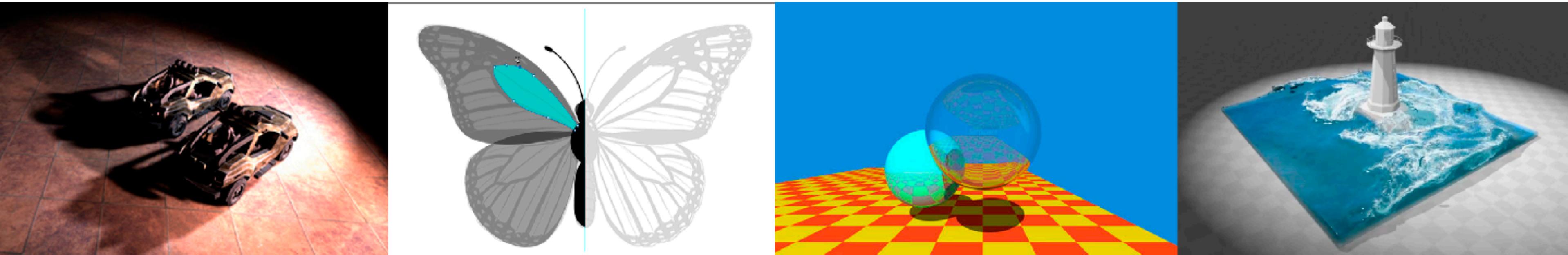


Introduction to Computer Graphics

GAMES101, Lingqi Yan, UC Santa Barbara

Lecture 18: Advanced Topics in Rendering



Announcements

- Homework 7 will be released soon
- Final project timeline
 - [Apr 14] Ideas will be released next Tuesday
 - [Apr 19] Submit your proposal one week later
 - [May 5] Submit your work
- Final project logistics
 - Work on Graphics topics, write code on your own
- Today's lecture
 - Advanced (?) light transport and materials
 - A lot, but extremely high-level. Mostly FYI.

Advanced Light Transport

Advanced Light Transport

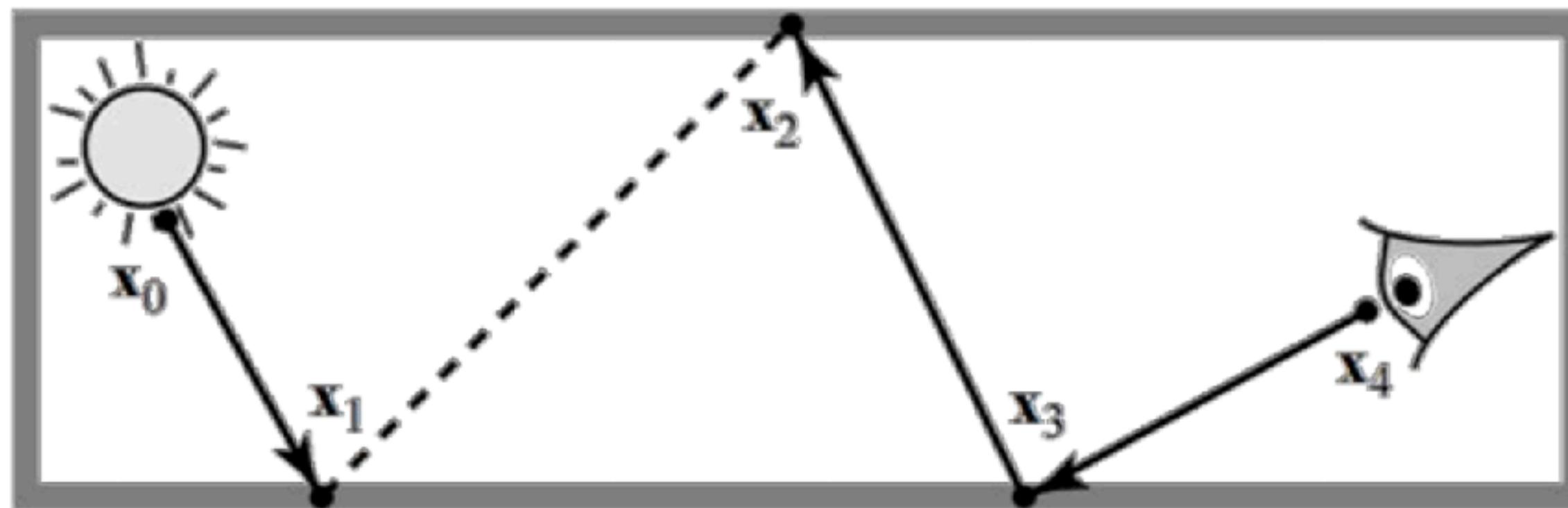
- Unbiased light transport methods
 - Bidirectional path tracing (BDPT)
 - Metropolis light transport (MLT)
- Biased light transport methods
 - Photon mapping
 - Vertex connection and merging (VCM)
- Instant radiosity (VPL / many light methods)

Biased vs. Unbiased Monte Carlo Estimators

- An **unbiased** Monte Carlo technique does not have any systematic error
 - The expected value of an unbiased estimator will always be the correct value, no matter how many samples are used
- Otherwise, **biased**
 - One special case, the expected value converges to the correct value as infinite #samples are used — **consistent**
- We'll look again at this page after introducing Photon Mapping

Bidirectional Path Tracing (BDPT)

- Recall: a path connects the camera and the light
- BDPT
 - Traces sub-paths from both the camera and the light
 - Connects the end points from both sub-paths



[Veach 1997]

Bidirectional Path Tracing (BDPT)

- Suitable if the light transport is complex on the light's side
- Difficult to implement & quite slow



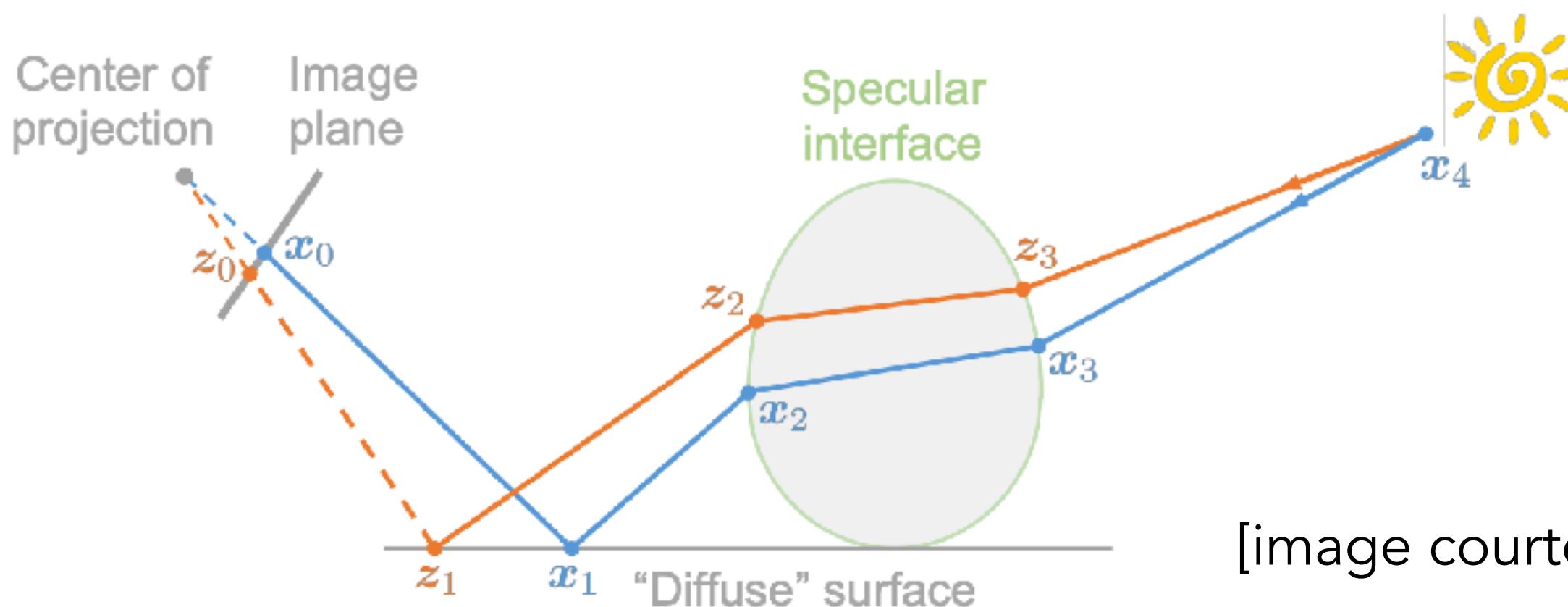
(a) Path tracer, 32 samples/pixel



(b) Bidirectional path tracer, 32 samples/pixel

Metropolis Light Transport (MLT)

- A Markov Chain Monte Carlo (MCMC) application
 - Jumping from the current sample to the next with some PDF
- Very good at **locally** exploring difficult light paths
- Key idea
 - Locally perturb an existing path to get a new path



[image courtesy of Shuang Zhao]

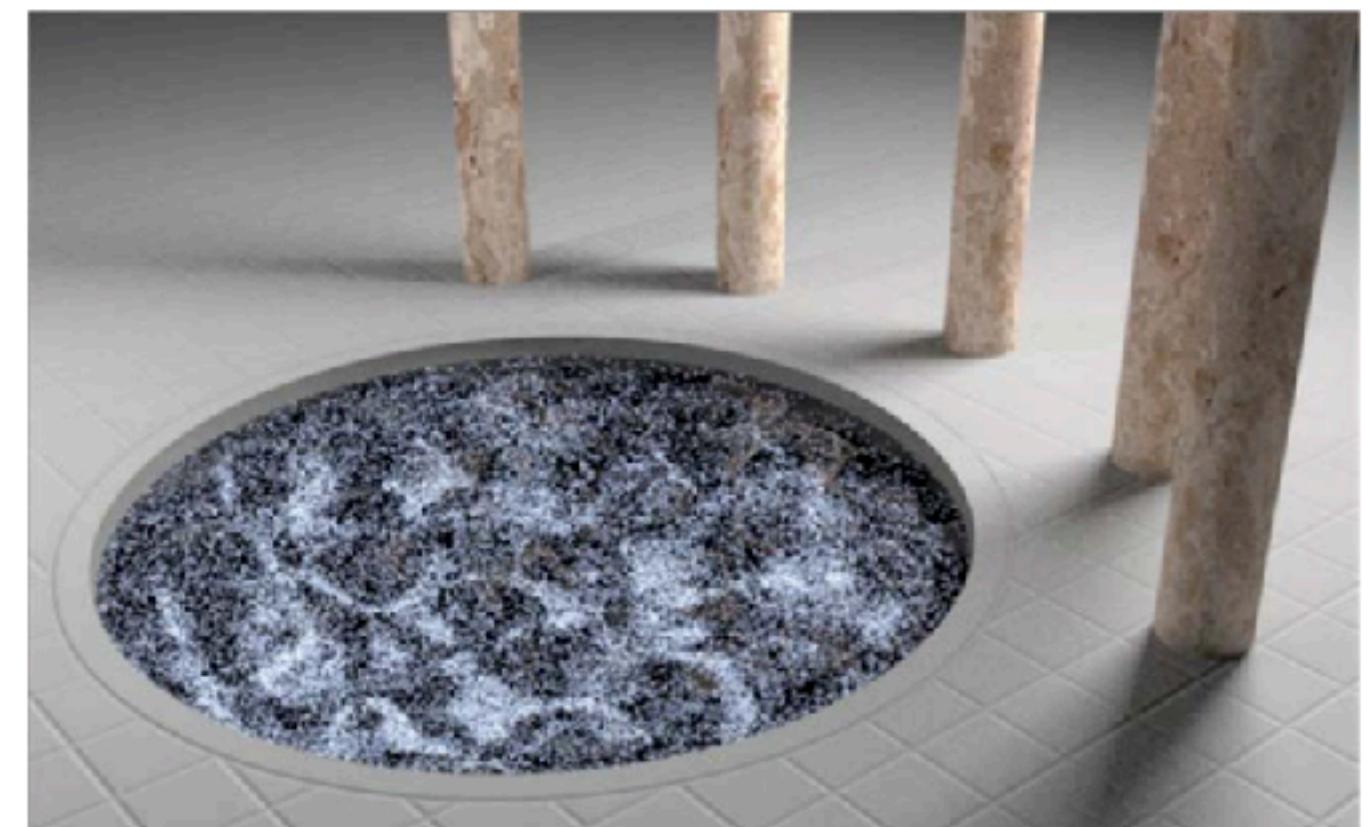
Metropolis Light Transport (MLT) — Pros

- Works great with difficult light paths
- Also unbiased

BDPT



MLT



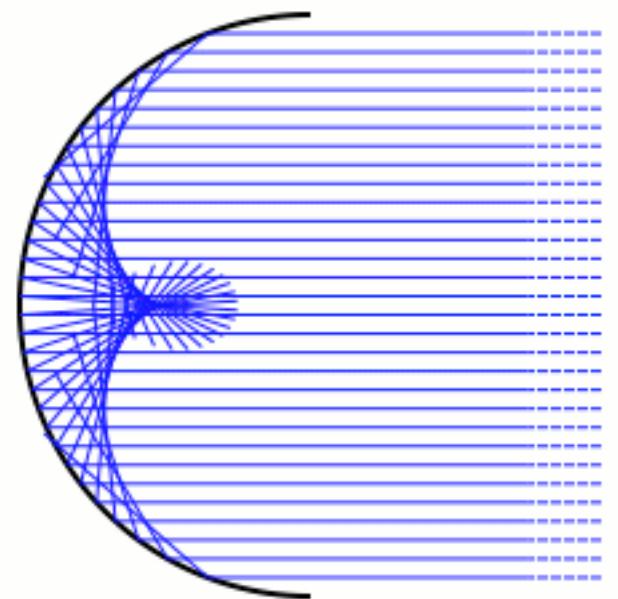
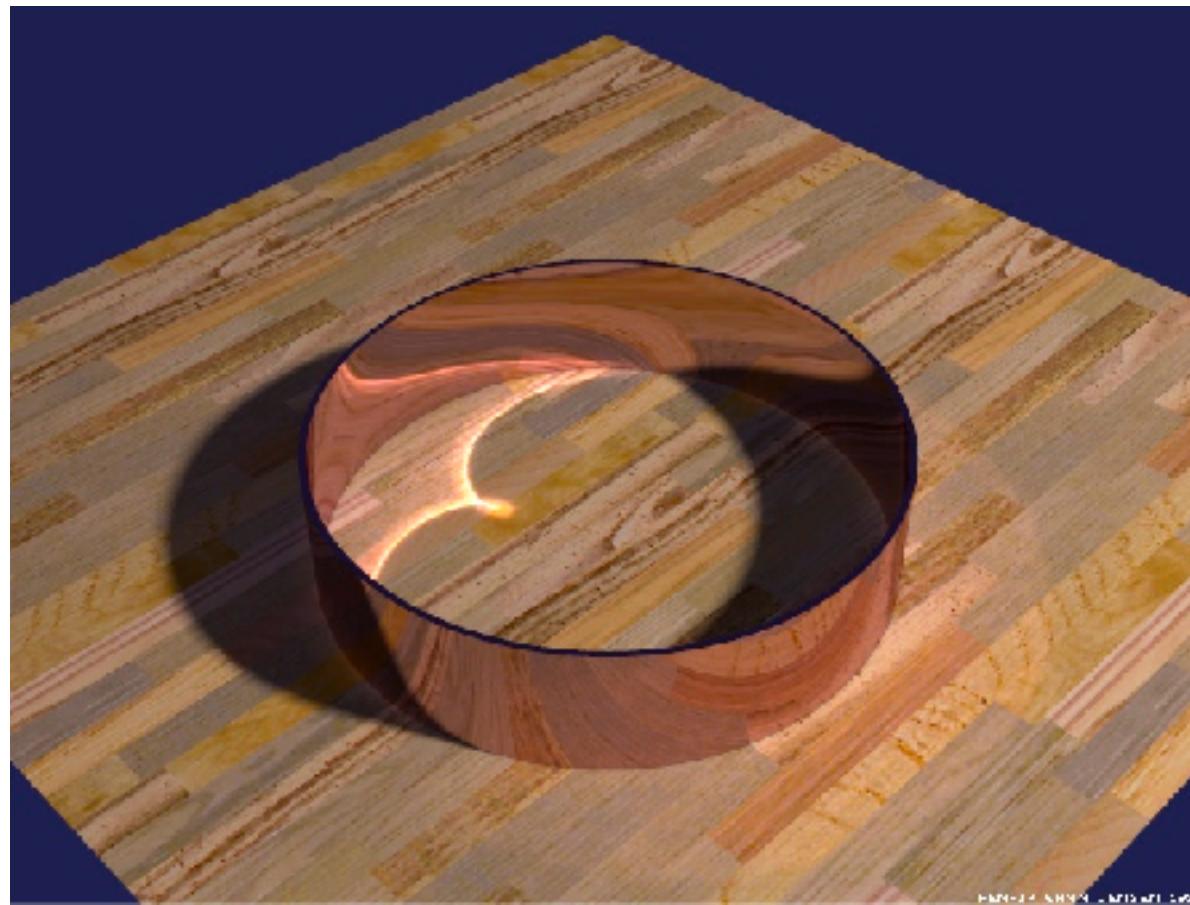
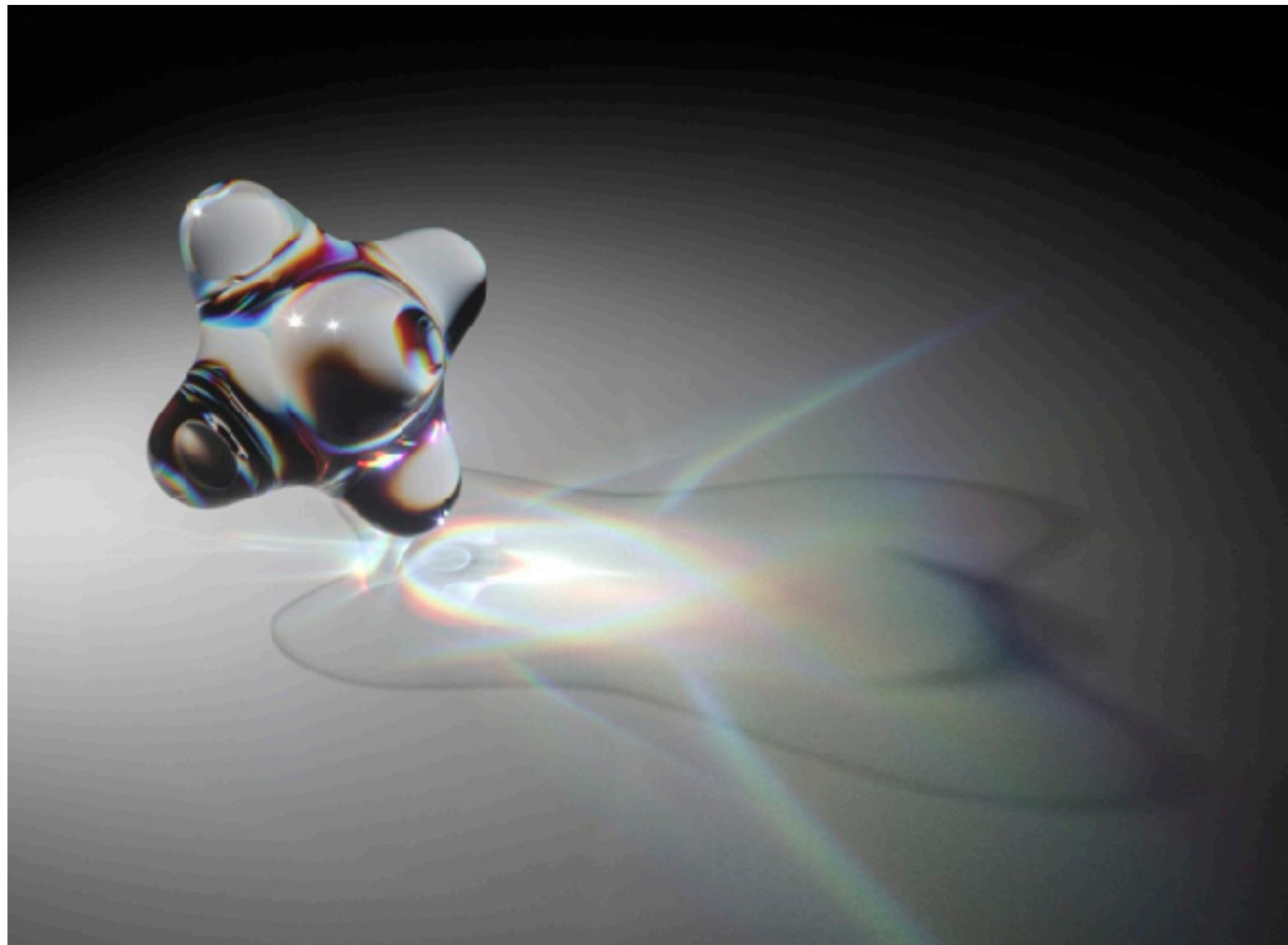
Metropolis Light Transport (MLT) — Cons

- Difficult to estimate the convergence rate
- Does not guarantee equal convergence rate per pixel
- So, usually produces “dirty” results
- Therefore, usually not used to render animations



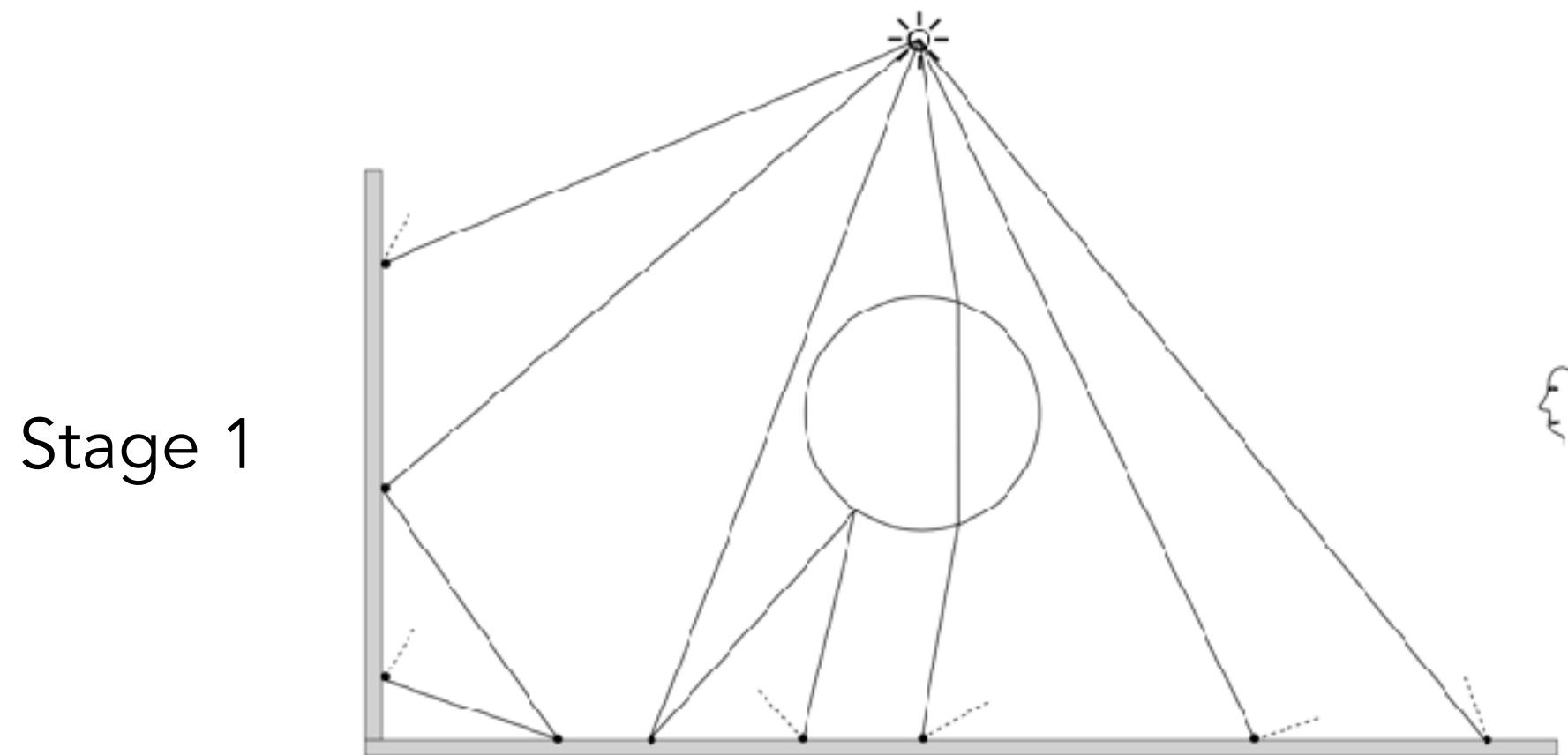
Photon Mapping

- A biased approach & A two-stage method
- Very good at handling Specular-Diffuse-Specular (SDS) paths and generating **caustics**



Photon Mapping — Approach (variations apply)

- Stage 1 — photon tracing
 - Emitting photons from the light source, bouncing them around, then recording photons on diffuse surfaces

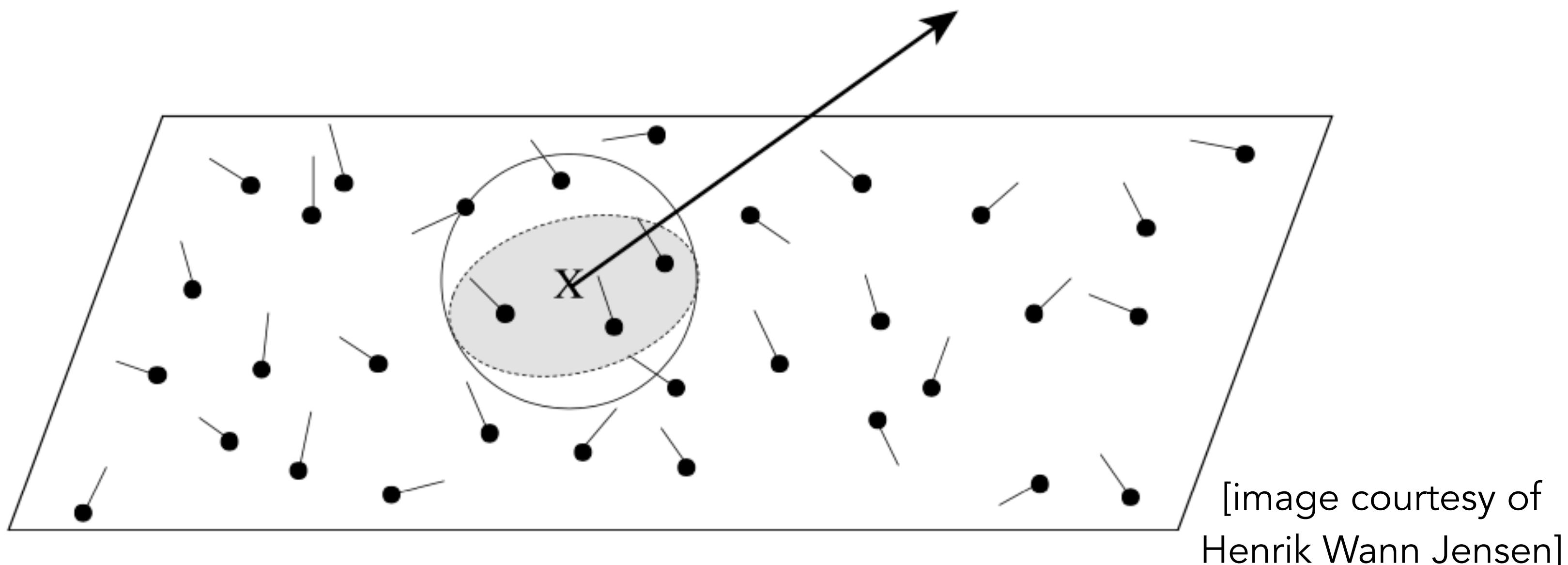


[image courtesy of
Henrik Wann Jensen]

- Stage 2 — photon collection (final gathering)
 - Shoot sub-paths from the camera, bouncing them around, until they hit diffuse surfaces

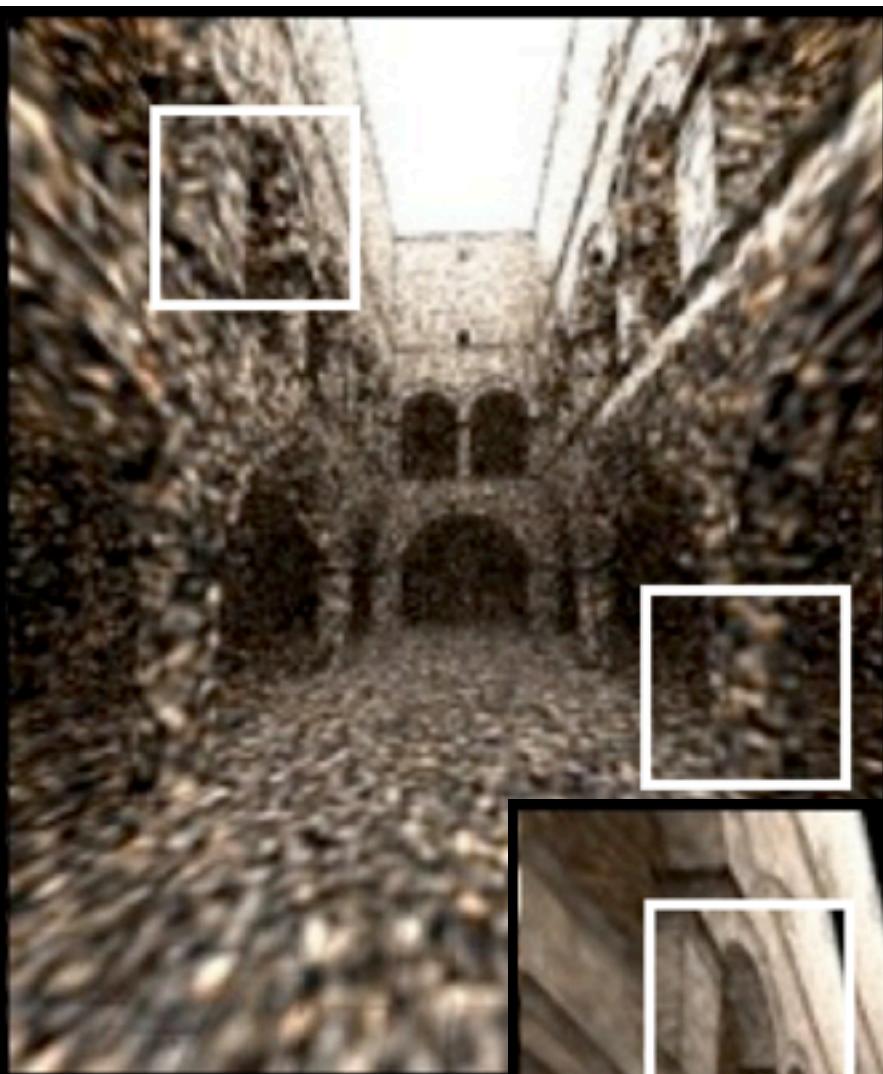
Photon Mapping

- Calculation — local density estimation
 - Idea: areas with more photons should be brighter
 - For each shading point, find the nearest N photons. Take the surface area they over

