Manifold Path Guiding
for Importance Sampling Specular Chains

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Connecting STORIES
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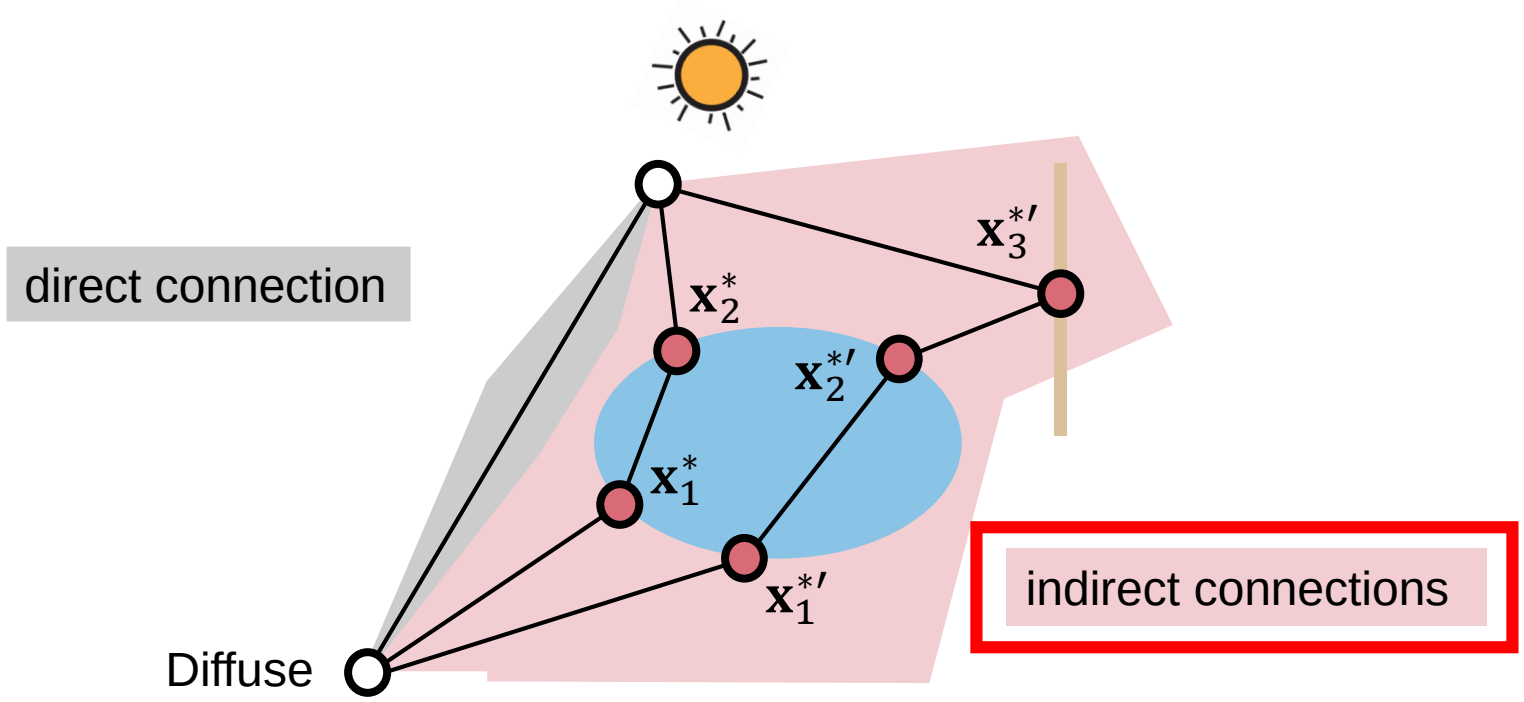
Caustics

- **Complex visual effects**
  - high-frequency details
  - curved specular surfaces
- **Produced by specular paths**
  - containing multiple specular vertices
- **A long-standing challenge** to unbiased Monte Carlo rendering

Specular chains connecting two endpoints

- Given **a point light** and **a shading point**
- How to connect them through **specular vertices**?



Path tracing

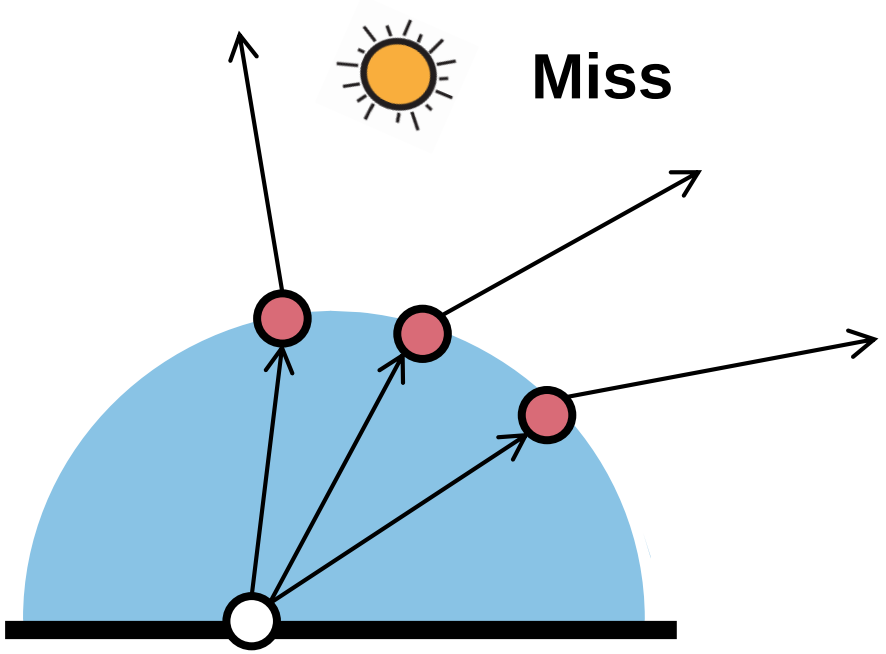
- **Most popular technique**
  - in physically-based rendering
- **Hard to generate caustics**
  - extremely high variance
  - fireflies

Path guiding

- **Prevalent technique in recent years**
- **Refining sampling distributions**
  - fitted from historical samples
- **Not good even if trained properly**
  - easily miss patterns

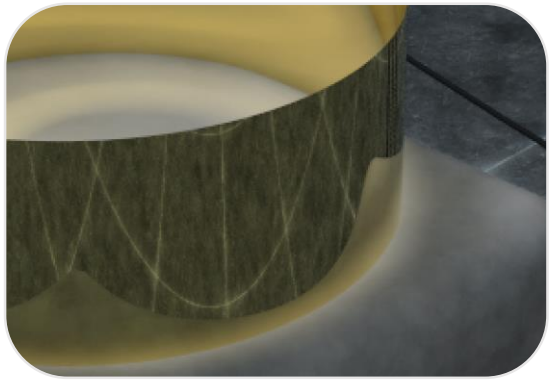
Ours (equal time)

Local sampling methods



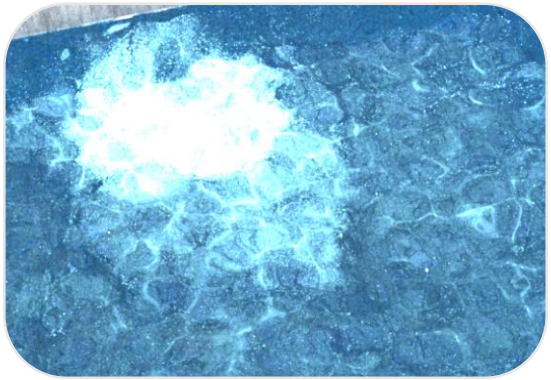
Nearly zero probability to sample a valid path!

