Daylight simulation for design & compliance

Fundamentals of Light

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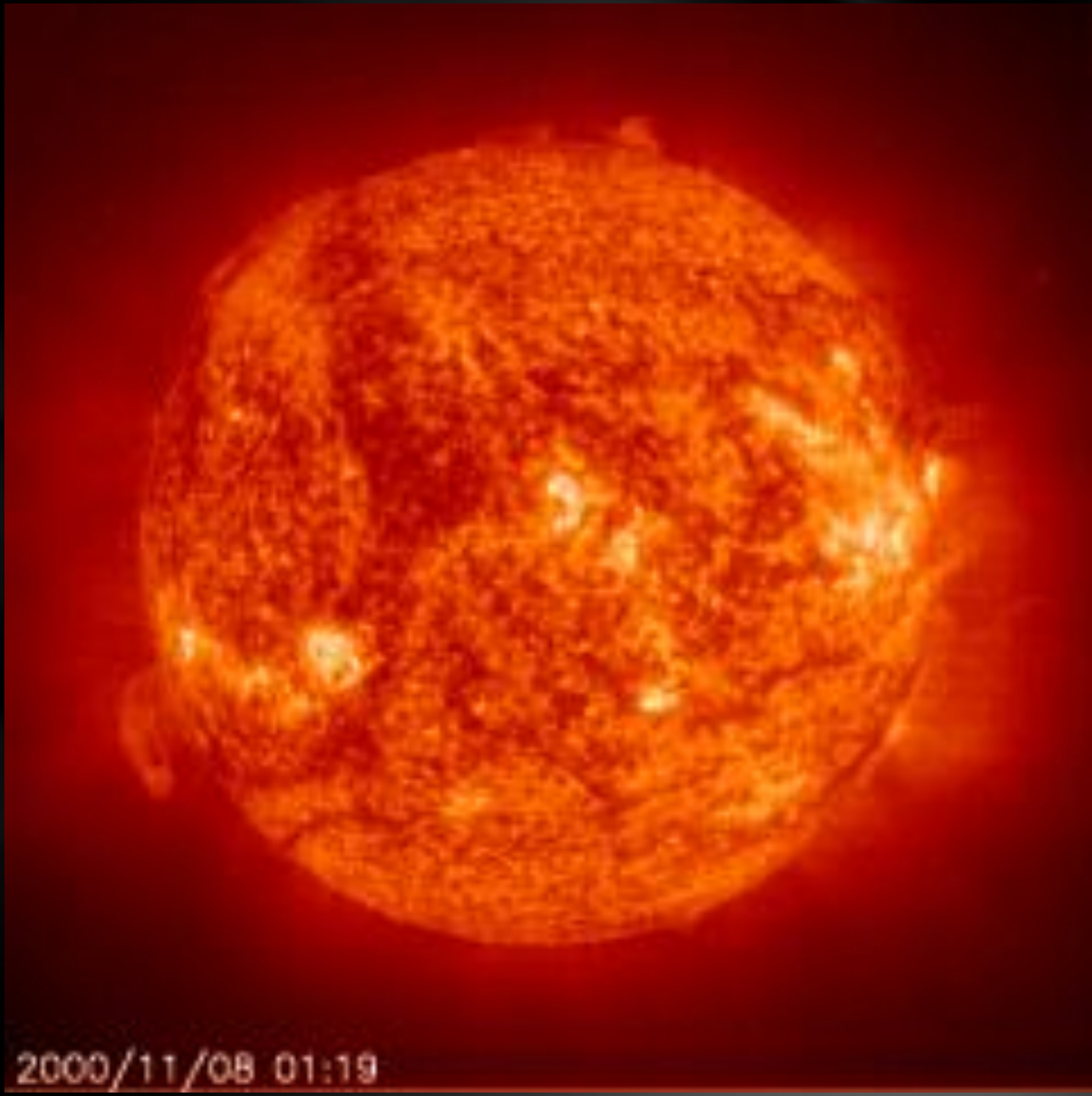
Fundamentals of Light and Daylight Simulation Software

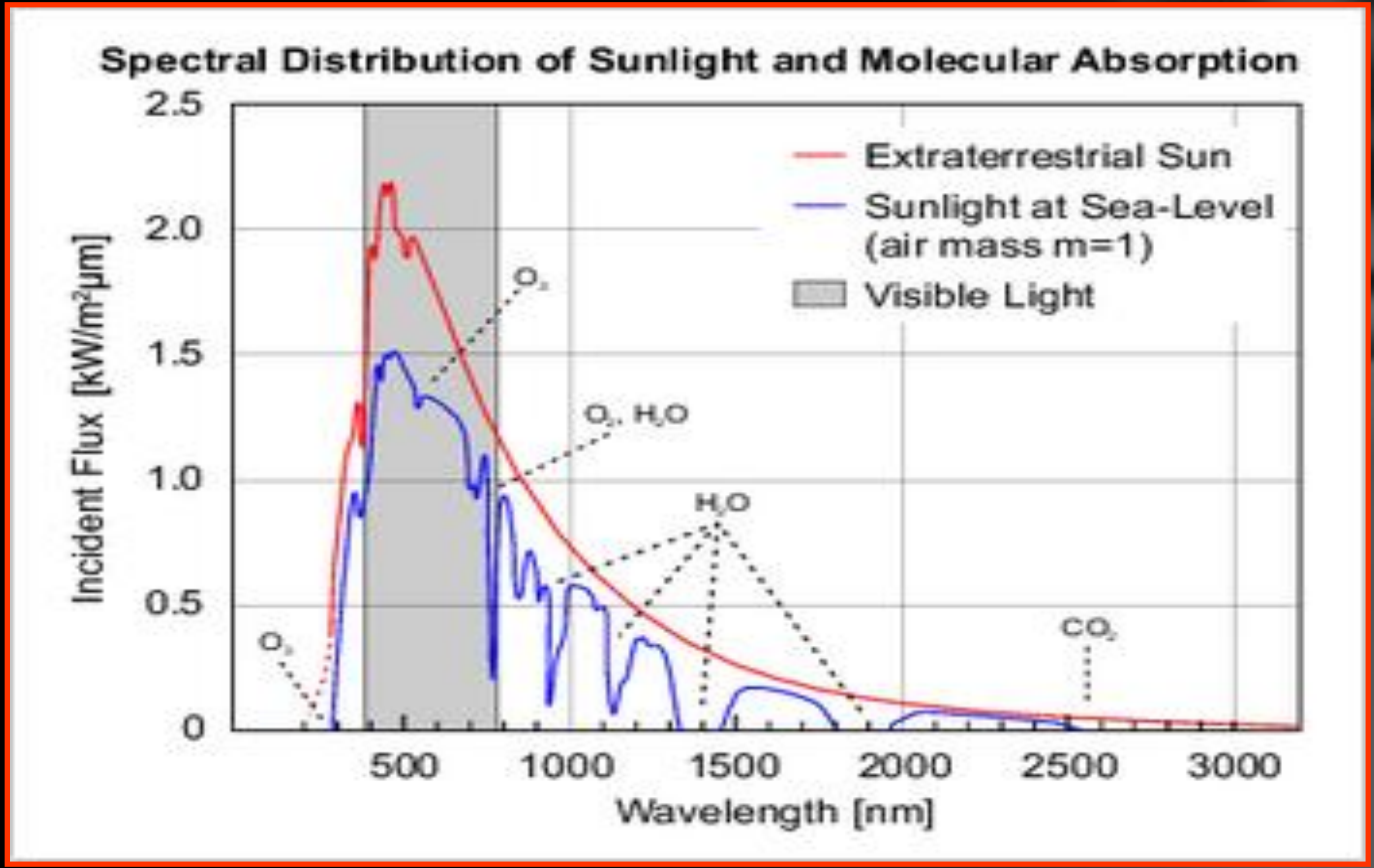
1. Light and the EM Spectrum
2. The Behaviour of Light
3. Material Properties
4. Simulation Software
5. Calculation Methods
6. Useful References

Our journey begins here….

