What am I looking at?

Forward and inverse appearance models

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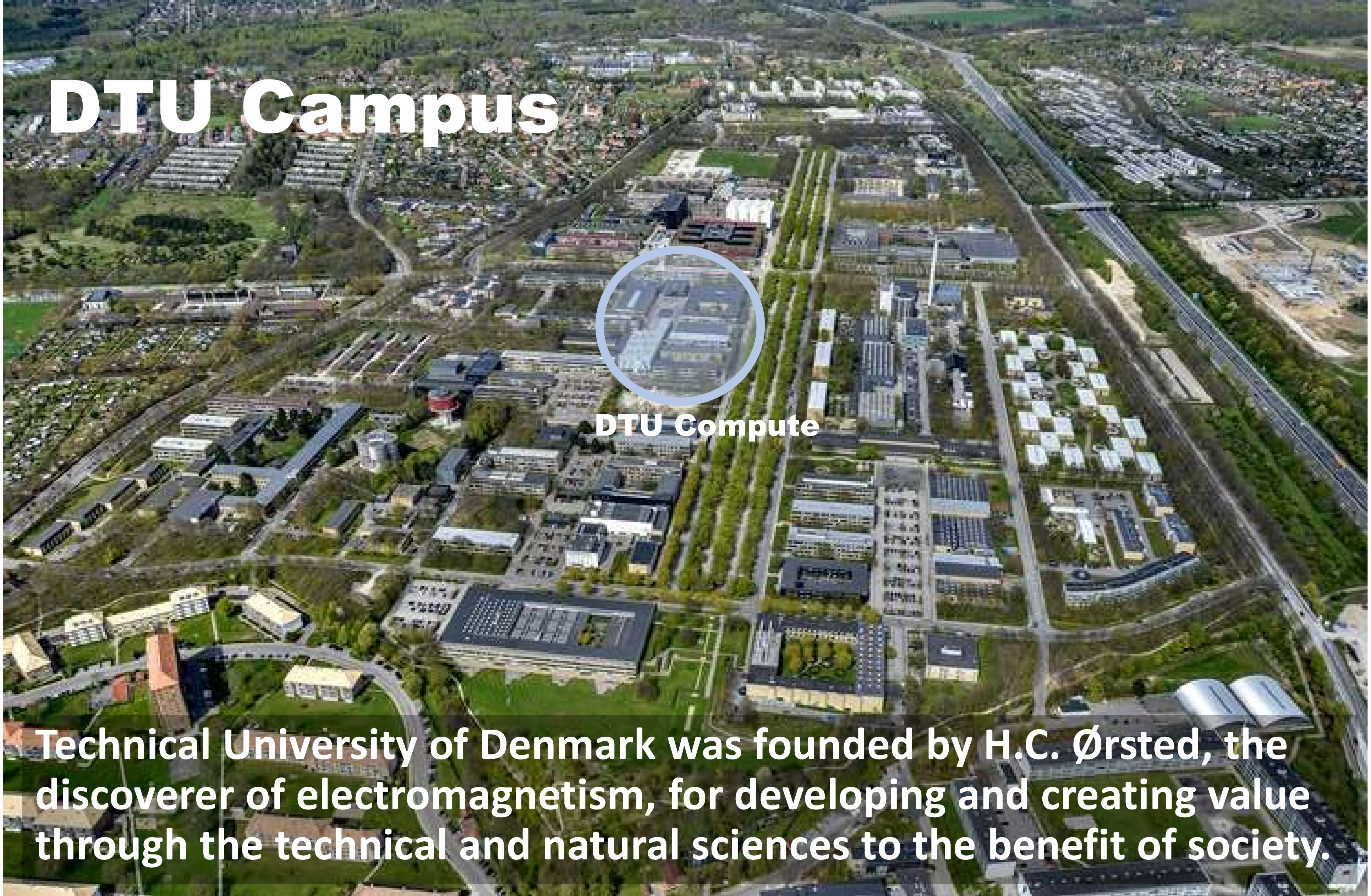
Technical University of Denmark

August 2020

[DTU, DIKU & AAU Summer School on Inverse Problems]()

DTU Campus



Technical University of Denmark was founded by H.C. Ørsted, the discoverer of electromagnetism, for developing and creating value through the technical and natural sciences to the benefit of society.

… spans the entire spectrum from fundamental mathematics across mathematical modelling to computer science, which is the basis of the modern digital world.

11 research sections, 400 employees, 100 permanent academic staff members (faculty)

Section for Image Analysis and Computer Graphics

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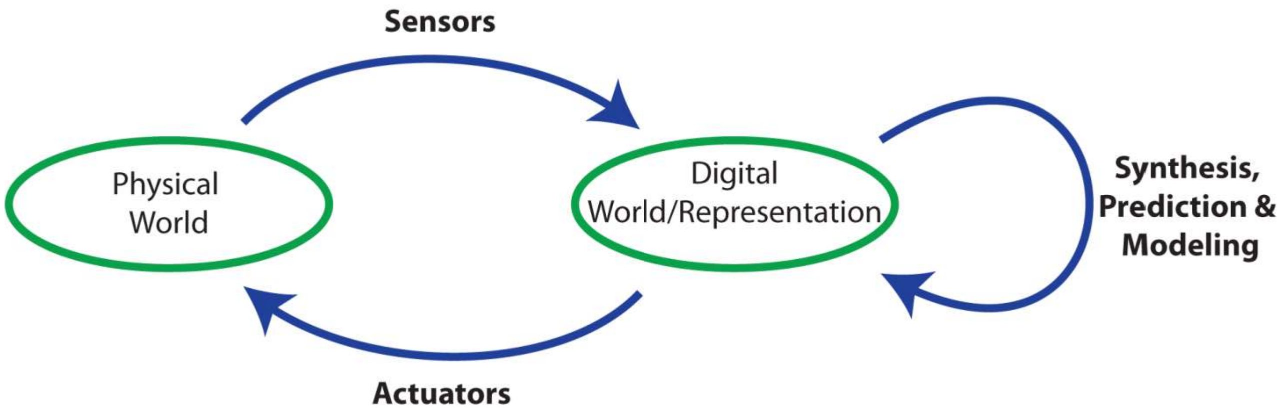
IMAGE ANALYSIS
medical

statistical
COMPUTER VISION
industrial

3D scan and print
GEOMETRIC DATA
processing

modeling
COMPUTER GRAPHICS
rendering



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Research overview

digital prototyping

quality assessment

synthetic data for learning

rendering

material appearance

additive manufacturing

digitizing cultural/natural heritage

visualization

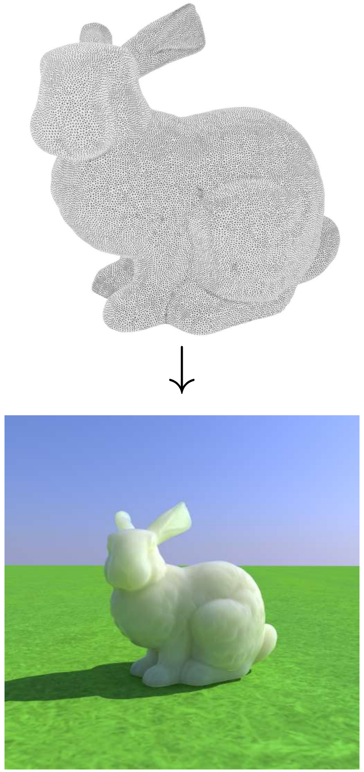
scatter correction in imaging

optical functional materials

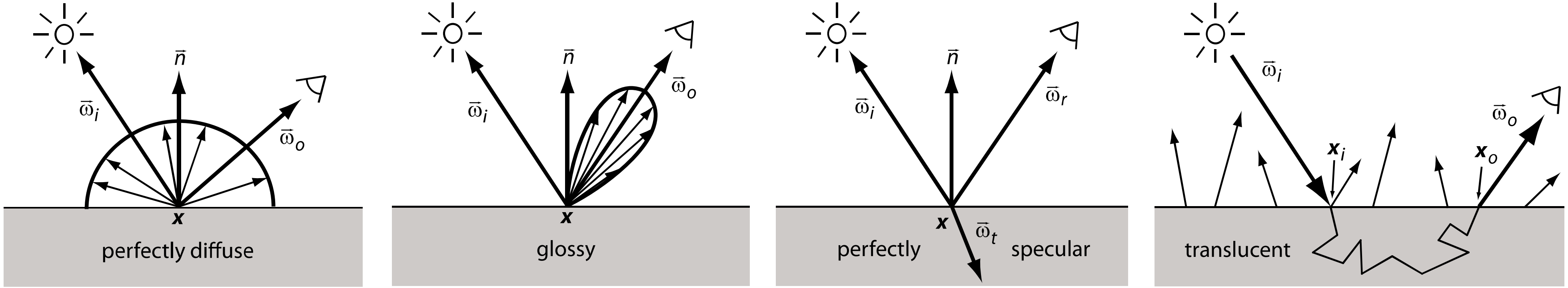
multiscale material modeling

Material appearance

- Light is what you sense.
- Matter is what you see.
- Geometry is an abstraction over the shapes that you see.
- Appearance is a combination of the three.

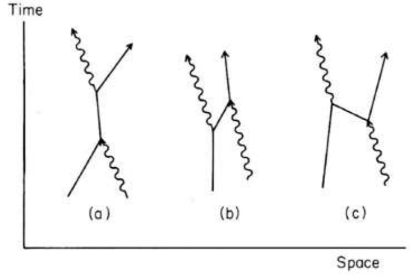


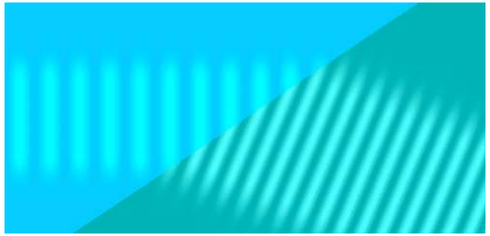
Reflectance: surface and subsurface scattering of light

