This paper appeared in *Journal of Graphics Tools*, 4(3):1–10. ACM 1999. (Printed in April 2000.)

Faster Photon Map Global Illumination

Per H. Christensen

Abstract. The photon map method is an extension of ray tracing that makes it able to efficiently compute caustics and soft indirect illumination on surfaces and in participating media. This paper describes a method to further speed up the computation of soft indirect illumination (diffuse-diffuse light transport such as color bleeding) on surfaces. The speed-up is based on the observation that the many look-ups in the global photon map during final gathering can be simplified by precomputing local irradiance values at the photon positions. Our tests indicate that the calculation of soft indirect illumination during rendering, which is the most time-consuming part, can be sped up by a factor of 5–7 in typical scenes at the expense of 1) a precomputation that takes about 2%–5% of the time saved during rendering and 2) a 28% increase of memory use.

1 Background: The Photon Map Method

The photon map method [Jensen 95, Jensen 96a, Jensen 96b, Jensen 96c] has the following desirable properties for computation of global illumination:

1. It can handle all combinations of specular, glossy, and diffuse reflection and transmission (including caustics).
2. Since the photon map is independent of surface representation, the method can handle very complex scenes, instanced geometry, and implicit and procedural geometry.
3. It is relatively fast.
4. It is simple to parallelize.

The photon map method consists of three steps: photon tracing, photon map sorting, and rendering.

1.1 Photon Tracing

In the photon tracing step, photons are emitted from the light sources and traced through the scene using Monte Carlo simulation and Russian roulette [Glassner 95]. When a photon hits an object, it can either be reflected, transmitted, or absorbed (decided probabilistically based on the material parameters of the surface).

During the photon tracing, the photons are stored at the diffuse surfaces they intersect on their path. Note that each emitted photon can be stored several times along its path. The information stored is the position, incident direction, power of the photon, and some flags. (Jensen showed how this information can be stored in 20 bytes [Jensen 96b], but it turns out that 18 bytes are actually sufficient here: 12 bytes for position, 4 bytes for compressed power [Ward 91], 1 byte to encode incident direction, and 1 byte for the flags.) This collection of information about the photon paths is the *global photon map*.

In addition, the photons that hit a diffuse surface coming from a specular surface are stored in a *caustic photon map*.

1.2 Sorting the Photon Maps

In the second step, the photons stored in the two photon maps are sorted so that it is quick to locate the photons that are nearest a given point. A kd-tree [Bentley 75, de Berg et al. 97] is used since it is a compact representation that allows fast look-up and gracefully handles highly nonuniform distributions. This step is usually by far the fastest of the three.

1.3 Rendering

In the rendering step, specular reflections are computed with standard ray tracing [Whitted 80, Glassner 89]. But when a ray intersects a diffuse surface, the incident illumination is computed in one of two ways [Jensen 96a]:

1. If the importance (that is, the contribution to the rendered image [Smits et al. 92, Christensen et al. 96]) is low, the total irradiance at the point is estimated from the power and density of the photons nearest to the point. (The procedure can be imagined as expanding a sphere around the point until it contains n photons and then using these n photons to estimate the irradiance.) The global photon map is used for this. Typically, 30–200 photons are used.

2. If the importance is high, direct illumination is computed by sampling the light sources, caustics (indirect illumination from specular surfaces) are computed from the caustic photon map, and soft indirect illumination (indirect illumination from diffuse surfaces) is computed with final gathering [Reichert 92, Christensen et al. 96] (a single level of distribution ray tracing [Cook 84]) using the global photon map.

In a final gather, the hemisphere above the point is sampled by shooting many rays and computing the radiance at the intersection points. For efficiency, the hemisphere can be importance sampled based on the incident direction of nearby (indirect) photons and the BRDF of the surface [Jensen 95], or it can be adaptively sampled [Ward, Shakespeare 98], or both. Either way, most final gather rays are shot in the directions that are most likely to contribute most to the illumination. The radiances at the points that the final gather rays hit are usually estimated using the global photon map (using the same method as described under 1. above), but with one exception: If the distance along the final gather ray is below a given threshold, a new simpler final gathering is done [Jensen 96a]. Very few final gather rays are needed in these secondary final gathers — we have found 12 to be sufficient.

