BSSRDF Importance Sampling

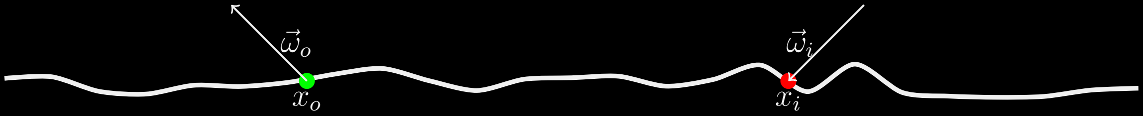
Alan King   Christopher Kulla   Alejandro Conty   Marcos Fajardo

SOLIDANGLE

SONY PICTURES imageworks

Background

Most materials scatter light below the surface



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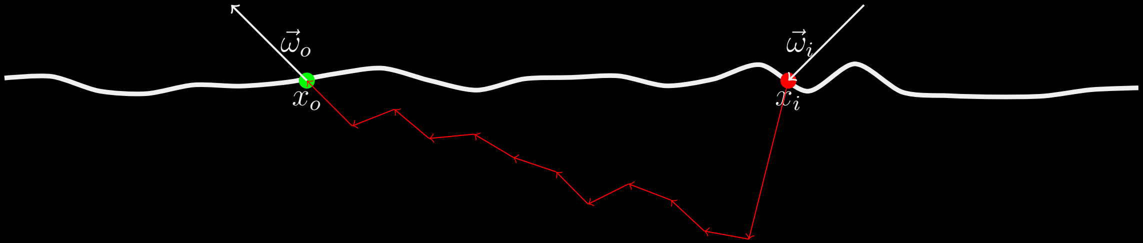

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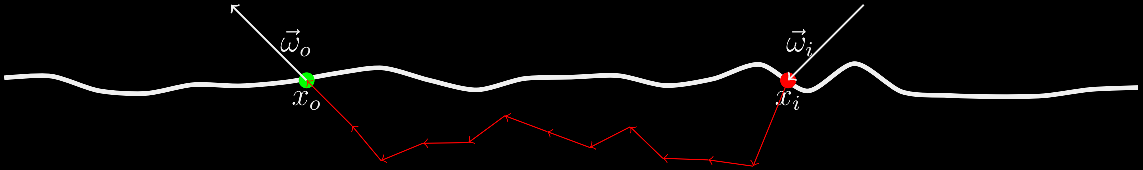

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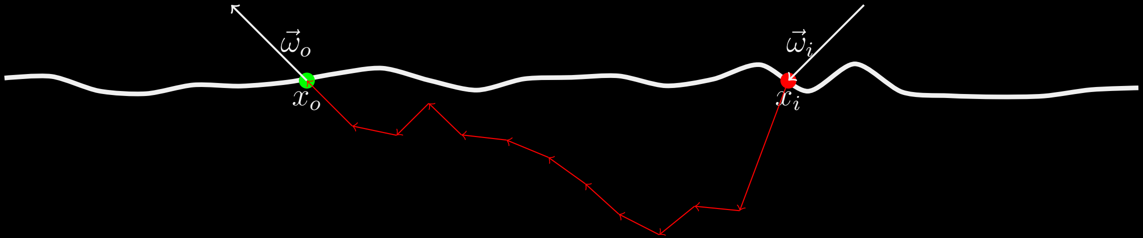

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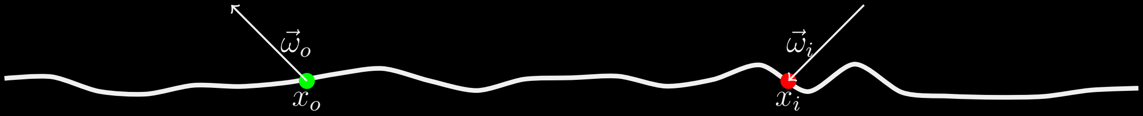
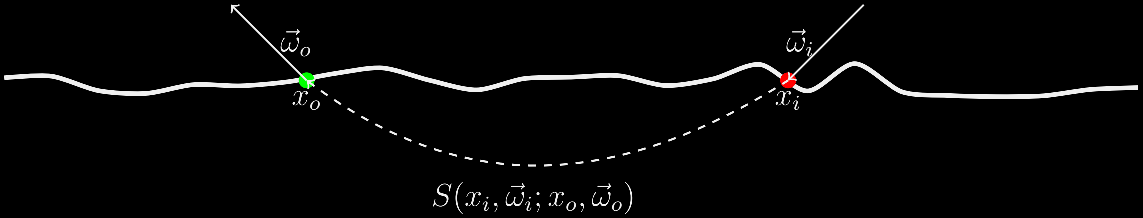


Background

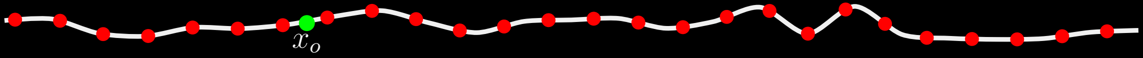
A BSSRDF* represents this process with a single formula (Jensen et al. [2001])



*Bidirectional Surface Scattering Distribution Function

Background

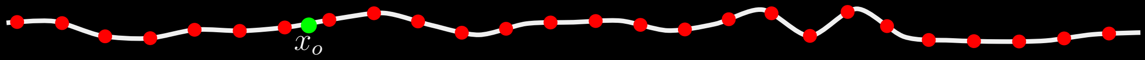
At each shading point, an integral over the entire surface must be performed



$$L_o(x_o, \vec{\omega}_o) = \int_A \int_{2\pi} S(x_i, \vec{\omega}_i; x_o, \vec{\omega}_o) L_i(x_i, \vec{\omega}_i)(\vec{\omega}_i \cdot \vec{n}_i) d\vec{\omega}_i dA(x_i)$$

Background

We will assume the BSSRDF is radially symmetric and mostly a function of distance
Our talk focuses on *evaluating* the integral, not the shape of the BSSRDF



$$L_o(x_o, \vec{\omega}_o) = \int_A R(||x_i - x_o||) \int_{2\pi} L_i(x_i, \vec{\omega}_i)(\vec{\omega}_i \cdot \vec{n}_i) d\vec{\omega}_i dA(x_i)$$

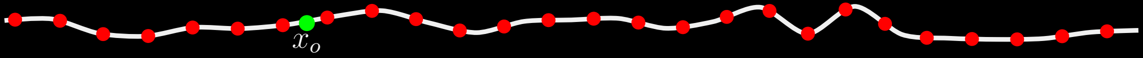
Background

BSSRDFs are still actively being researched! [Habel et al., 2013], [d'Eon and Irving, 2011], ...

