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# Rendering Participating Media with Streamed Photon Mapping

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**Abstract.** *The research on Streamed Photon Mapping method has shown its efficiency and potential. Significant caustic effects without an additional caustic map are its undeniable advantage. The method assumed that light spreads in a vacuum; however, such approach excluded the visualization of such phenomena as fog, smoke, or clouds. This paper presents a modification of the basic method of rendering with the help of photon streams, taking into account the simulation of light in dense mediums. The specifics of stream structure and the applied solutions allow to eliminate multiple assessment of the same photons as it occurred in the case of standard Volumetric Photon Mapping.*
**Keywords:** *global illumination, rendering, photon mapping, participating media.*

## 1. Introduction

The fundamental assumption of the idea of rendering was that rays of light scatter in a vacuum [1]; however, oftentimes a medium that affects the ray propagation (water, smoke, fog, etc.) may be found on the path of the light, which travels from one point to another. The particles of such medium are distributed in space at random and they may be of different sizes (diversified)[2]. The light that passes through such medium can collide with its particles and get absorbed or reflected, or may evade it just as well [3, 4]. The probability of such interaction depends on the density and size of the medium's particles. The relative probability is expressed with the following formula:

$$\delta_t = \delta_a + \delta_s \tag{1}$$

where:

- $\delta_t$ is Extinction coefficient ($m^{-1}$),
- $\delta_a$ is Absorption coefficient ($m^{-1}$),
- $\delta_s$ is Scattering coefficient ($m^{-1}$).

The absorption causes luminance to change into another form of energy, causing the decrease of energy that reaches the destination point. The absorption of electromagnetic radiation when passing through a partially absorbing and dispersing medium is described by the Beer-Lambert-Bouguer law [3]. In a general situation, this law states that the absorbance is directly proportional to the concentration and thickness of the medium layer through which the radiation passes:

$$L(x) = L(x_0)e^{-\int_{x_0}^{x} \delta_t(u)du} = L(x_0)\tau(x_0, x) \tag{2}$$

where:

- $L(x, \omega)$ is the Radiance in point $x$ from direction $\omega$ ($Wm^{-2}sr^{-1}$),
- $\delta_t(u)du$ is called the optical thickness,
- $\tau(x_0, x)$ is called Transmittance from $x_0$ to $x$.

Light scattering causes a change in the ray direction. The equation that takes into account all kinds of interactions of light and medium particles is called transport equation:

$$\begin{aligned} \frac{dL(x)}{dx} &= \delta_t(x)J(x) - \delta_t(x)L(x) = \\ = \delta_a(x)L_e(x) + \frac{\delta_s(x)}{4\pi}\int_{S^2} L(x, \omega_i)p(\omega_o, \omega_i)d\omega_i &- \delta_a(x)J(x) - \delta_s(x)L(x) \end{aligned} \tag{3}$$

where:

- $p(\omega_o, \omega_i)$ is the phase function which models the spatial, distribution of light dispersion

- $J(x)$ is the source radiance.

Global illumination methods are most frequently based on random observation of rays of light in a virtual environment [1]. A popular method of luminance calculation is the assessment of the density of the probability function. The algorithms use stochastic sampling to solve the light transport equation 3 by light path sampling along the points of the interaction of light with the dense medium. Most popular methods include Light Tracing [5, 6], Bidirectional Path-Tracing [7], Photon Mapping [8] and Metropolis Light Transport [9]. Expanding Streamed Photon Mapping for rendering participating media is a natural step in this case.

## 2. Streamed Photon Mapping

Streamed Photon Mapping method [10] is the extension of the classic Photon Mapping and it allows to obtain nice caustic effects at a significantly smaller cost than the traditional method. Its principal assumption is binding photons into groups with one leading photon during the propagation phase. The leading photon sets the direction of the stream in the scene, and is followed by the group of associated photons. The directions of propagation deviate from the direction set by the leading photon in the area designated by the stream width radius. During propagation, the total initial energy of the stream is evenly distributed among the associated photons. In the moment of the intersection, the verification of the type of material assigned to geometry at the point of the leading photon's intersection occurs. In the case of diffusion areas, for each associated photon in the stream, a random point is defined, in the area of the sphere whose radius is equal to the width of the stream, and which is formed around the new position of the leading photon. This point is used to set a new direction of the associated photon propagation taking into account additional attenuation mechanism. After the propagation of all the associated photons in the stream comes the verification if the maximum acceptable number of bounces of the leading photon from the diffusion surface has been achieved. In the case of a mirror or refracting surface, all the associated photons in the stream are eliminated, whereas their combined energy is assigned to the leading photon and causes the concentration of the photon stream energy as a result of mirror reflections and light refraction. Performed tests [11] have shown that in the streamed photon mapping one general photon map is sufficient to obtain clearly visible caustic effects. The papers of that time, like the classic Jensen method [12] did not consider, however, the density of the medium in which photon streams are propagated (for example, fog or smoke). The following chapter presents the extension of the stream method, which takes into account the medium of light transport.

