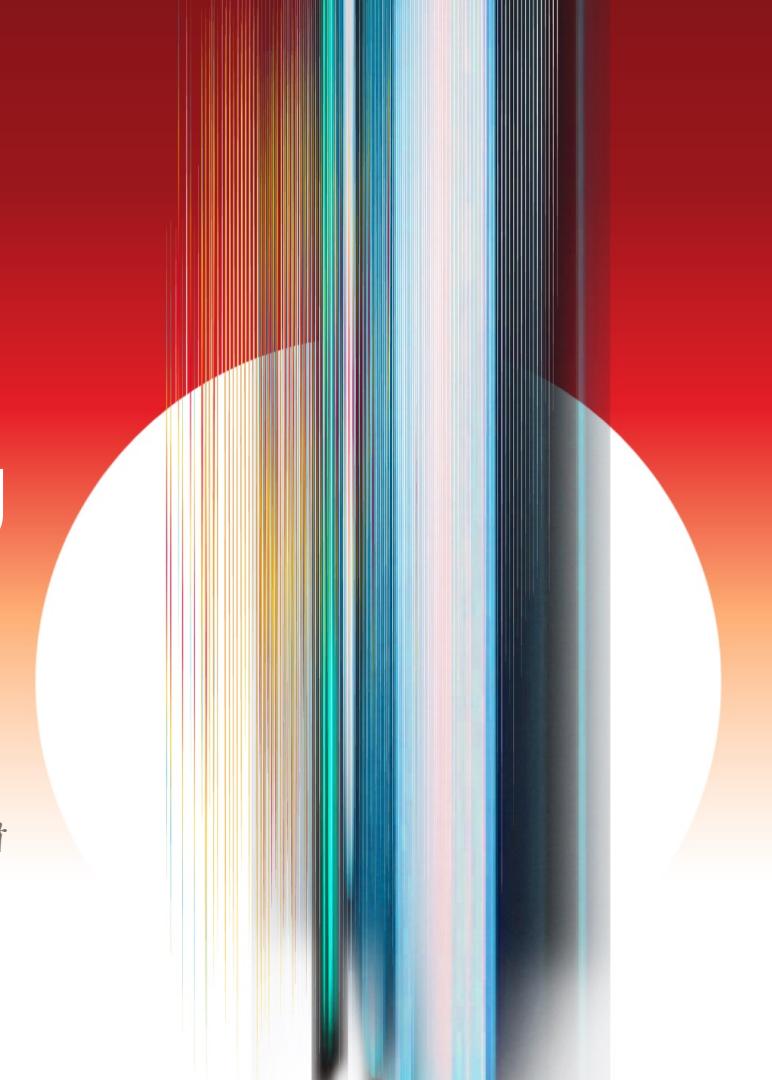


Differentiable Transient Rendering

Shinyoung Yi[†] Donggun Kim[†] Kiseok Choi[†]

Adrian Jarabo* Diego Gutierrez* Min H. Kim[†]

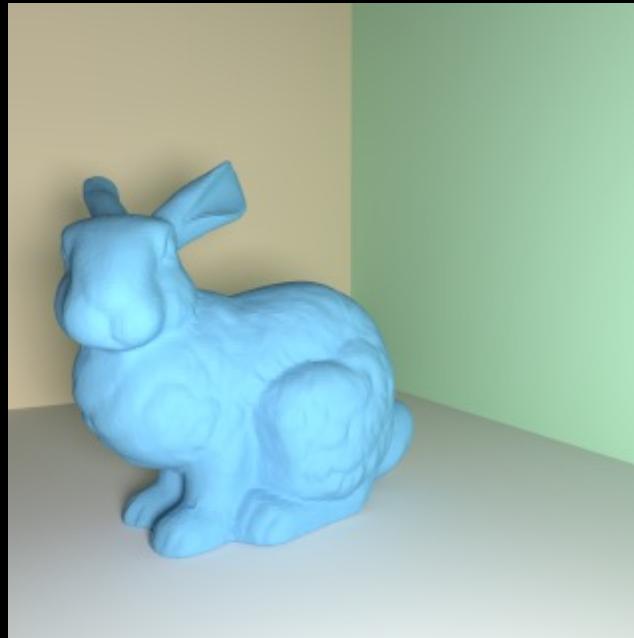


Rendering

vertex position
object transform
material properties
.....

↓

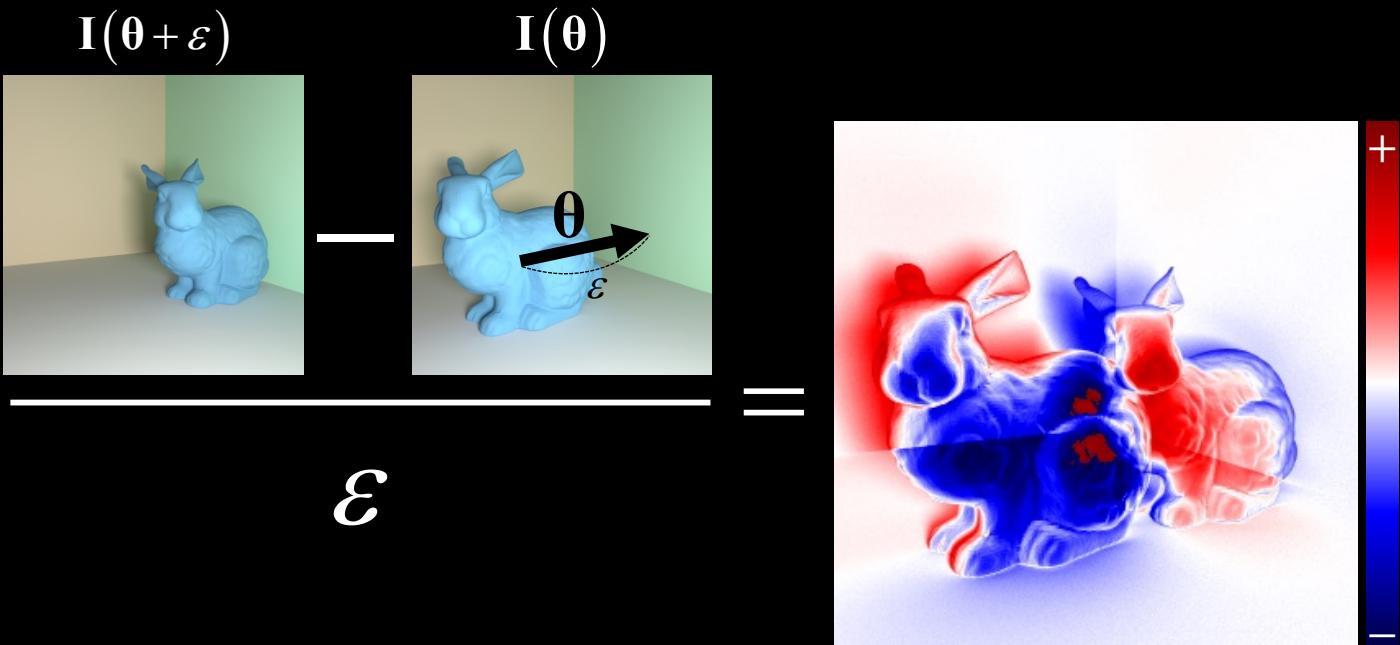
$$I(\theta) =$$
$$I \in \sim H \times W$$