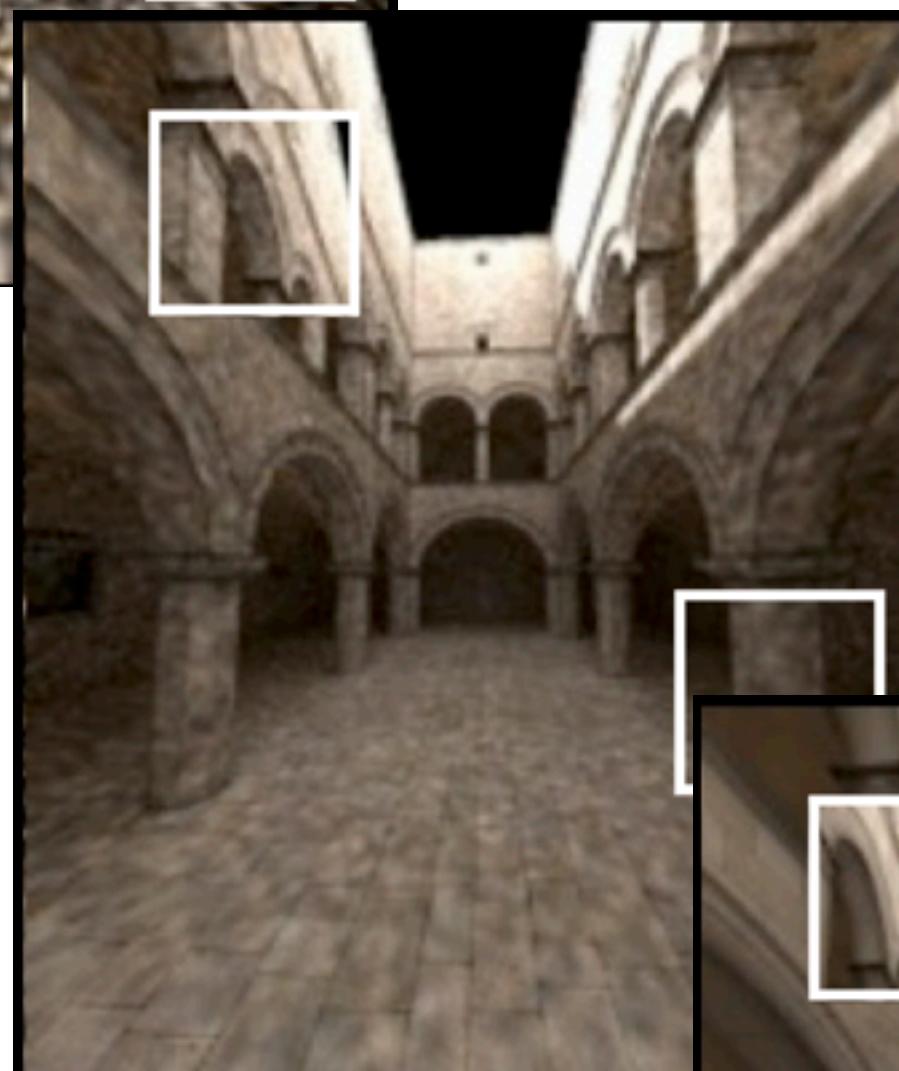


Photon Mapping

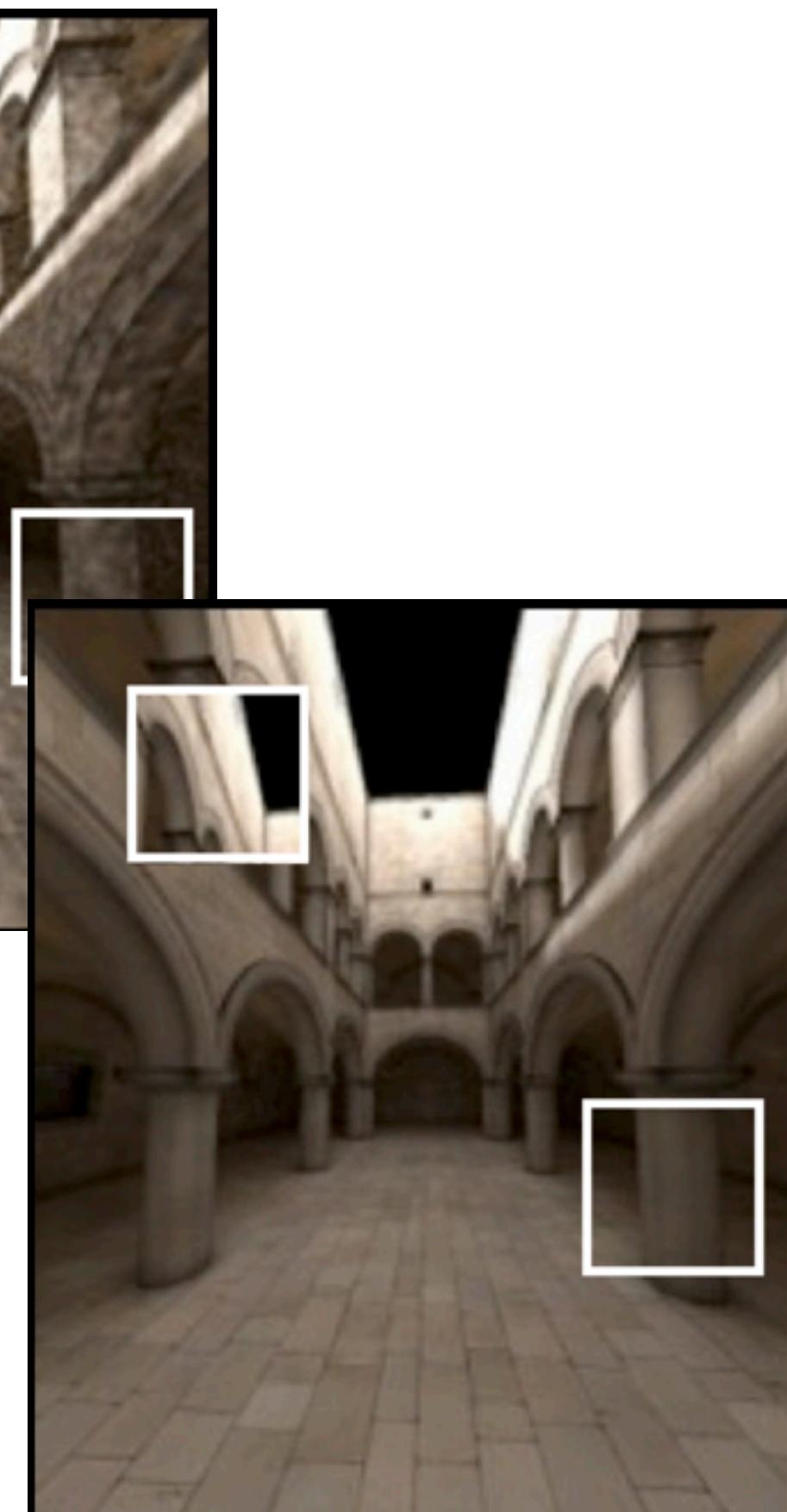
- Why biased?
- Local Density estimation
 $dN / dA \neq \Delta N / \Delta A$
- But in the sense of limit
 - More photons emitted ->
 - the same N photons covers a smaller ΔA ->
 - ΔA is closer to dA
- So, biased but consistent!



Small $N \leftrightarrow$ noisy



large $N \leftrightarrow$ blurry

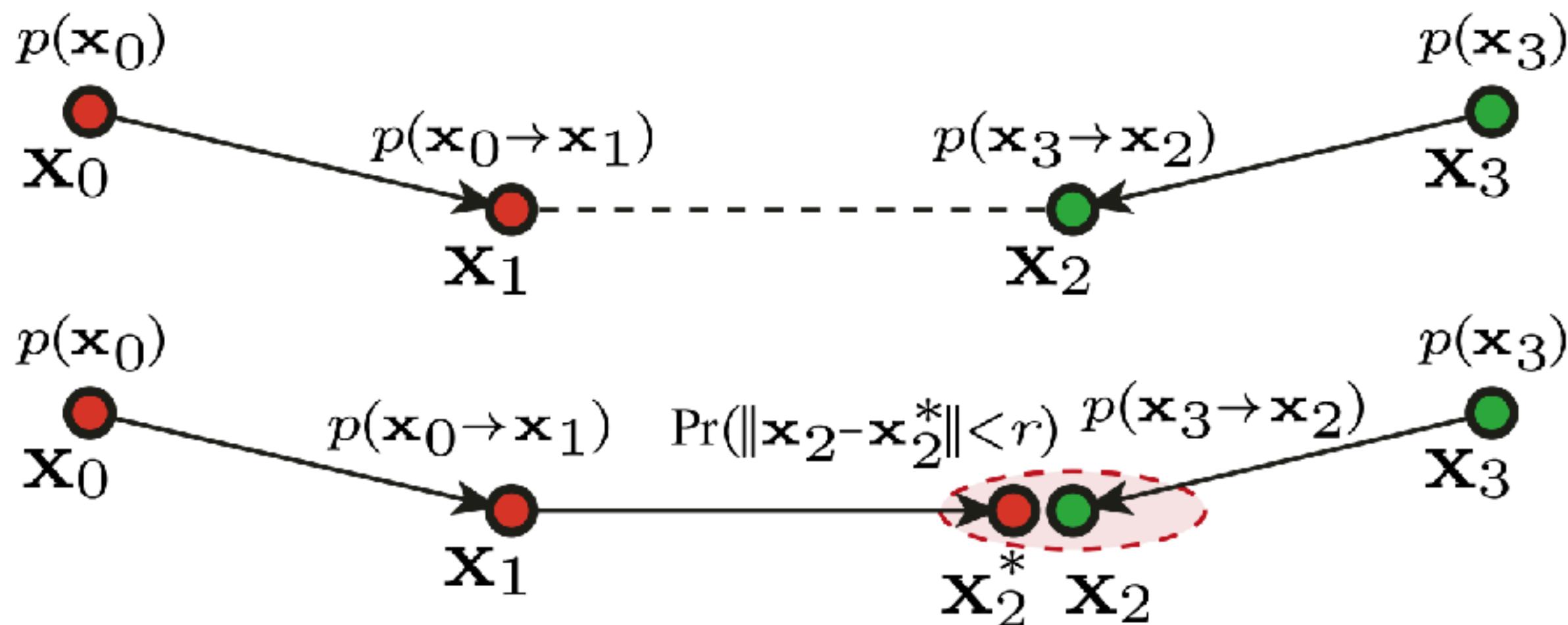


Photon Mapping

- An easier understanding bias in rendering
 - Biased == blurry
 - Consistent == not blurry with infinite #samples
- Why not do a “const range” search for density estimation?

Vertex Connection and Merging

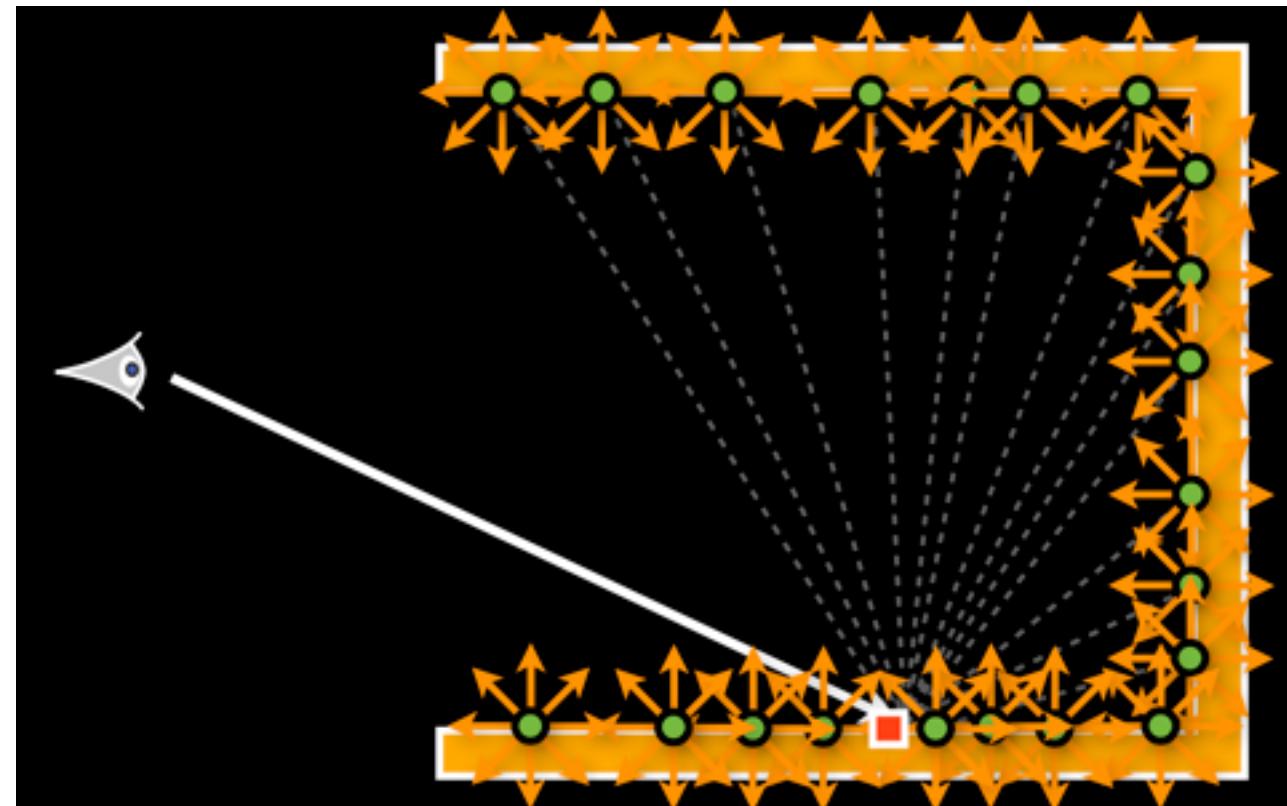
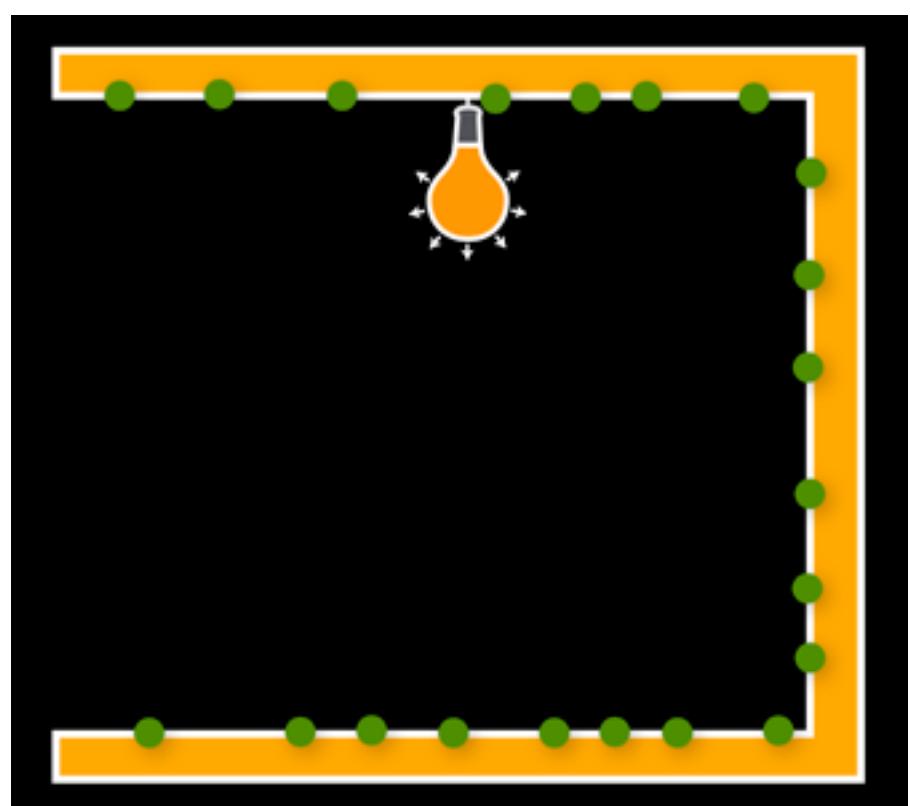
- A combination of BDPT and Photon Mapping
- Key idea
 - Let's not waste the sub-paths in BDPT if their end points cannot be connected but can be merged
 - Use photon mapping to handle the merging of nearby “photons”



[Georgiev et al. 2012]

Instant Radiosity (IR)

- Sometimes also called many-light approaches
- Key idea
 - Lit surfaces can be treated as light sources
- Approach
 - Shoot light sub-paths and assume the end point of each sub-path is a Virtual Point Light (VPL)
 - Render the scene as usual using these VPLs



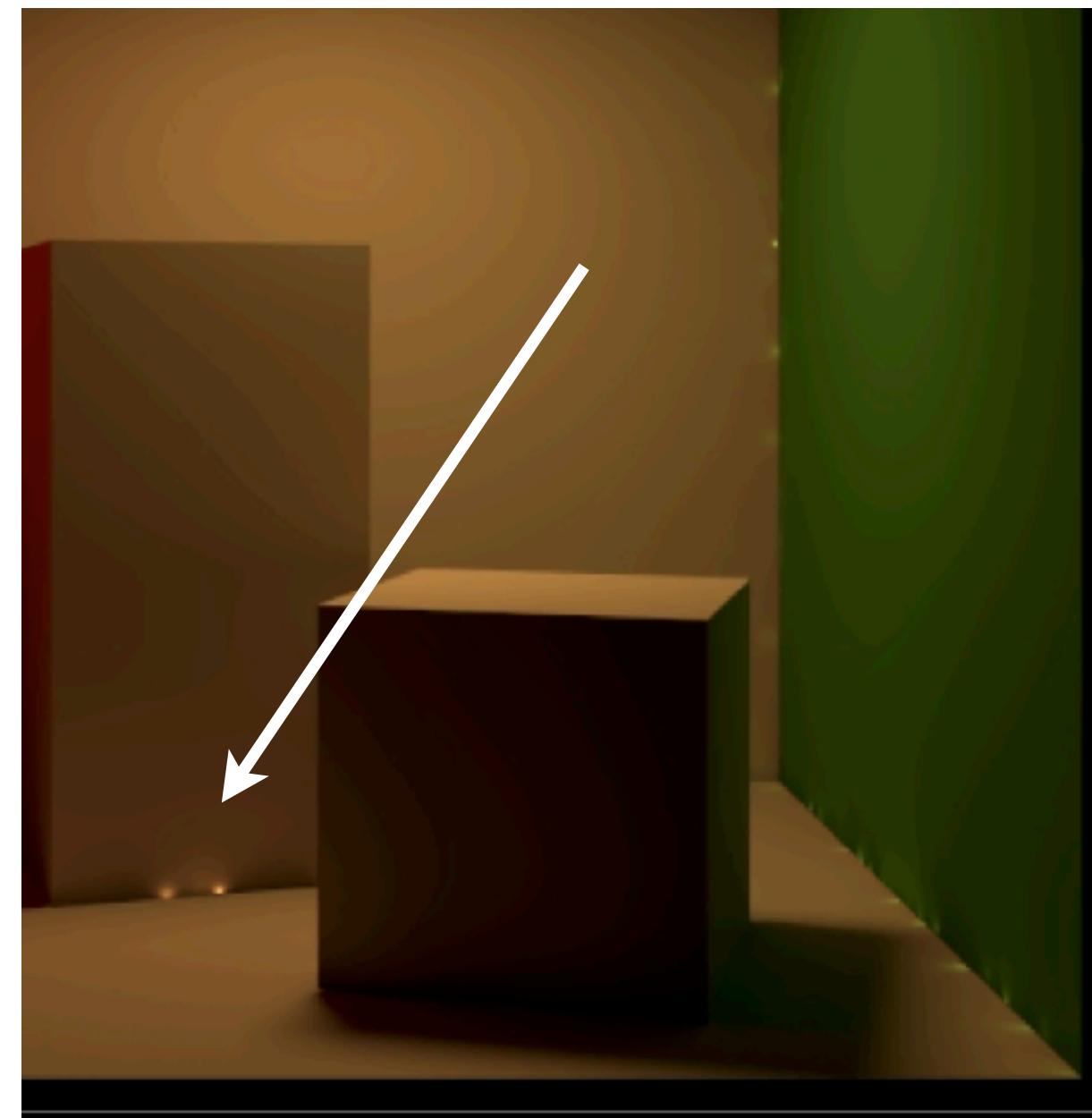
[image
courtesy of
Derek N.]

Instant Radiosity

- Pros: fast and usually gives good results on diffuse scenes
- Cons
 - Spikes will emerge when VPLs are close to shading points
 - Cannot handle glossy materials



[Liu et al. 2019] (many-light rendering, not IR)



[Rendered using Mitsuba]

Advanced Appearance Modeling

Advanced Appearance Modeling

- Non-surface models
 - Participating media
 - Hair / fur / fiber (BCSDF)
 - Granular material
- Surface models
 - Translucent material (BSSRDF)
 - Cloth
 - Detailed material (non-statistical BRDF)
- Procedural appearance

Non-Surface Models

Participating Media: Fog



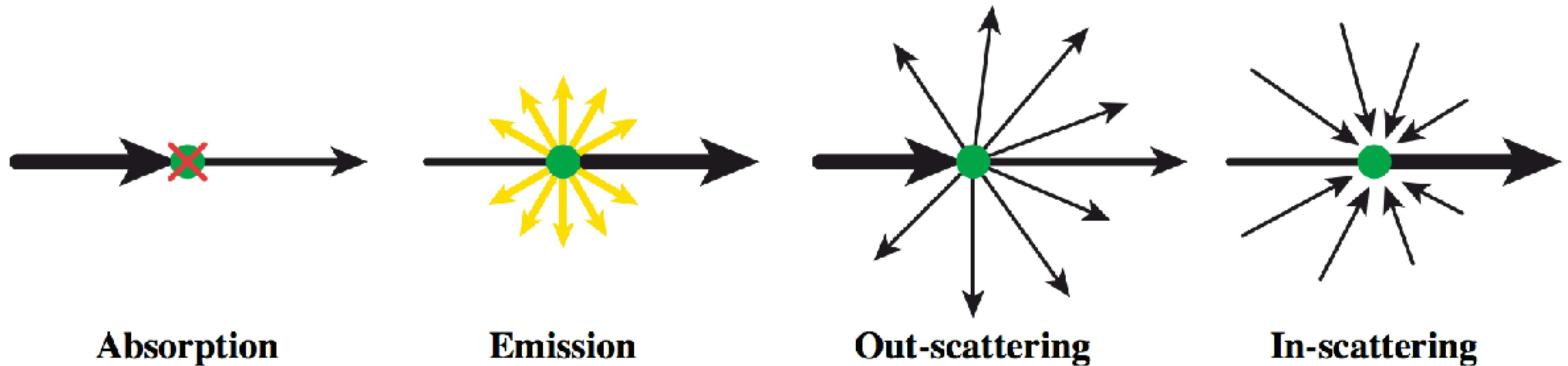
Participating Media: Cloud



[by thephotographer0]

Participating Media

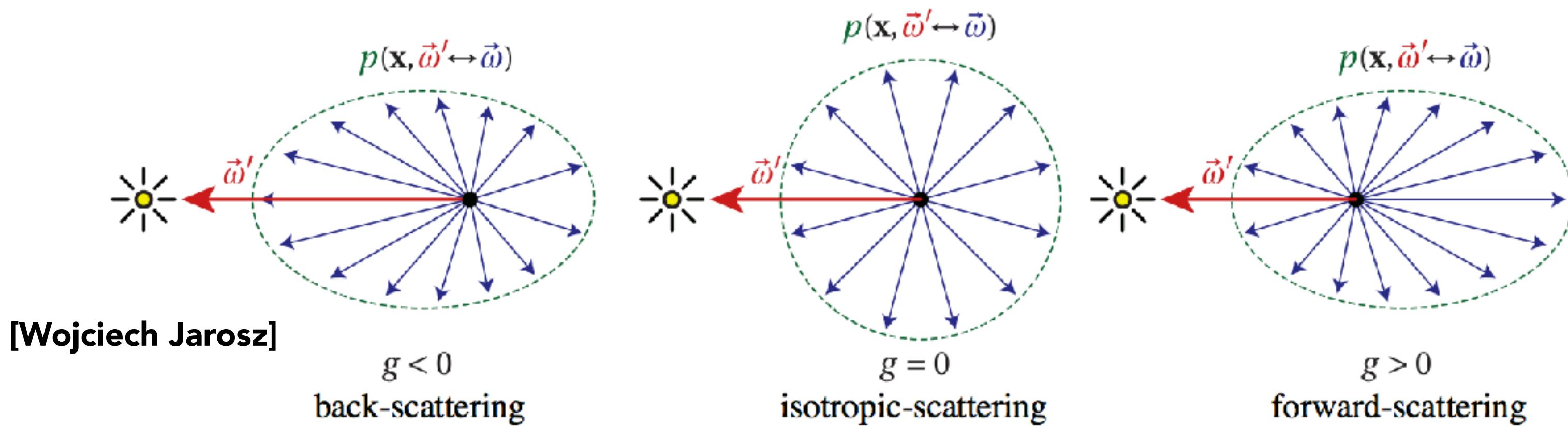
- At any point as light travels through a participating medium, it can be (partially) absorbed and scattered.



[Wojciech Jarosz]

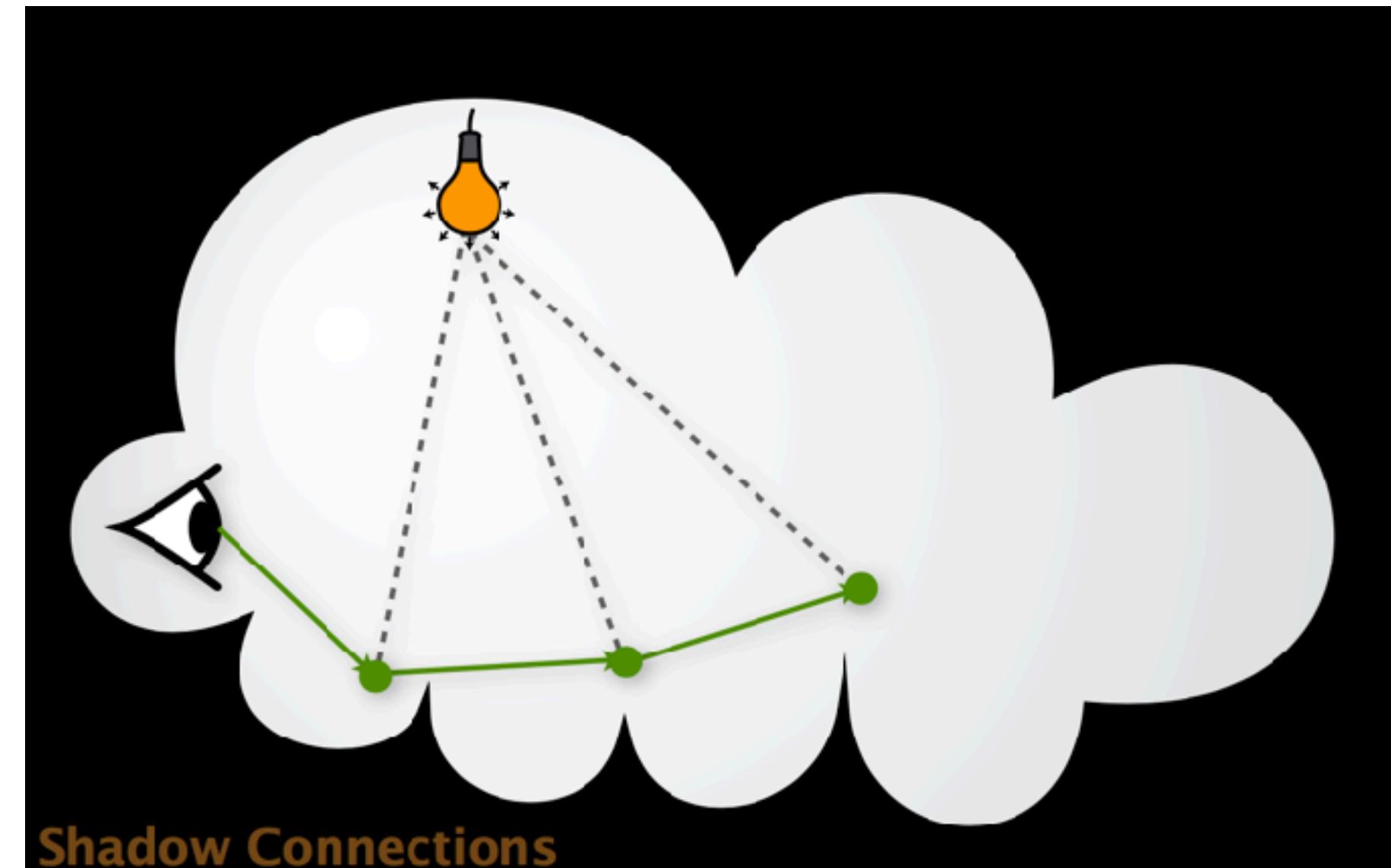
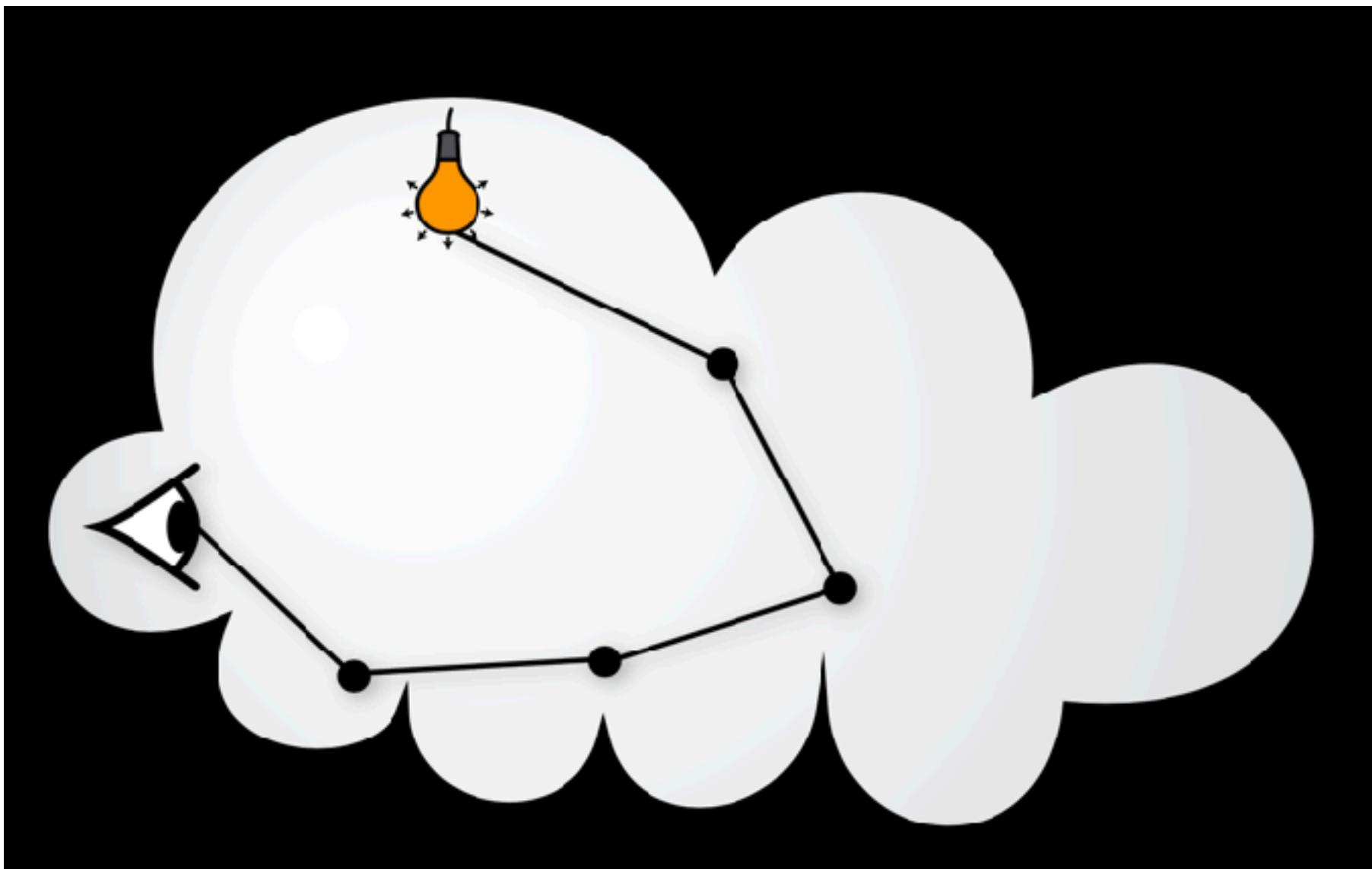
Participating Media

- Use Phase Function to describe the angular distribution of light scattering at any point x within participating media.



