Prediction of appearance of materials

The radiometric approach

French research group whose vocation is to organize and develop the scientific community around the appearance of materials

Axe 1 – Materials and fabrication

Axe 2 – Physical and sensory measurements

Axe 3 – Modeling and simulation

Axe 4 – Scanning and description

Axe 5 – Digital reproduction and rendering

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Shape, Texture, Translucency, Gloss, Color
are attributes of appearance

From material to appearance

Appearance attributes

Appearance

Color, gloss, translucency

Radiometry

Radiometric response

Spectral, angular and spatial distribution of reflected and transmitted light in the visible range

Electromagnetism

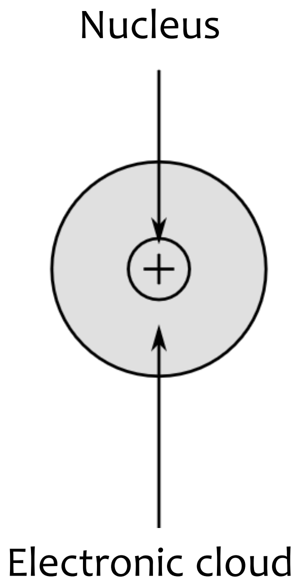
Intrinsic optical properties of the components

Complex refractive index

Complex refractive index

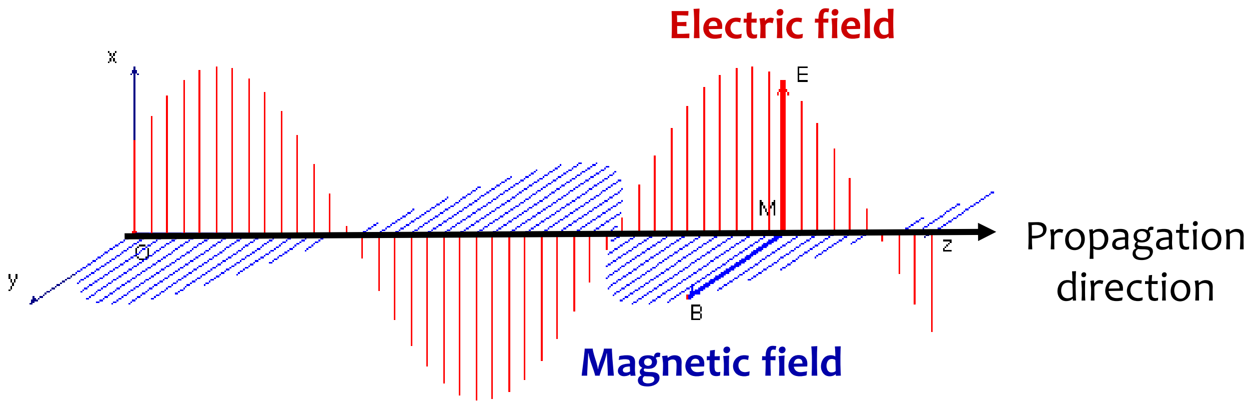
Matter

Set of electrical charges



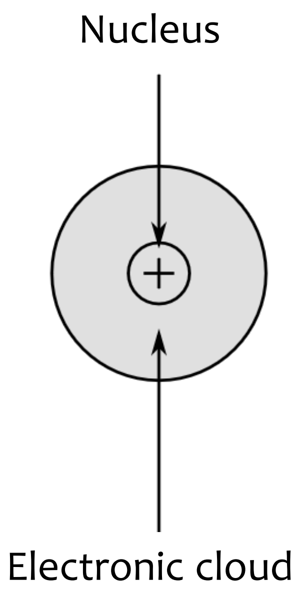
Light

Electromagnetic wave

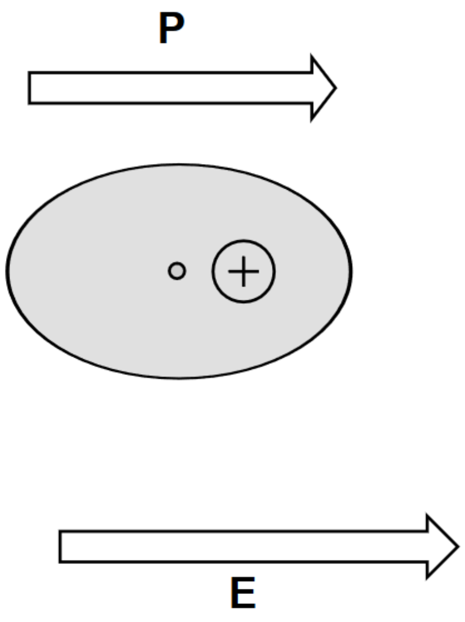


The **polarization direction** is the direction of the electric field **E** (perpendicular to the direction of propagation).

