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In this talk we are interesting in rendering scenes like these
The appearance of all of these photographs is due to light interacting with participating media
A popular technique for simulating complex lighting in participating media is volumetric photon mapping.

This technique has been used both in academia and industry because it is relatively efficient, very general, and it is robust to complex light paths where other algorithms typically fail (such as volume caustics).
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Friday, 7 September 12

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- **This Paper**

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Our Contribution

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- The derivation of our theory subsumes all previously published radiance estimators for participating media, and [CLICK] additionally adds several more ways to estimate radiance using the concept of photon beams.
- What results is a collection of 9 distinct estimators which have a number of interesting theoretical connections to existing work, and also allow for much more efficient rendering than previously possible.
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Volumetric photon mapping starts by shooting virtual photons from light sources.
Each photon that is emitted from the light propagates through the medium and gets scattered into different directions, until the photon exits the medium or is absorbed.
Volumetric photon mapping records the history of these scattering events and stores the vertices of these paths (the “photons”) into a volume photon map.
Now, in this particular case we have found 2 photons; however, at this location we are less lucky and find zero photons. One of the fundamental challenges here is that we do not know whether this location really should be very dark or whether we simply used too few photons in our simulation.
Our only recourse is to either increase the search region (which blurs the result and introduces bias) or use more photons (which increases both memory usage and render time).
The main idea behind this paper is that we can in fact do much better using only the information that is already available from the photon tracing pass. Standard photon mapping only considering the scattering locations, and this throwing away a lot of information that is present in the photon map.
In particular, if we instead considered the entire path of photons (and here I also extend each path segment to the end of the medium), at the same location we see that that two photons traveled nearby. If we could somehow use this information to compute the lighting, we would obtain a more accurate rendering.
This is one of the core ideas behind our paper, and is what gives rise to a concept we call photon beams.
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- During rendering, these photons are reused to quickly approximate the lighting using density estimation: where there are many photons the illumination is bright, and where there are few photons the illumination is dim. For example, at this red query point, we count the number of photons within the local region shown in blue and this corresponds to the radiance at that location.
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Ray Mapping
[Havran et al. 05]
[Herzog et al. 07]

- The use of photon paths or beams of light has been explored by other researchers.
- Ray mapping techniques consider the trajectory of photons when performing density estimation at surfaces in order to reduce boundary bias in corners.
- One of our 9 estimators can be seen as a generalization of these algorithms to participating media, where using beams actually has a much greater benefit, as we will see.
- Our estimators also have connections to beam tracing methods, but since we build off of photon mapping, we are geometry independent, and can easily incorporate multiple bounces of light.
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● Root-finding methods
  [Mitchell and Hanrahan 92]
  [Walter et al. 09]

• Techniques which try to directly compute such volumetric effects using root finding produce results without the blurring artifacts present in photon mapping; however, they tend to only be applicable in restricted settings (e.g. a single bounce of light)
• With the improved density estimators we present, volumetric photon mapping can produce extremely crisp results that are competitive with these direct methods, but at a fraction of the cost
To make our derivations a bit more succinct, we will for now assume homogeneous media. We use $\sigma_s \sigma_a$ and $\sigma_t$ to denote the scattering, absorption and extinction coefficients.

Additionally, we will assume that density estimation is performed using a global, fixed-size search region. Meaning, we don’t use something like k-nearest neighbor density estimation.

Finally, all of these assumptions are just to make our lives a little easier, and can be lifted in an actual implementation as I will show later on.

Using these assumptions, let’s look at the various radiance estimators we can use in participating media.
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Notation/Assumptions

- homogeneous media
- fixed-size search regions
- can be lifted later

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Radiance Estimation using Photon Points

- Point Query x Point Data (3D)
- Beam Query x Point Data (2D)
- Beam Query x Point Data (3D)
Radiance Estimation using Photon Points

- **Point Query x Point Data (3D)**
  - standard volumetric photon mapping [Jensen & Christensen 98]

- **Beam Query x Point Data (2D)**
  - splatting & beam radiance estimate [Boudet et al. 05], [Jarosz et al. 08]

- **Beam Query x Point Data (3D)**
  - new estimator
We can now turn to the new concept of photon beams
But first we need to more precisely define how we can use photon paths for density estimation
The traditional procedure is quite simple:

- [steps]
- For illustrative purposes let me superimpose the original rays that were shot during this process.
- We can see that we effectively placed one photon along each of these rays.
- This is the standard approach, but it is possible to shoot photons in any number of ways.
- In particular, we could instead deposit more than one photon along each of these rays, using a marching process analogous to ray marching, but for photons.
1) choose direction

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Traditional Photon Tracing

1) choose direction
2) propagate photon
3) deposit a photon
4) repeat

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2) propagate photon
3) deposit a photon
4) repeat

The traditional procedure is quite simple:

• [steps]
• For illustrative purposes let me superimpose the original rays that were shot during this process.
• We can see that we effectively placed one photon along each of these rays
• This is the standard approach, but it is possible to shoot photons in any number of ways
• In particular, we could instead deposit more than one photon along each of these rays, using a marching process analogous to ray marching, but for photons
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Could deposit more than one photon by marching along each ray

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- We call this process photon marching.
- Since we deposited many photons instead of one, each photon will have less power. This will depend on the marching step size.
- Also, the photons are attenuated due to transmittance as we move along each of these rays
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• Lets say we are interested in computing the inscattered radiance at this red point.
• Since we have a collection of photon points, we can accomplish this by simply using the standard Point Point 3D estimator
• We expand a search radius, and count all the photons that overlap the search region
• In order to derive the concept of photon beams, we consider what would happen as we decrease the photon marching step size. This will increase the number of photon points
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Friday, 7 September 12

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Radiance Estimation using “Discrete Photon Beams”
\[ L \approx \frac{1}{\mu_R(r^3)} \sum_i f(\theta_i) \Phi_i \int_{t_i^-}^{t_i^+} e^{-\sigma_i t} dt \]
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- integral computable analytically
analytic solution in homogeneous media

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**Point Query x Beam Data (3D blur)**

The integral is computable analytically.

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Analytic solution in homogeneous media.
related to: “track length”
estimators
[Spanier and Gelbard 69]

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generalization of photon ray splatting [Herzog et al. 07]
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Photon Points vs. Photon Beams

Ground Truth

- Simple scene with a point light
- With 100k photons points the type of artifacts you get look something like this
- And using only 5 thousand photon beams, each photon path looks like a thick line on the screen, leading to much higher density and coverage
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Estimating Beam Radiance with Photon Beams

- Beam Query x Beam Data (3D)
- Beam Query x Beam Data (2D)₁
- Beam Query x Beam Data (2D)₂
- Beam Query x Beam Data (1D)
Beam Query x Beam Data (2D blur)
\[ L \approx \frac{\sigma_s}{\mu_R(r^2)} \sum_i f(\theta_i) \Phi_i \int_{t_i^-}^{t_i^+} e^{-\sigma_{tc}} e^{-\sigma_{tb}} dt_c \]
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related to beam tracing
[Nishita and Nakamae 1994]

\[ L \approx \frac{\sigma_s}{\mu_R(r^2)} \sum_i f(\theta_i) \Phi_i \int_{t_i^-}^{t_i^+} e^{-\sigma_{tc} t_c} e^{-\sigma_{tb} t_b} dt_c \]
\[ L \approx \frac{\sigma_s}{\mu_R(r)} \sum_i f(\theta_i) \Phi_i e^{-\sigma_i t_i^c} e^{-\sigma_i t_i^b} \frac{1}{\sin \theta_i} \]
- Beam queries remove ray marching
Radiance Estimator Summary

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- Beam data increases data density
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- Lower blur dimension reduces bias and computation
Radiance Estimator Summary

- Beam queries remove ray marching
- Beam data increases data density
- Lower blur dimension reduces bias and computation
- use: Beam Query x Beam Data (1D)
- Standard photon shooting/tracing
- Store:
  - start power/position/direction (standard)
Implementation Details

