

Abstract

This work presents a web-based, open-source path tracer for rendering physically-based 3D scenes using WebGPU and the OpenPBR surface shading model. While rasterization has been the dominant real-time rendering technique on the web since WebGL’s introduction in 2011, it struggles with global illumination. This necessitates more complex techniques, often relying on pregenerated artifacts to attain the desired level of visual fidelity. Path tracing inherently addresses these limitations but at the cost of increased rendering time. Our work focuses on industrial applications where highly customizable products are common and real-time performance is not critical. We leverage WebGPU to implement path tracing on the web, integrating the OpenPBR standard for physically-based material representation. The result is a near real-time path tracer capable of rendering high-fidelity 3D scenes directly in web browsers, eliminating the need for pregenerated assets. Our implementation demonstrates the potential of WebGPU for advanced rendering techniques and opens new possibilities for web-based 3D visualization in industrial applications.

Acknowledgments

This report is intended to be a comprehensive documentation but also be generally accessible. The style should enable readers with different backgrounds to understand the content. To enable this, the report explains basic concepts and provides references for further reading and the possibility to dive deeper into the topic. To this avail, the report is intended to be fully self-contained and does not require any prior knowledge in the field of computer graphics.

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1 Introduction

This section provides an overview of concrete applications and high-level procedures of 3D renderers. Furthermore, it introduces prior work conducted in this field, highlighting the novel aspects of this work. The goal is to show the potential and applicability of the developed solution. Details on the involved concepts and technologies will be introduced in chapter 2 but may already be referenced briefly during the introduction.

1.1 Use Cases

The web is a versatile platform which can be used for a variety of applications. Most consumer devices have access to a web browser, which makes it an ideal platform for reaching a broad audience. Compared to native applications, web applications have the advantage of being platform-independent and do not require installation. This facilitates the distribution of applications and reduces the barrier of entry for users.

E-commerce is a key use case for product renderings. Commonly, these applications rely on taking pictures of the product. Like traditional physical catalogues, this approach struggles with highly configurable products due to the amount of images required to cover all possible configurations. Computer graphics addresses this challenge through product configurators for virtual assembly and visualization. They alleviate the need for physical processes, such as photography, and are scalable to a large number of configurations. This can be implemented by creating 3D models of the components and assembling them in a virtual environment.

As the number of components grows and the product evolves, these production models need to be kept coordinated with the marketing models used for end user visualization. To circumvent this issue, leveraging existing production *CAD* models, prevalent in mechanical engineering and product design, offers a significant advantage. These models contain geometric and material information, which eliminates the need for redundant 3D models for marketing purposes. Geometric information defines the shape of the product where material information in this context refers to the surface description of the shape. One real-world example of a company with production *CAD* data is EAO. They manufacture highly customizable industrial pushbuttons and operator panels. Due to the nature of the product, the number of possible assemblies grows almost exponentially with the number of components.

To illustrate the use case more universally, consider a product which is assembled of n component types. Each component type (i) has o_i different options. This gives the total number of possible configurations (t) as shown in Equation 1.1.

$$t = \prod_{i=1}^n o_i \quad (1.1)$$

For a product consisting of n component types where each component type has the same amount of options (o), the equation can be simplified to $t = o^n$. This shows the exponential growth of possible assemblies.

One example at EAO is a specific product family within the so-called series 45. It has 14 component types (n) and each component type has approximately 10 different options (o). This results in 10^{14} possible configurations (t) based on 140 different components. In addition, EAO has many more product series as well as product families with varying numbers of components and options. This constitutes the main use case considered for this thesis. The presented work uses EAO production models to demonstrate the feasibility and challenges of real-time rendering of highly configurable products, but similar use cases can be found in other industries.

A web-based configurator using computer graphics for virtual assembly is well suited to address such use cases where almost exponential growth in possible configurations is present.

1.2 CAD Data Preprocessing

To leverage production *CAD* models, the models need to be preprocessed as visualized in Figure 1.1.

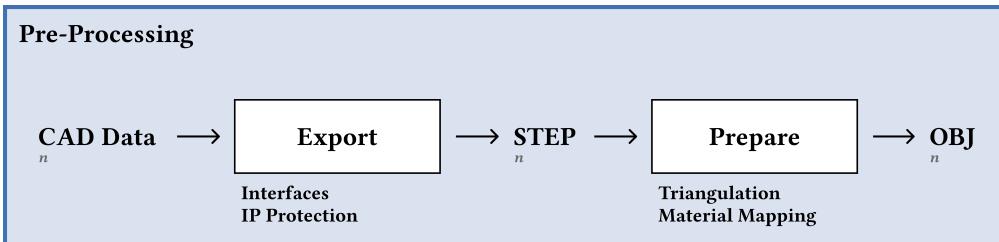


Figure 1.1: A two-step preprocessing stage is employed for offline as well as real-time rendering pipelines.

The preprocessing step must define a rule set for the assembly. This rule set provides data on what kind of components can be added to the assembly and where they can be attached to. This interface definition can be provided using meta information files. Alternatively, this can also be represented geometrically within the model by using identifiable shapes to attach components to. *STEP*¹ files are a common format for exchanging *CAD* data and can be used for this purpose, but as will be discussed in section 2.5, other formats are more suitable for rendering and address inherent limitations of *STEP* files.

¹*Standard for the Exchange of Product model data*, a standard formalized in ISO 10303 for product manufacturing information.

Another important consideration are intellectual property rights when using *CAD* models from production processes. The models may contain proprietary information which should not be disclosed to the end user. As described by Stjepandić et al. [1], steps to circumvent this issue may include data filtering. Filtering can be implemented by removing meta information such as constraints or by removing occluded parts of the model, essentially limiting the model to the hull of the assembly. As a positive side-effect, this can also reduce the complexity of the model, which can be beneficial for rendering performance.

Preprocessing includes triangulation of the meshes, which is a common requirement for rendering engines. Frequently, the triangulated meshes are fine-grained and consist of a large number of triangles. This can lead to performance issues when rendering the scene. One way to handle this is to simplify the meshes by decimating triangles. Procedures for this purpose are well-established and include algorithms for generating level of detail (*LOD*) artifacts [2].

While numerous *CAD* formats include material information, it is often unsuitable for rendering because it does not describe optical properties. To address this, a material mapping can be defined, translating *CAD* materials to a suitable representation for the rendering pipeline.

The concrete formats used for the preprocessing step are dependent on the *CAD* software. However, conversion tools exist for most common *CAD* formats and the general approach remains similar. After the preparation process, a rendering architecture paradigm can be employed to enable users to virtually assemble the product.

1.3 Rendering Architecture Paradigms

In order to render the assemblies based on the preprocessed information, three main paradigms can be employed for web-based applications: offline rendering, client-side real-time rendering, and remote real-time rendering. These paradigms differ significantly and the technology stack varies between them. Therefore, the choice of a suitable paradigm is pivotal for the implementation of the application.

Offline Rendering

Offline rendering requires pre-rendering all product configurations. This is theoretically possible for a finite number of configurations, but computationally expensive.

An offline rendering pipeline generates static images of the assembly, which are then displayed in the browser. This means that all possible assemblies need to be rendered and stored upfront. As the number of components increases, the number of possible combinations grows exponentially, which can lead to large amounts of storage and processing power being required, as shown in Figure 1.2.

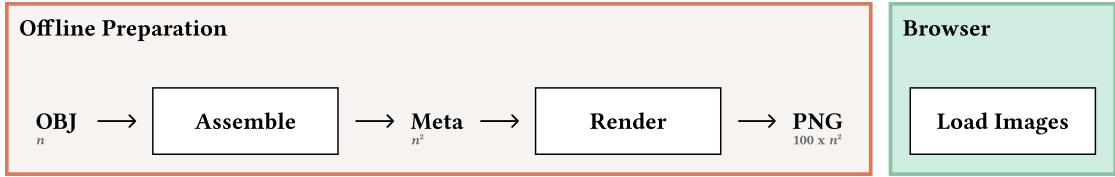


Figure 1.2: In an offline rendering setup, the number of images grows exponentially. The number of images increases further when offering 360° viewing.

Interactivity is limited by requiring all desired viewing angles to be defined upfront. 360° viewing experience using a single degree of freedom can be provided by rendering images in regular intervals. 100 images would be needed to get an image every 3.6°. These images can then be loaded in the browser as the user drags. However, if more degrees of freedom, different lighting situations, and zoom levels need to be supported, a similar growth in rendered images can be observed as for the assemblies.

In order to address latency, pre-loading images can be used. This may entail loading additional images in the background to enable a smooth user experience. However, this leads to increased bandwidth usage.

Client-Side Real-time Rendering

An alternative to offline rendering is real-time rendering. For real-time rendering, client-side rendering is a frequently used option. These approaches render the assemblies only as requested by the end user. This is the main benefit of using a real-time rendering pipeline, as illustrated in Figure 1.3. The rendering is done in the browser, limiting the server to serve the role of a file host and provide the geometry and material information in a 3D exchange format such as *glTF*². This approach is more flexible and can be used for a large number of configurations. The amount of data to be stored and processed offline grows linearly with the number of components, independent of the number of possible configurations.



Figure 1.3: A real-time rendering pipeline solely relies on having an adequate model for each component of the assembly. It does not require pre-rendering every possible configuration.

This approach limits the technology which can be used for rendering. The rendering is done in the browser, which means that it is dependent on the browser engine as well as

²*Graphics Library Transmission Format*, common 3D exchange format optimized for transmission and real-time rendering.

the specific device hardware. It restricts the complexity of the scene to the hardware constraints of the device.

Remote Real-time Rendering

For real-time rendering, an alternative paradigm is remote rendering [3], which employs a server to render the scene and stream the visualization to the browser. The main drawbacks of this approach are network latency, reliance on network stability, and operational cost for the server infrastructure, which frequently requires dedicated *GPUs*³ for rendering.

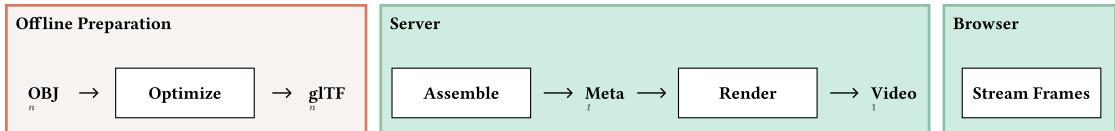


Figure 1.4: A remote rendering pipeline relies on a server to consistently stream the data in real-time to the client.

To fulfill thresholds frequently used for real-time rendering, the network latency should be below 20 ms. Recent studies have shown that this threshold is still a challenge, even when considering the fastest networks available at a given location. Many locations do not have access to any cloud data centers with a latency below 20 ms. [4]

Comparison

To evaluate the different paradigms, a set of criteria are defined. These criteria are used to show the advantages and disadvantages of each paradigm. The importance of each criterion is dependent on the specific use case and can be a primary determinant for the choice of paradigm.

Preprocessing Cost

Measure how much computation effort is required to prepare the data for rendering. Generally, lower is better. Offline rendering needs to pre-render all assemblies, essentially doing exhaustive rendering. Client-side rendering and remote rendering only need basic preprocessing.

Hosting Cost

The infrastructure cost involved in hosting the application during operations. Generally, lower is better. Offline rendering does not require application servers and mainly relies on storage for the generated images. Similarly, client-side rendering needs storage for the models. These two paradigms may employ *CDNs*⁴. Remote rendering requires a

³Graphics Processing Unit, specialized processor for parallel computation

⁴Content Delivery Network, distributed group of servers for caching content near end users.

rendering server, which can be costly and may induce additional complexity. In addition, bandwidth costs need to be considered.

Storage

The amount of data storage required for the application. Generally, lower is better. Offline rendering requires storage for all rendered images, possibly in multiple resolutions to support different types of devices. Client-side rendering only requires storage for the models, as does remote rendering.

Main Performance Dependency

The main bottleneck in terms of rendering performance for the end user. Offline rendering sends static images, a process which is highly optimized by browser engines and image compression algorithms. Rendering such images is faster than real-time rendering, which is heavily dependent on the device hardware. Remote rendering is dependent on the network connection.

Interactivity

The level of interactivity the user can expect. Generally, higher gives more flexibility. Offline rendering means all possible views need to be pre-rendered. Extending views requires additional pre-rendering, which optimally is done using a delta change detection to prevent re-rendering unchanged views. Client-side rendering and remote rendering enable real-time interaction of the user without constraints. They also enable easier experimentation with different view configurations and open the possibility for using content provided by the end user in the rendering process. Such content could be lighting condition, background, or additional objects.

Network Dependency

The reliance on a stable network connection. Generally, lower is better. Offline rendering needs to load the images, which is efficient. Client-side rendering requires an initial connection to download the models but is independent afterwards. Remote rendering consistently requires a stable connection to stream the rendered images.

Maximum Scene Complexity Dependency

The main bottleneck in terms of the complexity of the scene that can be rendered. Generally, using a server gives more flexibility as the provider has full control over the hardware capabilities. Offline rendering can handle complex scenes given dedicated hardware. Client-side rendering is dependent on the device, the weakest supported device defines the possible scene complexity. Nowadays, rendering models with millions of triangles is possible on mid-range devices. Remote rendering can handle complex scenes, but is limited to hardware constraints of real-time rendering, which does not cover huge scenes.

Assessment

Each of the paradigms has its own advantages, Table 1.1 highlights the strengths and weaknesses of each approach and provides a comparison of the criteria.

Rendering Paradigm	Offline	Real-time	
		Client-Side	Remote
Preprocessing Cost	High	Low	Low
Hosting Cost	Low	Low	High
Storage	High	Low	Low
Main Performance	network	device	network
Dependency			
Interactivity	Low	High	High
Network Dependency	Low	Low	High
Max Complexity Dependency	server	device	server

Table 1.1: High-level comparison between different rendering architecture paradigms.

Offline rendering is suitable for applications where pregenerating all images is feasible and limited interactivity is acceptable. Real-time rendering, either client-side or remote, is a suitable choice for applications where the number of possible configurations is high and interactivity is important. The choice between client-side and remote rendering depends on the network infrastructure and the complexity of the scene. Generally, client-side rendering setups can be extended to support remote rendering and offline rendering, while offline rendering setups as well as remote rendering setups are possibly not capable of client-side rendering due to technical constraints imposed by the available technology. Based on this assessment, this work focuses on client-side rendering, with the possibility to extend to other paradigms in the future.

1.4 Prior Work

This section highlights related work for web-based client-side real-time rendering. A rough overview of the different approaches is given, but more detailed information on concepts, technology, strengths and weaknesses, and the benefits ray tracing provides over rasterization will be discussed in section 2.3.

Rasterization is a rendering technique that projects 3D scene geometry onto a 2D plane. The technique has been widely adopted in real-time rendering due to its efficiency. However, rasterization has limitations in achieving photorealism. Effects such as shadow casting and reflection do not require additional techniques.

Ray tracing is a powerful technique for rendering photorealistic scenes, which inherently supports effects such as shadow casting and reflection. Historically, ray tracing has been

used in offline rendering due to its computational complexity. However, advancements in hardware have enabled real-time ray tracing in a variety of domains.

Web-based Real-Time Renderers

Different web-based real-time rasterizers exist. The main options include:

- *Three.js* [5] — most widely used web rendering engine.
- *Babylon.js* [6] — popular web rendering engine.
- *PlayCanvas* [7] — game engine for the web.
- *A-Frame* [8] — web framework for building virtual reality experiences.

In addition, *Unity*, a common game engine for desktop and mobile applications also supports *WebGL*⁵ [9].

