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ANALYSIS OF THE COMPUTATIONAL COMPLEXITY OF RENDERING METHODS

Bobko Oleksii
Postgraduate Student
Romanyuk Oleksandr
Doctor of Technical Sciences, Professor
Department of Software Engineering
Vinnytsia National Technical University, Ukraine

Abstract. This paper analyzes the main rendering methods in computer graphics with an emphasis on their computational complexity and application areas. Classical approaches to surface shading are considered. For each method, the asymptotic time complexity is evaluated both for the entire scene and for individual objects (using the Utah teapot model as an example). The prevalence of these methods in modern practice including the game industry, offline visualization, and scientific and medical graphics is also analyzed.

Keywords: rasterization, rendering, computational complexity, graphics algorithms, method prevalence.

Introduction. Rendering is an important stage in computer graphics that determines how images are generated from three-dimensional models and scenes. With the advancement of hardware and software technologies, rendering methods have evolved from simple surface-shading models to complex ray-tracing and global-illumination algorithms. Modern graphics applications and game engines must balance accuracy, photorealism, and frame generation speed. This requires a systematic analysis of the computational complexity of various methods, as well as an assessment of their practical applicability and prevalence across different domains from interactive graphics to offline visualization and scientific visualization.

The study of rendering algorithms includes the analysis of classical approaches such as Flat, Gouraud, Phong, and Blinn–Phong shading, as well as rasterization, ray tracing, path tracing, radiosity, and volume rendering. Attention is paid to the relationship between scene size, object complexity, and frame generation time, which enables a well-grounded selection of methods for specific tasks.

Goal. The aim of this work is to provide a systematic analysis of the computational complexity and prevalence of the main rendering methods, as well as to evaluate the time required to generate individual objects within a scene.

Results of the Study and Their Discussion. Rendering, as the process of transforming a three-dimensional scene description into a two-dimensional image, includes geometric processing, rasterization or ray tracing, computation of lighting, shadows, reflections, transparency, post-processing, and compression of the results. The computational complexity of each of these stages depends on the number of primitives, light sources, material properties, the spatial structure of the scene, and the algorithmic approaches used for optimization. Classical works on physically based rendering

emphasize that the complete solution of the global illumination equation has an exponential complexity due to multiple light reflections and the need to integrate over all directions [1], which necessitates the use of stochastic methods and approximate models. Rendering methods vary in their prevalence, as shown in Table 1.

Table 1 – Rendering methods

Method / model	**Prevalence**	**Basic spheres application**	**Comment**
Flat shading	Low	Educational examples , basic graphics	Almost not used in modern products
Gouraud shading	Low - medium	Old gaming engines , mobile graphics	Used in the 1990s–2000s; replaced by Phong/PBR
Phong shading	Medium	3D modeling , basic rendering lighting	Often used for fast previous viewing models
Blinn–Phong	Medium – high	Gaming engines , real time	Common in modern mobile and desktop games
Rasterization (GPU pipeline)	Very high	Games , VR/AR, real time	Basic method for modern interactive graphs
Ray casting	Low	Educational examples , simple visualizations	Used rarely in productive systems
Ray tracing (without structures)	Low	Research , offline visualization	Too slow for interactive using
Ray tracing with BVH/KD trees	Medium – high	Film industry , modern GPUs with support tracing	Actively is growing after implementation of RTX and DirectX Raytracing
Path tracing	Medium	Offline visualization , CGI, photorealistic image	Used in VFX, Pixar, Arnold, Cycles renderers
Radiosity	Low	Architectural visualization , diffuse lighting	Applicable offline renders ; replaced by PBR and global lighting
Volumetric rendering	Medium	Medical visualization , scientific graphics , effects smoke / fog	Often combined with rasterization or tracing
Hybrid rendering	Medium – high	Modern games with tracing , VFX	Uses rasterization for speed and tracing for accuracy reflections and shadows

The traditional rasterization pipeline, which underlies most graphics APIs, has a complexity that grows approximately linearly with the number of triangles and pixels. However, in real conditions this is modified by the complexity of shader programs, the depth of overdraw, and memory bandwidth. Studies of GPU architectures show that

rasterization efficiency is determined by the balance between the computational power of streaming multiprocessors and memory bandwidth [2]. If the number of geometric primitives is denoted as N and the number of pixels in a frame as P, then in a simplified analysis the time cost scales as $O(N + P)$. When multilayer materials and complex fragment shaders are considered, an additional factor appears that is related to the number of instructions per pixel. The actual complexity is also influenced by the cache hierarchy and the efficiency of batched vertex processing.