Prior works



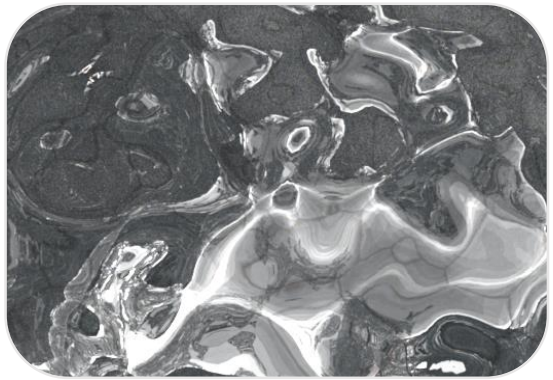
SPPM

[Hachisuka et al. 2009]



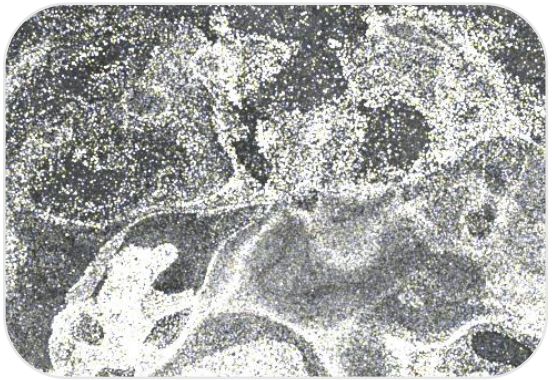
MEMLT

[Jakob and Marschner 2012]



MNEE

[Hanika et al. 2015]



SMS

[Zeltner et al. 2020]

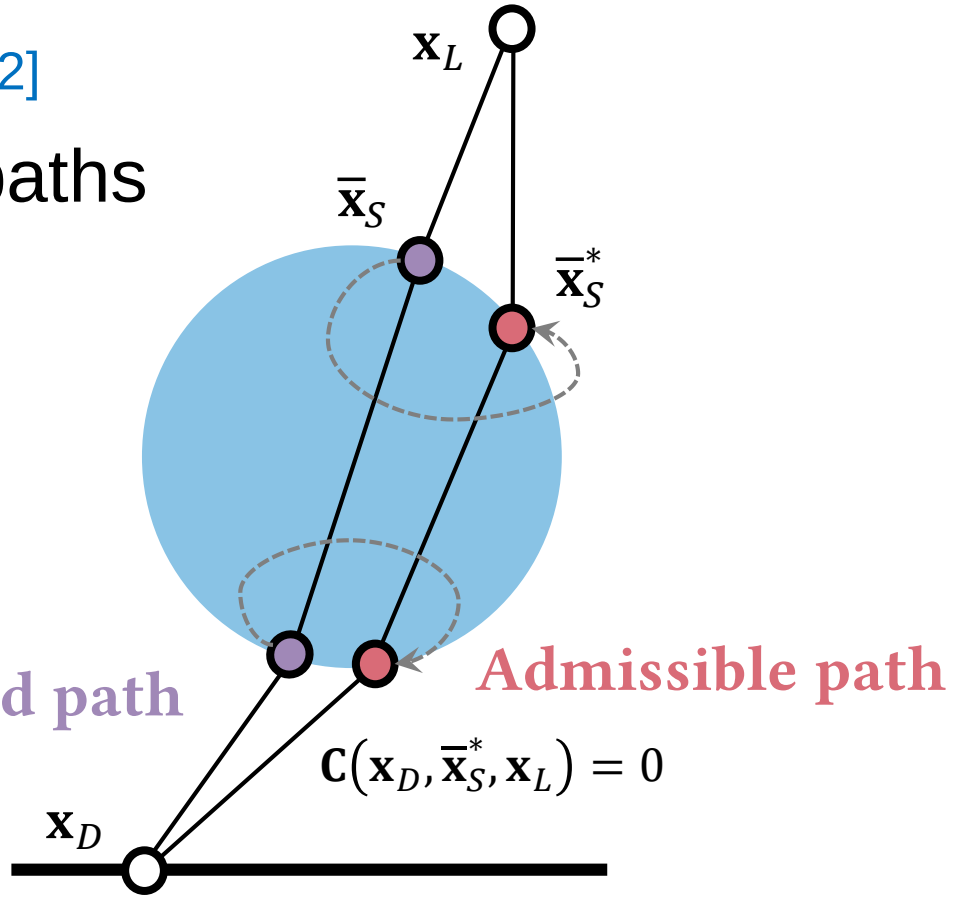
Manifold sampling

Manifold Walks [Jakob and Marschner 2012]

- Convert **seed** paths into **admissible** paths
- Work like Newton's iteration

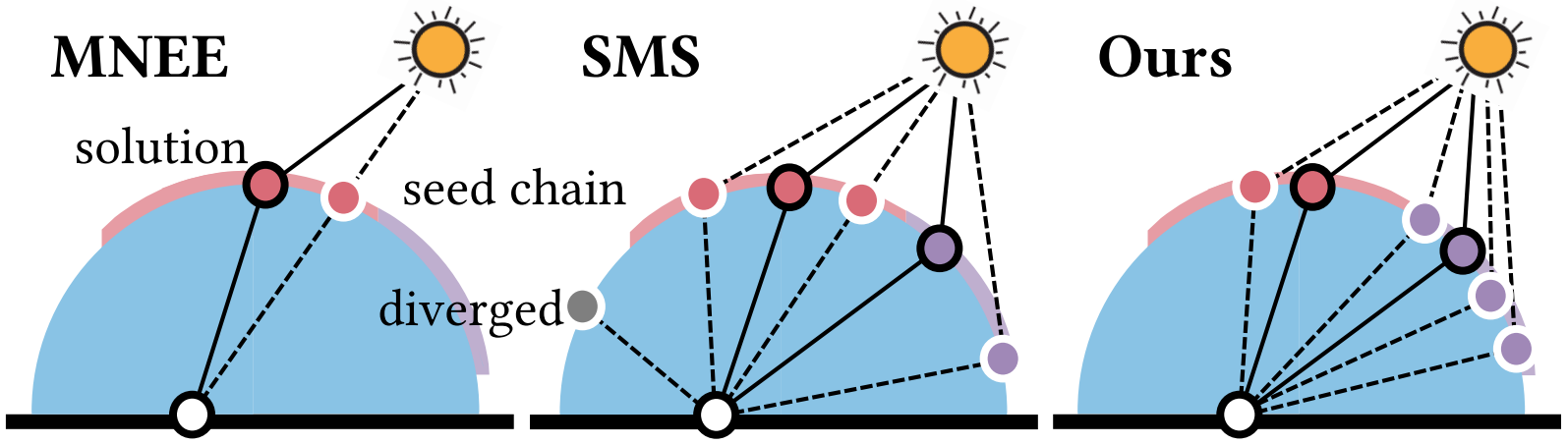
How to sample seed paths?