These engines focus on rasterization techniques and are widely used for web-based applications. The focus of these engines lies on real-time rendering performance as used in games, advertising campaigns, virtual reality (VR), augmented reality (AR), medical imaging, scientific visualization, and educational applications. However, they lack support for ray tracing.

Web Path Tracers

Path tracing is a specific ray tracing technique. There are a variety of path tracers available for the web. Most of them are based on *WebGL*. The first experiments of using *WebGL* for path tracing were implemented as early as 2010. One such example is the Google experiment demonstrating a Cornell Box [10] with basic primitive shapes such as spheres and planes [11].

Since then, a variety of open-source implementations for the web have been created. Some of the most widely known path tracers are based on *Three.js*. A more detailed comparison of these path tracers is provided in section 4.1.

- `three-gpu-pathtracer` [12] — One of the most widely known path tracers for the web developed by Johnson. This path tracer is implemented as a *Three.js* plugin and uses *WebGL* for rendering. It is bundled as a library and can be used to render scenes in the browser.
- `Three.js PathTracer` [13] — Path tracer based on *Three.js* developed by Loftis. This path tracer is also implemented as a *Three.js* plugin and uses *WebGL* for rendering. It does not provide a library, but can serve as a basis for further development.

⁵ *Web Graphics Library*, since 2011 the de-facto standard API for rendering 3D graphics on the web

- `dspbr-pt` [14] — Path tracer by Dassault Systèmes implemented in *WebGL*. It implements the Dassault Systèmes Enterprise PBR Shading Model (*DSPBR*). However, the implementation has not been updated in recent years.

All of these path tracers are based on *WebGL* and are either plugins for *Three.js* or support *Three.js* scene description.

WebGPU

WebGPU is a new web *API*⁶ for leveraging the power of *GPUs* and serves as a successor to *WebGL*. Various applications of *WebGPU* have been investigated in recent years. Examples include Dynamical.JS, a framework for visualizing graphs [15]; RenderCore, a research-oriented rendering engine [16]; and demonstrations of how to use *WebGPU* for client-side data aggregation [17].

Research on the performance comparison between existing 3D engines and *WebGPU* engines has been conducted as part of the development of FusionRender, which concluded that measurable performance gains can be achieved by using *WebGPU*, but only when effectively leveraging its novel design principles [18]. Similar findings have emerged from other independent studies, showing that *WebGPU* can be faster than *WebGL* [19, 20, 21].

Conclusion

Work has been conducted in related fields; this includes research into applicability of *WebGPU* as well as writing web-based path tracers using *WebGL*. However, the research suggests that no open-source path tracing library using *WebGPU* has been developed. In light of these findings, *WebGPU* presents a transformative opportunity. It is particularly well-suited for the development of a new real-time path tracing library for the web which provides an alternative approach to existing rasterization-based rendering engines.

⁶*Application Programming Interface*

2 Theory

This section provides an overview of the theoretical background required to develop a path tracer. It covers the basic concepts as well as details of the underlying algorithms and data structures. Additionally, details about the involved technology as well as a historic overview are provided.

2.1 Mathematics

This section highlights some basics about the mathematics involved in computer graphics and establishes a common understanding of concepts and notations referenced in the following sections. The section covers topics such as notation of vectors, matrices, integrals, and the Bachmann-Landau notation.

Vectors

Euclidean vectors are fundamental in computer graphics and are generally defined by a magnitude and a direction. In a three-dimensional space, a vector can be defined as $v = (x, y, z)$. This definition can be used to represent points in space (vertex) as well as directions.

The cross product (vector p) of two vectors $v = (x_1, y_1, z_1)$ and $w = (x_2, y_2, z_2)$ is defined as:

$$p = v \times w = (y_1 \cdot z_2 - z_1 \cdot y_2, z_1 \cdot x_2 - x_1 \cdot z_2, x_1 \cdot y_2 - y_1 \cdot x_2) \quad (2.1)$$

As visualized in Figure 2.1, the cross product gives a vector p which is orthogonal to the two input vectors v and w .

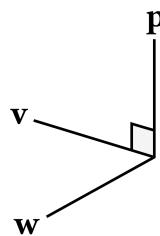


Figure 2.1: Cross product of two vectors v and w , resulting in a vector p orthogonal to v and w .

Matrices

Matrices are used to represent transformations in computer graphics. A matrix can be defined in row-major order as:

$$M = \begin{bmatrix} M_{1,1} & M_{1,2} \\ M_{2,1} & M_{2,2} \end{bmatrix} = \begin{bmatrix} a & b \\ c & d \end{bmatrix} \quad (2.2)$$

Ray

A ray can be defined as $r = (Q, d)$ where Q is the origin vertex of the ray and d is the direction.

Triangle

A triangle can be defined as $t = (Q, u, v)$ where Q is the position of the triangle and u and v are vectors defining the triangle. See Figure 2.2 for a visual representation.

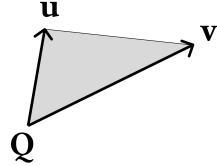


Figure 2.2: Triangle defined using three vertices, Q as the position and u, v as direction vectors starting at Q .

An alternative way to define a triangle is using three vertices, each in world space. The vertices can be defined as $v_1 = (x_1, y_1, z_1)$, $v_2 = (x_2, y_2, z_2)$ and $v_3 = (x_3, y_3, z_3)$. Converting between the two systems can be done using the following formulas:

$$Q = v_1 \quad (2.3)$$

$$u = v_2 - v_1 \quad (2.4)$$

$$v = v_3 - v_1 \quad (2.5)$$

A triangle has three normals, one for each vertex. The normal of a triangle can be calculated using the cross product of two edges of the triangle.

Frustum

The frustum is a geometric shape which is used to define the camera's view. See Figure 2.3 for a visual representation.

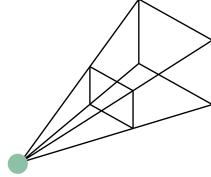


Figure 2.3: Frustum shape, the green dot indicates the position of a camera in perspective projection.

Integral

An integral is used to determine the area under a curve as visualized in Figure 2.4. The integral of a function $f(x)$ over an interval $[a, b]$ is defined as:

$$\int_a^b f(x) dx \quad (2.6)$$

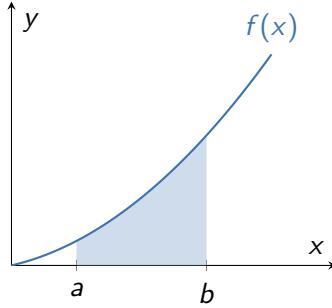


Figure 2.4: Visualization of integral, the area under the curve $f(x)$ between a and b .

In order to take an integral over a different domain S , which may represent a set of vectors representing directions, the integral can be defined as:

$$\int_S f(x) dx \quad (2.7)$$

Probability Theory

Variance is a measure of dispersion, defining large the difference between the average and the individual values in a set of numbers. It is calculated as the average of the squared differences from the mean. The variance of a set of numbers x_1, x_2, \dots, x_n is defined as:

$$\sigma^2 = \frac{1}{n} \sum_{i=1}^n (x_i - \mu)^2 \quad (2.8)$$

where μ is the mean of the set of numbers.

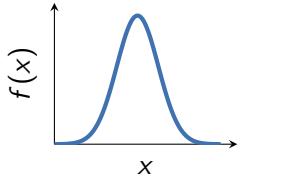
The standard deviation (σ) is the square root of the variance (σ^2). It is a measure of the dispersion of a set of numbers and can be used to determine a confidence interval. This interval is a range of values which has a certain probability of containing the value. High variance leads to a wide confidence interval which indicates that the data is spread out. The confidence interval as a \pm margin of error deviation from the mean is then defined as:

$$z \frac{\sigma}{\sqrt{n}} \quad (2.9)$$

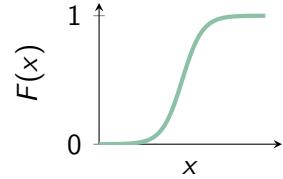
where z is the z-score of the desired confidence level, for example, 1.96 for a 95% confidence interval. n is the number of samples.

This can be used to assess the quality and reliability of measurements such as required for benchmarking.

Another important concept is the probability density function (*PDF*). It describes the likelihood of a random variable to take on a specific value. It is related to the cumulative distribution function (*CDF*) which describes the probability that the random variable will be less than or equal to a specific value.



(a) PDF visualized



(b) CDF visualized

Figure 2.5: *PDF* and *CDF* of normal distribution visualized

Bachmann-Landau Notation

The Bachmann-Landau notation, or more specifically, the Big O notation, is used to describe the behavior of a function as the input size grows. The notation is used to describe the upper bound of a function. For example, if a function $f(n)$ is $O(n^2)$, it means that the function grows at most quadratically with the input size n . The Big O notation is used to describe the growth of algorithms in terms of run time or space requirements.

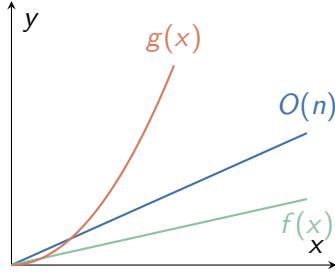


Figure 2.6: Example of Big O notation, the function $f(x)$ is $O(n)$, but $g(x)$ is not.

2.2 Physics

In order to generate images using computer graphics, understanding the physics is crucial. More specifically, the study of light and its perception is important. In physics, optics is the study of light. The field encompasses topics such as light propagation and optical properties of matter. Maxwell's equations are a set of equations in electromagnetism that describe the behavior of electromagnetic fields. Formulated by James Clerk Maxwell in the 19th century, they provide a mathematical framework for understanding the propagation of electromagnetic waves, including, but not limited to, visible light. Light can be described as a wave or as a particle, this is generally known as the wave-particle duality. [22]

Reflection

Reflection is the process of light bouncing off a surface. The angle of incidence equals the angle of reflection as visualized in Figure 2.7. An example of such an effect can be seen when looking at a mirror.

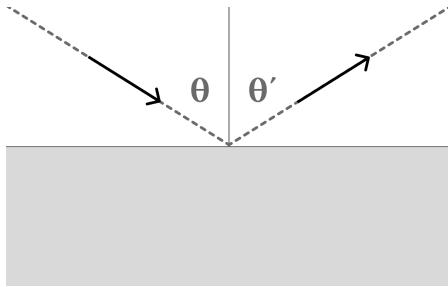


Figure 2.7: Reflection of light when hitting a surface.

This can be described using the law of reflection:

$$\theta = \theta' \quad (2.10)$$

Where θ is the angle of incidence and θ' is the angle of reflection.

Refraction

Refraction is the bending of light when passing through a medium as visualized in Figure 2.8. An example of such an effect is the distortion of underwater objects.

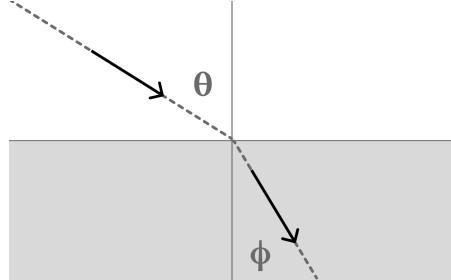


Figure 2.8: Refraction of light when passing through a medium.

It can roughly be defined by using Snell's law:

$$\frac{\sin \theta}{\sin \phi} = n \quad (2.11)$$

or in a more general form:

$$n_1 \sin \theta = n_2 \sin \phi \quad (2.12)$$

where n_1 and n_2 are the refractive indices of the two media and θ and ϕ are the angles of incidence and refraction respectively.

Leveraging Snell's law, Fresnel equations can be derived which describe not only the refraction but also the reflection of light when passing through a medium.

Material Properties

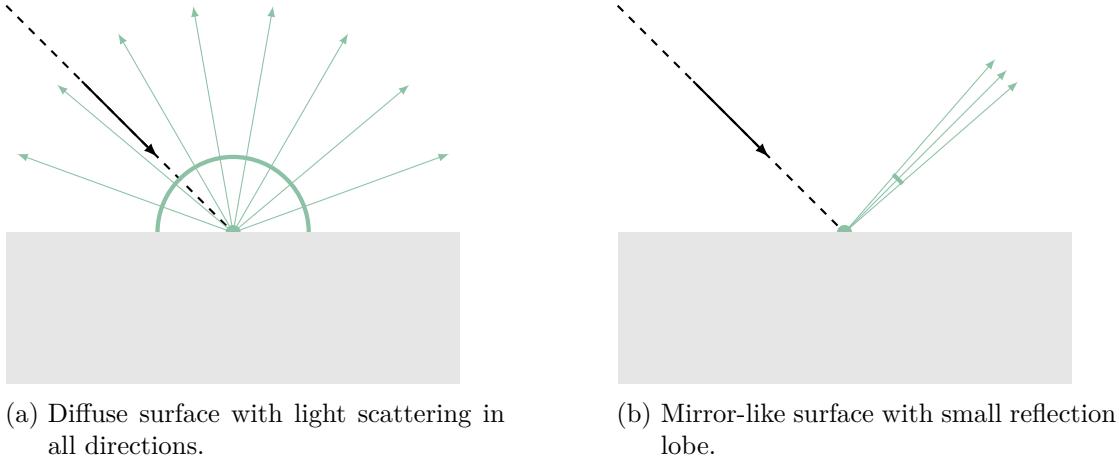
Common terminology used to describe the optical properties of materials is helpful to understand the behavior of light and the challenge of simulating it. Some of the most common terms are:

- Diffuse Reflection — light is scattered in all directions, independent of the viewing angle. An example of such a material is paper or chalk. As early as the 18th century, Lambert described the reflection of light on a surface [23]. Lambertian reflection is still used as a term for diffuse reflection.
- Specular Reflection — light is reflected in a specific direction. This leads to highlights on the surface.
- Roughness — defines how smooth the surface of the material is. A rough surface scatters light in many directions, while a smooth surface reflects light in a specific direction.

- Metallic — the material reflects light in a specific direction.
- Dielectric — materials which do not conduct electricity. These materials are not using metallic reflection.
- Absorption — defines how much of the light is absorbed by a material. In general, darker colors absorb more light than lighter colors. One prominent example is Vantablack, a highly absorbent material.
- Emission — the material emits light. An example of such a material is a light bulb or the sun.
- Scattering — the material scatters light. An example of such a material is fog or clouds.
- Subsurface Scattering — light penetrates the material and is scattered. An example of such a material is skin or marble.
- Isotropy — property of materials which have the same properties in all directions. An example of such a material is glass or water. Anisotropy on the other hand is a property of materials which have different properties in different directions. An example of such a material is wood or brushed metal.

Generalization

The mentioned laws are rough approximations of the real world. Additional phenomena such as absorption and emission of light also affect the appearance. In general, many surfaces have a combination of these effects and need to consider the incidence as well as outgoing light, necessitating a bidirectional reflection model. This model defines where the largest contribution to overall radiance comes from, commonly referred to as the reflection lobe. Simplified, the main contribution can be visualized using an arc indicating the direction of the most significant contribution. For example, a diffuse surface scatters light in all directions (Figure 2.9a), while a mirror-like surface reflects light in a specific direction (Figure 2.9b).



(a) Diffuse surface with light scattering in all directions.
(b) Mirror-like surface with small reflection lobe.

Figure 2.9: Bidirectional reflection models for two different types of surfaces with green arc indicating reflection lobe.

2.3 Computer Graphics

This section provides an overview of computer graphics, including its history, key concepts and applications.