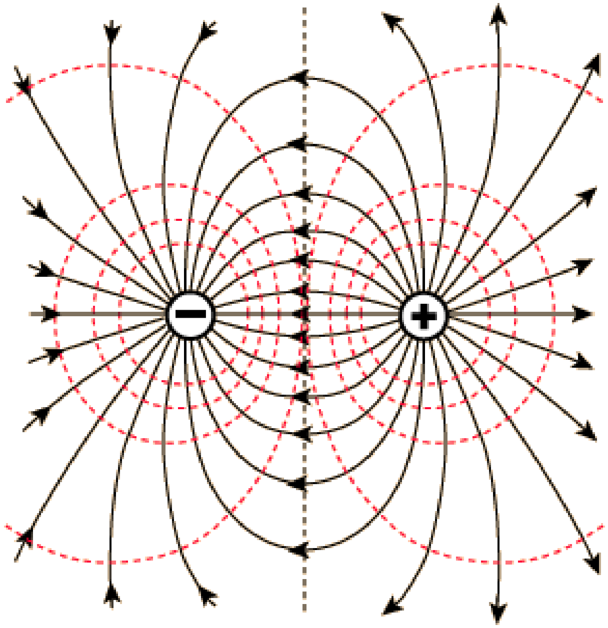
Complex refractive index



Subjected to an electric field **E** (i.e. light wave), matter becomes polarized

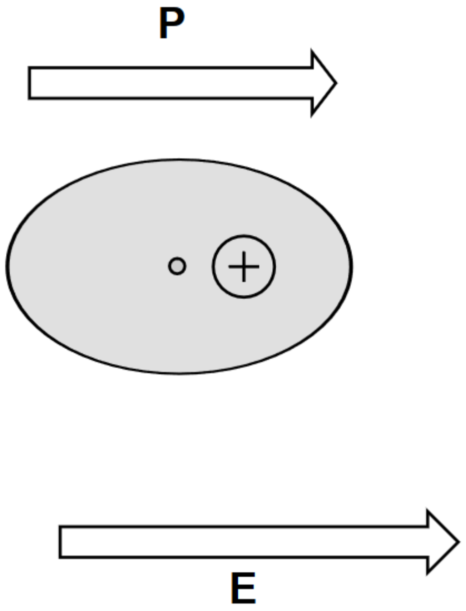


As a first approximation, it behaves like an electric dipole



Complex refractive index

The polarization vector **P** corresponds to a dipole moment per unit volume



Linearity assumption

$$\mathbf{P} = \left(\varepsilon - \varepsilon_0\right)\mathbf{E}$$

ε: dielectric permittivity

In optics, we prefer to use the **complex refractive index**

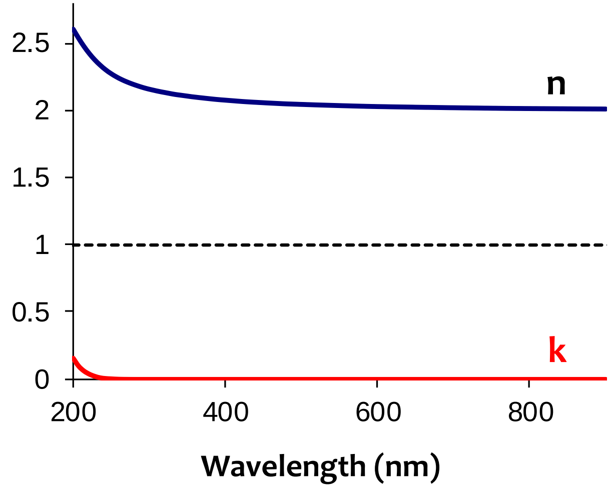
$$n + i\kappa = \sqrt{\frac{\varepsilon}{\varepsilon_0}}$$

Refractive index (n) **Extinction coefficient** (κ)

Complex refractive index

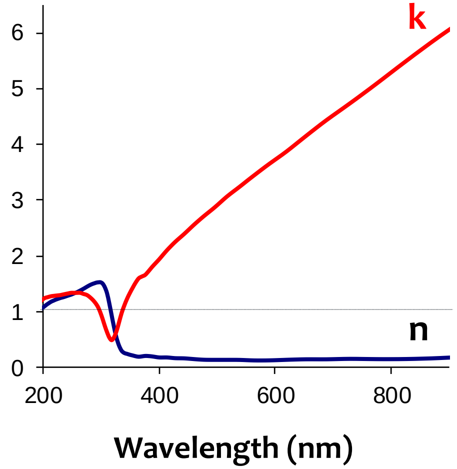
Complex refractive indices can be measured by ellipsometry or are tabulated

Dielectrics



Si_3N_4

Metals



Ag

From material to appearance

Appearance attributes

Appearance
Color, gloss, translucency

Radiometry

Radiometric response
Spectral, angular and spatial distribution of reflected and transmitted light in the visible range

Concentration and arrangement

Electromagnetism

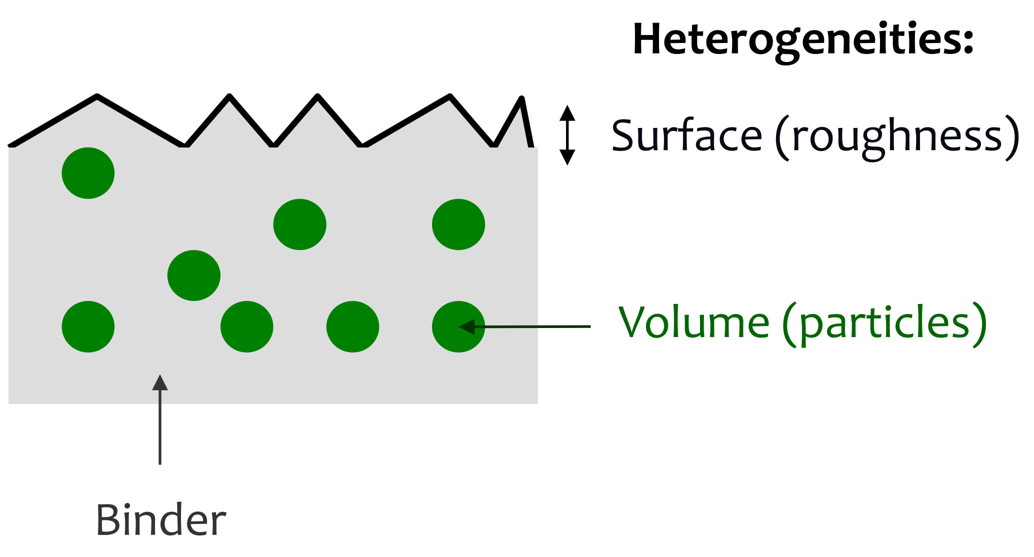
Transmission and reflection at interfaces

Absorption and scattering in volume

Geometric properties
(size, shape, organization)