- heuristically generated [Hanika et al. 2015]
- uniformly sampled [Zeltner et al. 2020]



Motivation

- MNEE finds **at most one solution**, resulting in **energy loss**
- SMS **uniformly** samples the seeds, which leads to **high variance**
- Goal: find paths that are not only **admissible** but also "**important**"



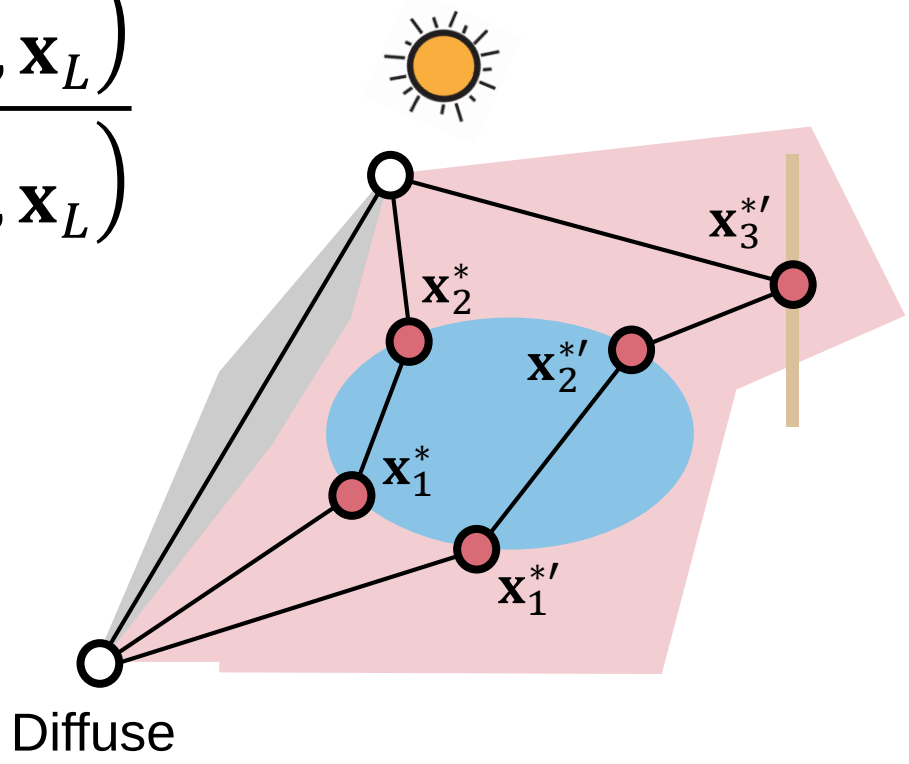
Problem formulation

- MC estimator

$$\left\langle \sum_{\overline{\mathbf{x}}_S^* \in \mathcal{P}_S^*} T\left(\mathbf{x}_D, \overline{\mathbf{x}}_S^*, \mathbf{x}_L\right) \right\rangle = \frac{1}{N} \sum_{i=1}^{N} \frac{T\left(\mathbf{x}_D, \overline{\mathbf{x}}_S^{*(i)}, \mathbf{x}_L\right)}{P\left(\overline{\mathbf{x}}_S^{*(i)} \middle| \mathbf{x}_D, \mathbf{x}_L\right)}$$

- Optimal importance sampling

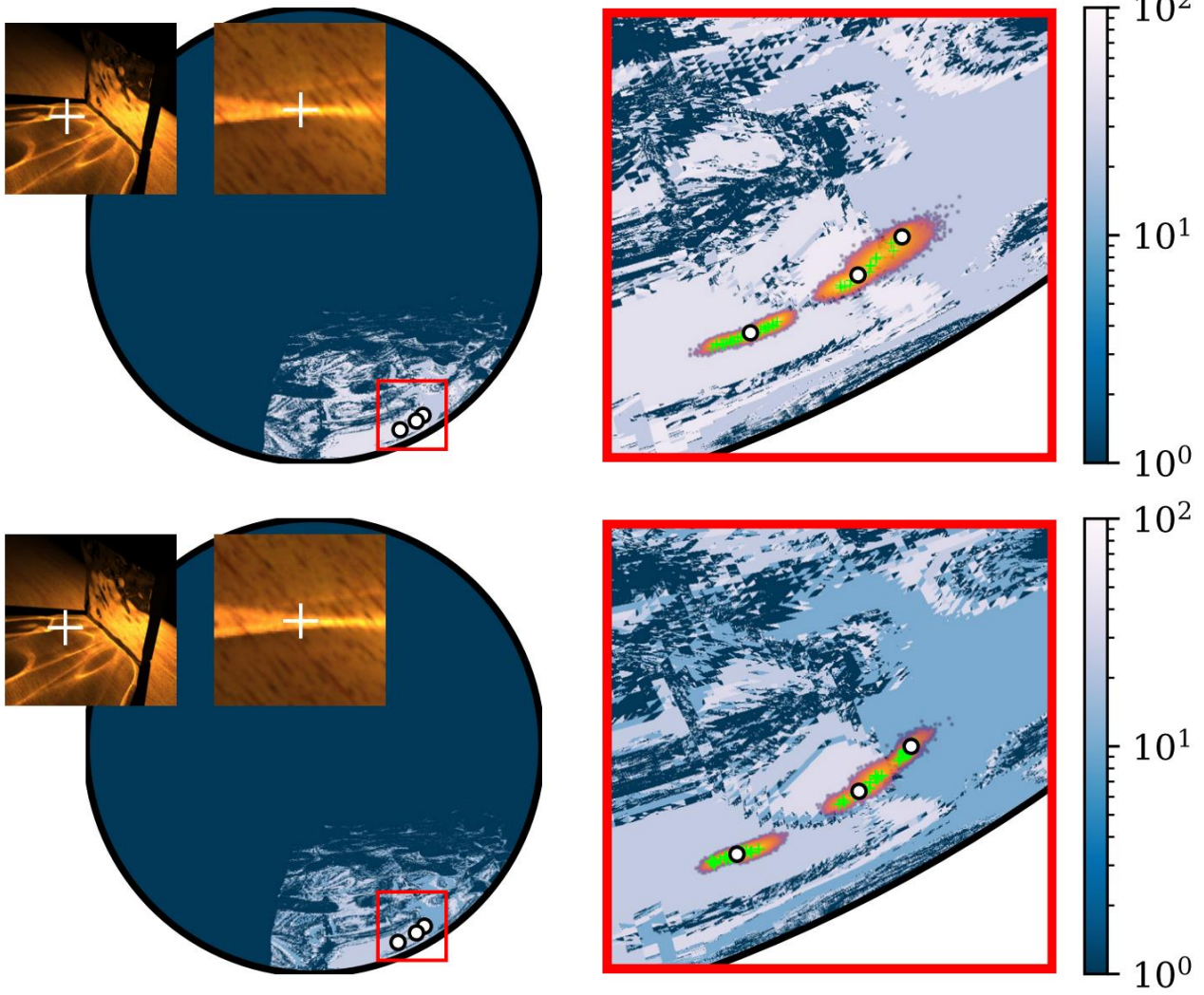
$$P\left(\overline{\mathbf{x}}_S^* \middle| \mathbf{x}_D, \mathbf{x}_L\right) \propto T\left(\mathbf{x}_D, \overline{\mathbf{x}}_S^*, \mathbf{x}_L\right)$$