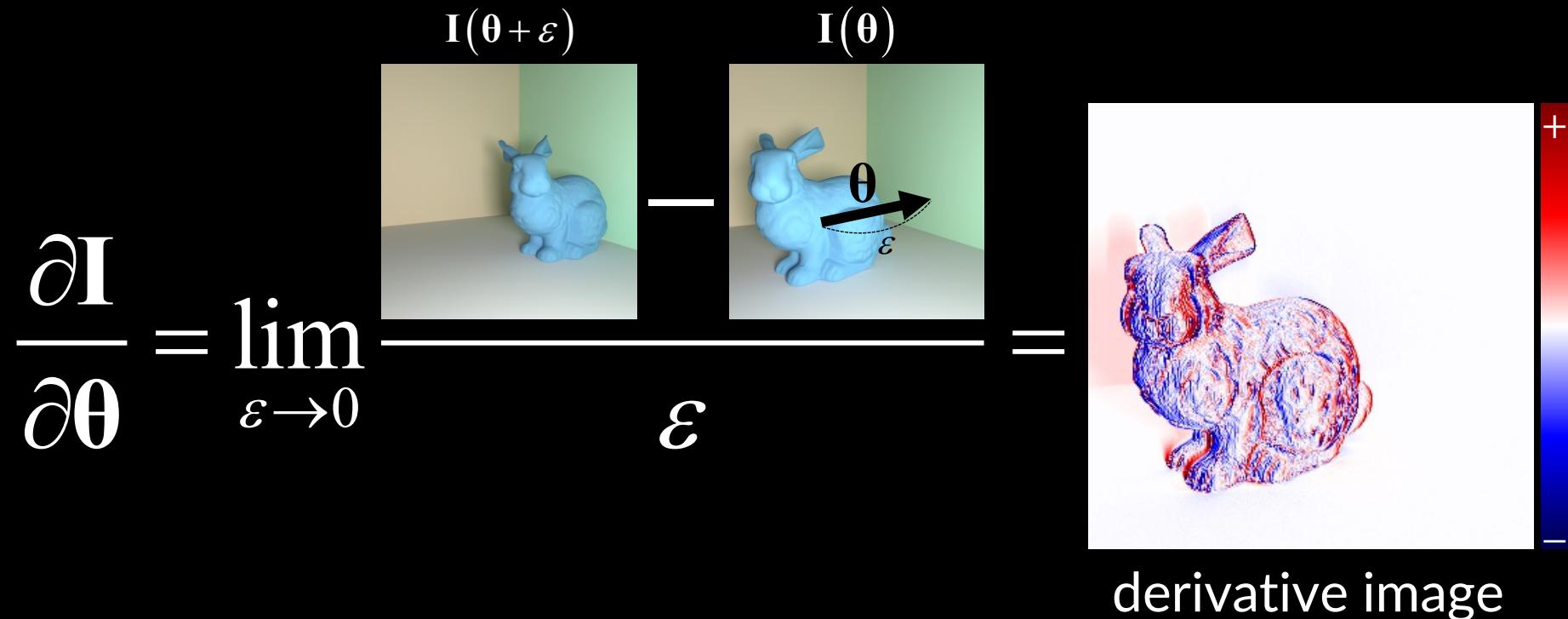
image

Differentiable Rendering

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

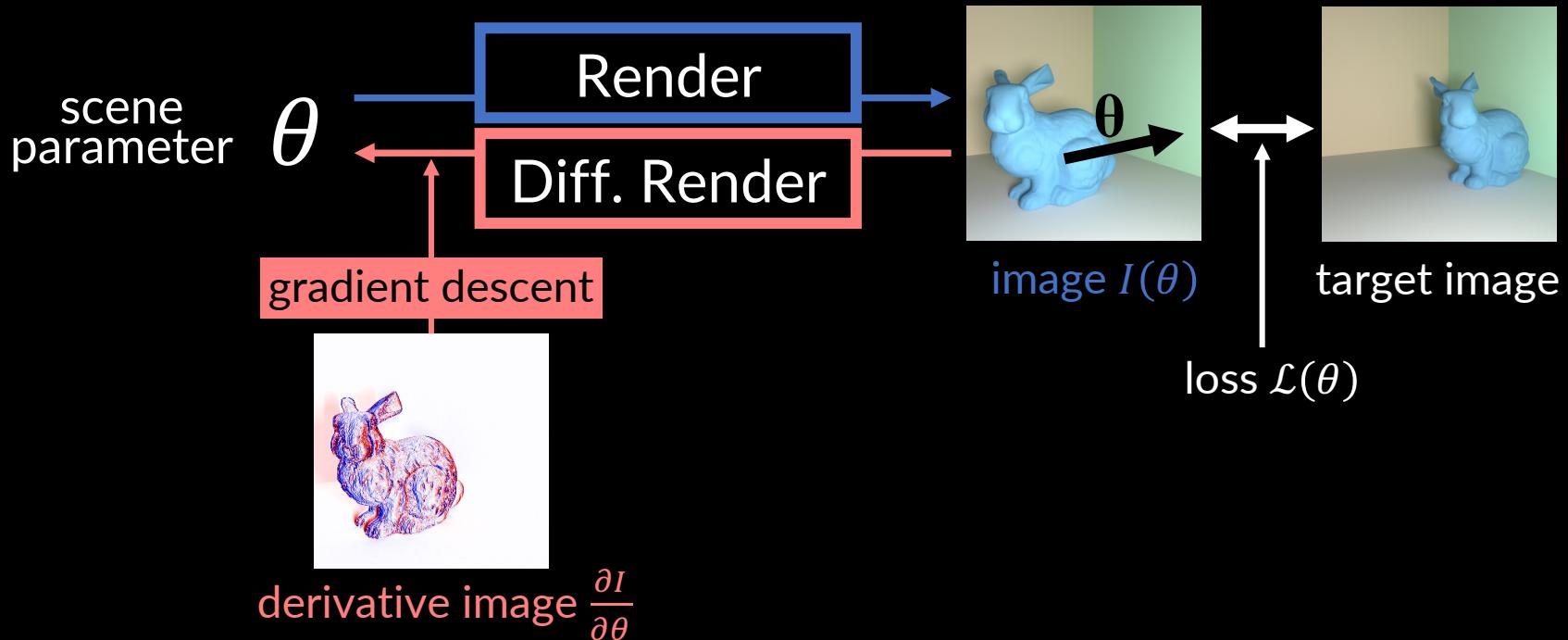


Differentiable Rendering



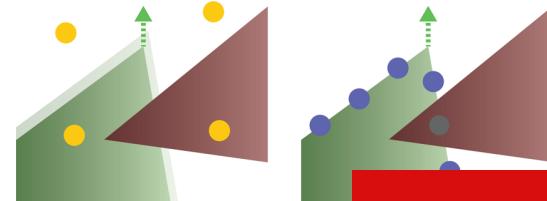
Why Differentiable Rendering?