- Core temperature $8x10^6$ to $40x10^6$ K.
- Effective black body temperature is 6000 K.
- Solar constant: extra-terrestrial flux from the sun received on a unit area perpendicular to the direction of propagation – mean Sun/Earth distance value is 1353 W/m^2.
- Actual extra-terrestrial radiation varies with time of year as earth-sun distance varies.



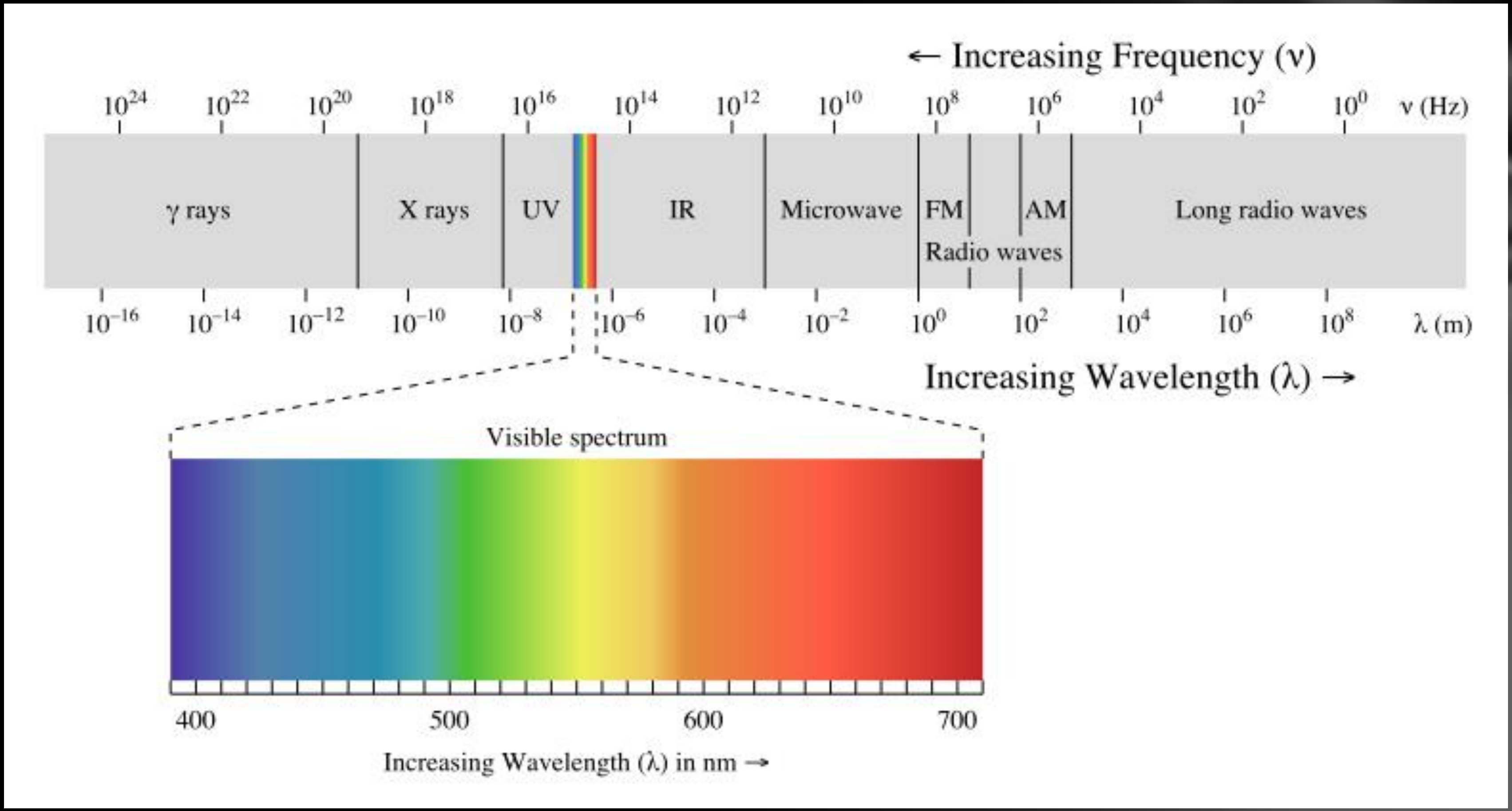
Light and the EM Spectrum



Light and the EM Spectrum

1. Radiation
   1. This is solar radiation
   2. Majority of solar energy comes from the visible and infrared parts of spectrum
   3. Scattering and absorption occur in the atmosphere
   4. Direct and diffuse components of radiation need accounting for
   5. Flux incident on an external opaque surface will be partially absorbed and partially reflected
      1. Absorbed component may be transmitted to interior surface via conduction and then surface convection and long wave exchange to increase internal temperature
      2. Absorbed component on outside surface will raise temperature and emit energy
   6. Short wave flux (Direct and Diffuse) incident on a transparent surface will be partially absorbed, reflected and transmitted
2. Long wave radiation

Light and the EM Spectrum



Light and the EM Spectrum

- Visible radiation (Light) has wavelengths of ~ 380-780 nm
- Ultraviolet Radiation (UV) has shorter wavelengths than visible:
  - UVA 400 -315 nm overlaps slightly with visible range
  - UVB 315-280 nm is most destructive as it can penetrate atmosphere and damage biological tissue
  - UVC 280-100 nm would be even more destructive but is absorbed by the atmosphere

Infrared Radiation

- IR has longer wavelengths than visible
- IR-A 780-1400 nm
- IR-B 1400-3000 nm
- IR-C 3000-10^6 nm

Light and the EM Spectrum

	Wavelength (μm)			
	0 - 0.38	0.38 – 0.78 (visible range)	> 0.78	**Total**
Fraction in range	0.07	0.47	0.46	1
Energy in range (W/m^2)	95	640	618	1353

It is important to view Light, as Energy in holistic building simulation…..

Light and the EM Spectrum

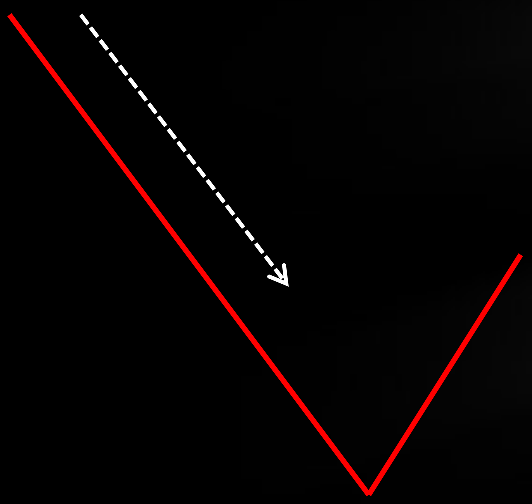
- Light is the visible portion of the EM spectrum from about 380 – 780 nm
- EM radiation in this range is absorbed by the photoreceptors of the human eye
- Wavelengths are associated with colours
- Eyes are most sensitive to green light at 550 nm (Spectral response of average eye for Photopic vision)
- The Illuminating Engineering Society of North America (IESNA) define light as: "radiant energy that is capable of exciting the retina and producing a visual sensation"

