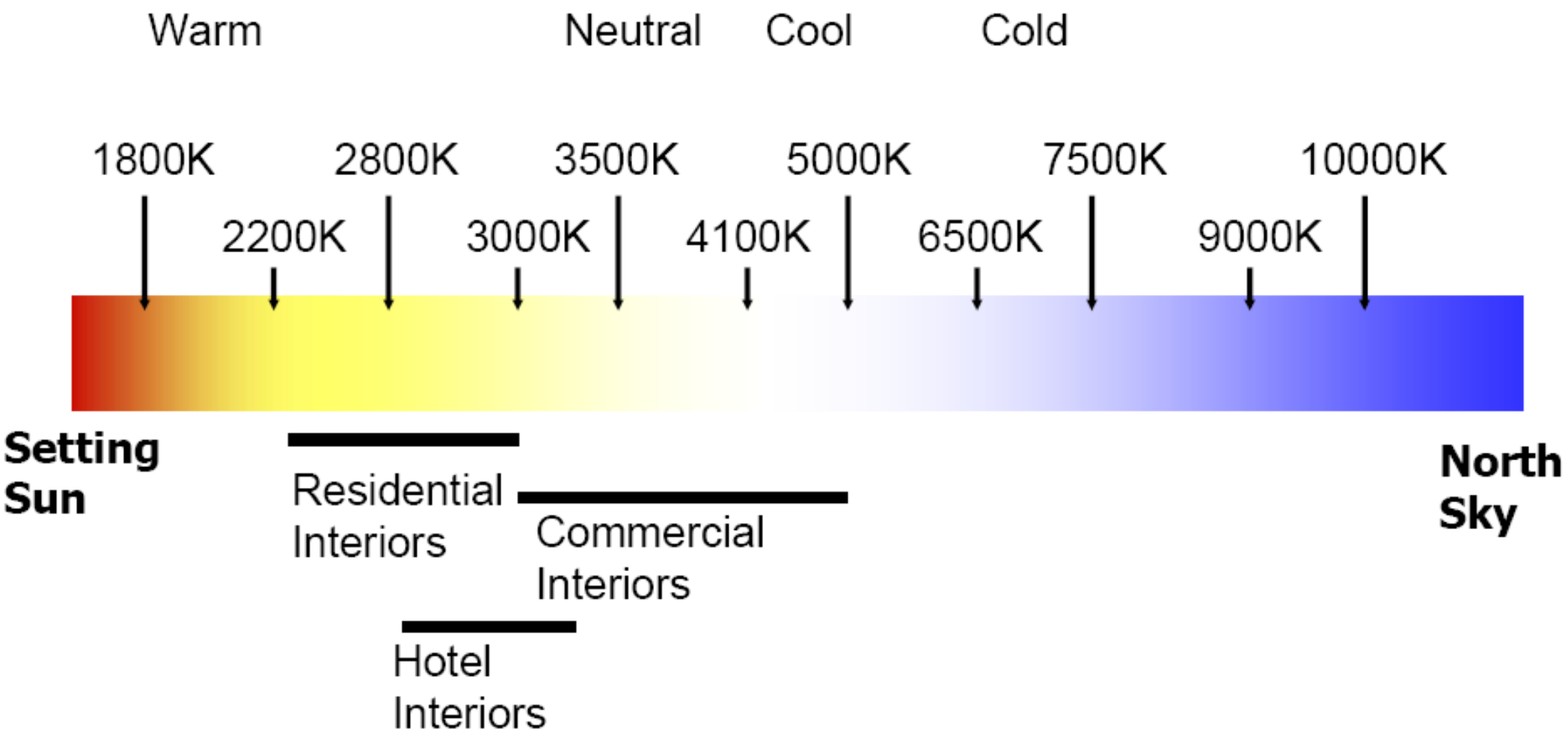


- Correlated colour temperature (CTT)
  - Used to specify source appearance
  - CCT equates the appearance of a source to a blackbody radiator operating at the same temp.
  - Expressed using Kelvin temp. scale
  - A lower CCT means longer wavelengths and warmer colour
  - Typical light source – 2,100 to 6,500 Kelvin