→ Inverse rendering

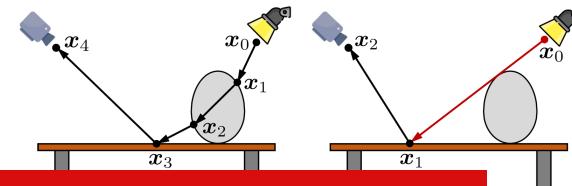


Differentiable Rendering

Edge sampling
Li et al. 2018

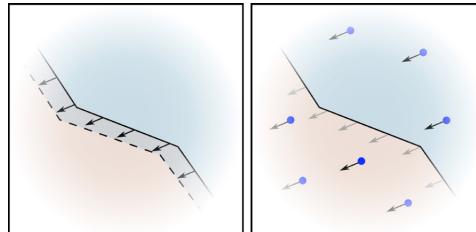


Path-space
Zhang et al. 2020

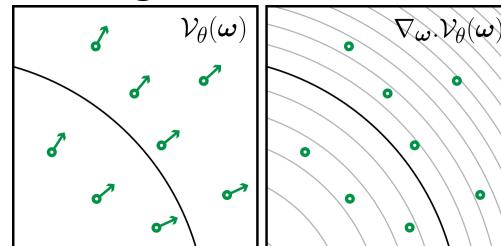


Only steady-state methods exist

Reparameterization
Loubet et al. 2019



Sampling
Bangaru et al. 2020



...

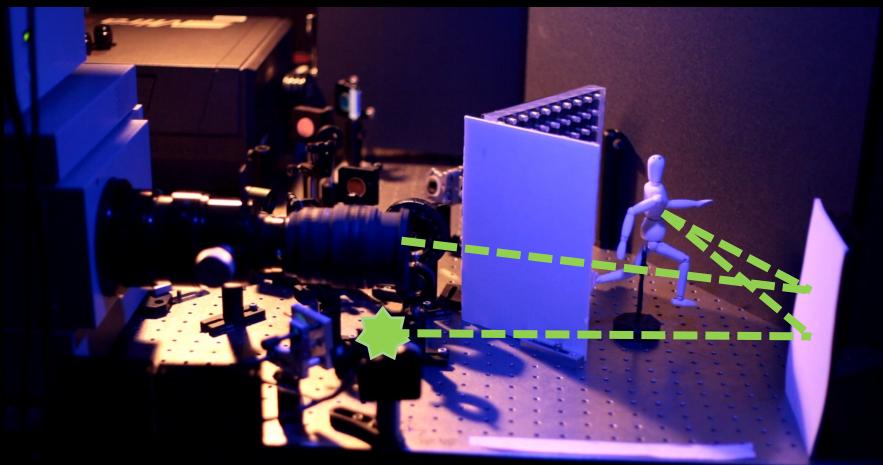
Why Transient?

Femto-photography



[Velten et al. 2013]

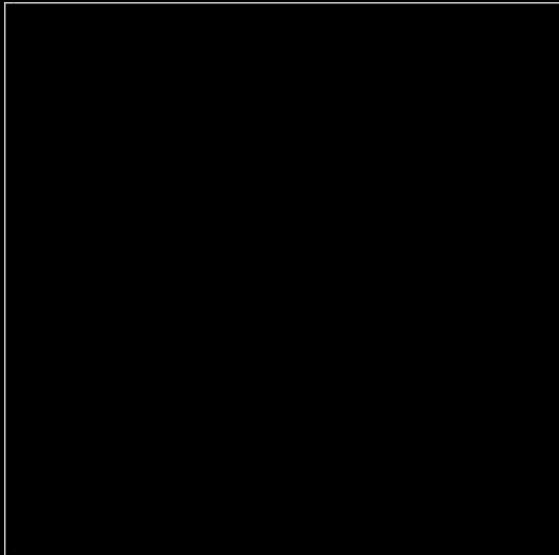
*Non-Line-of-Sight Imaging
(NLOS)*



[Velten et al. 2012], etc.

Transient Rendering

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

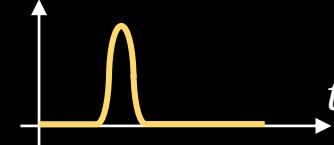


time:

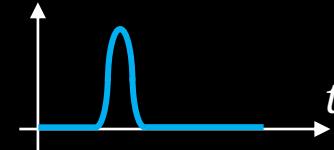


transient images

source L_e



sensor W_e

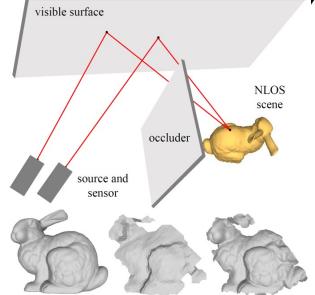


finite speed of light c

Inverse Methods of Transient Rendering

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

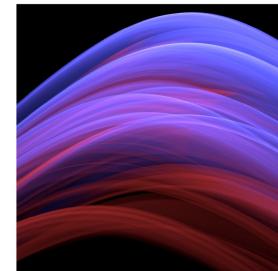
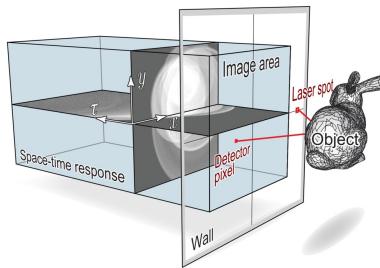
Tokyo 2019



