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IRP

Hybrid Relightable 3D Gaussian Rendering (sdmay25-40)

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Project Overview

- Turn videos into realistic 3D models.
- Render composite scenes containing 3D Gaussian and polygon models.
- Packaged into Unity, a popular game engine, for easy adoption.

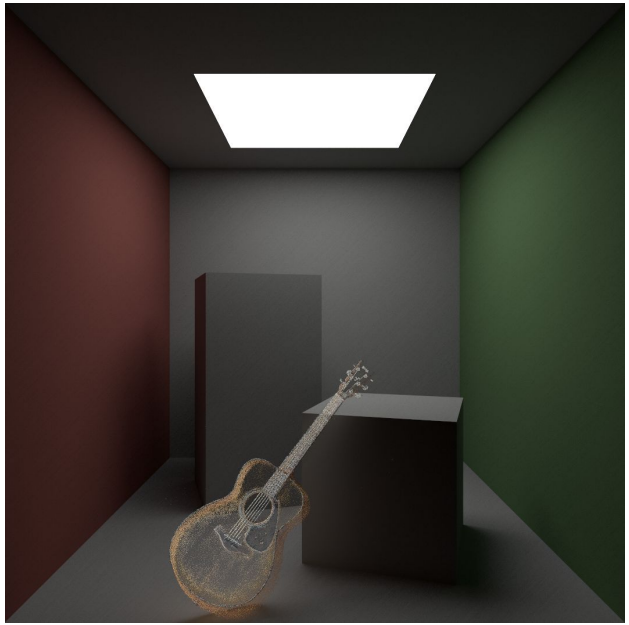

Figure 1: Hybrid Scene consisting of a Cornell box and a Gaussian model of a guitar.

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Intended Users

Users

- 3D Artist
- Neural Radiance Fields (NeRF) Users
- Non-Technical User

Industries

- Entertainment
- Marketing
- Real Estate

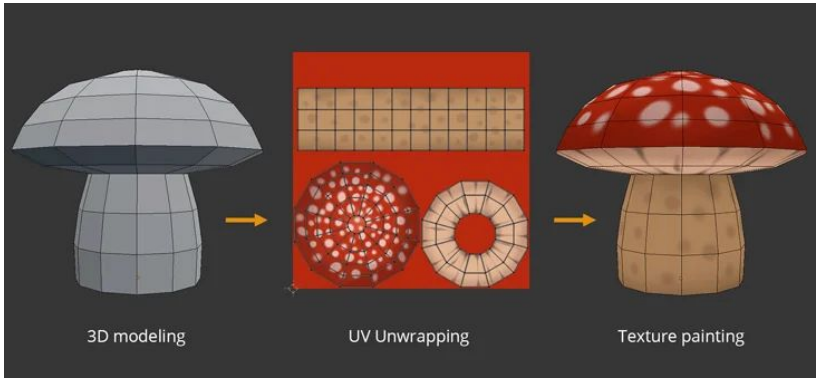

Figure 2: 3D modeling workflow for creating a mushroom
Source: https://game-ace.com/blog/3d-modeling-in-unity/

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Solving Engineering Problems

- Two major engineering problems were solved when choosing the system's techniques.
- The first was choosing a novel view synthesis method.
  - The system uses 3D Gaussian Splatting because it is the most modern practice and produces the highest quality models.
- The second was choosing a rendering approach (path tracing or rasterization).
  - The system uses path tracing to increase visual fidelity with realistic light propagation.

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Professional Responsibility

- The design fit in and provides value to society because it mitigates the challenges of manually re-creating real-world objects.
- Automatic reconstruction of 3D models reduces the reliance on manual modeling, raising concerns about job displacement; however, the system wouldn’t replace workers, as it lacks fine-grained creative control a 3D artist could achieve.

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Functional Requirements

- Create point clouds using Structure from Motion (SfM) techniques from videos or video frames
- Input SfM point clouds for Gaussian model optimization.
- Provide Gaussian model with position, opacity, covariance, and spherical harmonics for 3D Gaussian parsing.
- Input parsed 3D Gaussian model for Bounding Volume Hierarchy (BVH) generation.
- Provide Unity mesh objects for BVH generation.
- Input 3D Gaussian models, triangle meshes, mesh material data, and camera parameters for hybrid path tracer.
- Present the rendered texture from pipeline to Unity's camera.

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Non-Functional Requirements

- The system should be downloadable via Unity's package manager.
- The system should run in real-time at 30 FPS with dynamic updates.
- The system should generate an optimized Gaussian model from video in under an hour.
- The system should be CUDA compatible NVIDIA graphics card
- The system should work with python and these python libraries: plyfil, ipython, torch, opencv-python, torchvision, and tkinter

