Feasibility Study of Real Time Path Tracing

Or: How Much Noise Is Too Much?

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Abstract

This study aims to investigate the viability of a physically-based technique called **path tracing** in lieu of or in corporation with classical techniques in interactive media such as video games and visual effects tools.

Real time path tracing has been prohibitively expensive in regards to computational complexity. However, modern GPUs and even CPUs have finally gotten fast enough for real time path tracing to become a viable alternative to traditional real time approaches to rendering. Based on that assumption, this thesis presents the idea, algorithm and complexity behind path tracing in the first part and extrapolates feasibility and suitability of real time path tracing on consumer hardware according to the current state of technology and trends in the second part.

As part of the research, the author has implemented a path tracing 3D engine in modern C++ in order to empirically test the assumptions made in this thesis. The study found path tracing to be a viable rendering technique for average commodity hardware in approximately 4 years.

Acknowledgments

I would like to express my sincere gratitude to the teachers throughout school and university for the knowledge they've passed on.

I thank my friends for the laughs, horrible mistakes and awesome successes we shared with one another.

Furthermore, none of this would have been possible without the incredible efforts and love of my parents who have supported me throughout the years and enabled me to live a carefree life until I was ready to fend for myself.

Lastly, but certainly not least, I would like to declare my gratefulness to Alisa, whose endless love has given my life a new meaning.

We all make choices in life, but in the end, our choices make us.

Andrew Ryan

Contents

Acronyms

AABB axis-aligned bounding box

AO ambient occlusion

BRDF bidirectional reflection distribution function

BSP binary space partitioning

CPU central processing unit

CSG constructive solid geometry

FPS frames per second

GI global illumination

GPU graphics processing unit

HDR high dynamic range

MLT Metropolis light transport

PBR physically based rendering

RT real time

RGB red-green-blue

SIMD single instruction multiple data

SPP samples per pixel

SSAO screen-space ambient occlusion

1 Introduction

As part of the quest for ever-improving game graphics, researchers, graphics hardware developers and video game developers alike have been coming up with more and more convoluted and technically challenging ways of improving the graphics in interactive media such as games and visualizations in order to give users a deeper sense of immersion or to provide special effects artists with faster feedback.

While rendering techniques are currently shifting from the traditional fixed pipeline approach towards the new, fully programmable approach that lets developers implement deferred renderers that can more closely mimic reality by using multiple combined shading and lighting algorithms and rendering the scene multiple times for different buffers, the fundamental concept of rasterization-based rendering has largely remained the same.

The real world photon-collecting approach that actual cameras use has so far not been adopted for interactive media by the industry in any capacity because the computational cost has historically been prohibitively expensive. It is, however, used extensively (and has been in use since decades) for offline, non-interactive rendering of computer-generated movies and visualizations of scientific simulations.

This study assumes that the next logical step for the industry will be to adopt this method for real time media as well. For the purpose of this thesis, a renderer is considered *real time* when it manages to render a frame within $16.67ms$ since that equals 60 frames per second (FPS) which is the current de facto standard refresh rate for most available computer screens. Conversely, a renderer is called *offline* when it is not designed for interactive rendering which usually means that it will renderer an image or a batch of images over the course of a few days. The differences of real time and offline path tracing renderers will be explained in the next chapter.

1.1 Motivation

Real time path tracing (and physically based rendering in general) offers many benefits over traditional real time rendering methods such as better visuals and simpler implementation but also allows for completely new types of graphics such as realistic caustics [1] and even light dispersion [2] (using a prism, for instance) since path tracers might simulate wavelengths instead of plain red-green-blue (RGB) colors. Modern video games tend to rely on a growing number of tricks to keep them visually appealing as the consumer grows more demanding. They're called *tricks* in this study because they merely trick the beholder into seeing something that appears to be physically accurate when it is, in fact, not the result of a physically-based calculation and as such this study aims to keep tricks and emergent phenomena separated by language. Some notable tricks include screen-space ambient occlusion (SSAO) [3], motion blur [4], lens flares [5], chromatic aberration [6], depth of field [7] and light mapping [8].

