subsurface scattering

patrick coleman

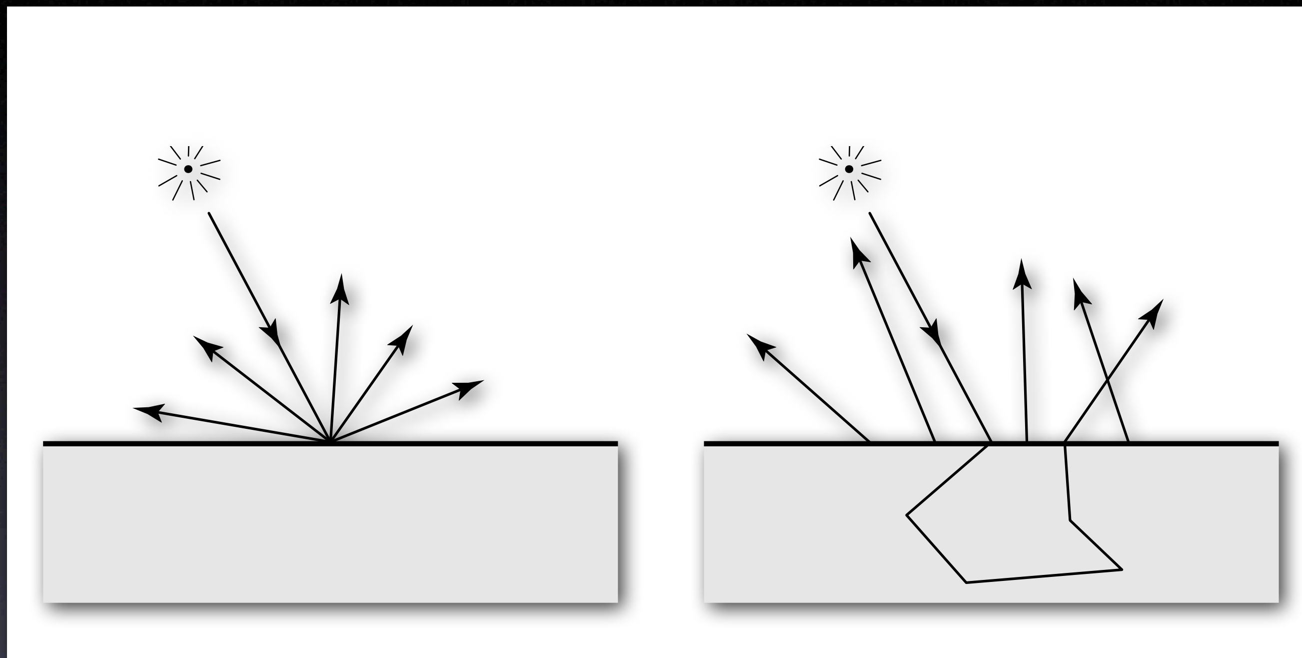
january 30, 2006

Pixar

Dror Bar-Natan

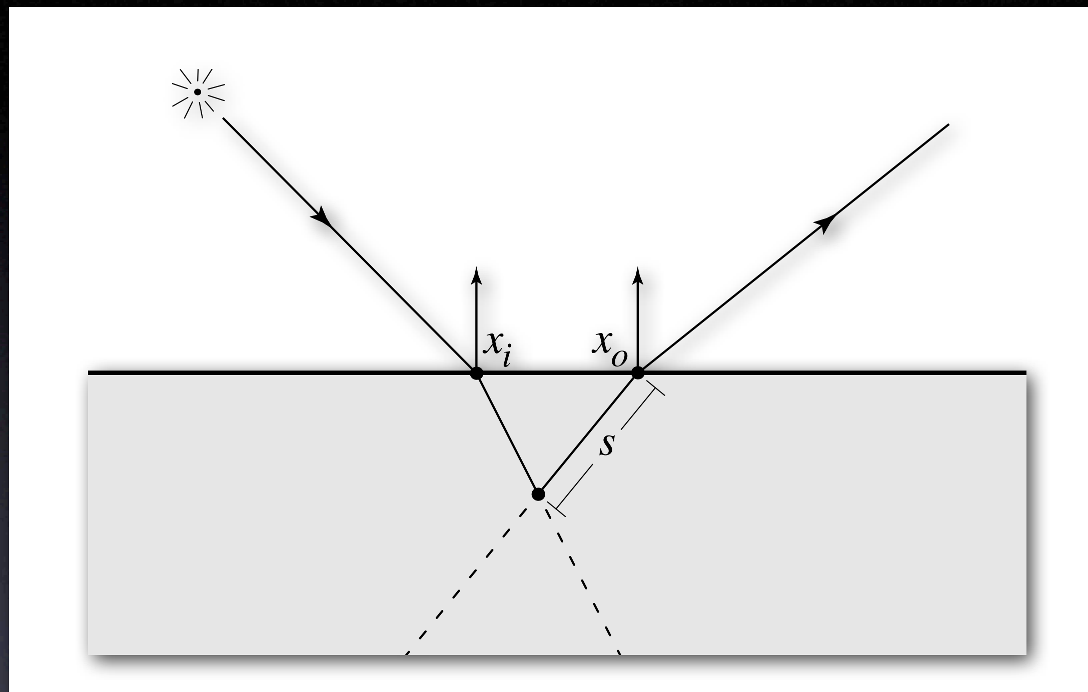
amazon.com

subsurface scattering



Jensen et al. 2001

BRDF vs. BSSRDF



Jensen et al. 2001

Fresnel effects

- absorption
- emission
- out scattering
- in scattering
- extinction

scattering processes

$$dL_o(\mathbf{p}, \mathbf{w}) = -\sigma_a(\mathbf{p}, \mathbf{w}) L_i(\mathbf{p}, -\mathbf{w}) dt$$

$$e^{\int_0^d \sigma_a(\mathbf{p}+t\mathbf{w})\mathbf{w} dt}$$

absorption

$$Q(p, w)$$

emission

$$dL_o(\mathbf{p}, \mathbf{w}) = -\sigma_s(\mathbf{p}, \mathbf{w}) L_i(\mathbf{p}, -\mathbf{w}) dt$$

out scattering

$$\sigma_t(\mathbf{w}, \mathbf{w}) = \sigma_a(\mathbf{w}, \mathbf{w}) + \sigma_s(\mathbf{w}, \mathbf{w})$$

extinction

$$tr(\mathbf{p} \rightarrow \mathbf{p}') = e^{-\int_0^d \sigma_t(\mathbf{p}+t\mathbf{w})dt}$$

transmittance

$$\tau(p \rightarrow p') = \int_0^d \sigma_t(p + tw, w)dt$$

optical thickness

- distance between partcles many times larger than radius
- describe with phase functions

in scattering

phase functions

$$(w \cdot \nabla)L(x,w) = -\sigma_t L(x,w) + \sigma_s \int_{4\pi} p(w,w')L(x,w')dw' + Q(x,w)$$

radiative transport

- bidirectional subsurface scattering reflectance distribution function
- bidirectional surface scattering distribution function
- bidirectional scattering surface reflectance distribution function

