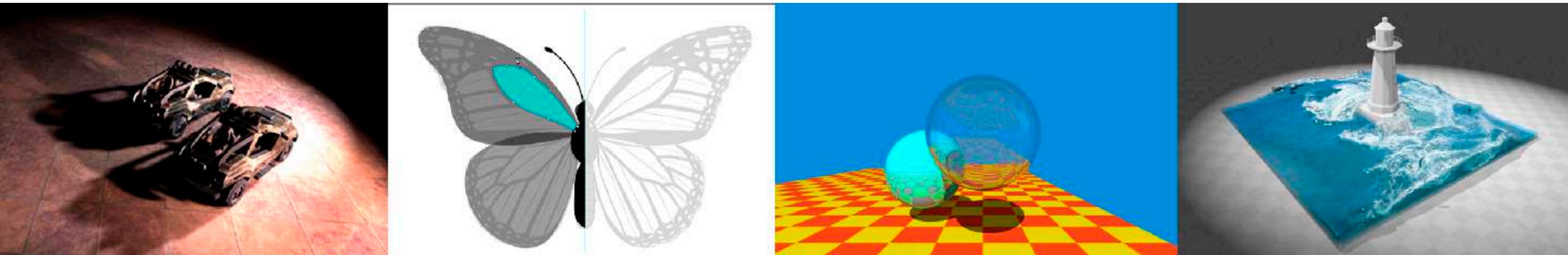


Introduction to Computer Graphics

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

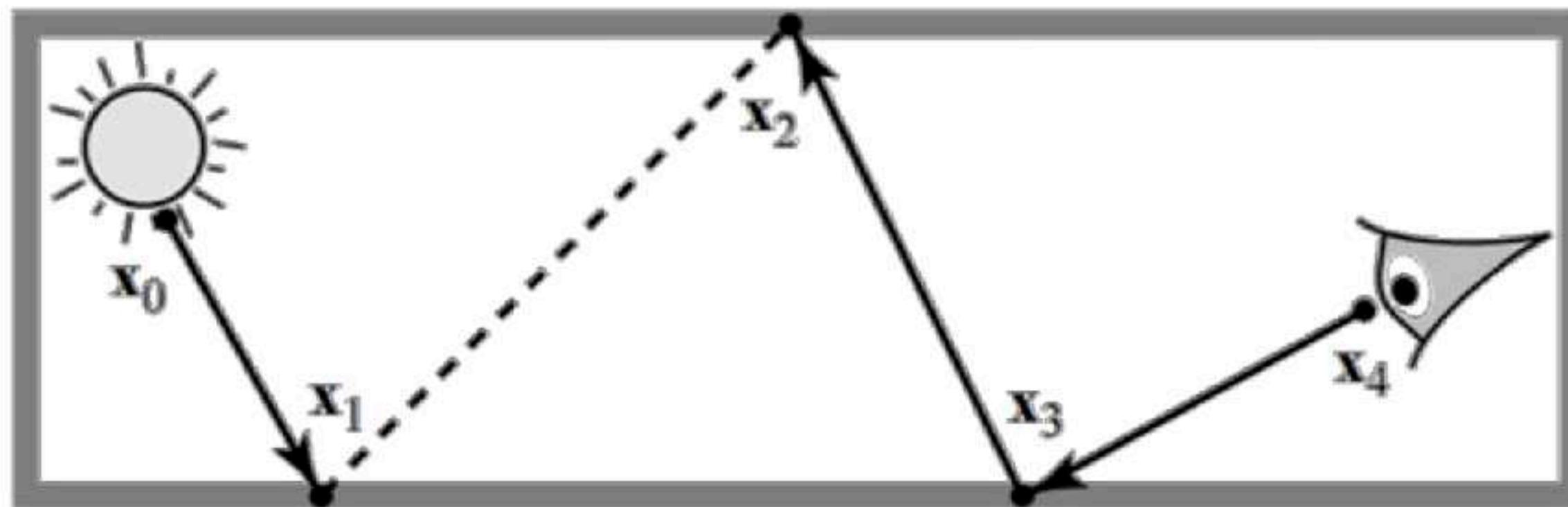
- Unbiased light transport methods
 - Bidirectional path tracing (BDPT)
 - Metropolis light transport (MLT)
- Biased light transport methods
 - Photon mapping
 - Vertex connection and merging (VCM)
- Instant radiosity (VPL / many light methods)

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



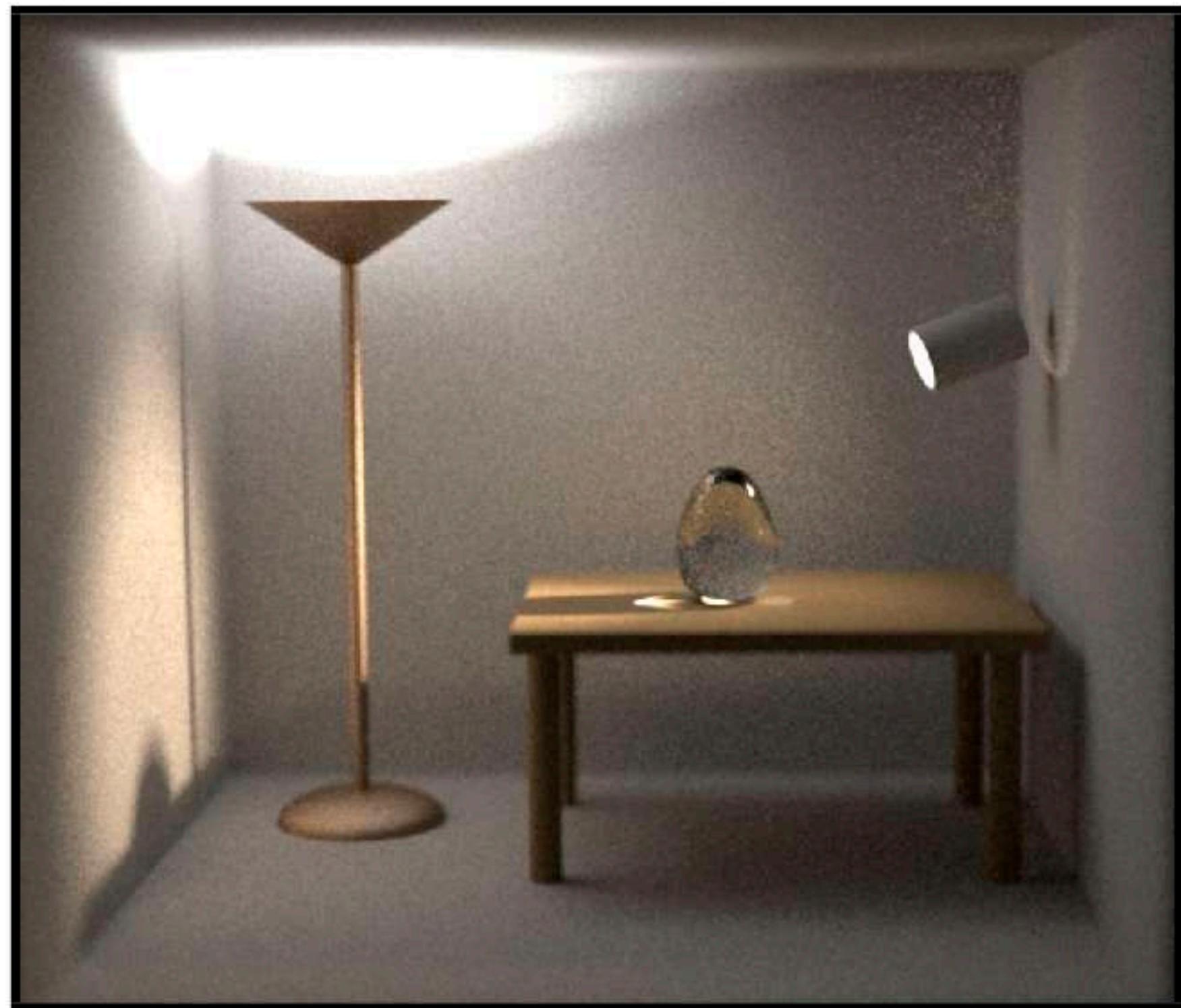
[Veach 1997]

Bidirectional Path Tracing (BDPT)

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



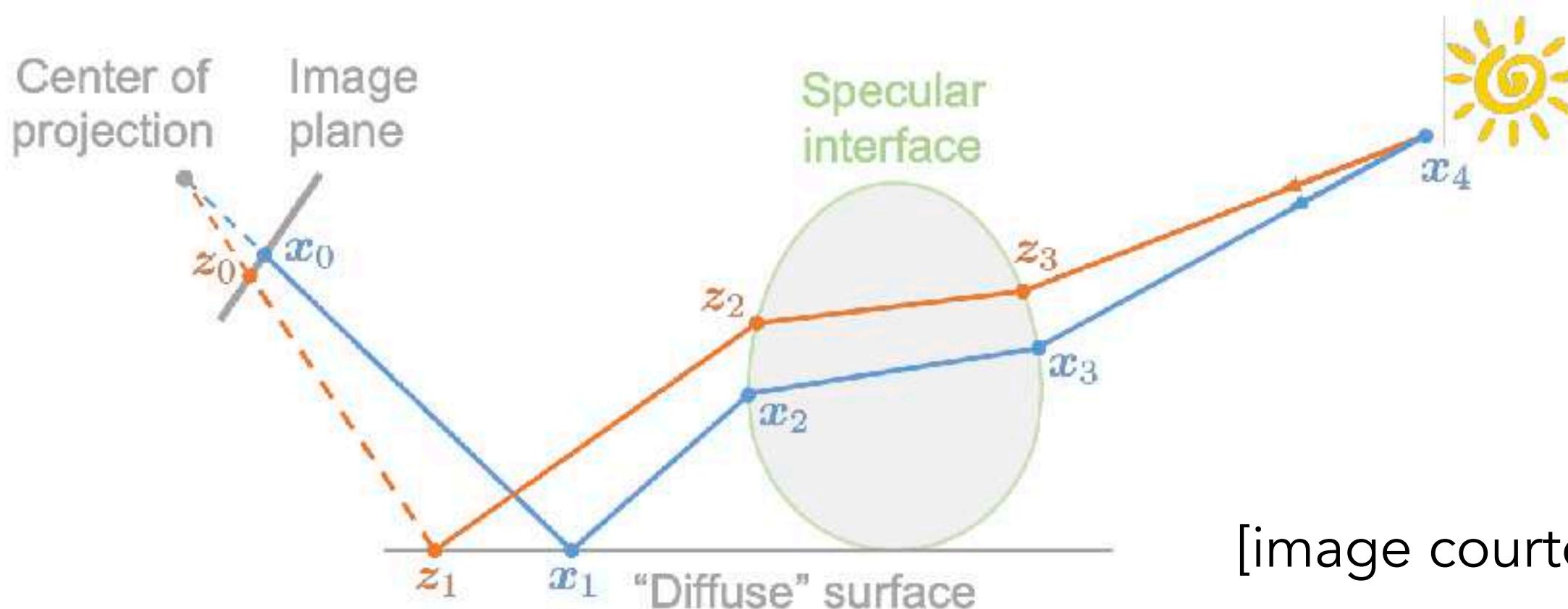
(a) Path tracer, 32 samples/pixel



(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

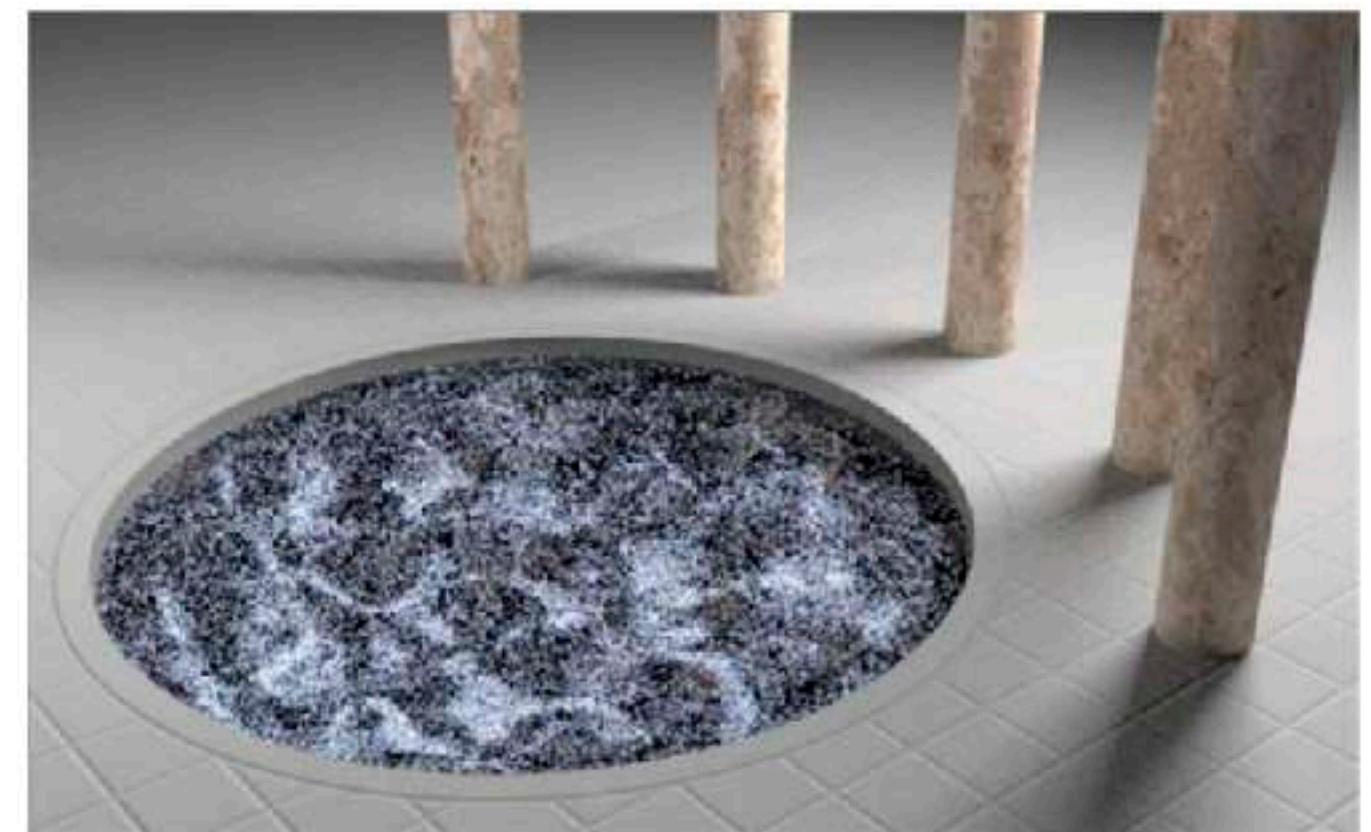


[image courtesy of Shuang Zhao]

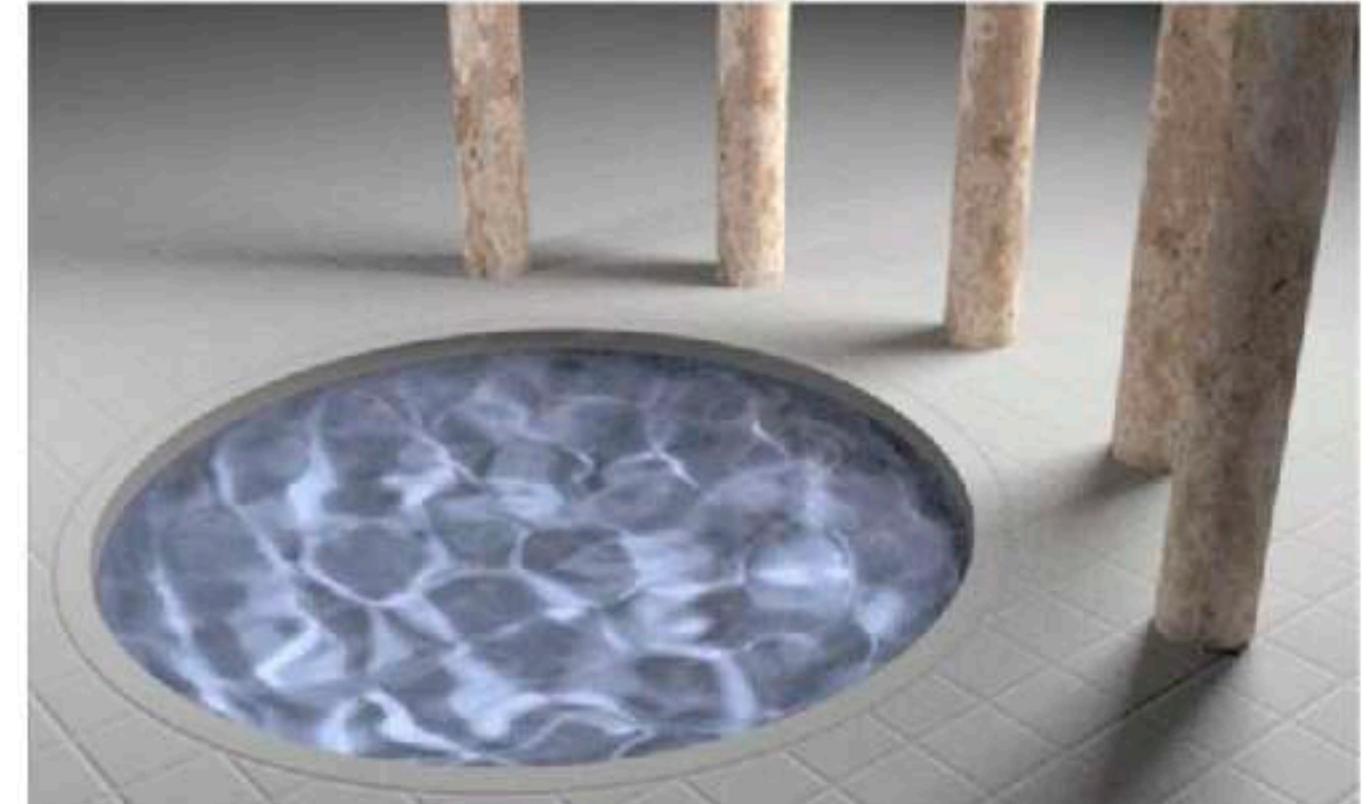
Metropolis Light Transport (MLT) — Pros

- Works great with difficult light paths
- Also unbiased

BDPT



MLT



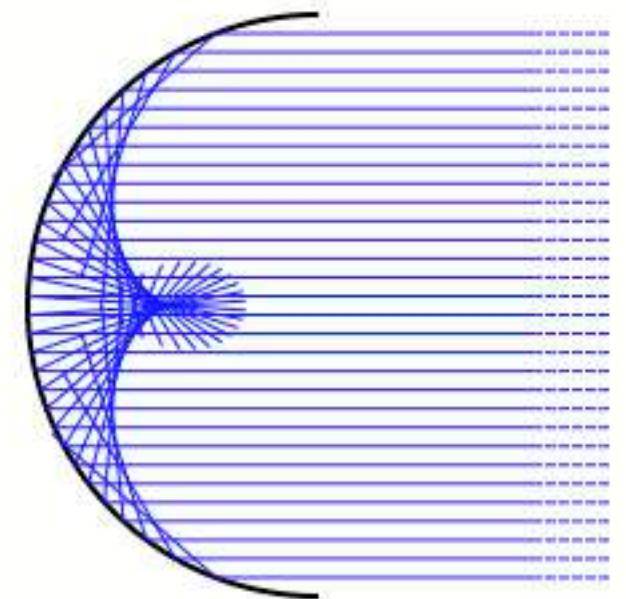
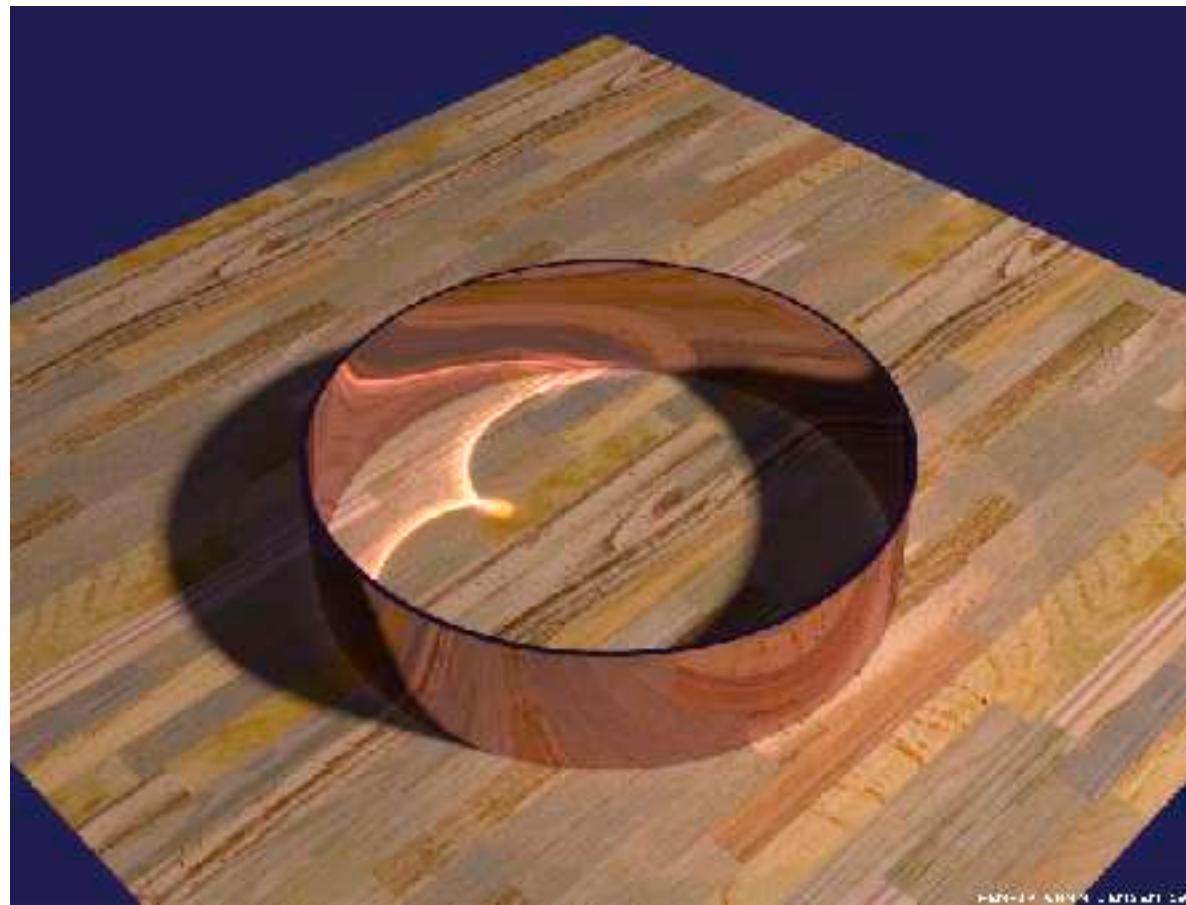
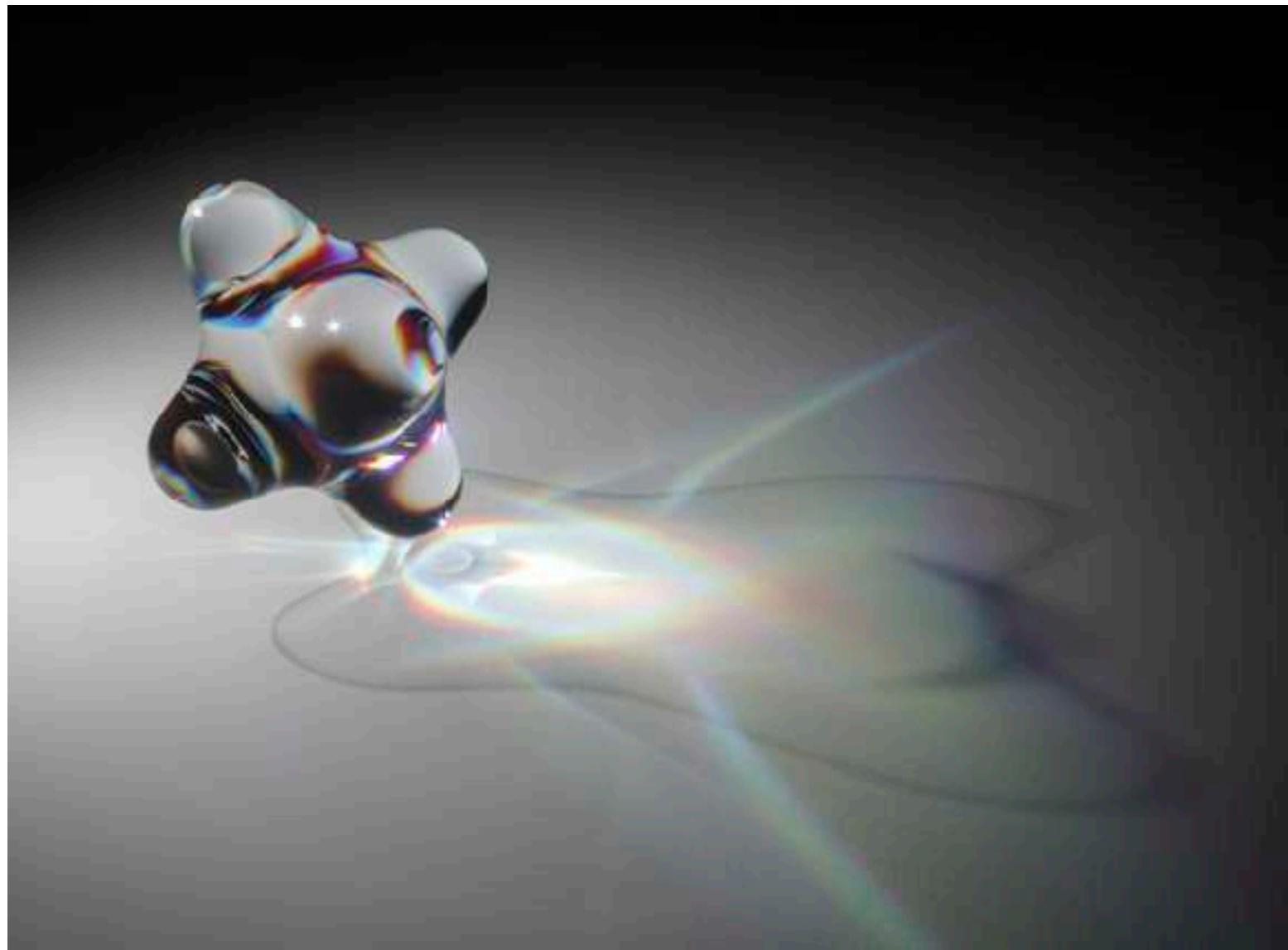
Metropolis Light Transport (MLT) — Cons

- 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



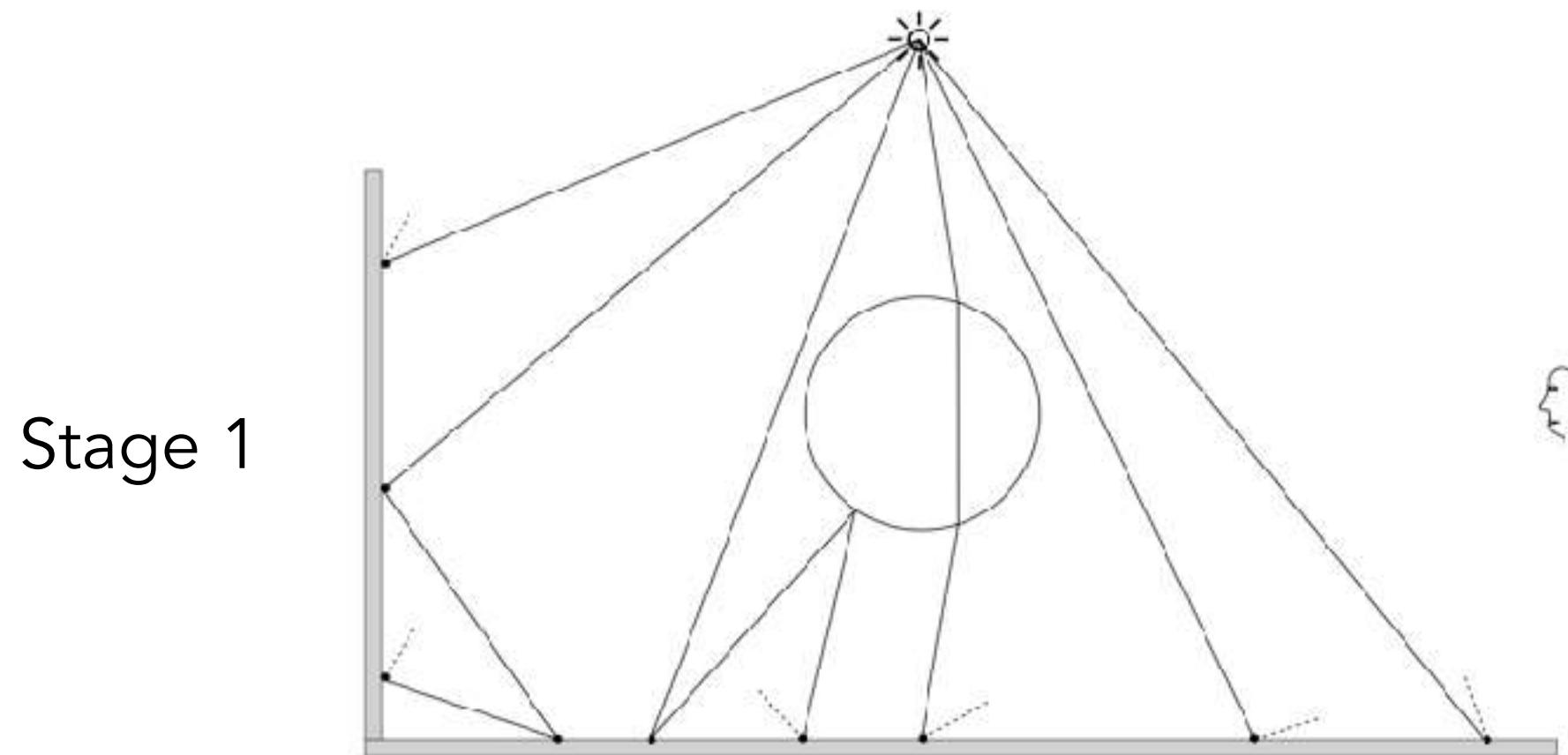
Photon Mapping

- 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

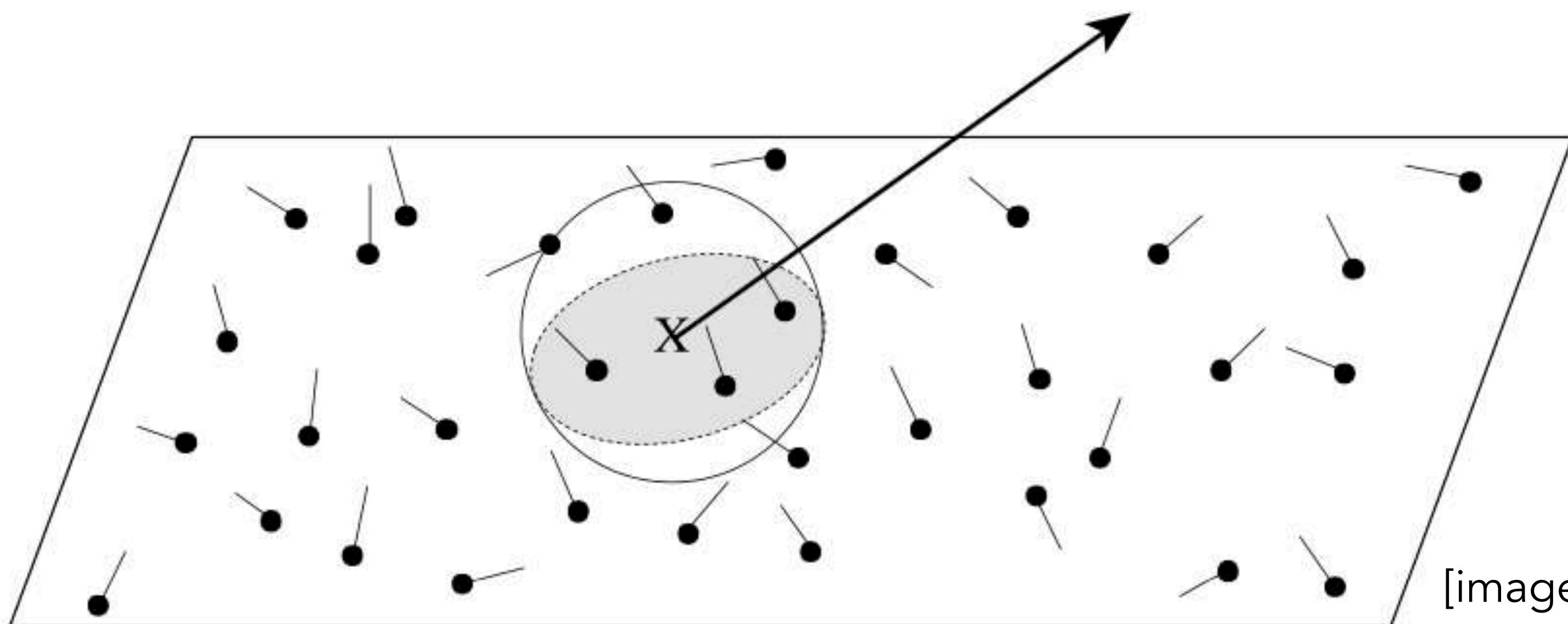


[image courtesy of
Henrik Wann Jensen]