2 Real Time Path Tracing Explained

This chapter will explain the concepts, mathematics, physics and algorithms behind path tracing, how real time path tracing differs from offline path tracing and the trade-offs made to achieve acceptable performance. It will also explain how path tracing differs from rasterization and other global illumination techniques.

2.1 Theoretical Basis

The fundamental problem solved by path tracing is the *rendering equation* originally described by James Kajiya [9]. This thesis uses the form from Wikipedia [10] since the author considers it easier to read:

$$L_{\mathrm{o}}(\mathbf{x}, \omega_{\mathrm{o}}, \lambda, t) = L_{\mathrm{e}}(\mathbf{x}, \omega_{\mathrm{o}}, \lambda, t) + \int_{\Omega} f_{\mathrm{r}}(\mathbf{x}, \omega_{\mathrm{i}}, \omega_{\mathrm{o}}, \lambda, t)\, L_{\mathrm{i}}(\mathbf{x}, \omega_{\mathrm{i}}, \lambda, t)\, (\omega_{\mathrm{i}} \cdot \mathbf{n})\, \mathrm{d}\,\omega_{\mathrm{i}}$$

For our purposes, this can be simplified by removing the time and wavelength components which we will not make use of:

$$L_{\mathrm{o}}(\mathbf{x}, \omega_{\mathrm{o}}) = L_{\mathrm{e}}(\mathbf{x}, \omega_{\mathrm{o}}) + \int_{\Omega} f_{\mathrm{r}}(\mathbf{x}, \omega_{\mathrm{i}}, \omega_{\mathrm{o}})\, L_{\mathrm{i}}(\mathbf{x}, \omega_{\mathrm{i}})\, (\omega_{\mathrm{i}} \cdot \mathbf{n})\, \mathrm{d}\,\omega_{\mathrm{i}}$$

This equation can be broken down into its individual parts to make it easier to explain and understand:

$$\boxed{L_{\mathrm{o}}(\mathbf{x}, \omega_{\mathrm{o}})} = \boxed{L_{\mathrm{e}}(\mathbf{x}, \omega_{\mathrm{o}})} + \boxed{\int_{\Omega} \boxed{f_{\mathrm{r}}(\mathbf{x}, \omega_{\mathrm{i}}, \omega_{\mathrm{o}})}\boxed{L_{\mathrm{i}}(\mathbf{x}, \omega_{\mathrm{i}})}\boxed{(\omega_{\mathrm{i}} \cdot \mathbf{n})}\, \mathrm{d}\,\omega_{\mathrm{i}}}$$

$\boxed{L_{\mathrm{o}}(\mathbf{x}, \omega_{\mathrm{o}})}$ is the **outgoing light** with $\mathbf{x}$ being a point on a surface from which the light is reflected from into direction ω_{o}.
$\boxed{L_{\mathrm{e}}(\mathbf{x}, \omega_{\mathrm{o}})}$ is the **emitted light** from point $\mathbf{x}$. Usually surfaces don't emit light themselves unless they are area lights.
$\boxed{\int_{\Omega} \ldots \mathrm{d}\,\omega_{\mathrm{i}}}$ is the integral over Ω which is the hemisphere at $\mathbf{x}$ (and thusly centered around $\mathbf{n}$). All possible values for ω_{i} are therefore contained in Ω.

$\boxed{f_\mathrm{r}(\mathbf{x},\ \omega_\mathrm{i},\ \omega_\mathrm{o})}$ is the **bidirectional reflection distribution function (BRDF)** which determines how much light is reflected from ω_i to ω_o at $\mathbf{x}$.
$\boxed{L_\mathrm{i}(\mathbf{x},\ \omega_\mathrm{i})}$ is the **incoming light** at $\mathbf{x}$ from ω_o. It is not necessarily *direct light*. The rendering equation also considers *indirect light* which is light that has already been reflected.
$\boxed{(\omega_\mathrm{i} \cdot \mathbf{n})}$ is the **normal attenuation** at $\mathbf{x}$. The incoming light ω_i is weakened depending on the cosine of the angle between ω_i and the surface normal $\mathbf{n}$.