Ray tracing, which has become practically viable due to specialized acceleration units in modern GPUs, has a different complexity structure. The basic algorithm generates a primary ray for each pixel and tests its intersection with all primitives in the scene, which in the naive case leads to a complexity of $O(PN)$. This is why the introduction of hierarchical acceleration structures, such as bounding volume hierarchies (BVH), became critically important [3]. The average complexity of intersection searches in a BVH approaches logarithmic behaviour with respect to the number of primitives, although it depends on the quality of tree construction and the spatial coherence of rays. In modern implementations, particularly in hardware ray-tracing platforms, studies show that the cost of building and updating the BVH can constitute a significant portion of the total frame time in dynamic scenes [4].

Stochastic global illumination methods, such as path tracing, exhibit complexity that grows linearly with the number of generated paths and the tracing depth. The number of samples per pixel determines image quality and noise level; therefore, achieving photorealism requires thousands of samples, which proportionally increases computational cost. Studies on optimizing Monte Carlo integration emphasize the importance of importance sampling and stratification to reduce variance without a proportional increase in computation time [1]. Analyzes of ray-tracing performance note that the use of hardware RT cores reduces constant factors in the complexity, while the asymptotic nature of the algorithm remains unchanged [5].

Another important factor is the complexity of material evaluation. Bidirectional reflectance distribution functions (BRDFs) may have different computational costs depending on the model. Analytical microfacet models require a relatively small number of operations, whereas tabulated or measured BRDFs involve interpolation in multidimensional spaces, increasing the cost of each shader invocation [1]. In the presence of multilayer materials with subsurface scattering or volumetric effects, computational complexity increases due to additional integration across the medium thickness.

Volume rendering represents a separate class of problems in which complexity is determined by the number of discretization steps along the ray and the resolution of the voxel grid. If a scene is described by a voxel structure containing M elements, a naive algorithm may have complexity $O(PM)$; however, the use of octrees or sparse voxel structures reduces the average number of evaluations [6]. At high data densities, memory bandwidth and cache efficiency play a decisive role.

The complexity of real-time rendering is largely defined by the frame budget. For a frame rate of 60 frames per second, the entire pipeline must complete in approximately 16 milliseconds. This imposes limits on the allowable number of primitives, shader

complexity, and the number of lighting samples. Research in interactive graphics highlights that optimization often targets reducing constant factors rather than changing asymptotic complexity, through batching, instancing, and early culling of invisible objects [7]. Frustum culling and occlusion culling reduce the effective value of N in rendering complexity, enabling scenes to scale to millions of polygons.

Parallelism is a defining characteristic of modern rendering systems. Graphics processors implement a massively parallel SIMD model that allows thousands of threads to be processed simultaneously. Theoretically, this does not change the complexity class, but it significantly affects practical execution time. Studies of GPU architectures show that performance is determined not only by the number of arithmetic units, but also by memory-access latency and scheduling efficiency [2]. Under uneven workloads, typical of ray tracing with varying reflection depths, thread divergence occurs, reducing parallel efficiency.

Another aspect is the complexity of building and updating data structures. In dynamic scenes, where objects move or deform, acceleration hierarchies must be rebuilt. BVH construction may range from linear to quasi-linear complexity depending on the algorithm, but for large numbers of objects it becomes a significant workload [3]. Some approaches employ incremental updates or hybrid structures to reduce per-frame costs [4].

The effect of image resolution on complexity is linear with respect to the number of pixels; however, modern supersampling and temporal reconstruction methods reduce the actual number of computations. Upscaling technologies based on neural networks demonstrate that part of the computation can be replaced by reconstruction from previous frames, effectively shifting the balance between rendering and post-processing [5]. This introduces a new class of complexity in which a significant portion of time is spent on matrix operations in deep neural networks.

Memory complexity is also critical. Storing geometry, textures, frame buffers, and acceleration structures requires substantial video memory resources. When memory demand exceeds available capacity, streaming becomes necessary, increasing access time and potentially altering asymptotic behaviour due to input/output operations. In large-scale scenes, such as city visualization or medical datasets, memory optimization becomes as important as computational optimization [6].

The analysis of hybrid algorithms that combine rasterization and ray tracing shows that total complexity is the sum of the complexities of the respective subsystems. For example, primary visibility may be computed via rasterization with linear dependence on the number of primitives, while reflections and shadows are computed using ray tracing with logarithmic BVH traversal. This approach reduces average frame time while maintaining high image quality [5].