Each final gather is quite time-consuming since many hundred rays are shot, but fortunately relatively few final gathers are needed since previous results can be stored and used for interpolation and extrapolation of the soft indirect illumination [Ward, Heckbert 92].

2 Faster Final Gathering

The most time-consuming part of rendering is the final gathering, in particular the computation of irradiance at the locations where final gather rays hit. During final gathering, the irradiance is computed repeatedly at nearly the same places — with rays from different final gathers hitting near each other. So, if we precompute the irradiance at selected locations, a lot of time can be saved.

2.1 Precomputation of Irradiances

One could precompute the irradiances at fixed distances on each surface. But that would adapt poorly to the large differences in irradiance variation from place to place. Instead, the photon positions are an ideal choice for precomputing irradiances since the photons are inherently dense in areas with large illumination variation. The computed irradiance and surface normal at the photon position can be stored along with the other photon information in the photon map; this increases storage with 5 bytes per photon (4 bytes for compressed irradiance [Ward 91] and 1 byte for encoding the direction of the surface normal). Using 23 bytes per photon instead of 18 is a storage increase of less than 28%.

Estimating the irradiance at a point takes time $O(\log N)$, where N is the number of photons in the global photon map. Precomputing irradiance at the N photon positions therefore takes $O(N \log N)$. To reduce the time spent on the precomputation of irradiances, one can choose to only compute the irradiance at some photon positions — for example every fourth photon. This reduces the precomputation time to one-fourth, but does not change the rendering time.

2.2 Final Gathering using Precomputed Irradiances

When the irradiance at a point is needed during final gathering, the nearest photon with a similar normal is found in the photon map and its precomputed irradiance used. ("Similar" means that the dot product of the normals has to be larger than a certain threshold, for example 0.9.)

Finding the nearest photon with a similar normal is only slightly slower, on average, than finding the nearest photon irrespective of normal. In the typical case, in which a flat or gently curving surface is not immediately adjacent to another surface, the nearest photon will always have an appropriate normal. Then, the only extraneous computation is a single dot product to check that the two normals agree. This only takes a small fraction of the time that was used to search the kd-tree to find that photon. Close to edges, the nearest photon sometimes happens to be on the wrong surface (and have the wrong normal). In this case, the first photon found is rejected and the search continues. Usually, the second or third found photon will have an acceptable normal. The additional dot products and searching required for this relatively rare case do not influence overall running time significantly.

Using the precomputed irradiance for the nearest photon means that the irradiance used for final gathering is approximated as a piece-wise constant function. Formally, the photon positions divide the surfaces in the scene into a Voronoi diagram with a constant irradiance within each cell. This approximation is acceptable because the difference between the irradiance at neighboring photon positions is relatively small (since many photons are used to compute each irradiance) and because we only use it for final gathering above a certain distance.

The precomputed irradiance of the nearest photon is also used if the importance of the irradiance is sufficiently low.

2.3 Discussion

This method gives a speed-up as long as there are more final gather rays than selected photon positions. In a typical scene, there are many more final gather rays than photons — often a factor of 10 or even 100. Therefore, the total number of irradiance estimates can be reduced by the same factor. This translates into a speed-up in the final gathering by a factor of 5–7 in typical scenes at the expense of a precomputation that takes only a few percent of the time saved during rendering.

Precomputing irradiances can probably also give a speed-up for rendering of global illumination in participating media [Jensen, Christensen 98] if the number of selected photon positions is smaller than the number of ray marching steps.

3 Results

The following tests were done on a Sony Vaio laptop with a single 233 MHz Pentium processor and 32 megabytes of memory.

3.1 Cornell Box

As a first test scene, we used a "Cornell box" with a chrome and a glass sphere. Emitting 220,000 photons resulted in 400,000 photons stored in the global photon map and 35,000 photons in the caustic photon map; this photon tracing took 10 seconds. Sorting the stored photons into two kd-trees also took 10 seconds. The photons stored in the global photon map are visualized in Figure 1(a).