- 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



[image courtesy of
Henrik Wann Jensen]

Photon Mapping

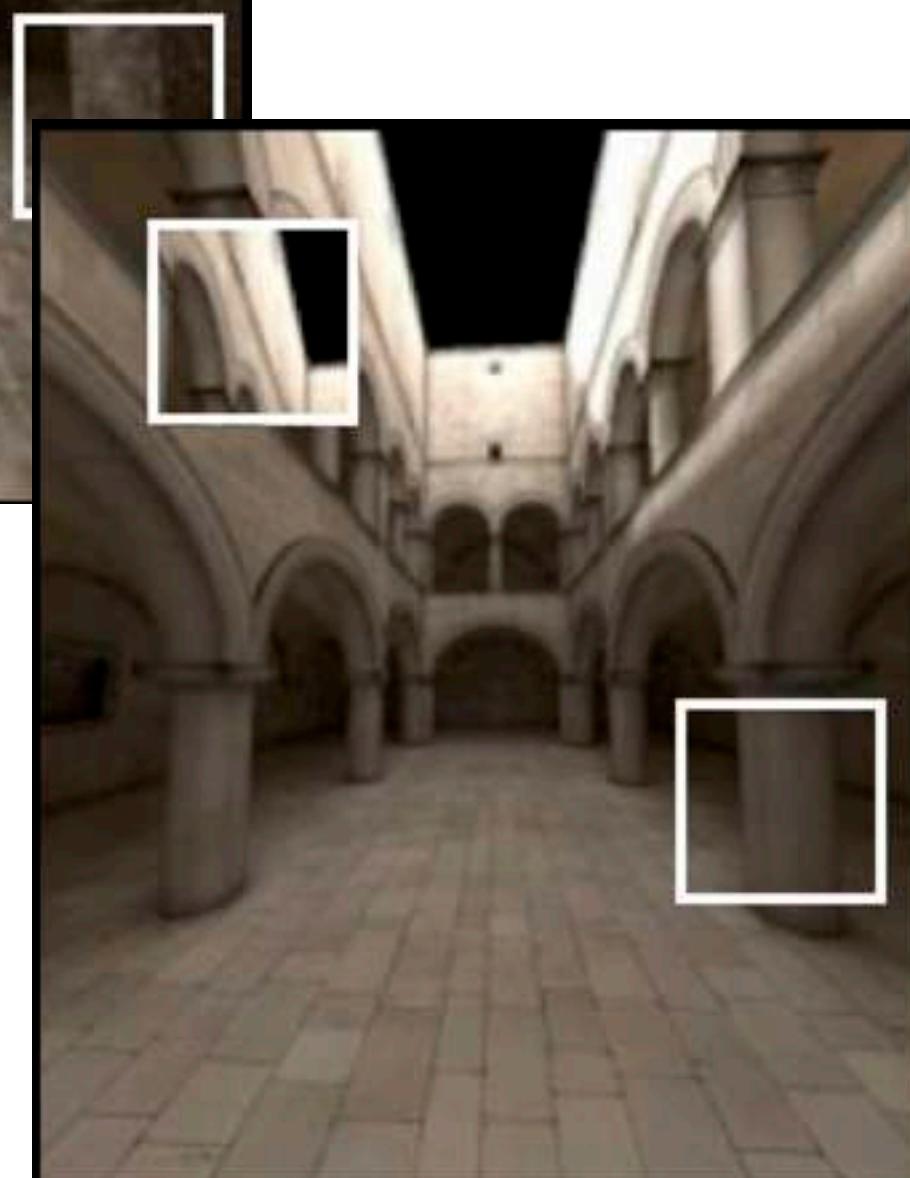
- Why biased?
- Local Density estimation
 $dN / dA \neq \Delta N / \Delta A$
- But in the sense of limit
 - More photons emitted ->
 - the same N photons covers a smaller ΔA ->
 - ΔA is closer to dA
- So, biased but consistent!



Small $N \leftrightarrow$ noisy



large $N \leftrightarrow$ blurry

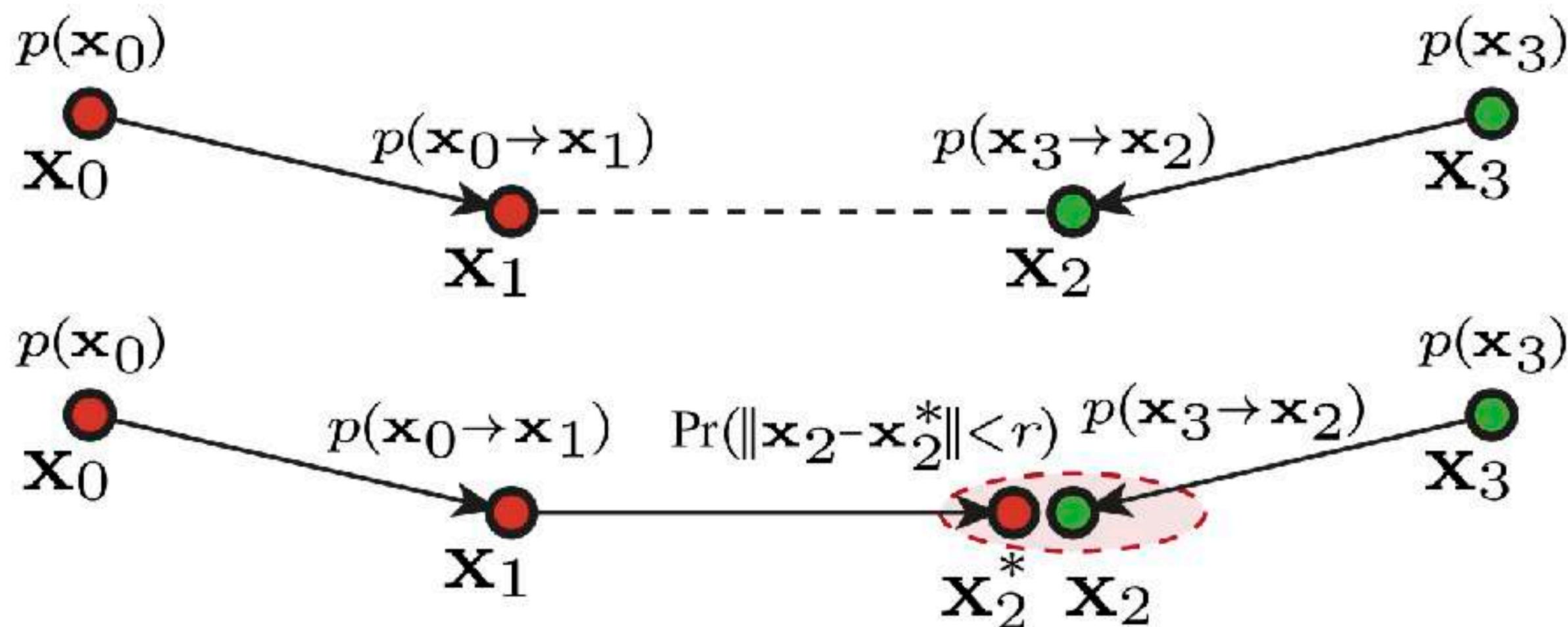


Photon Mapping

- 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

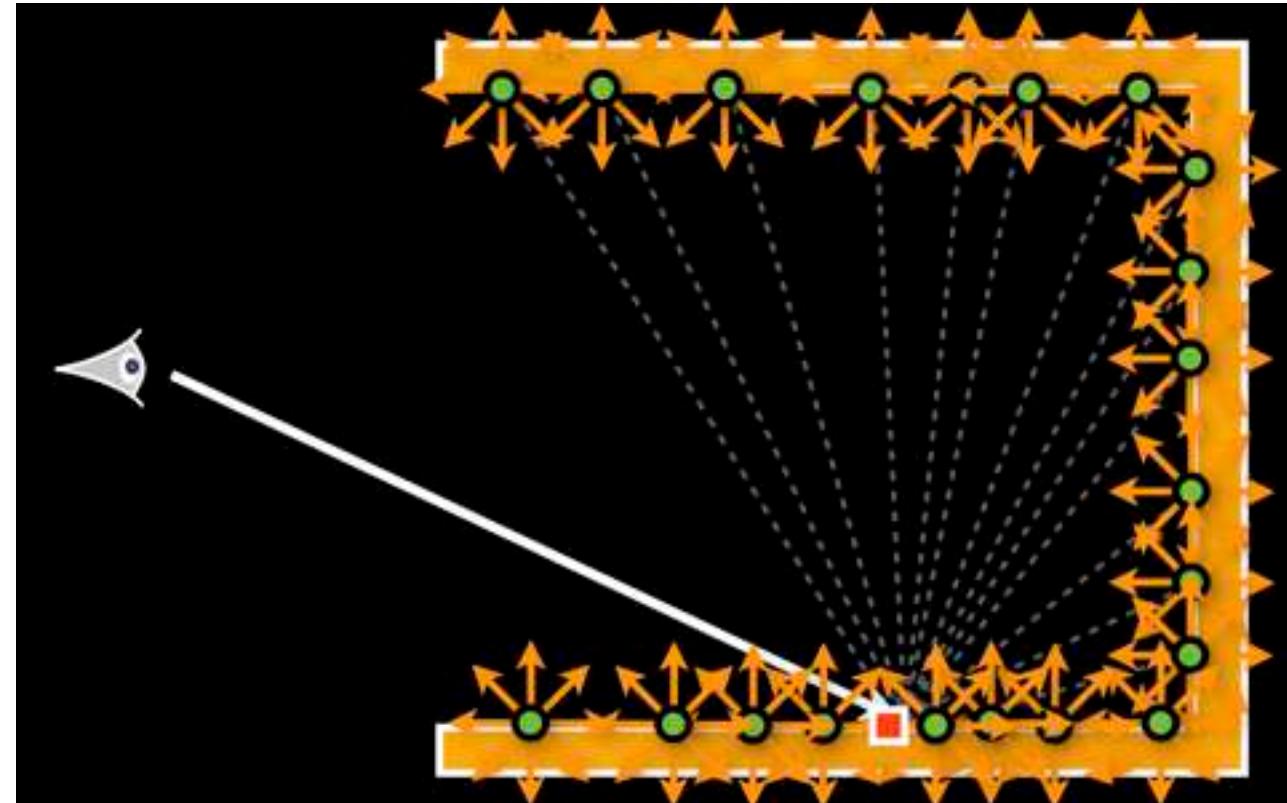
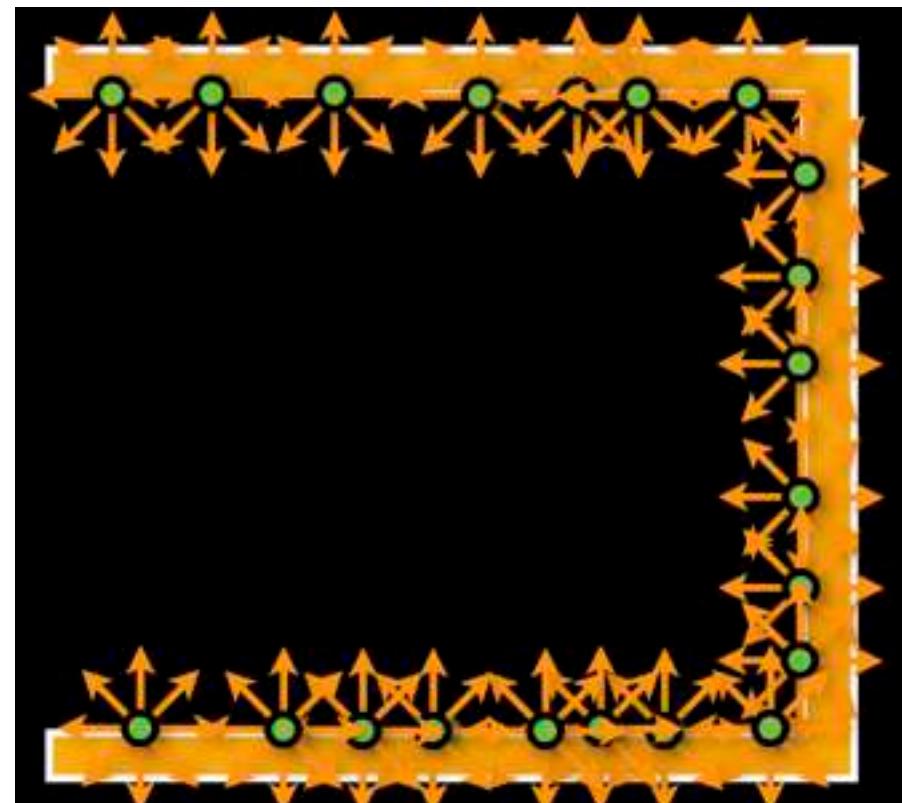
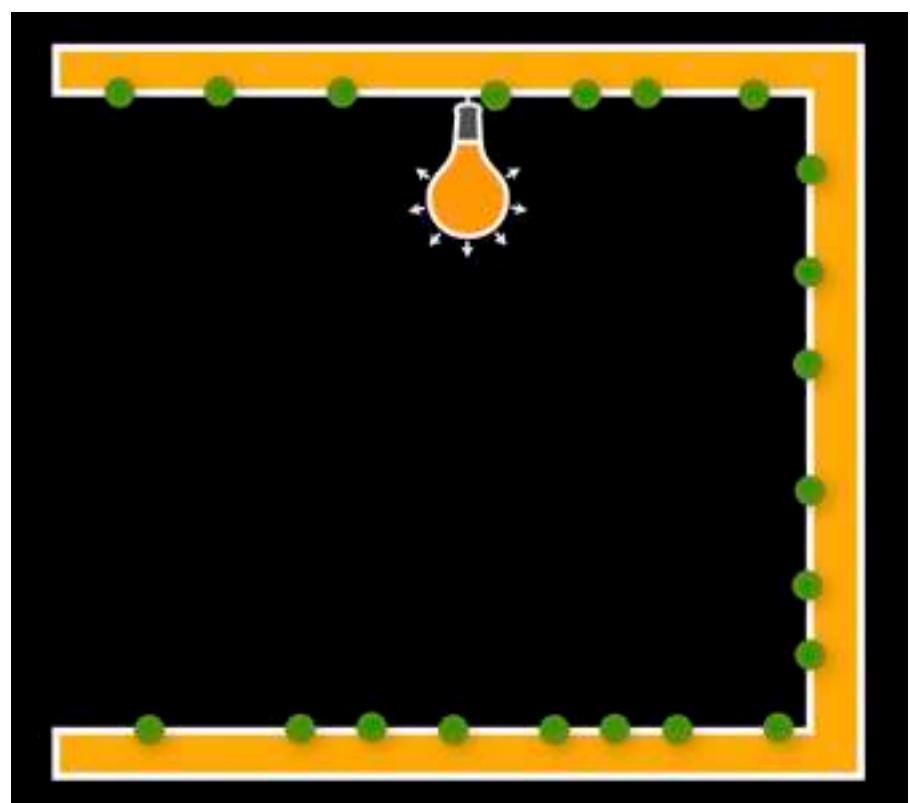
- A combination of BDPT and Photon Mapping
- Key idea
 - Let's not waste the sub-paths in BDPT if their end points cannot be connected but can be merged
 - Use photon mapping to handle the merging of nearby “photons”



[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



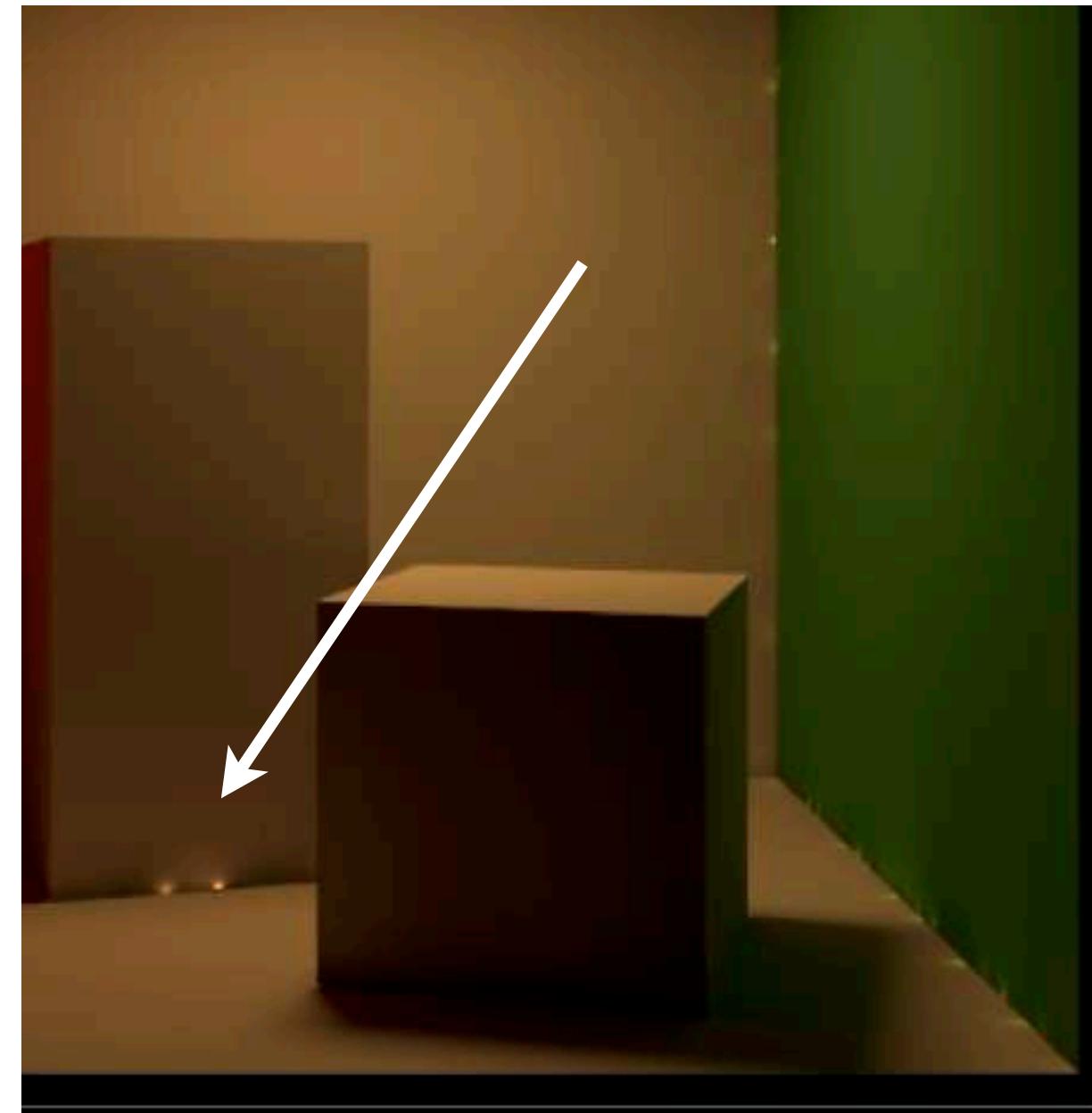
[image
courtesy of
Derek N.]

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



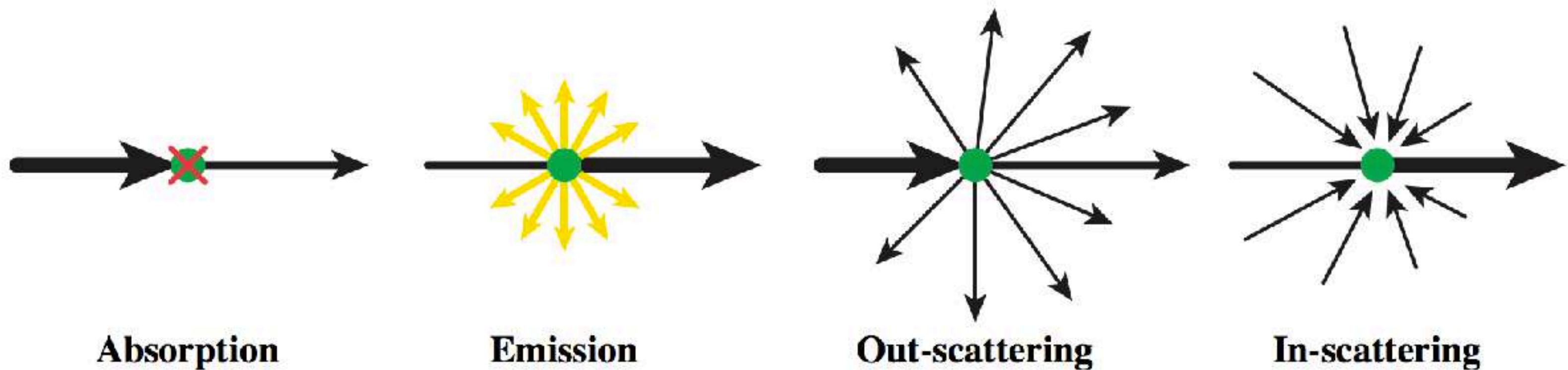
Participating Media: Cloud



[by thephotographer0]

Participating Media

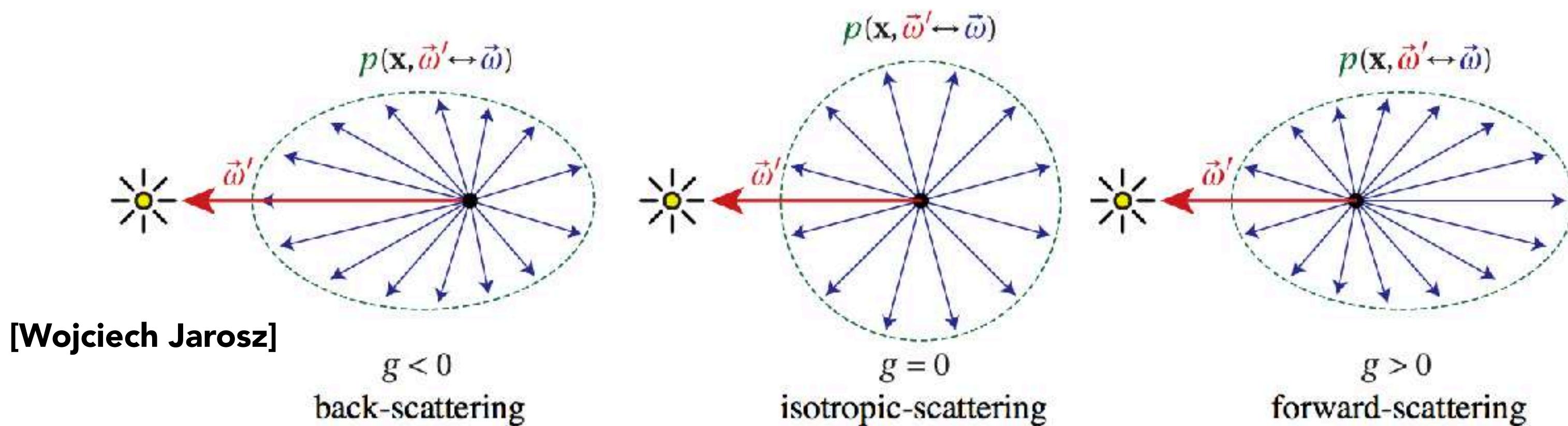
- At any point as light travels through a participating medium, it can be (partially) absorbed and scattered.



[Wojciech Jarosz]

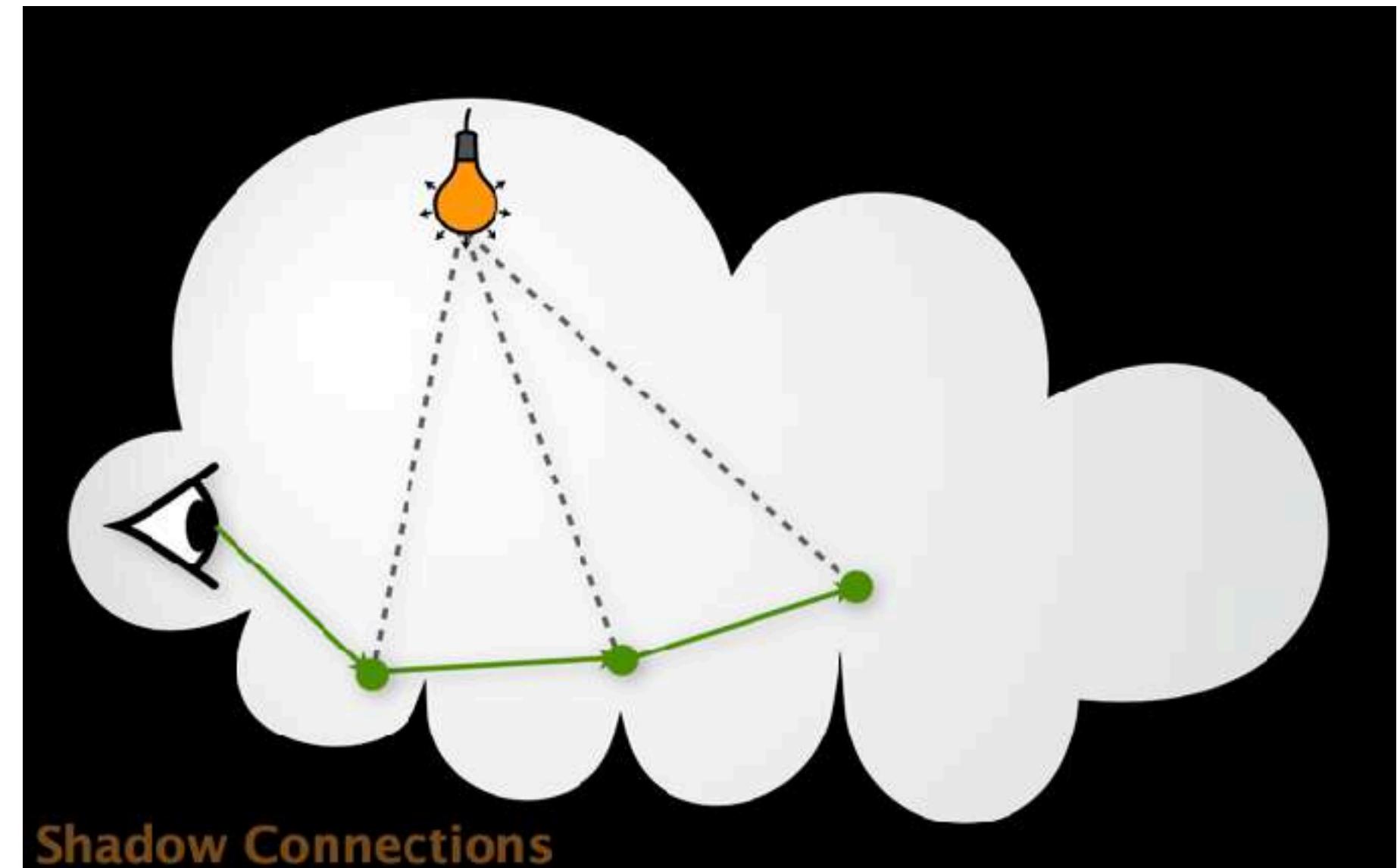
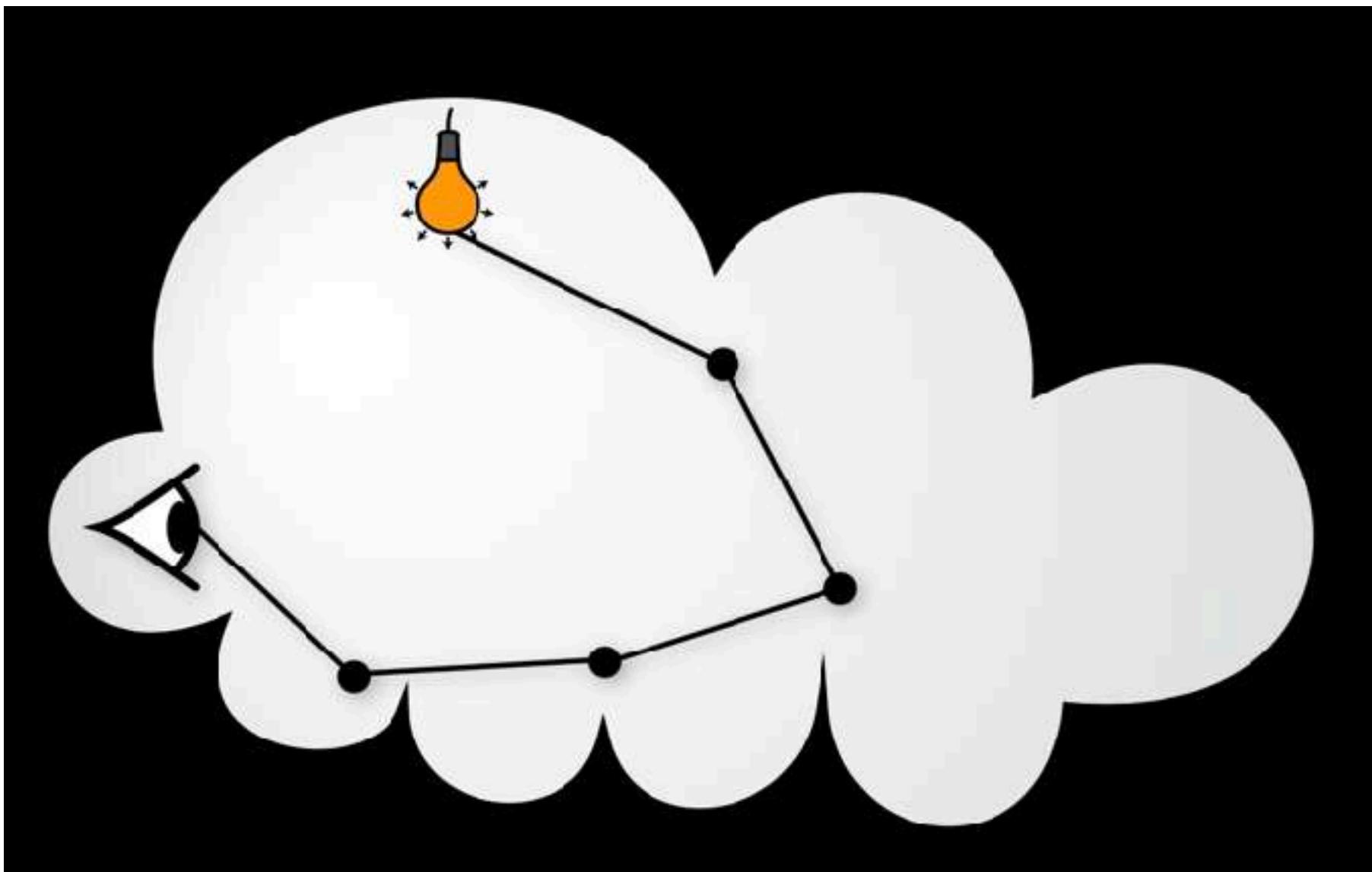
Participating Media

