Material Appearance Modeling: Rendering and Acquisition

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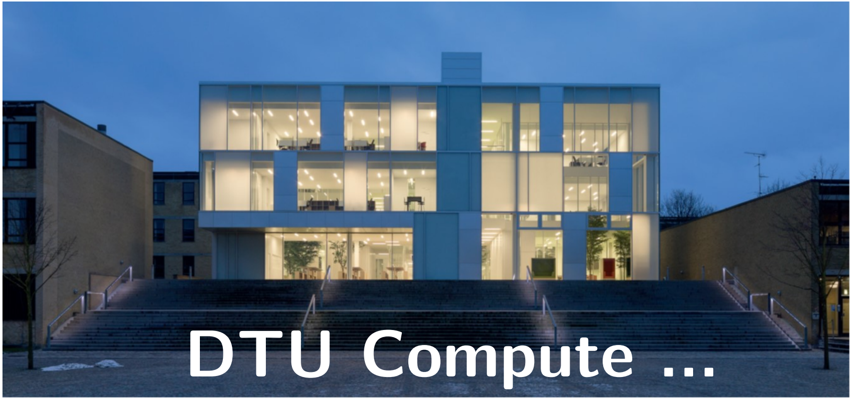

... spans the entire spectrum from fundamental mathematics across mathematical modeling to computer science, which is the basis of the modern digital world.

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medical

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3D scan and print
GEOMETRIC DATA
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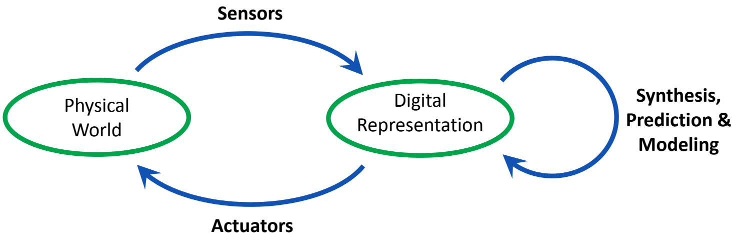

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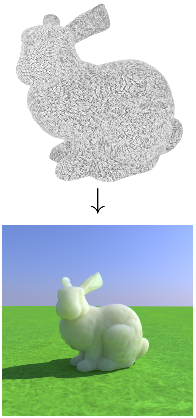
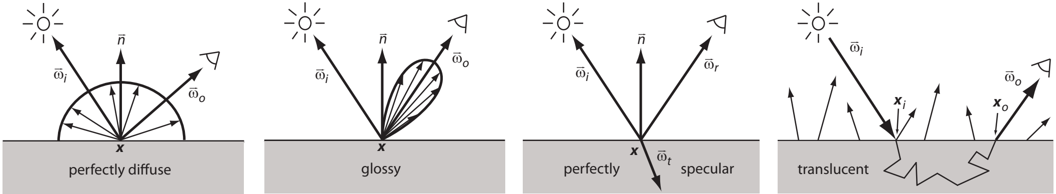
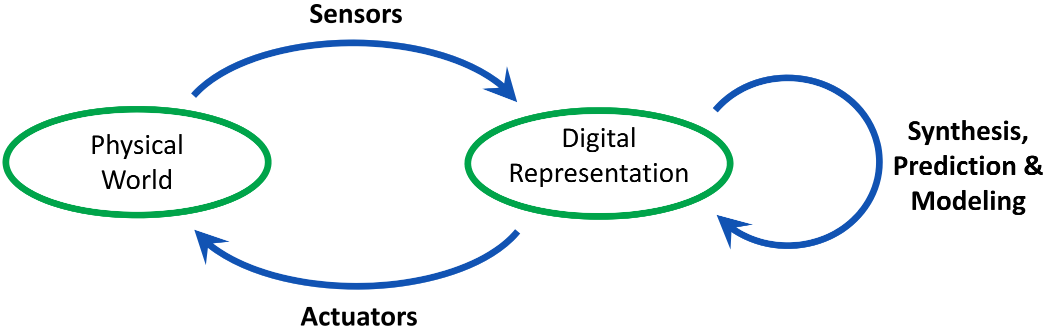
Material appearance

