SIGGRAPH ASIA 2021 TOKYO LIVE

Differentiable Transient Rendering

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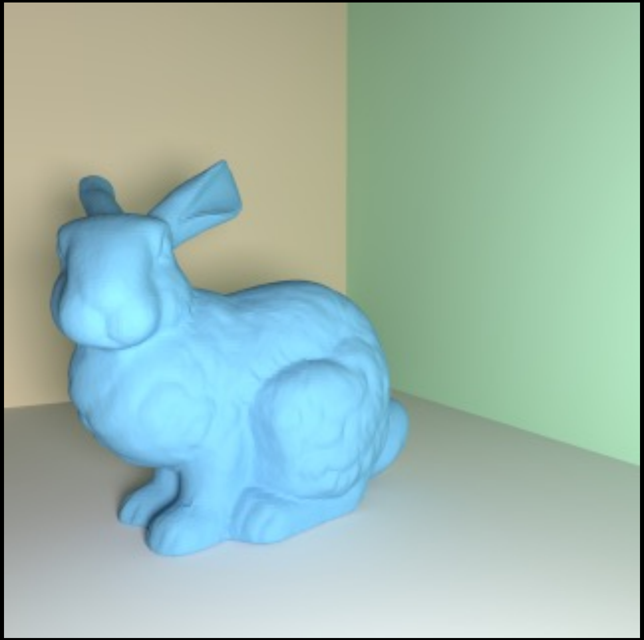
* Universidad Zaragoza

Rendering

vertex position
object transform
material properties
.....

$$\mathbf{I}(\boldsymbol{\theta}) =$$

$$\mathbf{I} \in \sim^{H \times W}$$

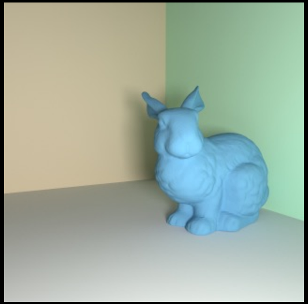


image

Differentiable Rendering

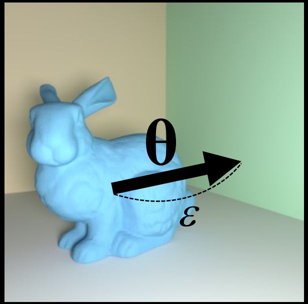
$$\frac{\partial \mathbf{I}}{\partial \boldsymbol{\theta}}$$

$\mathbf{I}(\boldsymbol{\theta}+\varepsilon)$



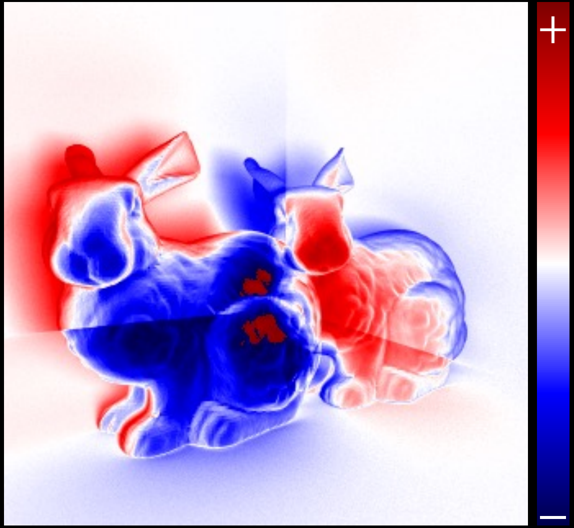
$-$

$\mathbf{I}(\boldsymbol{\theta})$



ε

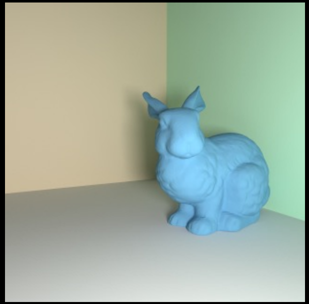
$=$



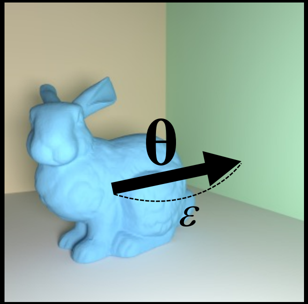
Differentiable Rendering

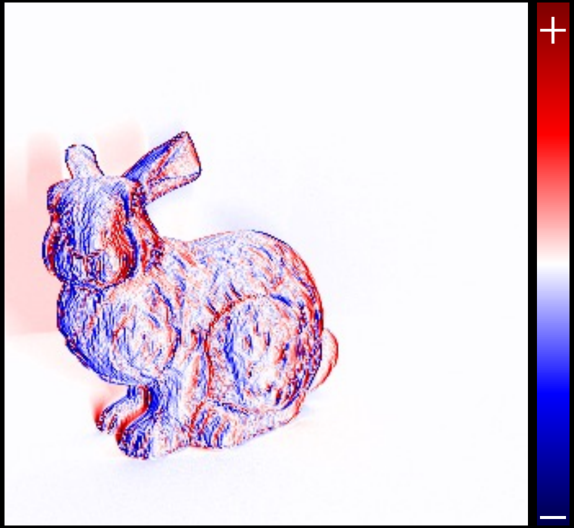
$$\frac{\partial \mathbf{I}}{\partial \boldsymbol{\theta}} = \lim_{\varepsilon \to 0} \frac{\mathbf{I}(\boldsymbol{\theta}+\varepsilon) - \mathbf{I}(\boldsymbol{\theta})}{\varepsilon} =$$