- 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

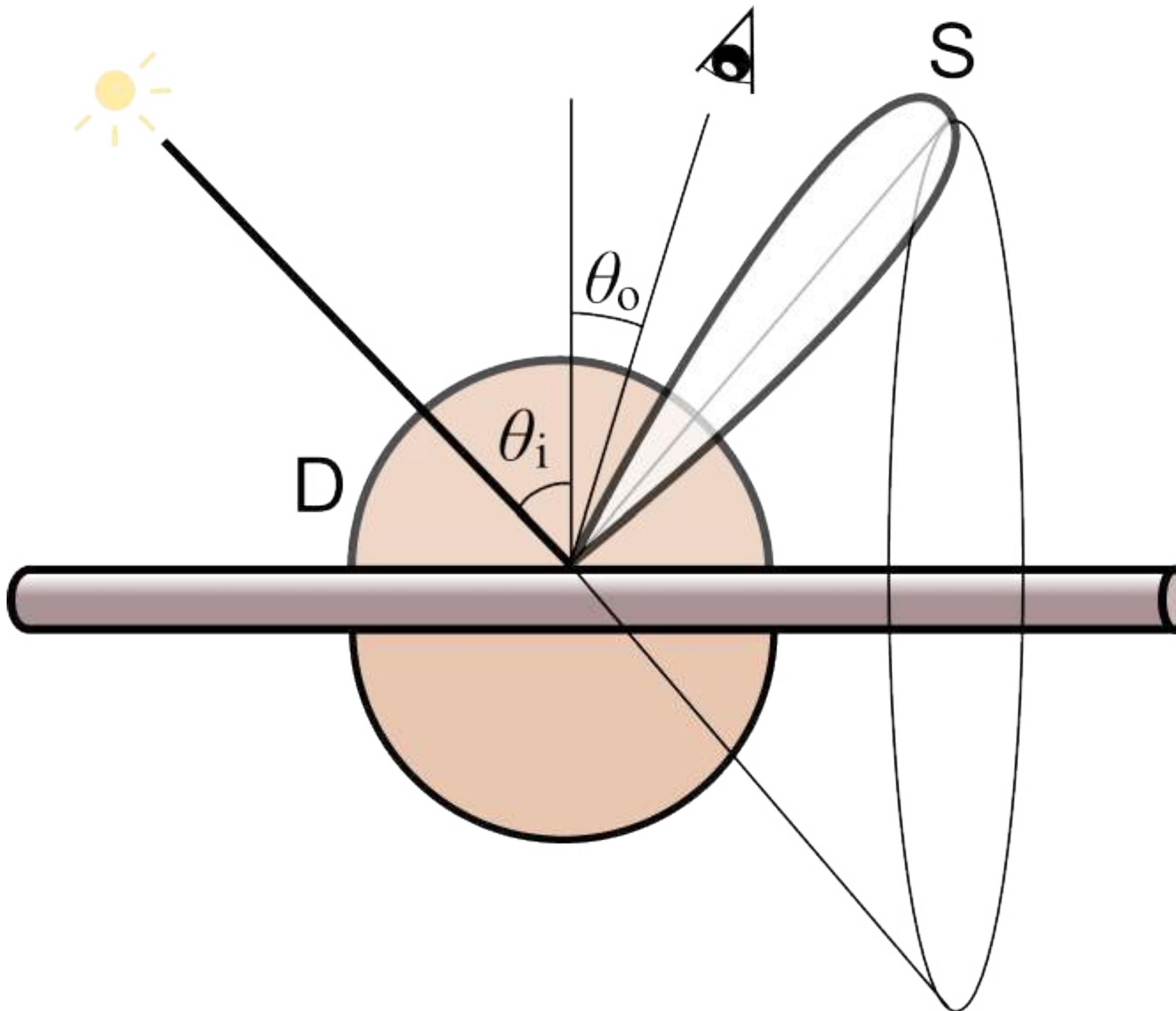


[Stomakhin et al. 2014]

Hair Appearance



Kajiya-Kay Model



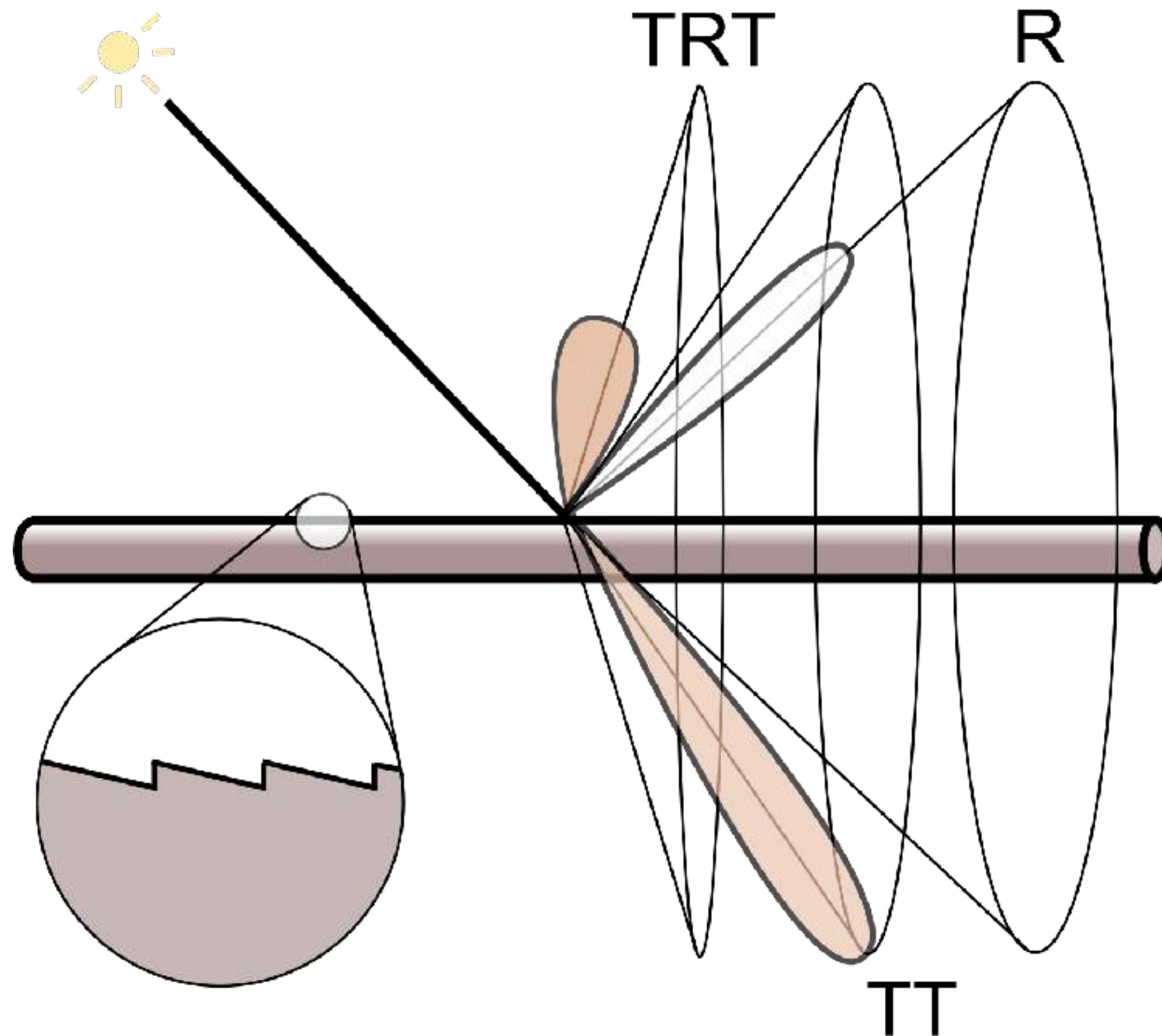
[Image courtesy of Chiwei Tseng]

Kajiya-Kay Model



[Yuksel et al. 2008]

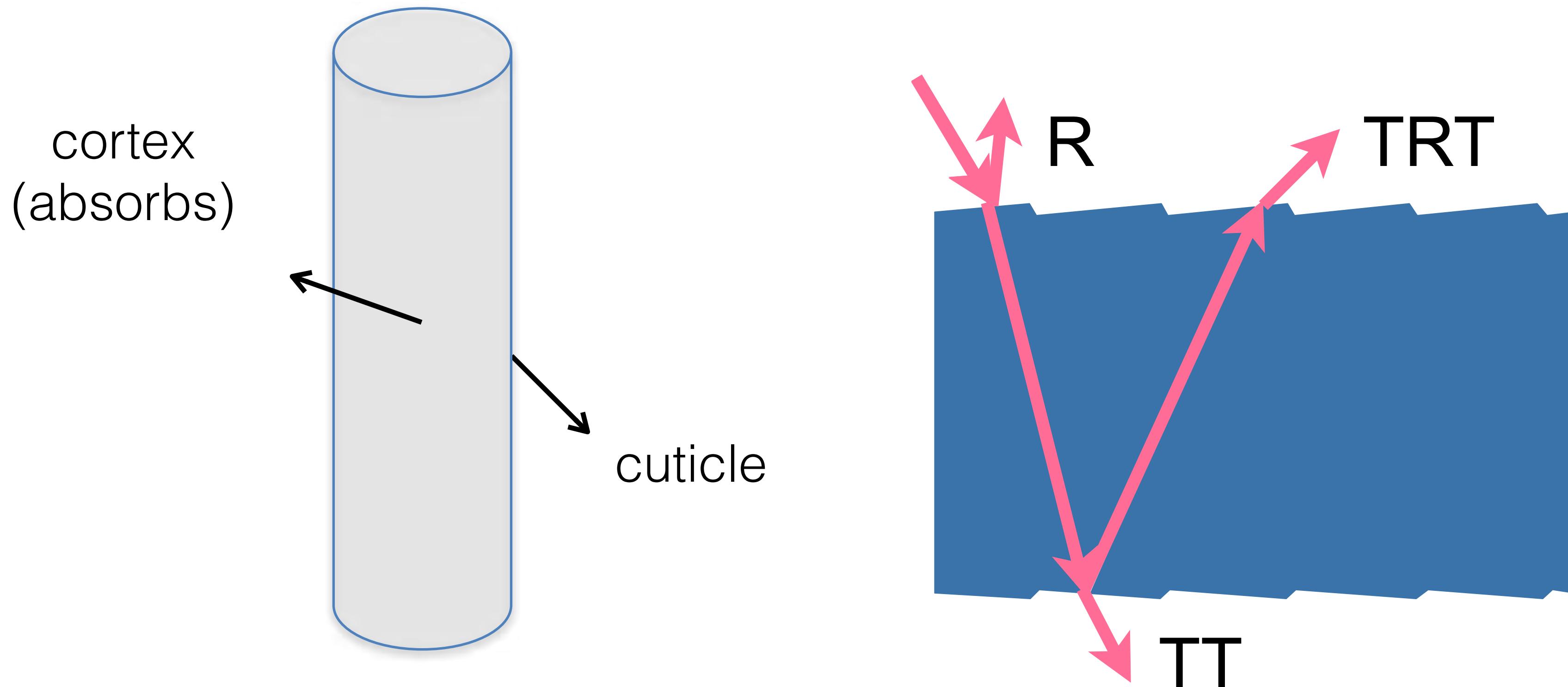
Marschner Model



[Image courtesy of Chiwei Tseng]

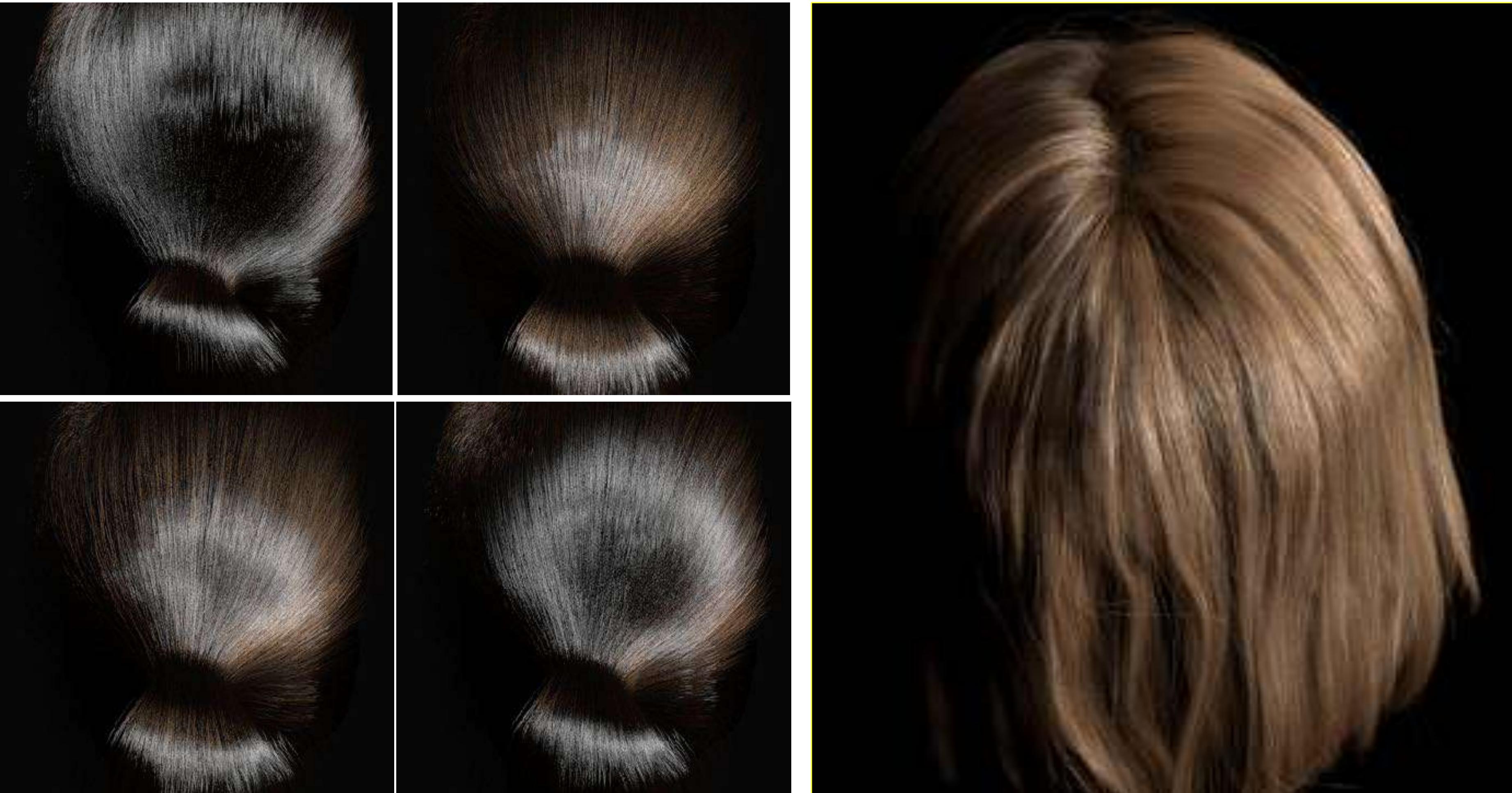
Marschner Model

- 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]

Hair Appearance Model: Application



[Zootopia. 2016 Disney]

Fur Appearance — As Human Hair

- Cannot represent diffusive and saturated appearance

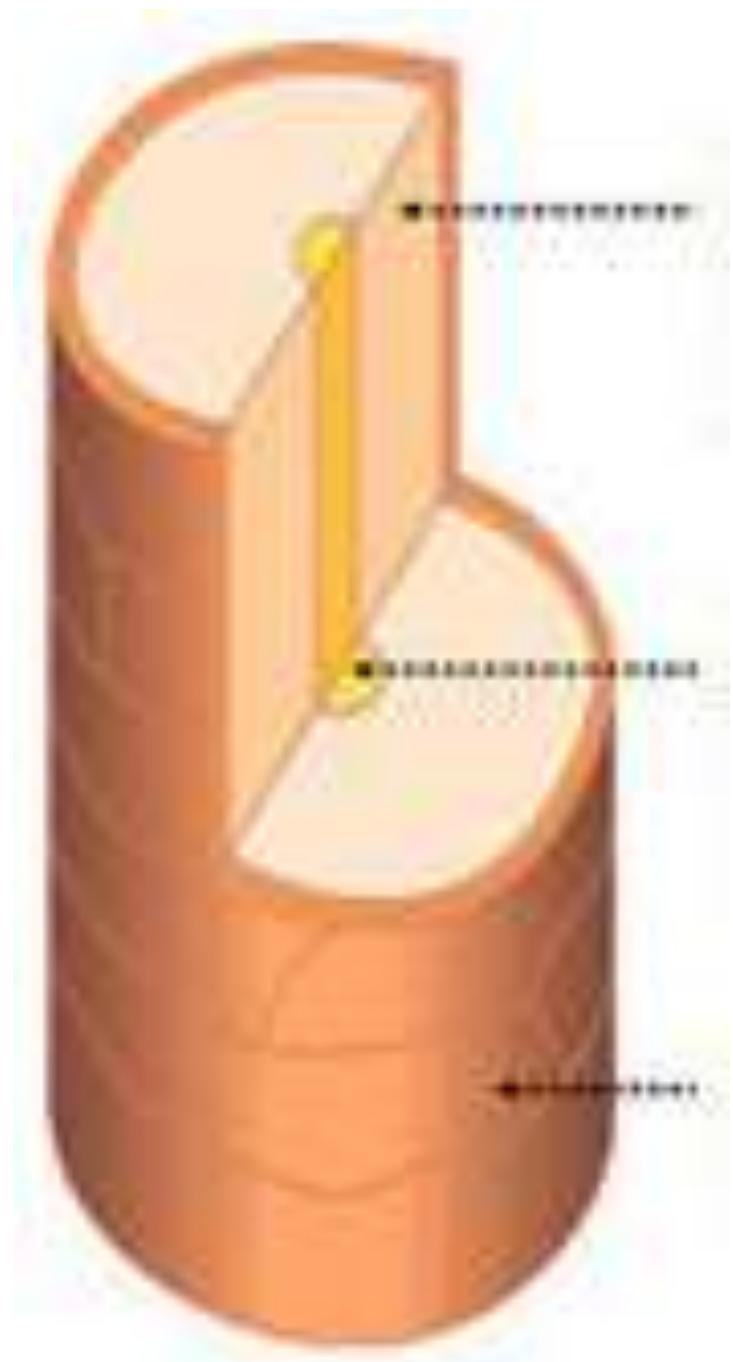


Rendered as human hair
[Marschner et al. 2003]



Rendered as animal fur
[Yan et al. 2015]

Human Hair vs Animal Fur



Cortex

- Contains pigments
- **Absorbs light**

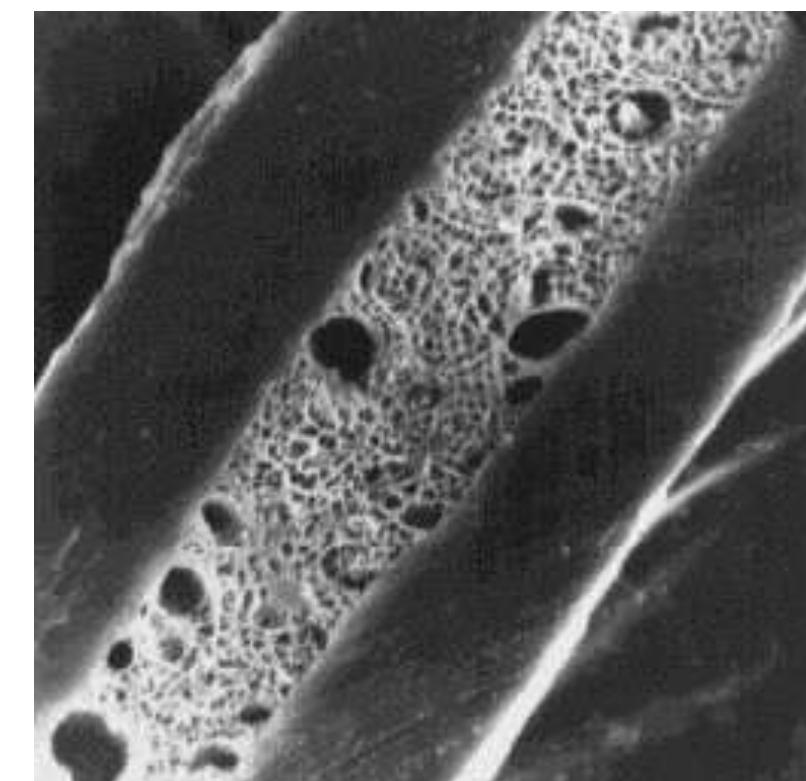
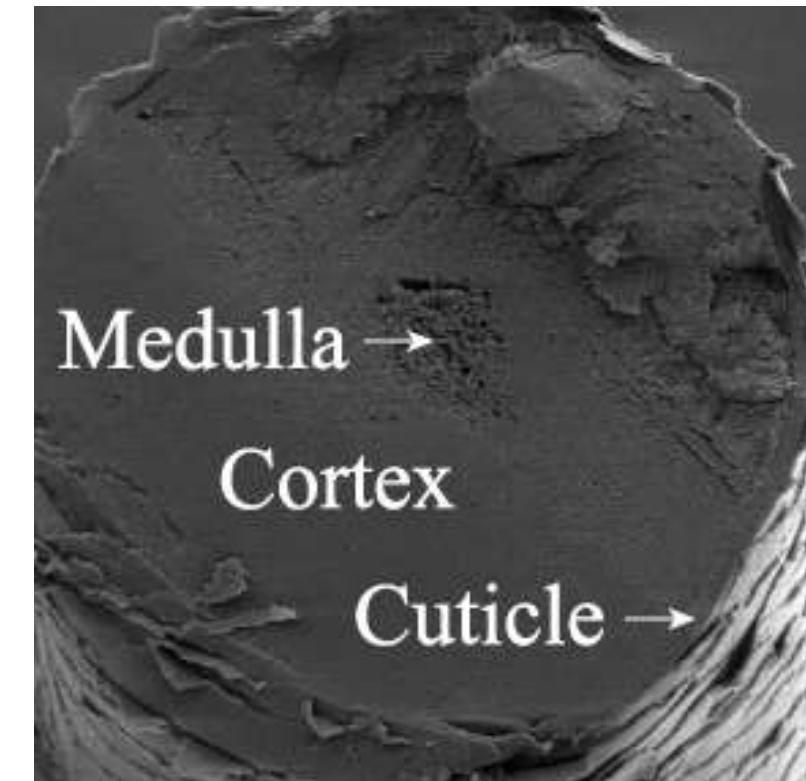
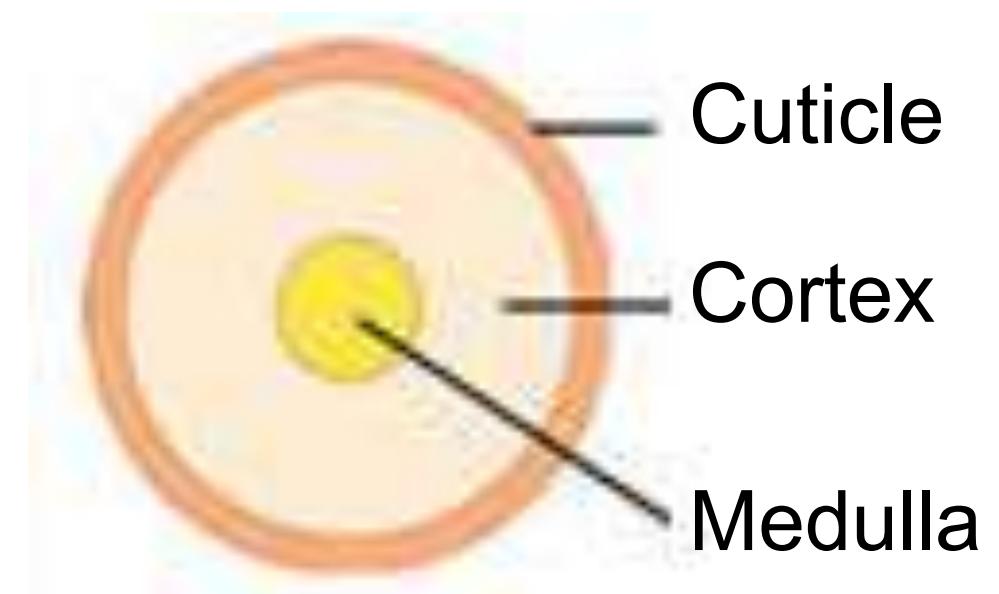
Medulla