Intrinsic optical properties of the components
Complex refractive index

Coating (paint, ink...) of a material

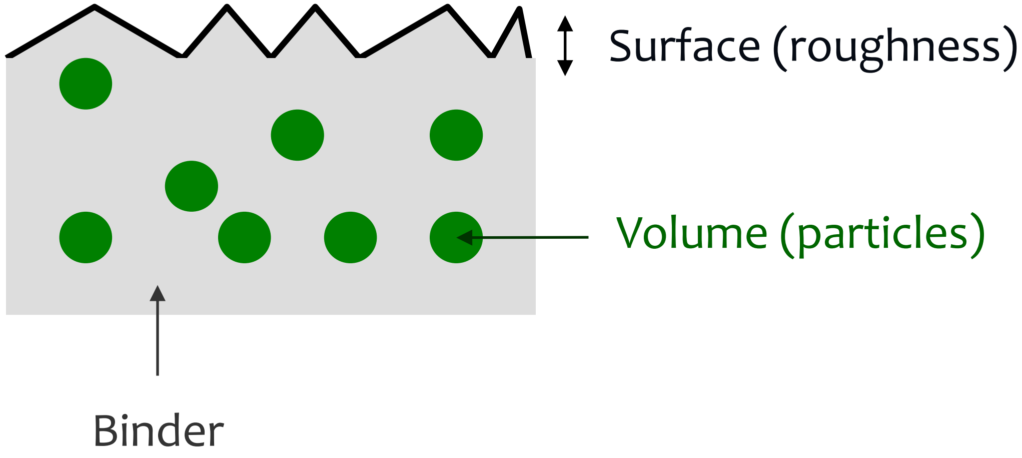


Elementary light-matter interactions

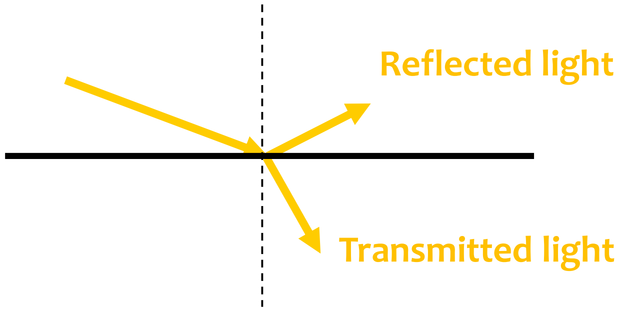
Coating (paint, ink…) of a material

Low size and/or concentration

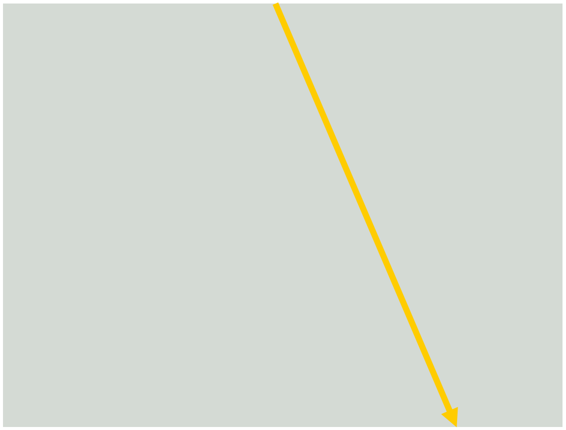
Heterogeneities:



"Effective" flat interface
(Snell-Descartes law, Fresnel relationships)



Homogeneous "effective" medium
(straight propagation, Beer-Lambert-Bouguer law)

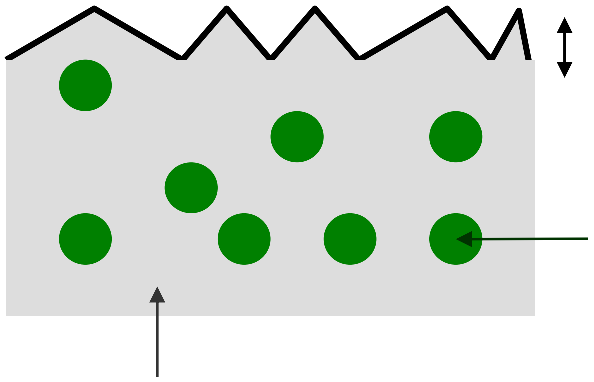


Elementary light-matter interactions

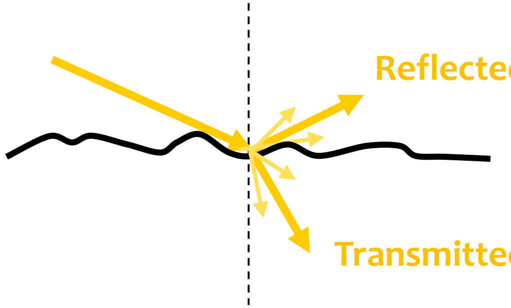
Coating (paint, ink...) of a material

High size and/or concentration

Heterogeneities:

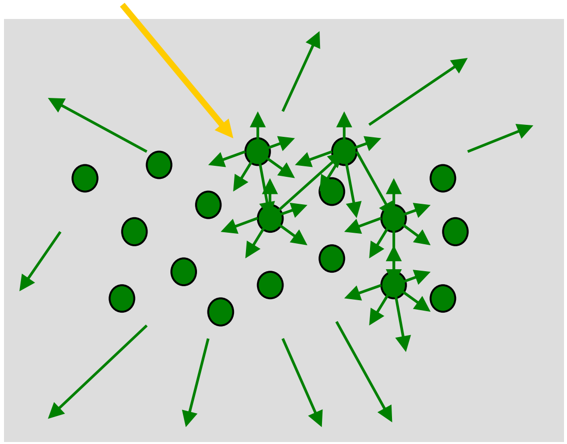


Scattering interface



Scattering medium

(absorption and multiple scattering by particles)



Mie theory

Sky

Rayleigh (r<<λ)

Isotrope scattering in $1/\lambda^4$

Cloud

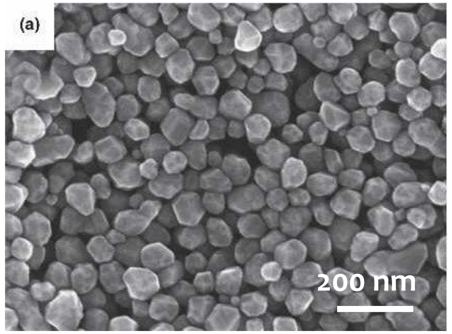
Geometrical optics (r>>λ)