In Figure 1(b), irradiance was computed at each image sample point from local irradiance estimates using 50 photons. In Figure 1(c), the irradiance was precomputed at all 400,000 global photon positions (also using 50 photons) and the irradiance at the nearest photon was used. Precomputing the irradiances took 58 seconds. There is no visual difference between Figures 1(b) and 1(c). In Figure 1(d), the irradiance was precomputed at only 100,000 photon positions, which took 15 seconds. The differences between Figures 1(c) and 1(d) can only be seen upon close inspection, and 1(d) is fully adequate for use in final gathering.

In Figure 1(e), the irradiances from Figure 1(d) are multiplied by the diffuse reflection coefficients at each image sample point to produce a radiance estimate. This is the scene as the final gathering "sees" it.

Figure 1(f) shows soft indirect illumination computed with final gathering based on radiance estimates as in Figure 1(e).

Figure 1(g) is the complete rendering. It contains direct illumination, specular reflection and refraction, caustics, and soft indirect illumination. Rendering this image at resolution 1024×1024 pixels with up to 16 samples per pixel took 5 minutes and 29 seconds. Out of this time, computing the soft indirect illumination took 2 minutes and 45 seconds. There were 11,800 final gathers with a total of 6.5 million final gather rays.

For comparison, rendering the same image without precomputing the irradiances takes approximately 20 minutes, out of which final gathering is responsible for 16 minutes. The resulting image is indistinguishable from Figure 1(g). In conclusion, precomputing the irradiances before rendering reduces the final gathering time by a factor of 5.8. The 15 seconds spent on precomputation constitute less than 2% of the 13 minutes and 15 seconds saved during final gathering.

Illumination effects to note in this image are the very smooth (purely indirect) illumination in the ceiling, the bright caustic under the glass sphere, and the three dim secondary caustics also under the glass sphere (focused light from the red, white, and blue bright spots on the walls).