- 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

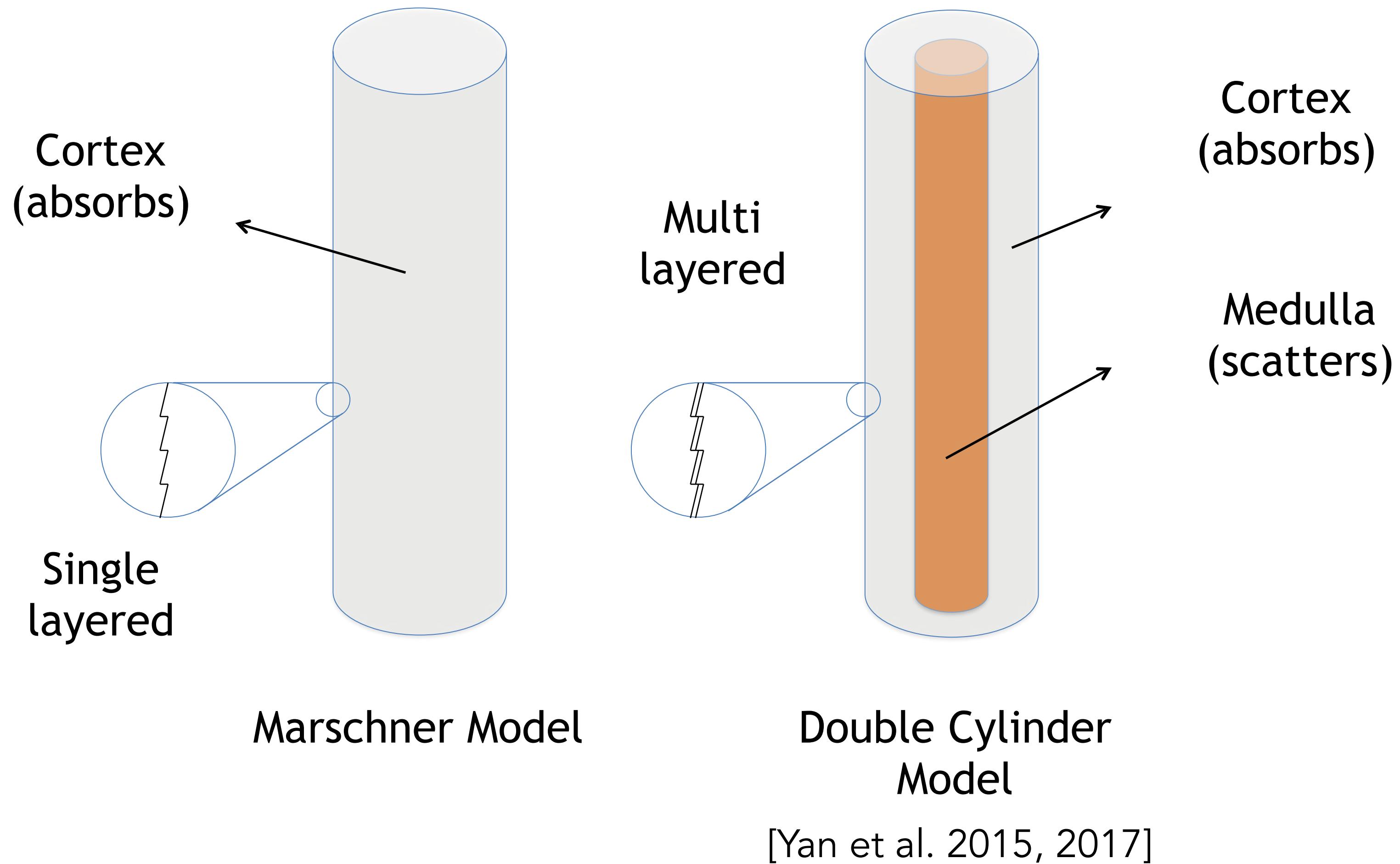


Without medulla

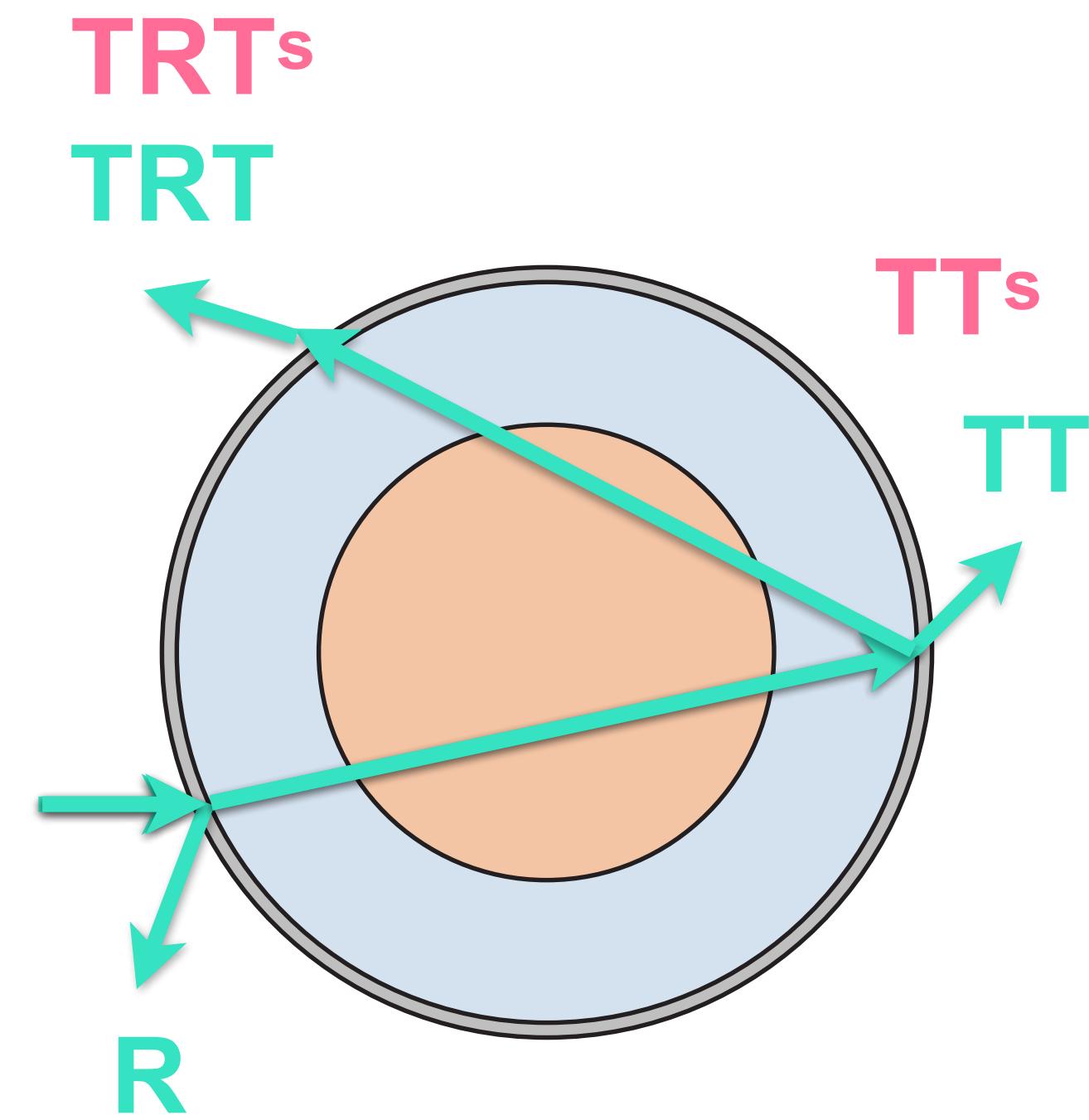
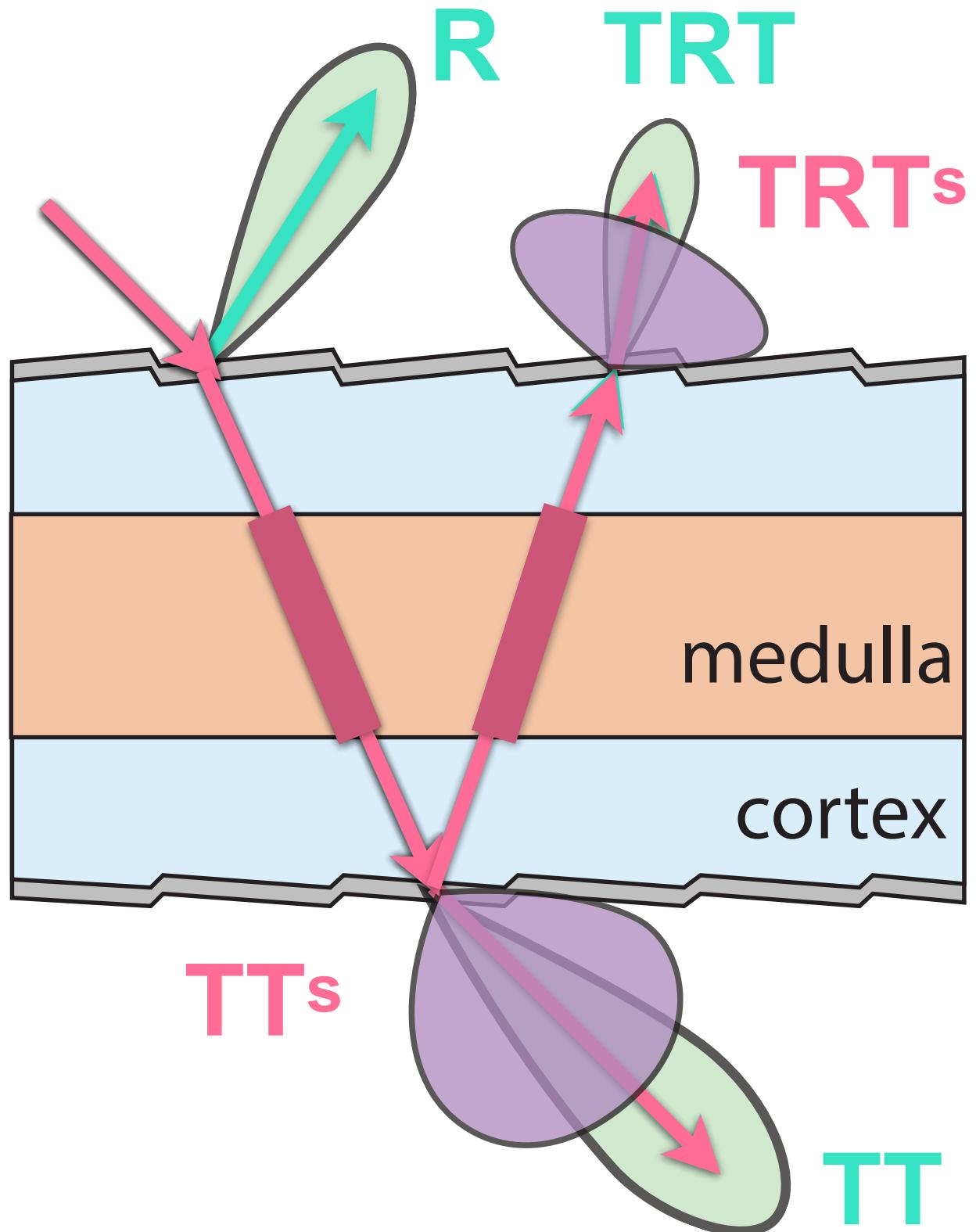


With medulla (**15%**)

Double Cylinder Model



Double Cylinder Model — Lobes



Double Cylinder Model — Lobes



All

R

TT

TRT

TTs

TRTs

600,000 fur fibers

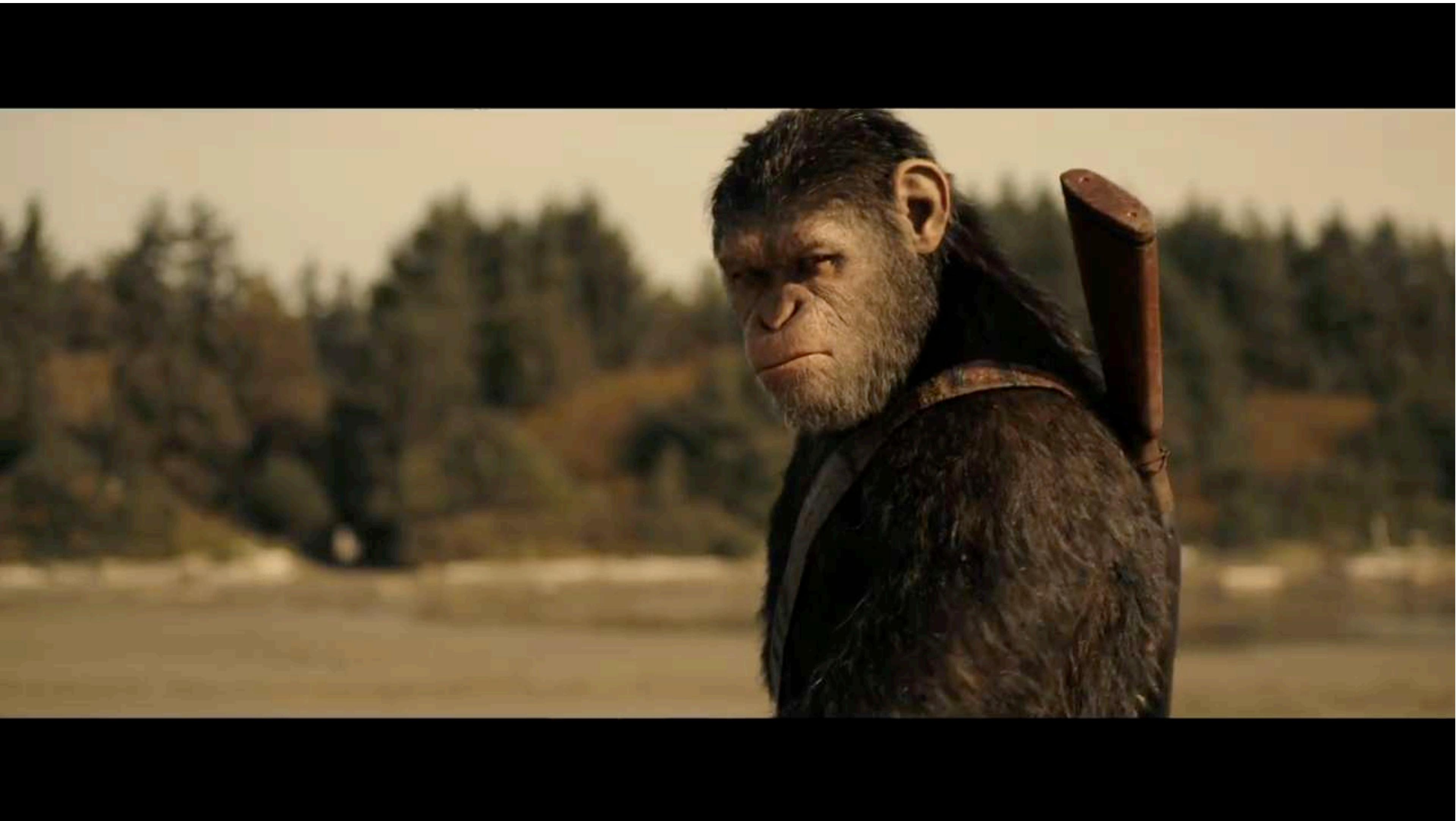
1024 samples / pixel

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

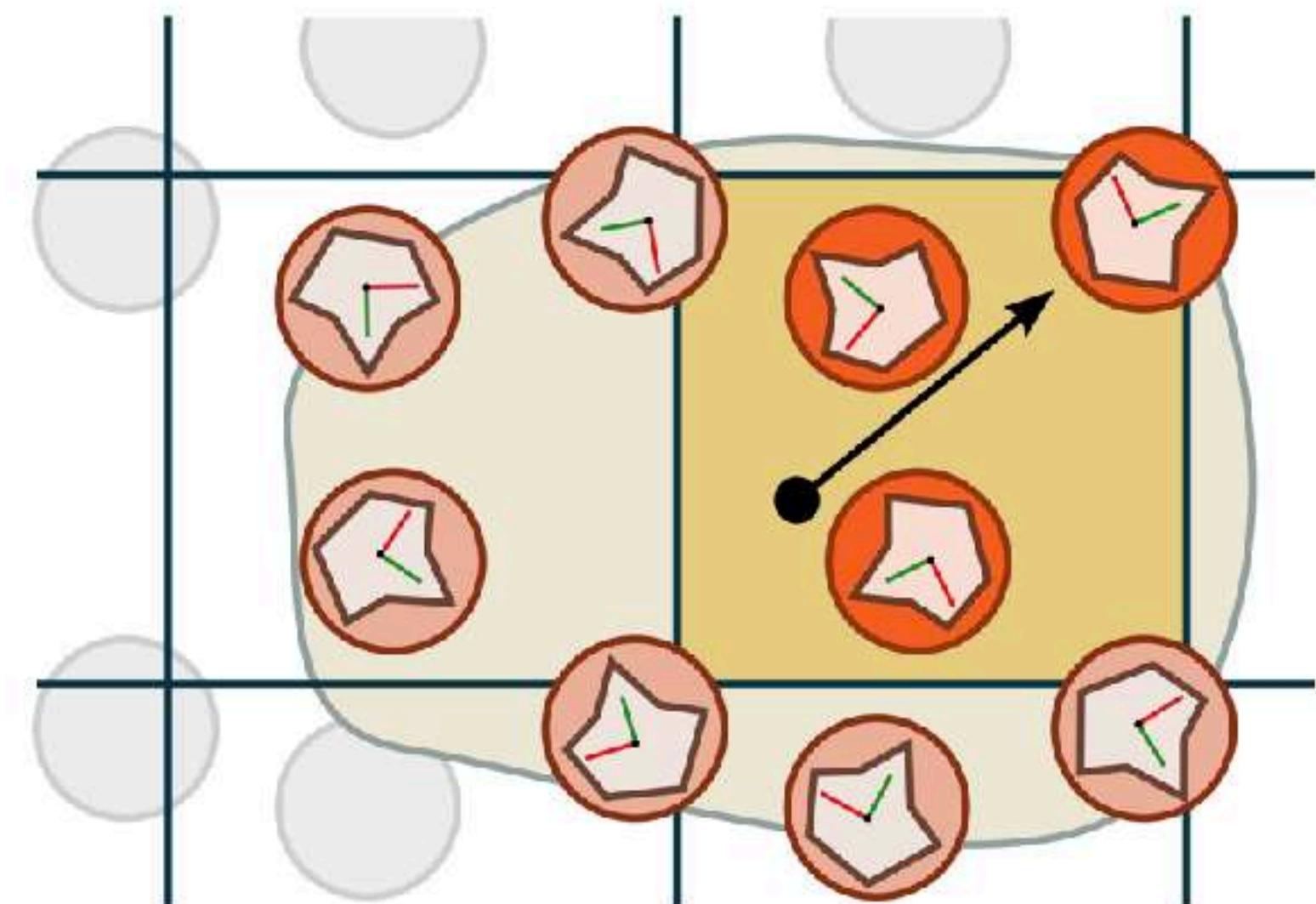
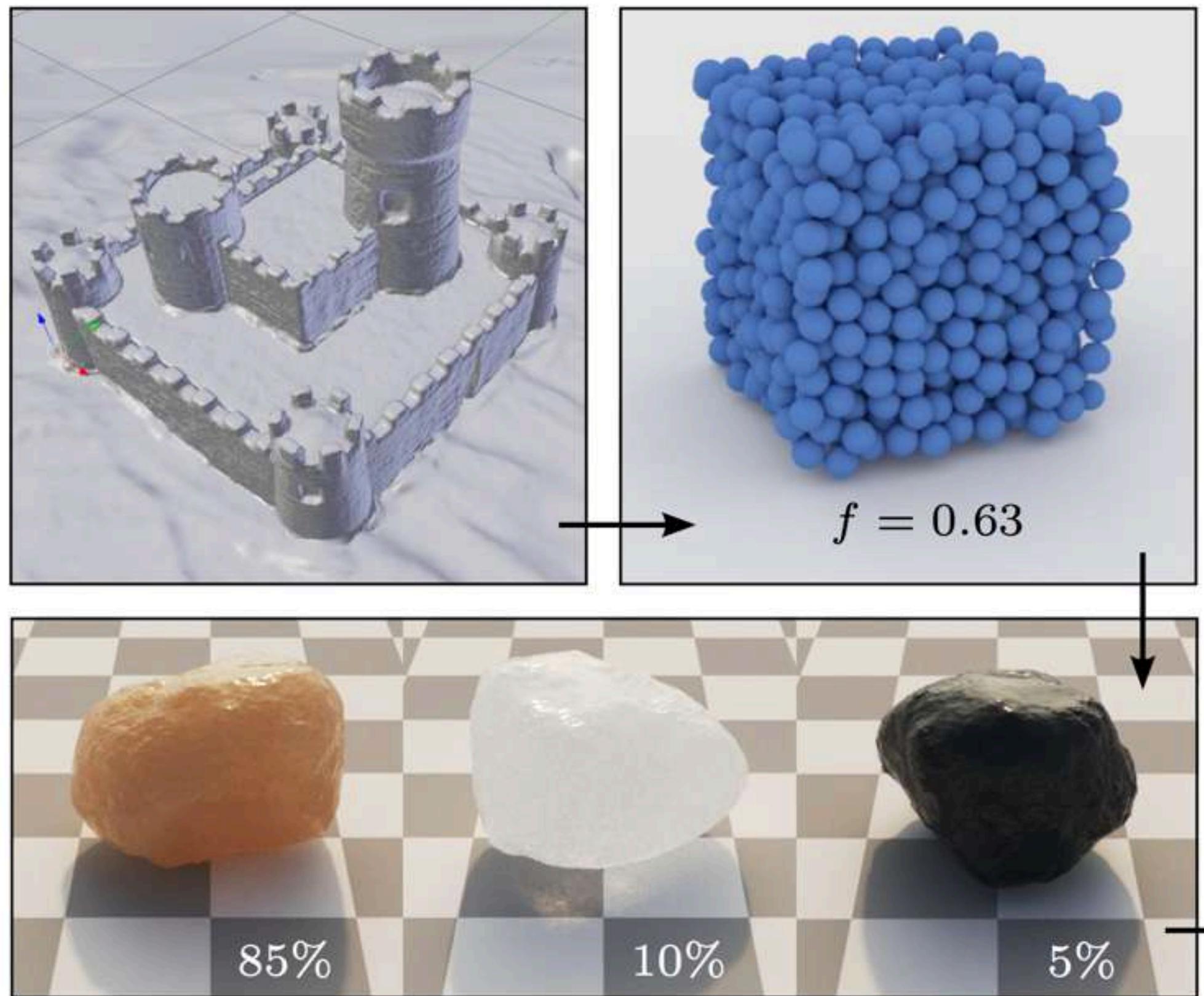
■ What is granular material?



[Meng et al. 2015]

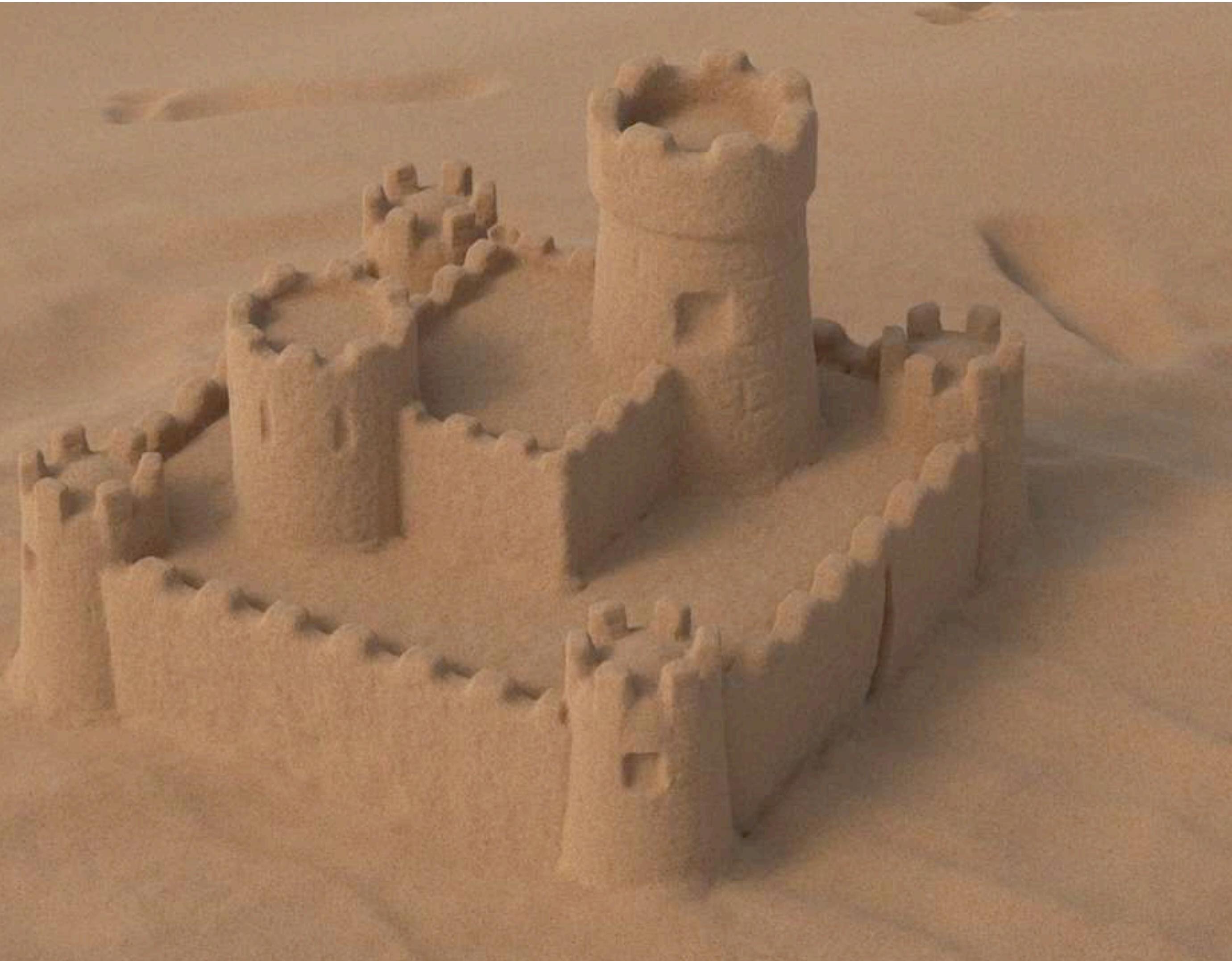
Granular Material

- 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



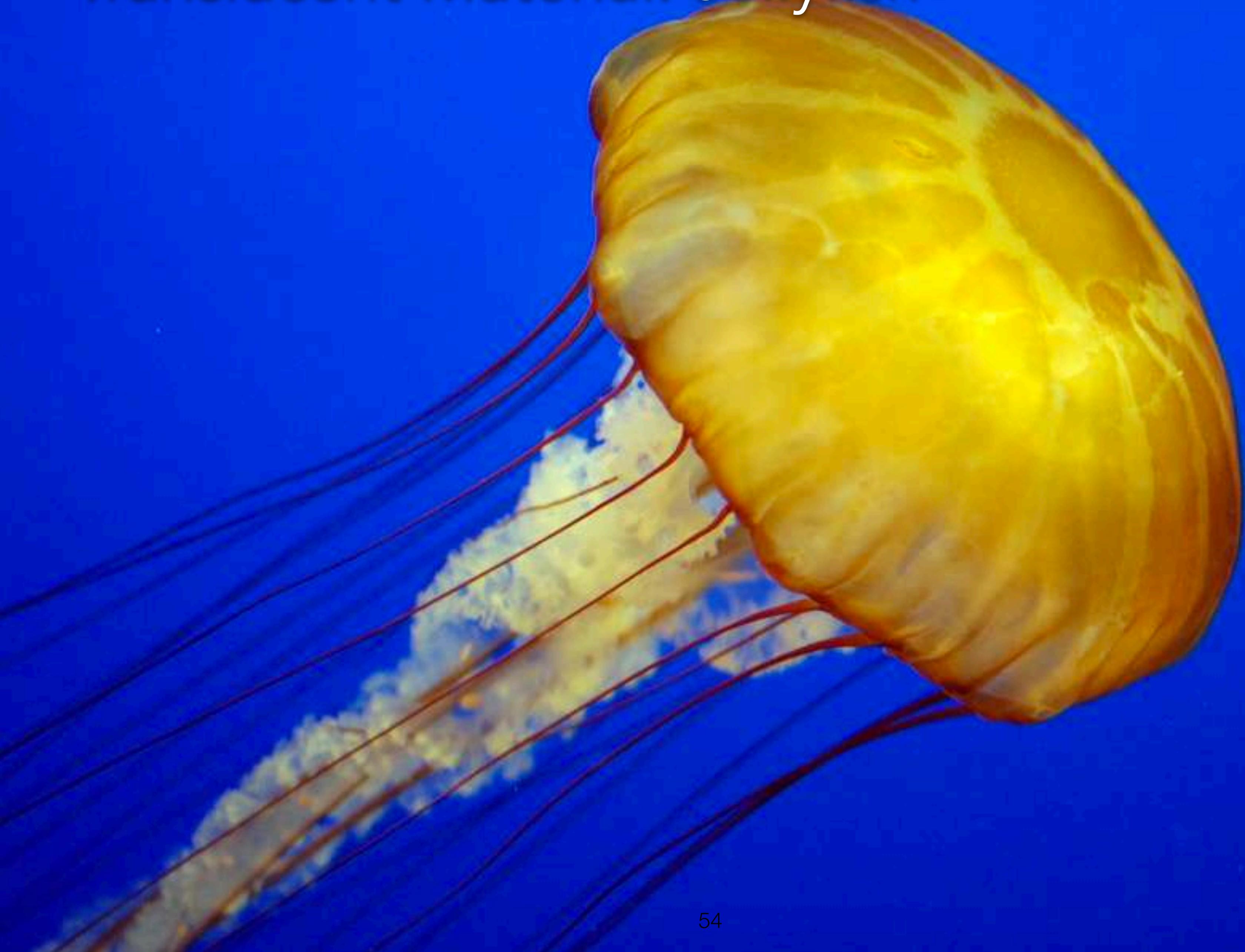
[Piper. 2016 Pixar]

Surface Models

Translucent Material: Jade



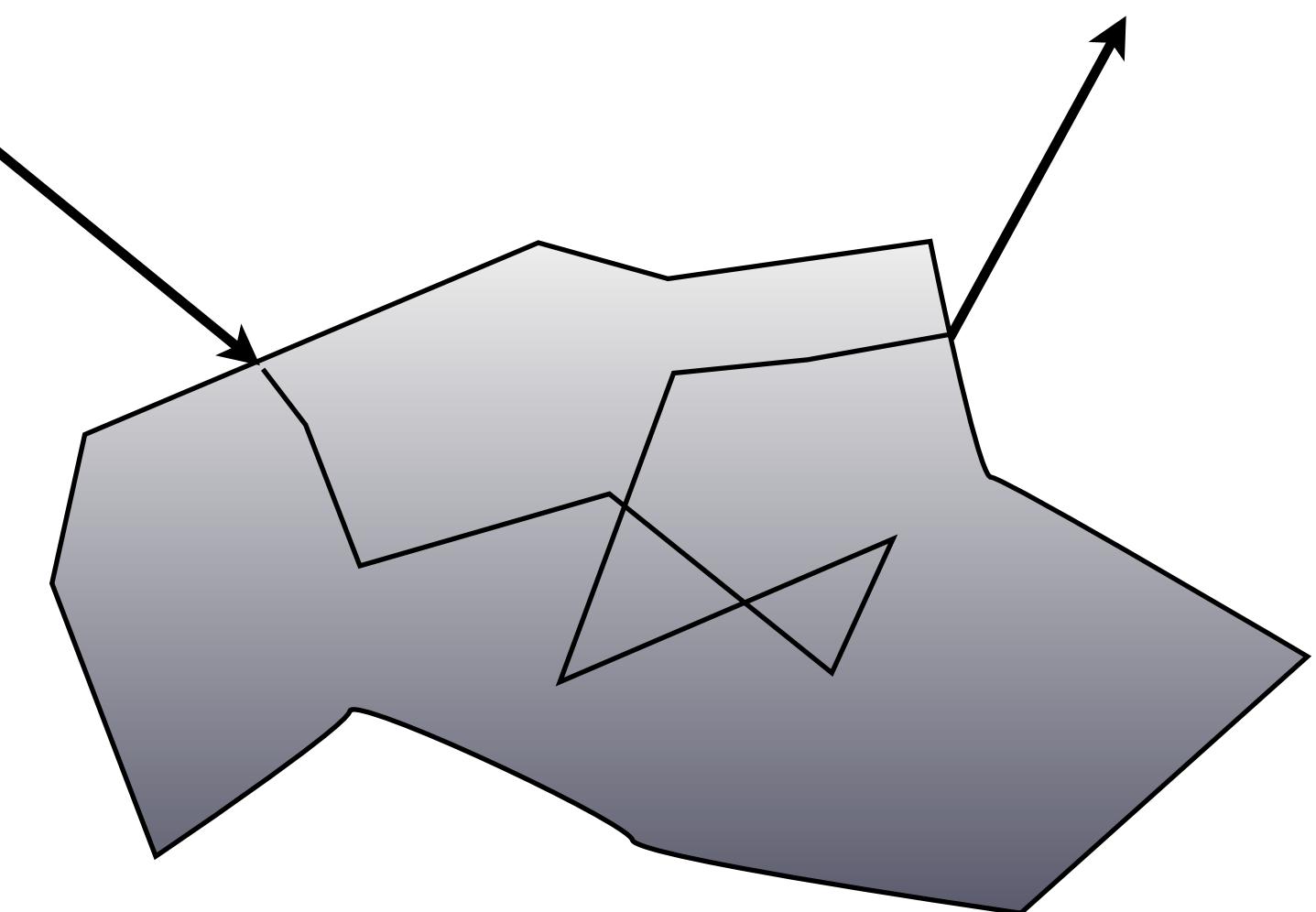
Translucent Material: Jellyfish



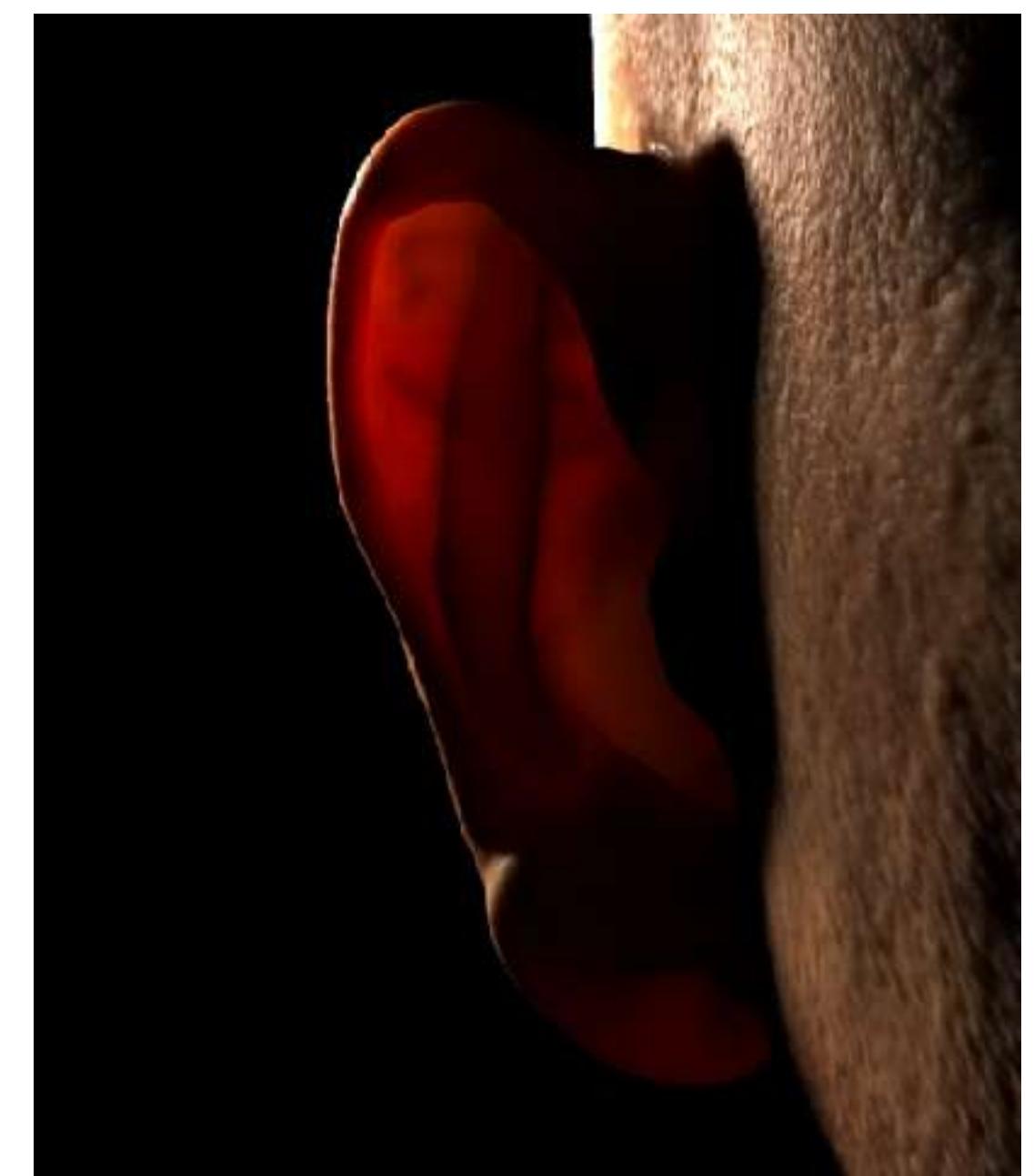
Subsurface Scattering

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]

