



# VU Rendering SS 2012

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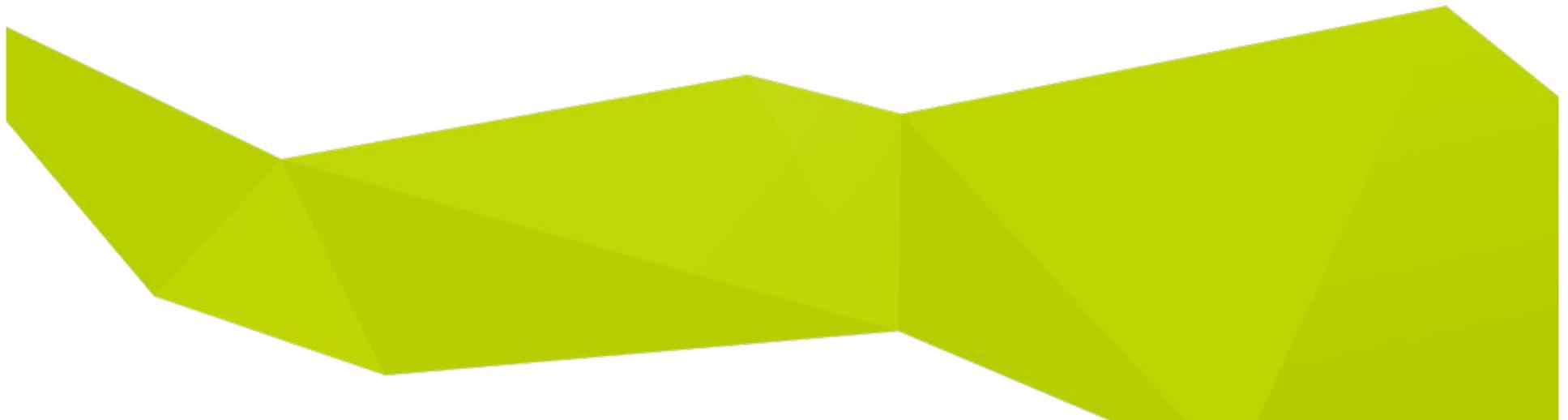
Unit 5: Spectral Rendering





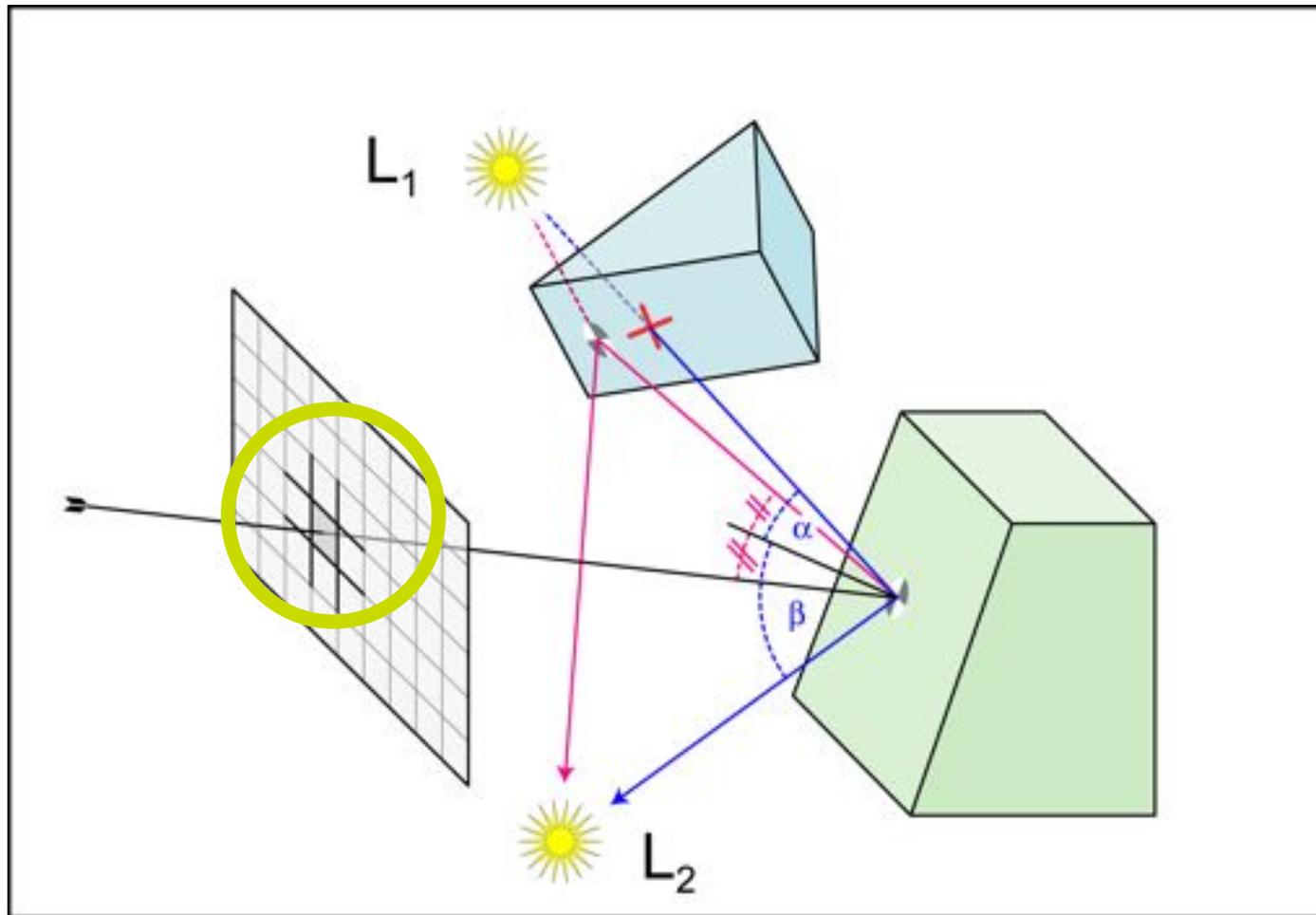
# Overview

1. Quantities used for light calculations in ray tracers
  - What is Light?
  - Colour space vs. Spectral rendering
2. Spectral Representations
3. Spectral Effects





What do we compute here?

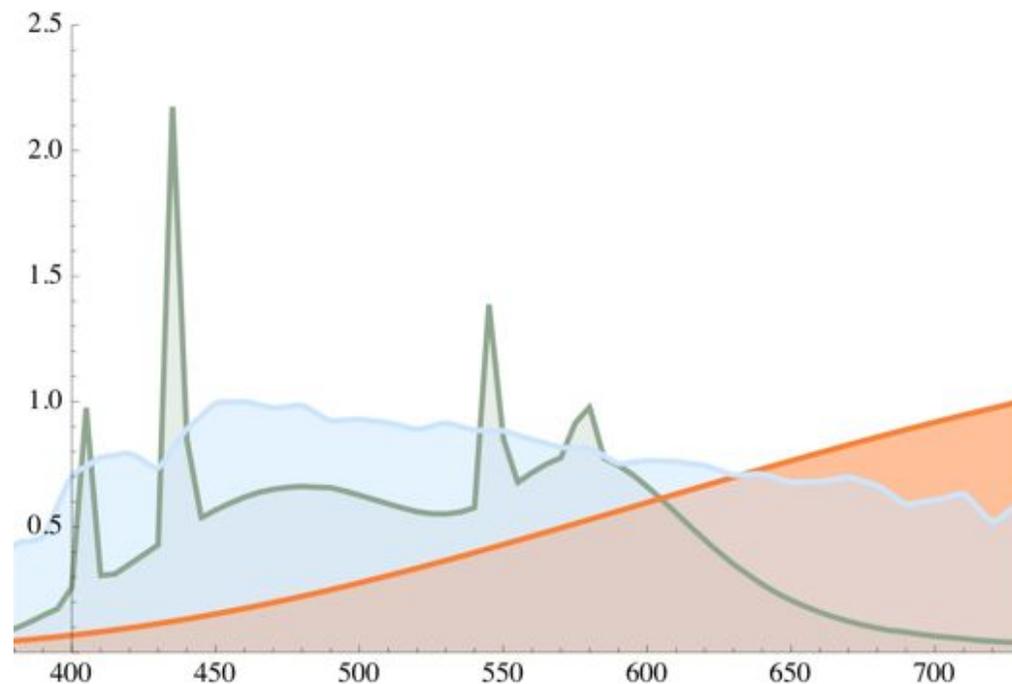






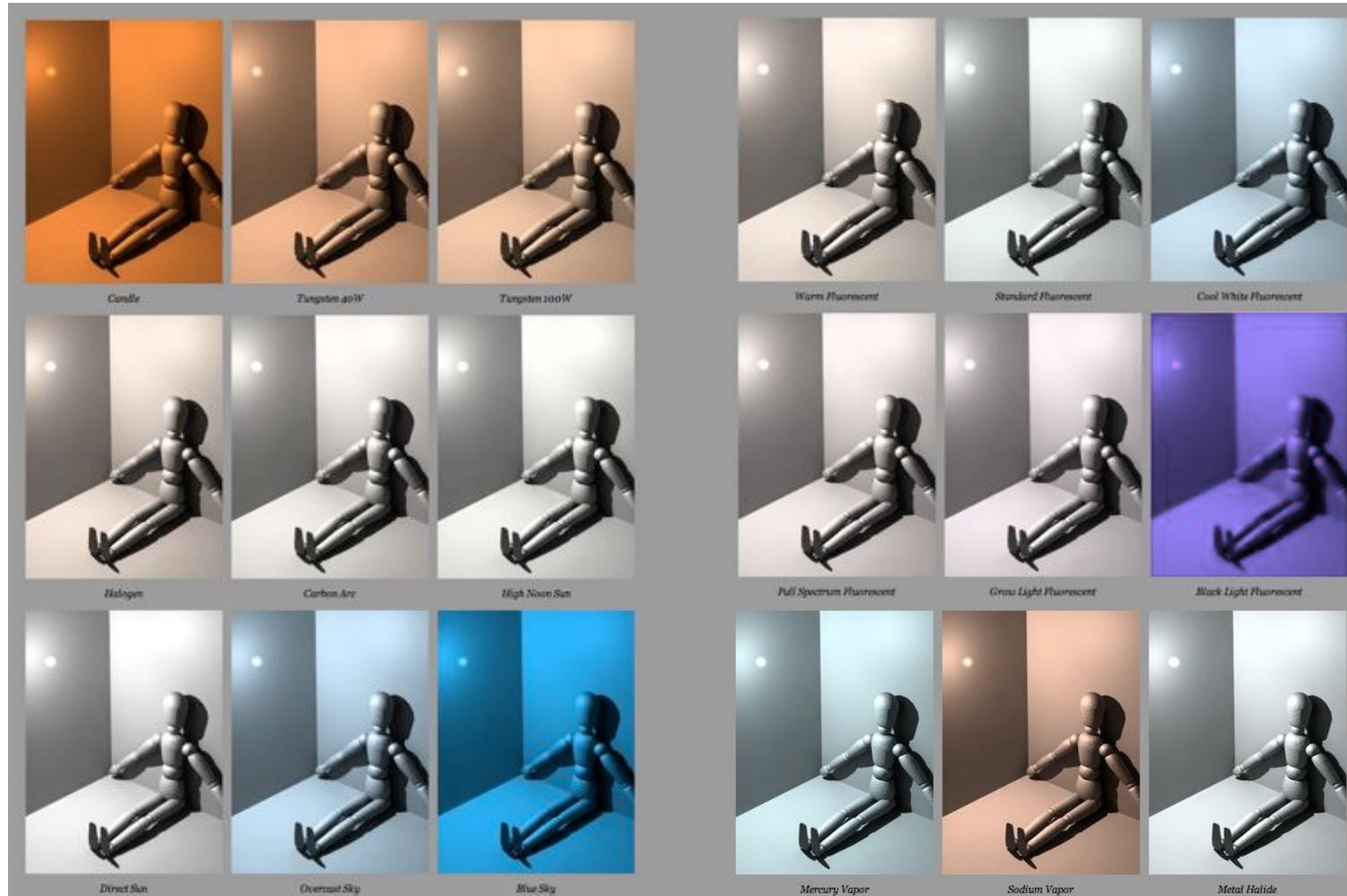
## Light - Spectrum

- Normally, a ray of light contains many different waves with individual frequencies
- The associated distribution of wavelength intensities per wavelength is referred to as the spectrum of a given ray or lightsource





# Lightsources Are Not White





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## Shading Calculation Quantities

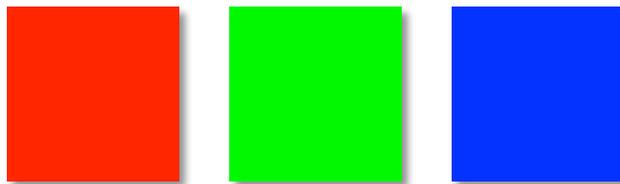
- Two main types of rendering engine exist:
  - Conventional colour space based renderers
    - RGB space (majority)
    - CIE XYZ space
  - Spectral Renderers
- Very few products available
  - Maxwell renderer, LuxRender, Indigo, ...
  - PBRT 2.0
  - Often few details of internal workings known



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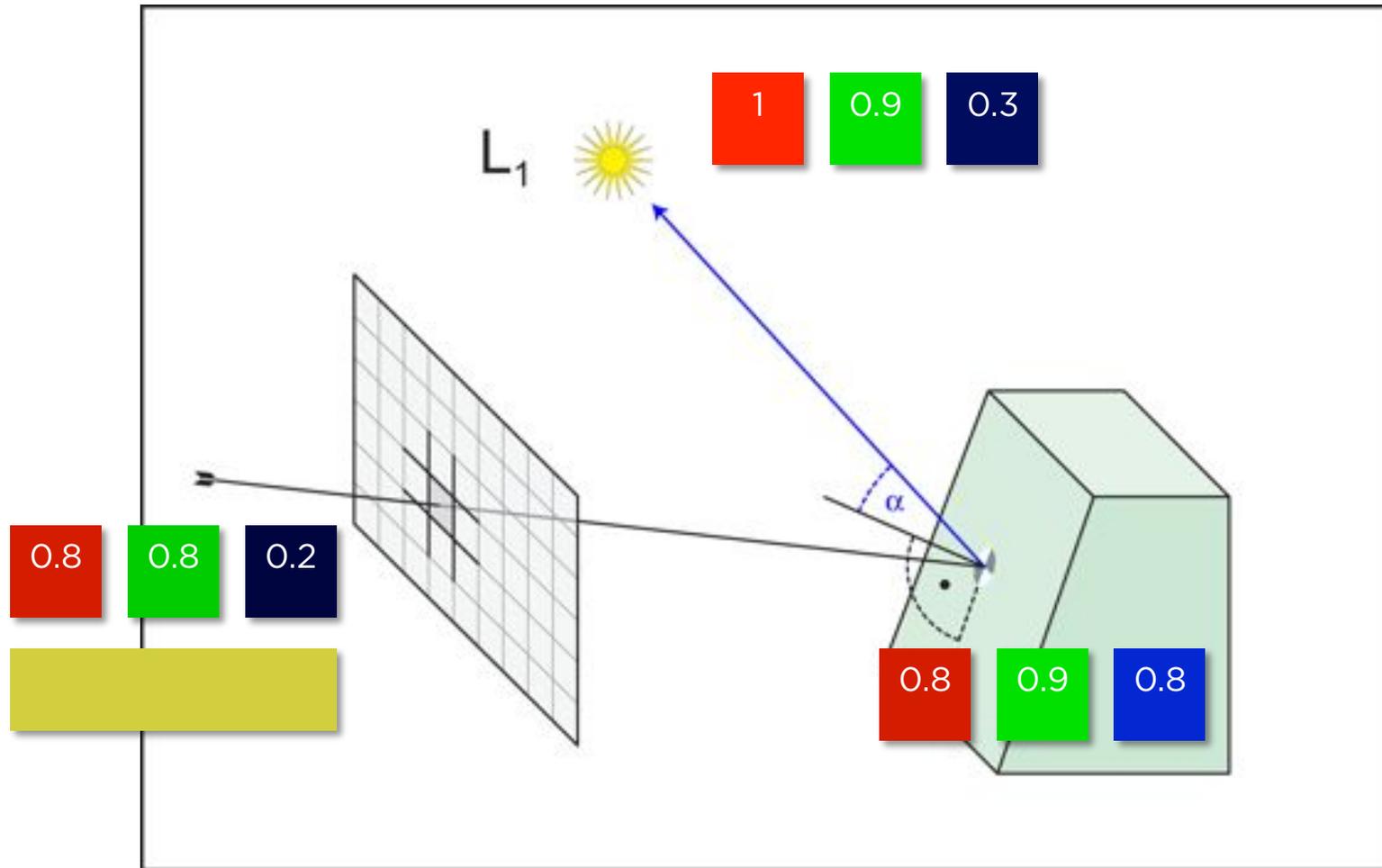
## RGB (Tristimulus) Rendering

- Three wavelength (corresponding to red, green, blue) define light source and material properties
- Process 3 samples separately throughout rendering calculation
- Device dependent
- RGB representation not ideal





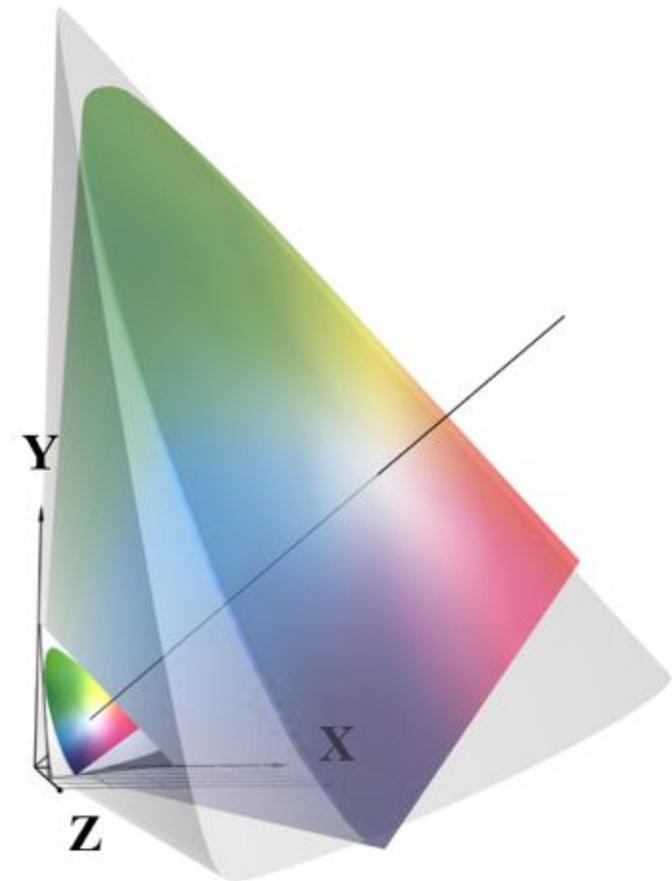
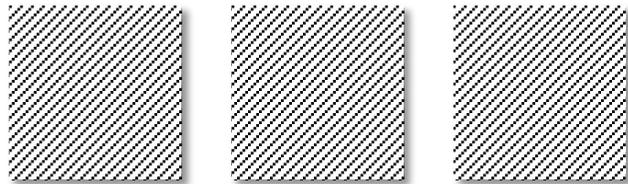
# RGB Light Propagation





## CIE XYZ

- A tristimulus colour system derived from RGB and based on imaginary primaries referred to as XYZ was defined in 1931
- All three are outside the human visual gamut
- Hence only positive XYZ values can occur
- Valid colours a subspace of the first octant - XYZ not closed under multiplication!