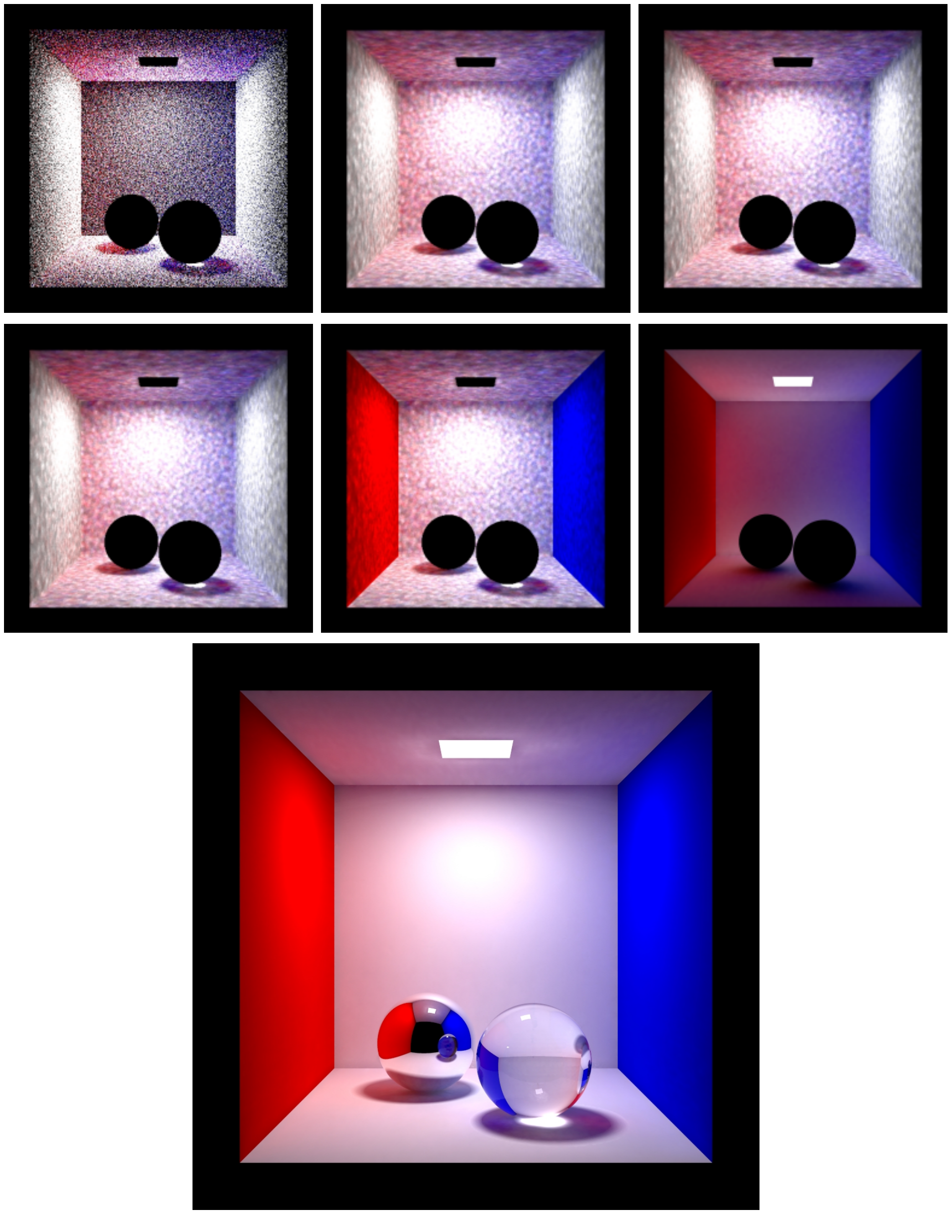

Figure 1: Cornell box with spheres: (a) Global photon map. (b) Irradiance estimates computed precisely at image sample points (dimmed for display). (c) Precomputed irradiance estimates at all 400,000 photon positions (dimmed for display). (d) Precomputed irradiance estimates at 100,000 photon positions (dimmed for display). (e) Radiance estimates based on (d). (f) Soft indirect illumination computed with final gathering. (g) Complete image with direct illumination, specular reflection and refraction, caustics, and soft indirect illumination.

3.2 Interior Scene

We also tested the method on a more complex scene, an interior scene with 1,050,000 polygons. Emitting and tracing 193,000 photons resulted in 500,000 photons stored in the global photon map. (We chose not to store photons in a caustic photon map for this scene since caustics are an orthogonal issue to the method described here.) Photon tracing took 39 seconds and sorting the photons took 12 seconds. The resulting photon map is shown in Figure 2(a).

In Figure 2(b), irradiance is computed at each image sample point from local irradiance estimates using 200 photons. In Figure 2(c), the irradiance was precomputed at all 500,000 photon positions (taking slightly less than 6 minutes) and the irradiance at the nearest photon was used. There is no visual difference between the images in Figure 2(b) and Figure 2(c).

In Figure 2(d), the irradiances from Figure 2(c) were multiplied by the diffuse reflection coefficient at each image sample point. This is the scene as the final gathering "sees" it.

Figure 2(e) is the complete rendering with direct illumination, specular reflection, and soft indirect illumination based on the precomputed irradiance estimates in Figure 2(c). Rendering this image at resolution 1024×768 pixels with up to 16 samples per pixel took 60 minutes, out of which 27 minutes were spent doing final gathering. There were 15,200 final gathers, with 11.7 million final gather rays. Doing the final gathering without precomputed irradiances takes 169 minutes, so the final gathering time is reduced by a factor 6.3. The 6 minutes spent on precomputation corresponds to 4.2% of the 142 minutes saved during rendering.

Acknowledgement. Thanks to Hoang-My Christensen, Pete Shirley, and the anonymous reviewer for many helpful suggestions to improve the structure, contents, and readability of this paper. Thanks to Dani Lischinski for providing the interior scene in Figure 2. It was originally created by Matt Hyatt at the Cornell Program of Computer Graphics, and later extended by Eric Stollnitz.

References

[Bentley 75] Jon L. Bentley. "Multidimensional binary search trees used for associative searching". *Communications of the ACM*, 18(9): 509–517 (September 1975).