Simple alternatives to the more sophisticated models include:

Cubic: $R(r) = \frac{10(R_{\max} - r)^3}{\pi R_{\max}^5}$

Gaussian: $R(r) = \frac{1}{2\pi\nu^2} e^{-r^2/2\nu^2}$



$$L_o(x_o, \vec{\omega}_o) = \int_A R(||x_i - x_o||) \int_{2\pi} L_i(x_i, \vec{\omega}_i)(\vec{\omega}_i \cdot \vec{n}_i) d\vec{\omega}_i dA(x_i)$$

Previous Work - Point Clouds (Jensen and Buhler [2002])

- Distribute points across the mesh

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- Compute lighting at each sample

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- Integrate by traversing data-structure

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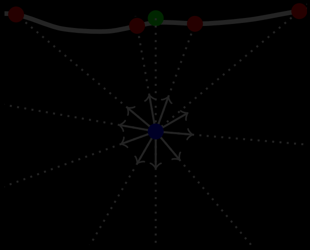
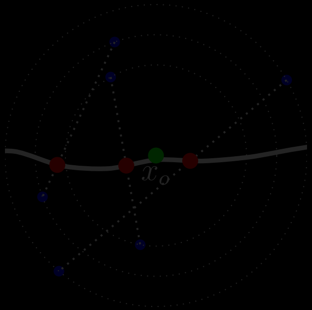
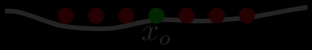
- Distribute points across the mesh
- Compute lighting at each sample
- Integrate by traversing data-structure
- Drawbacks
  - Additional memory
  - Requires a pre-pass
  - Unfriendly to progressive rendering
  - Point density $\approx$ mean free path
  - Flickering artifacts

Previous Work - Monte Carlo Methods

Three MC methods have been proposed



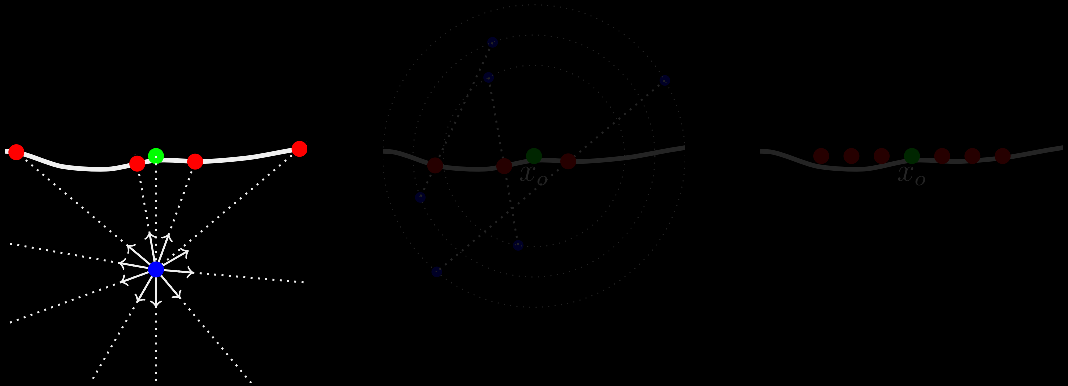




Previous Work - Monte Carlo Methods

Christensen et al. [2012]

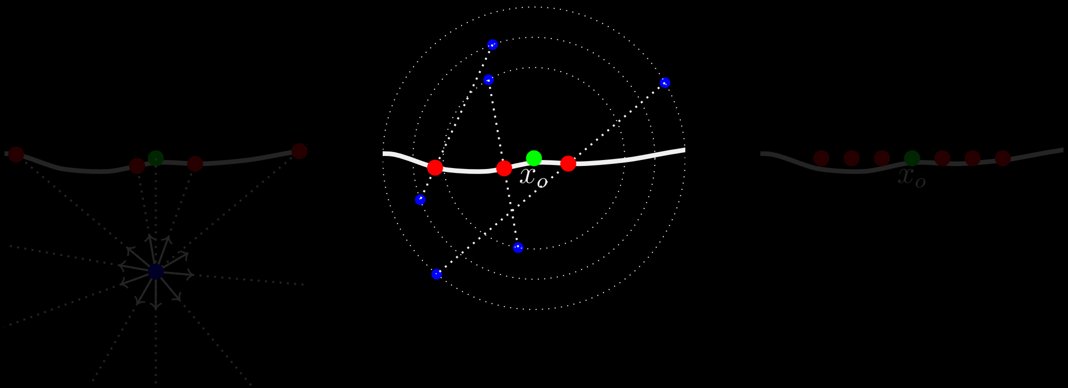
Multiresolution Radiosity Caching for Global Illumination in Movies



Previous Work - Monte Carlo Methods

Walter et al. [2012]

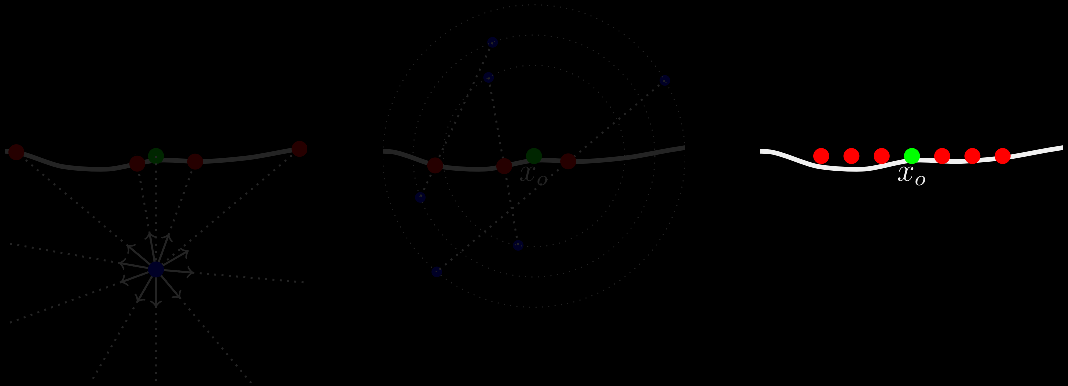
Bidirectional Lightcuts (Appendix B)



Previous Work - Monte Carlo Methods

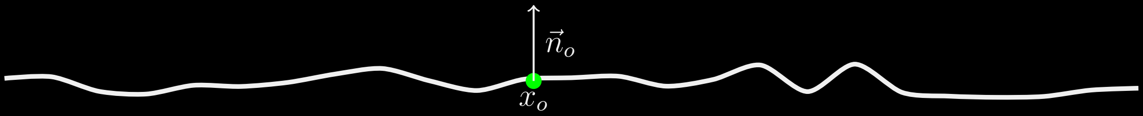
Jensen et al. [2001]

A Practical Model for Subsurface Light Transport



Previous Work (1/3) - Christensen et al [2012]

Choose a point below the surface



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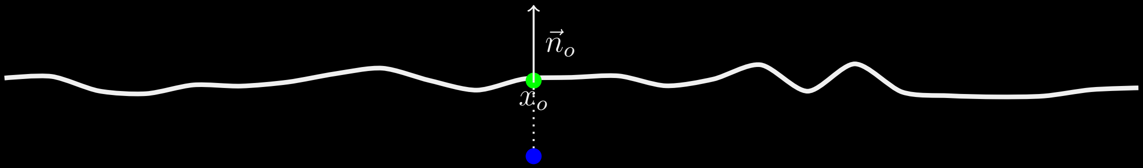
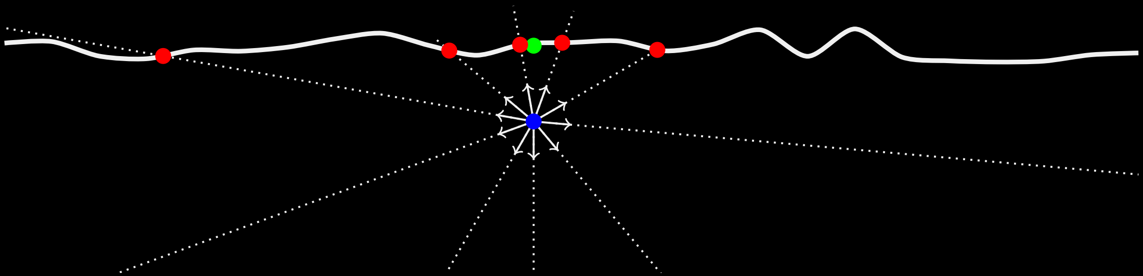


