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Specular Manifold Sampling for Rendering High-Frequency Caustics and Glints

Tizian Zeltner, Iliyan Georgiev, Wenzel Jakob

SIGGRAPH, 2020

Contents

Background

Background

GLINTS

https://www.pxfuel.com/en/search?q=sunlight+glittering+on+water

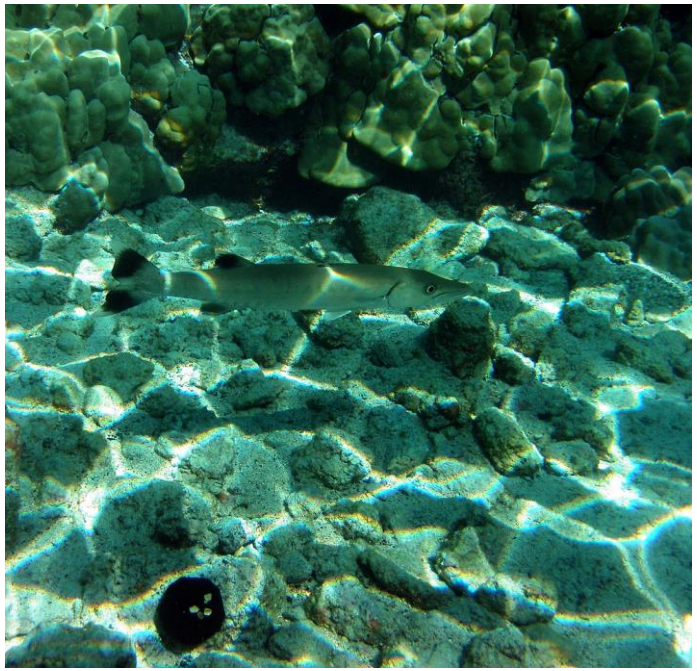
https://www.amazon.ca/Lulu-Home-Christmas-Ornaments-Decorations/dp/B07Y1S17ZW

https://www.reddit.com/r/cookware/comments/myoz4f/stainless_steel_pan_after_first_use_is_it_normal/

Background

CAUSTICS

https://dgreen.beauty/glass-caustics



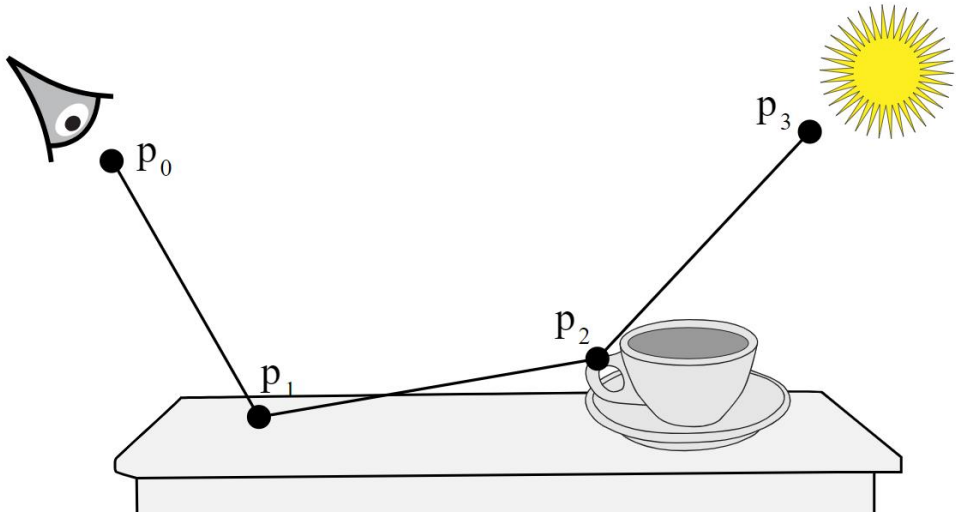
https://en.wikipedia.org/wiki/Caustic_%28optics%29#/media/File:Great_Barracuda,_corals,_sea_urchin_and_Caustic_(optics)_in_Kona,_Hawaii_2009.jpg

https://blenderartists.org/t/metal-cautics/1487055

Background

PATH TRACING recap

- Impossible to consider all incoming light paths to compute reflected energy
- **Branching factor 1:** generate single path from eye to light source
- Average sum of *N* samples per pixel -> radiance

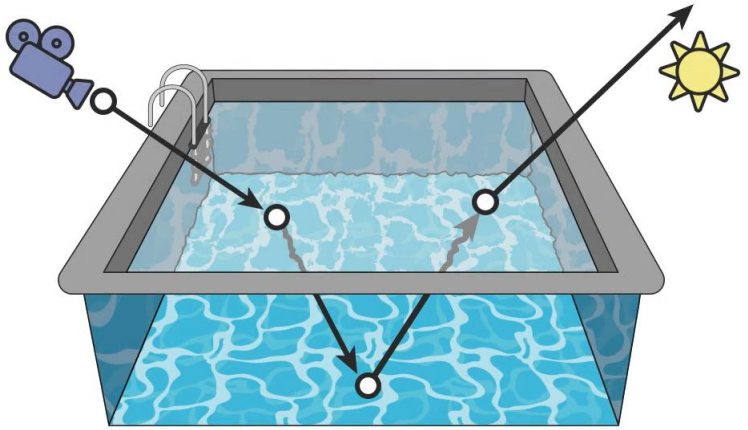


https://www.pbr-book.org/3ed-2018/Light_Transport_I_Surface_Reflection/path-annotated-2.svg