- Standard photon shooting/tracing

- Store:
  - start power/position/direction (standard)
  - also:
    - length of beam
    - some book keeping
Need to intersect each ray with all photon beams (expensive!)
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- Place photon beams in a BVH
- Need to intersect each ray with all photon beams (expensive!)
- Place photon beams in a BVH
  - split into sub-beams to reduce spatial overlap
• So with this algorithm, you could very easily produce images like this volume caustic
• We [click] shoot a photon path through the scene, and by [click] applying a fixed-width blur, each beam gets rendered as a cylindrical billboard
• However, you can see that there are some banding artifacts here, and this is because the blur does not adapt to the local density of beams. In certain regions we end up overblurring, and in other regions we underblur, and see the individual beams
• Standard photon mapping solves this by using k-nearest neighbor density estimation
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- Standard photon mapping solves this by using k-nearest neighbor density estimation.
• We solve this problem by using photon differentials
• We not only trace the beam itself, but also trace two differential rays. These additional rays are propagated through specular bounces and determine how the light locally converges and diverges.
• In the paper we also show how we extend this idea to handle area light sources and multiple scattering.
• We use this information differential information to change the blur width along the length of each beam [click]
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Fixed-width Beams

Photon Differentials
[Igehy 99, Schjøth et al. 07]

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- We use this information differential information to change the blur width along the length of each beam [click]
Fixed-width Beams

Adaptive-width Beams

• Which eliminates the banding artifacts in sparse regions, while avoiding overblur in dense regions
Results

- MacBook Pro 3.06 GHz Intel Core 2 Duo
Results

- MacBook Pro 3.06 GHz Intel Core 2 Duo
- Previous photon mapping state-of-the-art:
  - Beam Query x Point Data (2D) [Jarosz et al. 08]
Area light, single + multiple scattering

Photon Beams
17.3k Beams - 1:48
Area light, single + multiple scattering

Photon Beams
17.3k Beams - 1:48

Photon Points
280k Points - 1:49

Equal time
Cornell Box

Area light, single + multiple scattering

Photon Beams
17.3k Beams - 1:48

Photon Points
280k Points - 1:49
Equal time

Photon Points
9.3M Points 17:34
“Equal” Quality

Friday, 7 September 12
• Our second scene is this Bumpy Sphere scene courtesy of Bruce Walter
• This is effectively a dielectric interface filled with a scattering medium, and you can think of this as a ball of amber, and as light refracts through the deformed boundary it produces these intricate volume caustics inside the sphere.
Walter and colleagues developed a direct root-finding method to compute the amount of light that reaches a point within a triangular boundary.

The benefit of such a direct approach is that you can get extremely crisp results [click].

In comparison, standard photon mapping results in extremely blurred features unless you use a very large number of photons.
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• However [click], we can get an incredible increase in resolution if we simply use the same exact photon simulation but store the results as beams instead of points.
• In contrast to Walter’s method, it is easy to incorporate total internal reflection, and multiple scattering
• Also, you can see that in Walter’s method there is a bit of high-frequency noise. This is because it is still necessary to ray march within the medium. On the other hand, with a beam query, we obtain the entire integral through the medium in one lookup without the need for ray marching.
Bumpy Sphere

Rendered at 512x512 with up to 16 samples/pixel

- The benefits of photon beams also applies to animations.
- Here we show a comparison using point on the left and beams on the right, using the exact same photon simulation with 90k photons.
- We can see that photon beams not only resolve these fine details much more faithfully, they also reduce temporal flickering.
- Estimating radiance using beams is a bit more expensive, so we see that with the same number of points as beams the left animation renders faster.
• However, even if we shot 1.3M photons to equal time, photon beams still provides a significant quality improvement
Our next example is this animated lighthouse scene. The remarkable thing here is that we are able to resolve this lighting using only 700 beams, whereas at equal time (with 10k photon points) significant artifacts are present. Even if we shot 1M photons (at 9 times the render time) these artifacts remain.
Underwater Sun Beams

Rendered at 1024x576 with up to 16 samples/pixel

- Finally, in this example we are looking up at the sun from beneath ocean waves.
- The standard approach effectively point-samples these beams of refracted light, and this introduces flickering and undersampling, so the results are extremely blurry.
- On the other hand, with photon beams, each beam of light is represented much more naturally as a photon beam, sampling the lighting much more density.
- Even with 10M photons and 7.5X the render time, this looks worse than using just 25K photon beams.
Summary

- photon beams:
  - “up-res’ing” # of photons along paths
Summary

- photon beams:
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- thousands of beams vs. millions of photons
Summary

- photon beams:
  - “up-res’ing” # of photons along paths
- thousands of beams vs. millions of photons
- for volumetric photon mapping:
  - store photon beams, and query with a beam
Acknowledgements

- Bruce Walter
- Craig Donner
- NSF grant CPA 0701992
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- You