Exploitation of coherence

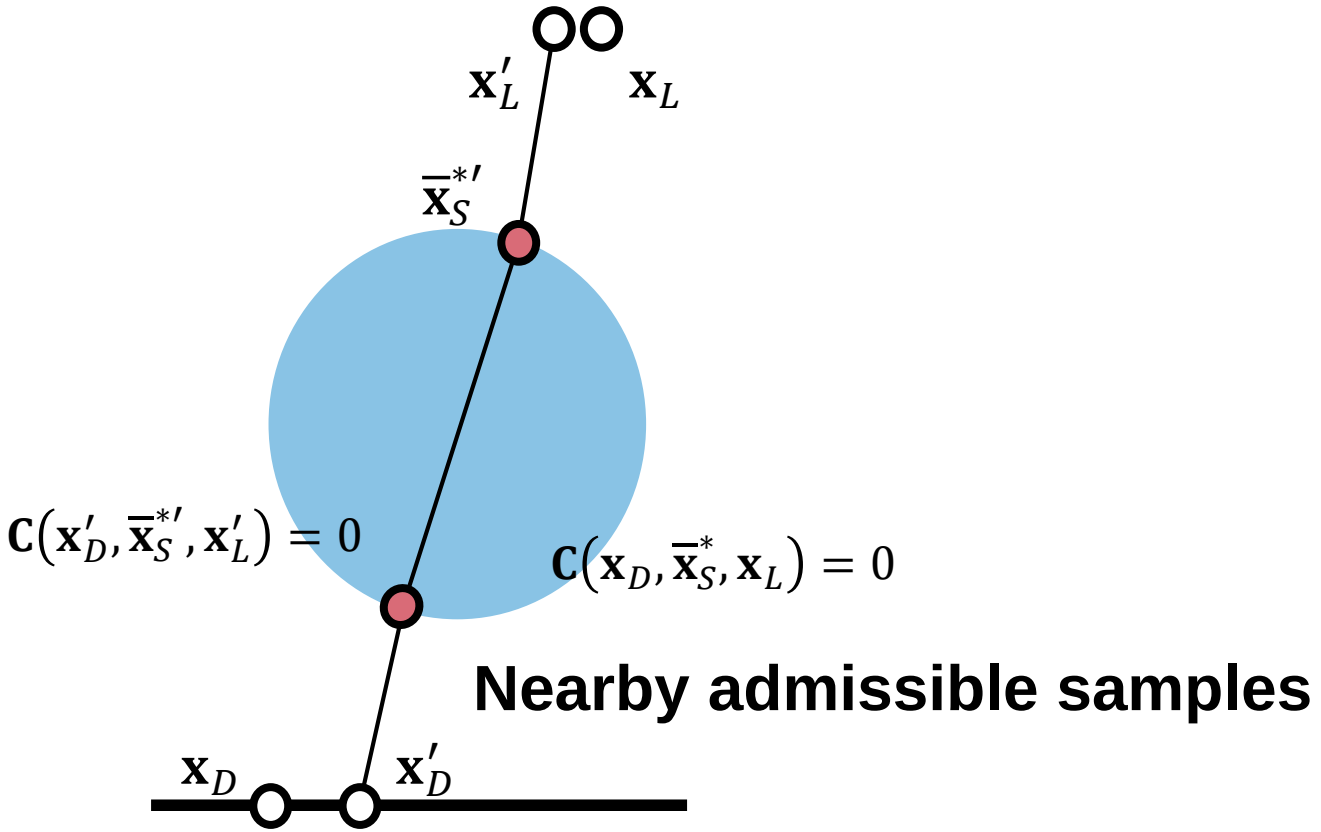
- Admissible chain of nearby configurations can be used as seeds to converge to an admissible chain of current configuration
- Throughputs of those two admissible chains are close

Importance sampling nearby solutions achieves importance sampling current ones!



Importance seed distributions

Utilize nearby admissible samples to generate the current seed



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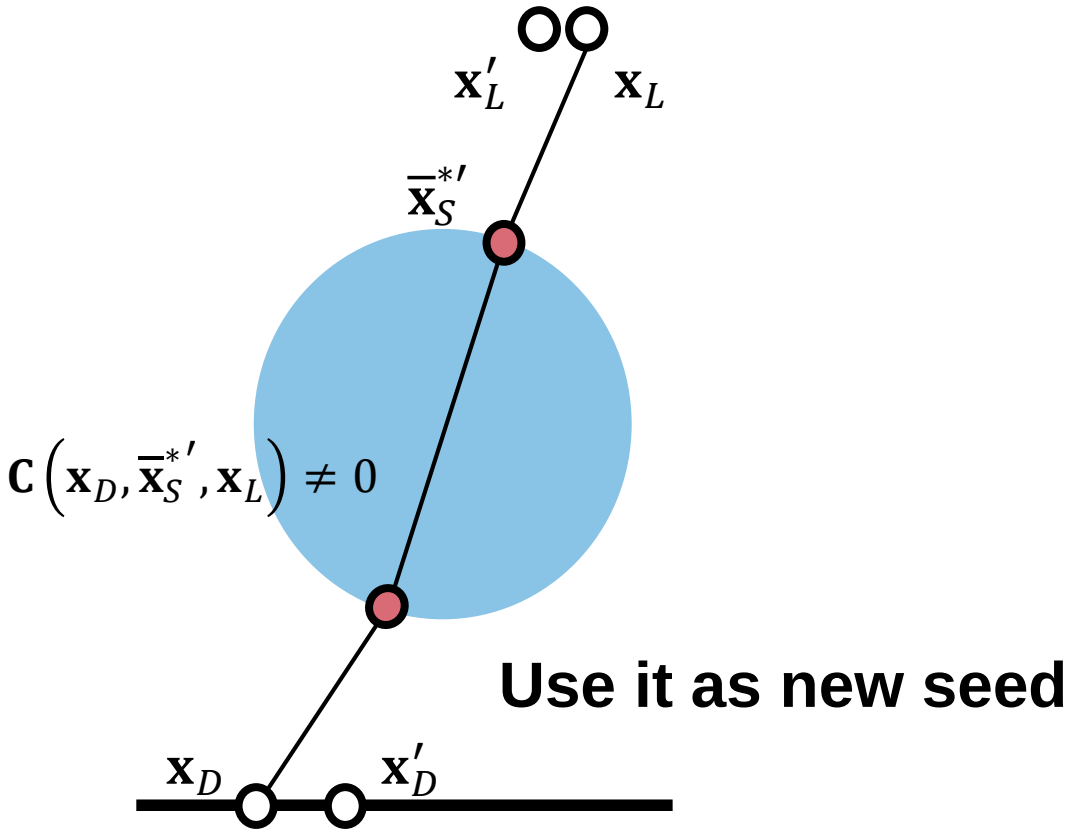