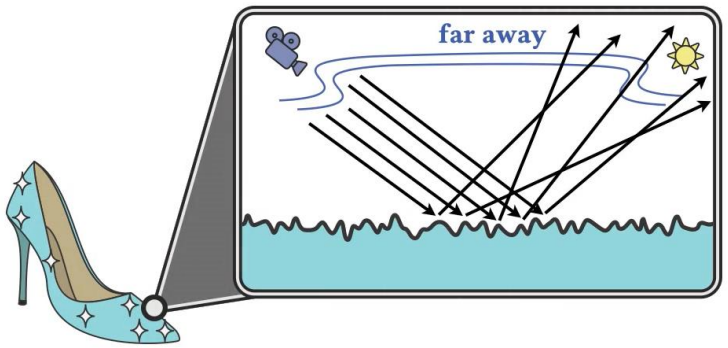
Background

PROBLEM

- Sampling of light paths when hitting specular surface
- Hitting light source by chance is unlikely given the circumstances
- A lot of **variance** rendering such scenes



Caustics



Glints

Images taken from video: https://rgl.epfl.ch/publications/Zeltner2020Specular

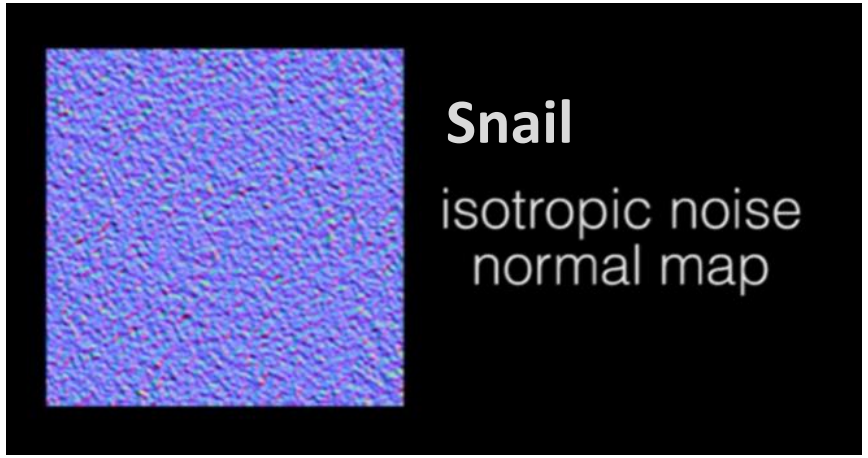
Caustics

Glints

Background

GLINT

- Yan et al. (2014, 2016) proposed specialized rendering methods for **normal-mapped surfaces**
- Don’t help with **other** specular path types
- Require many **gigabytes** of memory



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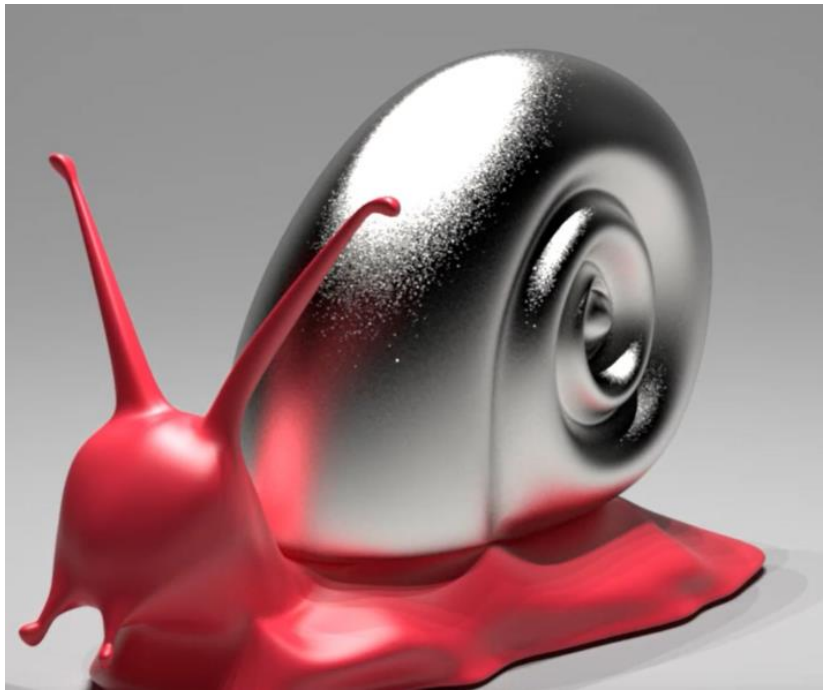


Images taken from video: https://rgl.epfl.ch/publications/Yan2014Rendering

Background

CAUSTICS

- Jakob and Marschner (2012) propose **Manifold Exploration**, further expanded by Hanika et al. (2015) to Manifold Next-Event Estimation