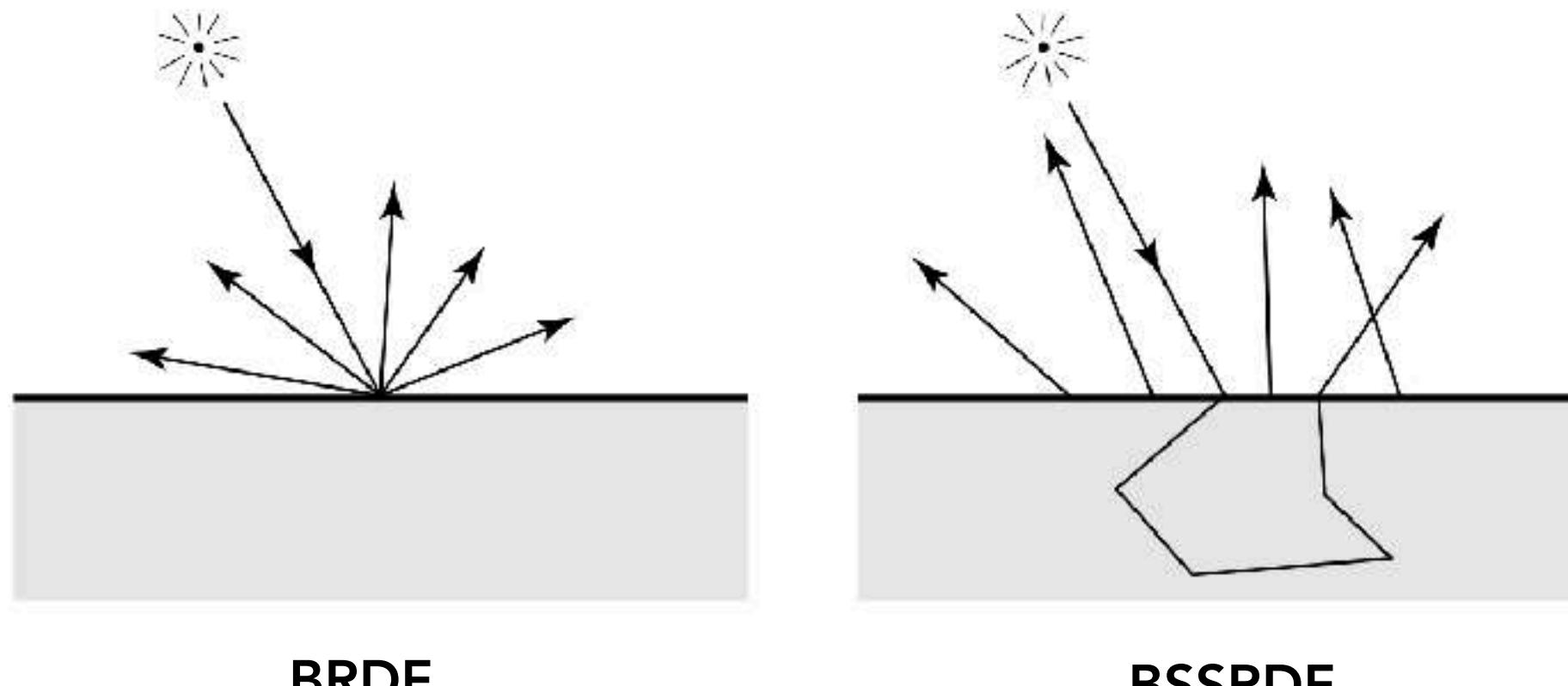
Scattering Functions

- 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 (!)

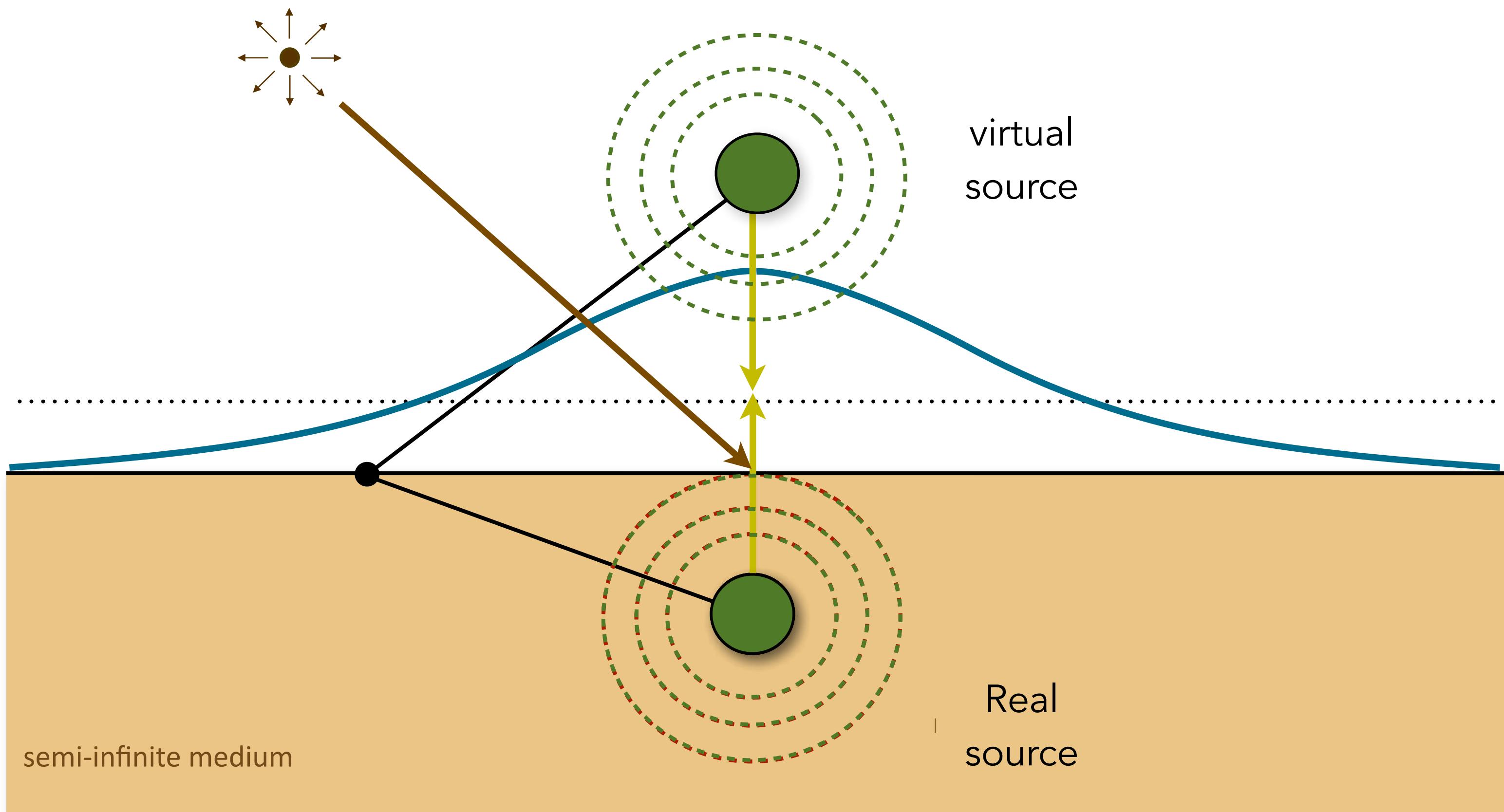
$$L(x_o, \omega_o) = \int_A \int_{H^2} S(x_i, \omega_i, x_o, \omega_o) L_i(x_i, \omega_i) \cos \theta_i d\omega_i dA$$



[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



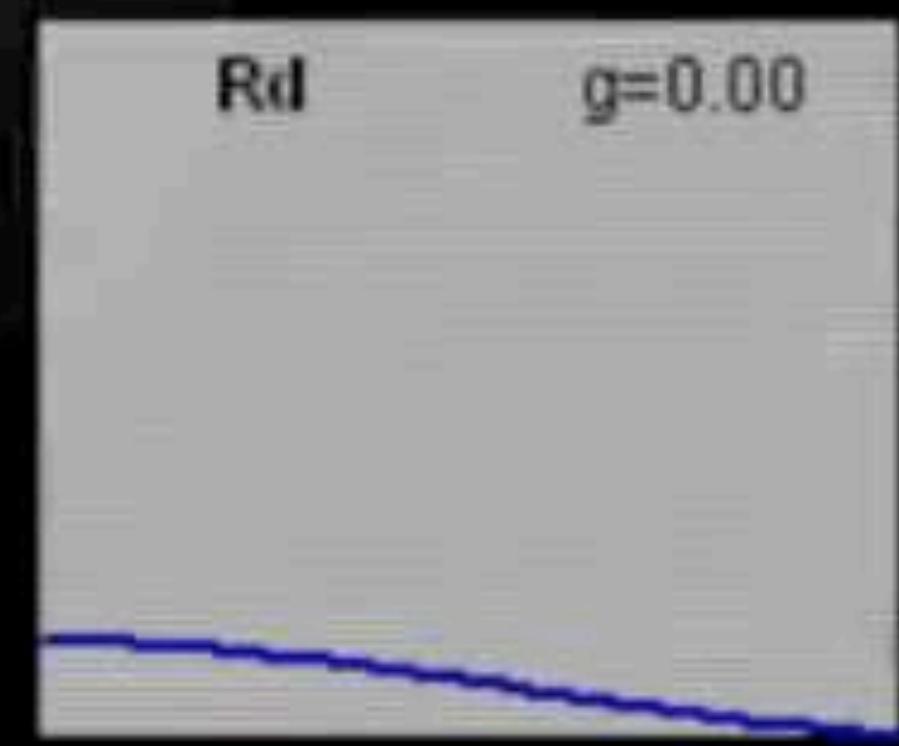
BRDF

[Jensen et al. 2001]



BSSRDF

BSSRDF: Demo



BSSRDF: Application



[Artist: Teruyuki and Yuka]



[Artist: Hyun Kyung]

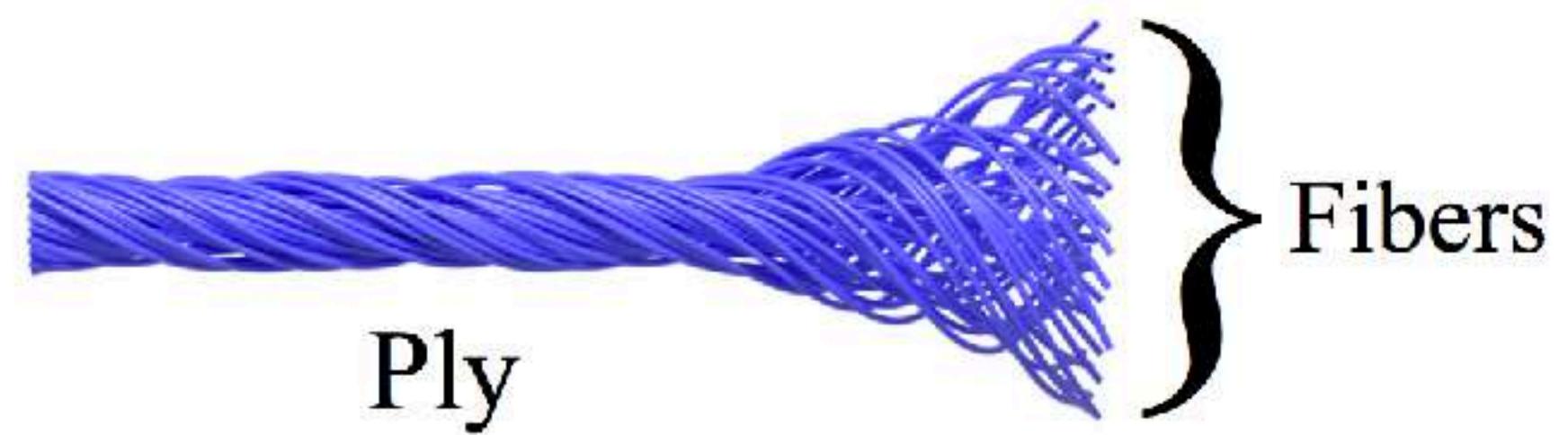
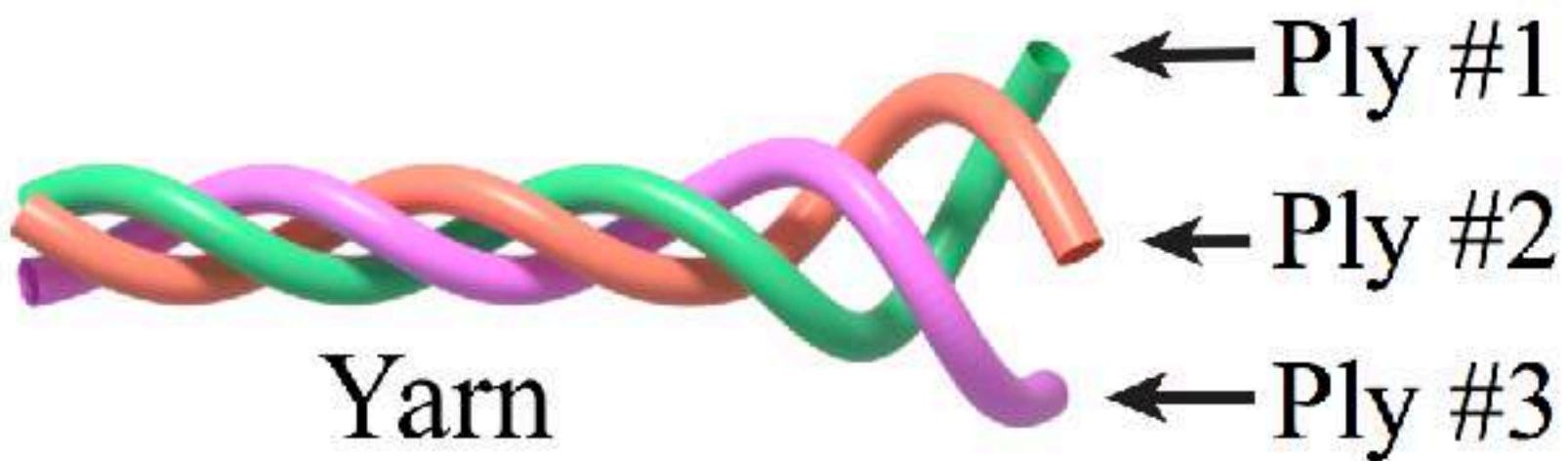


[Artist: Dan Roarty]

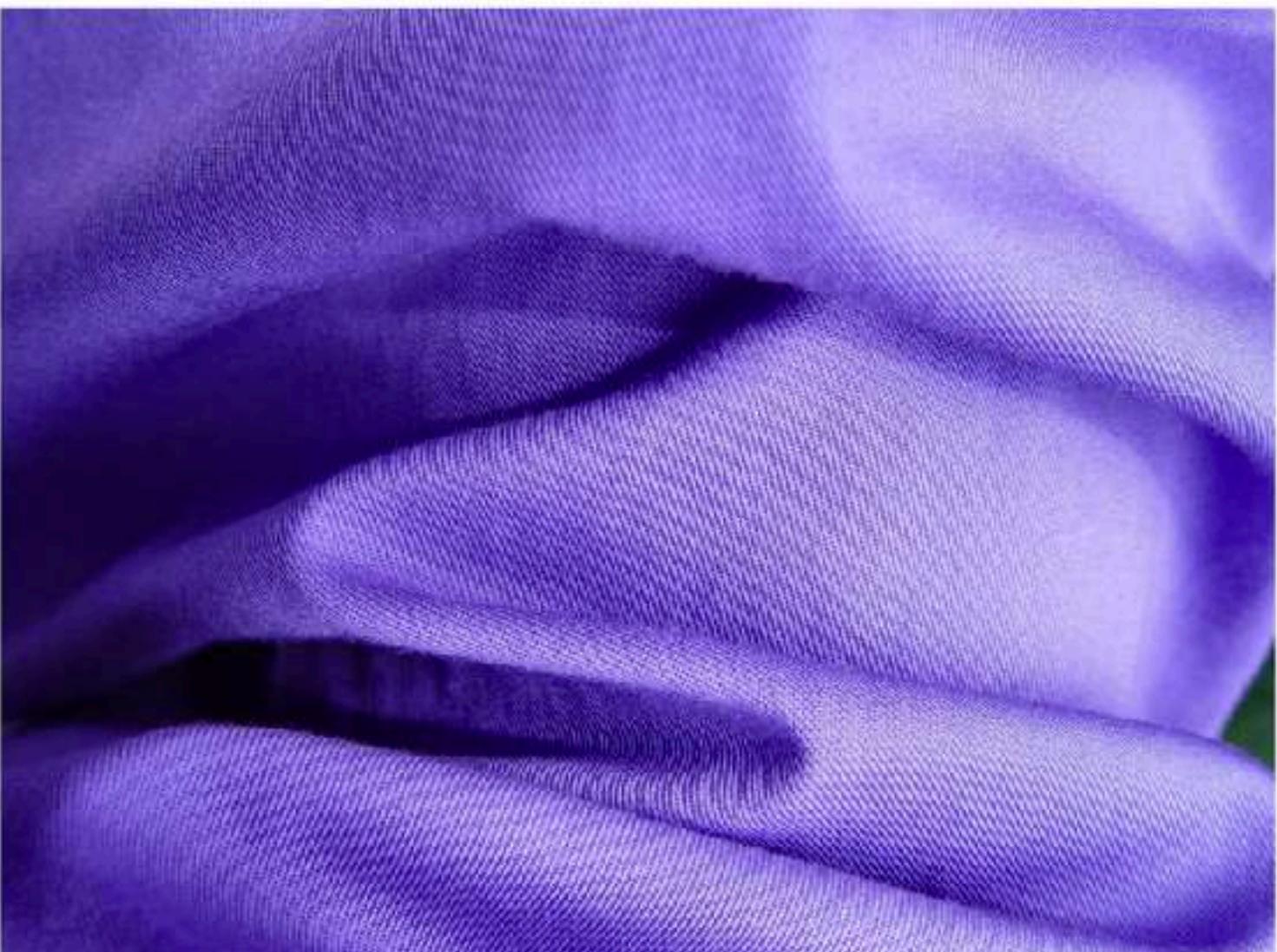
<https://cgelves.com/10-most-realistic-human-3d-models-that-will-wow-you/>

Cloth

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

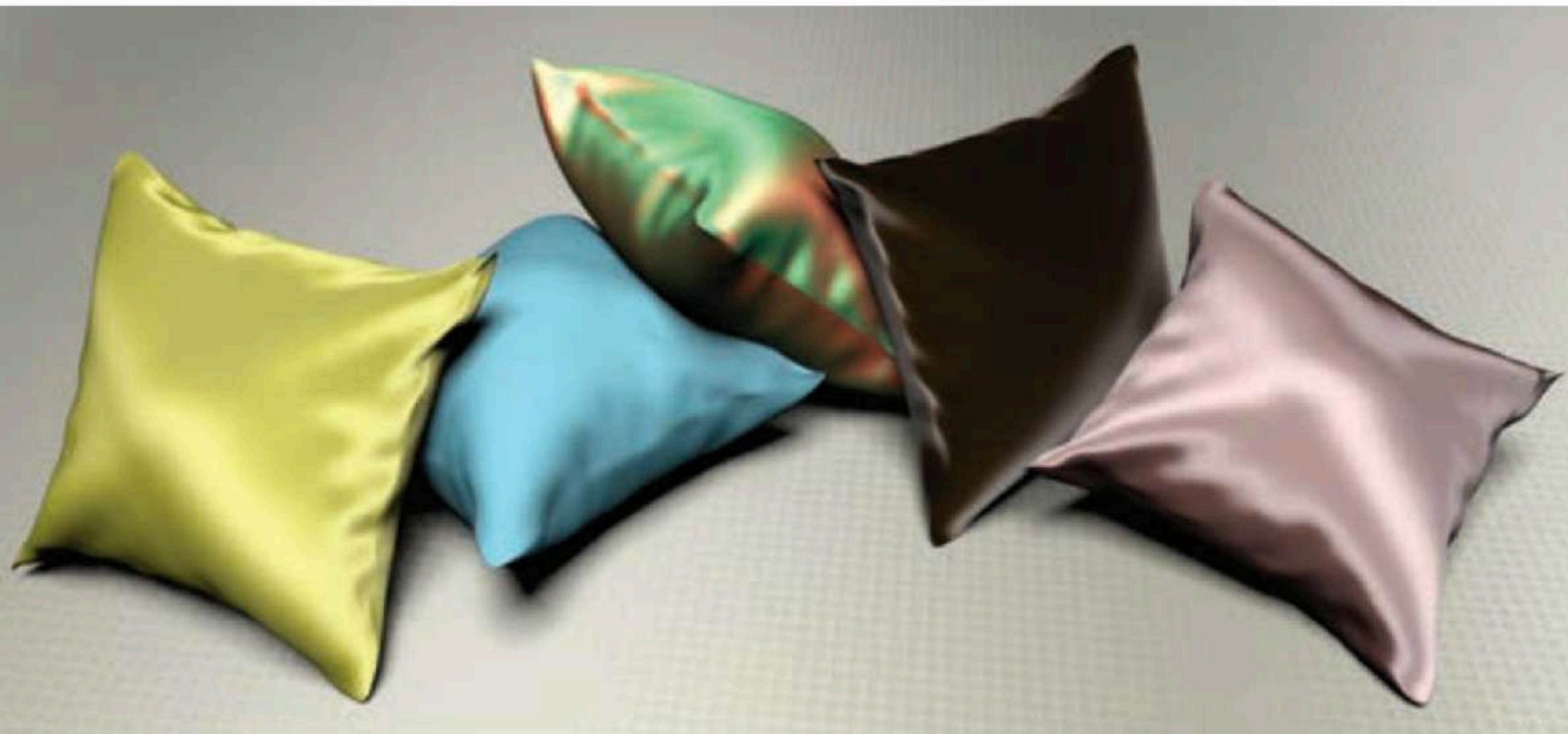
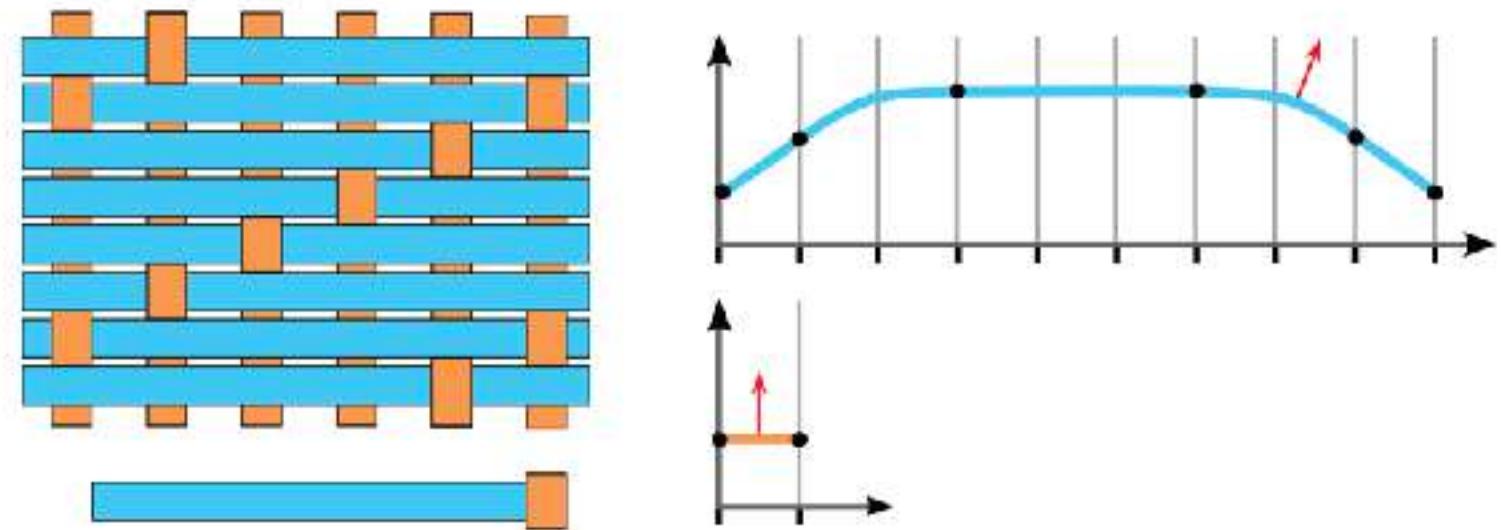


- Woven or knitted



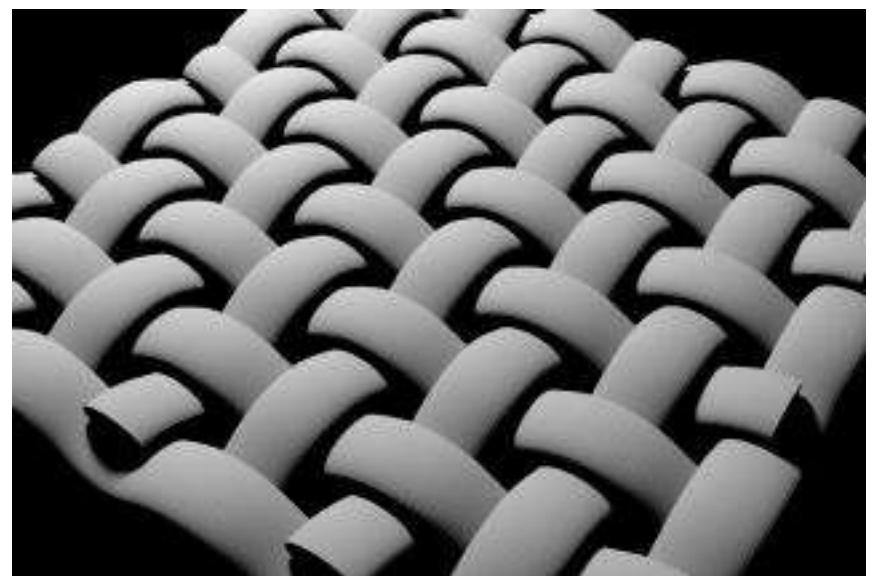
Cloth: Render as Surface

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

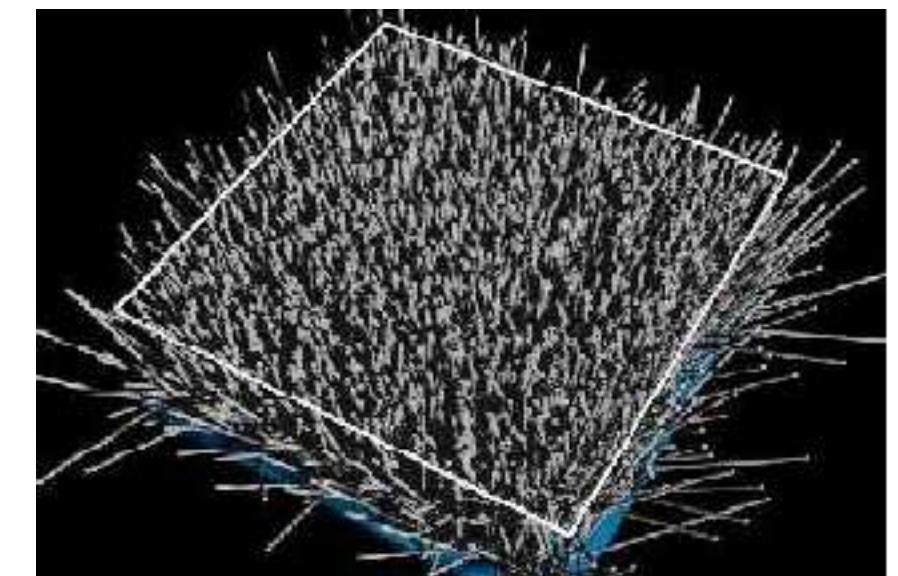
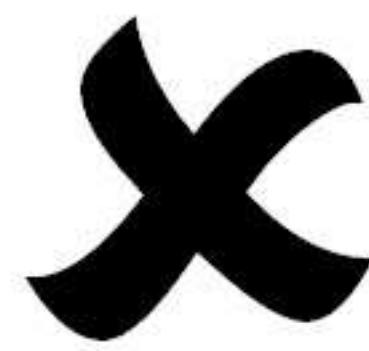


[Sadeghi et al. 2013]