Importance seed distributions

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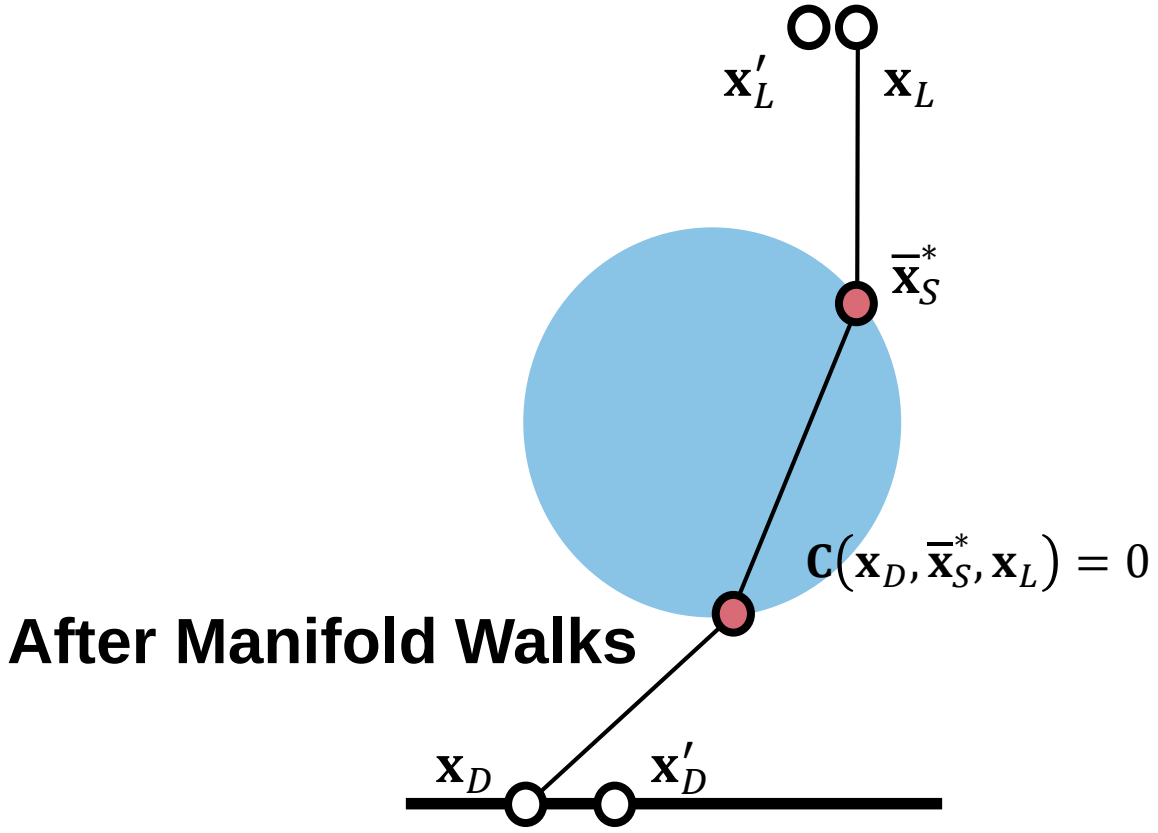
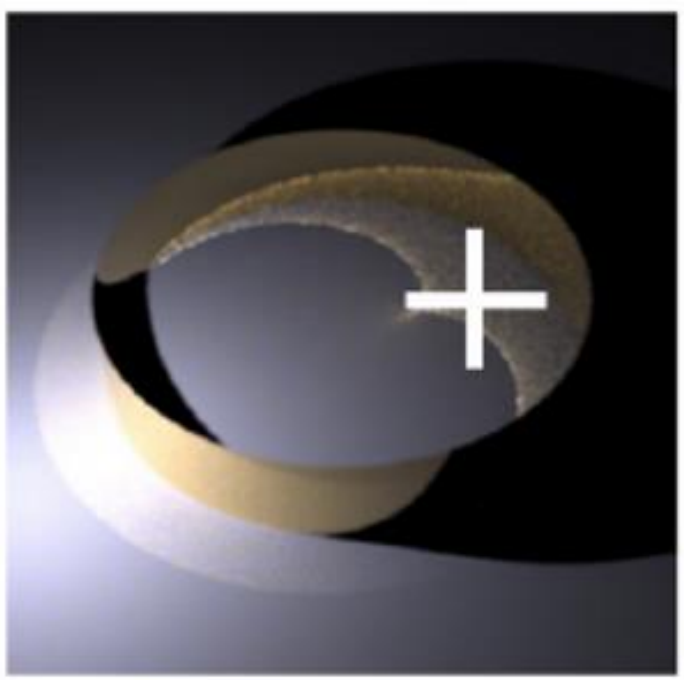
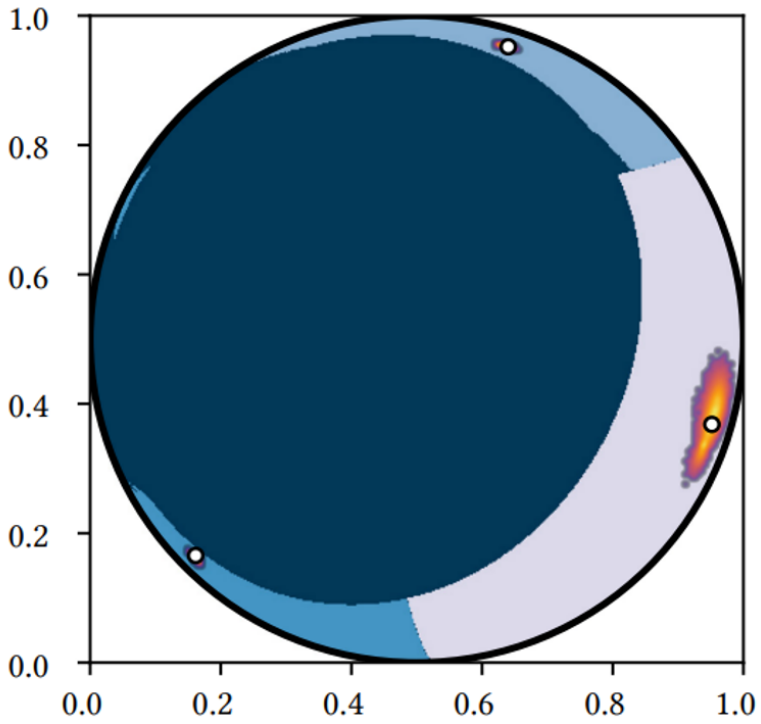
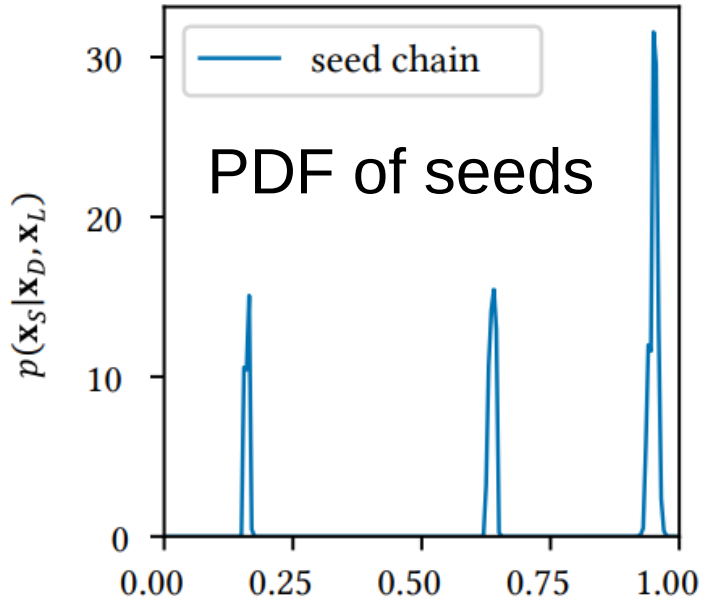
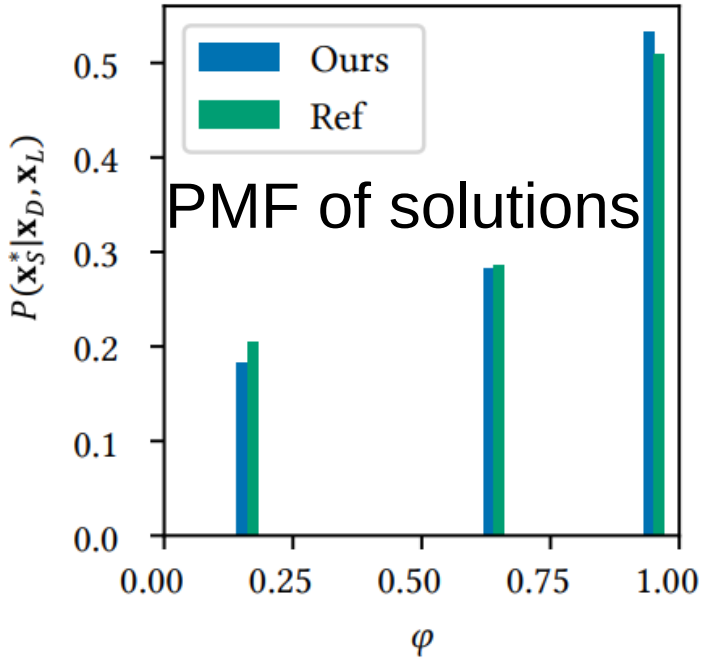