Participating Media: Rendering

- Randomly choose a direction to bounce
- Randomly choose a distance to go straight
- At each 'shading point', connect to the light



[Derek Nowrouzezahrai]

Participating Media: Application



[Big Hero 6, 2014 Disney]

Participating Media: Application



[Assassin's Creed Syndicate. 2015 Ubisoft]

Participating Media: Demo

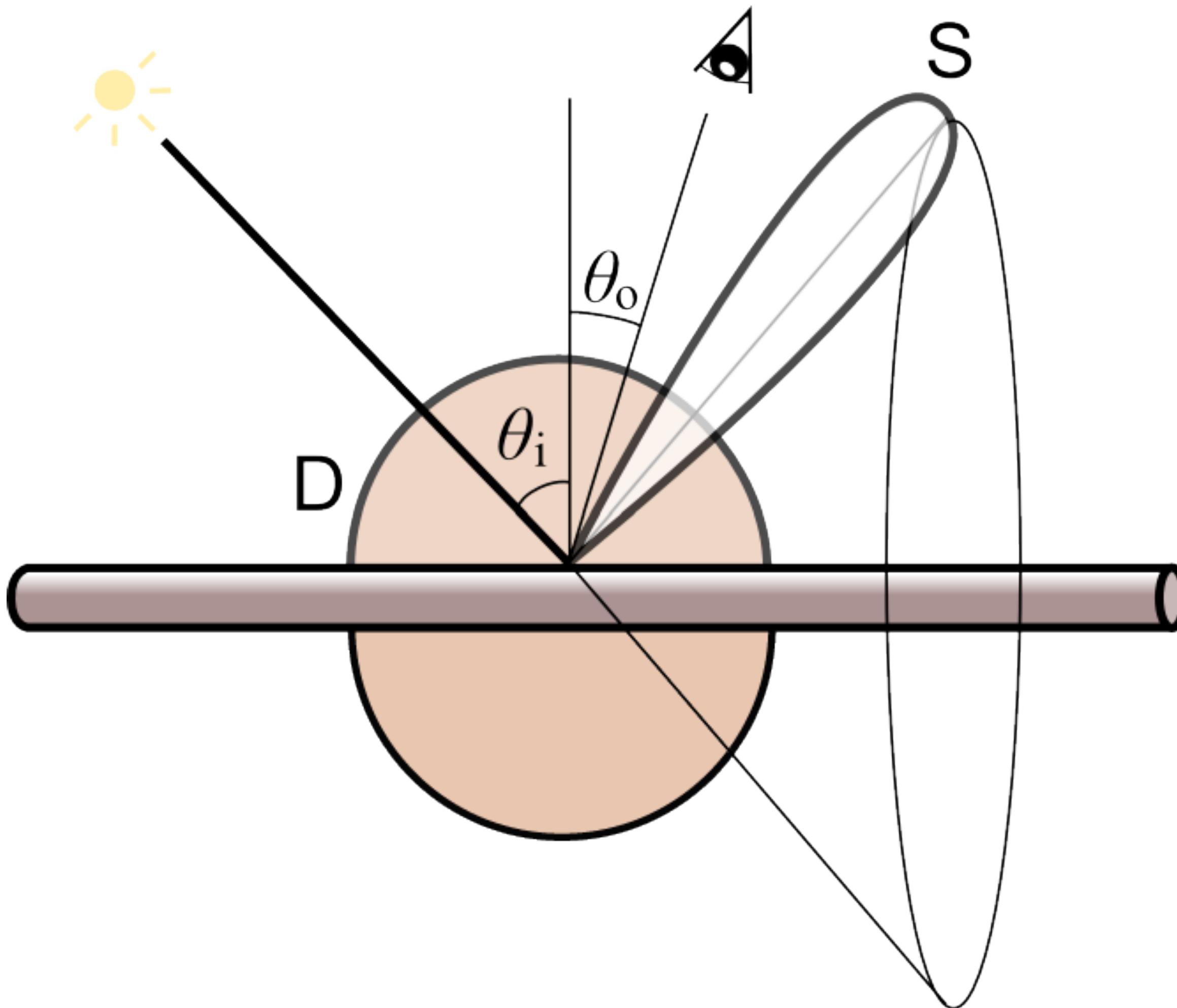


[Stomakhin et al. 2014]

Hair Appearance



Kajiya-Kay Model



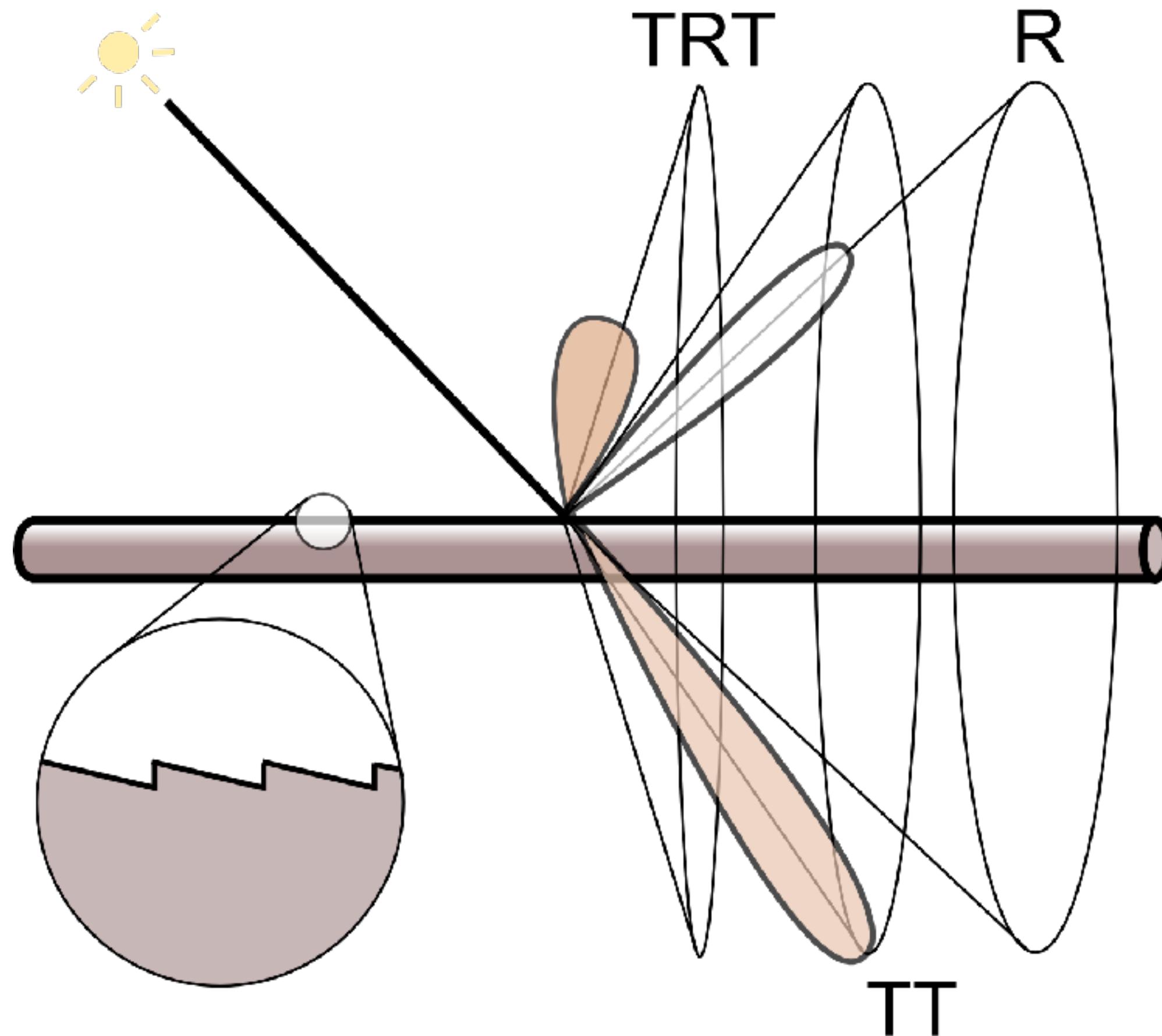
[Image courtesy of Chiwei Tseng]

Kajiya-Kay Model



[Yuksel et al. 2008]

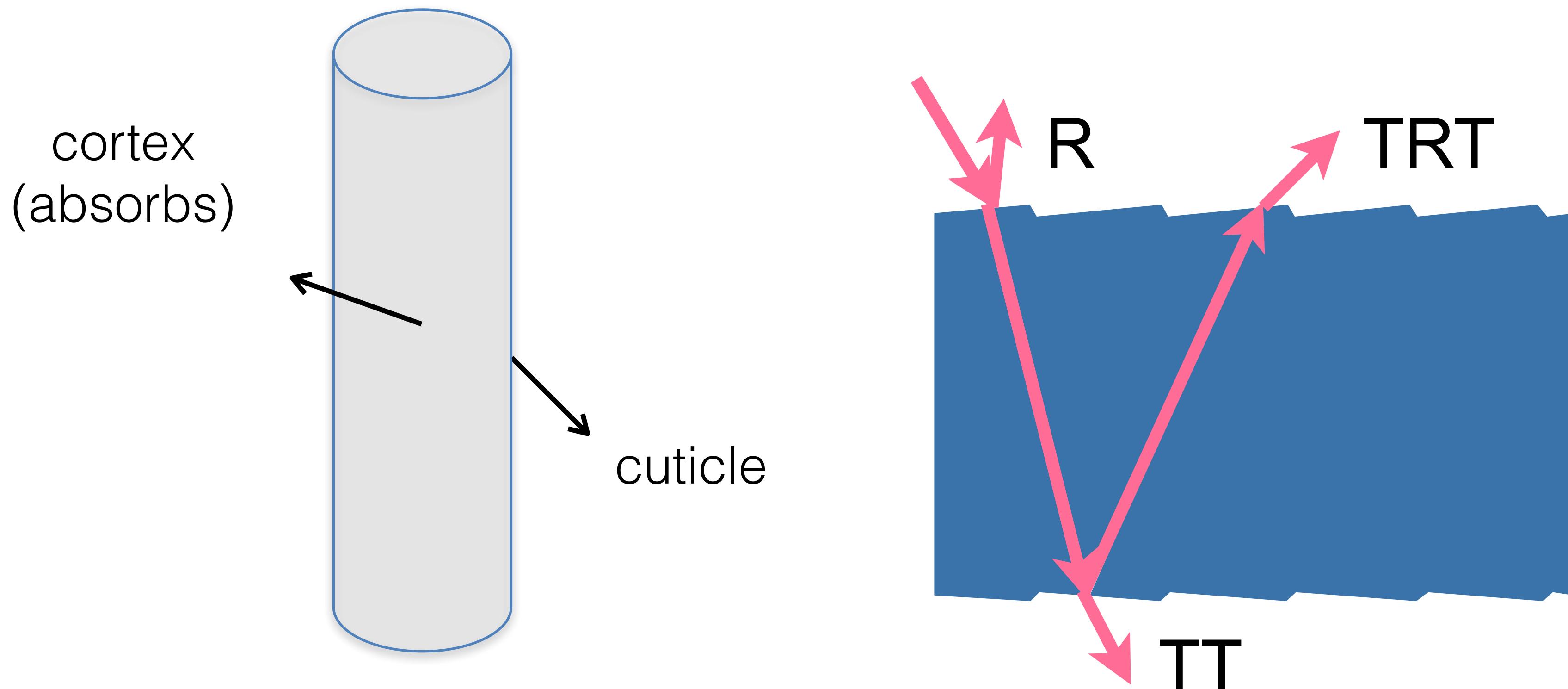
Marschner Model



[Image courtesy of Chiwei Tseng]

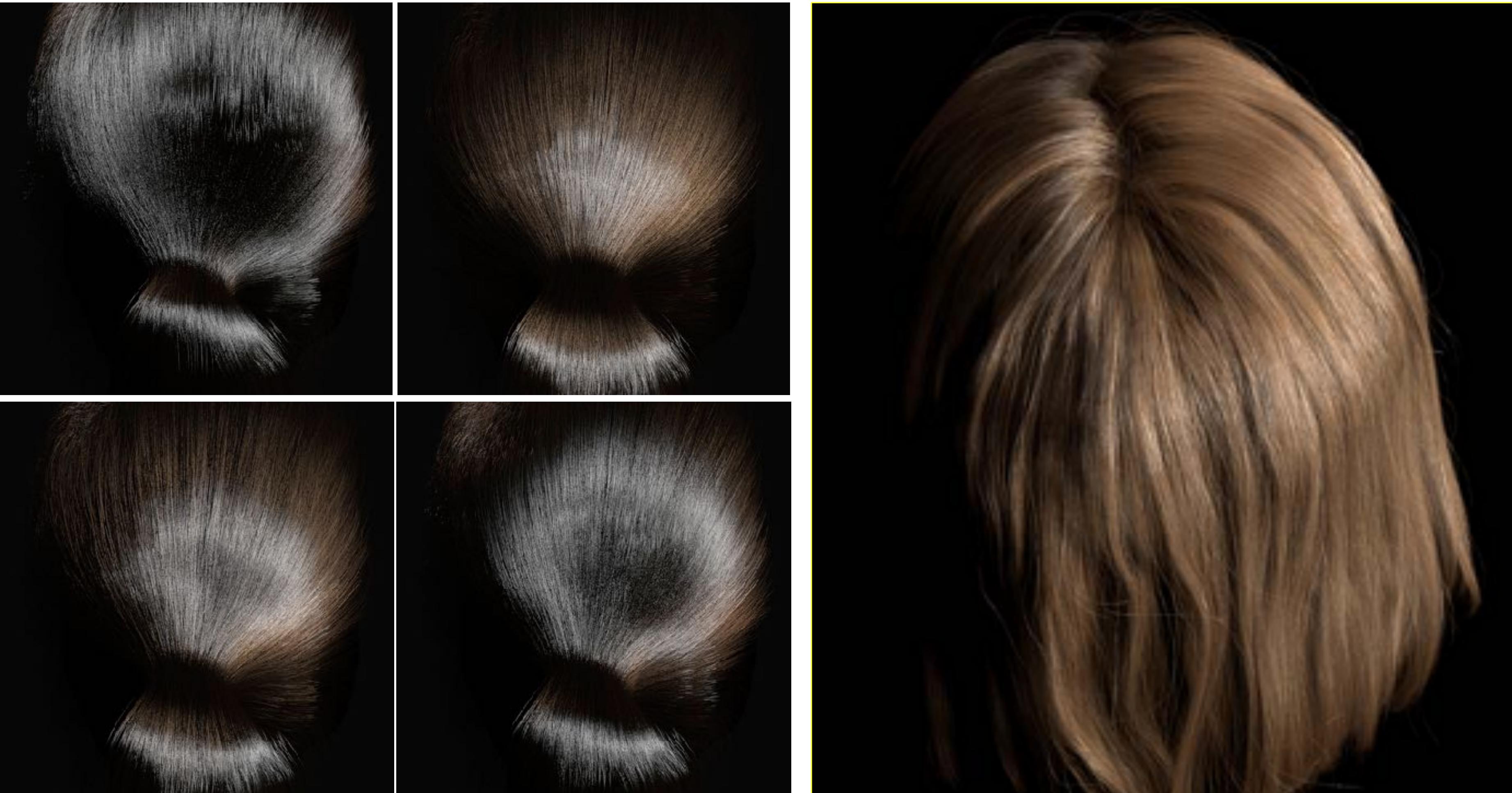
Marschner Model

- Glass-like cylinder
- 3 types of light interactions:
R, TT, TRT
(R: reflection, T: transmission)



[Marschner et al. 2003]

Marschner model



[Marschner et al. 2003]

[d'Eon et al. 2011]

Hair Appearance Model: Application



[Final Fantasy XV. 2016 Square Enix]

RajmanGamingHD

Hair Appearance Model: Application



[Zootopia. 2016 Disney]

Fur Appearance — As Human Hair

- Cannot represent diffusive and saturated appearance

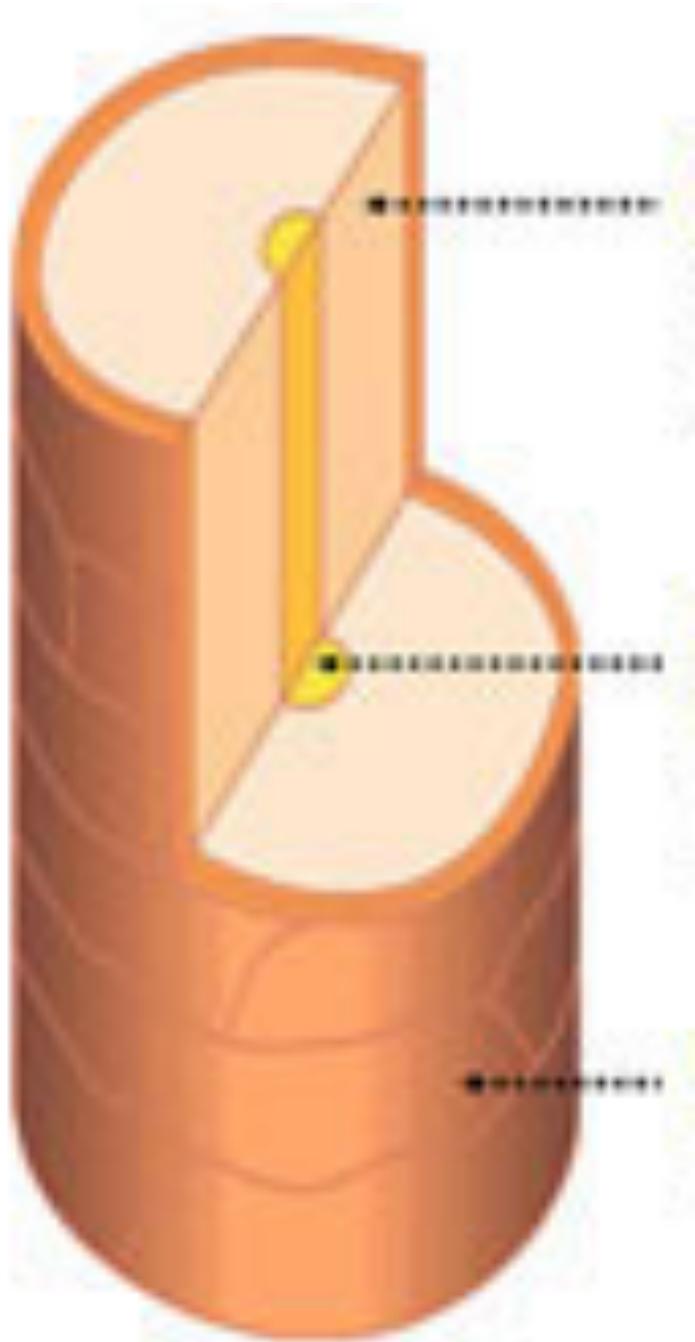


Rendered as human hair
[Marschner et al. 2003]



Rendered as animal fur
[Yan et al. 2015]

Human Hair vs Animal Fur



Cortex

- Contains pigments
- **Absorbs light**

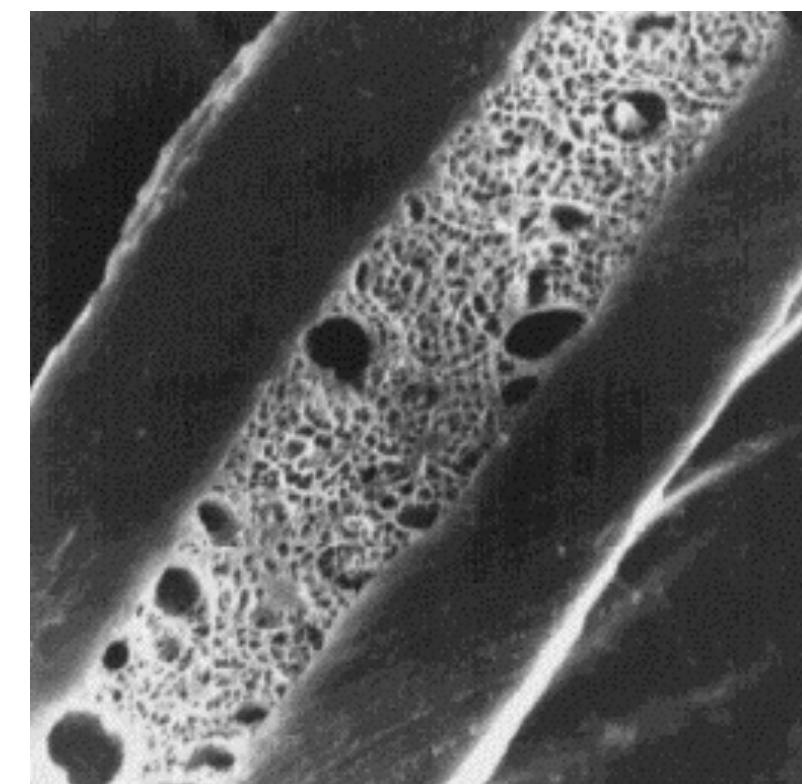
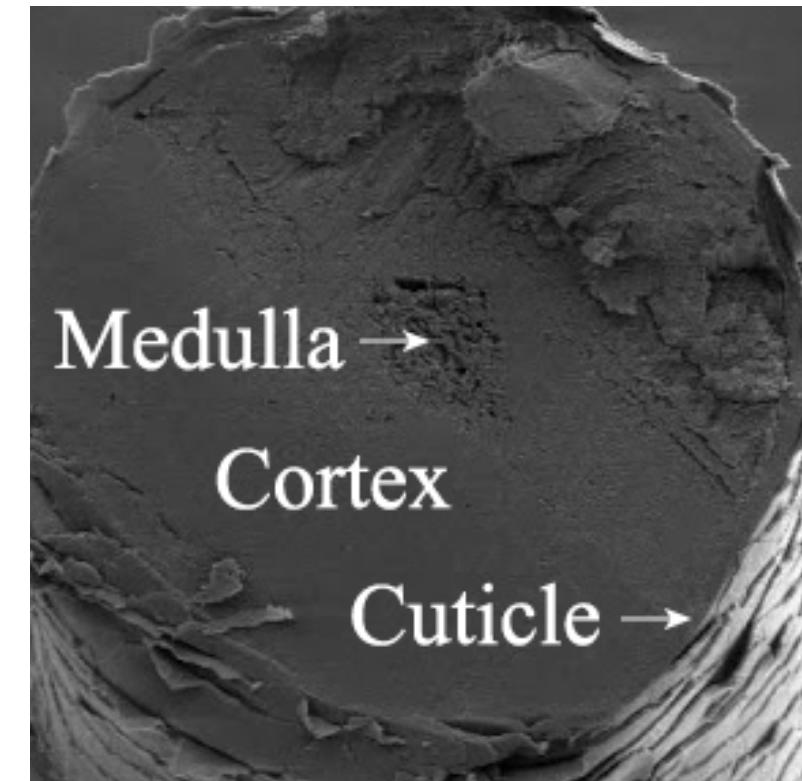
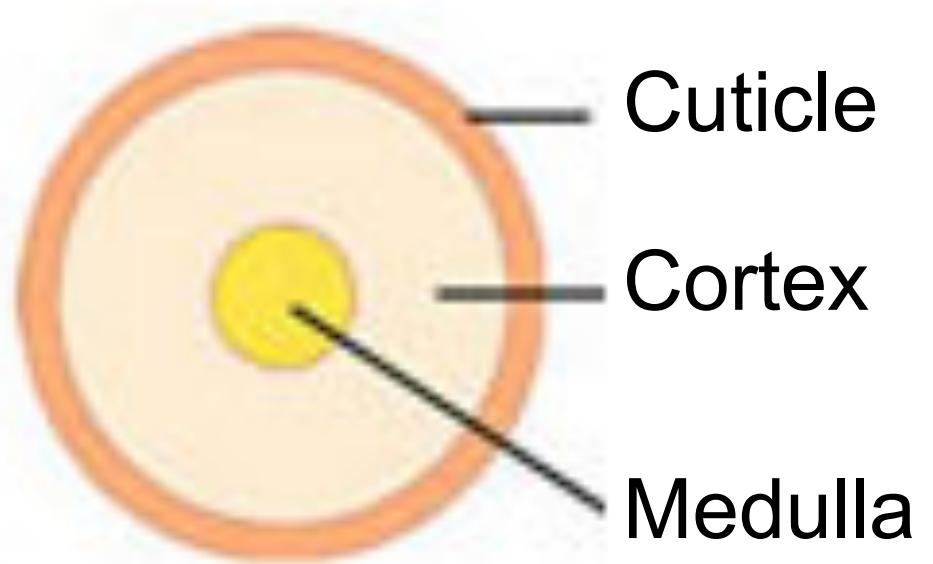
Medulla

- Complex structure
- **Scatters light**

Cuticle

- Covered with scales

Common for
hair/fur fibers



Human
Cougar

Difference between
hair/fur fibers

Importance of Medulla



Increasing medulla size

Importance of Medulla

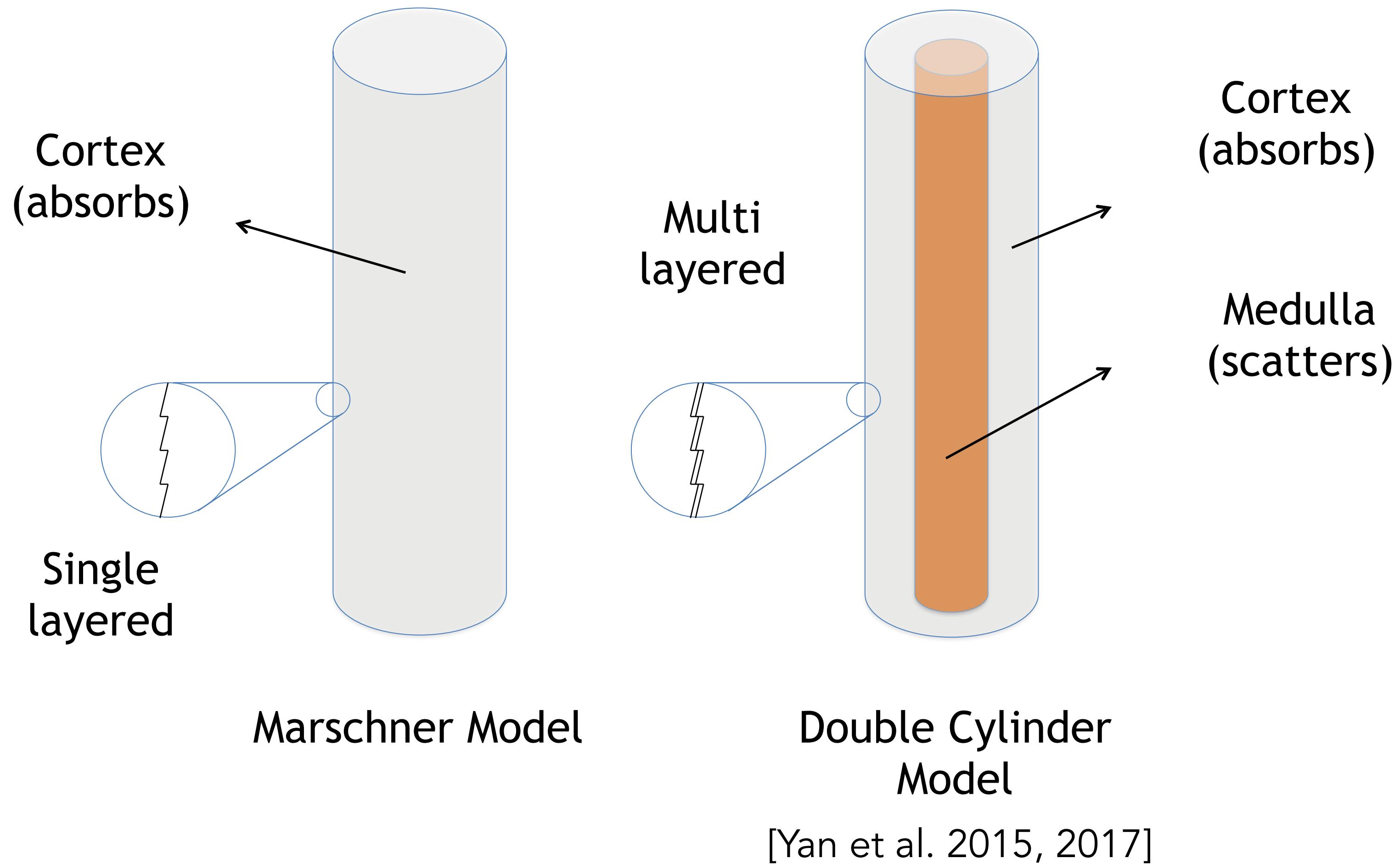


Without medulla

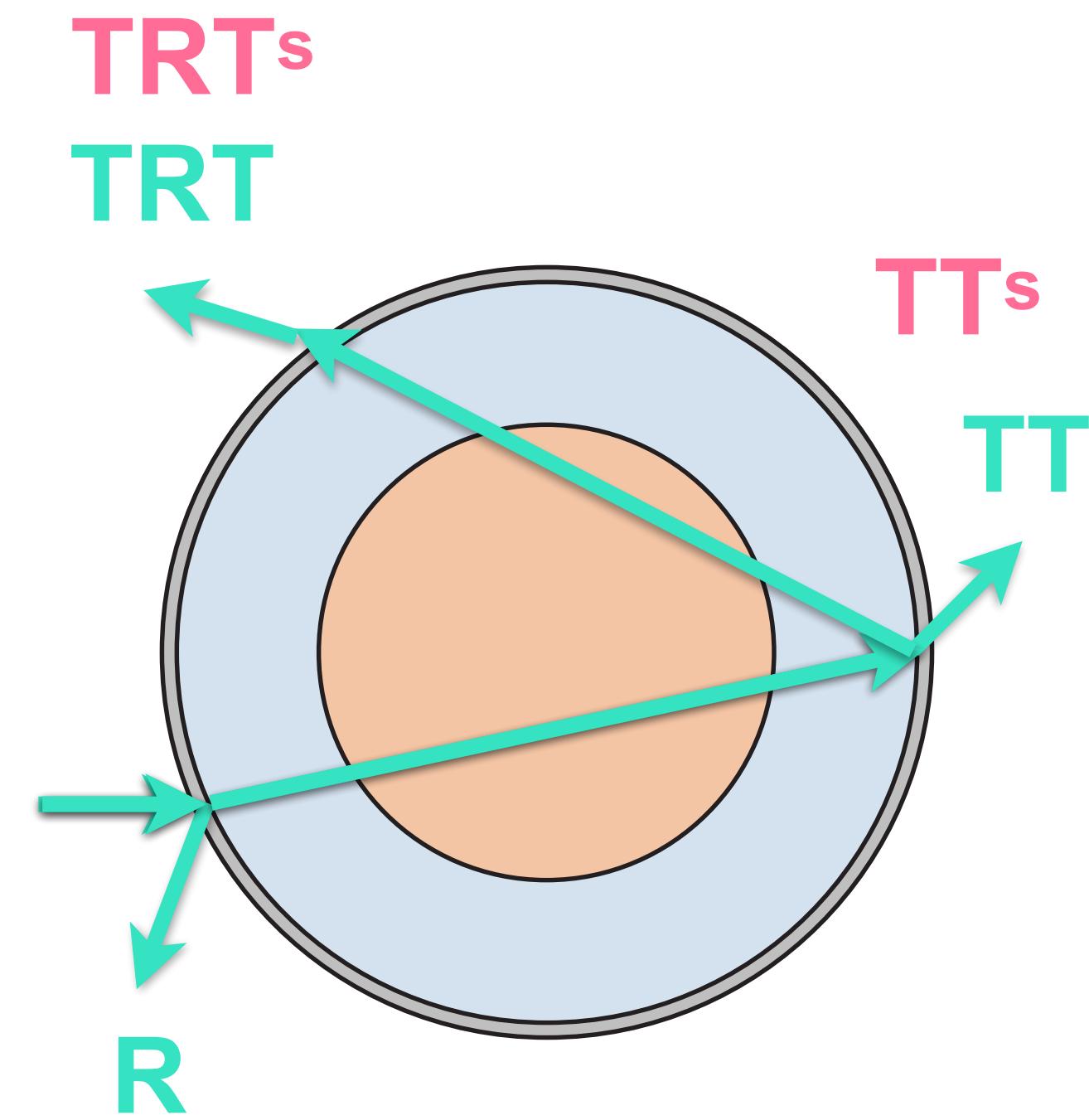
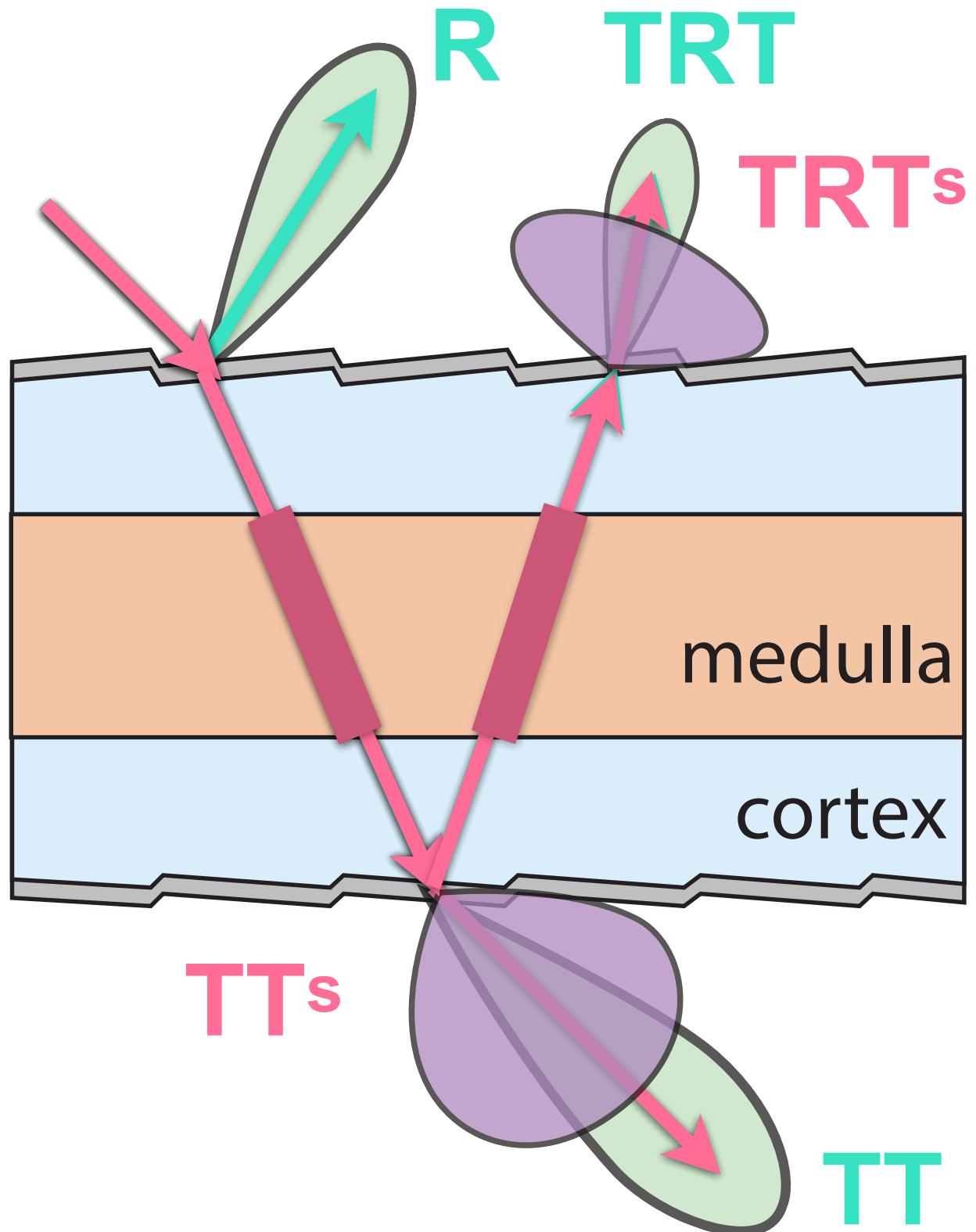