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



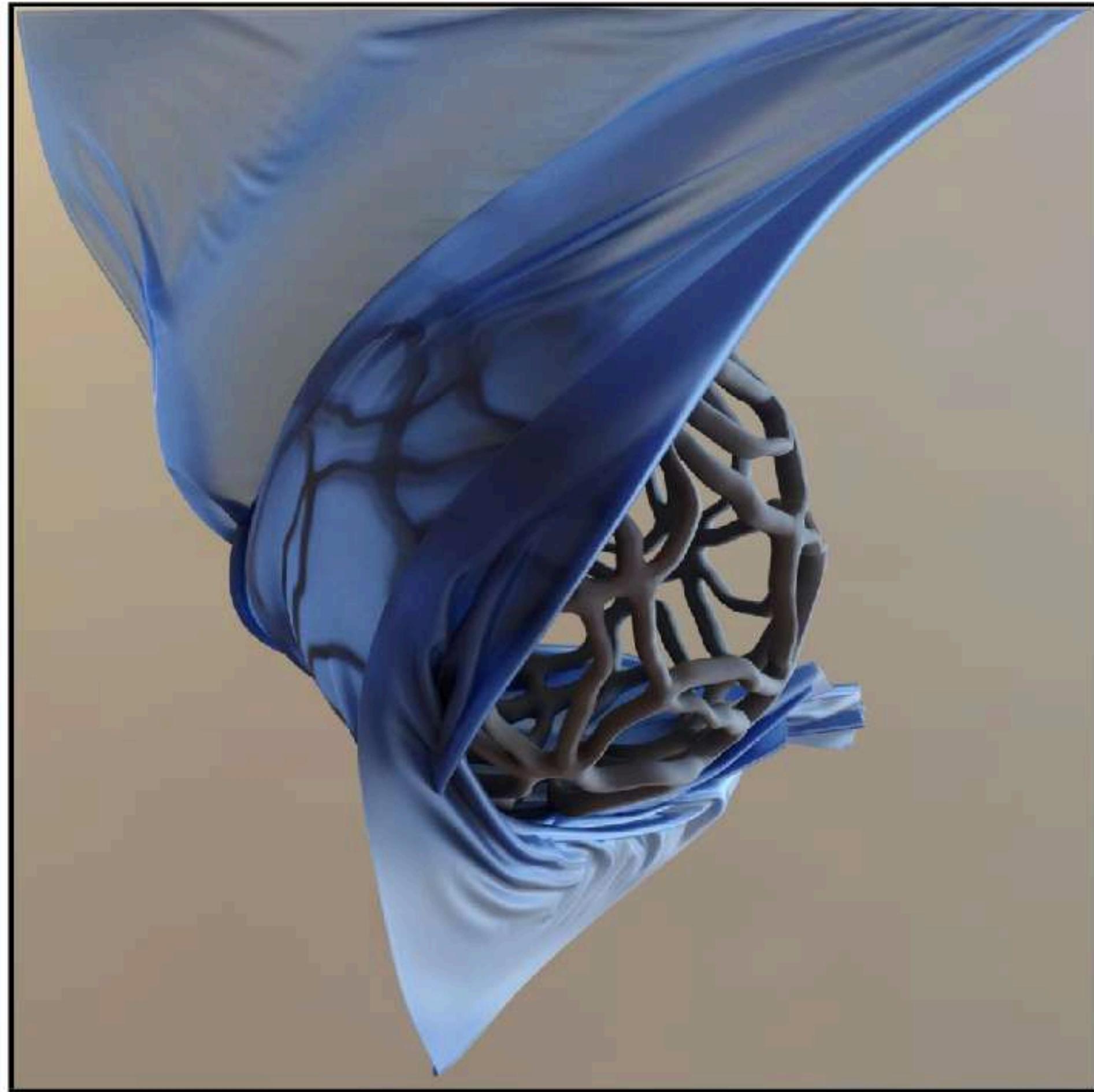
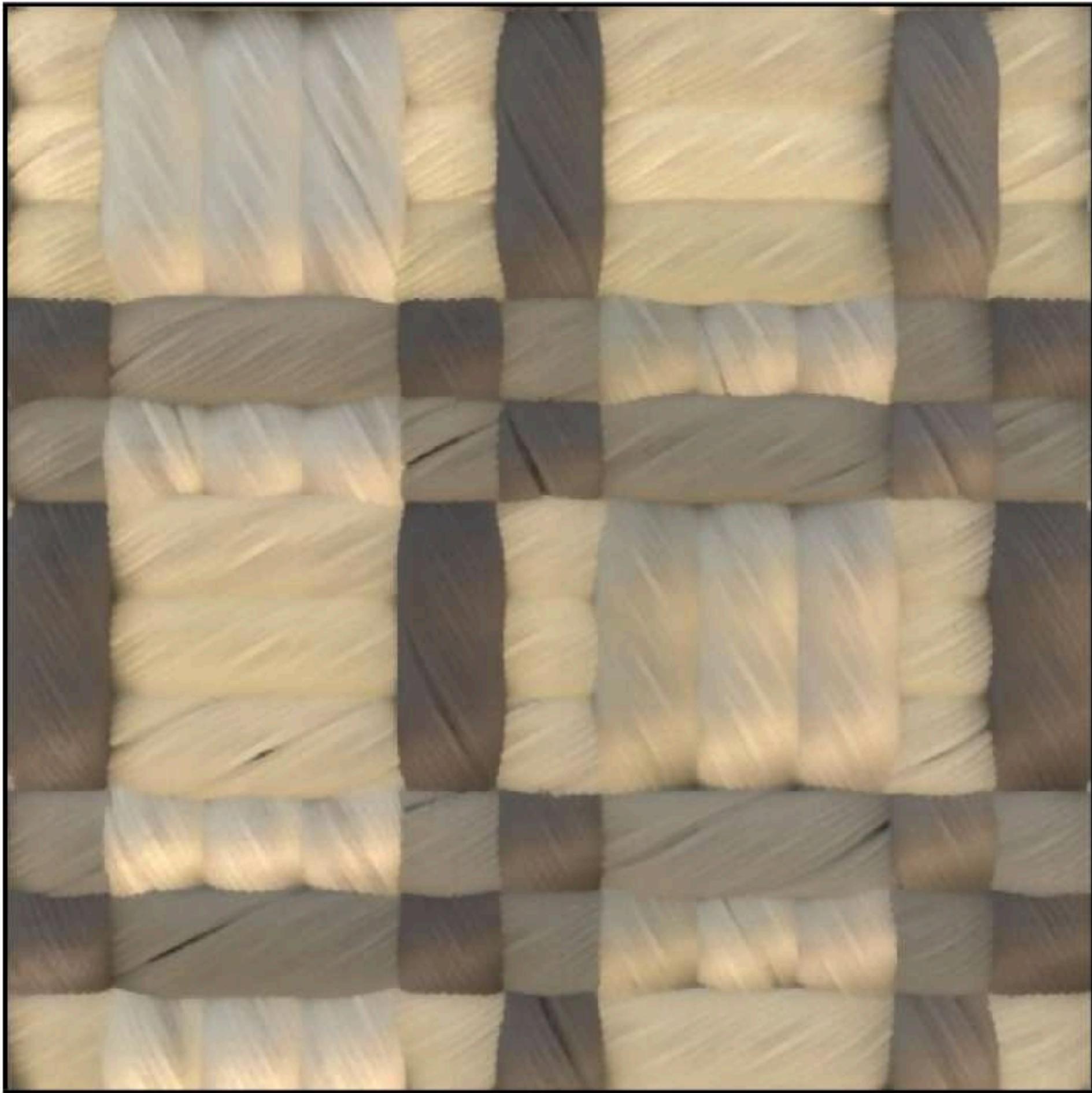
[Jakob et al. 2010]



[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]

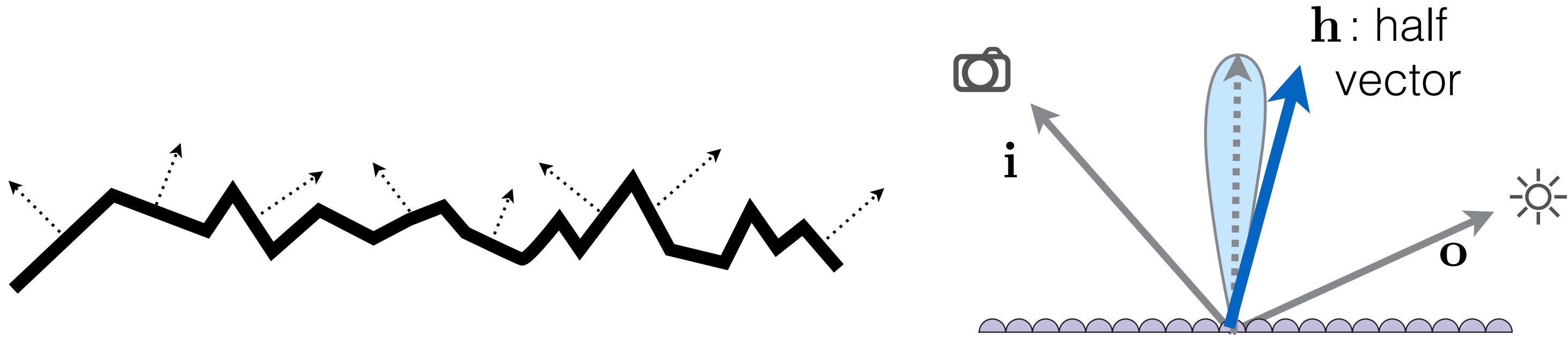


Why details?

[Yan et al.
2014, 2016]



Recap: Microfacet BRDF



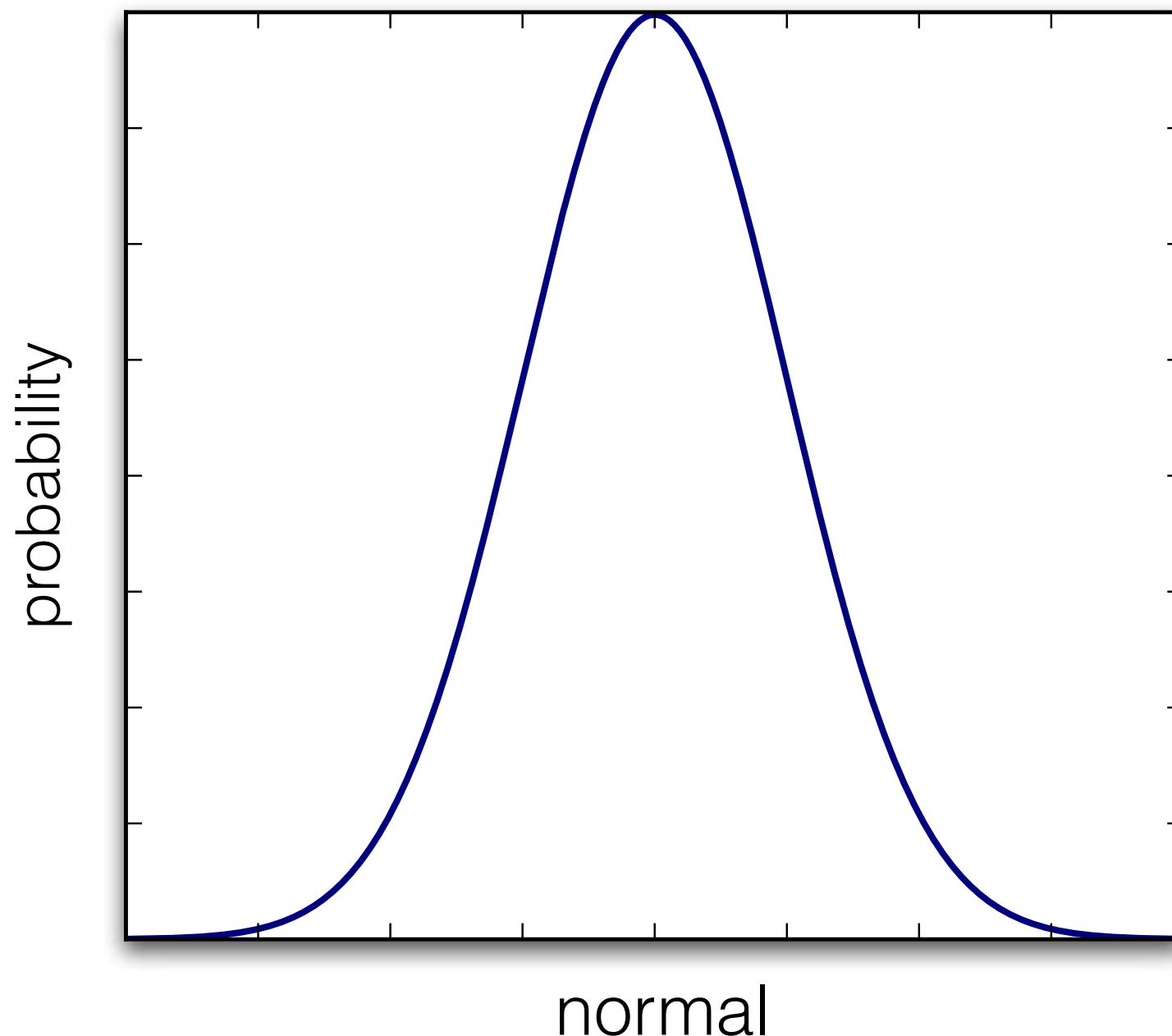
Surface = **Specular** microfacets + **statistical** normals

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

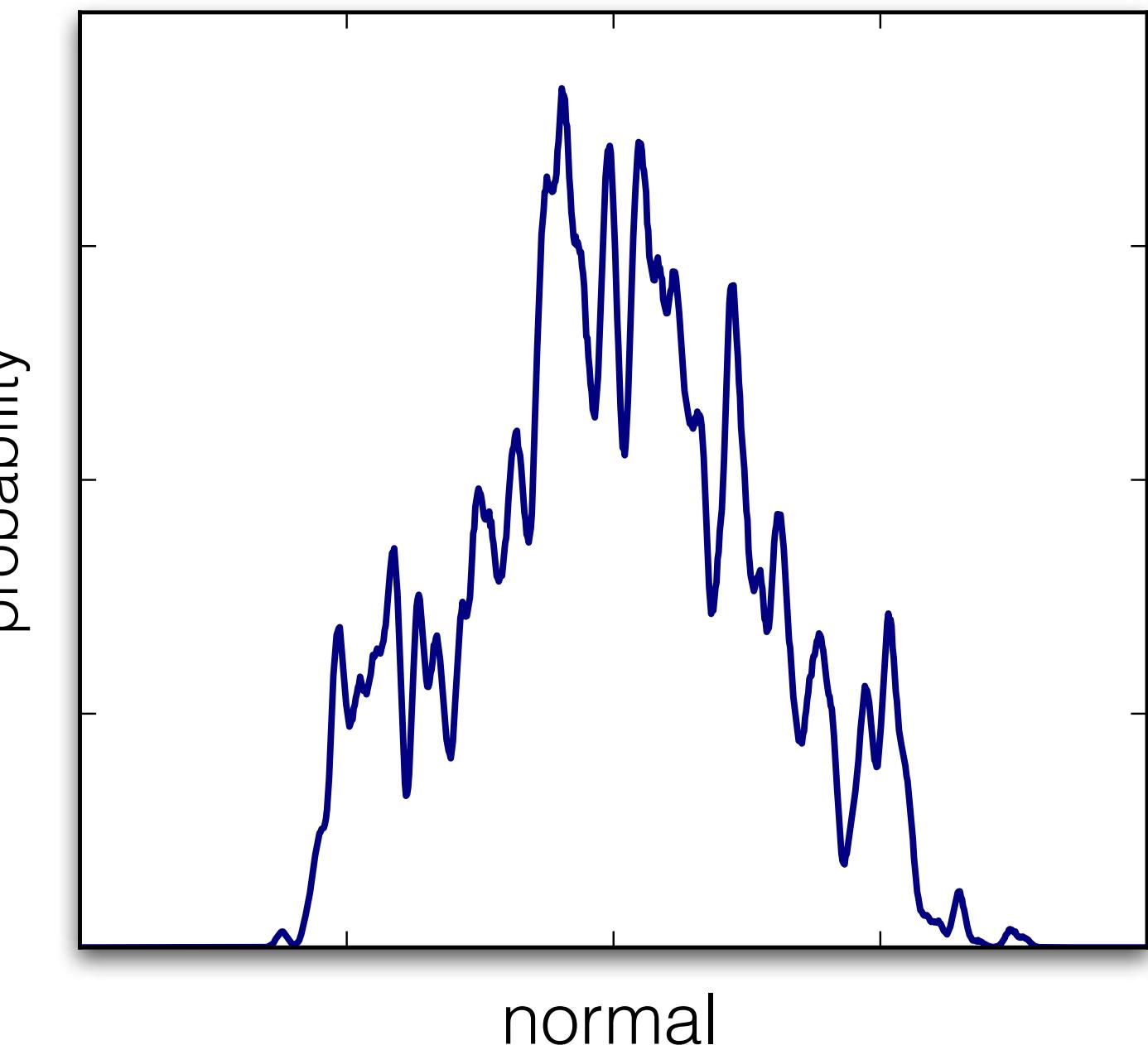
NDF: Normal
Distribution
Function

Statistical NDF vs. Actual NDF

Distribution of Normals (NDF)

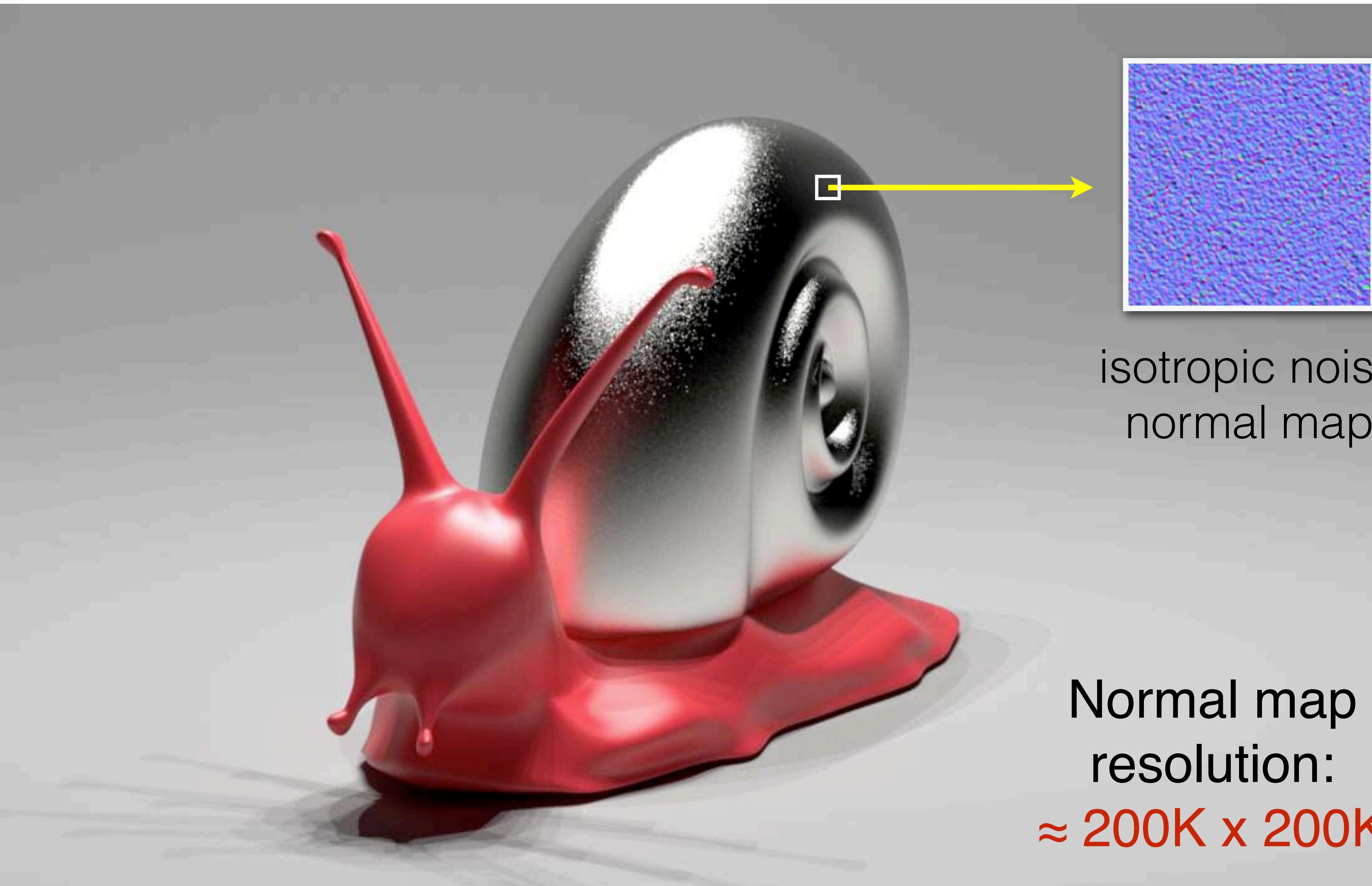


What we have
(microfacet — statistical)



What we want

Define details

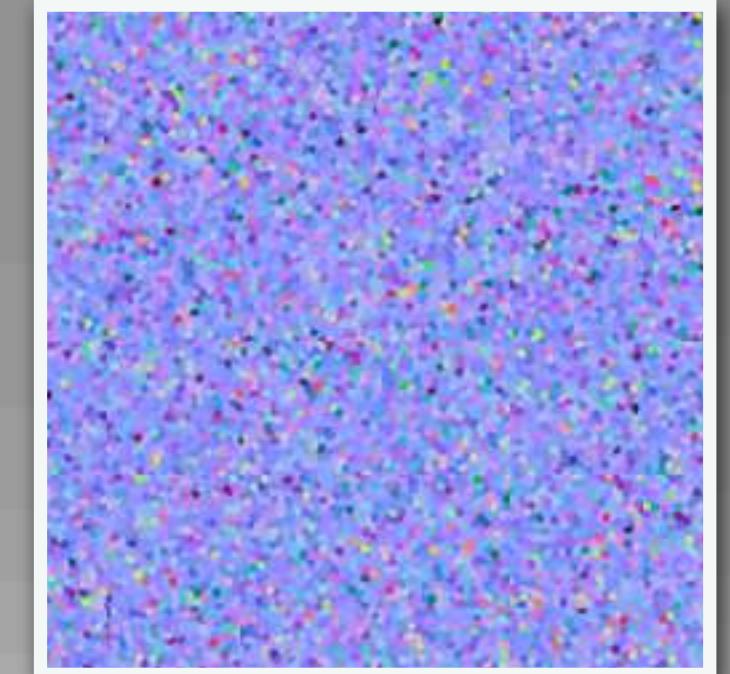


Normal map
resolution:
 $\approx 200K \times 200K$

Define details

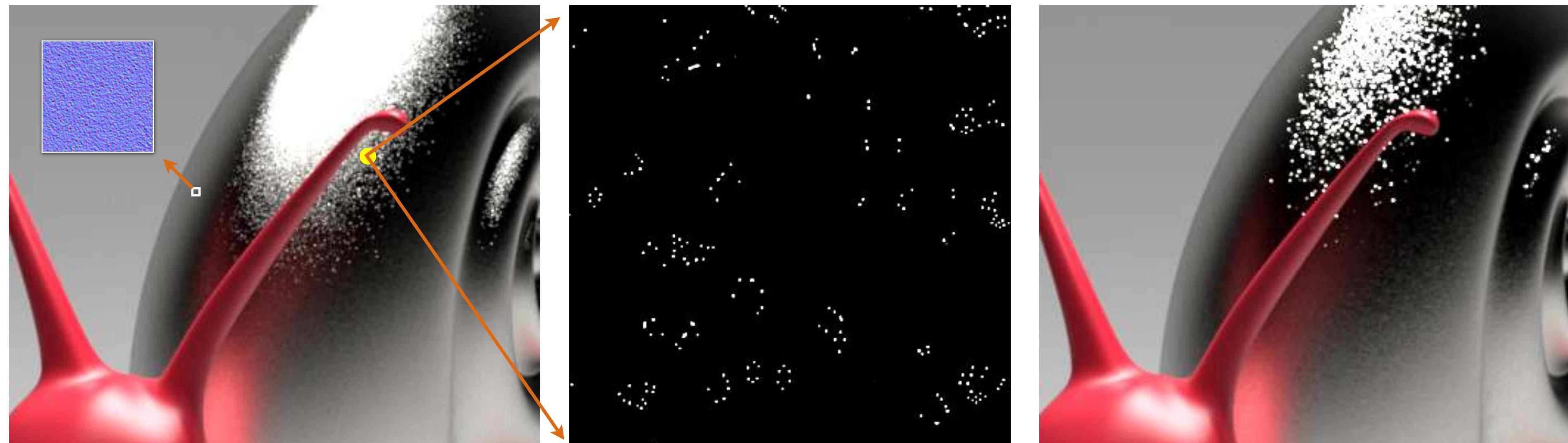


Different details



Metallic flakes

Rendering? Too difficult!