Validation




1.0
0.8
0.6
0.4
0.2
0.0
0.0
0.2
0.4
0.6
0.8
1.0

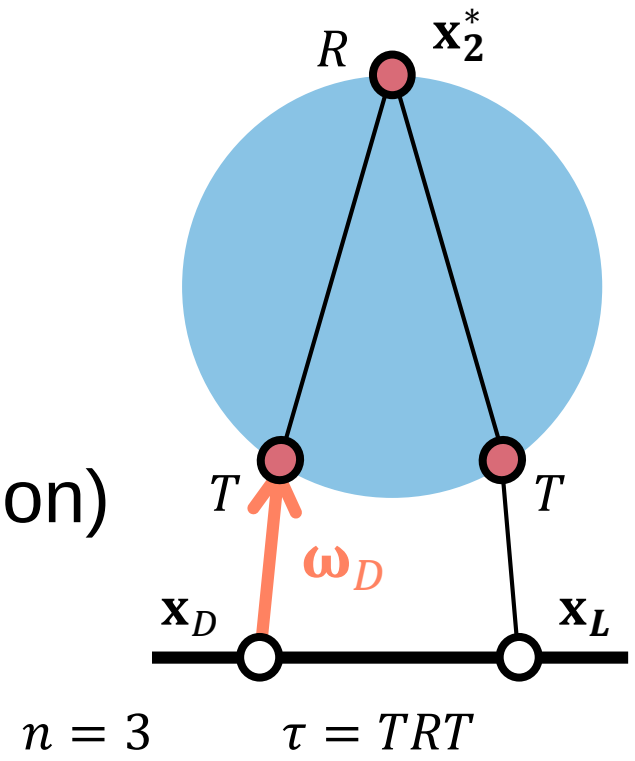

seed chain
PDF of seeds
$p(\mathbf{x}_S|\mathbf{x}_D,\mathbf{x}_L)$
30
20
10
0
0.00
0.25
0.50
0.75
1.00


Ours
Ref
PMF of solutions
$P(\mathbf{x}_S^*|\mathbf{x}_D,\mathbf{x}_L)$
0.5
0.4
0.3
0.2
0.1
0.0
0.00
0.25
0.50
0.75
1.00
φ

Dimensionality reduction

- Use all vertices to represent a specular chain?
- The dimensionality is too high!

- What we only need:
  - The length n (for ending)
  - The scattering type τ (reflection / refraction)
  - The first direction $\boldsymbol{\omega}_D$



Importance sampling seed chains

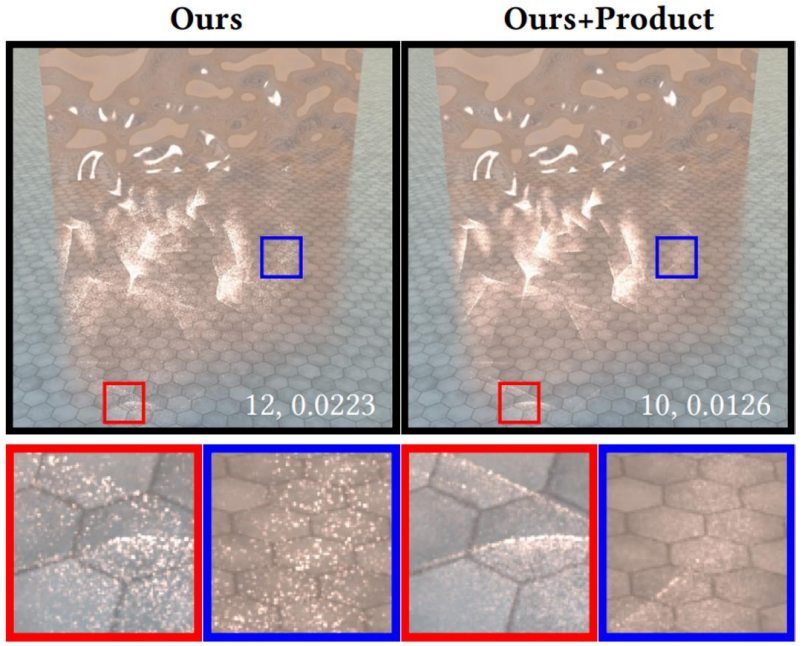
- We can sample the three terms in order

