Transient Photon Beams

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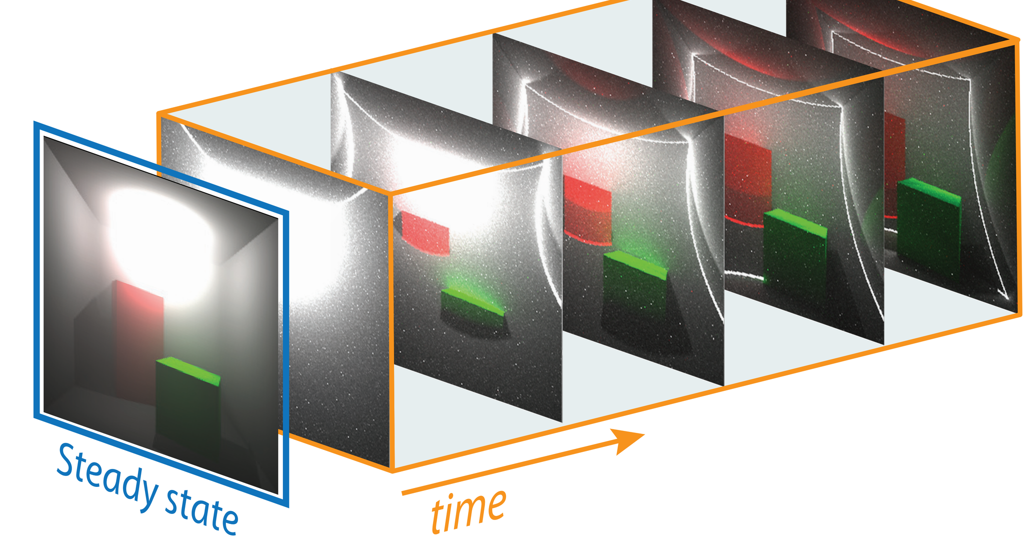
Recent advances on transient imaging and their applications have opened the necessity of forward models that allow precise generation and analysis of time-resolved light transport data. However, traditional steady-state rendering techniques are not suitable for computing transient light transport due to the aggravation of inherent Monte Carlo variance over time, specially problematic in participating media. We address this problem by presenting the first photon-based method for transient rendering of participating media that performs density estimations on time-resolved precomputed photon maps. We first introduce the transient integral form of the radiative transfer equation into the computer graphics community, including transient delays on the scattering events. Based on this formulation we leverage the high density and parameterized continuity provided by photon beams algorithms to present a new transient method that allows to significantly mitigate variance and efficiently render participating media effects in transient state.

Variance in transient rendering of participating media

Forward rendering models are a powerful tool to generate transient data under controlled synthetic setups. However, inherent variance of steady-state path tracing methods, becomes even more evident in transient state [1]. All radiance samples that traditionally fall into a single steady-state pixel of a 2D image, in transient state become distributed along the time dimension depending on their optical path. As we increase temporal resolution in transient path tracing algorithms, variance becomes aggravated since less samples fall into the time interval of a pixel. In particular, participating media are specially prone to variance and require dense sampling to obtain noise-free solutions.



Transient Radiative Transfer

While original formulation of the radiative transfer equation (RTE) [2] includes radiance propagation time, traditional steady-state rendering usually discards this temporal component. To render participating media in transient state, we need the time-resolved integral form of the RTE, accounting for time delays due to scattering events and radiance optical path.