1

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

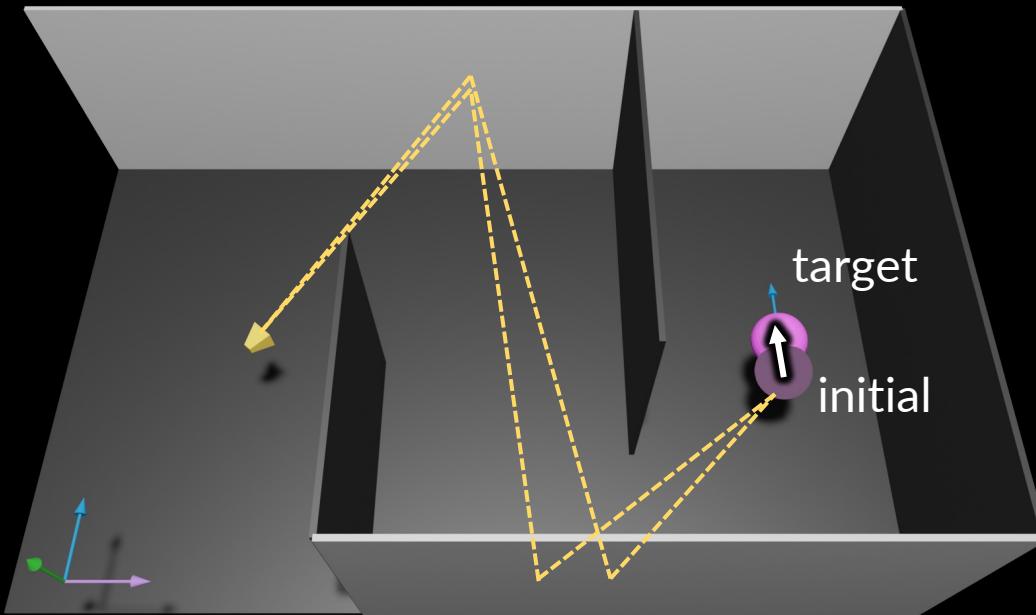
Iseringhausen and Hullin 2020



2

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

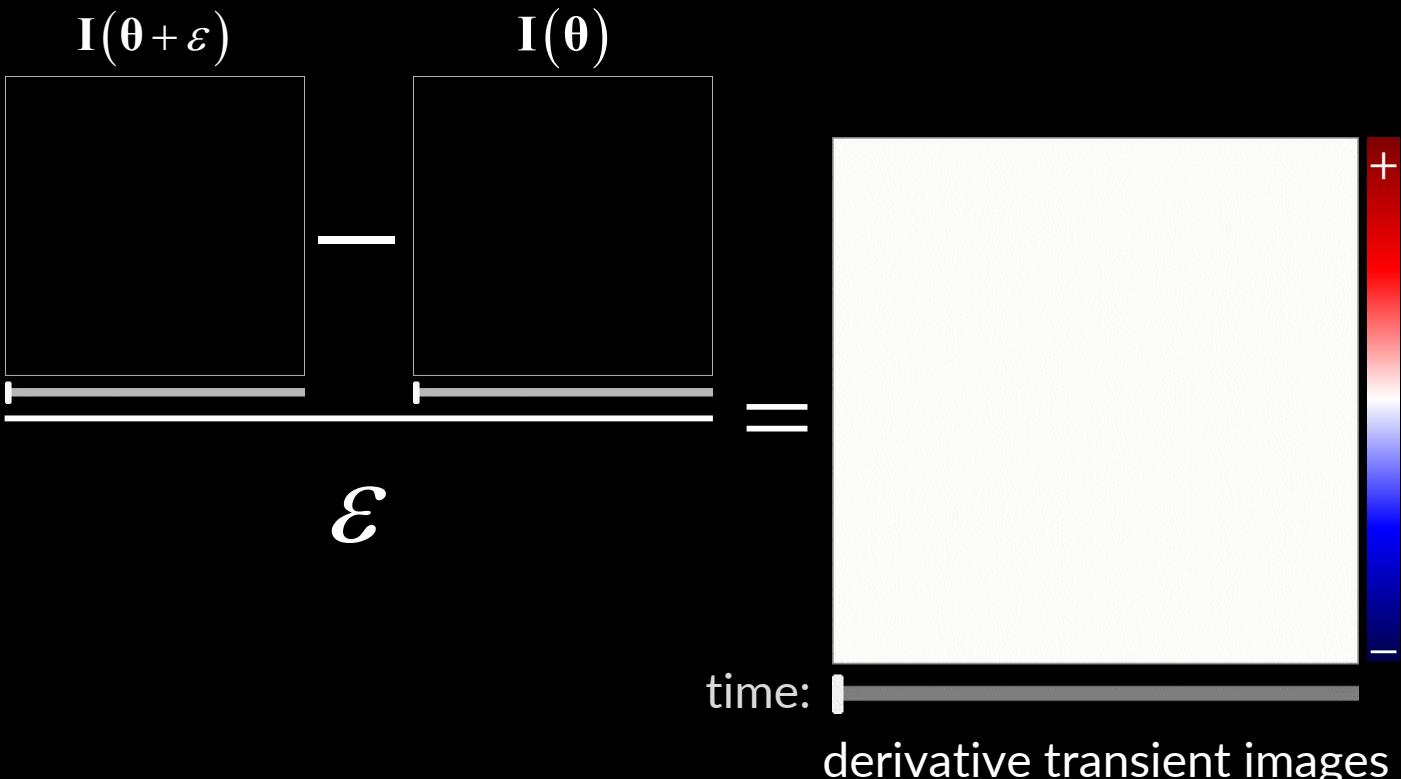
Differentiable Transient Rendering



Differentiable Transient Rendering

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

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



OUR METHOD

Path Integral

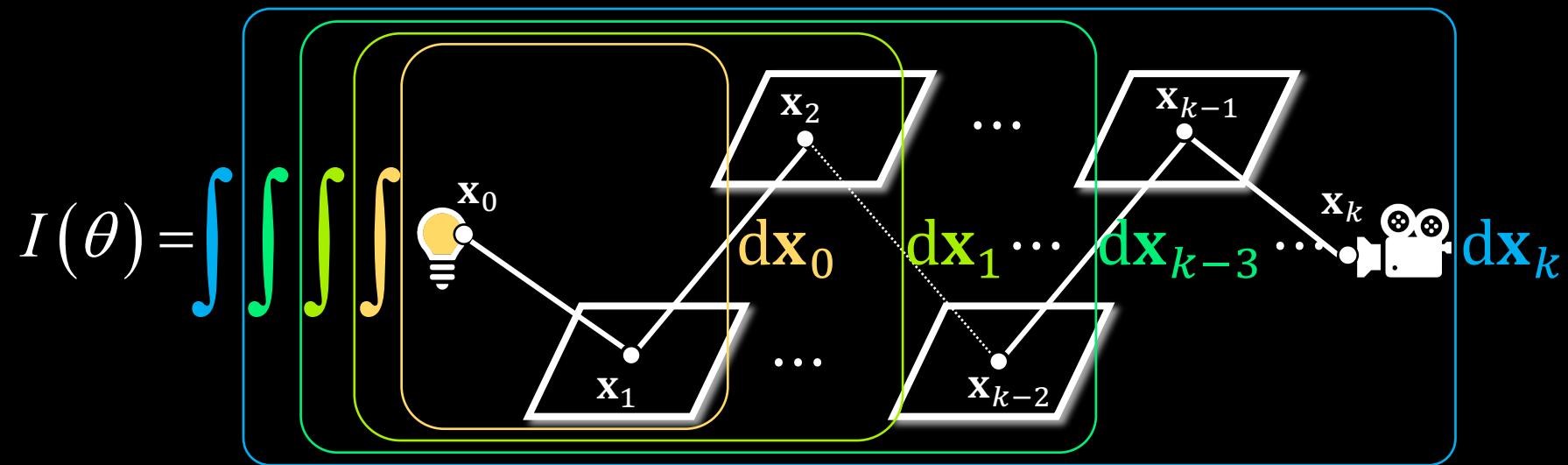
$$I(\theta) = \int dx_0 \dots dx_k$$

The diagram illustrates a path integral from a light source to a sensor. It consists of several rectangular planes representing surfaces. A light bulb icon at the top left is labeled x_0 . A camera icon at the bottom right is labeled x_k . A series of points x_1, \dots, x_{k-1} are marked on the surfaces. Arrows indicate the flow of light from x_0 through the surfaces to x_k . The regions between the surfaces are colored: gold for the first region, grey for the middle regions, and blue for the last region containing the sensor.