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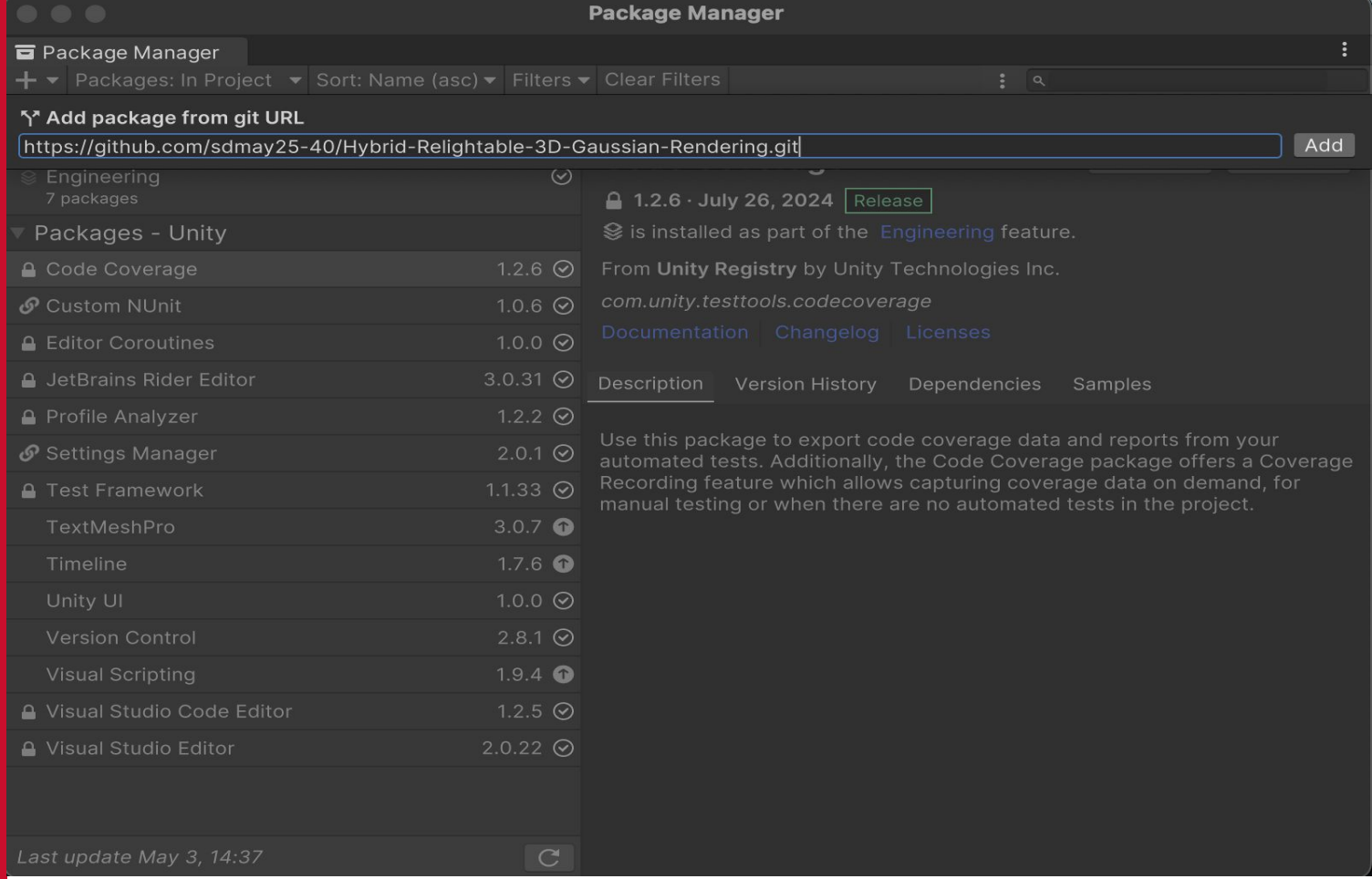

Figure 3: Unity package manager

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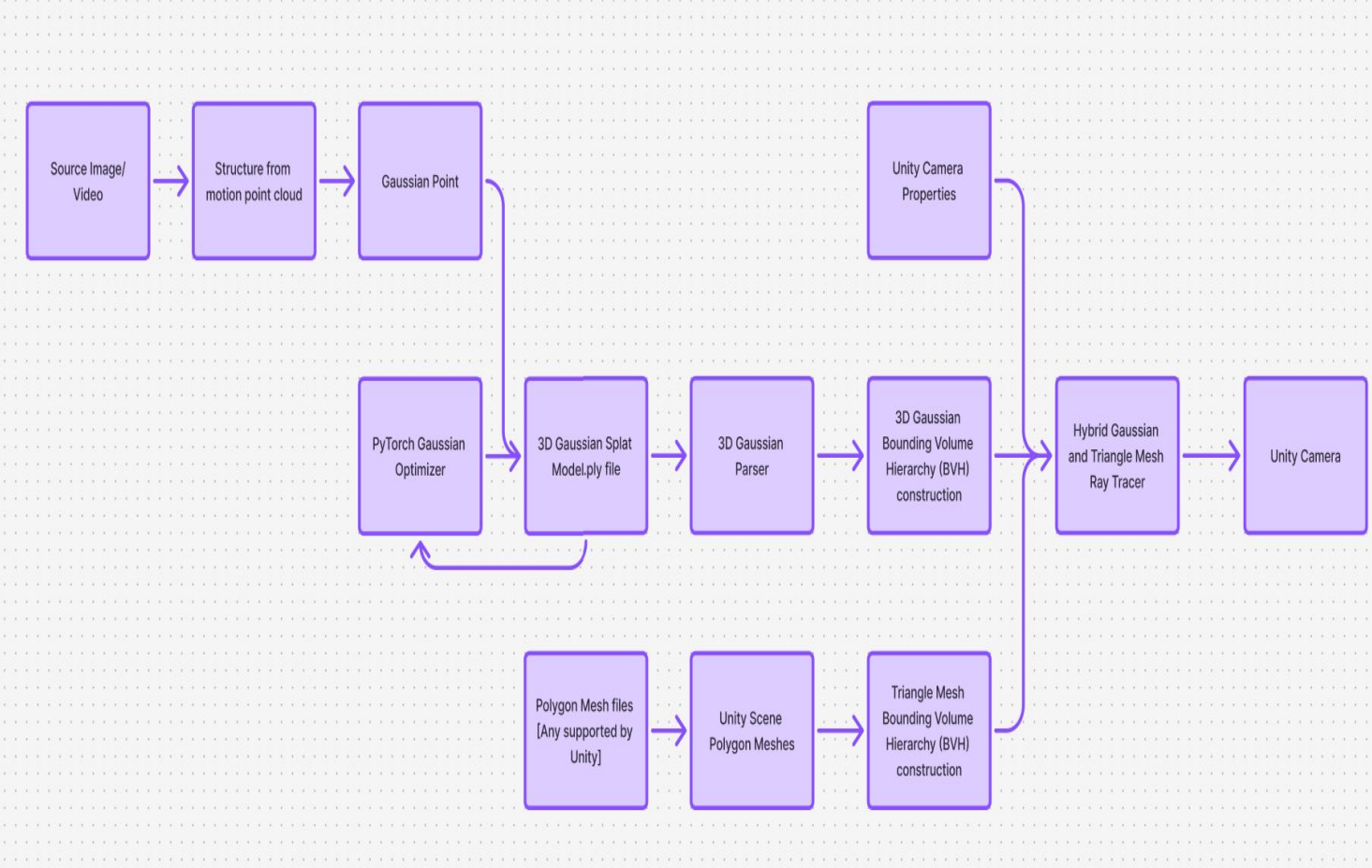