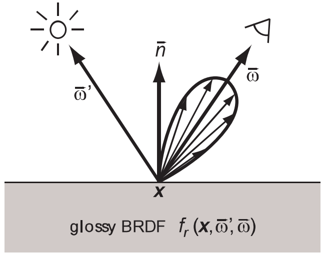


Optical properties

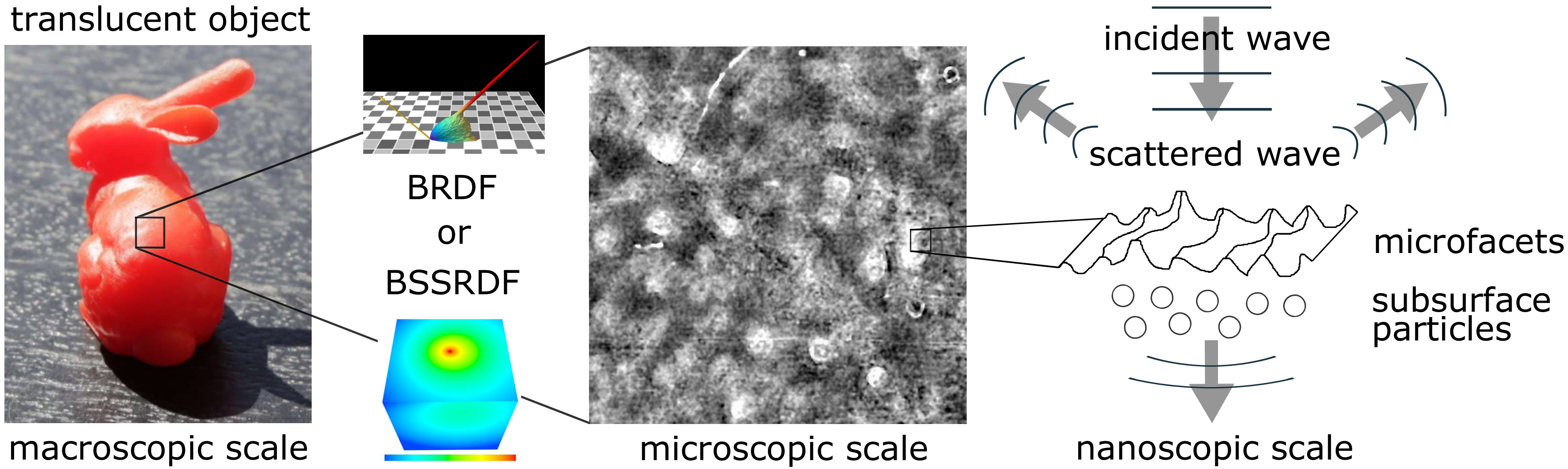
- Parameters that determine how light interacts with a material.
- Quantum and wave theories:
  - Quantum scale: photon-electron interactions in atomic systems.
  - Nanoscopic scale: charge and current densities in atomic systems.
  - Microscopic scale: polarisation and magnetisation vectors.
  - Macroscopic 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.







Optical properties at multiple scales



- Appearance matching: manual adjustment of optical properties is tedious and difficult.
- We can render objects with a plausible appearance but have a hard time matching the appearance of a manufactured item to that of its digital twin.
- Research challenge: **digital representations of real translucent objects**.
- Important aspects: **validation** (photo-render alignment), **acquisition** (inverse rendering), **application** (quality control).

Radiative transfer and scattering properties

- We follow a ray of light passing through a scattering medium.
- The parameters describing the medium are

  σ_a the absorption coefficient $[\mathrm{m}^{-1}]$
  σ_s the scattering coefficient $[\mathrm{m}^{-1}]$
  σ_t the extinction coefficient $[\mathrm{m}^{-1}]$ $(\sigma_t = \sigma_a + \sigma_s)$
  p the phase function $[\mathrm{sr}^{-1}]$
  ε the emission properties $[\mathrm{Wsr}^{-1}\mathrm{m}^{-3}]$ (radiance per meter).

- The radiative transfer equation (RTE)

$$
\begin{aligned}
(\vec{\omega} \cdot \nabla) L(\boldsymbol{x}, \vec{\omega}) \quad = \quad & -\sigma_t(\boldsymbol{x}) L(\boldsymbol{x}, \vec{\omega}) \\
& + \sigma_s(\boldsymbol{x}) \int_{4\pi} p(\boldsymbol{x}, \vec{\omega}', \vec{\omega}) L(\boldsymbol{x}, \vec{\omega}') \, \mathrm{d}\omega' \\
& + \varepsilon(\boldsymbol{x}, \vec{\omega}) \quad ,
\end{aligned}
$$

where L is radiance at the position $\boldsymbol{x}$ along the ray in the direction $\vec{\omega}$.

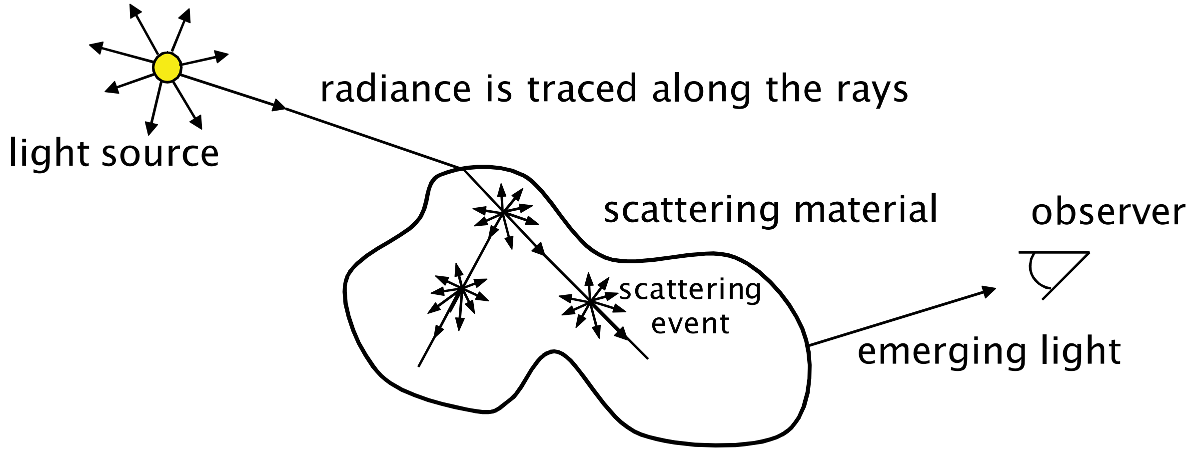
Computing appearance from scattering properties

- Prediction requires solving the radiative transfer equation:

$$(\vec{\omega} \cdot \nabla) L(\boldsymbol{x}, \vec{\omega}) = -\sigma_t(\boldsymbol{x}) L(\boldsymbol{x}, \vec{\omega}) + \sigma_s(\boldsymbol{x}) \int_{4\pi} p(\boldsymbol{x}, \vec{\omega}', \vec{\omega}) L(\boldsymbol{x}, \vec{\omega}') \, \mathrm{d}\omega' + \varepsilon(\boldsymbol{x}, \vec{\omega}) \, .$$

- The solution method of choice today:

  Stochastic ray tracing (Monte Carlo integration).

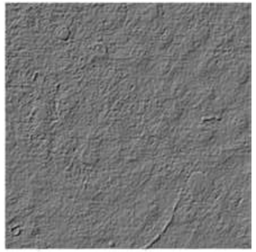


- How do we compute input scattering properties from the microgeometry of a material?

Models at different scales

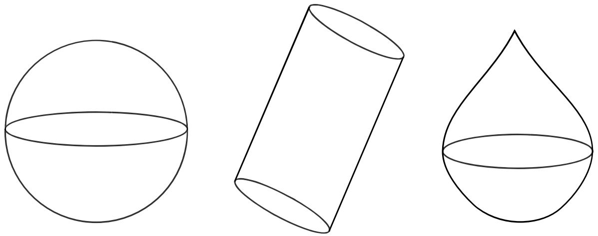
- We divide the microscopic scale into
  - Nano/micro: models considering explicit microgeometry.
  - Micro/milli: models using particle size or microfacet normal distribution functions.
- We divide the macroscopic scale into
  - BSSRDF: models where the points of incidence and emergence are different.
  - BRDF/BTDF: local models for opaque/thin objects.

microsurface

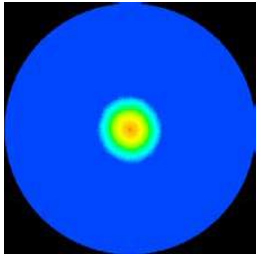


profilometry

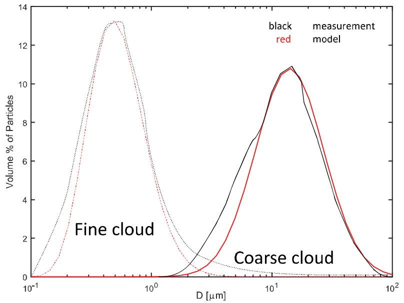
particles



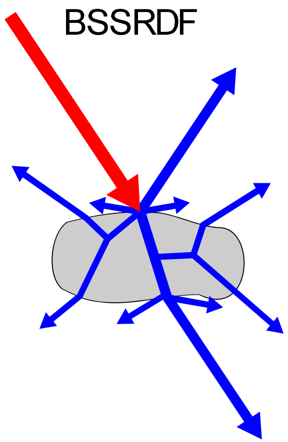
sphere cylinder raindrop

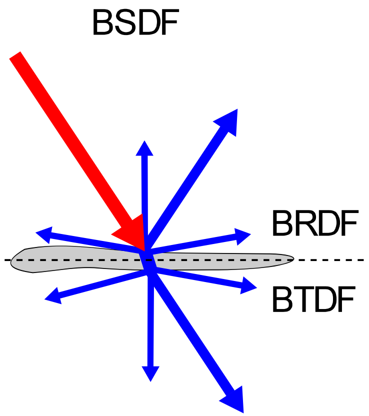


normal distribution



particle size distribution





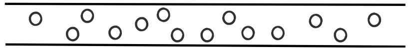
Formal models based on theory(t)

- Mathematical models for optical properties.
- Based on optics or radiative transfer theory.
- Early examples:

V-grooves

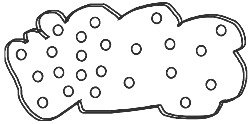
  - Torrance-Sparrow BRDF [TS67,Bli77,CT81]

single scattering in a layer



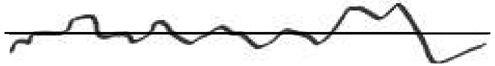
  - Chandrasekhar single-scattering BRDF/BTDF for layers [Bli82,HK93]

volume densities



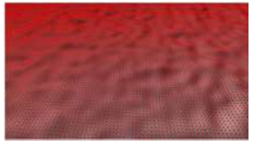
  - Scattering properties from densities [KV84,NIDN97,DEJ*99]

scalar diffraction by surface elements around a plane



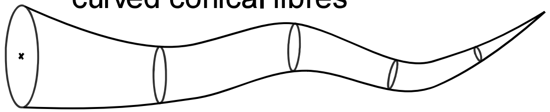
  - Kirchhoff approximation BRDF [Kaj85,HTSG91,Sta99]

microsurface

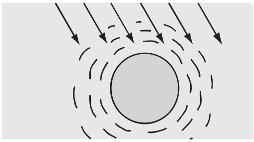


  - BRDF/BTDF from ray tracing of microgeometry [CMS87,WAT92,GMN94]

curved conical fibres

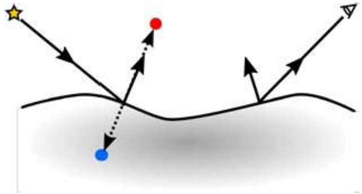


  - Fibre scattering model (BCSDF) [KK89,MJC*03,ZW07]



scattering by spherical particles

  - Lorenz-Mie scattering properties [Cal96,JW97,FCJ07]
  - Diffusion dipole BSSRDF [JMLH01,DJ05]