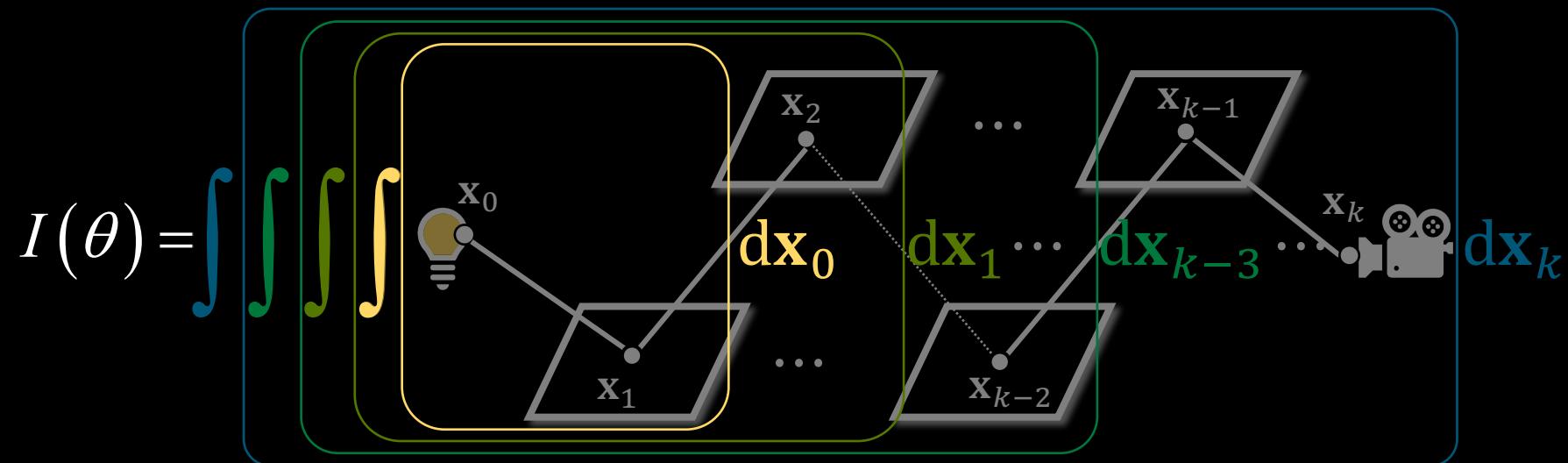
$L_e(x_0, x_1)$ $\mathfrak{T}(x_1, x_2, \dots, x_{k-2}, x_{k-1})$ $W_e(x_{k-1}, x_k)$

source emission path throughput sensor sensitivity

Path Integral



Differential Path Integral

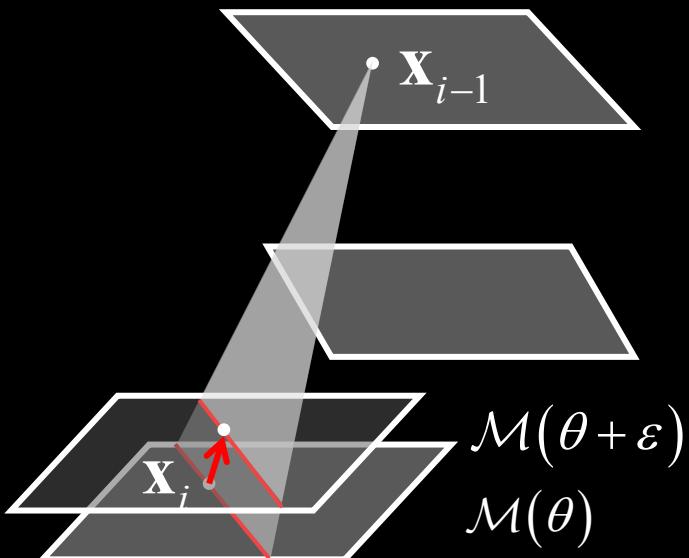


$$\frac{\partial I}{\partial \theta}(\theta) = \dots \frac{\partial}{\partial \theta} \int_{2D} \left[\dots \right] dx_0 \dots$$

Reynolds transport theorem

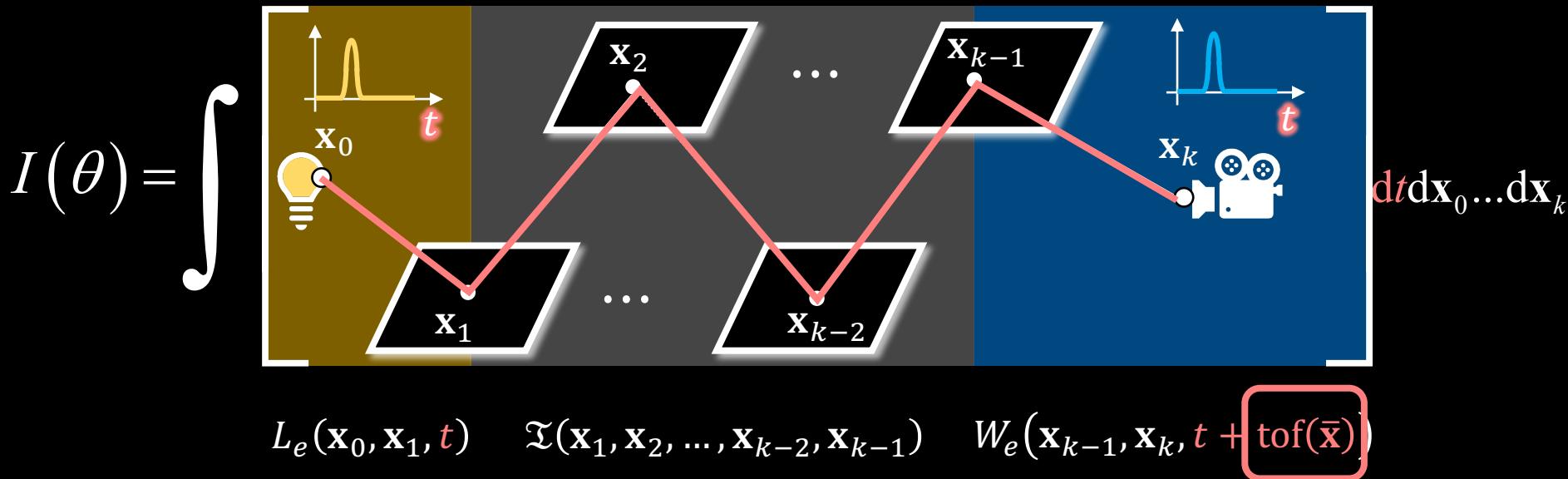
Differential Path Integral

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



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

Transient Path Integral



Transient Path Integral

$$I(\theta) = \int [\text{Diagram}] dt dx_0 \dots dx_k$$

The diagram illustrates a transient path integral. A red trajectory line starts at a lightbulb icon labeled x_0 and ends at a camera icon labeled x_k . The trajectory passes through several intermediate points labeled x_1, \dots, x_{k-1} , each represented by a white parallelogram. The trajectory is piecewise linear between these points. At each point x_i , there is a small vertical timeline with a yellow or blue bell-shaped curve representing the emission or detection signal at that specific time t . Red 'X' marks are placed at the start and end of the trajectory, indicating the integration limits. Below the diagram, three terms are listed: $L_e(x_0, x_1, t)$, $\mathfrak{T}(x_1, x_2, \dots, x_{k-2}, x_{k-1})$, and $W_e(x_{k-1}, x_k, t + \text{tof}(\bar{x}))$.

