GRTX
Efficient Ray Tracing for 3D Gaussian-Based Rendering

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Department of ECE
Seoul National University

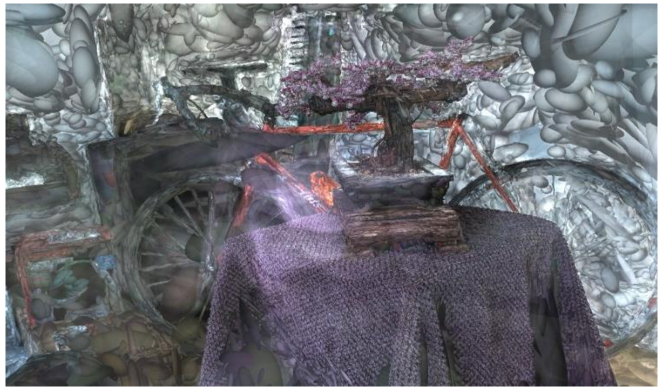
3D Gaussian-Based Rendering

3D Gaussian Splatting (3DGS)

3D Gaussian-Based Rendering

Rasterization

3D Gaussian Splatting (3DGS)



3D Gaussians

Rendered Image

Ray-tracing

3D Gaussian Ray Tracing (3DGRT)

e.g., EVER (Google) [1], DSYG (Meta) [2], 3DGRT (NVIDIA) [3]

[1] Alexander et al., EVER: Exact Volumetric Ellipsoid Rendering for Real-time View Synthesis (ICCV'25)
[2] Jorge et al., Don't Splat your Gaussians: Volumetric Ray-Traced Primitives for Modeling and Rendering Scattering and Emissive Media (SIGGRAPH'25)
[3] Nicolas et al., 3D Gaussian Ray Tracing: Fast Tracing of Particle Scenes (SIGGRAPH Asia'24)

3D Gaussian-Based Rendering

Rasterization

3D Gaussian Splatting (3DGS)

Limitation

Rasterization cannot
model complex light transports

Rendered Image

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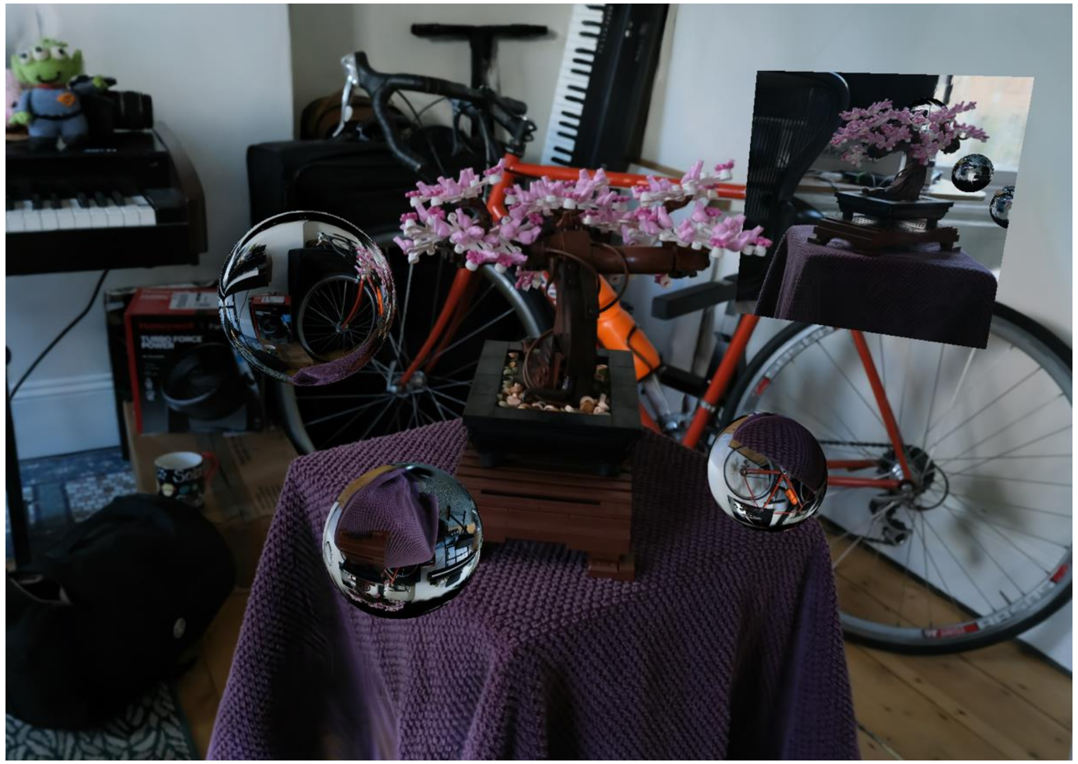

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R

model

Rendered Image

Ray-tracing

3D Gaussian Ray Tracing (3DGRT)

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Q: What is the key difference between **rasterization** and **ray-tracing**?

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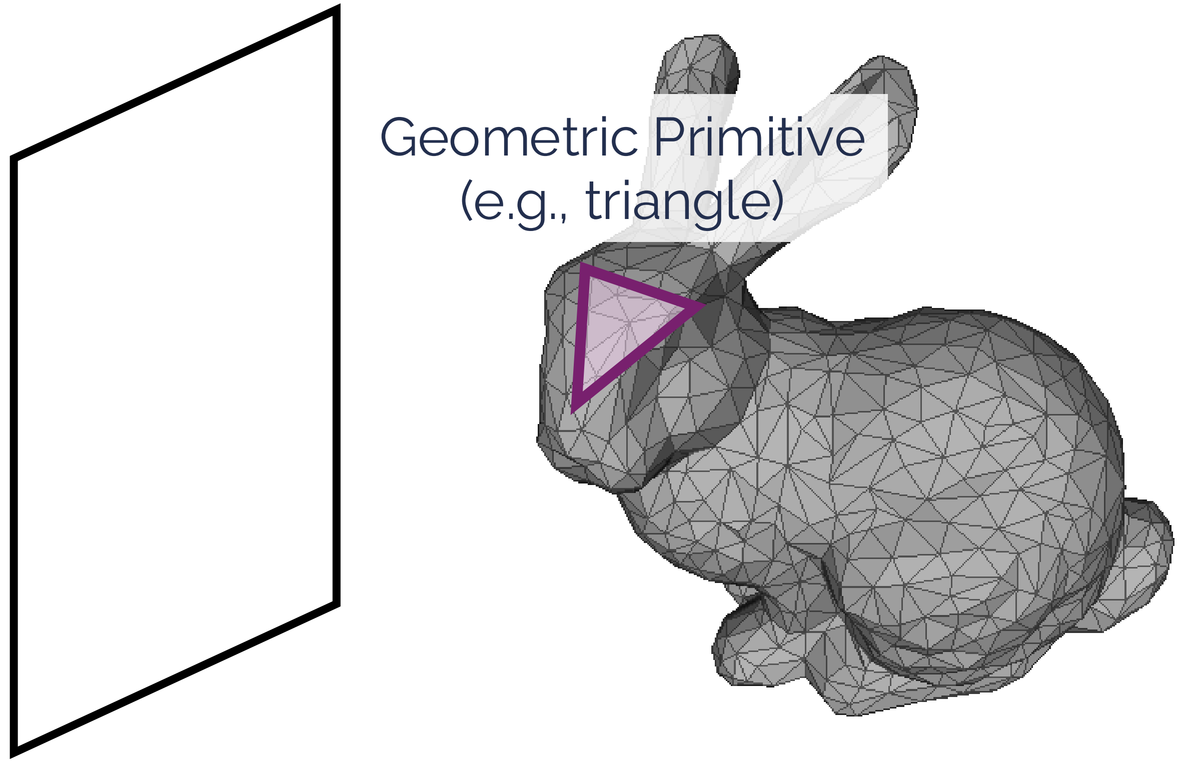
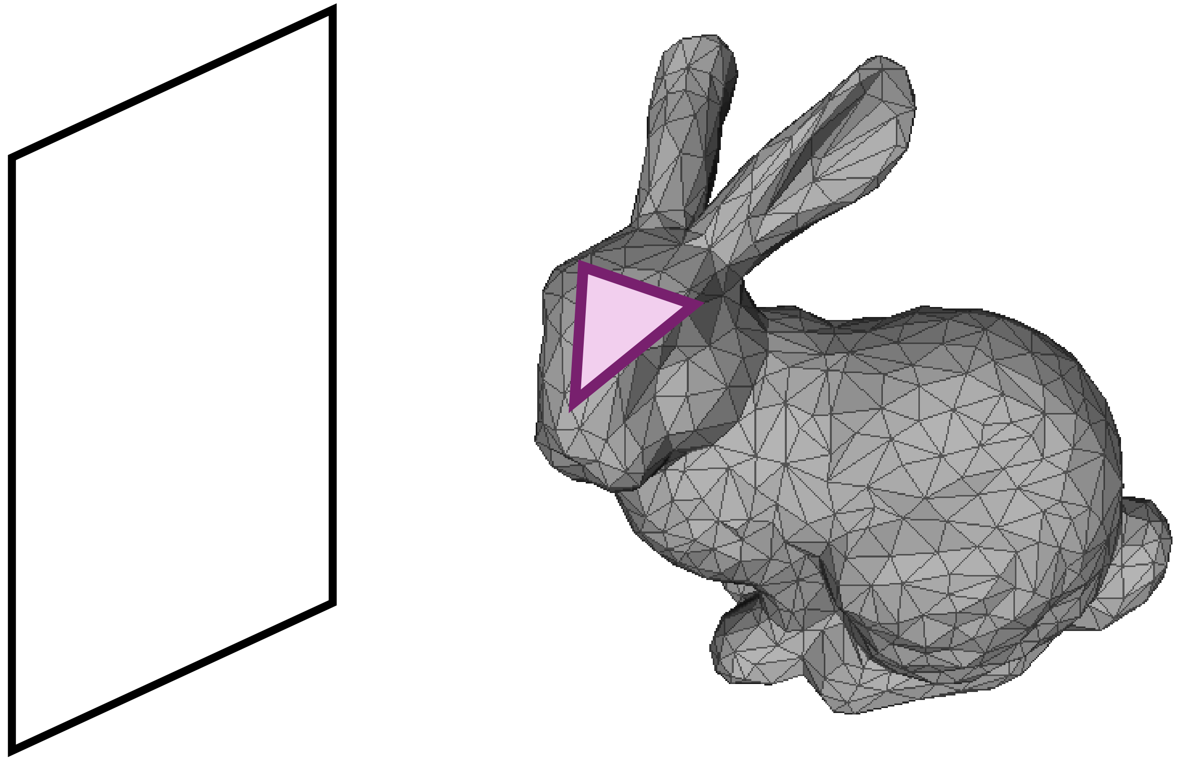
3D Gaussian-Based Rendering

Rasterization



Ray-tracing



3D Gaussian-Based Rendering

Rasterization

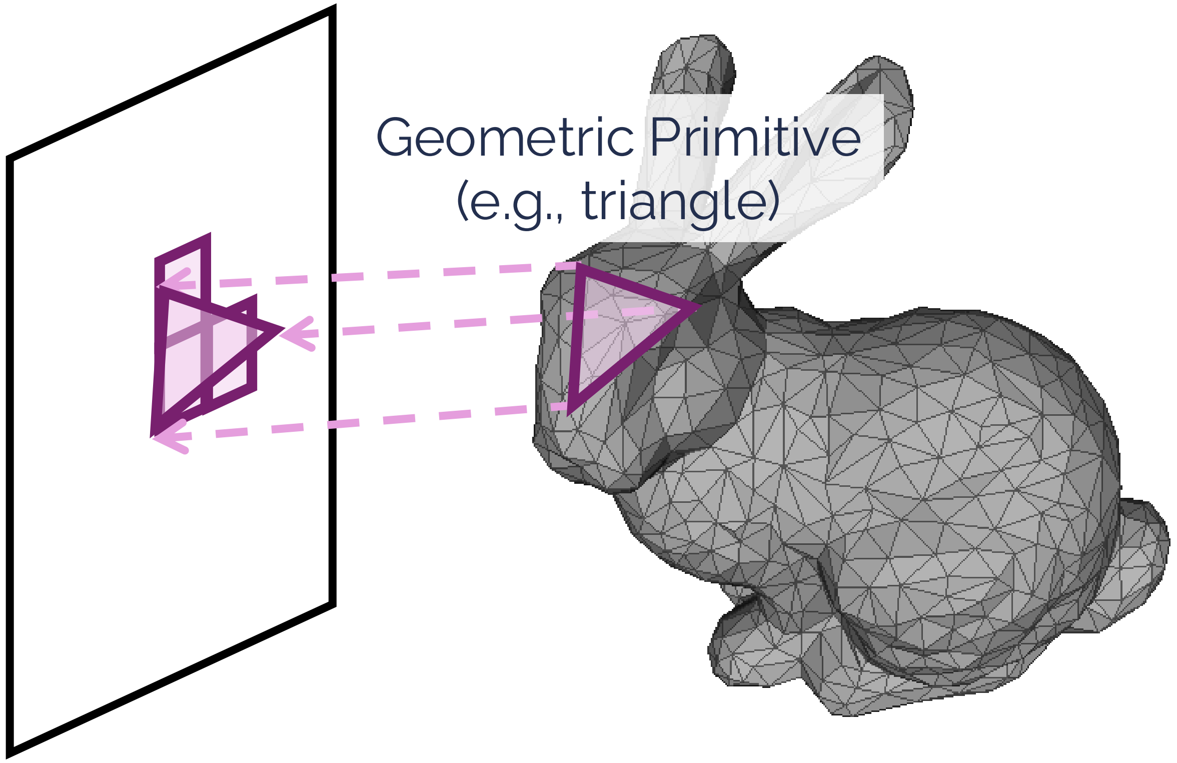


Image Plane

Ray-tracing

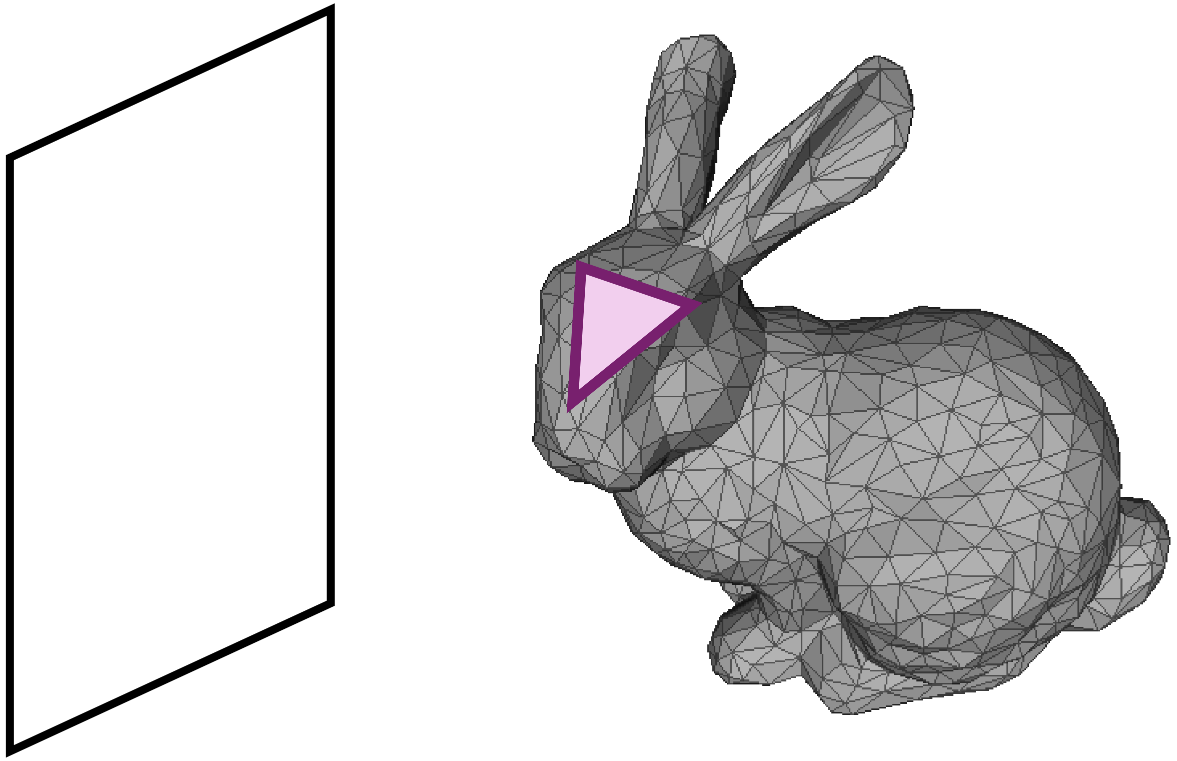


Image Plane

3D Gaussian-Based Rendering

Rasterization

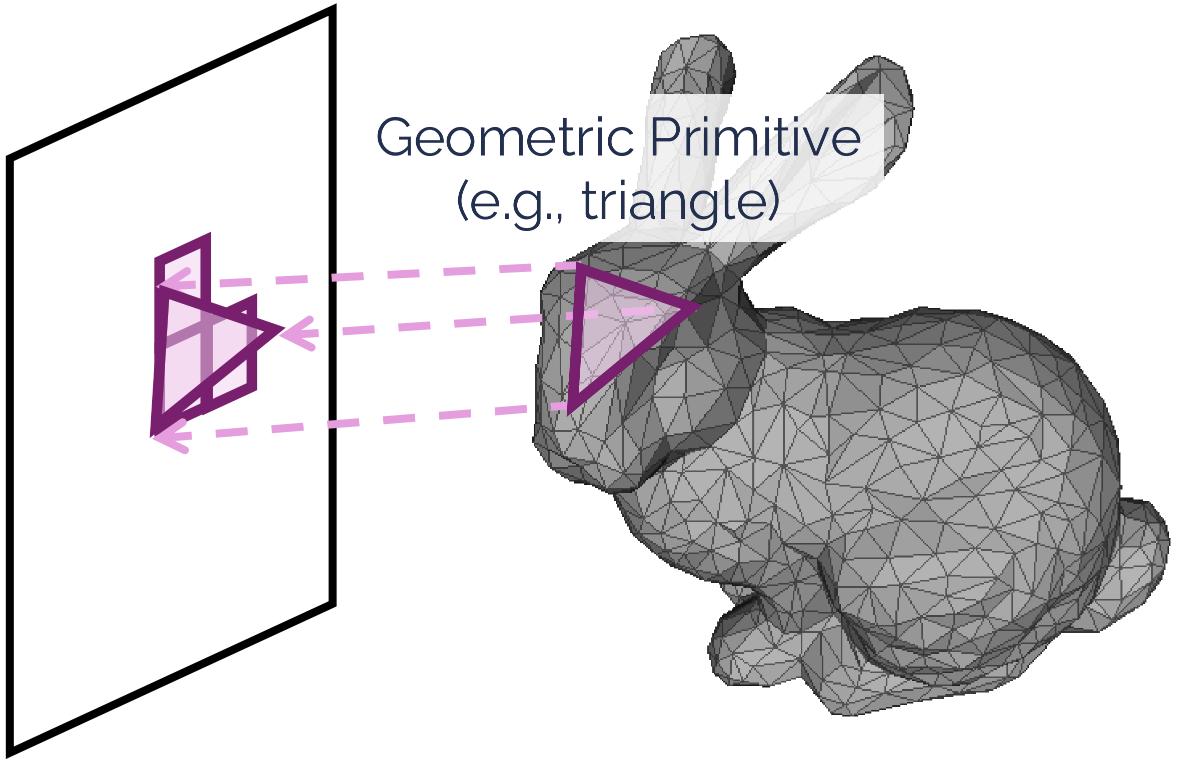


Image Plane

Ray-tracing

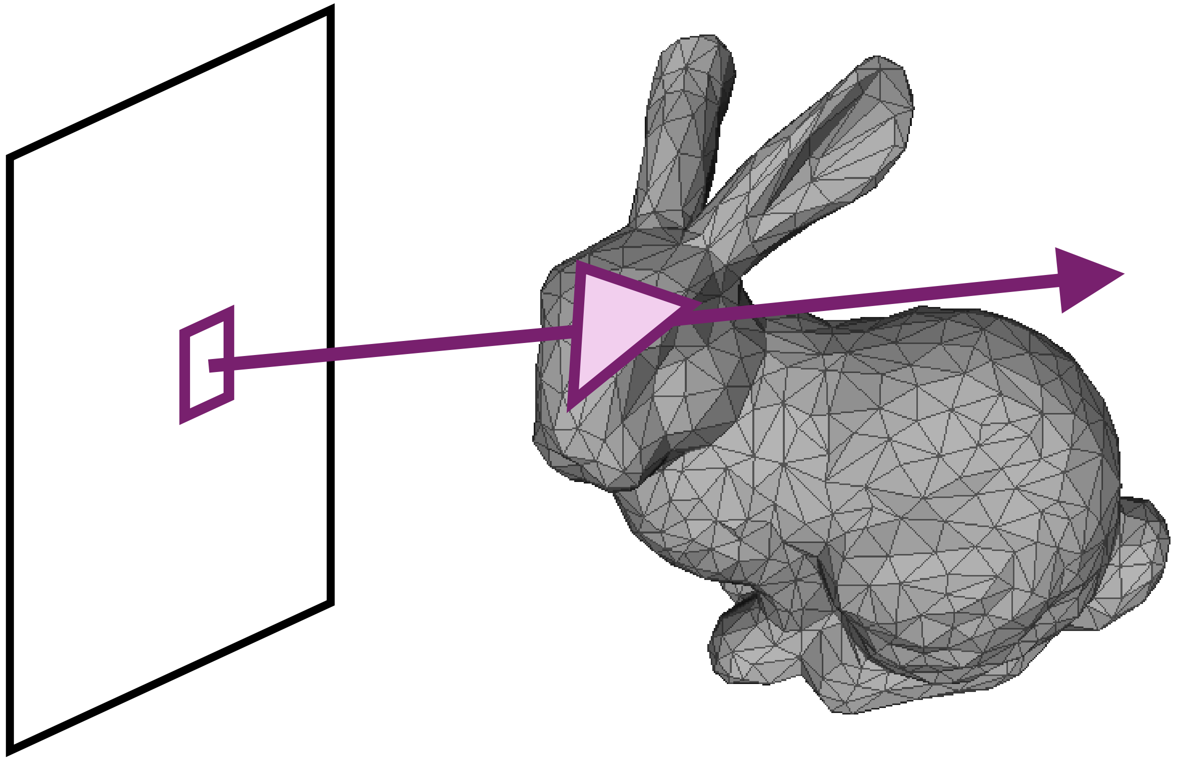


Image Plane

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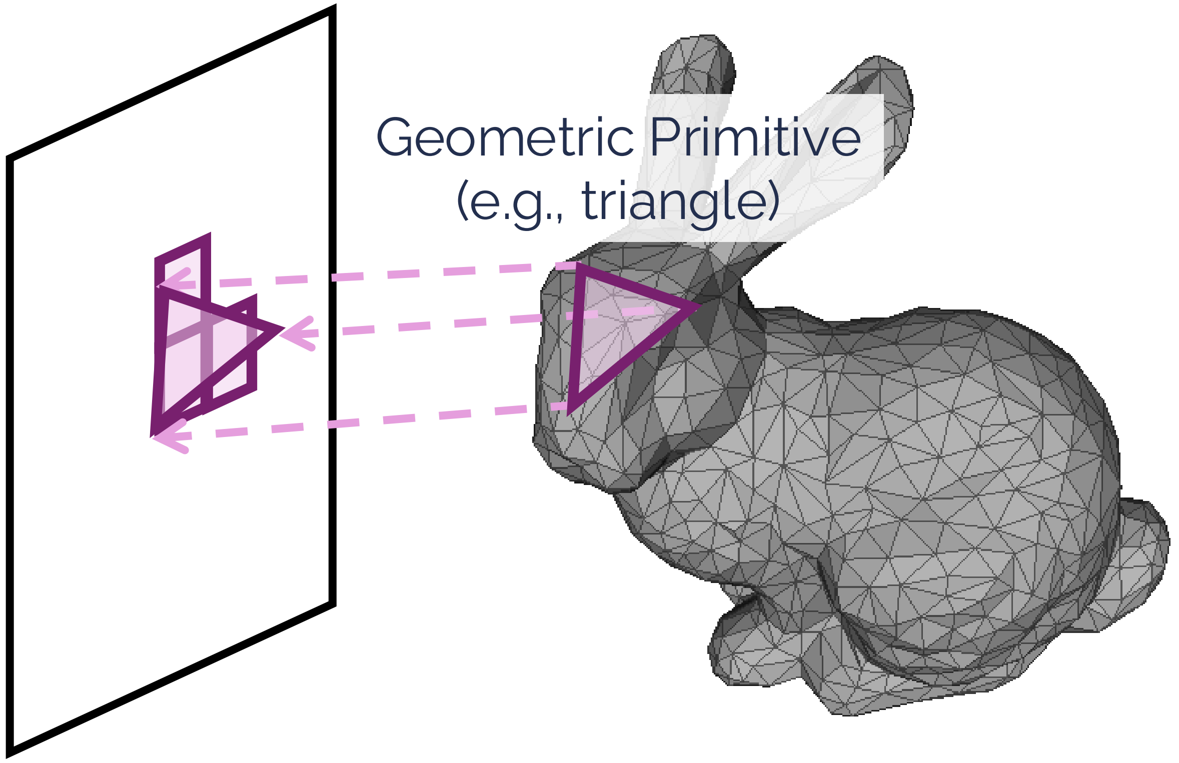
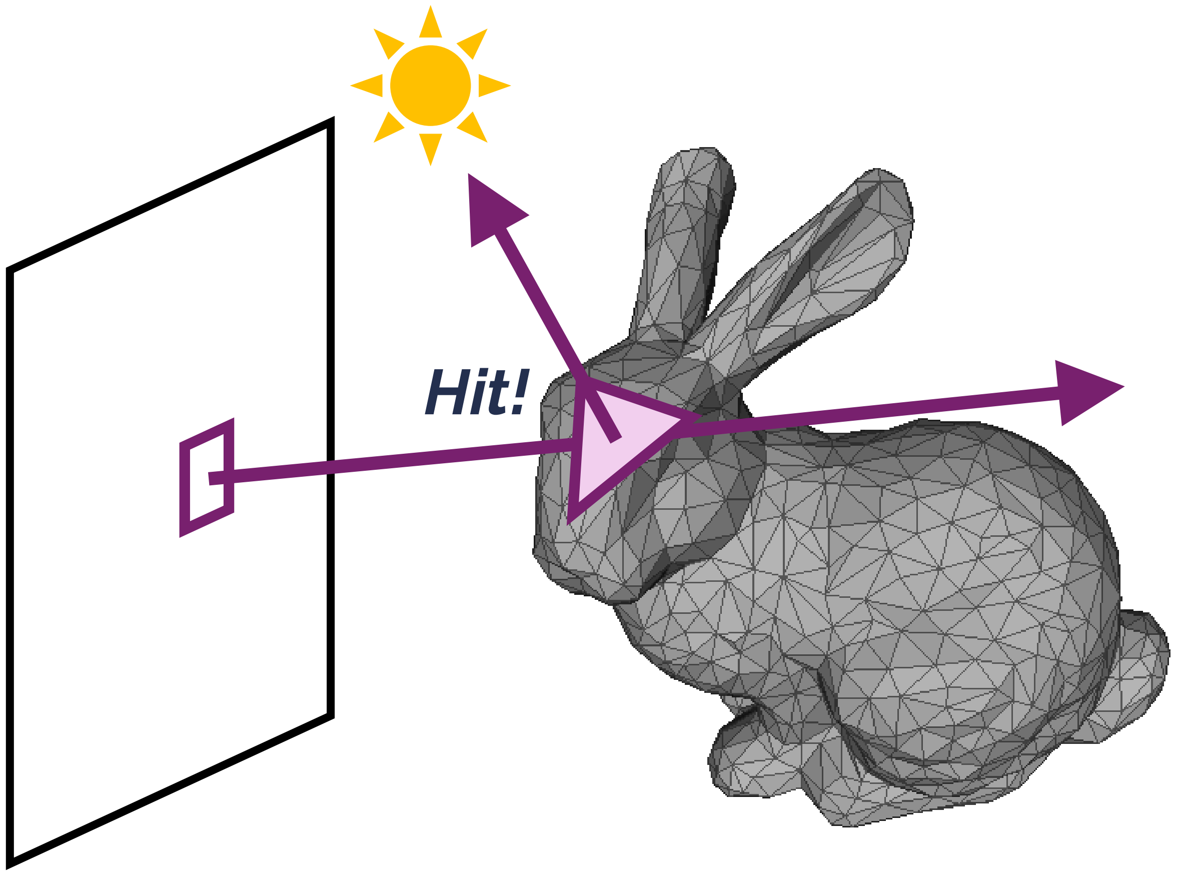
Rasterization