Medium radiance, *Transmittance*, *Surface radiance*, *Transmittance*, *Medium in-scattering*

$$L(\mathbf{x},\vec{\omega},t) = T_r(\mathbf{x},\mathbf{x}_s,t)L_s(\mathbf{x}_s,\vec{\omega},t-\Delta t_s) + \int_0^s T_r(\mathbf{x},\mathbf{x}_r,t)L_i(\mathbf{x}_r,\vec{\omega},t-\Delta t_r)\mathrm{d}r$$

Medum in-scattering, *Scattering*, *Phase function*, *Medum radiance*

$$L_i(\mathbf{x},\vec{\omega},t)=\int_\Omega\int_0^t \mu_s(\mathbf{x}_r,t-t')\rho(\mathbf{x},\vec{\omega}_i,\vec{\omega},t-t')L(\mathbf{x},\vec{\omega}_i,t)\mathrm{d}t'\mathrm{d}\vec{\omega}_i$$

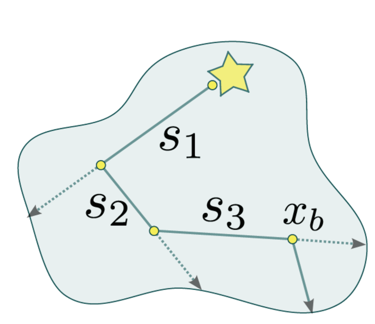
Time delay, *IOR*, *Speed of light*, *Constant IOR of medium*

$$\Delta t(\mathbf{x}_0 \leftrightarrow \mathbf{x}_1) = \int_{\mathbf{x}_0}^{\mathbf{x}_1} \frac{\eta(\mathbf{x})}{c}\mathrm{d}\mathbf{x} = \frac{\eta_m}{c}\|\mathbf{x}_0-\mathbf{x}_1\|$$

Transient Photon Beams

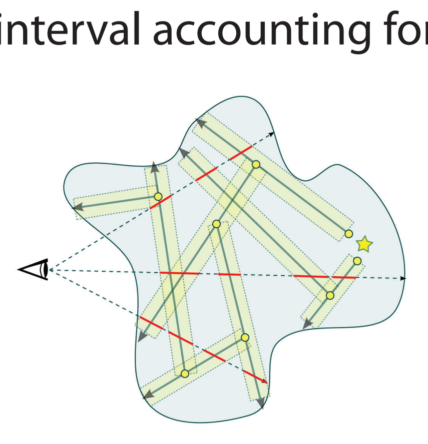
Steady-state methods based on *photon beams* [3] significantly mitigate variance in the final image by densely populating media with full photon trajectories and performing ray-beam density estimations during the rendering stage. We make the key observation that in transient state, these **continuous full photon trajectories** allow us to render media at **arbitrary temporal resultions** using closed-form density estimations. We leverage these properties to introduce a new transient rendering method based on photon beams, by keeping track of the time delays during photon propagation and density estimations. First, while Monte Carlo sampling the transient RTE, we need to keep track of each photon's time delays during its departure from the light source until it reaches its position within the medium.

Once the beam map is traced, during the rendering stage we need to account for the time delays due to ray-beam density estimations. Every ray-beam intersection is bounded by parameterized distances along the camera ray and the beam, which result in a time interval Δt in our time-resolved render. We finally distribute the closed-form computed radiance within this interval accounting for the photon initial time $t_{\mathbf{x}_b}$.