BSSRDF

$$L(x,w) = \int_{H^2}\int_S S(x',w';x,w)L(x,w')cos\theta' dw'$$

BSSRDF

- scattered light enters at one point
- based on linear trannsport theory
- infinite homogeneous plane
- constant illumination

analytic models

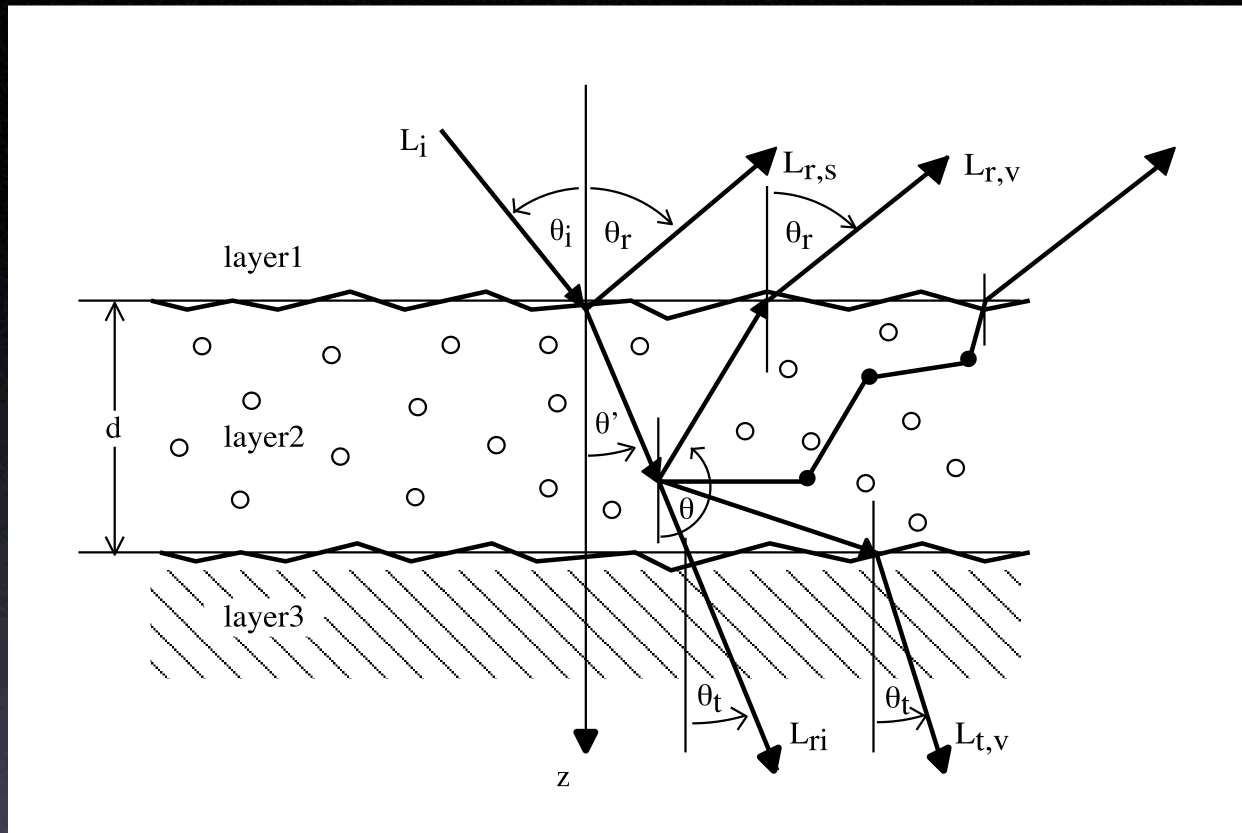
- HG phase function, Rayleigh scattering
- derived from a statistical model of scattering events
- layer of clouds or dust

Blinn 1982

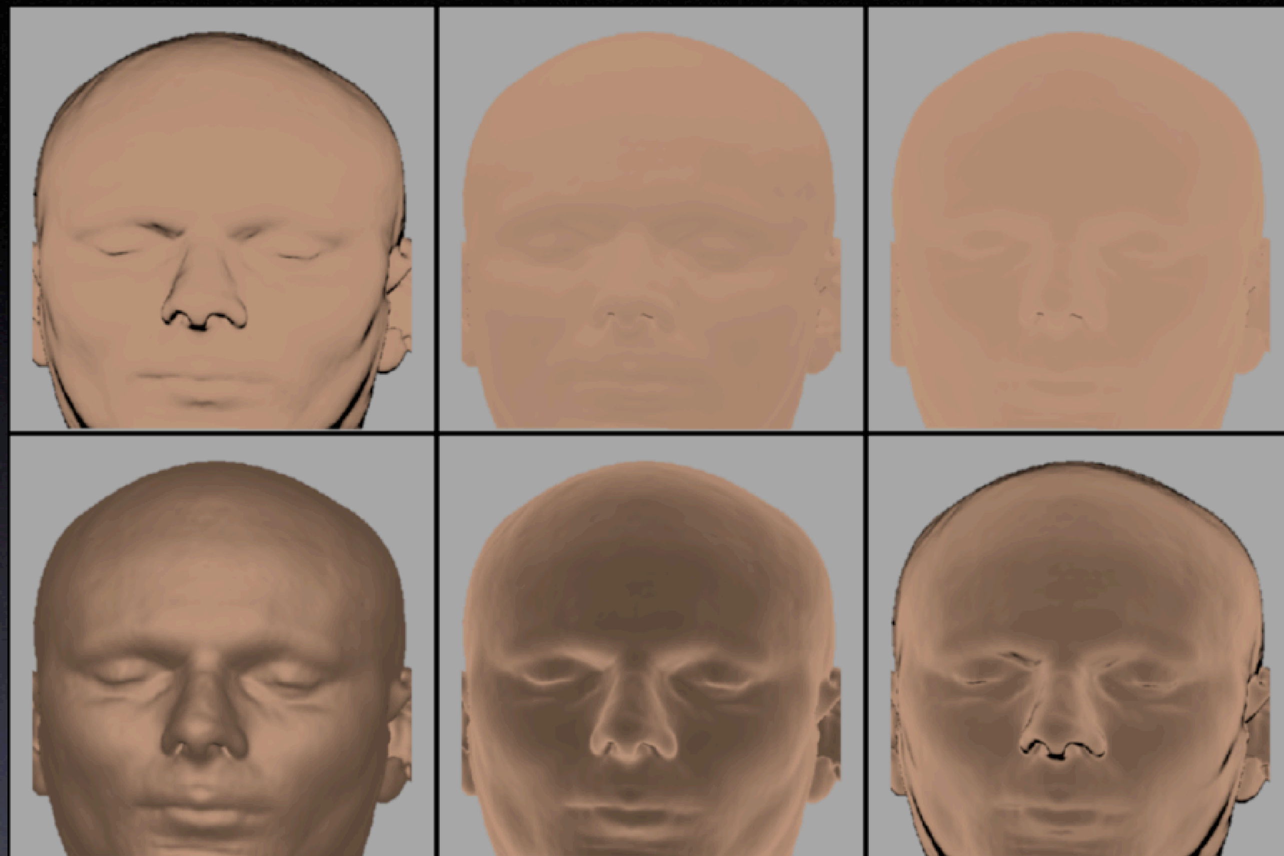
Blinn 1982

- derived from radiative transport theory
- multiple layers
- captures directional effects