Figure 4: Flow diagram of our project pipeline

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3D Gaussian Splatting

- To be able to create models we use 3D Gaussians.
- Think of a 3D Gaussian as a blurry dot in space.
- By combining and reshaping multiple 3D Gaussians we can build 3D objects.
- 3D Gaussians can have multiple different variables including position, spherical harmonics, opacity, and covariance.

Figure 5: The Gaussian point optimizer splits to better fit the intended shape.
Source: https://repo-sam.inria.fr/fungraph/3d-gaussian-splatting/

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Gaussian Showcase

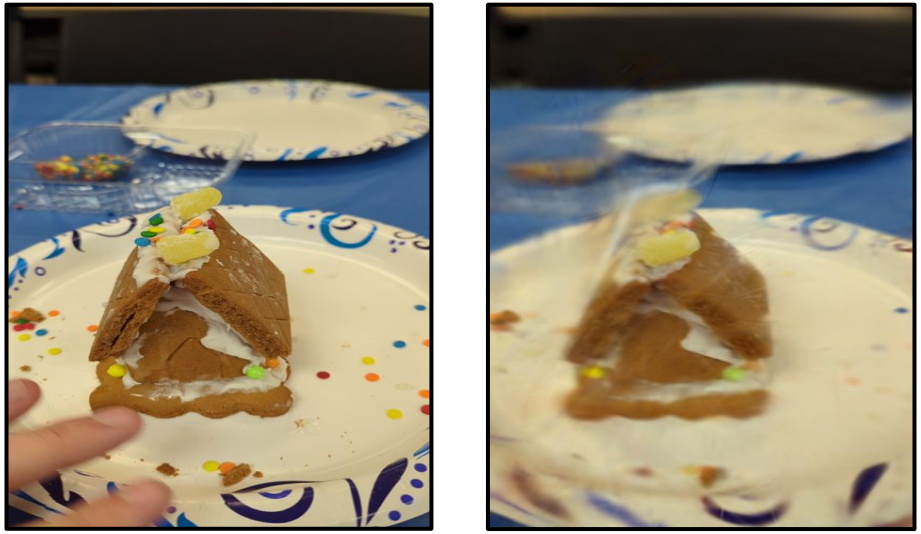

Figure 6: The image on the left showcases the original image and the image on the right showcases the model made up of Gaussians.

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Bounding Volume Hierarchy (BVH)

- In order for our raytracer to run in real time we need to make the process of finding intersections as efficient as possible
- A BVH speeds the process up by allowing the raytracer to efficiently check if the ray intersects the region of space a triangle is in.
- The BVH is made of a BST of Axis Aligned Bounding boxes.
- We implemented a BVH for both triangle and gaussian models

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Bounding Volume Hierarchy (BVH)