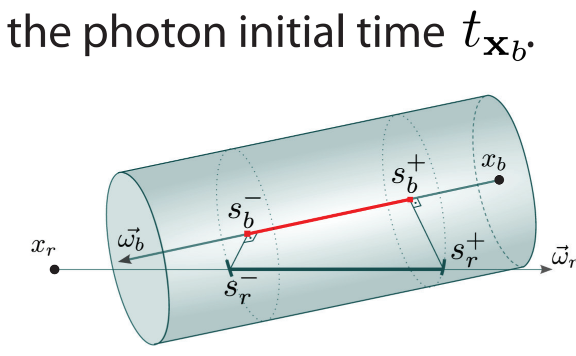


$$t_{\mathbf{x}_b}= \sum \Delta t(s_j)$$

Initial photon time

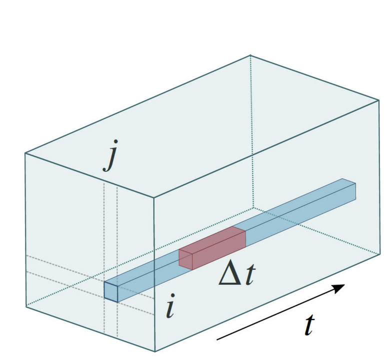


Density estimations at photon beams map



$$t_b = \frac{\eta_m}{c}s_b \quad t_r = \frac{\eta_m}{c}s_r$$

Ray-beam density estimation

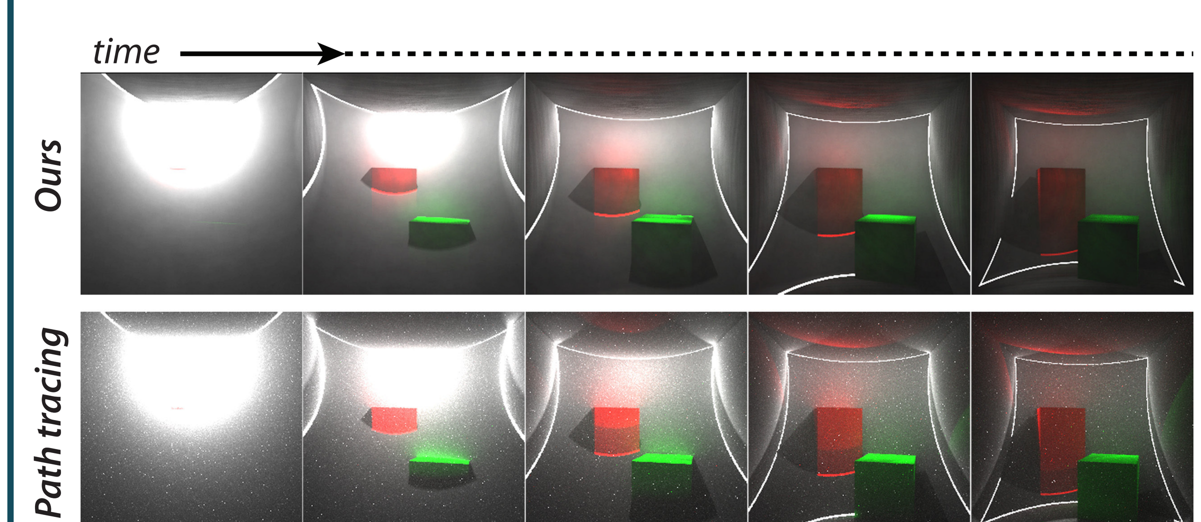


$$t^- = t_r^- + t_b^- \quad t^+ = t_r^+ + t_b^+$$
$$\Delta t = t_{\mathbf{x}_b} + [t^-, t^+]$$

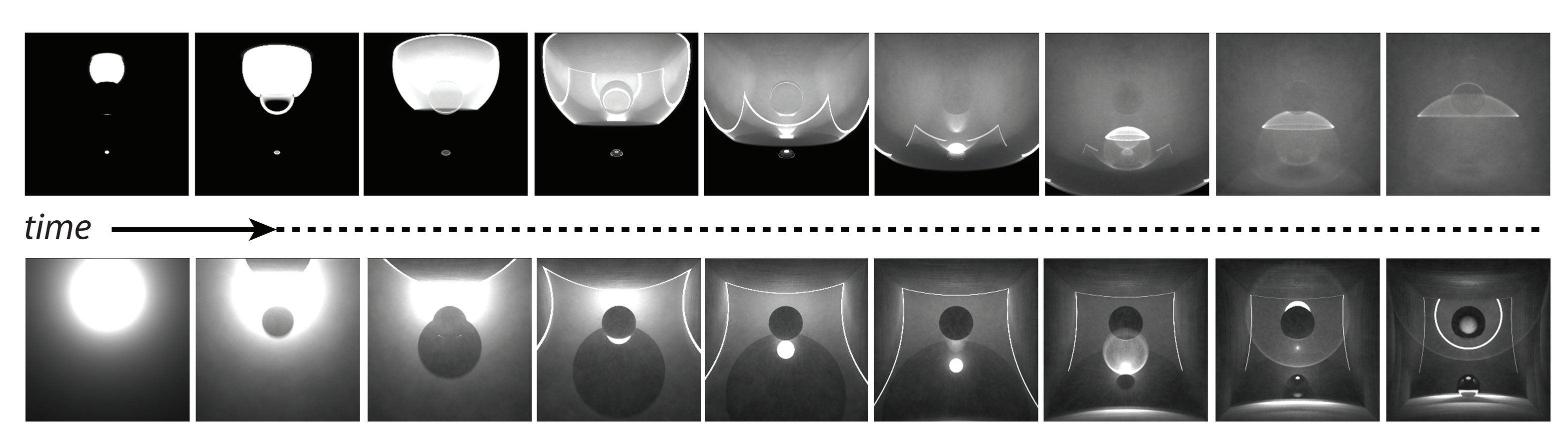
Time interval on the time-resolved render