Differential Transient Path Integral

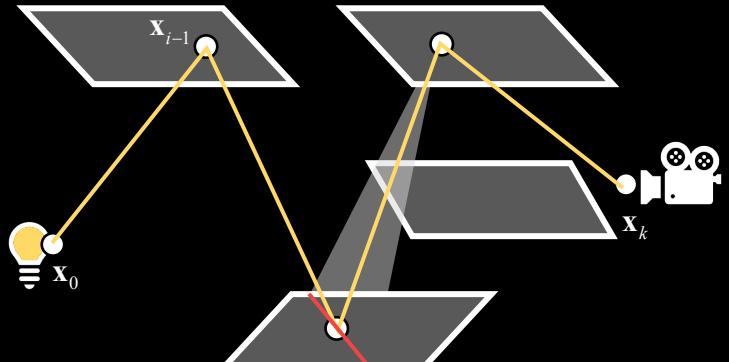
$$I(\theta) = \int \left[\text{Diagram showing a light source at } x_0 \text{ emitting light along a path through several surfaces (represented by trapezoids) ending at a camera at } x_k. \text{ Each surface has a time-varying intensity profile plotted against time } t. \right] dt dx_0 \dots dx_k$$

$$\frac{\partial I}{\partial \theta}(\theta) = \frac{\partial}{\partial \theta} \int_{2(k+1)-\text{dim.}} \left[\text{Diagram showing a light source at } x_0 \text{ emitting light along a path through several surfaces (represented by trapezoids) ending at a camera at } x_k. \text{ Each surface has a time-varying intensity profile plotted against time } t. \right] dx_0 \dots dx_k$$

Generalized transport theorem
[Seguin and Fried 2014]

Differential Transient Path Integral

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



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

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

Interior



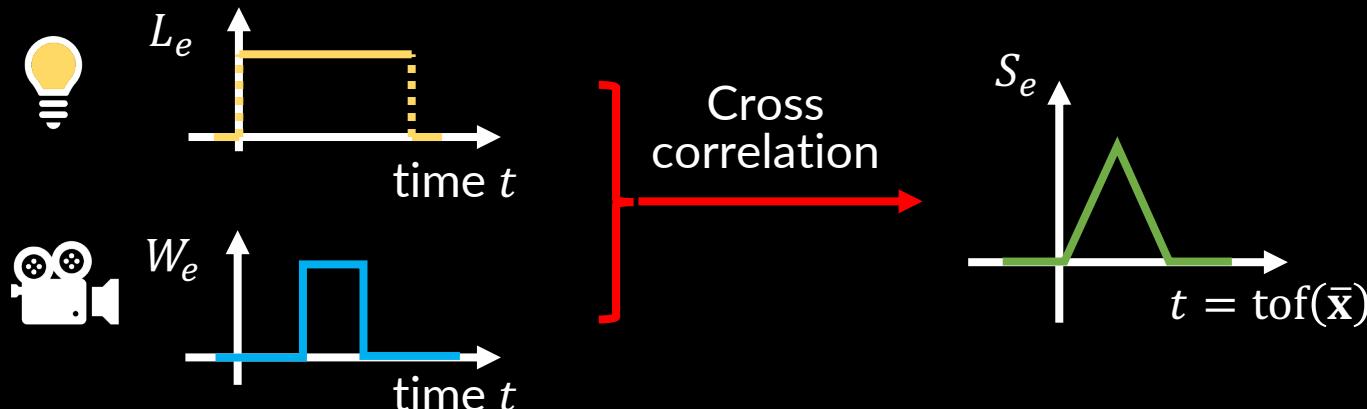
Boundary



Reducing Time-Integral

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

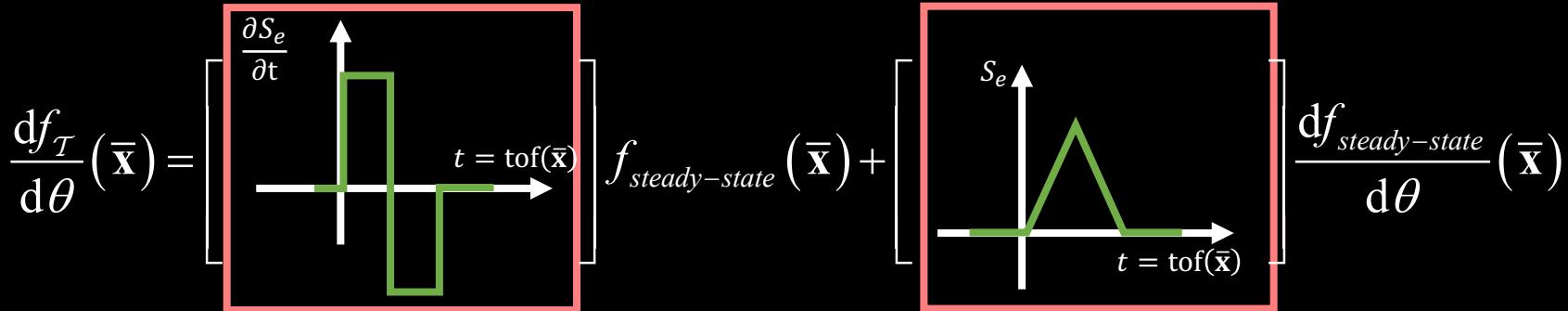
Correlated importance: $S_e(\bar{\mathbf{x}}) := \int_{-\infty}^{\infty} L_e(\mathbf{x}_0 \rightarrow \mathbf{x}_1, t) W_e(\mathbf{x}_{k-1} \rightarrow \mathbf{x}_k, t + \text{tof}(\bar{\mathbf{x}})) dt$



Differential Transient Path Integral

$$\frac{\partial}{\partial \theta} \int_{\Omega} f_{\tau}(\bar{\mathbf{x}}) d\mu(\bar{\mathbf{x}}) = \boxed{\int_{\Omega} \frac{\partial f_{\tau}}{\partial \theta}(\bar{\mathbf{x}}) d\mu(\bar{\mathbf{x}})} + \int_{\partial\bar{\Omega}} g_{\tau}(\bar{\mathbf{x}}) d\mu_{\partial\bar{\Omega}}(\bar{\mathbf{x}})$$

Interior term



Differential Transient Path Integral

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

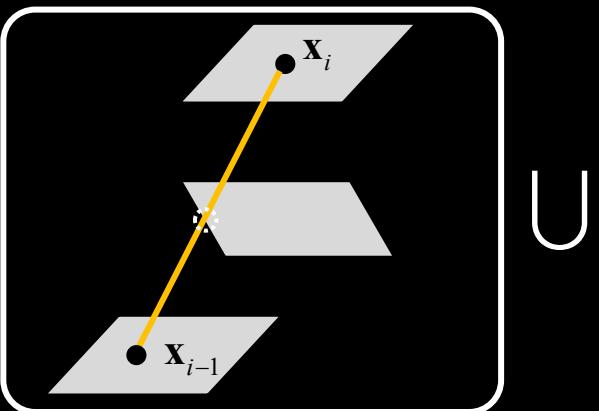
Boundary term

Visibility

$$\partial\bar{\Omega}$$

=

Boundary path space



Temporal

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

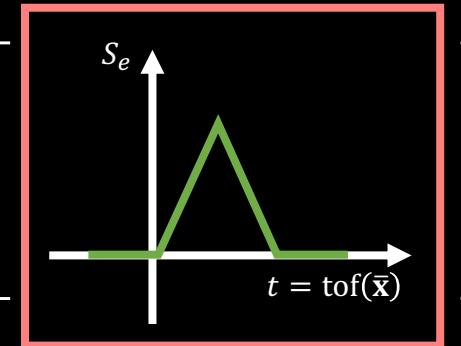
$$= \phi$$

(no Dirac delta source & sensor)