Hanrahan and Krueger 1990

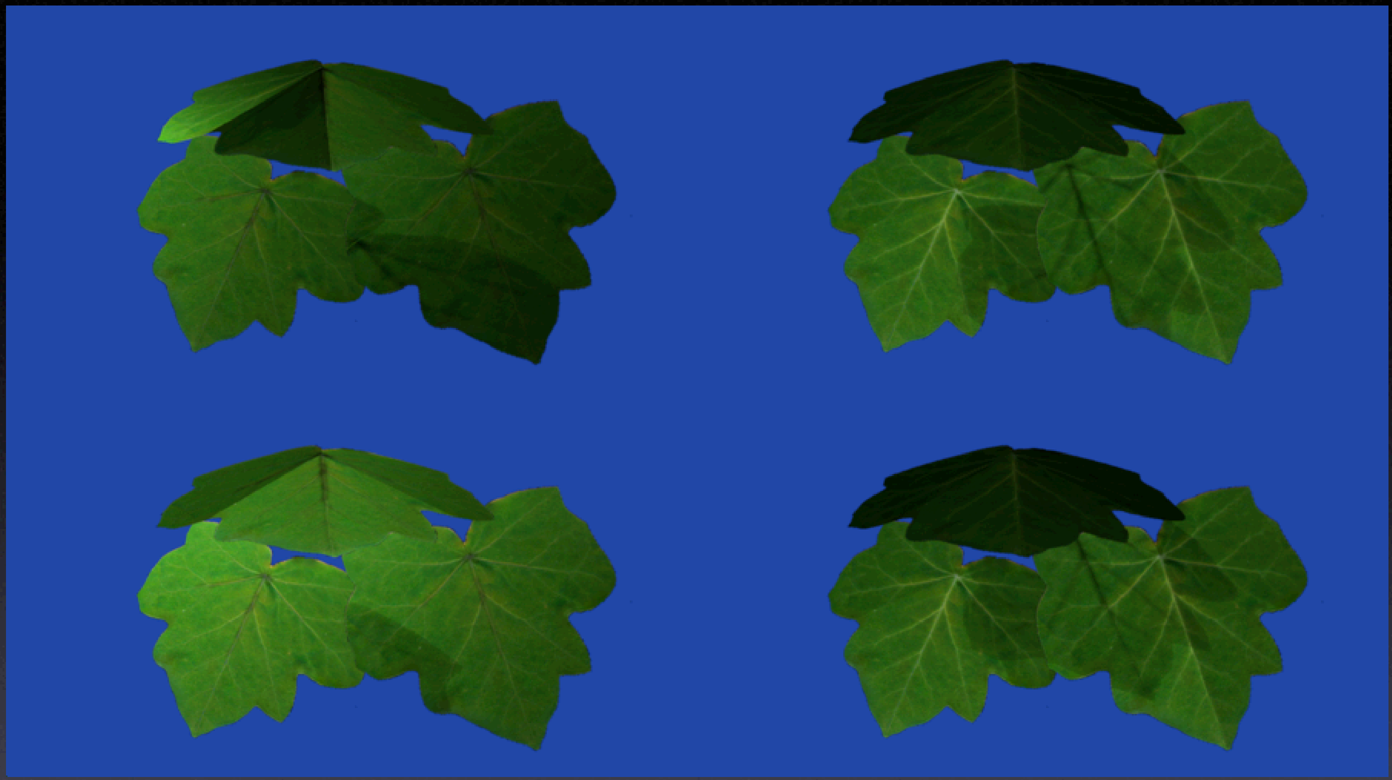


Hanrahan and Krueger 1990



Hanrahan and Krueger 1990

Hanrahan and Krueger
1990



Hanrahan and Krueger 1990

- convergence independent of dimension
- error decrease O(sqrt(N))

Monte Carlo

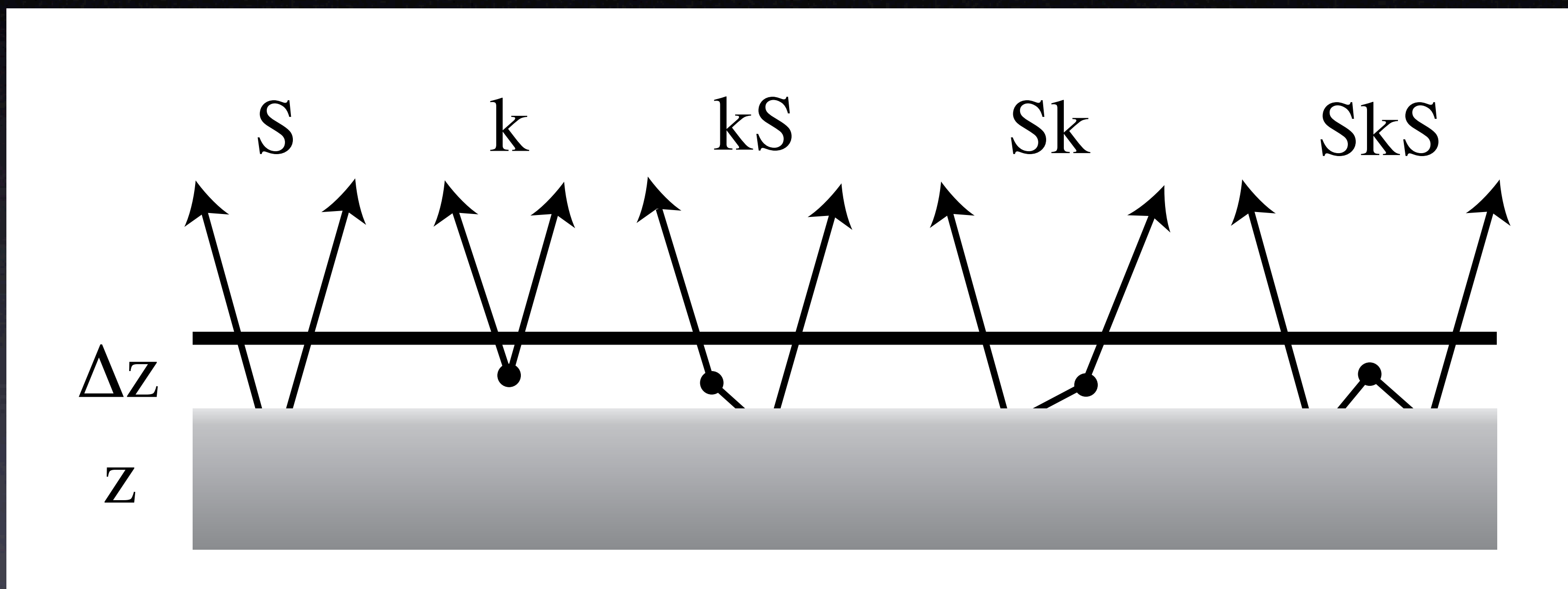
- application: weathered stone layer
- cast photon map into layer
- sample along penetration depth