Ray-tracing



3D Gaussian-Based Rendering

Rasterization

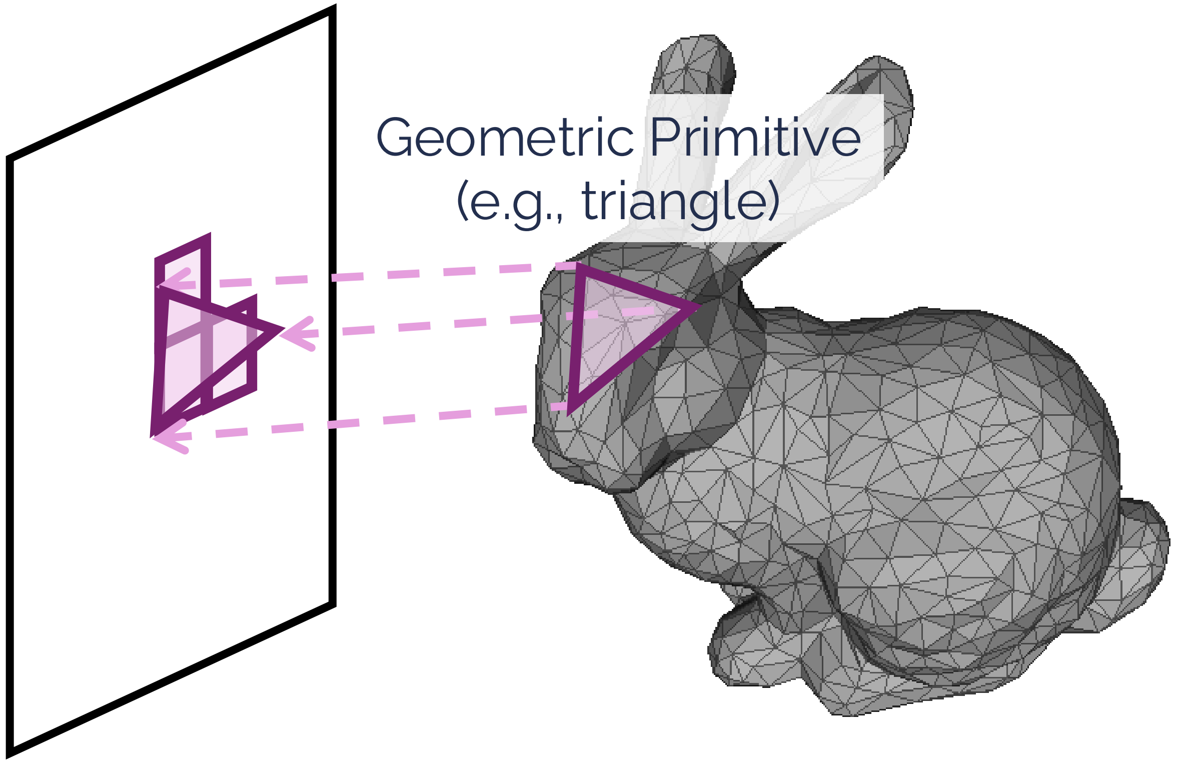


Image Plane

Ray-tracing

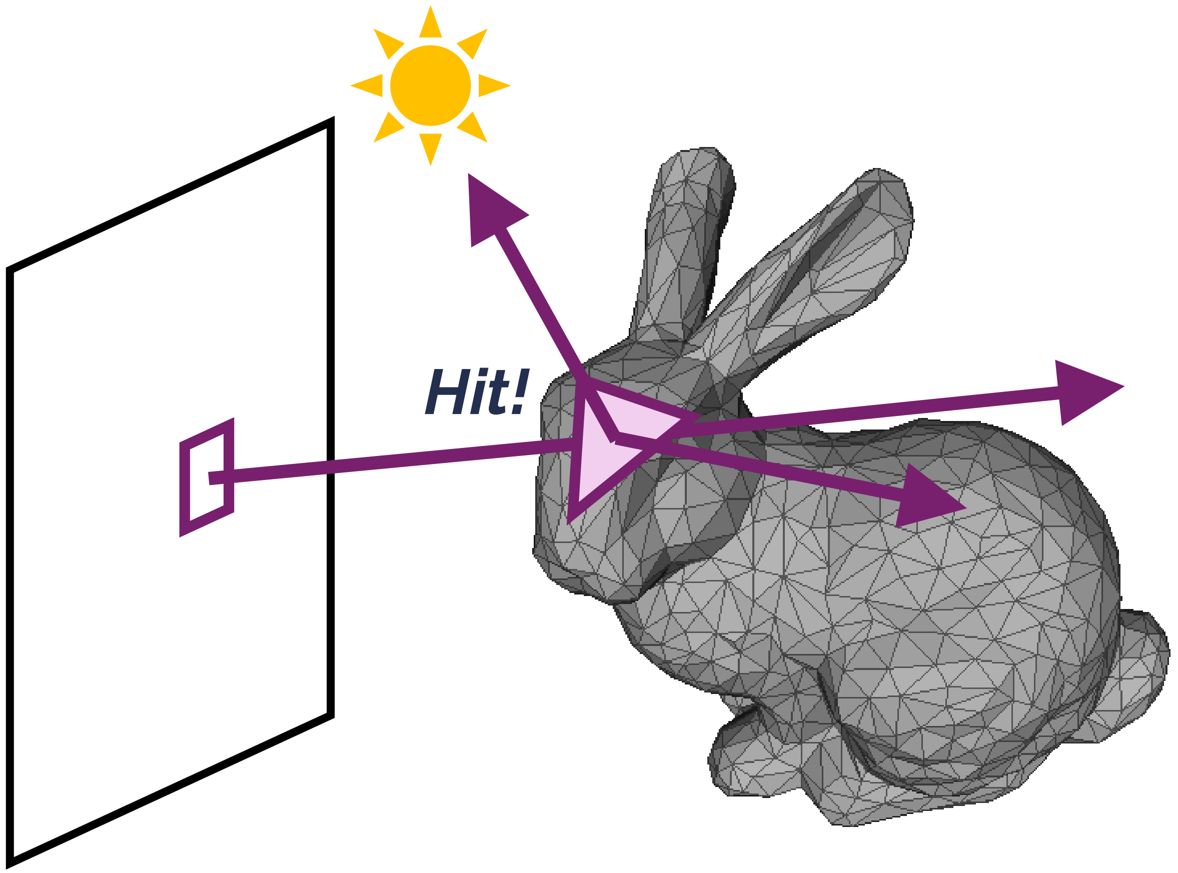


Image Plane

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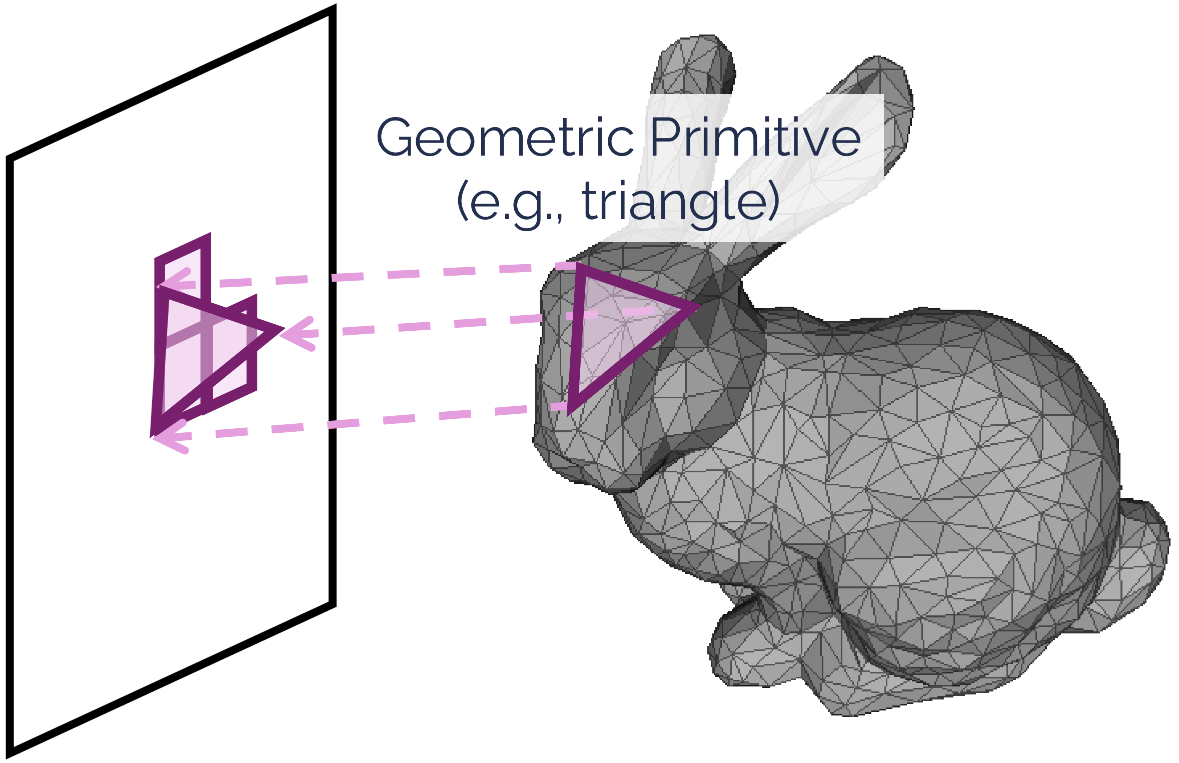

Image Plane

Ray-tracing

Bounding Volume Hierarchy (BVH)

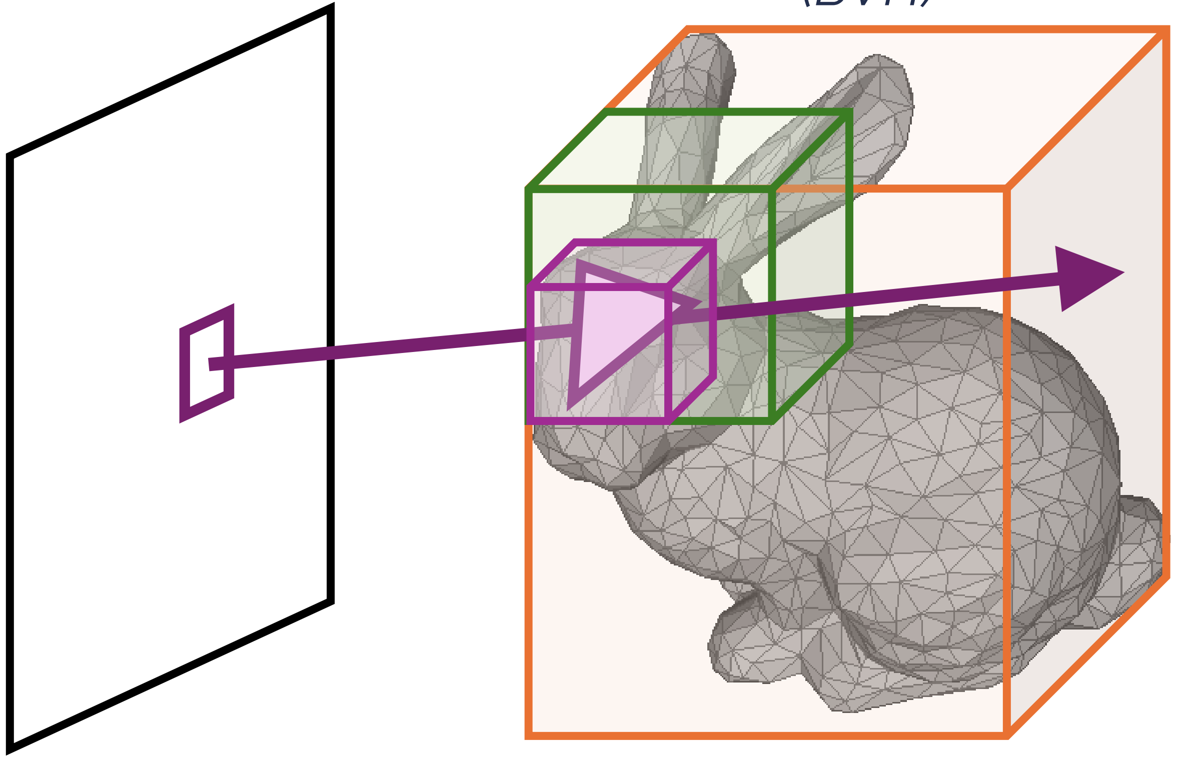

Image Plane

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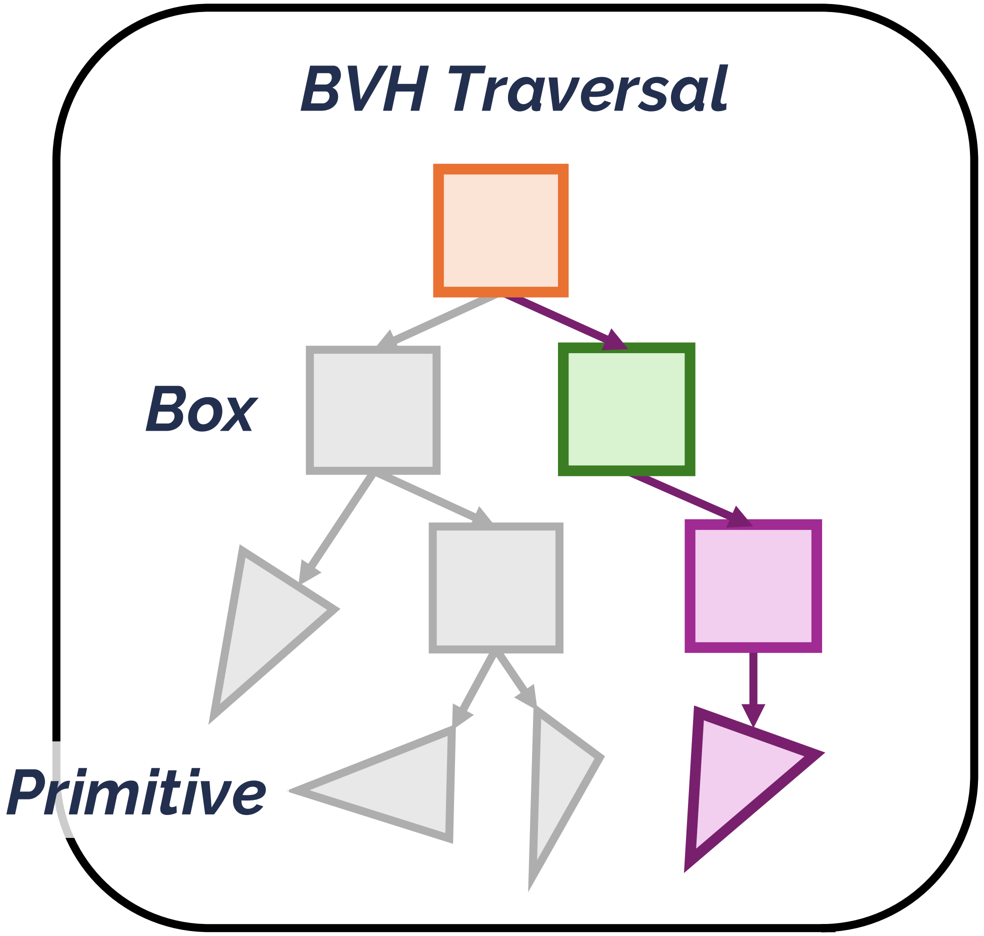

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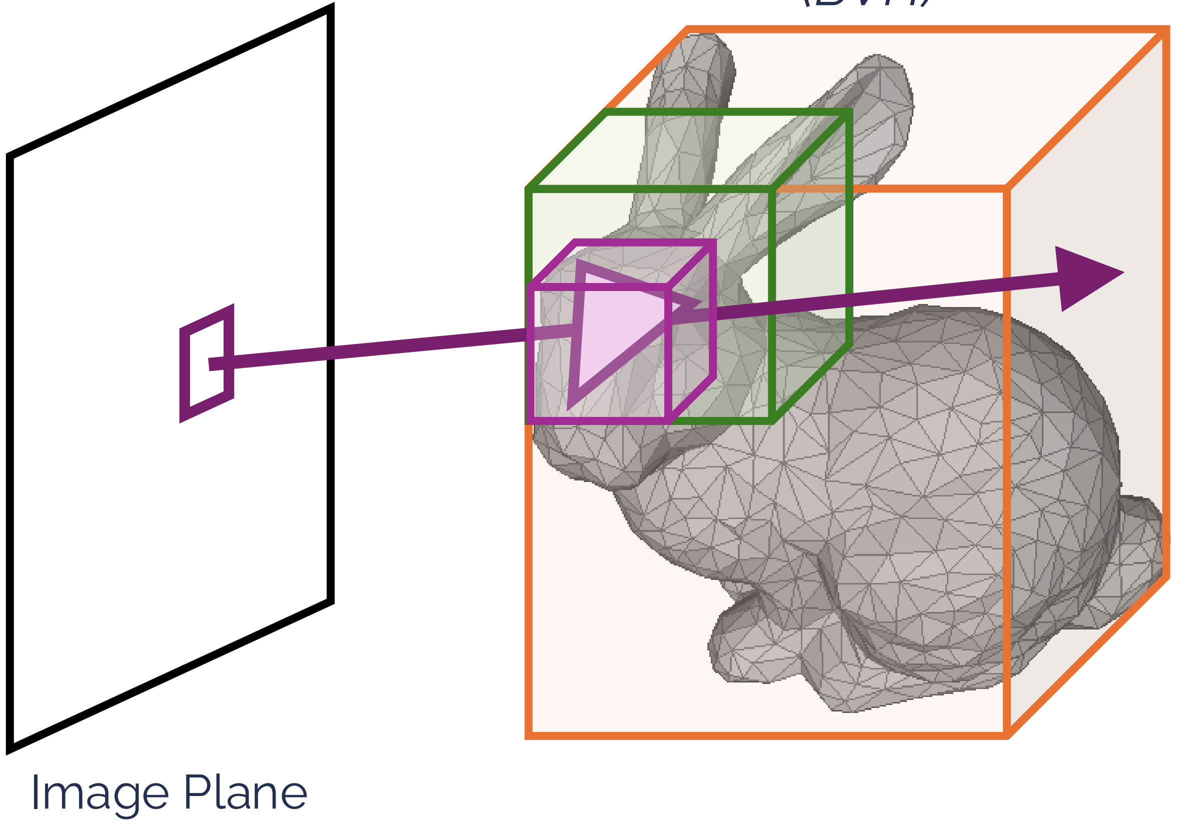

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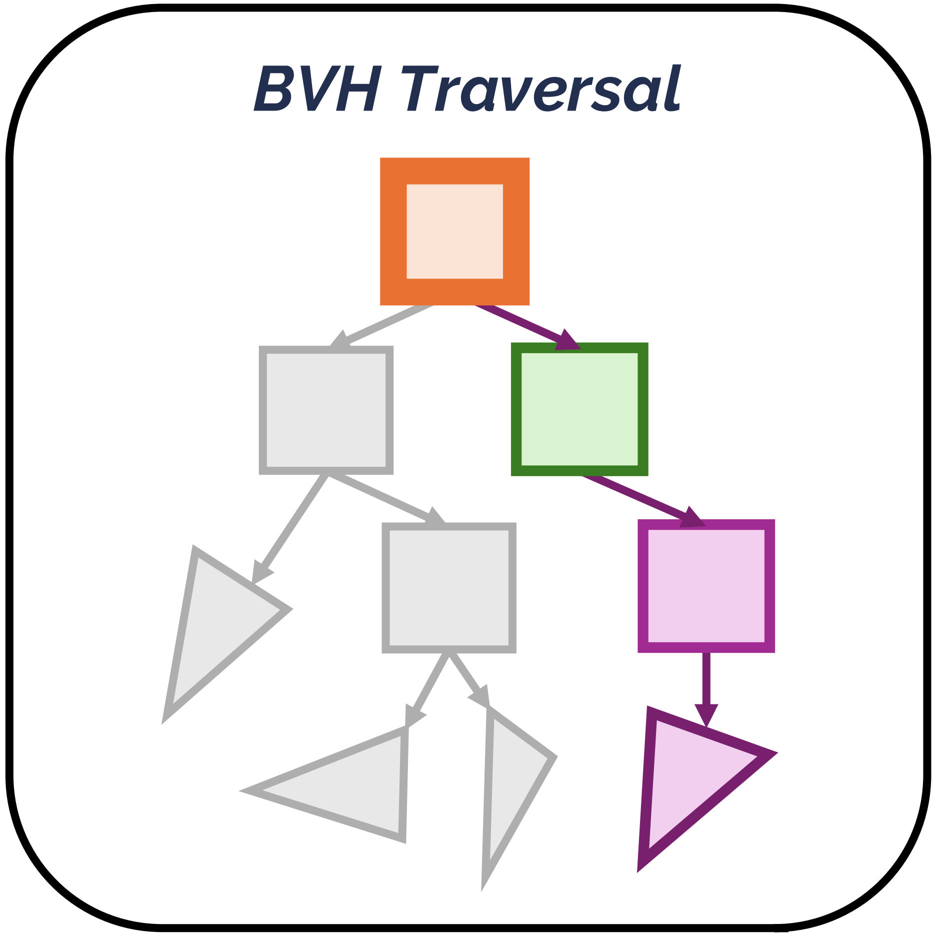
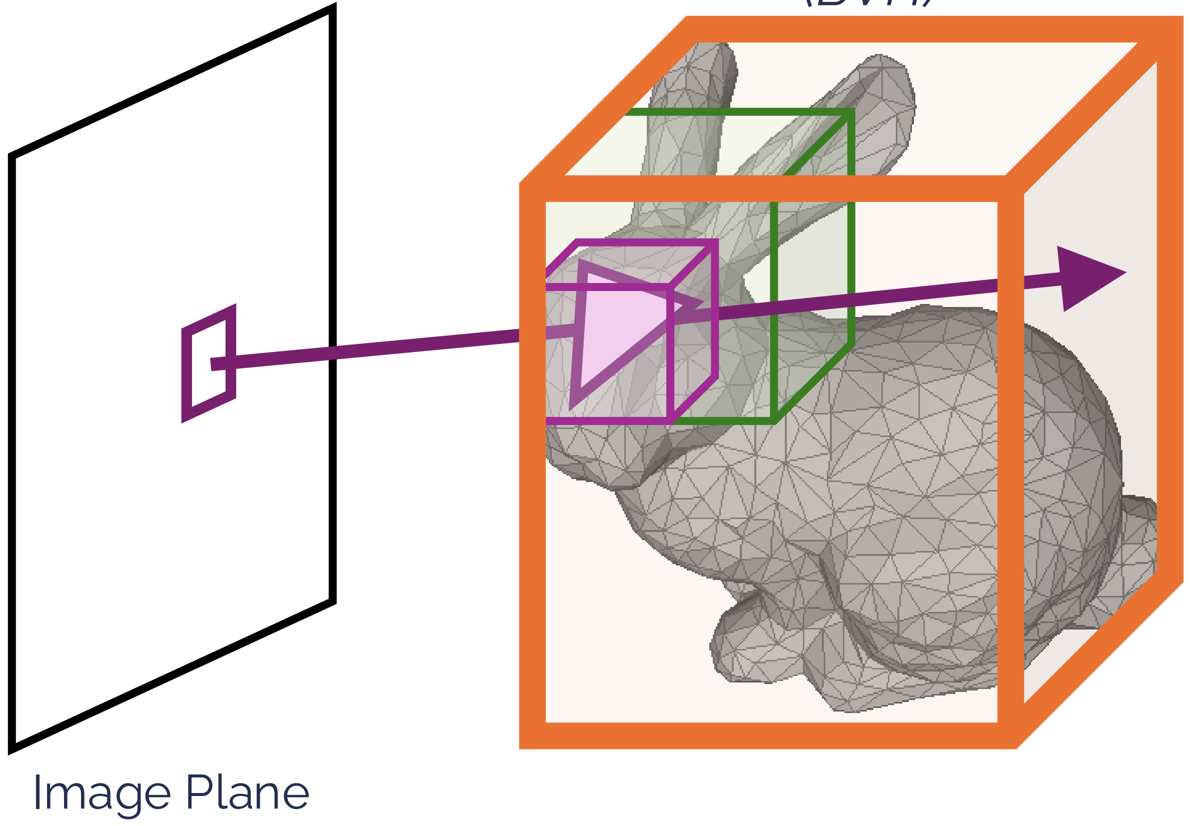