2.2 Path Tracing in Comparison to Other Techniques

2.2.1 Comparison to Rasterization

2.2.2 Comparison to Other Algorithms

2.3 History of Path Tracing

As with so many things in computer science and science in general, the modern idea of physically based rendering using path tracing builds upon many important past discoveries and algorithms such as ray tracing and ray casting. Arthur Appel is generally credited as being the father of *ray casting* as he was the first to describe the algorithm in a 1968 paper [11].

Ray casting is an important idea needed for *ray tracing* which was first published in a paper in 1980 by Turner Whitted [12].

Building upon ray tracing, an improved algorithm was published in 1986 by James T. Kajiya which used ray tracing combined with a Monte Carlo algorithm in order to create a new algorithm that was called *Monte Carlo ray tracing* [9]. Nowadays, Monte Carlo ray tracing is better known as *path tracing*.

It took another decade for path tracing to become the physically based rendering approach that it is known for today. In 1996, Eric Lafortune improved the algorithm by suggesting the usage of bidirectional path tracing [13] and finally the Metropolis light transport was suggested in 1997 by Eric Veach and Leonidas J. Guibas [14] to improve performance in complex scenes.

This was the last notable improvement to the algorithm, though many micro optimizations have since been published. All of these achievements and improvements are generally collapsed into the term *path tracing* since they do not diverge from the general algorithm but instead improve upon it.

It took longer still for the industry to become interested in path tracing. The early interest in ray tracing was of mostly academical and recreational nature. One of the most

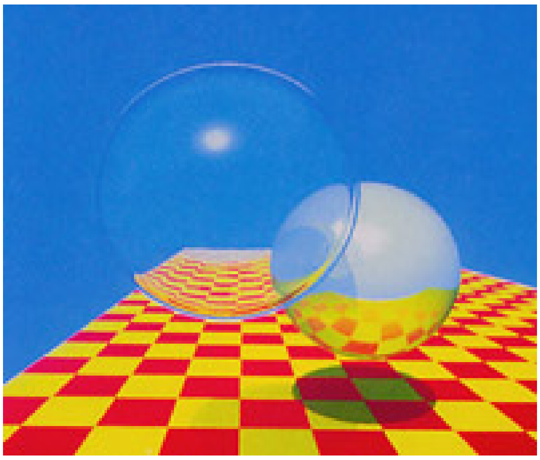

Figure 2.1: Turner Whitted's original 1980 [12] image showing off the usage of ray tracing for reflection, refraction and shadows.

notable creations of the early days of ray tracing is The Juggler created and published by Eric Graham in 1986 [15] on an Amiga 1000. It was a pre-rendered animation using ray tracing. Eric Graham stated that it took the Amiga 1 hour to render each frame [15].

Figure 2.2: Eric Graham's Juggler

While the animation seems very primitive compared to the animations of today, it was exceptional at the time. Ernie Wright's statement about The Juggler provides some contemporary context:

> Turner Whitted's paper (1980) is widely regarded as the first modern description of ray tracing methods in computer graphics. This paper's famous image of balls floating above a checkerboard floor took 74 minutes to render on a DEC VAX 11/780 mainframe, a $400,000 computer. The Juggler would appear a mere six years later, created and displayed on a $2000 Amiga. ([15])

The first feature-length computer-animated film, *Toy Story*, released in 1995 [16], is sometimes miscredited as being the first film using a ray tracing-like algorithm. However, it actually used traditional scanline rendering. The first feature-length film using ray tracing, *Cars*, was released much later, in 2006 [17] [18] and started a wave of interest in the movie industry.