Differential Transient Path Integral

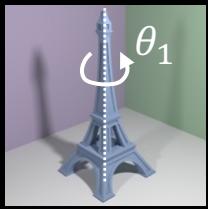
$$\frac{\partial}{\partial \theta} \int_{\Omega} f_T(\bar{x}) d\mu(\bar{x}) = \int_{\Omega} \frac{\partial f_T}{\partial \theta}(\bar{x}) d\mu(\bar{x}) + \int_{\partial\bar{\Omega}} g_T(\bar{x}) d\mu_{\partial\bar{\Omega}}(\bar{x})$$

Boundary term

$$\Delta f_T(\bar{x}) = \left[\begin{array}{c} S_e \\ \hline \text{---} & \text{---} \\ \text{---} & \text{---} \end{array} \right] \Delta f_{\text{steady-state}}(\bar{x})$$


RESULTS

Validation Using Finite Differences

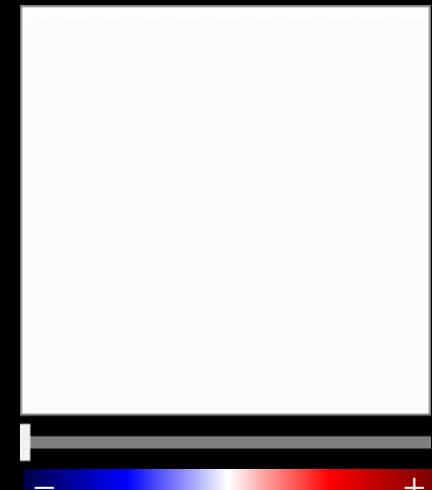
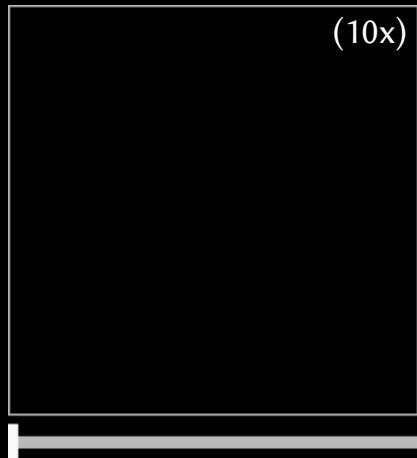


Transient images

Ours

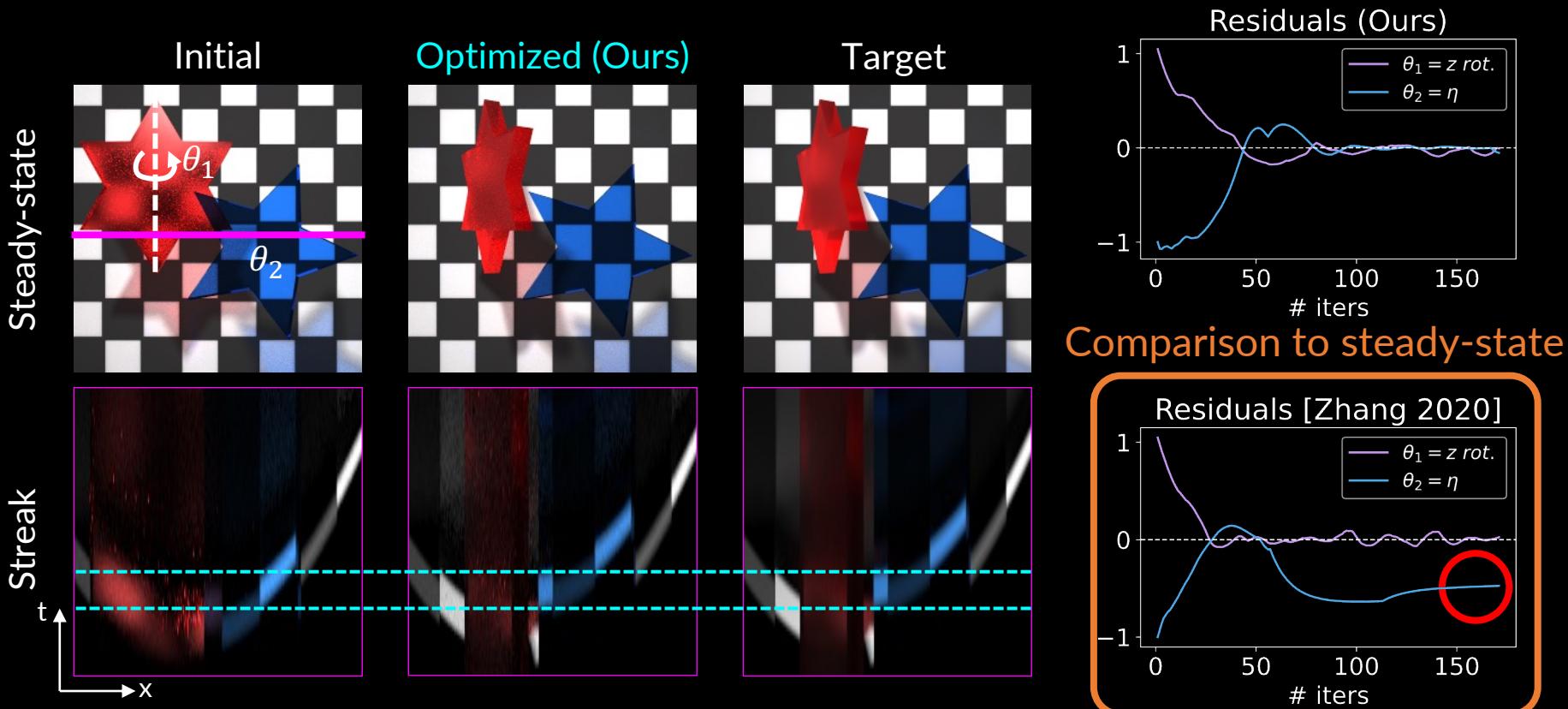
FD (reference)

Diff. (Ours – FD)