- 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

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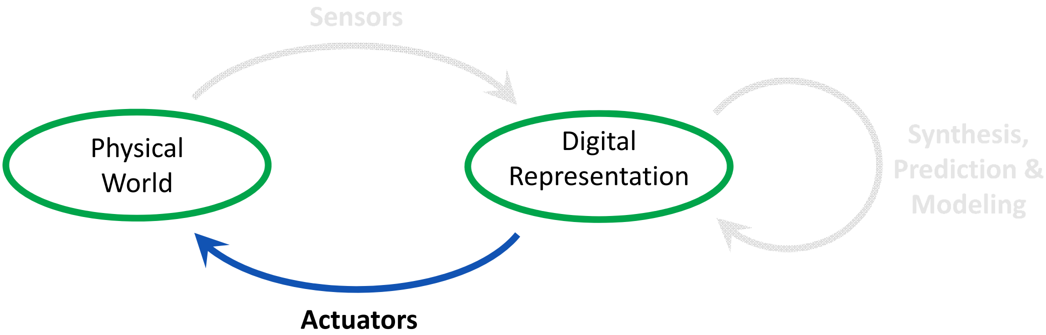
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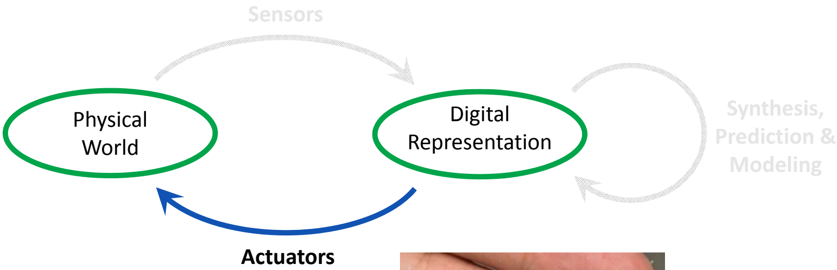
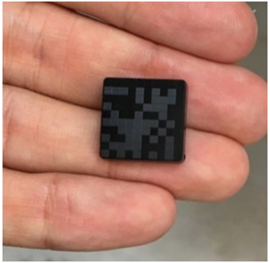
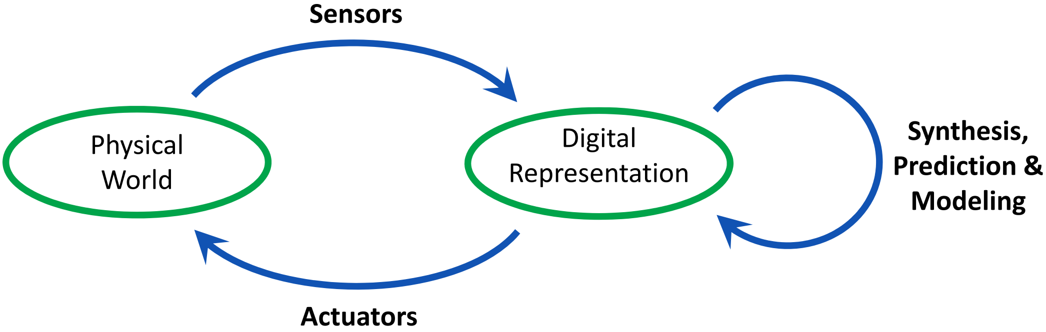
Appearance printing





appearance control in injection moulding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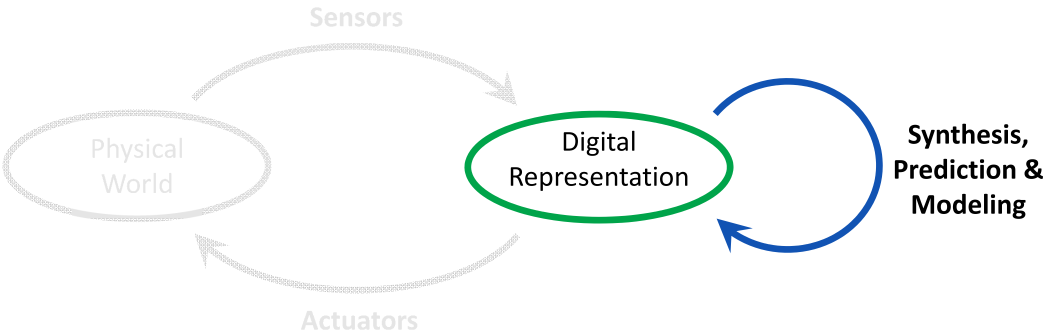
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Building models using particle composition and Lorenz-Mie theory

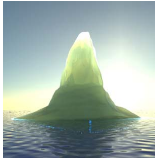
Particles:
Refractive index, concentration, size distribution, density

Host medium:
Refractive index, density, viscosity, surface tension

Global parameters:
temperature, gravity, pressure

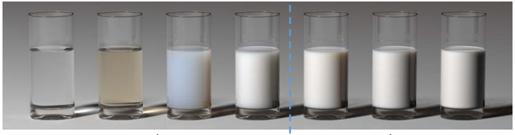
Model → Rendering & Simulation → Digital Prototype

algae in sea ice



[Frisvad 2008]

milk: water, vitamins, protein and fat particles



ingredients

products

[Frisvad et al. 2007a]

Light-material interaction in a volume

- Some light is absorbed.
- Some light scatters away (out-scattering).
- Some light scatters back into the line of sight (in-scattering).