Ray-tracing

Bounding Volume Hierarchy (BVH)



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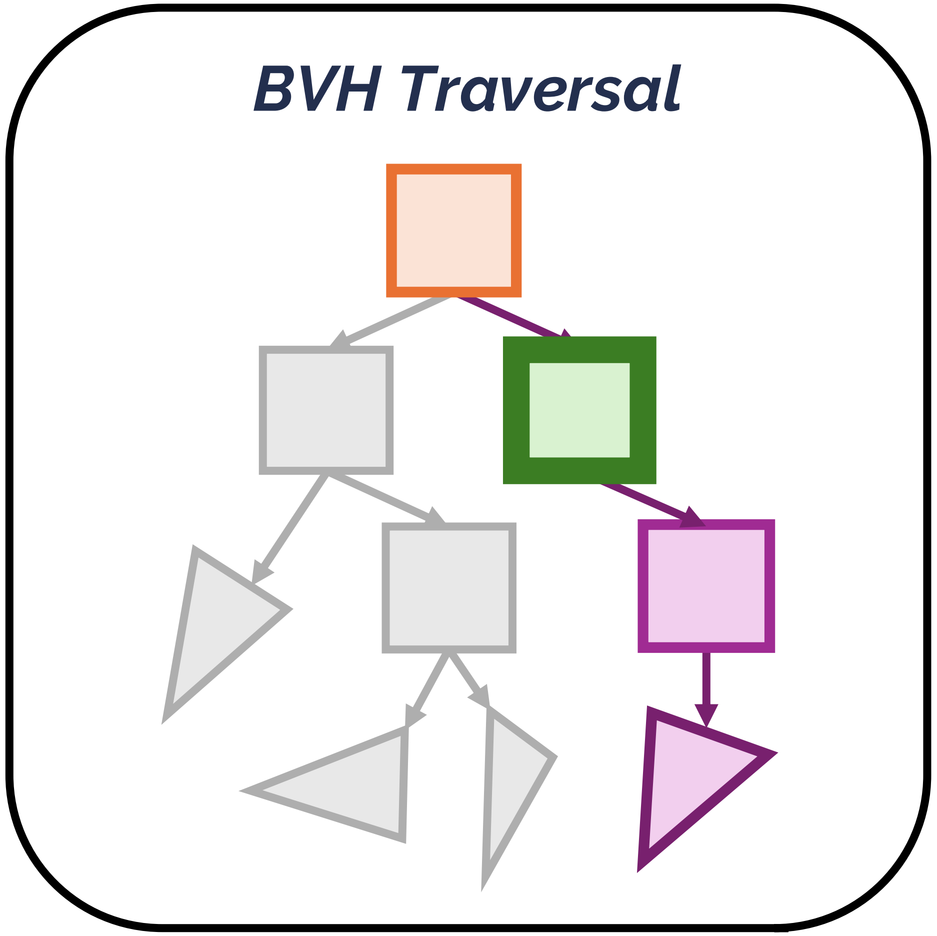

Ray-tracing

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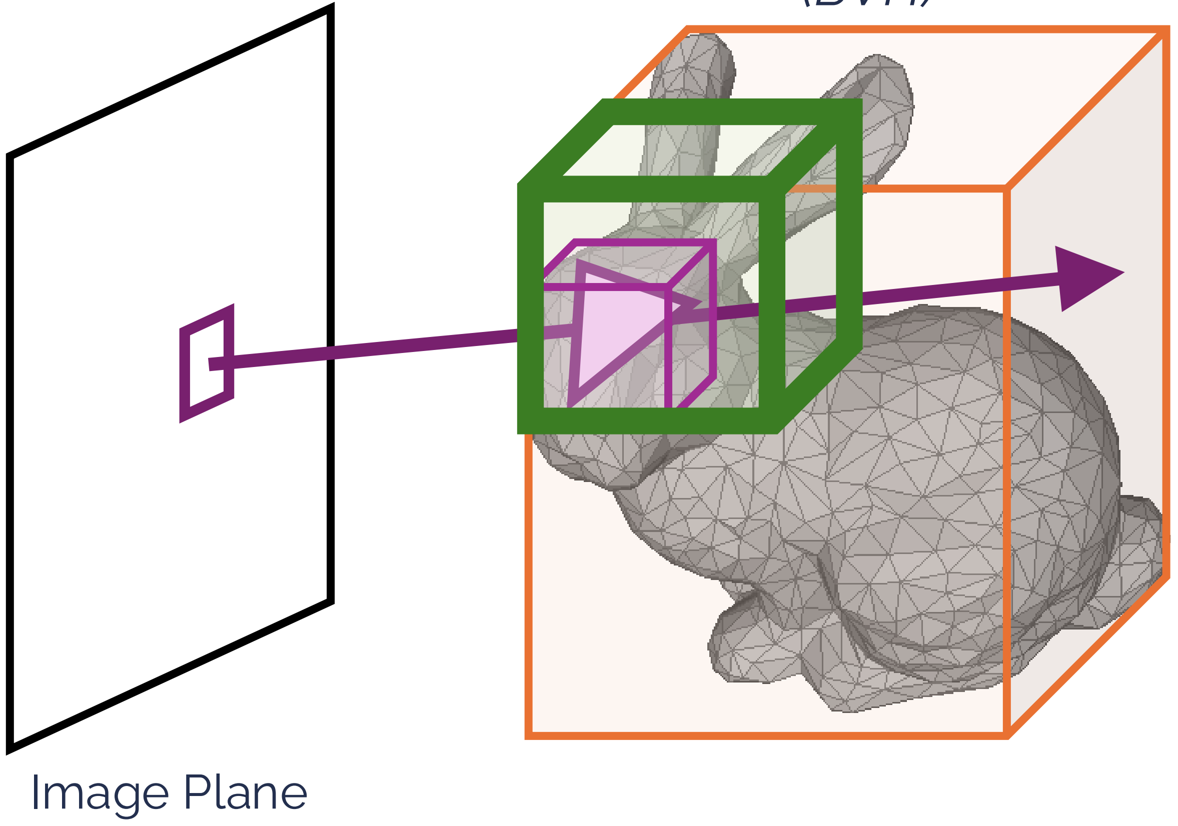

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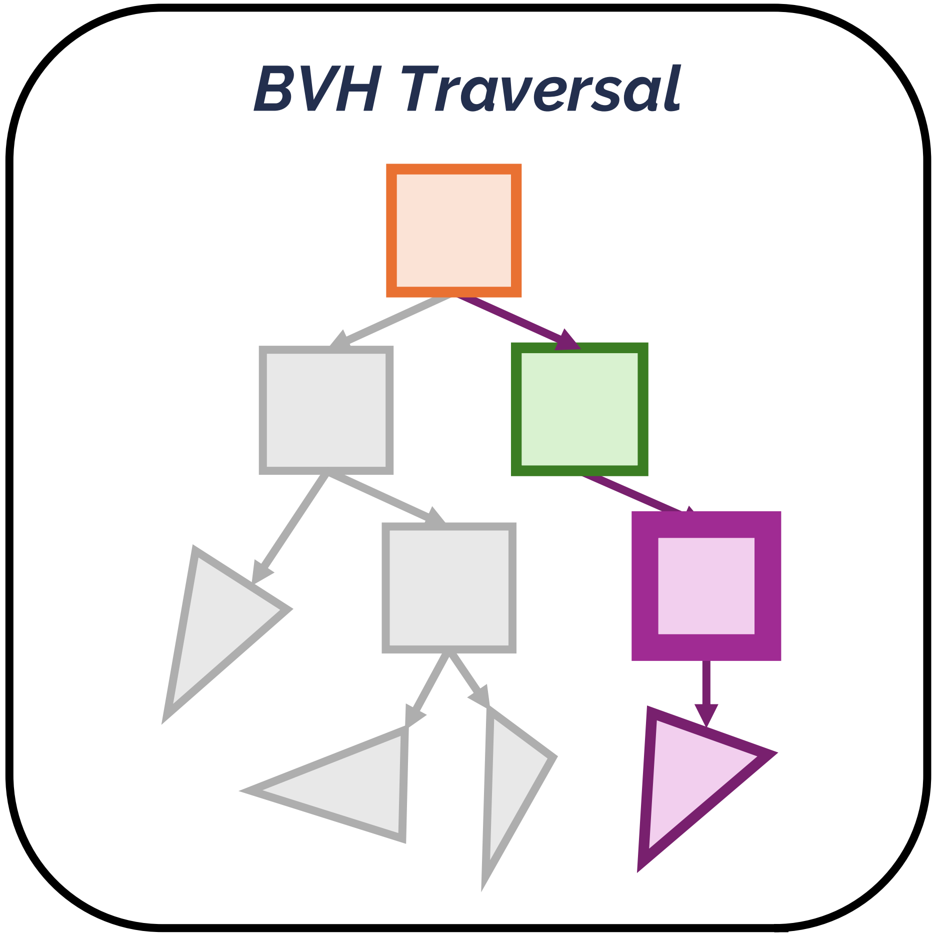

Ray-tracing

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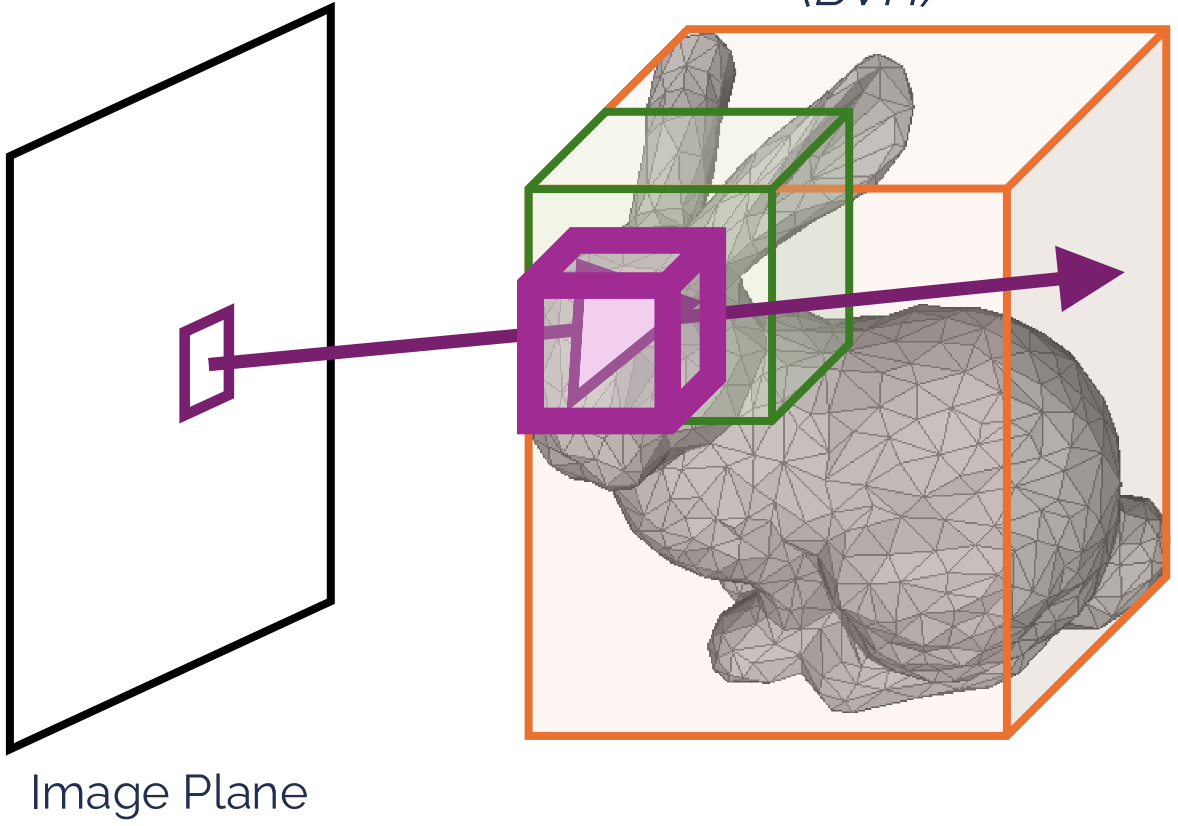

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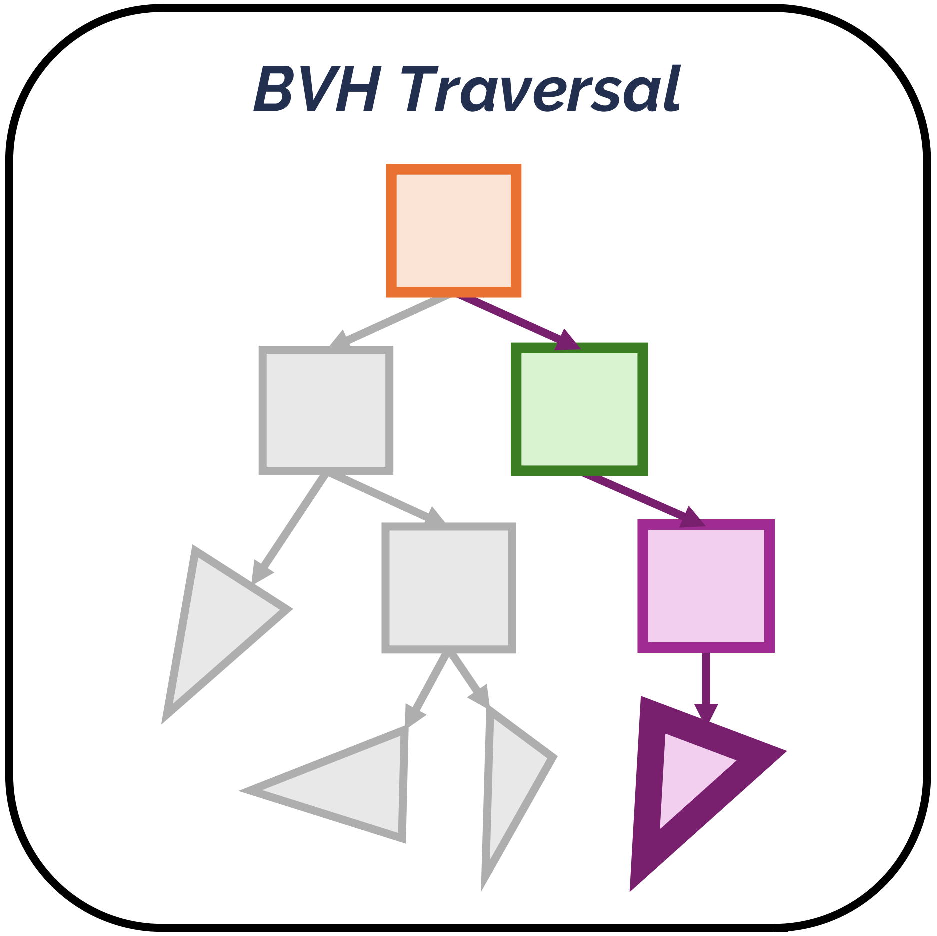

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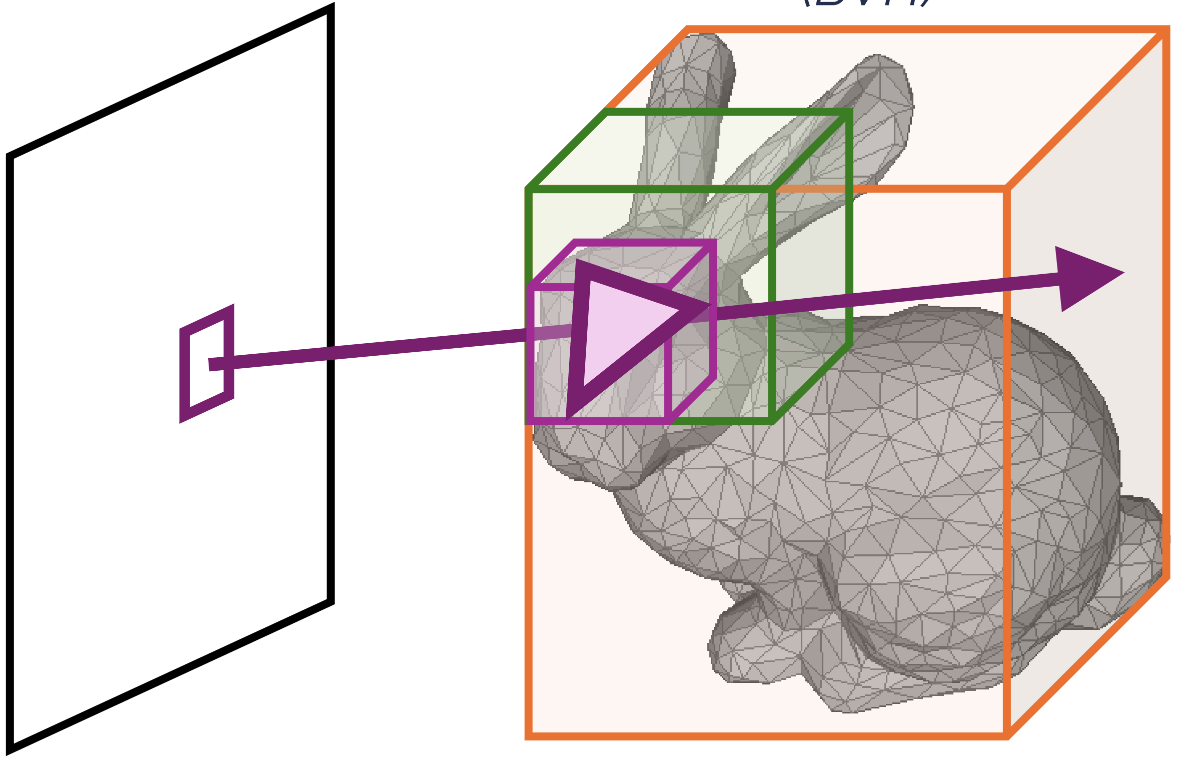

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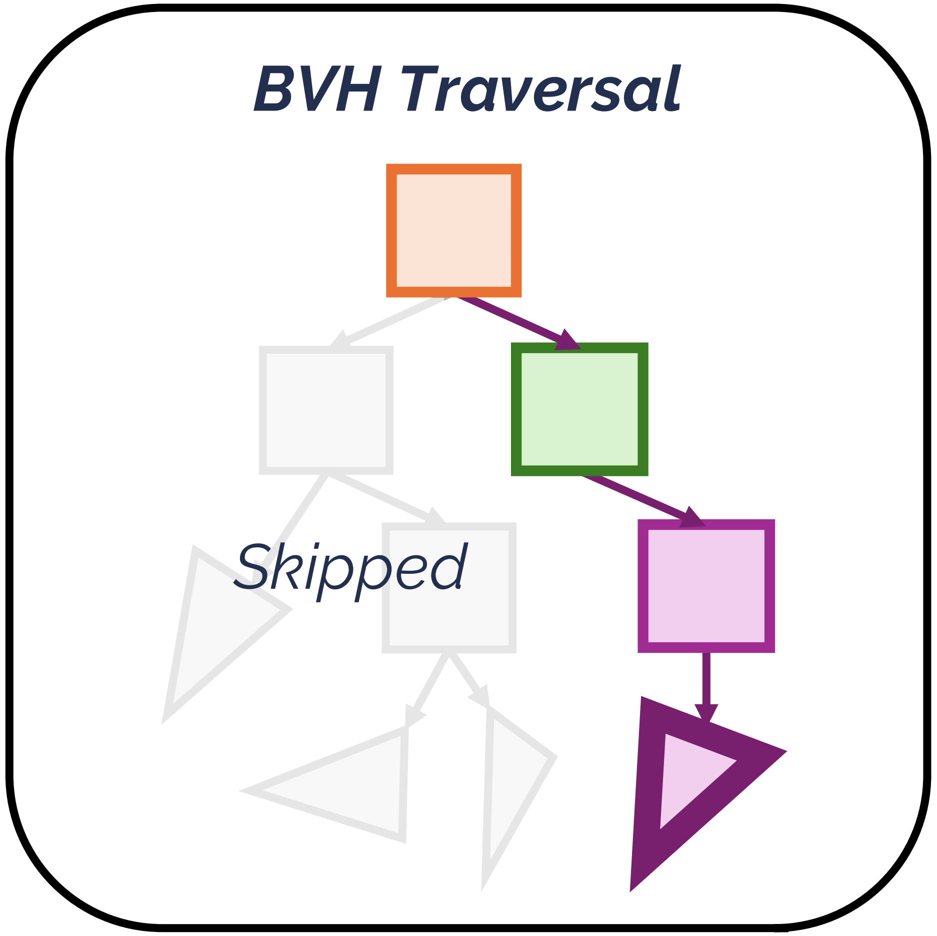

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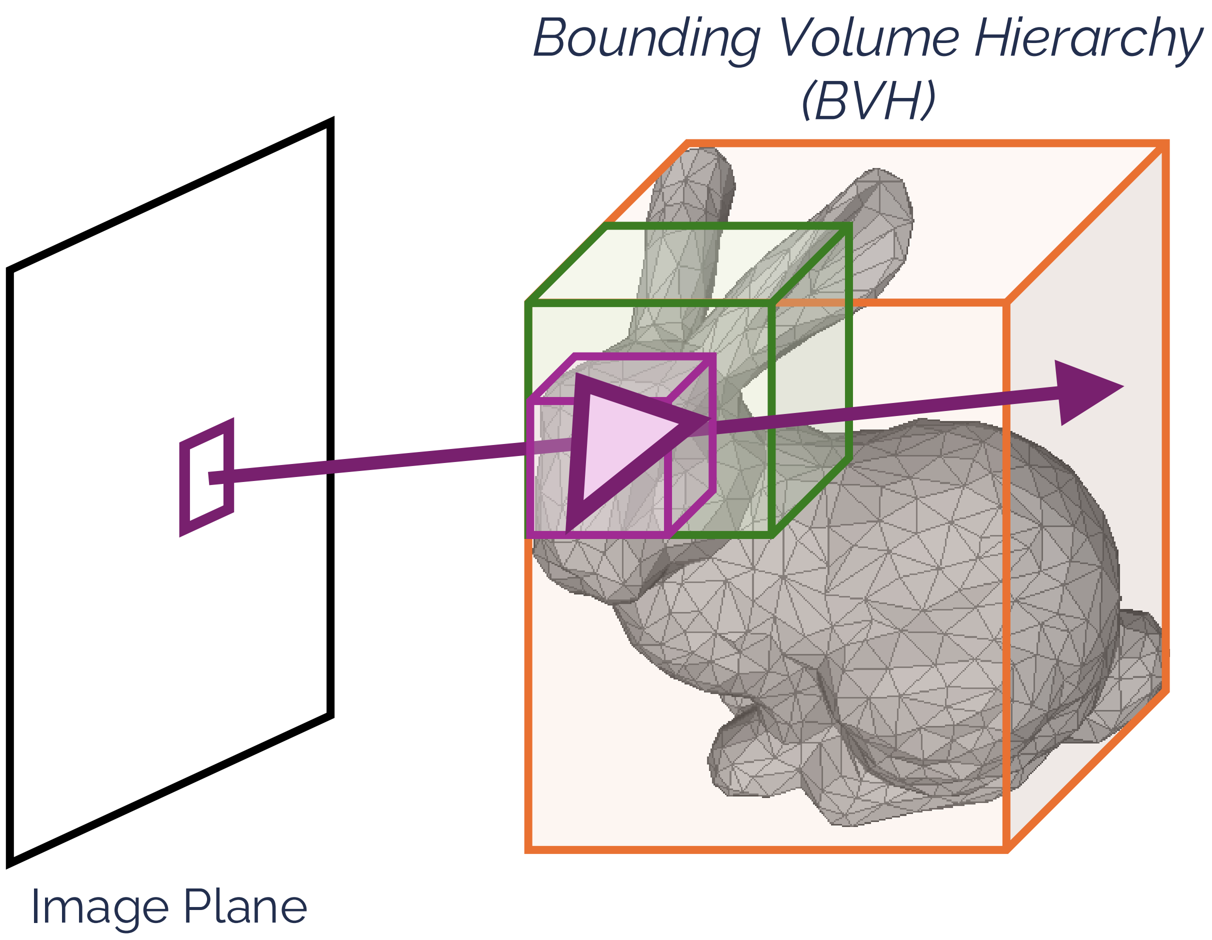