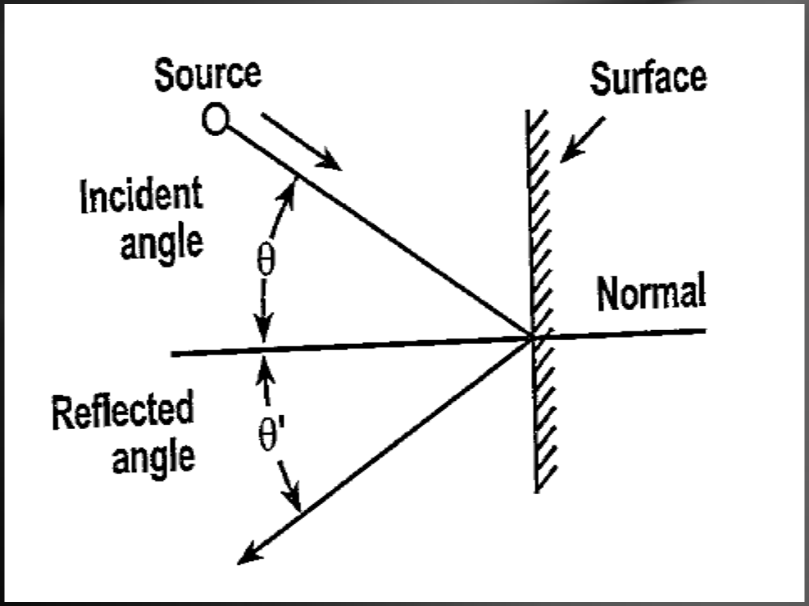
Behaviour of Light

- Reflection
- Refraction
- Transmission
- Absorption
- Diffusion (Scattering)
- Spectral response
- Units and conventions

Reflection (Specular)

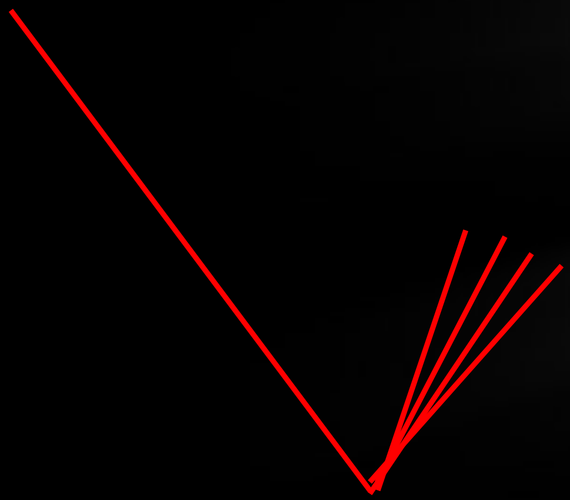
- Specular reflection – for instance that encountered with a mirror or polished surface, is when light is reflected away from the reflecting surface at the same angle as it is incident
- Specular reflections illustrate the law of reflection





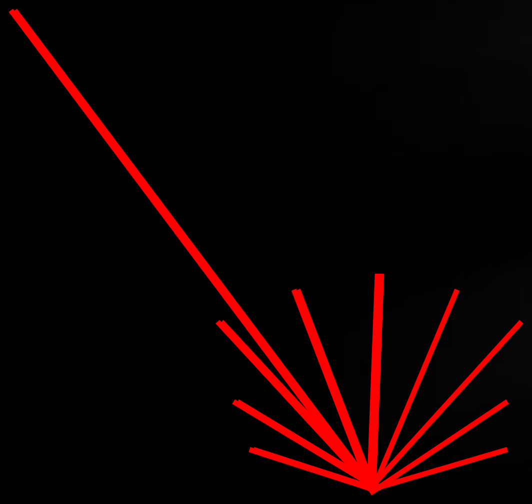
Reflection (Spread)

- Spread reflection occurs when an uneven surface reflects light at more than one angle, all of which are close to the incident angle



Reflection (Diffuse)

- Diffuse reflection is also known as Lambertian scattering and occurs when a rough or matt surface reflects light at many angles



Refraction

- When light passes from one material to another, it will refract. The light will change velocity and ‘bend’
- The incident angle of light and the material refractive index determines the amount of refraction which occurs
- N, the refractive index is the ratio of the speed of light in a vacuum to the speed of light in the material
- Speed of light in air is very similar to speed of light in a vacuum
- Therefore, N for air is 1.000293
- Consider light passing from air to glass…

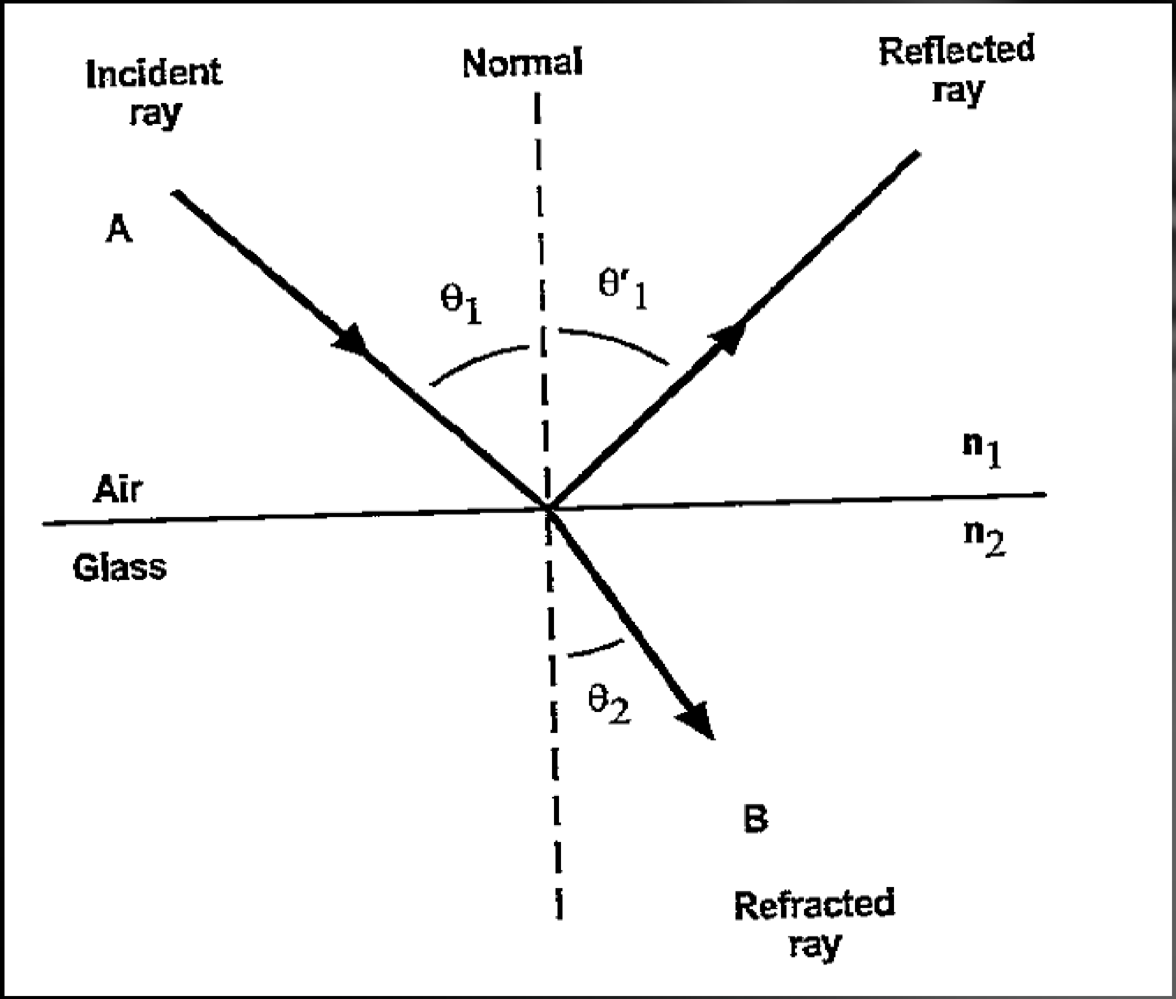
Refraction

Snells law is the law of refraction:

$N_1 \sin\Theta_1 = N_2 \sin\Theta_2$

N1 is the refractive index of air
N2 is the refractive index of glass
Θ_1 is the incident angle of light
Θ_2 is the refracted angle

Snell's law also shows that light travelling from a medium with a low N to a high N bends towards the normal and from high to low N it bends away from Normal



Refraction

Material	Refractive Index
Diamond	2.419
Ice	1.309
Sodium Chloride (Salt)	1.544
Glass (typical)	1.52
Water	1.333
Air	1.000293
CO_2	1.00045

*measured with wavelength 589 nm in vacuum

Reflection and Refraction

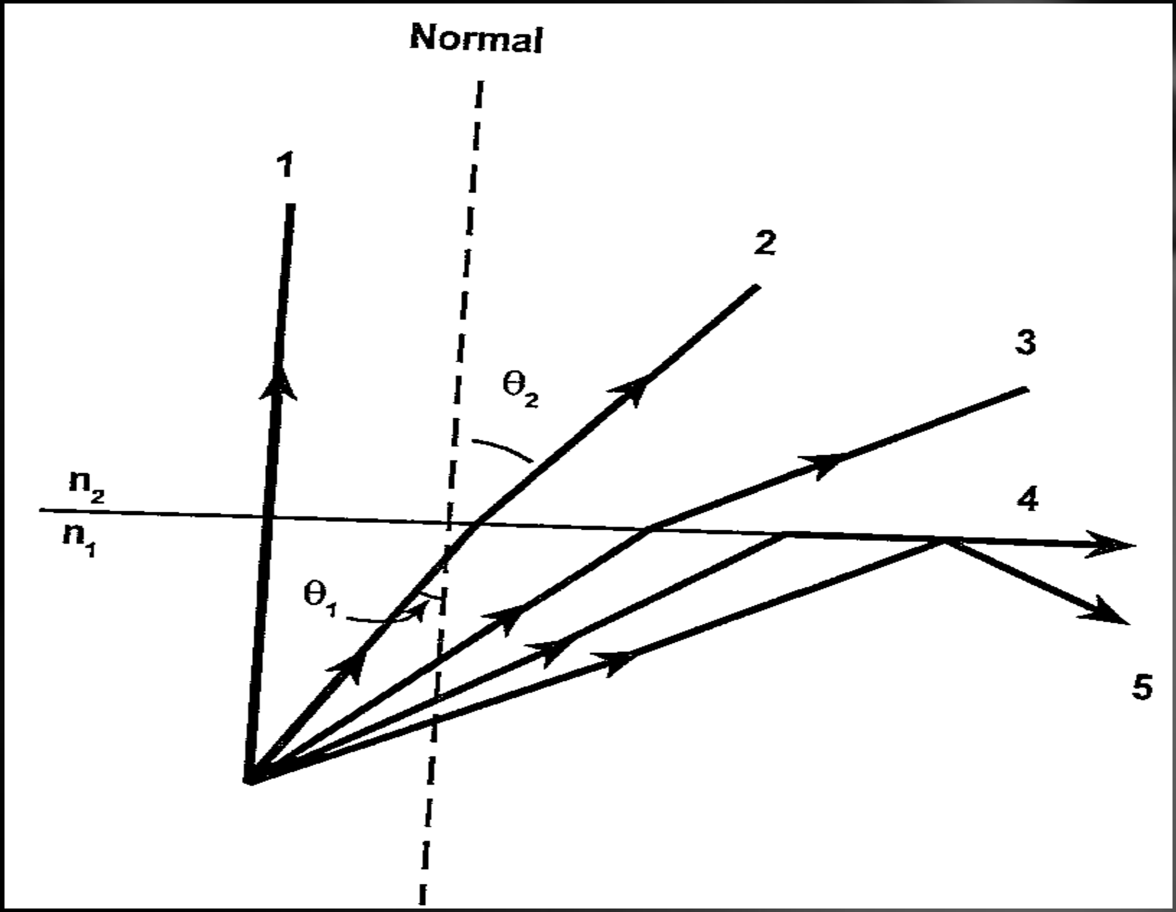
- A transparent surface which transmits most of the incident light will still reflect light at both of it's surfaces
- This reflection happens when light travels through a change is refractive index
- At normal incidence, Fresnel's Law of reflection states:
  - $R_\lambda = (N_2 – N_1)^2 / (N_2 + N_1)^2$
  - R_λ is the reflection loss
  - For example (Air and Glass at normal incidence):
    - $(1.52 – 1)^2 / (1.52 +1)^2$
    - = 0.0426
    - ~ 4% reflection loss at each of the two boundaries with air
    - Reflection loss increases with angle of incidence

Total internal reflection

- Recap that light moving from a high N to low N, bends away from normal e.g. light moving from glass to air
- If a beam of light's incidence angle increases away from normal it reaches an angle called the critical angle Θ_c
- This is where light is refracted along boundary of two materials and not through the materials
- At angles greater than Θ_c the light is reflected back into the material
- This is called total internal reflection
- Fiber Optics make use of this phenomenon

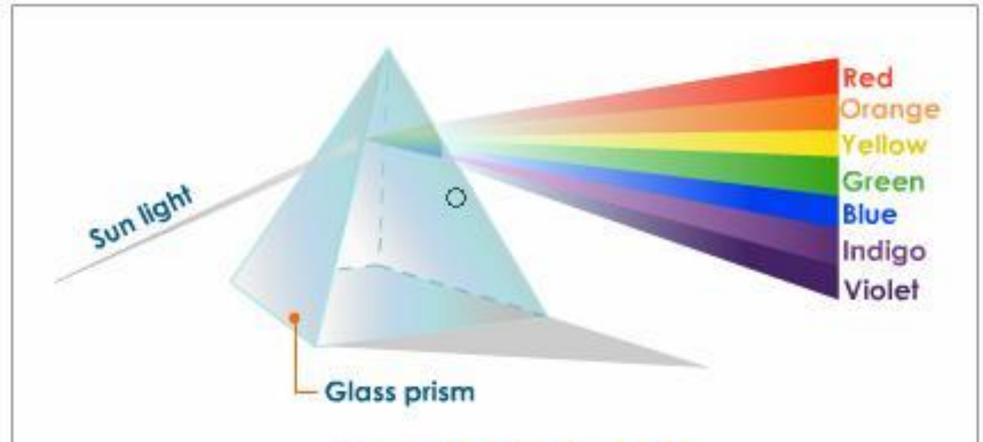
Total internal reflection

- Light beams 1, 2 and 3 are below the critical angle and refraction takes place as normal
- Light beam 4 is at the critical angle and is thus refracted at the boundary between the two mediums
- Light beam 5 is at an angle greater than the critical angle and is reflected back totally



Dispersion

- Refractive index is a function of the wavelength of incident light
- Materials have higher N for shorter wavelengths e.g. blue light bends more than red light
- This is called dispersion
- When white light passes through non-parallel faces of a prism it splits into its spectral components



Dispersion of White Light

Absorption

- A material can absorb light (instead of transmitting it)
- It can absorb all of part of the incident light, normally converting it to heat and absorb light at some wavelengths while transmitting light at others, this is called selective absorption
- For example: coatings to prevent solar gains will let visible light through while absorbing heat gains from near infrared.
- The amount of light absorbed is given by Lambert's Law (exponential):
- $I = I_o e^{-\alpha x}$
- I is the light transmitted (varies with wavelength of light)
- I_o is the intensity of light entering the material, α is the absorption coefficient and x is the thickness of the material