  (absorption + out-scattering = extinction)

- Historical origins:

Bouguer [1729, 1760]	A measure of light. Exponential extinction.
Lambert [1760]	Cosine law of perfectly diffuse reflection and emission.
Lommel [1887]	Testing Lambert's cosine law for scattering volumes.
	Describing isotropic in-scattering mathematically.
Chwolson [1889]	A theory for subsurface light diffusion (similar to Lommel's).
Schuster [1905]	Scattering in foggy atmospheres (plane-parallel media).
	Reinventing the theory in astrophysics.
King [1913]	General equation which includes anisotropic scattering (phase function).
Chandrasekhar [1950]	The first definitive text on radiative transfer.

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 $[\mathrm{W sr^{-1} m^{-3}}]$ (radiance per meter).
- The radiative transfer equation (RTE)

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

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

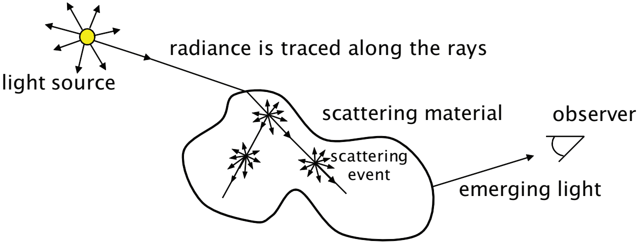
Computing appearance from scattering properties

- 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:

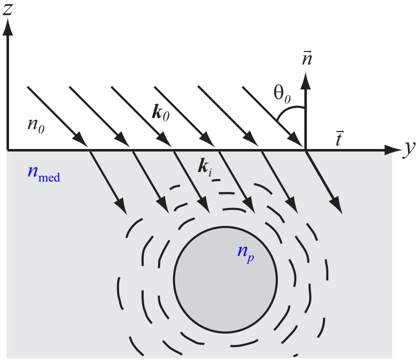
  Stochastic ray tracing (Monte Carlo integration).



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

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)

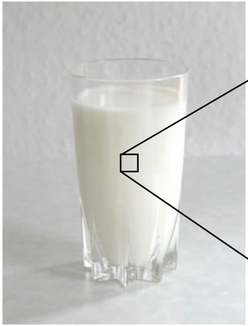
- Using the Riccati-Bessel functions ψ_n and ζ_n, the expressions for the Lorenz-Mie coefficients are

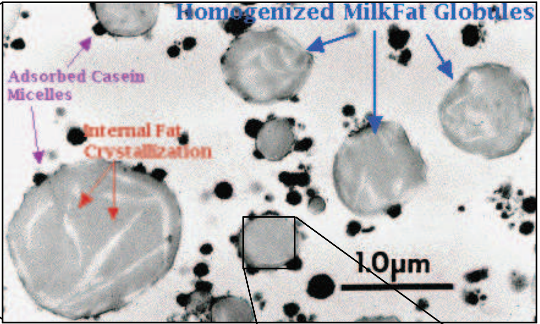
$$\begin{aligned} a_n &= \frac{n_{\mathrm{med}}\psi_n'(y)\psi_n(x) - n_p\psi_n(y)\psi_n'(x)}{n_{\mathrm{med}}\psi_n'(y)\zeta_n(x) - n_p\psi_n(y)\zeta_n'(x)} \\ b_n &= \frac{n_p\psi_n'(y)\psi_n(x) - n_{\mathrm{med}}\psi_n(y)\psi_n'(x)}{n_p\psi_n'(y)\zeta_n(x) - n_{\mathrm{med}}\psi_n(y)\zeta_n'(x)} \end{aligned}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

  - 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

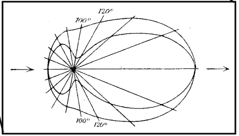
$$x = \frac{2\pi r n_{\mathrm{med}}}{\lambda} \quad , \quad y = \frac{2\pi r n_p}{\lambda} .$$

From particles to appearance





Courtesy of University of Guelph



Lorenz–Mie theory provides the link

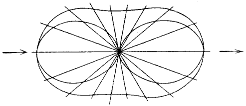
Scattering by spherical particles

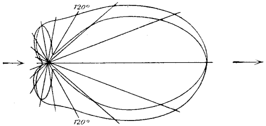
- The Lorenz-Mie theory:

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

- 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



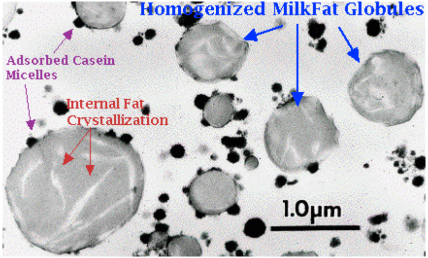


large particle

Quantity of scattering

- Lorenz-Mie theory continued:
  The scattering and extinction cross sections of a particle:

$$
\begin{aligned}
C_s &= \frac{\lambda^2}{2\pi|n_{\mathrm{med}}|^2}\sum_{n=1}^{\infty}(2n+1)\left(|a_n|^2+|b_n|^2\right) \\
C_t &= \frac{\lambda^2}{2\pi}\sum_{n=1}^{\infty}(2n+1)\mathrm{Re}\left(\frac{a_n+b_n}{n_{\mathrm{med}}{}^2}\right) \quad .
\end{aligned}
$$