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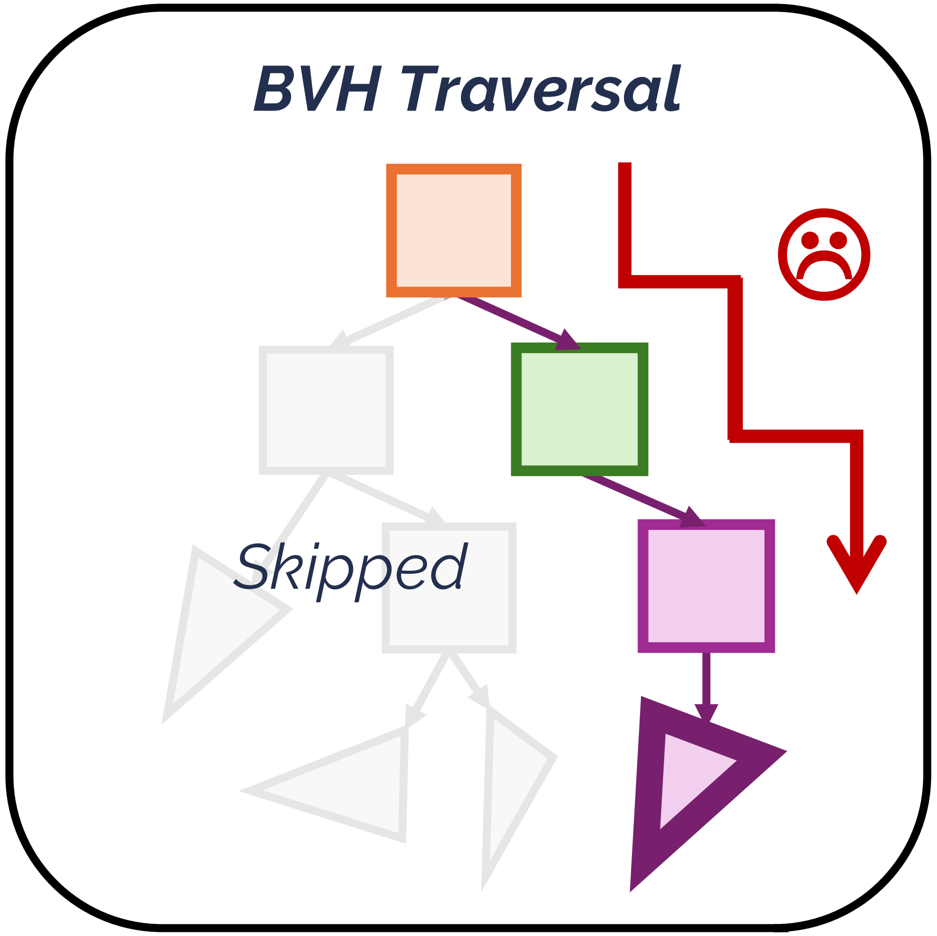

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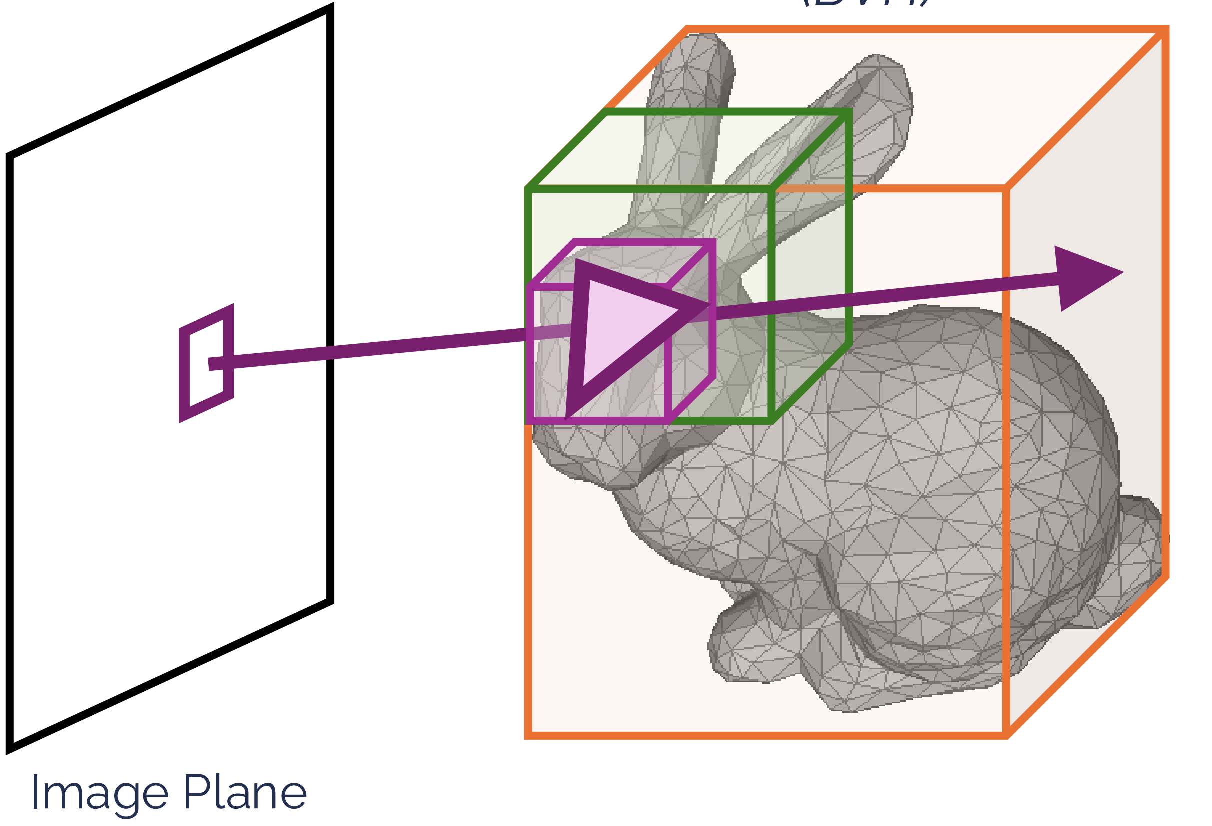

Ray Tracing Accelerators in GPUs

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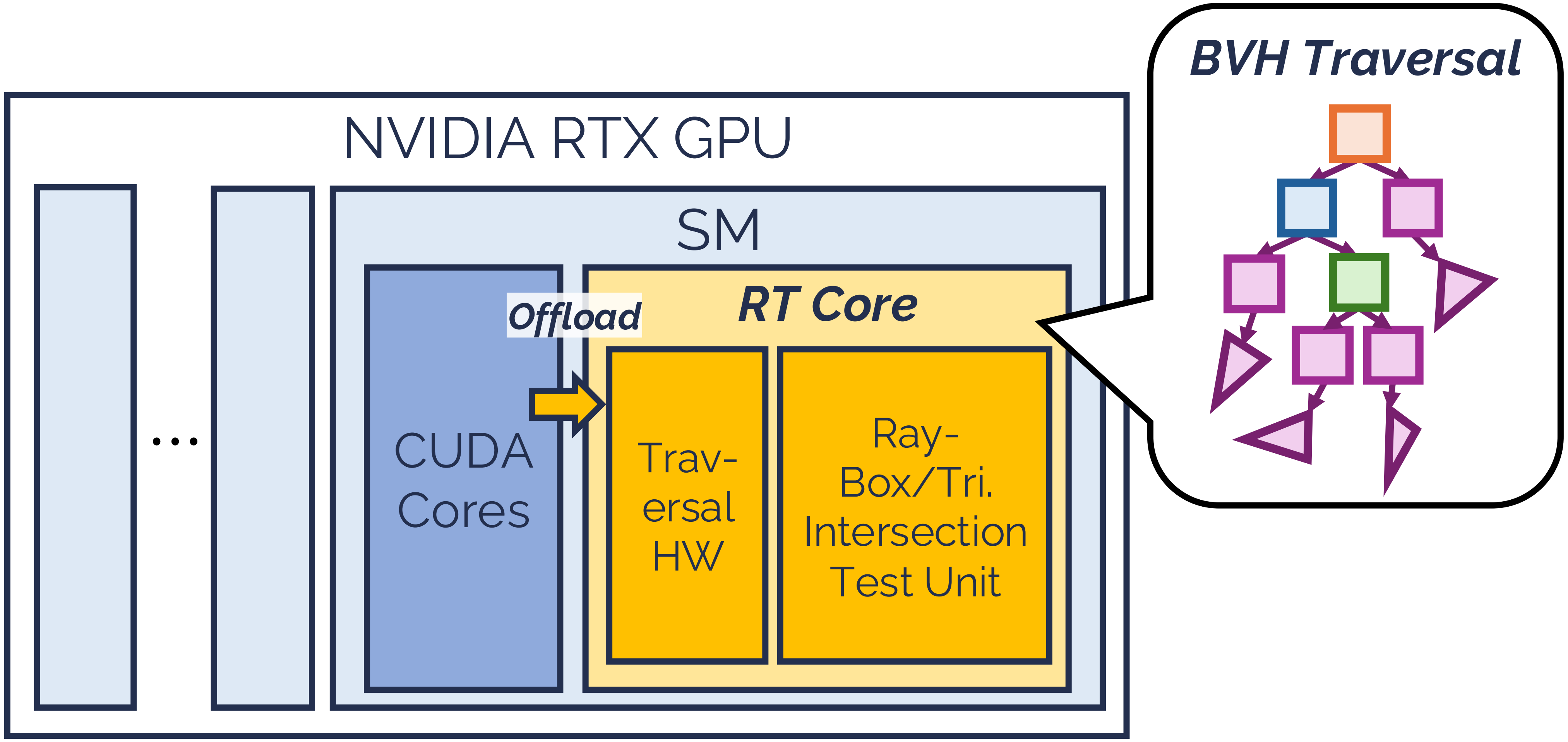

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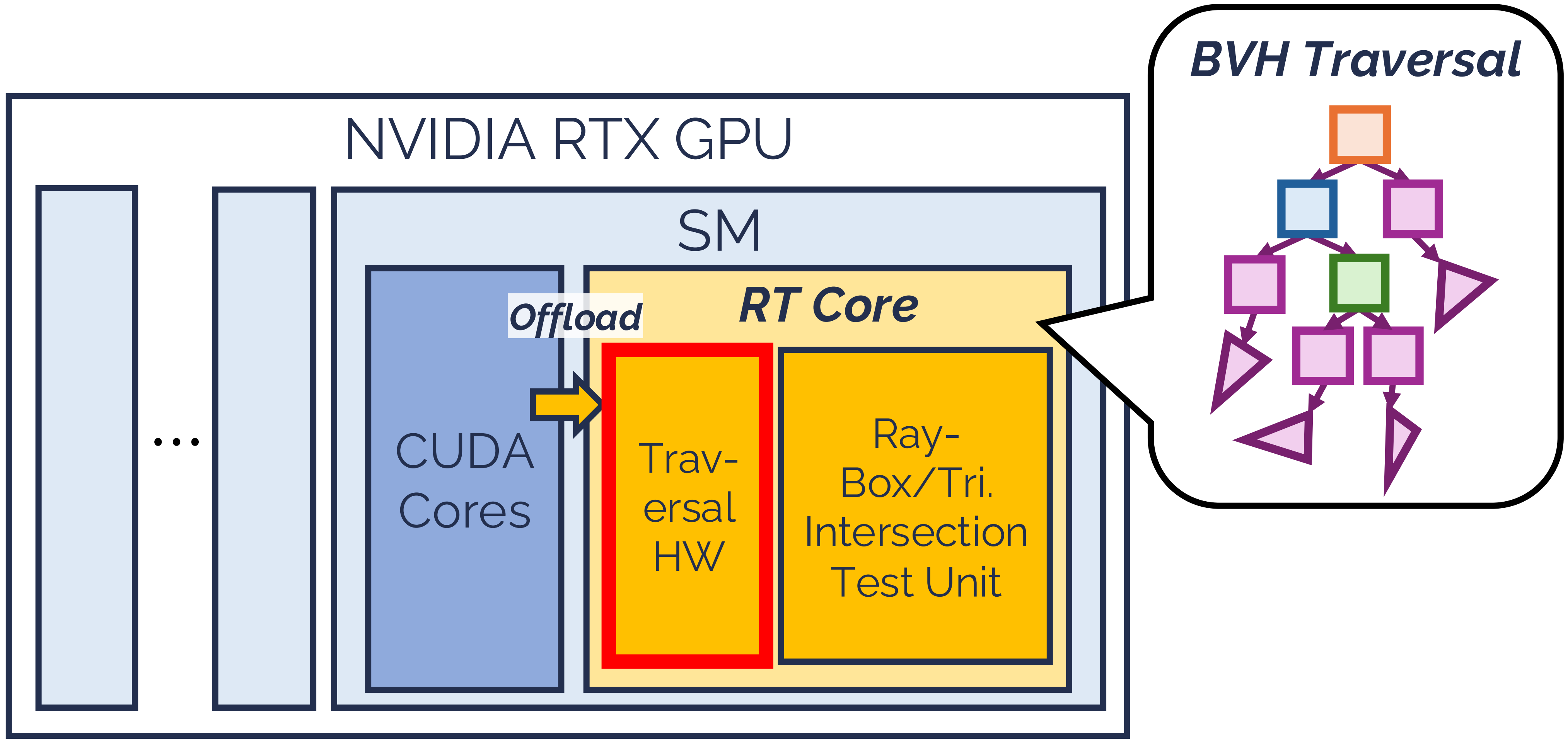

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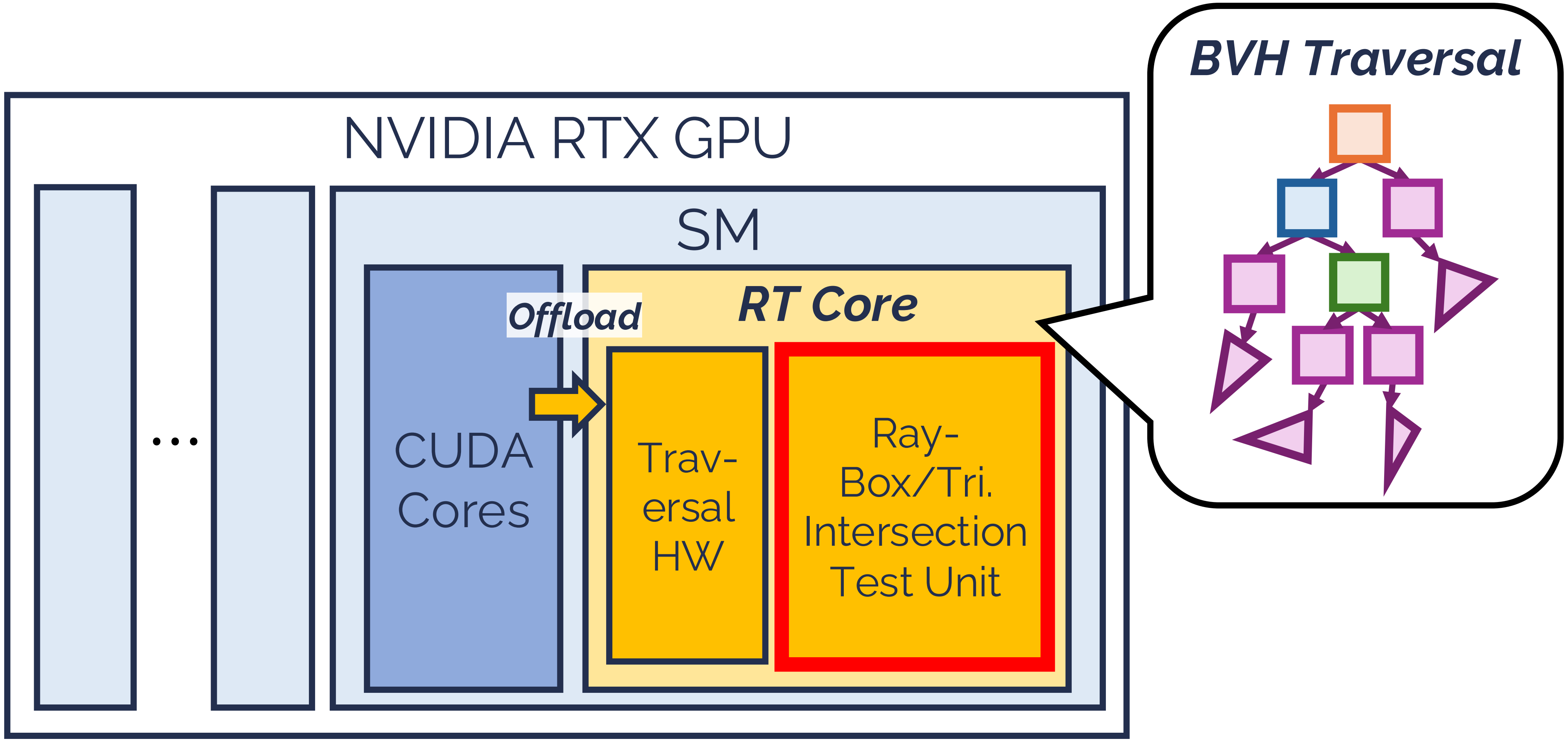
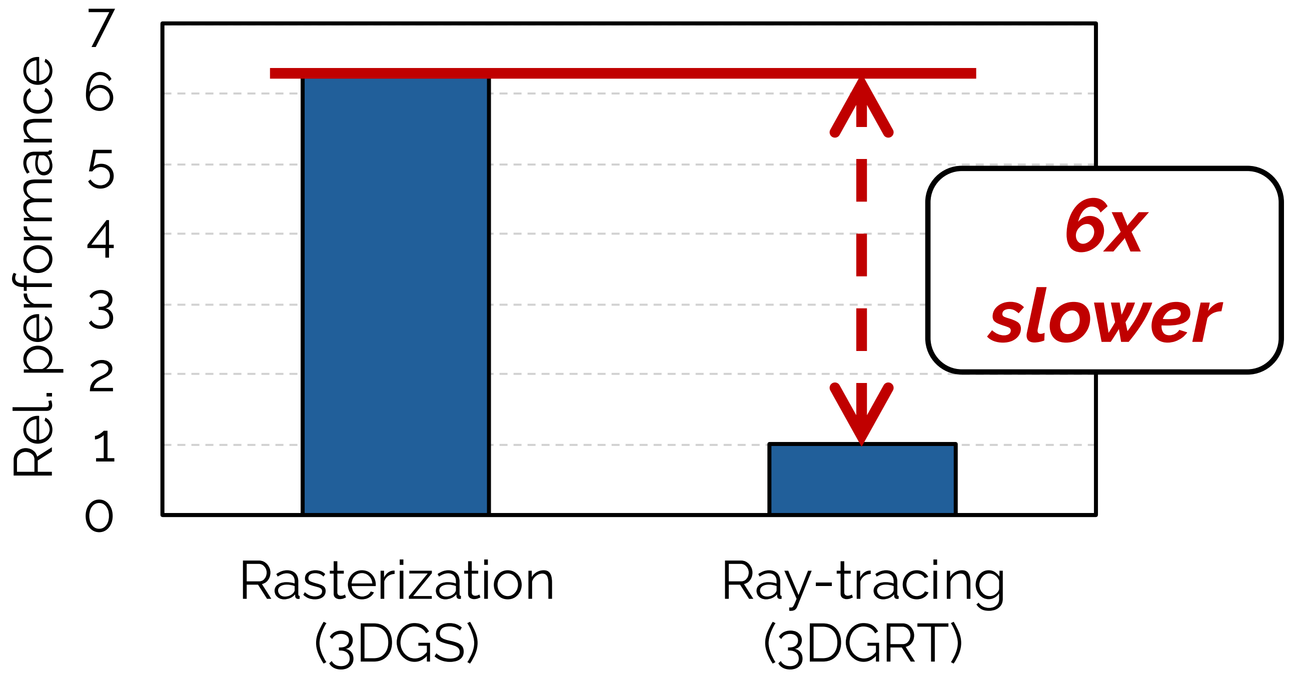


Goal of This Work



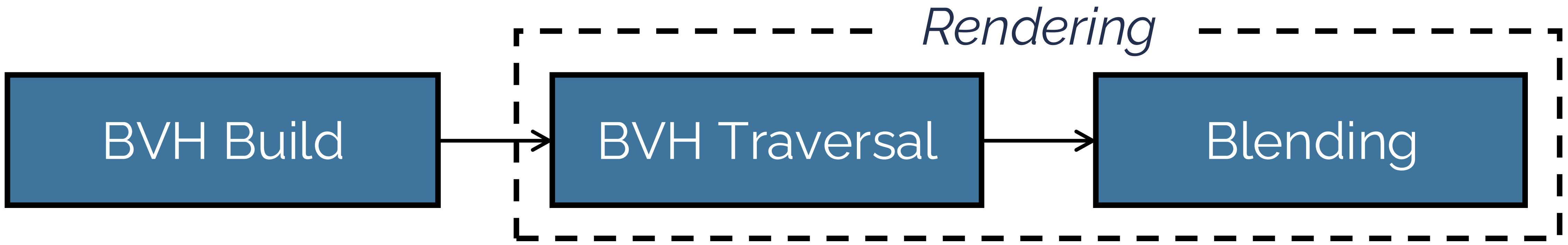
Goal

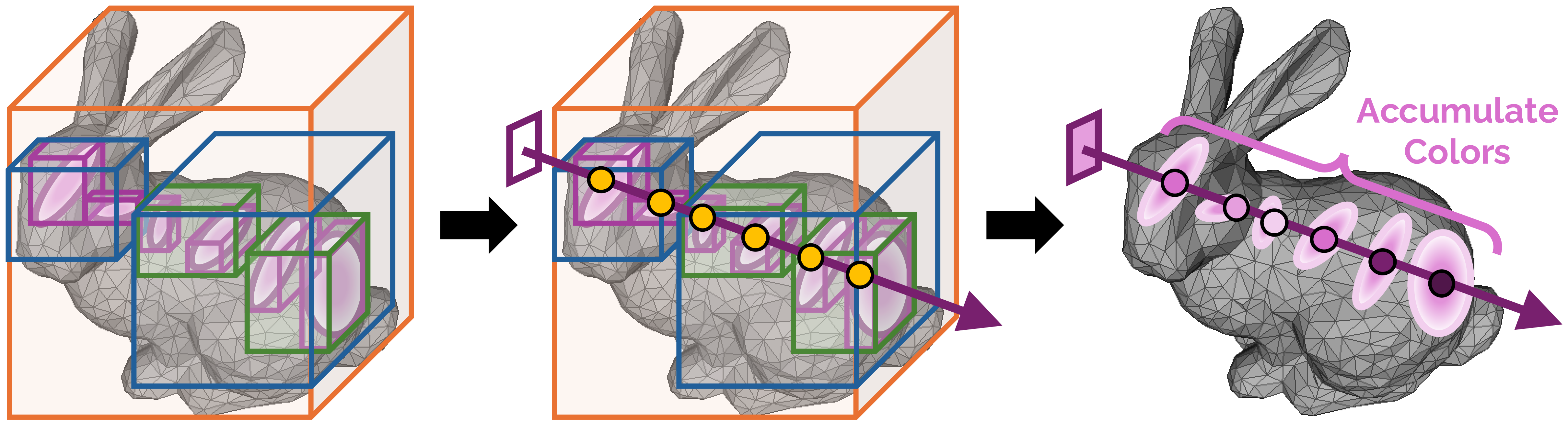
Reduce the performance gap with **SW-HW optimizations for Gaussian ray-tracing**

Outline

- **Background**
  - 3D Gaussian-based Rendering: Rasterization vs. Ray-tracing
  - Ray Tracing Accelerators in Modern GPUs
- **Gaussian RT Optimizations & Limitations**
- **GRTX: SW-HW Optimizations for Gaussian Ray Tracing**
  - GRTX-SW: Two-Level Acceleration Structure for Gaussian Primitives
  - GRTX-HW: HW Extension for Traversal Checkpointing and Replay
- **Evaluation**
- **Conclusion**