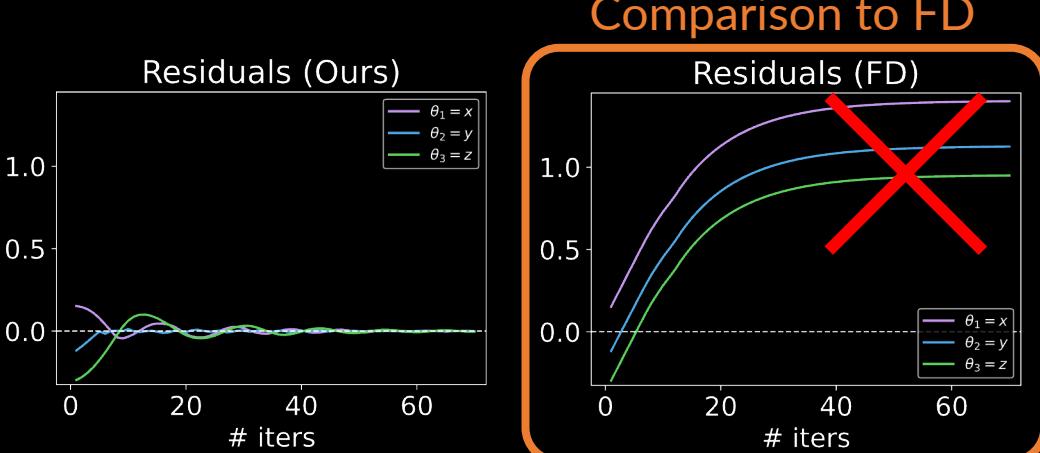
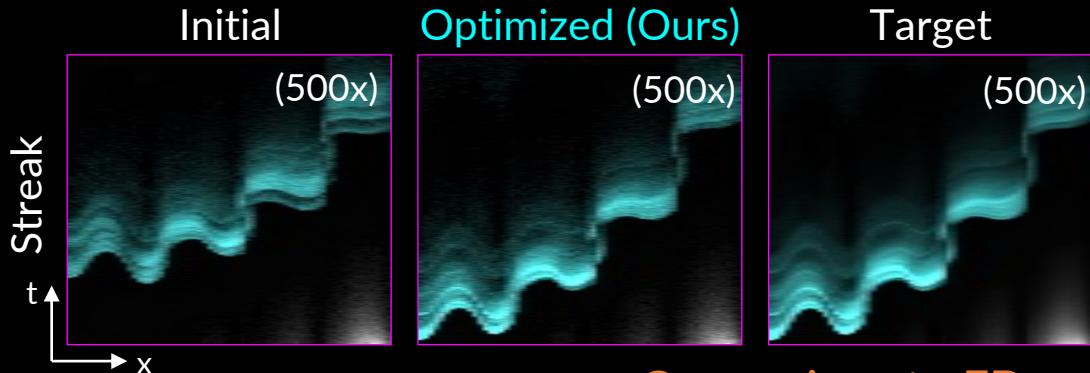
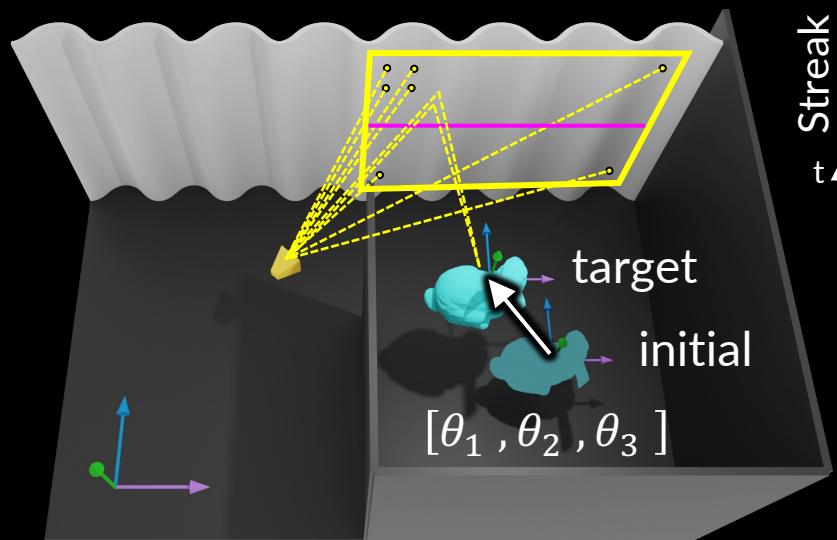


APPLICATION

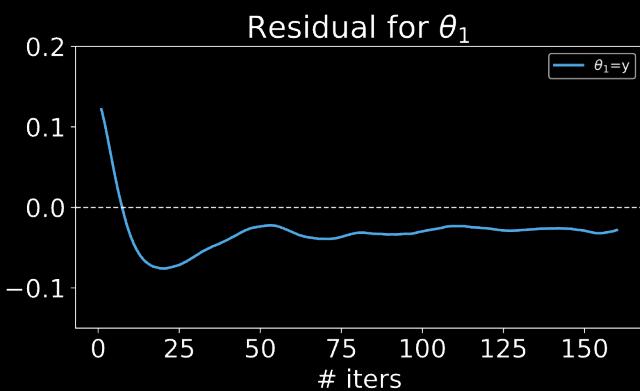
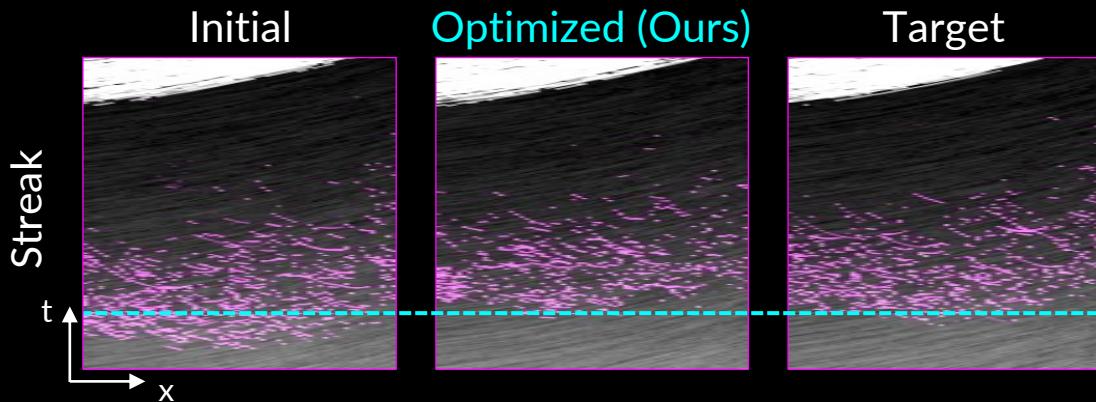
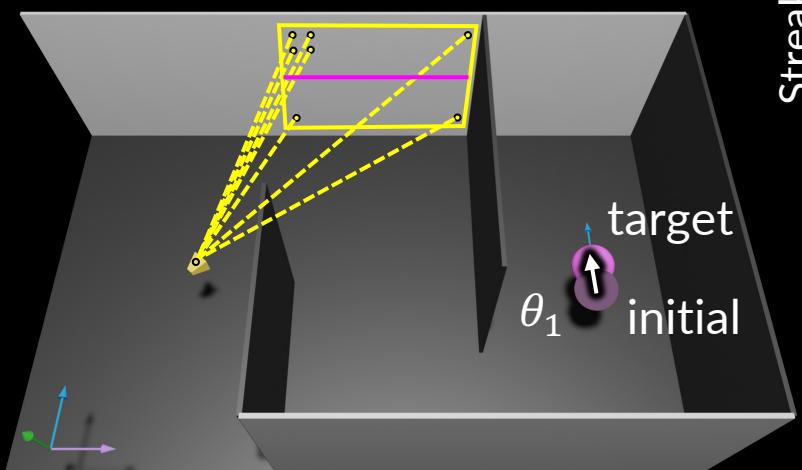
Transparent Objects



NLOS Tracking with Wavy Wall



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]



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TOKYO INTERNATIONAL FORUM, JAPAN

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