Efficient Sorting and Searching in Rendering Algorithms

Tutorial outline and bibliographies

Eurographics 2014 Tutorial

Organizers and Presenters

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Version 1.0

February 26, 2014

Abstract

In the tutorial we show the connection between rendering algorithms and sorting and searching as classical problems studied in computer science. We provide both theoretical and empirical evidence that for many rendering techniques most time is spent by sorting and searching. In particular we discuss problems and solutions for visibility computation, density estimation, and importance sampling. For each problem we mention its specific issues such as dimensionality of the search domain or online versus offline searching. We will present the underlying data structures and their enhancements in the context of specific rendering algorithms such as ray tracing, photon mapping, and hidden surface removal.

Organizers bibliographies

Vlastimil Havran is an associate professor at the Czech Technical University in Prague. He defended his Ph.D. dissertation on ray shooting algorithms in 2001 at the Czech Technical University in Prague. Later he joined the computer graphics group at Max-Planck-Institute for Informatics in Saarbruecken. He became a research associate at the same institute in 2003, started as assistant professor at the Czech Technical University 2006 and become associate professor in 2011. He has contributed to the topic of sorting and searching by his dissertation on ray shooting algorithms which started the area of interactive ray tracing. In addition to sorting and searching he worked on various other topics in rendering such as global illumination algorithms and surface reflectance representations.

Jiří Bittner holds a Ph.D. in Computer Science from the Czech Technical University in Prague. His main research interests include visibility preprocessing, occlusion culling, real-time rendering, and computational geometry. He has also been active in development of two commercial products dealing with real-time rendering of large scenes. He was affiliated with the Vienna University of Technology between 2003 and 2006, since then he returned to the Czech Technical University in Prague as senior researcher and later become assistant professor.

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Tutorial Content

Slides

Slides of this structure are given in a separate file with landscape orientation.

Introduction
Sorting and Searching Techniques
Hierarchical data structures
Ray Tracing
Rasterization and Culling
Photon Maps and Ray Maps
Irradiance Caching
GPU Sorting and Searching
Conclusion

References

This material contains bibliographic references structured as shown below.

Tutorial Web Page

The updated version of this tutorial presented at Eurographics 2014 can be found under the following URL:

http://dcgi.felk.cvut.cz/~havran/eg2014tut/

Acknowledgements

We would like to thank Robert Herzog, Michael Wimmer, Peter Wonka, Tommer Leyvand, David Luebke, Hansong Zhang and other colleagues for providing us various materials used in the tutorial. This work has been partially supported by the Czech Science Foundation under the research program number P202/12/2413 (OPALIS).

1 Motivation for the Tutorial

The half-day tutorial covers the use of efficient sorting and searching techniques in the context of rendering algorithms. The topic itself is important for performance and usability of the known algorithms as well as the design of future ones. We show that although the problems and their solutions in rendering substantially differ, their common denominator remains sorting and searching. Additionally it is often the case that most of the computational time for rendering is spent by searching even if spatial sorting has been used in preprocessing.

An efficient sorting and representation of the resulting ordered information is a necessary base to carry out efficiently the repetitive searching during rendering. We would like to give an introduction to the basic techniques and issues related to multidimensional sorting and related data structures required for efficient searching. This we want to follow by showing the concepts of searching in particular rendering algorithms.

In the tutorial we will address both deterministic and stochastic rendering algorithms for visibility computation (ray shooting and z-buffer), irradiance caching, photon mapping, and BRDF importance sampling. These algorithms employ methods like spatial indexing, nearest neighbor searching, intersection searching, range searching, or point location.

In Section 2 we give the outline of the tutorial, in Section 3 we target the audience of the tutorial. In section 3 we give bibliographic references related to this tutorial.

2 Tutorial Overview – Half Day (2$\times$ 90 minutes)

The tutorial is divided into two logical parts. The first part will cover the basic description of the sorting and searching and the topic of ray shooting (90 minutes). The second part will cover other applications of searching in rendering algorithms completed by *Questions & Answers* section. A more detailed outline of the tutorial is presented bellow.

Part I – 90 minutes

2.1 Introduction and Outline

The scope of the tutorial and the connection to sorting and searching. Recalling the rendering equation, density estimation.

2.2 Sorting and Searching Techniques

Generalization of sorting and searching operations, giving overview of the problem. Recalling O(N log N) bounds and traditional sorting techniques and related algorithmic issues for sorting based on comparisons, O(N) lower bound for sorting with limited input precision (radix sort). Notion of performance of searching algorithms: query time, preprocessing time, the size of the data structures, the practicality of algorithmic solutions, hidden constants behind the big O notation.

2.3 Problem Dimensionality

Most problems of image synthesis are dealing with three-dimensional space. There are several problems which can be formulated in four-dimensional space (spatio-temporal domain). We will also discuss other problems which via surface parametrization can be reduced to two-dimensional space.

2.4 Hashing

Direct hashing techniques, perfect hashing, use in caching algorithms, external memory data structures, etc.