Since the early days of computing, researchers have explored ways to process visual information using computers. While the field also encompasses aspects such as image processing or two-dimensional graphics, the main focus of this thesis is on three-dimensional computer graphics. While this includes topics such as animation, geometry processing, the main topics covered are geometry representation, rendering and shading.

2.3.1 Global Illumination

Research to render advanced lighting effects using computer graphics was conducted as early as the 1960s. One of the earliest papers describing approaches to render shadow casting was written as early 1968 by Appel [24]. In order to describe the phenomena, encountered in real life, a more advanced shading model was required.

To describe these phenomena, the term global illumination was coined by Whitted in 1979 [25]. It describes a complete shading model that simulates real lighting and reflection as accurately as possible [26].

While global illumination commonly refers to a subset of effects, the term is used here to encompass a wide range of effects. Simulating real lighting includes effects such as:

- Shadow Casting — The absence of light as obstructed by other objects.
- Reflection — As in the case of mirror-like objects, but also for specular and metallic reflection.

- Color Bleeding — Special type of reflection, where a surface is colored by reflection of colored light.
- Ambient Occlusion — Special type of shadow casting, where light transport as impacted by nearby objects is considered. This is frequently encountered on objects with complex topology.
- Refraction — As encountered when light passes through a medium such as water or glass.
- Caustics - Effect produced by either reflection or refraction of light.

Refraction and caustics were not encountered in the use cases of this thesis and are therefore not covered in detail.

Figure 2.10 shows a visualization of the most notable effects. The image shows a floor with a white diffuse material, two walls with a red diffuse material and a specular sphere. The sphere casts a shadow onto the floor, the walls are reflected onto the sphere, the prominent red color bleeds onto the white floor.

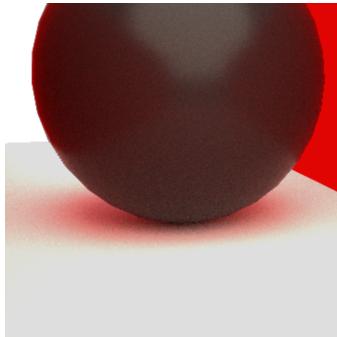


Figure 2.10: Image showing the different kinds of effects which can be achieved using global illumination.

2.3.2 Rasterization

In order to visualize 3D scenes using a computer, different rendering approaches have been developed. Two of the most common approaches are rasterization and ray tracing. Rasterization will be described in more detail in this section, ray tracing will be discussed in the next section.

Rasterization is a rendering technique which maps the geometry of a 3D scene onto a 2D plane. It is well-suited for real-time rendering due to its efficiency. The process of rasterization can be broken down into multiple steps and is commonly referred to as the graphics pipeline. The stages of the pipeline are shown in Figure 2.11.

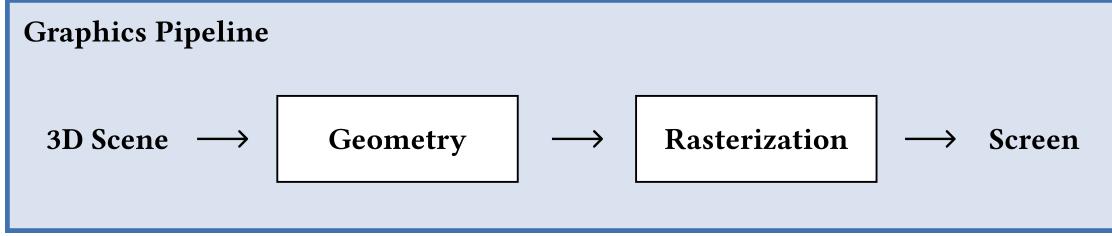


Figure 2.11: The main steps of the graphics pipeline used for rasterization.

As a pre-requisite, the 3D scene is defined. The scene consists of vertices which are grouped to triangles forming the geometry. The geometry stage iterates over all triangles and uses camera configuration to perform view projection as described in subsection 2.3.4, changing the position of the vertices to the camera's perspective. The rasterization stage converts the continuous geometry into discrete fragments. When having overlapping triangles, the depth buffer is used to determine which fragment is closer to the camera and therefore visible. The fragment processing stage determines the color of every pixel. Finally, the frame buffer is output to the screen.

One of the main limitations is the lack of support for global illumination. For example, shadows are generally not cast, reflections are not visible, color bleeding is not considered, and ambient occlusion is not simulated.

Advanced Techniques

To address these limitations, the graphics pipeline can be extended with additional steps such as post-processing effects or advanced rendering techniques.

Various methods have been developed to address these limitations, including pre-baked shadow, environment [27] and light maps; screen space reflections (SSR) [28]; screen space ambient occlusion (SSAO) [29]; and screen space directional occlusion (SSDO) [30].

Environment Maps

Environment maps can be used to simulate reflections. The technique uses a texture which is mapped to the environment of the scene and is used to simulate reflections. The technique does not support reflections occurring dynamically in the scene.

Shadow Maps

Shadow maps are employed to store shadow information for a scene based on the available light sources. These shadows are pregenerated, before being employed in the rendering process. While this technique is very suitable for use cases where the scene is static, there are limitations when the scene is dynamic and the different components of an assembly cast shadow on each other.

Multi-pass Rendering

Multi-pass rendering is a technique which is used for a multitude of use cases, but among other things can be used to simulate reflections. Instead of rendering the scene in a single pass, the scene is rendered multiple times with different configurations. For example, to simulate reflections, the scene is first rendered from the perspective of the reflective object and then renders a second pass from the camera while leveraging the first pass as a texture.

Conclusion

Each of these methods addresses only a specific limitation of rasterization. Some of them only partially alleviate the issue. These approaches induce complexity, may need to be computed at the assembly level, and can be computationally expensive. An alternative technique which resembles reality more closely could alleviate these issues: ray tracing.

2.3.3 Ray Tracing

Ray Tracing is a rendering technique which simulates light transport in a scene. The main idea is to cast rays from the camera into the scene and compute the color of the object the ray intersects with. In contrast to a rasterizer, which iterates over the triangles of the scene, ray tracing iterates over the pixels of the image. For each pixel, a ray is cast into the scene. By adding additional bounces of the light ray, the technique can simulate global illumination.

Early algorithms were based on recursive ray tracing [25]. These algorithms determine intersection with geometry and iteratively generate branches as shown in Figure 2.12. For each pixel, a primary ray is cast into the scene. When intersecting with a surface, the algorithm considers the light sources and generates secondary rays. These rays are then recursively traced and radiance is calculated until a maximum depth is reached.

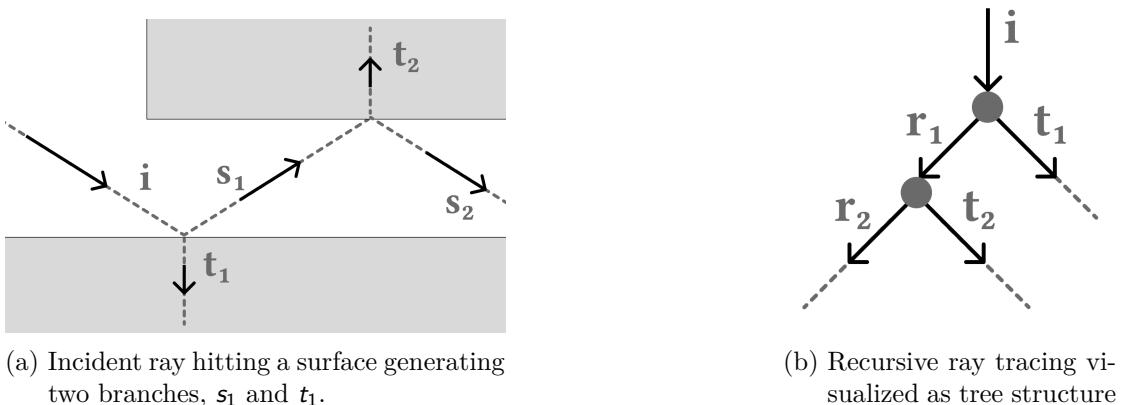


Figure 2.12: Recursive ray tracing as described by Whitted [25].

Due to the computational complexity of these early algorithms, ray tracing was not widely adopted until the 1980s.

During these years, one of the main concepts was the introduction of the rendering equation by Kajiya in 1986 in a paper which also coined the term path tracing. Generally, path tracing can be seen as a Monte Carlo integration of the rendering equation which is defined as:

$$I(x, x') = g(x, x')[\epsilon(x, x') + \int_S p(x, x', x'') I(x', x'') dx''] \quad (2.13)$$

where $I(x, x')$ is the radiance from point x to point x' . x for example being the camera position and x' the intersected object. $g(x, x')$ is a geometry term determining how much light is transmitted. This depends on the distance and possibly occlusions such as transparent surfaces. $\epsilon(x, x')$ is the emitted radiance, generally used for light sources. The integral term is taken over $S = \cup S_i$ which is the union of all surfaces. $p(x, x', x'')$ is the bidirectional reflection function, which describes how light from all possible directions x'' is reflected at the surface. [31]

Some of the first widely used ray tracing software was POV-Ray, which was released in 1991 [32]. Blue Moon Rendering Tools (*BMRT*) [33], a renderer compliant with *RenderMan*¹, was released in the mid 90s and was one of the first ray tracing renderers to be used in the industry. In 2003 *RenderMan* included ray tracing capabilities [34].

Further research into light transport techniques such as bidirectional light transport or Metropolis light transport has been conducted in the 1990s [35]. Concrete techniques will be described in the next section.

Monte Carlo Integration

Monte Carlo integration is a statistical technique to approximate the solution integral numerically. At the core of the integration lies an estimator which can be defined as:

$$G = \frac{1}{M} \sum_{i=1}^M g(X_i) \quad (2.14)$$

where G is the estimate of the solution, g is the function to be approximated and X_i is the random sample. Taking M samples and averaging the results provides an estimate of the solution. [36]

In the context of ray tracing, Monte Carlo integration is used to approximate the rendering equation, as defined in Equation 2.13. Applying the principle of Monte Carlo, the radiance of a pixel can be approximated by iteratively casting rays into the scene and averaging the results.

While Monte Carlo integration is a powerful technique, it heavily relies on the quality of the estimator which is employed. Using importance sampling can improve the rate of convergence. Importance sampling is a technique which leverages a proposal *PDF*, different from the target *PDF*, to estimate the expected value of a target function. By

¹A rendering software for photorealistic 3D rendering developed by Pixar

sampling more frequently in regions where the function has a higher value, the variance of the estimator can be reduced. In order to account for the probability distribution and prevent bias in the estimator, the estimator can be defined as:

$$G = \frac{1}{M} \sum_{i=1}^M \frac{g(X_i)}{p(X_i)} \quad (2.15)$$

where $p(X_i)$ is the probability distribution of the function to be approximated [37]. To do the sampling, different strategies can be considered. For example, one can use the material properties to determine where to cast the rays. A highly-reflective surface such as a mirror will apply the law of reflection, while a diffuse surface will scatter the rays in all directions. This strategy is yielding solid results for scenes with large light sources and reflective surfaces as illustrated in Figure 2.13b. However, for scenes with small light sources and diffuse surfaces, the strategy can lead to high variance as shown in Figure 2.13a. The variance is visible to the human eye as noise in the image.

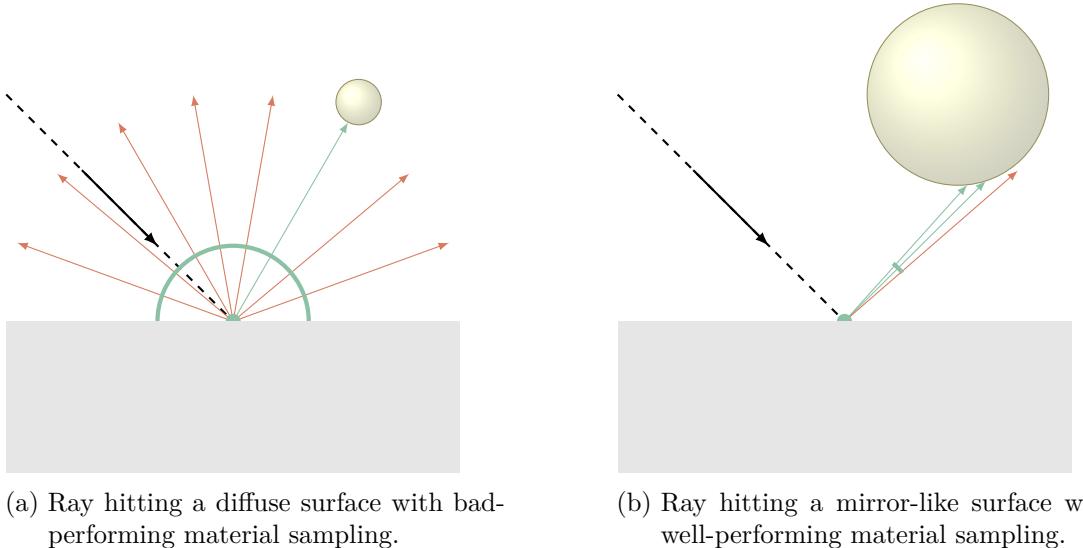
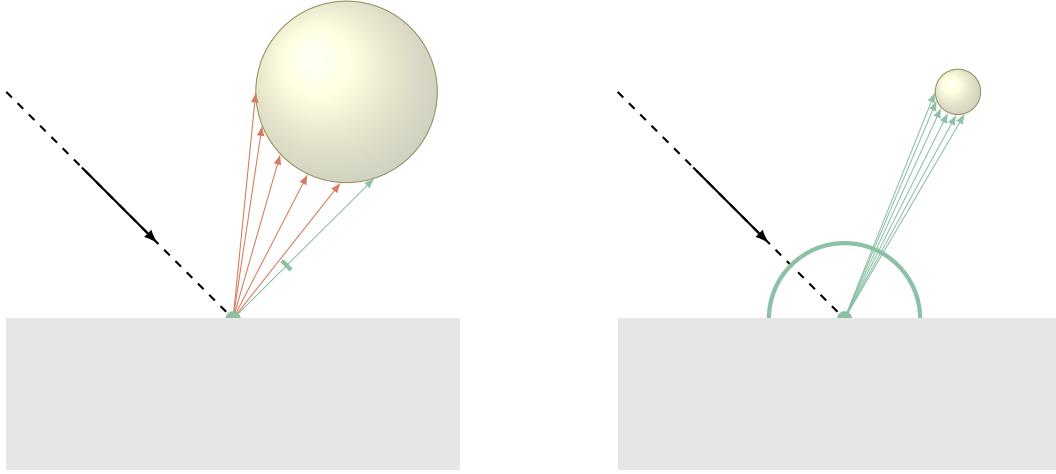


Figure 2.13: Material sampling strategy weakness and strength

Using light source sampling as an alternative sampling strategy can alleviate this issue. As shown in Figure 2.14b, it can significantly reduce the variance of the estimator when having diffuse surfaces and small light sources. Conversely, the strategy can lead to high variance when having large light sources and reflective surfaces as shown in Figure 2.14a.



(a) Ray hitting a mirror-like surface with bad-performing light source sampling.

(b) Ray hitting a diffuse surface with well-performing light source sampling.

Figure 2.14: Light source sampling strategy weakness and strength

Both strategies are good candidates under different circumstances. To leverage the benefits of both strategies, Veach extended importance sampling in 1997 [35] by introducing multiple importance sampling (*MIS*). The idea is to combine multiple sampling strategies to improve the overall estimator.