Overview of Gaussian Ray Tracing





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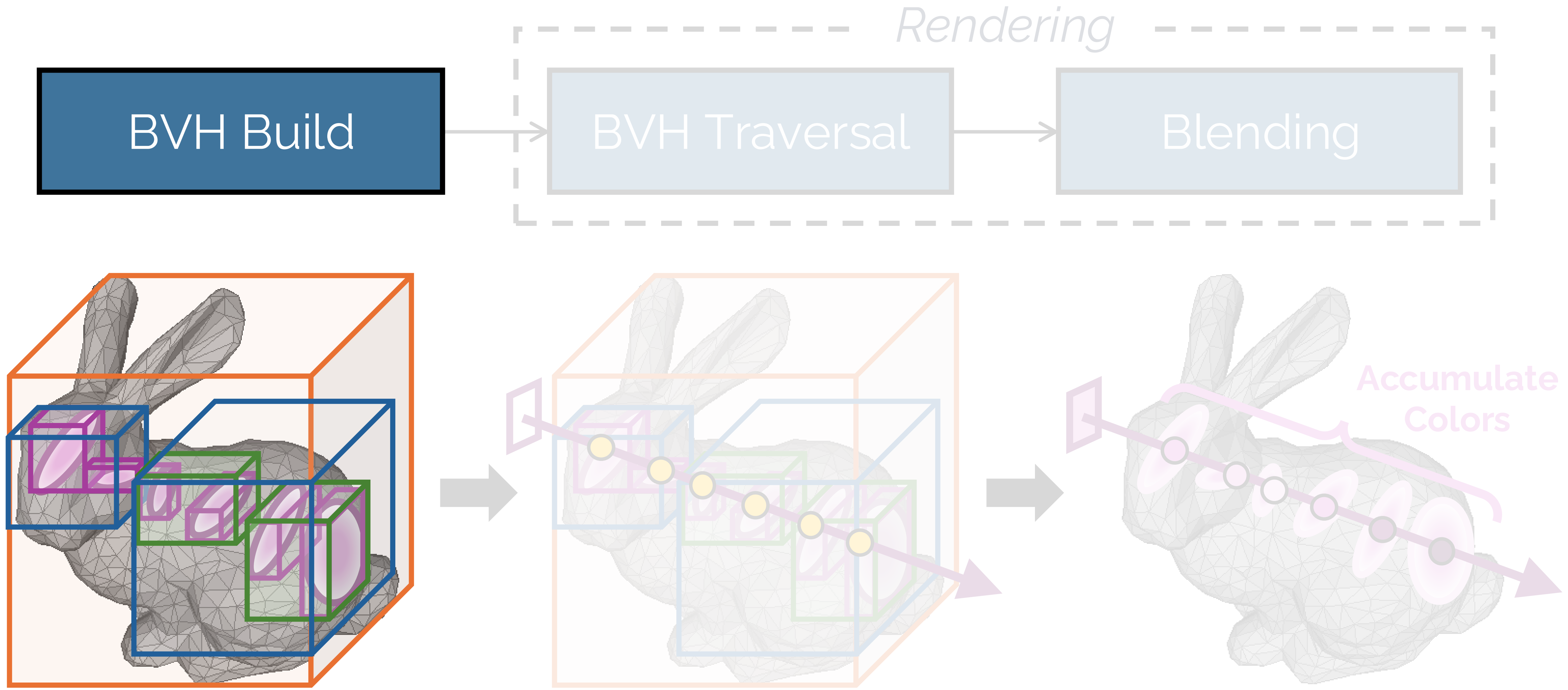
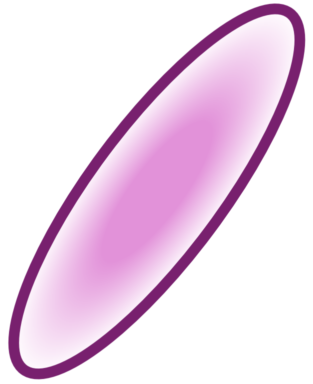
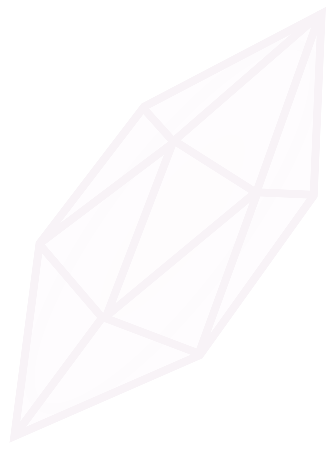
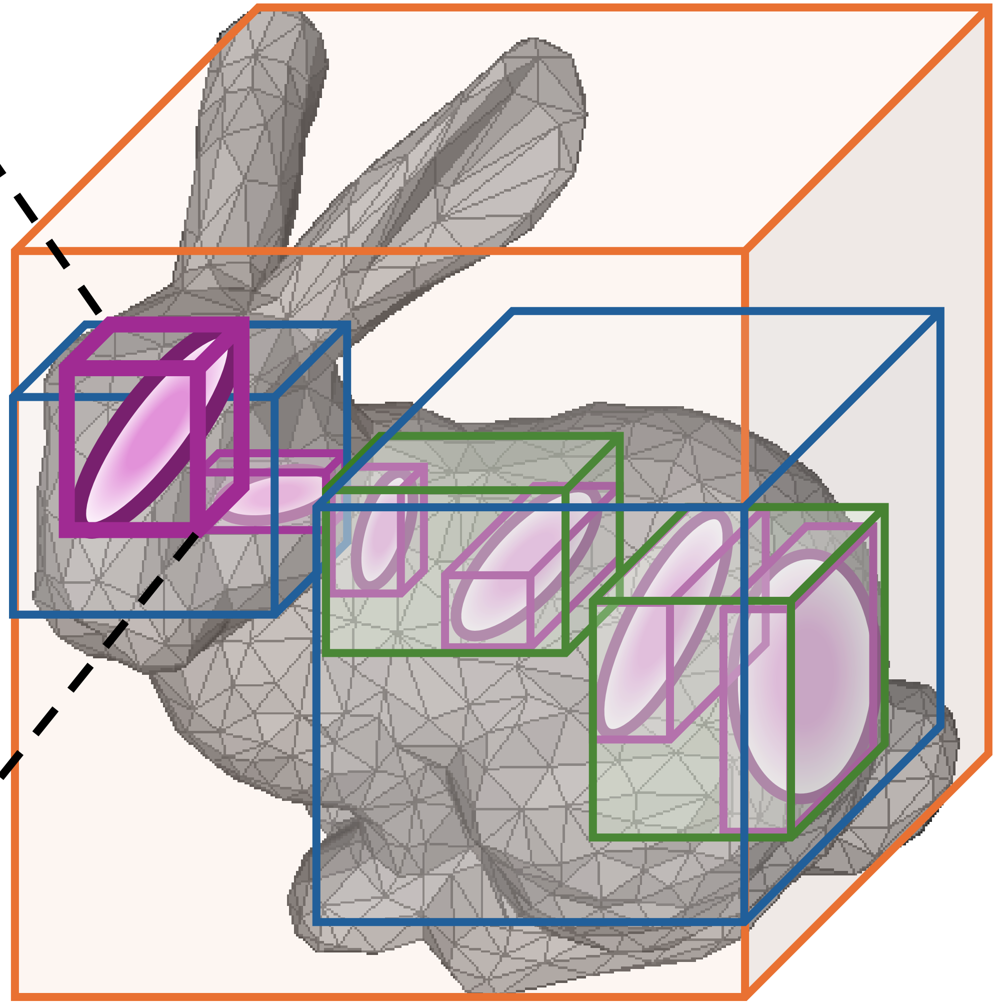


Gaussian RT Optimizations & Limitations

Primitive Types

	 Gaussian Primitive	 Bounding Triangle Mesh
☺	Compact BVH (1 Gaus. = 1 Prim.)	HW-based intersection test
☹	**SW-based intersection test**	**Large BVH** **(1 Gaus. = 20 Prims.)**



Gaussian RT Optimizations & Limitations

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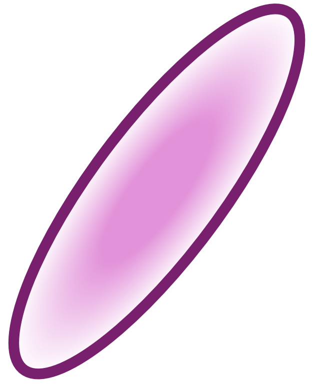
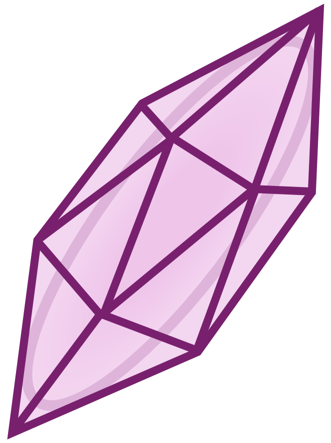
	 Gaussian Primitive	 Bounding Triangle Mesh
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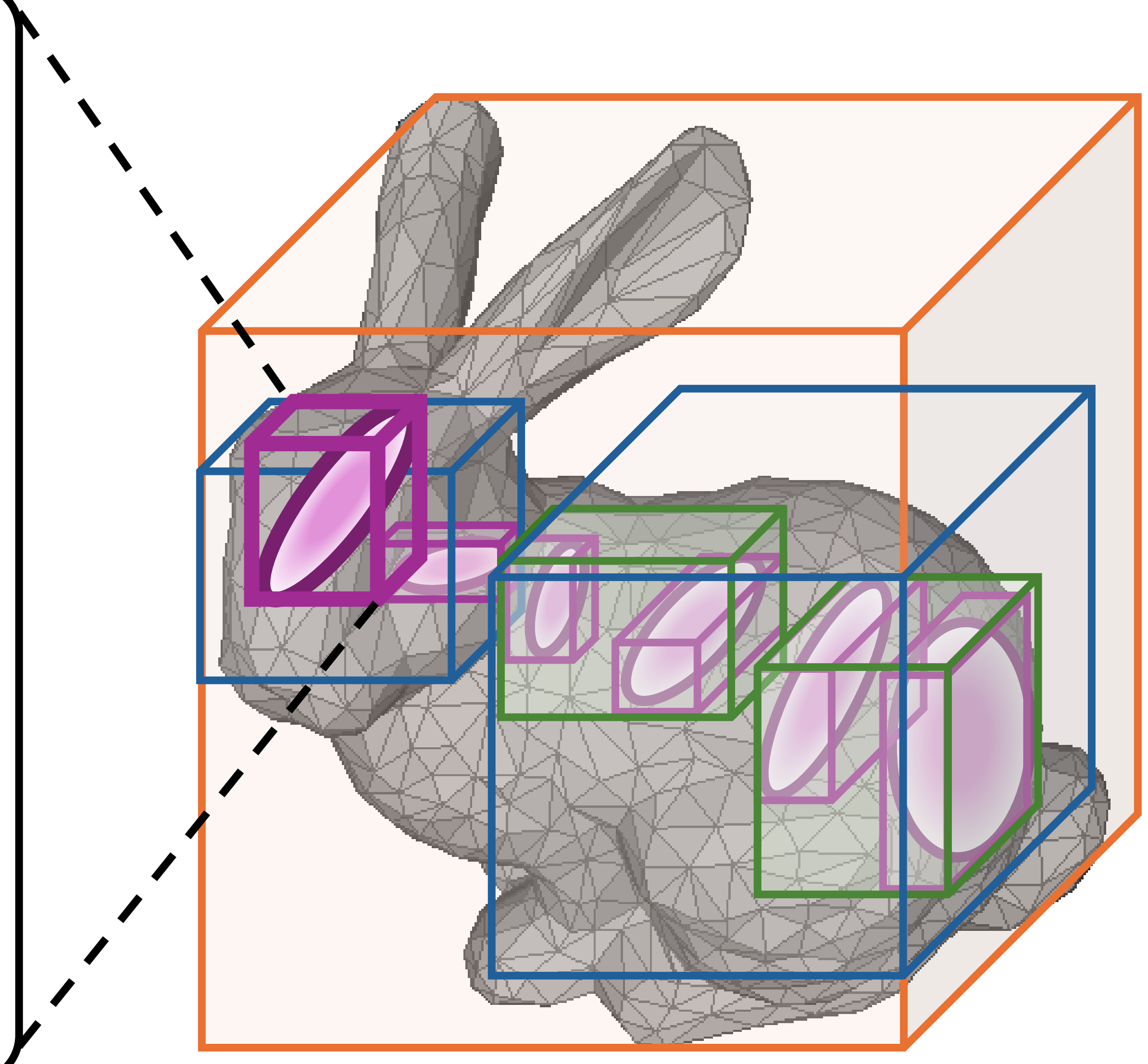
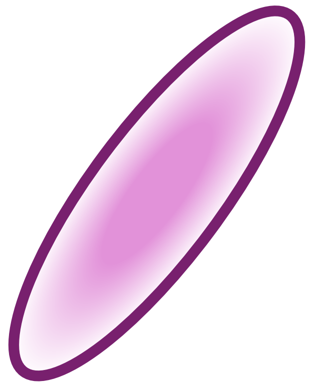
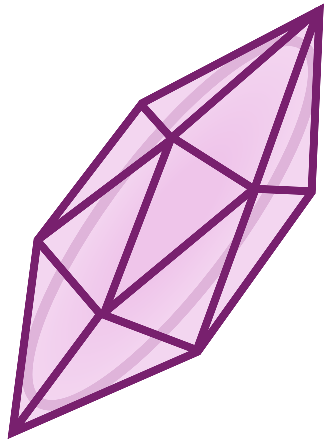


Gaussian RT Optimizations & Limitations

Primitive Types

	 Gaussian Primitive	 Bounding Triangle Mesh
☺	Compact BVH (1 Gaus. = 1 Prim.)	HW-based intersection test
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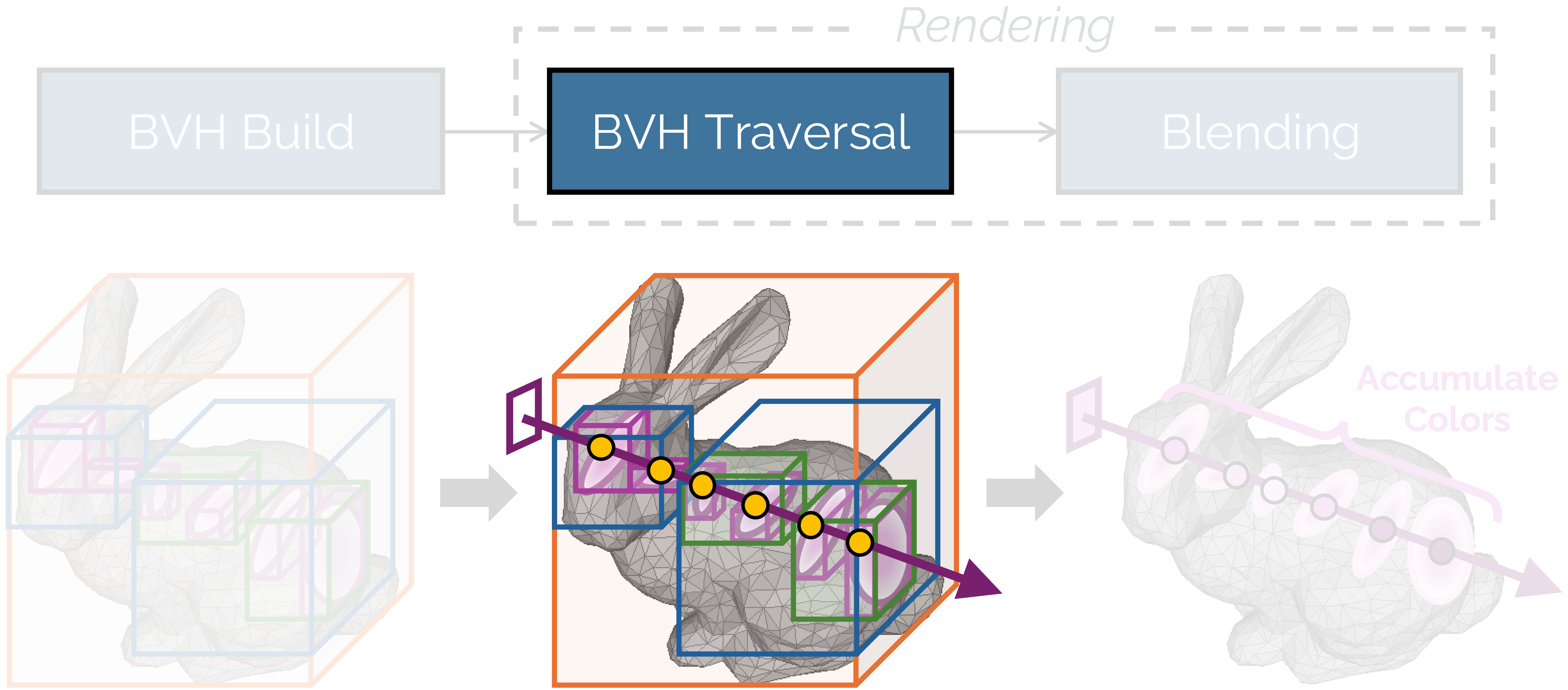
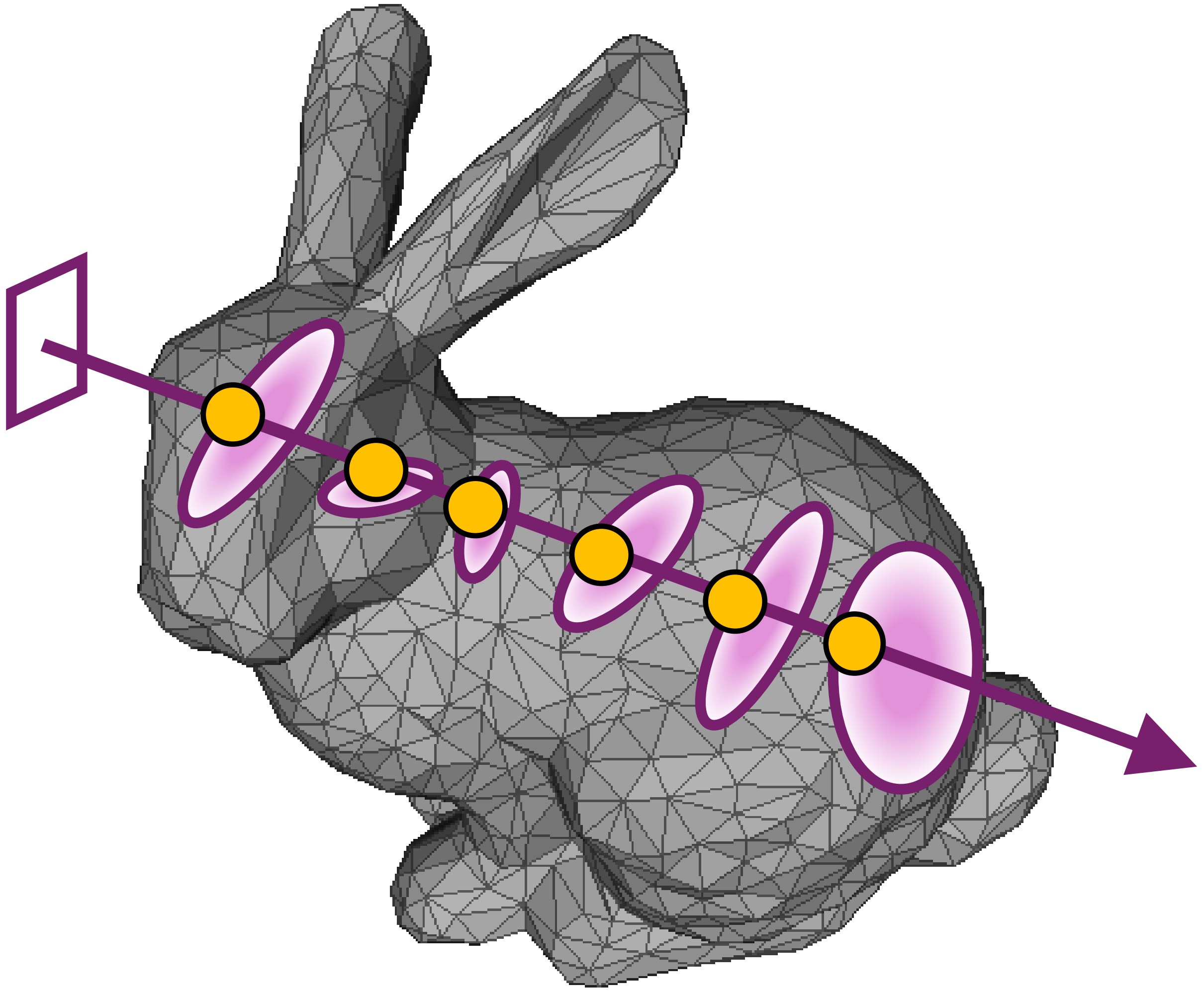
Problem 1

Bloated BVH size and increased **memory footprint**

Gaussian RT Optimizations & Limitations



Gaussian RT Optimizations & Limitations



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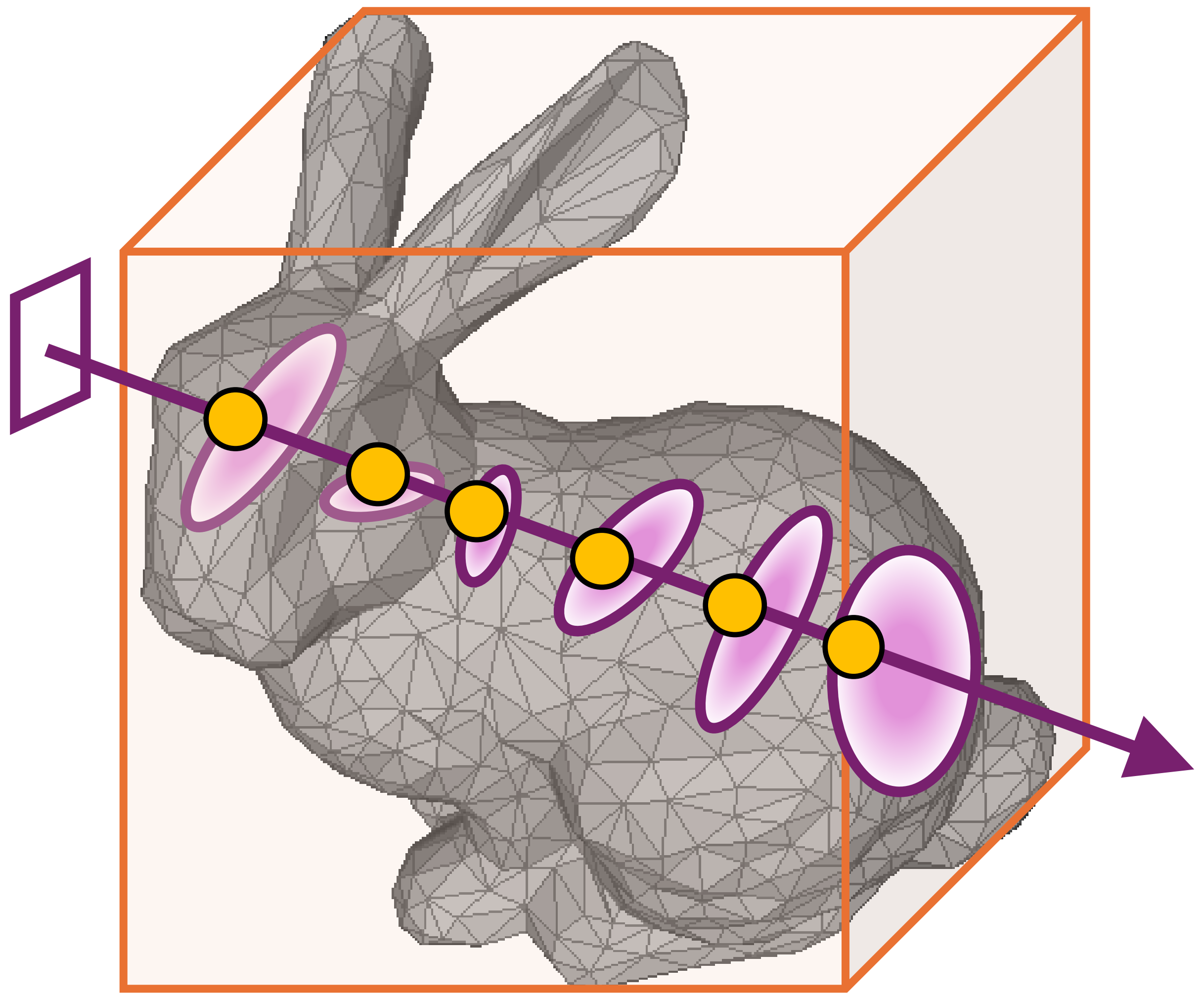