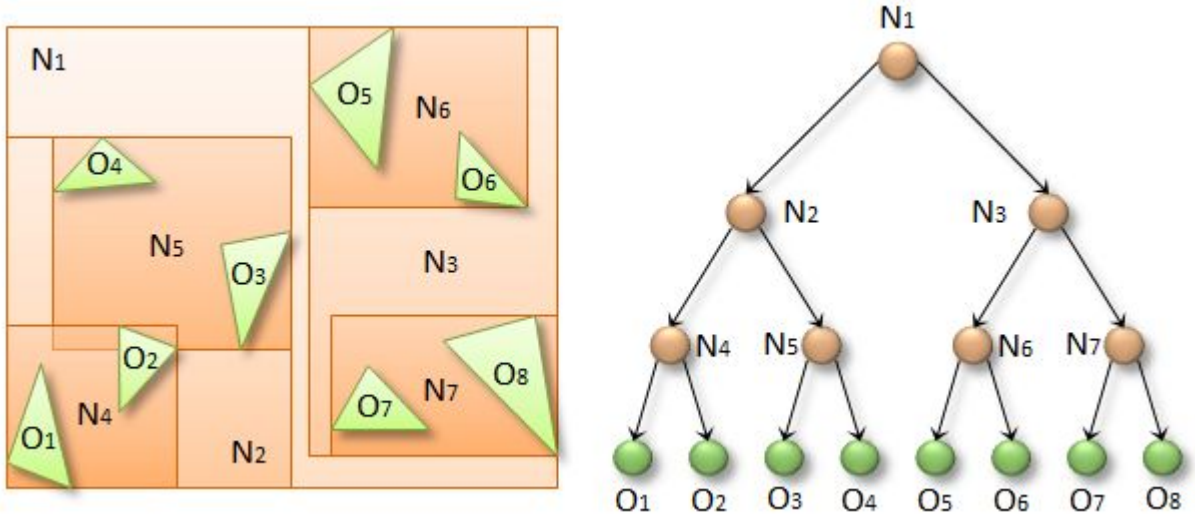

Figure 7: Diagram showing how an example BVH works
Source: https://developer.nvidia.com/blog/thinking-parallel-part-ii-tree-traversal-gpu/

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Hybrid Path Tracer

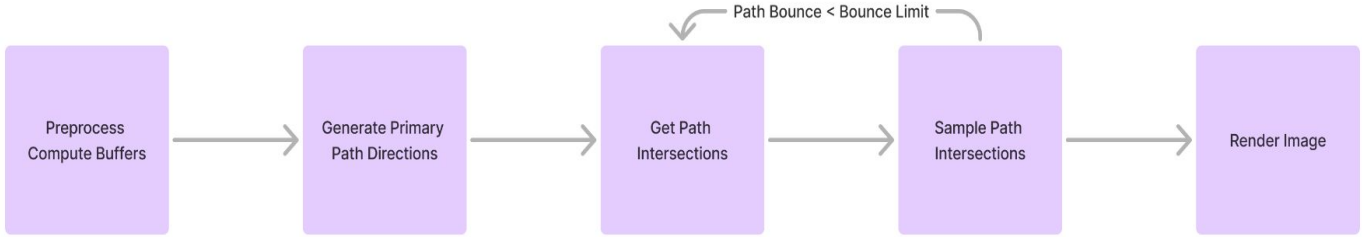

Figure 8: High-level overview of rendering pipeline

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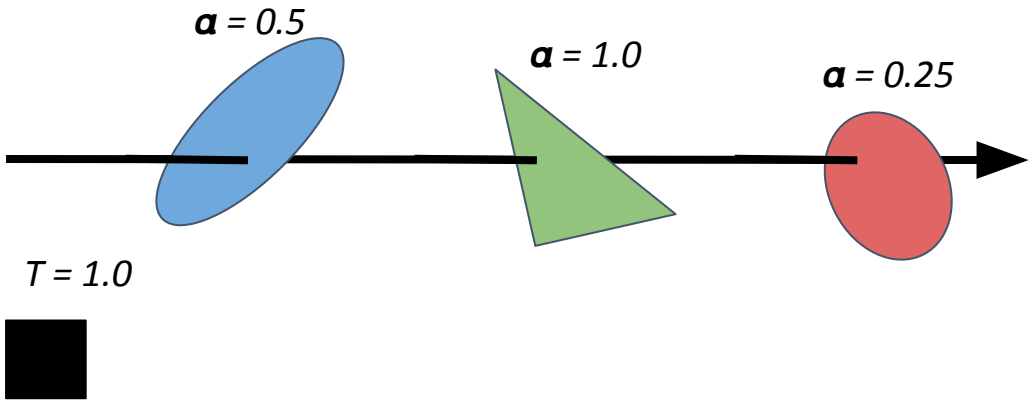
Determining Intersections in Composite (Hybrid) Scenes

- The system traces the scene until the path's accumulated transmittance reaches a minimum T value.
- Intersection contributions are weighted by opacity and transmittance.



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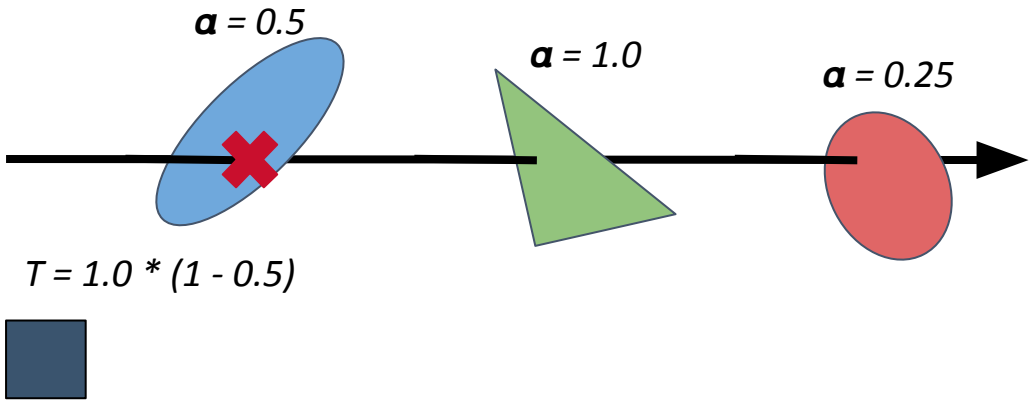