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

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]: http://people.compute.dtu.dk/jerf/code/

Particle contents (examples)

- Natural water
  - Refractive index of host: saline water.
  - Mineral and alga contents: user input in volume fractions.
  - Refractive indices of mineral and algae: empirical formulae.
  - Shape of mineral and algal particles: spheres.
  - Size distributions: power laws.
- Icebergs
  - Refractive index of host: pure ice.
  - Brine and air contents: depend on temperature, salinity, and density.
  - Refractive index of brine and air: empirical formula, measured absorption spectrum, and $n_{\mathrm{air}} = 1.00$.
  - Shape of brine pores and air pockets: closed cylinders and ellipsoids.
  - Size distributions: power laws.
- Milk
  - 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.

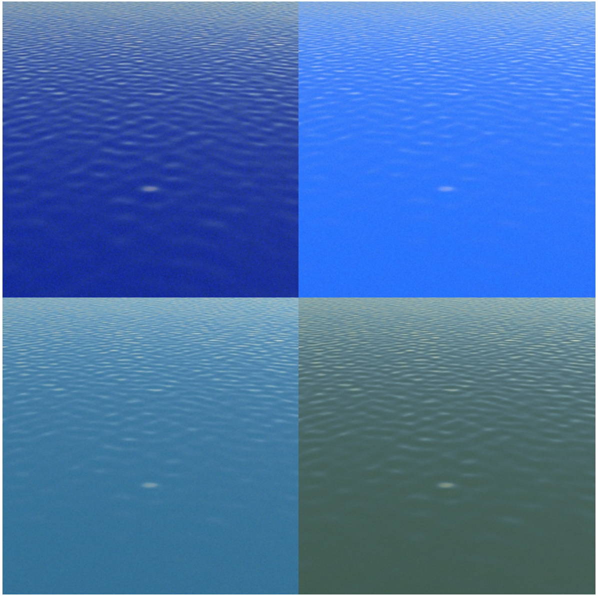
Case study: natural waters

- Glacial melt water with rock flour mixing with purer water from melted snow to give Lake Pukaki in New Zealand its beautiful bright blue colour.