Forward scattering independent of λ

A question of scale, concentration and organization

<<λ : nanometric scale

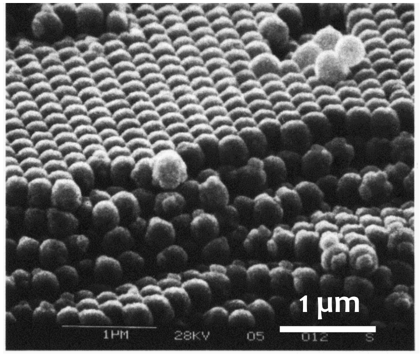
Homogeneous effective medium



Ag nanoparticles (80 nm) in solution

~λ : hundreds of nanometers

Diffractive and interferential effects

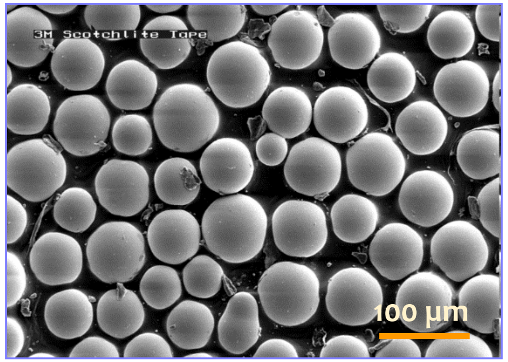


Opale

Arrangement of SiO_2 spheres (300 nm)

>>λ : micrometric scale

Optic geometric approach

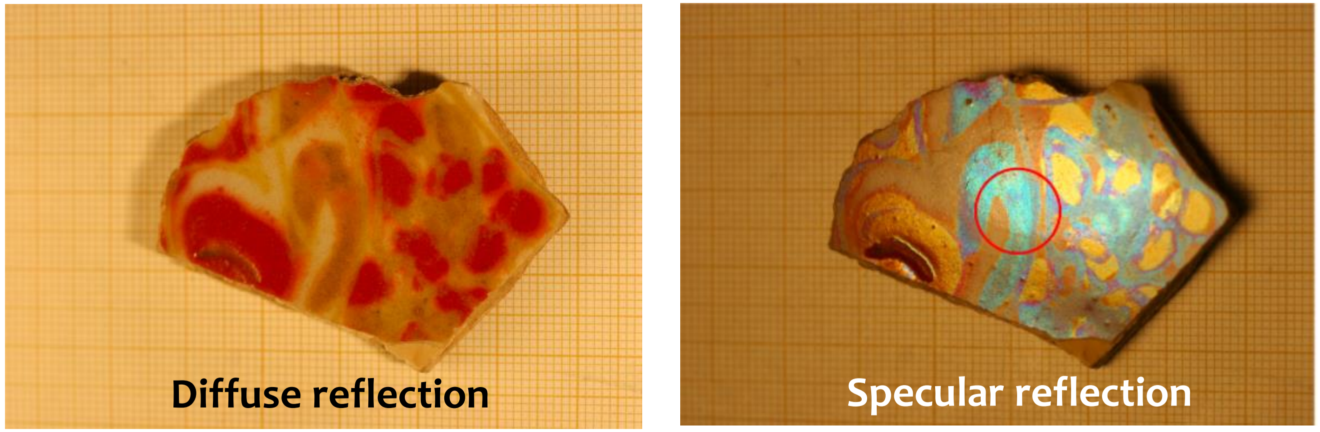


Retroreflective coating

Microbeads (80 µm) of SiO_2

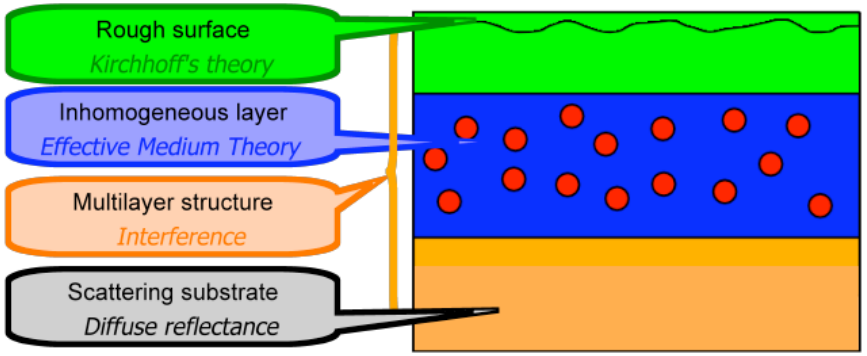
A question of scale, concentration and organization