Dorsey 1999

Dorsey 1999

- abstraction of scattering functions
- layer-to-layer interaction described by a set of adding equations

Pharr 2000



Pharr 2000

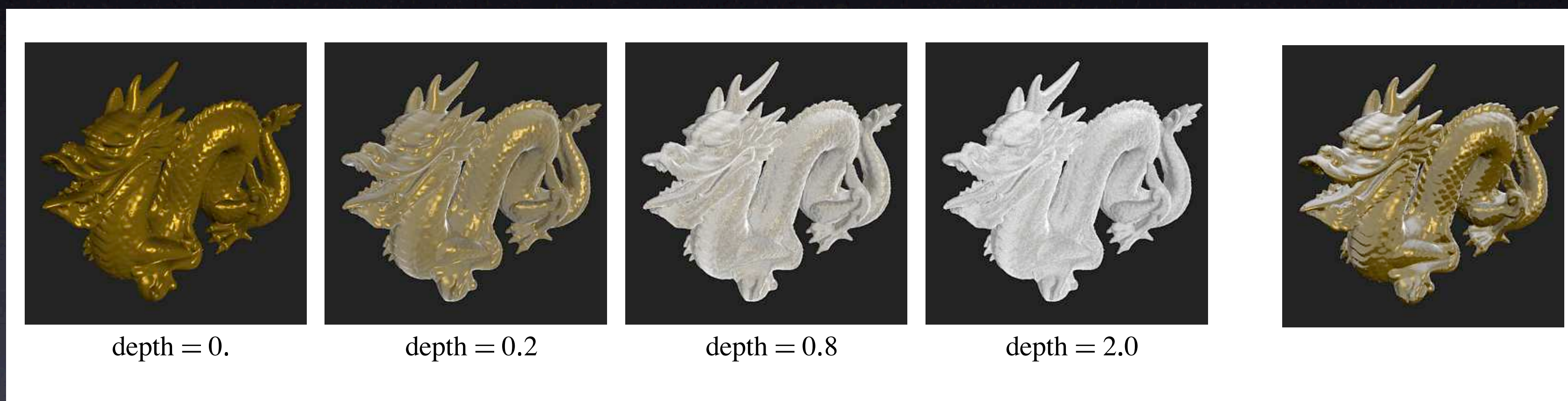
$$\mathbf{S}(z) = \int_0^z e^{-\sigma_t (1/\mu_i + 1/\mu_o)(z-z')} \big(\mathbf{k}(z') + \mathbf{k}(z')\mathbf{S}(z') + \mathbf{S}(z')\mathbf{k}(z') + \mathbf{S}(z')\mathbf{k}(z')\mathbf{S}(z')\big)\,\mathrm{d}z'.$$

Pharr 2000

$$S(z, r_i \to r_o) = \int_0^z e^{-(\sigma_t(x_i)/\mu_i + \sigma_t(x_o)/\mu_o)(z-z')} \Bigg(k(r_i(z') \to r_o(z')) + \frac{1}{4\pi} \int_{\mathcal{R}^+_{\mathcal{M}^2(z')}} k(r_o \to -r')\, S(z', r_i \to r')\, \frac{dr'}{\mu^2_{r'}} +$$

$$\frac{1}{4\pi} \int_{\mathcal{R}^+_{\mathcal{M}^2(z')}} S(z', r' \to r_o)\, k(r_i \to r')\, \frac{dr'}{\mu^2_{r'}} + \frac{1}{16\pi^2} \int_{\mathcal{R}^+_{\mathcal{M}^2(z')}} \int_{\mathcal{R}^+_{\mathcal{M}^2(z')}} S(z', r'' \to r_o)\, k(-r' \to -r'')\, S(z', r_i \to r')\, \frac{dr'}{\mu^2_{r'}} \frac{dr''}{\mu^2_{r''}} \Bigg) dz'$$

Pharr 2000



Pharr 2000

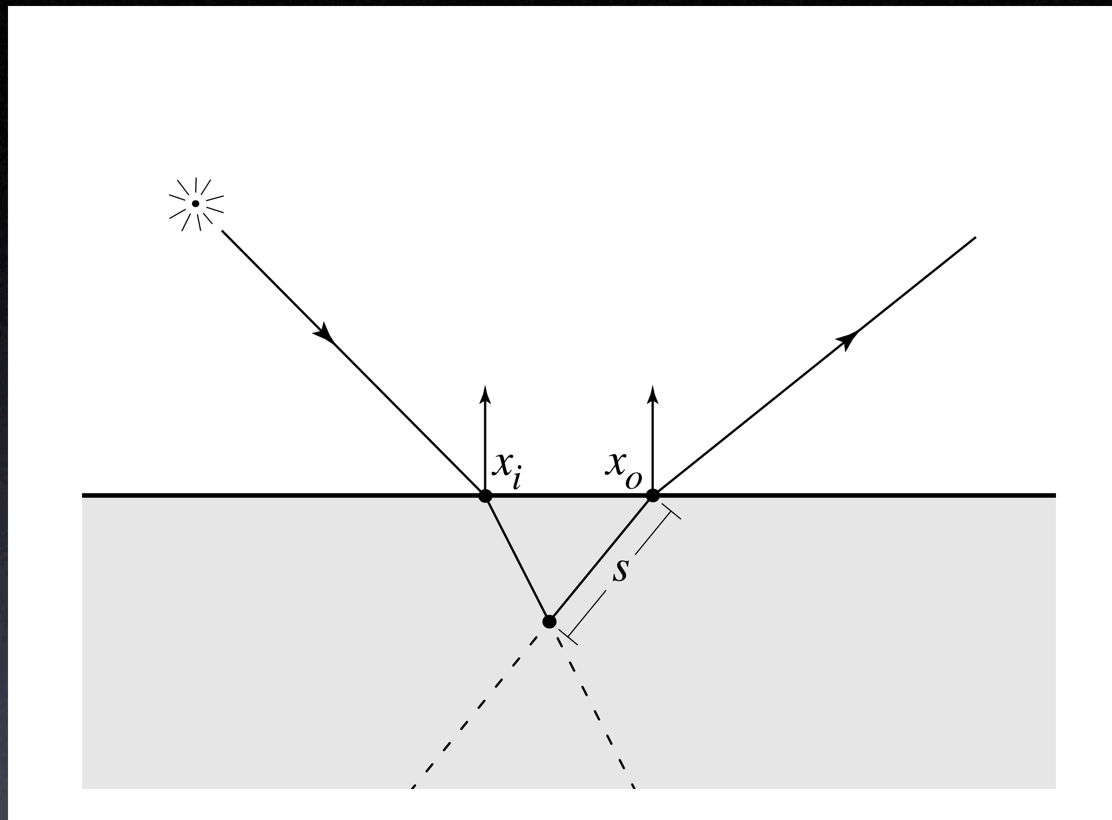
- assumes homogeneous media
- fast evaluation for multiple scattering with many events (milk, skin)
- diffusion for multiple scattering introduced by Stam in 95 for participating media