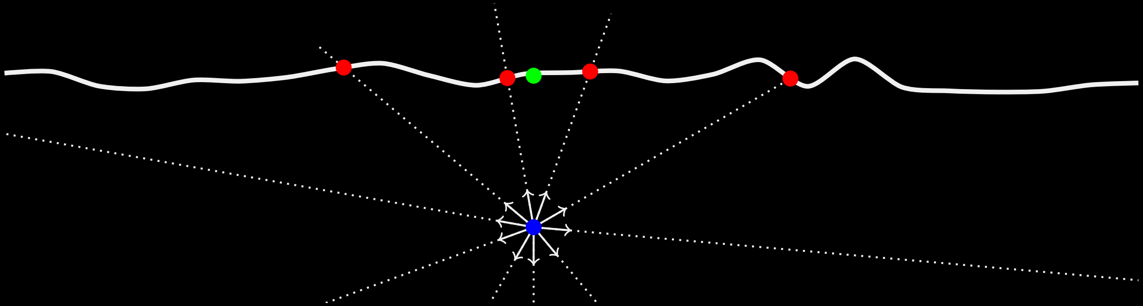
Previous Work (1/3) - Christensen et al [2012]

Trace rays uniformly



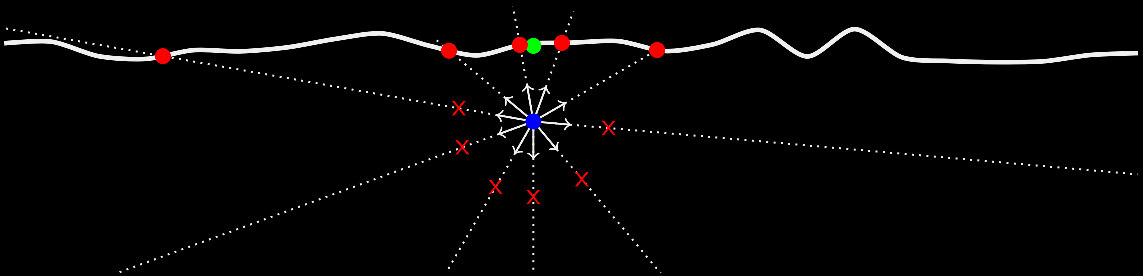
Previous Work (1/3) - Christensen et al [2012]

Distribution depends on distance to surface



Previous Work (1/3) - Christensen et al [2012]

Samples have uniform probability but very different weights



Previous Work (2/3) - Walter et al [2012]

Choose a radius with a pdf derived from $R(r)$

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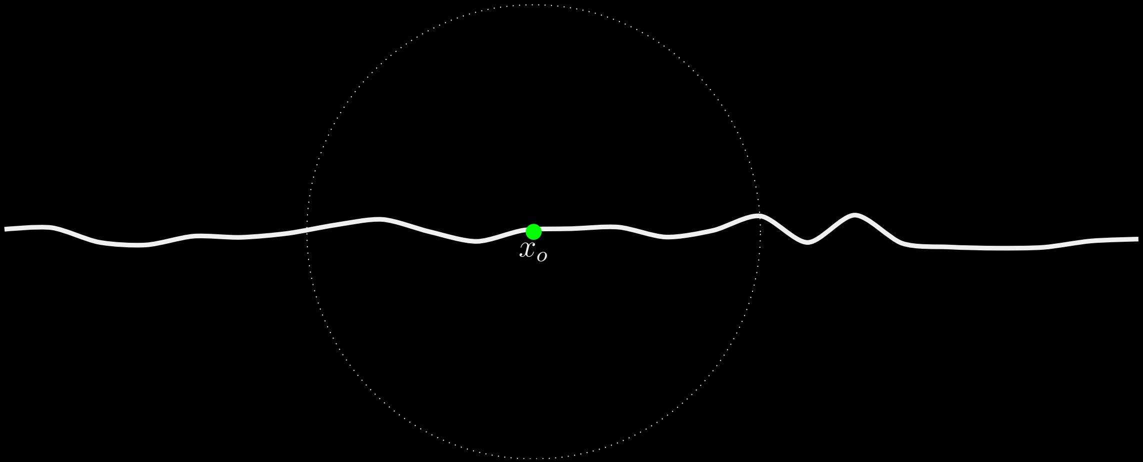
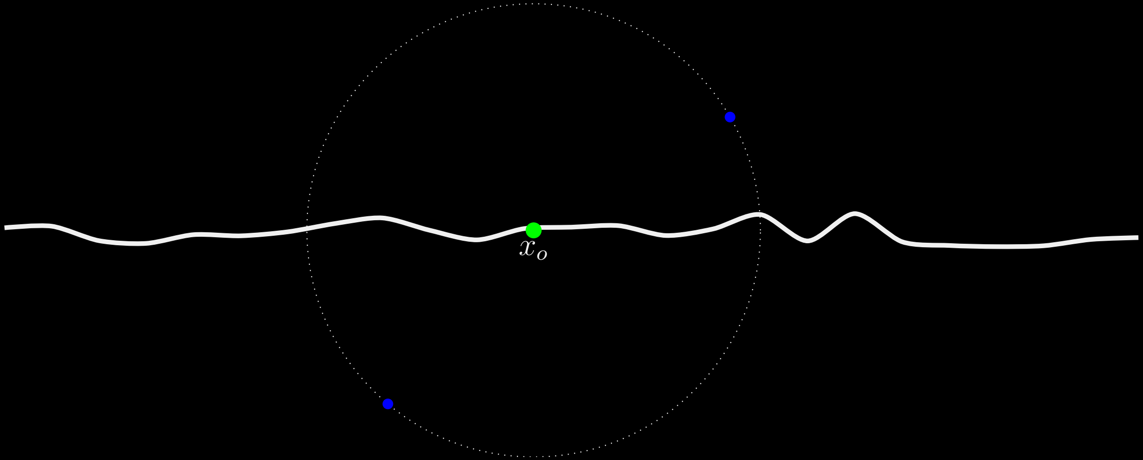
Choose a radius with a pdf derived from $R(r)$



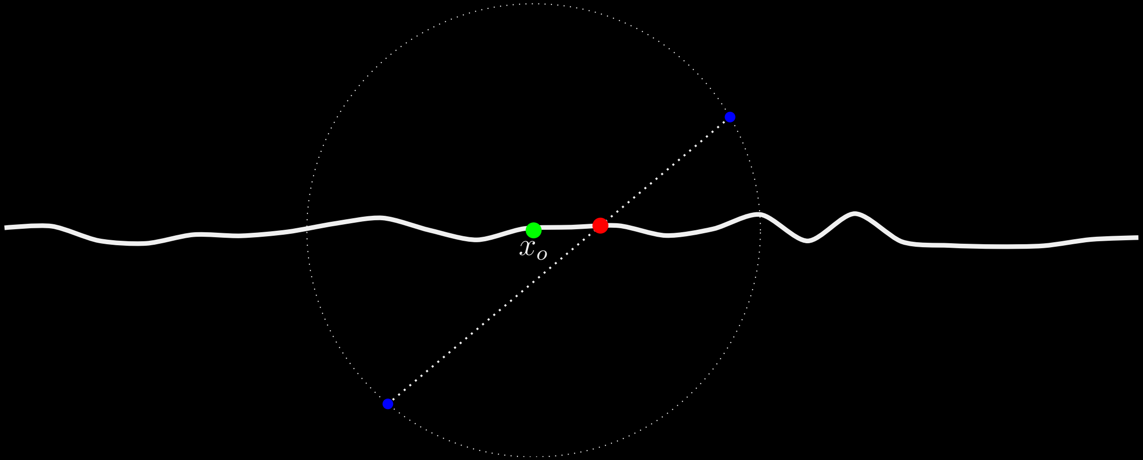
Previous Work (2/3) - Walter et al [2012]

