EG 2020 STAR presentation

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Survey of Models for Acquiring the Optical Properties of Translucent Materials

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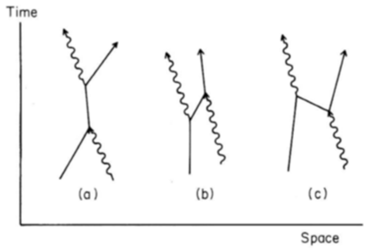
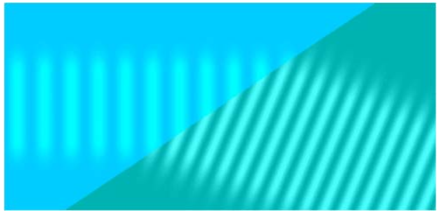
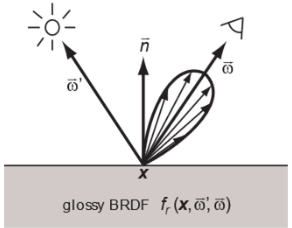
Optical properties

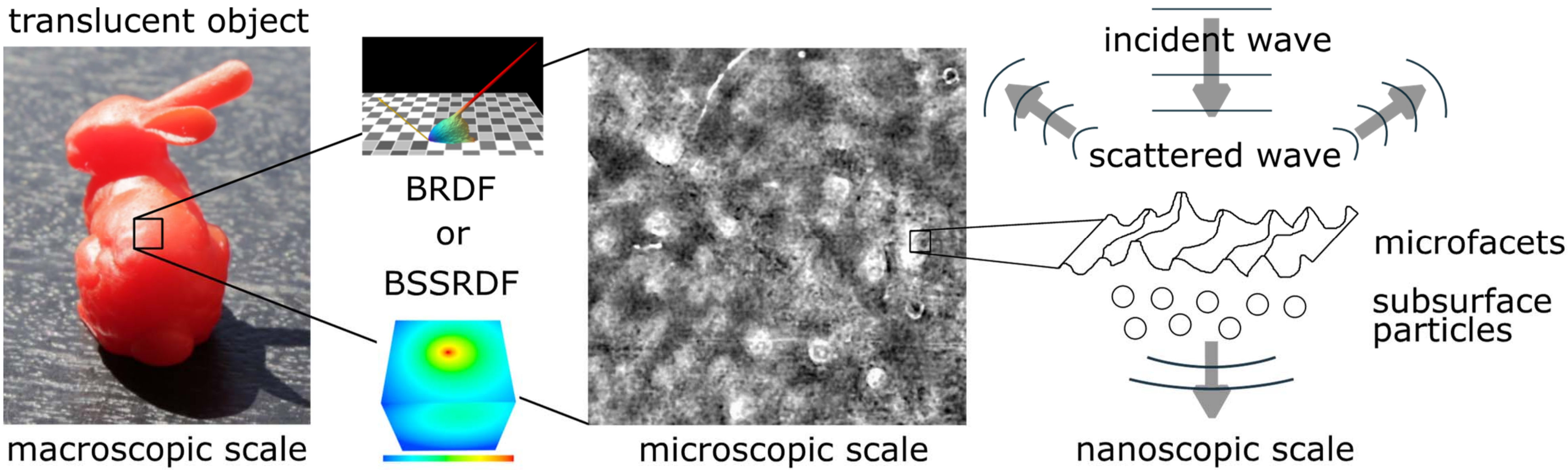
- Parameters that determine how light interacts with a material.
- Quantum and wave theories:
  - Quantum scale: photon-electron interactions in atomic systems.
  - Nanoscopic scale: charge and current densities in atomic systems.
  - Microscopic scale: polarisation and magnetisation vectors.
  - Macroscopic scale: permittivity, permeability, conductivity.
- Radiative transfer theory:
  - Microscopic scale: complex index of refraction.
  - Mesoscopic scale: surface BSDF, scattering cross section, phase function.
  - Macroscopic scale: scattering properties, BSSRDF, BRDF, BTDF.







