Efficient Caustic Rendering with Lightweight Photon Mapping

Pascal Grittmann\textsuperscript{1,3} Arsène Pérard-Gayot\textsuperscript{1} Philipp Slusallek\textsuperscript{1,2} Jaroslav Křivánek\textsuperscript{3,4}

\textsuperscript{1}Saarland University \quad \textsuperscript{2}DFKI Saarbrücken \quad \textsuperscript{3}Charles University, Prague \quad \textsuperscript{4}Render Legion
The Idea Behind Guiding

• Importance sampling of the $L_i/W_i$ term (path tracing / particle tracing)
• Combine with importance sampling of the BSDF
• Ideally results in perfect importance sampling of the entire Light Transport Equation (LTE)!

• **How to importance sample $L_i$?**
• Many approaches
• Usually store a representation of $L_i$ at some point in the scene and interpolate them
• Methods differ in what representations they choose and how they obtain them
Reduces Variance

(plotted with low pass filter)
Photon Mapping Already Does Guiding [Jen96]

- Heuristic classification of materials as “glossy”
- Projection of caustic-casters
- “Caustic map”
Path Guiding Using the Photon Map

- One of the first approaches to guide
- Uses nearby photons to construct a histogram of incident radiance
- Samples a cell of this histogram and a direction within the cell (uniformly)
- Histogram is a grid, each cell maps to a part of the hemisphere

<table>
<thead>
<tr>
<th></th>
<th>0</th>
<th>0</th>
<th>0</th>
<th>0</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>2</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>0</td>
<td>0</td>
<td>4</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
</tbody>
</table>

The red photon has a luminance of 2. The blue one a luminance of 4.
Gaussian Mixture Models – Vorba et al. 2014

• Fits mixtures of gaussians to the incident radiance/importance at a set of points in the scene
• Project hemisphere onto plane, incident directions as bivariate Gaussians over that plane
• Gaussians are easy to sample and easy to update
• Long training pass before actual rendering (~15-30 min)
Vorba GMM – Training Phase

start

a) (unguided) importon tracing

b) delete photon map
c) guided photon tracing

train & cache importance distrib.
d) update radiance distrib.

e) update importon tracing
f) guided importon tracing

train & cache radiance distrib.
g) delete importon map

rendering
Guide Photons According to Visual Importance

- [PP98] [VKS*14] [SOHK16]
- Using importance sampling or MCMC

Example Scene  Visual importance
Our Method

• Guide emission based on visual importance
• Limit to paths with high variance form the path tracer

Example Scene | Visual importance of all photons | Our Method: only “useful” photons

P. Grittmann et al. – Lightweight Photon Mapping
Our Method Relies Only on Path Probabilities

• No (implicit) material classification
• Accounts for the (relative) size of the light source
The Lightweight Photon Mapping Algorithm

• Based on VCM / UPS – [GKDS12] [HPJ12]
• Goal: More efficient solution for large scenes with a few small caustics
• MIS Combination of
  • Light Tracer
  • Photon Mapper
  • Path Tracer
Motivation / Idea

• Existing methods: Try to be unbiased for all estimators
  • Looses main advantage of MIS!
• Why not ignore estimators that we know will contribute little?
  • A la maximum heuristics or alpha-max heuristics – but only where necessary

• Can restricting costly estimators to regions of high variance result in more efficient combined algorithms?

P. Grittmann et al. – Lightweight Photon Mapping
The Notion of “Useful” Photons

\[ \frac{N_{\text{min}}}{p_{\text{PM}}(y)} \frac{\pi r^2}{p_{\text{PT}}(y|y_k)} > 1 \]

“The \textit{photon mapper} can reach a point within \( r \) with higher probability than the \textit{path tracer}, using only \( N_{\text{min}} \) light paths”
How Many Photons Should We Trace?  
- One Per Pixel Influenced by Caustics

- VCM: One light path per pixel
- With guiding: Fewer light paths are needed!

\[ I = I_{PM} + I_{LT} + I_{PT} \]

\[ I_{PM} + I_{LT} \]

\[ \frac{I_{PM} + I_{LT}}{I_{PM} + I_{LT} + I_{PT}} > 1\% \]

P. Grittmann et al. – Lightweight Photon Mapping

Rendered Image
PM / LT Contribution (exposure +5)
Pixel Classification
Is that Number of Light Paths Optimal?