Choose two random points on this sphere



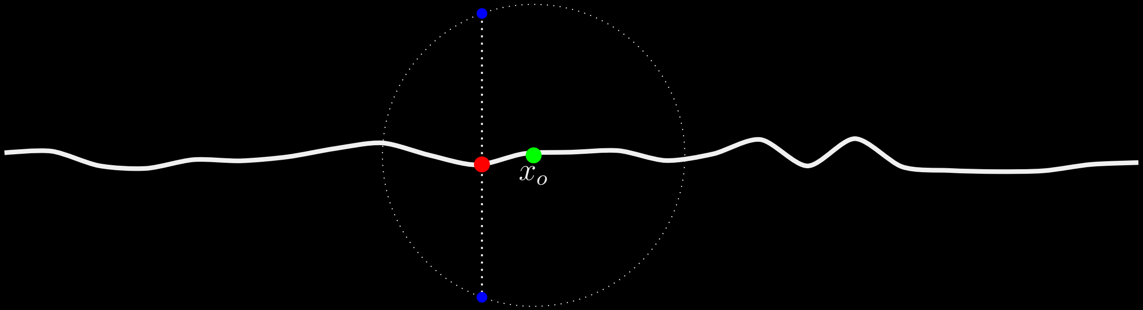
Previous Work (2/3) - Walter et al [2012]

Intersect ray segment with surface



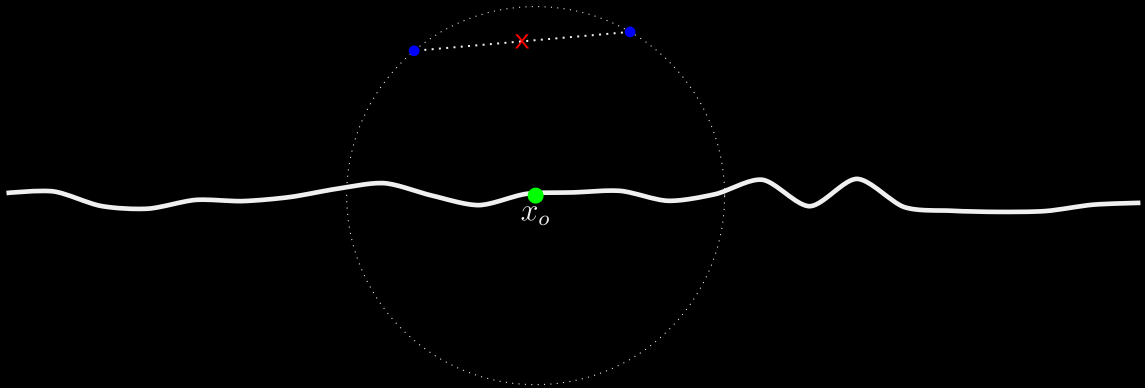
Previous Work (2/3) - Walter et al [2012]

Requires 5 random numbers (r, θ_a, ϕ_a, θ_b, ϕ_b)



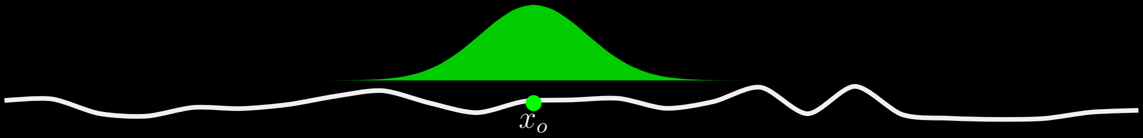
Previous Work (2/3) - Walter et al [2012]

Some rays do not produce any samples



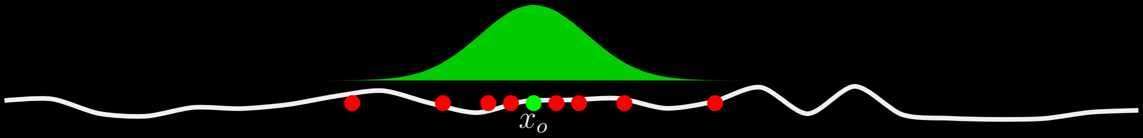
Previous work (3/3) - Jensen et. al [2001]

Distribute points on disk around x_o according to $R(r)$



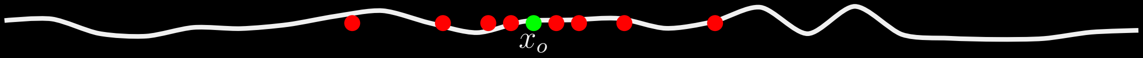
Previous work (3/3) - Jensen et. al [2001]

Optimal distribution for flat planes



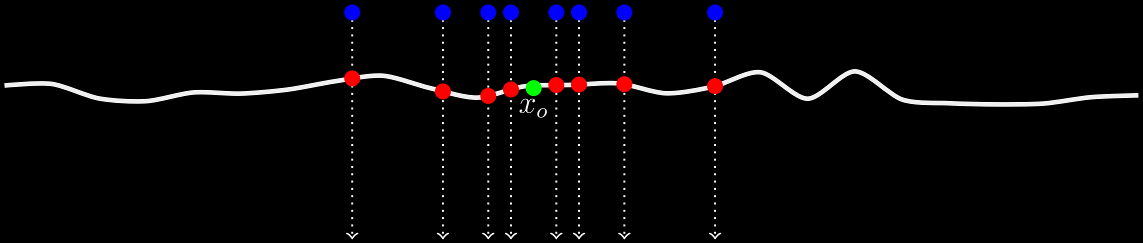
Previous work (3/3) - Jensen et. al [2001]

Samples do not lie on the surface in general case



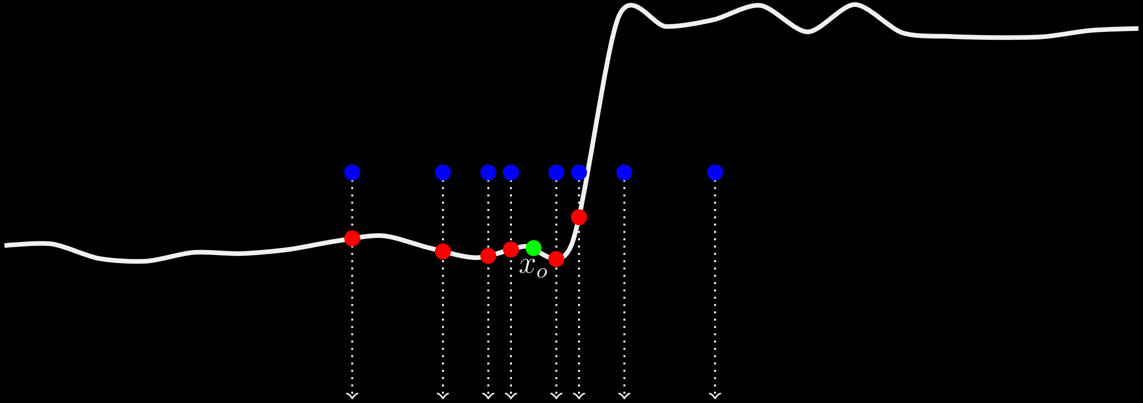
Previous work (3/3) - Jensen et. al [2001]