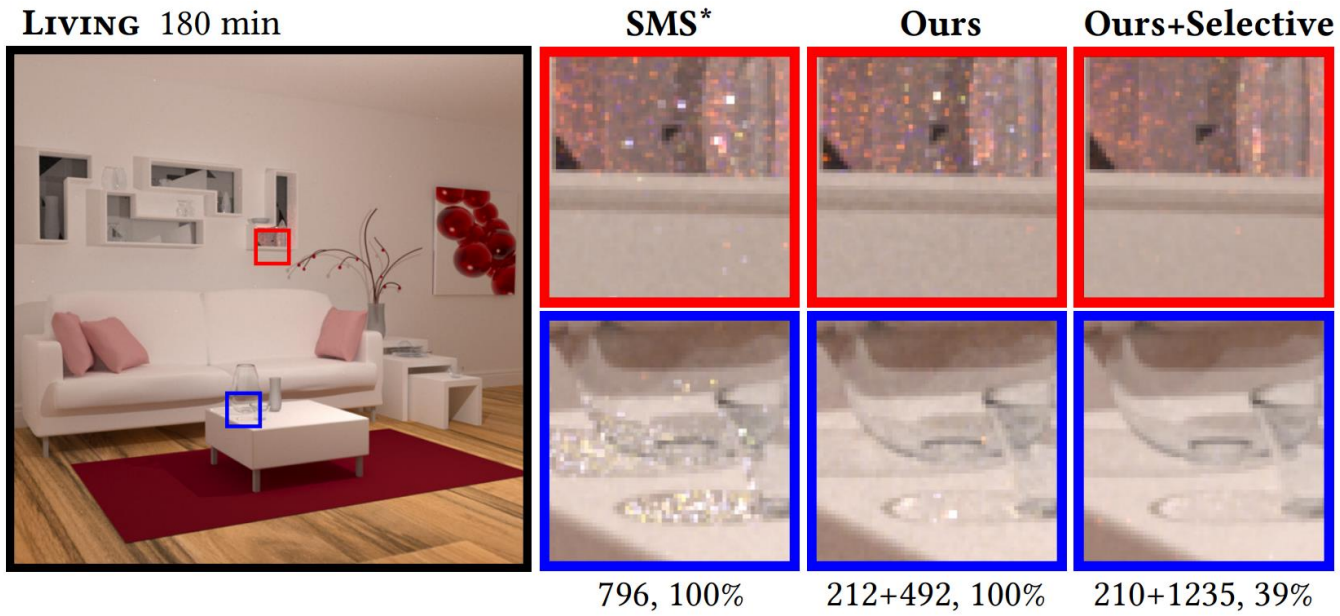
$$p(\mathbf{x}_S|\mathbf{x}_D,\mathbf{x}_L) = P(n|\mathbf{x}_D,\mathbf{x}_L)P(\tau|\mathbf{x}_D,\mathbf{x}_L,n)p(\boldsymbol{\omega}_D|\mathbf{x}_D,\mathbf{x}_L,\tau)$$

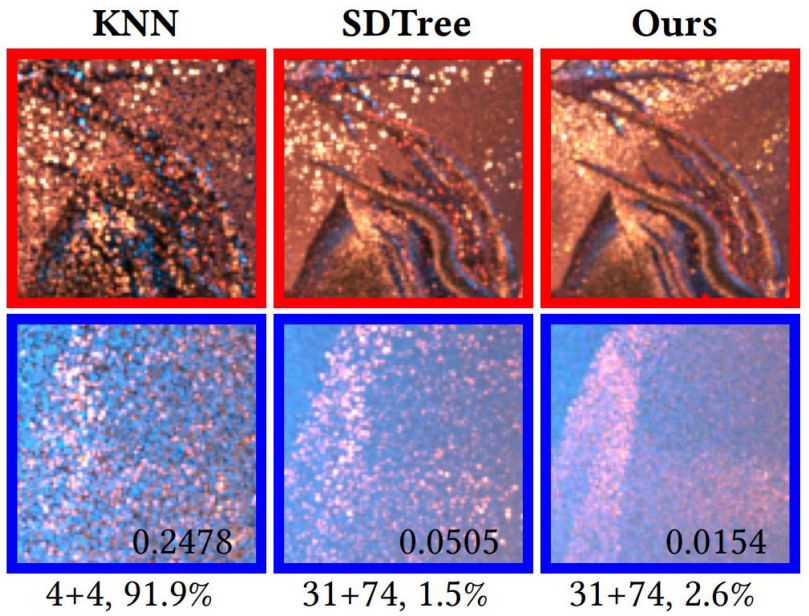
- Fitting distributions from nearby sub-path samples
- **Sampling the chain length n and the scattering type τ**
  - Building discrete distributions
- **Sampling the direction $\boldsymbol{\omega}_D$**
  - Density estimation
  - No analytic PDF eval required! (Diff. from conventional guiding)

Practical considerations

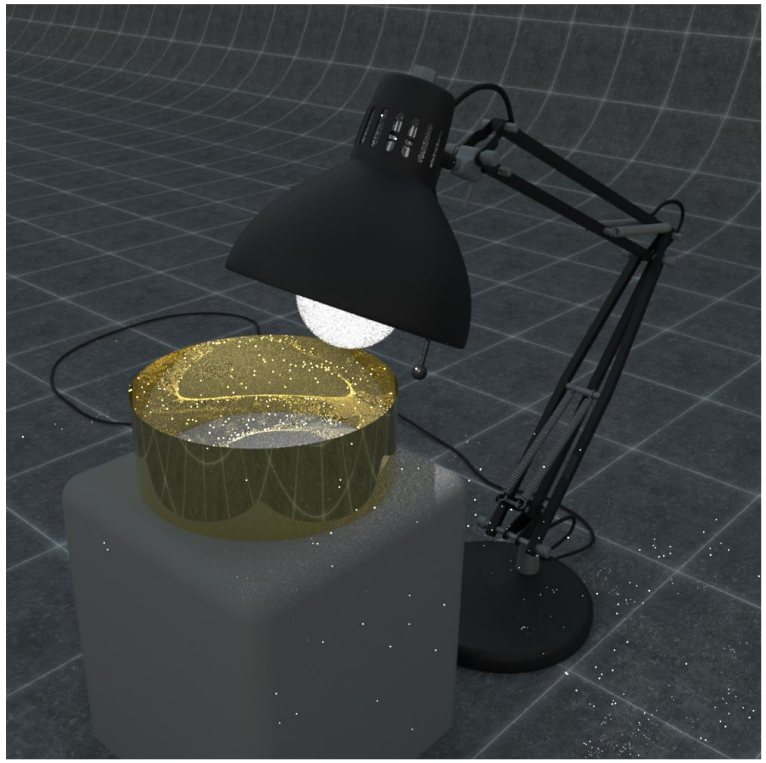
- Spatio-directional structures
- Product importance sampling
- Selective activation