With medulla (**15%**)

Double Cylinder Model



Double Cylinder Model — Lobes



Double Cylinder Model — Lobes



All

R

TT

TRT

TTs

TRTs

600,000 fur fibers

1024 samples / pixel

36.9 min / frame



Hamster

Double Cylinder Model: Application



[War for the Planet of the Apes. 2017 movie] (2018 Oscar Nominee for Best Visual Effects)

Double Cylinder Model: Application



[The Lion King (HD). 2017 movie] ([2019 Oscar Nominee for Best Visual Effects](#))

Granular Material

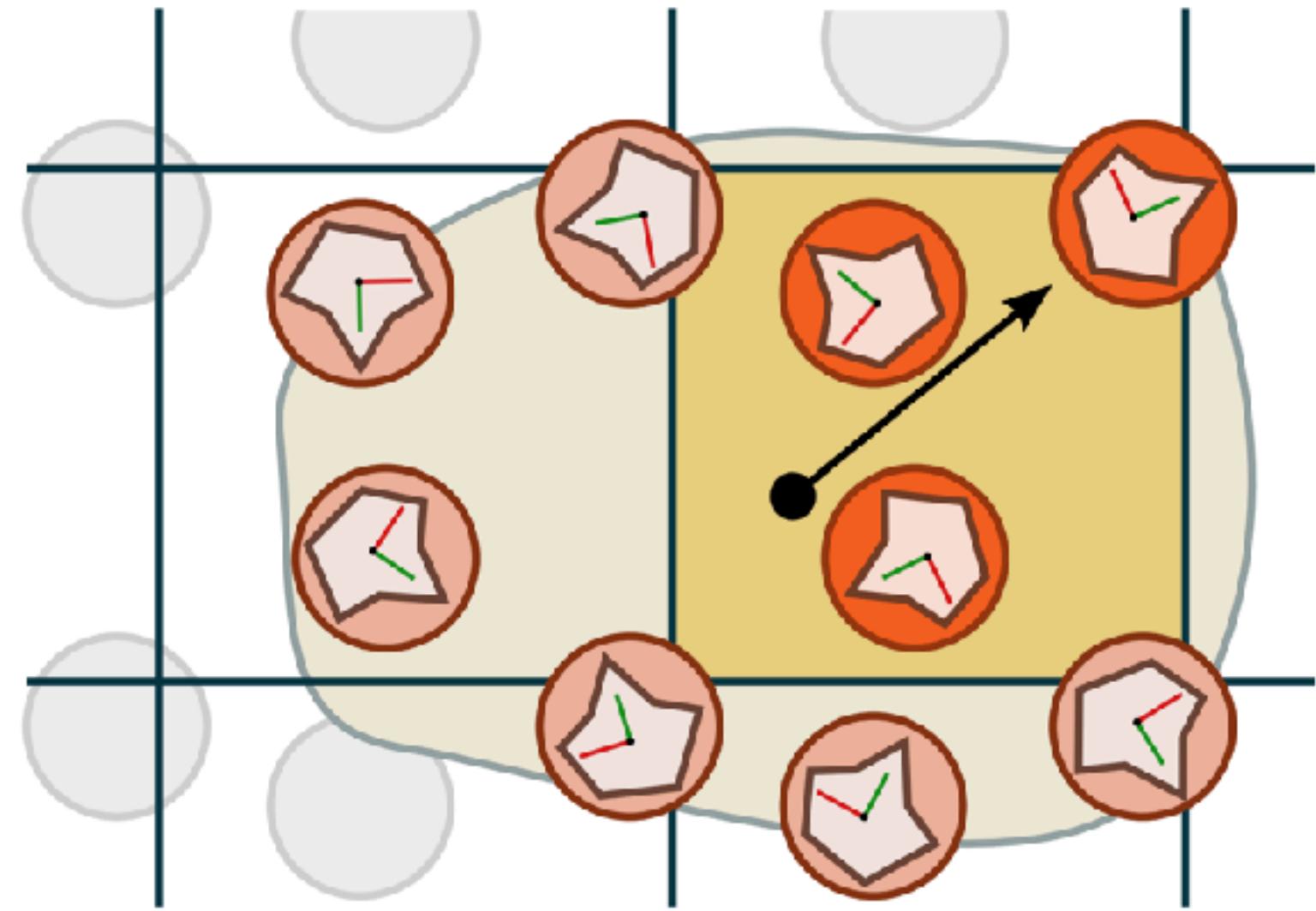
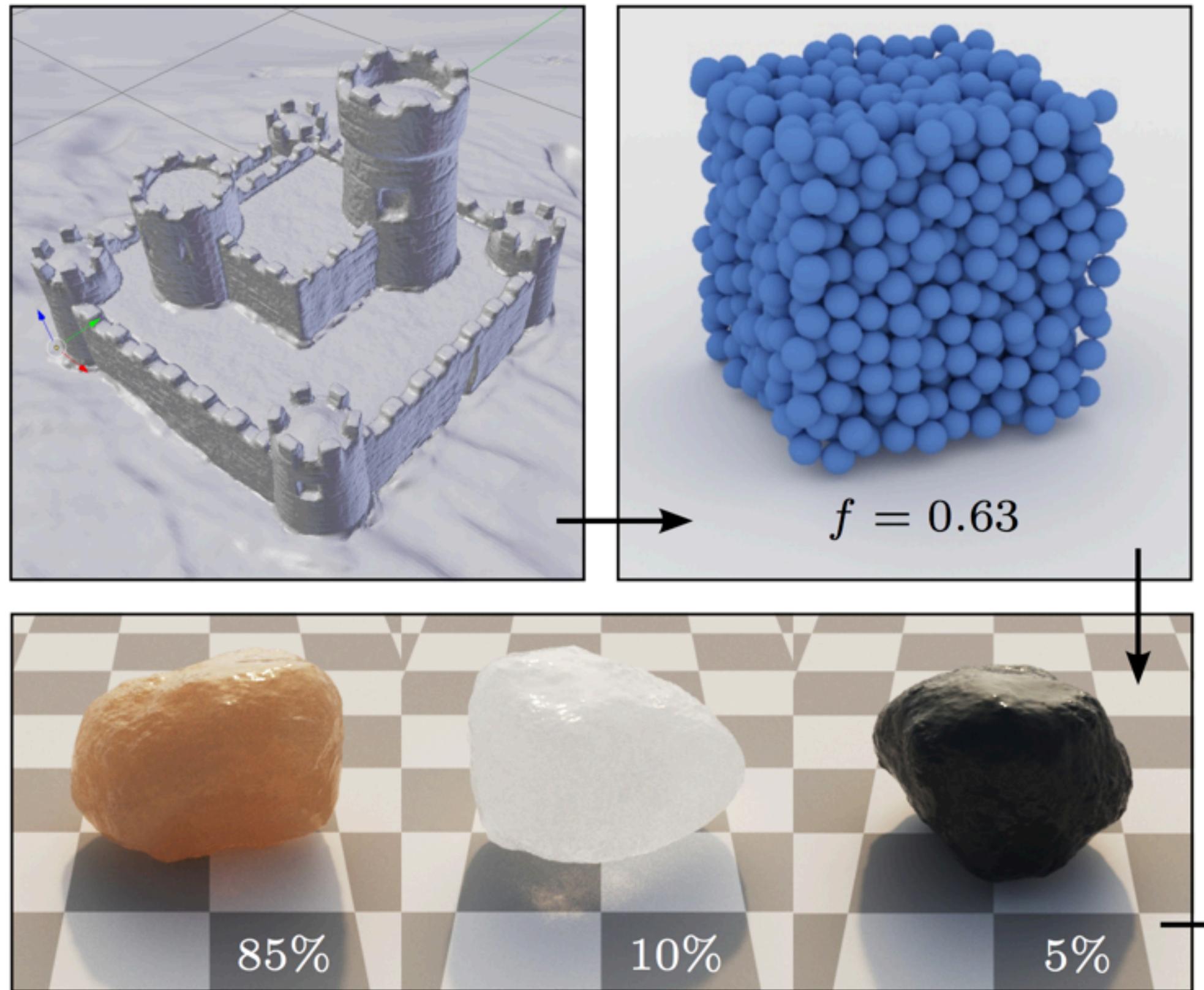
- What is granular material?



[Meng et al. 2015]

Granular Material

- Can we avoid explicit modeling of all granules?
 - Yes with **procedural** definition.



[Meng et al. 2015]

Granular Material



© Disney

[Meng et al. 2015]

Granular Material: Application



[Piper. 2016 Pixar]

Surface Models

Translucent Material: Jade



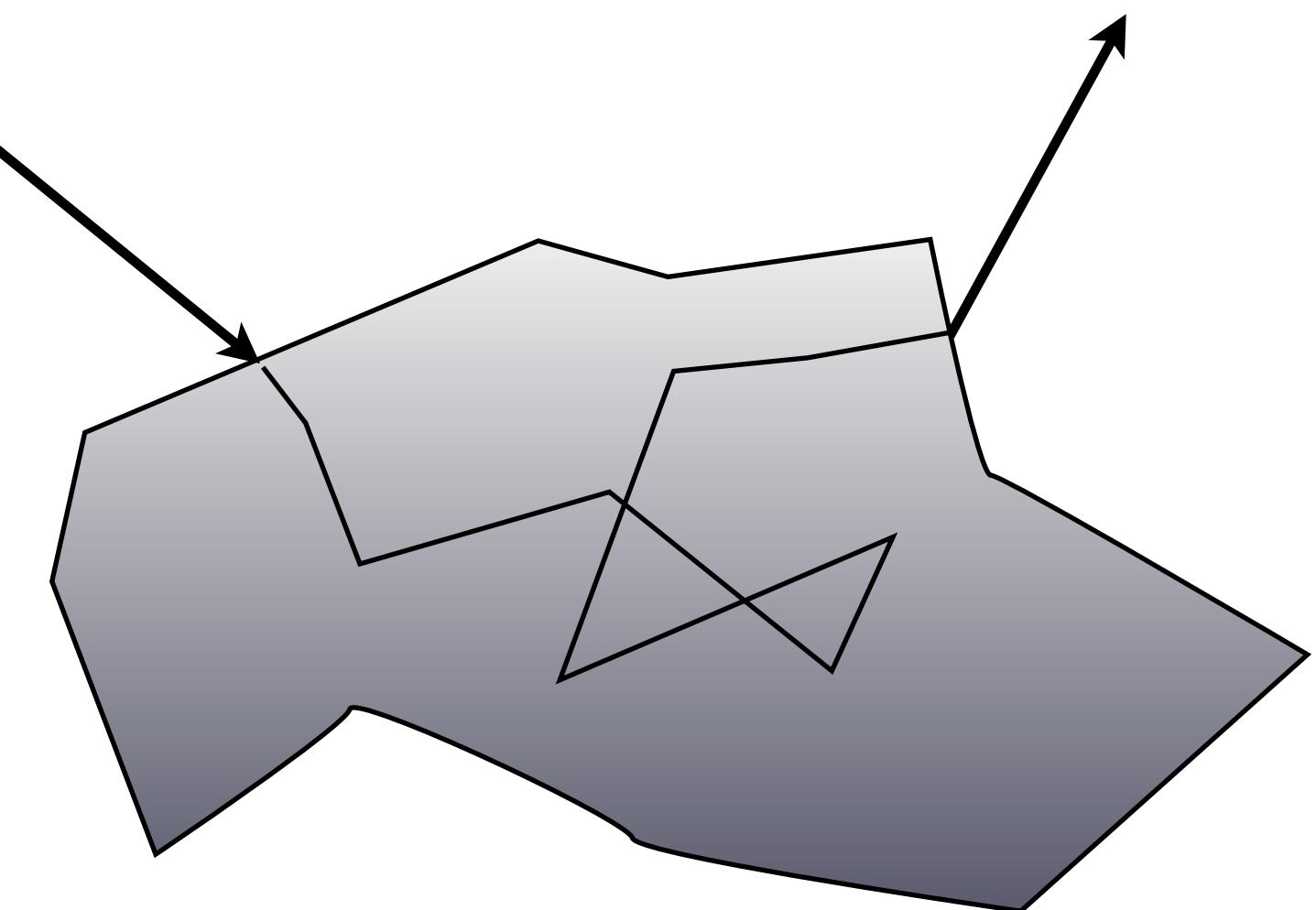
Translucent Material: Jellyfish



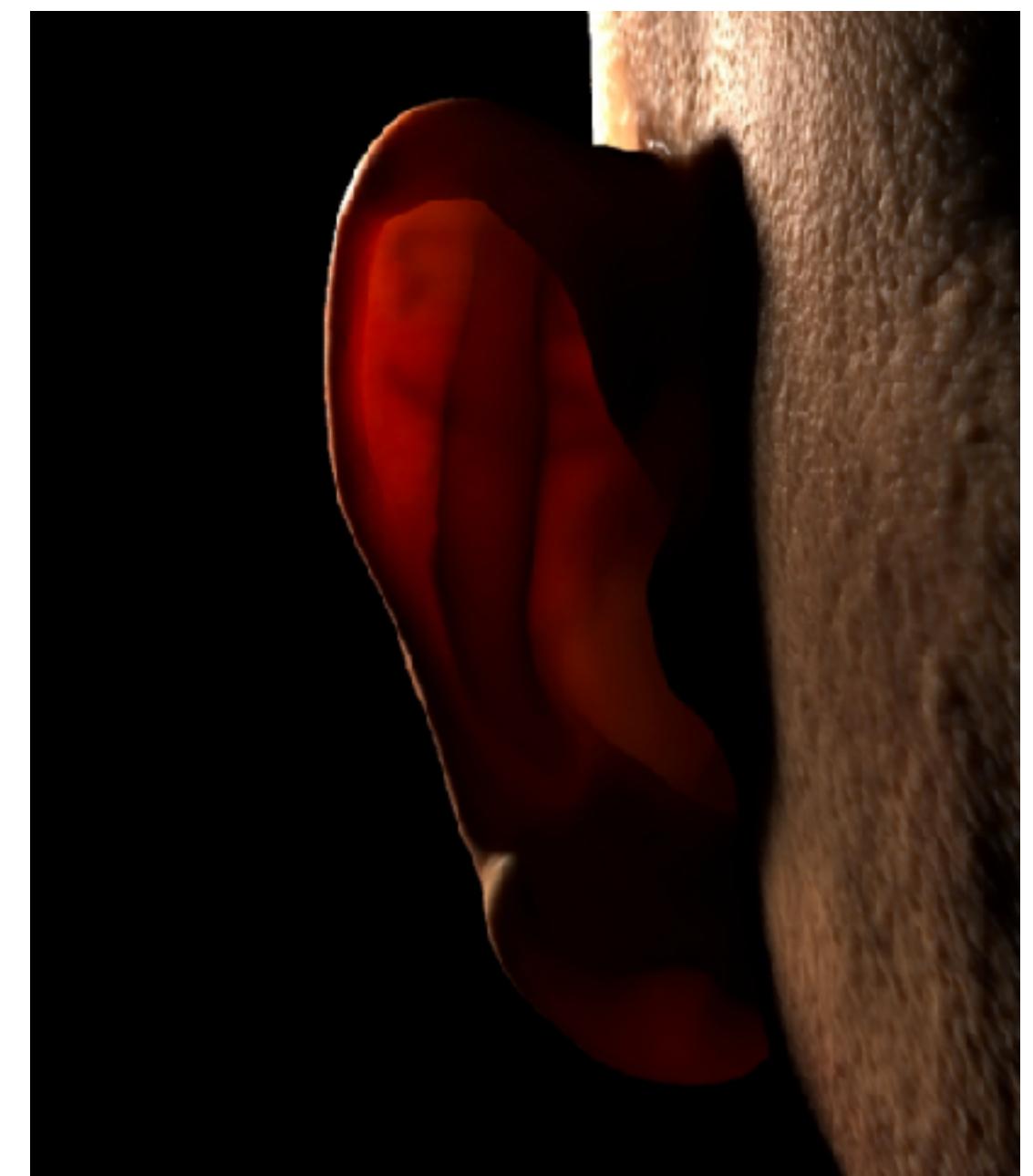
Subsurface Scattering

Visual characteristics of many surfaces caused by light exiting at different points than it enters

- Violates a fundamental assumption of the BRDF



[Jensen et al 2001]



[Donner et al 2008]

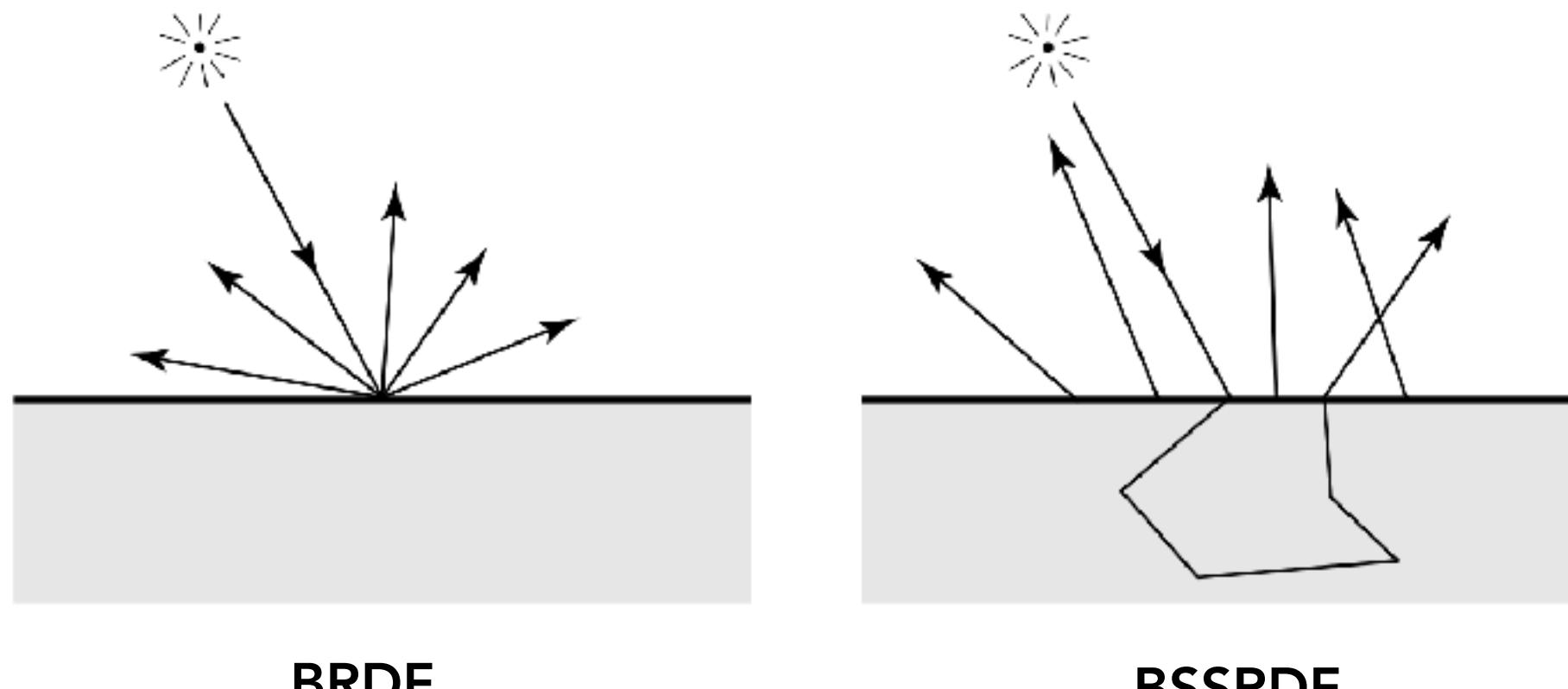
Scattering Functions

- BSSRDF: generalization of BRDF; exitant radiance at one point due to incident differential irradiance at another point:

$$S(x_i, \omega_i, x_o, \omega_o)$$

- Generalization of rendering equation: integrating over all points on the surface and all directions (!)

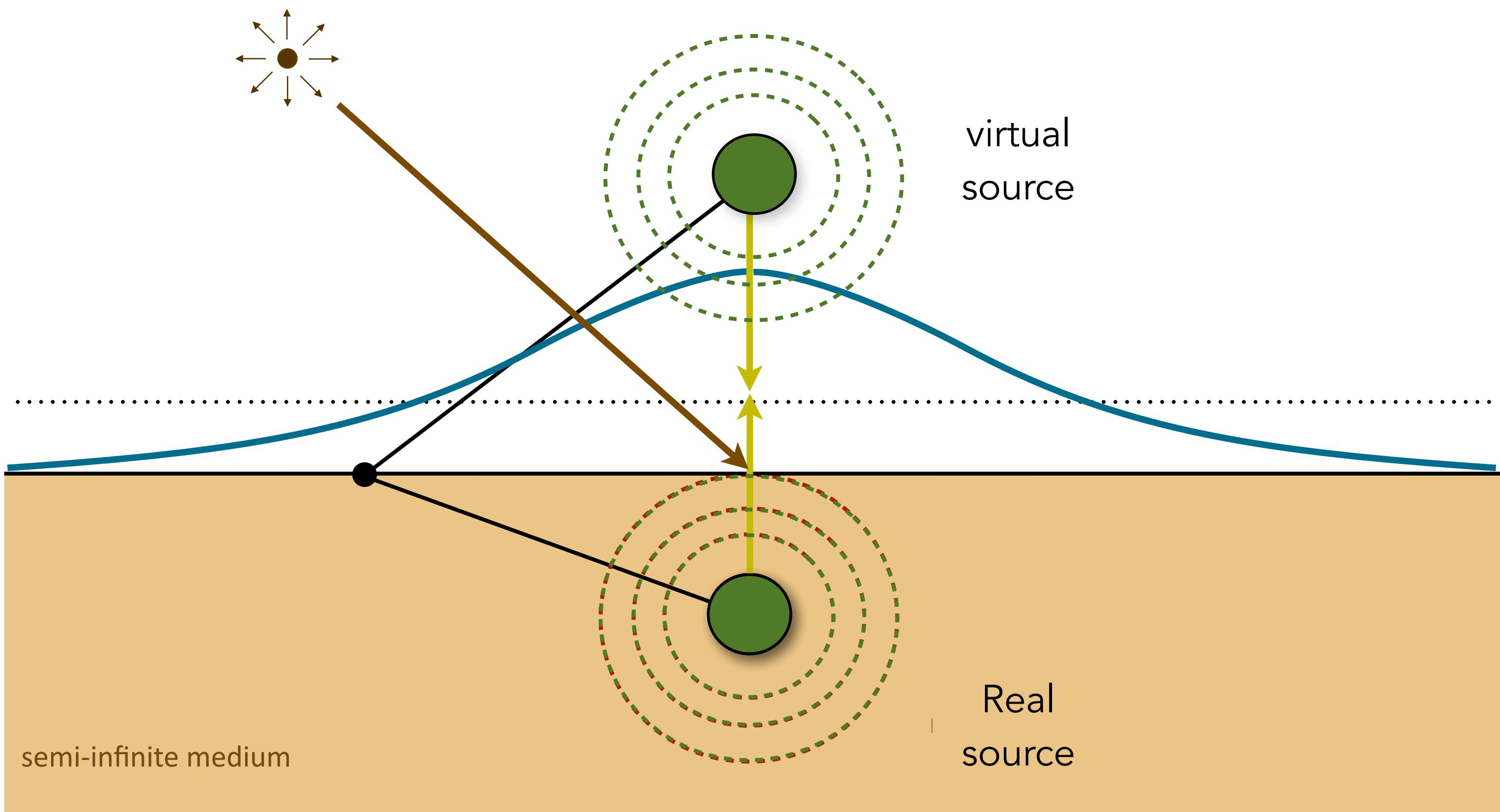
$$L(x_o, \omega_o) = \int_A \int_{H^2} S(x_i, \omega_i, x_o, \omega_o) L_i(x_i, \omega_i) \cos \theta_i d\omega_i dA$$



[Jensen et al. 2001]

Dipole Approximation [Jensen et al. 2001]

- Approximate light diffusion by introducing two point sources.