Oceanic and coastal waters

Cold Atlantic

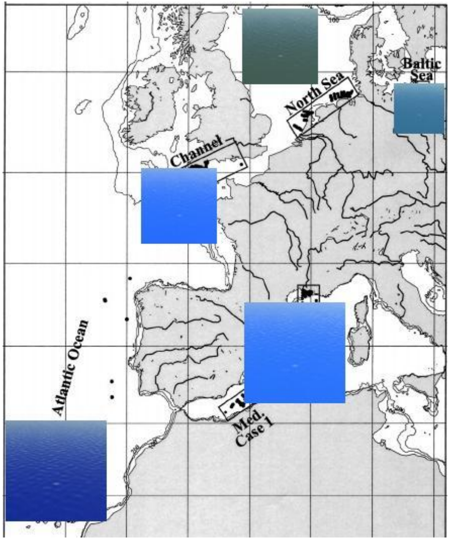
Mediterranean



Baltic

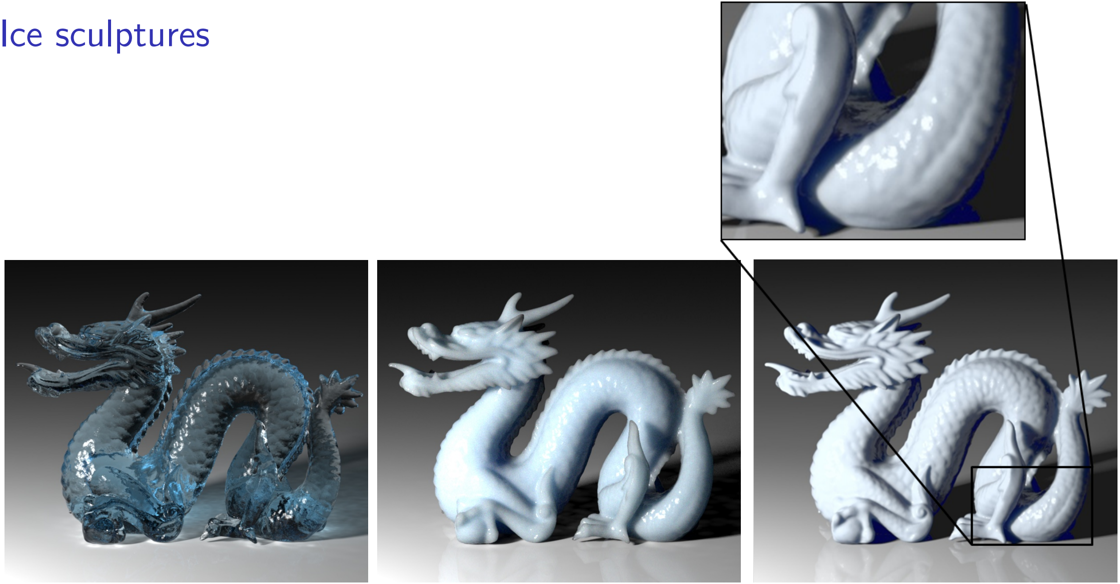
North Sea

Oceanic and coastal waters



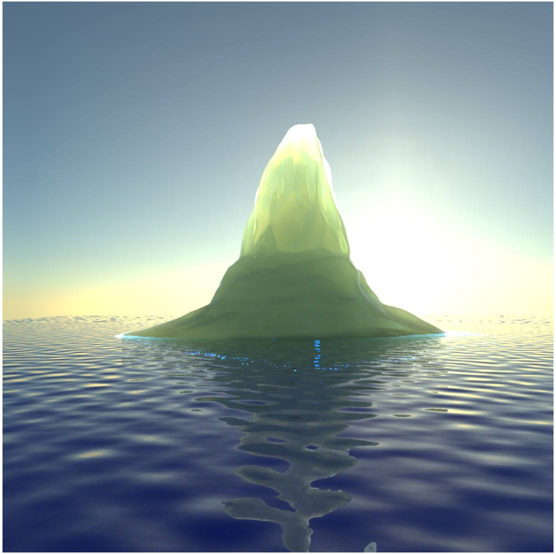
Case study: icebergs

Ice sculptures



pure ice | compacted snow | white ice

Algal ice



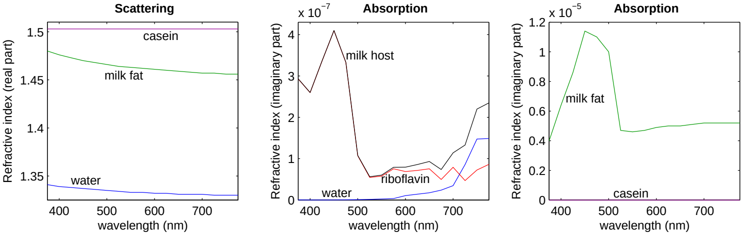
Green algae on iceberg.
(Photo courtesy Gerhard Dieckmann)

Case study: milk

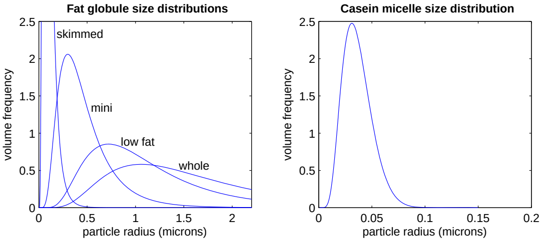
- Reddish on forward scattering, subtle bluish on side scattering, white on back scattering.

Measurements used for the milk model

- Refractive indices:



- Particle size distributions:



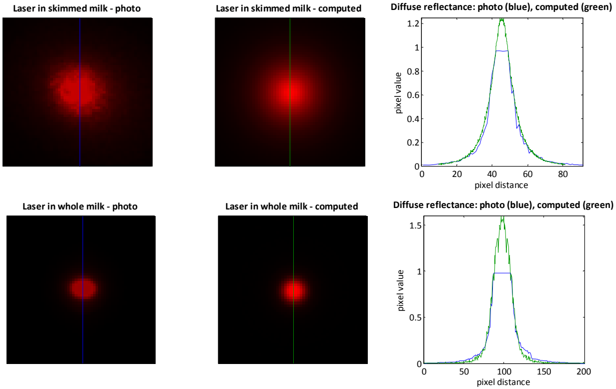
Predicting appearance based on a content declaration

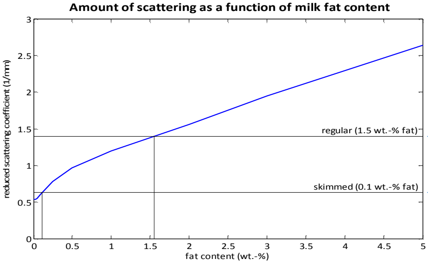
water vitamin B2 protein fat skimmed low fat whole

- 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)

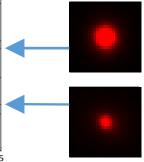
Simplistic model validation

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



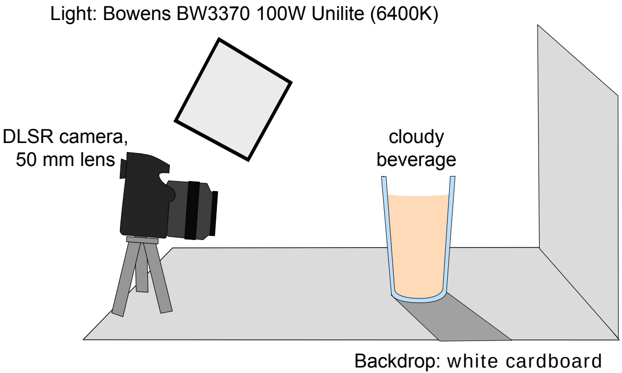


Captured images used for estimating the reduced scattering coefficient:



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:

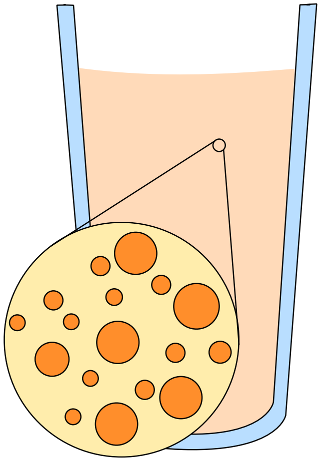
- predicting the visual effect of modifying production parameters;
- analyzing a given product with cameras.

Apple juice appearance model

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

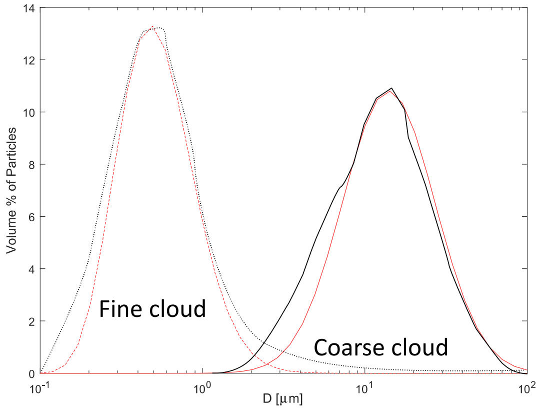
- Optical properties given by complex indices of refraction: $n = n' + i\, n''$.

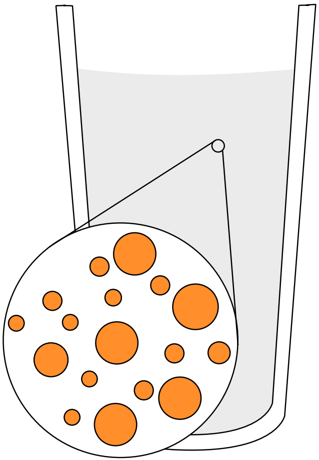
- We can relate these refractive indices to production parameters:
  - Particle concentration.
  - Storage time.
  - Handling of apples.
  - ...



Apple juice appearance model

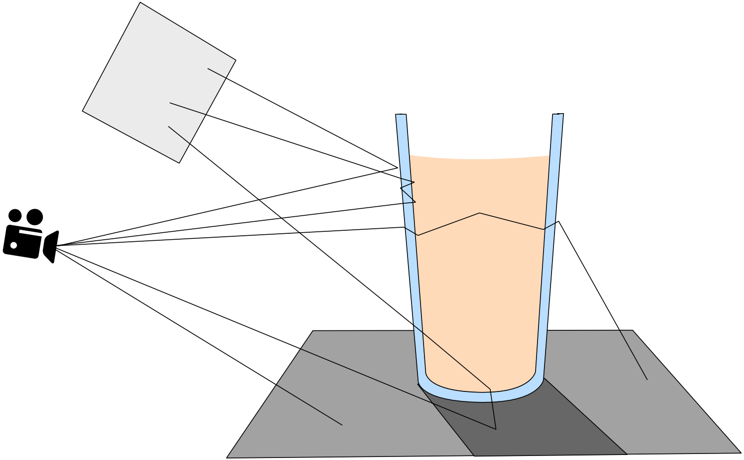
- We use a bimodal particle size distribution $\hat{N}$ from Zimmer et al. [1994], scaled to the desired volume concentration v of particles ($N = \hat{N}v/\hat{v}$).