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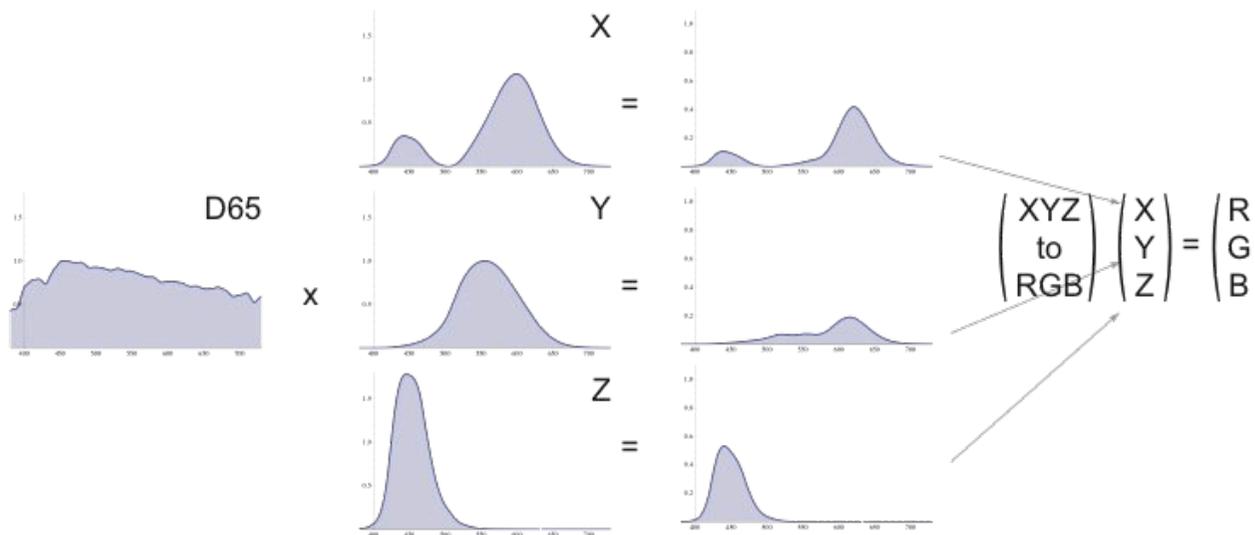
## CIE XYZ vs. RGB

- Problem does not exist for RGB spaces:
  - They occupy the entire first octant, are closed under multiplication
- RGB cannot represent all visible colours
  - XYZ is no alternative due to the discussed problems!
- Older literature still recommends using XYZ!
- Alternative: **Spectral Rendering**



# Spectral Rendering Steps

- (Get spectrum)
- Prepare spectrum
- Process spectral samples separately throughout rendering calculation
- Compute final display color using CIE color matching functions and standard transformations





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## Step 1: Measuring Spectra

- Spectra can be measured with a spectroradiometer
- First step: Calibration of measurement device
- Reference standard needed
  - A source of known emissivity
    - Blackbody
    - Reference Lamps
  - A detector with an exactly known response
  - A surface with exactly known reflectivity



## Reference Lamps

- Specially designed lamps of known SPD as standards
- Repeatability of lamp manufacturing is good enough to duplicate these standard lamps
- Tungsten halogen lamps of 1000, 200 and 45 W was developed for general use
- Burning time of these devices is limited





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## Gretag Macbeth Spectrolino

- Handheld device, nowadays called iOne
- 10nm resolution, 380 to 780nm
- Not particularly useful without the accompanying software
- Serial interface fully documented
- Less repeatability, less inter-device agreement than previous device
- Several similar devices are being offered by the industry





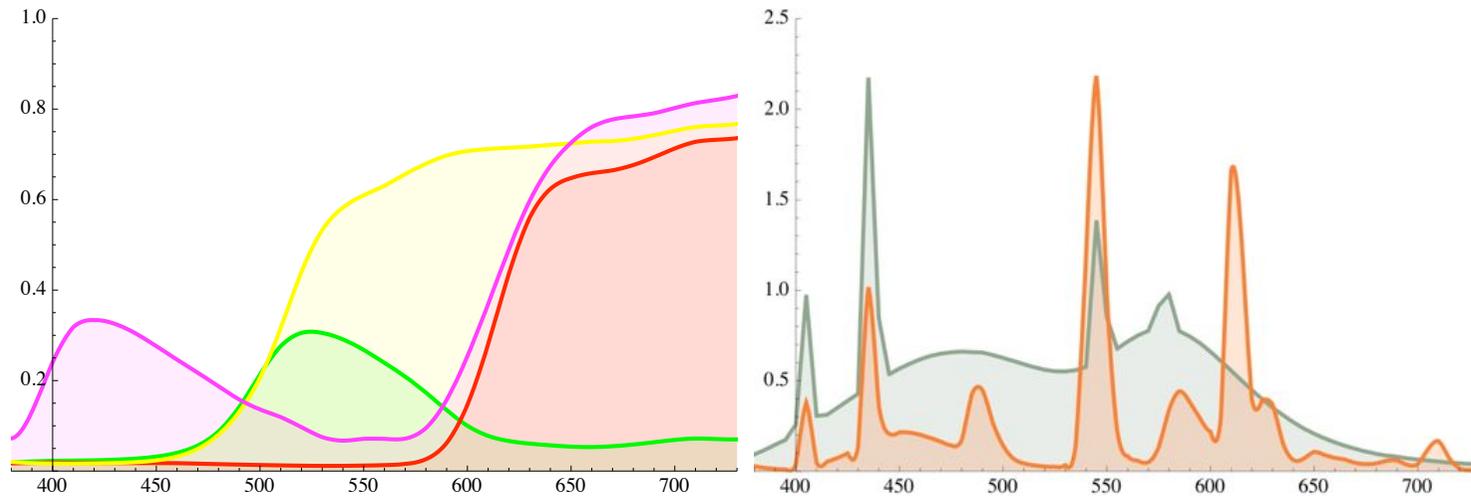
## Spectroscan

- Used for fast, routine scanning of opaque and transparent colour charts and printouts
- Main use: colour charts are created during printing equipment calibration
- A Spectrolino-type device is used as measurement device





## Step 2: Preparation

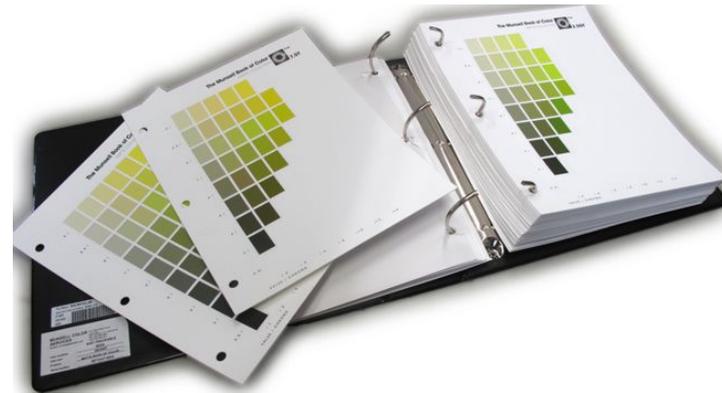


- Represent light as frequency distribution
  - Usually smooth
  - Sometimes sharp peaks (fluorescent light sources, spectral colours)
- How do we store the data?



## Colour Collections

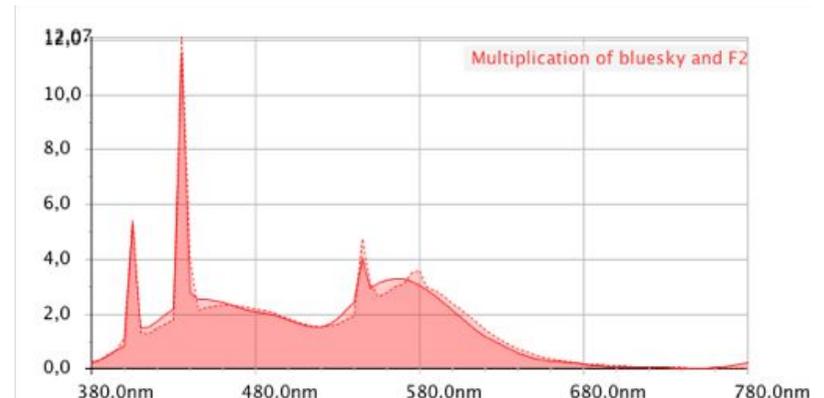
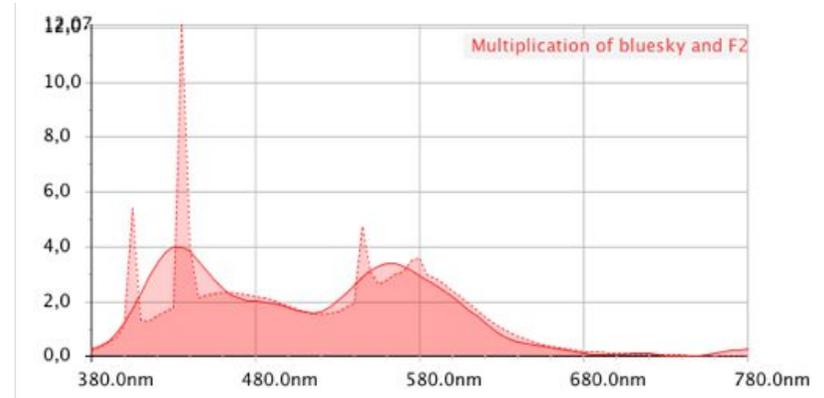
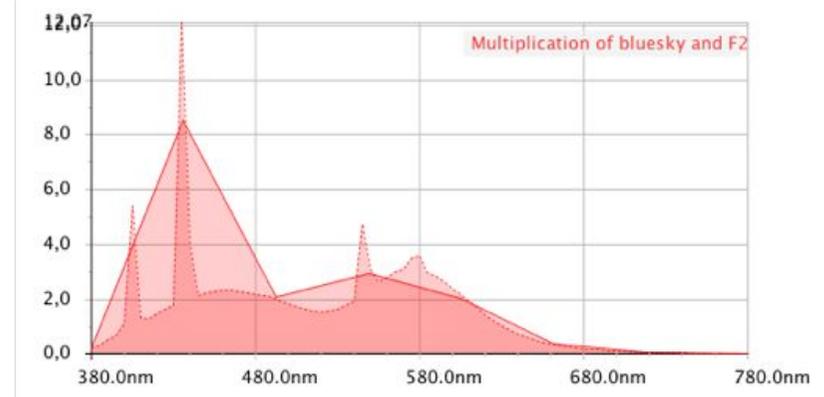
- Munsell Book of Color
  - Based on the Munsell system
  - 1269 colours
- NCS Colour Atlas
  - 1 750 colours
- RAL
  - RAL Classic: 190 colours
  - RAL Design: 1714 colours





## How to discretize these distributions?

- Regularly sampled spectra
  - Aliasing
  - Fast Convolution
- Linear or higher order representations
  - Efficient storage
  - Slow convolution
- Hybrids
  - Slow, but even more efficient w/r to storage

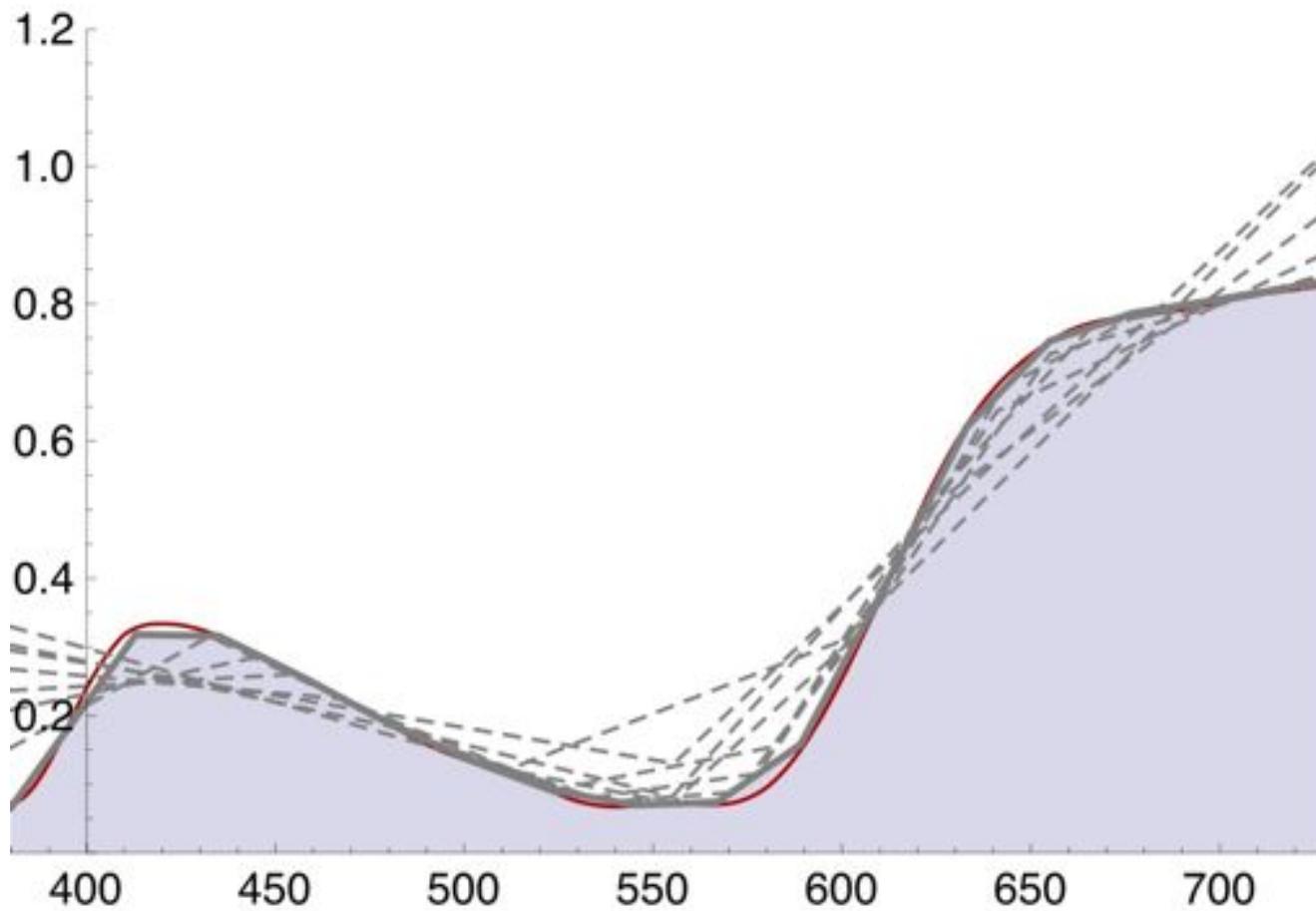




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## How Many Samples Do We Need?