Russian Roulette

Russian roulette is a technique for improving efficiency by employing probabilistic path termination. It selectively discards paths with low expected radiance contribution. If a path contributes zero radiance to the final image, it can be terminated early without affecting the radiance of the final image. However, if the path has a small but non-zero contribution, discarding it introduces bias into the calculation. Russian roulette solves this by introducing a probability of termination which is inversely proportional to the radiance of the path. Paths with low radiance are more likely to be terminated. Paths which are continued are scaled by the inverse probability of termination. This ensures to account for the bias introduced by the termination.

Mathematically Russian roulette is commonly formulated as shown in equation 2.16 [37].

$$I' = \begin{cases} \frac{I - qc}{1-q} & \xi > q \\ c & \text{otherwise} \end{cases} \quad (2.16)$$

where I is the radiance of the path. q is the probability of termination, which can be calculated for example based on the radiance of the path. ξ is a random number between 0 and 1. c is the contribution of the path which is terminated, commonly set to zero. I' is the scaled radiance of the path.

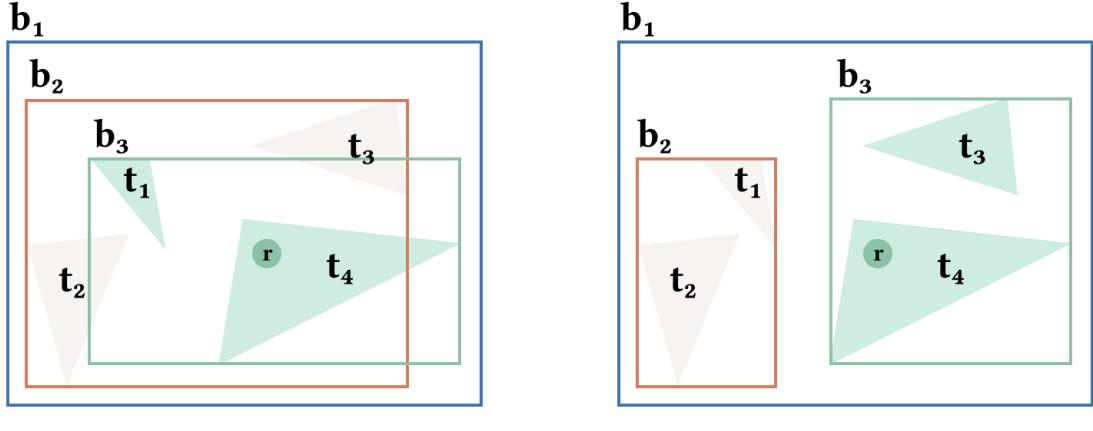
Intersection Testing

When casting a ray into the scene, the first step in a ray tracer is to determine where the ray intersects with the geometry of the scene.

A brute force approach could be to determine the intersection distance for each object to the ray and picking the one with the lowest distance. Given the fact, that common objects consist of thousands of triangles (n) and ray tracing many rays, this approach is not efficient as it would worst case require $O(n)$ intersection tests for each ray.

In order to accelerate the intersection testing, various approaches have been developed. The bounding volume hierarchy (*BVH*) is an acceleration structure which is leveraged to speed up the ray intersection tests. This method is widely used in ray tracing and has been studied for a long time [38]. The core idea is to group adjacent objects in a bounding volume and structure the hierarchy in a way that all child elements of a node are contained in the bounding volume of the parent node. The nodes, employed for storing the bounding volume are often axis-aligned bounding boxes (*AABB*). This allows for early rejection of branches which are not intersected by the ray. By employing a *BVH*, the number of intersection tests (n) can be reduced from $O(n)$ to $O(\log(n))$.

An *AABB* (b) can be defined as $b = (\min, \max)$ where \min and \max are the minimum and maximum vertices of the bounding box. The boxes are then grouped into a hierarchy where the maximum and minimum vertices of the children define the bounding box of the parent. This is visualized in Figure 2.15. Good performance of the *BVH* depends on the quality of the hierarchy. A badly constructed *BVH* can lead to a higher number of intersection tests as visualized in Figure 2.15a because intersections need to be tested against all elements: three bounding boxes and four triangles. For a well-constructed *BVH*, the algorithm can reduce the number of intersection tests as visualized in Figure 2.15b by doing the minimum amount of intersection tests: b_1 , which intersects, b_2 which can be discarded after checking and then b_3 necessitates further intersection tests for the two contained triangles. For such a small number of triangles, the overhead of the *BVH* exceeds the benefits, but for larger scenes, the performance gain is significant as the amount of tests can be halved for well-balanced trees.



(a) Badly-constructed *BVH* which requires seven intersection tests for r , essentially testing against all objects.

(b) Well-constructed *BVH* which reduces the required intersection tests for r to four.

Figure 2.15: Sample 2D *BVH* visualization which contains four triangles (t_1 to t_4) and their corresponding bounding boxes b_1 as parent and b_2 as well as b_3 as the children. b_1 is visualized bigger than need be to improve readability. The color of the triangles indicates to which bounding box they belong. r indicates the ray to be tested for intersection.

Hybrid Approaches

Ray Tracing and Rasterization are not mutually exclusive. Hybrid approaches have been developed which leverage a multi-paradigm approach. One such example is PICA, a real-time ray tracing experiment developed by NVIDIA [39]. The rendering pipeline is split into multiple stages, consisting of global illumination, shadow, reflection, direct lighting. Each stage could be implemented using different techniques where the strategy could be chosen based on the requirements of the scene as well as the available computational resources.

2.3.4 Common Techniques

While rasterization and ray tracing are inherently different techniques, they face similar challenges. Notable frequently encountered challenges and their differences in rasterization and ray tracing are discussed in the following sections.

View Projection

In order to render an image, a virtual camera needs to be defined. Given a vertex as $p = (x, y, z)$, the view projection is responsible for transforming the vertex into normalized device coordinates. The view projection matrix is a 4×4 matrix which depends on the projection type.

Depending on the use case, different types of camera projection can be used. The most common types are perspective and orthographic projection. Perspective projection simulates the way the human eye perceives the world, objects which are further away appear smaller. Whereas orthographic projection does not take the distance into account and objects appear the same size regardless of their distance. Orthographic projection is frequently used in domains such as architecture.

These two projection types differ in the view projection matrix. For perspective projection, the following parameters need to be defined:

near (n) The distance from the camera to the near clipping plane.

far (f) The distance from the camera to the far clipping plane.

fov (θ) The *field of view* angle, measured in degrees.

aspect ratio (r) The ratio of the viewport's width to its height.

The clipping plane parameters n and f are primarily used in rasterization to determine the camera frustum. Using equations 2.17 and 2.18, the view projection matrix P for perspective projection is defined in equation 2.19.

$$h = 2n \cdot \tan\left(\frac{\theta}{2} \underbrace{\pi/180}_{\text{deg to rad}}\right) \quad (2.17)$$

$$w = rh \quad (2.18)$$

$$P = \begin{bmatrix} \frac{2n}{w} & 0 & 0 & 0 \\ 0 & \frac{2n}{h} & 0 & 0 \\ 0 & 0 & -\frac{f+n}{f-n} & -\frac{2fn}{f-n} \\ 0 & 0 & -1 & 0 \end{bmatrix} \quad (2.19)$$

The elements $P_{1,1}$ and $P_{2,2}$ adjust the field of view and therefore the perspective effect. The elements $P_{3,3}$, $P_{3,4}$ and $P_{4,3}$ adjust the near and far clipping planes. In comparison to rasterization, the view projection matrix is used differently in ray tracing. In rasterization, every vertex is transformed by the view projection matrix. In ray tracing, the view projection matrix is only applied to the camera rays.

For orthographic projection, no such projection matrix is required in ray tracing. Instead, parallel rays are cast from the camera grid.

Random Number Generator

To simulate light transport, the path tracer needs to pick random directions. Generating a random direction vector, defined as $v = (x, y, z)$, can be achieved by picking three random numbers independent of one another. This pivotal part of path tracing is done

using a random number generator (*RNG*). In rasterization, the necessity for *RNG* is less common, but may still be required for certain effects. Unlike other programming languages, *WGLS* does not have a built-in *RNG*. Therefore, a custom *RNG* is required. There are a variety of *RNGs* available which differ in important characteristics. Some of the characteristics to consider when choosing a suitable *RNG* are:

- Statistical Quality – The *RNG* should generate numbers that are statistically random. This means that the numbers should be uniformly distributed and have a low correlation between them.
- Period – The length of the cycle before the sequence of generated numbers starts to repeat itself.
- Time Performance – The time it takes to generate a random number. This is influenced by the algorithm as well as the hardware which may support dedicated instructions.
- Space Usage – The amount of memory required to store state.

Based on the use case, other factors such as prediction difficulty or others such as highlighted by O'Neill [40] may be important. Cryptography for example requires randomness of the *RNG* to prevent an adversary from predicting secret keys. Options to generate the randomness require additional signals [41] or may require special hardware such as LavaRand [42]. Many generators are pseudorandom generators. These generators are deterministic and require a seed to start the sequence. For cryptographically secure generators, the seed must be random. However, for a path tracer, there is no need for cryptographic security. Instead, it is more important to have high performance and having a long period to avoid repetition. Therefore, a pseudorandom number generator with non-cryptographically secure seed is used.

One option for such a pseudorandom generator is using Xorshifts such as described by Marsaglia [43]. The algorithm can be defined as shown in Figure 2.16. *x* is the state of the *RNG* and *a*, *b* and *c* are constants which are chosen to achieve good statistical properties. Frequent choices for these constants are *a* = 13, *b* = 17 and *c* = 5.

```

1 x ^= x << a;
2 x ^= x >> b;
3 x ^= x << c;

```

Figure 2.16: Xorshift *RNG* implementation in *WGLS*.

Alternatives to Xorshift are available, such as the Mersenne Twister [44]. The Mersenne Twister is a pseudorandom number generator which has a long period and good statistical properties. However, it is slower than Xorshifts [40]. More recently, *PCG*² has been proposed as an alternative to these options. *PCG* is a family of fast generators.

²Permuted Congruential Generator, a family of random number generators

Anti-aliasing

Aliasing is a common issue in computer graphics. It occurs when the resolution of the screen is not sufficient to represent the scene accurately. One such example is jagged edges on diagonal lines. Anti-aliasing techniques can be employed to reduce the effect. The negative effect of aliasing is demonstrated in Figure 2.17a.



(a) Rendering showing aliasing.

(b) Rendering with anti-aliasing applied.

Figure 2.17: The two images show the effect of aliasing and anti-aliasing.

In ray tracing, aliasing can be alleviated by randomizing the direction of the rays for the different samples taken. The result of applying anti-aliasing can be seen in Figure 2.17b. In rasterization, similar solution strategies can be employed. Supersampling is a common technique which renders the scene at a higher resolution and then downsamples the image by averaging the colors of the pixels. More elaborate techniques such as deep learning super sampling (DLSS) implemented by NVIDIA [45] can be used to further improve the quality of the image in real-time rendering.

Tone Mapping

When simulating light transport, the radiance of the scene can exceed the displayable range. Tone mapping is a technique used to map the high dynamic range (*HDR*) input generated by the renderer to a lower dynamic range. The basic idea is to adjust the radiance of the scene to more closely resemble realistic lighting conditions. One common algorithm to do so is the Reinhard tone mapping operator [46]. In recent years, special tone mappers have been developed for dedicated use cases. One example is the Khronos PBR Neutral Tone Mapper [47] which is designed to work well with rendering true-to-life colors. See Figure 2.18 for a comparison of tone mapping with and without the Khronos PBR Neutral Tone Mapper.

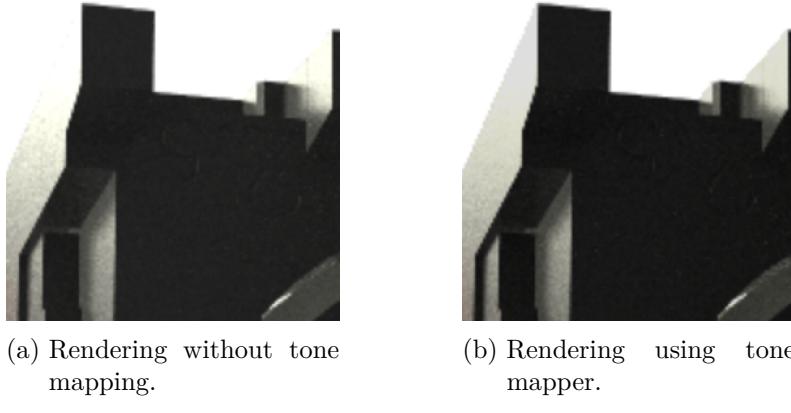


Figure 2.18: Comparison of tone mapping with slight changes in luminance of specular reflection. The upper part is barely visible without tone mapping as it blends into the background due to the high luminance.

2.4 Computer Graphics Technology

This section provides an overview of the technology used to render 3D scenes. It will introduce the hardware as well as the software used in the field with a focus on technology relevant for this thesis by introducing *WebGPU* and its core concepts.

Parallel Processing

Sequential processing is limited in terms of performance. As the amount of data to process grows, the time to process the data grows linearly. Computer graphics exhibits a large number of problems which can be parallelized. The idea of parallelization for data processing is not new. In 1966, Flynn introduced a classification system for computer architectures based on the instruction streams and data streams they can process in parallel [48, 49]. Already in 1970, Watkins described an algorithm for computer graphics leveraging a specialized processor for parallel processing [50]. Further research such as Chap, a *SIMD*³ graphics processor proposed in 1984 by Levinthal and Porter as part of Lucasfilm introduced a special purpose processor executing a single instruction on multiple data points [51].

GPU

The first so-called consumer graphics processing units (*GPU*), the GeForce 256 produced by NVIDIA [52], were developed in the 1990s and extend upon research conducted in the decades prior such as so-called superworkstations introduced by Silicon Graphics in the 1980s [53]. These workstations were special-purpose computers which were optimized for computer graphics. The *GPU* on the other hand is a specialized processor that is well-suited for workloads which require parallel processing and can be installed on

³*Single Instruction, Multiple Data*, type of parallel processing of data points with a single instruction

a standard computer. While *CPU* parallelization on consumer hardware is generally limited to a few cores, modern *GPUs* have thousands of compute units which enable *SIMD* processing.

Due to computational complexity, ray tracing techniques have been limited to offline rendering for a long time. Early ray tracers such as *BMRT* were developed focusing on leveraging *CPU* for computations. The introduction of *GPUs* has lead to further research on how to optimize speed for techniques related to ray tracing. One such example of research for a well-established technique is *BVH* construction on the *GPU* [54] instead of *CPU*. Leveraging *GPU* has been a focus of research and has enabled real-time ray tracing in recent years. Notable developments include reservoir-based spatio-temporal importance resampling (*ReSTIR*) [55] and subsequent improvements [56, 57].

Nowadays GPUs are prevalent in consumer hardware such as smartphones, tablets, laptops and desktops and their use case is not limited to computer graphics. GPUs are used in a wide range of applications, such as machine learning, scientific computing and data processing. Devices, which do not have a discrete GPU, often use an integrated GPU which is part of the CPU.

Modern GPU hardware offers support for hardware-accelerated ray tracing. Examples include NVIDIA RTX [58], Apple Metal on M3 [59] and others. These examples demonstrate an increasing trend towards hardware-accelerated ray tracing in recent years, however many devices and *APIs*, including *WebGPU*, do not yet support hardware-accelerated ray tracing.