2.5 Bucketing

Description of sorting based on the limited precision of input data called bucketing (radix sort, distribution sort etc.). The connection to grid-like data structures with O(1) access time used in rendering applications.

2.6 Hierarchical Data Structures

Description of hierarchical concept including object hierarchies (possibly overlapping), spatial subdivisions, and hybrid hierarchical data structures. Branching factor of the hierarchy, memory layout of the data structures, cost models used for construction. Augmented data structures for hierarchies such as neighbor links or proximity clouds.

2.7 Static versus Dynamic

Description of the following settings:

- *static data structures* built once and used for queries without any change of input data.
- *dynamic data structures* built with certain input data, however, allowing efficient update of input data without necessity of rebuilding the data from the scratch.

2.8 Online versus Offline

Description of the following settings:

- *Online* – queries are processed one by one (sequential processing). This is a typical and the simplest way how the search is applied in rendering algorithms.
- *Offline* – queries are processed at once or at some batches. It is also often referred to as aggregate search or batched search. The speedup from these techniques will be quantified.

2.9 Ray Tracing

Ray tracing determines a first object hit by the given ray. A naive ray tracing algorithm would test every object for intersection with a given ray and select the nearest one from the found intersections. The query time is then $O(n)$ where n is the number of objects in the scene. Much research has been done in order to reduce this time complexity. The key idea of most techniques is to narrow the search domain for a given ray by organizing (sorting) scene objects in a spatial data structure (often called spatial index). Each entry in the spatial index is associated with a list of objects. Then for a given ray we use the spatial index to determine only those objects which constitute a potential intersection. This is achieved by traversing through entries of the spatial index.

As an alternative to spatial indices we can use directly the ray domain to sort the objects. Similarly as in the spatial index each entry of the ray space index contains a list of intersection candidates. The traversal of the ray space index can then be implemented using a simple point location.

We will discuss several common spatial indices (kD-tree, octree, BVH) and present their extensions which aim to further reduce the expected running time of the algorithm. We also discuss a ray space index based on kD-trees and their connection to quick sort, the other paradigms such as clustering based approaches, optimzation of some data structures after building etc.

Part II – 90 minutes

2.10 Rasterization and Visibility Culling

Z-buffer provides a powerful tool for solving the casting problem for a specific set of coherent rays. In particular it handles bounded set of rays with common center of projection. Z-buffer uses bucket like sorting of the objects. Every bucket corresponds to objects intersecting a given pixel of the screen. By incremental updates it can determine the nearest object for every bucket.

Two additional culling methods are usually combined with z-buffered rendering to increase its performance. The *view frustum culling* and *occlusion culling*. View frustum culling discards all objects which cannot contribute to the z-buffer since they lie outside of the current view frustum. Occlusion culling eliminates all objects which cannot contribute since they are occluded by some other objects.

Both methods make heavy use of sorting searching. View frustum culling uses a spatial index to organize the scene. Then it uses a constraint traversal of this index to determine objects intersecting the given view frustum. Occlusion culling methods commonly use sorting of occluder projections in order to determine whether other scene objects are also occluded. We show a close relation between ray casting and z-buffer techniques with occlusion culling.

2.11 Photon Maps and Ray Maps

Photon map algorithm uses nearest neighbor search in order to estimate photon density. In particular for a given query point it uses k-nearest neighbor search on set of points (photons). The original paper provides an efficient method to organize photons in a kD-tree. We will also show an alternative approach which also sorts the query points.

Ray maps provide an extension to the photon map algorithm as they organize the whole photon paths instead of the hit points. We will discuss possibilities of maintaining a set of rays using both primal space and ray space. Further we show that an optimized primal space implementation of the algorithm can achieve performance not far from that of the photon map query.

2.12 Irradiance Caching

Irradiance cache is used to interpolate illuminance from already known samples. In order to do that it needs to locate all spheres containing a given query point. The original method uses octree to sort the spheres. We will present also more advanced techniques based on half-space reporting via transform to the four dimensional space.

2.13 BRDF and BTF

Importance sampling using cumulative distribution function and binary search or binary-interpolation search. Other techniques of importance sampling based on the searching. The BTF compression techniques used based on sorting and searching.

2.14 CPU and GPU

Differences when implementing data structures on CPUs and GPUs as consequence of the different computer architecture, paralelization, stream based versus cache-based computer architecture architecture, data alignment in memory, critical sections, atomic counters etc.

3 Target Audience

The tutorial assumes audience familiar with the area of rendering based on z-buffer and ray tracing. In particular we assume basic knowledge of ray tracing, global illumination in particular photon maps, irradiance caching, BRDF. An elementary knowledge of sorting and searching algorithms is assumed. Less known basic concept such as density estimation and importance sampling will be detailed during the tutorial.

References

On further pages we present survey of bibliographics about rendering papers which use and discuss (either directly or indirectly) sorting and/or searching algorithms. The list of references consists of several parts, which correspond to the topics discussed in tutorial. The list of references is definitely not complete and it will become outdated in future.

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Photon Mapping, Irradiance Caching, and Ray Maps

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