$\mathbf{I}(\boldsymbol{\theta}+\varepsilon)$



$\mathbf{I}(\boldsymbol{\theta})$

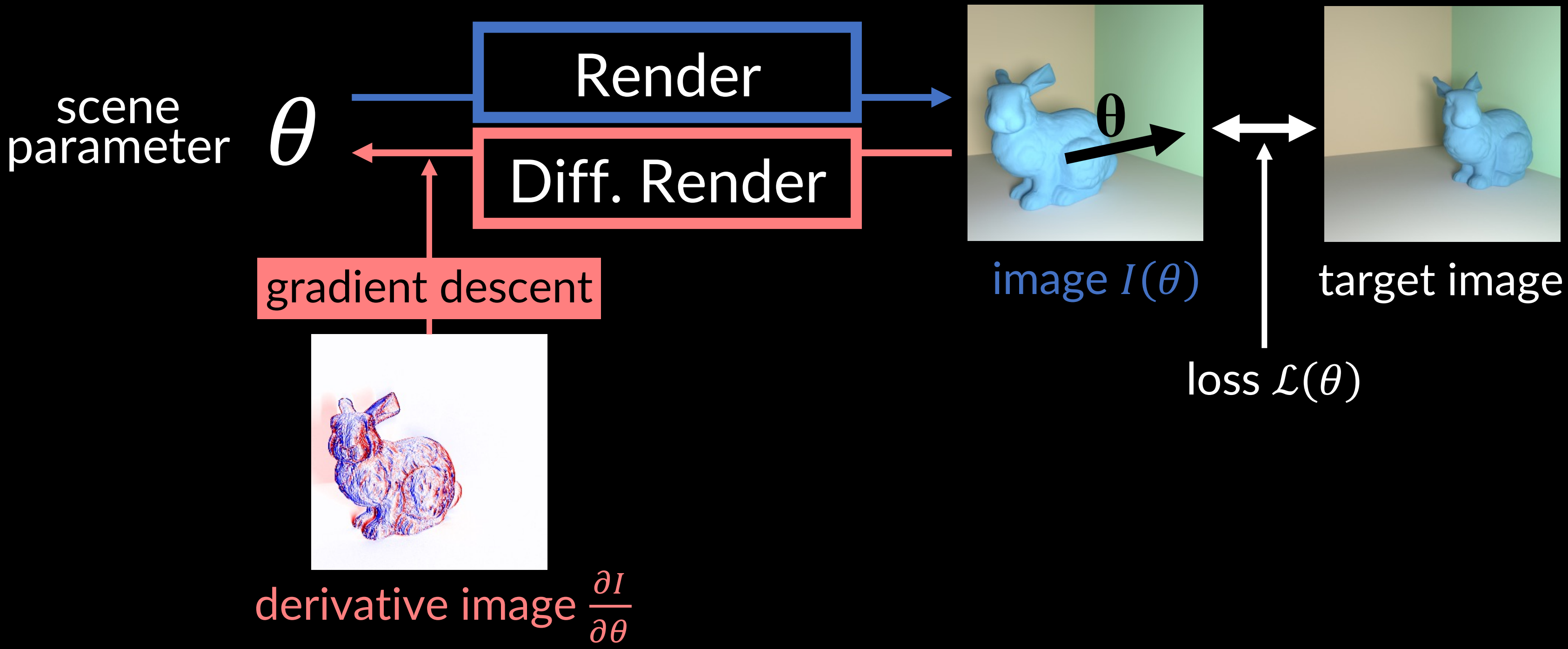




derivative image

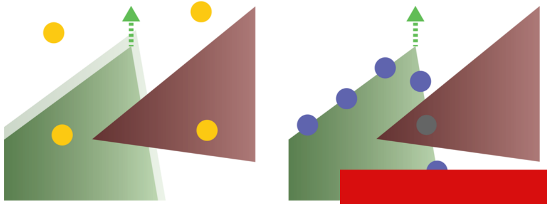
Why Differentiable Rendering?

➔ Inverse rendering

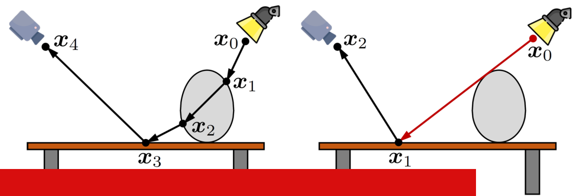


Differentiable Rendering

Edge sampling
Li et al. 2018



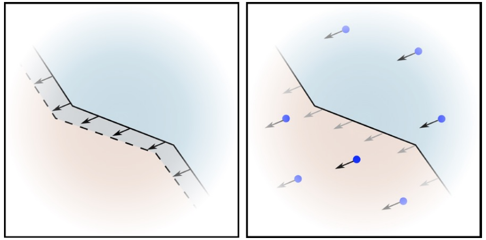
Path-space
Zhang et al. 2020



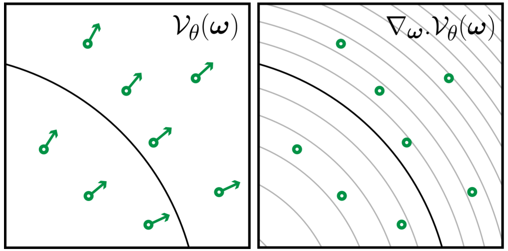
Only steady-state methods exist

• • •

Reparamete
Loubet et al. 2019



pling
Bangaru et al. 2020

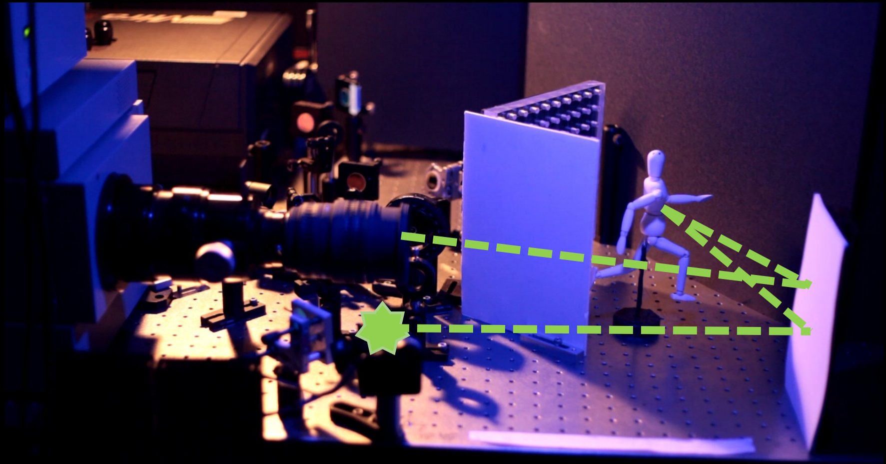


Why Transient?

Femto-photography

[Velten et al. 2013]

Non-Line-of-Sight Imaging (NLOS)



[Velten et al. 2012], etc.

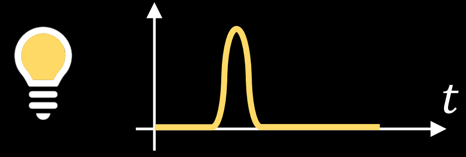
Transient Rendering

$$\mathbf{I}(\boldsymbol{\theta}) \in \sim^{H \times W \times T}$$

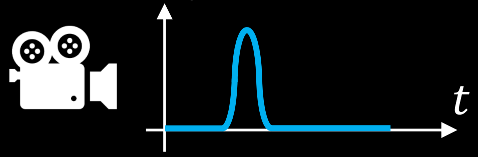
time:

transient images

source L_e



sensor W_e

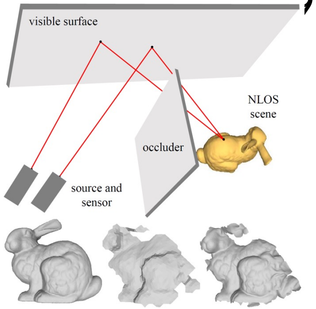


finite speed of light c

Inverse Methods of Transient Rendering

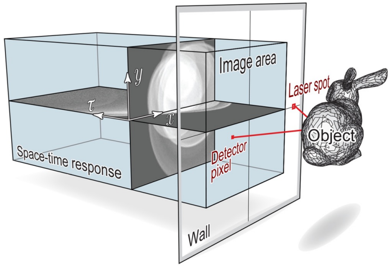
Beyond Volumetric Albedo – A Surface Optimization Framework for Non-Line-of-Sight Imaging