diffusion for multiple scattering

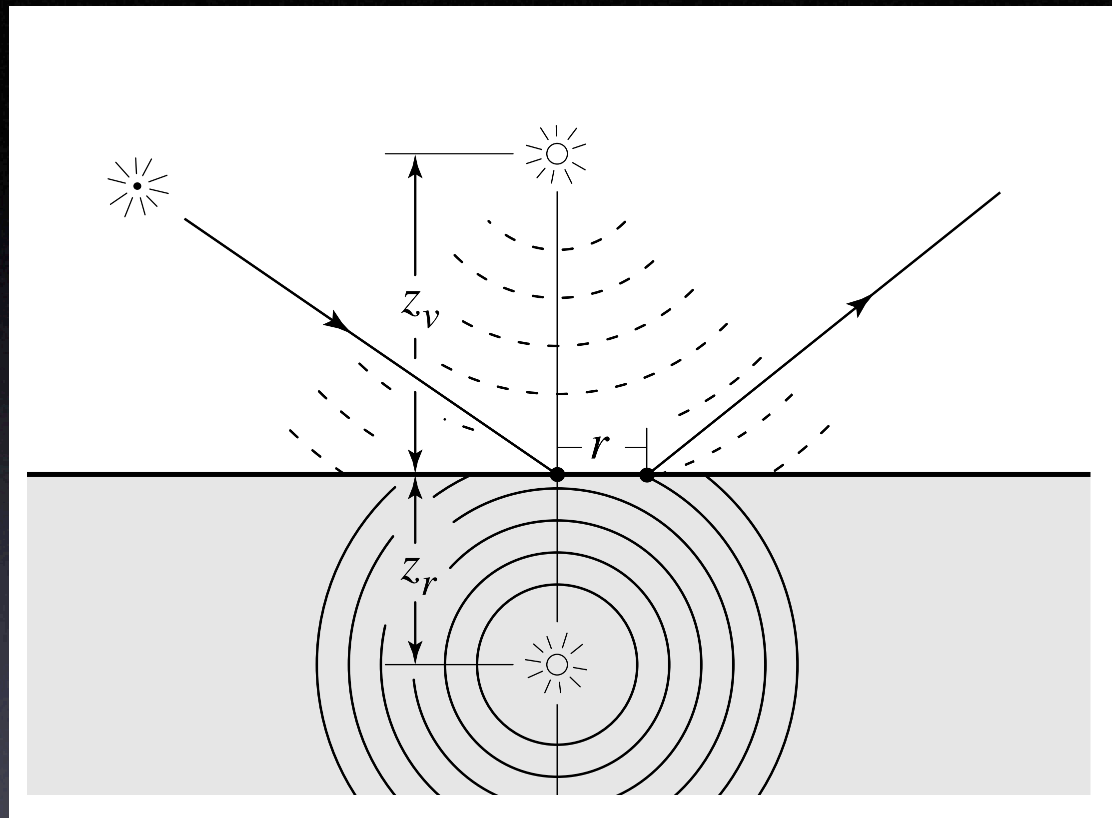
$$S(x_i, w_i; x_o, w_o) = S_d(x_i, w_i; x_o, w_o) + S^{(1)}(x_i, w_i; x_o, w_o)$$

- exact single scattering
- dipole approximation of diffusion model for multiple scattering