our result

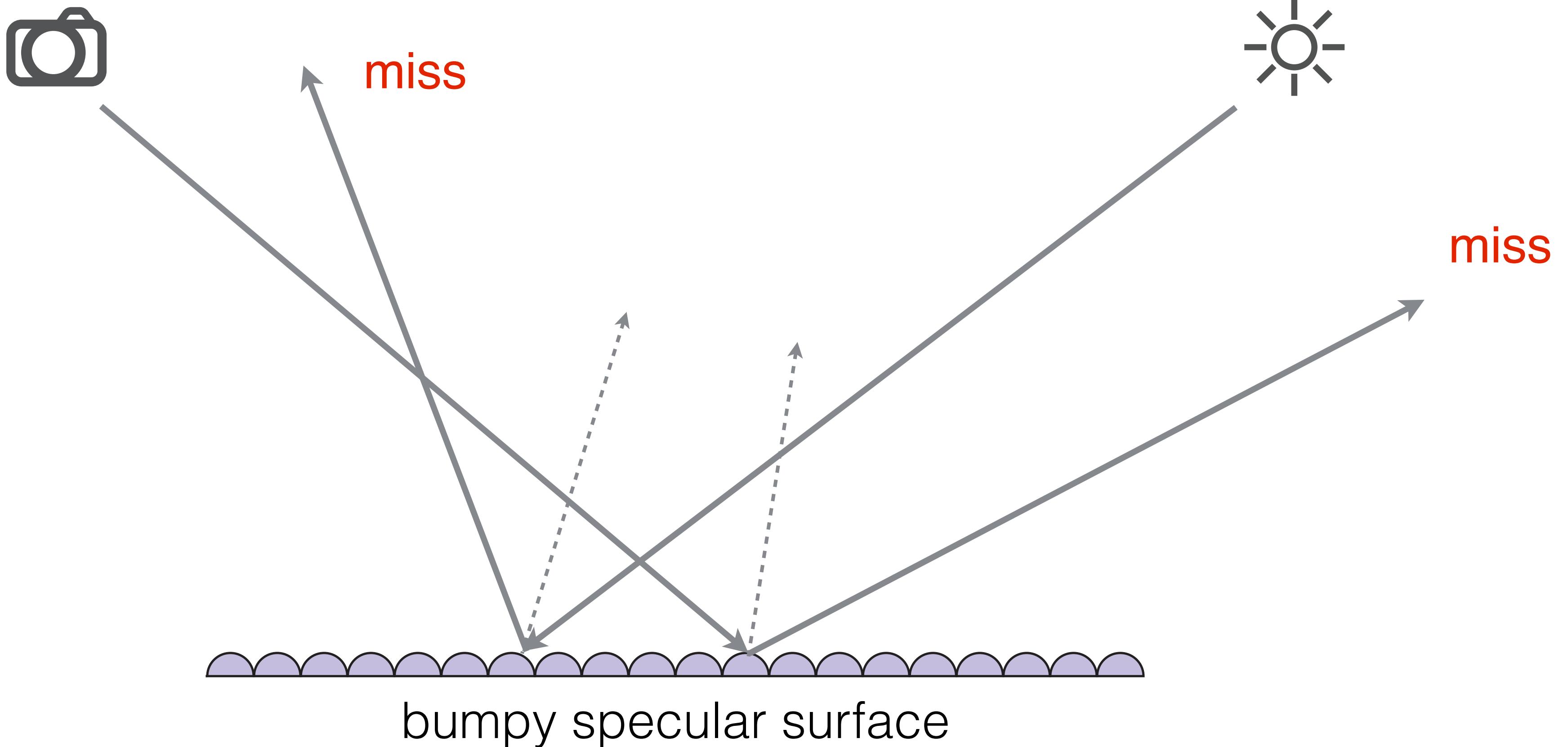
zoom of
a single pixel

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

Difficult path sampling problem

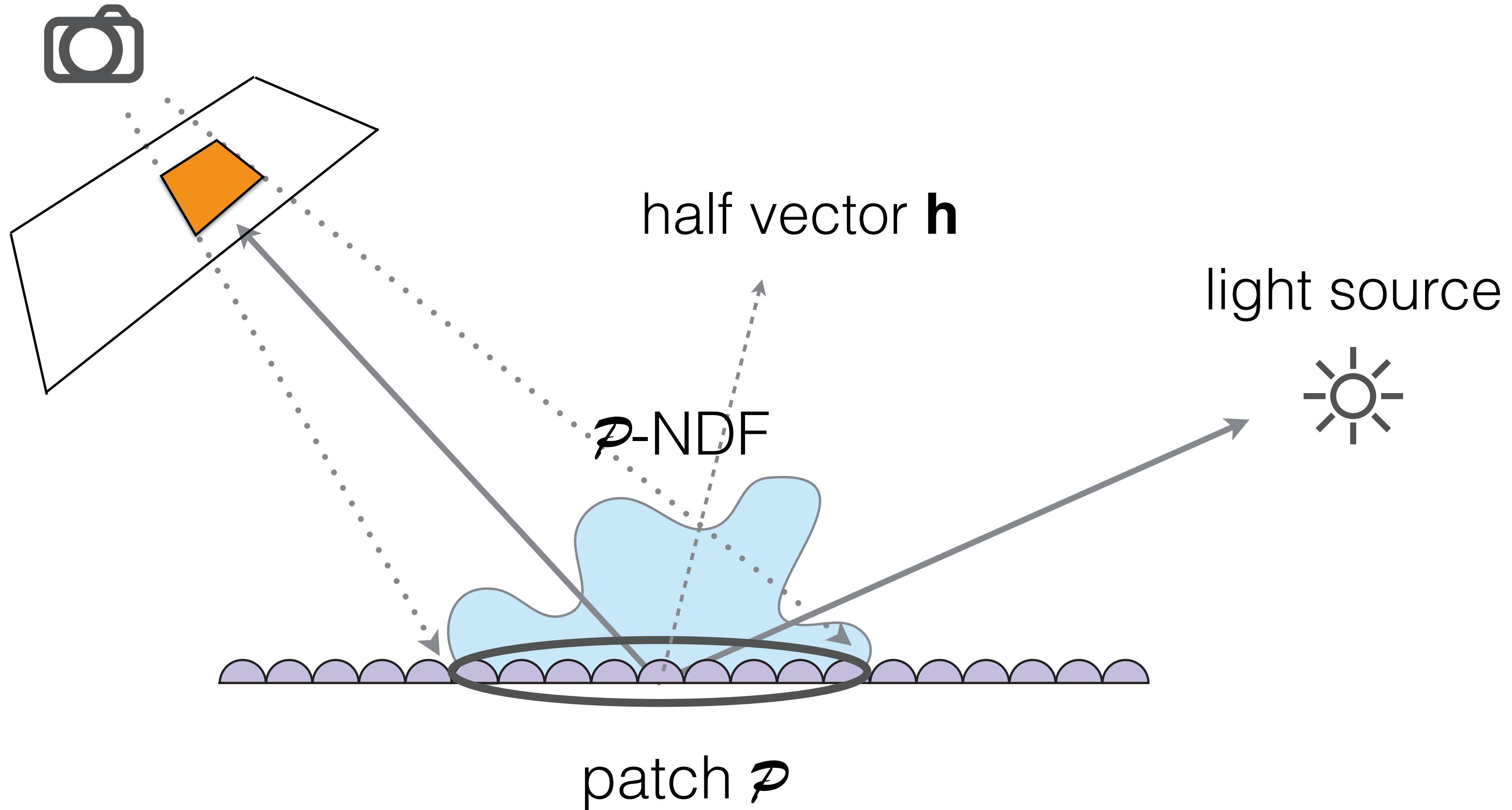
pinhole camera

lightsource

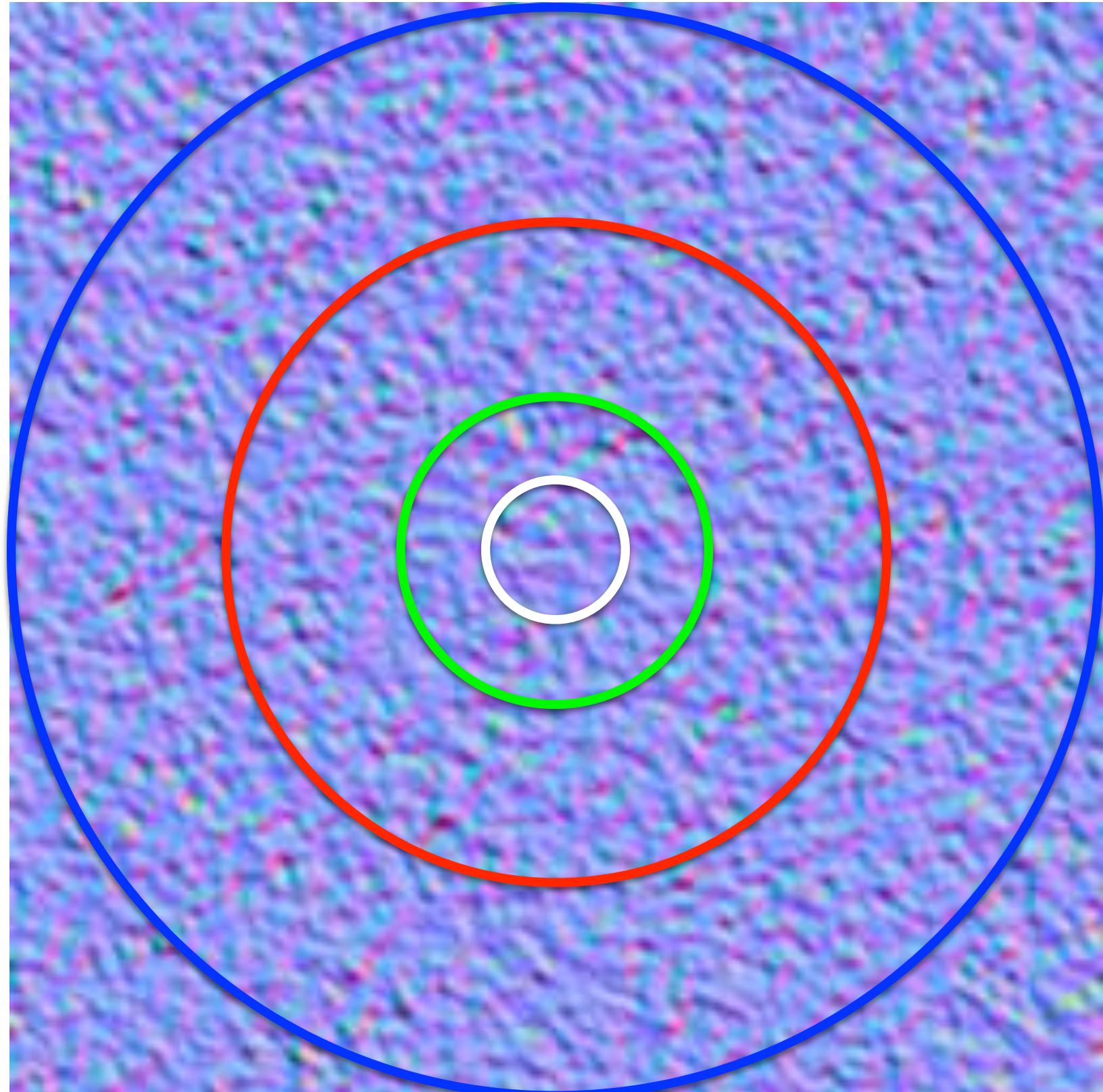


Solution: BRDF over a pixel

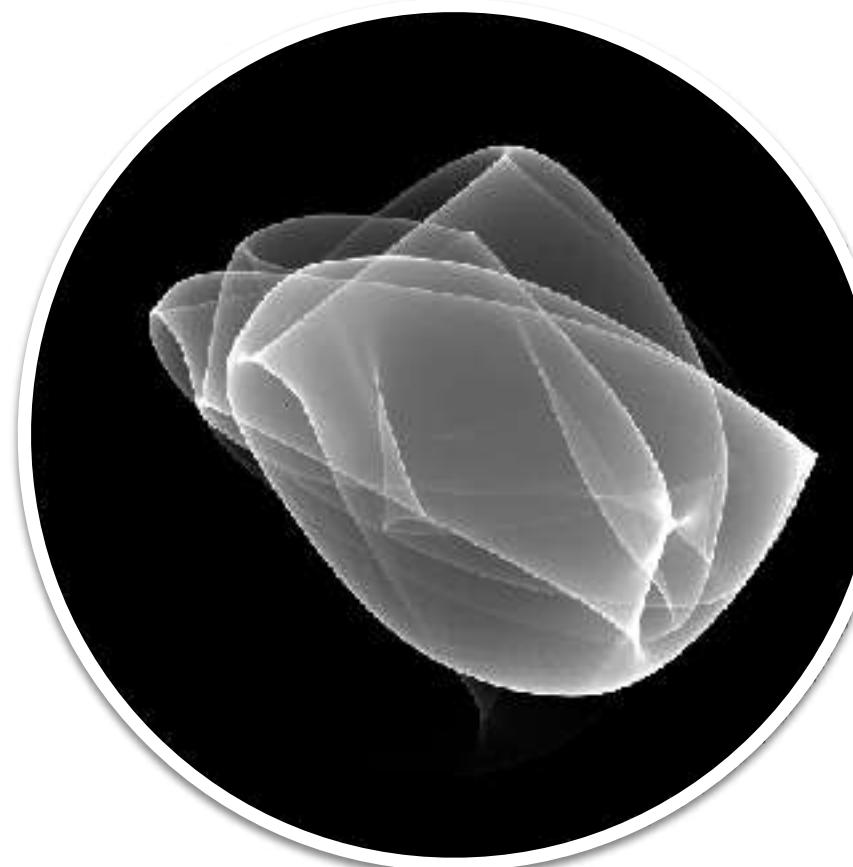
pinhole camera



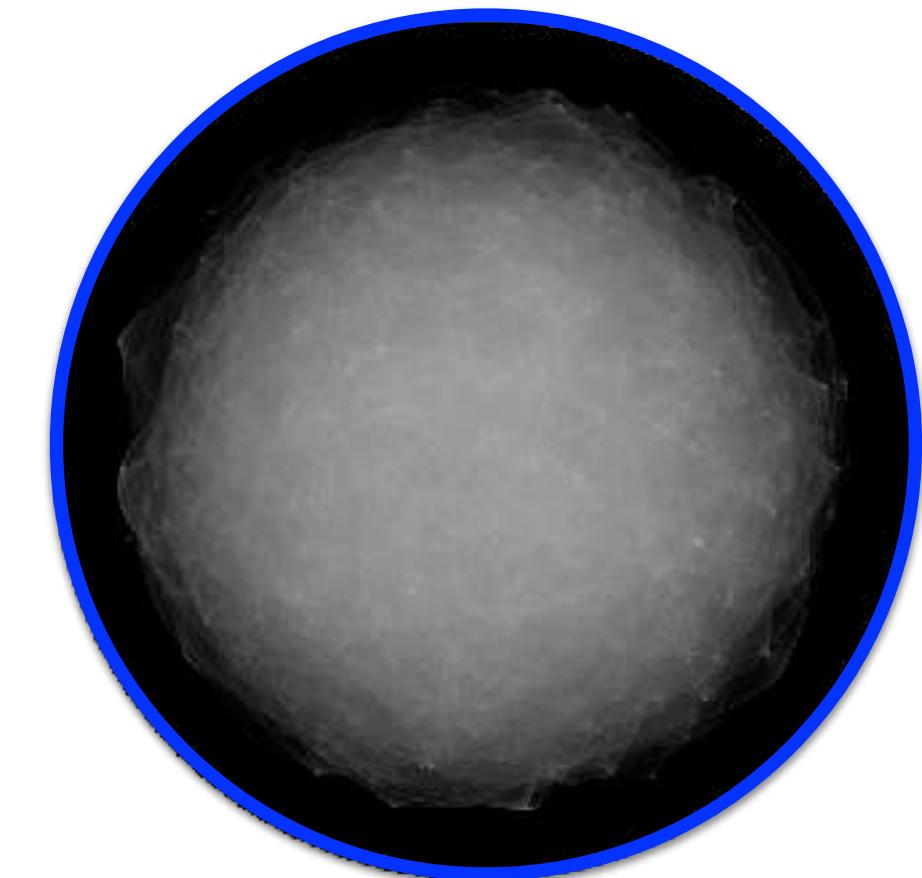
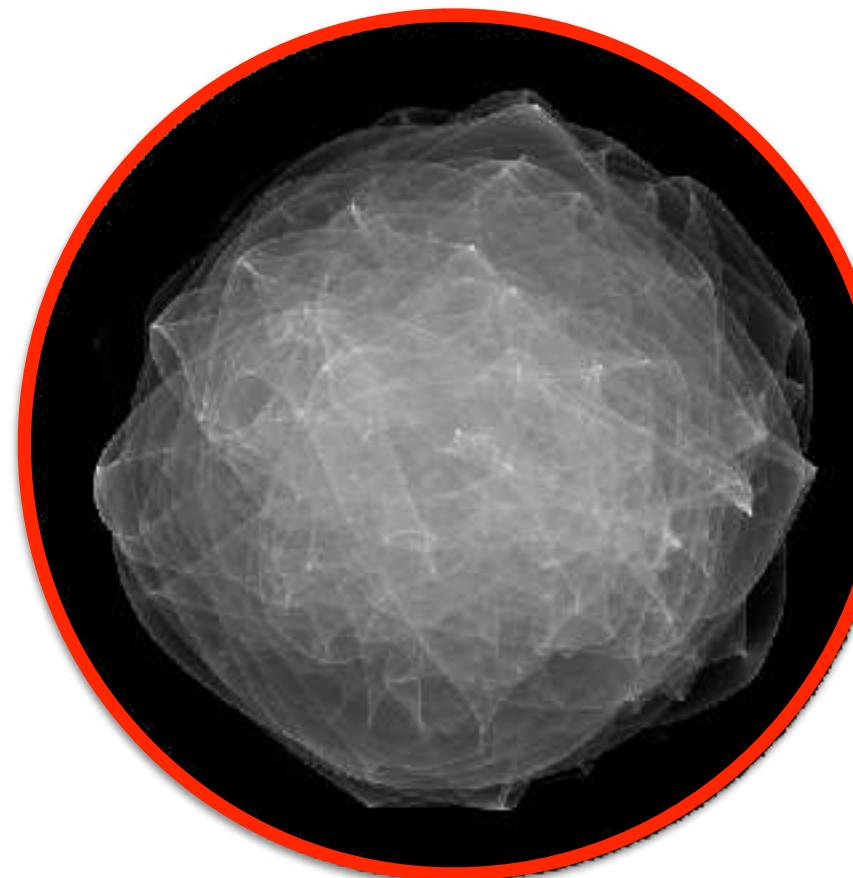
p-NDFs have sharp features



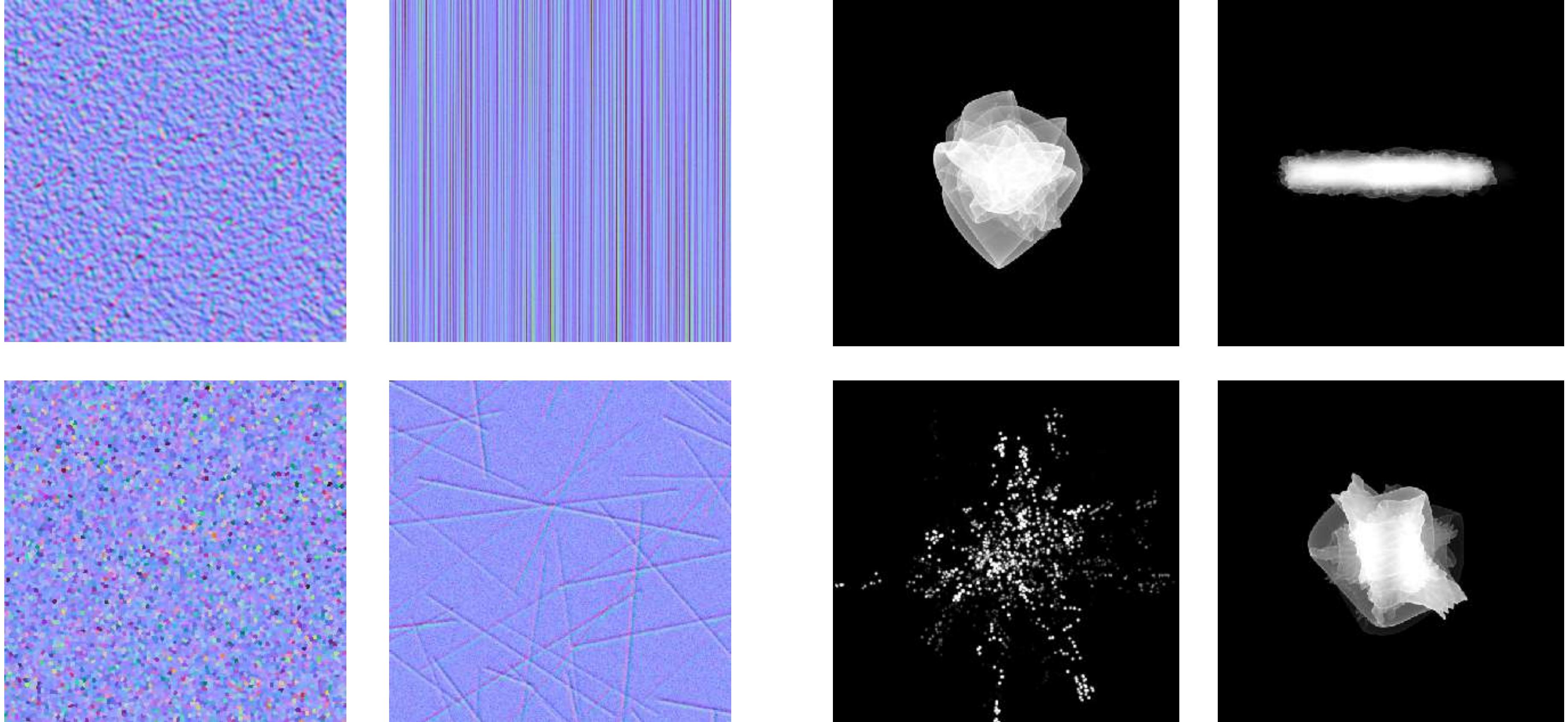
normal map



\mathcal{P} -NDFs



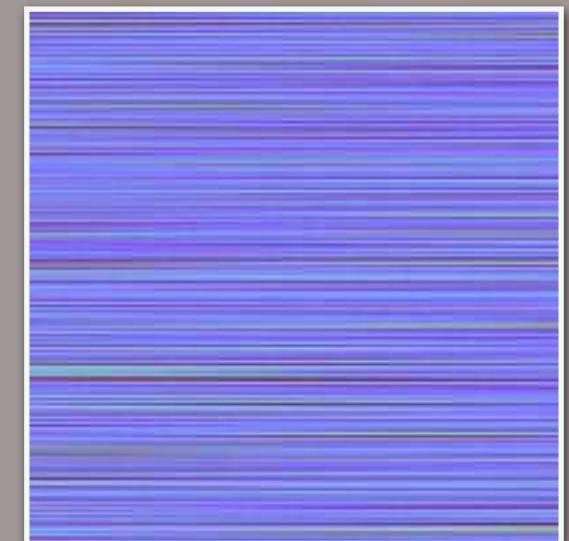
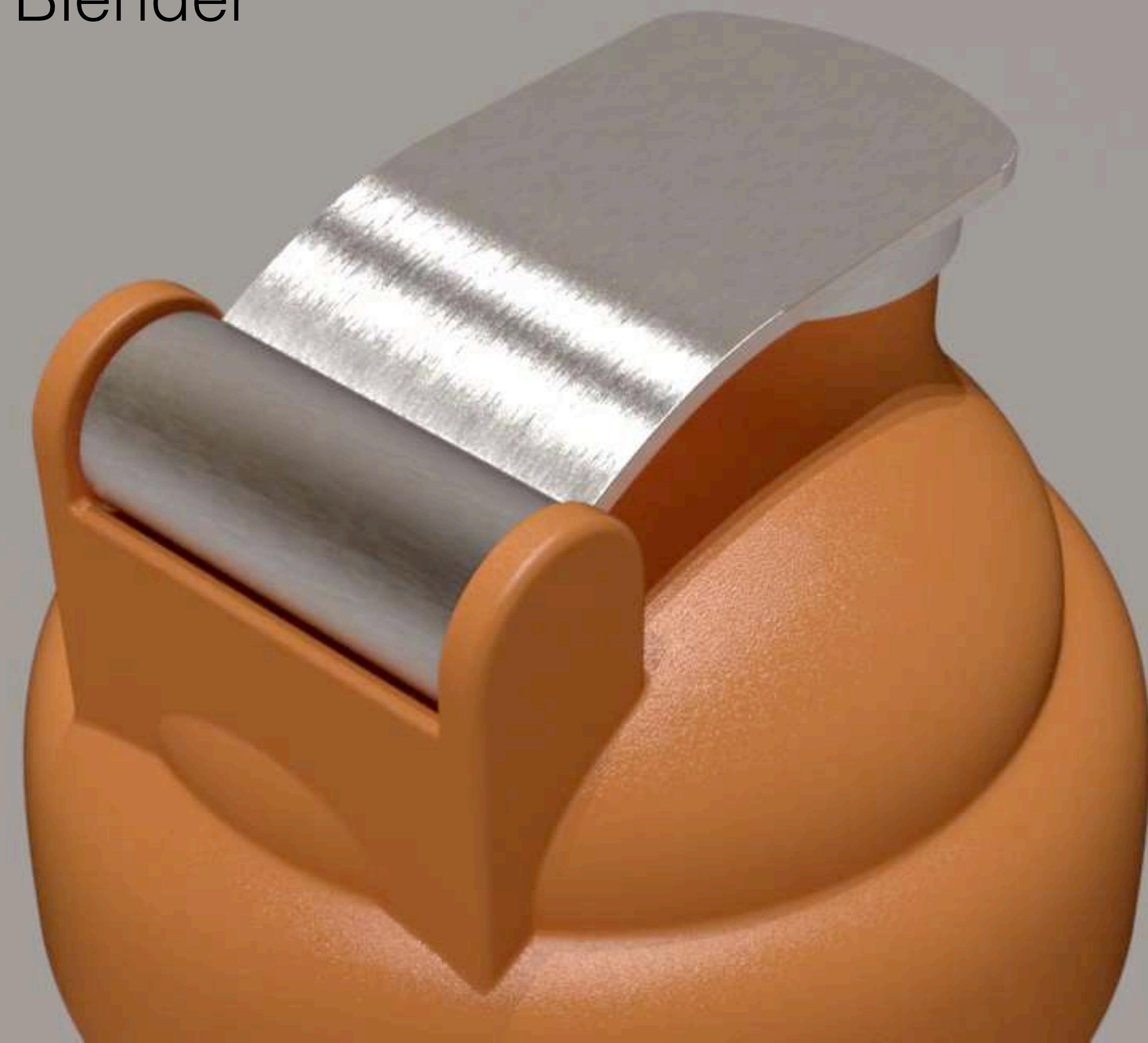
p-NDF shapes



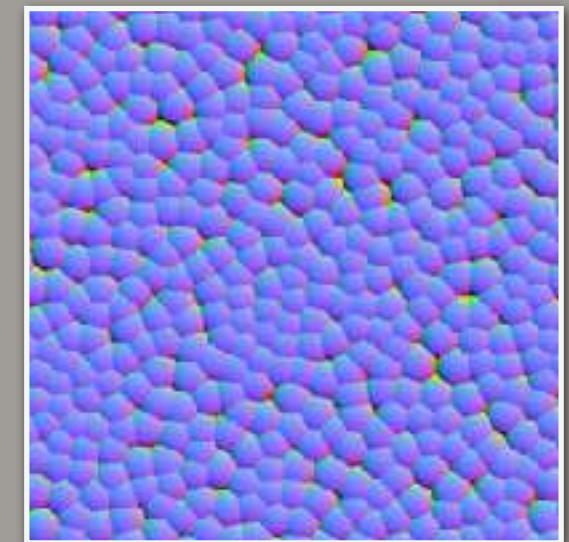
normal maps

\mathcal{P} -NDFs

Blender



brushed metal

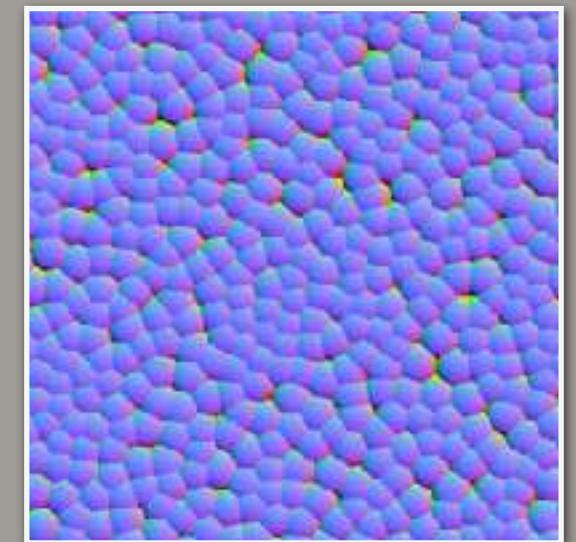


ellipsoid bumps

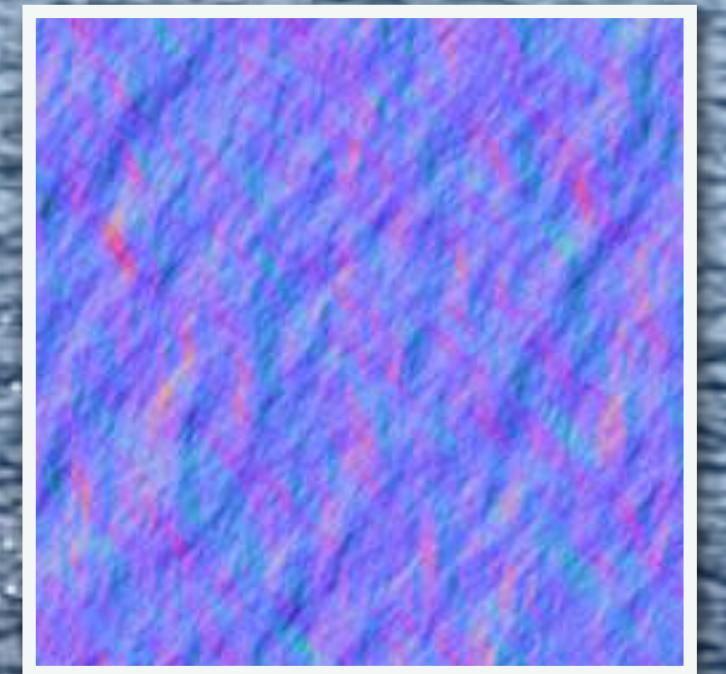
Blender: Zoom



brushed metal



ellipsoid bumps



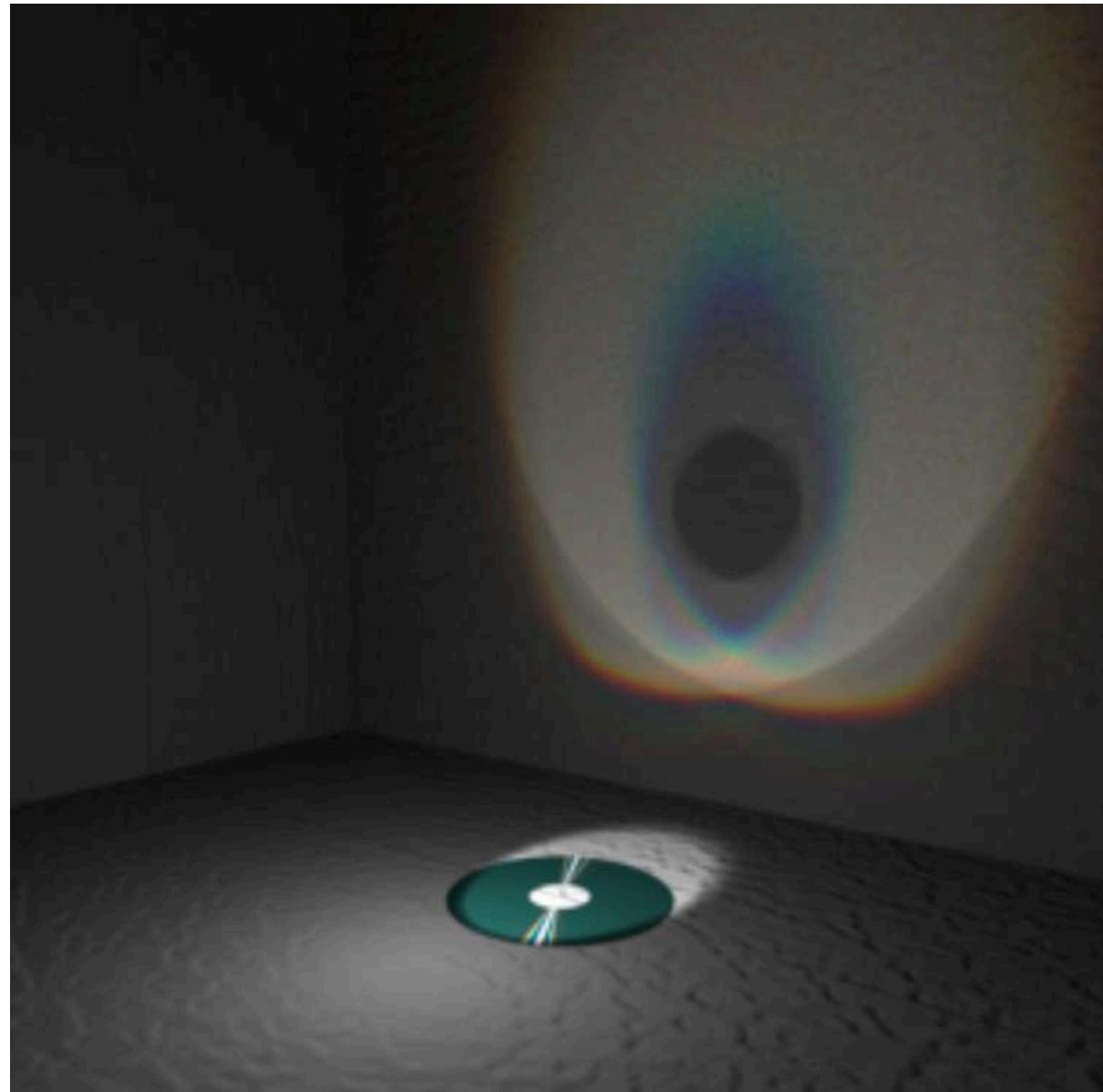
Ocean waves

Detailed / Glinty Material: Application



[Rise of the Tomb Raider. 2016 Square Enix]

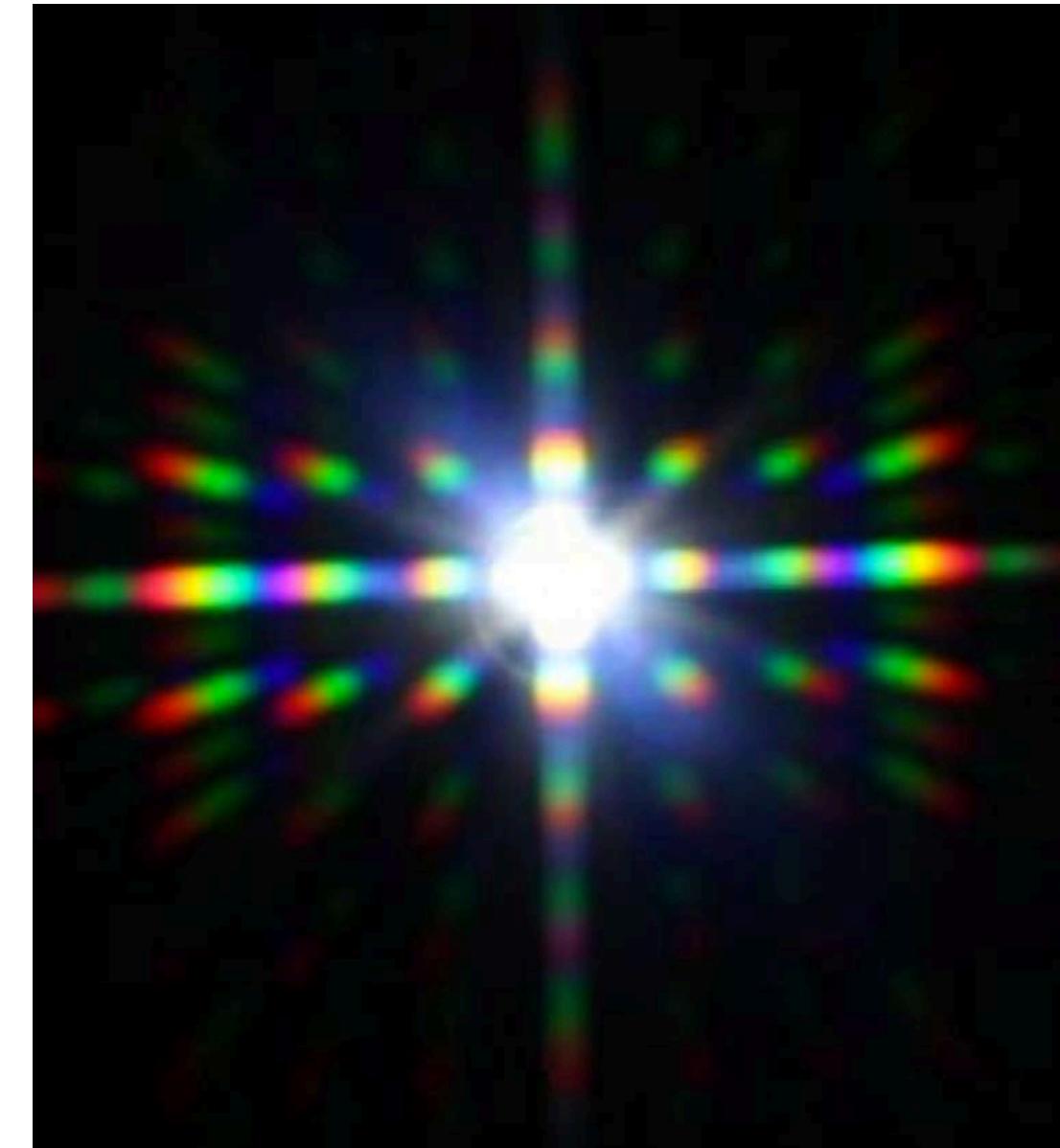
Recent Trend: Wave Optics



compact disk (CD)
[Cuypers 11]

