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Realtime Global Illumination using Dynamic Radiance Volumes

Master Thesis

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Abstract

Illumination and thus rendering is a computationally complex problem since correct lighting requires the interaction of every surface point with the entire scene. Accurate global illumination has become the standard in non-interactive applications, i.e. mainly in movies. During the last few years it has become more and more important in interactive applications like simulations and games as well. The visual importance, especially of the first indirect light bounce, is obvious for most scenes which would be widely unlit otherwise. Today, many games use a mixture of pre-computed and real-time techniques to achieve approximations of global illumination.

In this thesis, we present a new technique for completely dynamic real-time global illumination that works without any pre-computation. We compute single indirect bounce lighting using cascaded regular grids of light caches. Which caches need to be lit is determined at runtime. This allows fast processing and a very low memory footprint. Indirect light is obtained from a reflective shadow map, and saved into a spherical harmonics representation for each cache. It can then later be interpolated across several light caches. To compute accurate indirect shadows we use voxel cone tracing within a pre-filtered binary voxelization. Additionally, we propose hemispherical per-cache environment maps for a radiance representation that provides enough accuracy to enable indirect specular effects.

The work introduces the reader into the topic of global illumination and gives an overview over many related and similar approaches. The extensive evaluation section of this thesis shows that our technique has a very low memory footprint, works well with high screen resolutions and achieves competitive results both in terms of performance and quality. Improvements can be made especially in the area of performance of the indirect specular lighting and shadowing under higher quality configurations.

Index of Notation

The notations used in this paper are almost identical to those used in the book *Physically Based Rendering* [PH10]. Photometric quantities and relations are explained in more detail in [Section 2.1](#).

Mathematical

x	Point in 3D space
\vec{xy}	Normalized direction vector from x to y
\mathbf{v}	Direction vector in 3D space
p_x, \mathbf{v}_x	x component of point / vector
$\mathbf{v} \cdot \mathbf{w}$	Dot product of vectors \mathbf{v} and \mathbf{w}
$(\mathbf{v} \cdot \mathbf{w})^+$	Dot product of vectors \mathbf{v} and \mathbf{w} with negative values clamped to zero
$\mathbf{v} \times \mathbf{w}$	Cross product of vectors \mathbf{v} and \mathbf{w}
$\ \mathbf{v}\ $	Euclidean length of vector \mathbf{v}
$\hat{\mathbf{v}}$	Normalized vector \mathbf{v}

Quantities & Functions

A	Area
ω	Solid Angle
ϕ	Radiant Flux , light power
I	Radiant Intensity , flux density per solid angle
E	Irradiance , flux density per area
L	Radiance , flux density per area per solid angle
ρ	Reflectance , ratio between incoming and outgoing flux
f_r	BRDF , function on the relation between irradiance and outgoing radiance

1 Introduction

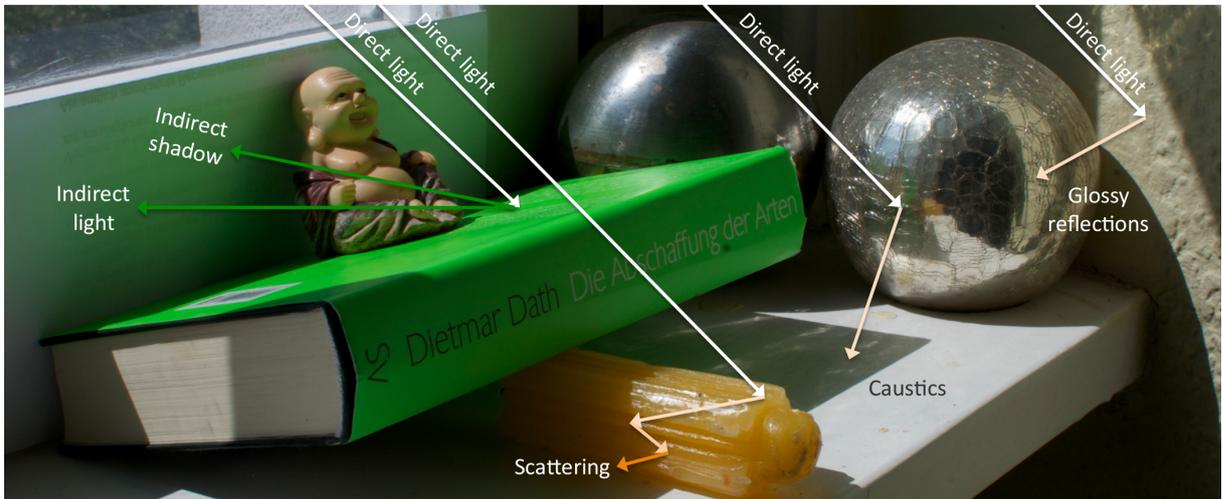


Figure 1.1: [RDGK12] Photography of a scene with various global illumination effects: Diffuse and specular bounces, caustics and scattering.