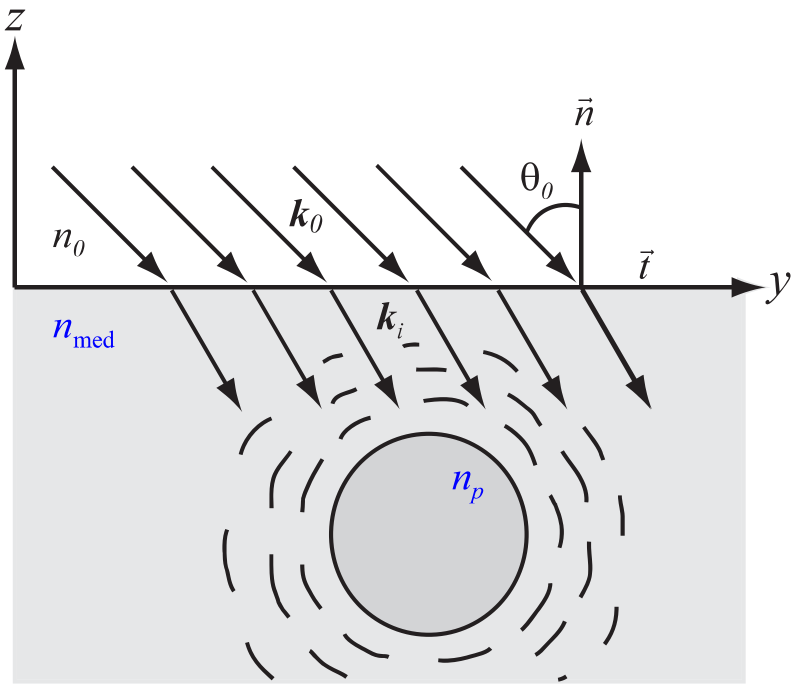
dipole models

Forward simulation(→)

- Computing optical properties at a more macroscopic scale.
- Formulate a measurement equation and evaluate it by simulation.
- Use microscale information to find a macroscopic function.
- Examples:
  - Microfacet normal distribution → BRDF/BTDF [TS67,Bli77,CT81,HTSG91,Sta99]
  - Explicitly defined microsurface → BRDF/BTDF [Kaj85,CMS87,WAT92,GMN94]
  - Fibre geometry → scattering properties [KK89]
  - particle concentrations → BRDF [HM92,Cal96]
  - Spherical particle → scattering properties [Cal96,JW97]
  - Explicitly defined microsurface → microfacet normal distribution [Sta99]
  - BSSRDF → BRDF [JMLH01]

Scattering of a plane wave by a spherical particle

- A plane wave scattered by a spherical particle gives rise to a spherical wave.
- The components of a spherical wave are spherical functions.
- To evaluate these spherical functions, we use spherical harmonic expansions.
- Coefficients in these spherical harmonic expansions are referred to as Lorenz-Mie coefficients a_n and b_n.



- Lorenz [1890] and Mie [1908] derived formal expressions for a_n and b_n using the spherical Bessel functions j_n and y_n.
- These expressions are written more compactly if we use the Riccati-Bessel functions: $\psi_n(z) = z\, j_n(z) \quad , \quad \zeta_n(z) = z(j_n(z) - i\, y_n(z))\,,$ where z is (in general) a complex number.

The Lorenz-Mie coefficients (a_n and b_n)

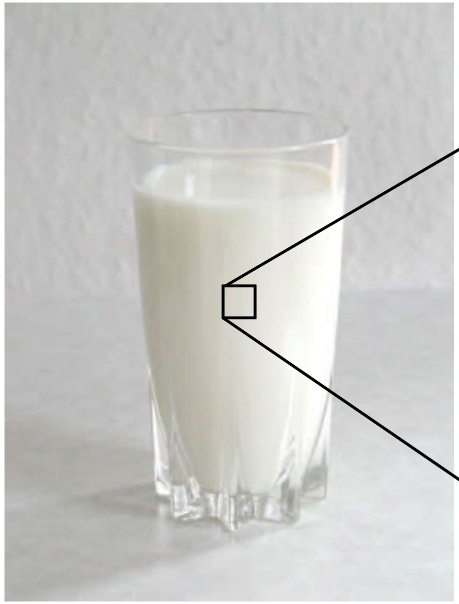
- Using the Riccati-Bessel functions ψ_n and ζ_n, the expressions for the Lorenz-Mie coefficients are

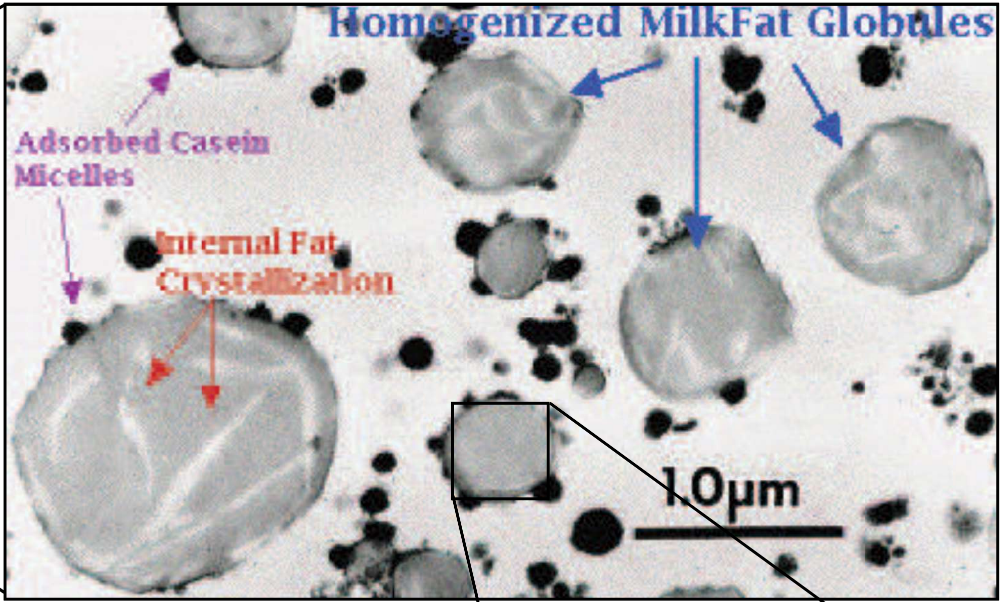
$$a_n = \frac{n_{\mathrm{med}}\psi_n'(y)\psi_n(x) - n_p\psi_n(y)\psi_n'(x)}{n_{\mathrm{med}}\psi_n'(y)\zeta_n(x) - n_p\psi_n(y)\zeta_n'(x)}$$
$$b_n = \frac{n_p\psi_n'(y)\psi_n(x) - n_{\mathrm{med}}\psi_n(y)\psi_n'(x)}{n_p\psi_n'(y)\zeta_n(x) - n_{\mathrm{med}}\psi_n(y)\zeta_n'(x)} .$$

  - Primes $'$ denote derivative.
  - n_{med} and n_p are the refractive indices of the host medium and the particle respectively.
  - x and y are called size parameters.
- If r is the particle radius and λ is the wavelength *in vacuo*, then x and y are defined by

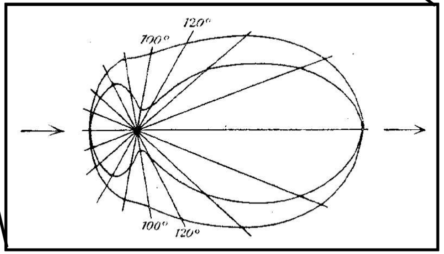
$$x = \frac{2\pi r n_{\mathrm{med}}}{\lambda} \quad , \quad y = \frac{2\pi r n_p}{\lambda} .$$

From particles to appearance





Courtesy of University of Guelph



Lorenz–Mie theory provides the link

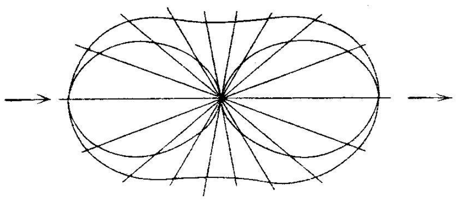
Scattering by spherical particles

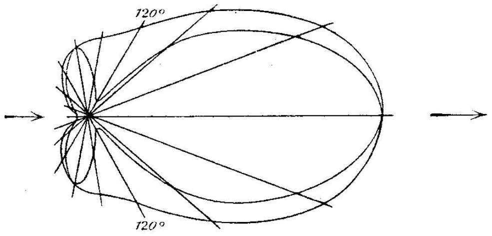
- The Lorenz-Mie theory:

$$
\begin{aligned}
p(\theta) &= \frac{|S_1(\theta)|^2 + |S_2(\theta)|^2}{2|k|^2 C_s} \\
S_1(\theta) &= \sum_{n=1}^{\infty} \frac{2n+1}{n(n+1)} \left(a_n \pi_n(\cos\theta) + b_n \tau_n(\cos\theta) \right) \\
S_2(\theta) &= \sum_{n=1}^{\infty} \frac{2n+1}{n(n+1)} \left(a_n \tau_n(\cos\theta) + b_n \pi_n(\cos\theta) \right) \quad .
\end{aligned}
$$

- a_n and b_n are the Lorenz-Mie coefficients.
- π_n and τ_n are spherical functions associated with the Legendre polynomials.

small particle





large particle

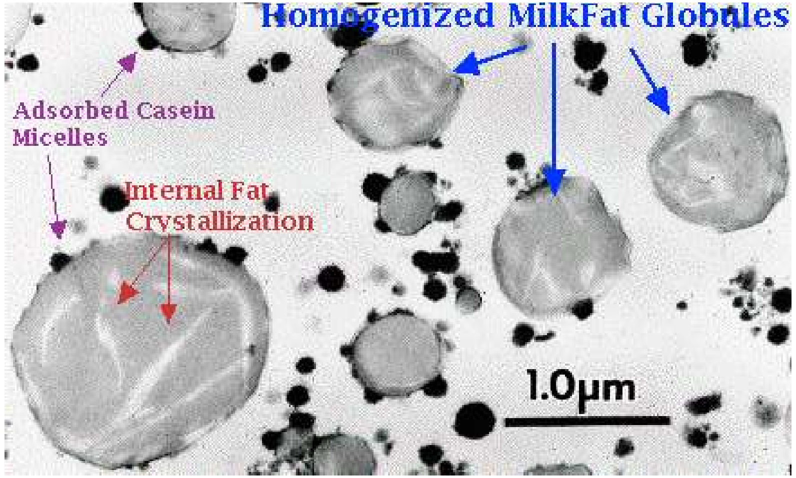
Quantity of scattering

- Lorenz-Mie theory continued:

  The scattering and extinction cross sections of a particle:

$$C_s = \frac{\lambda^2}{2\pi|n_{\mathrm{med}}|^2}\sum_{n=1}^{\infty}(2n+1)\left(|a_n|^2+|b_n|^2\right)$$

$$C_t = \frac{\lambda^2}{2\pi}\sum_{n=1}^{\infty}(2n+1)\mathrm{Re}\left(\frac{a_n+b_n}{{n_{\mathrm{med}}}^2}\right) .$$



Bulk optical properties of a material

- Input is the desired volume fraction of a component v and a representative number density distribution $\hat{N}$. We have

$$\hat{v} = \frac{4\pi}{3} \int_{r_{\text{min}}}^{r_{\text{max}}} r^3 \hat{N}(r) \, \mathrm{d}r \quad ,$$

  and then the desired distribution is $N = \hat{N} v / \hat{v}$.
- Use this to find the bulk properties σ_s (and σ_t likewise)

$$\sigma_s = \int_{r_{\text{min}}}^{r_{\text{max}}} C_s(r) N(r) \, \mathrm{d}r \quad .$$

Computing scattering properties

- Input needed for computing scattering properties:
  - Particle composition (volume fractions, particle shapes).
  - Refractive index for host medium n_{med}.
  - Refractive index for each particle type n_p.
  - Size distribution for each particle type (N).