Absorption

- The absorption coefficient can be further broken down into two
- β, absorption per unit concentration coefficient and
- C, the concentration of the material
- This then considers the thickness and concentration of absorbing material:
- $I = I_o e^{-\beta C x}$
- Units for β are in moles per litre

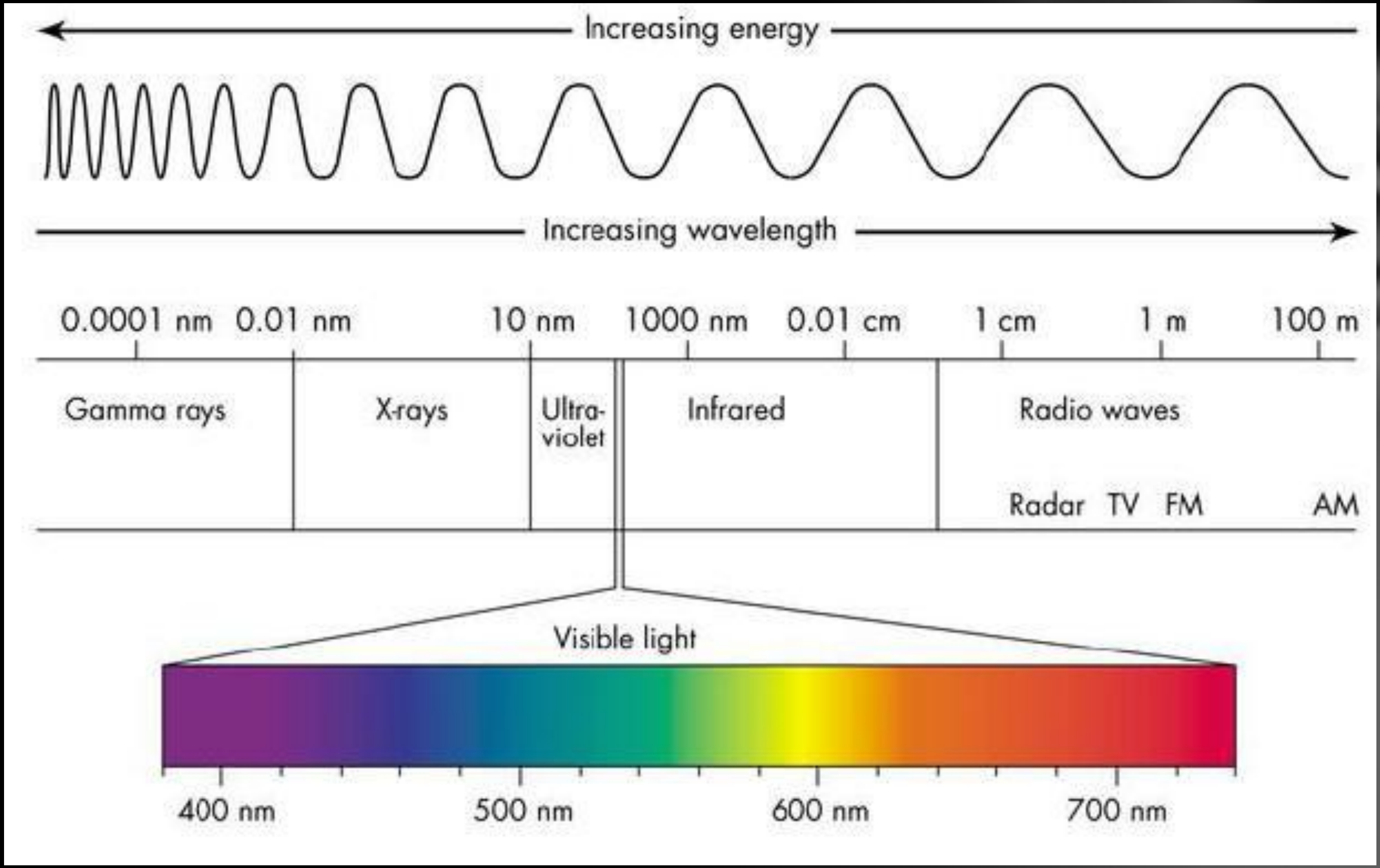
Transmission

- Light passing through an object is being “transmitted” through that object
- Reflection, refraction, absorption and diffusion all affect light transmission

Diffusion (Scattering)

- When light is incident on a rough surface, it is reflected or transmitted in many directions at once, this is called diffusion or scattering
- Amount of scattering depends on:
  - Difference in refractive index between the two materials
  - Size and shape of particles of diffusing material compared to the wavelength of light
  - For example, air molecules are the right size to scatter light with shorter wavelengths giving us the blue sky
  - Bidirectional scatter distribution function (BSDF) quantifies scatter and its effects