1.1 Introduction

Everything that human eyes can perceive is the result of light reaching the retina after interacting with matter. The way light interacts with our environment is very complex and always depends on a global context. There is a variety of natural phenomena like indirect light, (indirect) shadowing, (glossy) reflections and scattering which are impossible to simulate by local lighting models. The photography in [Figure 1.1](#) demonstrates a few of them. Compared to the simulation of local light effects which only take an isolated surface point into consideration, the simulation of realistic global illumination effects as they occur in nature is extremely challenging both in terms of computational and algorithmic complexity.

Images which lack these global effects look synthetic and are often missing important cues which are needed to understand the interrelations of the depicted objects. Wherever 3D-scenes need to be displayed in an either believable or aesthetic manner, the simulation of global illumination becomes important. Some of these applications are movies, architectural visualizations, video games and professional training simulations. While the specific demands of these applications vary greatly, the underlying principles are the same as they are governed by the physical laws of light which are familiar to our visual system. Generally, these applications can be divided in two categories: Interactive and non-interactive. Where a non-interactive application like a movie or single images can afford computation times of several days, interactive applications need to compute at least

parts of the simulation just-in-time to provide the user with the expected feedback on his actions. A simulation is usually called interactive if images are rendered in less than 50ms (20 frames per second). However, frame rates need to be much higher to be comfortable for the user. Fast paced games usually profit from much better rendering times of more than 16ms (about 60 frames per second) [CCD06] and the vendors of the upcoming virtual reality displays recommend even shorter rendering times of about 11-8ms (90-120 frames per second) to reduce motion sickness [Pre14]. Naturally, real-time rendering that is performed on personal computers usually makes use of a set of approaches and algorithms, that differ from offline rendering which often runs on large computer clusters.

1.2 Motivation



Figure 1.2: Screenshot from the 2008 video game *Mirrors Edge*, featuring pre-computed indirect lighting.

In this work we want to introduce a new global illumination approach that is aimed for real-time rendering and does not need any pre-computation. To be able to display the aforementioned light effects in real-time, interactive applications often make use of various pre-computation steps under the assumption that specific parts of the scene do not change. In the extreme case this means that both scene and lighting conditions are assumed to be completely static which allows to compute a large variety of effects up-front. This has been common practice in many games for over a decade now, as can be seen for example in *Mirrors Edge* in [Figure 1.2](#) where only the characters and very few dynamic objects are lit at runtime.

Obviously such techniques imply many restrictions on the design of virtual worlds and

Bibliography

- [AMD15a] AMD. *APP Profiler Kernel Occupancy*, 2015. URL: <http://developer.amd.com/tools-and-sdks/archive/amd-app-profiler/user-guide/app-profiler-kernel-occupancy/>.
- [AMD15b] AMD. *Developer Guides, Manuals & ISA Documents*, 2015. URL: <http://developer.amd.com/resources/documentation-articles/developer-guides-manuals/>.
- [AMHH08] Tomas Akenine-Möller, Eric Haines, and Natty Hoffman. *Real-Time Rendering 3rd Edition*. A. K. Peters, Ltd., Natick, MA, USA, 2008.
- [Bli77] James F. Blinn. Models of light reflection for computer synthesized pictures. *ACM SIGGRAPH Computer Graphics*, 11(2):192–198, 1977.
- [Cam15] Camouflaj. République tech demo, April 2015. URL: <https://www.assetstore.unity3d.com/en/#!/content/34352>.
- [CCD06] Mark Claypool, Kajal Claypool, and Feissal Damaa. The effects of frame rate and resolution on users playing first person shooter games. In *Multimedia Computing and Networking*, volume 6071, January 2006.
- [CG12] Cyril Crassin and Simon Green. Octree-based sparse voxelization using the gpu hardware rasterizer. In Patrick Cozzi and Christophe Riccio, editors, *OpenGL Insights*, pages 303–319. CRC Press, July 2012.
- [Cho15] Michael Chock. *NV_conservative_raster OpenGL Extension*. Nvidia, March 2015. URL: https://www.opengl.org/registry/specs/NV/conservative_raster.txt.
- [CNS⁺11] Cyril Crassin, Fabrice Neyret, Miguel Sainz, Simon Green, and Elmar Eisemann. Interactive indirect illumination using voxel cone tracing. *Computer Graphics Forum*, 30(7):1921–1930, September 2011.
- [DCB⁺04] Zhao Dong, Wei Chen, Hujun Bao, Hongxin Zhang, and Qunsheng Peng. Real-time voxelization for complex polygonal models. In *Computer Graphics and Applications, 12th Pacific Conference*, pages 43–50, 2004.
- [DGR⁺09] Zhao Dong, Thorsten Grosch, Tobias Ritschel, Jan Kautz, and Hans-Peter Seidel. Real-time indirect illumination with clustered visibility. In *Vision, Modeling, and Visualization Workshop, VMV '09*, pages 187–196, 2009.
- [DKH⁺14] Carsten Dachsbacher, Jaroslav Křivánek, Miloš Hašan, Adam Arbree, Bruce Walter, and Jan Novák. Scalable Realistic Rendering with Many-Light Methods. *Computer Graphics Forum*, 33(1):88–104, February 2014.
- [DL06] William Donnelly and Andrew Lauritzen. Variance shadow maps. In *Symposium on Interactive 3D Graphics and Games, I3D '06*, pages 161–165, 2006.