- Lorenz-Mie theory uses a series expansion. How many terms should we include?
- Number of terms to sum $M = \left\lceil |x| + p|x|^{1/3} + 1 \right\rceil$.
  - Empirically justified [Wiscombe 1980, Mackowski et al. 1990].
  - Theoretically justified [Cachorro and Salcedo 1991].
  - For a maximum error of 10^{-8}, use $p = 4.3$.

- Code for evaluating the expansions in the Lorenz-Mie theory is available online [Frisvad et al. 2007]: https://people.compute.dtu.dk/jerf/code/

Case study: milk

skimmed

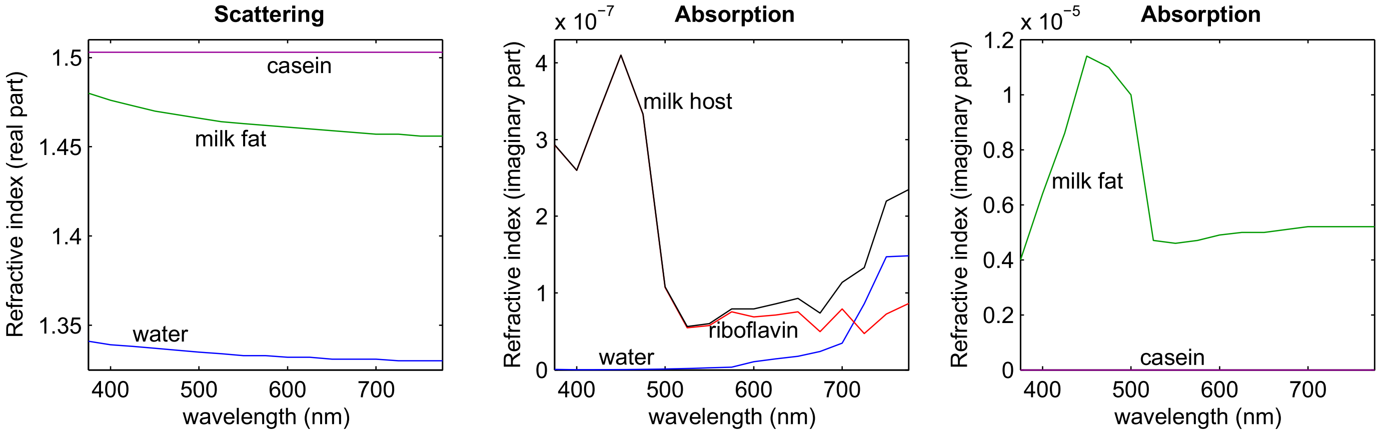
low fat

whole

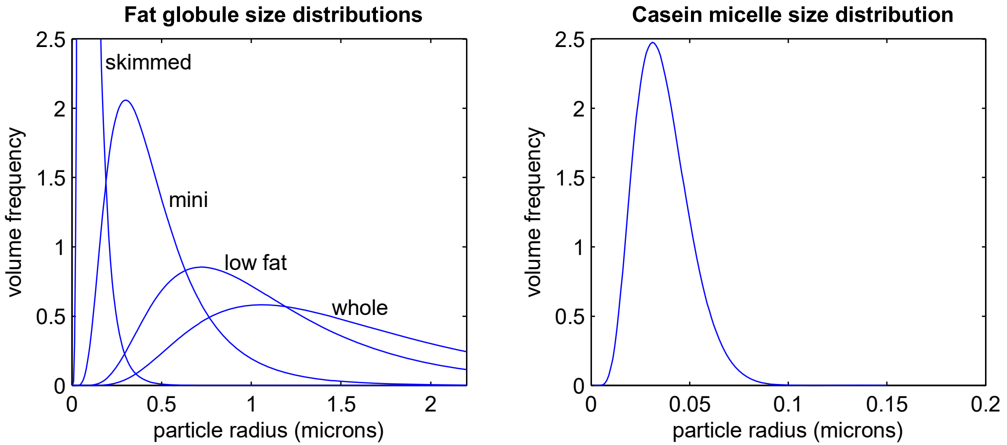
- Refractive index of host: water + dissolved vitamin B2.
- Fat and protein contents: user input in wt.-%.
- Refractive index of milk fat and casein: measured spectra.
- Shape of fat globules and casein micelles: spheres and a volume to surface area ratio.
- Size distributions: log-normal with mean depending on fat content and homogenization pressure.

Measurements used for the milk model

- Refractive indices:



- Particle size distributions:



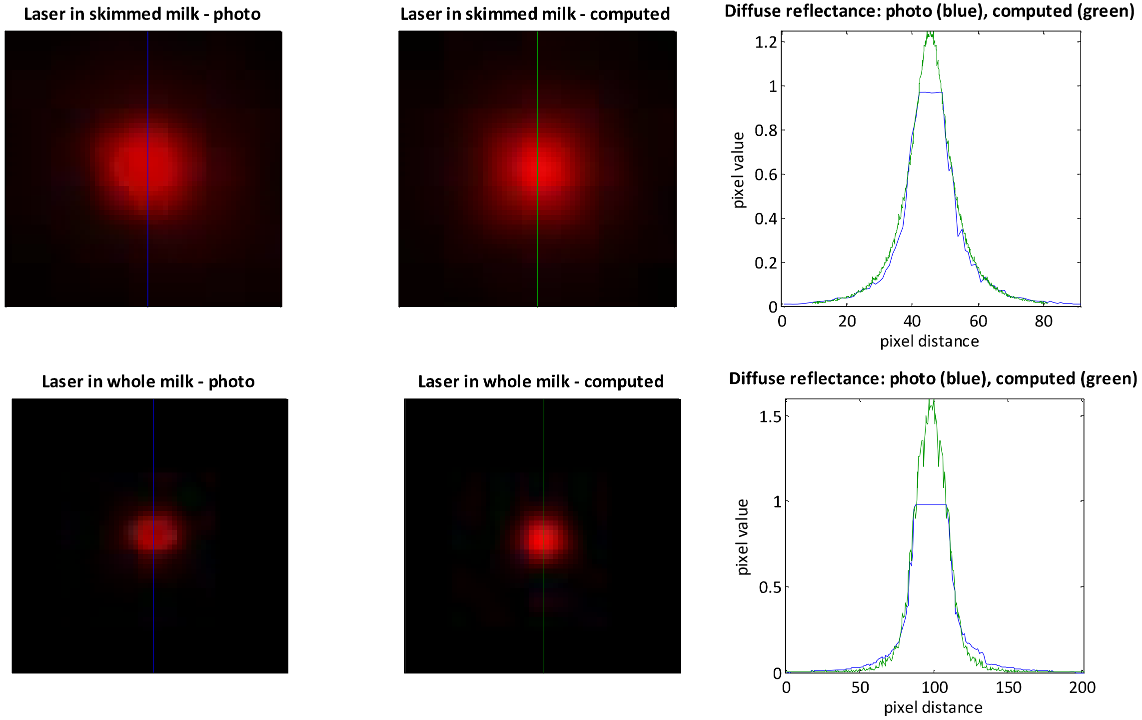
Predicting appearance based on a content declaration

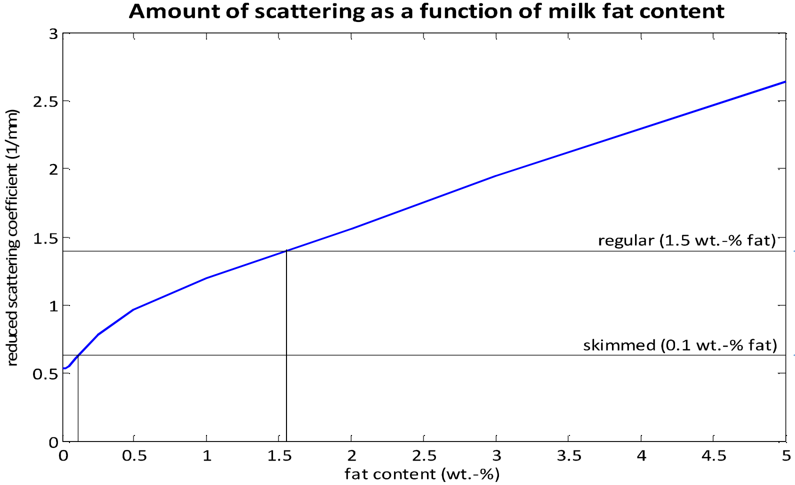
water vitamin B2 protein fat skimmed low fat whole

- Vitamin B2 content: 0.17 mg / 100 g
- Protein content: 3 g / 100 g
- Fat content: 0.1 g (skimmed), 1.5 g (low fat), 3.5 g (whole) / 100 g
- Homogenization pressure: 0 MPa (model: [0, 50] MPa)

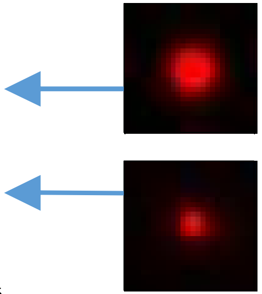
Simplistic model validation

- Camera
- Tripod
- Laser pointer
- Cup (use black cup)