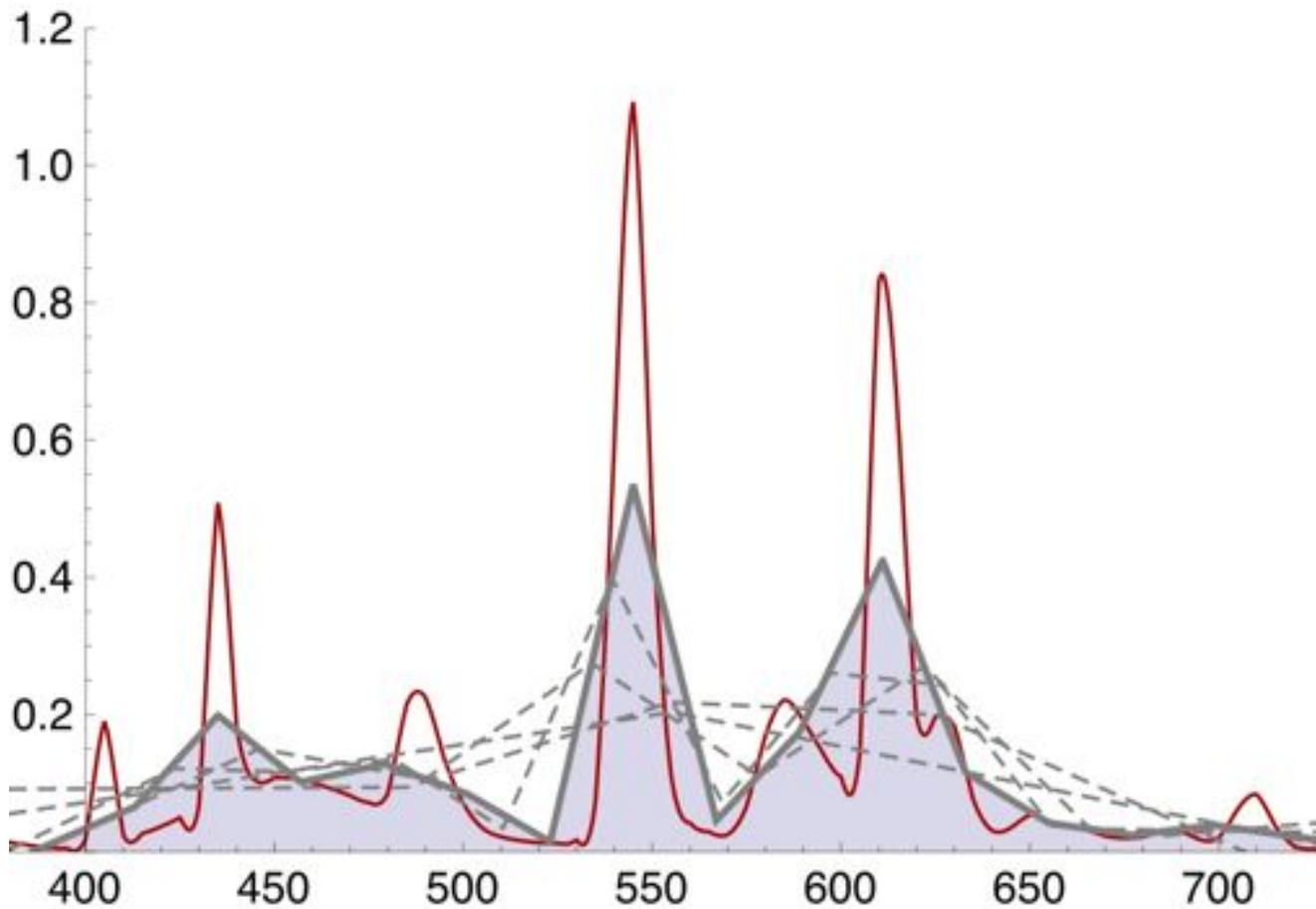
- Depends on spectrum



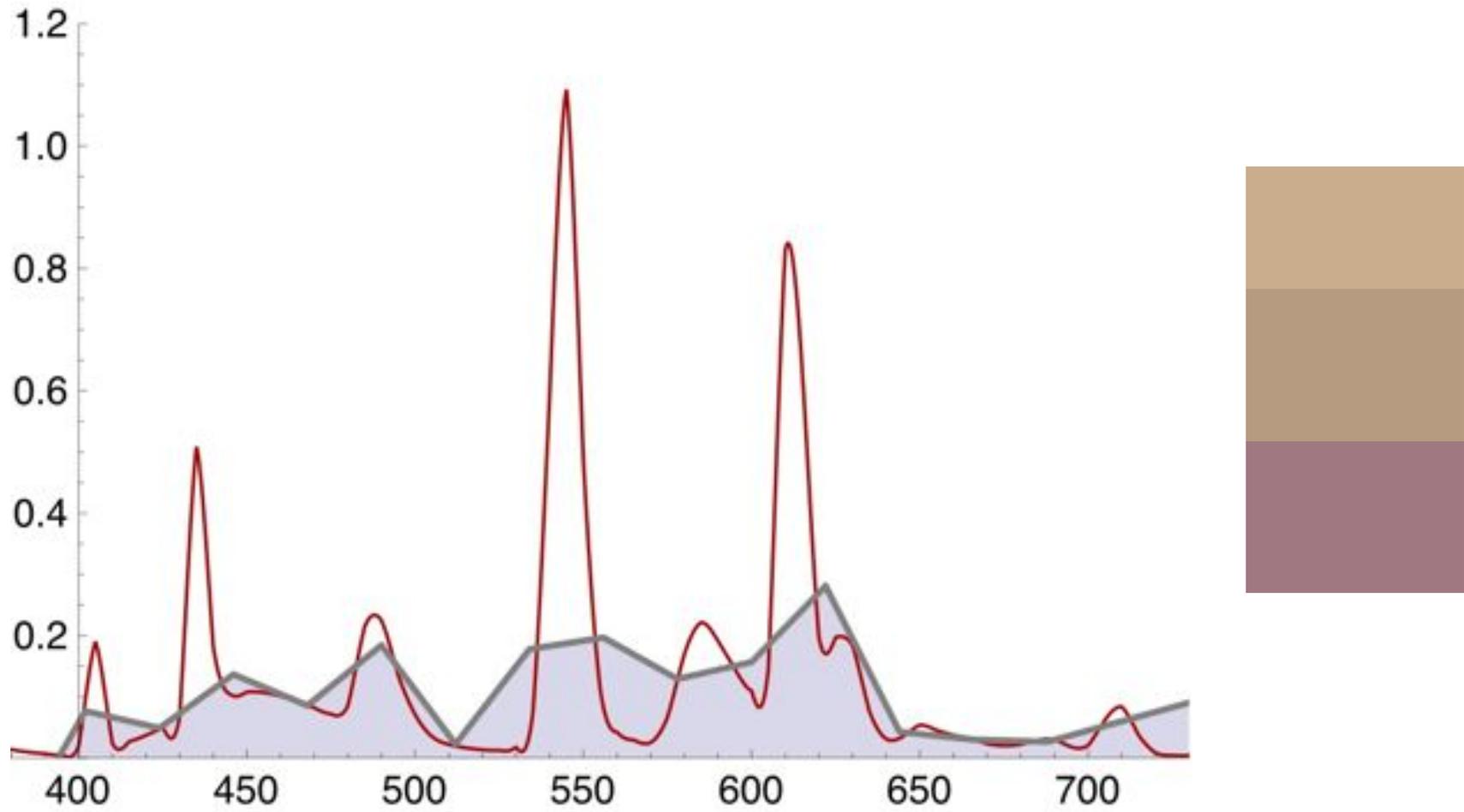


## Fluorescent Spectra (CIE F11)

- More samples are needed for spectra with sharp peaks

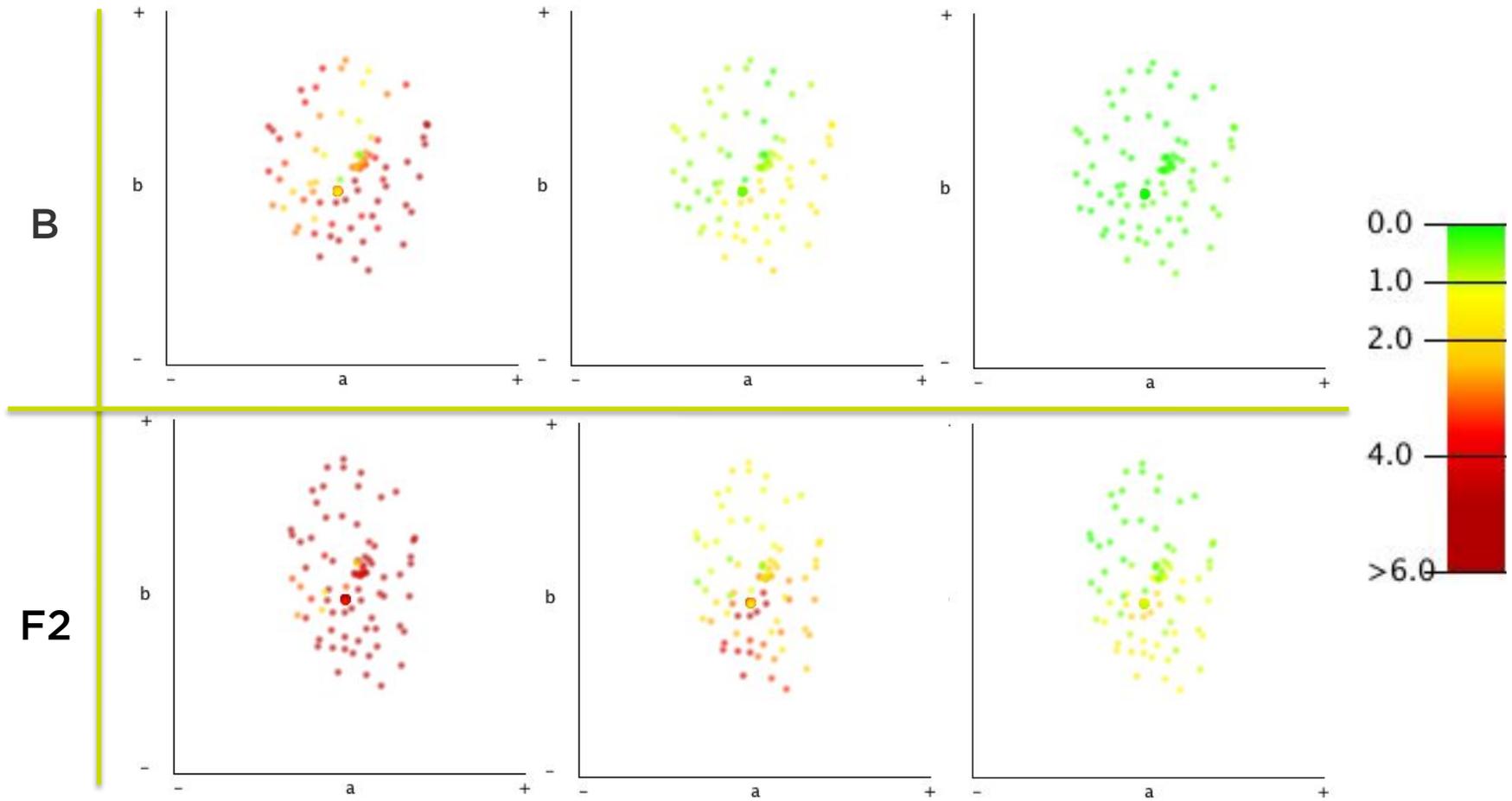


# CIE F11 - Representations



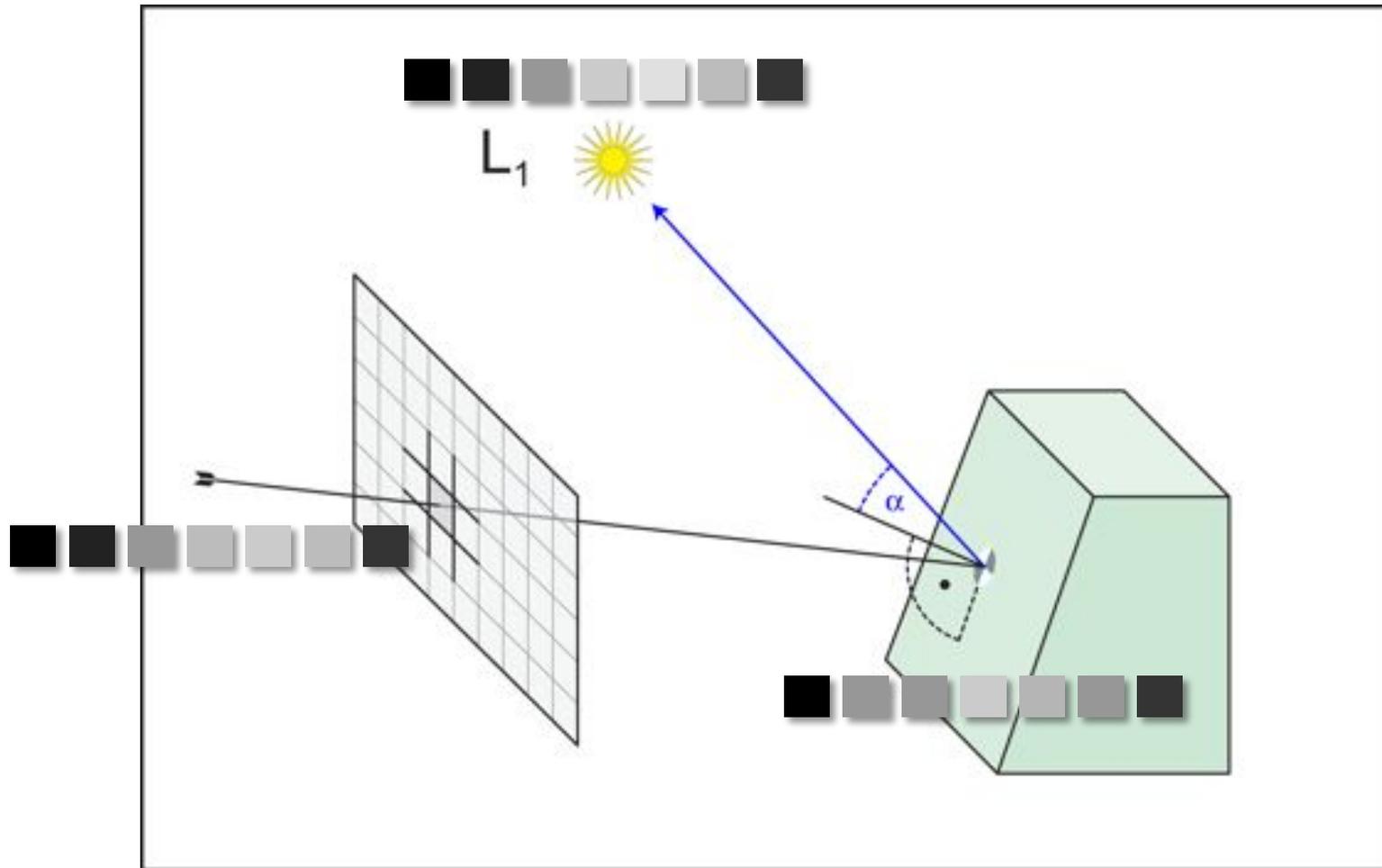


# Error Map Sampling Points



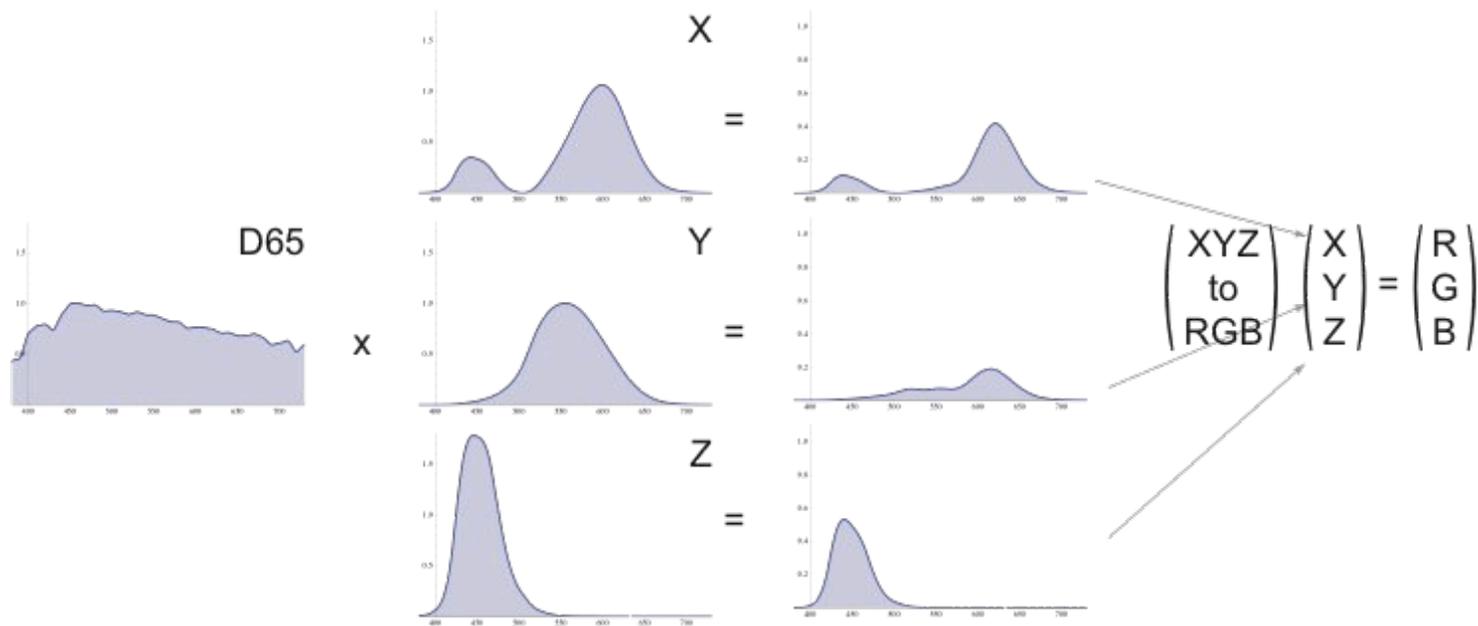


## Step 3: Rendering





## Step 4: Conversion to RGB





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## Spectral vs. RGB

### RGB Rendering

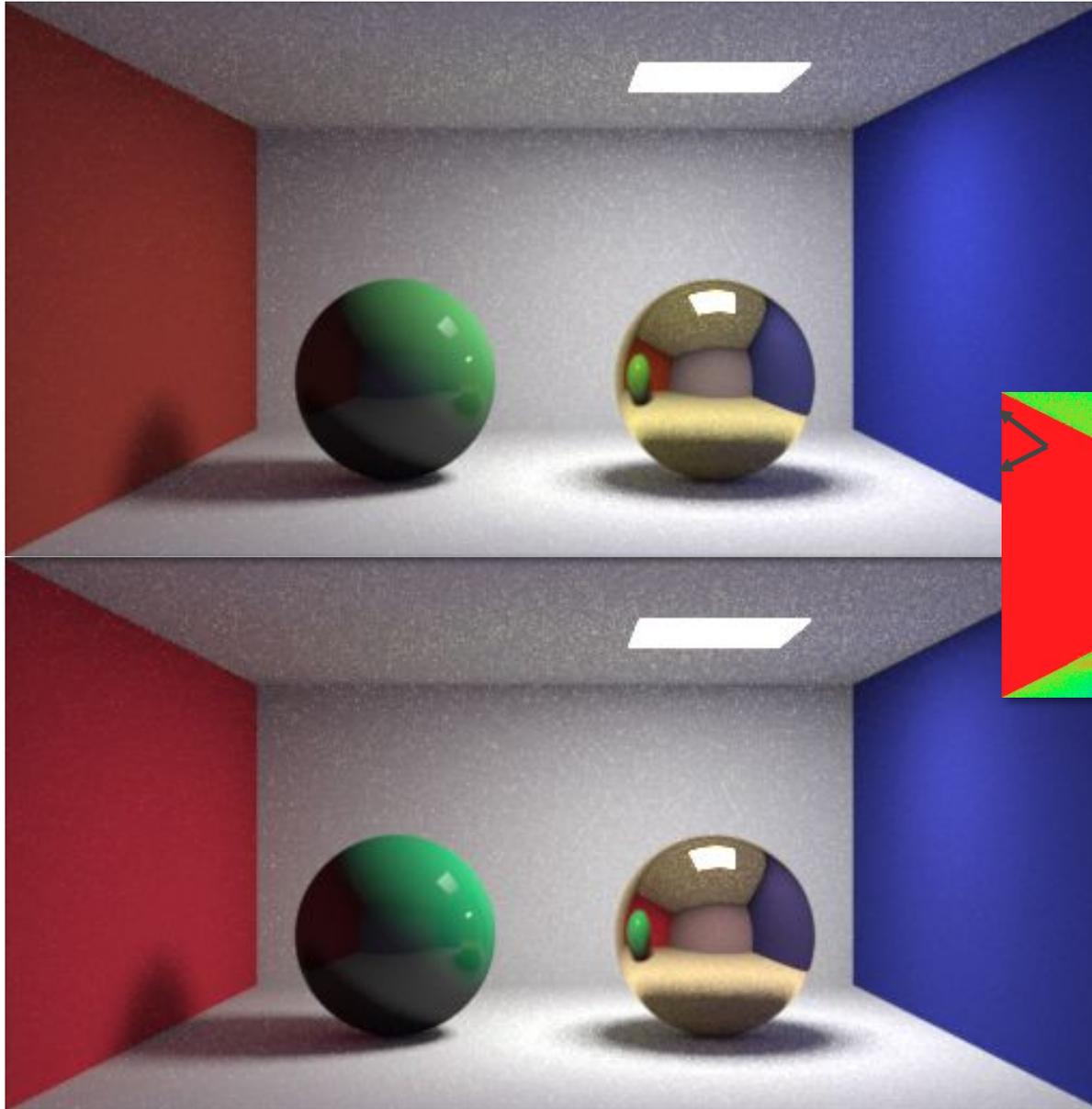
- + Fast, widely supported
- Limited accuracy (sharp spectra, different illuminants)

### Spectral Rendering

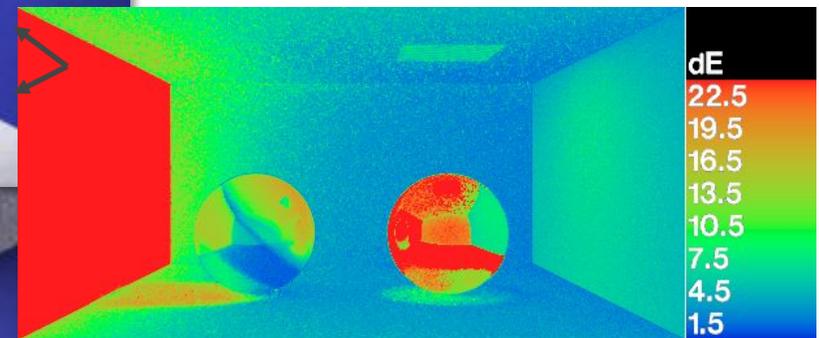
- + Accuracy, prediction of nature possible
- High cost, Aliasing, data mixing, input data, more complicated to write



# Comparison Spectral/Tristimulus



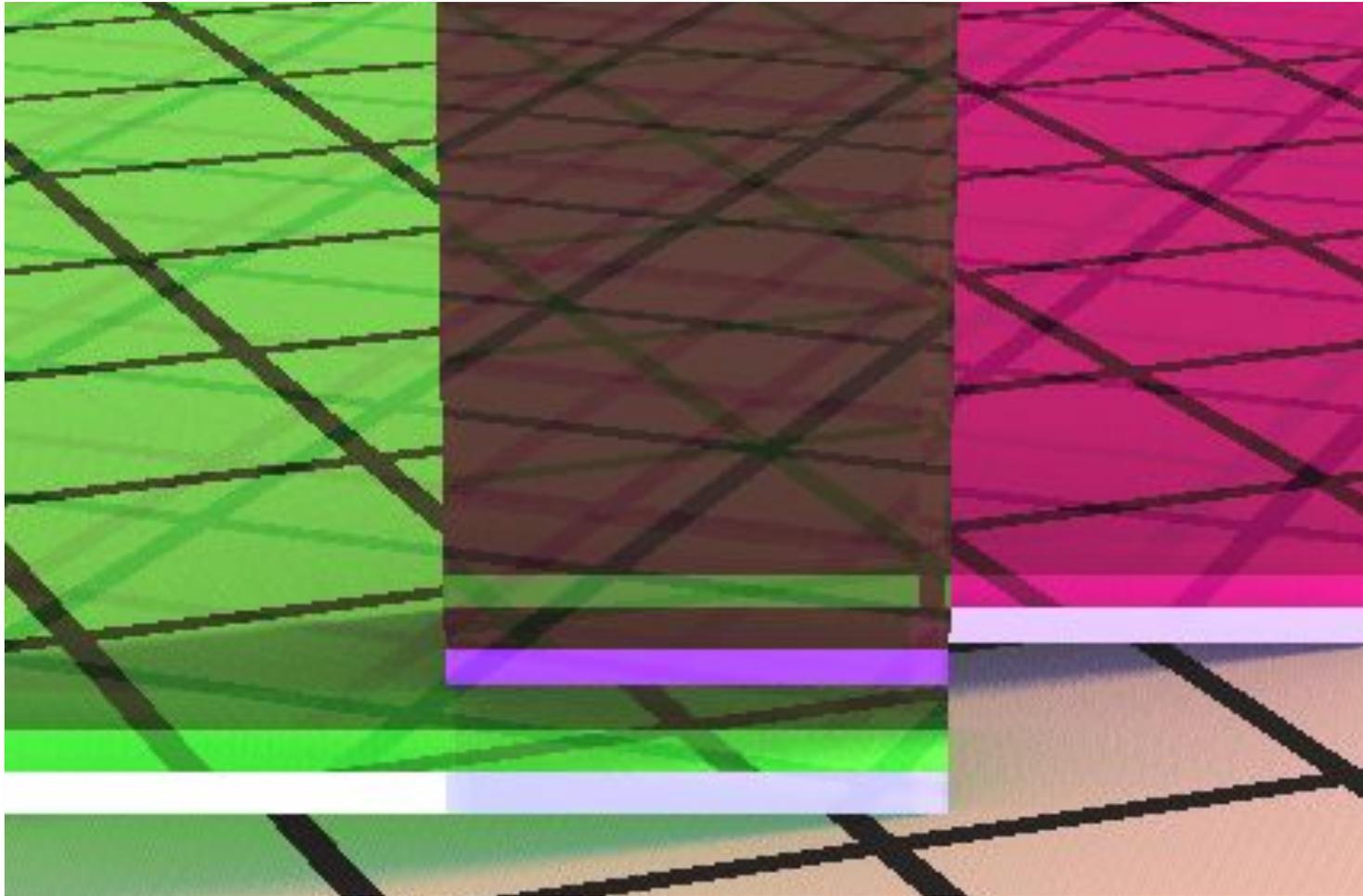
Full spectral rendering



Naïve tristimulus rendering (CIE XYZ)