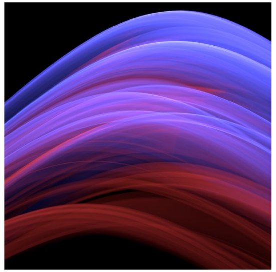
Tsai et al. 2019



None-line-of-sight Reconstruction Using Efficient Transient Rendering

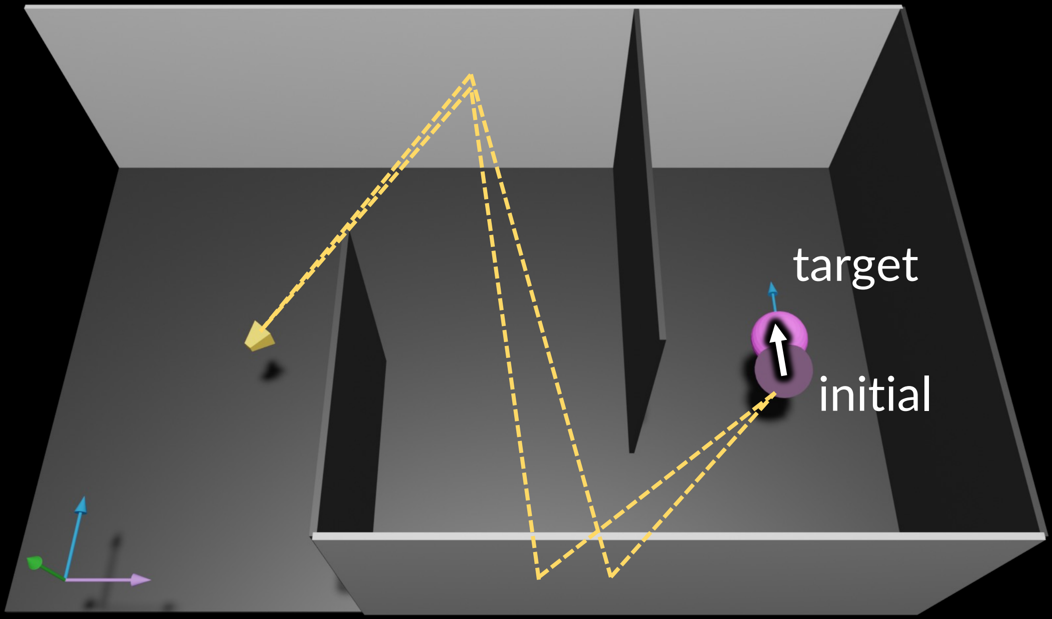
Iseringhausen and Hullin 2020





- Limited to three bounces
- No general-purposed differentiable renderer

Differentiable Transient Rendering



Differentiable Transient Rendering

$$\frac{\partial \mathbf{I}}{\partial \boldsymbol{\theta}} = \lim_{\varepsilon \to 0} \frac{\mathbf{I}(\boldsymbol{\theta}+\varepsilon) - \mathbf{I}(\boldsymbol{\theta})}{\varepsilon} =$$

$\mathbf{I} \in \sim^{H \times W \times T}$

\+

–

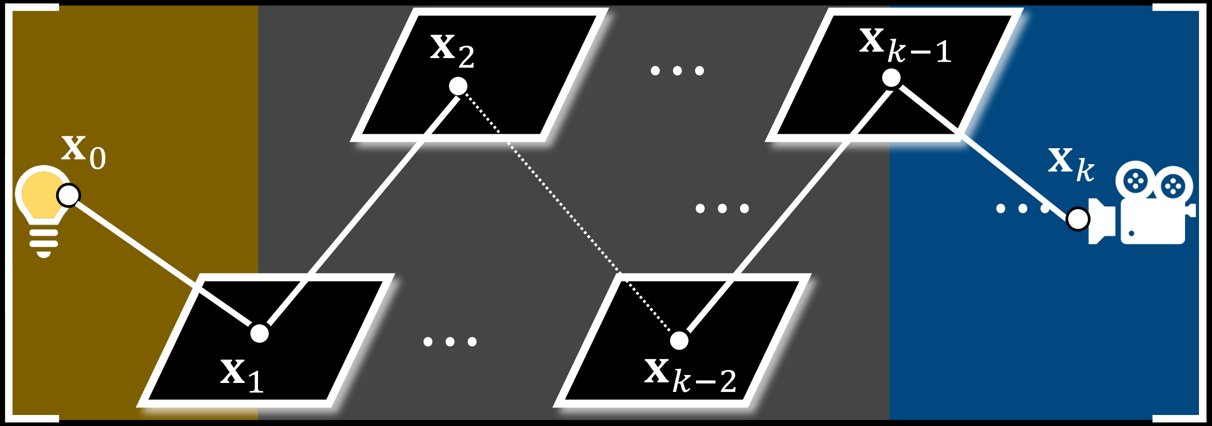
time:

derivative transient images

OUR METHOD

Path Integral

$I(\theta) = \int$



$d\mathbf{x}_0 \ldots d\mathbf{x}_k$

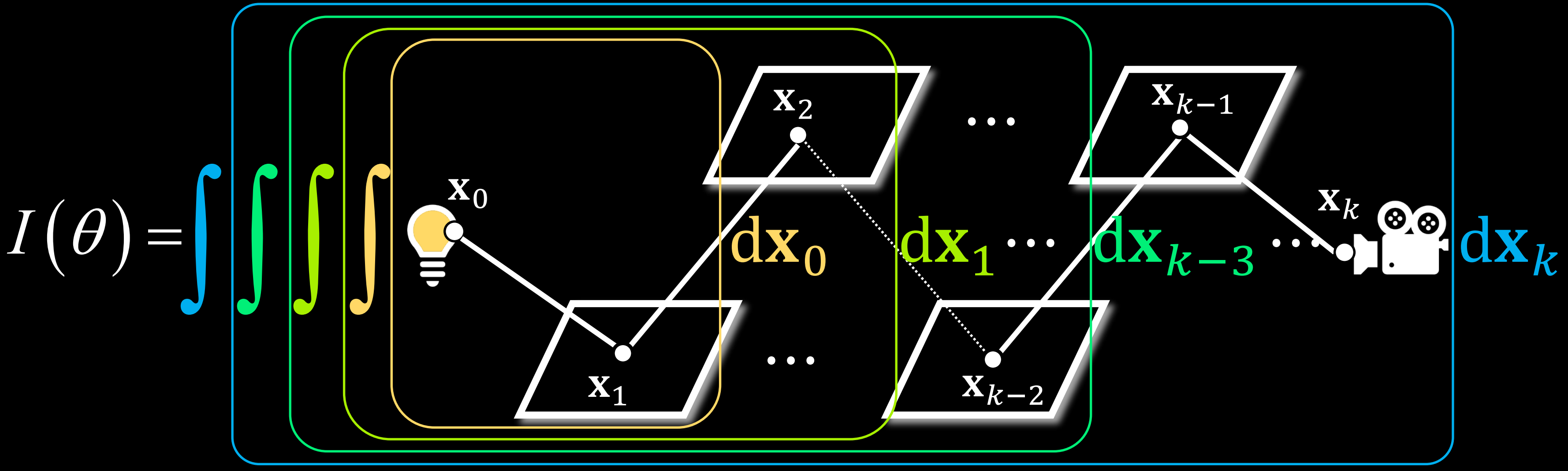
$L_e(\mathbf{x}_0, \mathbf{x}_1)$ — source emission

$\mathfrak{T}(\mathbf{x}_1, \mathbf{x}_2, \ldots, \mathbf{x}_{k-2}, \mathbf{x}_{k-1})$ — path throughput