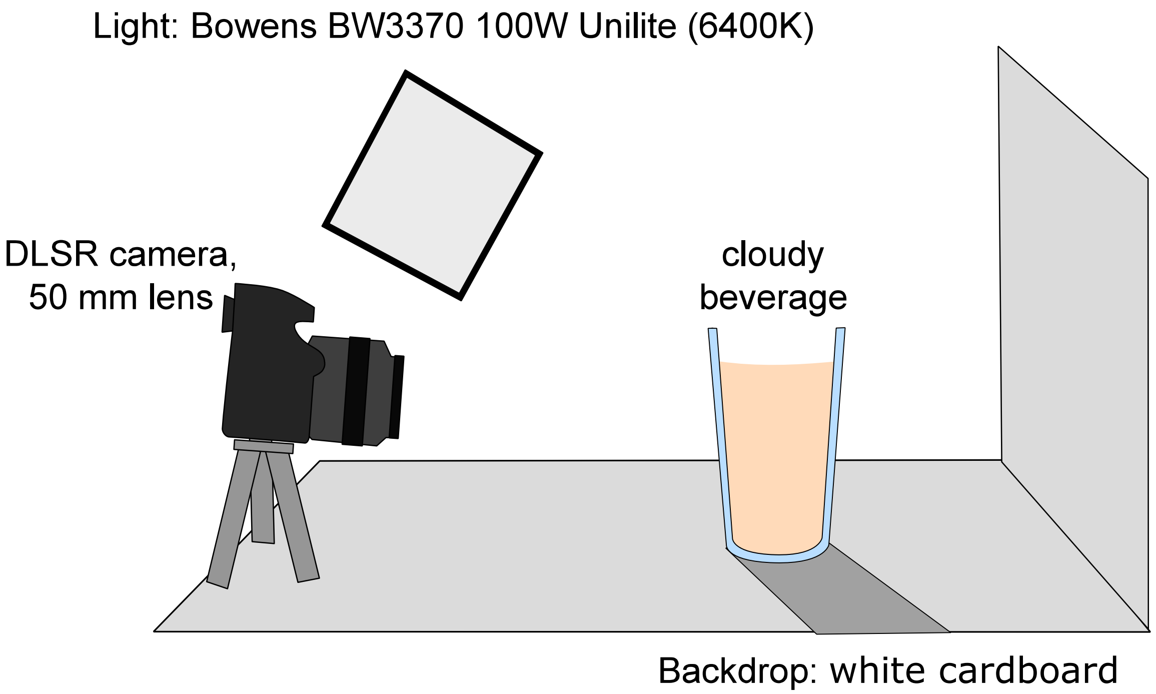


Captured images used for estimating the reduced scattering coefficient:



Predicting appearance

Scene



organic low fat milk

rendering photograph

- Digital scene modeled by hand to match physical scene (as best we could)

Case study: cloudy apple juice

> *The visual appearance of a cloudy drink is a decisive factor for consumer acceptance. [Beveridge 2002]*

Let us see if we can use Lorenz-Mie theory to create an appearance model useful for:

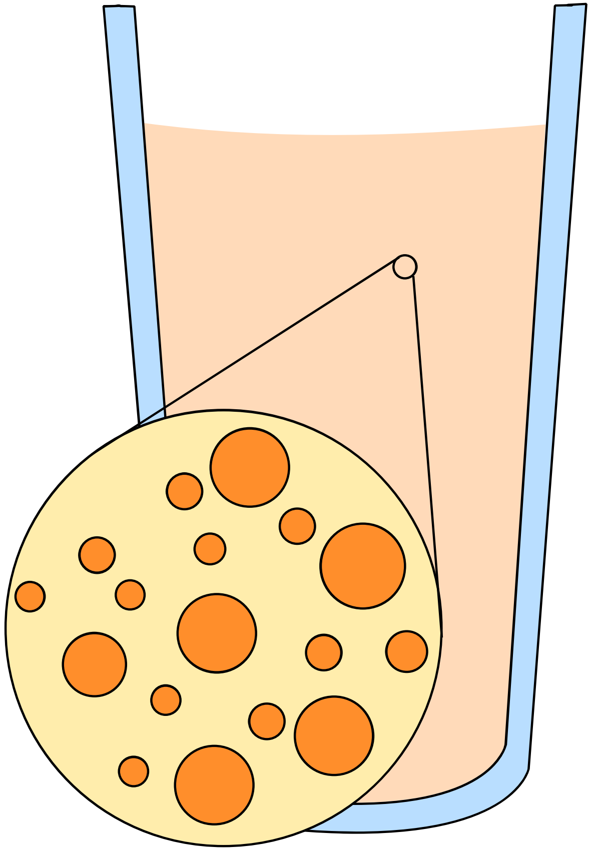
- predicting the visual effect of modifying production parameters;
- analyzing a given product with cameras.

Apple juice appearance model

- Host medium is water with dissolved solids (mostly sugars).
- Particles are browned apple flesh.

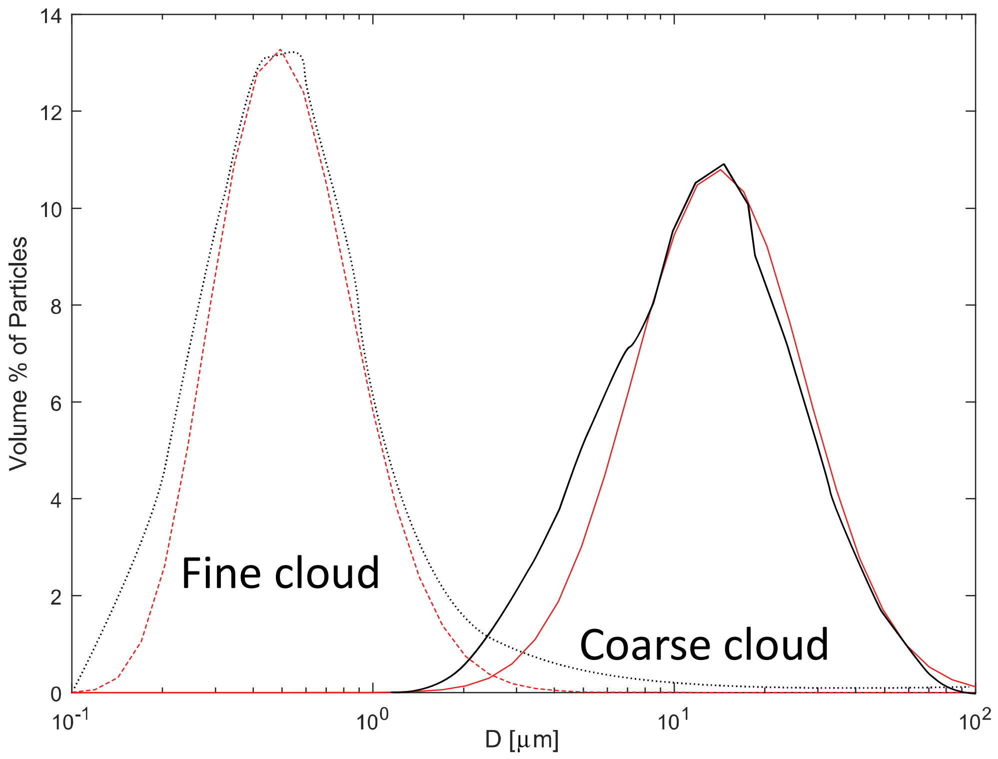
- Optical properties given by complex indices of refraction: $n = n' + i\, n''$.

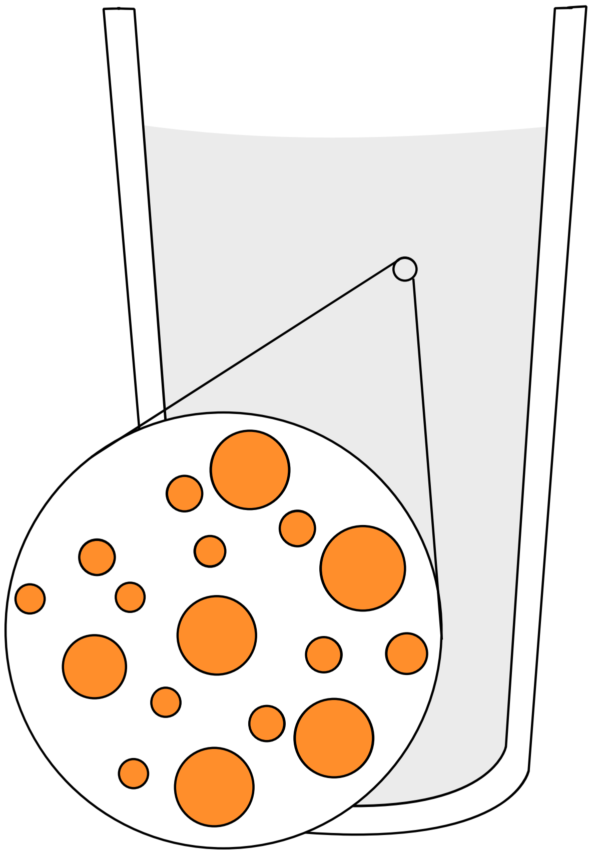
- We can relate these refractive indices to production parameters:
  - Particle concentration.
  - Storage time.
  - Handling of apples.
  - ...



Apple juice appearance model

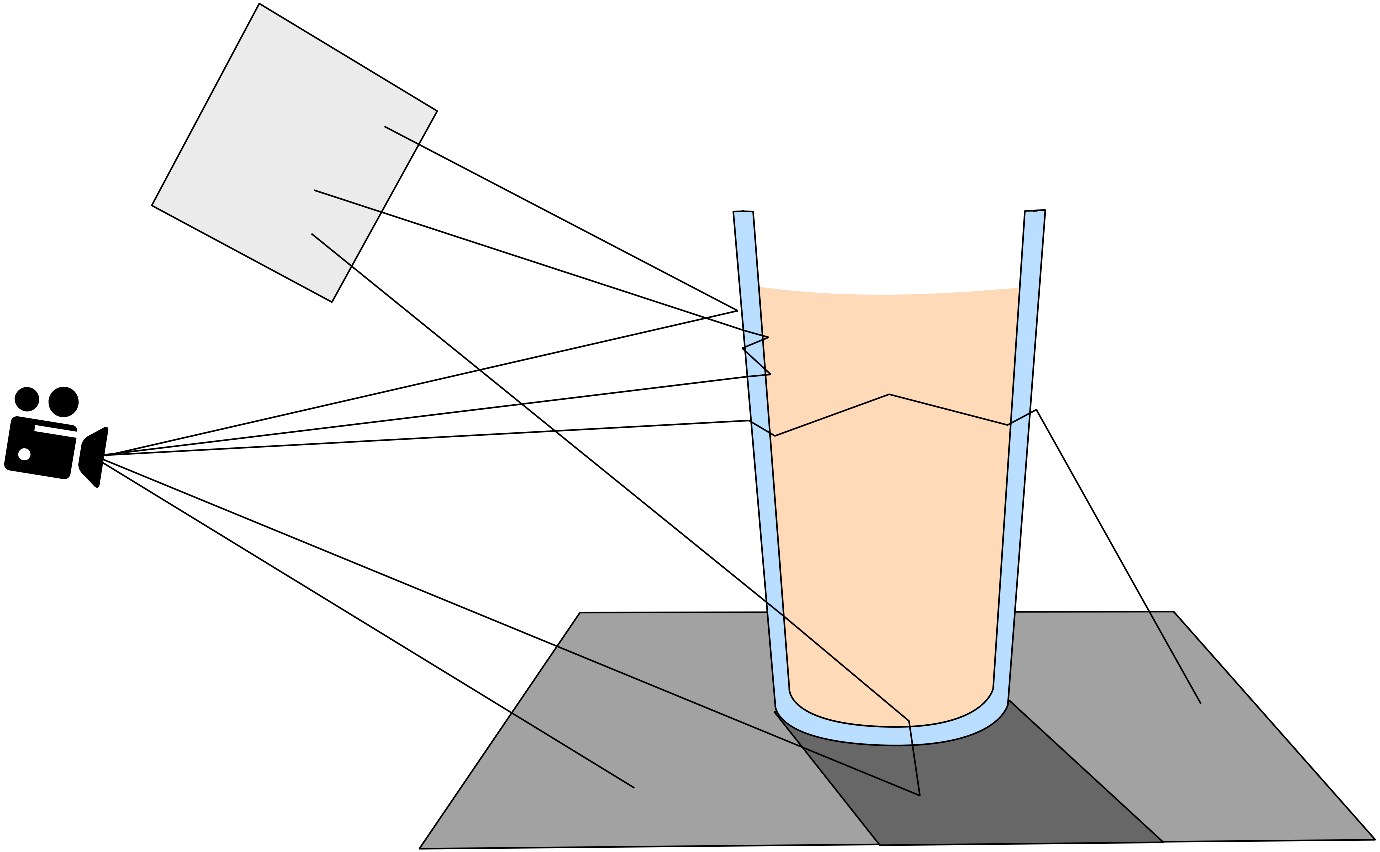
- We use a bimodal particle size distribution $\hat{N}$ from Zimmer et al. [1994], scaled to the desired volume concentration v of particles ($N = \hat{N}v/\hat{v}$).





