The Path to Path-Traced Movies

Per H. Christensen
Pixar Animation Studios
per@pixar.com

Wojciech Jarosz
Dartmouth College
wojciech.k.jarosz@dartmouth.edu
# Foundations and Trends® in Computer Graphics and Vision

Volume 10, Issue 2, 2016

Editorial Board

**Editors-in-Chief**

<table>
<thead>
<tr>
<th>Brian Curless</th>
<th>Luc Van Gool</th>
</tr>
</thead>
<tbody>
<tr>
<td>University of Washington</td>
<td>KU Leuven and ETH Zurich</td>
</tr>
</tbody>
</table>

**Editors**

<table>
<thead>
<tr>
<th>Marc Alexa</th>
<th>Mike Gleicher</th>
<th>Jean Ponce</th>
</tr>
</thead>
<tbody>
<tr>
<td><em>TU Berlin</em></td>
<td><em>University of Wisconsin</em></td>
<td><em>Ecole Normale Supérieure</em></td>
</tr>
<tr>
<td>Kavita Bala</td>
<td>Richard Hartley</td>
<td>Long Quan</td>
</tr>
<tr>
<td><em>Cornell University</em></td>
<td><em>ANU</em></td>
<td><em>HKUST</em></td>
</tr>
<tr>
<td>Ronen Basri</td>
<td>Aaron Hertzmann</td>
<td>Cordelia Schmid</td>
</tr>
<tr>
<td><em>Weizmann Institute</em></td>
<td><em>Adobe Research, USA</em></td>
<td></td>
</tr>
<tr>
<td>Peter Belhumeur</td>
<td>Hugues Hoppe</td>
<td></td>
</tr>
<tr>
<td><em>Columbia University</em></td>
<td><em>Microsoft Research</em></td>
<td></td>
</tr>
<tr>
<td>Andrew Blake</td>
<td>C. Karen Liu</td>
<td>Amnon Shashua</td>
</tr>
<tr>
<td><em>Microsoft Research</em></td>
<td><em>Georgia Tech</em></td>
<td><em>Hebrew University</em></td>
</tr>
<tr>
<td>Chris Bregler</td>
<td>David Lowe</td>
<td>Peter Shirley</td>
</tr>
<tr>
<td><em>Facebook/Oculus</em></td>
<td><em>UBC</em></td>
<td><em>University of Utah</em></td>
</tr>
<tr>
<td>Joachim Buhmann</td>
<td>Jitendra Malik</td>
<td>Noah Snavely</td>
</tr>
<tr>
<td><em>ETH Zurich</em></td>
<td><em>UC Berkeley</em></td>
<td><em>Cornell University</em></td>
</tr>
<tr>
<td>Michael Cohen</td>
<td>Steve Marschner</td>
<td>Stefano Soatto</td>
</tr>
<tr>
<td><em>Microsoft Research</em></td>
<td><em>Cornell University</em></td>
<td><em>UCLA</em></td>
</tr>
<tr>
<td>Paul Debevec</td>
<td>Shree Nayar</td>
<td>Richard Szeliski</td>
</tr>
<tr>
<td><em>USC ICT</em></td>
<td><em>Columbia University</em></td>
<td><em>Microsoft Research</em></td>
</tr>
<tr>
<td>Julie Dorsey</td>
<td>James O’Brien</td>
<td>Joachim Weickert</td>
</tr>
<tr>
<td><em>Yale University</em></td>
<td><em>UC Berkeley</em></td>
<td><em>Saarland University</em></td>
</tr>
<tr>
<td>Fredo Durand</td>
<td>Tomas Pajdla</td>
<td>Song Chun Zhu</td>
</tr>
<tr>
<td><em>MIT</em></td>
<td><em>Czech TU</em></td>
<td><em>UCLA</em></td>
</tr>
<tr>
<td>Olivier Faugeras</td>
<td>Pietro Perona</td>
<td>Andrew Zisserman</td>
</tr>
<tr>
<td><em>INRIA</em></td>
<td><em>Caltech</em></td>
<td><em>University of Oxford</em></td>
</tr>
<tr>
<td>Rob Fergus</td>
<td>Marc Pollefeys</td>
<td></td>
</tr>
<tr>
<td><em>New York University</em></td>
<td><em>ETH Zurich</em></td>
<td></td>
</tr>
</tbody>
</table>

Full text available at: [http://dx.doi.org/10.1561/0600000073](http://dx.doi.org/10.1561/0600000073)
Editorial Scope

Topics

Foundations and Trends© in Computer Graphics and Vision publishes survey and tutorial articles in the following topics:

- Rendering
- Shape
- Mesh simplification
- Animation
- Sensors and sensing
- Image restoration and enhancement
- Segmentation and grouping
- Feature detection and selection
- Color processing
- Texture analysis and synthesis
- Illumination and reflectance modeling
- Shape representation
- Tracking
- Calibration
- Structure from motion
- Motion estimation and registration
- Stereo matching and reconstruction
- 3D reconstruction and image-based modeling
- Learning and statistical methods
- Appearance-based matching
- Object and scene recognition
- Face detection and recognition
- Activity and gesture recognition
- Image and video retrieval
- Video analysis and event recognition
- Medical image analysis
- Robot localization and navigation

Information for Librarians

Foundations and Trends© in Computer Graphics and Vision, 2014, Volume 10, 4 issues. ISSN paper version 1572-2740. ISSN online version 1572-2759. Also available as a combined paper and online subscription.
The Path to Path-Traced Movies