Common Strategies

Certain basic definitions have established as common practices for these *APIs*. The term shader is used to describe a program which runs on the *GPU*. It is frequently used to describe in conjunction with different shader types which are used as part of the so-called graphics pipeline in rasterization. The pipeline in its basic form consists of two steps which are executed on the *GPU* in sequence:

- Vertex Shader — The vertex shader is responsible for transforming the vertices of the geometry into screen space. The output of the vertex shader is a set of vertices which are then rasterized.
- Fragment Shader — The fragment shader is responsible for determining the color of the fragments which are generated by the rasterizer. The fragment shader is executed for each fragment which is generated by the rasterizer.

In addition to this standard graphics pipeline, many *APIs* also support custom code which does not need to be used exclusively for rendering. This code can be used for general-purpose computing and is generally referred to as *GPGPU*. Shaders which are used for *GPGPU* are often called compute shaders.

2.4.1 OpenGL

OpenGL is an *API* for rendering 3D graphics. After its introduction in 1992, it was

widely adopted. Subsequently, the standard has been ported to other platforms and has been extended with new features. The *API* has its own shading language called OpenGL Shading Language (*GLSL*).

To date, *OpenGL* is still widely used in the industry, but it has been replaced by more modern *APIs* in recent years.

2.4.2 Modern Graphics APIs

While *OpenGL* and derivatives such as *OpenGL ES*⁴ have been widely adopted, the introduction of a number of new *APIs* has changed the landscape. The standards share an understanding of giving developers more control over the hardware and can be more efficient than *OpenGL*. Modern hardware-accelerated features such as ray tracing are more easily accessible using these new *APIs*. Some of the most notable *APIs* are:

- *Vulkan* — Developed by the *Khronos Group*⁵, Vulkan is a low-level *API* which is supported on a wide range of platforms.
- *Metal* — Developed by Apple, Metal is a low-level *API* which is supported on Apple devices.
- *DirectX 12* — Developed by Microsoft, DirectX is a collection of *APIs* which are supported on Windows platforms.

None of these *APIs* are supported in the browser, which makes them unsuitable for the discussed use case.

2.4.3 WebGL

WebGL is a graphics *API* based on *OpenGL ES* 2.0 for the web. It was initially released in 2011 and has since been adopted by all major browsers.

WebGL is designed to offer a rendering pipeline, but does not offer *GPGPU* capabilities. There have been efforts to extend with compute shaders, but efforts by the *Khronos Group* have been halted in favor of focusing on *WebGPU* instead.

In order to provide *GPGPU* capabilities, workarounds have been developed. The basic idea is to render the output of a fragment shader to a texture and interpreting the output as binary data instead of color information. There are libraries such as GPU.js which provide *GPGPU* capabilities using *WebGL*. Tensorflow.js, a library for training and deploying Machine Learning models, use similar techniques in the *WebGL* backend. Since its introduction, *WebGL* has been extended with new features. *WebGL* 2.0, which is based on *OpenGL ES* 3.0, was released in 2017. Of the major browsers, Safari was the last to support it out of the box in 2021. Since *WebGL* 2.0 no new major versions have been released but new features have been added. This makes it evident that while *WebGL* is to remain a viable choice for rendering 3D graphics in the browser for the foreseeable future, it is likely to be superseded by *WebGPU* in the long term.

⁴ *OpenGL for Embedded Systems*, subset of OpenGL designed for embedded systems like smartphones

⁵ consortium for developing interoperability standards for 3D graphics

2.4.4 WebGPU

WebGPU is a new web standard, being developed by *W3C*⁶ which is no longer based on *OpenGL*, unlike its predecessor *WebGL* [60]. One of the main capabilities is support for *GPGPU* by design. While all major browser vendors have announced intent to support *WebGPU*, to date only Chrome has shipped *WebGPU* for general use on desktop as well as mobile. The standard is still in development and new features are being added. Common 3D engines such as *Babylon.js*, *Three.js*, *PlayCanvas* and *Unity* have announced support for *WebGPU*.

Implementations

Three major implementations of *WebGPU* exist:

- *Dawn* — Developed by Google, *Dawn* is a C++ library which provides a *WebGPU* implementation. It is used in Chromium-based browsers [61].
- *wgpu* — A Rust library which provides a *WebGPU* implementation. It is used in Firefox and *Deno*⁷ [62].
- WebKit WebGPU — Developed by Apple, WebKit is used in Safari [63].

As the standard is under active development, there are differences between the implementations as well as the specification [64]. Thanks to alignment and the extensive conformance test suite [65], the implementations are largely compatible. Generally, these implementations run natively on modern graphics *APIs* such as *Vulkan*, *Metal* and *DirectX 12*. Some also support *OpenGL* and *WebGL* as a fallback.

Core Concepts

It is a low-level *API* when compared to *WebGL*. Users get access to the *GPU* via adapters which abstract the underlying hardware. *WebGPU* fully supports common *GPU* strategies as described in paragraph 2.4. Most of the commands are then executed on a logical device which is created using the adapter.

For a compute pipeline, one needs to define a pipeline layout which consists of multiple bind group layouts. These define the memory layout of the data which is passed to the *GPU*. The code to be executed is defined in a shader module. The compute pipeline is then created by combining the shader module and the pipeline layout. See Figure 2.19 for a visual representation of the core concepts in *WebGPU*. When using a graphics pipeline, similar steps are required, but two shader module configurations are required.

⁶World Wide Web Consortium, a non-profit organization dedicated to developing web standards

⁷JavaScript runtime, alternative to Node.js

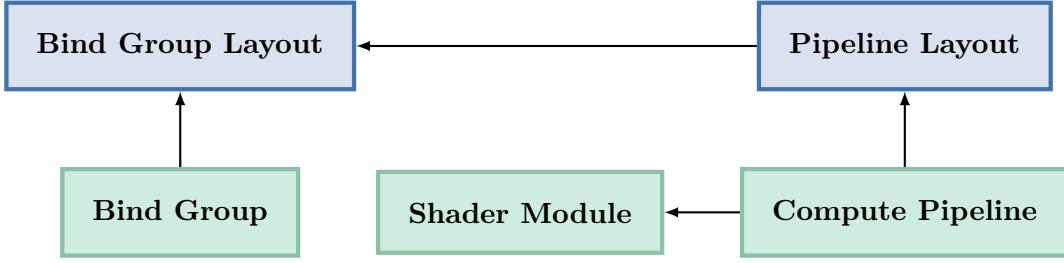


Figure 2.19: Core concepts in WebGPU, the arrow direction indicates references to. Blue elements are independent of concrete references to data and code while green elements are concrete references.

Having set up the compute pipeline, one needs to define the bind groups which contain the data. Using a command encoder, the compute pipeline can be dispatched to the *GPU* for execution.

Shading Language

WebGPU introduces a new shading language called *WebGPU Shading Language (WGLS)* [66]. The language is statically typed and supports a variety of data structures required for computer graphics as well as general-purpose computing.

Every compute pipeline, or render pipeline, requires an entry point as shown in Figure 2.20, which can then be defined as shown in Figure 2.21. Note that for *WGLS* functions, the return type definition is optional.

```

1 device.createComputePipeline({
2   layout: computePipelineLayout,
3   compute: {
4     module: computeShaderModule,
5     entryPoint: "computeMain",
6   },
7 });

```

Figure 2.20: JS code defining entry point for compute pipeline.

```

1 @compute
2 @workgroup_size(1, 1, 1)
3 fn computeMain(@builtin(global_invocation_id) global_id: vec3<u32>) {
4   // ...
5 }

```

Figure 2.21: *WGLS* code defining the entry point for a compute pipeline.

Attributes such as `@compute` are used to provide additional information to the compiler.

In this case, it denotes the entry point for the compute pipeline and is mandatory as it enables usage of specific attributes such as `@builtin` which may only be used on entry points.

Similar to other shading languages, it does not support recursion because cycles are not permitted in any kinds of declarations. *WGSL* supports common high-level helpers such as Swizzling, which is a class of operations which facilitate managing vector elements. For example, given a vector `let v = vec3f(x, y, z)`, the operation `v.xy` returns a vector `(x, y)`.

Buffers

Data needs to be transferred between the CPU and the GPU within bind groups. Buffers are the primary method to store data. Depending on the type of data to be transferred, different types of buffers can be used:

- Uniforms — Uniform Buffers are optimized for data which is read-only on the GPU and is the same for all vertices or fragments. Such information could be the projection matrix.
- Storage — Storage Buffers are intended for read-write access on the GPU. The limits of the buffer are higher than for uniform buffers.
- Vertex — Alternative to storage buffers, intended for vertex data.
- Index - Buffers which contain indices for the vertices.

Memory Alignment

WGSL supports `struct` for defining data structures. However, when passing data between the CPU and the GPU, memory alignment needs to be considered. Alignment is a constraint, restricting the memory address at which a data structure can be stored. Having strict memory alignment enables use of more efficient hardware instruction sets, or address hardware requirements.

Each type in *WGSL* has specific alignment requirements which are independent of the size. For example, a `vec3f` has a size of 12 bytes, but requires an alignment of 16 bytes. So for a struct definition such as can be seen in Figure 2.22, the struct requires 32 bytes of memory to store 20 bytes of data as illustrated in Figure 2.23. The excess 12 bytes are used for padding.

```
1  struct ThreeFields {
2    a: f32,
3    b: vec3f,
4    c: f32
5 }
```

Figure 2.22: *WGSL* struct containing three fields of type `f32` and `vec3f`.

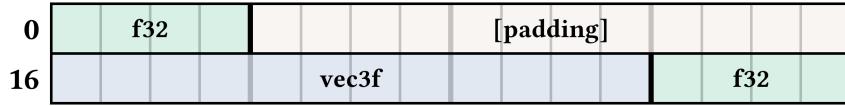


Figure 2.23: Memory Alignment with padding for struct defined in Figure 2.22.

Memory alignment is opaque while writing *WGSL* code, it is relevant when providing data to the GPU. For creating buffers, the alignment requirements need to be considered. When using JavaScript to create buffers, the standard Web *APIs* such as `Float32Array` or `Uint32Array` can be used to provide data. In order to write data to the `struct` in Figure 2.22, the views can be created as shown in Figure 2.24.

```
1 const ValueBuffer = new ArrayBuffer(32);
2 const a = new Float32Array(ValueBuffer, 0, 1);
3 const b = new Float32Array(ValueBuffer, 16, 3);
4 const c = new Float32Array(ValueBuffer, 28, 1);
```

Figure 2.24: JS code providing views to access the `struct`.

2.5 Exchange Formats

In order to exchange 3D scenes between a multitude of applications, various standardized formats have been developed. These formats are optimized for different use cases depending on the requirements of the application. For the purpose of this thesis, the focus is on formats which are well-suited for real-time rendering on the web. In comparison to other use cases, certain aspects are more important on the web. These aspects include:

- Efficiency – It should be optimized for transmission and loading. While data compression algorithms such as *Gzip*⁸ can alleviate some of the issues during transmission, pure text-based formats are generally less efficient than binary formats.
- Feature Set – The format should support a wide range of features such as geometry, materials and scene graph.
- Interoperability – The format should be widely supported by 3D engines and applications.

The following section categorizes the formats based on their use case and highlights some of the most widely known formats.

⁸GNU zip, file format and software application for compression and decompression.

General Purpose Formats

One of the most widely used formats is Wavefront *OBJ* which was established in the 1980s. The format is text-based and has basic support for materials and textures via a companion file *MTL*⁹. However, it lacks support for more advanced features such as animations. Additionally, due to its encoding, it is not well-suited for delivery over the web compared to more modern alternatives.

Formats such as the proprietary *FBX*¹⁰ by Autodesk established in 2006 can address the shortcomings in terms of advanced features. The format is supported by a wide range of applications. One of the main disadvantages is the proprietary nature of the format which can make it difficult to integrate in applications which do not have access to the SDK.

Specialized Formats

For specific use cases, specialized formats have been developed. One such example is *STEP* which is standardized in ISO 10303. The format is widely used in product manufacturing and offers support for a wide range of modelling features. The *ASCII*¹¹ encoding of the format is human-readable but is not well suited for real-time rendering requirements of the web due to transmission size and parsing complexity [67]. Parsing complexity is exhibited by the large number of different entities which can be defined in the format.

Another such format is *STL*¹² which is widely used in 3D printing and supports binary as well as *ASCII* encoding. It lacks support for advanced features such as material representation, animations and scene graph.

Interoperability Formats

The aforementioned formats have shortcomings in terms of interoperability and feature set for complex 3D scenes. Special formats have been developed to address issues encountered in complex 3D scenes such as encountered in the film industry.

Other formats such as *COLLADA*¹³ have been developed to improve transporting 3D scenes between different applications. It is XML-based and has been established in 2004 and has since been managed by the *Khronos Group*. The latest release of the format was in 2008.

One notable format is *USD*¹⁴, which has been open-sourced by Pixar in 2016. Similar to *COLLADA*, the format is designed with interoperability in mind, and is widely supported by 3D engines and applications. The main focus of *USD* is support for complex scenes

⁹ *Material Template Library*, a companion file format to *OBJ* for material definitions

¹⁰ *Filmbox*, proprietary 3D exchange format nowadays managed by Autodesk

¹¹ *American Standard Code for Information Interchange*, character encoding standard for electronic communication

¹² *Stereolithography*, 3D exchange format developed by 3D Systems

¹³ *Collaborative Design Activity*, 3D exchange format managed by *Khronos Group*

¹⁴ *Universal Scene Description*, 3D exchange format

and complex collaboration workflows, which are common in the film industry but are less relevant for the use case in this thesis.

Runtimes Formats

For usage in end-user applications, such as for the use cases in this thesis, the *glTF* format is well-suited [68]. It has been established in 2015 and is designed to be efficient for transmission and loading of 3D scenes. The standard is developed by the *Khronos Group* and is widely supported by 3D engines and applications. The format supports 3D geometry, materials, animations, scene graph and other features.

Technically, the format offers two different encoding formats which differ in file ending:

- **.g1b** – Binary format which is optimized for transmission and loading.
- **.gltf** – Text-based format which is human-readable.

glTF is designed to be extensible and a variety of extensions have been developed to support features such as mesh compression using Draco. The hierarchy structure of a *glTF* file is shown in Figure 2.25. Many of the official extensions extend the material nodes to support more advanced features. Its focus on transmission and loading efficiency makes it well-suited for the web.

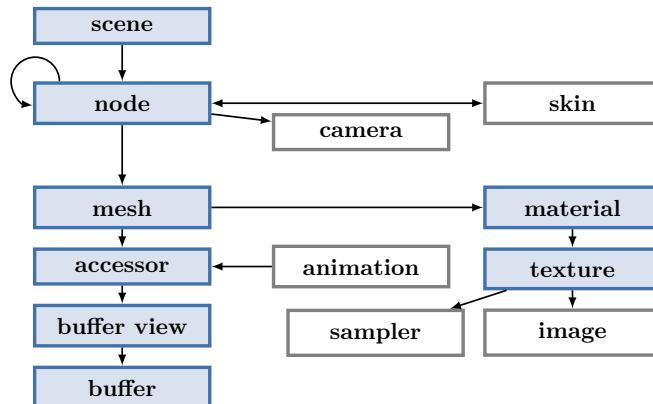


Figure 2.25: *glTF* hierarchy starting with the **scene** object. Arrows indicate parent-child relationships. Gray objects are not mentioned in this thesis.

2.6 Physically Based Rendering

Defining the geometry is one part of the equation. Another major part is defining materials. Materials define how a surface interacts with light. The core idea of physically based rendering (*PBR*) is to simulate the interaction of light using physical models. Instead of fine-tuning parameters for a specific look and feel and having to adjust based on desired lighting situations, *PBR* aims to define a material which behaves consistently

in different lighting situations. It is therefore an approach based on physical principles such as those described in section 2.2.