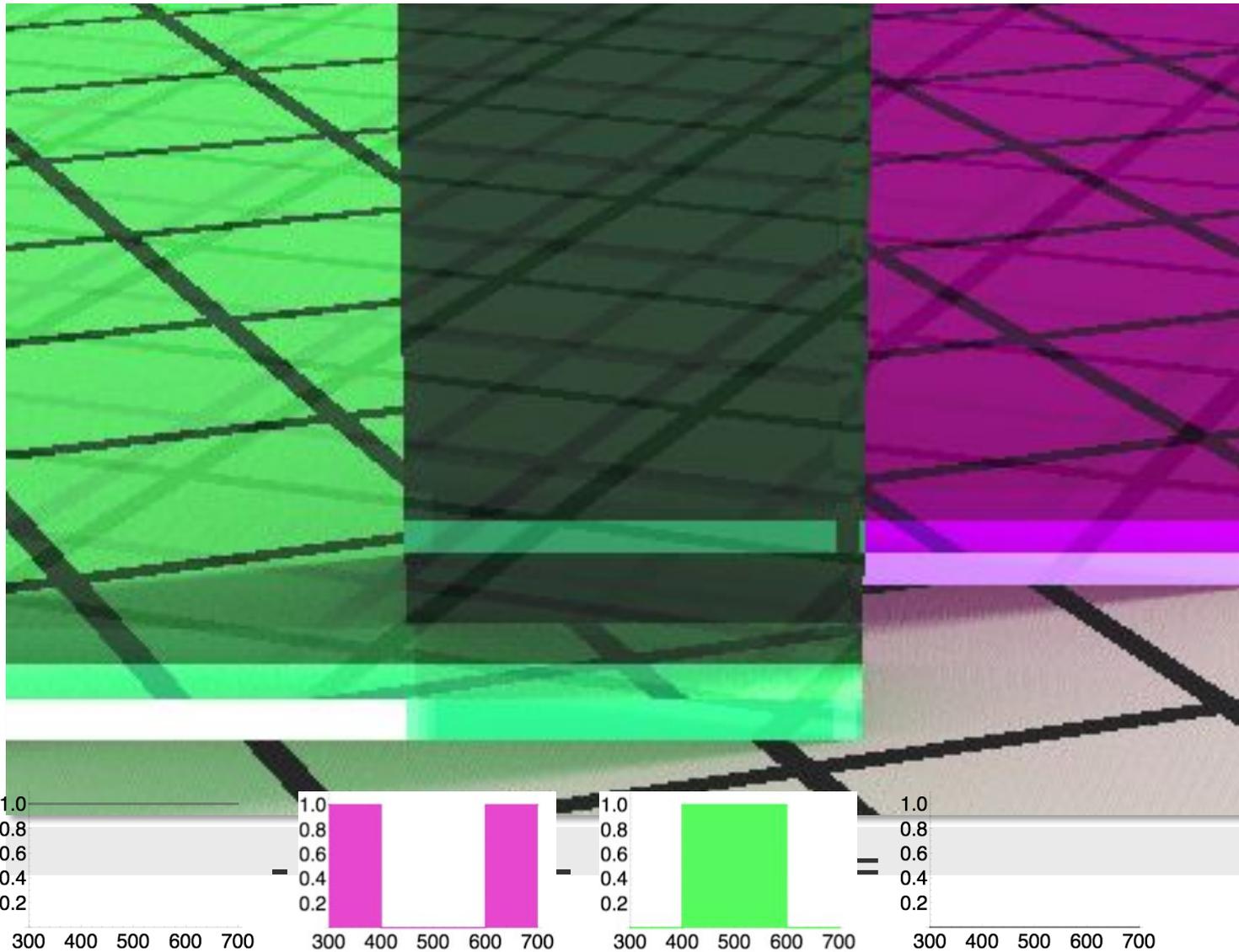
# RGB Rendering



$$(255,255,255) - (147,51,187) - (70,106,148) = (77,0,39)$$



# 16 Spectral Samples





## Spectral Effects

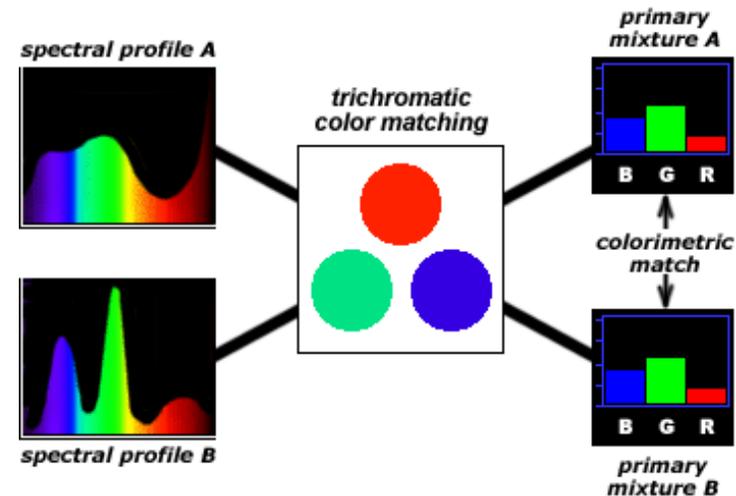


- Effects that require spectral representation of light:
  - Metamerism
  - Volume absorption
  - Dispersion (prisms, rainbows)
  - Interference and diffraction
  - Fluorescent materials and light sources
- RGB insufficient to accurately reproduce such effects



# Metamerism

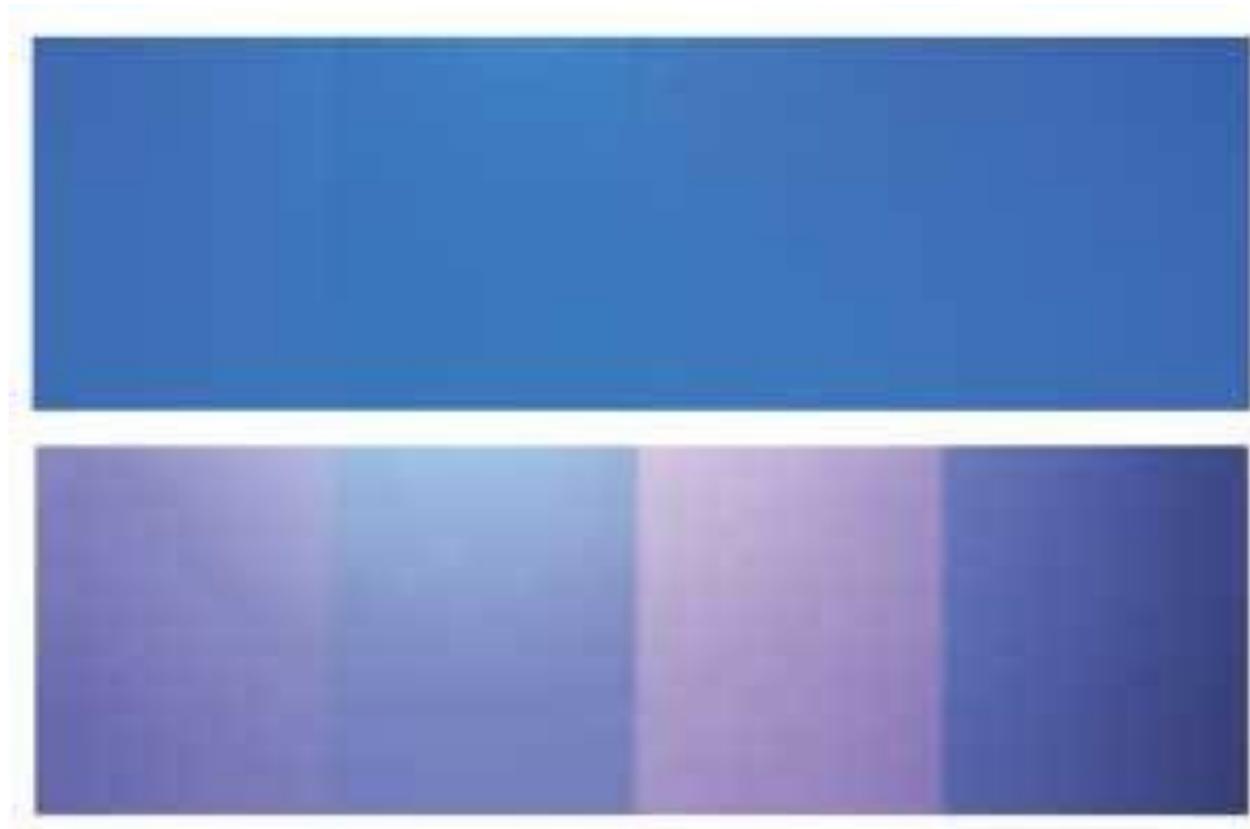
- Occurs frequently
- One of the most interesting problems in the paint and pigment industry
- Makes prediction of object appearance by colourspace renderer impossible





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## Metamerism Example

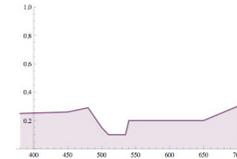
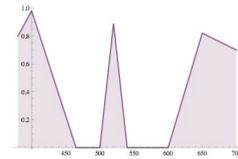


4 patches of different types of blue paint, illuminated with white LED and a quartz-halogen white light