- [DMAC03] Frédéric Drago, Karol Myszkowski, Thomas Annen, and Norishige Chiba. Adaptive logarithmic mapping for displaying high contrast scenes. *Computer Graphics Forum*, 22(3):419–426, September 2003.
- [Dog13] Hawar Doghramachi. Rasterized voxel-based dynamic global illumination. In Wolfgang Engel, editor, *GPU Pro 4*, pages 155–171. CRC Press, 2013.
- [DS05] Carsten Dachsbacher and Marc Stamminger. Reflective shadow maps. In *Symposium on Interactive 3D Graphics and Games, I3D '05*, pages 203–231, 2005.
- [ED06] Elmar Eisemann and Xavier Décoret. Fast scene voxelization and applications. In *Symposium on Interactive 3D Graphics and Games, I3D '06*, pages 71–78, 2006.
- [ED08] Elmar Eisemann and Xavier Décoret. Single-pass gpu solid voxelization for real-time applications. In *Proceedings of Graphics Interface, GI '08*, pages 73–80, 2008.
- [FC00] Shiaofen Fang and Hongsheng Chen. Hardware accelerated voxelization. *Computers and Graphics*, 24(3):433–442, June 2000.
- [Gie11] Fabian Giesen. A trip through the graphics pipeline, 2011. URL: <https://fgiesen.wordpress.com/2011/07/09/a-trip-through-the-graphics-pipeline-2011-index/>.
- [Gre03] Robin Green. Spherical harmonic lighting: The gritty details. In *Archives of the Game Developers Conference*, 2003.
- [GSHG98] Gene Greger, Peter Shirley, Philip M Hubbard, and Donald P Greenberg. The irradiance volume. *IEEE Computer Graphics and Applications*, 18(2):32–43, March 1998.
- [Gue07] Paul Guerrero. Approximative real-time soft shadows and diffuse reflections in dynamic scenes. Master’s thesis, Institute of Computer Graphics and Algorithms, Vienna University of Technology, October 2007. URL: <http://www.cg.tuwien.ac.at/research/publications/2007/guerrero-2008-dip/>.
- [HKWB09] Miloš Hašan, Jaroslav Křivánek, Bruce Walter, and Kavita Bala. Virtual spherical lights for many-light rendering of glossy scenes. In *ACM SIGGRAPH Asia 2009 Papers, SIGGRAPH Asia '09*, pages 143:1–143:6, 2009.
- [HM12] Ladislav Hrabcak and Arnaud Masserann. Asynchronous buffer transfers. In Patrick Cozzi and Christophe Riccio, editors, *OpenGL Insights*, pages 391–414. CRC Press, July 2012.
- [Hof14] Naty Hoffmann. Physics and math of shading. In *Siggraph PBR Course. 2k Games*, 2014.
- [Hol11] Daniel Holbert. Saying "goodbye" to shadow acne, 2011. Poster presented at Games Developer Conference, San Fransisco. URL: http://www.dissidentlogic.com/old/images/NormalOffsetShadows/GDC_Poster_NormalOffset.png.

Statement of Authorship / Selbstständigkeitserklärung

Hiermit erkläre ich, dass ich die vorliegende Masterarbeit selbstständig und ausschließlich unter Verwendung der angegebenen Literatur und Hilfsmittel angefertigt habe.

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