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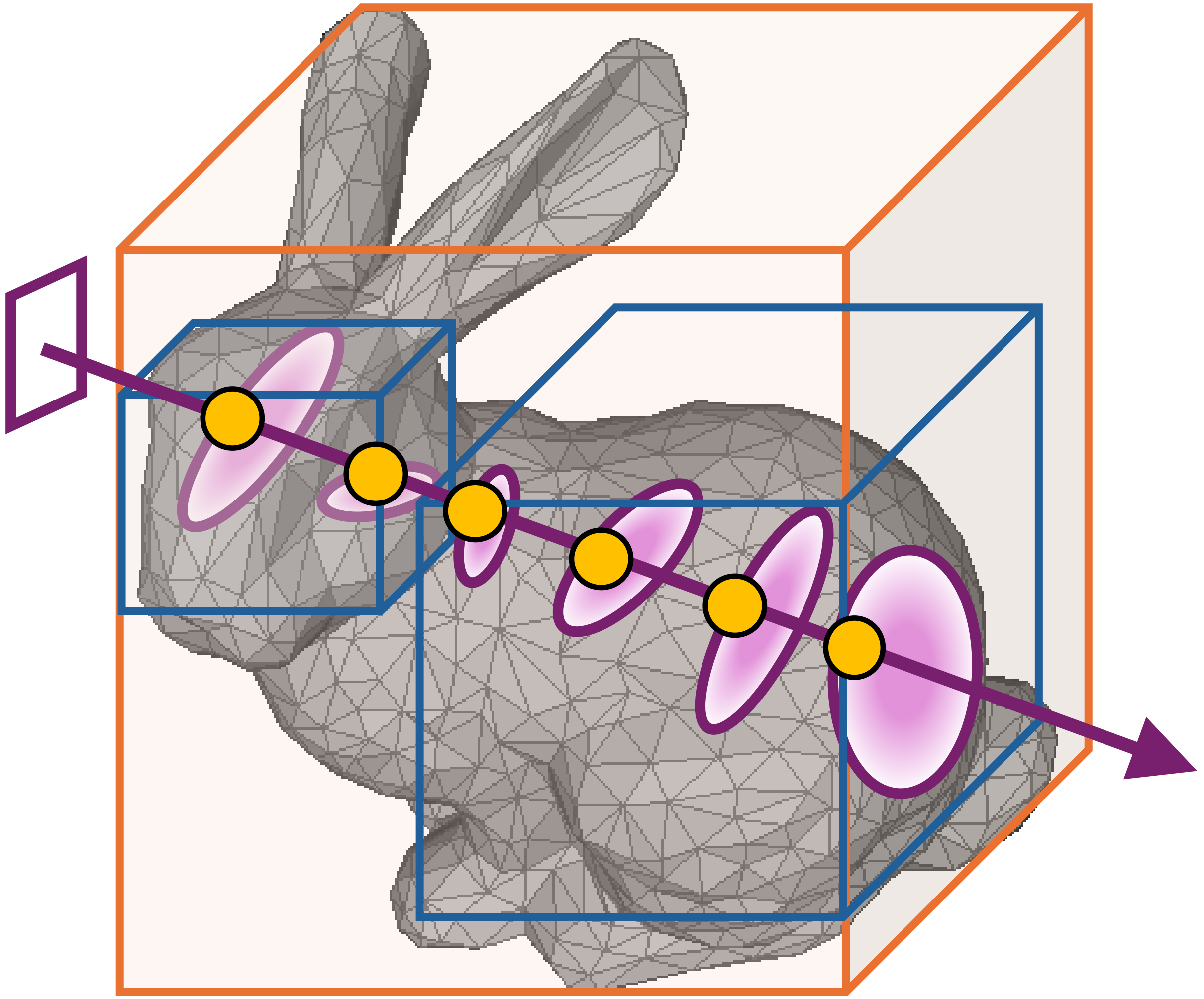

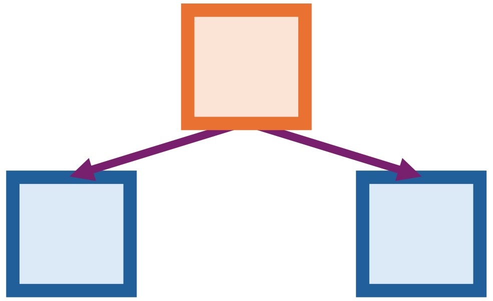

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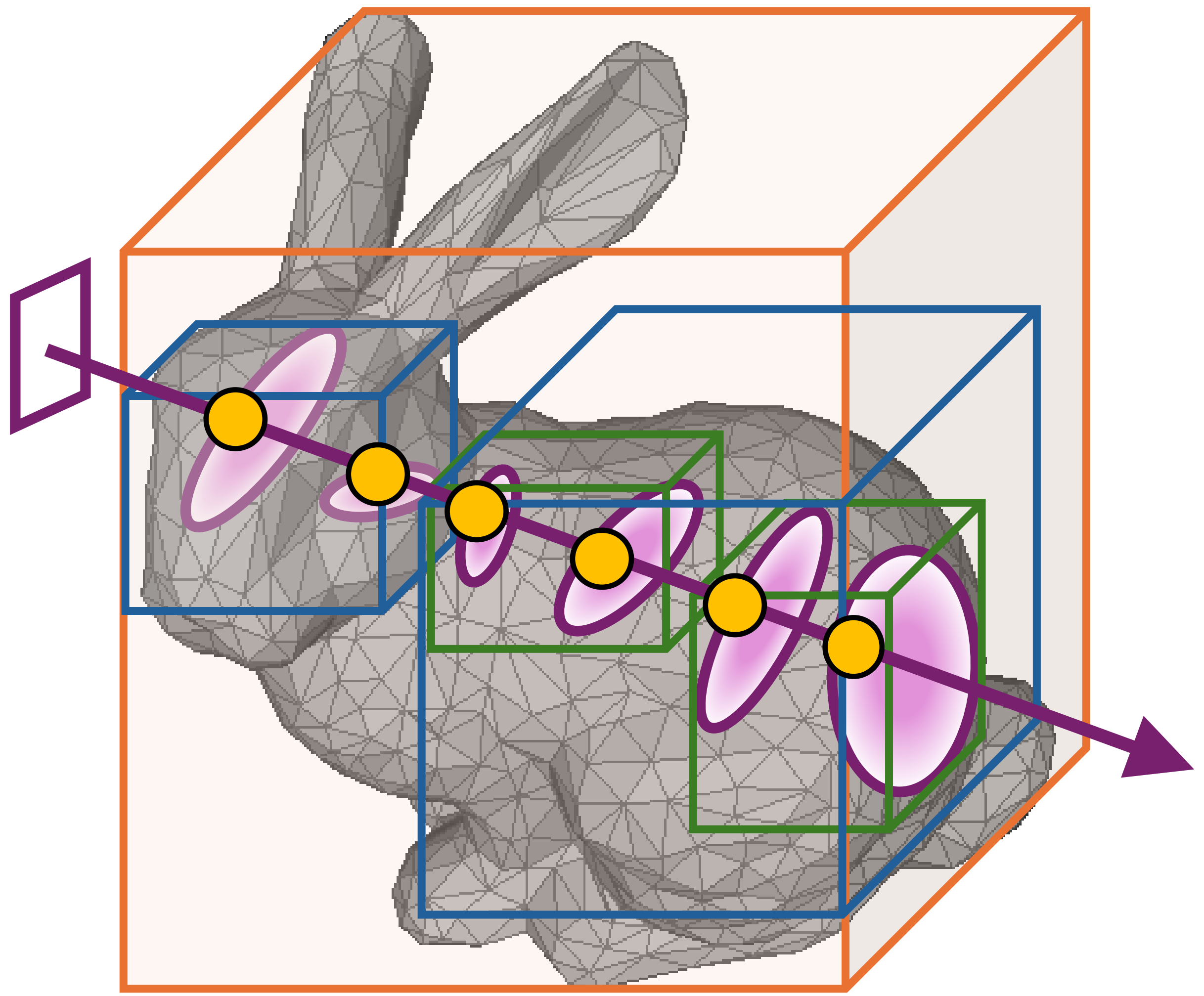
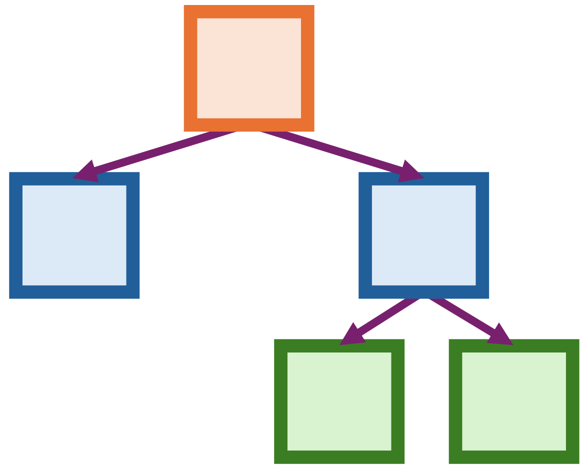
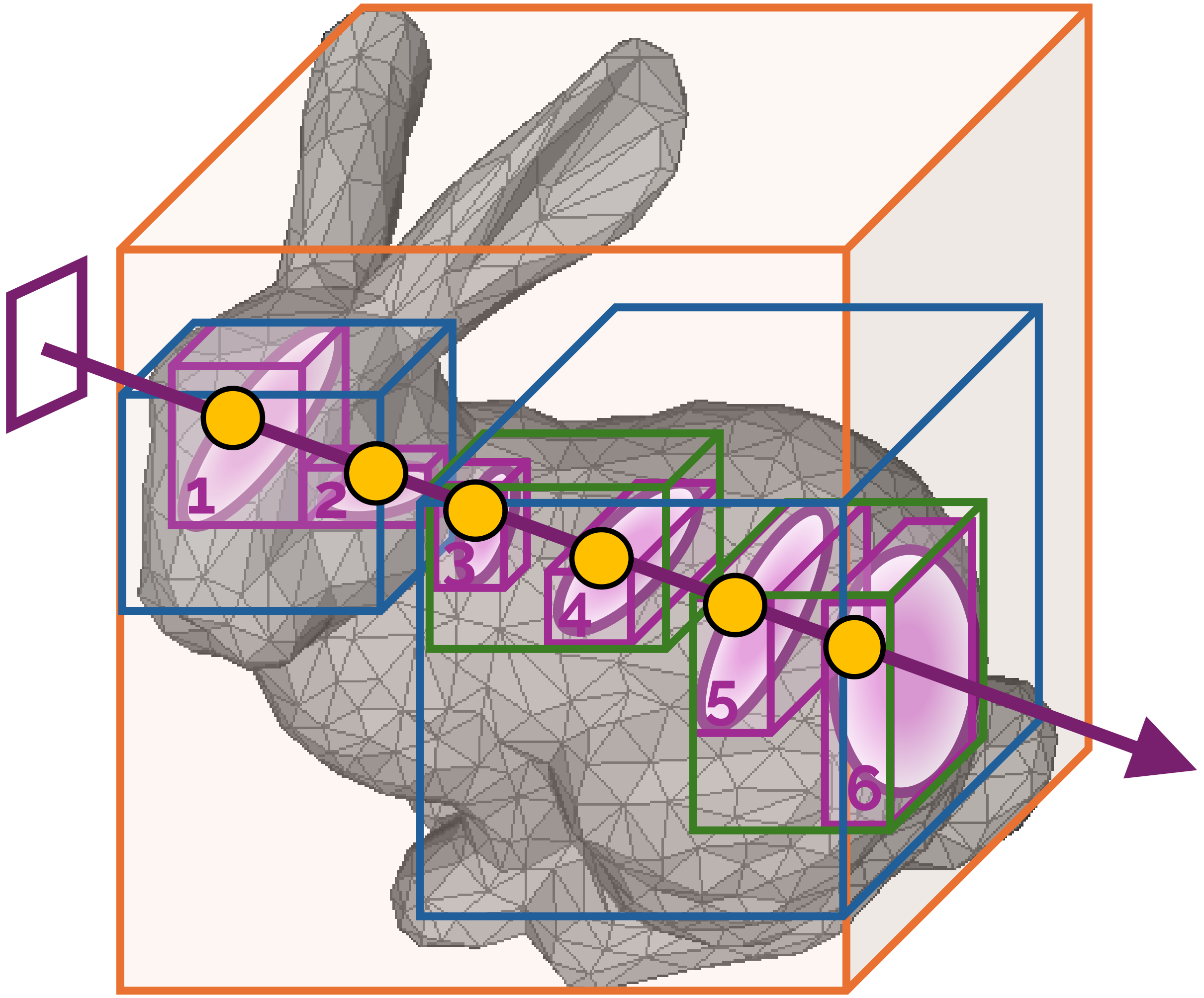
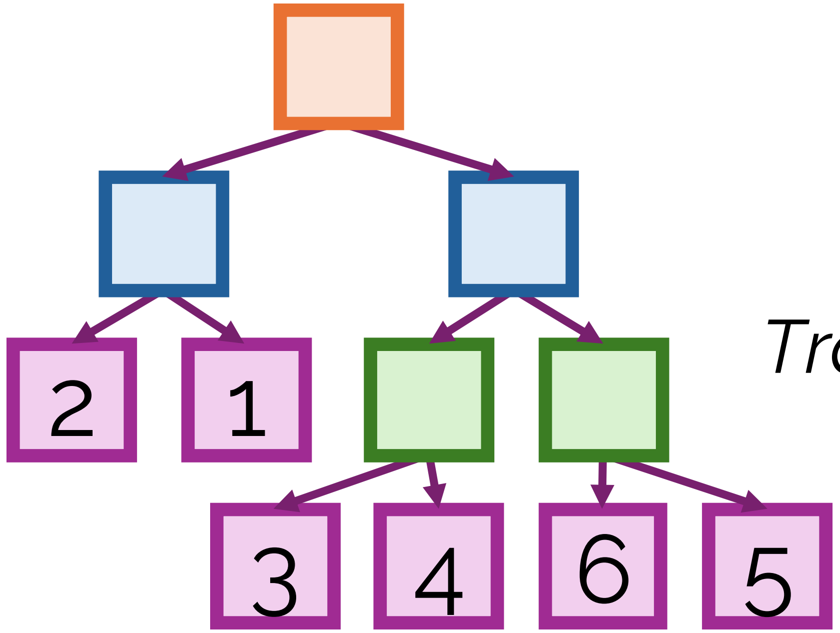