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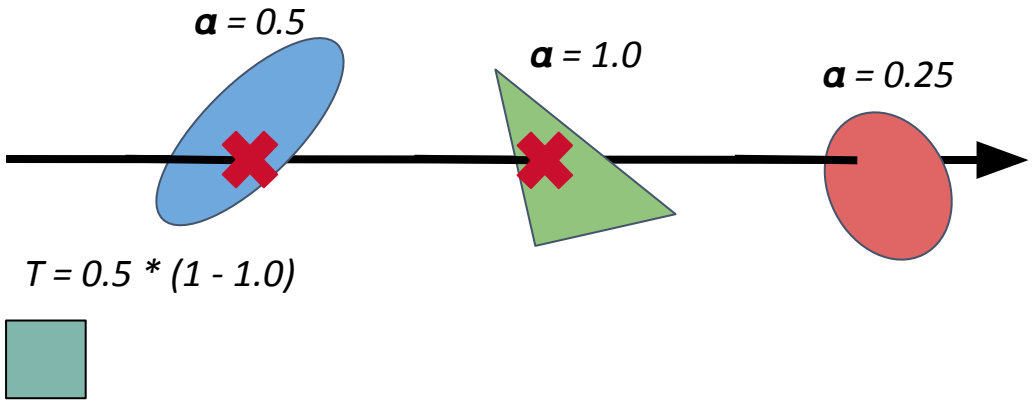

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The Rendering Equation

- Used to calculate color at intersection points.

$$L_o(x, V) = L_e(x, V) + \int_\Omega f_r(x, L, V) L_i(x, L)(L \cdot N) dL$$

Outgoing Light Emissive Light Reflected Incoming Light

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The Rendering Equation

- Used to calculate color at intersection points.

$$L_o(x, V) = L_e(x, V) + \frac{1}{n} \sum_{i=1}^{n} \frac{f_r(x, L, V) L_i(x, L)(L \cdot N)}{pdf(L)}$$

Outgoing Light Emissive Light Reflected Incoming Light

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Risk Identification and Mitigation

- Integrating the machine learning and ray tracing components.
  - Mitigated by communicating between teams and making modifications when necessary.
- Bad data sets being used for training
  - To mitigate this we used well known, high quality datasets.
- Less than real time performance.
  - Mitigated by the use and rigorous testing of BVHs.

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Testing

- Unit Testing:
  - pixel-level image comparisons with visual tools to validate ML outputs
  - Render single Gaussians to complex scenes for accuracy.
- Interface Testing: Validate PyTorch data handoff to rendering within Unity
- Integration testing: Validate added functionality improves performance
- System Testing: Render complex scenes derived from original video input.

Machine Learning Testing

ML Applications

- Structure from Motion
  - 3D structures from 2D images
- Gaussian Point Optimizer
  - Position, opacity, covariance, spherical harmonics (color)

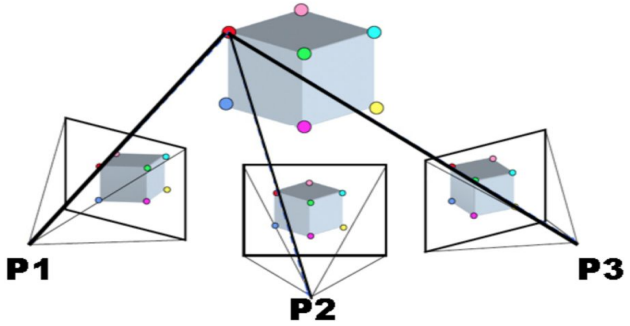

Figure 9: Structure for Motion (SfM) generates an approximate 3D shape using images from different perspectives.

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Structure From Motion

- **COLMAP** is a 3D reconstruction library for SfM, supporting feature extraction, matching, and point cloud generation.

Figure 10: Point cloud of a horse statue

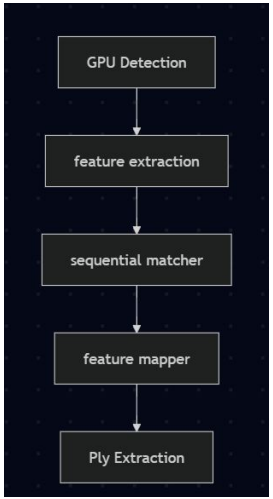

Figure 11: SfM pipeline

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Gaussian Point Optimizer

- Optimizes parameters like the position and covariance of our Gaussians.
- Retrieves the sparse point cloud from SfM.
- Compares the pixels of the 2D images from the sparse point cloud to ground truth images.
- Configures the parameters of the Gaussians to match the ground truth images.

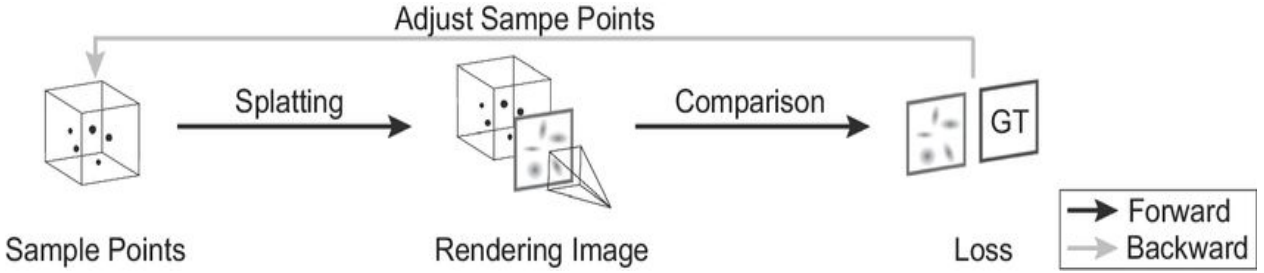

Figure 12: Flow chart of Gaussian point optimizer loop
Source: https://www.researchgate.net/figure/Pipeline-of-Gaussian-Splatting-Pipeline-of-Gaussian-Splatting-First-initial-sample_fig4_378904778