Multiscale modelling

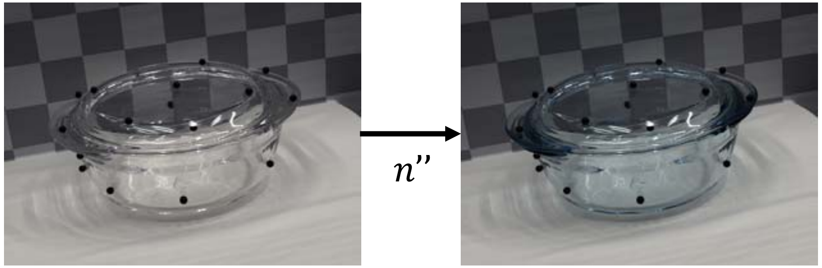


- With simulation of light propagation, we can compute macroscopic optical properties by considering geometry at different scales.

Index of refraction (or refractive index)

- Combining permittivity (ε), permeability (μ), and conductivity (σ):
- $n_{\text{med}} = n' + i\,n'' = c\sqrt{\mu\left(\varepsilon + i\,\frac{\sigma}{\omega}\right)}$
  - ω is angular frequency.
  - c is the speed of light *in vacuo*.
- Real part $n' \approx \frac{c}{v}$
  - v is the phase velocity of the light wave.
- Imaginary part $n'' \approx \frac{\sigma_a \lambda}{4\pi}$
  - σ_a is the absorption coefficient.
  - λ is the wavelength *in vacuo*.

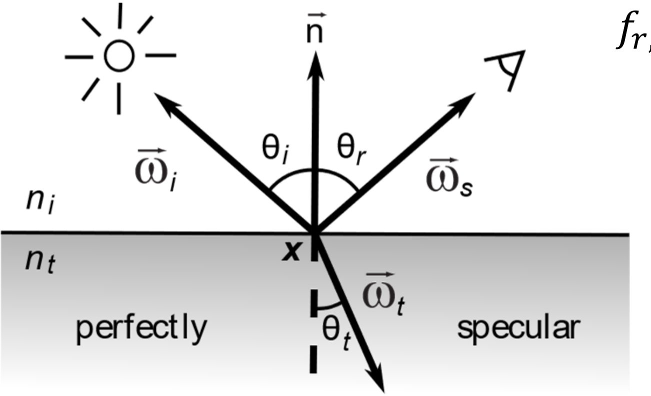
varying the real part n'



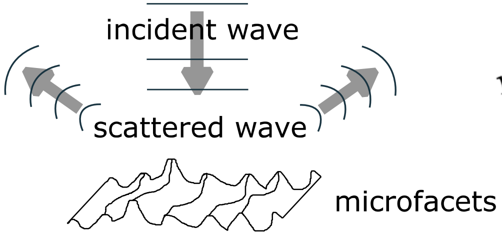
Including absorption

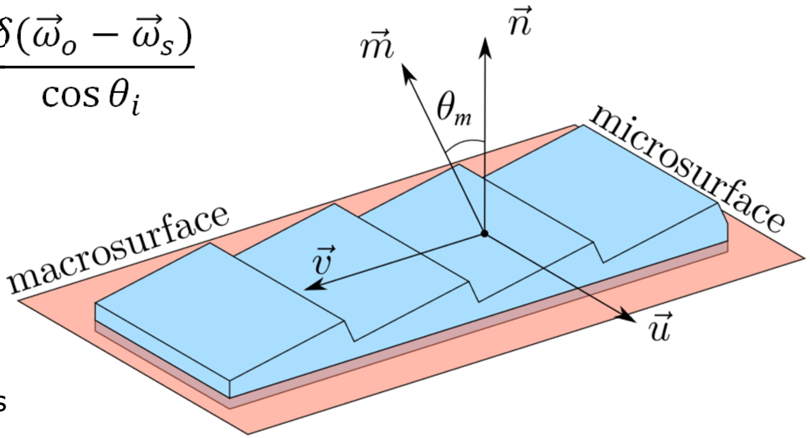
Microfacet BSDF

- A surface is **optically smooth** if the surface roughness R_q is sufficiently small compared with the wavelength λ.
- Rayleigh smooth-surface criterion: $R_q < \lambda/(8\cos\theta_i)$.
- Considering smooth microgeometry we can use n_{med} as input for analytic or computational solutions for Maxwell's equations.
- Example: Fresnel reflectance F for a microfacet BSDF.