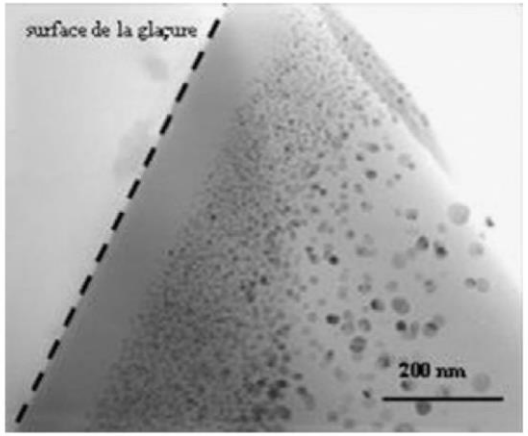
Enamels with metallic glaze



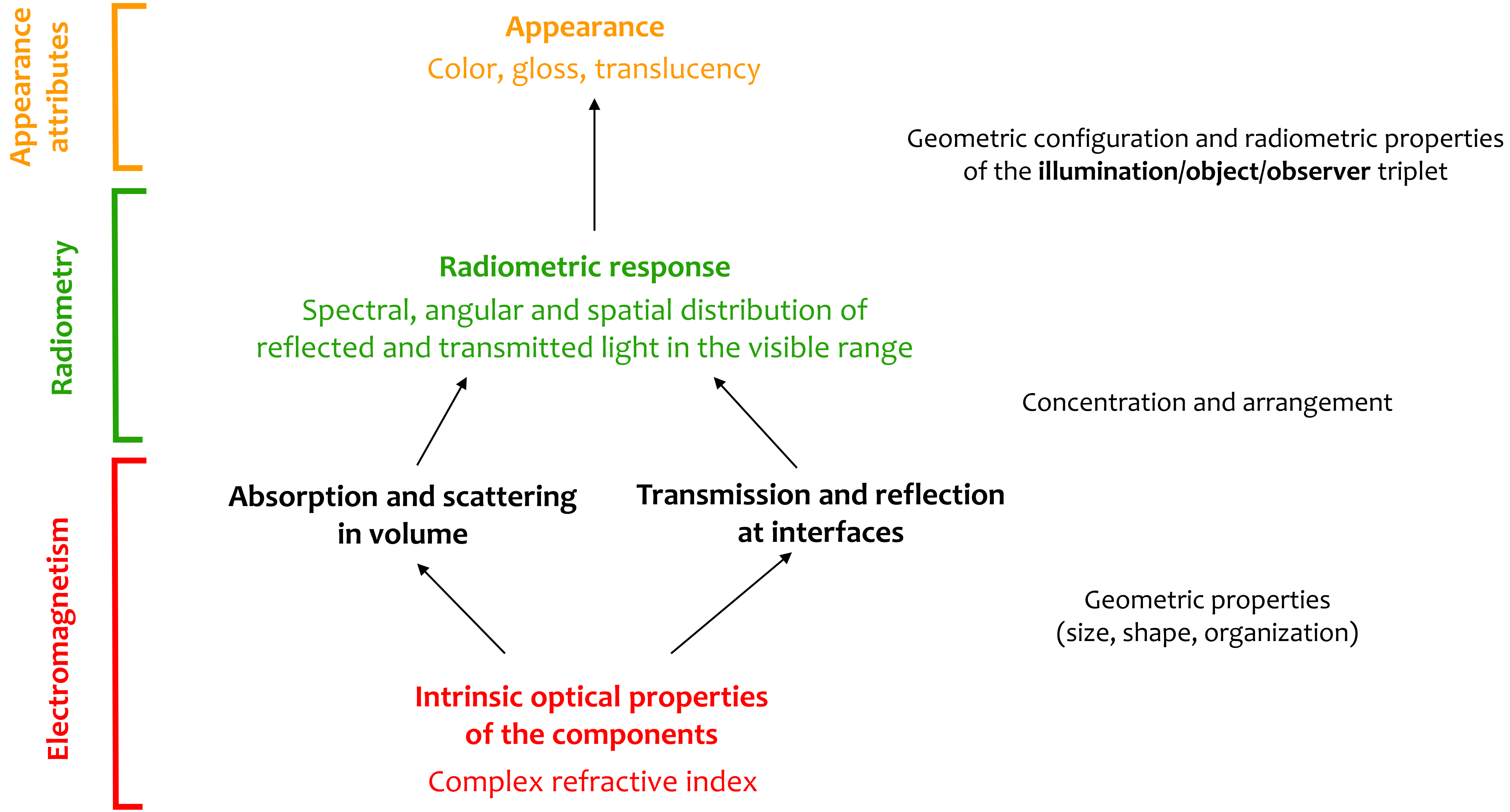
J. Lafait *et al.*, Comptes Rendus Physique (2009)

Locally → multilayer approach





From material to appearance



From radiometry to appearance

The spectral, angular and spatial variations of the scattered light

can be linked to **the attributes of appearance**

→ Psycho-visual experiments

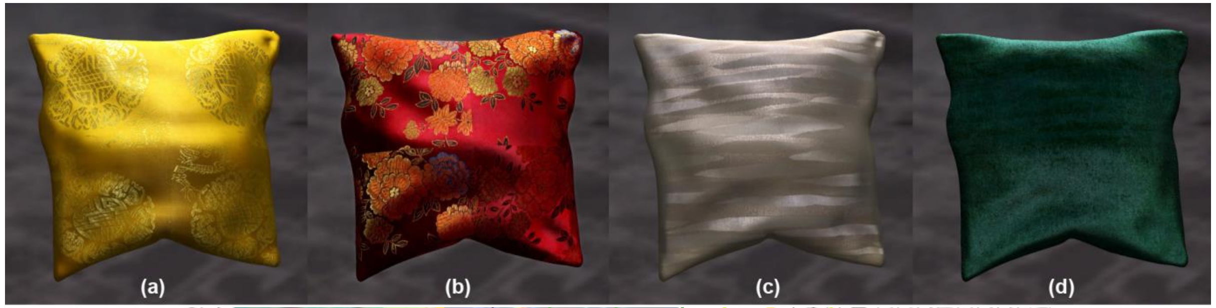
→ Standardization by CIE for diffuse colors

→ Much remains to be done for others appearance attributes

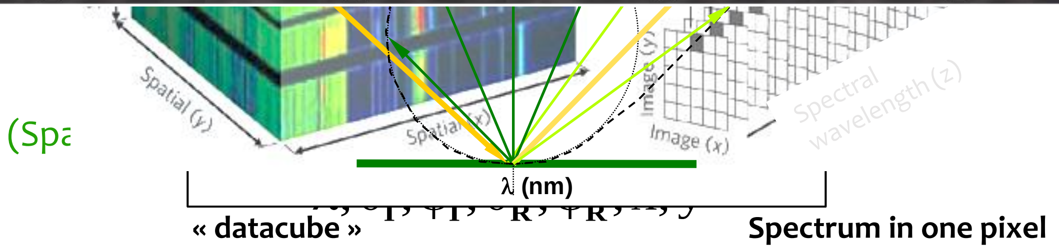
From radiometry to appearance

The spectral, angular and spatial variations of the scattered light

can be linked to **the attributes of appearance**



Translucency



No spatial variation

No angular variations

Gloss ⟷ **BRDF** $\lambda, \theta_I, \varphi_I, \theta_R, \varphi_R$

« Goniocolorimetry »