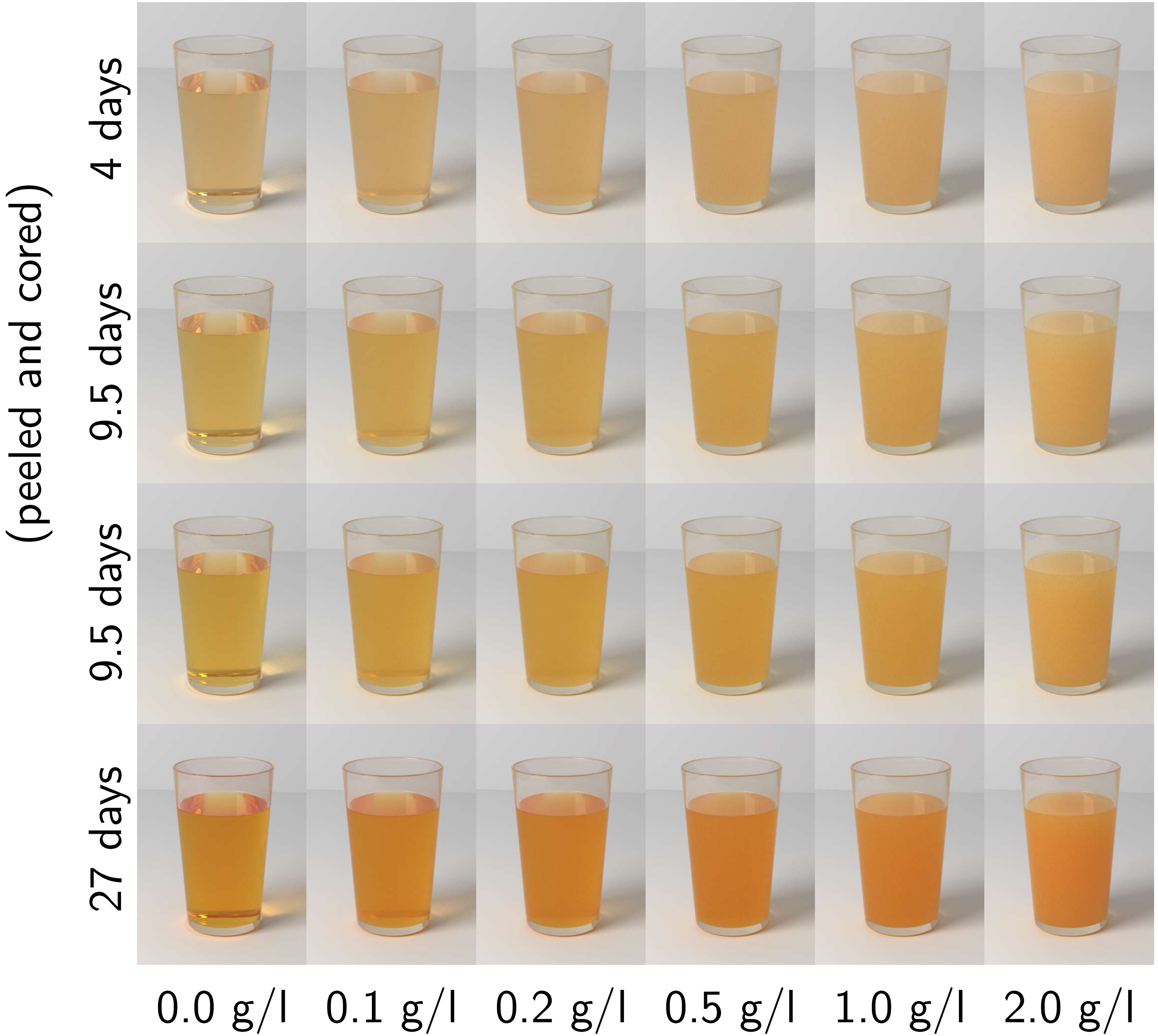
Rendering

- We can neither use single scattering nor diffusion theory.
- Thus, we use progressive unidirectional path tracing (Monte Carlo).
- Accounting for refractive indices using different interfaces.



Results

- Varying particle concentration v (horizontally).
- Varying storage time and handling (vertically).