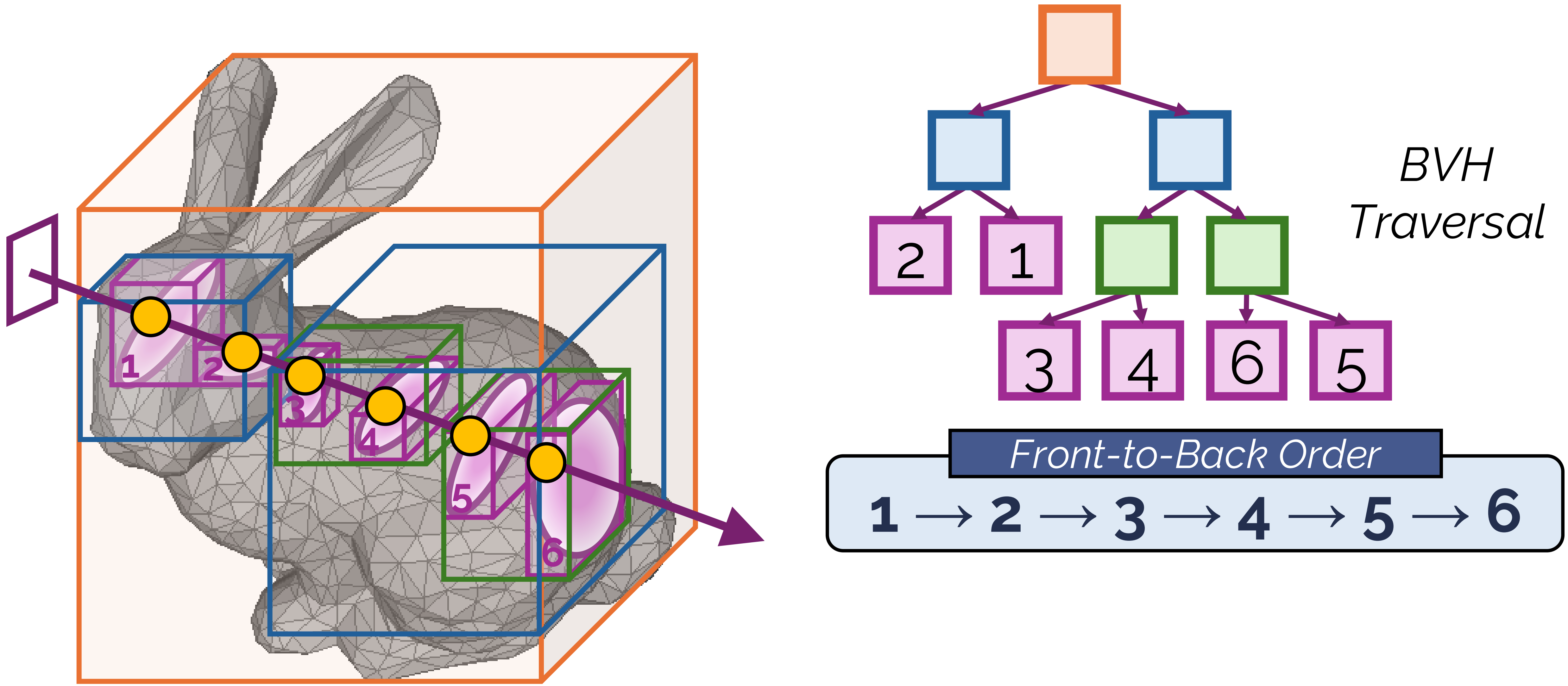
Gaussian RT Optimizations & Limitations



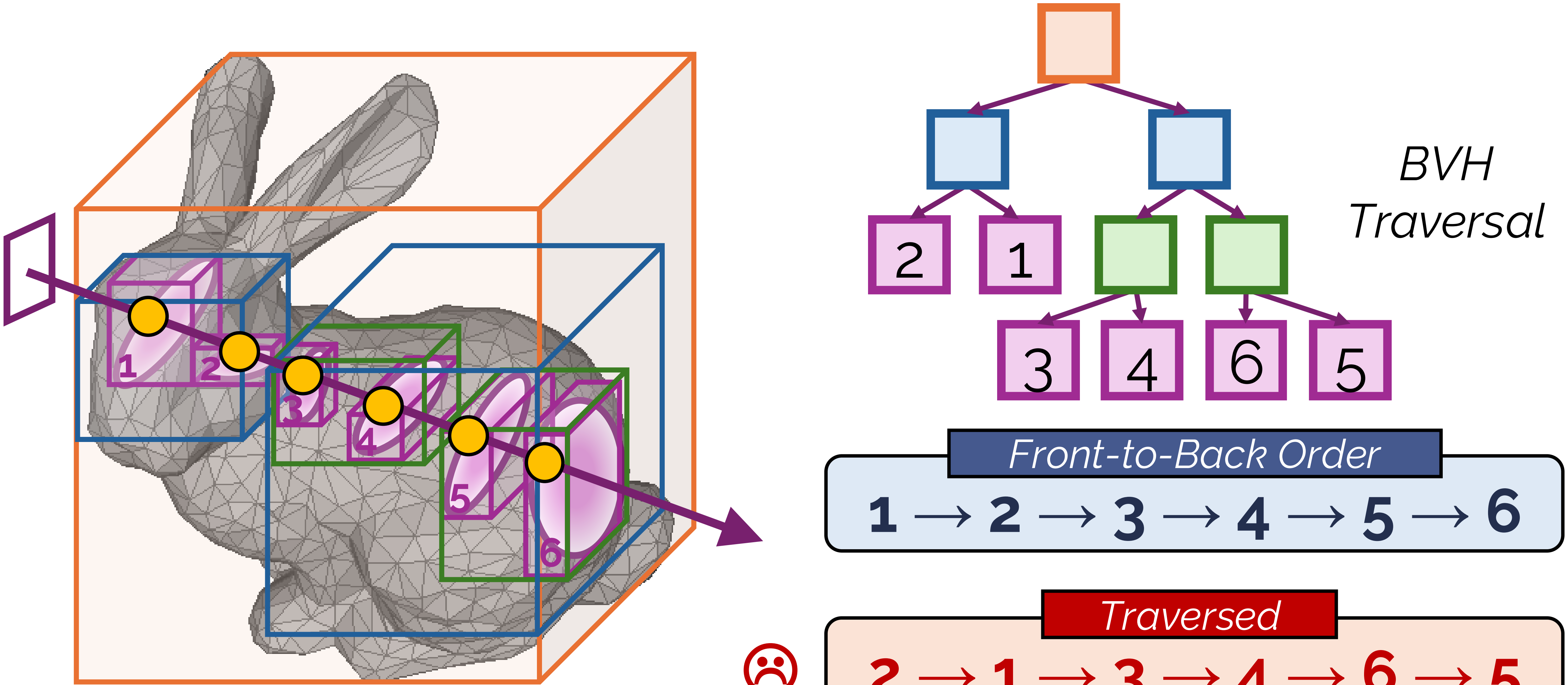


BVH Traversal

Gaussian RT Optimizations & Limitations



Gaussian RT Optimizations & Limitations



Front-to-Back Order

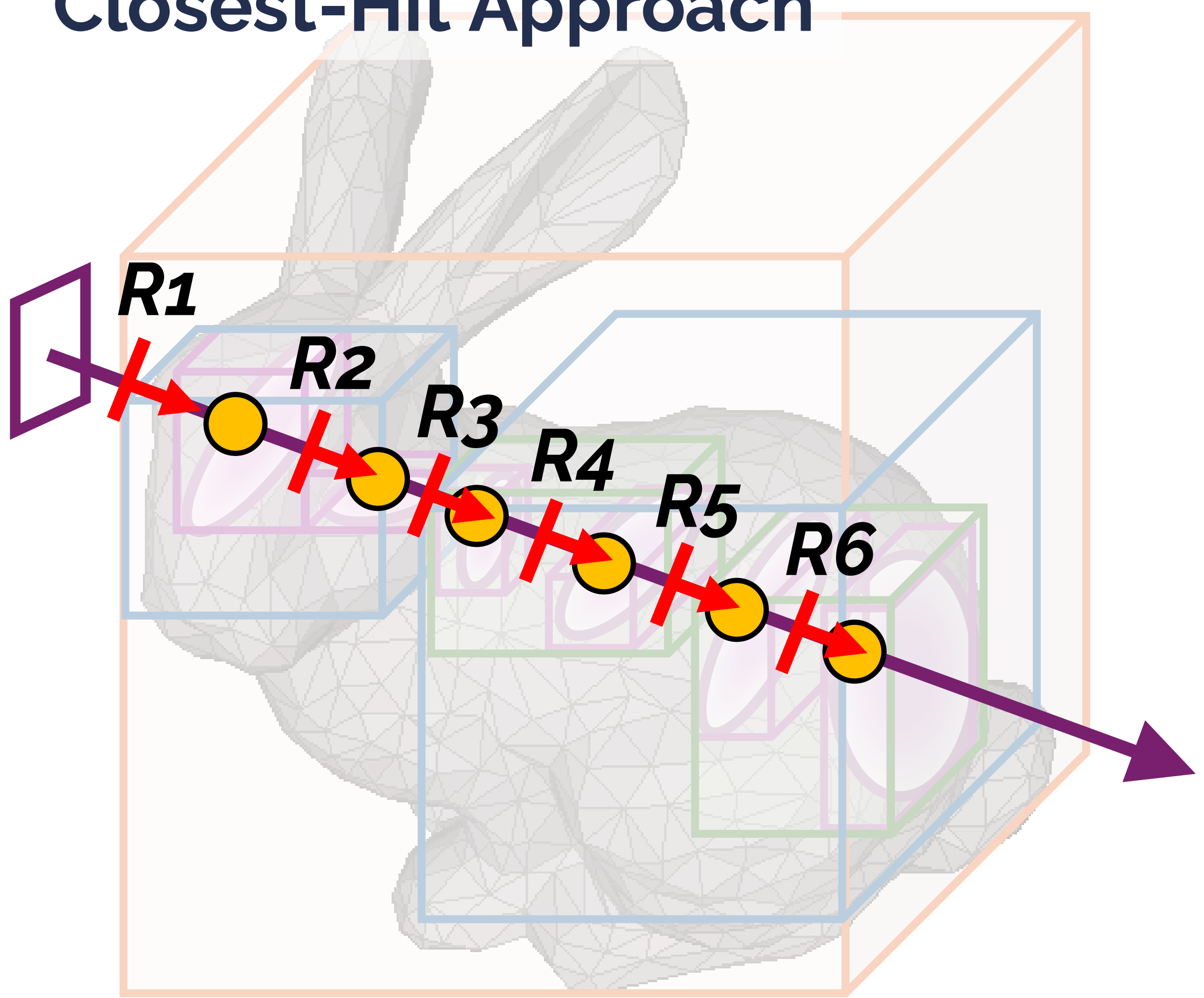
1 → 2 → 3 → 4 → 5 → 6

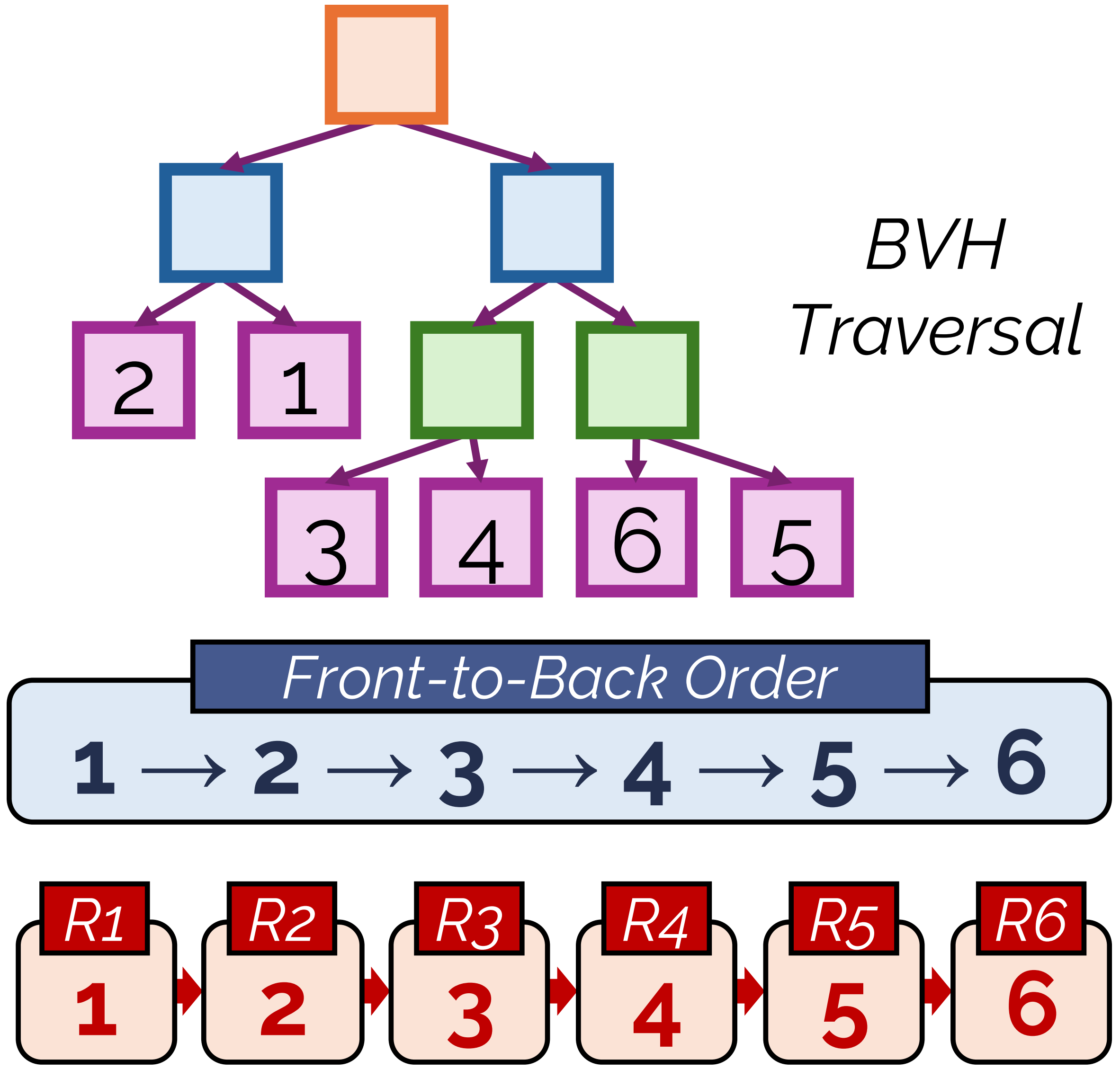
Traversed

☹ 2 → 1 → 3 → 4 → 6 → 5

Gaussian RT Optimizations & Limitations

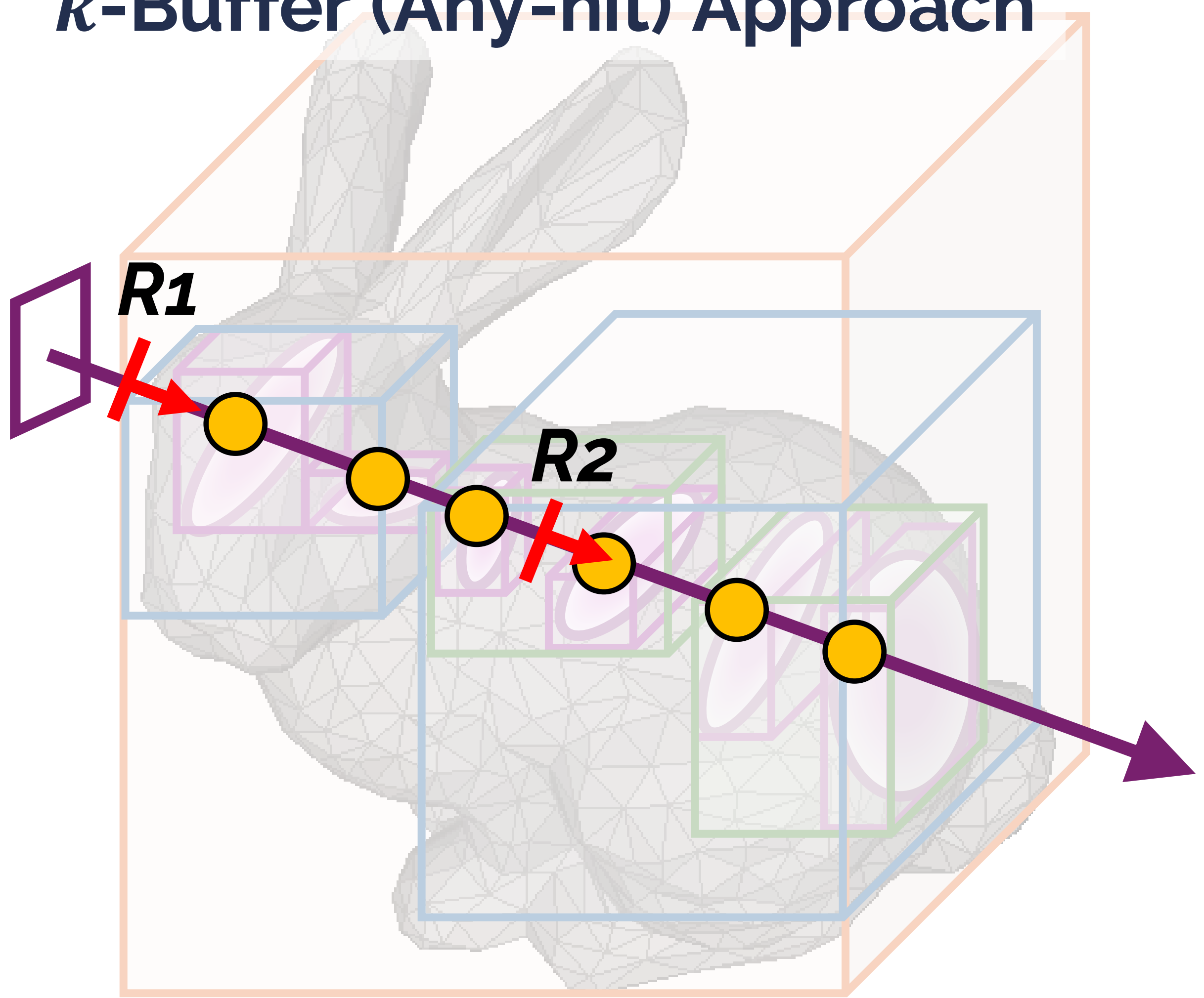
Closest-Hit Approach

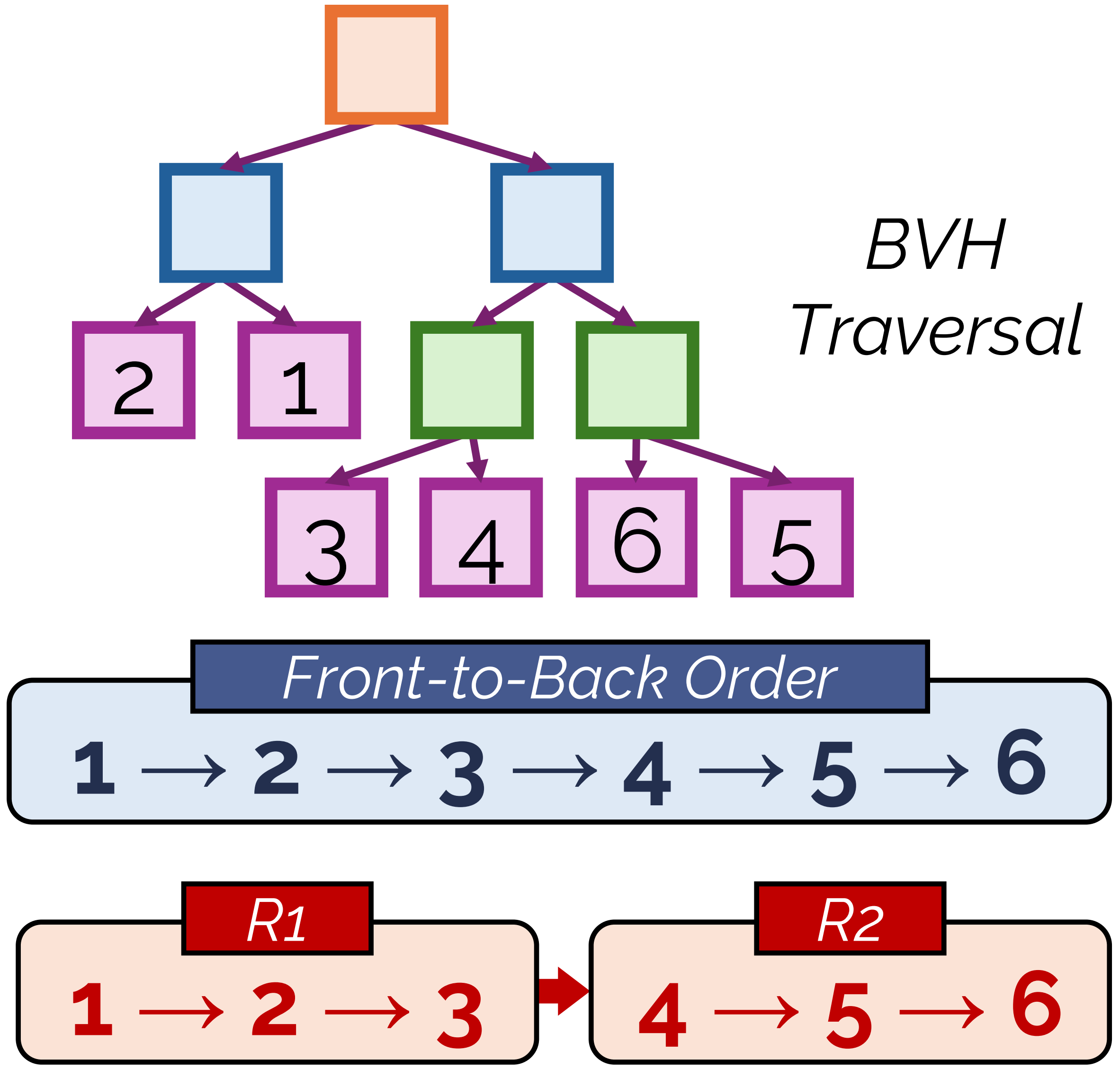




Gaussian RT Optimizations & Limitations

k-Buffer (Any-hit) Approach





Gaussian RT Optimizations & Limitations

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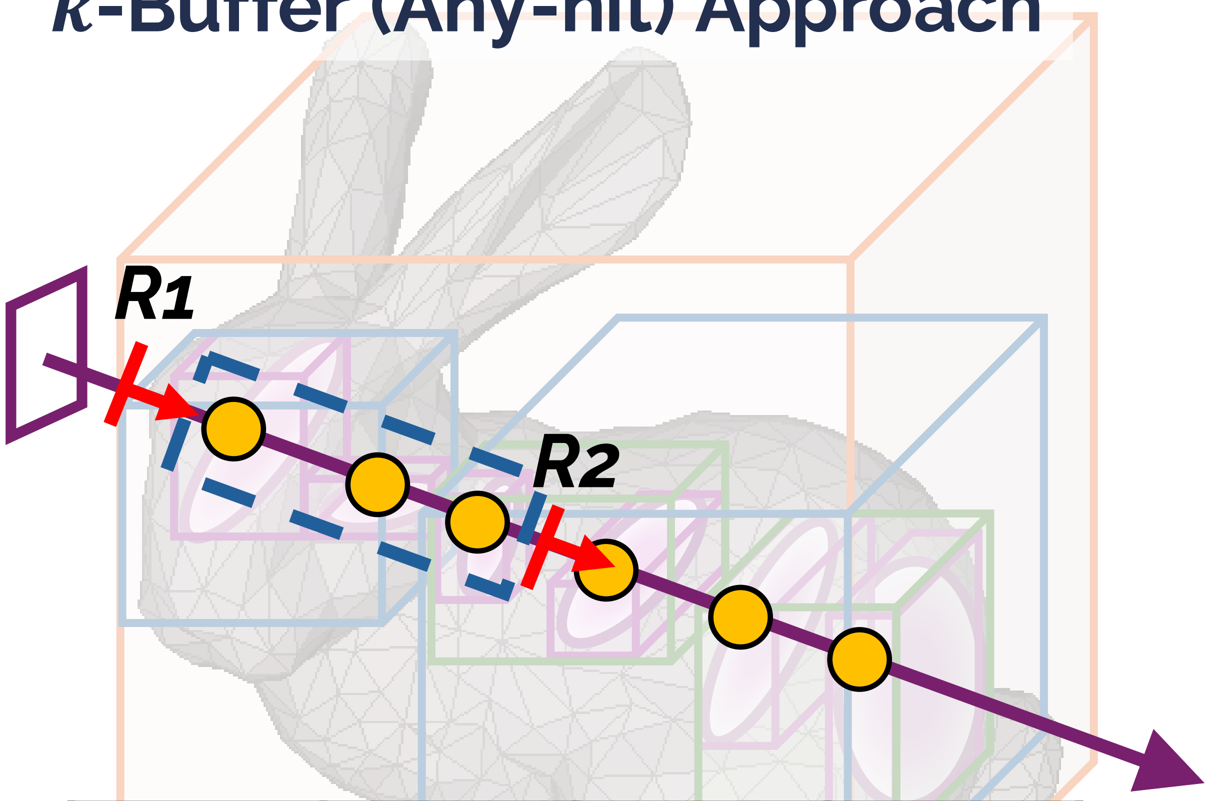
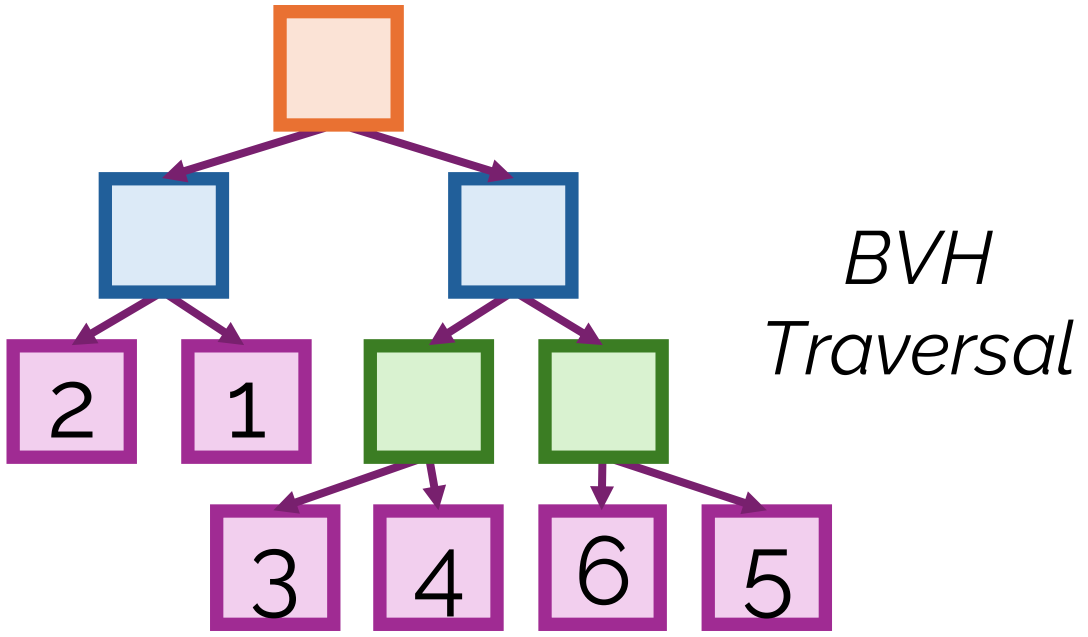


Ray 1	1	2	3
Gaus. ID			
Distance			

k-buffer ($k = 3$)



Front-to-Back Order

$1 \rightarrow 2 \rightarrow 3 \rightarrow 4 \rightarrow 5 \rightarrow 6$

R1

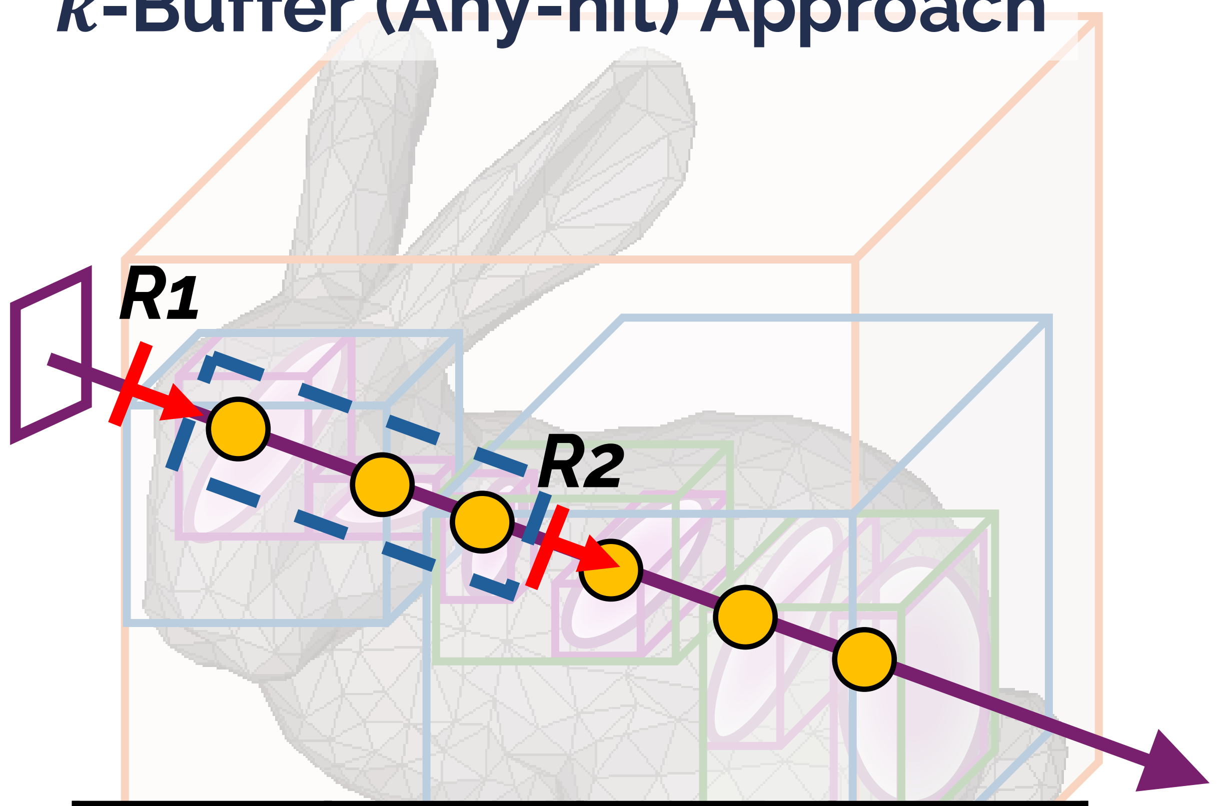
$1 \rightarrow 2 \rightarrow 3$

R2

$4 \rightarrow 5 \rightarrow 6$

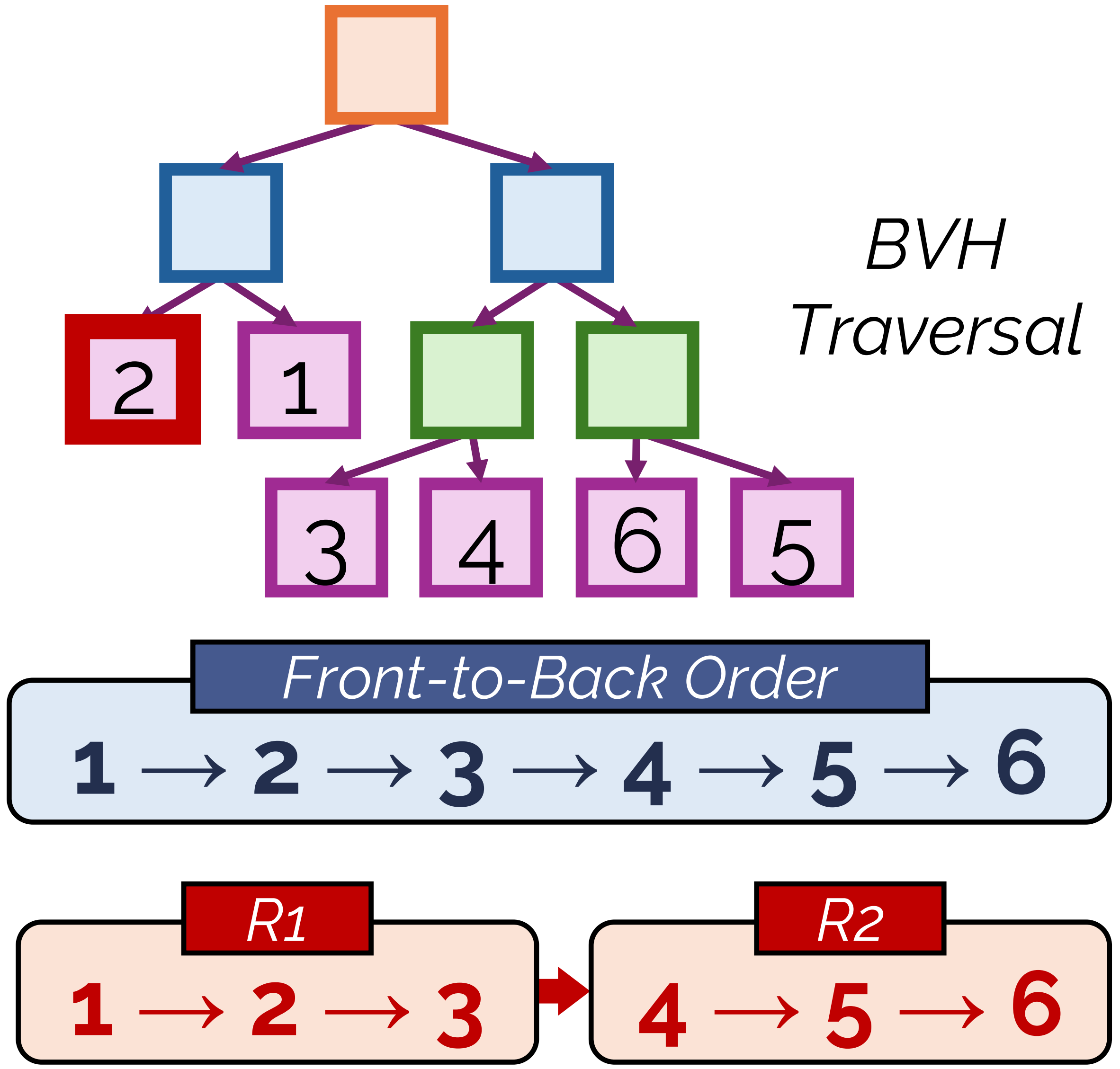
Gaussian RT Optimizations & Limitations

k-Buffer (Any-hit) Approach



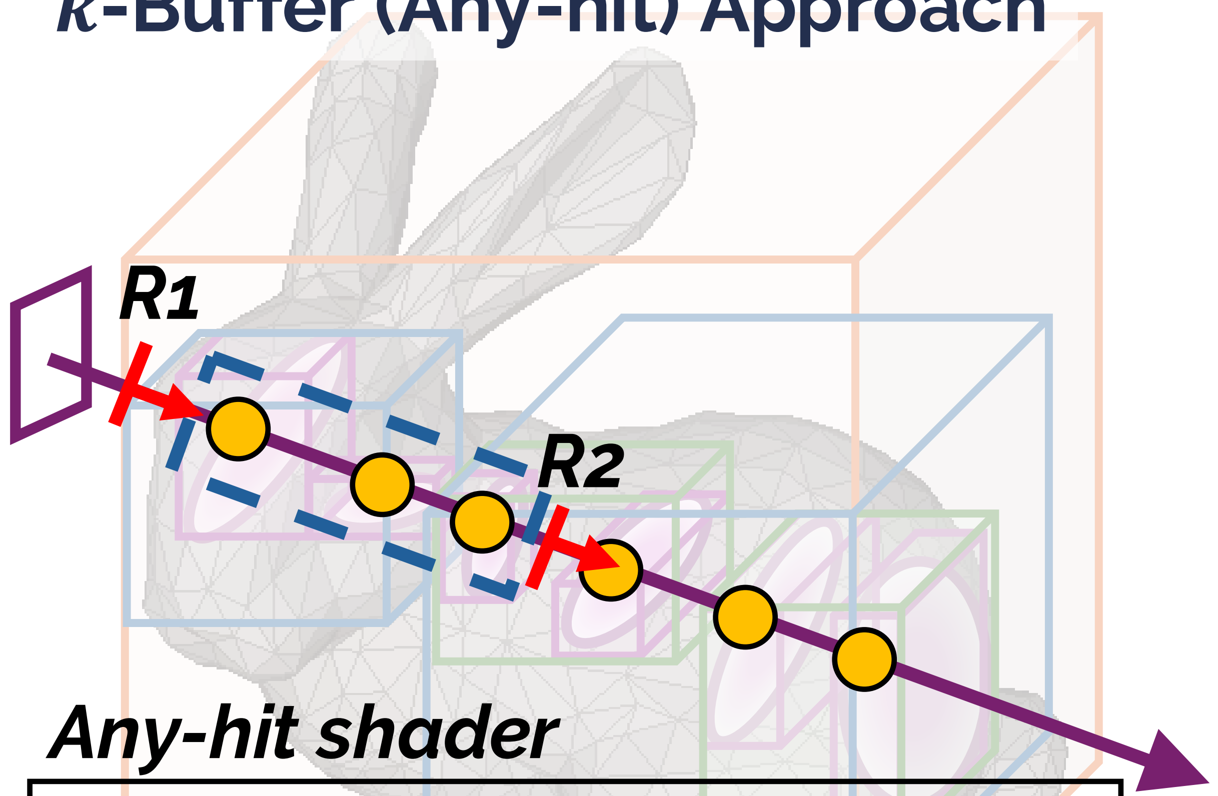
Ray 1	1	2	3
Gaus. ID			
Distance			

k-buffer ($k = 3$)