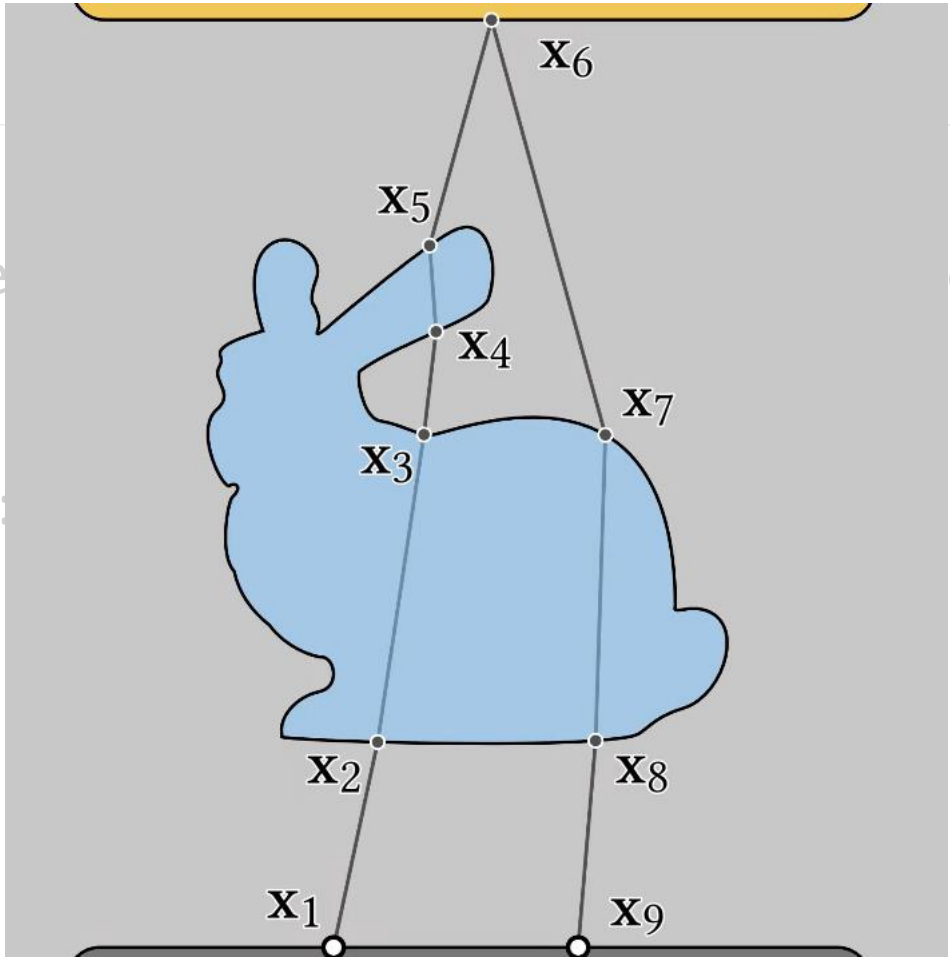
- Light transport path: $\bar{\mathbf{x}}$ (sequence of vertices $x_0, \ldots, x_n$)

Background

CAUSTICS

- Jakob and Marschne**on**, further expanded by Hanika Estimation

- Light transport path:



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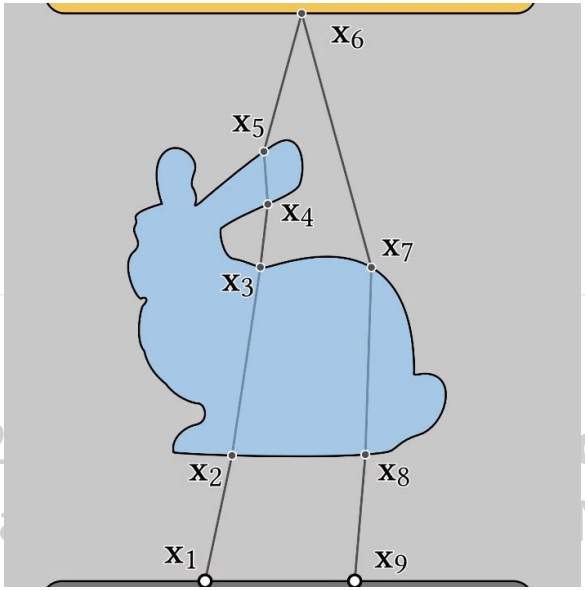
- Jakob and Marschner (2 **d Exploration**, further expanded by Hanika et a Next-Event Estimation



- Light transport path: $\bar{\mathbf{x}}$ (sequence of vertices x_0, ..., x_n)
- **Physical constraints** imposed on each vertex
- Constraints characterized by functions $\mathbf{c}_i$ associated with $\mathbf{x}_i$
- **Valid** specular path **satisfies constraints** -> combined into $C(\bar{\mathbf{x}}) = \begin{bmatrix} \mathbf{c}_2 \\ \mathbf{c}_3 \\ \mathbf{c}_4 \\ \mathbf{c}_5 \\ \mathbf{c}_6 \\ \mathbf{c}_7 \\ \mathbf{c}_8 \end{bmatrix}$

$\mathcal{S} =$ **light paths that satisfy physical laws**

$$\mathcal{S} = \{\bar{\mathbf{x}} \mid C(\bar{\mathbf{x}}) = 0\}$$

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CAUSTICS

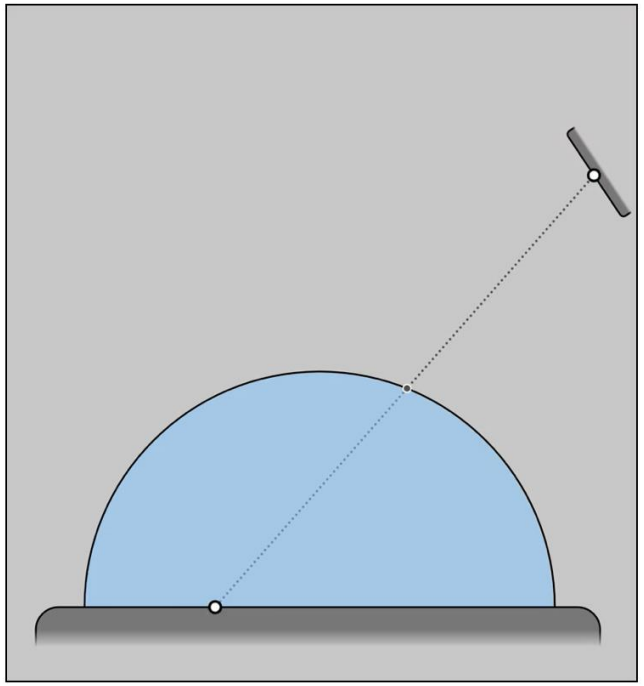
- Jakob and Marschner (2012) propose Manifold Exploration, further expanded by Hanika et al. (2015) to **Manifold Next-Event Estimation**