Hery [2003] proposed a simple top-down projection



Previous work (3/3) - Jensen et. al [2001]

Still not robust to all cases

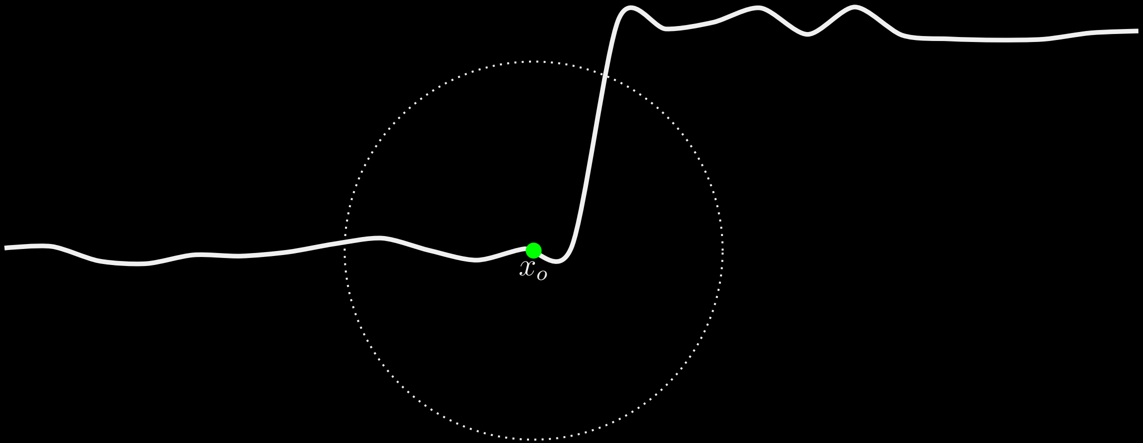


Our approach

- Based on Jensen's disk sampling approach
- Introduce a robust projection method
- Extend method to weighted sums of profiles

Our approach

Define $R_{\max}$ to make search volume well defined



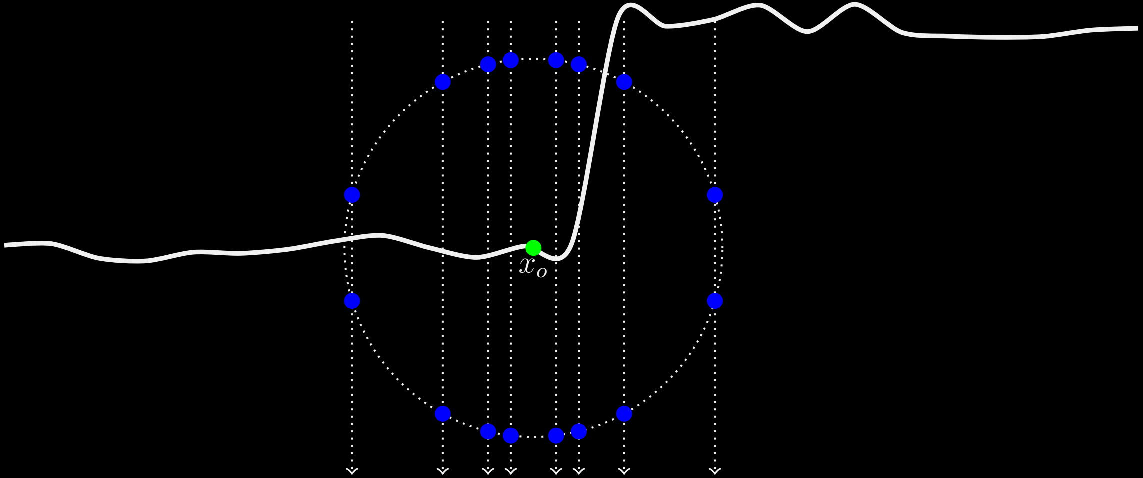
(Not a strict requirement, but keeps probe rays short)

Our approach

Distribute samples on disk above the surface according to $R(r)$

Our approach

Probe along normal direction, find all hits inside sphere



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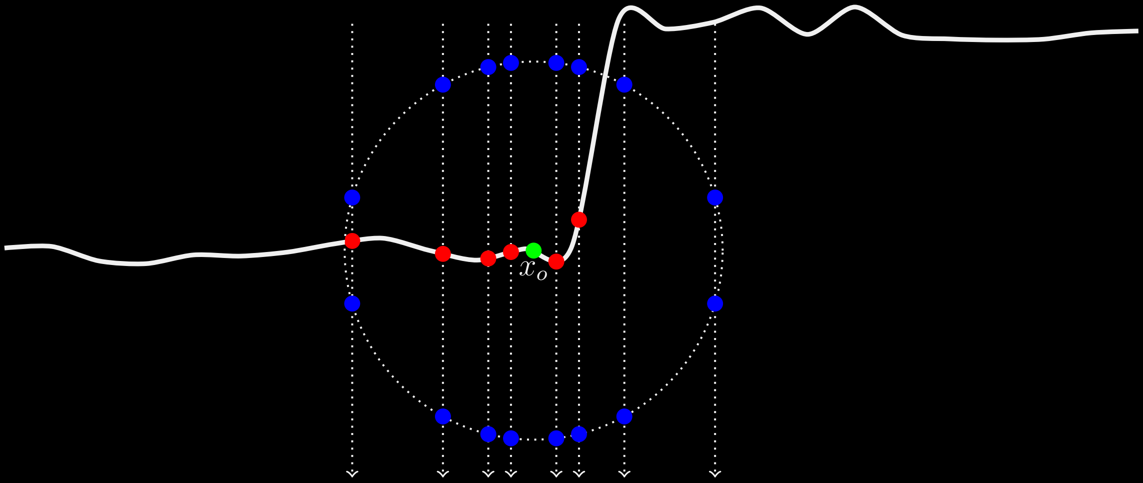
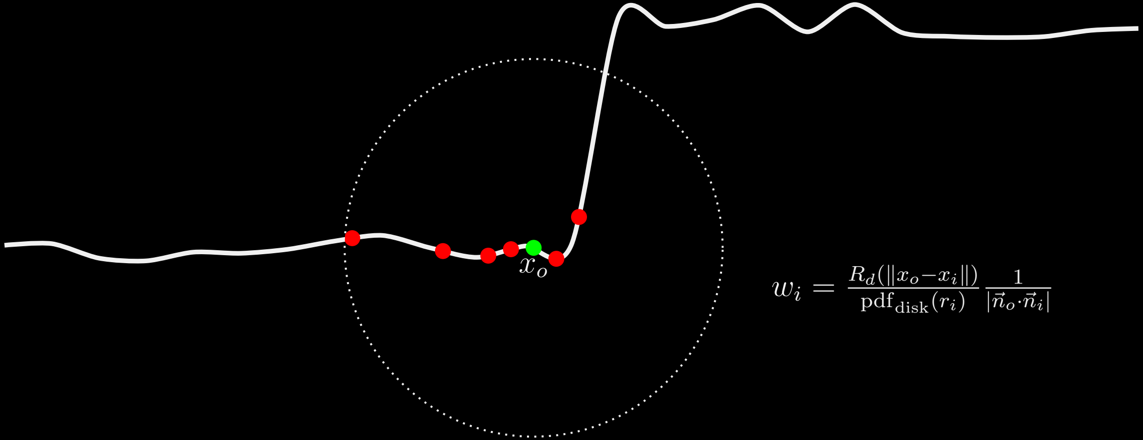