# 3. Proposed approach

Jensen's extension of the classic Photon Mapping that takes into account light transport in scenes [8] is based on the ray marching algorithm. The probability of scattering or absorption is tested for every photon that passes through the dense medium in determined distances. When either of them occurs, the information about the energy and position of the photon is stored in the photon map. Ray marching is used again during rendering. The in-scattered radiance is approximated on the basis of encountered photons in spherical areas around subsequent points set on the path of the ray that travels through the dense medium. The modification of the Streamed Photon Mapping illustrated below uses ray marching algorithm in a similar manner as volumetric Photon Mapping during the first stage, which is the stream propagation.

## 3.1. Stream propagation in dense mediums

When encountering dense medium on its path (Fig. 1), the stream of photons is subjected to the following algorithm:

1. In the subsequent intervals on the path of the ray on which the leading photon travels, which are determined depending on the homogeneity of the medium, the possibility of the interaction with the medium depending on the determined value of probability correlated with the medium density is tested:

    (a) if there is no interaction of the leading photon with the medium, there is a shift to point 1,

    (b) if there is interaction of the leading photon, there is a shift to point 2.

2. The information about the stream is marked on the volumetric photon map.

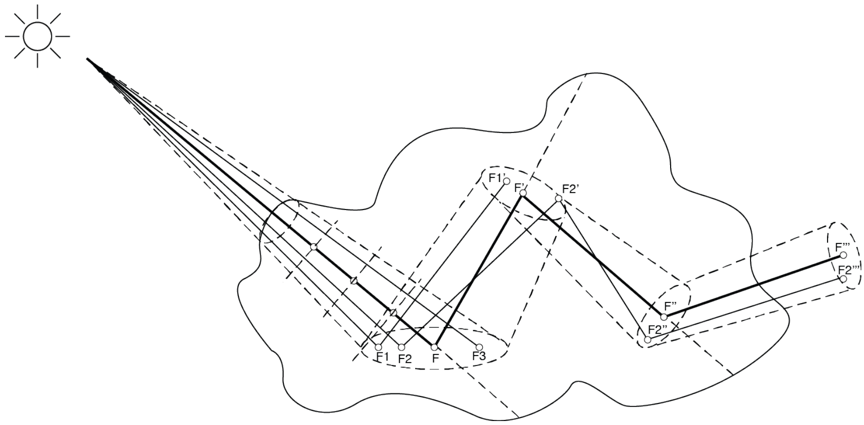


Figure 1: Diagram of the photon stream propagation inside a dense medium

3. Proportionally to the value determining the degree of absorption of the medium, part of all the associated photons of the stream are eliminated. Afterwards, a new direction of the leading photon propagation is determined, whereas for every associated photon that has not been absorbed, a new position inside the sphere, with the radius equal to the radius of the stream width around the new leading photon position, is randomly selected.

4. If the leading photon has not left the dense medium and all its photons have not been absorbed, there is a return to point 1.

## 3.2. Stream rendering inside dense mediums

The density estimation in the case of volumetric Photon Mapping [8] requires multiple search of the photon map by a single ray passing through the dense medium. Such approach, apart from the high cost of calculation, may also cause radiance overestimation as a result of taking into account the same photons in subsequent steps with excessive frequency of searches or it may lead to underestimation if the intervals between subsequent steps are too large. In order to avoid the above-described situations, stream rendering in dense mediums uses the beam tracing method, similarly to the solution proposed in [13]. Each photon stream stored in the volumetric stream map has a corresponding sphere whose center is the leading photon of this stream and whose radius is equal to the ray responsible