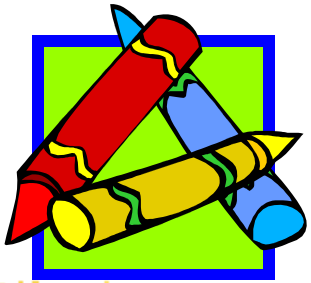
(* See also http://en.wikipedia.org/wiki/Color_temperature)

Effects of colour on lighting design



[Source: www.benyalighting.com]

Colour



- Colour rendering index (CRI)
  - Used to evaluate light sources based on how well particular sample colours are rendered relative to a standard source at the same CCT
  - CRI index is a value from 0 to 100 that is a measure of the deviation in colour appearance that occurs when test colours are illuminated by the test source and the standard source
    - (A greater deviation results in a lower CRI value)

(* See also http://en.wikipedia.org/wiki/Color_rendering_index)

red-rich source

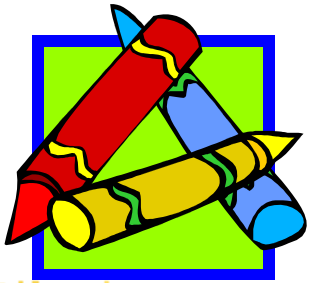
blue-rich source

Colour rendering index (CRI or Ra) of common lamp types

(Source: Philips Lighting, http://www.lighting.philips.co.in)

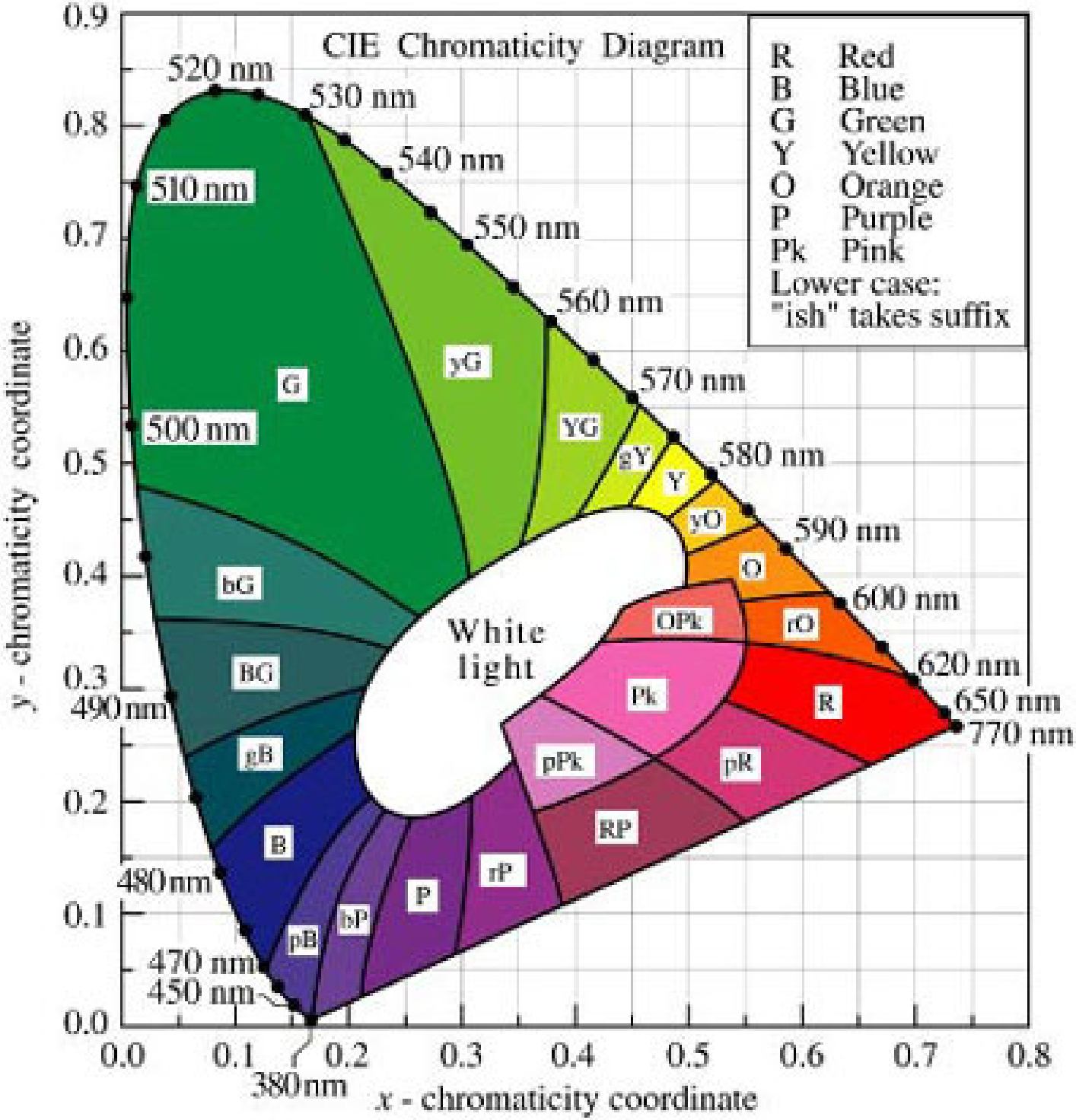
Lamp type	Ra
Incandescent	100
Fluorescent	
Colour / 33	65
Colour / 54	72
Colour / 82/ 83/ 84	86
Colour / 93/ 94/96	93
Low pressure sodium (SOX)	(- 44)
High pressure sodium (SON)	26
High pressure mercury (HPL – N)	45
Blended light (ML)	60
Metal Halide (HPI)	70