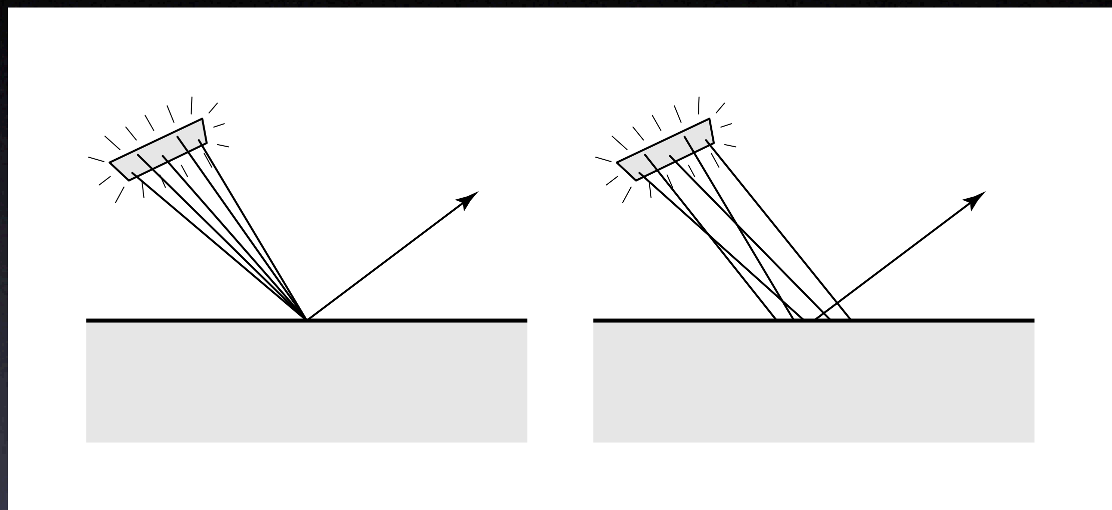
Jensen 2001



single scattering



multiple scattering



MC evaluation

Jensen 01

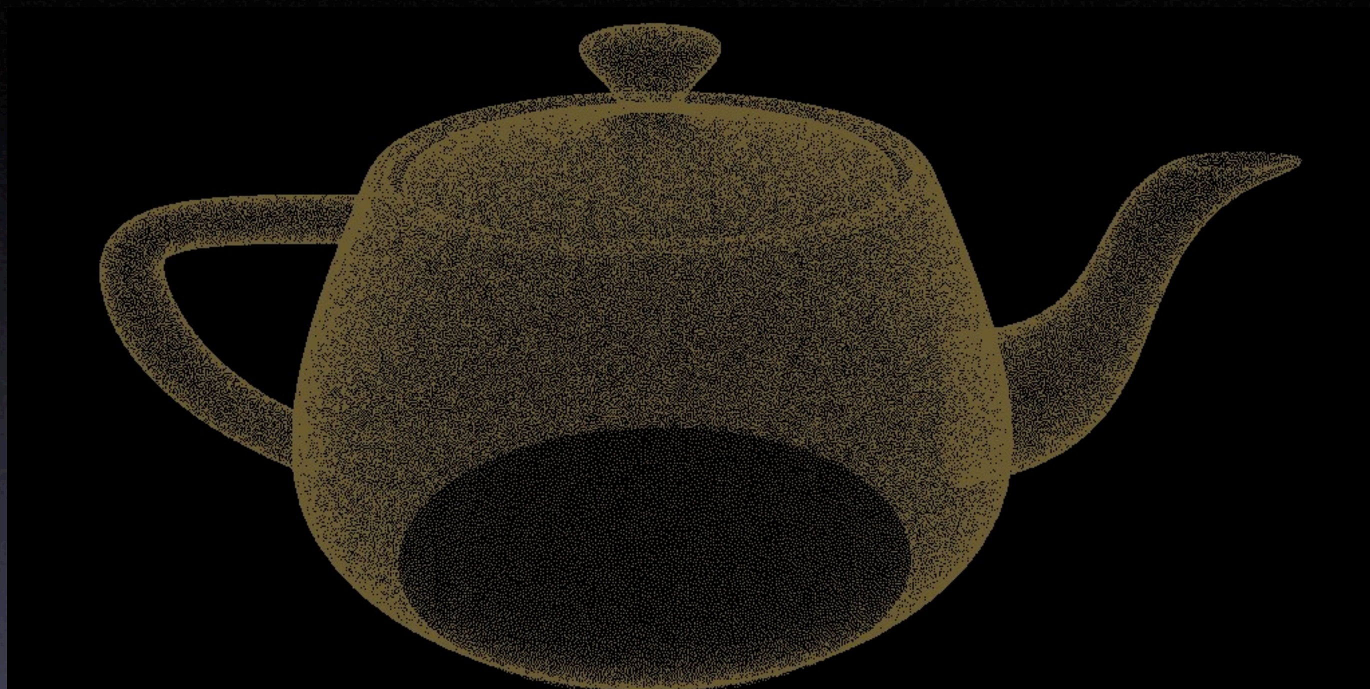
Jensen 01

Jensen 01

Jensen 01

- decouple sample irradiance computation from diffuse approximation computation
- hierachical evaluation of multiple scattering term

Jensen 02



Jensen 02

- build octree model of (irradiance, centroid, total area)
- depth criteria: solid angle for evaluation point to total area < eps.

Jensen 02

Jensen 02

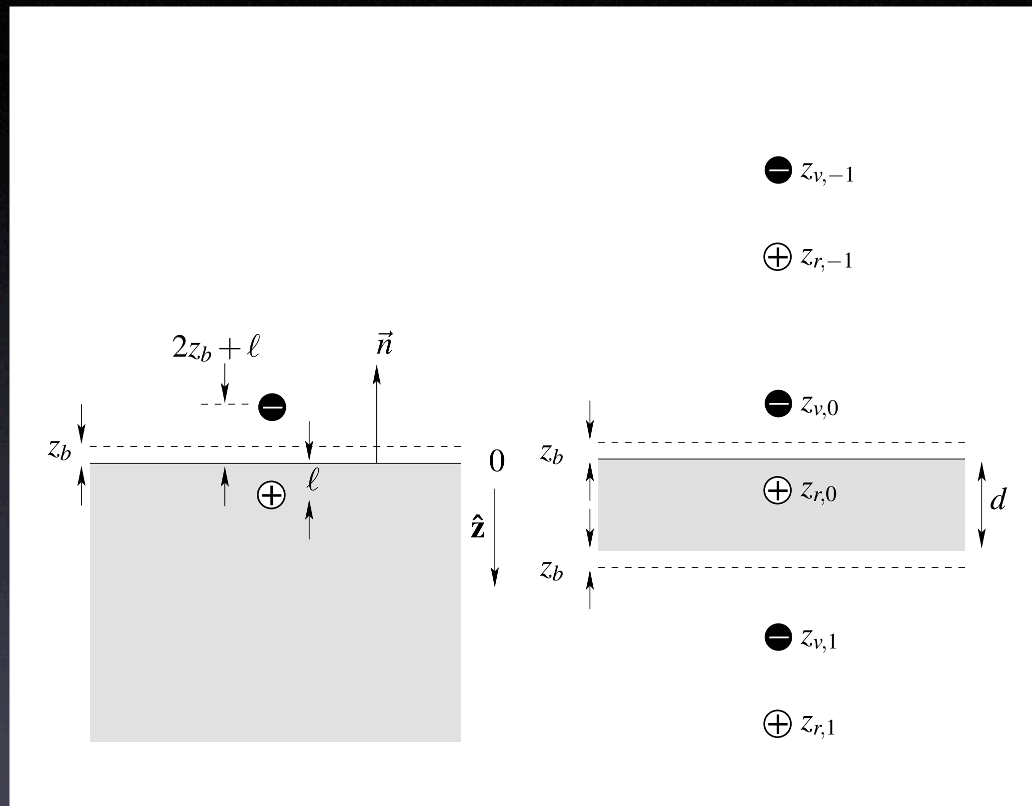
Jensen 02

- dipole diffusion approximation breaks down
- assumption of infinite depth: no transmittance though to opposite side

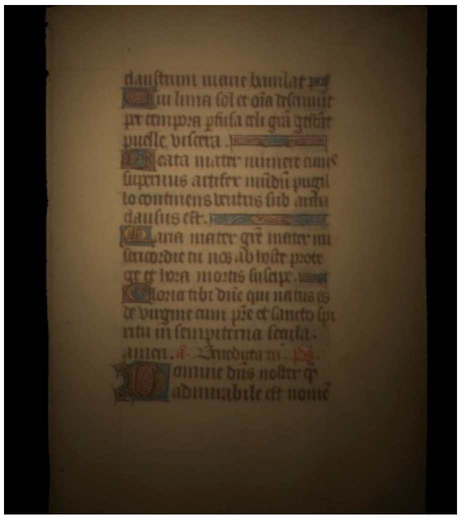
thin objects

- multipole approximation
- frequency space Kubelka Munk model for interaction among multiple layers
- rough surfaces: replace fresnel attenuation with a BRDF