$W_e(\mathbf{x}_{k-1}, \mathbf{x}_k)$ — sensor sensitivity

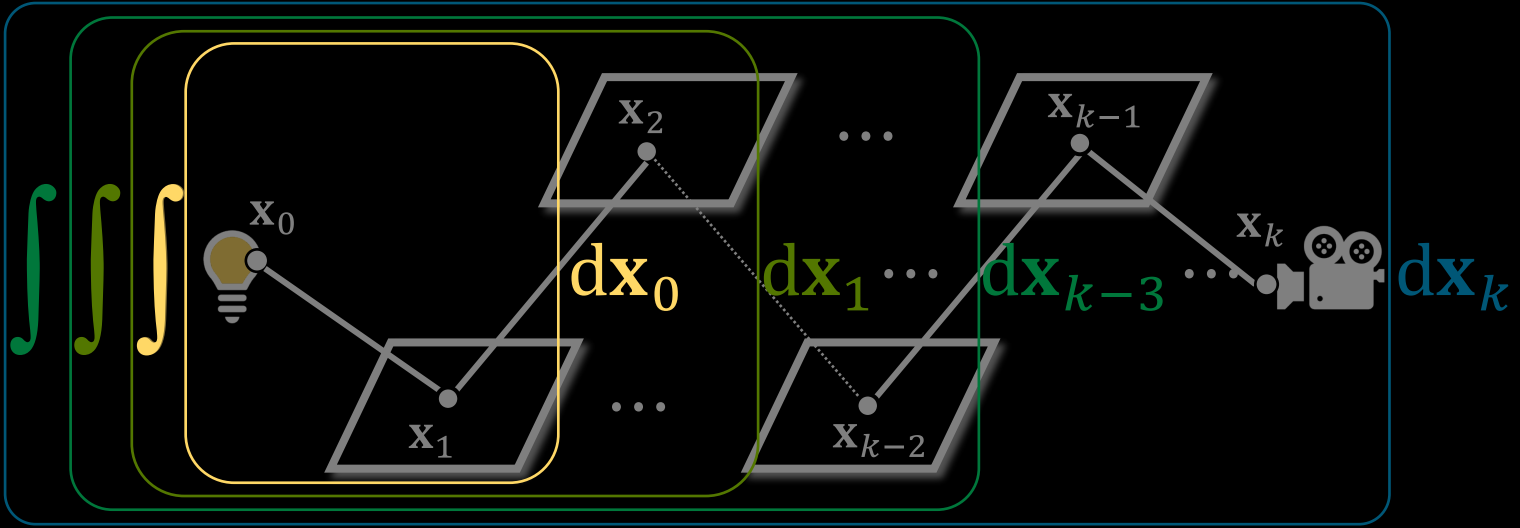
[Veach 1997]

Path Integral



Differential Path Integral

$$I(\theta) = \int \int \int \int \; \mathrm{d}\mathbf{x}_0 \; \mathrm{d}\mathbf{x}_1 \cdots \mathrm{d}\mathbf{x}_{k-3} \cdots \mathrm{d}\mathbf{x}_k$$



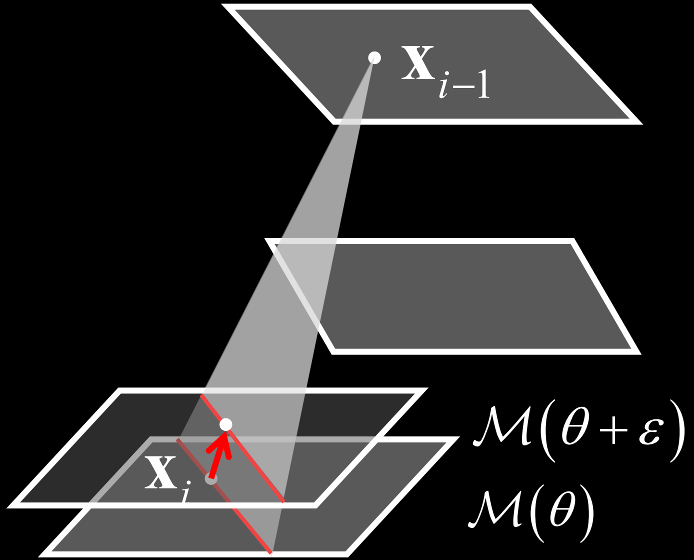
$$\frac{\partial I}{\partial \theta}(\theta) = \cdots \frac{\partial}{\partial \theta} \int_{2D} \quad \mathrm{d}\mathbf{x}_0 \cdots$$

Reynolds transport theorem

[Zhang et al. 2020]

Differential Path Integral

Reynolds Transport Theorem for 2D surfaces in $\mathbb{R}^3$



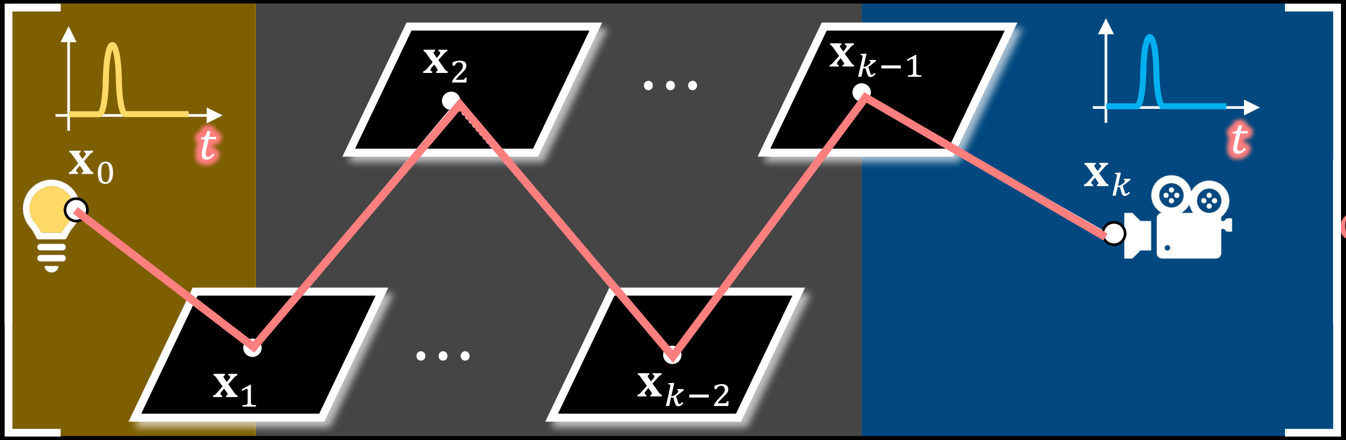
Interior Boundary

$$\frac{\partial}{\partial\theta}\int_{\mathcal{M}(\theta)} f(\mathbf{x}_i)\,\mathrm{d}\mathbf{x}_i = \int_{\mathcal{M}(\theta)} \frac{\partial f(\mathbf{x}_i)}{\partial\theta}\,\mathrm{d}\mathbf{x}_i + \int g(\mathbf{x}_i)\,\mathrm{d}\mathbf{x}_i$$

[Zhang et al. 2020]