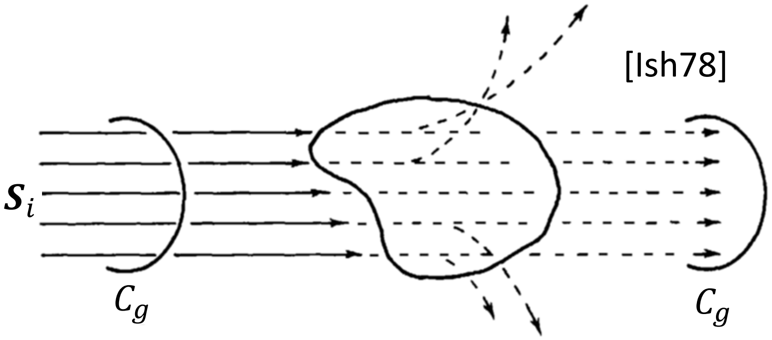
$$f_{r,m}(\boldsymbol{x}_m, \vec{\omega}_i, \vec{\omega}_o) = F\left(\vec{m}, \vec{\omega}_i, \frac{n_t}{n_i}\right)\frac{\delta(\vec{\omega}_o - \vec{\omega}_s)}{\cos\theta_i}$$





Particle phase function and cross sections

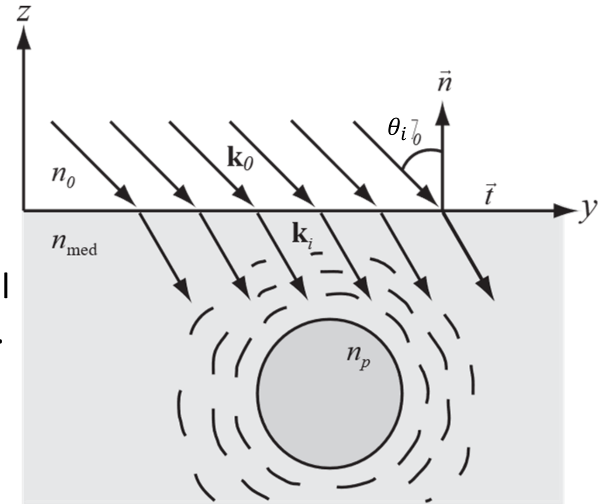
- Particle cross sections
  - C_g is the geometric cross section.
  - C_s is the scattering cross section.
  - C_a is the absorption cross section.
  - $C_t = C_s + C_a$ is the extinction cross section.

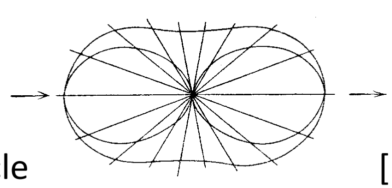


[Ish78]

- Particle phase function
  - $p_m(\vec{\omega}_i, \vec{\omega}_o)$ is the far field distribution of the scattered light.
  - $g = \int_{4\pi} p_m(\vec{\omega}_i, \vec{\omega}_o)\,(\vec{\omega}_i \cdot \vec{\omega}_o)\,\mathrm{d}\omega$ is the asymmetry parameter in [-1,1].

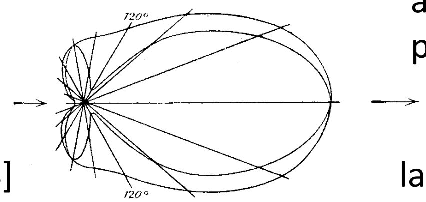
Example: Insert $x = \frac{2\pi r n_{\mathrm{med}}}{\lambda}$ and $y = \frac{2\pi r n_p}{\lambda}$ in Lorenz-Mie theory to compute C_s, C_t, and p of a spherical particle of radius r.





small particle

[Mie08]



large particle

Scattering properties of a medium

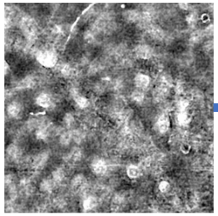
[FCJ07]

- Using a particle size distribution $N(r)$: $\sigma_s = \int_{r_{\min}}^{r_{\max}} C_s(r) N(r)\, \mathrm{d}r$
  - σ_s is the scattering coefficient.
  - Similarly for σ_a (absorption coefficient) and p (ensemble phase function).
- Using a microfacet normal distribution $D(\vec{m})$:

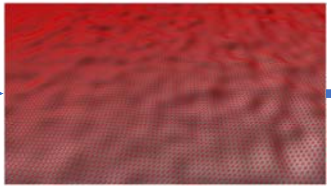
[WMLT07]

$$f_s(\vec{\omega}_i, \vec{\omega}_o, \vec{n}\,) = \int \left| \frac{\vec{\omega}_i \cdot \vec{m}}{\vec{\omega}_i \cdot \vec{n}} \right| f_m(\vec{\omega}_i, \vec{\omega}_o, \vec{m}) \left| \frac{\vec{\omega}_o \cdot \vec{m}}{\vec{\omega}_o \cdot \vec{n}} \right| G(\vec{\omega}_i, \vec{\omega}_o, \vec{m})\, D(\vec{m})\, \mathrm{d}\omega_m$$

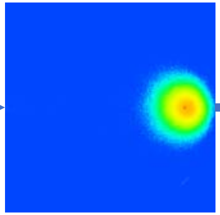
  - G is a geometrical attenuation term (shadowing/masking).
- Or we can use explicitly defined microgeometry



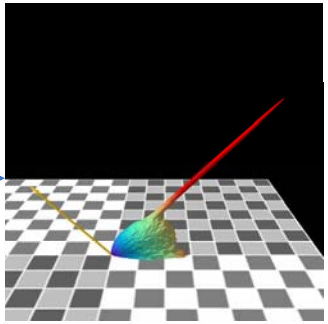
profilometry



triangle mesh



simulation

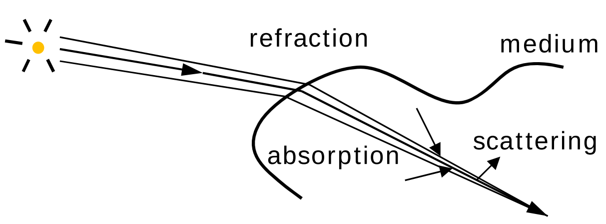


BSDF

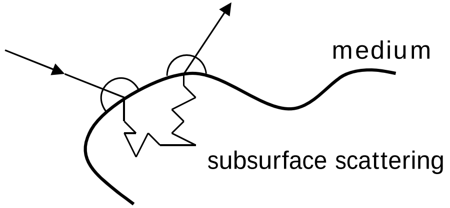
Global scattering function (BSSRDF)

- From local to global formulation using scattering operators [Pre65].

$$L_r = L_i \mathbf{S} = L_i \mathbf{F}_s \sum_{j=0}^{\infty} \mathbf{S}^j \mathbf{F}_s$$



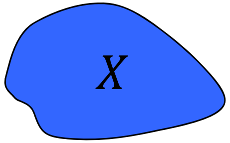
Local



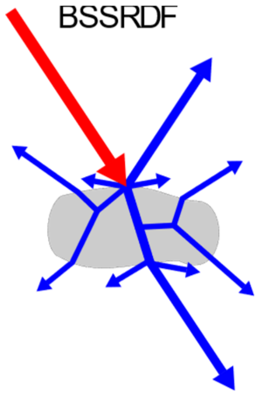
Global

  - $\mathbf{F}_s$ is surface scattering
  - $\mathbf{S}^0$ is direct transmission
  - $\mathbf{S}^j$ for $j > 0$ is subsurface scattering (with j scattering events)

- For



$\longrightarrow \bullet\, \boldsymbol{x}$, $\mathbf{S} \rightarrow \sigma_s p(\vec{\omega}_i, \vec{\omega}_o)$



- Continuous boundary and interior leads to the BSSRDF:

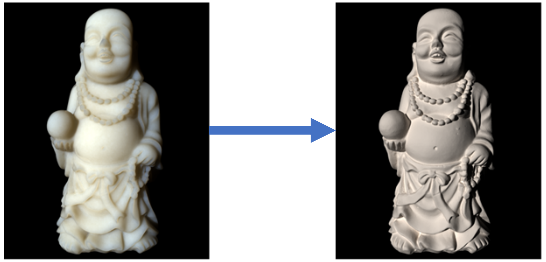
$$S(X; \boldsymbol{x}_i, \vec{\omega}_i; \boldsymbol{x}_o, \vec{\omega}_o) = \lim_{\substack{X_i \to \boldsymbol{x}_i \\ \Omega_i \to \vec{\omega}_i}} \frac{L_i \mathbf{S}(\boldsymbol{x}_o, \vec{\omega}_o)}{L_i(X_i, \Omega_i) A_{i\perp}(X_i) \omega_i(\Omega_i)} = \frac{\mathrm{d}L_r(\boldsymbol{x}_o, \vec{\omega}_o)}{L_i(\boldsymbol{x}_i, \vec{\omega}_i) \mathrm{d}A_{i\perp}\, \mathrm{d}\omega_i} = \frac{\mathrm{d}L_r(\boldsymbol{x}_o, \vec{\omega}_o)}{\mathrm{d}\Phi_i(\boldsymbol{x}_i, \vec{\omega}_i)}$$

Macroscopic BRDF/BTDF

- Object with homogeneous scattering properties.
- Uniform irradiation of the object over an area A_i around $\boldsymbol{x}_o$.
  - A_i is large enough to include all $\boldsymbol{x}_i$ with subsurface scattering to $\boldsymbol{x}_o$.
- The BRDF is then

$$f_r(\boldsymbol{x}, \vec{\omega}_i, \vec{\omega}_o) = \int_{A_i} S(X; \boldsymbol{x}_i, \vec{\omega}_i; \boldsymbol{x}_o, \vec{\omega}_o)\, \mathrm{d}A_i = \frac{\mathrm{d}L_r(\boldsymbol{x}, \vec{\omega}_o)}{\mathrm{d}E(\boldsymbol{x}, \vec{\omega}_i)}$$

- The equation is the same for the BTDF, but then $\vec{\omega}_i \cdot \vec{n}_o < 0$.
  - $\vec{n}_o$ is the surface normal at the point of observation.
- Macroscopic BRDF/BTDF works well for opaque/thin objects.
- Not a good approximation for solid translucent objects.

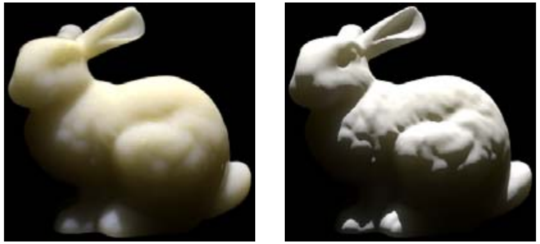


Lambertian BRDF approximation

Appearance of translucent materials

- Varying the transport mean free path $\frac{1}{\sigma_t'} = \frac{1}{\sigma_a + (1-g)\sigma_s}$

$1/\sigma_t'$ increasing $\rightarrow$



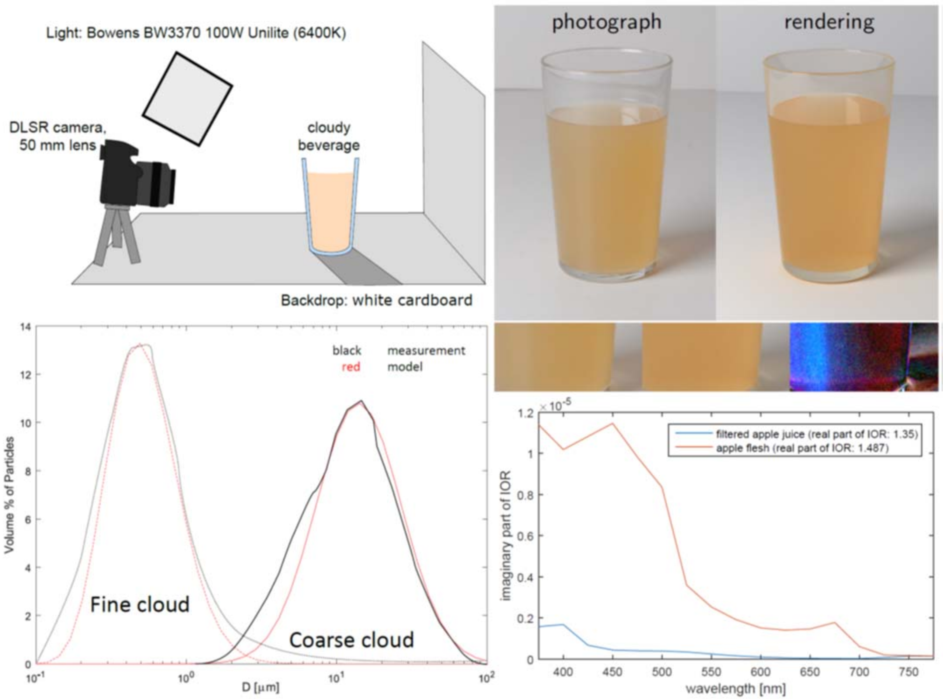
- Varying surface roughness
- Varying lighting environment
- Varying colours (absorption and scattering spectra)