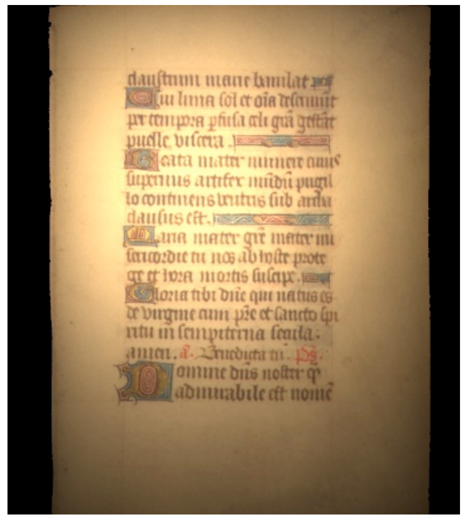
Donner 05



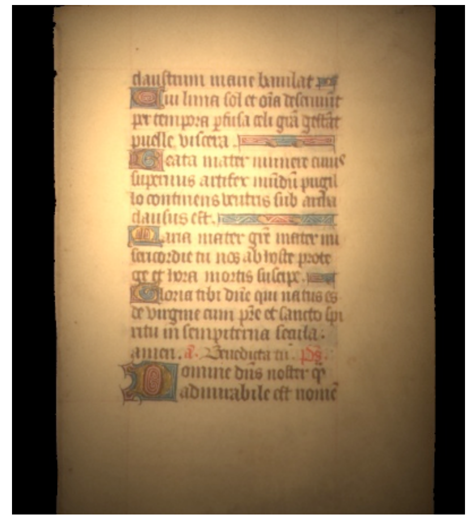
Donner 05



Dipole model



Multipole model



Monte Carlo reference

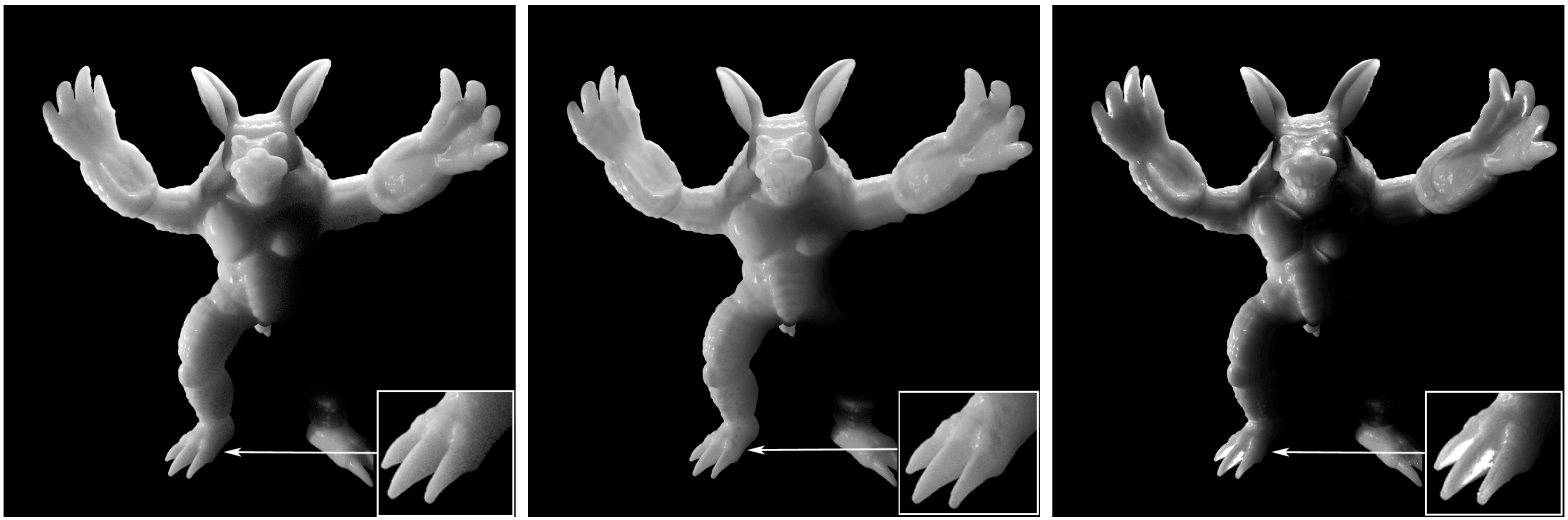
Donner 05

Donner 05

Donner 05

- MC evaluation until ray passes a depth threshold
- diffusion approximation in core

Li 05



a. Monte Carlo (246 min) b. Hybrid method (33 min) c. Jensen et al. (10 min)

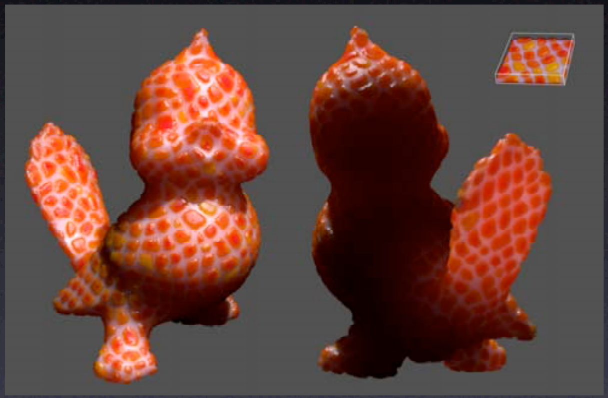
Li 05

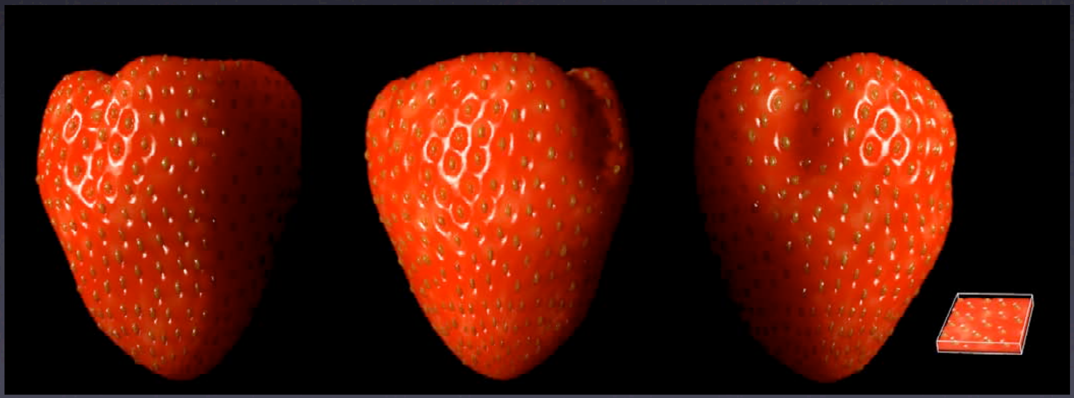
- diffusion approximation for multiple scattering blurs out local variation

nonhomogeneities

- model mesostructure and volumetric nonhomogeneity in region near surface
- fit “shell texture function” to high quality data in volume
- evaluate core using diffusion approximation
- evaluate shell with STF