Per H. Christensen
Pixar Animation Studios
per@pixar.com

Wojciech Jarosz
Dartmouth College
wojciech.k.jarosz@dartmouth.edu
# Contents

1 Introduction .......................... 2

2 Illumination .......................... 5
   2.1 Direct and indirect illumination ......... 5
   2.2 Indirect illumination types ............... 6

3 Path Tracing ......................... 8
   3.1 Origins of path tracing ................. 8
   3.2 Simple path tracing .................... 9
   3.3 Depth of field and motion blur ........... 11
   3.4 Path tracing in movies .................. 12

4 Other Rendering Techniques: A Retrospective ... 13
   4.1 Reyes .................................. 14
   4.2 Ray casting ............................ 15
   4.3 Recursive ray tracing ................. 15
   4.4 Distribution ray tracing ............... 16
   4.5 Photon mapping ....................... 19
   4.6 Point-based global illumination ....... 21
   4.7 Preview renderers ..................... 23

5 Advanced Path Tracing ................. 25
Abstract

Path tracing is one of several techniques to render photorealistic images by simulating the physics of light propagation within a scene. The roots of path tracing are outside of computer graphics, in the Monte Carlo simulations developed for neutron transport. A great strength of path tracing is that it is conceptually, mathematically, and often-times algorithmically simple and elegant, yet it is very general. Until recently, however, brute-force path tracing techniques were simply too noisy and slow to be practical for movie production rendering. They therefore received little usage outside of academia, except perhaps to generate an occasional reference image to validate the correctness of other (faster but less general) rendering algorithms. The last ten years have seen a dramatic shift in this balance, and path tracing techniques are now widely used. This shift was partially fueled by steadily increasing computational power and memory, but also by significant improvements in sampling, rendering, and denoising techniques. In this survey, we provide an overview of path tracing and highlight important milestones in its development that have led to it becoming the preferred movie rendering technique today.
Rendering computer-generated (CG) movies is tough. There are 130,000 high-resolution frames in a 90-minute movie, with each frame requiring computation of typically two million pixel colors (many more for IMAX movies). This is several hundred billion pixel colors that will be scrutinized by the movie director and by audiences worldwide. The images are often computed with motion blur and depth of field, to mimic these characteristic effects (limitations) of real cameras. The images must be free of visual noise—one particularly pesky type of noise is occasional bright pixels known as “fireflies”. There can be no spatial or temporal aliasing (affectionately known as “jaggies” and “crawlies”) in the images. The color of each pixel depends not only on what object is visible in that pixel (including its orientation, material, texture, illumination, etc.), but also—through shadows and reflected light—on objects in other parts of the scene. The surface color calculations have to be programmable, with the computations specified in stand-alone programs called “shaders”. Typical scenes contain huge amounts of geometry and texture data, often straining the available memory even on high-end computers. There are often dozens of textures specifying the material properties of each surface, and a scene can contain
millions of surfaces. With all the data that goes into rendering each frame, production-strength renderers are sometimes jokingly referred to as data management systems with images as a by-product. Rendering times are crucial as well, both for quick test images during the development of the movie, and for the final-quality frames that will appear in movie theaters.

Figure 1.1(a) shows a frame from the first computer-generated animated feature film: Pixar’s Toy Story from 1995. This movie was rendered with the RenderMan renderer using the Reyes scan-line algorithm \[25\] with shadow maps and reflection maps \[4\]. For many years, the Reyes algorithm was the work-horse of most CG and visual effects work at major studios.

The last 15 years has seen hybrid renderers combining the Reyes algorithm for directly visible objects with ray-traced shadows and reflections. Soft indirect illumination has been computed with a variety of methods, including distribution ray tracing and point-based global illumination.

At the same time, other renderers, such as Arnold, pushed for a complete switch to path tracing. Compared to Reyes-based hybrid renderers, path tracing is a simpler and more brute-force approach. It has its roots in a statistical sampling method called Monte Carlo, which was first used for particle simulation in nuclear engineering. Path tracing can render shadows and reflections in a conceptually simple recursive
manner, but on the other hand it is more noisy and less memory efficient than some Reyes hybrids. Path tracing is not necessarily the fastest method to render final movie-quality images with indirect illumination, depth of field, and motion blur: for example, point-based global illumination has no noise, and distribution ray tracing with irradiance gradients and radiosity caching is better able to exploit sample domain coherency. However, path tracing’s natural ability to handle complex light transport effects, along with its potential to simplify the production pipeline, reduce iteration time during layout and lighting, and improve overall workflow, are enticing advantages.

Figure 1.1(b) shows a frame from the recent movie Finding Dory. Here all the direct visibility, shadows, reflections, refractions, indirect diffuse illumination, and subsurface scattering are computed with RenderMan’s implementation of path tracing.

Even though the algorithmic developments for the switch to path tracing have been under way for quite some time, there is a fairly sudden wave of studios switching their pipelines over. One might even talk about a path tracing “revolution” [61]. This article is our attempt to retrace the steps the industry has taken on its journey to path-traced movies. We will identify major hurdles that stood in the way of that transition, describe the technical milestones that pushed the field forward over the last couple of decades, and discuss the combination of circumstances that came together to propel the CG and VFX movie industry into a path-traced world. Since the journey is not yet complete, we will also discuss on-going challenges and open questions that practitioners and researchers will need to address in the years to come.
References


References


References


References


References


References


References


References


References