Patch-based quantitative comparison

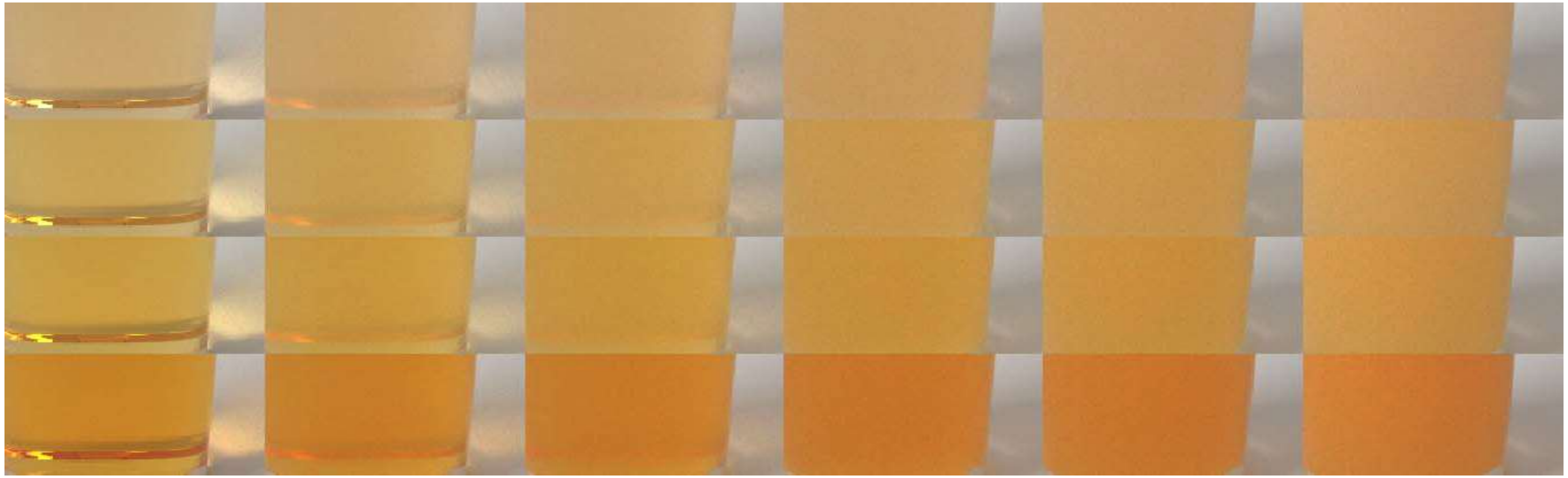
Reference

4 days

9.5 days, peeled

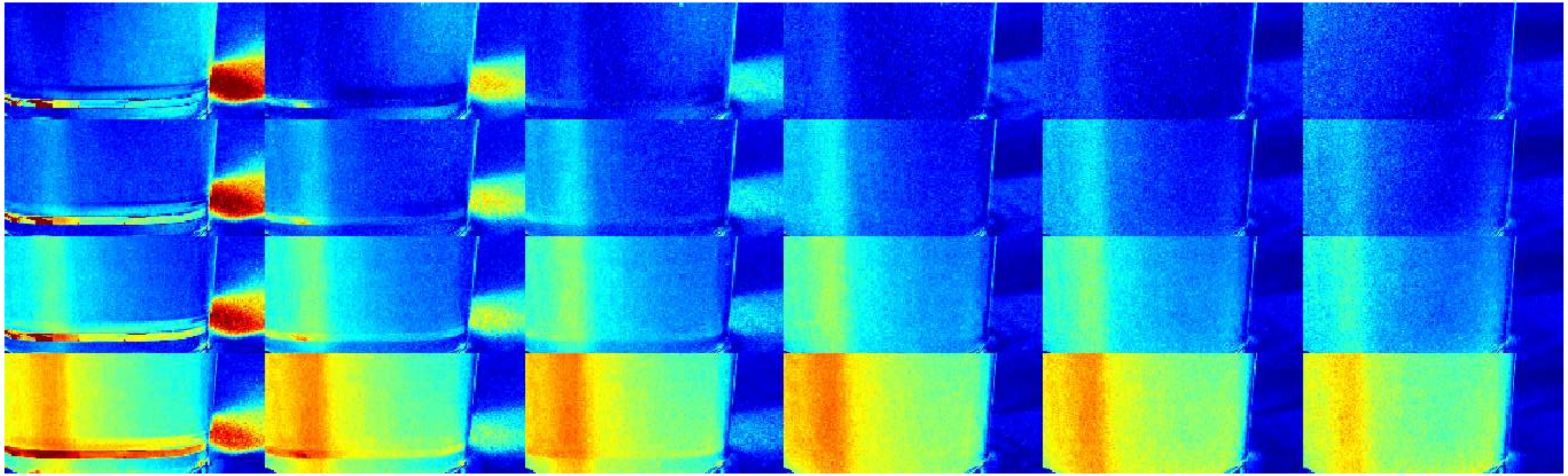
9.5 days

27 days



0.0 g/L 0.1 g/L 0.2 g/L 0.5 g/L 1.0 g/L 2.0 g/L

Patch-based quantitative comparison



Visual comparison - MAM 2016 rendering

rendering

photograph

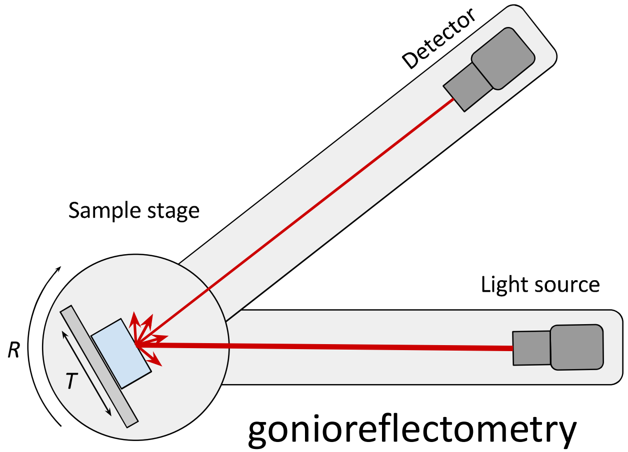
Visual comparison - EPJH 2019 rendering

rendering

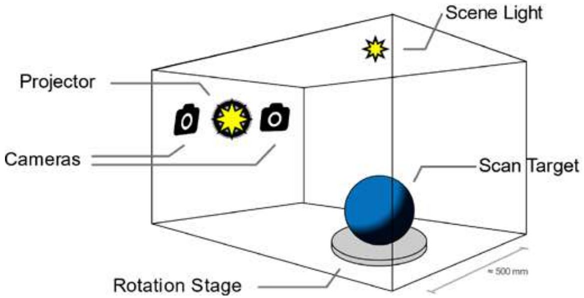
photograph

Experimental(x) measurements

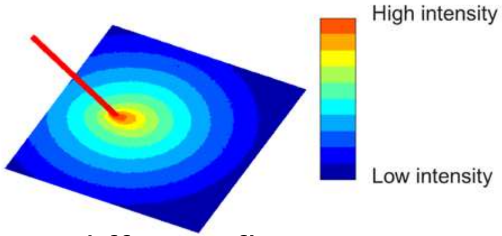
- Instrumentation for acquiring optical properties.
- Based on radiometry or one of the formal models.
- Early examples:
  - (x2) Gonioreflectometric BRDF measurement [TS66,War92]
  - (x2/x3) Bidirectional Texture Function (BTF) [DVGNK99,DHT*00,TWL*05]
  - (x3) SVBRDF on 3D surface (structured light) [MWL*99,LKG*01,WMP*06]
  - (x2/x3) Diffuse reflectometry for scattering properties [JMLH01,GLL*04,TWL*05]
  - (x2) BRDF from curved sample geometry [MPBM03,NDM05]
  - (x1) Fibre scattering measurement [MJC*03,ZRL*09]



gonioreflectometry



structured light scanning



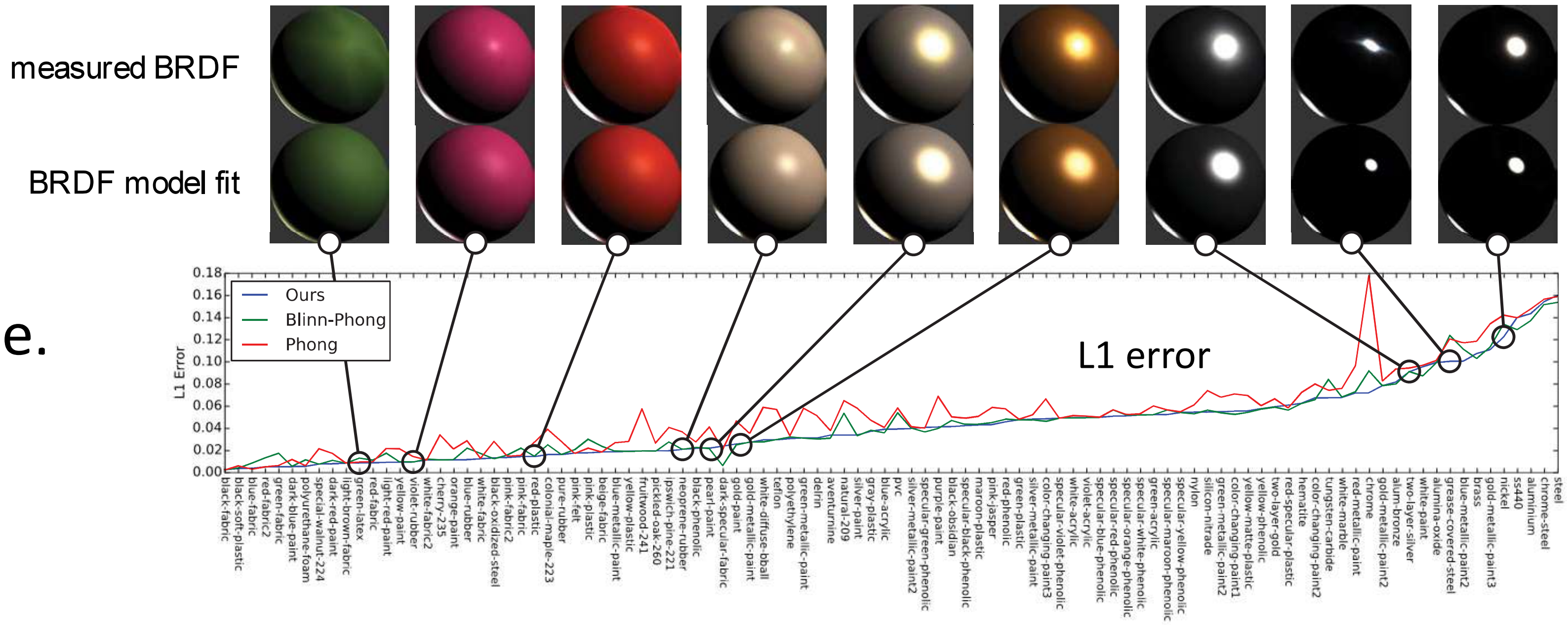
diffuse reflectometry

Inverse technique(←)

[Nielsen et al. SIGGRAPH Asia 2014 Posters]

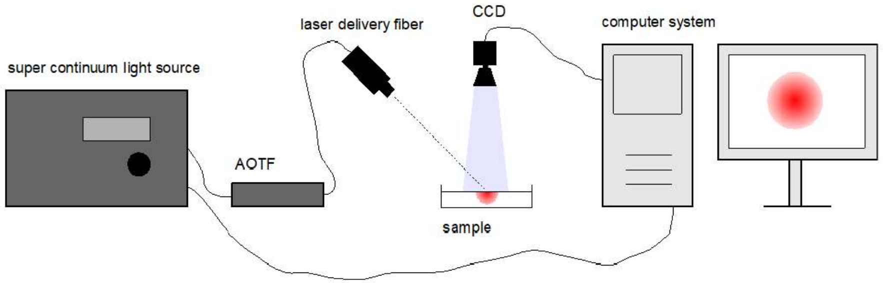
- Compute microscale information by measuring at a macroscopic scale.

Example: model parameters ← BRDF

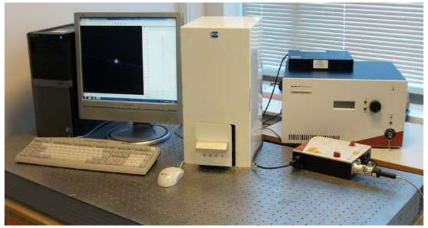


- Examples:
  - BSSRDF ← diffuse reflectometry [JMLH01,GLL*04,TWL*05,DWd*08]
  - Composition parameters ← BRDF/BTDF measurement [EĎKM04,NDM05,WMLT07]
  - BSSRDF ← structured light scan [PVBM*06,WMP*06,WZT*08,GHP*08]
  - Scattering properties ← photographing diluted liquid [NGD*06]
  - Fibre assembly microgeometry ← multiview photography [JMM09]

Example: spectral scattering properties ← diffuse reflectance

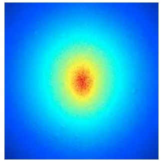


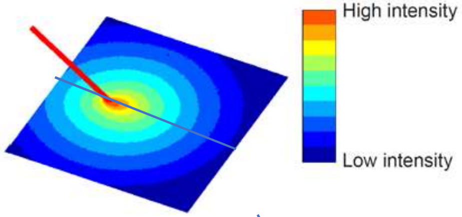
lab setup



in situ setup

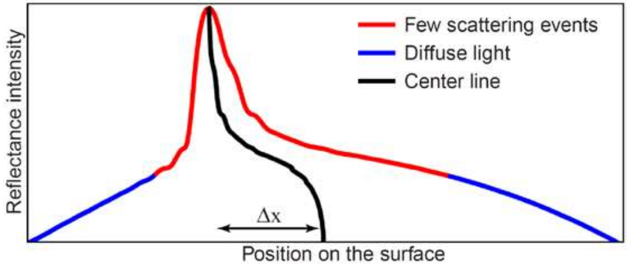
sample image
(log transformed, false colours)



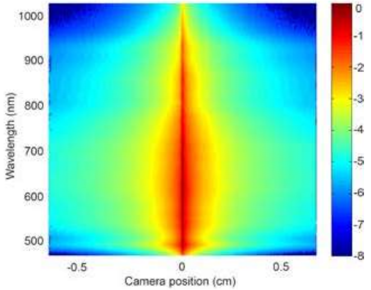


Infer optical properties using an analytic subsurface scattering model

extract profile

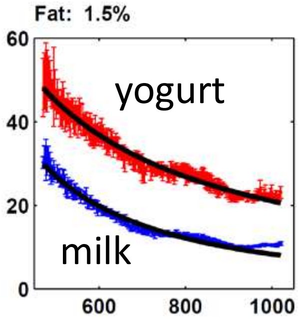


spectroscopy

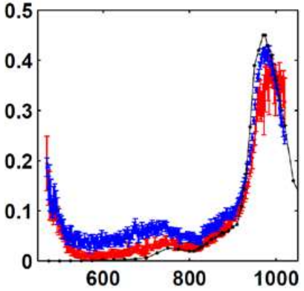


oblique incidence reflectometry

reduced scattering [1/cm]