[image from Habel et al. 2013]

BRDF



[Jensen et al. 2001]

BSSRDF



[Jensen et al. 2001]

BRDF vs BSSRDF

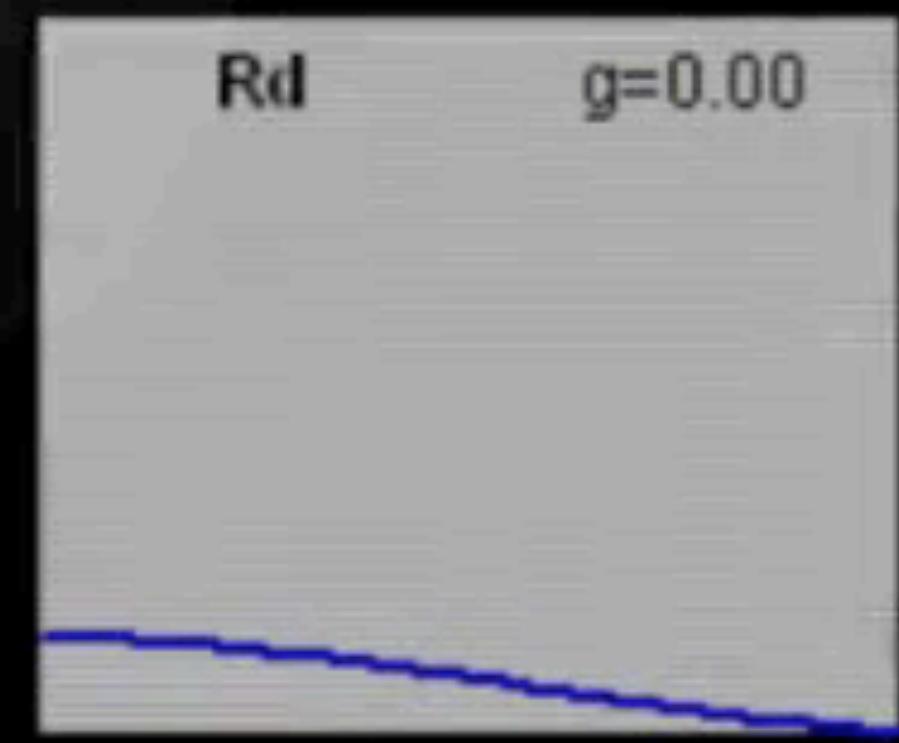


BRDF

BSSRDF

[Jensen et al. 2001]

BSSRDF: Demo



BSSRDF: Application



[Artist: Teruyuki and Yuka]



[Artist: Hyun Kyung]

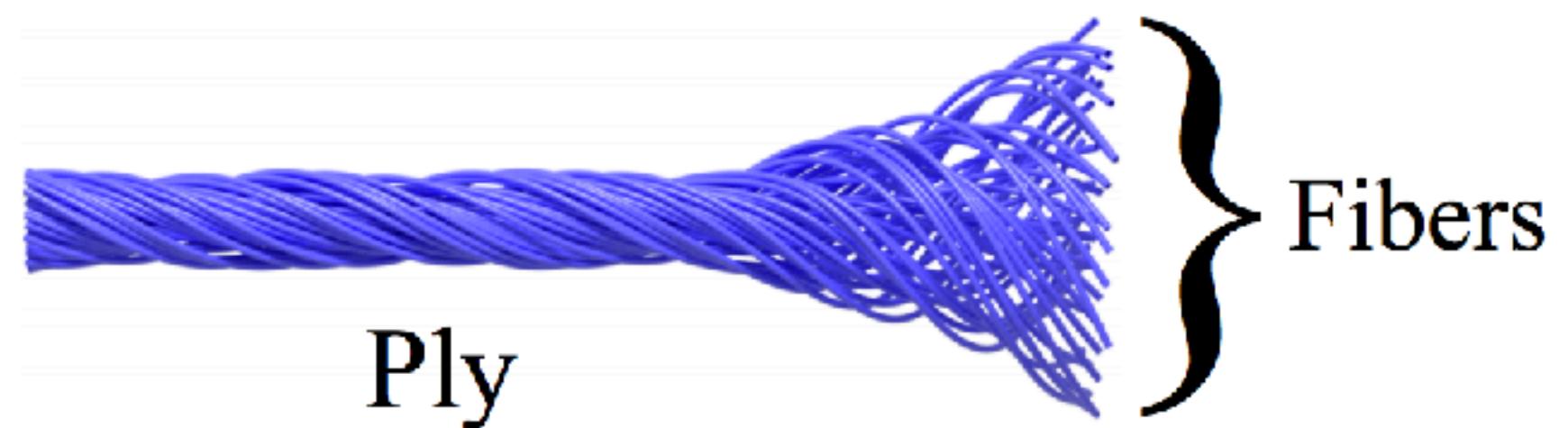
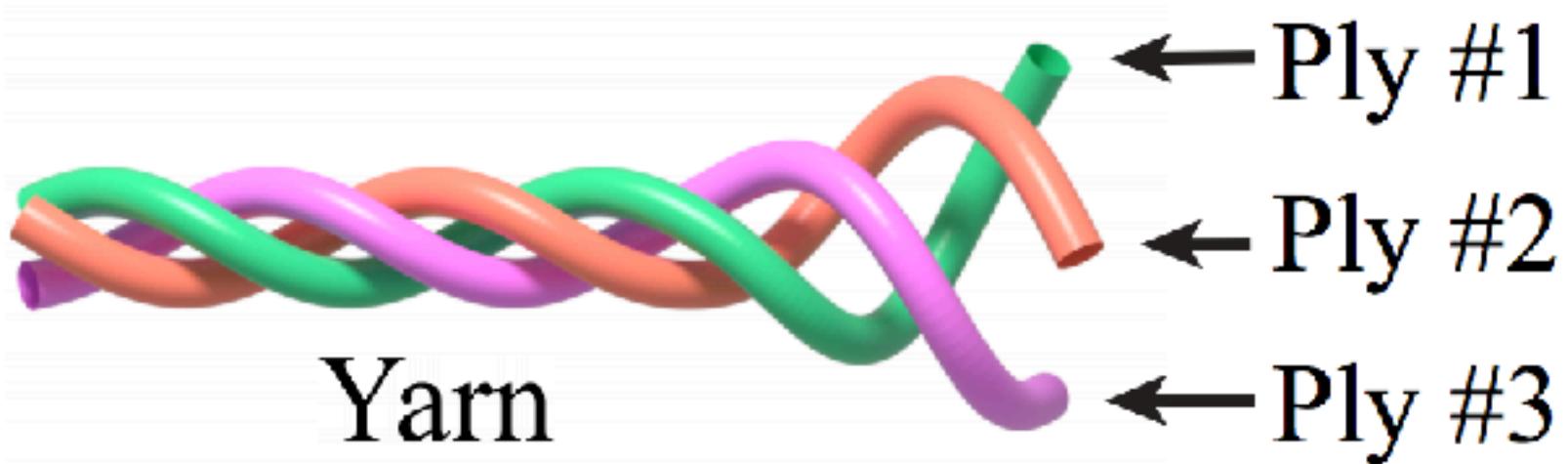


[Artist: Dan Roarty]

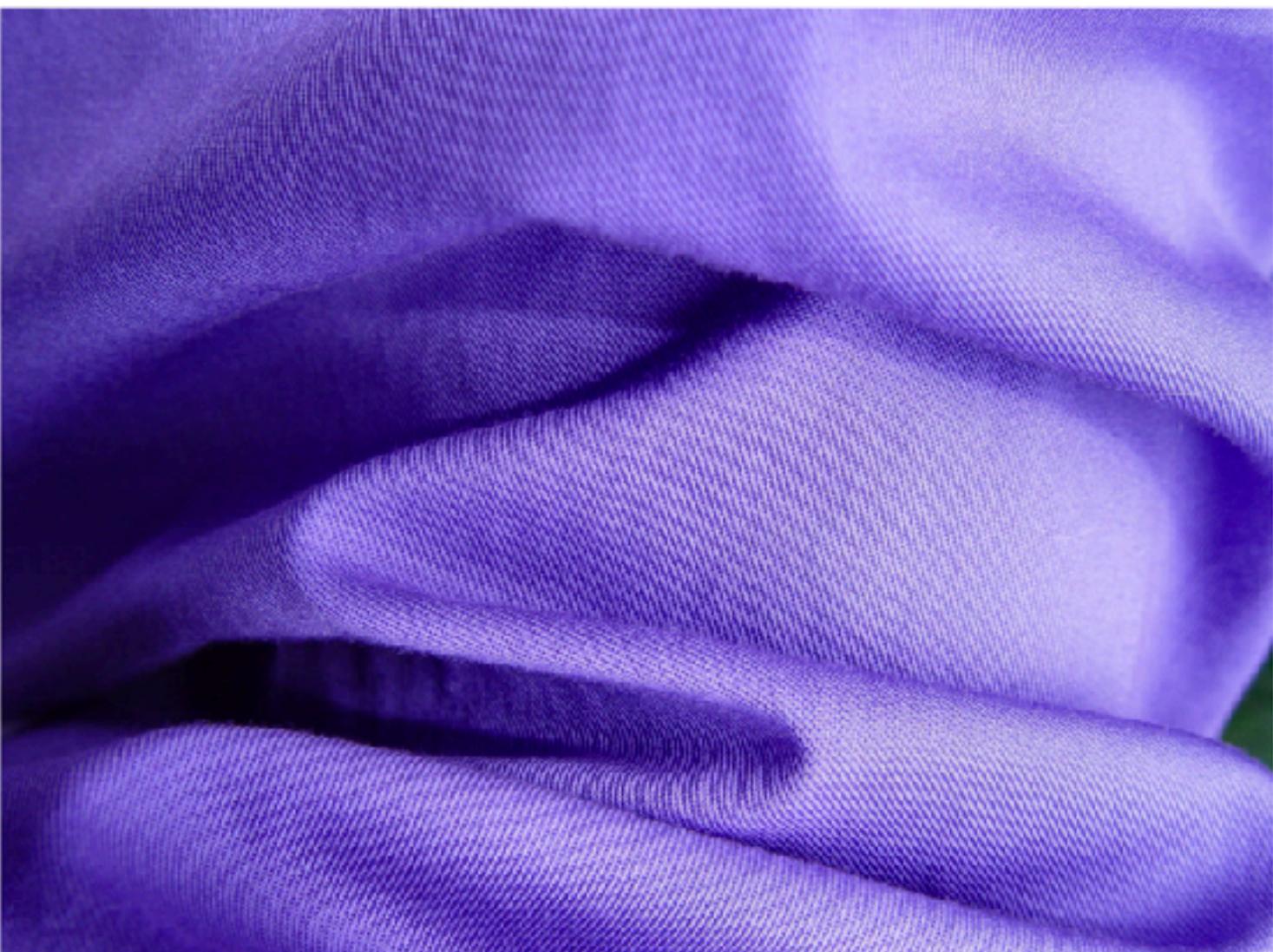
<https://cgelves.com/10-most-realistic-human-3d-models-that-will-wow-you/>

Cloth

- A collection of twisted fibers!
- Two levels of twist

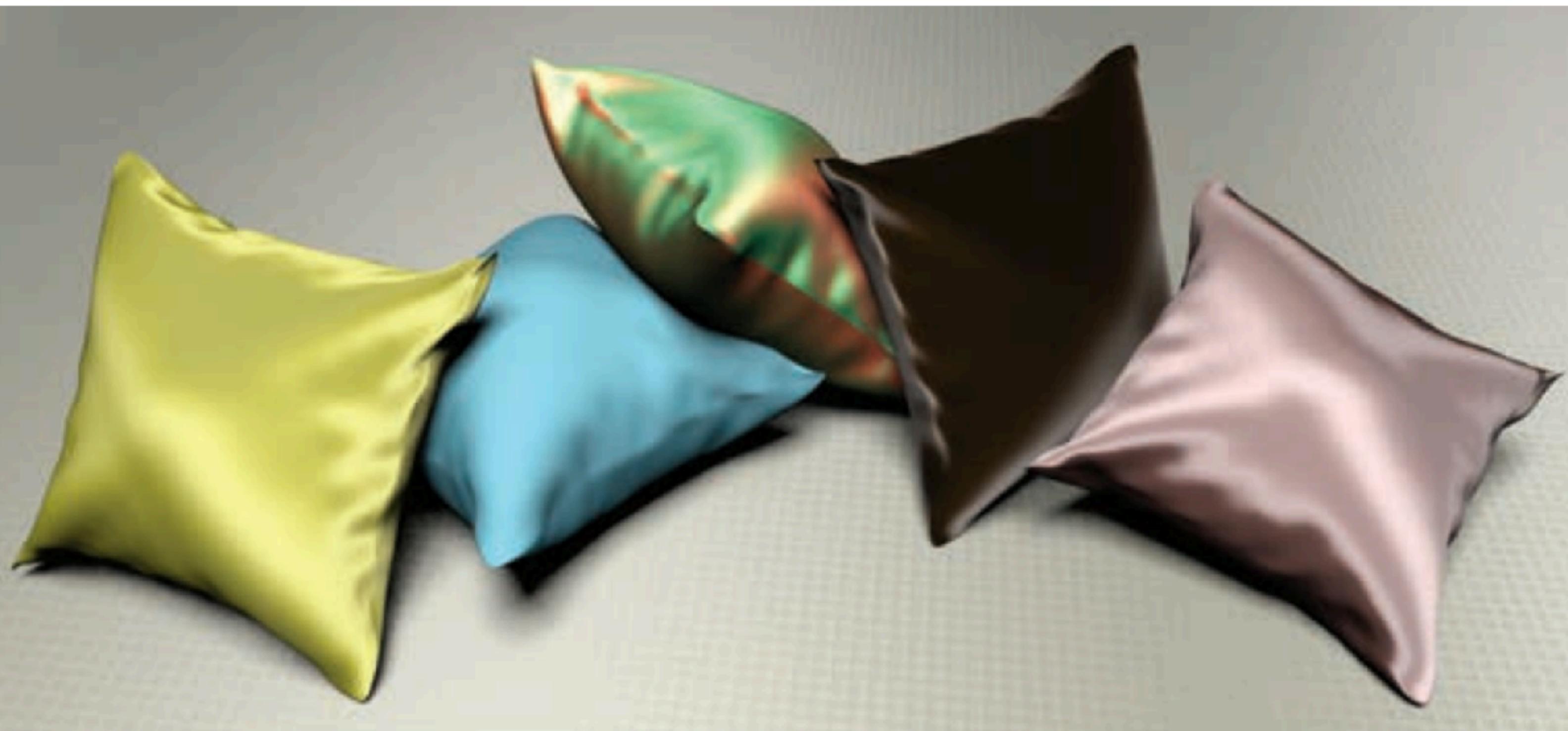
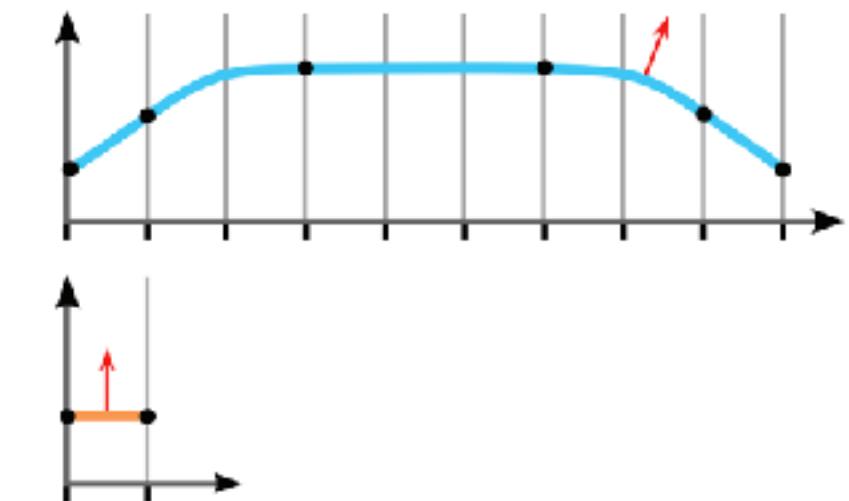
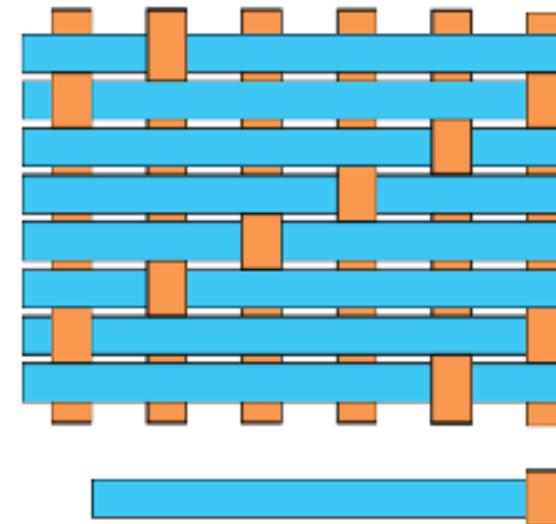


- Woven or knitted



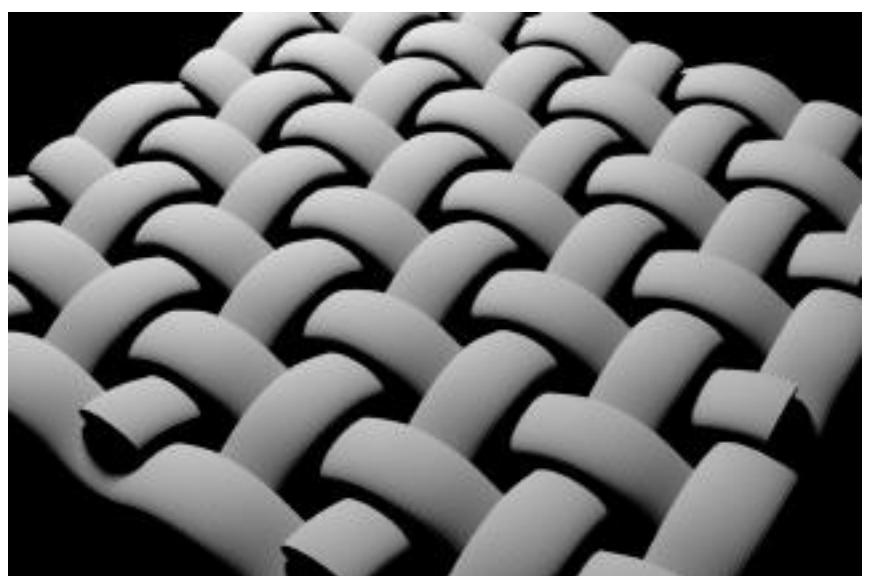
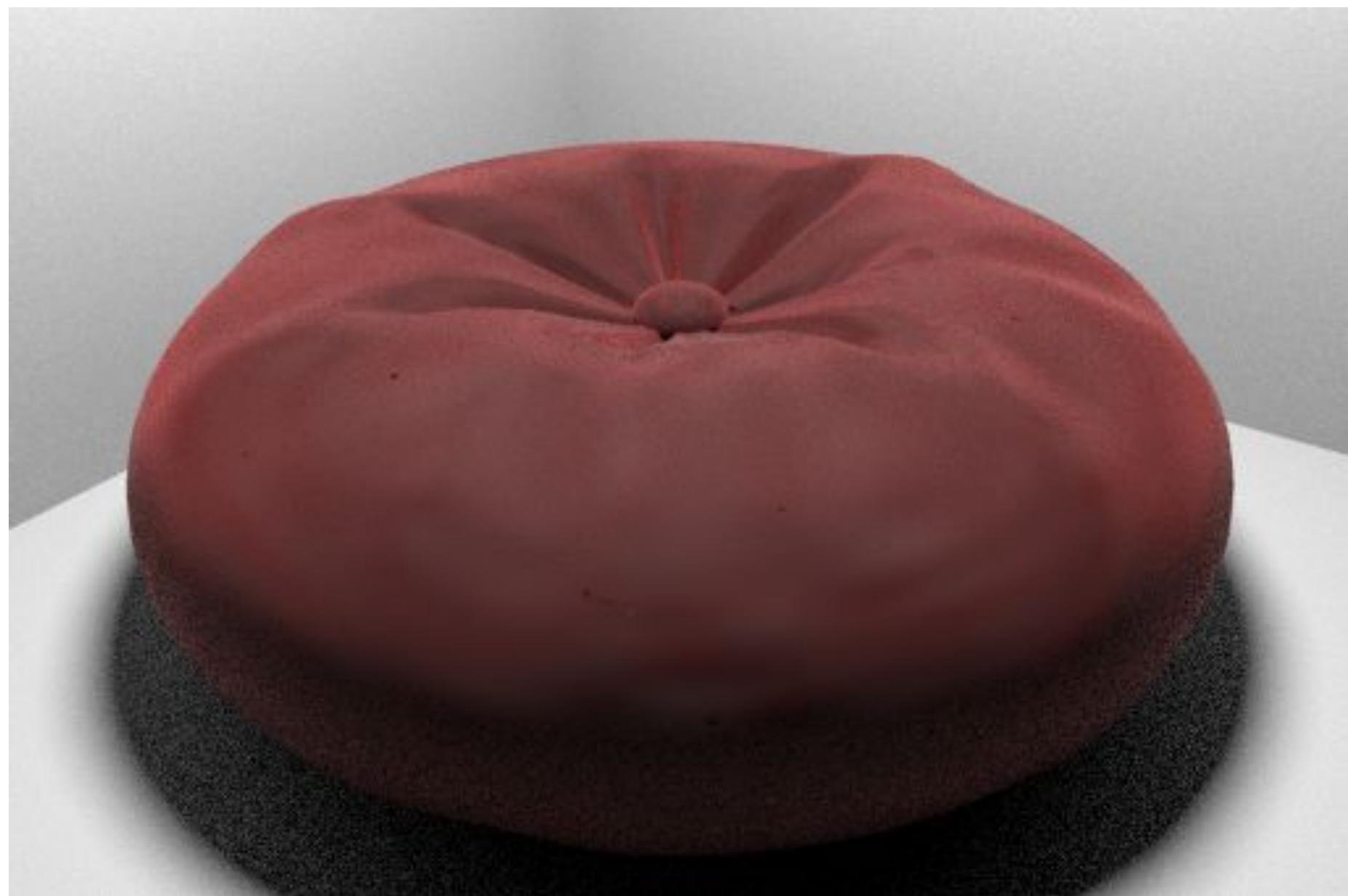
Cloth: Render as Surface

- Given the weaving pattern, calculate the overall behavior
- Render using a BRDF

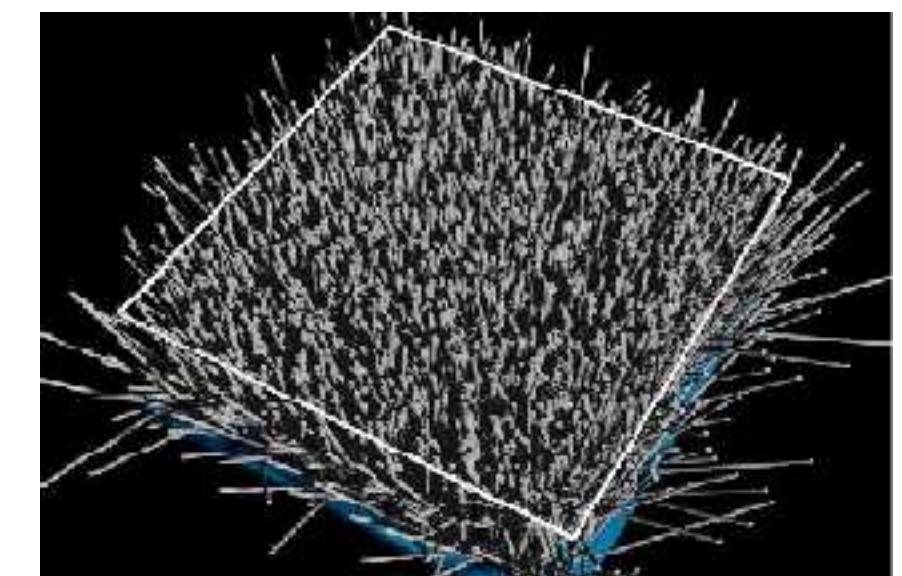
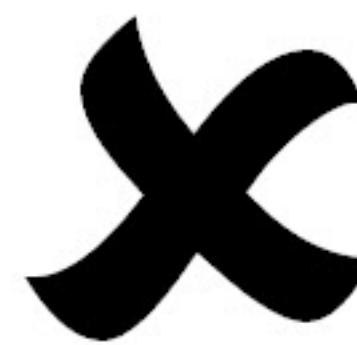


[Sadeghi et al. 2013]

Render as Surface — Limitation



[Westin et al. 1992]



Cloth: Render as Participating Media

- Properties of individual fibers & their distribution -> scattering parameters
- Render as a participating medium



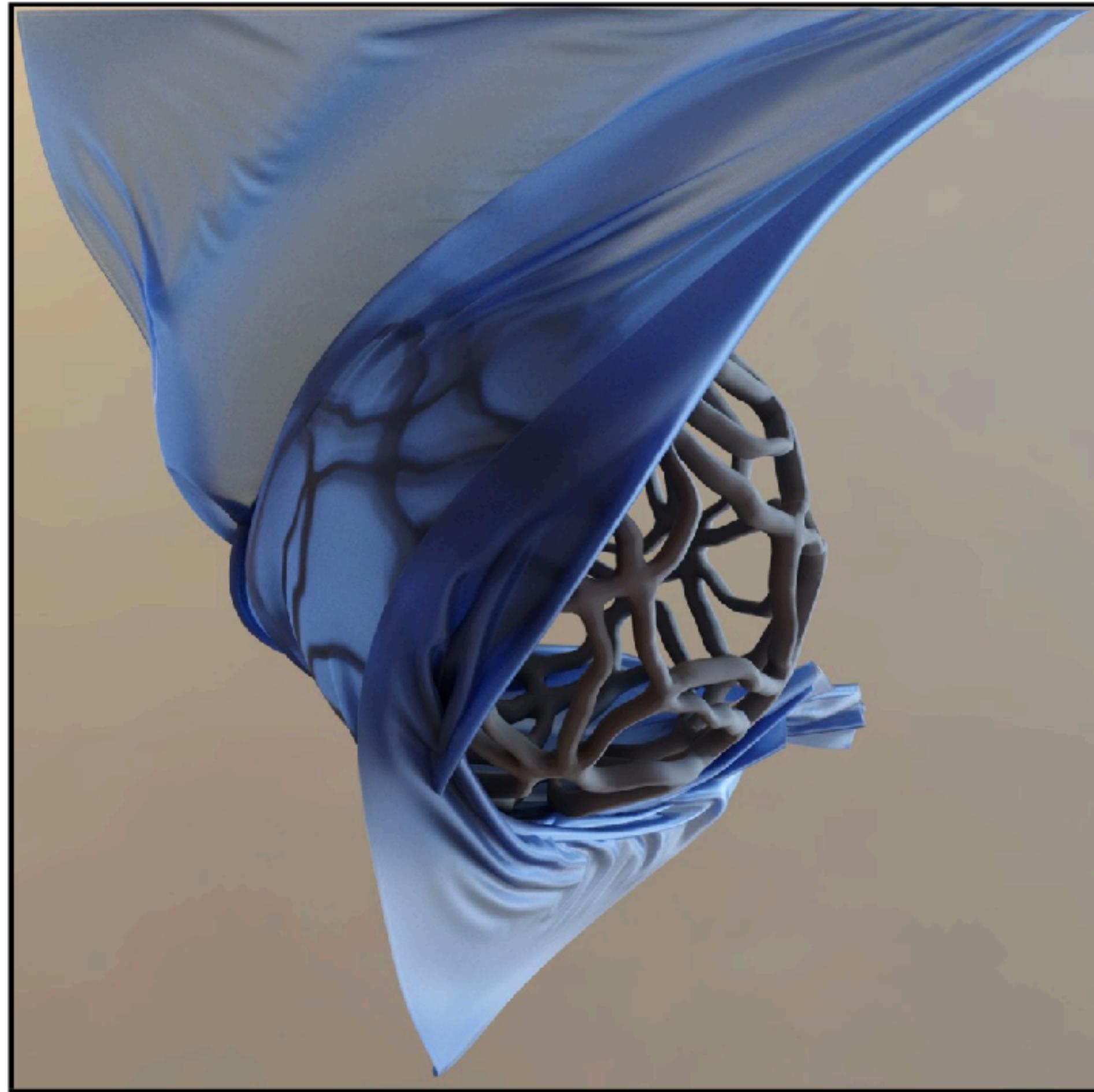
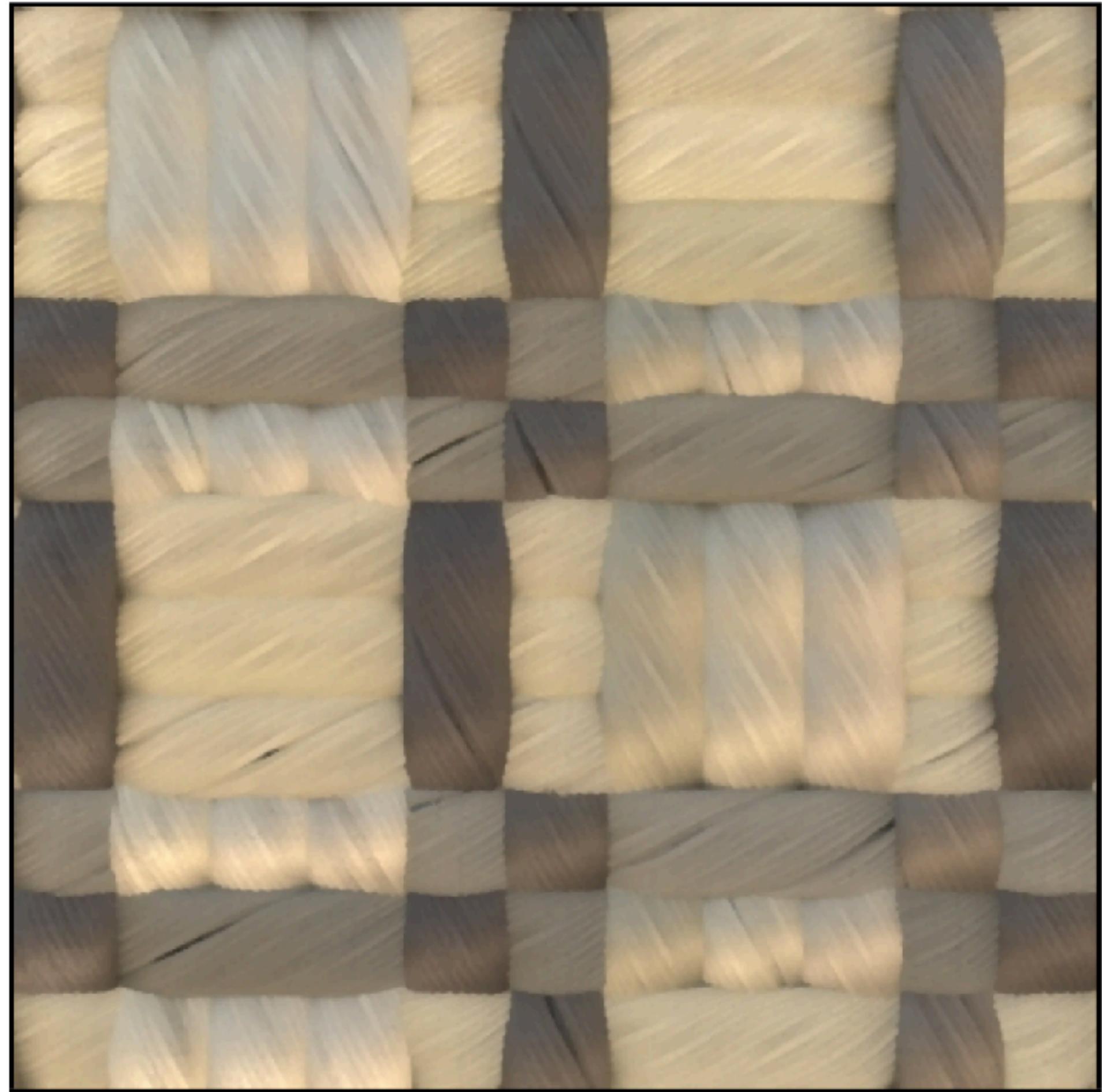
[Jakob et al. 2010]



[Schroder et al. 2011]

Cloth: Render as Actual Fibers

- Render every fiber explicitly!



[Kai Schroder]

Cloth: Demo



[Shuang et al. 2012]

Cloth: Application



[The BFG. 2016 Disney]

Detailed Appearance: Motivation

- Not looking realistic, why?



[Car rendered in NVIDIA Iray]



[Mouse rendered in Autodesk 3DS Max]

Real world is more complicated



[Real photograph of a car]



[Real video of a mouse]

Why details?

Microfacet
model



Why details?

[Yan et al.
2014, 2016]

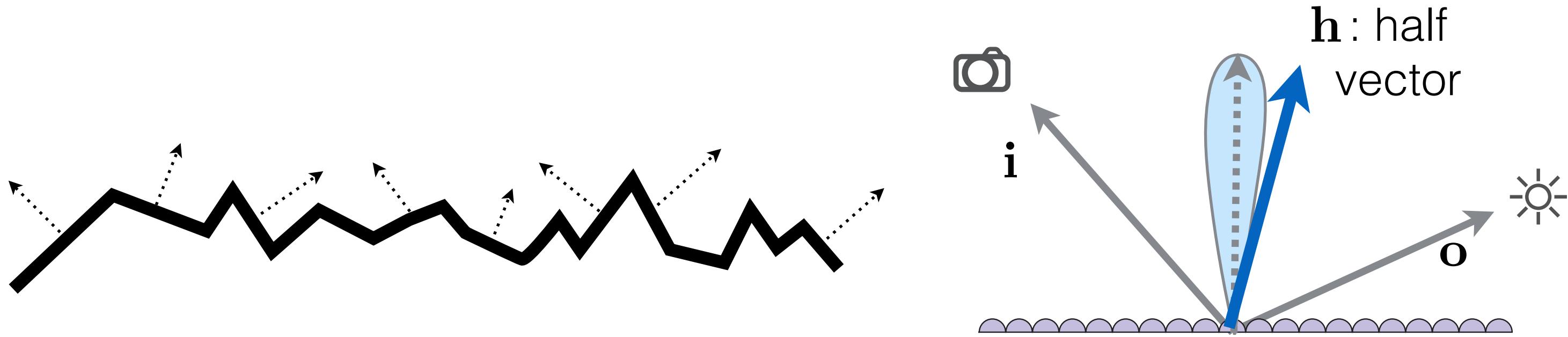


Why details?