Research into *PBR* has been conducted for a similar amount of time as ray tracing. And just like ray tracing, the computational complexity of the algorithms has limited the adoption of *PBR* in real-time rendering for a long time. *PBR* has generally coincided with the rise of ray tracing as it is a natural fit for the physics based approach on light transport. One prominent example of a *PBR* system is *pbrt*, an open-source renderer with an associated literate programming book which has won an Academy Award for formalizing and providing reference implementation for *PBR* [37].

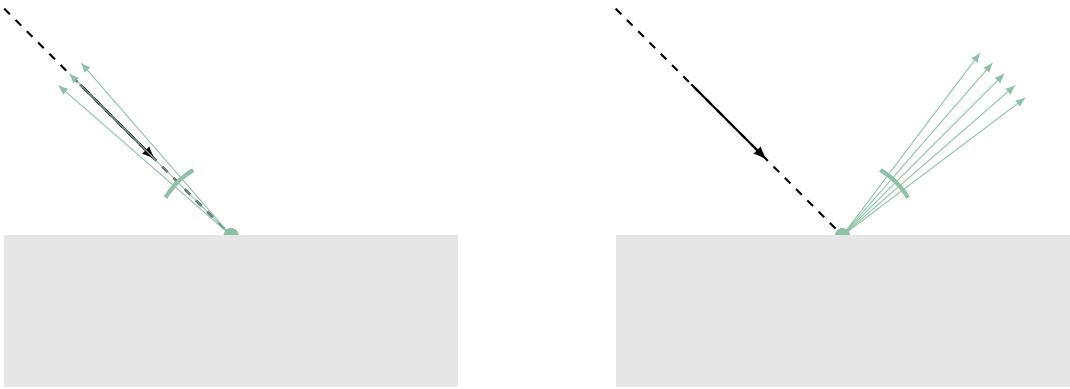
PBR and ray tracing are not mutually dependent as *PBR* can be used in rasterization as well. In contrast to how ray tracing is inherently addressing shortcomings of rasterization by leveraging an entirely different approach, *PBR* is a more incremental improvement extending existing shading techniques with more sophisticated models. Many ray tracers use simple non-standardized *PBR* models which are suitable to demonstrate basic effects of global illumination, but are not suitable for high-fidelity rendering of complex scenes. Not having a clear standard makes alignment between different tools hard to manage and can lead to inconsistencies in the final rendering.

In general, there is no *PBR* standard. Instead, a variety of different models have been developed over time. In recent years however, a convergence towards a common set of principles has been observed and certain aspects of *PBR* are found in most models. This section explains these common principles and standards which can be used to obtain consistent renderings.

2.6.1 BxDF

The definition of the bidirectional distribution functions (*BxDF*) is a key concept in PBR. The *x* stands for the different kinds of distributions to consider. In general, the functions describe how light is reflected or transmitted. The two functions are usually abbreviated as *BRDF*, the *r* standing for reflectance, and *BTDF*, the *t* standing for transmittance. The combination of the two is often referred to as *BSDF*, the *s* standing for scattering [37].

These functions define the distribution of light in different directions as described in subsubsection 2.2. Samples of different kinds of *BRDFs* can be seen in Figure 2.26. Many objects exhibit a combination of different reflectance distributions.



(a) Retroreflective reflection, as can be encountered in materials such as velvet.

(b) Glossy reflection, as can be encountered in materials such as plastic.

Figure 2.26: Special types of reflectance distributions using the same visualization as Figure 2.9. [37].

2.6.2 Microfacet Theory

While the macroscopic appearance of a material is visible to the human eye, the microscopic structure of the material is crucial in determining how light interacts with the material. Microfacet theory is a model which describes this microscopic structure. The distribution of the normals of the microfacet is described by a distribution function.

2.6.3 Material Description

While the principles of *PBR* are well-established, the material description in 3D formats is not uniform. A variety of different approaches have been developed. In addition to many exchange formats such as *glTF* having their own material definition, different shading models exist independent of these formats. Similar to exchange formats, a variety of different use cases are addressed by material description models. While some shading models are optimized for real-time rendering, others are optimized for film production.

Shader Design

Based on the focus of the material description models, they differ in how they need to be implemented. Flexible node-based systems permit the creation of custom shaders. This gives a lot of flexibility to the user as arbitrary shaders can be created. However, this flexibility comes at a cost. The underlying implementation needs to convert the node graph into shader code which can be executed on the *GPU*. The flexibility increases surface area of the *API* and therefore increases the complexity of implementation and optimization. In addition, managing a large number of custom shaders can be challenging as many shaders have similar features.

An alternative approach is to use an *uber shader*. The term does not have a strict definition, but generally it is used to describe a shader program which can be adjusted

using parameters to achieve different looks. The shader program is fixed and does not allow for customization of the shader graph. This approach often leads to a more complex shader with many parameters which can be difficult to manage, but it is easier to optimize as the shader program is fixed.

Technically, a node-based system also supports an *uber shader* approach, but a *uber shader* does not support a node-based system.

Material Description Standards

Many exchange formats, such as *glTF*, support material description as part of the standard. The material description in *glTF* supports a *PBR* approach which is based on the metallic-roughness material model [68]. However, the *PBR* material description in *glTF* is limited in terms of feature set, by lacking features such as subsurface scattering, and is not intended to become an open standard across a variety of applications.

Over the years, different parties have developed their own shading models. Some prominent options include:

- Disney Principled BRDF [69] – Developed by Disney in 2012, the model is not necessarily physically correct and focuses on being art directable and limiting parameters. While the model is influential, it is not an established standard and lacks reference implementation even though it has been adopted by some applications, including *RenderMan* [70].
- Autodesk Standard Surface [71] – Developed by Autodesk, the goals are similar to Disney in that the parameter set is kept small in order to be easier to use. The model is developed as an open standard with a reference implementation in *OSL*¹⁵. However, the standard has not seen much development in recent years.
- Adobe Standard Material [72] – Developed by Adobe, the model is also influenced by the Disney Principled BRDF as well as Autodesk Standard Surface. It has a full specification and has been adopted by Adobe in their applications.
- *DSPBR* [73] – Developed by Dassault Systèmes, it is also influenced by the Disney Principled BRDF. The specification is detailed and the model is designed for industrial use cases.

In addition to these standards, many real-time rendering engines such as *Unity* and *Unreal*¹⁶, modeling software such as *Blender*¹⁷ and *Rhino3D*¹⁸ have their own shading models. Supporting many different shading models in a web-based real-time rendering application can be challenging, making the need for a common material description standard more apparent. This is where new material description standards come into

¹⁵ *Open Shading Language*, shading language for production global illumination renderers maintained by Academy Software Foundation

¹⁶ Unreal Engine, cross-platform game engine developed by Epic Games

¹⁷ open-source 3D computer graphics software toolset

¹⁸ *Rhinoceros*, proprietary 3D computer graphics and CAD toolset

play. These are open standards developed by multiple companies to address the siloed development of prior shading models, intended to be used across different applications. *MaterialX* is an open standard which was originally developed by Lucasfilm in 2012. The standard has since been adopted by the *ASWF*¹⁹ as an open standard with support from a variety of companies. While not strictly limited to *PBR*, the standard provides a wide range of features to describe physically based materials [74]. *MaterialX* supports extensive shader generation capabilities. This permits to re-use shaders across different applications and frameworks and aids in understanding the used approximations.

2.6.4 OpenPBR

OpenPBR is a surface shading model hosted by the *ASWF* as an open standard [75]. It differs from *MaterialX* in that it is providing an *uber shader* approach instead of a node-based approach. Version 1.0 of the standard was released in June of 2024 [76].

It serves as a combination of Autodesk Standard Surface and Adobe Standard Material and is being worked on by both companies. The potential of this standard is to provide a common shading model which can be used across different applications. One notable adopter of the standard is NVIDIA Omniverse, which has shipped support of the standard [77]. *Blender* has reworked their Principled BSDF shader to be based on *OpenPBR* [78]. These promising signs indicate that the standard has the potential to be widely adopted.

The *OpenPBR* specification includes a reference implementation in *MaterialX*. This allows to use the shader generation of *MaterialX* in order to get a reference implementation in *GLSL* or *OSL*.

The *uber shader* approach is defined by having a fix set of inputs which can be adjusted, but it does not allow for custom node graphs as *MaterialX* does. The standard is designed for photorealistic material description. The first release of the standard is focused on surface shading and does not support specialized workflows such as advanced hair or volumetric effects like fog, smoke, and dust.

The specification is focused on physical aspects and does not specify implementation details. Implementations have an unambiguous target in terms of how it should look like, but have flexibility in terms of the degree of fidelity. While this makes alignment between different applications harder, it also allows for flexibility in the implementation of the standard, which is especially important for real-time rendering.

Formalism

The structures consists of multiple layers to describe the material as visualized in Figure 2.27. The layers are:

- Base — Substrate of the material which can be a mixture of metal or dielectric.
- Coat — An optional layer of dielectric material.

¹⁹ *Academy Software Foundation*, organization promoting development and adoption of open-source software in the motion picture industry

- Fuzz — An optional layer representing reflection from micro-fibers.

The layers are set up to be adjacent mediums where the *BSDFs* of the individual interfaces are combined.

The substrate is defined as a mixture of metal, translucent base, subsurface, and the gloss diffuse layer. These slabs are combined using a mix operation. The operation is defined as a weighted sum of the different layers. The weights are defined by the user and can be adjusted to achieve different looks.

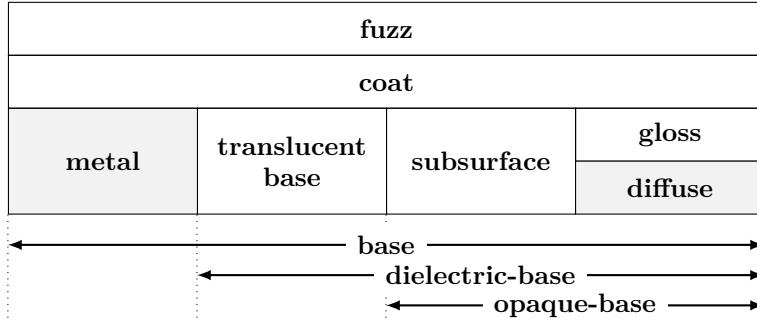


Figure 2.27: The different layers of the *OpenPBR* shading model. The workflow supports a variety of features such as metallic, glossy and diffuse reflection renderings which are important for industrial use cases.

Diffuse reflection is based on the Oren-Nayar model reflection model which extended the Lambertian model to include rough surfaces [79].

Assessment

While there is a large variety of material description standards, *OpenPBR* is a promising candidate. The focus on surface shading is well-suited for the use case of this thesis. In comparison to other standards, it is having significant industry backing, being adopted by major parties in the computer graphics industry such as Adobe, Autodesk and NVIDIA. Its design principles such as focusing on physical aspects and not specifying implementation details as well as the *uber shader* approach make it well-suited for real-time rendering.

3 Results

As discussed in the introduction and theory chapters, the goal of this work is to implement a web-based path tracer. The path tracer is designed to be used for product visualization based on *CAD* data, leveraging the *OpenPBR* surface shading model.

The concrete result of this work consists of multiple parts. The report serves as the primary documentation of the work but does not contain all details. The library and code documentation is published under the *MIT license*¹ on GitHub with an accompanying website. See <https://www.github.com/StuckiSimon/strahl> for details. The library is published on the *npm*² registry as `strahl`. In addition, a dedicated short paper has been published for WEB3D '24: The 29th International ACM Conference on 3D Web Technology [80]. The short paper includes the main insights and results of this work.

This section focuses on the implementation details of the path tracer. It also highlights the reasoning behind design decisions and provides insights into the performance of the renderer and its usability for the described use case.

For references to the implementation of the path tracer, a consistent notation is used. For example *CODE#ABC* refers to the code with the same comment. All relevant places are marked in code using the same reference, this permits using search features to find all references to a specific code section.

3.1 Implementation

The goal of the implementation is to be compatible with a large variety of devices and make the setup for consumers simple. Therefore, it is implemented and tested mainly in Chrome, which uses *Dawn* as the underlying implementation of *WebGPU*. Most notably, this means that dedicated features from other implementations such as *wgpu* cannot be used. Neither can experimental extensions be leveraged.

The path tracer is designed to be integrated into existing web projects. The package is installable via *npm*, but could also be downloaded and included manually. The full documentation is available on the website.

Figure 3.1 illustrates the procedure of the path tracer. Scene preparation is performed on the CPU. This setup needs to be done once per visualization. Subsequent sampling of the scene is carried out repeatedly on the GPU, which constitutes the most computationally intensive part of the process.

¹Permissive license originating at the Massachusetts Institute of Technology (MIT)

²package manager for JavaScript

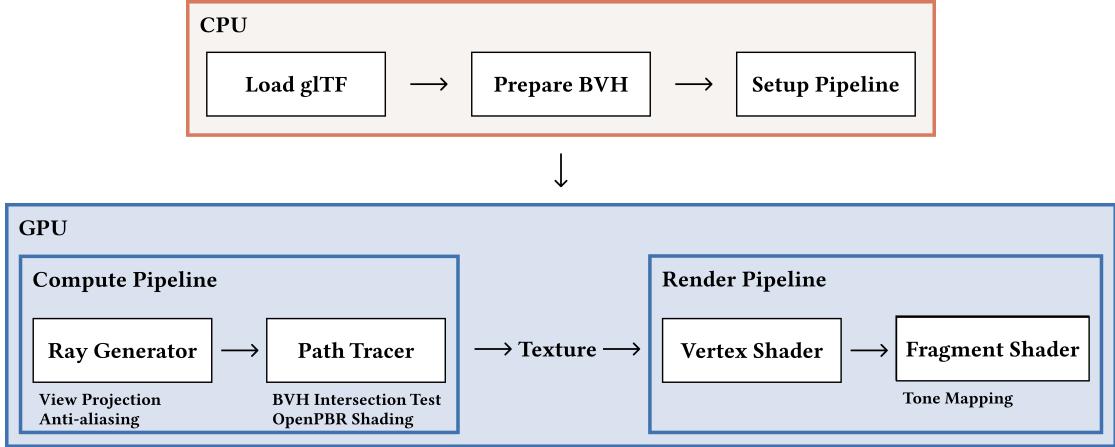


Figure 3.1: Path Tracer Pipeline, distinguishing GPU and CPU tasks. The stages of the compute pipeline and render pipeline are executed sequentially.

3.2 Scene Description

In order to be easy to integrate for developers familiar with existing web-based rendering engines, the renderer utilizes many of the scene description constructs provided by *Three.js*. This includes the representation of geometry using `BufferGeometry`, camera using `PerspectiveCamera`, and arbitrary camera controls such as `OrbitControls`. This also enables to use a variety of loaders for different file formats such as *OBJ* or *glTF*. However, due to its advantages for transmission, it's advised to use the *glTF* which can be imported using the loader provided by *Three.js*.

Scene Preparation

The main process involved with setting up the scene is the preparation of the *BVH*. For *BVH* construction, well-established solutions for the web are available. The path tracer uses `three-mesh-bvh` [81]. This method builds the *BVH* on the *CPU*, the code for transferring the *BVH* to the *GPU* is in *CODE#BVH-TRANSFER*.