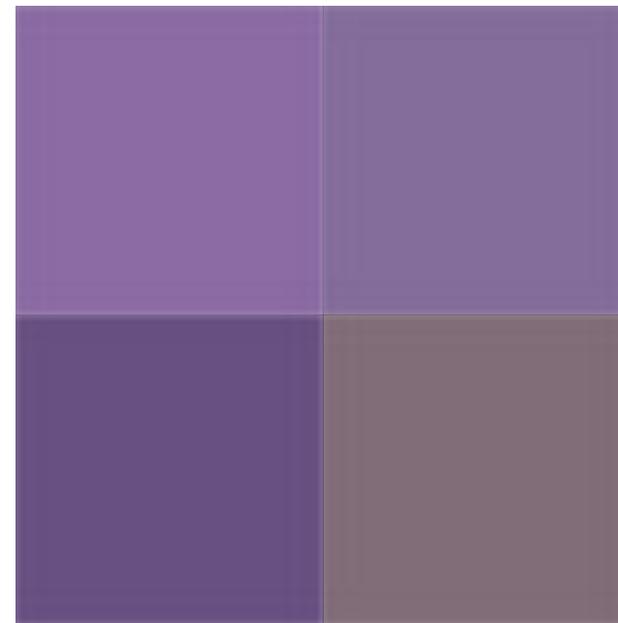
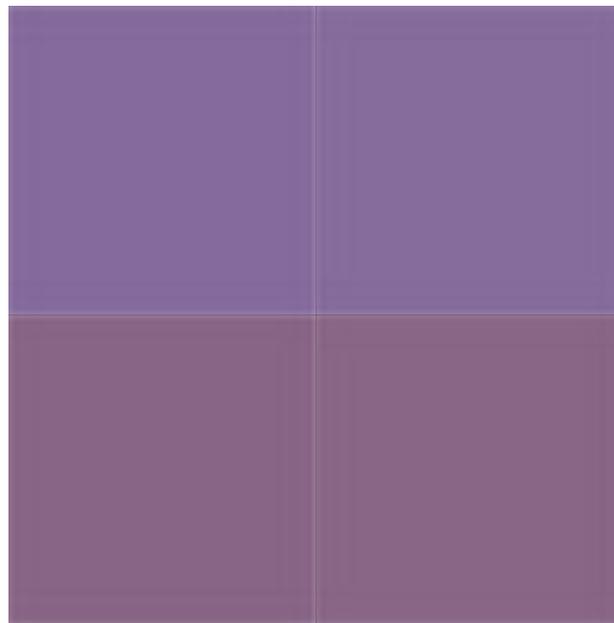
# RGB vs. Spectral: Metamerism

(128,92,50) (128,93,49)



White light

CIE F2





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## Dispersion

- Wavelength dependency of interference and refraction
  - Linear for interference
  - Nonlinear for refraction
- Sellmeier coefficients for glass and crystals characterize behaviour



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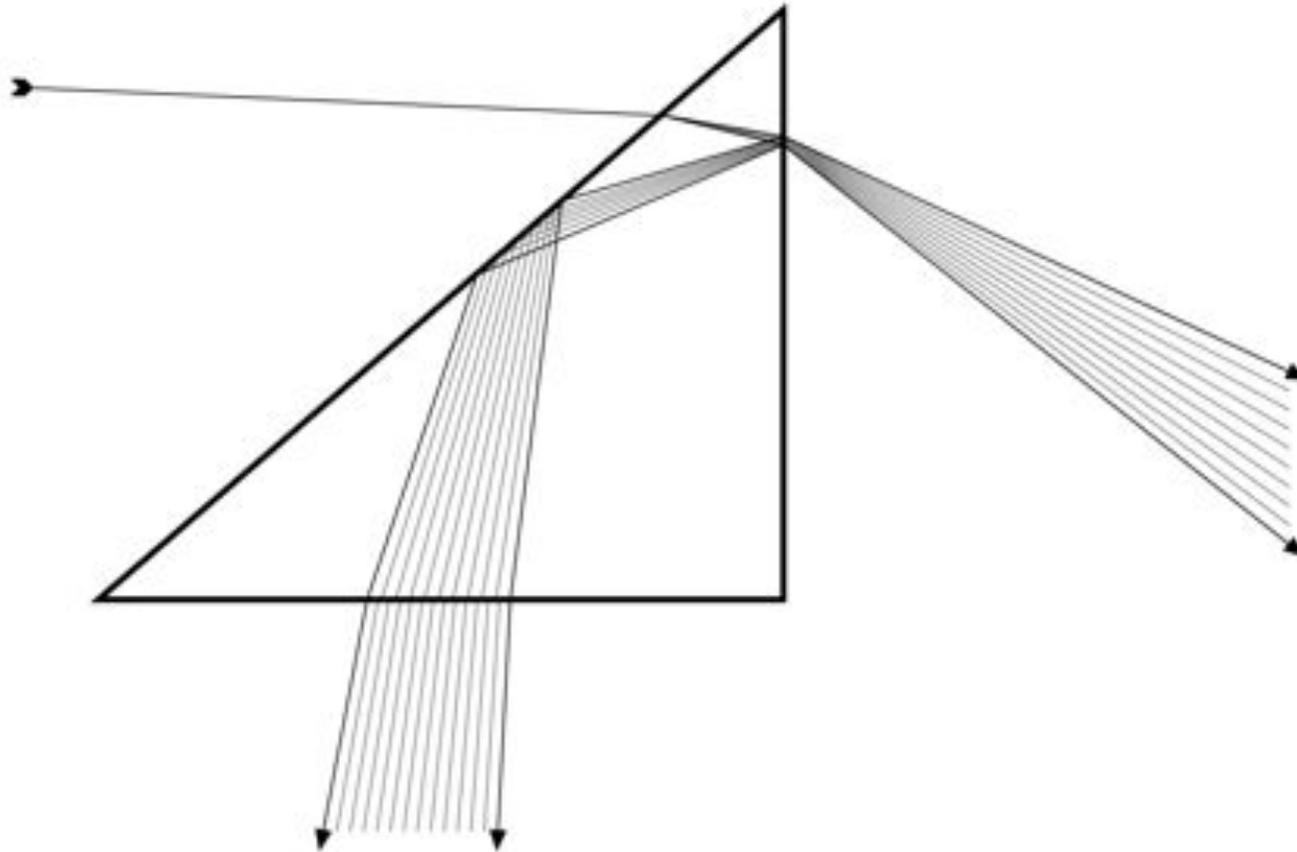
## Dispersion Example





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# Intersection Geometry





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## Sellmeier 's Formula

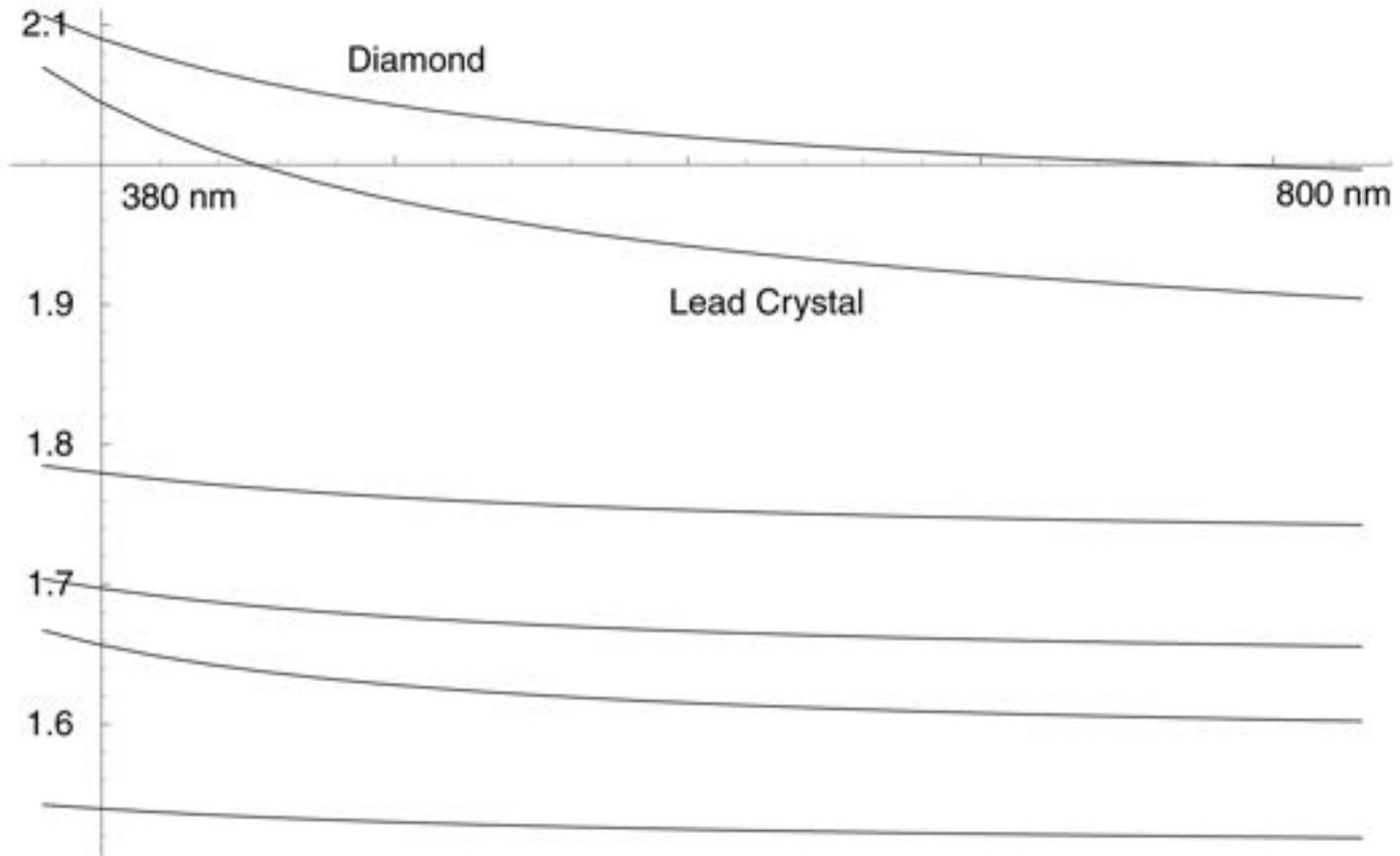
- Approximation to dispersion curves of real materials

$$n_{\lambda}^2 = 1 + \sum_{i=0}^n \frac{A_i \lambda^2}{\lambda^2 - \lambda_i^2}$$

- Sum of quadratic terms with empirical coefficients
- Alternative: Cauchy 's formula



# Sample Dispersions





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## Dispersion Sampling

- Either:
  - Breadth-first in a normal raytracer (turning it into a partial distribution raytracer)
    - Regular sampling yields aliasing artifacts
    - Stochastic jitter by a single offset for all channels
  - Single wavelength in a path tracer (but choose wavelength only once!)



# Dispersion Sampling 1



8 Samples



16 Samples



## Dispersion Sampling 2



8 Samples

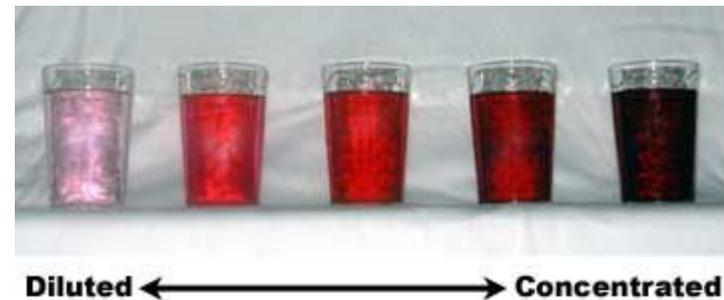
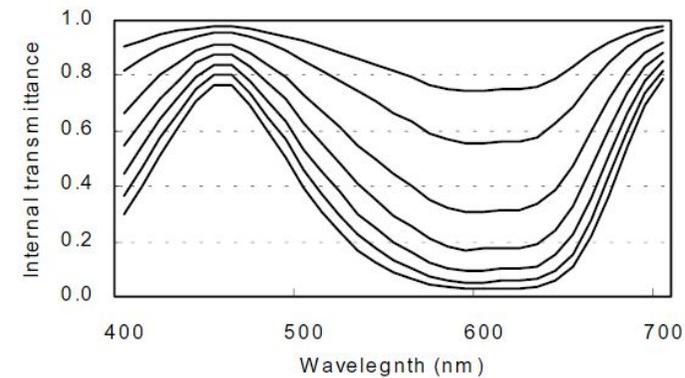


16 Samples



## Volume Absorption

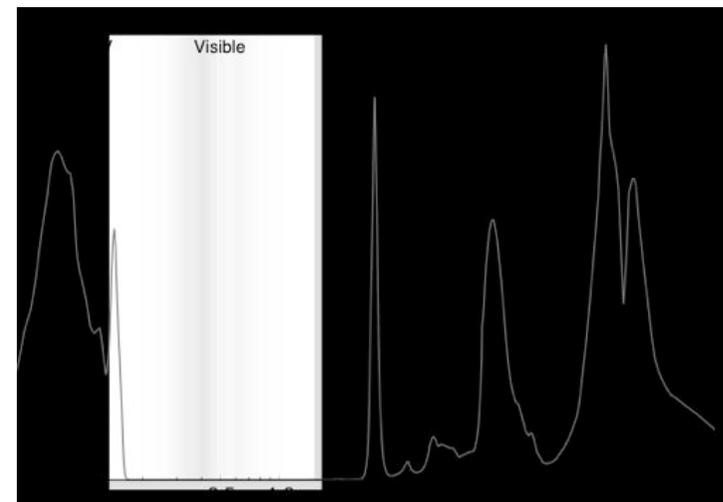
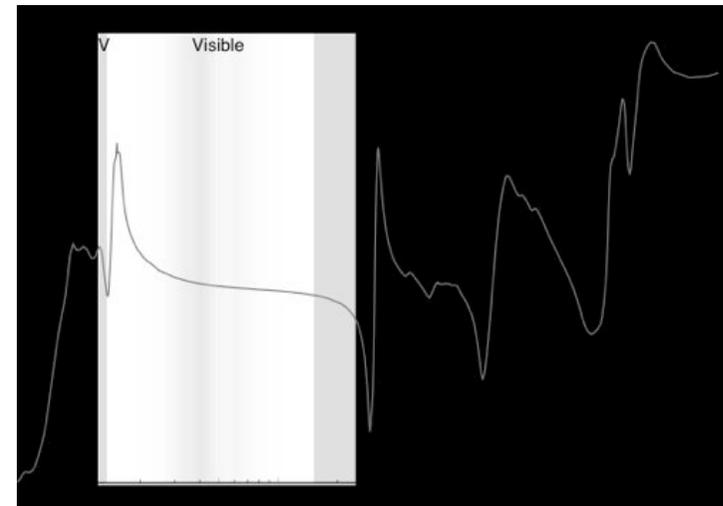
- Prediction of absorption in transparent materials difficult for colourspace renderers
- Deepening of colours not easy to match in colour space





## Dependency Absorption - IOR

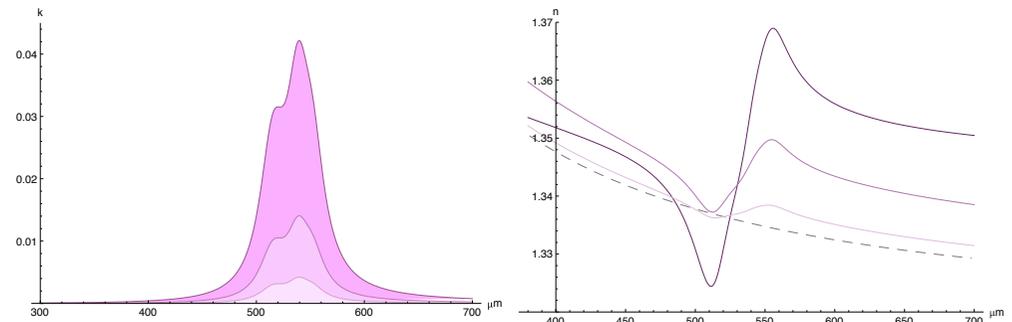
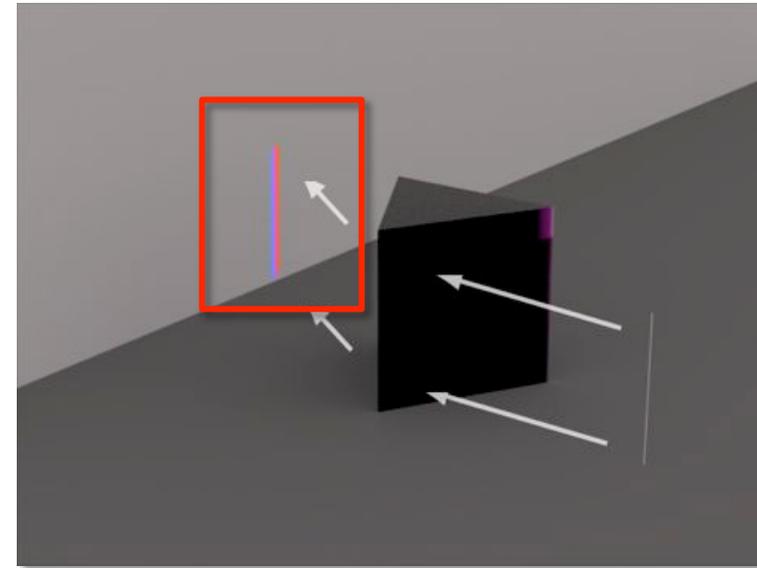
- AD occurs around absorption frequencies
- Reason:
  - Before absorption band - dipoles are in phase
  - After absorption band - dipoles are out of phase
- IOR and absorption influence each other





## Experiment

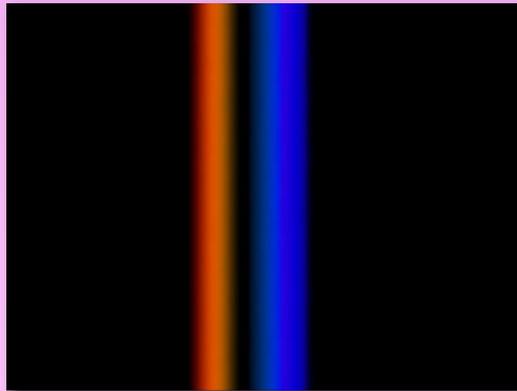
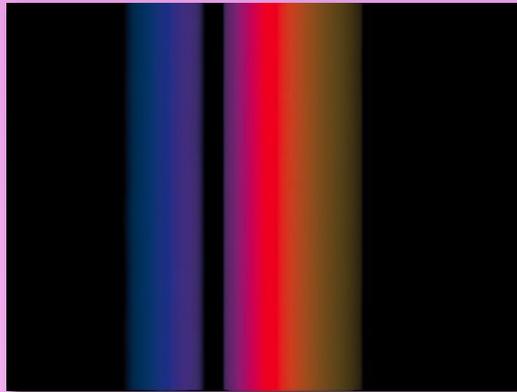
- Classical optical experiment
- Rose bengal diluted in water
- Three different concentrations
- Comparison with prisms that neglect the influence of the absorption on the index of refraction