MNEE

1 Create seed path with straight-line connection

2 Run Newton solver to find valid refraction path

$$C(\bar{\mathbf{x}}) \neq \mathbf{0}$$



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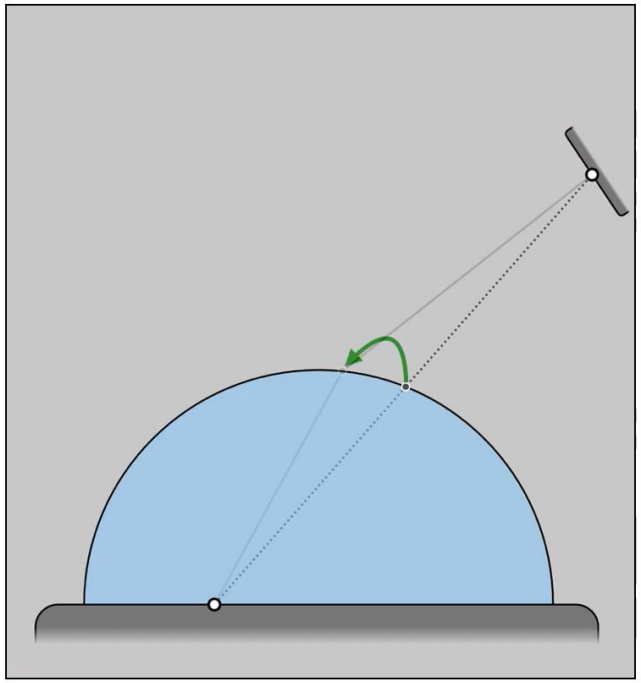
MNEE

1 Create seed path with straight-line connection

2 Run Newton solver to find valid refraction path

$$\bar{\mathbf{x}}_{n+1} = (\nabla C(\bar{\mathbf{x}}_n))^{-1} \cdot C(\bar{\mathbf{x}}_n)$$

... until $C(\bar{\mathbf{x}}) = \mathbf{0}$



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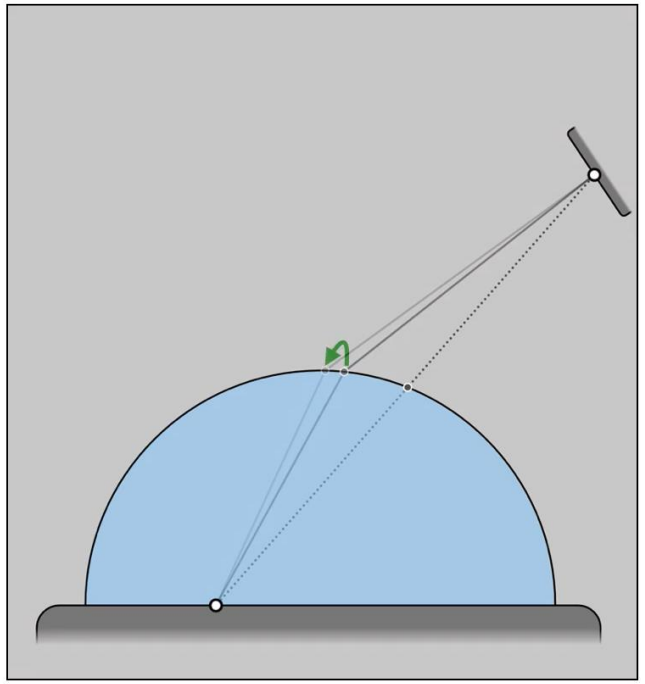


Background

CAUSTICS

- Jakob and Marschner (2012) propose **Manifold Exploration**, further expanded by Hanika et al. (2015) to **Manifold next-event estimation**
- **Limitation:** finds only one solution path in complex geometries even though more are possible

Background

CAUSTICS

Background

CAUSTICS

Contribution

- **Specular manifold sampling (SMS):** rendering caustics, including multiple solutions, *unbiased*
- Extensions:
  - **biased** SMS variant -> reduced variance
  - variant for rendering **glints** -> minimal memory requirements