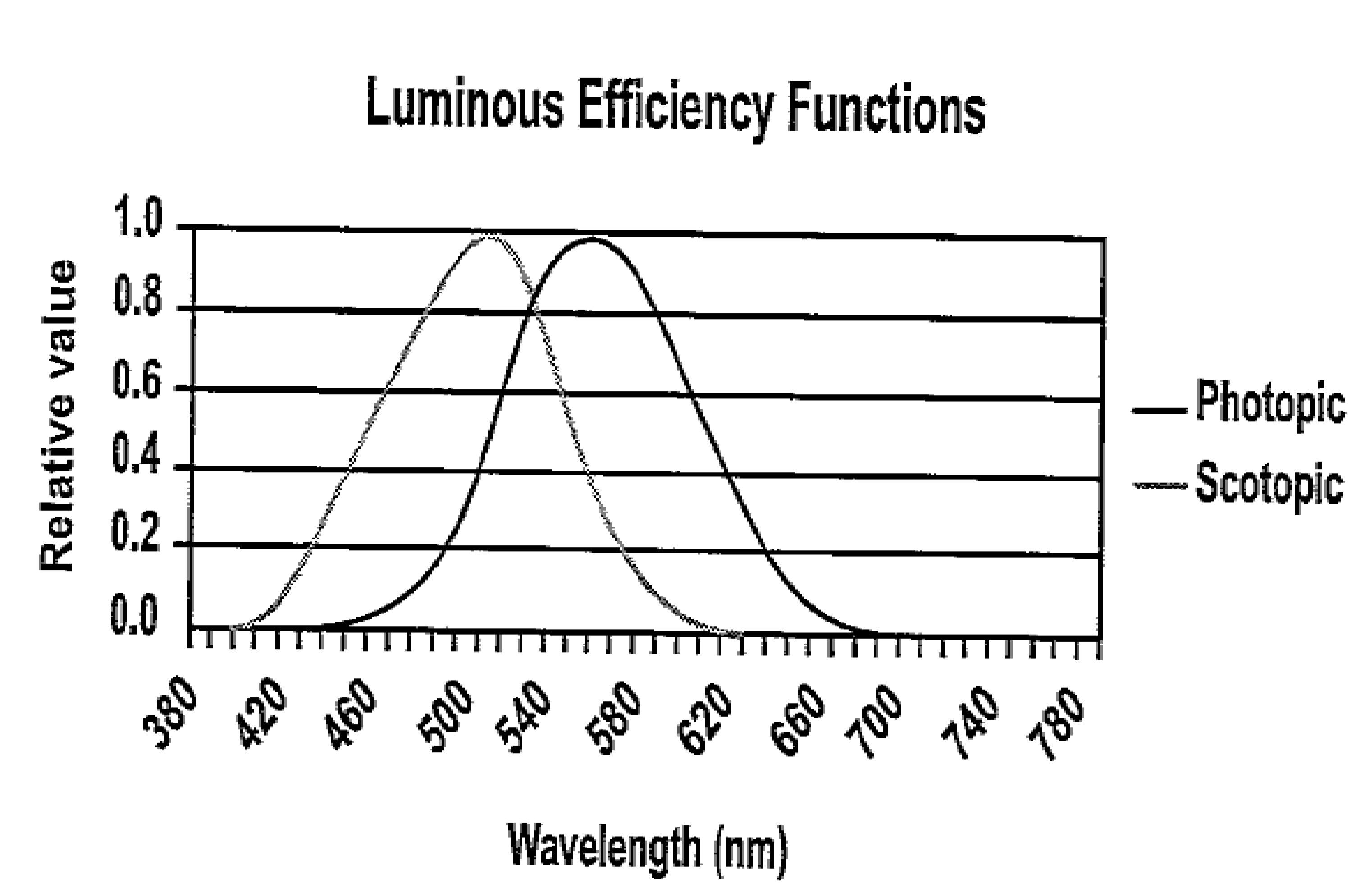
Spectral response



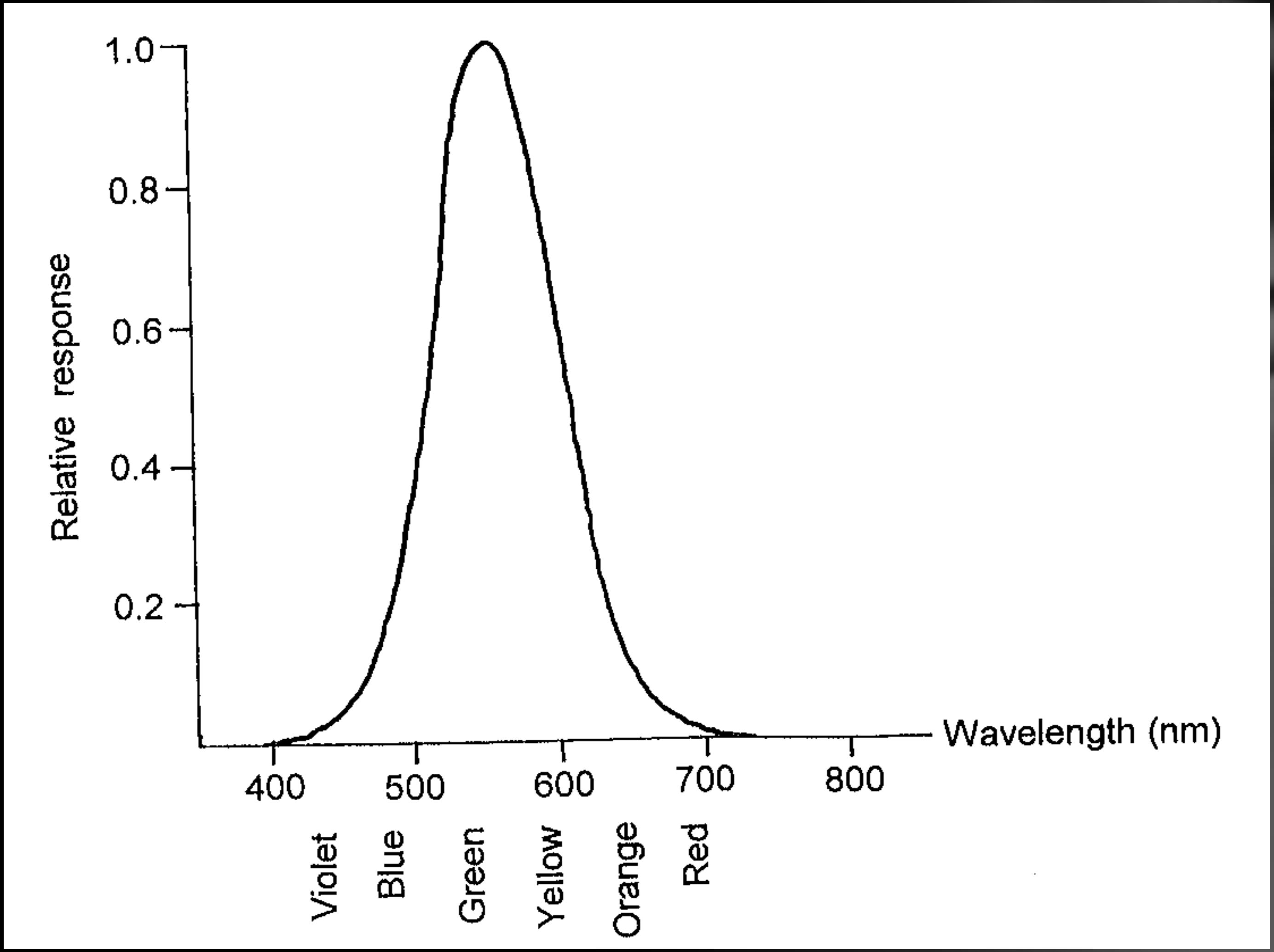
Spectral response

- The human eye is more sensitive to some wavelengths than others
- The eye contains two types of photo-receptors, CONES and RODS
- In bright light the cones dominate – PHOTOPIC vision
- In dim light the rods dominate – SCOTOPIC vision
- In between both rods and cones are used – MESCOPIC vision
- Relative sensitivity of cones (photopic) peaks at 555 nm
- Relative sensitivity of rods (scotopic) peaks at ~507 nm

Spectral response



Spectral response



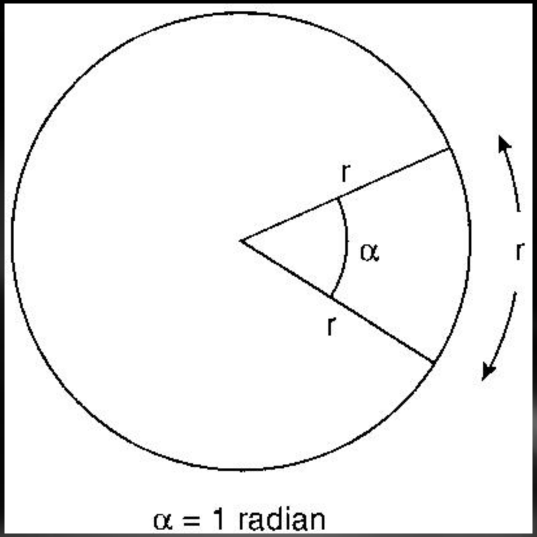
Units & conventions

- The CIE has chosen a wavelength of 555 nm – peak of the Photopic sensitivity function as a standard reference wavelength of the lumen.
- By definition: there are 683 lm/W at 555 nm wavelength
- Lumens at all other wavelengths are scaled by their Photopic and scotopic luminous efficiency functions
- Example: at 507 nm there are 1700 lm/W in Scotopic and only 304 lm/W when Photopic function is used.
- The convention is to use the Photopic luminous efficiency function in nearly all light measurements

Units & Conventions

- In radiometry, the common unit is the Watt (W), a measure of radiant flux (power in j/s)
- In photometry, the common unit is the Lumen (lm) which measures luminous flux
- 1 watt = 683 Lumens for light at 555 nm
- For light at other wavelengths the conversion will vary depending on the spectral response of the eye
- Irradiance is measured in W/m^2
- Illuminance is a measure of visible flux density (photometric flux) and is measured in Lux (lm/m^2)