[Yan et al.
2014, 2016]



Recap: Microfacet BRDF



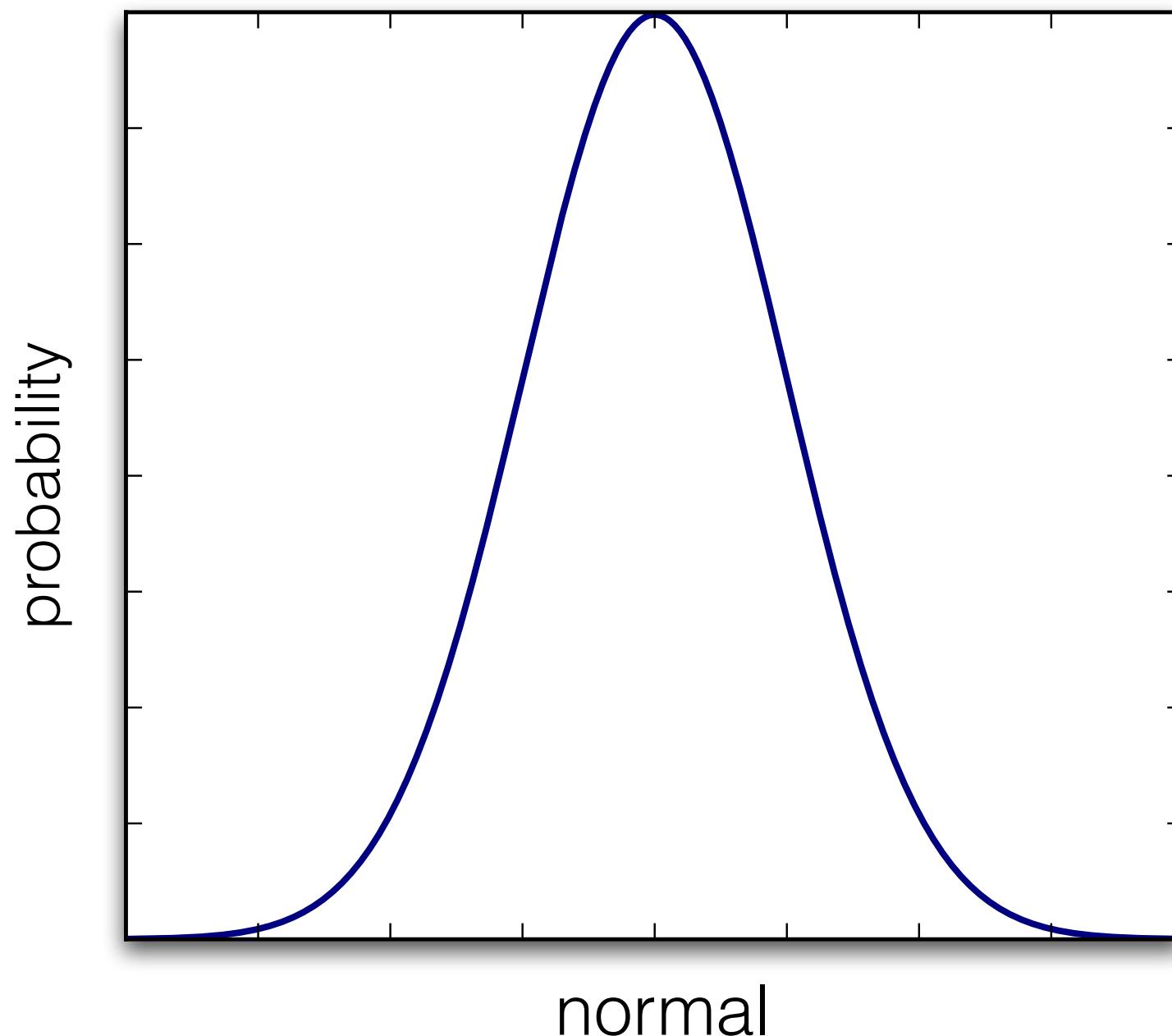
Surface = **Specular** microfacets + **statistical** normals

$$f(\mathbf{i}, \mathbf{o}) = \frac{\mathbf{F}(\mathbf{i}, \mathbf{h}) \mathbf{G}(\mathbf{i}, \mathbf{o}, \mathbf{h}) \mathbf{D}(\mathbf{h})}{4(n, \mathbf{i})(n, \mathbf{o})}$$

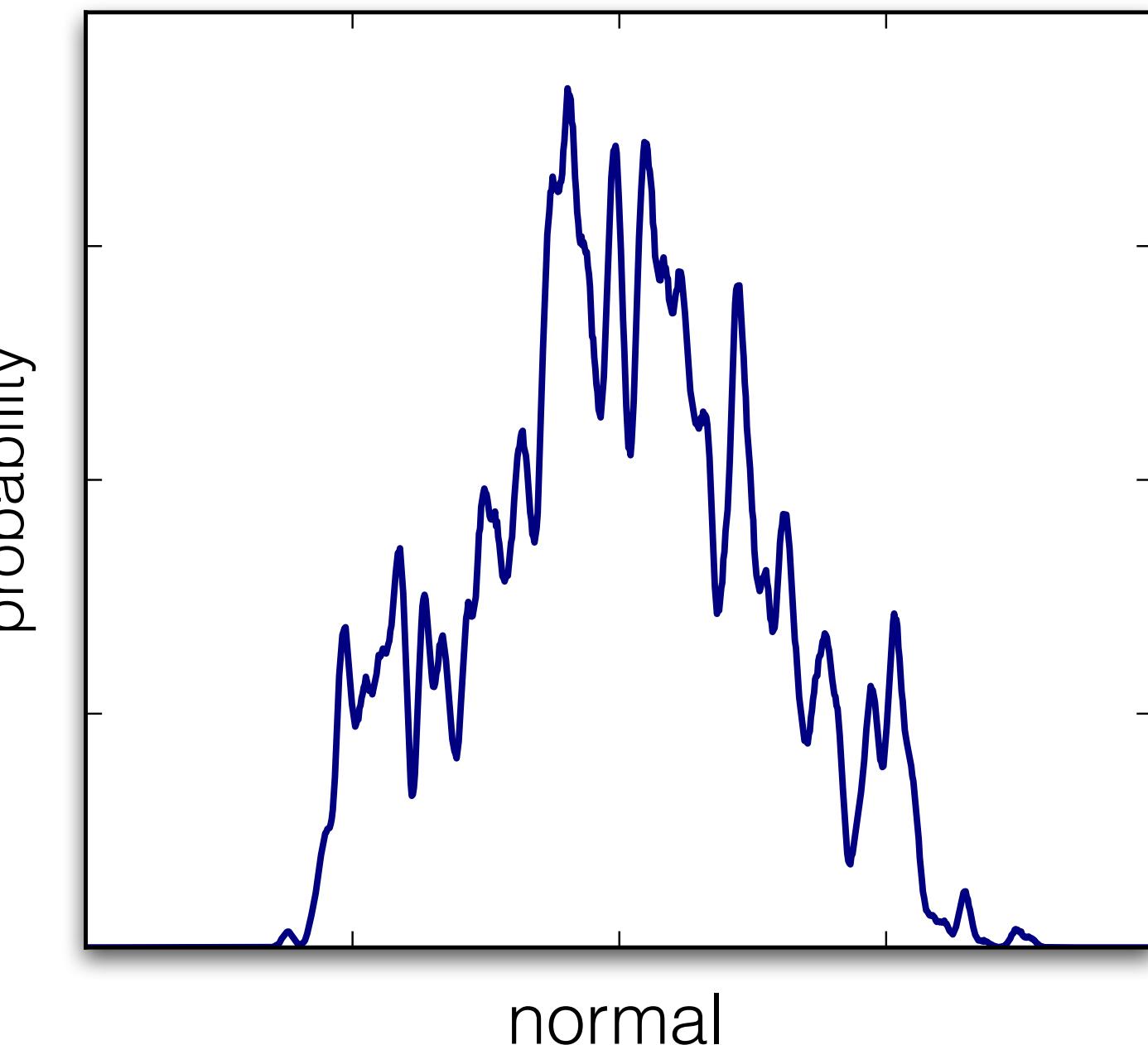
NDF: Normal
Distribution
Function

Statistical NDF vs. Actual NDF

Distribution of Normals (NDF)

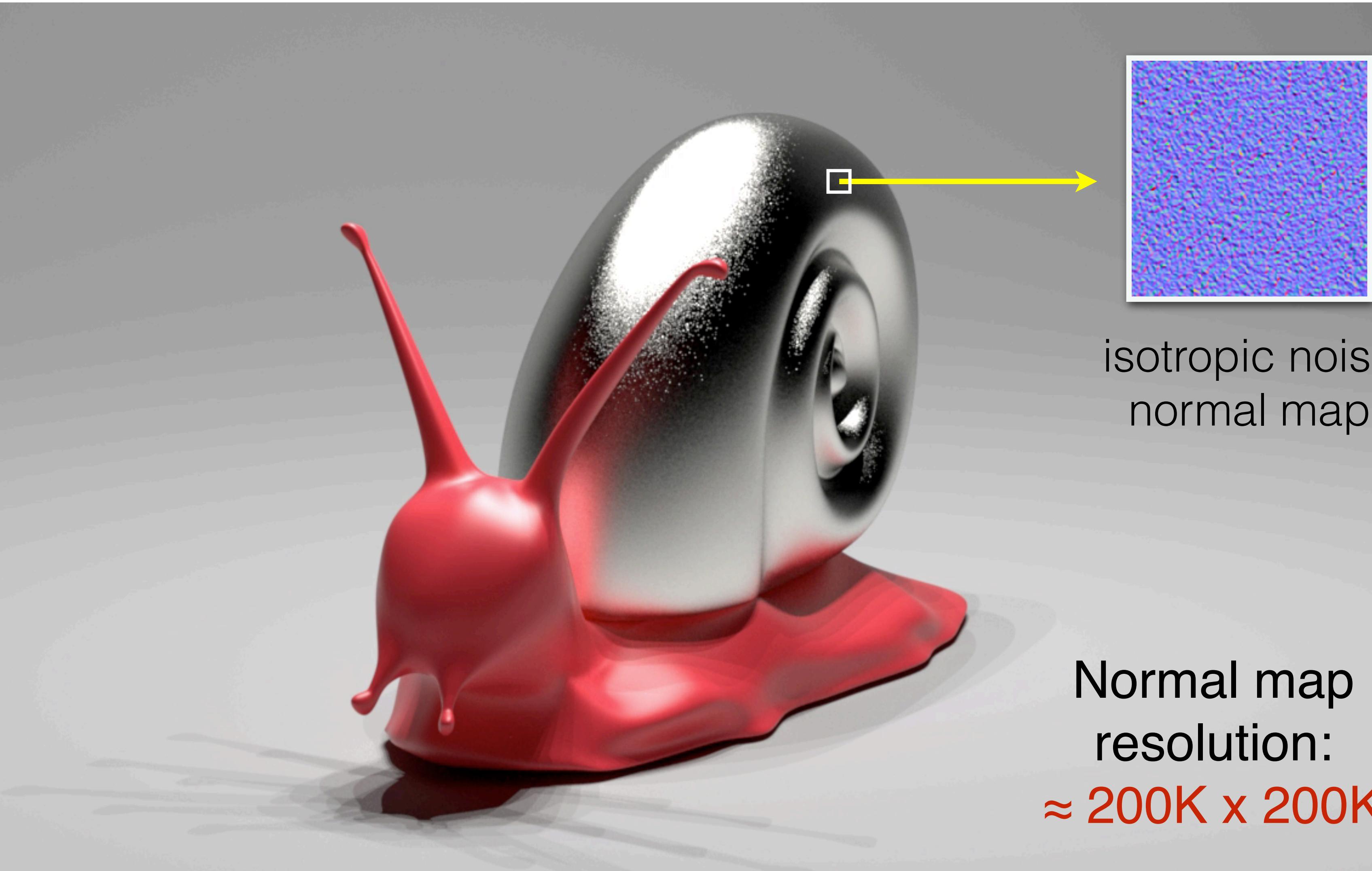


What we have
(microfacet — statistical)



What we want

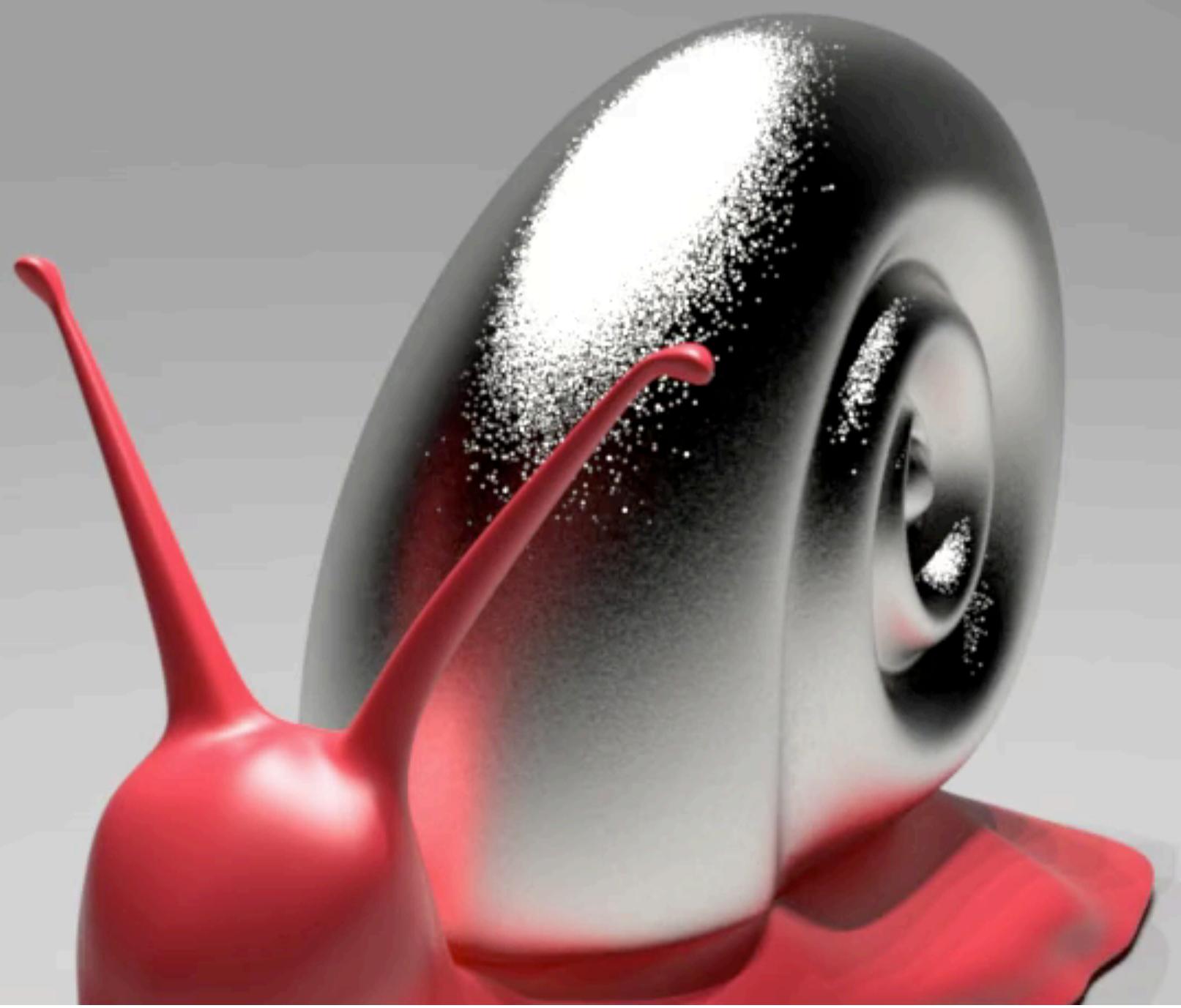
Define details



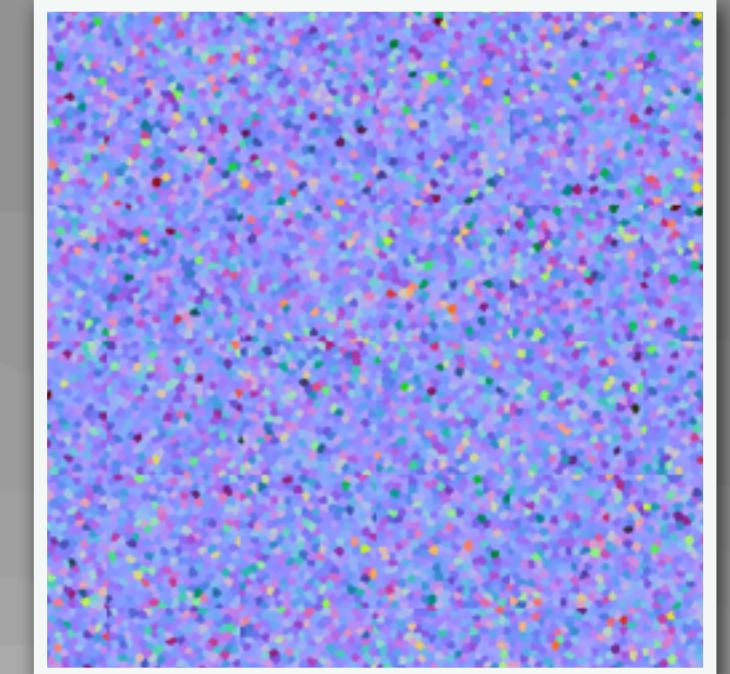
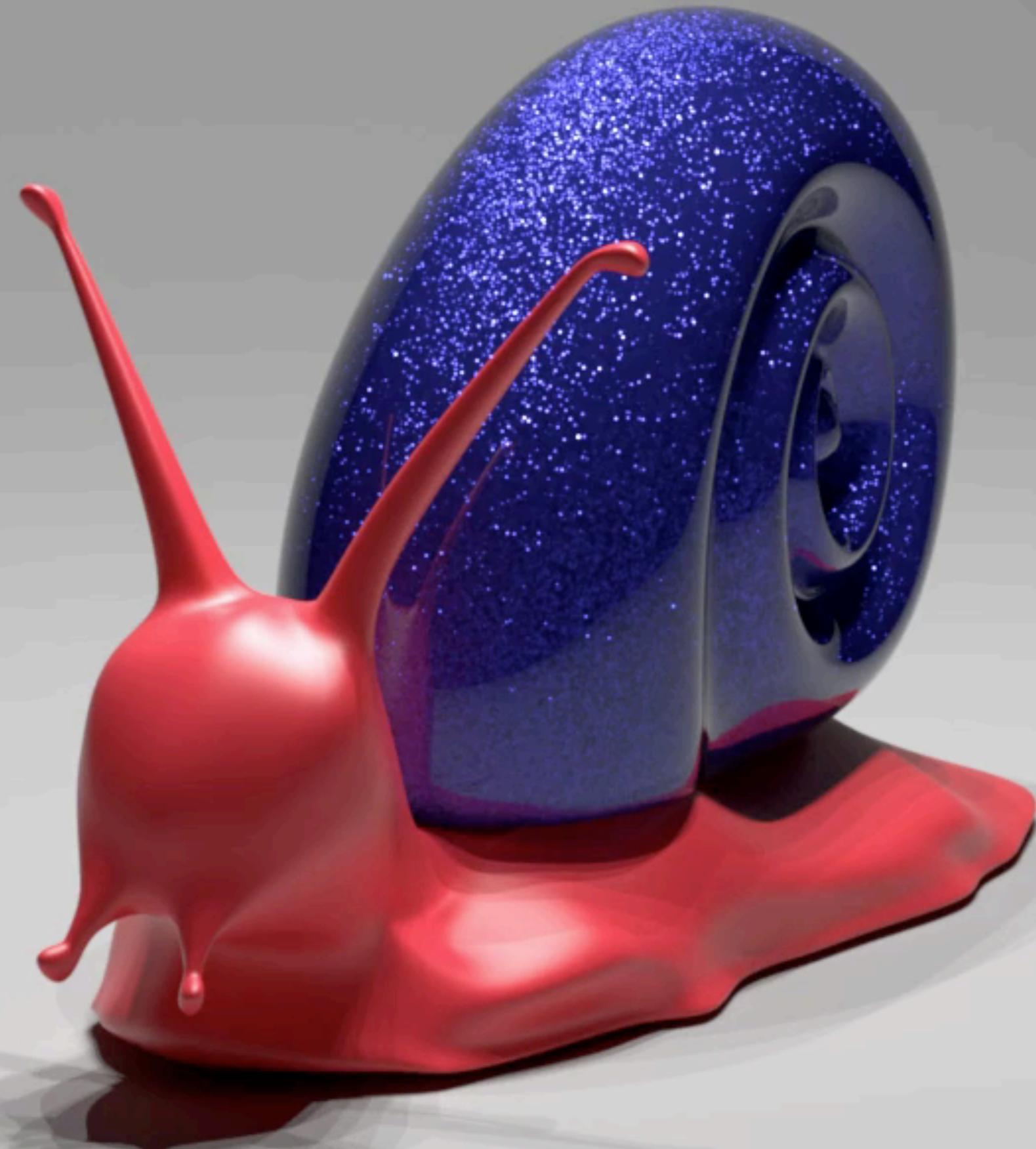
isotropic noise
normal map

Normal map
resolution:
 $\approx 200K \times 200K$

Define details

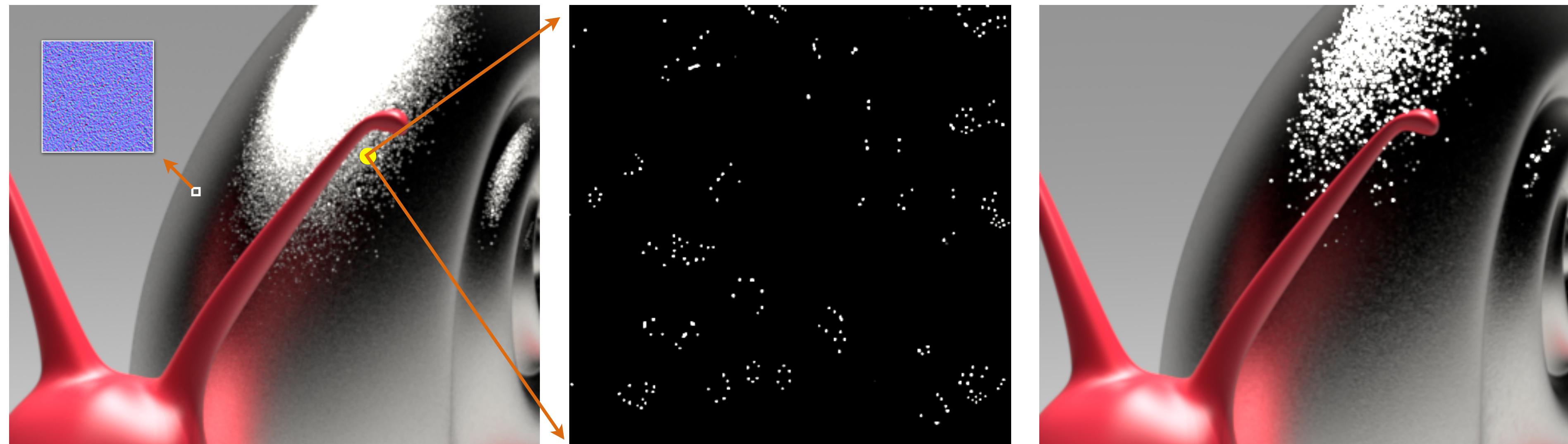


Different details



Metallic flakes

Rendering? Too difficult!



our result

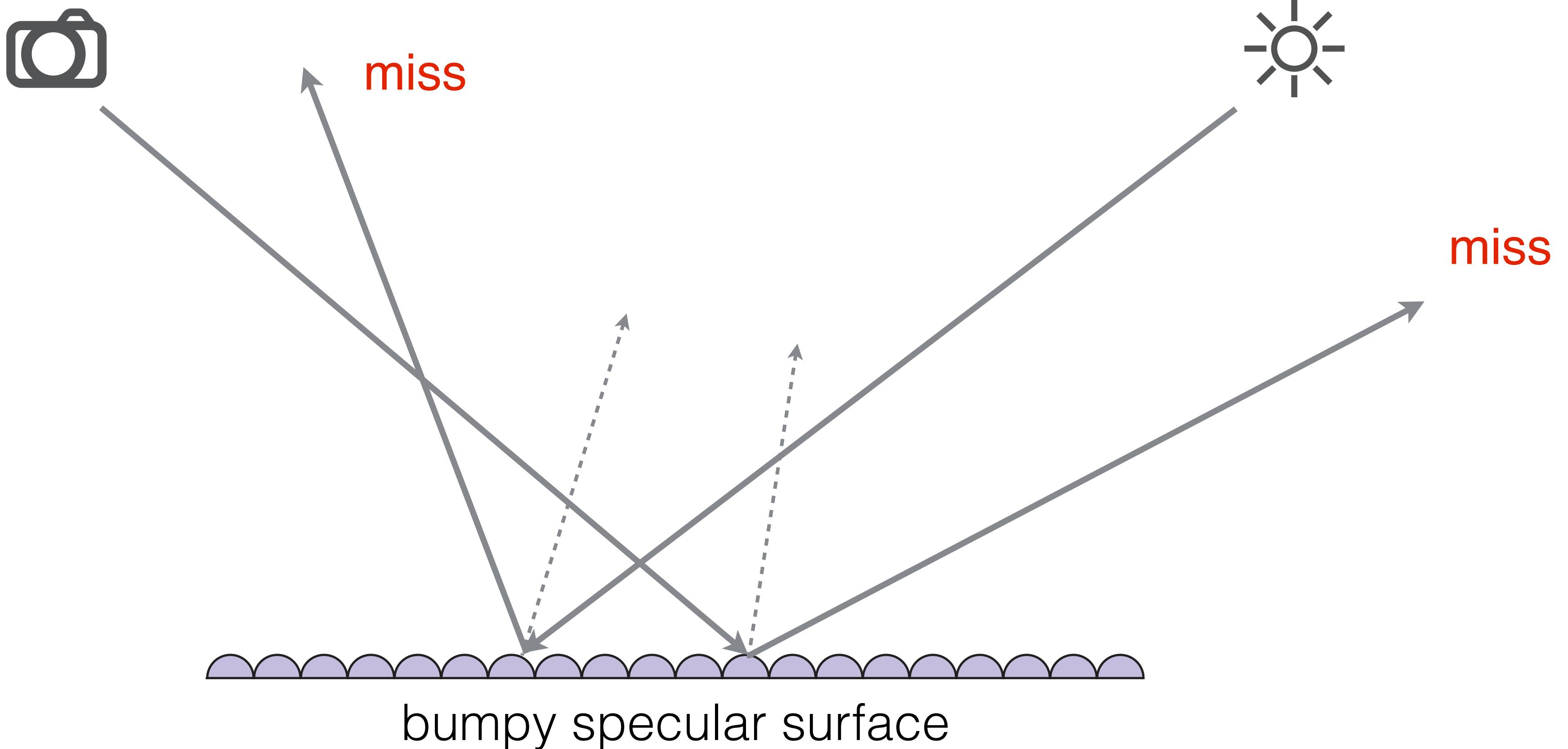
zoom of
a single pixel

naive sampling (2h)
(>> 21.3 **days** to converge)