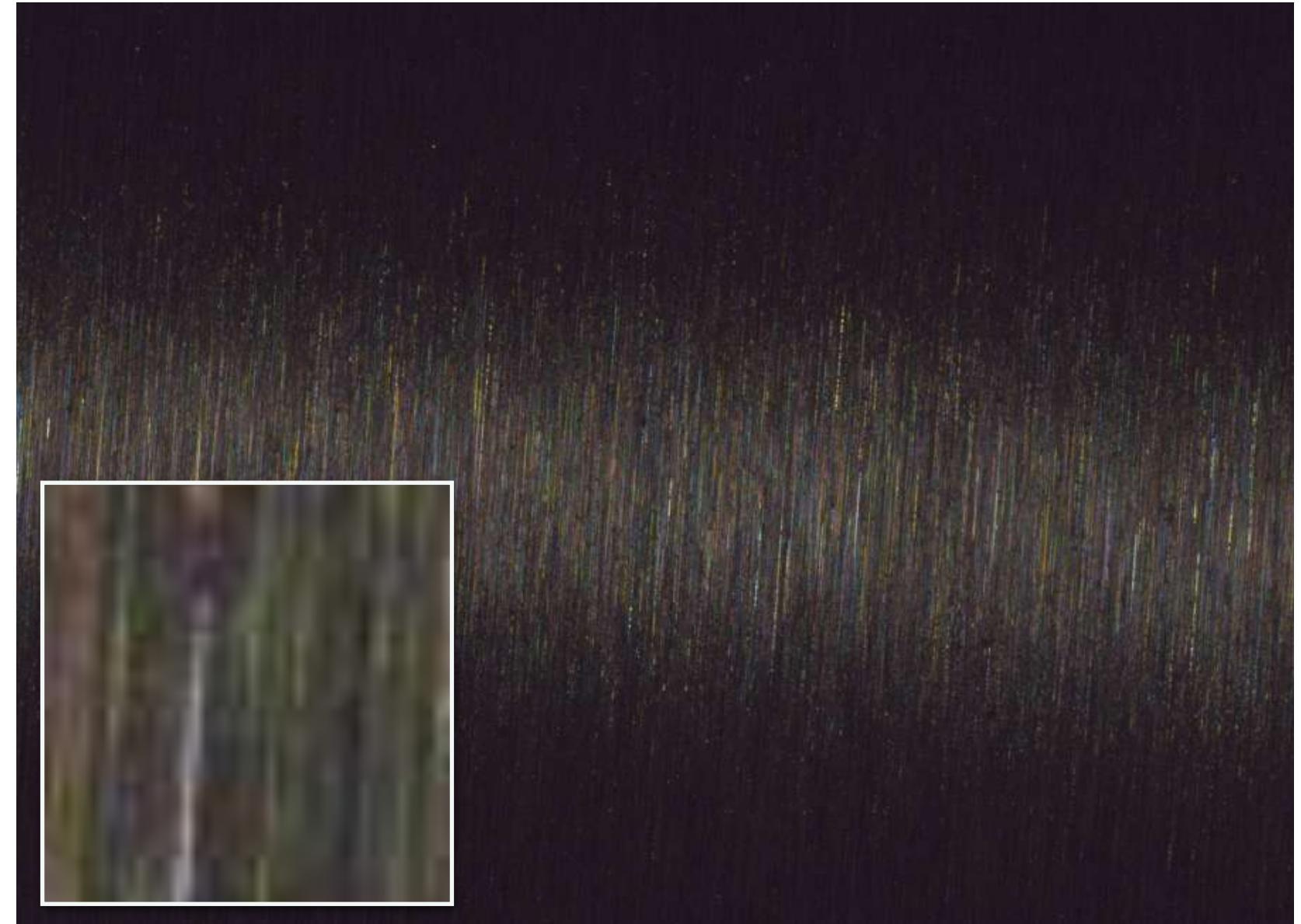
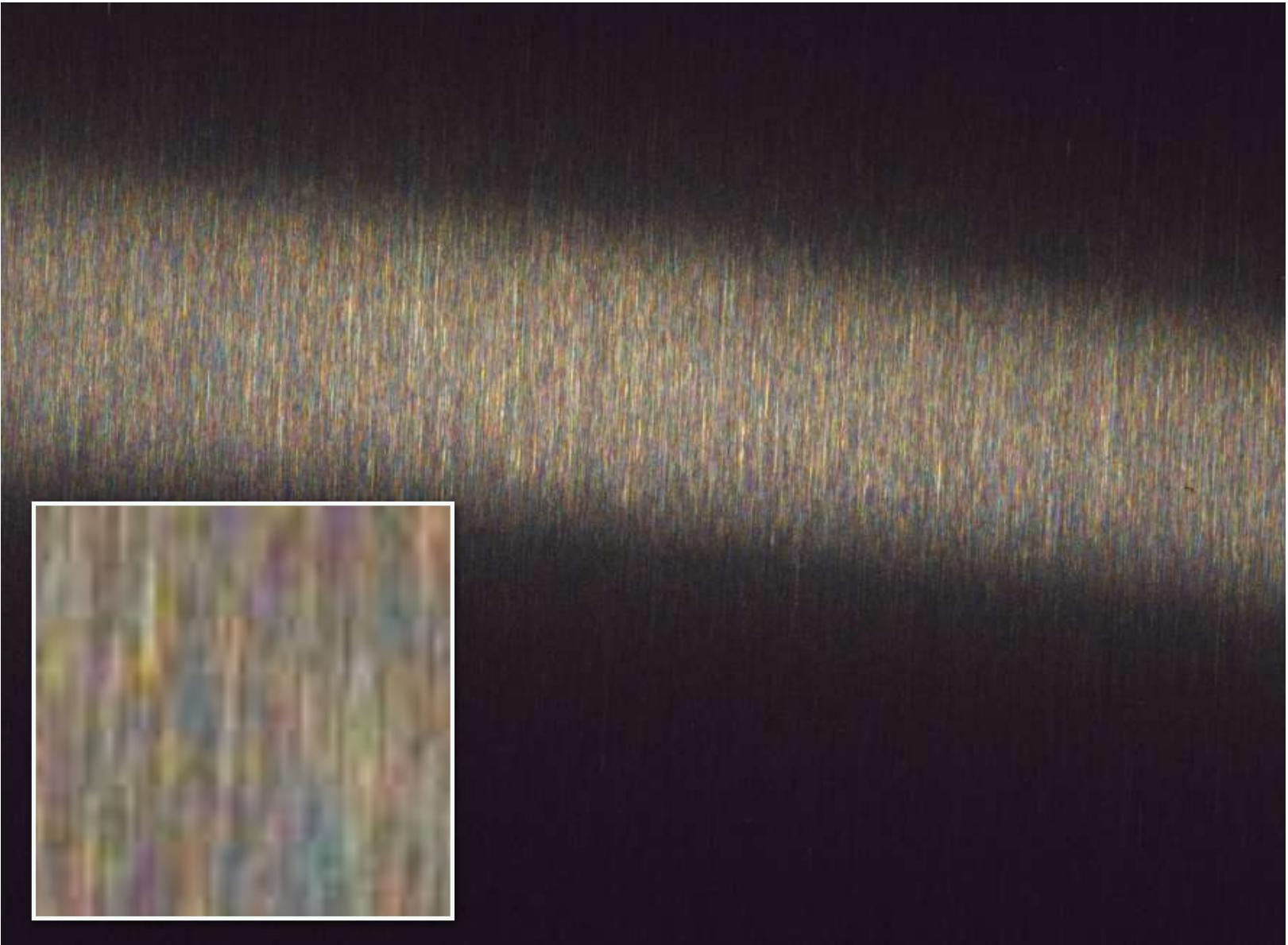


metallic film
[Laurent 17]



phone screen
[Toisoul 17]

Observations



photos of scratched metal

Observations



photo of a Macbook

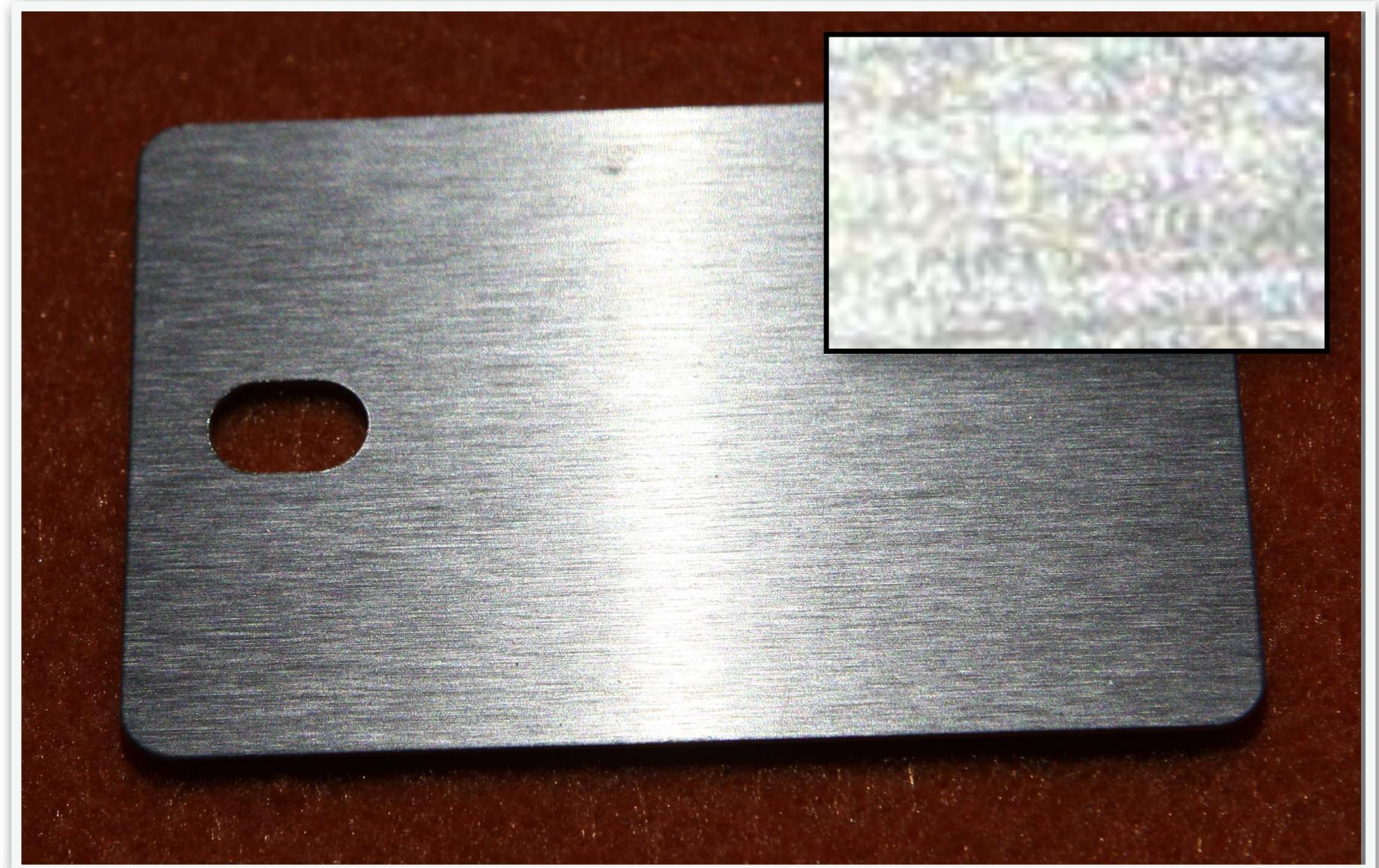
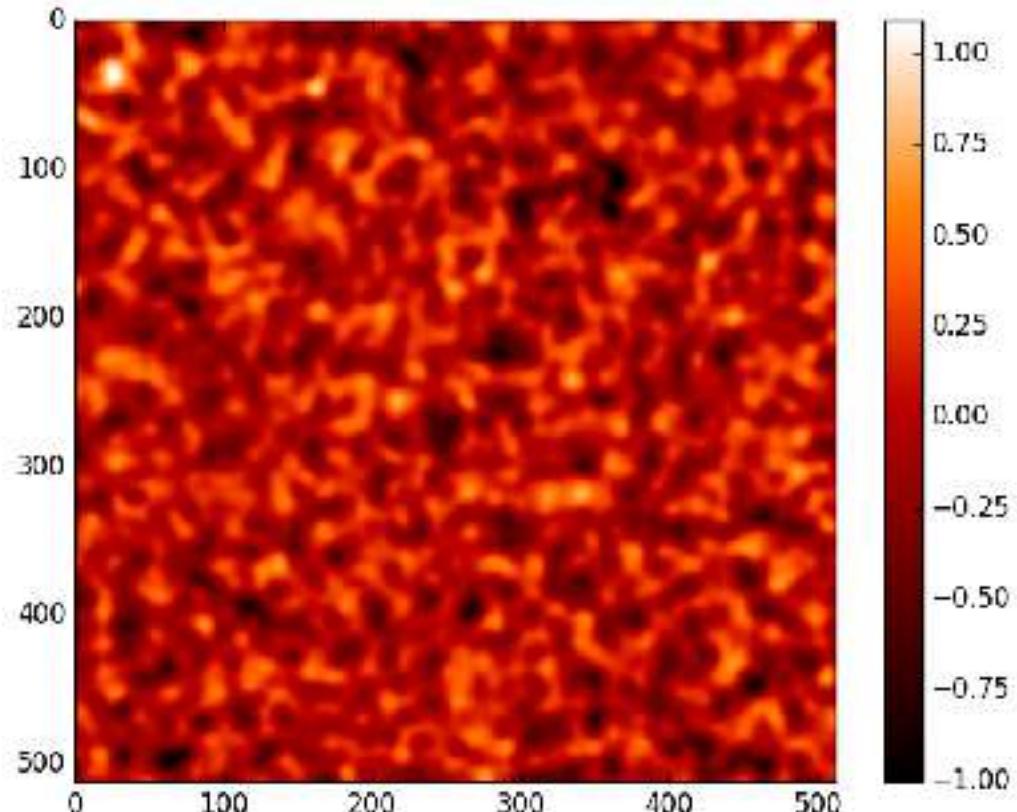


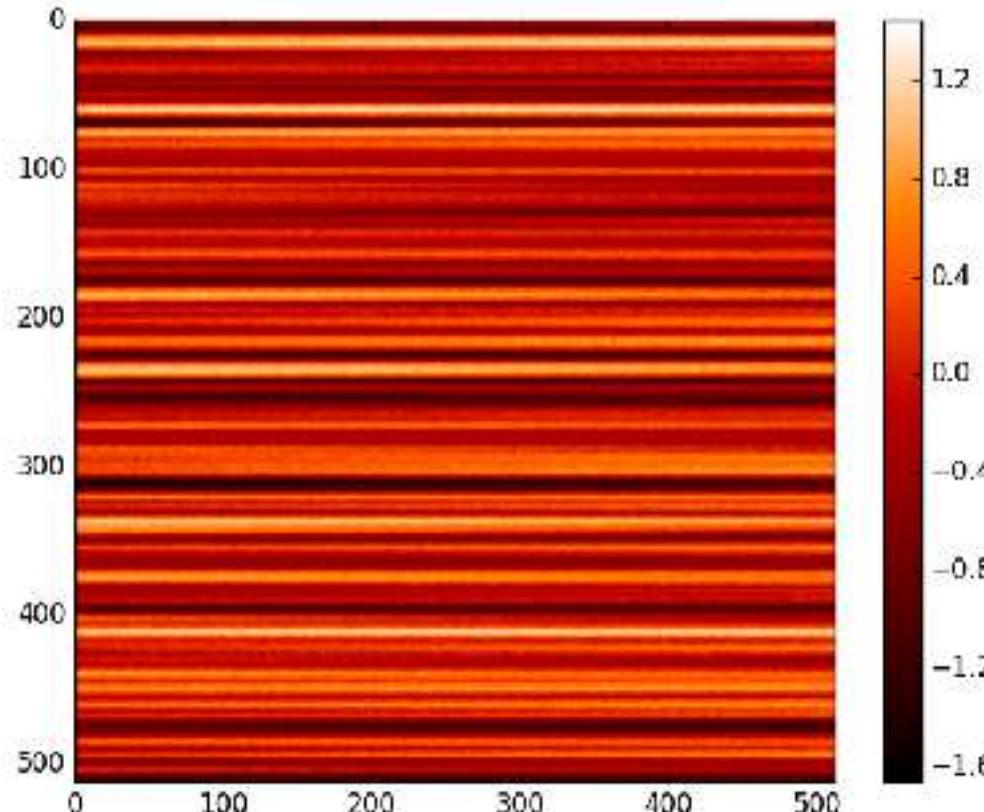
photo of an aluminum patch

Detailed Material under Wave Optics

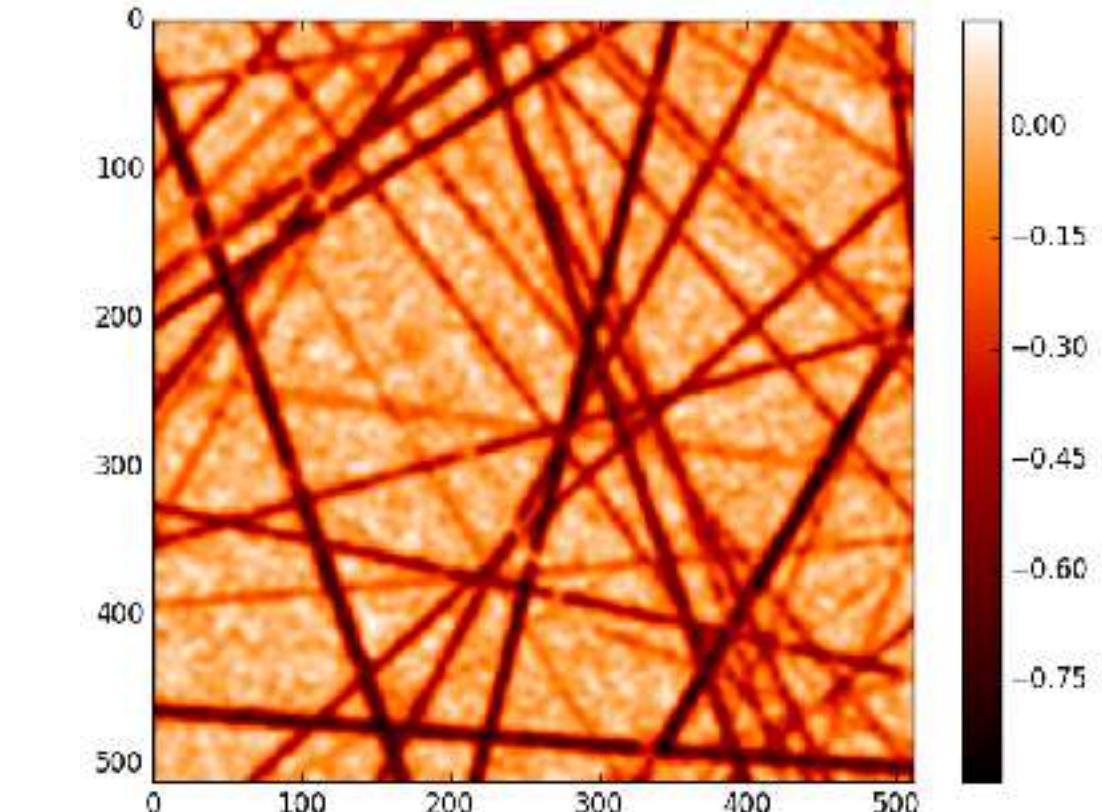
Heightfields



isotropic

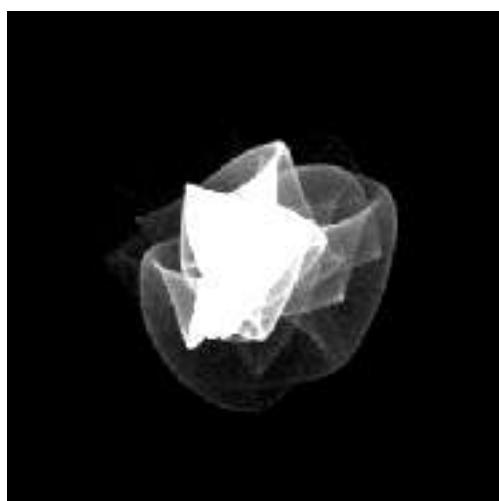


brushed



scratched

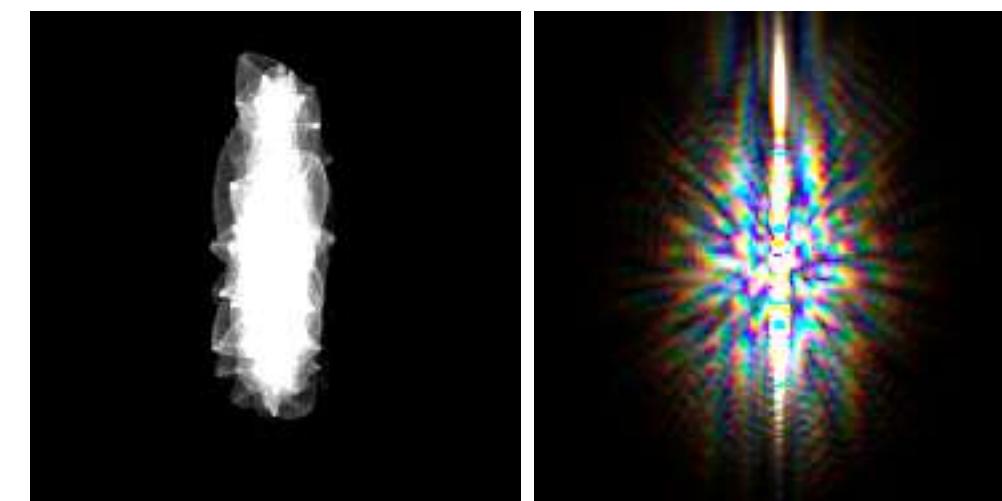
BRDFs



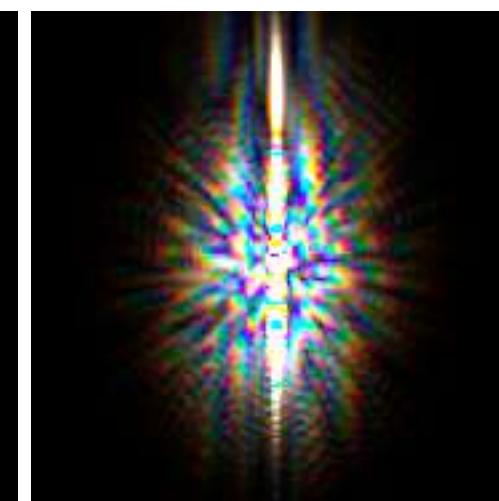
geometric



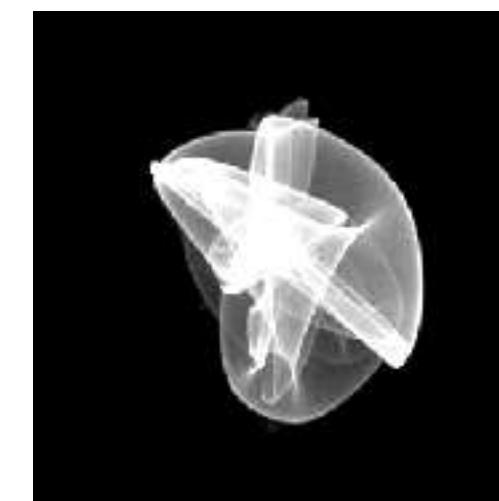
wave



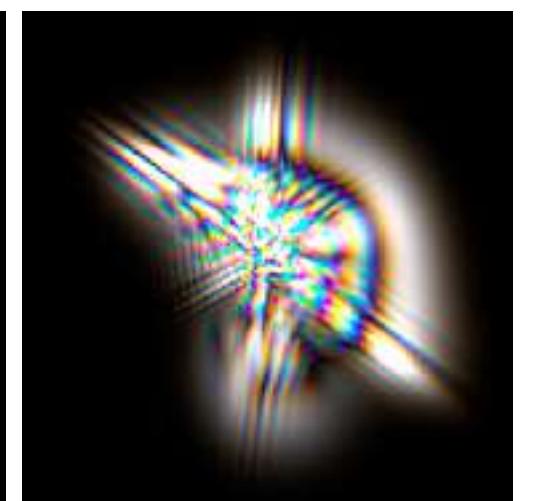
geometric



wave



geometric



wave

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

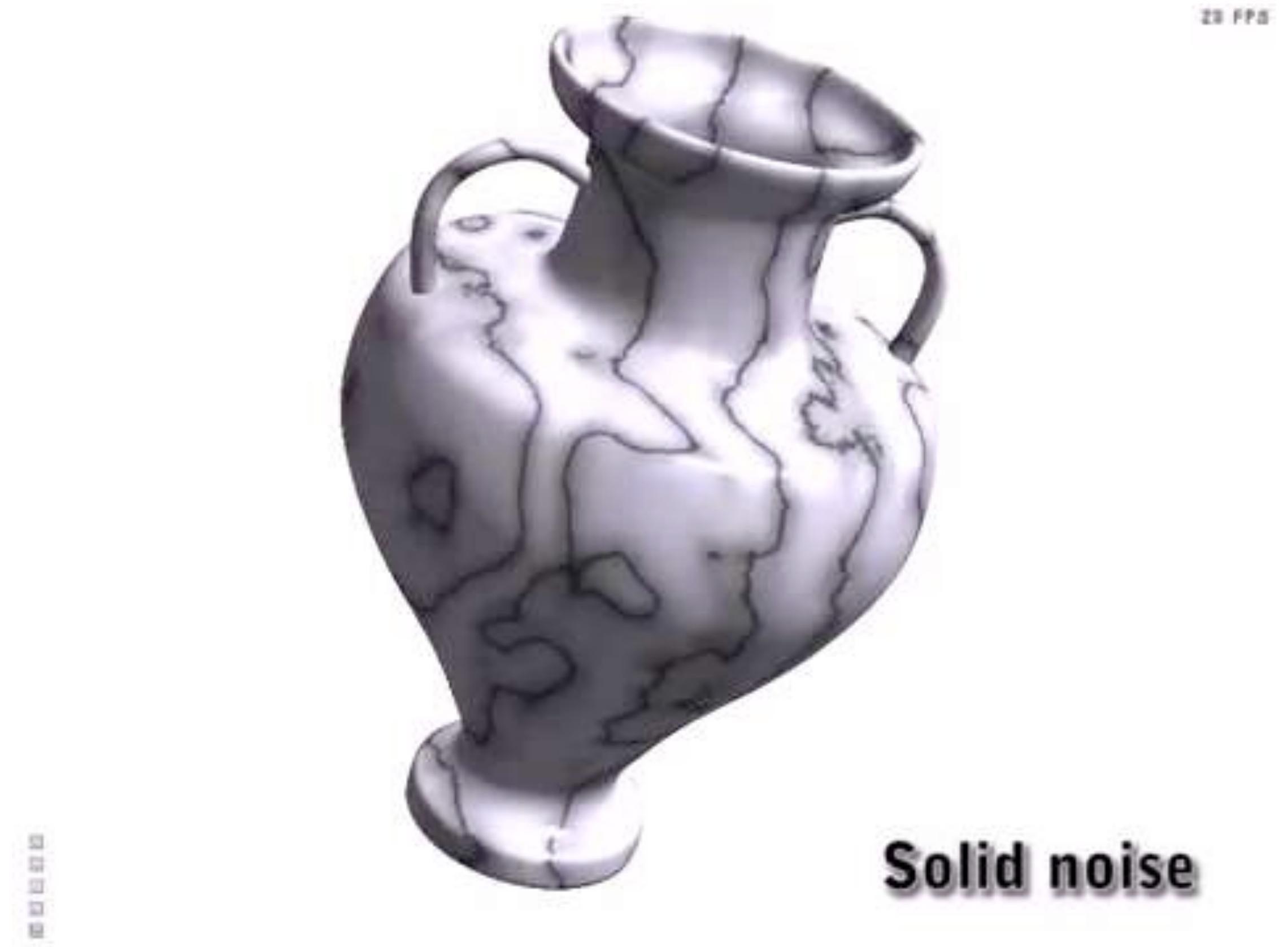
- Can we define details without textures?
 - Yes! Compute a noise function on the fly.



[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)

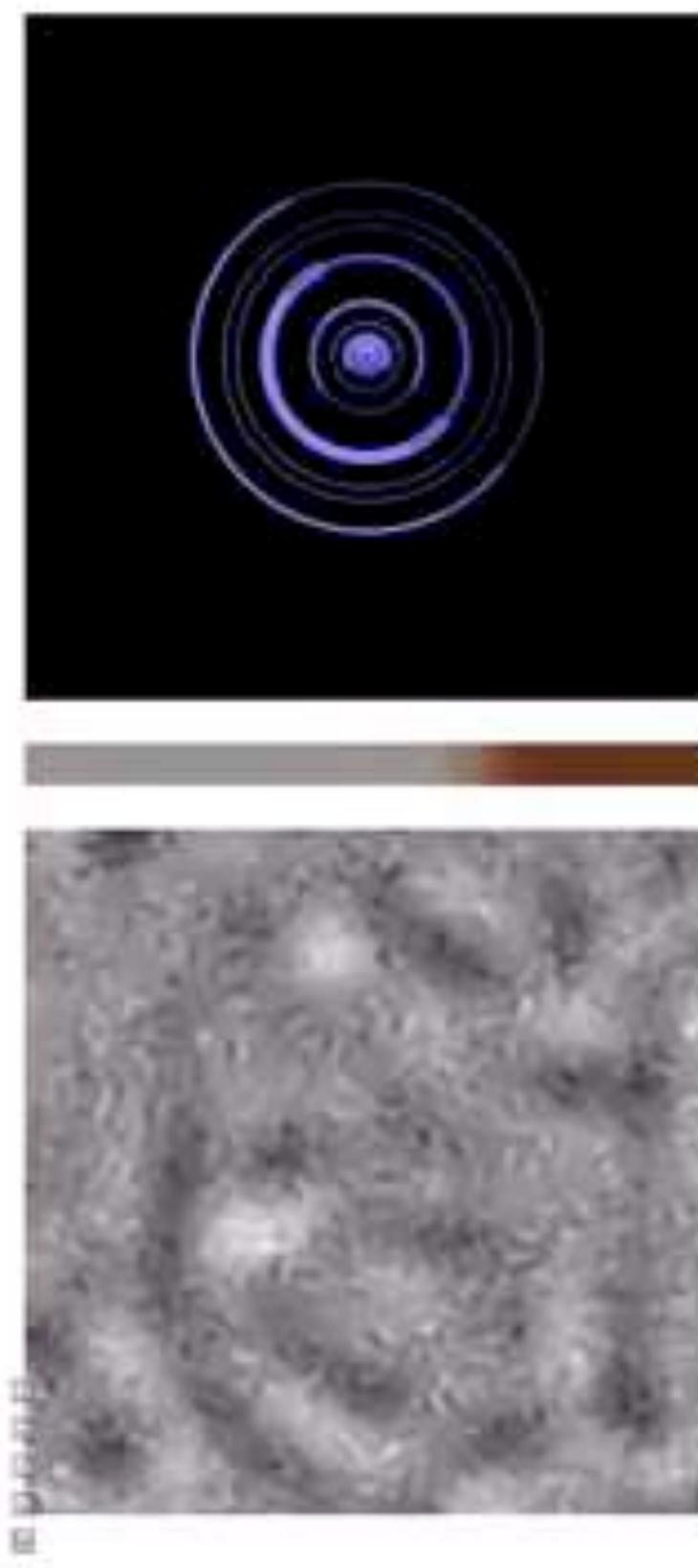
Example:

```
if noise(x, y, z) > 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!)