Results

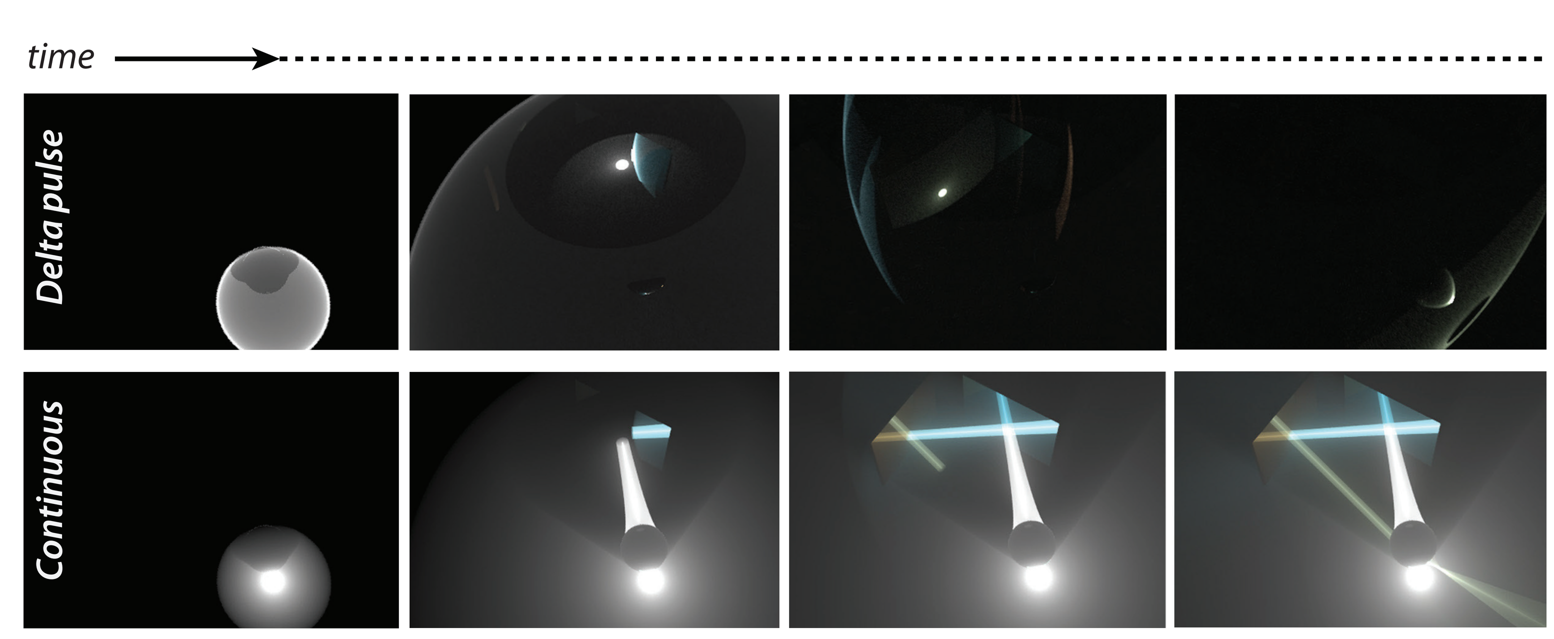
Our method successfully reduces variance in a wide variety of scenarios, producing noise-free transient renders of participating media showing single and multiple scattering, caustics and delays due to different indices of refraction.