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Gaussian Point Optimizer

Figure 13: Truth image compared to model of a horse statue during training

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Gaussian Point Optimizer

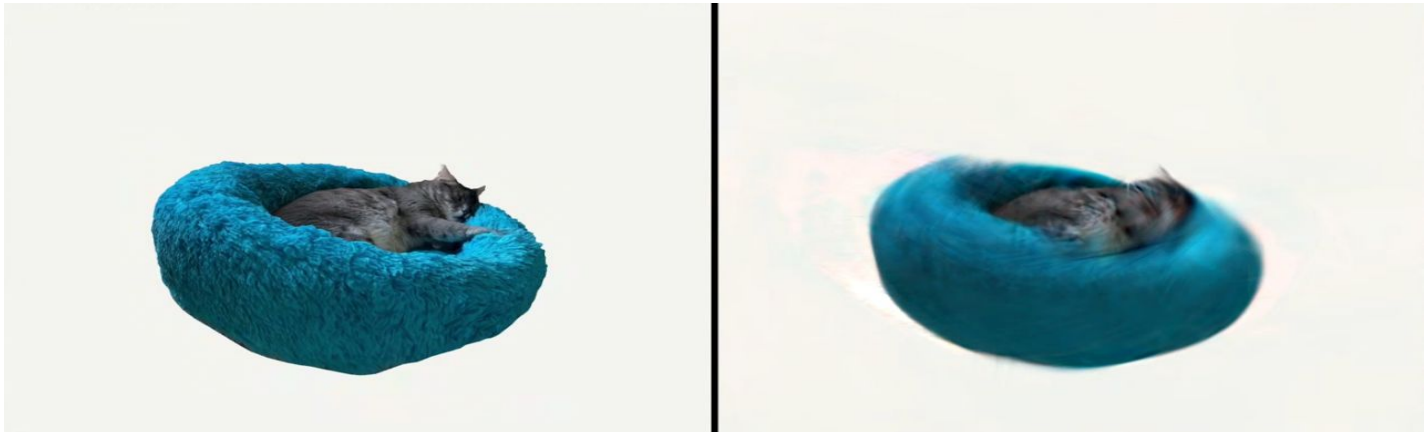

Figure 14: Truth image compared to model of a cat during training

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Testing the 3D Gaussian Parser

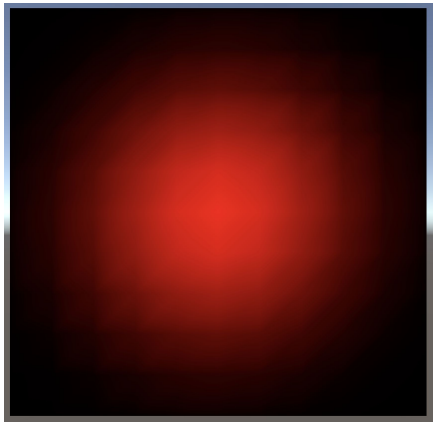

Figure 15: A Gaussian with its center in the middle a plane

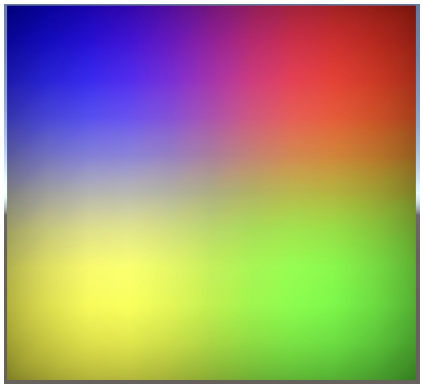

Figure 16: Four different colored Gaussians placed on a plane such that they overlap at the edges.

Figure 17: A Gaussian centered on a plane stretched (scaled in the y direction) and rotated.

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Bounding Volume Hierarchy (BVH)

- Our triangle BVH is implemented in C# and constructs an individual BVH for every Unity mesh in the scene.
- Our gaussian BVH is also implemented in C# and constructs a BVH bottom up by first creating an AABB for every Gaussian.

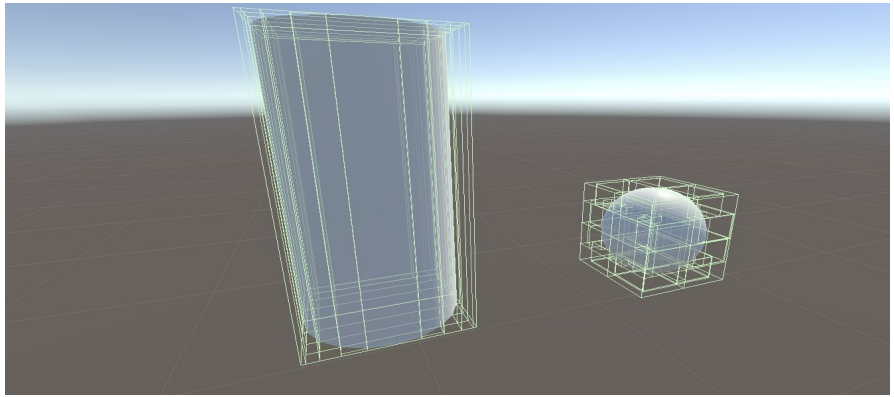

Figure 18: The bounding boxes created by our implementation for a cylinder and a square

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Testing the BVH

- To test the BVH the performance of the same scene was measured when rendered with and without a BVH.
- There was a major performance increase when using the BVH.