In order to address memory alignment, as described in subsubsection 2.4.4, the path tracer uses `webgpu-utils` [82]. The library enables a straightforward way to map data to buffers and align them correctly. See *CODE#MEMORY-VIEW* for creation of definition and *CODE#BUFFER-MAPPING* for mapping of data to buffers.

Memory Management (GPU+CPU)

3.3 Ray Generator

The ray generator is responsible for casting rays into the scene according to the view projection. The path tracer employs a backward ray tracing approach, tracing rays from the camera into the scene.

View Projection

For many applications, especially photorealistic rendering, perspective projection is used. Based on the assessed use cases, the path tracer uses perspective projection only. See *CODE#VIEWPROJECTION* for implementation.

Random Number Generator

The path tracer uses PCG-RXS-M-XS variant as described by O’Neill [40] in combination with Xorshift as described by Marsaglia [43]. See *CODE#RNG* for implementation.

In order to set up the Monte Carlo method, the *RNG* needs to be employed in a suitable manner. As it is a pseudorandom generator, it necessitates a seed to start the generation. If the seed is identical for all pixels, the results of a single sample will frequently share similar patterns in adjacent surfaces as shown in Figure 3.2a. The result for independent seeds differs in a stark manner as shown in Figure 3.2b.

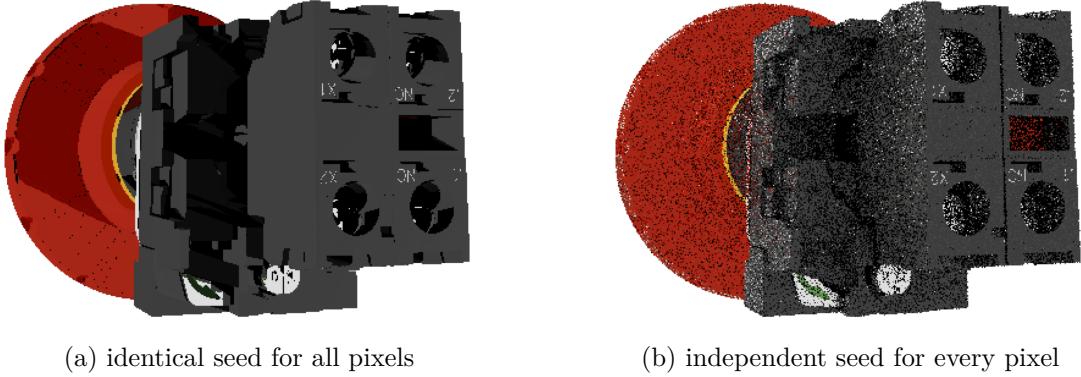


Figure 3.2: Both images consist of only one sample.

When increasing the sample count, the differences in the setup remain visible. Adjacent surfaces show similar patterns as shown in Figure 3.3a, which resemble image compression artifacts encountered in aggressively compressed *JPEGs*³. In contrast, the renderings with independent seeds show stark differences in adjacent pixels akin to noise as shown in Figure 3.3b. As shown in Figure 3.3c compared to Figure 3.3d, the anti-aliasing is less noticeable when using independent seeds.

³*Joint Photographic Experts Group*, common method for lossy image compression

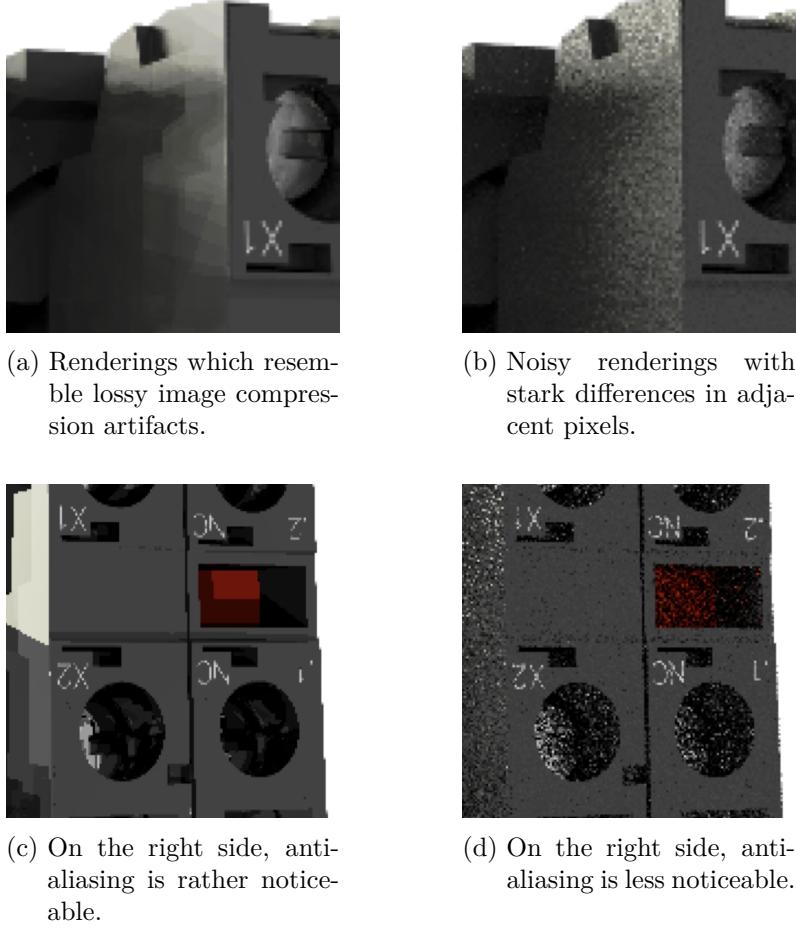


Figure 3.3: Magnified images of renderings with low sample count showing difference based on seed setup. Left column has identical seed for all pixels of a sample, but varying seeds for different samples. Right column has independent seeds for every pixel of a sample as well as across samples.

Anti-Aliasing

The implementation of the strategy indicated in 2.3.4 is implemented in *CODE#ALIASING*.

3.4 Path Tracer

Intersection tests based on the *BVH* are implemented in *WGSL*, see *CODE#BVHTESTS*. For each intersection, sampling is done according to the *MIS* scheme.

The surface shading method is based on *OpenPBR* reference implementation in *MaterialX* as well as the reference viewer by Portsmouth [83].

The renderer uses RGB^4 as the color space.

3.5 Render Pipeline

The output of the path tracing compute shader is a texture, which is then passed to a rasterizer. The rasterizer renders the texture to the canvas using a fullscreen quad consisting of two triangles. Tone mapping is done using the Khronos PBR Neutral Tone Mapper described in subsubsection 2.3.4. See *CODE#TONE-MAPPER* for implementation. Progressive rendering is a technique to render an image in multiple passes. Each render pass improves the quality of the image. This enables the user to see the rough image quickly and refine it over time.

3.6 Benchmark

In order to assess the effectiveness of certain measures, a benchmark is defined to measure the performance of the path tracer. This benchmark is used for quantitative evaluation of the path tracer. Prior sections, such as anti-aliasing as described in section 3.3 focused on qualitative aspects of the path tracer. Depending on the use case, the benchmark can be adjusted to focus on different aspects. However, the core design of the benchmark remains the same. Generally, measurements are taken for the entirety of a stage instead of focusing on individual routines within a stage. This gives a more holistic view of the performance of the path tracer.

A total of 100 samples per pixel with a ray depth of five was used. The image was rendered in Chrome 126 at a resolution of 512×512 pixels. Experiments were conducted with different model complexities. The simplified versions are decimated meshes of the original, which consists of roughly one million triangles. The LOD artifacts are shown in Figure 3.4. The first two levels are intended to be visually similar, while the third level is a simplified version intended to demonstrate the effect of non-manifold geometry for ray tracing.

Unless otherwise specified, the benchmarks are conducted on a MacBook Pro with Apple Silicon M1 Max. The measurements were calculated using the mean time of 30 runs with a confidence interval of 95% given as \pm standard deviation from the mean time in milliseconds as discussed in subsubsection 2.1.

⁴red, green, and blue, common system for color representation in computer graphics



Figure 3.4: The three LOD artifacts and their short names in brackets, from left to right: 1,068,735 triangles (high), 106,873 triangles (mid), 10,687 triangles (low). The left and middle figures share similar visual fidelity characteristics.

3.6.1 Russian Roulette

As described in subsubsection 2.3.3, Russian roulette is a technique used to do probabilistic path termination. The code is implemented in *CODE#RUSSIAN-ROULETTE*. The benchmark results are shown in Table 3.1.

	With Russian roulette	Without Russian roulette
High	2361.77 ms \pm 11.27 ms	2583.40 ms \pm 12.84 ms
Mid	2018.03 ms \pm 8.76 ms	2135.94 ms \pm 8.14 ms
Low	2028.04 ms \pm 10.78 ms	2200.00 ms \pm 8.91 ms

Table 3.1: Benchmark results for Russian roulette optimization.

3.6.2 Overall Performance

The results for CPU performance were recorded using the Performance API and are presented in Table 3.2. The results for GPU performance were recorded using *WebGPU* timestamp queries and are presented in Table 3.3. All measurements were calculated using the mean time of 30 benchmark samples, with a 95% confidence interval given as \pm standard deviation from the mean time in milliseconds.

Triangles	Apple M1 Max	AMD/NVIDIA
1,068,735	327.57 ms \pm 0.56 ms	383.10 ms \pm 4.06 ms
106,873	45.49 ms \pm 0.31 ms	41.77 ms \pm 0.43 ms
10,687	10.53 ms \pm 0.24 ms	8.43 ms \pm 0.22 ms

Table 3.2: BVH setup time based on model complexity

Triangles	Apple M1 Max	AMD/NVIDIA
1,068,735	2,319.45 ms ± 11.14 ms	1,058.73 ms ± 59.47 ms
106,873	1,992.11 ms ± 8.49 ms	790.20 ms ± 3.79 ms
10,687	2,031.38 ms ± 9.87 ms	790.83 ms ± 4.18 ms

Table 3.3: GPU path tracer time based on model complexity

3.7 Use Case Scenarios

The *CAD* data used by EAO is a good fit for a path tracer. While not certain strengths of the ray tracing approach, such as caustics, are not relevant for the use case, and other strengths, such as reflections are not fully utilized, the path tracer still provides a suitable candidate for the use case. The complexity of the geometry does not pose a significant challenge for the path tracer, even for relatively high triangle counts. Using *PBR* fits the use case and provides sufficient adjustment possibilities for the materials.

4 Discussion and Outlook

This section discusses the results, and experience gained by implementing a project using *WebGPU* in detail. In addition, a discussion of the results is provided and possible future work is outlined.

The path tracer focuses on the given use case and is therefore not a general-purpose rendering engine. For example, it does not offer a physics engine, support for animations, or other features that are common in general-purpose rendering engines such as *Three.js*, *Babylon.js* or alternatives. Generally, the ray tracing technique is slower than rasterization-based approaches and is therefore not a silver bullet for all use cases. The results indicate that the developed path tracer is a viable option in the discussed use case of e-commerce. Additionally, the proposed rendering architecture paradigm can reduce operating costs by eliminating the need to host a rendering pipeline or remote rendering service.

4.1 Comparison to Prior Work

The three existing open-source path tracers for the web are alternatives to the renderer developed in this work. While comparing them based on quantitative measures such as *FPS*¹ is not meaningful as the number of samples differs across the renderers, it is still possible to define a set of criteria to compare them.

WebGPU Support

WebGPU is a new technology and support for it is likely to become more important in the future. The three alternatives currently do not support *WebGPU* and still rely on *WebGL*.

PBR Standard

As discussed in paragraph 2.6.3, a variety of standards exist for *PBR*. While *OpenPBR* is a new standard, it has already seen adoption by the industry. `three-gpu-pathtracer` and `Three.js PathTracer` currently use custom *PBR* standards or partially support *glTF* PBR extensions. `dspbr-pt` uses the *DSPBR* standard.

¹*Frames per second*, measure of rate at which consecutive images are rendered and displayed

Documentation

In order to be usable by developers, the renderer should be well-documented. `strahl` and `three-gpu-pathtracer` provide documentation. `Three.js PathTracer` and `dspbr-pt` provide minimal documentation.

npm Package

The availability of an *npm* package can simplify the integration of the renderer into existing projects. `strahl`, `three-gpu-pathtracer`, and `dspbr-pt` provide an *npm* package. `Three.js PathTracer` does not provide a package.

Last Update

The last update of the renderer is an indicator of the activity of the project. `strahl`, `three-gpu-pathtracer`, and `Three.js PathTracer` have been updated in 2024. `dspbr-pt` has not been updated since 2022.

Assessment

Table 4.1 contains a high-level comparison between the four renderers. The renderer developed in this work is the only one that supports *WebGPU* and uses the *OpenPBR* standard. The renderer is provides an alternative to the existing renderers.

	<code>strahl</code>	<code>three-gpu-pathtracer</code> [12]	<code>Three.js PathTracer</code> [13]	<code>dspbr-pt</code> [14]
<i>WebGPU</i> Support	Yes	No	No	No
<i>PBR</i> Standard	<i>OpenPBR</i>	Custom	Custom	<i>DSPBR</i>
Documentation	yes	yes	minimal	minimal
<i>npm</i> Package	yes	yes	no	yes
Last Update	2024	2024	2024	2022

Table 4.1: High-level comparison between the four open-source path tracers for the web.

4.2 Findings

The main novelty introduced in this work is the development of a path tracer with *WebGPU* using the *OpenPBR* surface shading model. *WebGPU* and *OpenPBR* are promising endeavors for the future of 3D rendering, but relatively new and not yet widely adopted.

State of WebGPU

As highlighted in the report, *WebGPU* is a promising technology for *GPGPU* computations in the browser. However, to date there are certain limitations in terms of support and features.

Browser Support

Due to the current state of support for *WebGPU* in Safari and Mozilla Firefox, the production readiness of *WebGPU* is still limited. Safari has announced plans to support *WebGPU* and has launched a preview version [84]. Firefox also has plans to support *WebGPU* [85]. Thanks to the extensive conformance test suite [65], it is more likely that the different implementations will be compatible with each other.

The main browser which supports *WebGPU* to date is Chrome. *WebGPU* has shipped to general use on desktops in May of 2023 [86]. Since January 2024, *WebGPU* is also supported on modern Android devices [87].

This means that it's straightforward to use *WebGPU* on most modern devices with the notable exception of Apple iOS and iPadOS devices.

Ray Tracing

To date, *WebGPU* does not support some features that are common in modern rendering *APIs* and would be beneficial for the path tracer. The most prominent example is hardware-accelerated ray tracing. *APIs* such as Vulkan support hardware-accelerated ray tracing [88]. This entails helpers for building common acceleration structures, such as *BVH*, as well as ray querying functions to determine intersections. *WebGPU* does not yet support these features, but there are discussions ongoing to add extensions [89] as well as a demonstration implemented in a Dawn fork [90].

Debuggability

None of the major browser engines, Chrome, Firefox, and Safari, provide debugging as part of the developer tools. Tools for inspecting *WebGPU* applications exist [91, 92], but are limited in terms of feature set. While they are helpful to inspect the pipelines, capture frames, and inspect resources, they do not provide debugging capabilities such as breakpoints, stepping or variable inspection. For specific setups, there are methods to setup profiling [93], but these are not integrated into the browser developer tools and are dependent on the concrete machine hardware. Improvements in this area would be beneficial for productivity.

Stability

To date, there are reports of stability issues with *WebGPU*. This includes crashes of the browser, but on macOS using Chrome system-wide crashes have been observed with faulty *WebGPU* code. Such issues can look like shown in Figure 4.1. Due to the early

stage of the technology and the complexity of the underlying system, such stability issues ought to be expected. As implementations mature, these issues are likely to be resolved.