Transient Path Integral

$$I(\theta) = \int$$



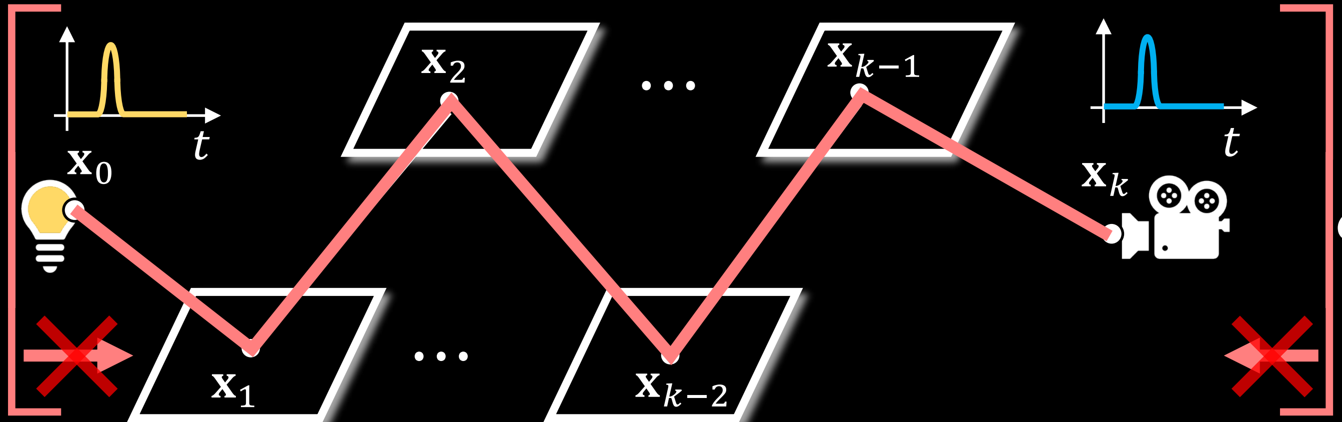
$$dt\, d\mathbf{x}_0 \ldots d\mathbf{x}_k$$

$$L_e(\mathbf{x}_0, \mathbf{x}_1, t) \quad \mathfrak{T}(\mathbf{x}_1, \mathbf{x}_2, \ldots, \mathbf{x}_{k-2}, \mathbf{x}_{k-1}) \quad W_e\left(\mathbf{x}_{k-1}, \mathbf{x}_k, t + \mathrm{tof}(\bar{\mathbf{x}})\right)$$

[Jarabo et al. 2014]

Transient Path Integral

$I(\theta) = \int$

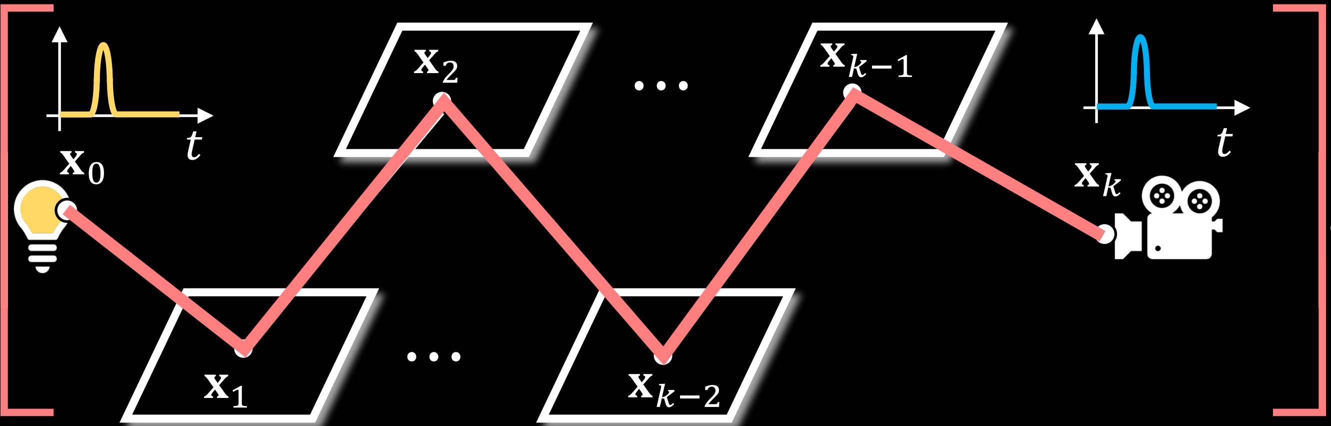


$dt\,d\mathbf{x}_0 \ldots d\mathbf{x}_k$

$L_e(\mathbf{x}_0, \mathbf{x}_1, t) \quad \mathfrak{T}(\mathbf{x}_1, \mathbf{x}_2, \ldots, \mathbf{x}_{k-2}, \mathbf{x}_{k-1}) \quad W_e\left(\mathbf{x}_{k-1}, \mathbf{x}_k, t + \mathrm{tof}(\bar{\mathbf{x}})\right)$

Differential Transient Path Integral

$$I(\theta) = \int \Big[\quad \Big] dt\, d\mathbf{x}_0 \ldots d\mathbf{x}_k$$

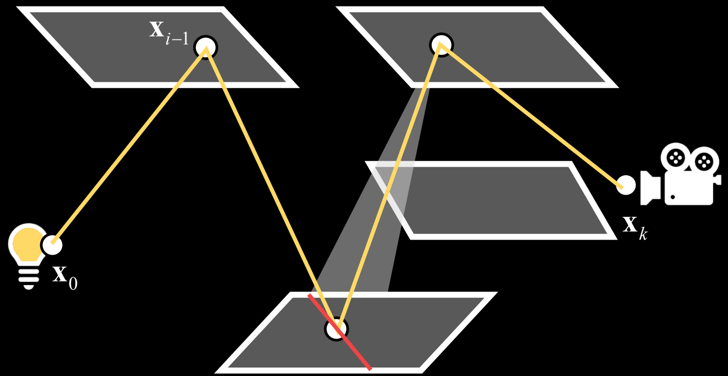


$$\frac{\partial I}{\partial \theta}(\theta) = \frac{\partial}{\partial \theta} \int_{2(k+1)-\text{dim.}} \Big[\quad \Big] d\mathbf{x}_0 \ldots d\mathbf{x}_k$$

Generalized transport theorem
[Seguin and Fried 2014]

Differential Transient Path Integral

Generalized Transport Theorem for $2(k+1)$-dim. manifold in $\mathbb{R}^{3(k+1)}$



$$\bar{\mathbf{x}} = \left(\mathbf{x}_0, \mathbf{x}_1, \ldots, \mathbf{x}_{k-1}, \mathbf{x}_k\right)$$

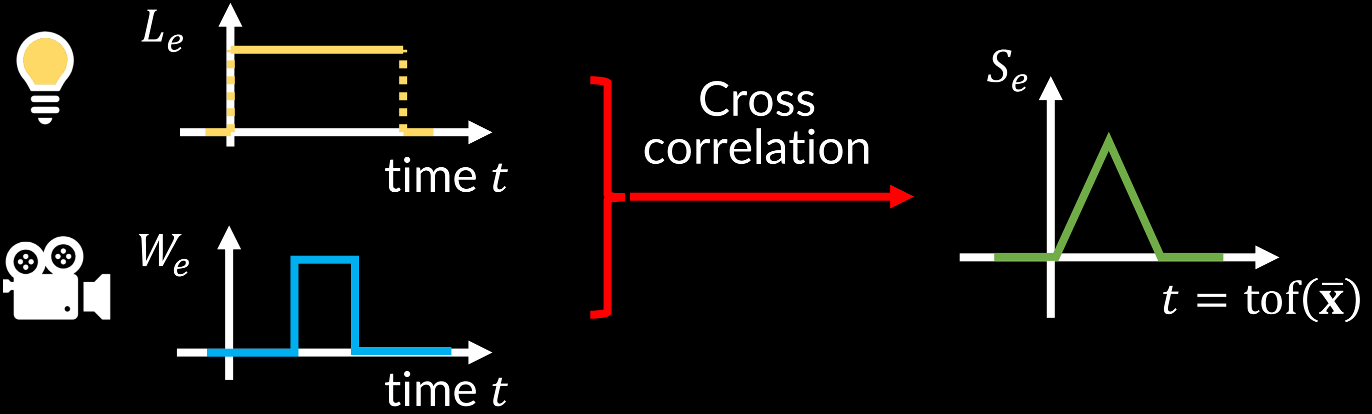
Interior | Boundary

$$\frac{\partial}{\partial\theta}\int f(\bar{\mathbf{x}})\,\mathrm{d}\bar{\mathbf{x}} = \int \frac{\partial f(\bar{\mathbf{x}})}{\partial\theta}\,\mathrm{d}\bar{\mathbf{x}} + \int \frac{\partial}{\partial\theta} f(\bar{\mathbf{x}})\,\mathrm{d}\bar{\mathbf{x}} =$$