Colour



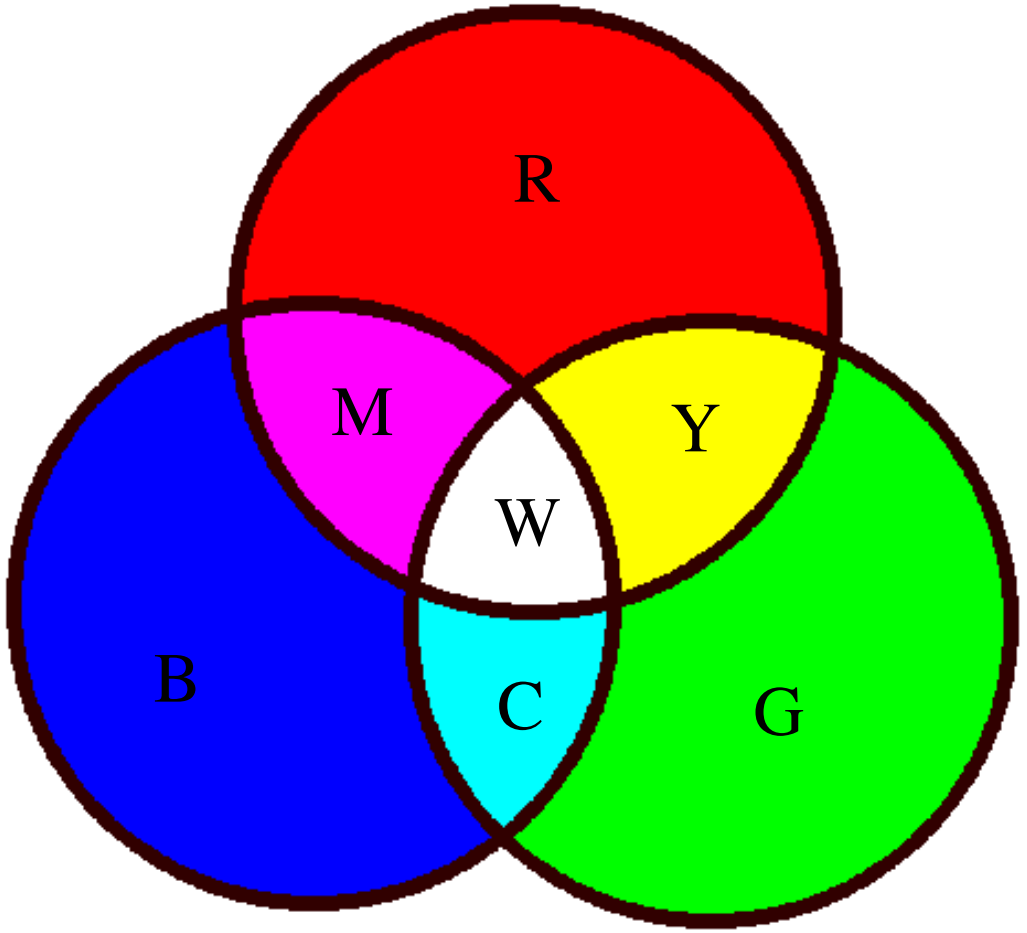
- CIE Chromaticity Coordinates*
  - The system used for the specification of CCT
  - Based on three coordinates (x, y, z)
  - CIE chromaticity diagram describes how colours can be mixed
- Additive colour mixing
  - Primary colours – Red, Green, Blue
  - Other colours of the spectrum are achieved by mixing the primaries
  - White light = equal concentration of the primaries