→ Optimal for large scenes with small Caustics

P. Grittmann et al. – Lightweight Photon Mapping
Is that Number of Light Paths Optimal?

→ Complex SDS paths require more samples from the path tracer

P. Grittmann et al. – Lightweight Photon Mapping
Is that Number of Light Paths Optimal?

→ For scenes that are trivial except for the caustics, a higher number would be more efficient
Results

Impact of the Full Method with Our Test Scenes
Photon Densities in the Cornell Box Variations

Reference

Photon density – Guiding with all Photons

Photon density – Our

P. Grittmann et al. – Lightweight Photon Mapping
Photon Densities in the Cornell Box Variations

Reference

Photon density – Guiding with all Photons

Photon density – Our

P. Grittmann et al. – Lightweight Photon Mapping
Photon Densities in the Cornell Box Variations

Reference

Photon density – Guiding with all Photons

Photon density – Our

P. Grittmann et al. – Lightweight Photon Mapping
Photon Densities in the Cornell Box Variations

P. Grittmann et al. – Lightweight Photon Mapping
The Torus – Simple Example, Directional Light

Result identical to existing guiding approaches.
Car Scene – Large Exterior Scene, Small Caustics

Equal-time comparison (60 seconds)

P. Grittmann et al. – Lightweight Photon Mapping
Car Scene – Large Exterior Scene, Small Caustics

Equal-time comparison (60 seconds)

Unguided Importance Ours Reference

\[
\begin{align*}
\text{Time (seconds)} & \quad \text{RMSE} \\
\text{Unguided} & \quad 0 \\
\text{Importance} & \quad 0 \\
\text{Ours} & \quad 0 \\
\text{Reference} & \quad 0
\end{align*}
\]
Figure 8: Equal-time comparison after one minute of rendering for the CAR scene. In this scene, the path tracer cannot sample some of the caustics at all (directional light source and perfect specularity). Our method results in half the number of light paths getting traced and therefore also a significantly lower number of photons. The contribution-based guiding (VM+EG) results in even more photons than the uniform emission, because fewer light paths miss the scene entirely.

P. Grittmann et al. – Lightweight Photon Mapping
<table>
<thead>
<tr>
<th>Algorithm:</th>
<th>Path Tracer</th>
<th>VM</th>
<th>VM+EG</th>
<th>Ours</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>RMSE:</td>
<td>5397.38</td>
<td>6219.95</td>
<td>4765.8</td>
<td>4488.86</td>
<td>-</td>
</tr>
<tr>
<td>Photons per Iteration (Average):</td>
<td>-</td>
<td>2,408,366</td>
<td>2,418,036</td>
<td>1,337,252</td>
<td>-</td>
</tr>
<tr>
<td>Light Paths per Iteration:</td>
<td>-</td>
<td>518,400</td>
<td>498,460</td>
<td>362,475</td>
<td>-</td>
</tr>
</tbody>
</table>

**Figure 10:** Equal-time comparison after one minute of rendering for the **STILL LIFE** scene. Here, the difference between our method and contribution-based guiding (VM+EG) is slightly less visible than in the **CAR** scene (Fig. 8). This is because the majority of the image is influenced by caustics.
Figure 11: Equal-time (one minute) and equal-iteration-count convergence rate (log-RMSE) for some of our test scenes. Our method has either better or identical convergence rates in all our test scenes, even on a per-iteration level.
Limitations

• Only for caustic-casters directly in front of the light source
• Resorts to path tracing for (diffuse) indirect illumination
Efficient Caustic Rendering with Lightweight Photon Mapping

Restrict costly estimators to a subset of the domain

→ More efficient MIS combination

Unguided  Importance  Ours  Reference

Reference

Importance driven

Our