The first example of *real time* path tracing was likely produced by the demo scene [19] which was quick to adopt it [20] for the purpose of producing complex graphics rendered and generated on the fly. One notable example of this is the WebGL Path Tracing by Evan Wallace made in 2010 [21] which runs in most modern web browsers, making path tracing very accessible.

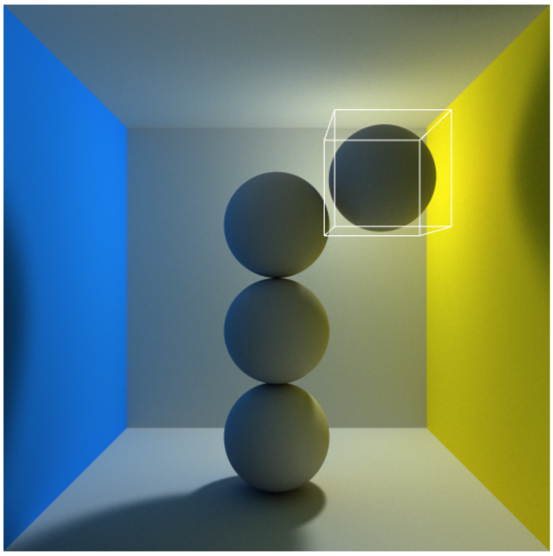

Figure 2.3: WebGL Path Tracer by Evan Wallace

Another example is the demo *5 faces* by Fairlight from 2013 [22] which uses a real time ray tracer running on the GPU to render a complex scene at 30 FPS.

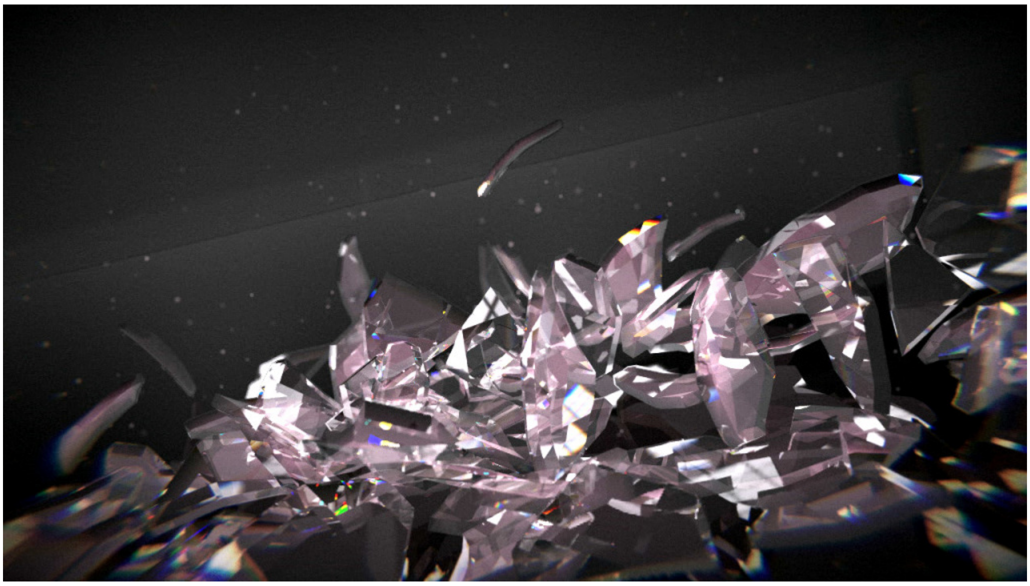

Figure 2.4: 5 faces by Fairlight

In the past, some critics have offered critical insights about why it might not be a viable alternative to rasterization on consumer hardware in the short term [23] [24].

2.4 Current State of Technology

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3 Research

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3.1 Results

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3.2 Evaluation

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4 Conclusion

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4.1 Outlook

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