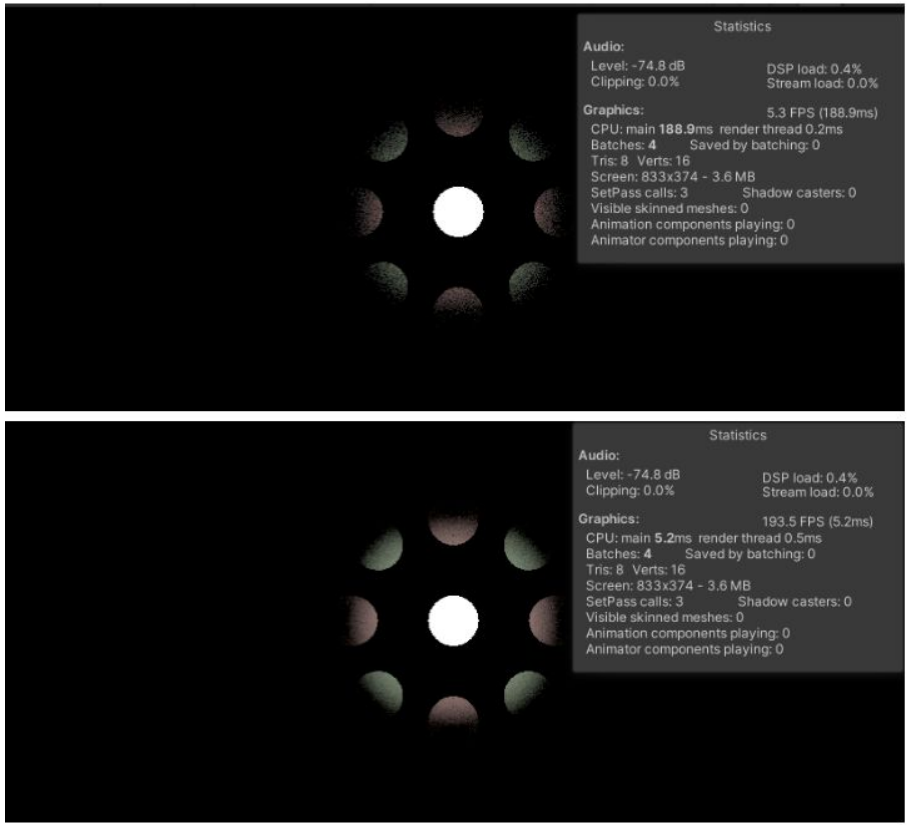

Figure 19: Performance comparison, in FPS, between a scene without a BVH (top) and one with a BVH (bottom)

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Triangle Mesh Ray Tracer Prototype

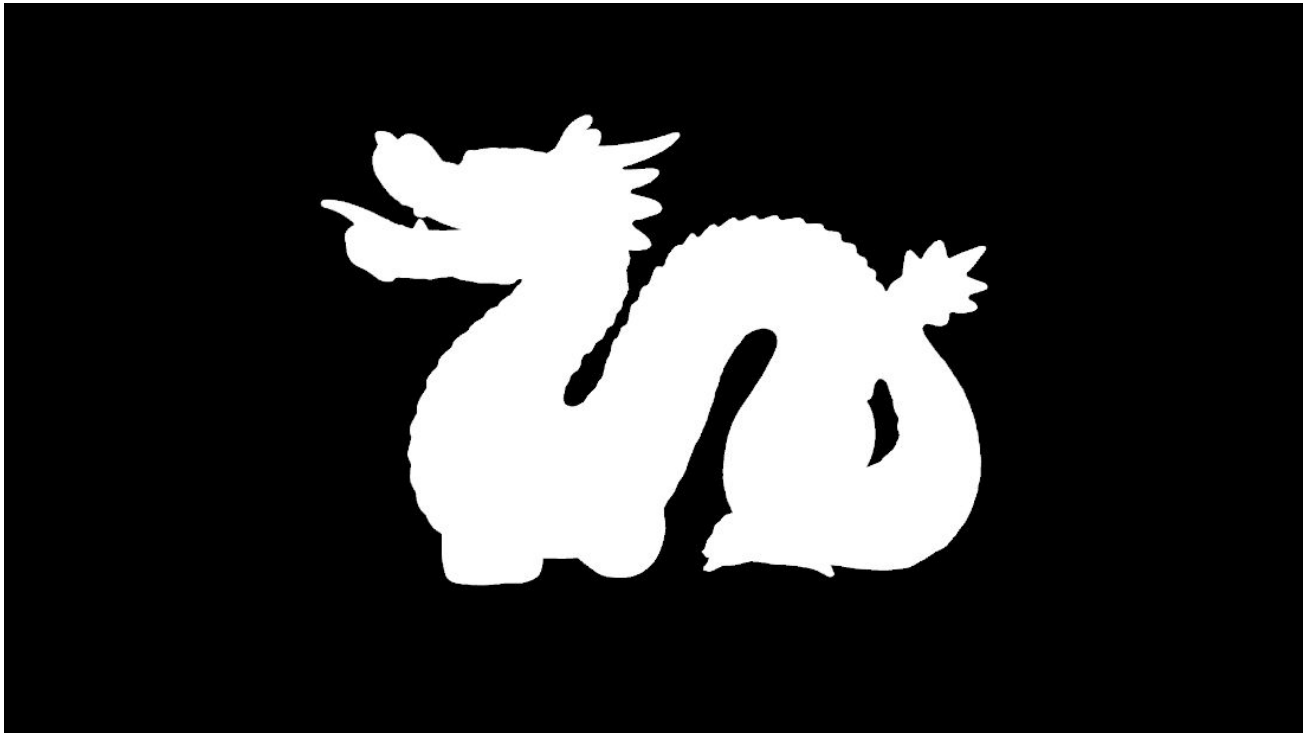

Figure 20: Rendered image of Stanford Dragon demonstrating ray-triangle intersections and material albedo.