Method

Method

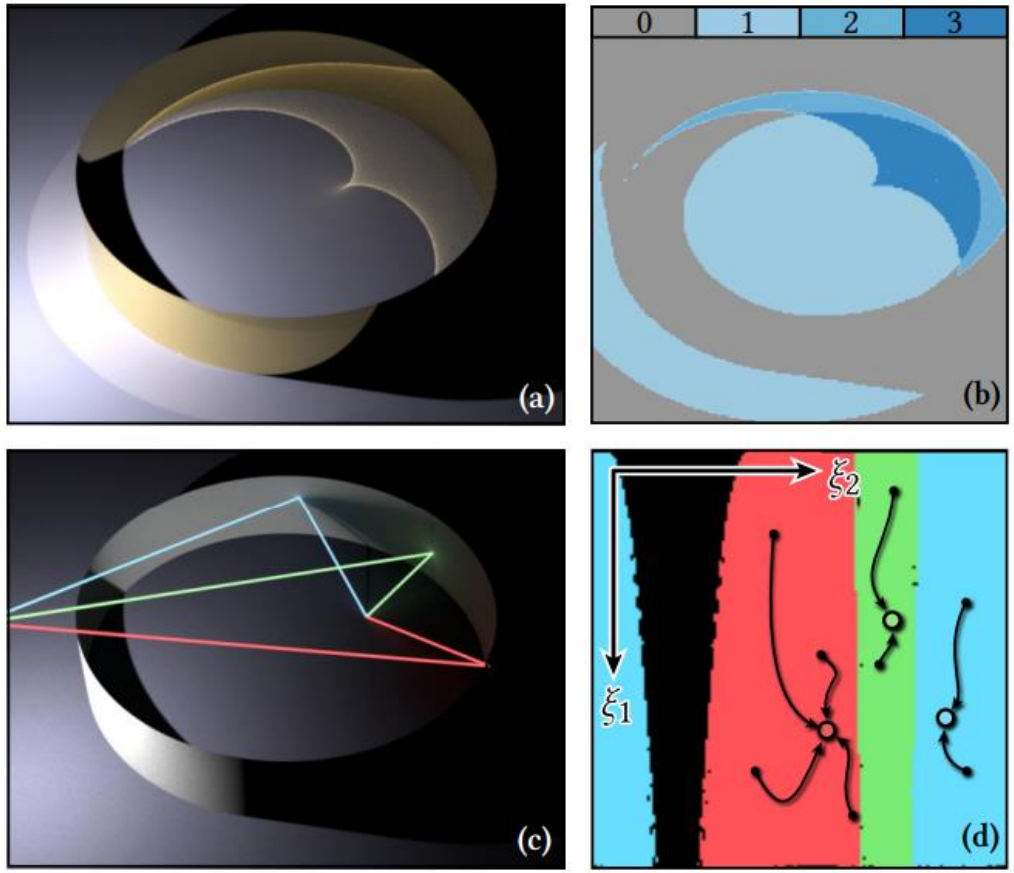
SMS for caustics

a) Multiple solution paths are possible

b) Number of solutions at shading point

c) Three solution paths at particular point

d) Basins of convergence -> area = probability of finding solution, **p_k**



Method

SMS for caustics

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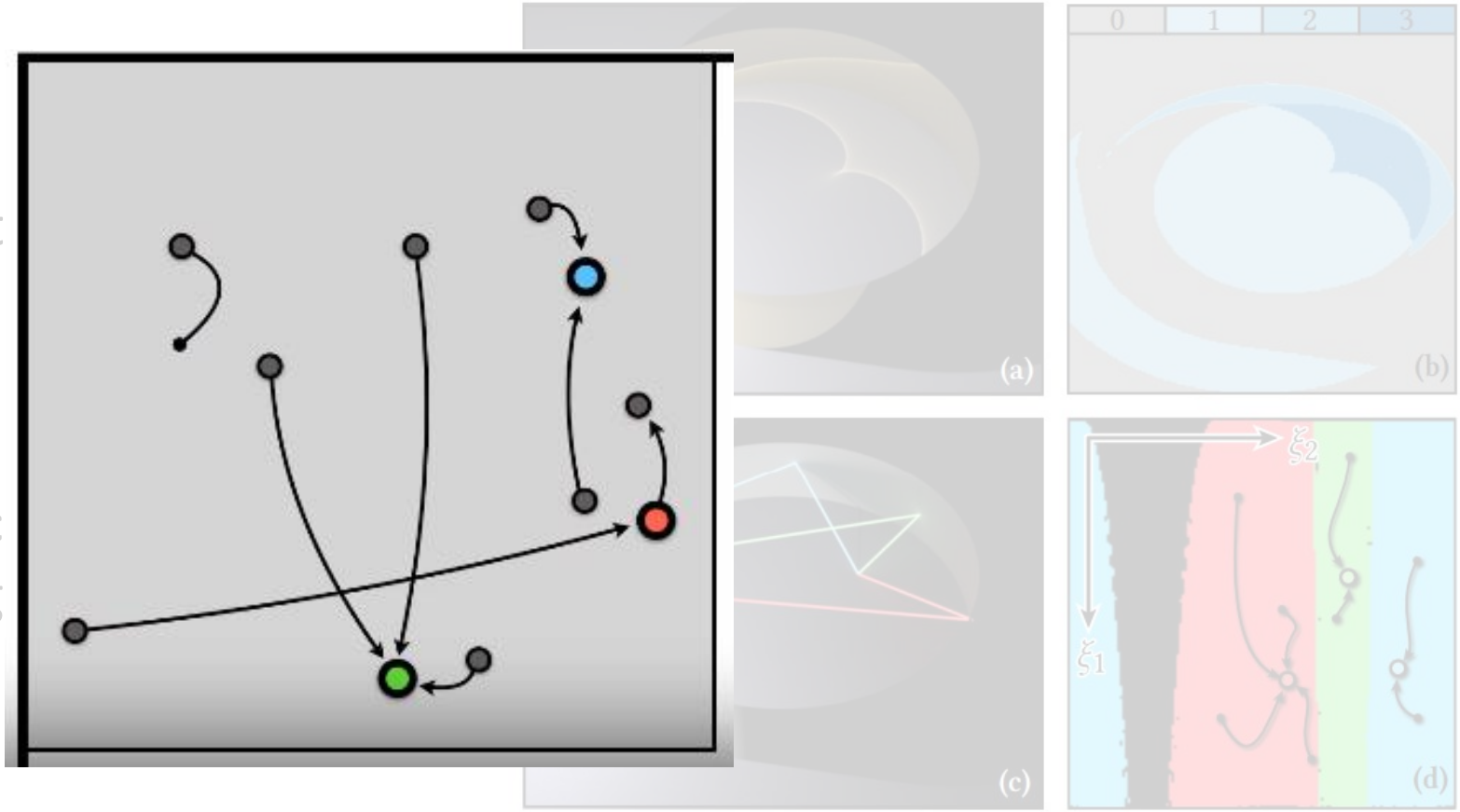