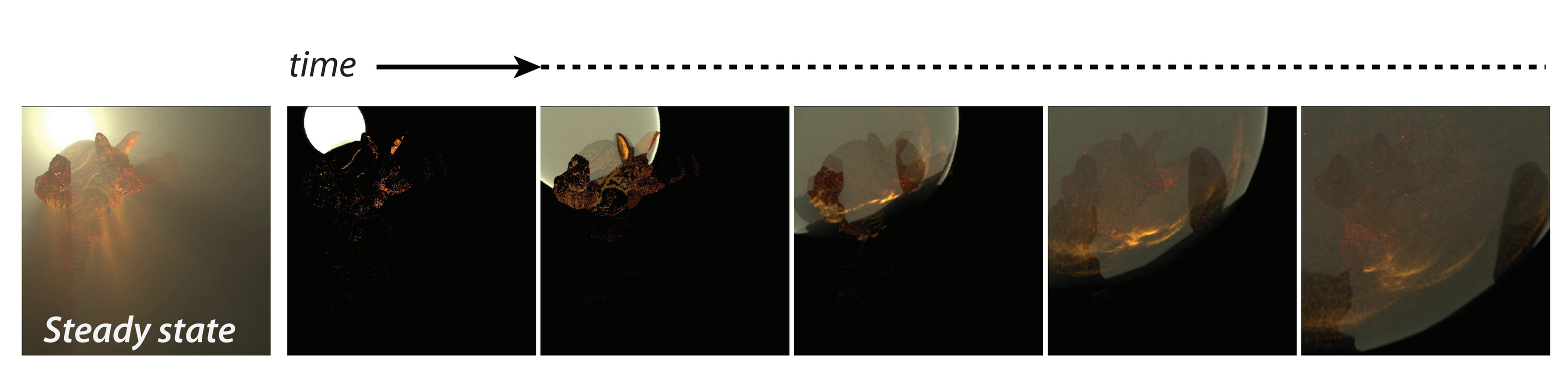
Equal-time comparison between transient path tracing (bottom) and our transient photon beams (top) on a Cornell box scene . Our method successfully reduces noise thanks to continuous beam trajectories which allow us to use very high time resolutions.



Comparison of single and multiple scattered media radiance within a Cornell box with a refractive glass top ball and a mirror bottom ball. Top row shows propagation of light without accounting for the observer time. Bottom row, accounts for the observer time and shows light propagation as we would actually see it on an ultra-fast capture. Removing observer time (top) shows more clearly how light wavefronts propagate locally, allowing us to appreciate indirect bounces in the media and multiple scattering as they follow the direct wavefront.



Comparison of the same time-resolved render of the scene using Dirac delta (top) and continuous emission (bottom). The scene depicts two colored mirrors which reflect the caustic produced by a refractive glass ball with IOR = 1.5, that delays the light propagation within the ball. Last image on the continuous emission shows the final formed image.



Delta emission on a glass Armadillo, showing the temporal evolution of caustics going through the complex geometry. The higher index of refraction of glass and the longer paths within the Armadillo allow us to see how caustics exit by the front side at different timings. Left image shows the steady state render.

Graphics and Imaging Lab

REFERENCES
[1] A. Jarabo, J. Marco, A. Muñoz, R. Buisan, W. Jarosz, and D. Gutierrez. 2014. *A Framework for Transient Rendering.* ACM Trans. Graph. 33, 6 (2014).
[2] S. Chandrasekhar. 1960. *Radiative Transfer.* Dover
[3] W. Jarosz, D. Nowrouzezahrai, I. Sadeghi, and H. W. Jensen. 2011. *A comprehensive theory of volumetric radiance estimation using photon points and beams.* ACM Trans. Graph. 30, 1 (Feb. 2011).

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