Our approach

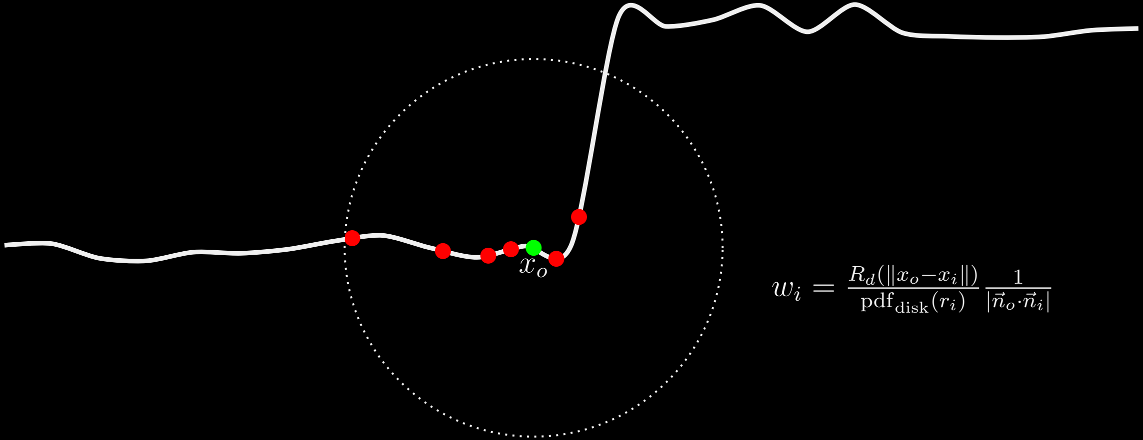
In flat regions, $|\vec{n}_o \cdot \vec{n}_i| \to 1$ and $r_i \approx \|x_o - x_i\|$ so $w_i \approx 1$



$$w_i = \frac{R_d(\|x_o - x_i\|)}{\mathrm{pdf}_{\mathrm{disk}}(r_i)} \frac{1}{|\vec{n}_o \cdot \vec{n}_i|}$$

Our approach

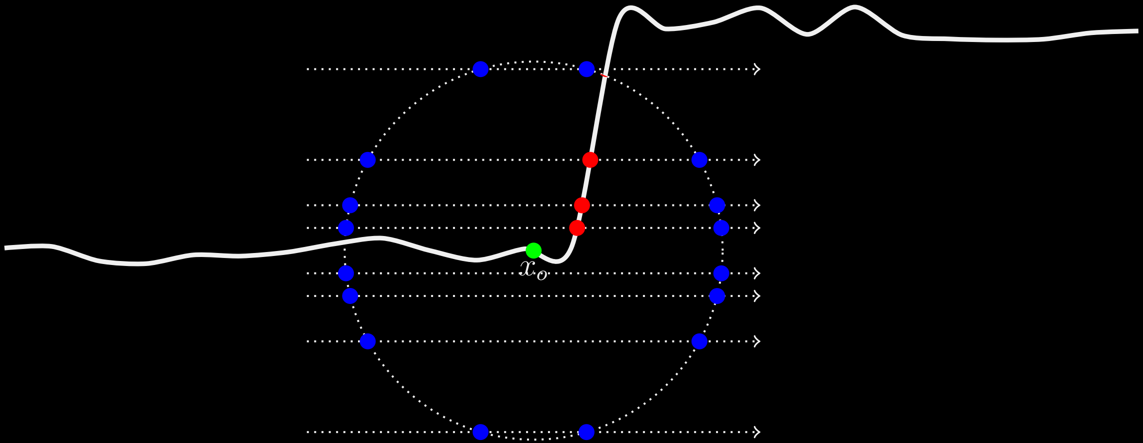
In perpendicular regions: $|\vec{n}_o \cdot \vec{n}_i| \to 0$ and $r_i \neq \|x_o - x_i\|$ so $w_i \to \infty$



$$w_i = \frac{R_d(\|x_o - x_i\|)}{\mathrm{pdf}_{\mathrm{disk}}(r_i)} \frac{1}{|\vec{n}_o \cdot \vec{n}_i|}$$