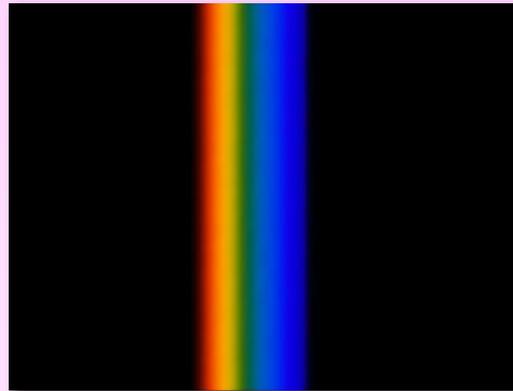
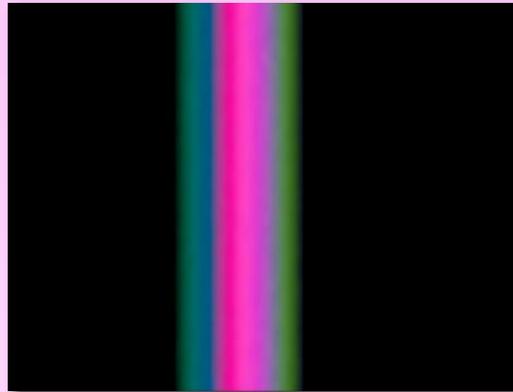


## Rainbow for Varying Concentrations

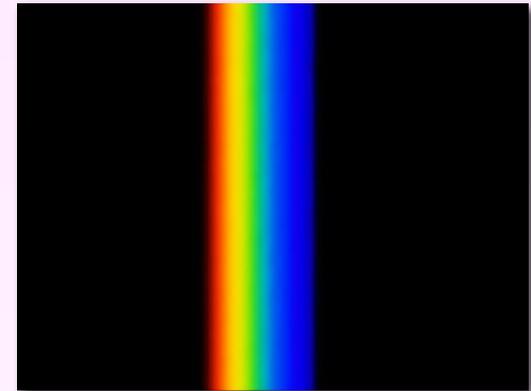
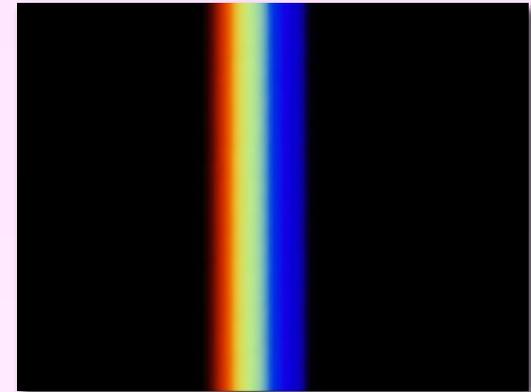
10 percent



3.3 percent



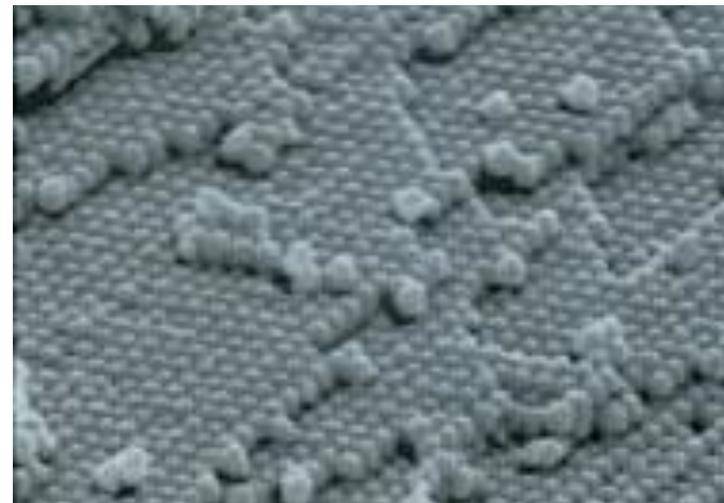
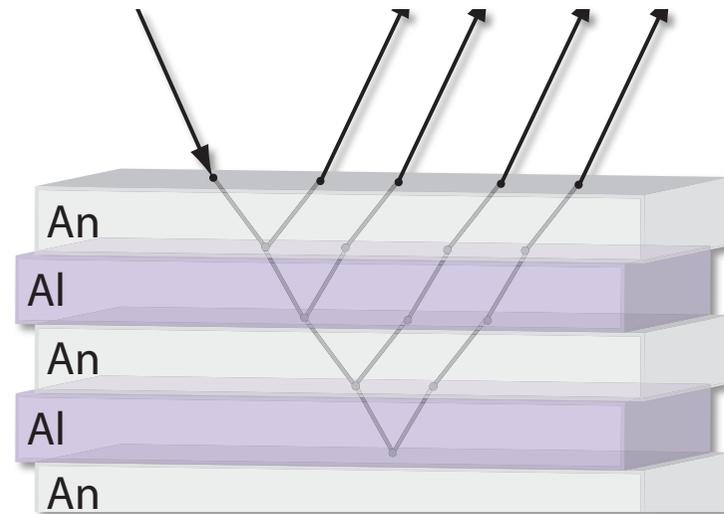
1 percent





## Structural Colour

- Very small structures can evoke effects that depend on the wavelength of the incident light
- Interference: Subtly different propagation times lead to selective cancellation or reinforcement
- Diffraction in small structure

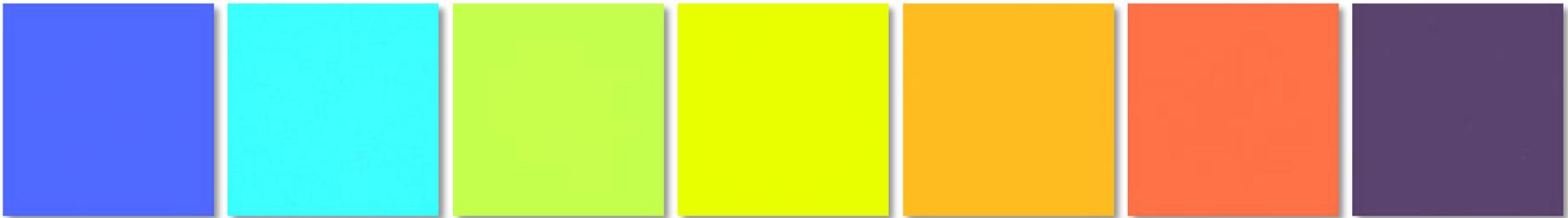




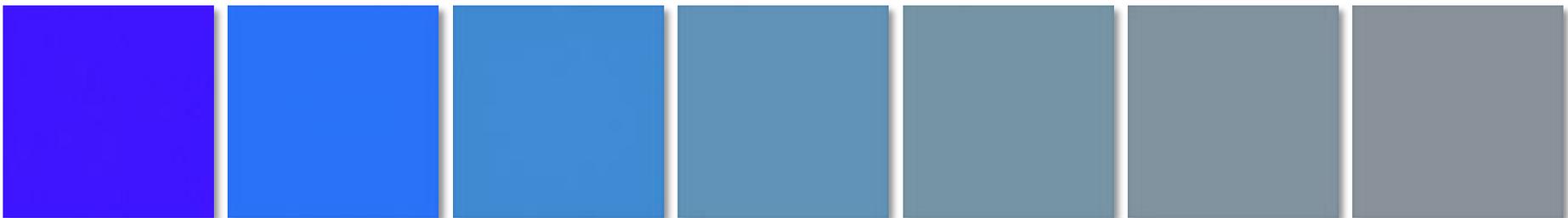
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## Interference: Influence of the Structure

Shifts toward longer wavelengths with increasing thickness



With increasing variance, effect vanishes

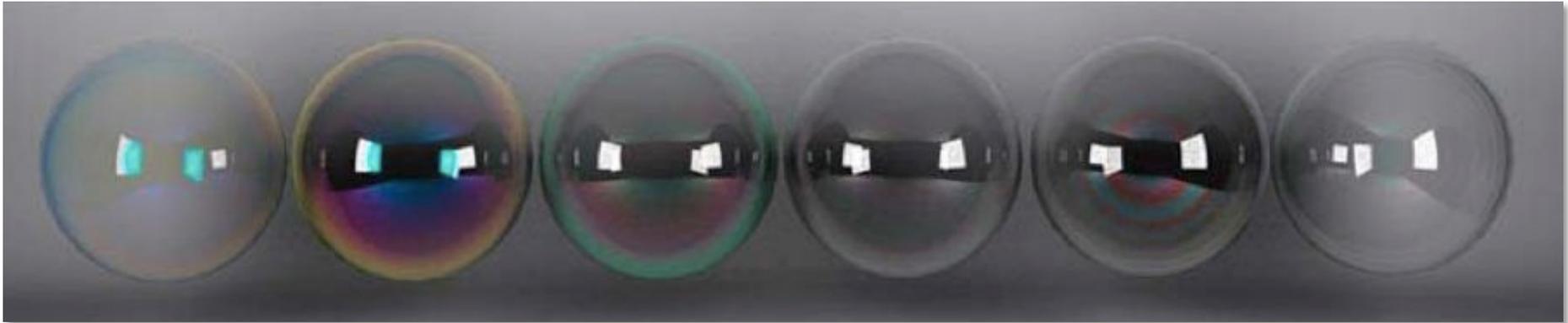




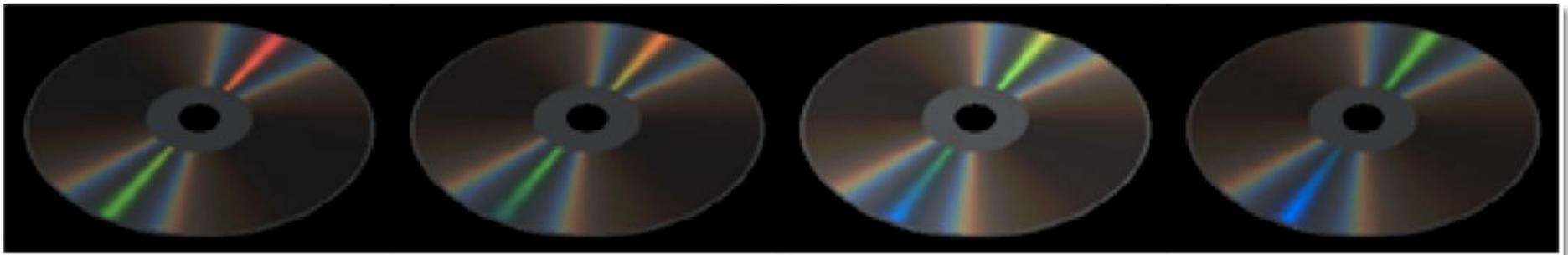
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# Renderings

- Thin Layers



- Diffraction

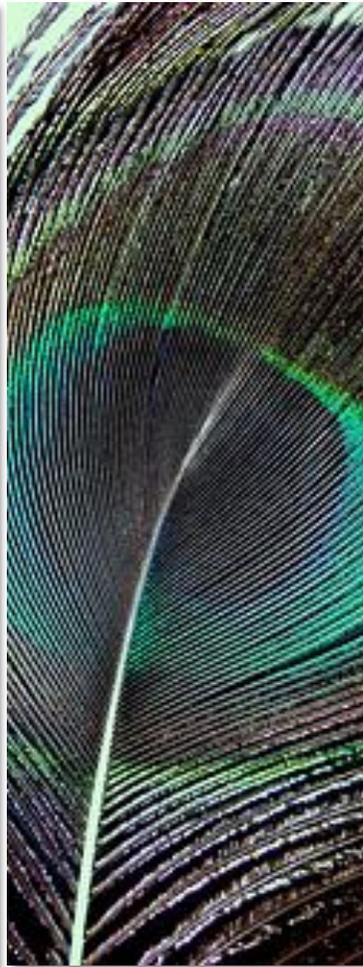




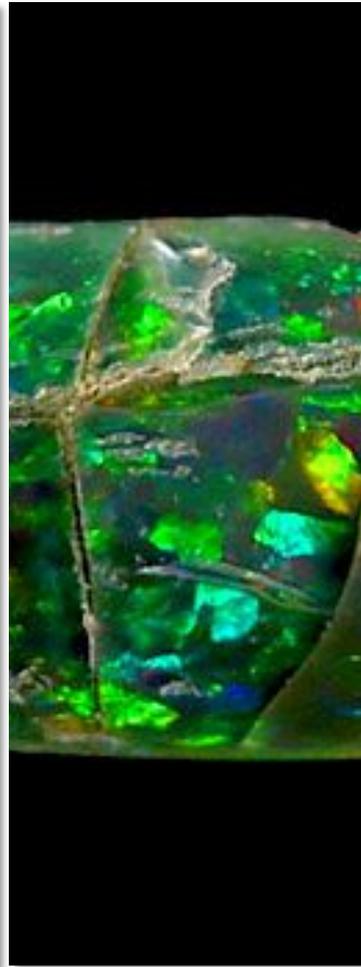
# Interference and Diffraction in Nature



Morpho butterfly



Peacock



Opal



Labradorite



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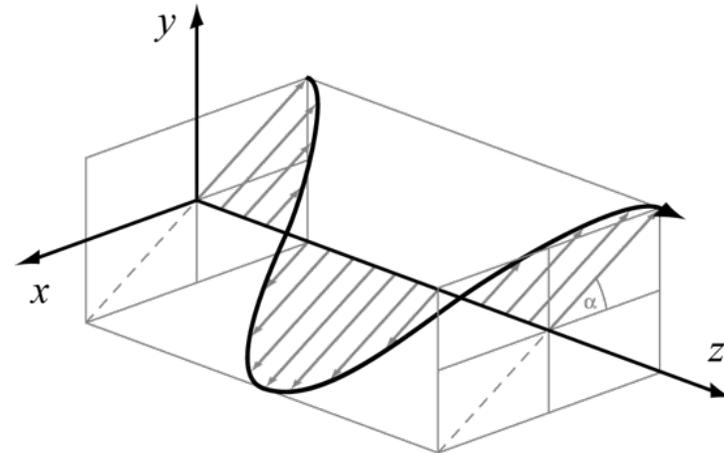
## Polarisation Support

- Light cannot be described by its intensity alone
- Polarised light occurs quite frequently in nature
- Essential for predictive rendering of
  - crystals and transparent objects
  - outdoor scenes
- Sometimes visible with the naked eye
- **Most scenes look plausible without it**



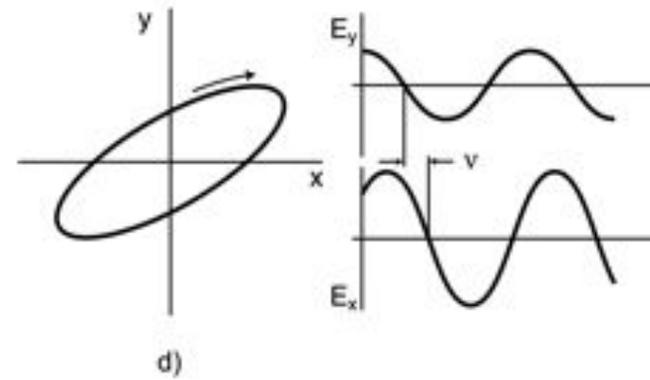
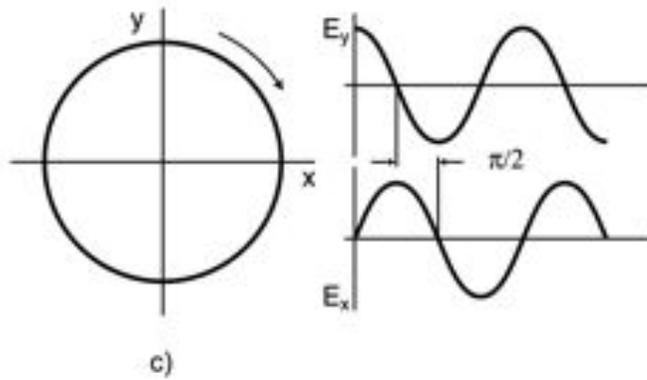
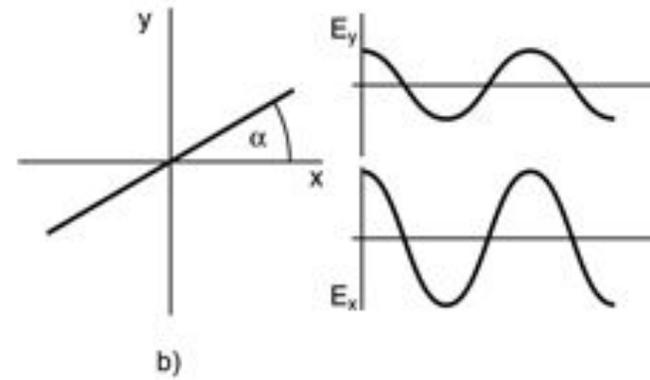
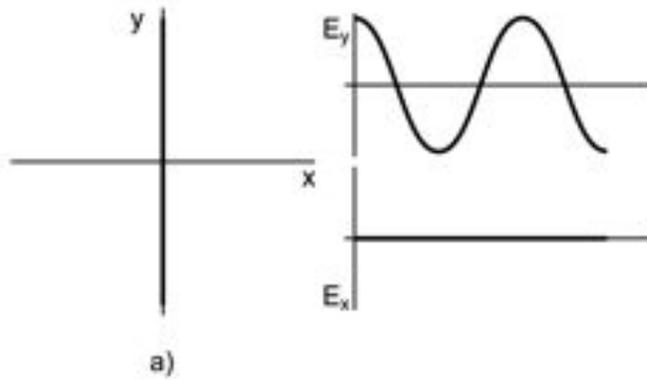
## Polarisation: Basics