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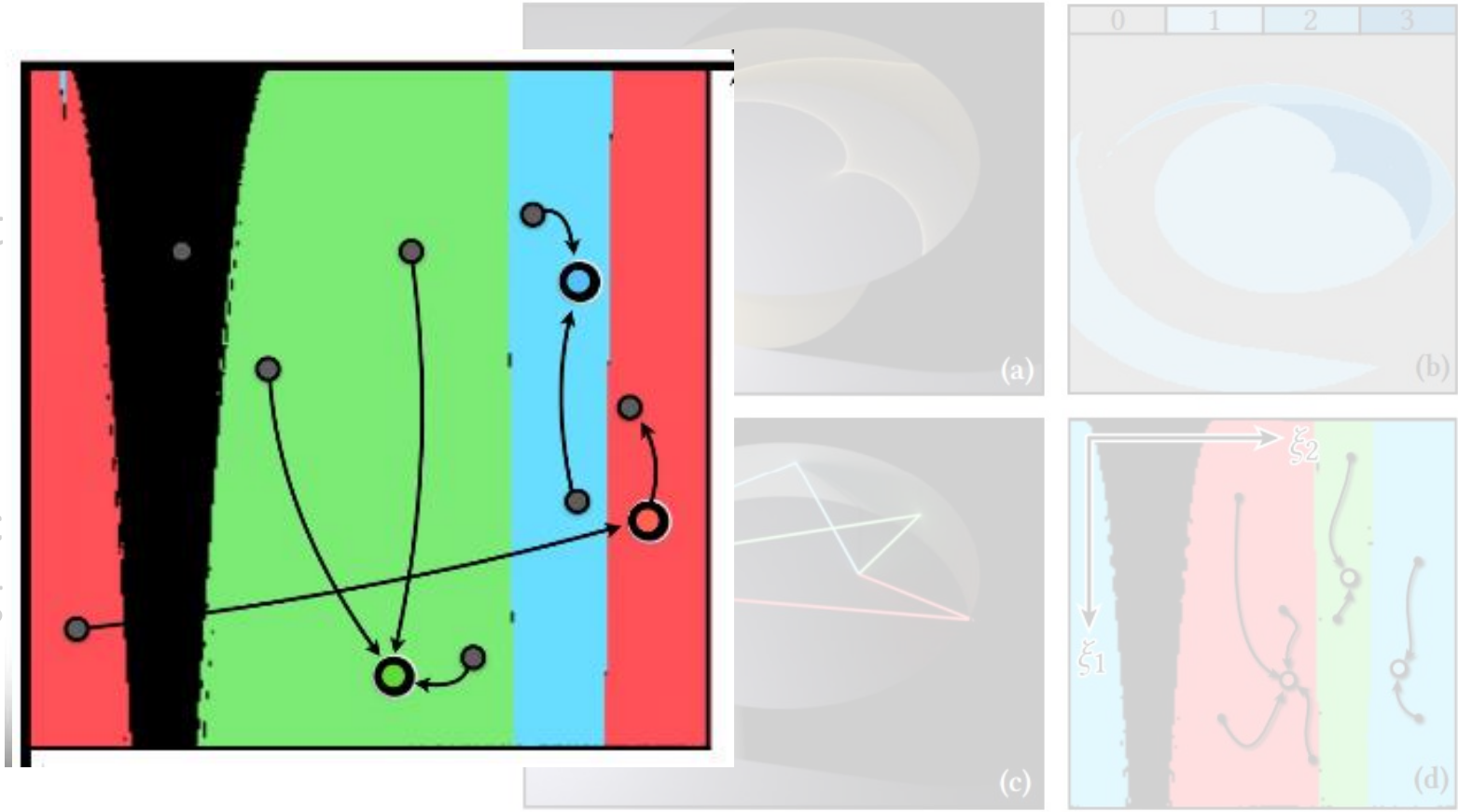


Method

SMS for caustics

- Probability needed for MC sampling
- Estimation of probability again with MC
  - But this estimation can be 0 …

$$\langle I \rangle = \frac{1}{N} \sum_{i=1}^{N} \frac{f(\bar{\mathbf{x}}_i)}{p(\bar{\mathbf{x}}_i)}$$

1. Move integral from denominator to numerator -> **inverse,** 1/p_k
2. Unbiased estimation involves **repeated manifold walks** from different points each time
3. Run repeated manifold walks until solution is found
4. Number of trials then provides an unbiased estimate of 1/p_k

Method

SMS for caustics

- If geometry is smooth, small number of solutions and large convergence basins
- Only few trial iterations are required

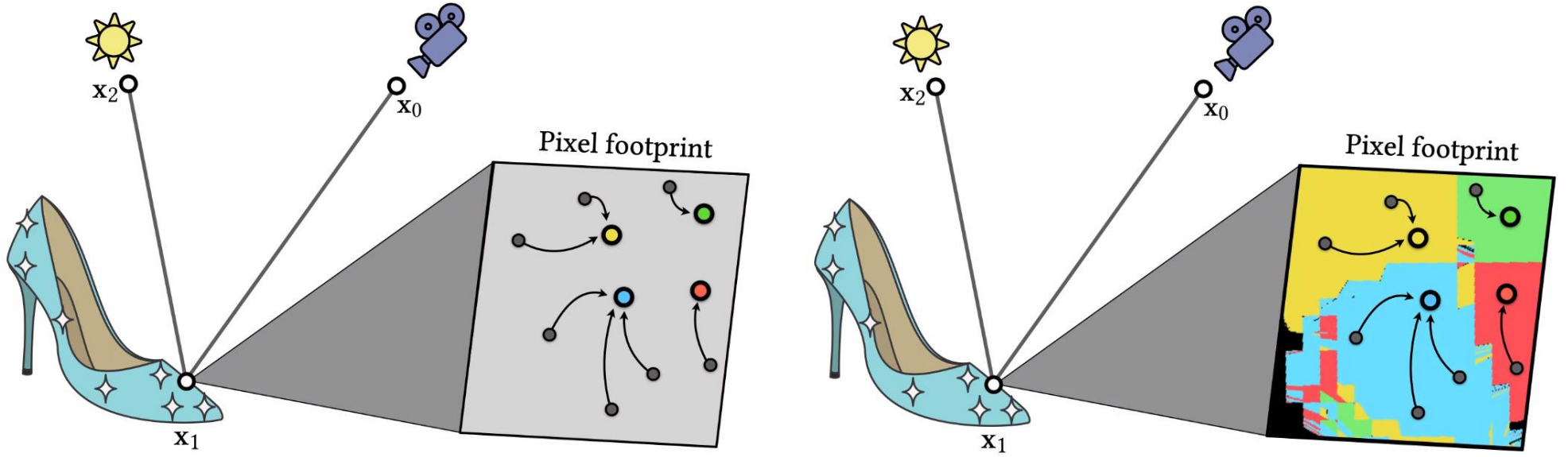
- **Complex** -> many solutions -> smaller convergence basins -> larger number of required trial iterations
- **Variance** can become very large if p_k is small