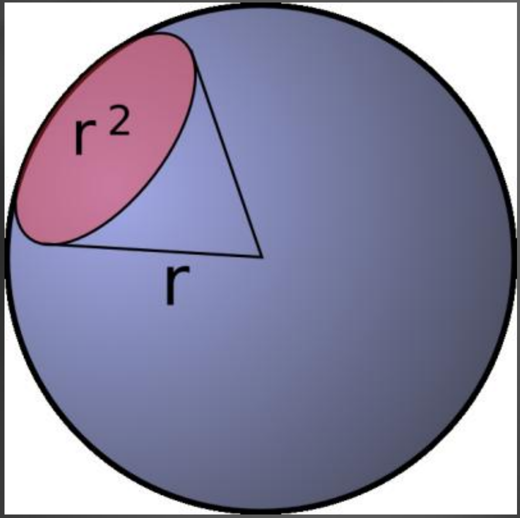
Units & Conventions



- A solid angle is a 3D equivalent to a 2D angle
- 2D angle is measured in radians
- 3D angle is measured in steradians
  - "the solid angle subtended at the centre of a sphere by an area on its surface numerically equal to the square of the radius"
  - E.g. one steradian section of a sphere with radius 1m would subtend a surface area of 1 m^2
- Luminous intensity is the amount of visible power per

unit solid angle measured in candelas

- 1 Candela = 1 lm/sr



Material properties

- How does building simulation software treat materials with respect to their properties?

Material Type		Transparent Layer
Name		am1pilk\1
Description		4MM CLEAR FLOAT
Width (mm)		4.0
Conductivity (W/m²·C)		1.0
Vapour Diffusion Factor		99999.0
Solar Transmittance		0.82
Solar Reflectance	External	0.07
	Internal	0.07
Light Transmittance		0.90
Light Reflectance	External	0.08
	Internal	0.08
Emissivity	External	0.84
	Internal	0.84

Glazing Parameters

Light		Solar Energy (EN410)				Pilkington Shading Coefficients		
Transmittance	Reflectance	Direct Transmittance	Direct Reflectance	Direct Absorptance	Total Transmittance (G Value)	Short Wavelength	Long Wavelength	Total
0.760	0.120	0.498	0.193	0.308	0.616	0.573	0.136	0.709

Material properties

Construction layers (outside to inside)

Description	Thickness (m)	Conductivity (W/(m·K))	Type of glass or blind	Gas	Convection coefficient W/m²·K	Resistance (m²K/W)	Transmittance	Outside reflectance	Inside reflectance	Refractive index	Outside emissivity	Inside emissivity
PILKINGTON K 6MM	0.0060	1.0600	Uncoated				0.690	0.090	0.090	1.526		
Cavity	0.0120					0.3247						
CLEAR FLOAT 6MM	0.0060	1.0600	Uncoated				0.780	0.070	0.070	1.526		

g-value (BS EN 410) 0.6406

g-value (BFRC) 0.5189

Frame occupies 10.00% of the total area

THETA = Angle of incidence
T(D) = Short wave solar transmission (directly transmitted fraction)
T(R) = Long wave + convection from inner pane (retransmitted fraction)

THETA	0°	10°	20°	30°	40°	50°	60°	70°	80°	90°
T(D)	0.542	0.540	0.535	0.526	0.512	0.486	0.435	0.330	0.143	0.000
T(R)	0.096	0.097	0.098	0.100	0.102	0.104	0.104	0.096	0.071	0.000

Short-wave shading coefficient 0.6225

Long-wave shading coefficient 0.1107

Total shading coefficient 0.7333

Material properties

- Both of these use the Fresnel equations to calculate transmission and absorption and reflection at non-normal incidences
- From entered data you get “derived parameters” relating to solar transmission, reflection and absorption at 10 intermediate angles
- Angles used for direct beam and for diffuse, hemispherically averaged data is used
- This relates to “solar” to comply with space heating and cooling load calculations
- Not applied vigorously for daylight simulation
- “derived parameters” are interpolated using assumptions and are generalised parameters applied to many types of transparent material
- Not based on observations and/or manufacturers data

Material properties (E+)

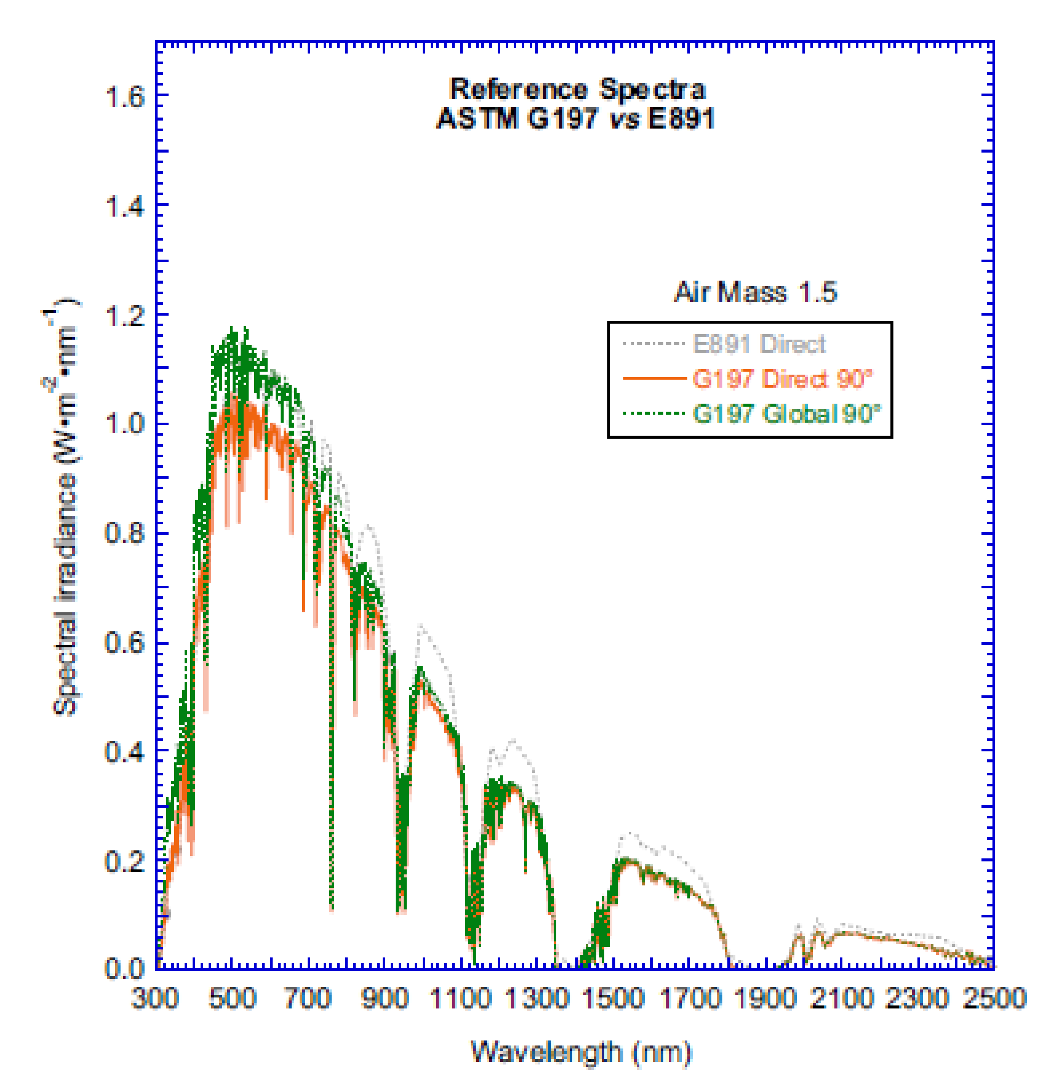
- In E+, optical properties of individual glass layers are given by these quantities at normal incidence as a function of wavelength:
  - Transmittance, front reflectance and back reflectance (and Refractive Index)
- Remembering that each variable is a function of wavelength:
  - E+ can calculate spectral average values by integrating over wavelengths
  - Spectral average solar and visible properties are:

$$P_s = \frac{\int P(\lambda) E_s(\lambda) d\lambda}{\int E_s(\lambda) d\lambda}$$