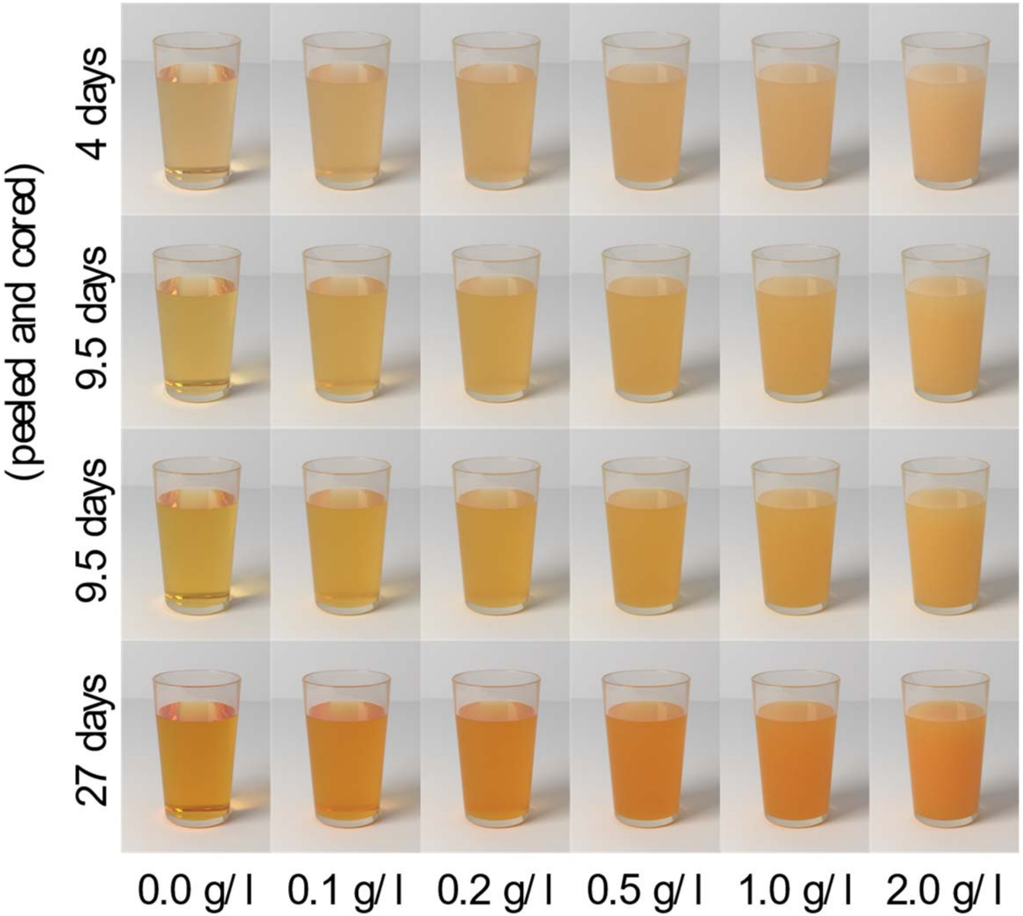
Influence of particle content

[DFKB16]

- Apple juice example
  - Particle concentration (horizontally).
  - Storage time and handling (vertically).

[FK19]





Discussion

- Translucent objects require optical properties describing both surface and subsurface scattering.
- What is the best appearance specification for translucent objects?

- Influence of surface roughness [LFD*20]