- Introduce bias by **fixing budget of M samples** for number of trial iterations

Method

SMS for glints

- Recall: previous works were expensive and used a lot of memory
- Similar to caustics: sample individual solutions **within pixel**, run SMS

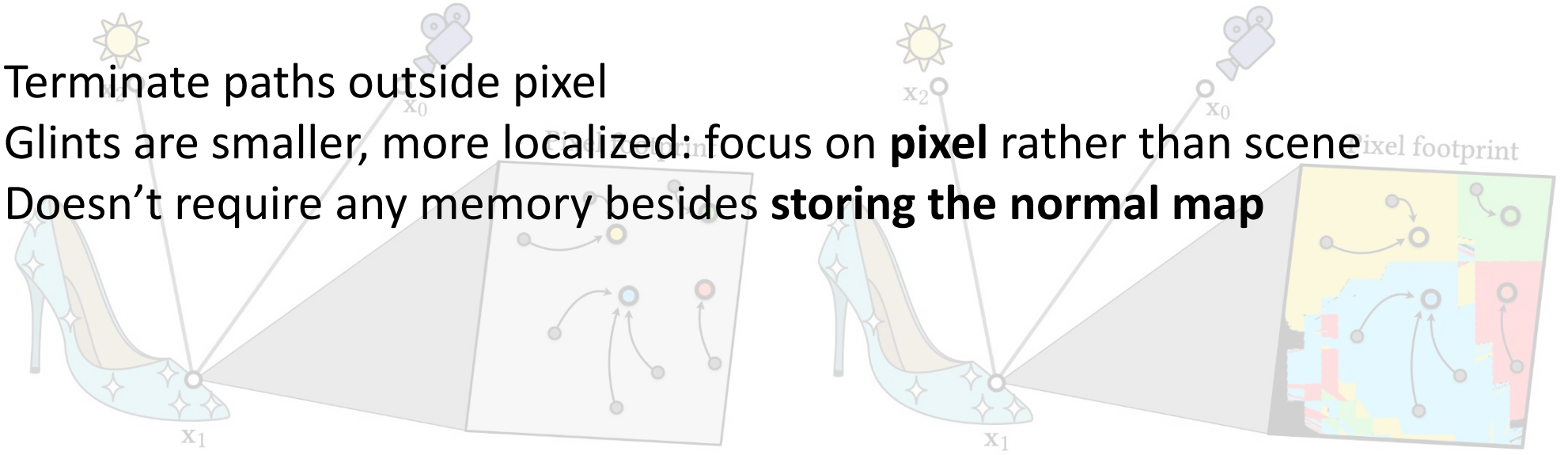


Method

SMS for glints

- Recall: previous works were expensive and used a lot of memory
- Similar to caustics: sample individual solutions **within pixel**, run SMS

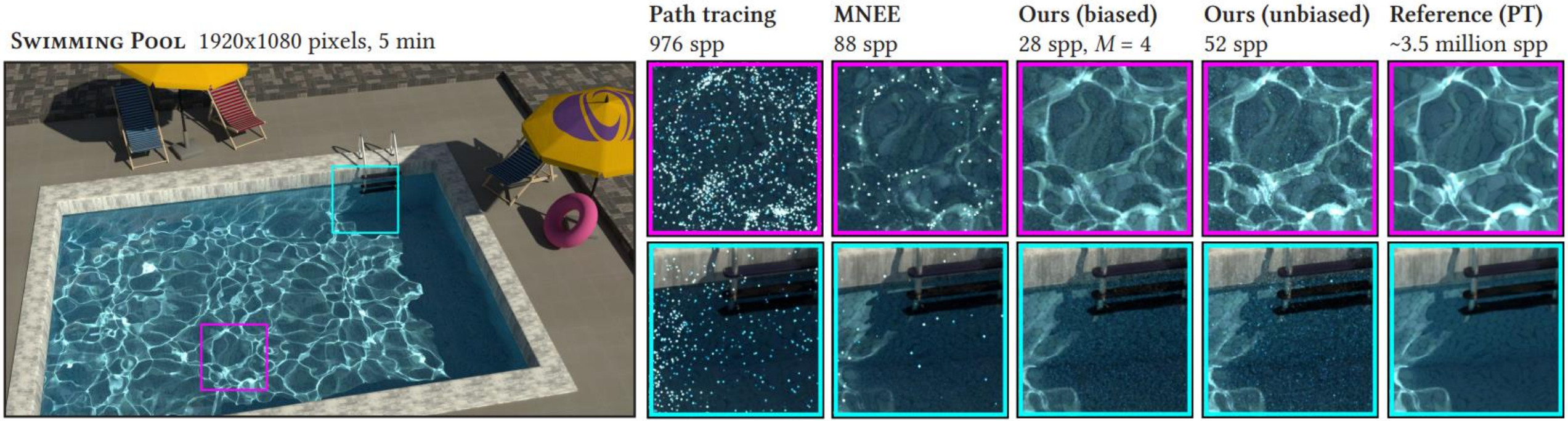
- Terminate paths outside pixel
- Glints are smaller, more localized: focus on **pixel** rather than scene
- Doesn’t require any memory besides **storing the normal map**