[de Berg et al. 97] Mark de Berg, Marc van Kreveld, Mark Overmars, and Otfried Schwarzkopf. *Computational Geometry — Algorithms and Applications*. Berlin: Springer-Verlag, 1997.

[Christensen et al. 96] Per H. Christensen, Eric J. Stollnitz, David H. Salesin, and Tony D. Derose. "Global illumination of glossy environments using wavelets and importance". *ACM Transactions on Graphics*, 15(1): 37–71 (January 1996).

Figure 2: Interior: (a) Global photon map. (b) Irradiance estimates computed precisely at the image sample points (dimmed for display). (c) Precomputed irradiance estimates at all 500,000 photon positions (dimmed for display). (d) Radiance estimates based on (c). (e) Complete image with direct illumination, specular reflection, and soft indirect illumination.

[Cook 84] Robert L. Cook. “Distributed ray tracing”. *Computer Graphics (Proc. SIGGRAPH 84)*: 137–145 (July 1984).

[Glassner 89] Andrew S. Glassner. *An Introduction to Ray Tracing*. London: Academic Press, 1989.

[Glassner 95] Andrew S. Glassner. *Principles of Digital Image Synthesis*. San Francisco: Morgan Kaufmann Publishers, 1995.

[Jensen 95] Henrik Wann Jensen. “Importance driven path tracing using the photon map”. In *Rendering Techniques ’95 (Proceedings of the 6th Eurographics Workshop on Rendering)*, pp. 326–335. Vienna: Springer-Verlag, 1995.

[Jensen 96a] Henrik Wann Jensen. “Global illumination using photon maps”. In *Rendering Techniques ’96 (Proceedings of the 7th Eurographics Workshop on Rendering)*, pp. 21–30. Vienna: Springer-Verlag, 1996.

[Jensen 96b] Henrik Wann Jensen. “Rendering caustics on non-Lambertian surfaces”. In *Proceedings of Graphics Interface’96*, pp. 116–121. San Francisco: Morgan Kaufmann Publishers, May 1996. (Later published in *Computer Graphics Forum*, 16(1): 57–64, (March 1997).)

[Jensen 96c] Henrik Wann Jensen. *The Photon Map in Global Illumination*. Ph.D. dissertation, Technical University of Denmark, September 1996.

[Jensen, Christensen 98] Henrik Wann Jensen and Per H. Christensen. “Efficient simulation of light transport in scenes with participating media using photon maps”. *Computer Graphics (Proc. SIGGRAPH 98)*, pp. 311–320 (July 1998).

[Reichert 92] Mark C. Reichert. *A Two-Pass Radiosity Method Driven by Lights and Viewer Position*. Master’s thesis, Cornell University, January 1992.

[Smits et al. 92] Brian E. Smits, James R. Arvo, and David H. Salesin. “An importance-driven radiosity algorithm”. *Computer Graphics (Proc. SIGGRAPH 92*, 26(2): 273–282 (July 1992).

[Ward 91] Gregory Ward. “Real pixels”. In *Graphics Gems II*, edited by James R. Arvo, pp. 80–83. Cambridge, MA: Academic Press, 1991.

[Ward, Heckbert 92] Gregory Ward and Paul Heckbert. “Irradiance gradients”. In *Proceedings of the 3rd Eurographics Workshop on Rendering*, pp. 85–98. Eurographics, May 1992.

[Ward, Shakespeare 98] Gregory Ward Larson and Rob Shakespeare. *Rendering with Radiance — The Art and Science of Lighting Visualization*. San Francisco: Morgan Kaufmann Publishers, 1998.

[Whitted 80] Turner Whitted. “An improved illumination model for shaded display”. *Communications of the ACM*, 23(6): 343–349 (June 1980).

Web Information

The images are available on the web at
http://www.acm.org/jgt/papers/Christensen99

Per H. Christensen, Square USA, 55 Merchant Street #3100, Honolulu, HI 96813. (per.christensen@acm.org)

Received June 24, 1999; accepted December 22, 1999.