2D variation λ, x, y ⟷ **Texture**

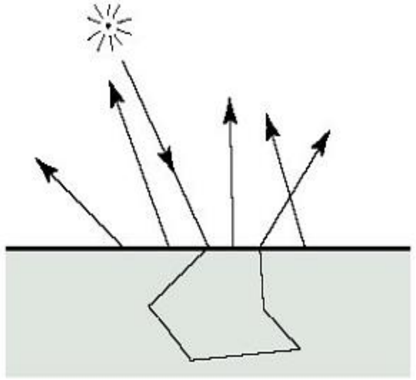
If Lambertian

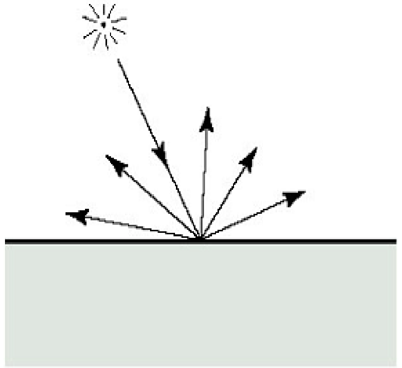
If homogeneous

Color ⟷ **Reflectance** λ

From radiometry to appearance

BSSRDF





BRDF

From material to appearance

Radiometric response

Spectral, angular and spatial distribution of reflected and transmitted light in the visible range

↑

Direct problem

Parameters describing the object

Complex refractive indices of each component

Size, shape, concentration and organisation of the heterogeneities (surface and volume)

The more you want a complete description of the radiometric response, the more you need to know the material accurately

→ a lot of strategies to simulate an average response

From material to appearance

Radiometric response

Spectral, angular and spatial distribution of reflected and transmitted light in the visible range

↓ **Inverse problem**

Parameters describing the object

Complex refractive indices of each component

Size, shape, concentration and organisation of the heterogeneities (surface and volume)

→ Identify components

→ Quantify their concentrations, sizes, shapes

Example 1: interreflections in a cavity

James Turrell, *Afrum I (White)*, Guggenheim collection (1967)

Example 1: interreflections in a cavity

Interreflections in a diffuse V-cavity

Variation of the perceived radiance

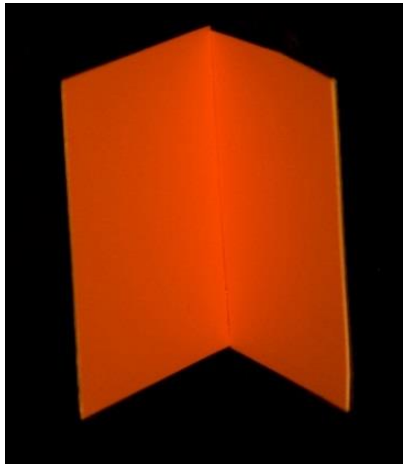
depending on whether the illumination light is collimated or diffuse