Results

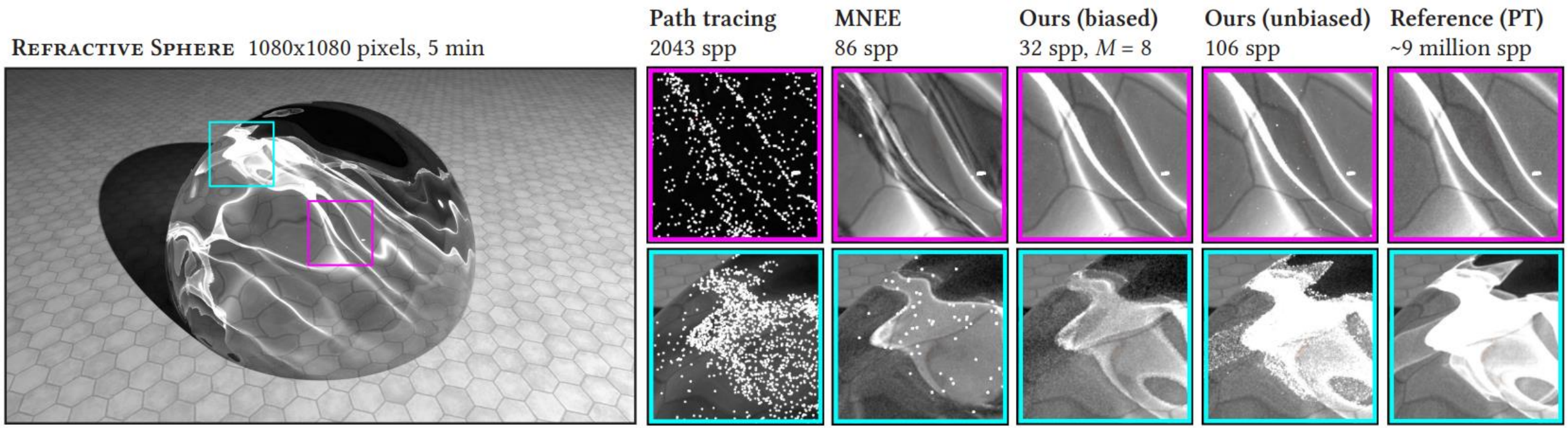
Results

CAUSTICS



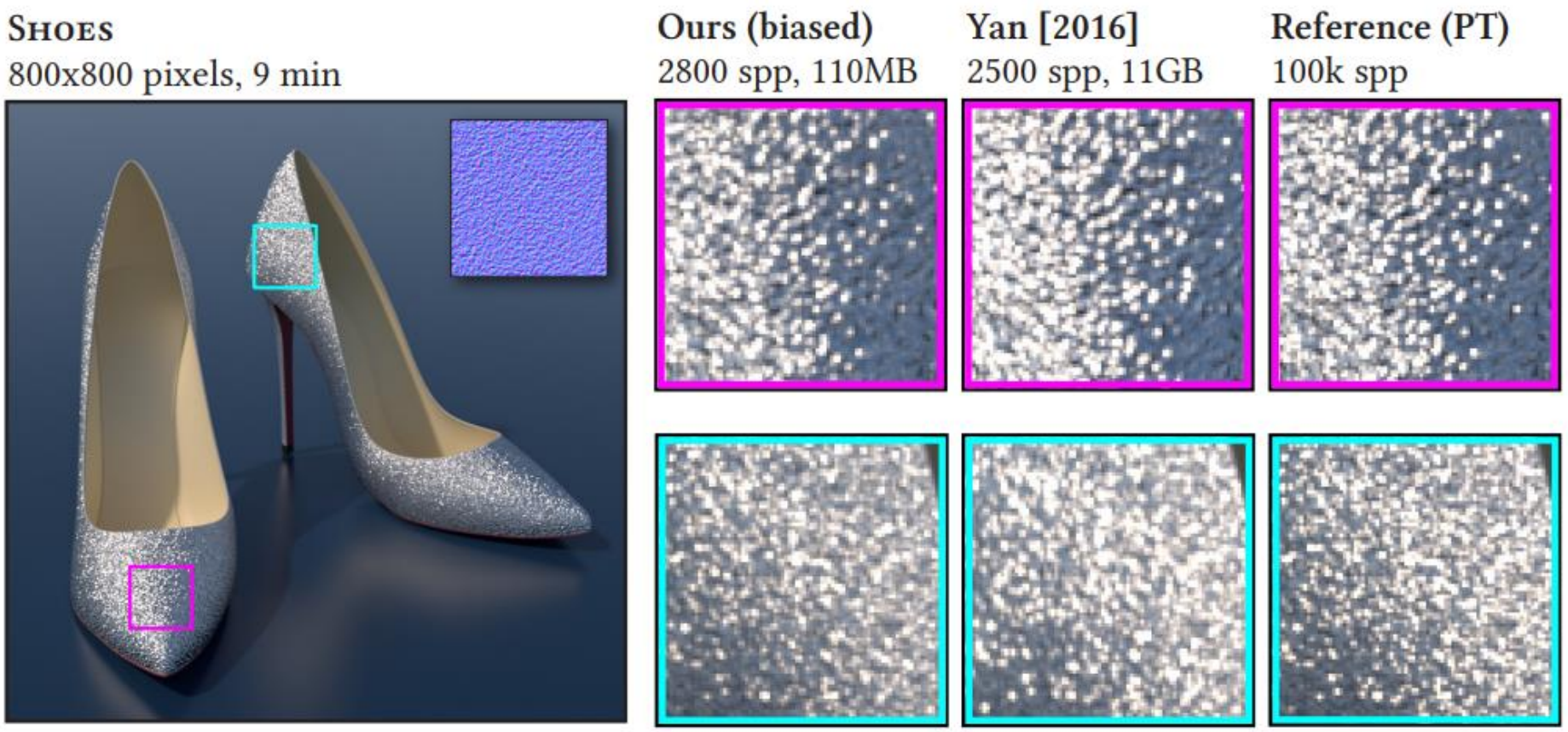
Results

CAUSTICS



Results

GLINTS



Conclusions

- Paper introduced simple and powerful **specular path sampling (SMS)** technique: unbiased strategy for rendering caustics in a pure Monte Carlo setting
- Biased SMS variant to reduce **variance** -> high-frequency noise
- SMS variant for rendering glints with minimal memory requirements

Thank you

References:

- Tizian Zeltner, Iliyan Georgiev, and Wenzel Jakob. 2020. Specular Manifold Sampling for Rendering High-Frequency Caustics and Glints. In Transactions on Graphics (Proceedings of SIGGRAPH) 39(4).