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Testing Physically Based Rendering

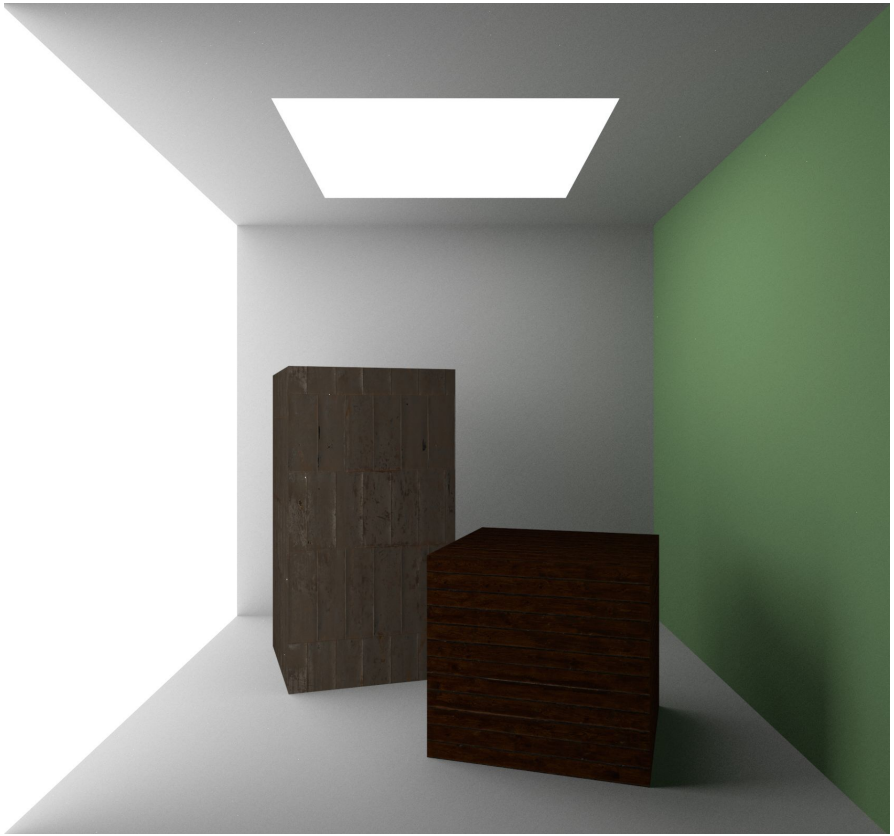

Figure 21: Modified Cornell Box with PBR materials

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Implications and Next Steps

Implications

- The program significantly speeds up the time needed to generate real-world 3D model.

Next Steps

- Improve the training speed
- Increase the quality of the Gaussian models
- Implement the material predictor

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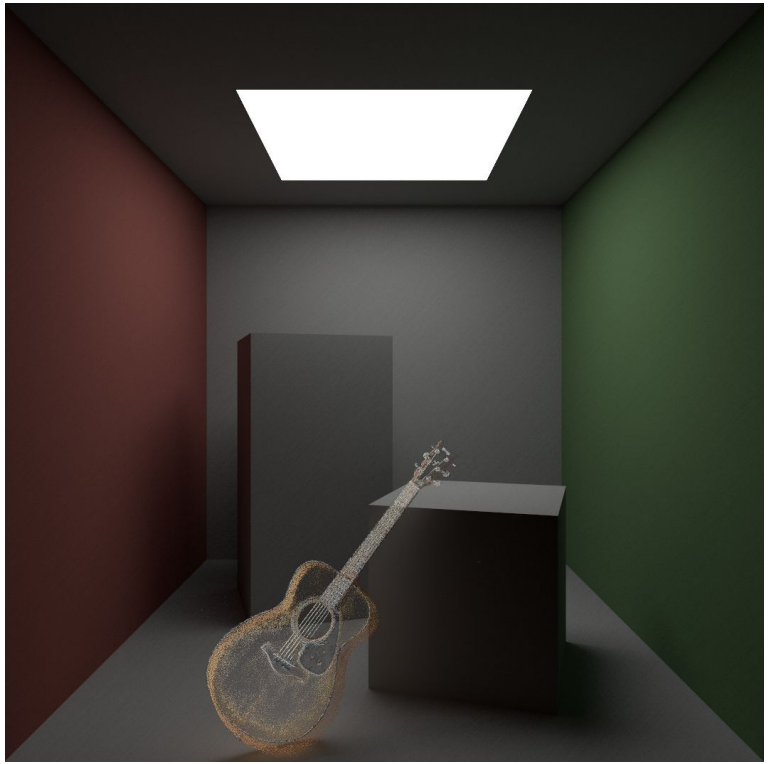
Questions?



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THANK YOU