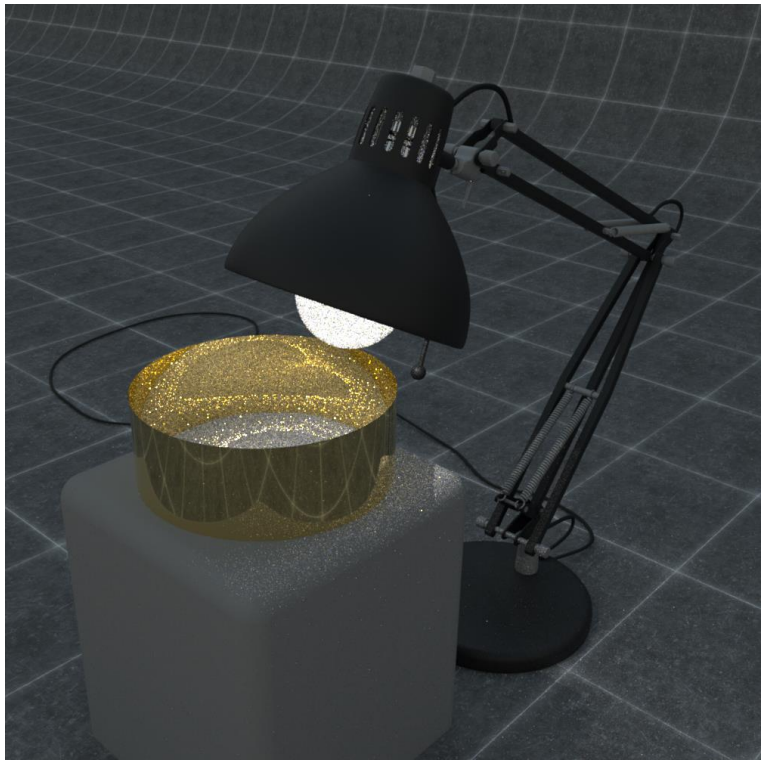




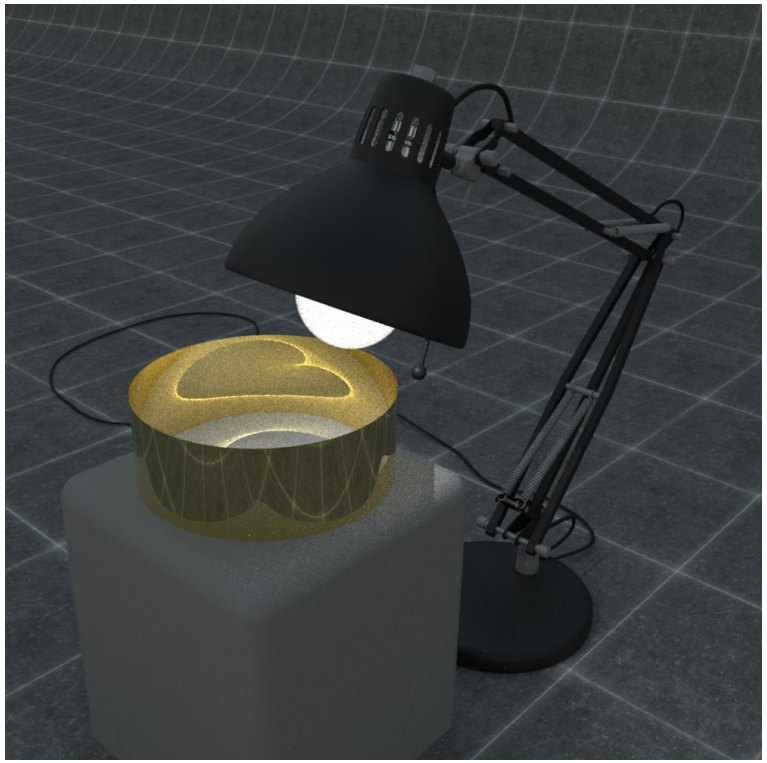
Equal-time comparisons



PAVMM Path Guiding
[Ruppert et al. 2020]

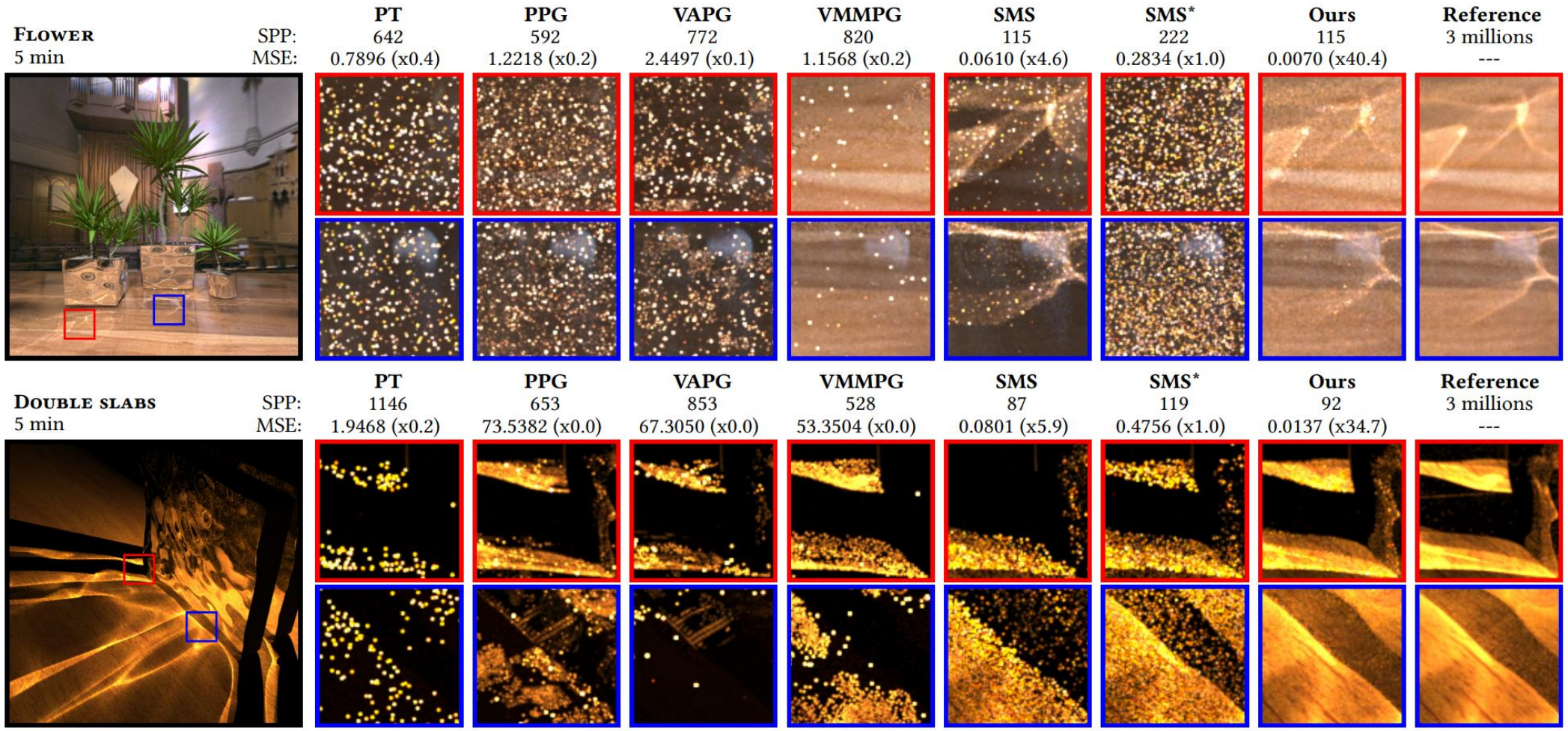


SMS*
[Zeltner et al. 2020]



Ours

Equal-time comparisons



Conclusion

- The first generic method for importance sampling specular chains
- Seed chain sampling plays an important role
- Make manifold-based methods more efficient
- Promote new interests in MC rendering

- Source code and scripts available on GitHub

GitHub Repo

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Thank You

GitHub Repo