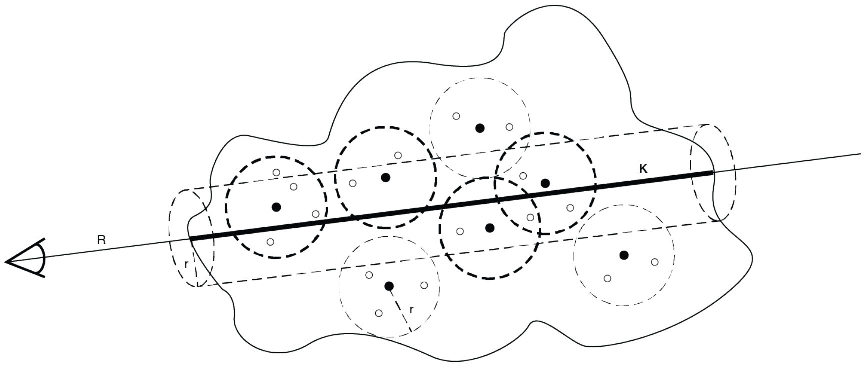


Figure 2: Diagram illustrating the search for the neighbouring photons inside the dense medium through the intersection of the ray (*R*) from the camera with the spheres with radius (*r*) around the leading photons. Filled spots correspond to leading photons, spots without filling correspond to associated photons

for the search for the neighbouring photons. If the ray from the camera, which passes through the dense medium, intersects the sphere around the leading photon (Fig. 2), then the energy of its stream is also taken into account when performing radiance approximation. This is how the volumetric stream map is searched only once for a given ray, while none of the found streams is counted twice.

The in-scattered radiance is estimated on the basis of the following equation:

$$L = \frac{\sum E_s}{\Pi r^2 K} \tag{4}$$

where:

- $E_s$ is energy of the searched photon stream on the ray's path (R),
- $K$ is the length of the ray that passes through a dense medium,
- $r$ is radius of the search for neighbouring photon streams.

## 4. Results

Images obtained as a result of the proposed method for propagation and photons stream rendering in dense mediums are illustrated on Fig. 3. Cornell Box with

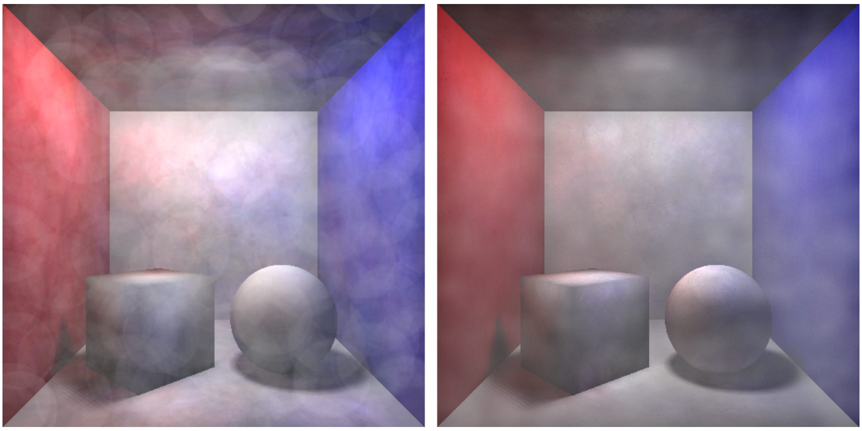

Figure 3: Test scene for the same dense medium with the probability of interaction of 50%, rendered with different parameters using Streamed Photon Mapping method: on the left 1'000 streams of photons emitted, 10 associated photons in each stream, stream radius equal to 2.5 scene units, a maximum of 4 bounces for each stream; on the right: 10'000 streams of photons emitted, 100 associated photons in each stream, stream radius equal to 2.5 scene units, a maximum of 4 bounces for each stream

objects with diffusive surfaces was used as the test scene. The probability of the interaction and photon stream absorbance in the result of the transport through the dense medium was 50% for both images, with different numbers of emitted rays and associated photons.

## 5. Conclusions and future works

Streamed Photon Mapping method makes it possible to generate photorealistic images taking into account caustic effects, multiple scattering, and color bleeding. The results have shown that the proposed extension of the method allows for scene rendering with participating media. The fact of the interaction of streams with dense mediums is an important decisive factor in the photorealism of the generated images. The beam tracing algorithm used in this stage of rendering allowed to reduce underestimations of illuminance in the dense mediums, which manifested itself in underexposition in certain areas or overestimations which contributed to their overexposition. The quality of the rendered images depends on the number of emitted streams and the initial number of associated photons. For the future research works, in order to improve the accuracy of the calculations, it is important to test the kernel density estimation filters that make the effect of the found photon stream dependent on the distance to the examined ray.

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