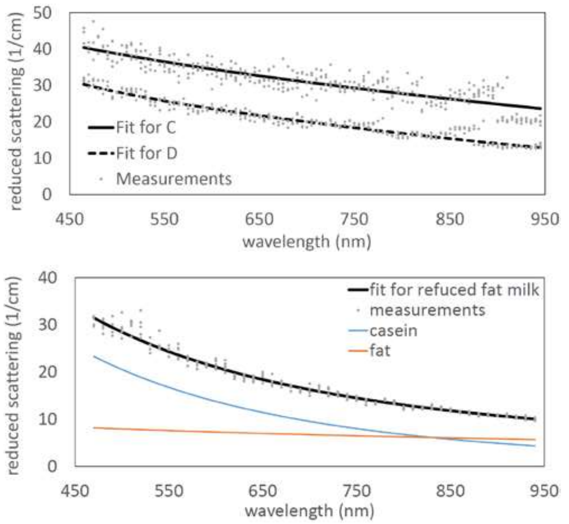
absorption [1/cm]



wavelength [nm]   wavelength [nm]

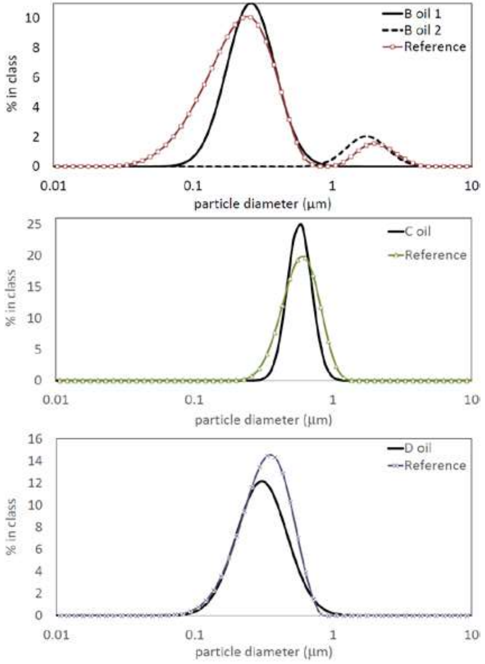
[Abildgaard et al. Non-invasive assessment of dairy products using spatially resolved diffuse reflectance spectroscopy. *Applied Spectroscopy 69*(9):1096-1105, 2015.]

Example: Particle size distributions ← optical properties

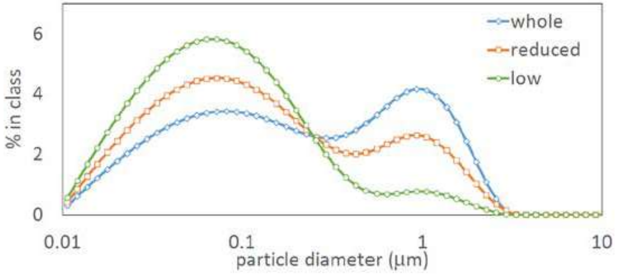


Nelder-Mead simplex search with a low-parameter size distribution function to fit measured scattering coefficients [5] with Lorenz-Mie theory [2].

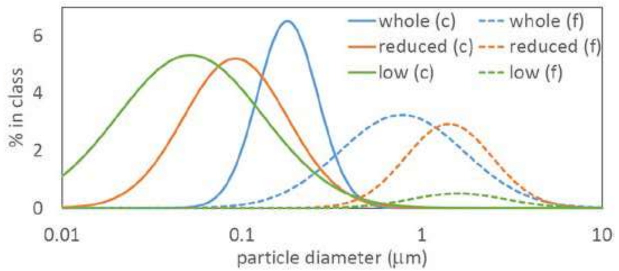
Oil-in-water emulsions



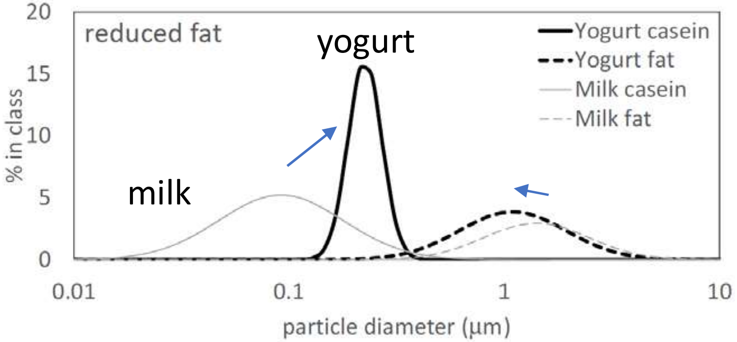
Commercial milk products



↑ Mastersizer ↑ ↓ our approach ↓



Fit results compared with particle size distributions measured with a Malvern Mastersizer 3000.



Effect of protein gel structure formation on apparent particle size distributions. This is useful for estimating viscosity or mouthfeel.

Abildgaard et al. 2016. Noninvasive particle sizing using camera-based diffuse reflectance spectroscopy. *Applied Optics 55*(14), pp. 3840-3846, May 2016.

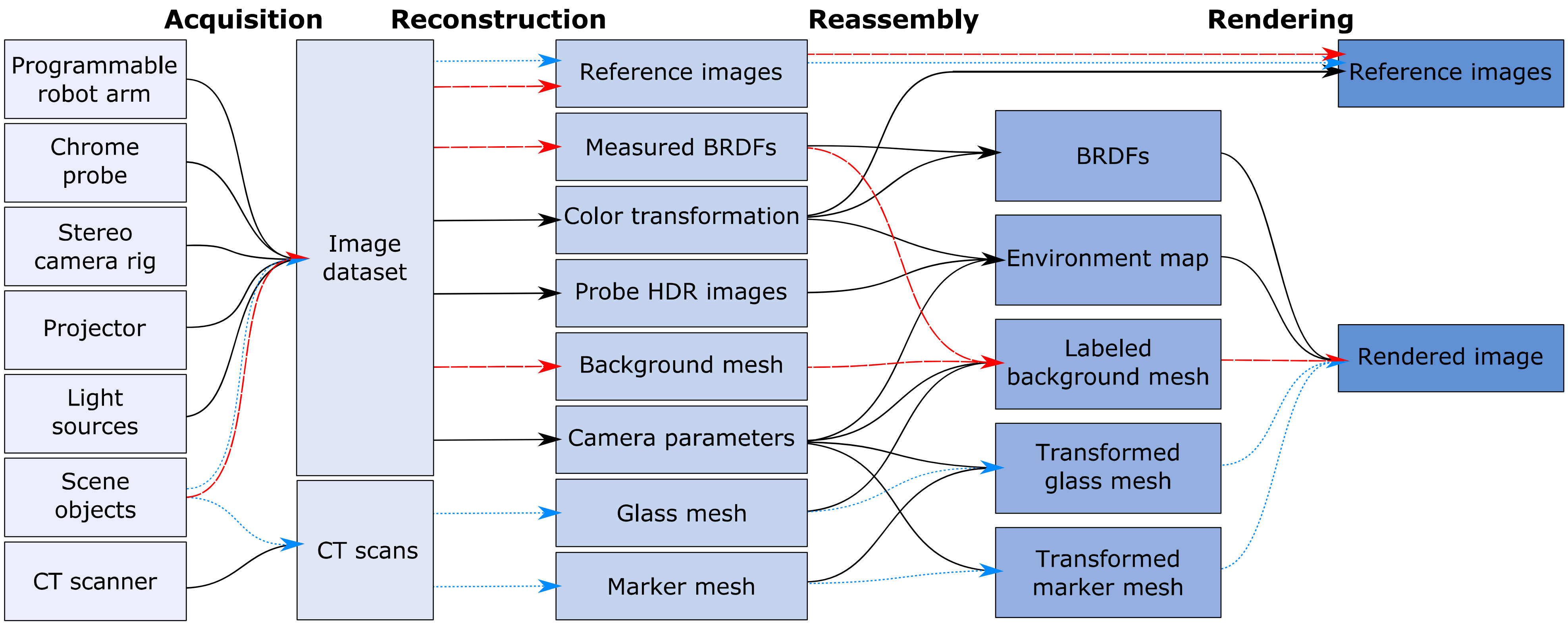
The input challenge

- Light transport simulation has come a long way, but renderings can only be as realistic/accurate as the input parameters permit.

- How do we get plausible input parameters?
  - Modeling (example: light scattering by particles).
  - Measuring (example: diffuse reflectance spectroscopy).

- Suppose we would like to go beyond visual comparison.
- How do we assess the appearance produced by a given set of input parameters?
  - Full digitization of a scene.
  - Reference photographs from known camera positions.
  - Pixelwise comparison of renderings with photographs.

Multimodal digitization pipeline

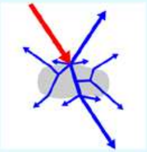


- Data available at **http://eco3d.compute.dtu.dk/pages/transparency**

References

- Stets, J. D., Dal Corso, A., Nielsen, J. B., Lyngby, R. A., Jensen, S. H. N., Wilm, J., Doest, M. B., Gundlach, C., Eiriksson, E. R., Conradsen, K., Dahl, A. B., Brentzen, J. A., Frisvad, J. R., and Aans, H. Scene reassembly after multimodal digitization and pipeline evaluation using photorealistic rendering. *Applied Optics 56*(27), pp. 7679–7690, September 2017.

More info on optical properties (forward and inverse models)



Survey of models for acquiring the optical properties of translucent materials
Jeppe Revall Frisvad, Søren Alkærsig Jensen, Jonas Skovlund Madsen, António Correia, Li Yang, Søren Kimmer Schou Gregersen, Youri Meuret, and Poul-Erik Hansen
Computer Graphics Forum (EG 2020) 39(2), pp. 729-755. May 2020. [webpage]

Survey of Models for Acquiring t
people.compute.dtu.dk/jerf/cg-opt-props.html

EG 2020: Overview of graphics models for acquiring the optical properties of translucent materials

Marker taxonomy (with associated markers in parentheses):

- Formal model based on theory(t).
- Experimental(x) measurements with fibres(1), flat or spherical or cylindrical surfaces(2), or arbitrary 3D surfaces(3).
- Colour/density(c) or wavelength(λ).
- Isotropic(i) or anisotropic(a) surface reflectance.
- Homogeneous($\cdot$) or heterogeneous($\star$) material.
- Diffuse($\vert$) or directional($\backslash$) subsurface scattering.
- Forward simulation($\rightarrow$) and/or inverse technique($\leftarrow$).

Paper title	author-year	ref. marker	nano/micro	micro/milli	BSSRDF	BRDF/BTDF
Off-specular peaks in the directional distribution of reflected thermal radiation	Torrance and Sparrow [1966]	[TS66]				$x2\lambda i\cdot\vert$
Theory for off-specular reflection from roughened surfaces	Torrance and Sparrow [1967]	[TS67]		$t\lambda i\cdot\vert\ \rightarrow$		$t\lambda i\cdot\vert$
Models of light reflections for computer synthesized pictures	Blinn [1977]	[Bli77]		$tci\cdot\vert\ \rightarrow$		$tci\cdot\vert$
A reflectance model for computer graphics	Cook and Torrance [1981]	[CT81]		$t\lambda i\cdot\vert\ \rightarrow$		$tci\cdot\vert$