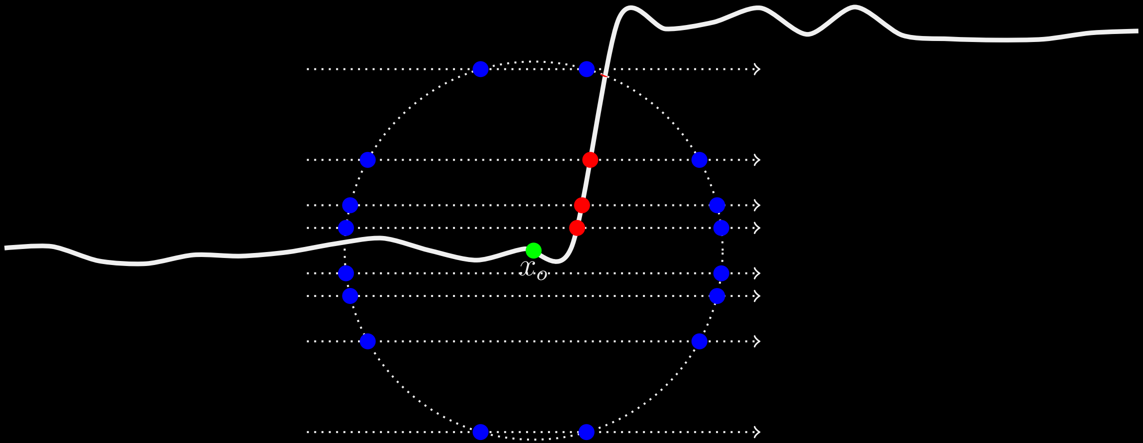
Our approach

We solve this by probing along *orthogonal* directions as well



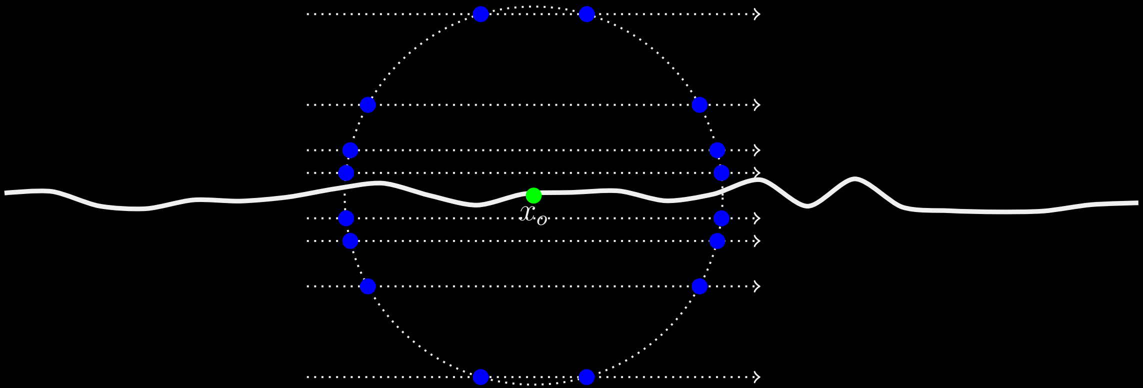
Our approach - Axis MIS

Combine estimators with *multiple importance sampling* to keep the best of each

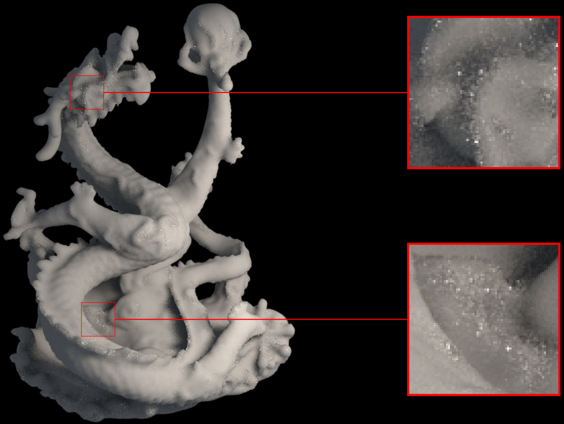


Our approach - Axis MIS

Some performance is lost in flat regions for more uniform variance overall

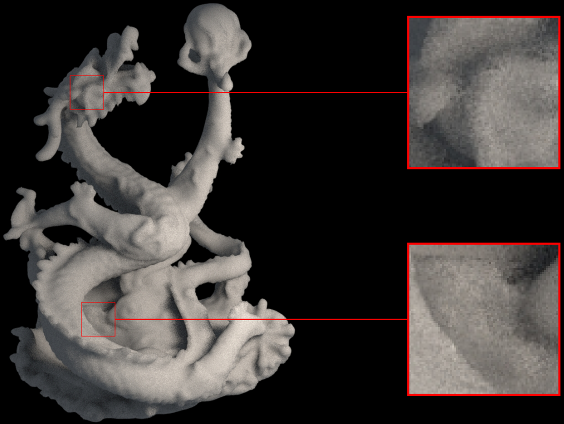


Axis MIS - Results



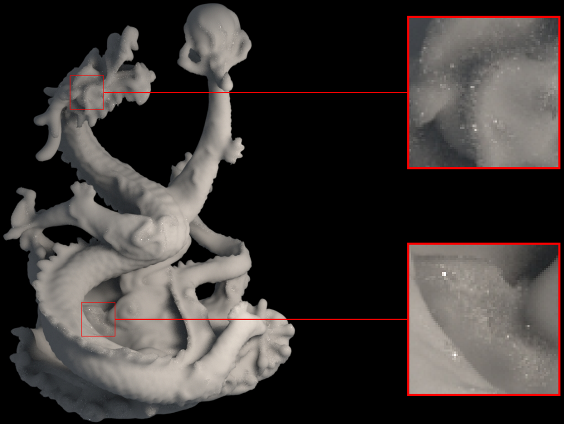
16 paths / pixel
Probe along N only

Axis MIS - Results



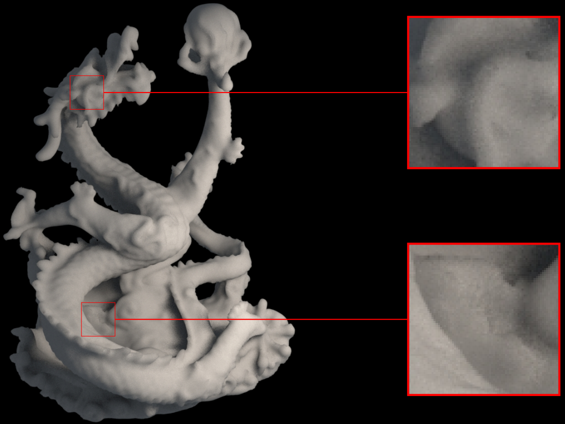
16 paths / pixel
Probe along U,V,N with MIS

Axis MIS - Results



64 paths / pixel
Probe along N only

Axis MIS - Results



64 paths / pixel
Probe along U,V,N with MIS

Implementation details

- Choice of axes is arbitrary, we found shading tangent frame works best
- Assign probabilities $(\vec{u}\colon \frac{1}{4}, \vec{v}\colon \frac{1}{4}, \vec{n}\colon \frac{1}{2})$
- Re-use random number of axis selection for random radius
- Shade *all* hits encountered along the probe ray to handle thin regions
- Or stochastically choose *one* hit among all probe hits if splitting is not desirable
- Trace probe rays directly against the surface, bypassing scene hierarchy

Color MIS - Weighted Sums of BSSRDFs

Complex materials like skin are best expressed as weighted sums of simple profiles

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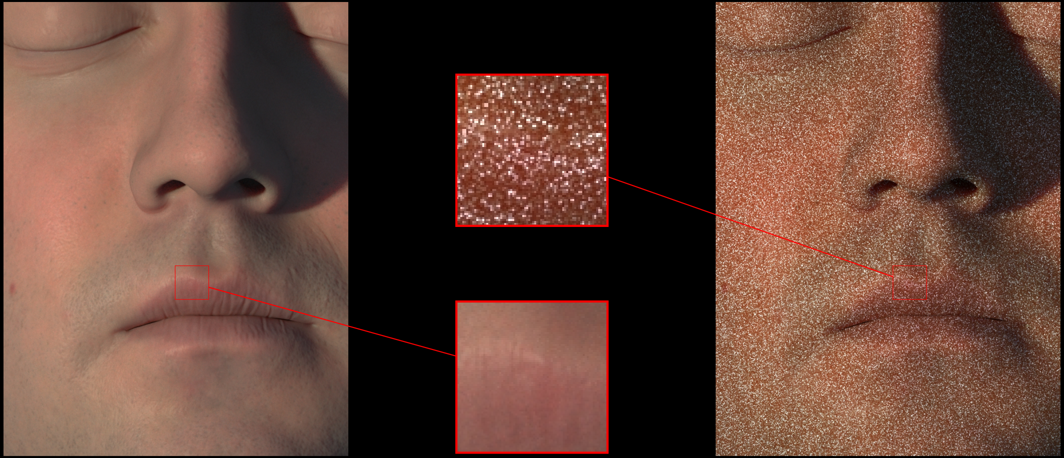
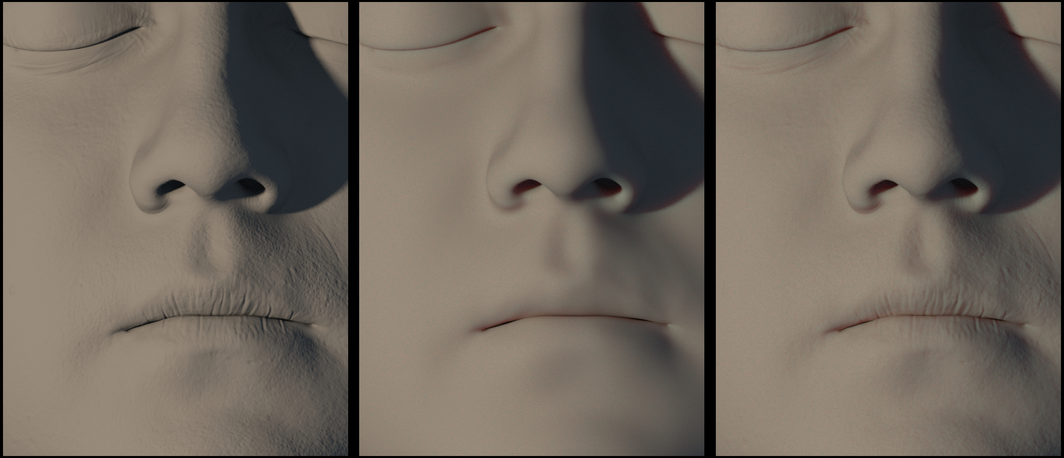
Color MIS - Weighted Sums of BSSRDFs