Reducing Time-Integral

$$I(\theta) = \int_{\Omega} \int_{-\infty}^{\infty} L_e(\mathbf{x}_0 \to \mathbf{x}_1, t) \mathfrak{T}(\bar{\mathbf{x}}) W_e(\mathbf{x}_{k-1} \to \mathbf{x}_k, t + \mathrm{tof}(\bar{\mathbf{x}})) \mathrm{d}t \, \mathrm{d}\mu(\bar{\mathbf{x}})$$

Correlated importance: $S_e(\bar{\mathbf{x}}) := \int_{-\infty}^{\infty} L_e(\mathbf{x}_0 \to \mathbf{x}_1, t) W_e(\mathbf{x}_{k-1} \to \mathbf{x}_k, t + \mathrm{tof}(\bar{\mathbf{x}})) \mathrm{d}t$

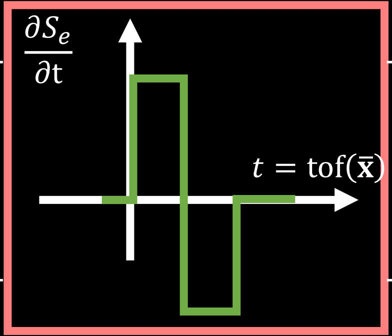


Differential Transient Path Integral

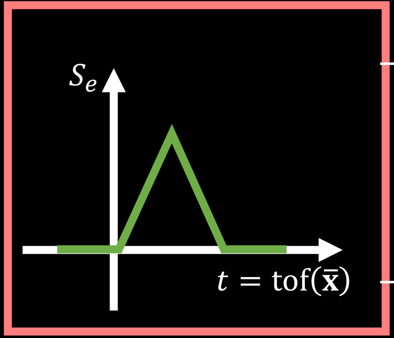
$$\frac{\partial}{\partial\theta}\int_{\Omega} f_{\mathcal{T}}(\bar{\mathbf{x}})\,\mathrm{d}\mu(\bar{\mathbf{x}}) = \int_{\Omega}\frac{\partial f_{\mathcal{T}}}{\partial\theta}(\bar{\mathbf{x}})\,\mathrm{d}\mu(\bar{\mathbf{x}}) + \int_{\partial\bar{\Omega}} g_{\mathcal{T}}(\bar{\mathbf{x}})\,\mathrm{d}\mu_{\partial\bar{\Omega}}(\bar{\mathbf{x}})$$

Interior term

$$\frac{\mathrm{d}f_{\mathcal{T}}}{\mathrm{d}\theta}(\bar{\mathbf{x}}) = \Bigg[$$



$$\Bigg] f_{steady-state}(\bar{\mathbf{x}}) + \Bigg[$$



$$\Bigg] \frac{\mathrm{d}f_{steady-state}}{\mathrm{d}\theta}(\bar{\mathbf{x}})$$

Differential Transient Path Integral

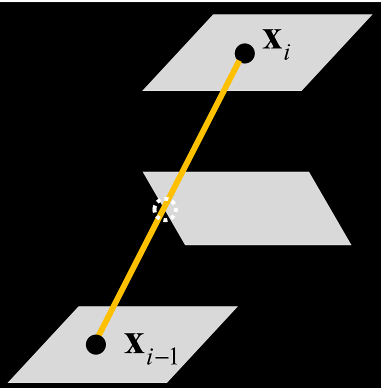
$$\frac{\partial}{\partial\theta}\int_{\Omega} f_{\mathcal{T}}(\bar{\mathbf{x}})\,\mathrm{d}\mu(\bar{\mathbf{x}}) = \int_{\Omega}\frac{\partial f_{\mathcal{T}}}{\partial\theta}(\bar{\mathbf{x}})\,\mathrm{d}\mu(\bar{\mathbf{x}}) + \int_{\partial\bar{\Omega}} g_{\mathcal{T}}(\bar{\mathbf{x}})\,\mathrm{d}\mu_{\partial\bar{\Omega}}(\bar{\mathbf{x}})$$

Boundary term

$\partial\bar{\Omega}$ = Visibility ∪ Temporal

Boundary path space

Visibility



∪

Temporal

where $S_e(\mathrm{tof}(\bar{\mathbf{x}}))$ become discontinuous

$= \phi$

(no Dirac delta source & sensor)

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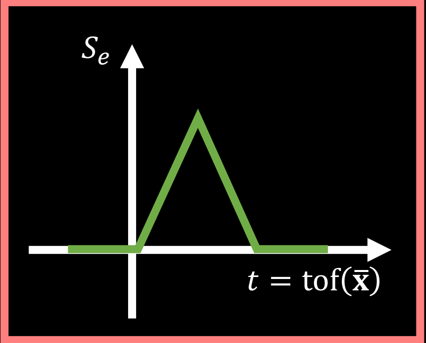
Differential Transient Path Integral

$$\frac{\partial}{\partial\theta}\int_{\Omega} f_{\mathcal{T}}(\bar{\mathbf{x}})\,\mathrm{d}\mu(\bar{\mathbf{x}}) = \int_{\Omega}\frac{\partial f_{\mathcal{T}}}{\partial\theta}(\bar{\mathbf{x}})\,\mathrm{d}\mu(\bar{\mathbf{x}}) + \int_{\partial\bar{\Omega}} g_{\mathcal{T}}(\bar{\mathbf{x}})\,\mathrm{d}\mu_{\partial\bar{\Omega}}(\bar{\mathbf{x}})$$

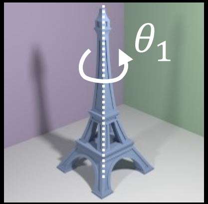
Boundary term

$$\Delta f_{\mathcal{T}}(\bar{\mathbf{x}}) = \left[\ \cdot\ \right] \Delta f_{steady-state}(\bar{\mathbf{x}})$$