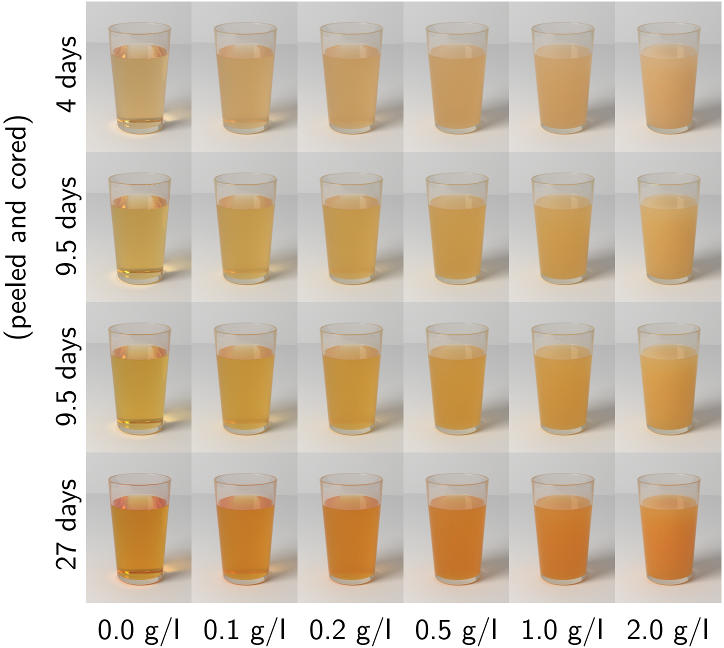
Rendering

- 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

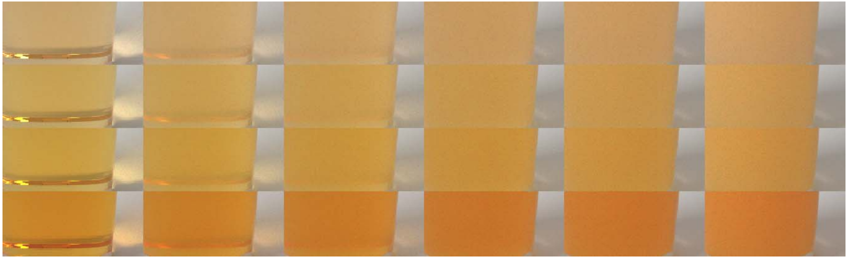
Reference

4 days

9.5 days, peeled

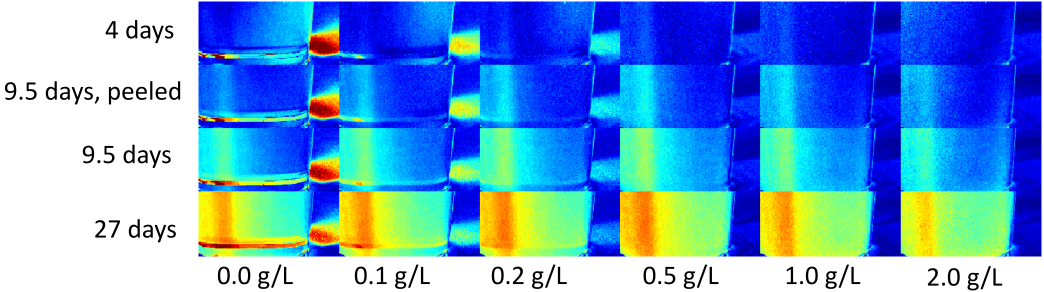
9.5 days

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

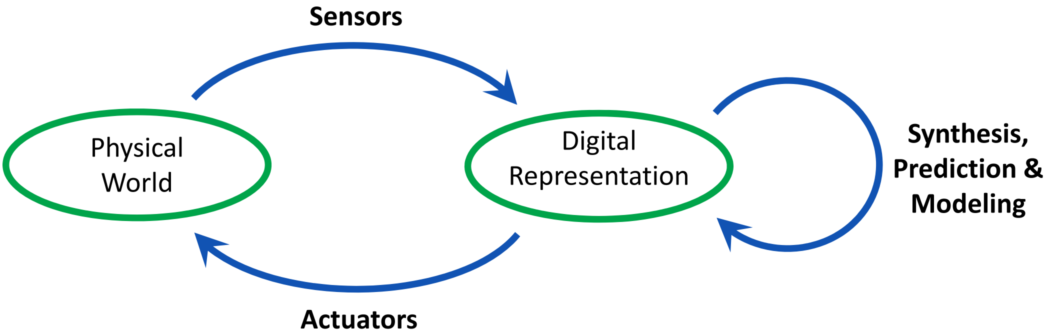
Patch-based quantitative comparison



Visual comparison

rendering

photograph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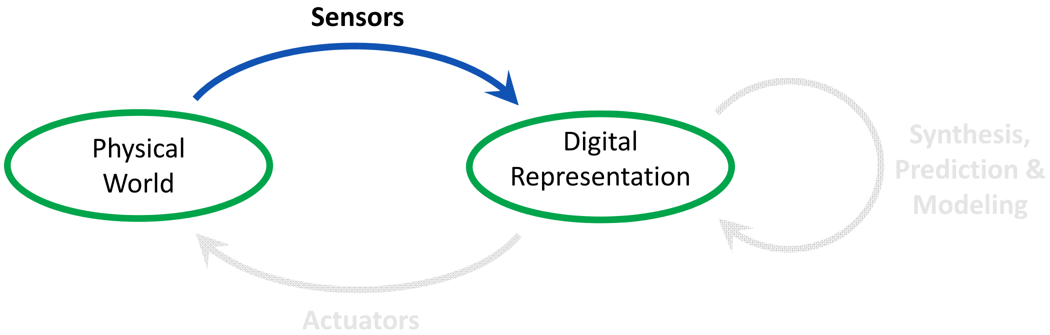
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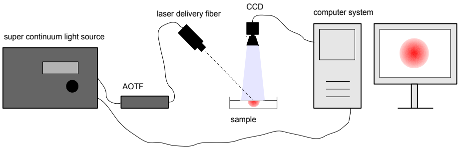
The input challenge

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

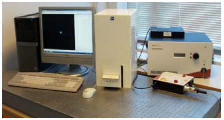
- How do we get plausible input parameters?
  - Modeling (example: light scattering by particles).
  - Measuring (example: diffuse reflectance spectroscopy).