MIS between profiles allows more efficient sampling than using the widest alone

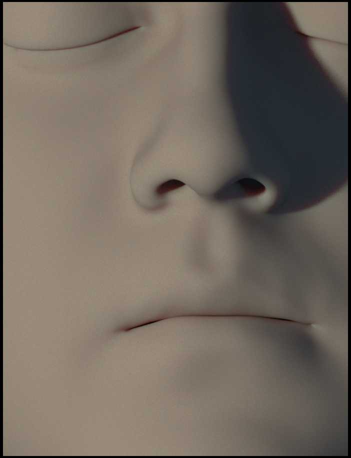
Results - Bonus Features



Fine details like bump are easy to preserve with a traced approach

Results - Bonus Features

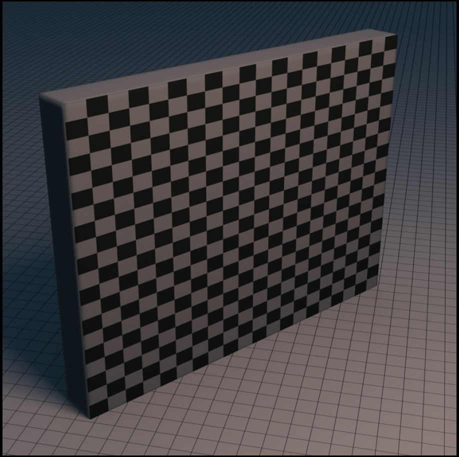
Diffuse BRDF

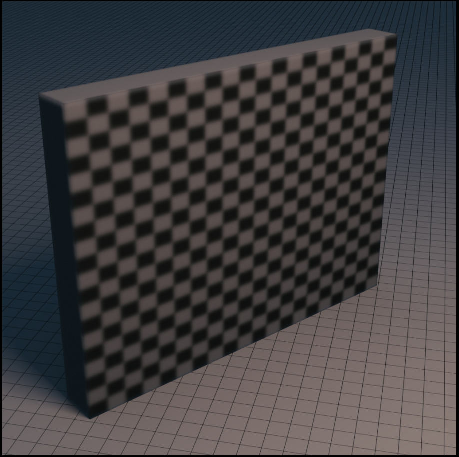


BSSRDF (no bump)

BSSRDF (with bump)

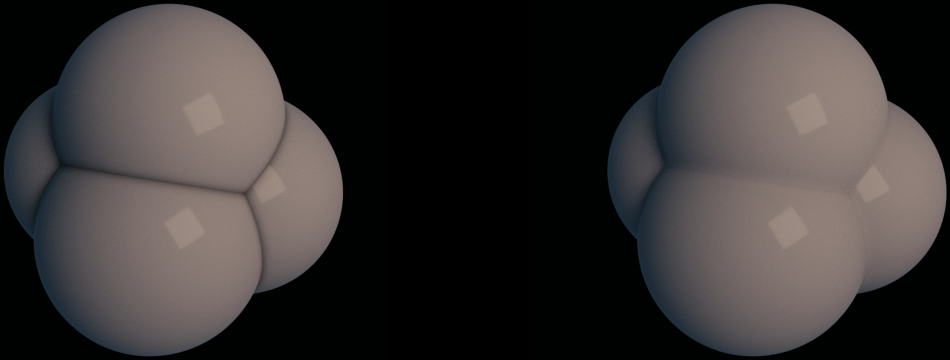
Results - Bonus Features





Albedo may be blurred along with illumination as well

Results - Bonus Features



Easy to blur across meshes to avoid seams

Results - Bonus Features

- Bi-directional extension is straightforward
- Create “virtual” vertex to continue path from
- Select probe hits stochastically if multiple are found

Results - Bonus Features

- Motion blur is always correct with traced approach
- Point clouds usually locked to a single instant
- Important for fast animation or large receivers

Production Results

Hotel Transylvania (©2012 Columbia Pictures Industries, Inc.)

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Oz the Great and Powerful (©2013 Disney Enterprises, Inc.)

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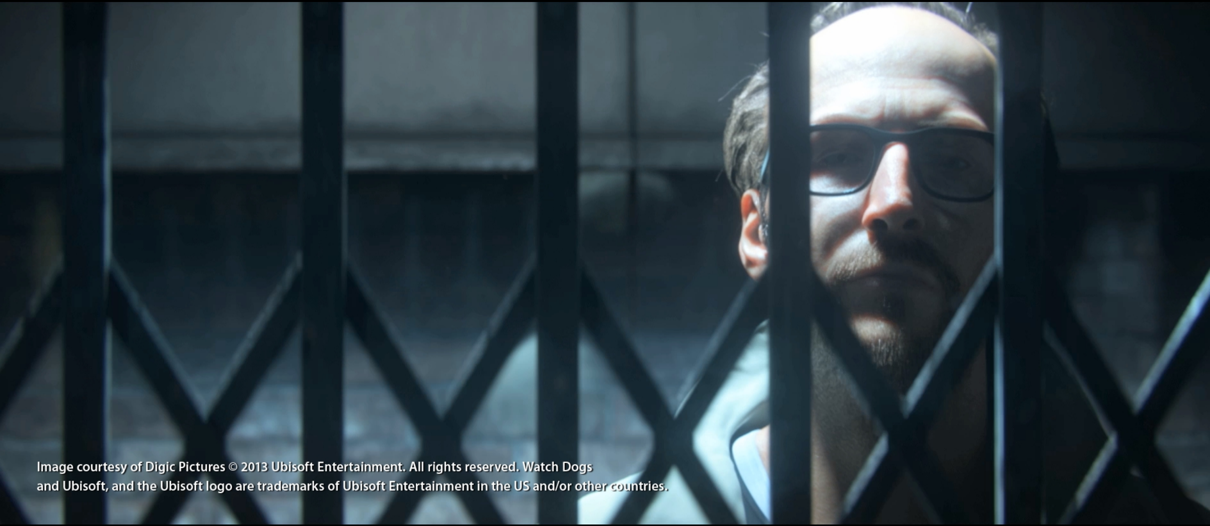

Conclusion & Future Work

- Introduced a simple importance sampling method for BSSRDFs
- Only requires two random numbers and supports weighted sums of profiles
- Replaced a much more complex point cloud implementation
- Much easier for artists to use

- Perform a more detailed comparison with previous work
- Extend technique to work with non-radially symmetric profiles

Thanks for listening!

Questions?

Acknowledgments: Head Model ⓘ Lee Perry-Smith, Dragon Model ⓘ Artec Group