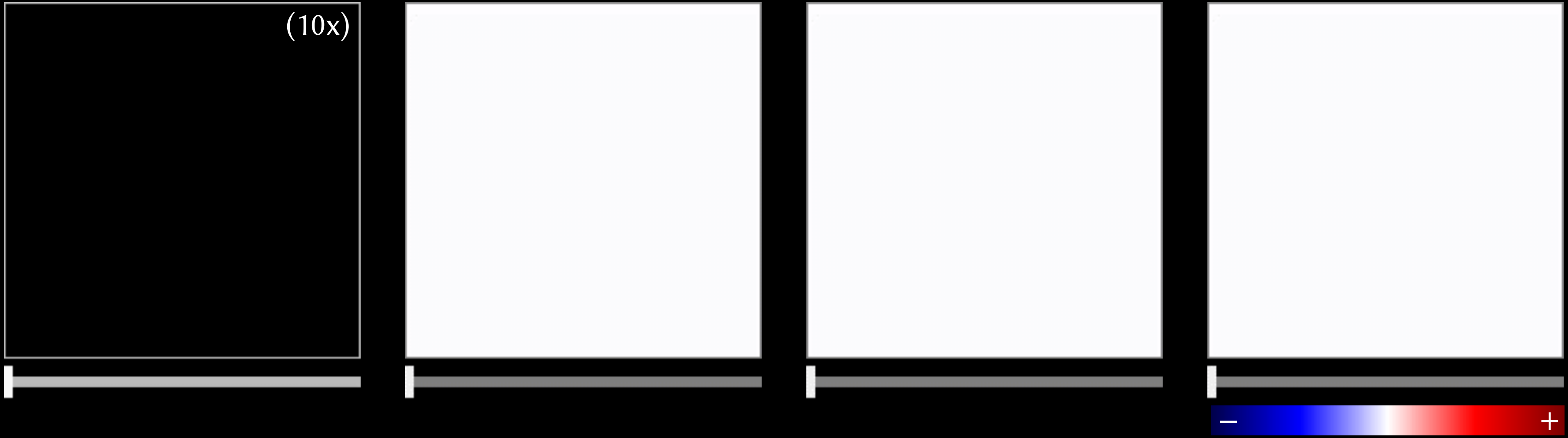


RESULTS

Validation Using Finite Differences



Transient images | Ours | FD (reference) | Diff. (Ours – FD)



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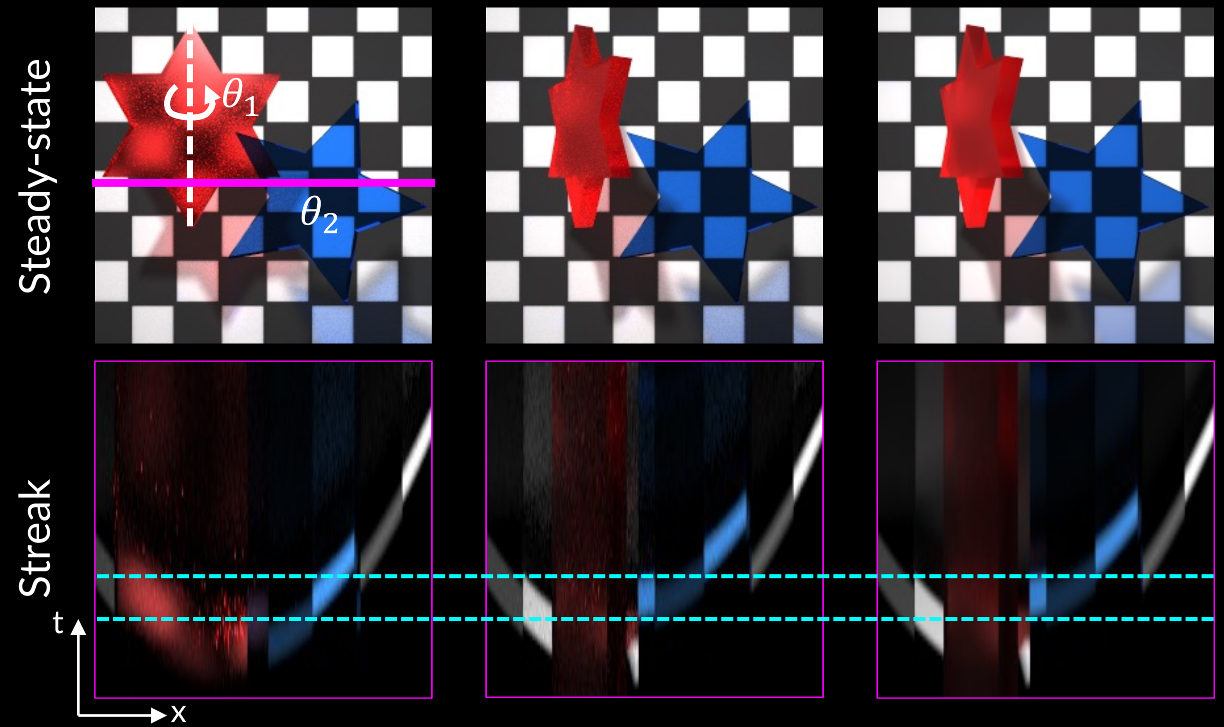
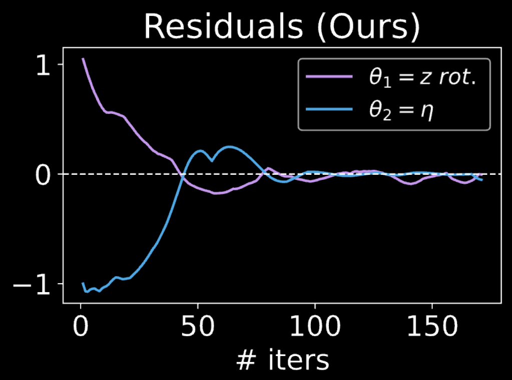
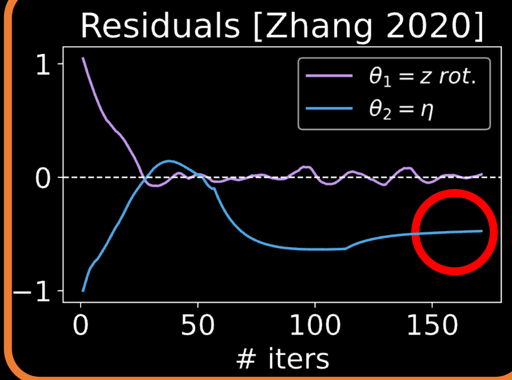
APPLICATION