In the context of large scenes, special attention is given to level-of-detail (LOD) algorithms. Reducing polygon counts for distant objects decreases effective rendering complexity without noticeable quality loss. Studies show that adaptive LOD methods can reduce GPU workload severalfold with minimal perceptual impact [7]. This demonstrates that complexity analysis must account not only for mathematical properties of algorithms, but also for psychovisual aspects.

Thus, the computational complexity of rendering is determined by many factors: the number of geometric primitives, image resolution, material complexity, number of light sources, tracing depth, acceleration structures, and hardware architectural features. A generalized summary of rendering methods with emphasis on asymptotic computational complexity is presented below.

Table 2 – Asymptotic complexity main methods rendering

Method / model	**Main idea**	**Asymptotic complexity (time)**	**Comment of dominant parameter**
Flat shading	Lighting is calculated one time on proving ground	O(N + P)	Dominates number primitives and pixels ; minimum costs on fragment
Gouraud shading	Lighting at the peaks followed by interpolation	O(V + P)	Cost transferred to the top stage ; linear dependence
Phong shading	Interpolation normals , lighting on each pixel	O(P L)	Basic load - fragmented stage ; linear on pixels and lights
Blinn–Phong	Simplified Phong variant	O(P L)	And itself asymptotics , but less coefficient
Rasterization (full GPU pipeline)	Projection primitives and pixel shading	O(N + P L)	Geometry + fragmentary stage ; usually P dominates
Ray casting (without secondary rays)	One beam on pixel	O(P N)	Naive search all primitives
Ray tracing (without structures acceleration)	Primary and secondary rays	O(P N D)	Growing linearly with depth tracing
Ray tracing with BVH	Hierarchical search intersections	O(P D log N)	Logarithmic dependence from quantities primitives
Path tracing	Stochastic tracing ways	O(P S D log N)	Dominate number samples and depth
Radiosity	Energetic exchange between surfaces	$O(M^2)$ or $O(M^3)$	Quadratic or cubic dependence from number of patch elements
Volumetric rendering (ray marching)	Integration along beam	O(P K)	K - quantity steps discretization along beam
Hybrid rendering	Combination rasterization and tracing	O(N + P · L + P · D · log N)	Total complexity component

Designation: N - quantity geometric primitives (triangles); V - number vertices; P - number pixels frame; L - number sources light; S - quantity samples on pixel; D - maximum depth tracing (number secondary rays); M - number superficial elements (patches) in radiosity.

Let's give numerical modeling time formation models Utah teapot for different separate abilities (see in table 3) Conditions modeling: – ~8,000 triangles teapot; scene ~100,000 triangles in total; 4 sources of light; depth tracing D = 4; for path tracing S = 64 samples; conditional modern mid-range GPU class.

Table 3 – Indicative time formation kettle (ms on frame)

Method	1280×720 (720p)	1920×1080 (1080p)	3840×2160 (4K)	Nature scaling
Flat shading	0.3–0.5 ms	0.6–0.9 ms	2–3 ms	~ linearly from P
Gouraud shading	0.4–0.6 ms	0.8–1.2 ms	2.5–3.5 ms	~ linearly from P
Phong shading	0.8–1.5 ms	1.5–3 ms	6–10 ms	~ P L
Rasterization (PBR)	1–2 ms	2–5 ms	8–16 ms	~ P L
Ray tracing (BVH)	3–6 ms	6–15 ms	25–60 ms	~ P D log N
Path tracing (64 spp)	20–40 ms	40–80 ms	150–300 ms	~ P S D log N
Radiosity (after preprocessing)	0.7–1 ms	1–2 ms	4–6 ms	~P
Bulk (K≈64)	4–8 ms	8–18 ms	35–80 ms	~ P K

Conclusions. Analysis computational difficulties methods rendering showed that classic models shading have relatively low complexity and are effective for small scenes or previous viewing models. Rasterization, which is used in modern GPUs, provides high speed *formation* frame and is the main method for interactive graphs. Tracing rays and path tracing provide photorealism and accuracy lighting, however much slower and require hardware acceleration or optimized structures data. Prevalence methods rendering strongly depends on class tasks: rasterization and Blinn-Phong remain dominant in the game industries, then how path tracing and radiosity are used mainly in offline visualization and CGI.

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