(* See also http://hyperphysics.phy-astr.gsu.edu/hbase/vision/ciecon.html)



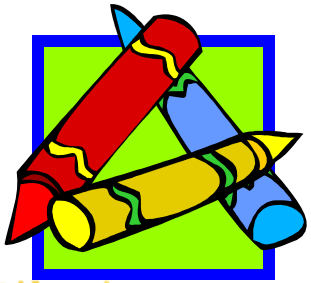
CIE chromaticity diagram

R = Red
G = Green
B = Blue
Y = Yellow
W = White
M = Magenta
C = Cyan

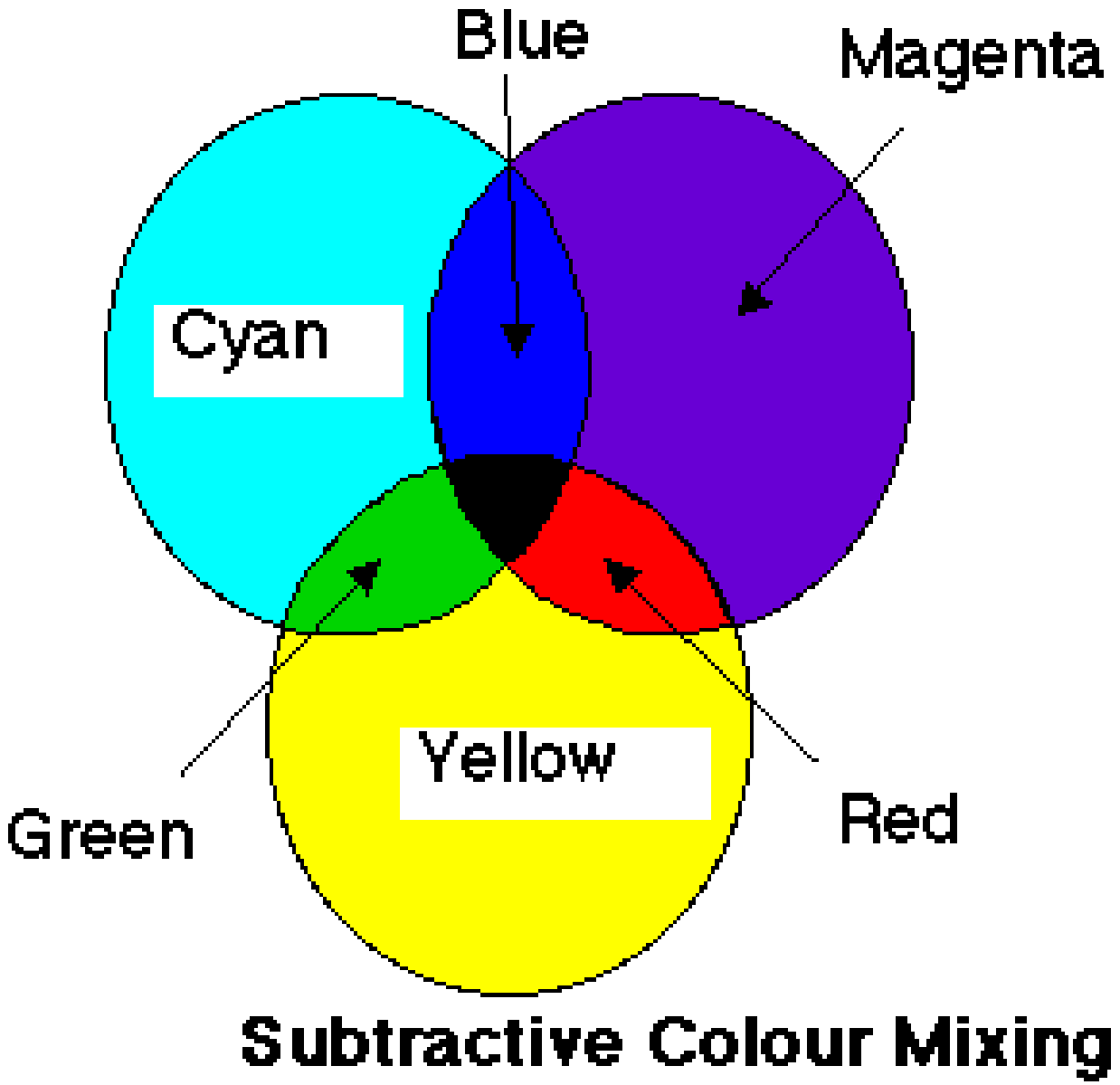


Additive colour mixture

Colour

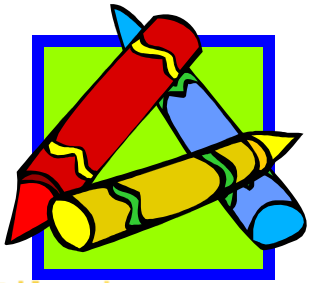


- Subtractive colour mixing
  - Involves one source (broadband)
  - Selective reduction/elimination of certain wavelengths
  - Subtractive primaries – Red, Blue, Yellow
  - Adding these three primaries results in no colour experience

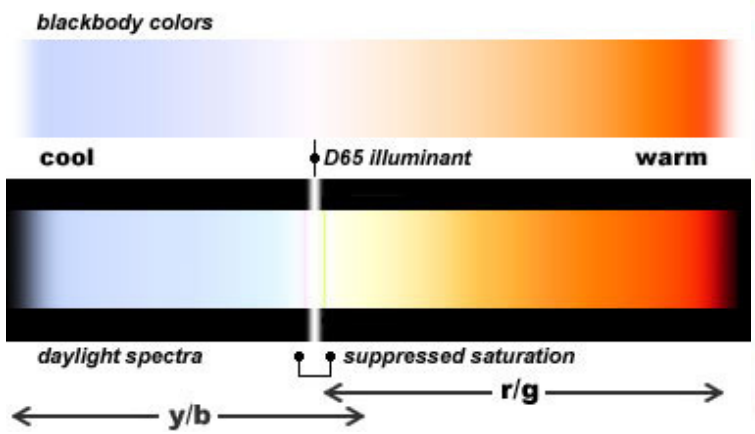


Subtractive colour mixture

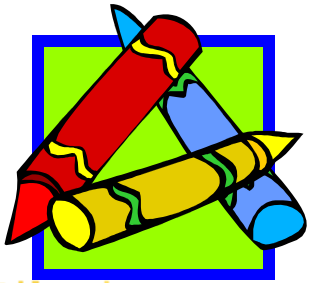
Colour



- Daylight and colour
  - Daylight has excellent colour rendering quality with a CRI of 100
  - Colour temperature is high – cool or bluish-white
  - If electric light sources are used in a daylighted area, those of high colour temperature are preferred



Colour



- Light sources
  - Colour rendering and colour temperature differ with spectral power distribution
    - Incandescent – good colour rendering (halogen has a higher colour temperature)
    - Fluorescent – range of colour temperature and colour rendering ability
    - High intensity discharge (HID) – mercury, metal halide and high pressure sodium provide a range of colour temperature and colour rendering ability