Transparent Objects

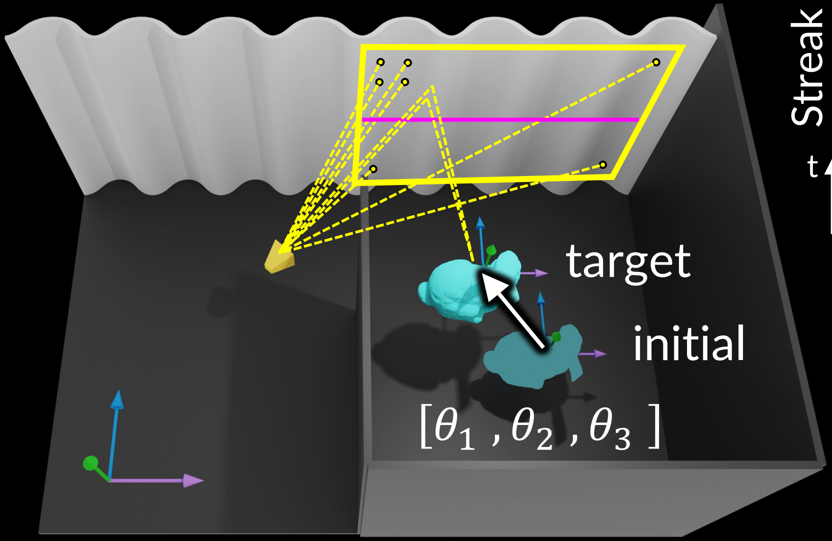


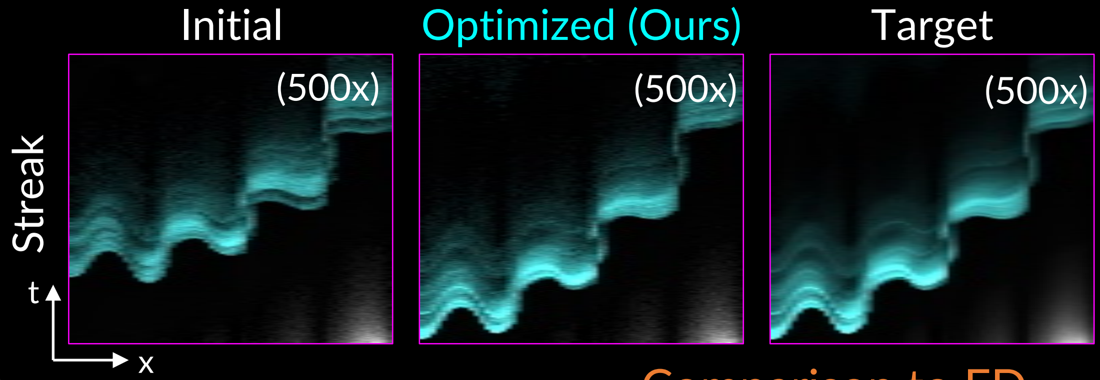


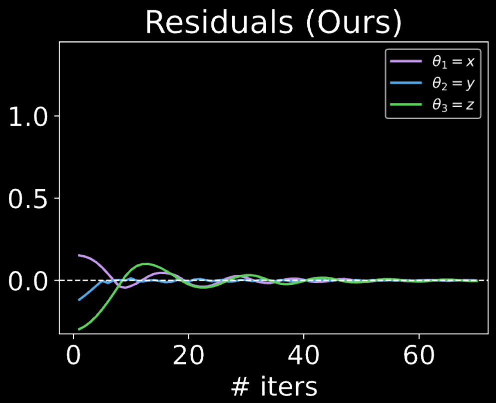
Comparison to steady-state



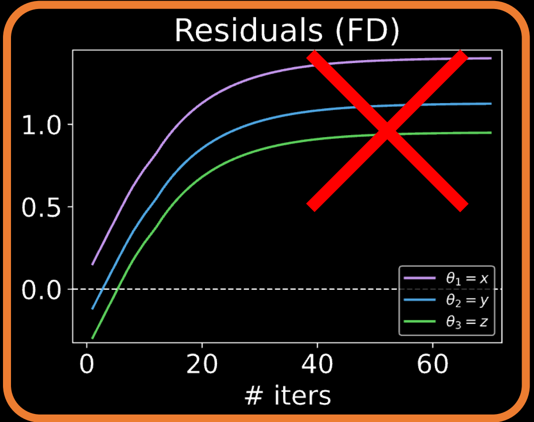
NLOS Tracking with Wavy Wall



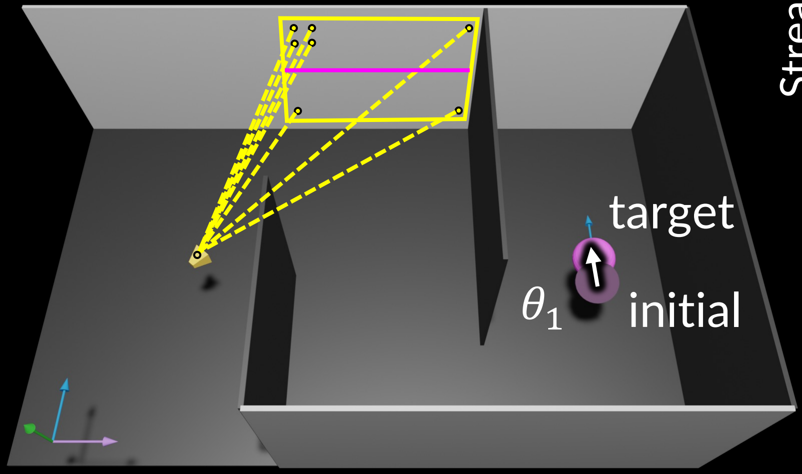


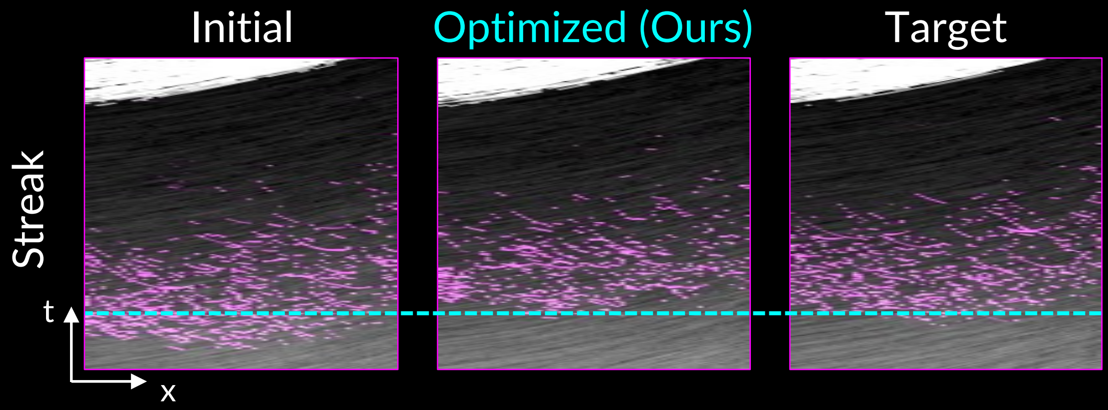


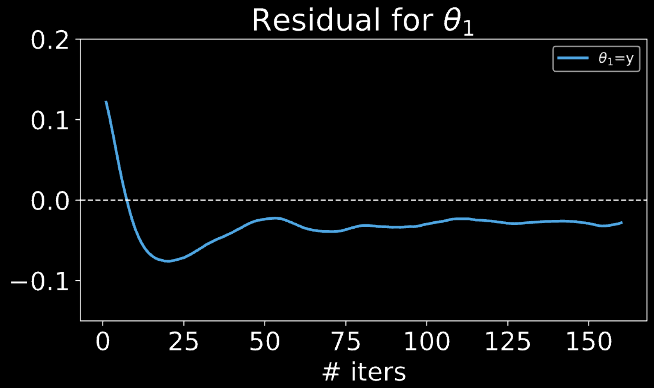
Comparison to FD



NLOS Tracking with Two Corners







Conclusion

- Deriving differential transient path integral using the generalized transport theorem
- Monte Carlo differentiable transient renderer using the correlated importance function
- Applications to challenging inverse transient rendering scenarios including looking around two corners

Limitation and Future Work

- Memory
  → combine with *radiative backpropagation*
  [Nimier-David et al. 2020; Vicini et al. 2021]

- Geometry optimization using differentiable rendering
  → combine with *Large Steps in Inverse Rendering of Geometry*
  [Baptiste Nicolet et al. 2021]

SIGGRAPH ASIA 2021 TOKYO

CONFERENCE 14 - 17 DECEMBER 2021
EXHIBITION 15 - 17 DECEMBER 2021
TOKYO INTERNATIONAL FORUM, JAPAN

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LIVE

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