Chen 04

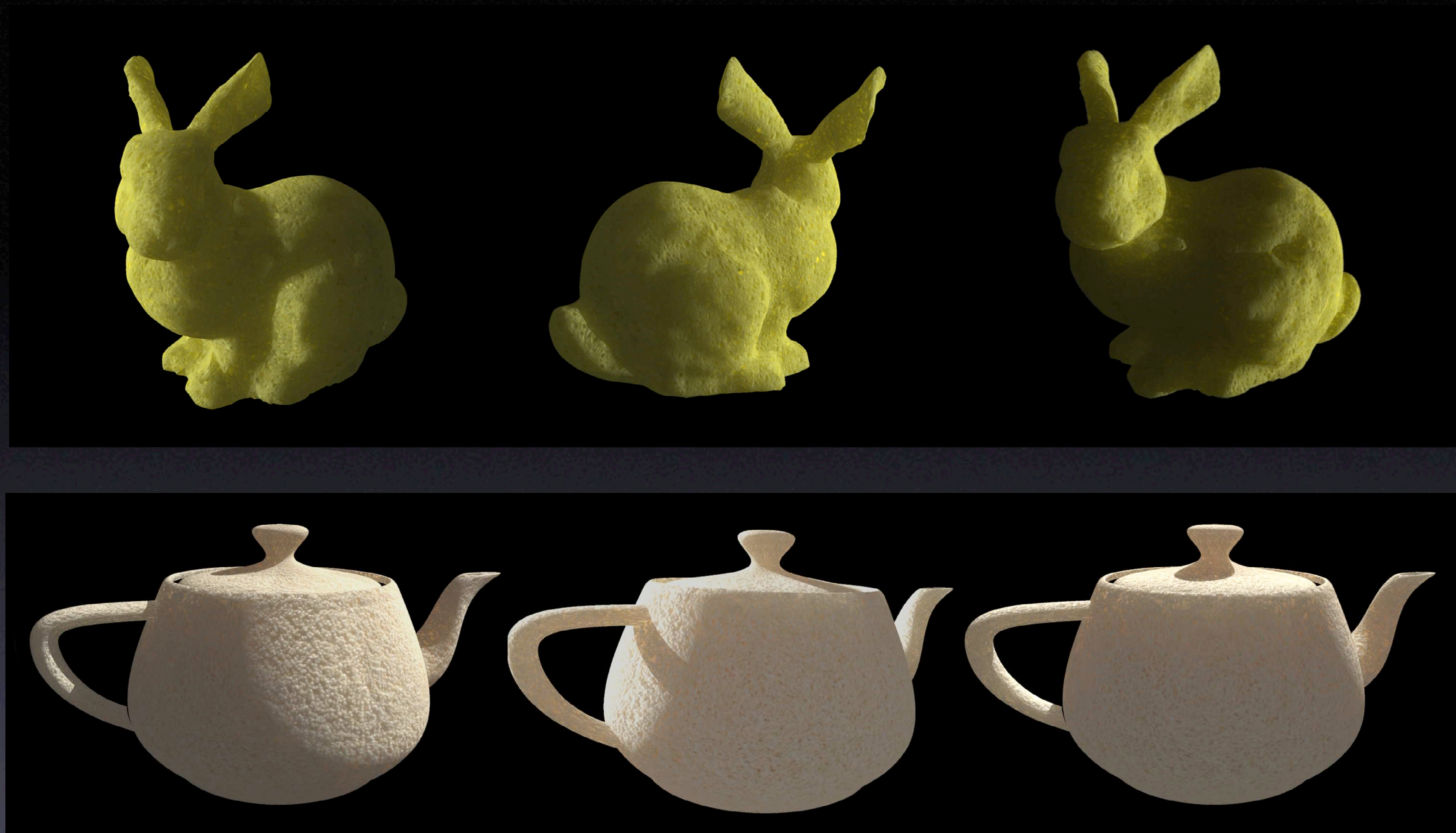




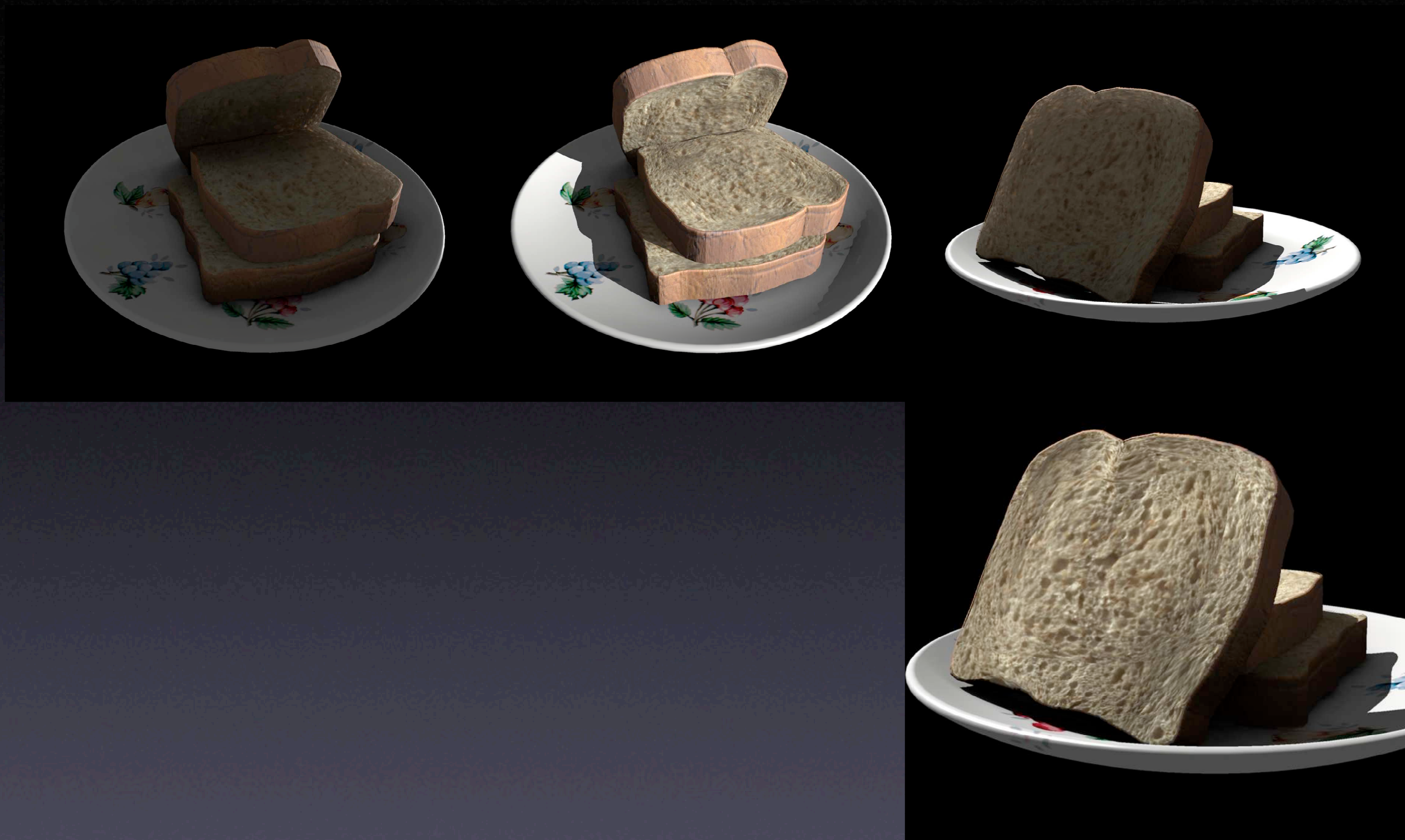
Chen 04

- two scale model: fine nonhomogeneities, course diffusion approximation
- local scattering effects: local reflectance, mesostructure entrance function, mesostructure exit function
- texture synthesis of local model.

Tong 05



Tong 05



Tong 05