- Normally each sample of a spectrum en-codes just radiant intensity (or attenuation)
- Light is a transversal wave
- Polarisation describes oscillation of light wave
- Polarisation state can be described by taking the  $(x, y)$  components of the wavetrain and their phase difference into account



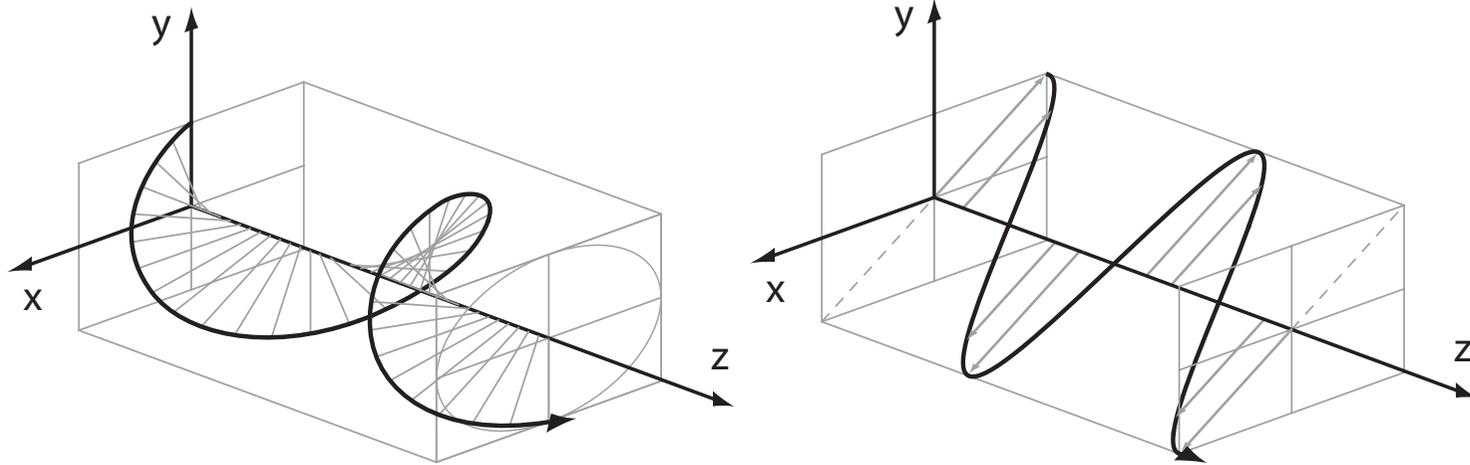


# Polarisation Examples





## Waveform vs. Polarisation

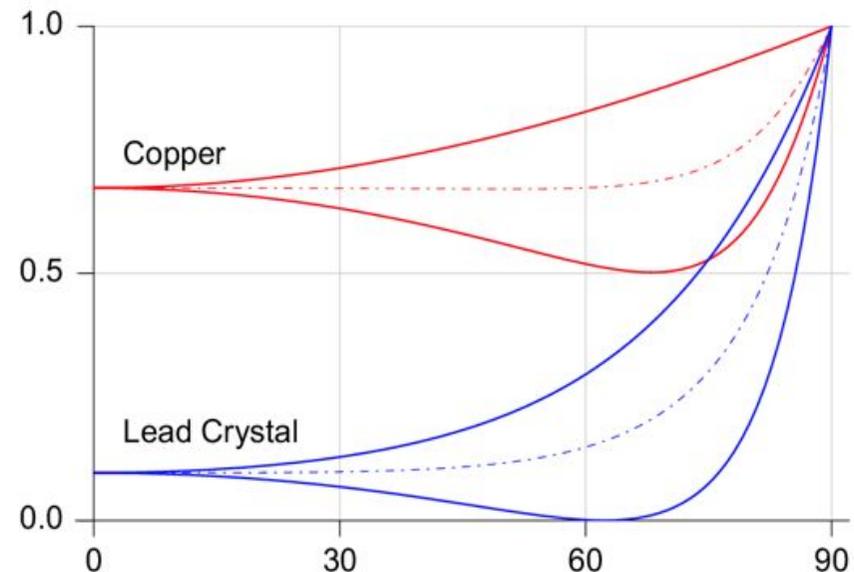


- Trace of the wave-vector for two photons
  - Individual photons / wave-trains are always polarised!
- These two photons have the same frequency
  - We perceive them as having the same colour!
- Only potential difference: interaction with objects



## Why Does This Matter?

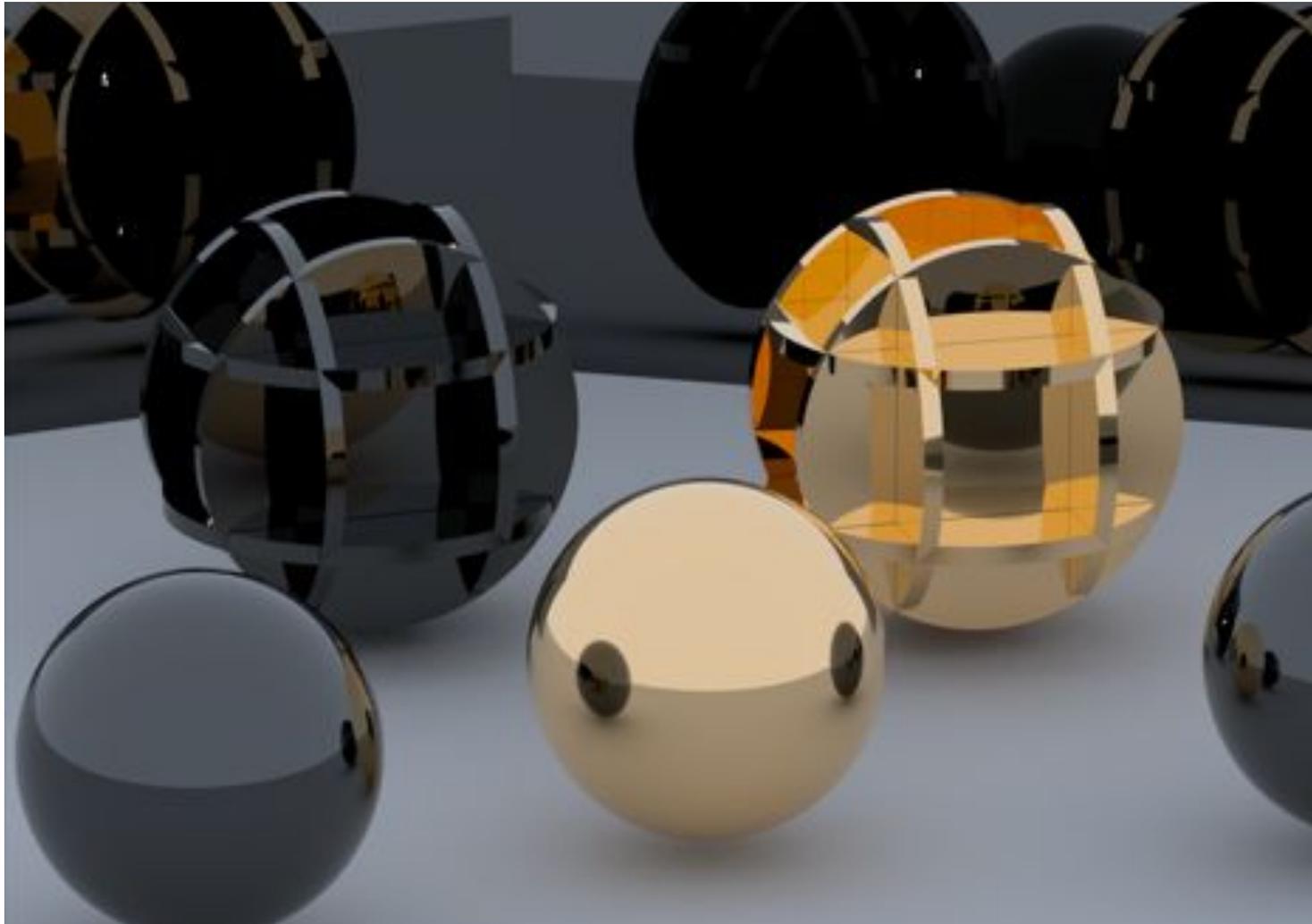
- Specular surfaces are governed by the Fresnel terms
- These show a large discrepancy for different orientations of already polarised incoming light - like e.g. skylight
- Specular scenes with water, glass, car roofs etc. all are affected





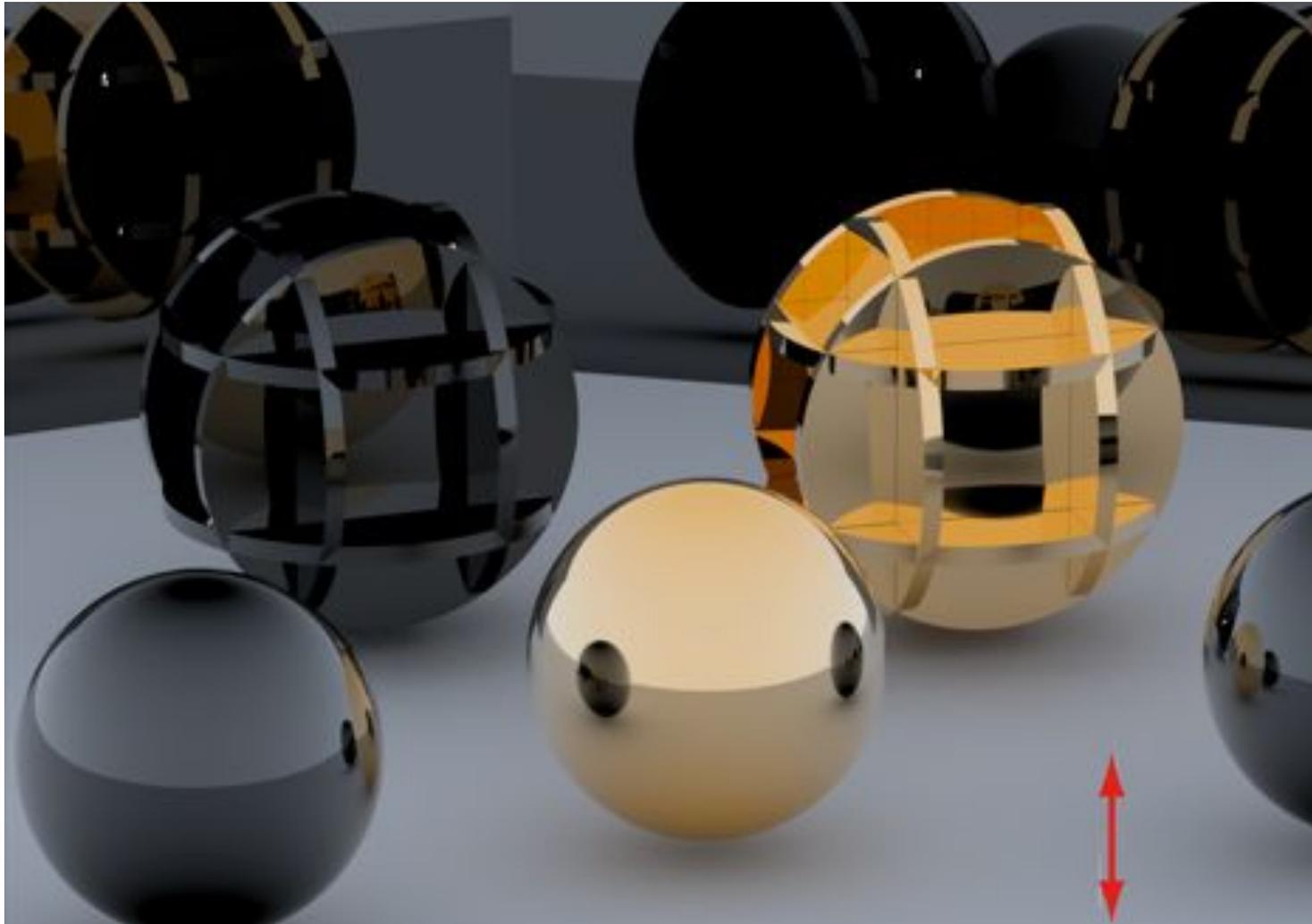
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## Specular Surfaces





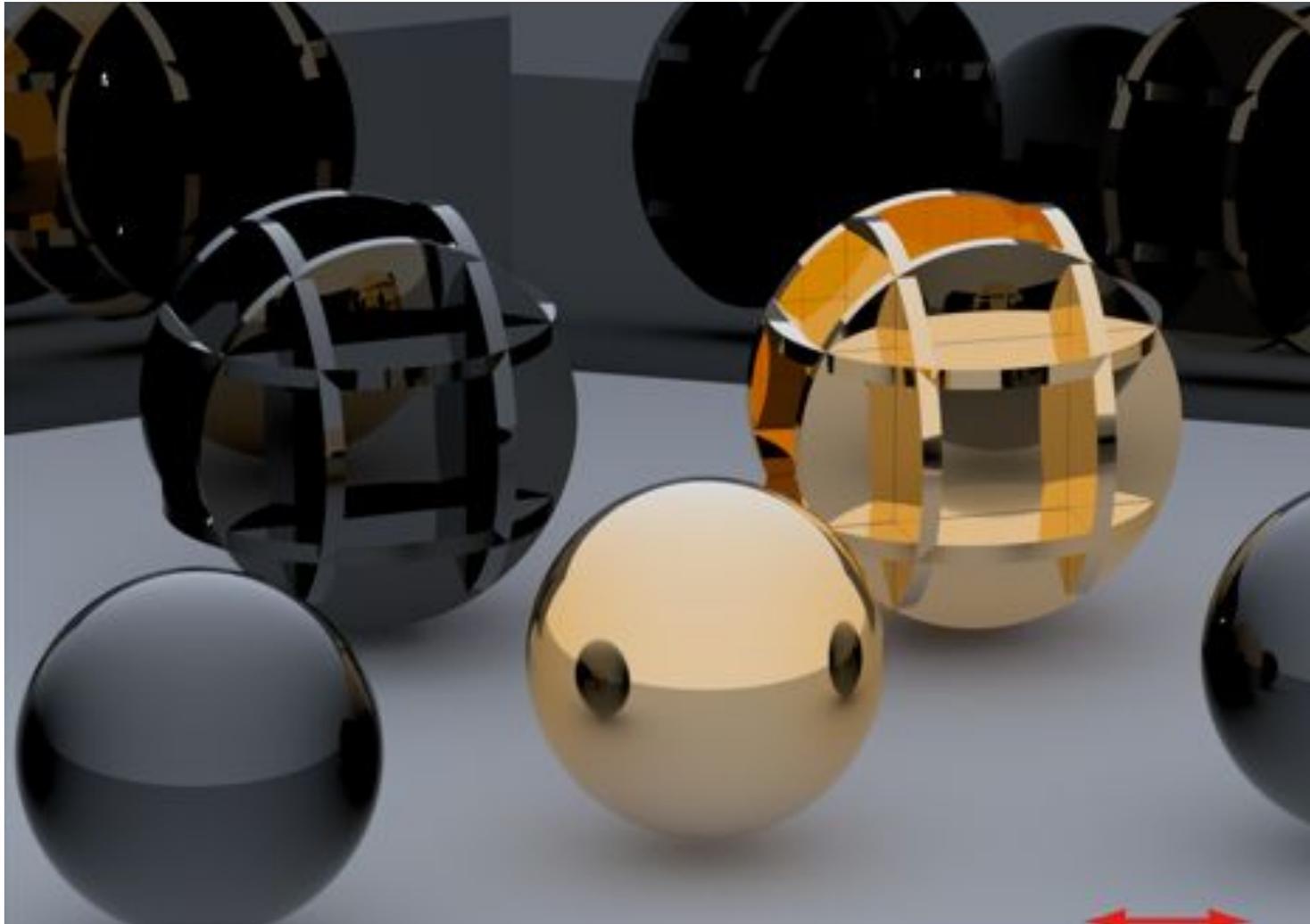
## Linear Filter Vertical





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## Linear Filter Horizontal





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## Reflection Without Filter