Assumptions and parameters

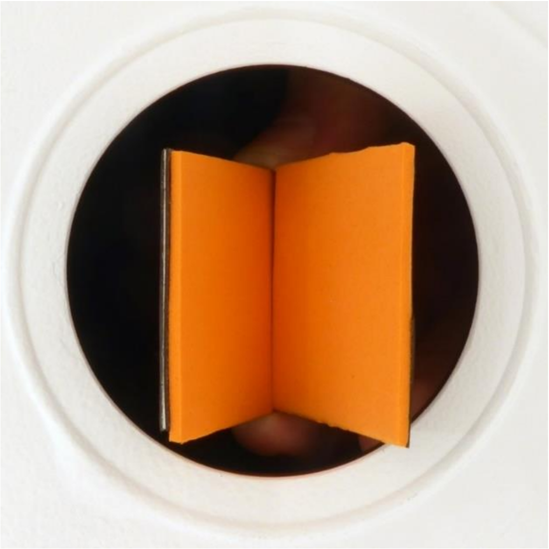
Infinitely long V-cavity

Lambertian material of reflectance ρ

Aperture angle of the cavity α



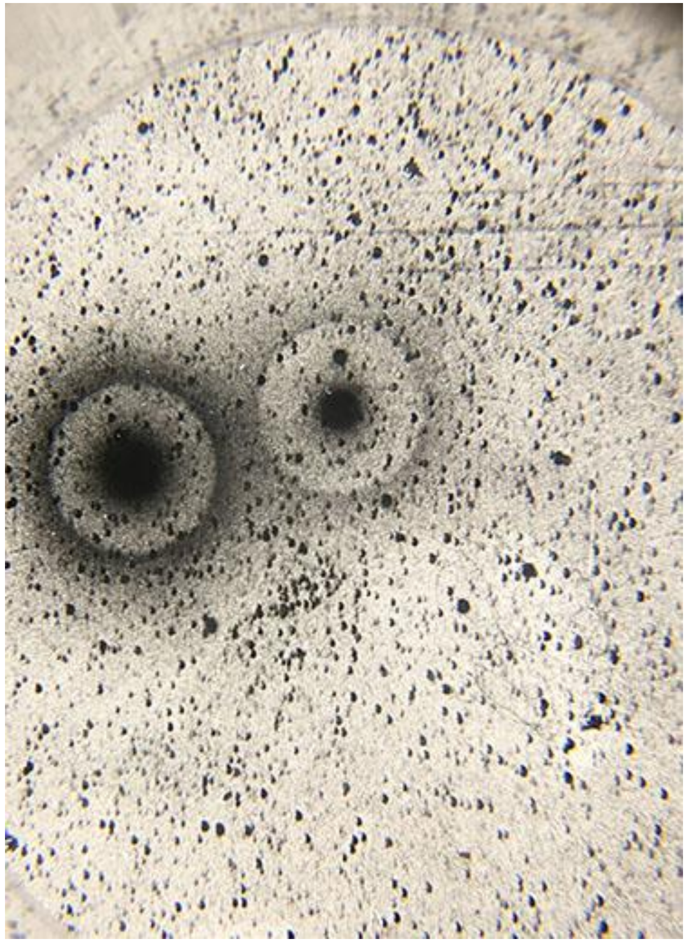
Frontal illumination



Diffuse illumination

D. Saint-Pierre *et al.*, Material Appareance in Electronic Imaging (2018)

Example 2: halo in a transparent coating

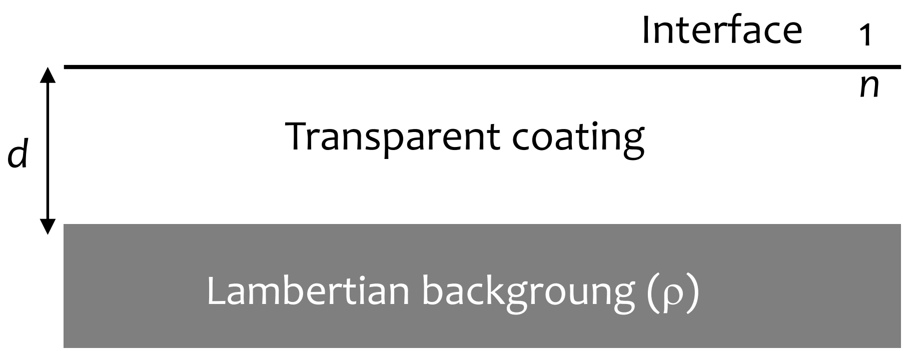


Photograph on glass plate of the Milky Way (in negative). E.E. Barnard, about 1892-1895

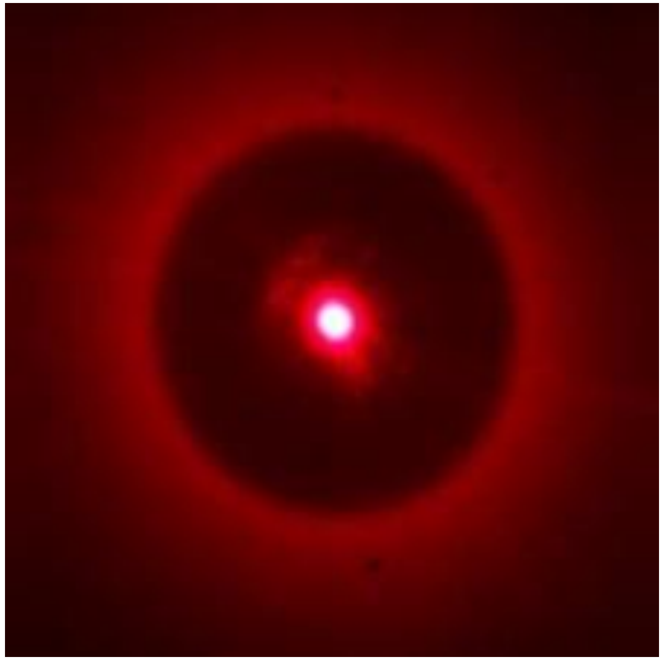
Example 2: halo in a transparent coating

Global radiometric response

Assumptions and parameters



Halo in a transparent coating on a diffuse substrate



4 mm thick glass plate in optical contact with a paper, illuminated with a red laser diode © Morgane Gerardin

L. Simonot *et al.*, JOSA A (2018)

Some issues

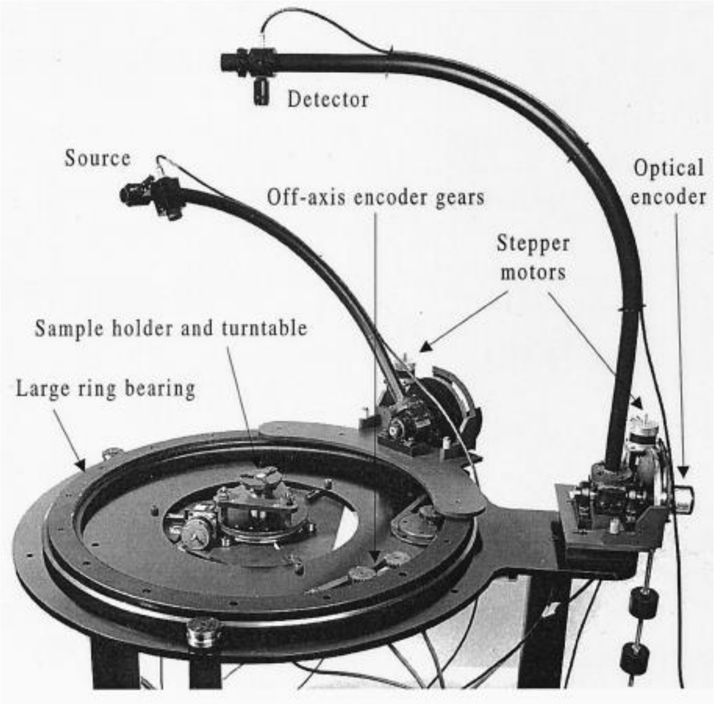
Limitations related to radiometric measurement possibilities

- There are no standardized measurements of BSSRDF

- BRDF measurements have low signal-to-noise ratios especially at grazing angles and often poor angular resolution

- Even for spectral measurements, it is difficult to measure reflectances of translucent materials.