- 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.

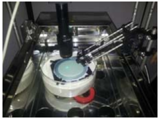
Measuring scattering properties using diffuse reflectance spectroscopy



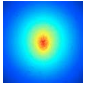
lab setup

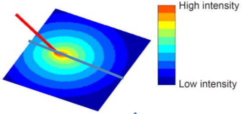


in situ setup



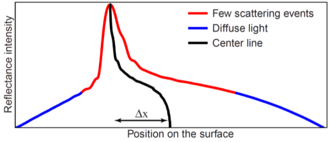
sample image
(log transformed, false colours)



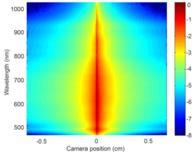


Infer optical properties using an analytic subsurface scattering model

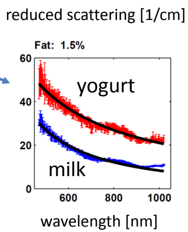
extract profile

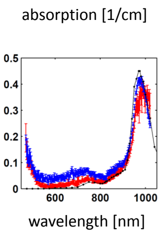


spectroscopy



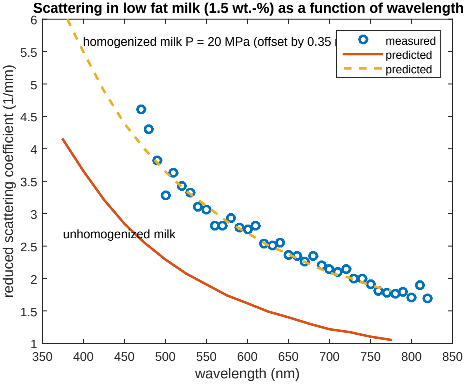
oblique incidence reflectometry

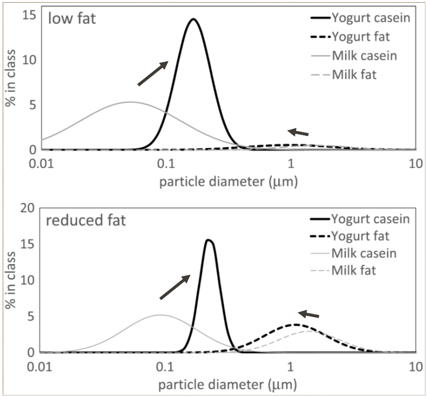




- Proper version of the simplistic approach used for validation of the milk model.

Using measured scattering properties for product analysis

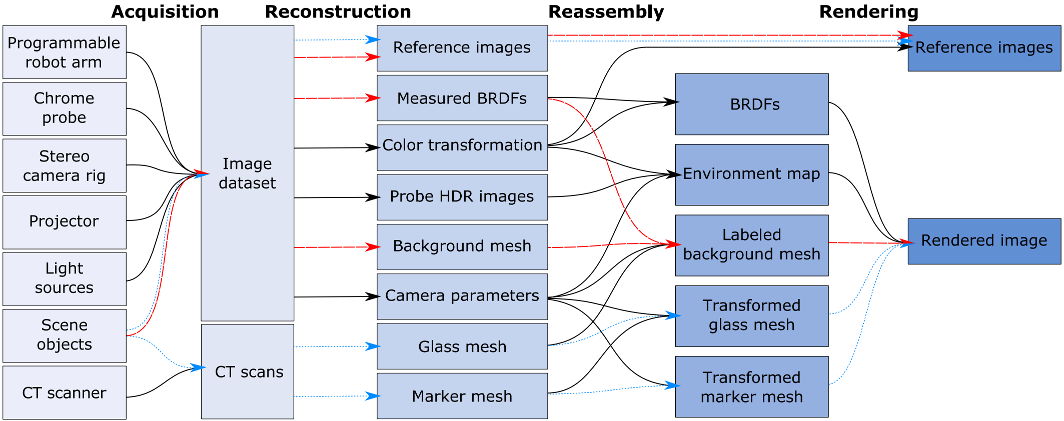




inferring
milk homogenization
(pressure)

inferring
milk fermentation
(apparent particle size distribution)

Multimodal digitization pipeline

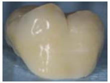


[pipeline video] [overview video]

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

Thank you for your attention

[Larsen et al. 2012]

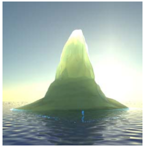


render photo

[Frisvad et al. 2005]

[Andersen et al. 2016]

algae in sea ice



[Frisvad 2008]

[Stets et al. 2017]

[Dal Corso et al. 2016]

organic low fat milk

unfiltered apple juice