Difficult path sampling problem

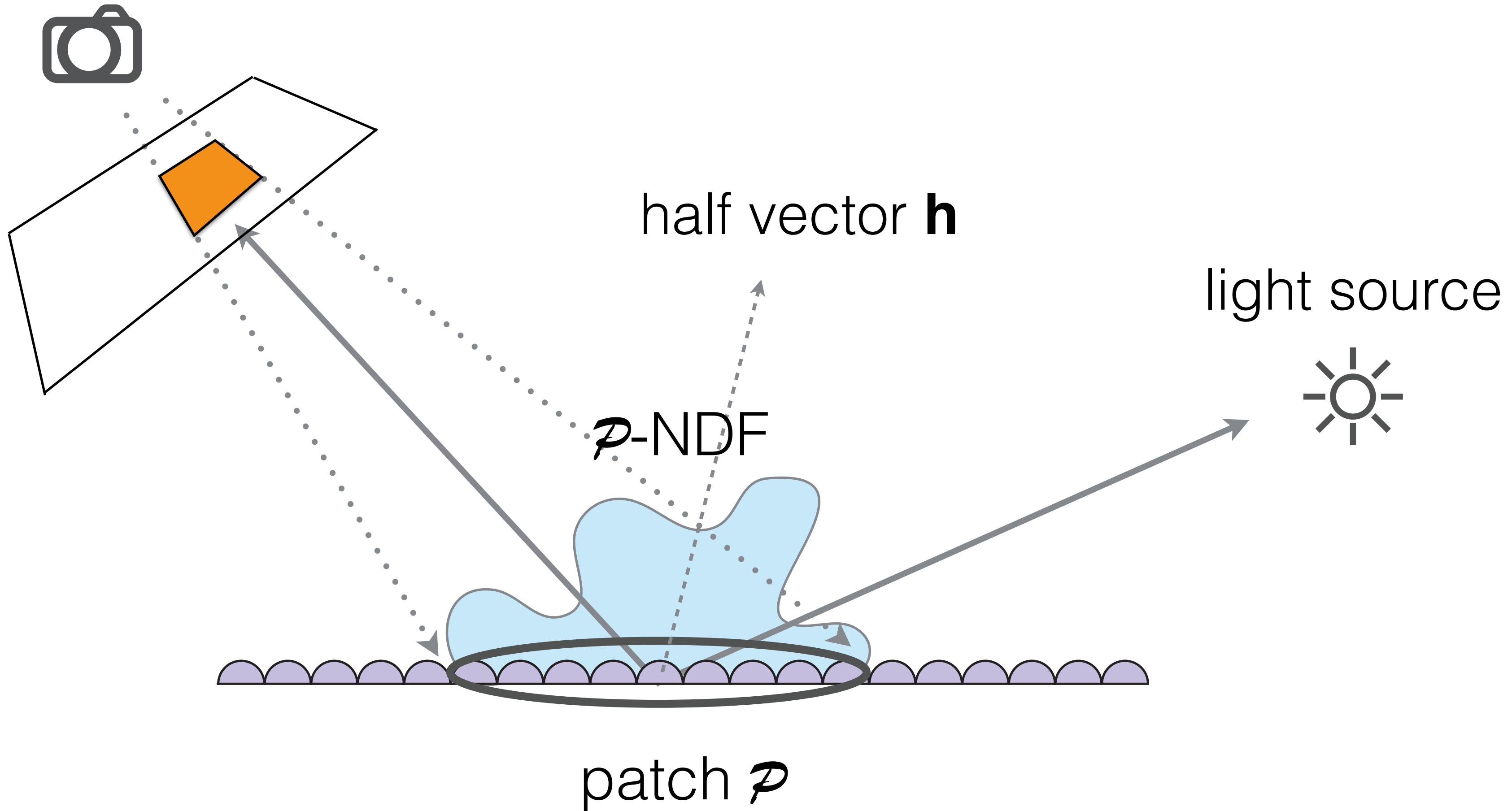
pinhole camera

lightsource

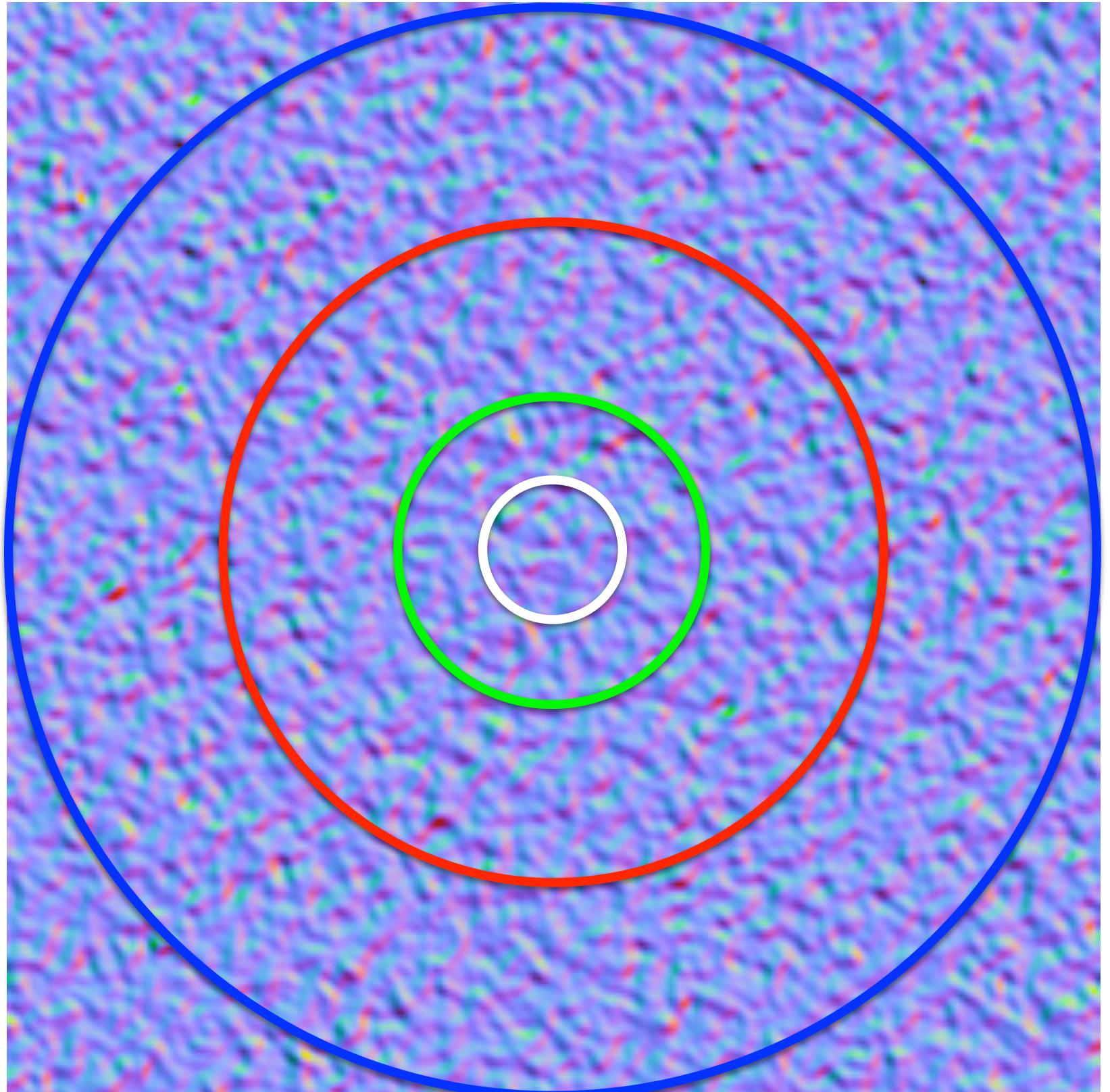


Solution: BRDF over a pixel

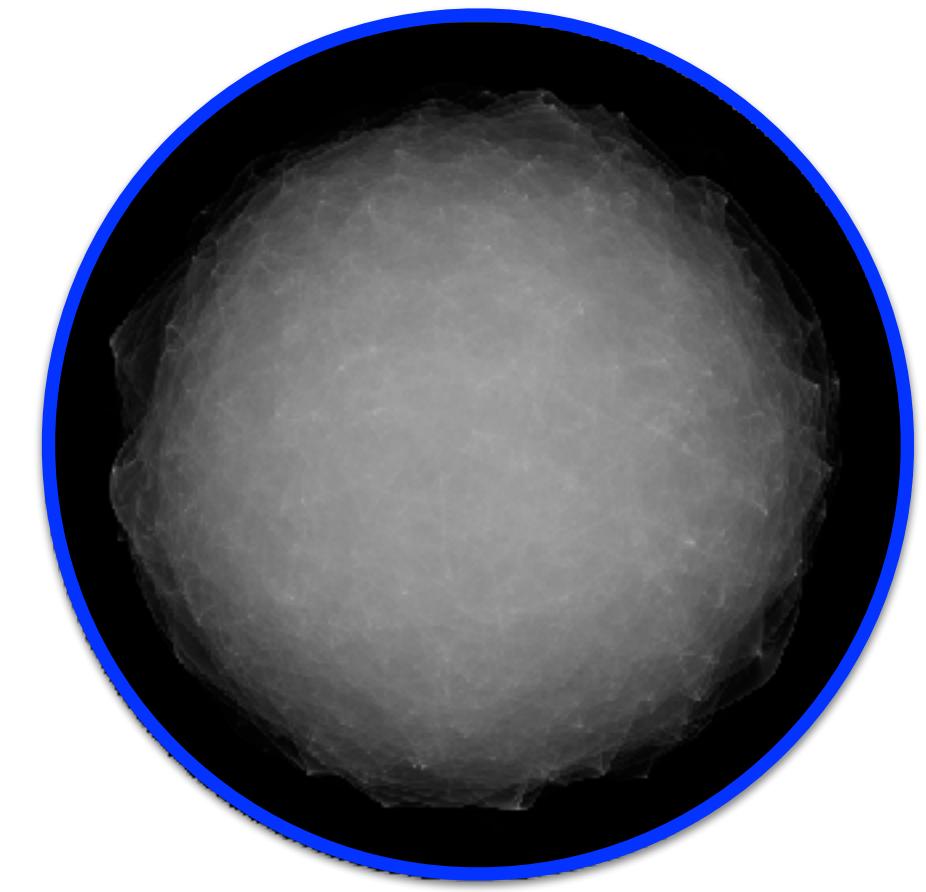
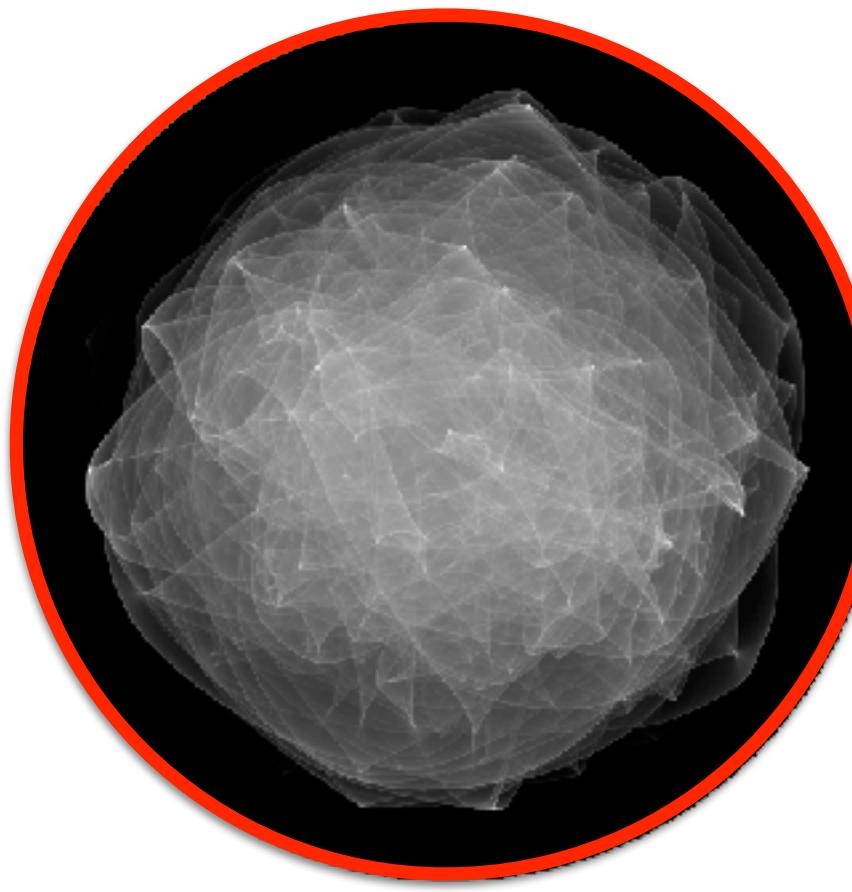
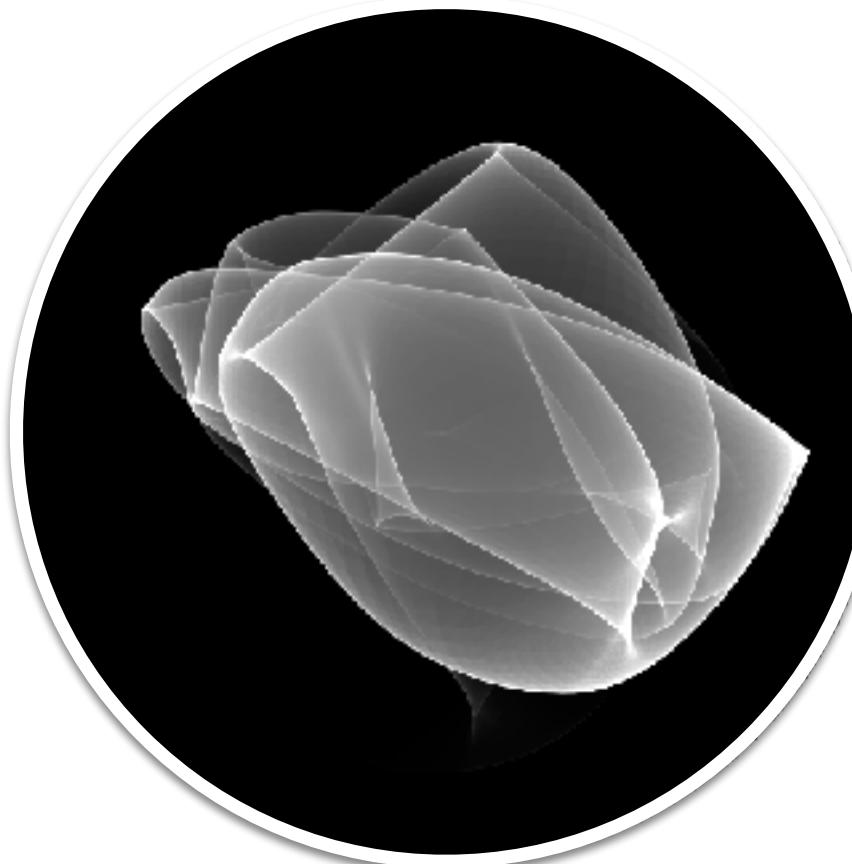
pinhole camera



p-NDFs have sharp features

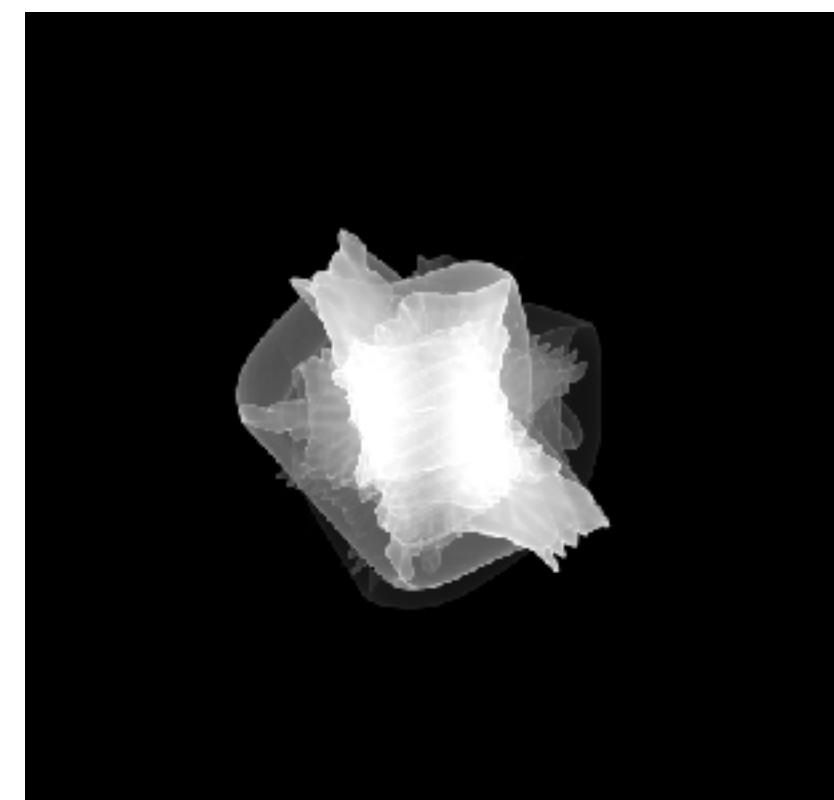
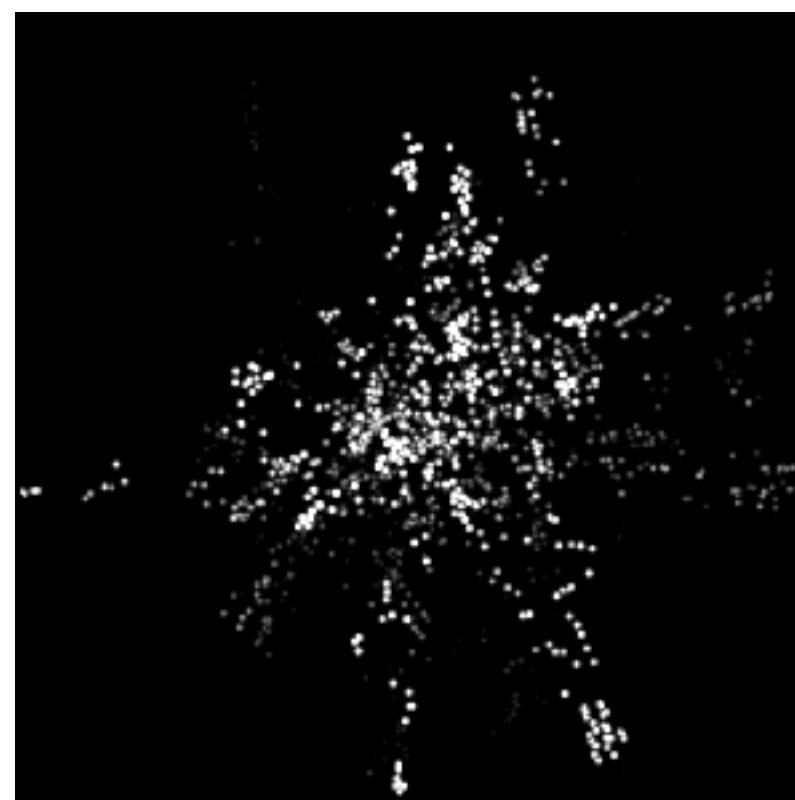
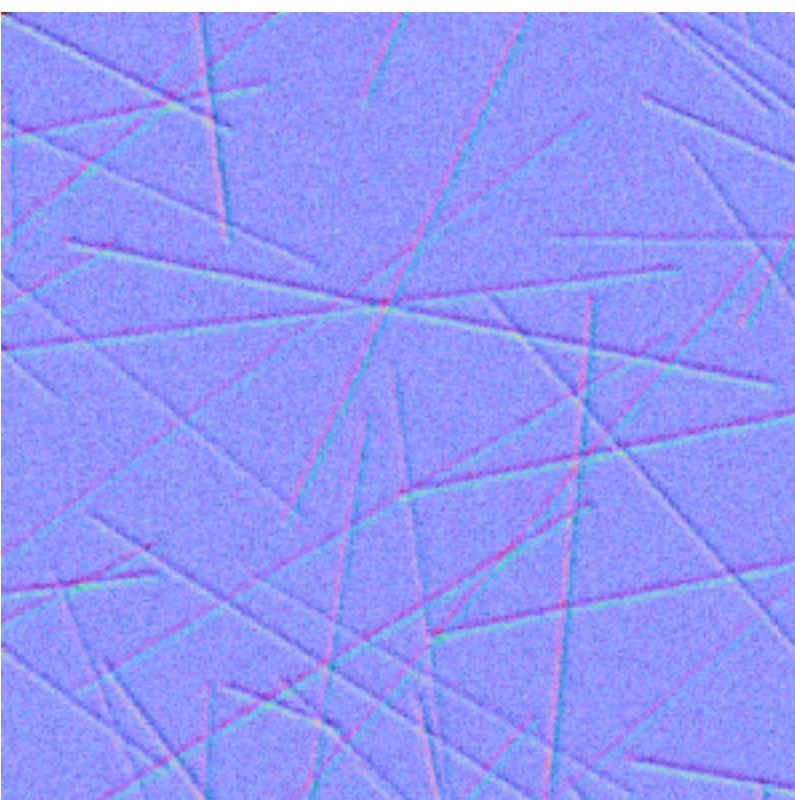
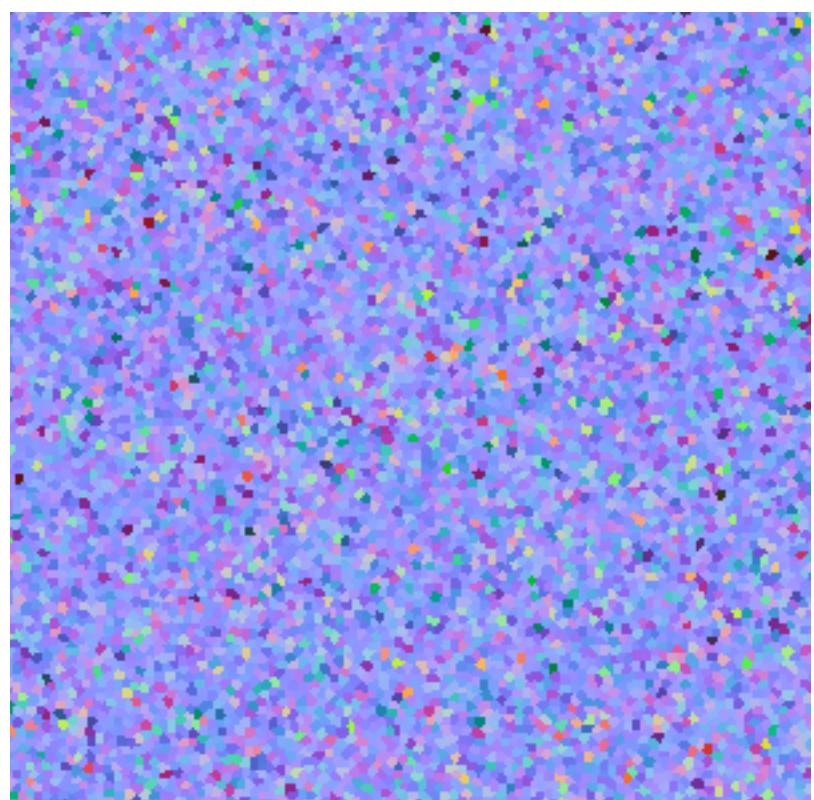
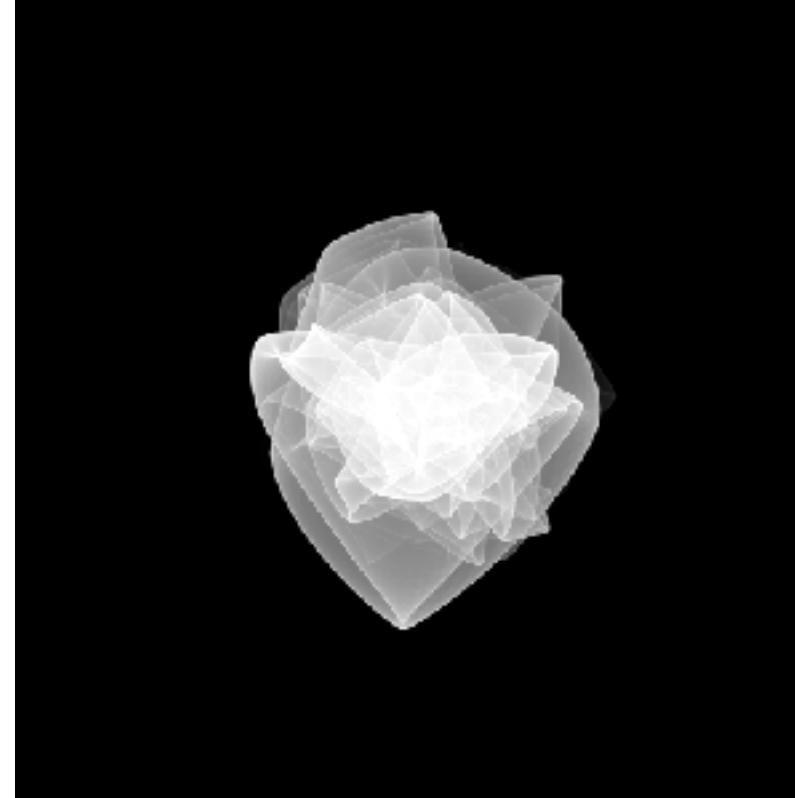
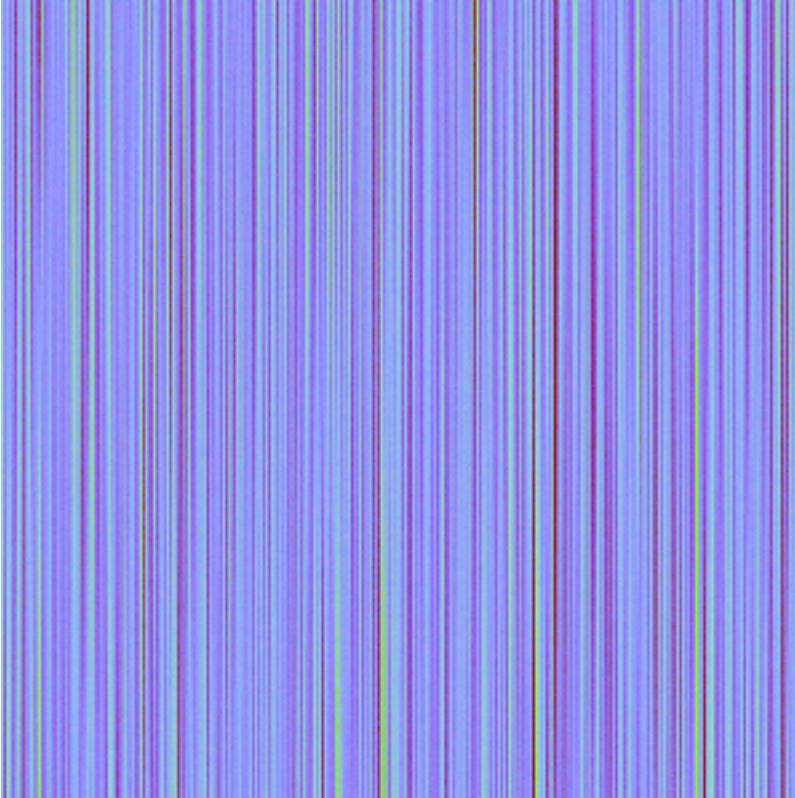
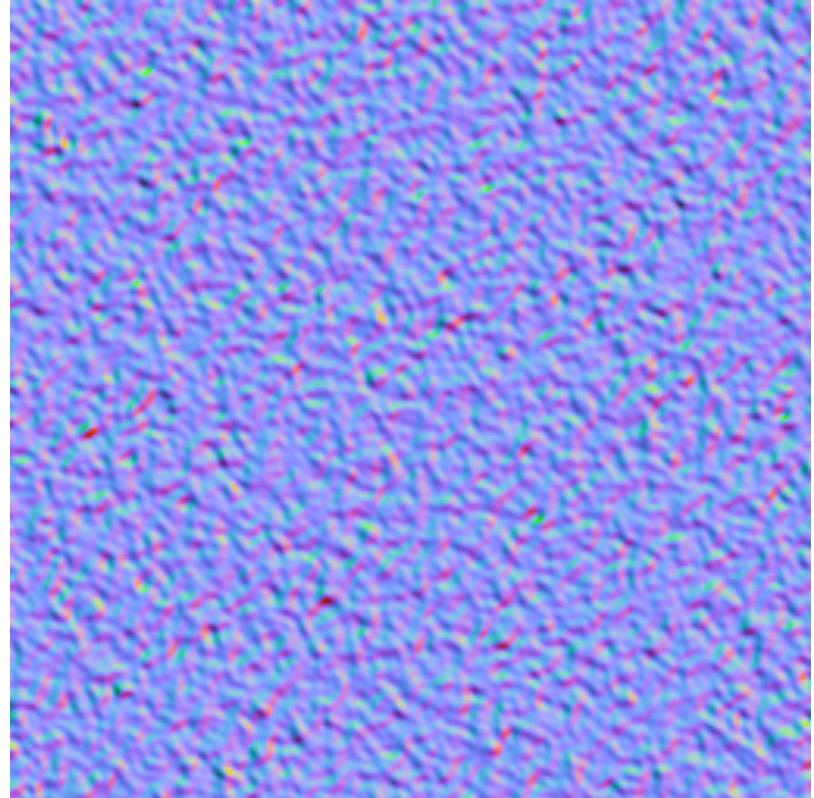


normal map



\mathcal{P} -NDFs

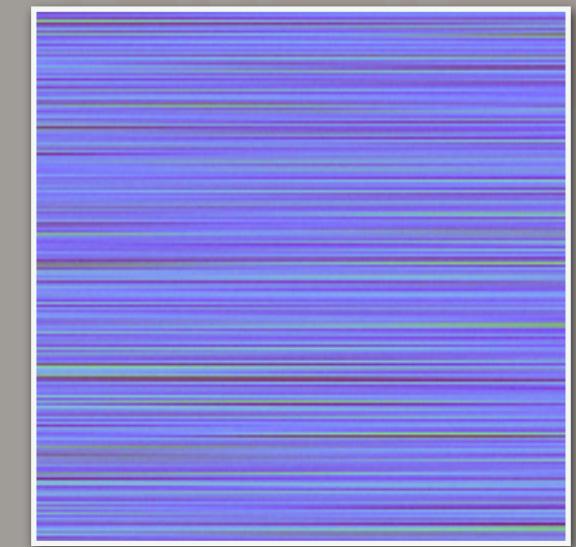
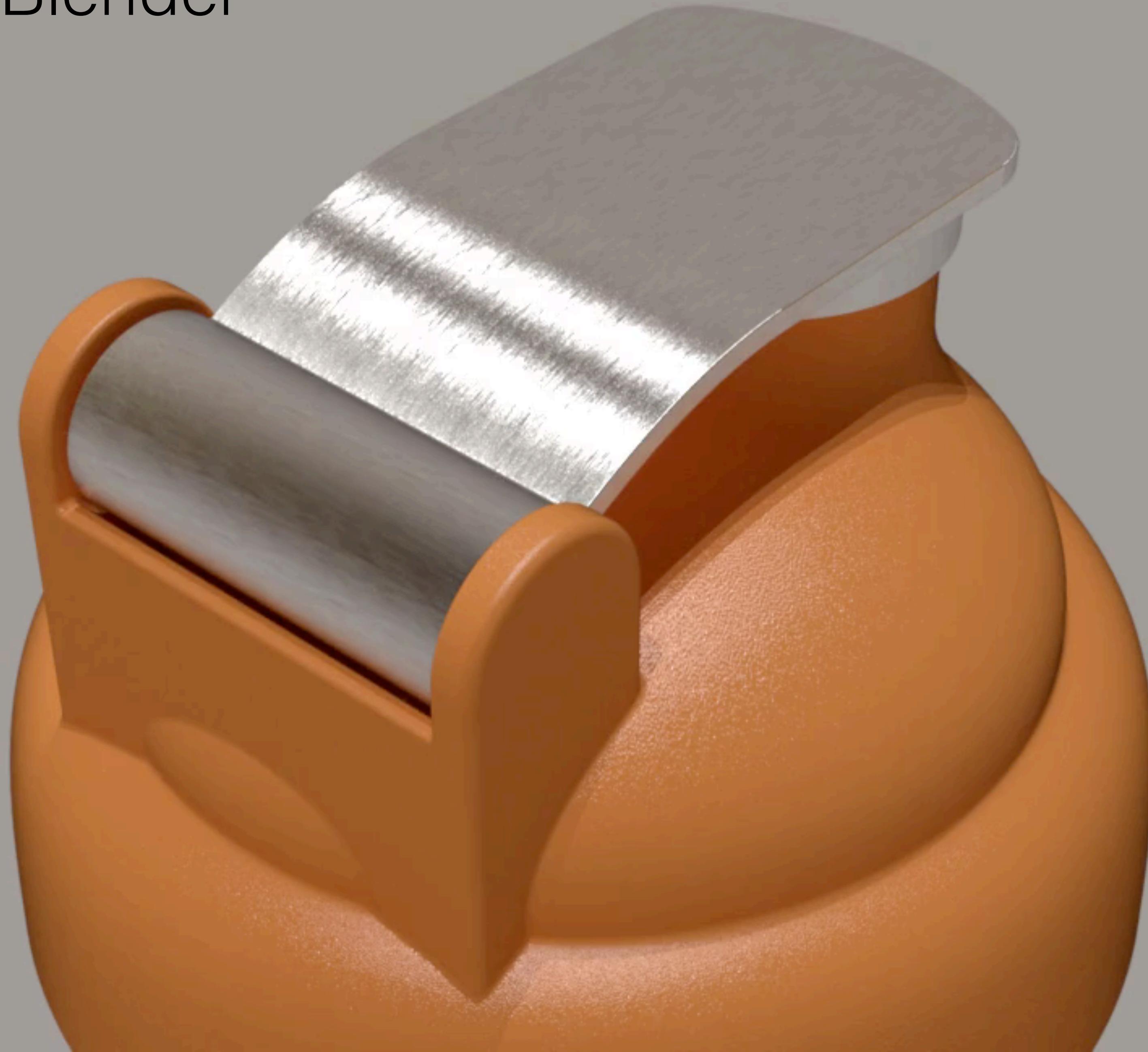
p-NDF shapes



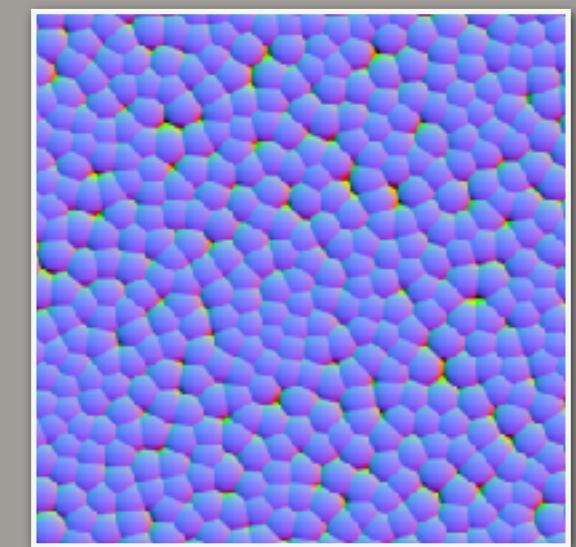
normal maps

\mathcal{P} -NDFs

Blender

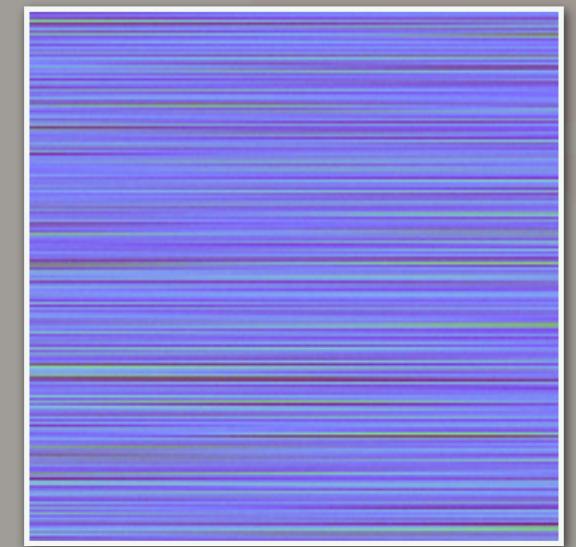


brushed metal

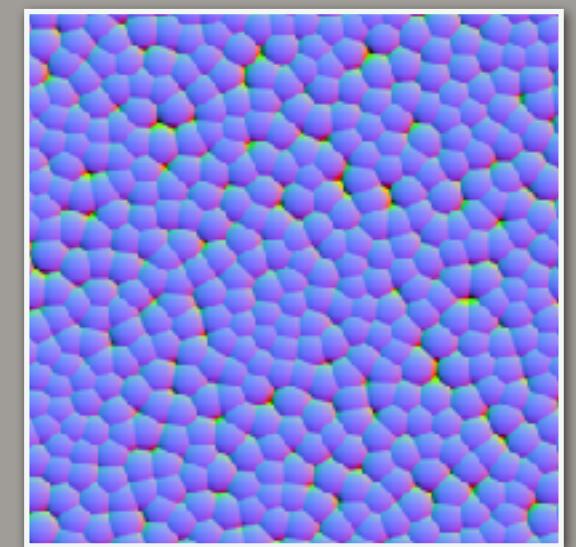


ellipsoid bumps

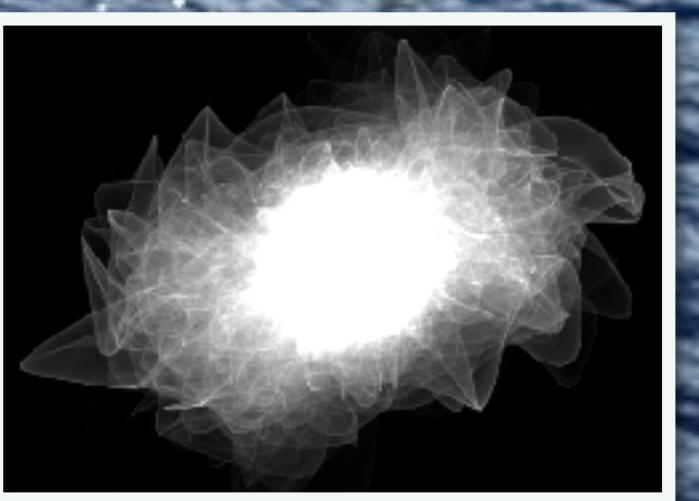
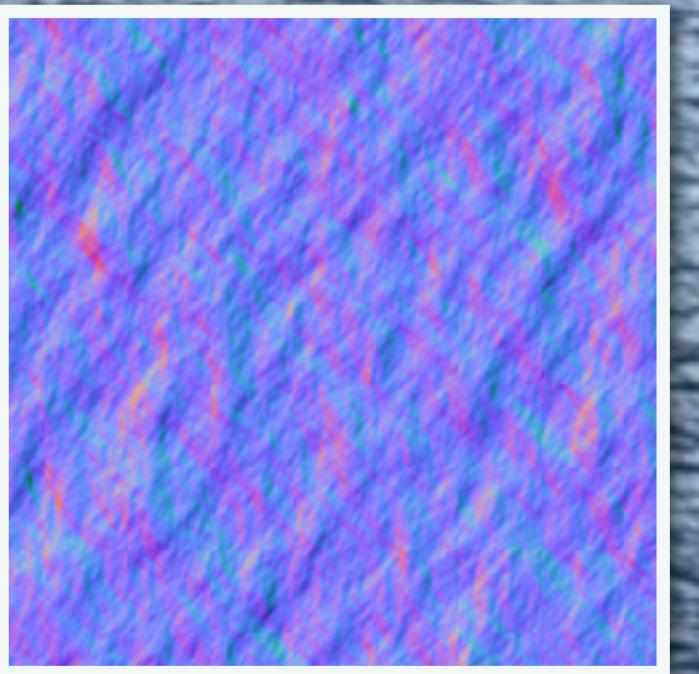
Blender: Zoom



brushed metal



ellipsoid bumps



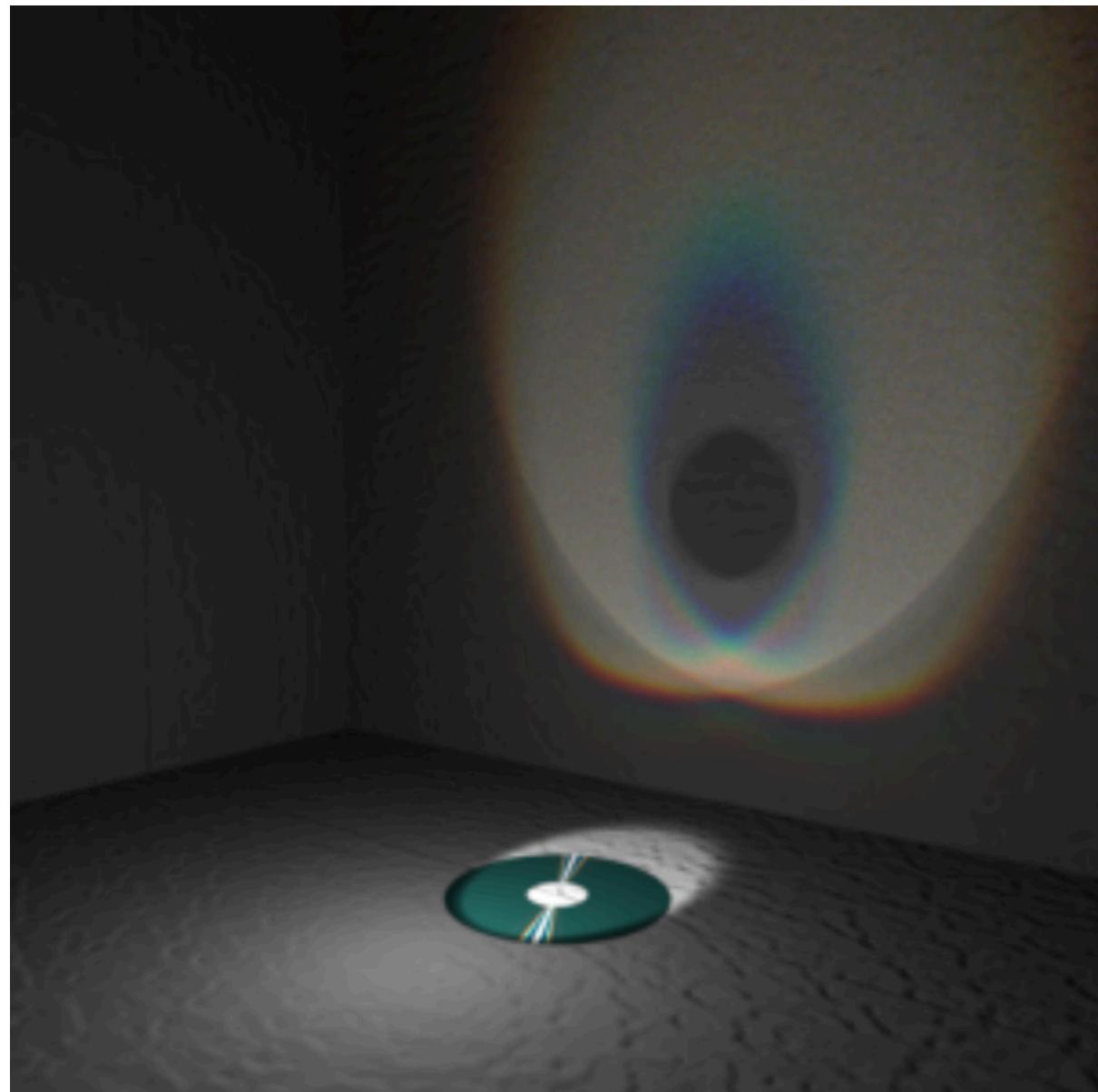
Ocean waves

Detailed / Glinty Material: Application



[Rise of the Tomb Raider. 2016 Square Enix]