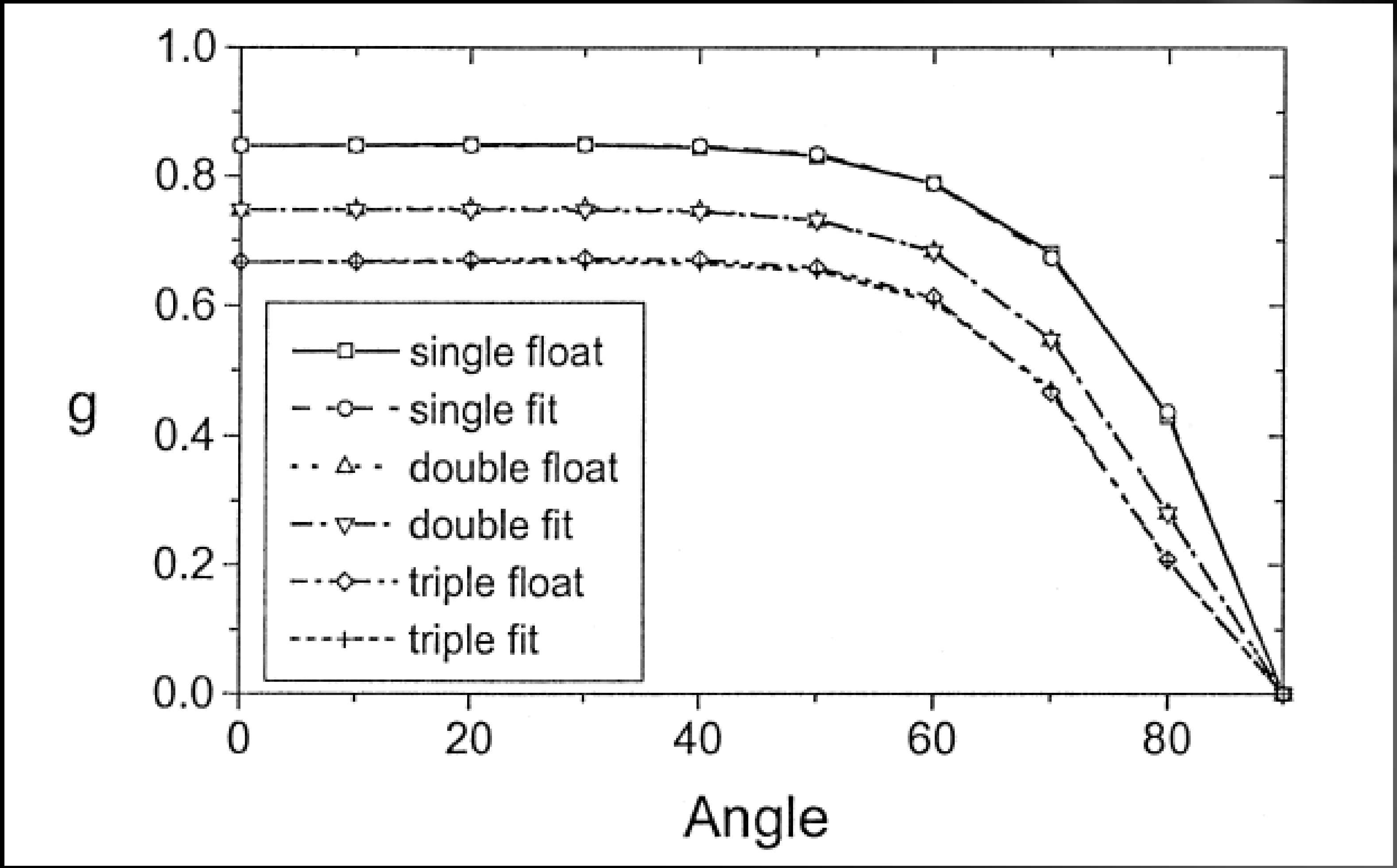
$$P_v = \frac{\int P(\lambda) E_s(\lambda) V(\lambda) d\lambda}{\int E_s(\lambda) V(\lambda) d\lambda}$$

- E_s (λ) is the solar spectral irradiance function and V (λ) is the Photopic response function of the eye
- Using values of terrestrial solar global spectral irradiance in W/m²-micron and based on ISO 9845-1 and ASTM E 892

Material properties



Material properties – angular dependence



CIE Overcast Sky

- The CIE overcast sky represents the luminance distribution of the sky under heavily overcast conditions (Without Sun) where the sky is diffuse
- The total unobstructed illumination of a heavily overcast sky is 5000 lux on the horizontal plane
- Luminance L increases with altitude, zenith L is x3 greater than horizon
- It is rotationally symmetrical about the vertical axis and the building thus becomes insensitive to orientation
- Dependencies on solar angle and direct/beam radiation become futile
- Refer to what is said in earlier slides…

Software

- Daylight simulation software:
  - Radiance (Many commercial and non commercial interfaces), AGI32, Photopia, Light-Tools, Flucs-DL, Light Pro, Lumen-Designer, Adeline (R), Relux, Dialux, Sky-vision, Daysim (R), many artificial lighting packages
  - Plug-ins and add on to Radiance (P-map, Radzilla)
  - Daysim has a Google Sketchup Plugin and can be used to determine daylight factors and climate based daylight modelling
  - Both are free to download

Calculation methods

1. Radiosity
    1. Assumes all surfaces are perfectly diffusing
    2. Divides a room into a number of elements (discretisation)
    3. Reflections between each element and other elements which can receive light from it are simulated, number of calculations = to the square of number of elements
    4. Specular reflections can be modelled (theoretically) but takes time and memory
    5. Progressive radiosity starts with an estimate of surface luminances then refines it
    6. The solution converges when sufficient refinement has been achieved.
2. Ray-Tracing
    1. Backward ray-tracing is where a light ray is traced back from target plane/point until it reaches a surface, it is then further traced back to a light source
    2. If surface is specular or transparent, the ray follows the adjusted path of reflection or transmission to next surface before it is traced to a light source
    3. In basic ray tracing, diffuse inter-reflections are ignored and an ambient value akin to internally reflected component is added overall
    4. Other methods emit more rays at each intersection point for more accuracy – increases computation time

Calculation methods

- Forward ray tracing traces the rays from the light source to the target point
- Better at handling specular reflections
- Photon-map is a forward ray tracer plug-in for Radiance
- Suitable for spaces with Sunpipes and innovative daylighting technologies
- Currently used by Monodraught and University of Nottingham to research into Sunpipes along with long term in-situ monitoring and lab testing of domes, diffusers and reflective materials

Summary

- The behaviour of light needs to be reflected properly in building simulation, both for daylight simulation and thermal/energy studies
- Software tools can present challenges to integrating novel daylighting technologies which require more detailed modelling to gauge their full effects on a building
- The CIE overcast sky and DF methodology prevent these technologies from being evaluated properly
- Example: Sunpipes integration for BREEAM points

References

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- Radiance Cookbook (Axel Jacobs 2010)
- EnergyPlus Engineering Reference 2010
- Illumination Fundamentals, Lighting Research Centre
- Solar radiation modelling, T Muneer
- TAS Constructions Database
- IES Constructions Database
- Daysim User Guides (www.daysim.com)

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