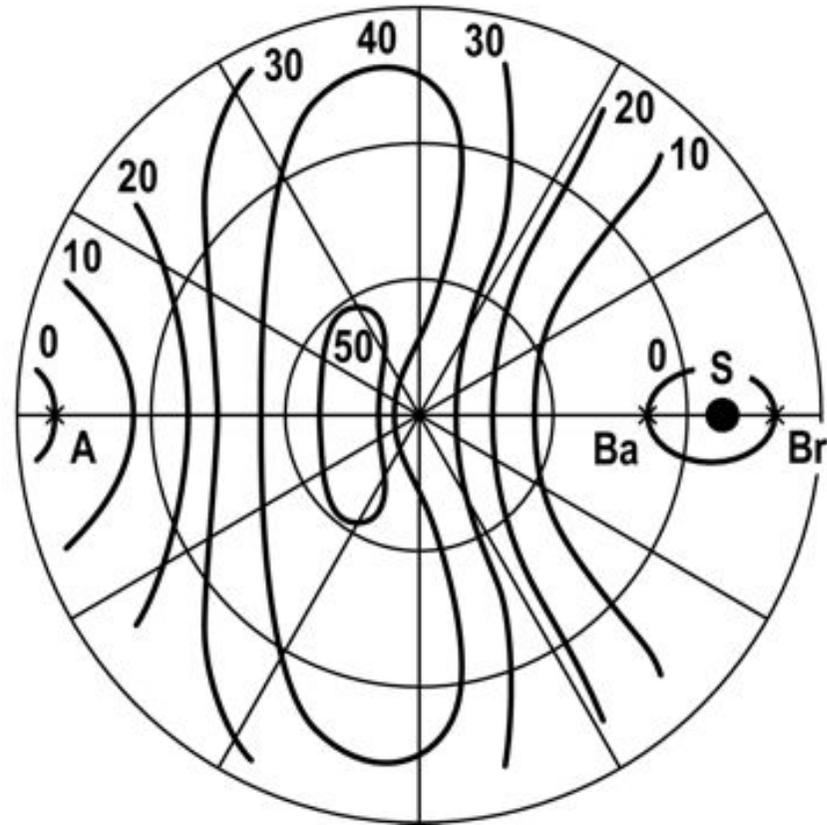
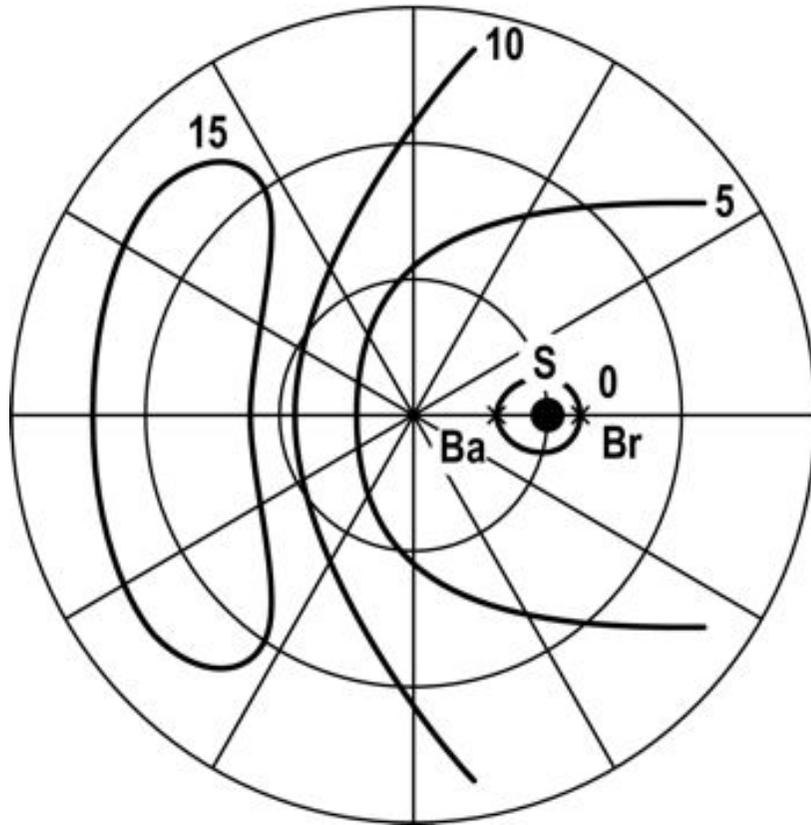
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## Reflection With Polarising Filter





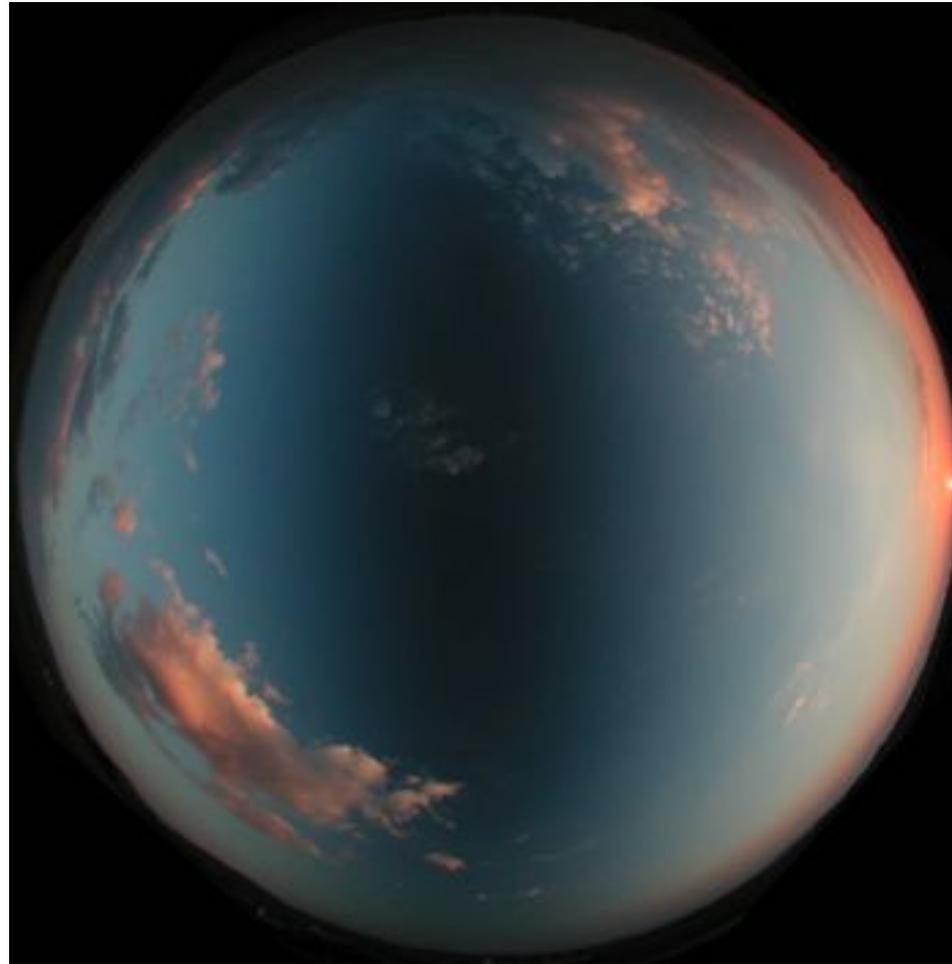
# Skylight Polarisation





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## Sky Polarisation Pattern





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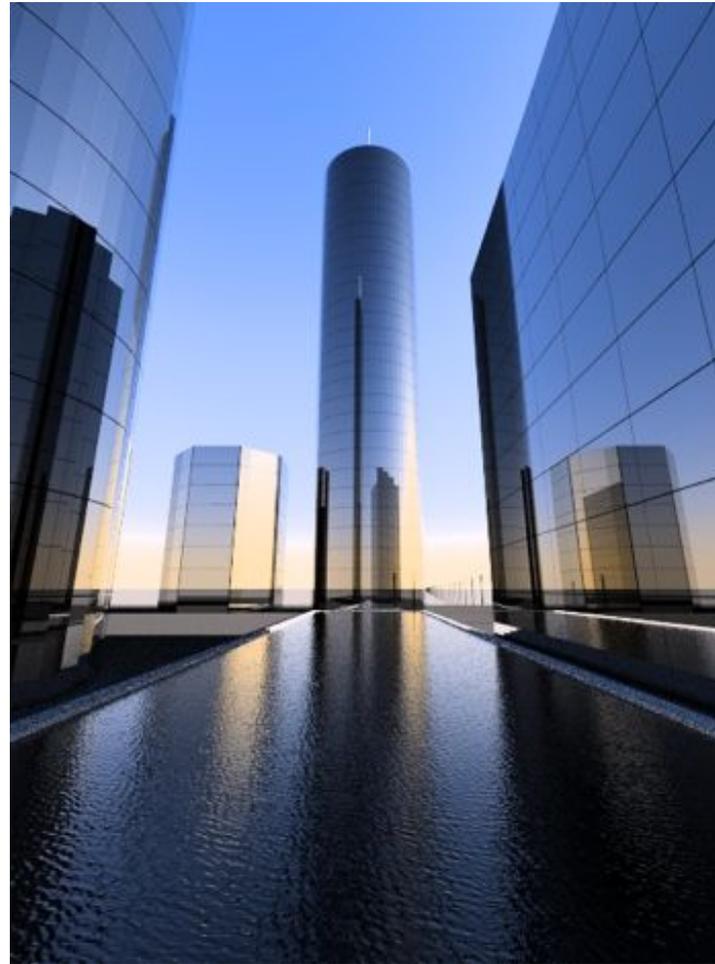
# Nonpolarising Renderer





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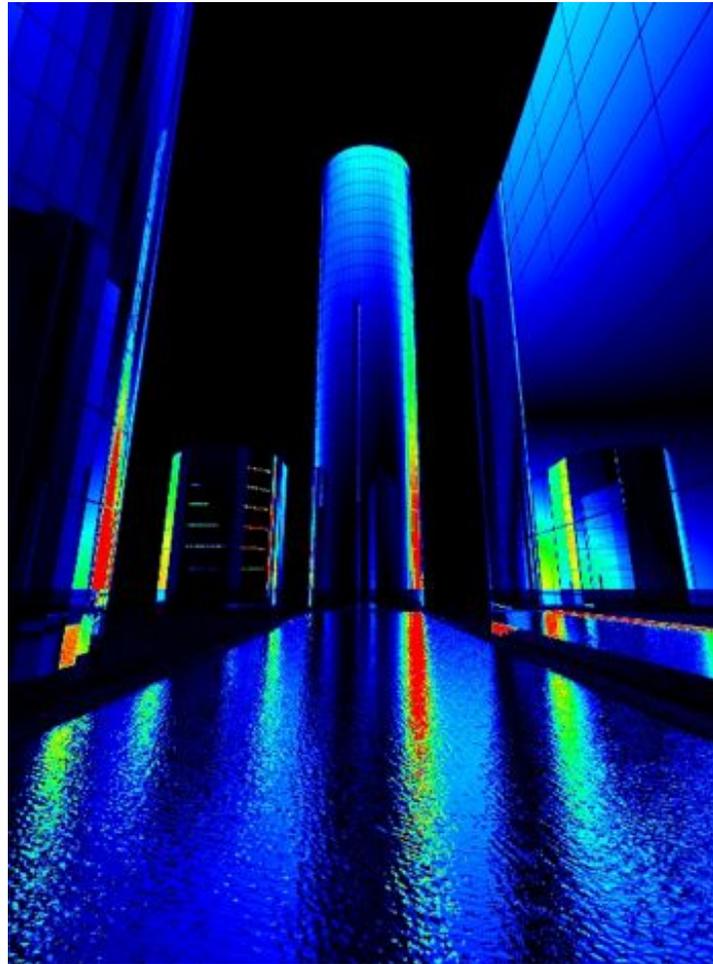
## Polarised Skylight





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## Difference





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## Light vs. Attenuation

- Two types of energy-related entities exist in a rendering system:
  - **Radiant intensity**, e.g. emissions from lightsources („light“)
  - **Attenuation**, i.e. the influence of surfaces and media („importance“, or „filter“)
- In most rendering systems they are not properly distinguished, and use the same data structures (i.e. RGB values)
- Both polarisation and fluorescence break this



## Describing Polarisation #1

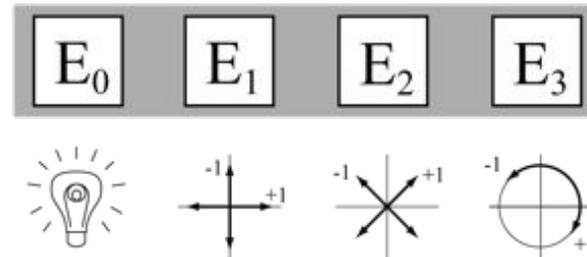
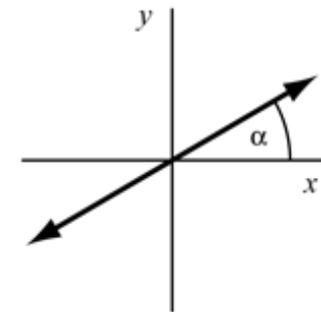
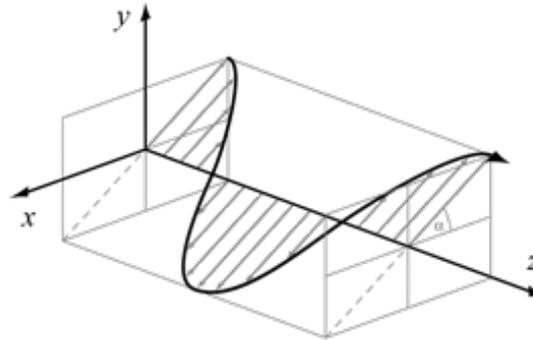
- Light: **Coherency Matrices** (CM)
  - 2 x 2 Hermitian matrix
  - Mathematically elegant
  - Complex components
  - Trace = intensity
- Filter (importance): **CM modifiers**
  - 2 x 2 complex values

$$J = \begin{pmatrix} \langle E_x E_x^* \rangle & \langle E_x E_y^* \rangle \\ \langle E_y E_x^* \rangle & \langle E_y E_y^* \rangle \end{pmatrix}$$



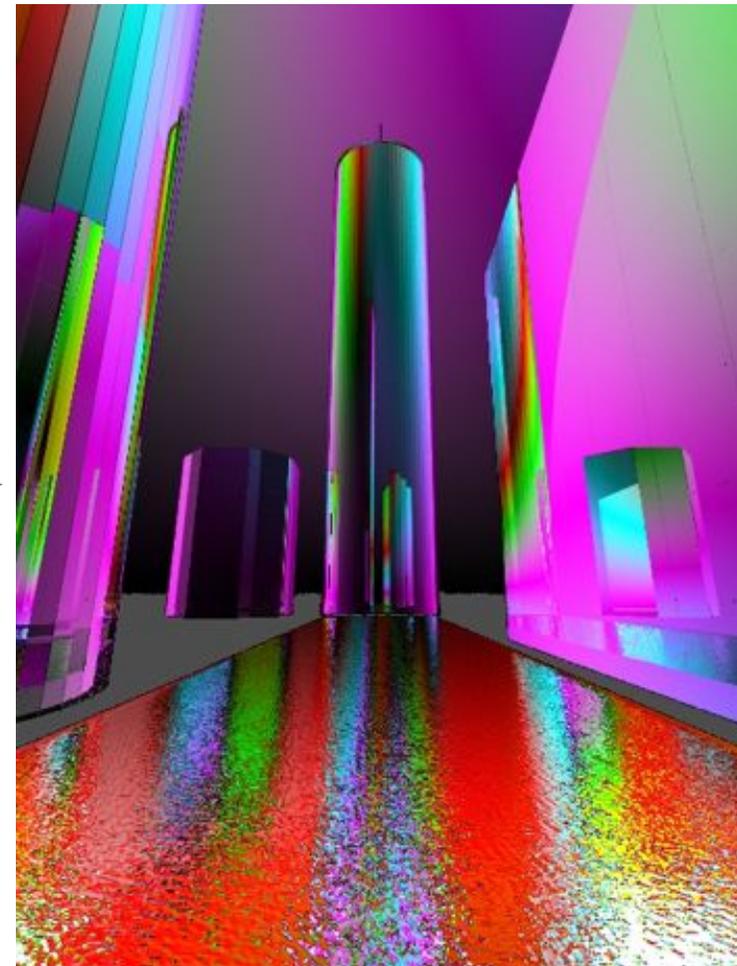
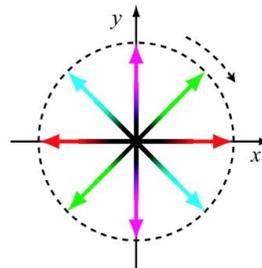
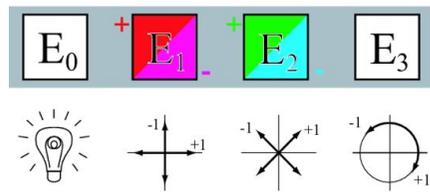
## Describing Polarization #2a

- Light: **Stokes vectors**
  - 4-vector with real elements
  - Range of first component is 0 to infinity, others -1 to 1
  - Blends in with nonpolarizing implementations





# Polarisation Falsecolour



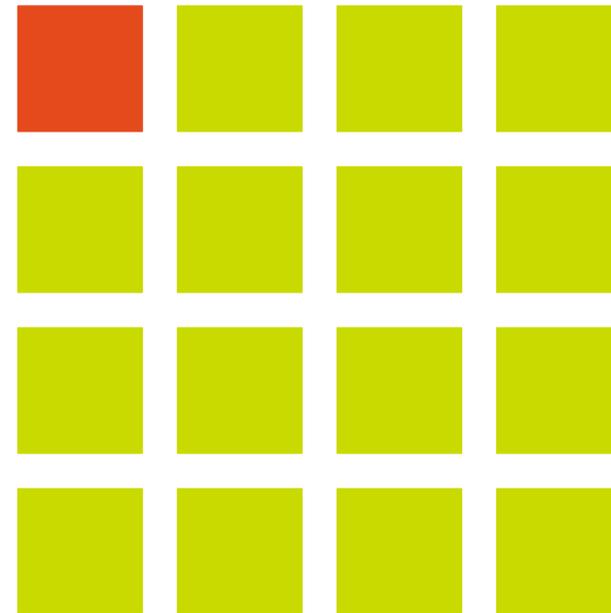
Stokes Components



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## Describing Polarisation #2b

- Filter: **Müller matrices**
  - 4 x 4 real matrices
  - Element (0,0) is non-polarising filter
  - Interaction of all components with each other is encoded





## Filter examples

i	0	0	0
0	0	0	0
0	0	0	0
0	0	0	0

depolarizer

i	0	0	0
0	i	0	0
0	0	i	0
0	0	0	i

plain filter

	1	$\cos 2\phi$	$\sin 2\phi$	0
1	$\cos 2\phi$	$\cos^2 2\phi$	$\cos 2\phi \cdot \sin 2\phi$	0
2	$\sin 2\phi$	$\cos 2\phi \cdot \sin 2\phi$	$\sin^2 2\phi$	0
	0	0	0	0

ideal linear polarizer



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# Polarisation and Spectral Rendering





# Stress Birefringency





The End  
Thank you for your attention!