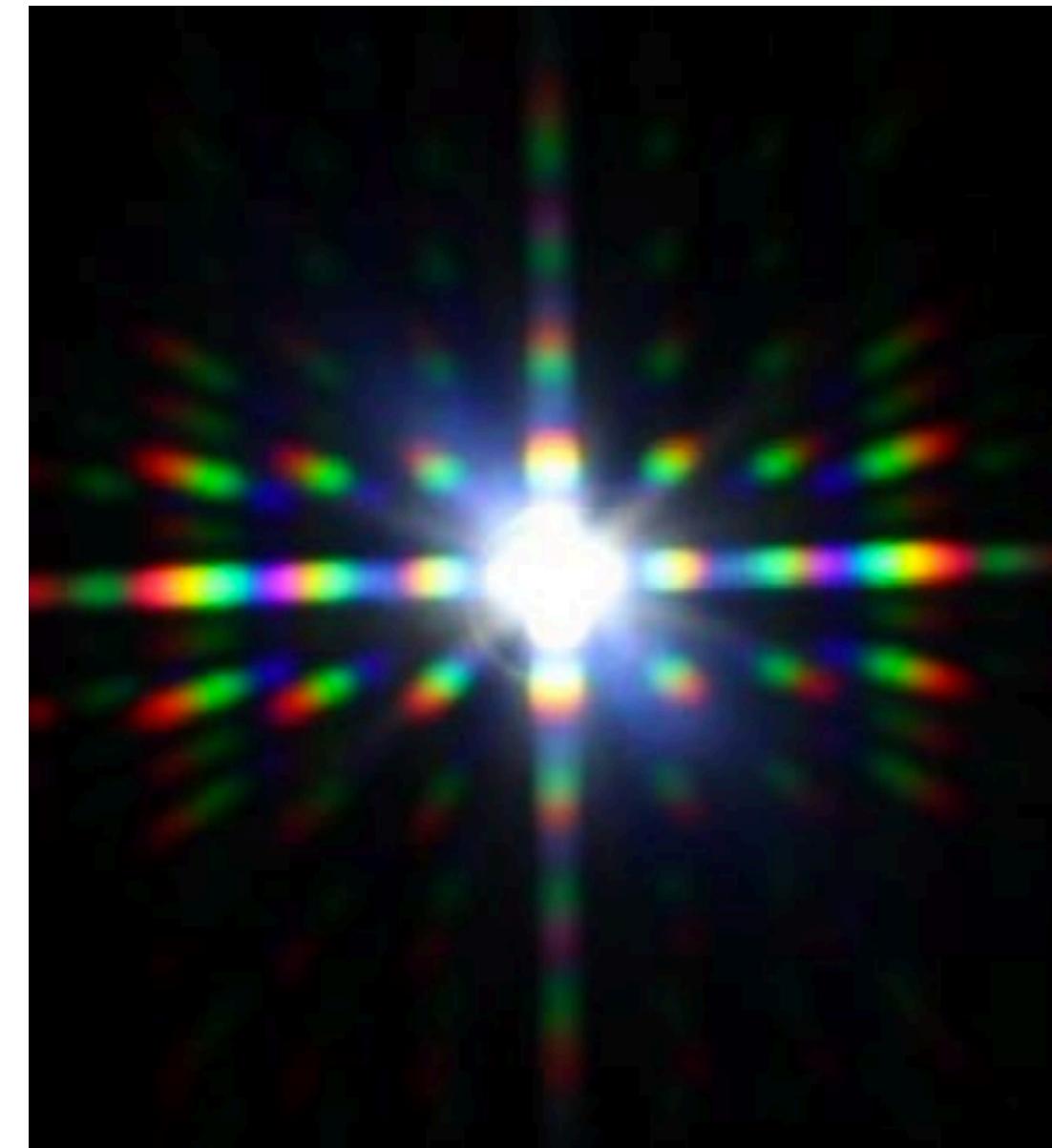
Recent Trend: Wave Optics



compact disk (CD)
[Cuypers 11]

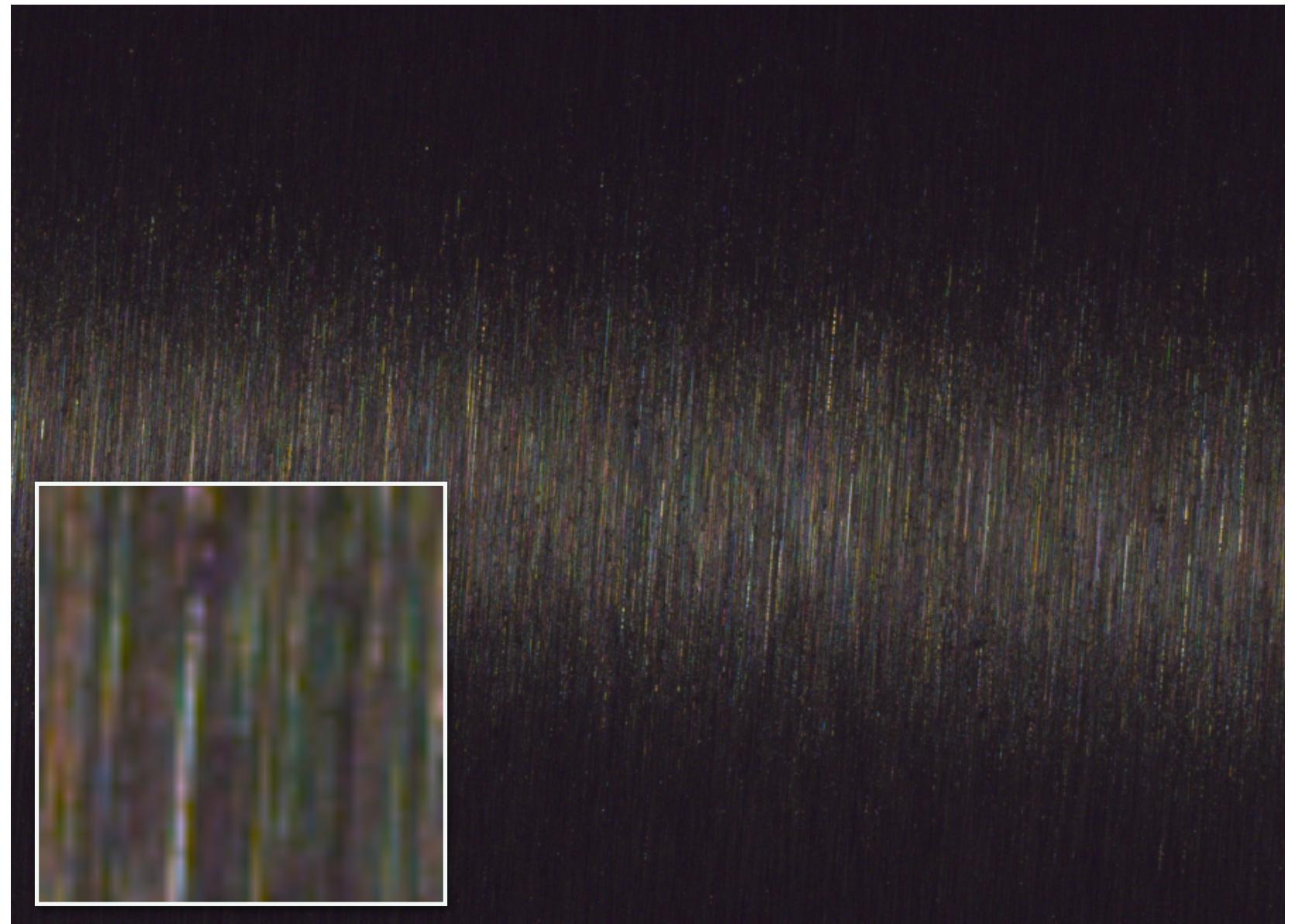
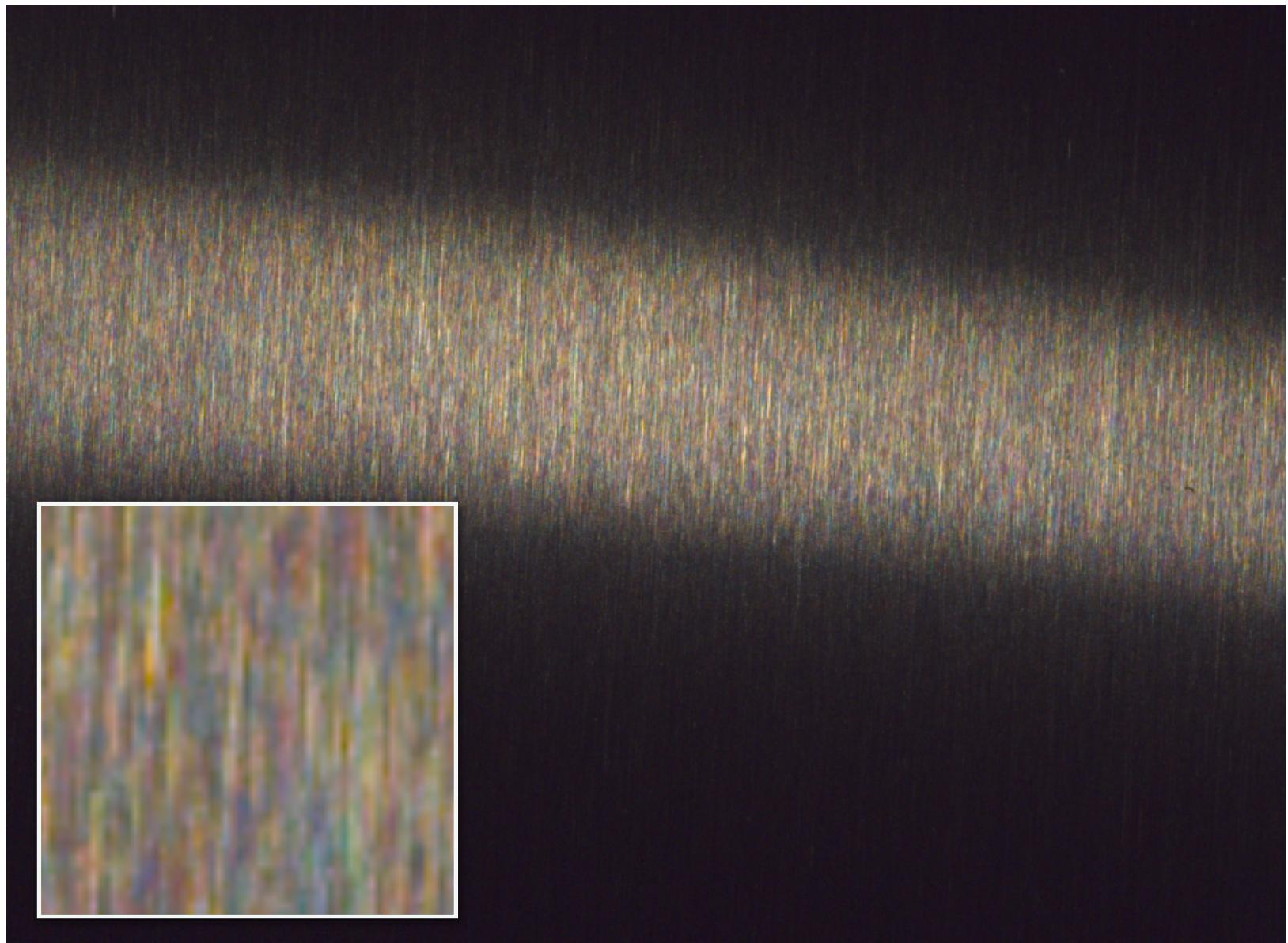


metallic film
[Laurent 17]



phone screen
[Toisoul 17]

Observations



photos of scratched metal

Observations



photo of a Macbook

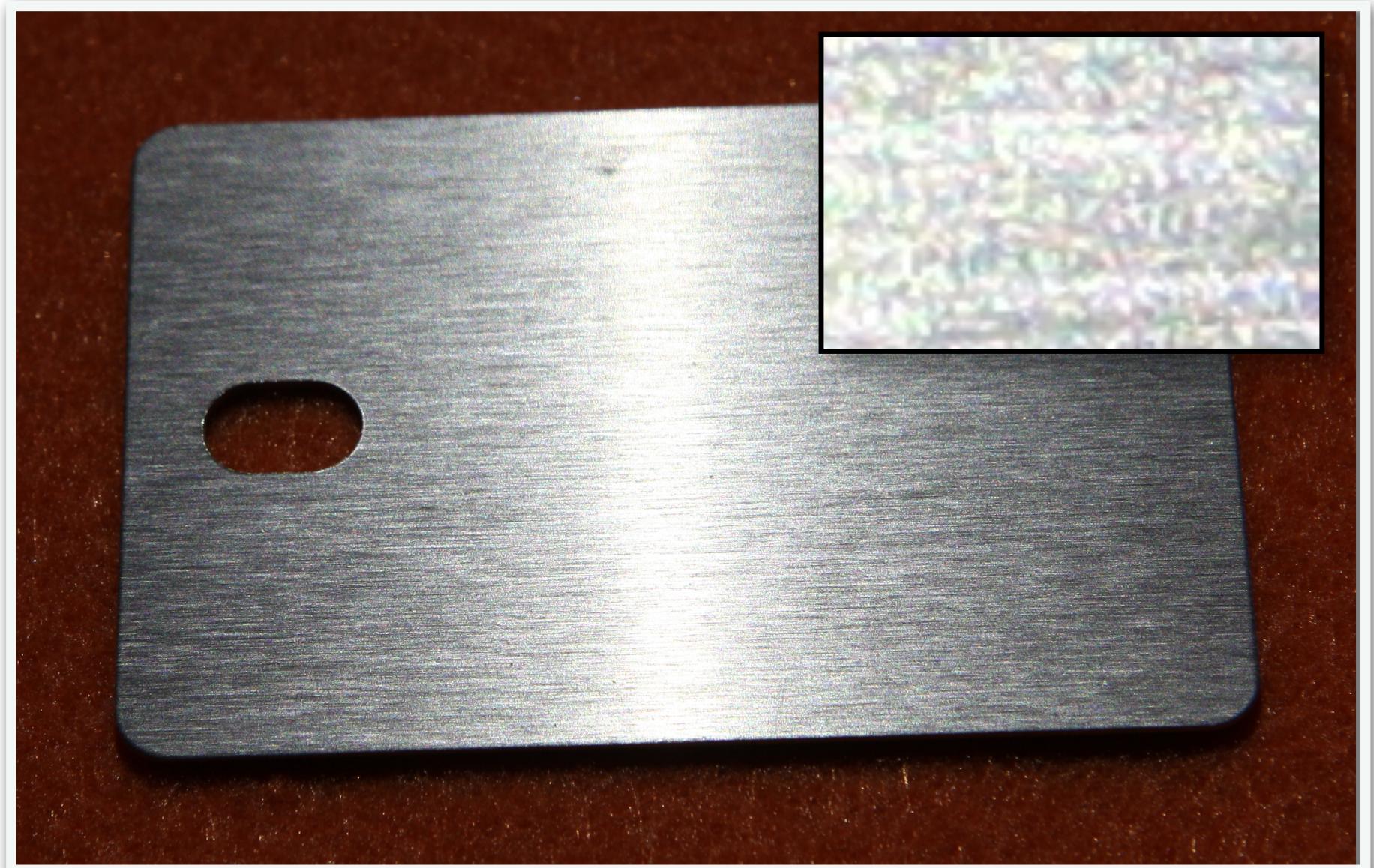
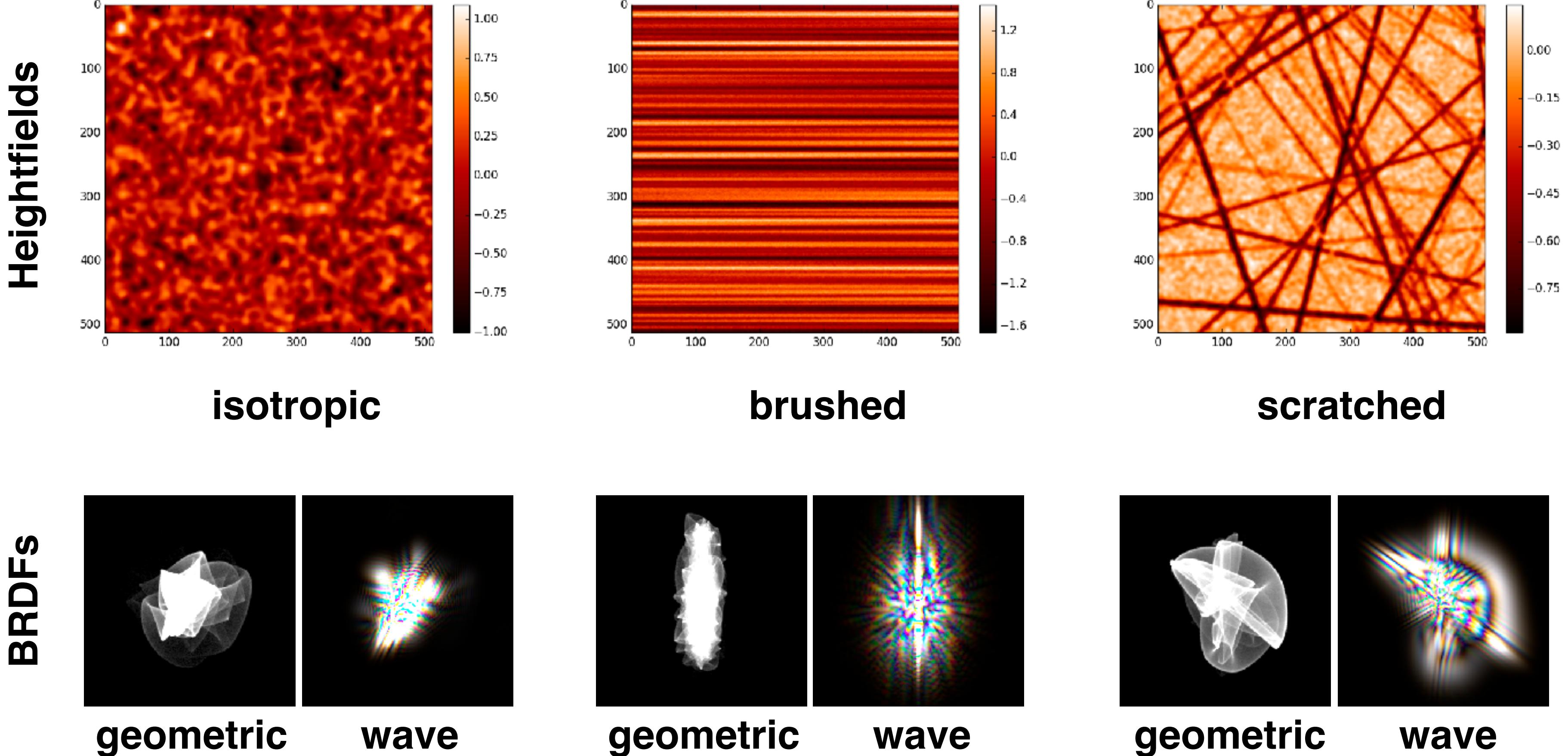


photo of an aluminum patch

Detailed Material under Wave Optics



Detailed Material under Wave Optics



MacBook rendered using wave optics

[Yan et al. 2018]

fn

control

alt

option

 *command*



fn

control

alt

option



command

What is it about?

Wave optics



Procedural Appearance

Procedural Appearance

- Can we define details without textures?
 - Yes! Compute a noise function on the fly.

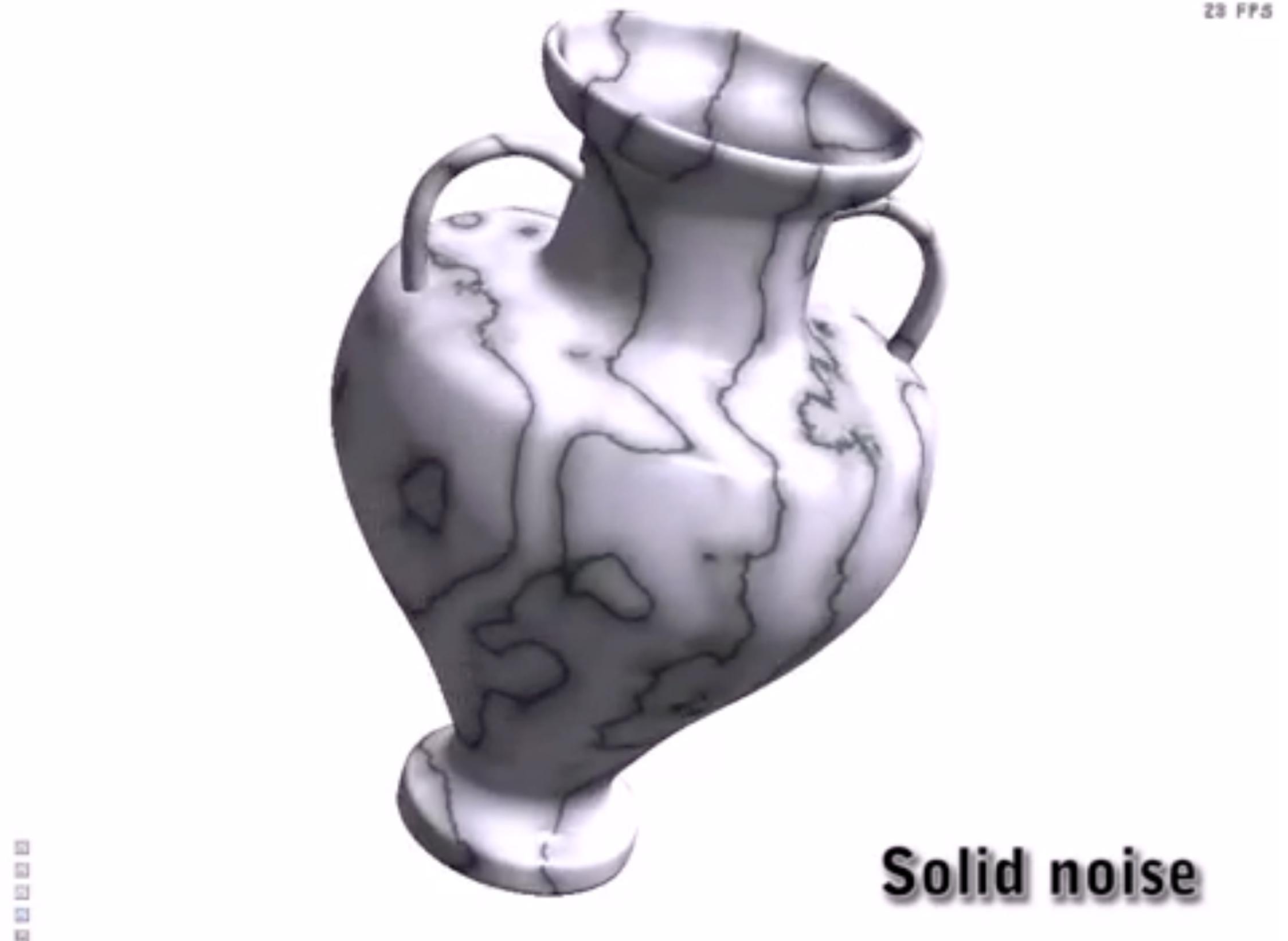


[Lagae et al. 2009]

Procedural Appearance

- Can we define details without textures?

- Yes! Compute a noise function on the fly.
 - 3D noise -> internal structure if cut or broken



[Lagae et al. 2009]

Procedural Appearance

- Can we define details without textures?
 - Yes! Compute a noise function on the fly.
 - Thresholding
(noise -> binary noise)

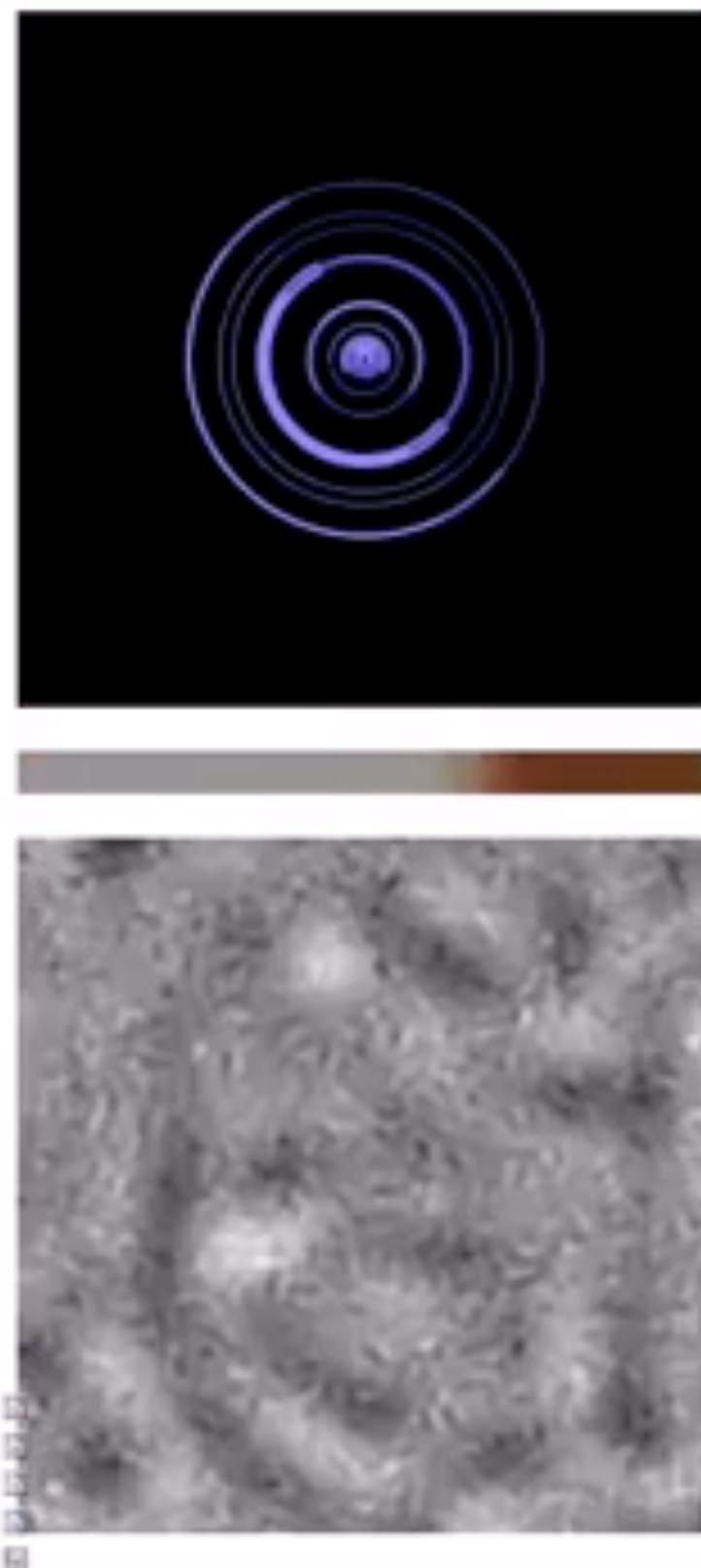
Example:

if $\text{noise}(x, y, z) > \text{threshold}$:

 reflectance = 1

else:

 reflectance = 0



Procedural Appearance

- Complex noise functions can be very powerful.



Procedural Appearance

- Complex noise functions can be very powerful.



[Steve Worley]

Procedural Appearance

- Complex noise functions can be very powerful.



[Liu et al. 2016]

Procedural Appearance

- Complex noise functions can be very powerful.



video of alternative pattern

[Liu et al. 2016]

Thank you!

(And thank Prof. Ren Ng for many of the slides!)