→ Need to collaborate with metrologists



D.R. White *et al.*, Applied Optics (1998)

Some issues

Error estimation between simulations and measurements

- rms error doesn't represent the difference in perception → ΔE in colorimetry
- Which error for BRDF? Which weight for the diffuse part and for the specular lobe?
- Sparse measured data: interpolation/extrapolation errors

Some issues

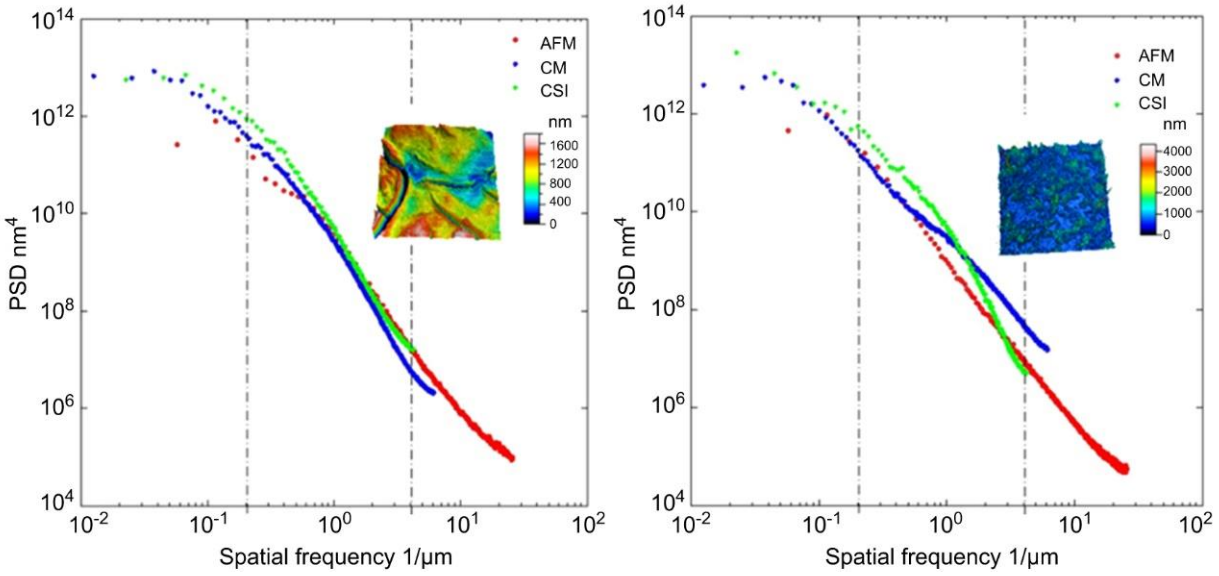
Know, measure or estimate the parameters describing the materials

How to measure complex refractive indices for non-flat (rough surface, powder) or non-opaque materials?

Some issues

Know, measure or estimate the parameters describing the materials

Measurement of surface topography: which spatial frequency range has an impact on the radiometric response?



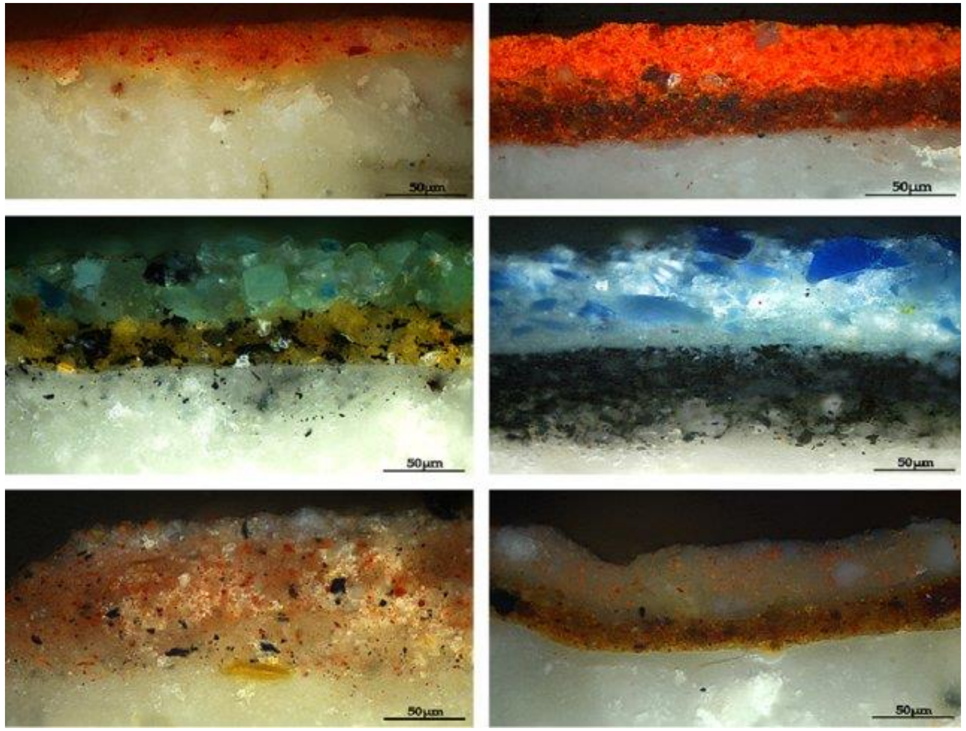
O. Flys et al., Surface Topography: Metrology and Properties (2015)

Coherence scanning interferometer (CSI)
Confocal microscope (CM)
Atomic force microscope (AFM)

Some issues

Know, measure or estimate the parameters describing the materials

How to have a correct evaluation of the size, shape and organisation of the particles?



Cross-sections of several shades in the St Stephen wall paintings
S. Daniila, Journal of Archaeological Science (2008)

From material to appearance

Radiometric response

Spectral, angular and spatial distribution of
reflected and transmitted light in the visible range

Model parameters cannot be measured independently.
Models generally feed on themselves!

Parameters describing the object

Complex refractive indices of each component

Size, shape, concentration and organisation
of the heterogeneities (surface and volume)

Model parameters

Roughness parameter / slope distribution

Absorption and scattering coefficients / phase function

Conclusion

Radiometric approach is possible for ideal situations and a small number of parameters

Combined approach (radiometry and machine learning) could be efficient for more complex systems

Appearance prediction models should be adapted to measurements facilities