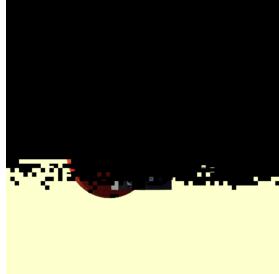


Figure 4.1: Example of a provoked WebGPU crash on macOS, note the black squares which correspond in size to the dispatched workgroup size.

OpenPBR

The integration of the *OpenPBR* surface shading model enables realistic material representation. As it is a new standard and no stable version has been released when first implementing the path tracer, aligning it with the standard was challenging. To date only few open-source projects have implemented the standard. Since the standard has reached a stable version during the work on this thesis, aligning effort between the implementation and the standard has reduced. The use of *PBR* and the latest industry standards is beneficial and provides good quality results. The adoption track of *OpenPBR* is promising and the standard is likely to be extended in the future.

4.3 Future Work

In order to accommodate for other use cases, the renderer could be extended in various ways. The following section outlines possible future work which includes extending *PBR* capabilities, improving performance, extending to other rendering architecture paradigms, general improvements for the *WebGPU* community, and aligning the renderer with other standards.

Rendering Effects

The focus on the defined use case means that certain rendering effects are not implemented. These include:

- Refraction.
- Caustics.
- Depth of Field - Depth of field is the effect of objects at different distances from the camera being in focus or out of focus.

- Motion Blur - Motion blur is the effect of objects moving quickly appearing blurred.
- Volumetric Effects.
- Hair and Fur.

While refraction, caustics, depth of field, and motion blur are a question of light transport, volumetric effects, hair and fur are features that are not part of the *OpenPBR* specification.

Spectral Rendering

Instead of the *RGB* color space, spectral rendering uses the full spectrum of visible light by modeling the light as a function of wavelength. This can improve the realism of the rendered images. Spectral rendering is well-suited for *PBR* and is therefore a natural extension of the current implementation. It is also possible to support both *RGB* and spectral rendering.

Texture Support

While not critical for the given use case, texture support is a common feature in rendering engines. The current implementation does not use textures. The renderer could be extended to support sampling *OpenPBR* parameters from textures. This would enable more complex material variations and possibly improve the realism of the rendered images.

This should not be confused with texture mapping frequently used in rasterization-based rendering engines. Texture mapping is a technique to apply images to surfaces to simulate surface details. In path tracing, textures are used to sample material properties such as base color, roughness, or metallicness.

Full OpenPBR support

The current implementation only supports the features of the *OpenPBR* surface shading model that are required for the given use case. The full *OpenPBR* specification includes additional features that could be implemented to improve the realism of the rendered images. These include:

- Subsurface Scattering - Subsurface scattering is the effect of light entering a surface and being scattered beneath the surface before exiting at a different point. This effect is common in materials such as skin, wax, or marble.

[list all features](#)

Alignment of OpenPBR and glTF PBR

Further improvements can be achieved by aligning *glTF* PBR with *OpenPBR*, focusing on real-time rendering. This alignment could reduce the computational resources required for surface shading.

Web Worker Support

Web Workers are a web technology that allows running scripts off the main thread. This can be used to offload *CPU*-heavy tasks to a separate thread to prevent blocking the main thread which is responsible for rendering the user interface.

BVH Construction

The current implementation builds the *BVH* on the *CPU* and transfers it to the *GPU*. Corresponding research [54] suggests that moving parts of the construction to the *GPU* directly could improve performance. This would reduce the amount of data that needs to be transferred between the *CPU* and the *GPU*. The new *GPGPU* capabilities of *WebGPU* further enable this approach.

TypeScript Support for Memory Management

While `webgpu-utils` [82] is useful for memory management, it does not provide TypeScript support for the generated definitions based on the underlying *WGSL* code. Type safety could reduce the likelihood of errors in the code. As an alternative, runtime checks could be implemented to ensure that the data is correctly mapped to all fields of the underlying structure.

Independence of *Three.js*

For ease-of-use for developers, the renderer is using *Three.js* helpers. This aids developers familiar with *Three.js* to get started with the renderer as configuration for scene loading and camera configuration is similar. However, the renderer does not depend on *Three.js* and could be used independently. The main drawback of the dependence is the increased bundle size. Possibly, `three-mesh-bvh` [81] could also be exchanged for an alternative library or self-implemented as described in section 4.3. By removing the dependency, the bundle size could be reduced. To support developers, a binding to *Three.js* could be provided on top of the independent renderer.

Offline and Remote Rendering

As highlighted in section 1.3, it is possible to extend a real-time client-side renderer to be used in offline and remote rendering scenarios. In order to implement offline rendering, one could opt to use a headless browser such as Puppeteer, a *Node.js*² library which provides a high-level *API* to control browsers. An alternative is to use `wgpu`, but this would necessitate a rewrite of the renderer. Possibly, the rewritten renderer could also be used in the web context by using *WebAssembly*³.

For remote rendering, the renderer could be extended to render images on demand and encode them as video streams.

²JavaScript runtime, frequently used for executing JavaScript outside of the browser

³Portable Binary-code format for executable programs available in modern browser engines

WebGPU Compatibility Mode

There is a proposal under active development which aims to extend the reach of *WebGPU* by providing a slightly restricted subset of WebGPU [94]. Considering the suggested limits of the compatibility mode, it could be possible to deploy the renderer onto a wider range of devices. However, it is important to consider that path tracing is a computationally expensive task and might not be suitable for all devices. Therefore, increasing the reach might not be beneficial in all cases.

Automatic Shader Conversion

During the specification phase of *WebGPU*, the relation to *SPIR-V*⁴ was discussed [95]. In general, many of the modern shading languages can be compiled to one another. Projects such as Tint, which is part of *Dawn* [61] or Naga [96] could be used to compile shaders from different frontends to different backends. Similarly, other engines such as *Three.js* with *TSL*⁵ have their own shading languages which support a variety of backends [97]. Parts of *MaterialX* shader generation could be used to generate shaders for *WebGPU* and update them automatically as *OpenPBR* is updated.

Low-Level Performance Optimizations

This target is likely at odds with the goal of providing automatic shader generation. The current implementation is not optimized for performance. Therefore, it is likely that optimizations of the *WGSL* code could improve the performance of the renderer. Due to the nature of the design of *OpenPBR*, it would be possible to do optimizations and get better real-time rendering performance.
Automatic shader generation is helpful, but likely not as optimized as a carefully tuned implementation. However, both endeavors are of interest for potential benefits.

Sampling Performance Optimizations

Path tracing is computationally expensive and requires multiple samples per pixel to achieve accurate results. Consequently, the sampling process is noticeable during interactions with the scene. One technique to improve perceived interaction quality is to overlay the rendering with a rasterization preview during interactions. To reduce the number of samples required for higher quality renderings, techniques like neural radiance caching (NRC) [98] or reservoir-based spatio-temporal importance resampling (ReSTIR) [55] could be employed in future work.

Denoisers

Optimizations in the render pipeline could also be achieved by using denoising algorithms applied as post-processing steps could enhance the quality of the results. Options include

⁴*Standard Portable Intermediate Representation*, intermediate language for parallel computing and graphics developed by Khronos Group

⁵*Three.js Shading Language*, shading language used in *Three.js* which supports *GLSL* as well as *WGSL*

blockwise multi-order feature regression (BMFR) [99] and Open Image Denoise (OIDN) [100].

Qualitative Assessment

The provided results highlight the quantitative performance of the renderer. However, due to the nature of a renderer, qualitative assessment based on visual inspection is also used to determine the quality of the rendered images. This could be extended to include more advanced metrics such as peak signal to noise ratio (PSNR), structural similarity (SSIM) [101], or learned perceptual image patch similarity (LPIPS) [102].

Such a comparison could be based on reference scenes such as the Cornell Box [10] or the Sponza Atrium [103]. To assess the differences, a number of tests could be conducted:

- Offline Renderer Comparison - Comparison to other offline renderers such as Cycles [104], Mitsuba [105] or *pbrt* [37].
- Rasterization Renderer Comparison - Comparison to rasterization-based web renderers such as *Three.js* or *Babylon.js*.
- Web-based Path Tracer Comparison - Comparison to other web-based path tracers such as *three-gpu-pathtracer* [12], *Three.js PathTracer* [13], or *dspbr-pt* [14].

4.4 Conclusion

For the given use case of using production *CAD* data with manifold assembly configurations and customer-specific materials, the path tracer developed in this thesis is a suitable choice. *WebGPU* has significant potential for years to come and adoption of *OpenPBR* by the wider industry is a promising sign of the possible longevity of the chosen technology and standards. As shown in section 3.6, the performance is sufficient for near real-time renderings of complex *CAD* models on the web. The use of *WebGPU* over *WebGL* as well as incorporating *OpenPBR* provides a distinction to existing open-source path tracers for the web. The open-source nature of the project facilitates extension and serves as inspiration for other initiatives.

5 Index

5.1 Glossary

A-Frame Open-source 3D engine for the web based on WebGL 12

AABB *Axis-Aligned Bounding Boxes*, bounding volume aligned with the coordinate axes 28

API *Application Programming Interface* 13, 34–36, 39, 43, 56, 59, 63, 64

ASCII *American Standard Code for Information Interchange*, character encoding standard for electronic communication 40

ASWF *Academy Software Foundation*, organization promoting development and adoption of open-source software in the motion picture industry 45

Babylon.js Open-source 3D engine for the web based on WebGL and WebGPU 12, 36, 54, 61

Blender open-source 3D computer graphics software toolset 44, 45

BMRT *Blue Moon Rendering Tools*, early free and open-source ray tracing software which was RenderMan compatible 25, 34

BRDF *Bidirectional Reflectance Distribution Function*, describes the reflection of light off a surface 42

BSDF *Bidirectional Scattering Distribution Function*, describes the interaction of light with surfaces 42, 46, 62

BTDF *Bidirectional Transmittance Distribution Function*, describes the transmission of light through a surface 42

BVH *Bounding Volume Hierarchy*, common tree-based acceleration structure 28, 29, 34, 48, 50, 56, 59, 74

BxDF *Bidirectional Distribution Functions*, describe the interaction of light with surfaces, commonly used interchangeably with *BSDF* 42

CAD *Computer-Aided Design*, use of computers to aid in modeling a design 5–7, 44, 47, 53, 61, 65

CDF *Cumulative Distribution Function*, describes the probability that a random variable is less than or equal to a given value 17, 74

CDN *Content Delivery Network*, distributed group of servers for caching content near end users. 9

COLLADA *Collaborative Design Activity*, 3D exchange format managed by *Khronos Group* 40

CPU *Central Processing Unit*, the main processing unit of a computer 34, 48, 59

Dawn Open-source and cross-platform WebGPU implementation developed by Google 36, 47, 60

Deno JavaScript runtime, alternative to Node.js 36

DirectX 12 *API* developed by Microsoft for 3D graphics and computing 35, 36

DSPBR *Dassault Systèmes PBR Shading Model*, specification for PBR shading model 13, 44, 54, 55

FBX *Filmbox*, proprietary 3D exchange format nowadays managed by Autodesk 40

FPS *Frames per second*, measure of rate at which consecutive images are rendered and displayed 54

GLSL *OpenGL Shading Language*, shading language used in *OpenGL* 35, 45, 60, 65

glTF *Graphics Library Transmission Format*, common 3D exchange format optimized for transmission and real-time rendering. 8, 41, 43, 44, 48, 54, 58, 75

GPGPU *General-Purpose GPU* Programming, using GPUs for non-graphics tasks 34–36, 56, 59

GPU *Graphics Processing Unit*, specialized processor for parallel computation 9, 13, 33, 34, 36, 37, 43, 48, 59

gzip *GNU zip*, file format and software application for compression and decompression. 39

HDR *High Dynamic Range*, signal with a large range of luminance values 32

JPEG *Joint Photographic Experts Group*, common method for lossy image compression 49

Khronos Group consortium for developing interoperability standards for 3D graphics 35, 40, 41, 63

LOD *Level of Detail*, defines finer or coarser representations of a model 7

MaterialX Open standard for rich material definition 45, 50, 60

Metal *API* developed by Apple for 3D graphics and computing 35, 36

MIS *Multiple Importance Sampling*, technique to combine multiple sampling strategies in Monte Carlo integration 27, 50

MIT license Permissive license originating at the Massachusetts Institute of Technology (MIT) 47

MTL *Material Template Library*, a companion file format to *OBJ* for material definitions 40

Node.js JavaScript runtime, frequently used for executing JavaScript outside of the browser 59

npm package manager for JavaScript 47, 55

OBJ *OBJ* geometry file format, a simple text-based format for 3D models 40, 48, 64

OpenGL *Open Graphics Library*, cross-platform API for rendering 2D and 3D graphics 34–36, 63

OpenGL ES *OpenGL for Embedded Systems*, subset of OpenGL designed for embedded systems like smartphones 35

OpenPBR Open specification of surface shading model 45–47, 50, 54, 55, 57, 58, 60, 61, 75

OSL *Open Shading Language*, shading language for production global illumination renderers maintained by Academy Software Foundation 44, 45

PBR *Physically Based Rendering*, rendering technique that simulates real-world materials 41–45, 53–55, 57, 58

pbrt open-source ray tracing renderer, described in the book Physically Based Rendering [37] 42, 61

PCG Permuted Congruential Generator, a family of random number generators 31

PDF *Probability Density Function*, describes the likelihood of a random variable 17, 25, 74

PlayCanvas Open-source 3D engine for the web based on WebGL 12, 36

RenderMan A rendering software for photorealistic 3D rendering developed by Pixar 25, 44

RGB *red, green, and blue*, common system for color representation in computer graphics 51, 58

Rhino3D *Rhinoceros*, proprietary 3D computer graphics and *CAD* toolset 44

RNG Random Number Generator 31, 49, 74

SIMD *Single Instruction, Multiple Data*, type of parallel processing of data points with a single instruction 33, 34

SPIR-V *Standard Portable Intermediate Representation*, intermediate language for parallel computing and graphics developed by Khronos Group 60

STEP *Standard for the Exchange of Product model data*, a standard formalized in ISO 10303 for product manufacturing information. 6, 40

STL *Stereolithography*, 3D exchange format developed by 3D Systems 40

Three.js Open-source 3D engine for the web based on WebGL 12, 13, 36, 48, 54, 59–61, 65

TSL *Three.js Shading Language*, shading language used in *Three.js* which supports *GLSL* as well as *WGSL* 60

uber shader Shader design that offers parameter configuration but no custom shader code 43–46

Unity Proprietary, cross-platform game engine developed by Unity Technologies 12, 36, 44

Unreal Unreal Engine, cross-platform game engine developed by Epic Games 44

USD *Universal Scene Description*, 3D exchange format 40

Vulkan Open standard for cross-platform 3D graphics and computing 35, 36

W3C *World Wide Web Consortium*, a non-profit organization dedicated to developing web standards 36

WebAssembly Portable Binary-code format for executable programs available in modern browser engines 59

WebGL *Web Graphics Library*, since 2011 the de-facto standard API for rendering 3D graphics on the web 12, 13, 35, 36, 54, 61

WebGPU A new standard for 3D graphics on the web 13, 33–37, 47, 52, 54–57, 59–61

wgpu Open-source and cross-platform WebGPU implementation 36, 47, 59

WGSL *WebGPU Shading Language* 31, 37–39, 50, 59, 60, 65, 74, 75

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