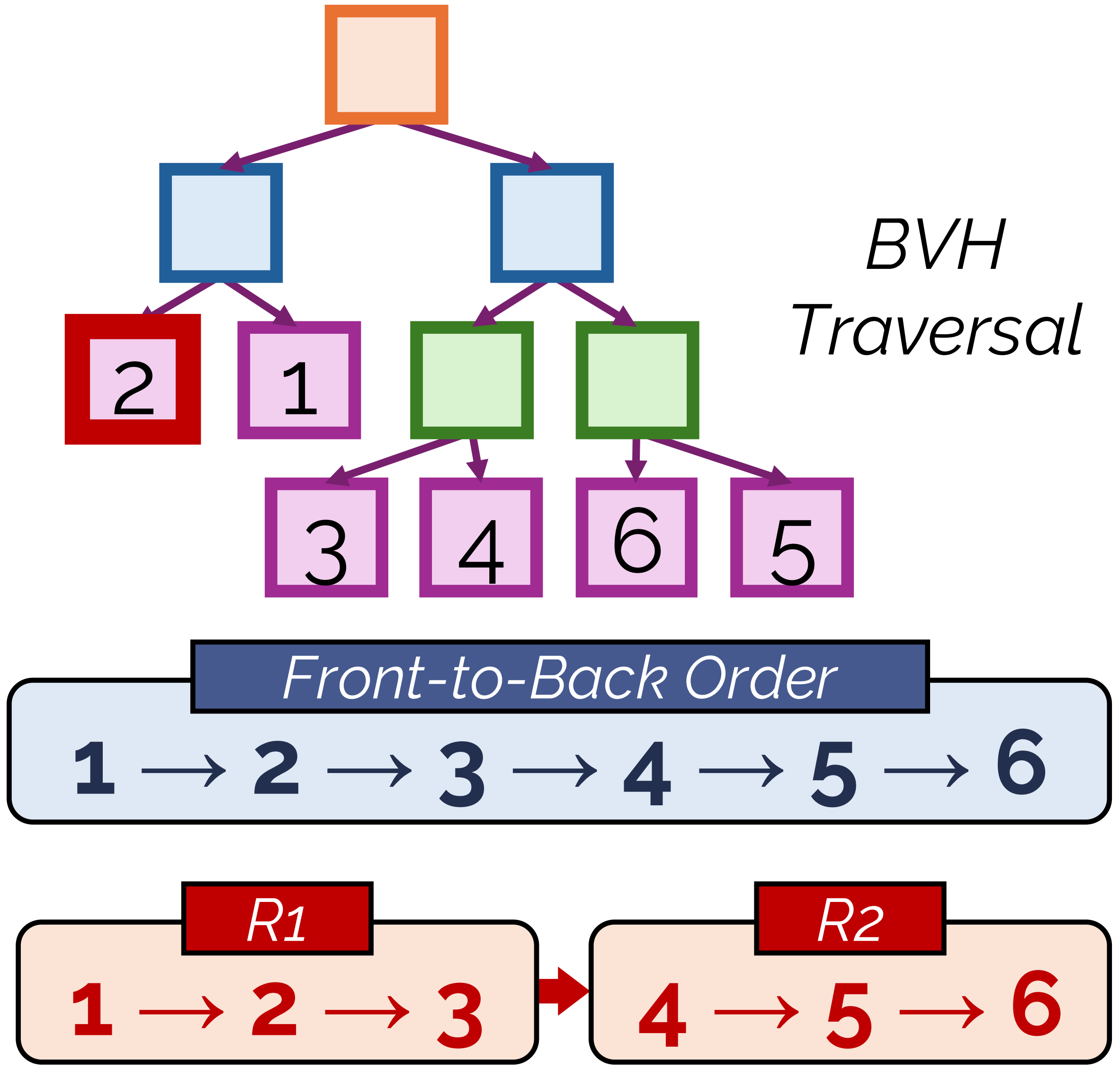
Gaussian RT Optimizations & Limitations

k-Buffer (Any-hit) Approach



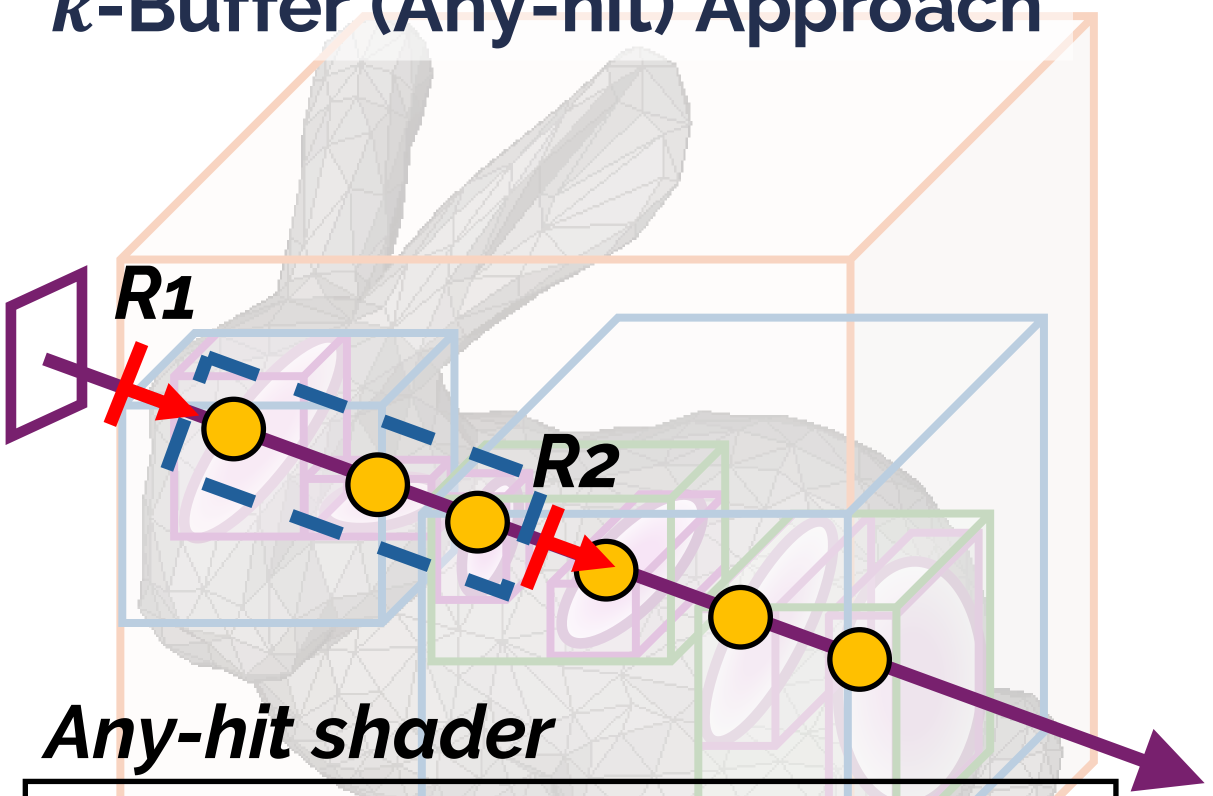
Ray 1	1	2	3
Gaus. ID			
Distance			

k-buffer ($k = 3$)



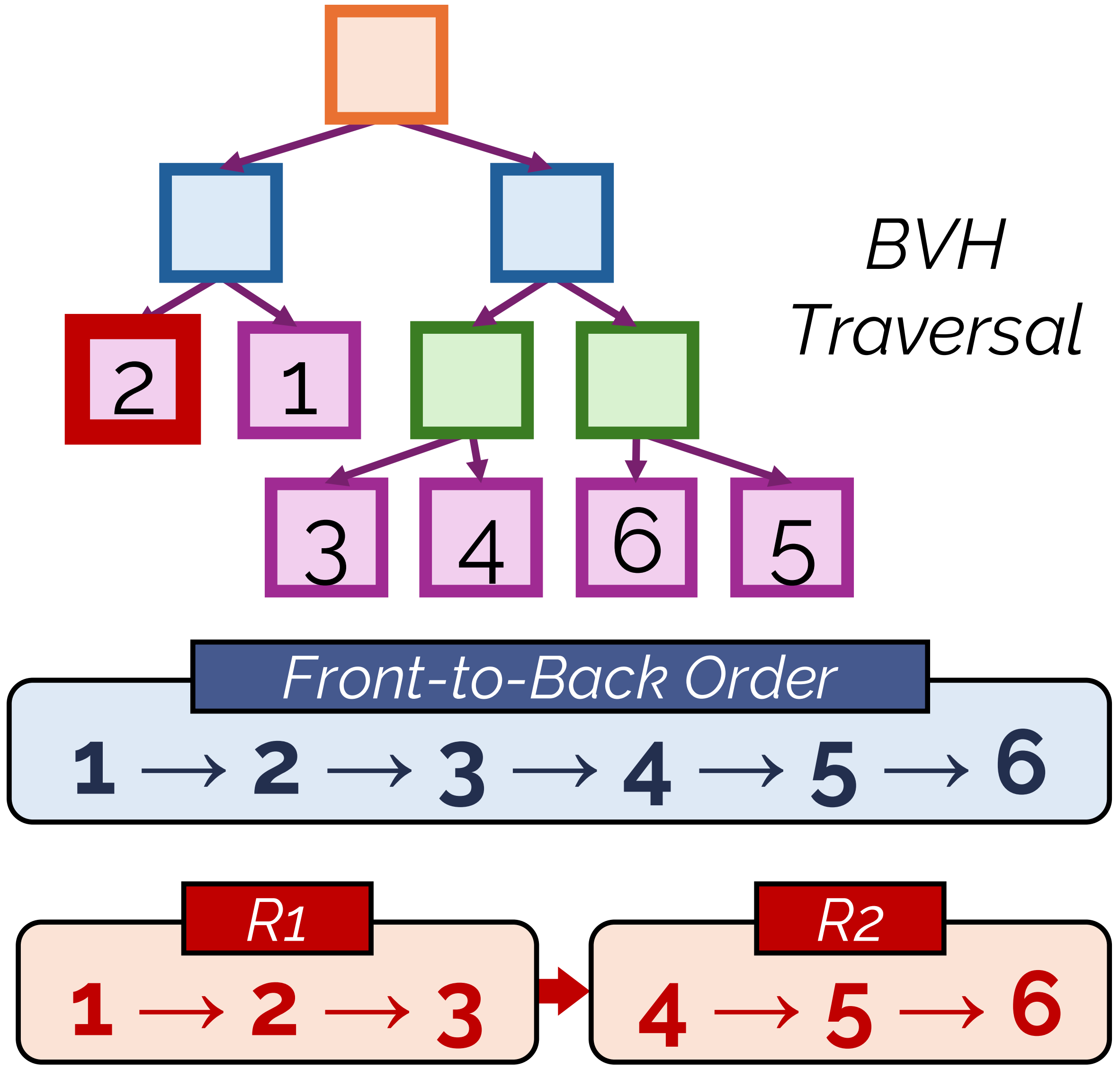
Gaussian RT Optimizations & Limitations

k-Buffer (Any-hit) Approach



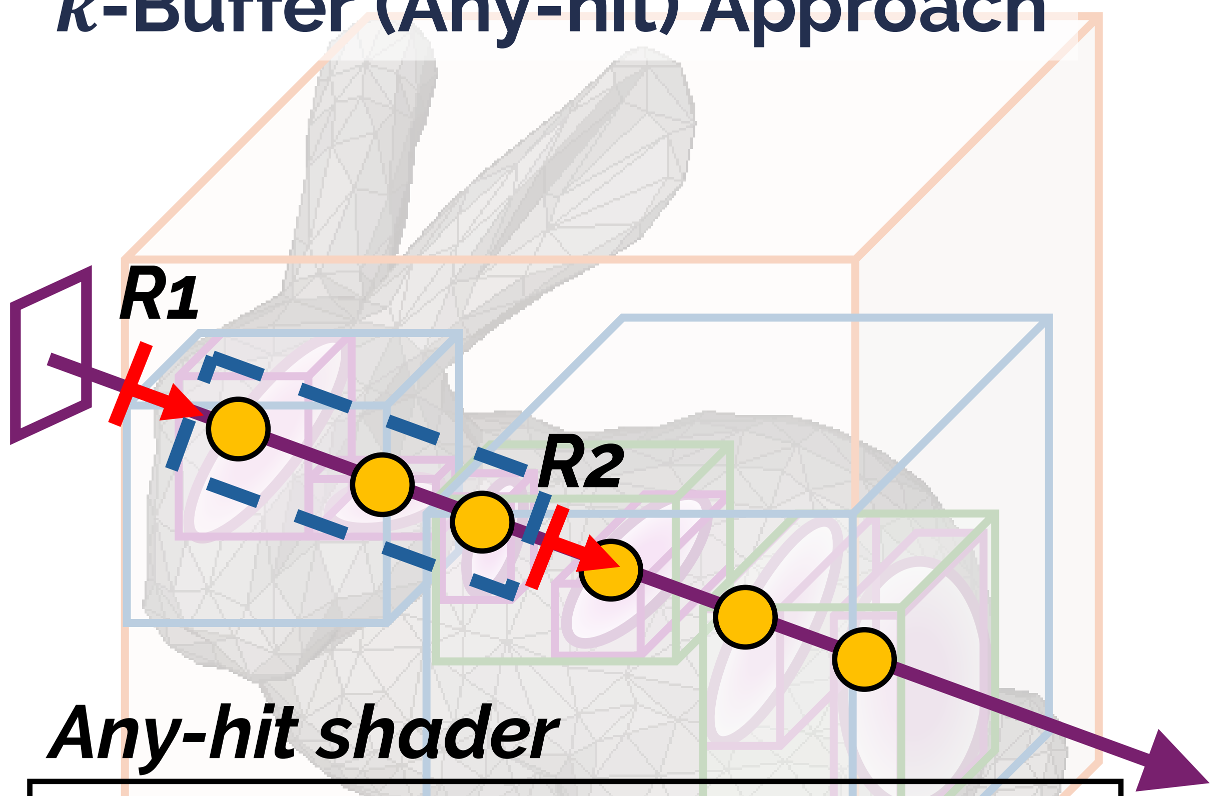
Ray 1	1	2	3
Gaus. ID	2		
Distance	3.7		

k-buffer ($k = 3$)



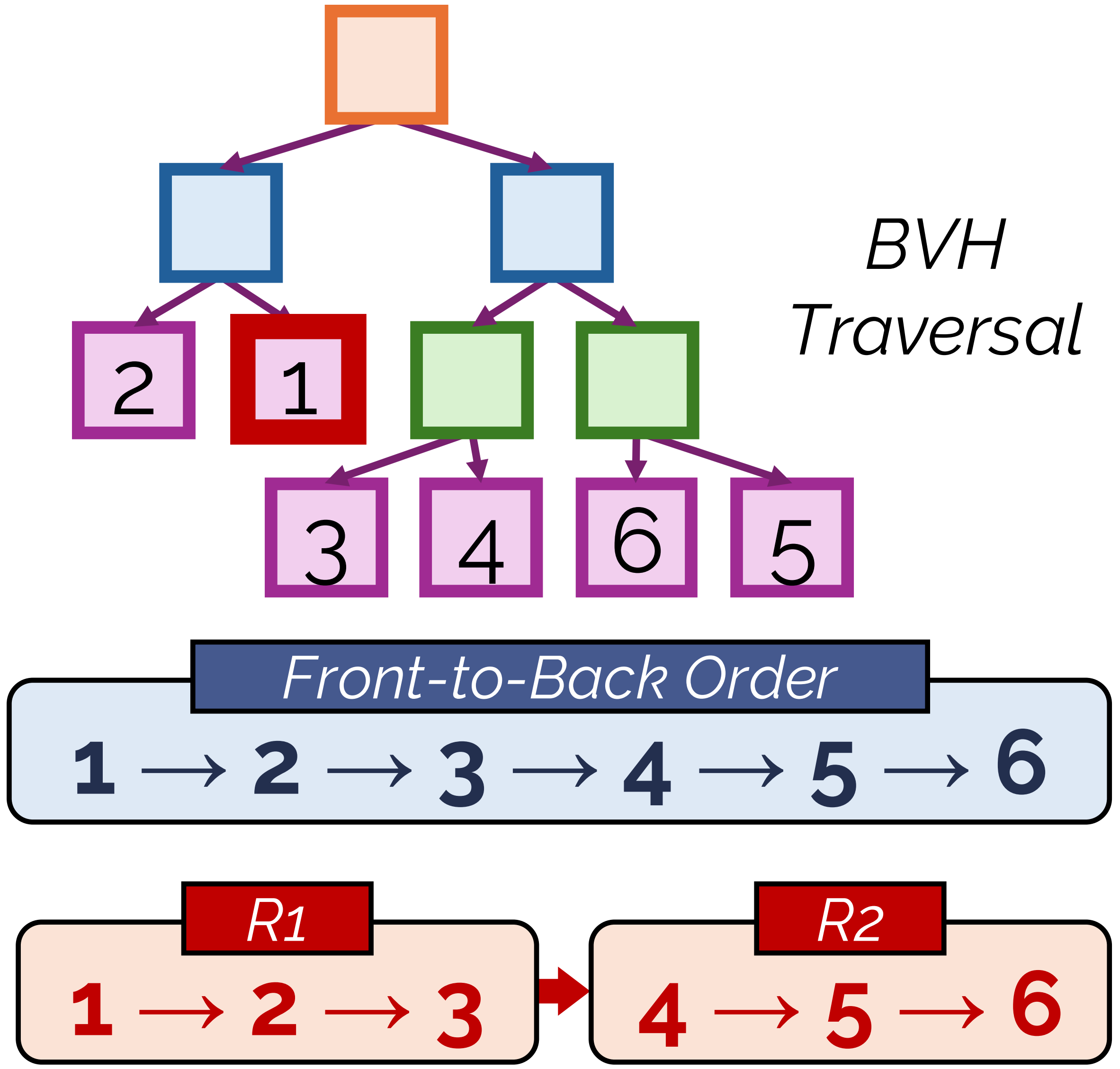
Gaussian RT Optimizations & Limitations

k-Buffer (Any-hit) Approach



Ray 1	1	2	3
Gaus. ID	1	2	
Distance	1.4	3.7	

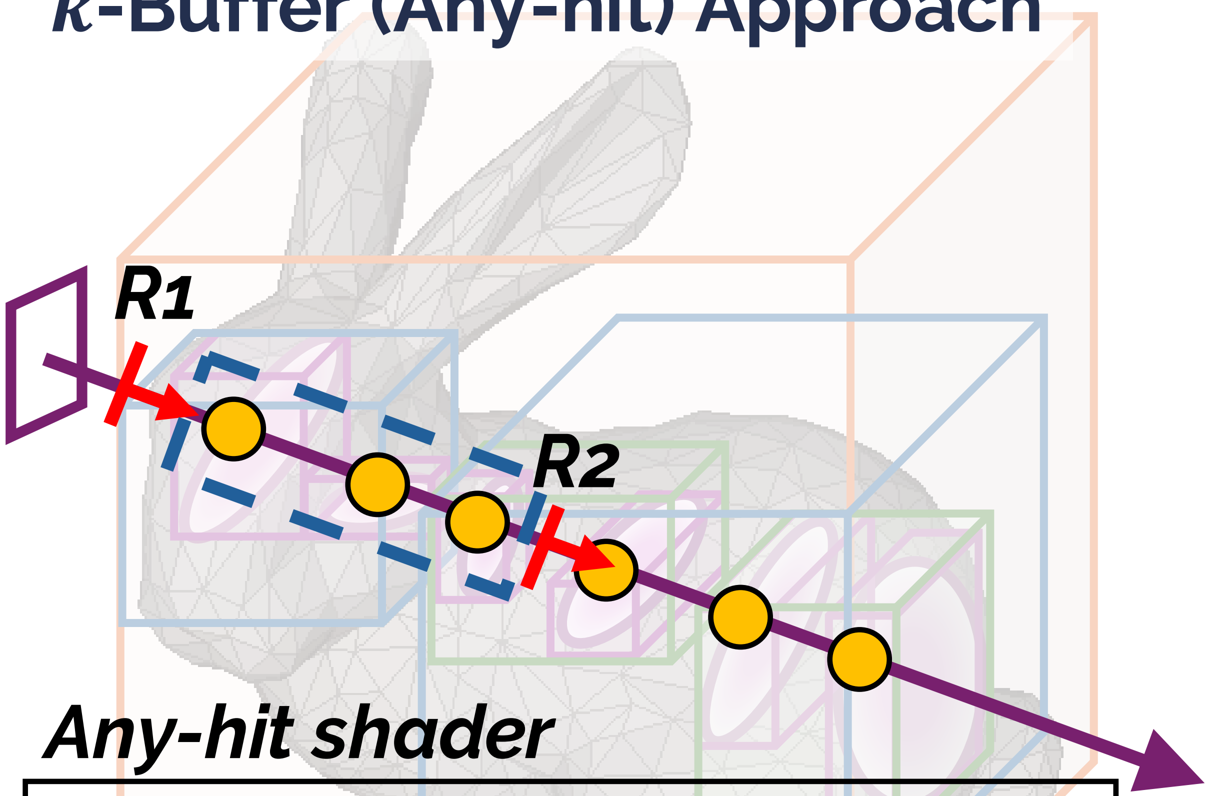
k-buffer ($k = 3$)



2
1
3
4
6
5
BVH Traversal
Front-to-Back Order
$1 \rightarrow 2 \rightarrow 3 \rightarrow 4 \rightarrow 5 \rightarrow 6$
R1
$1 \rightarrow 2 \rightarrow 3$
R2
$4 \rightarrow 5 \rightarrow 6$

Gaussian RT Optimizations & Limitations

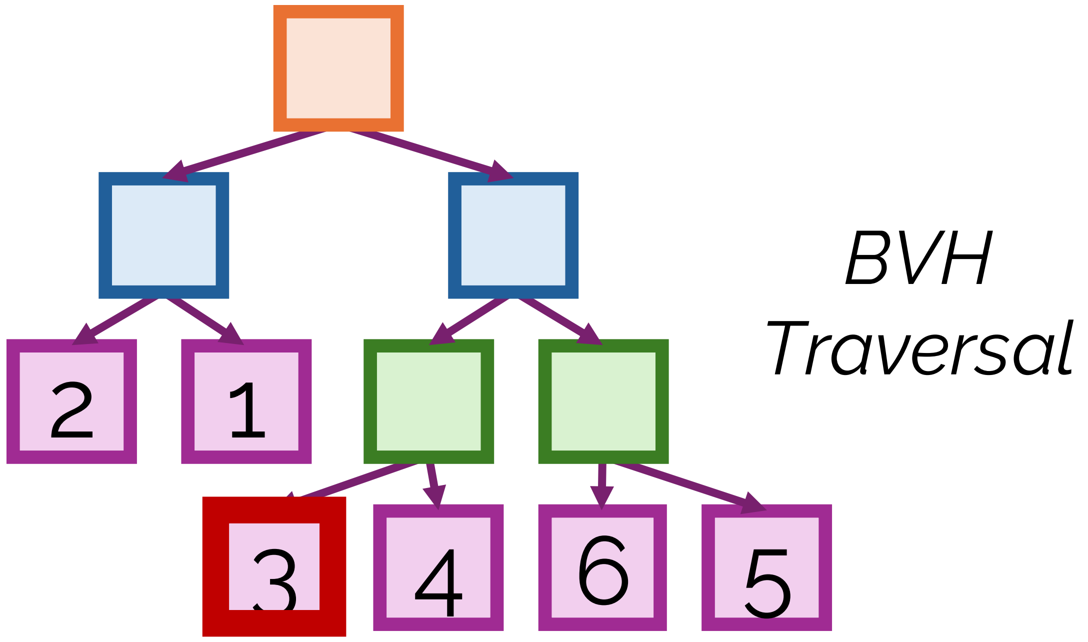
k-Buffer (Any-hit) Approach



Any-hit shader

Ray 1	1	2	3
Gaus. ID	1	2	**3**
Distance	1.4	3.7	**5.2**

k-buffer ($k = 3$)



Front-to-Back Order

$1 \rightarrow 2 \rightarrow 3 \rightarrow 4 \rightarrow 5 \rightarrow 6$

R1

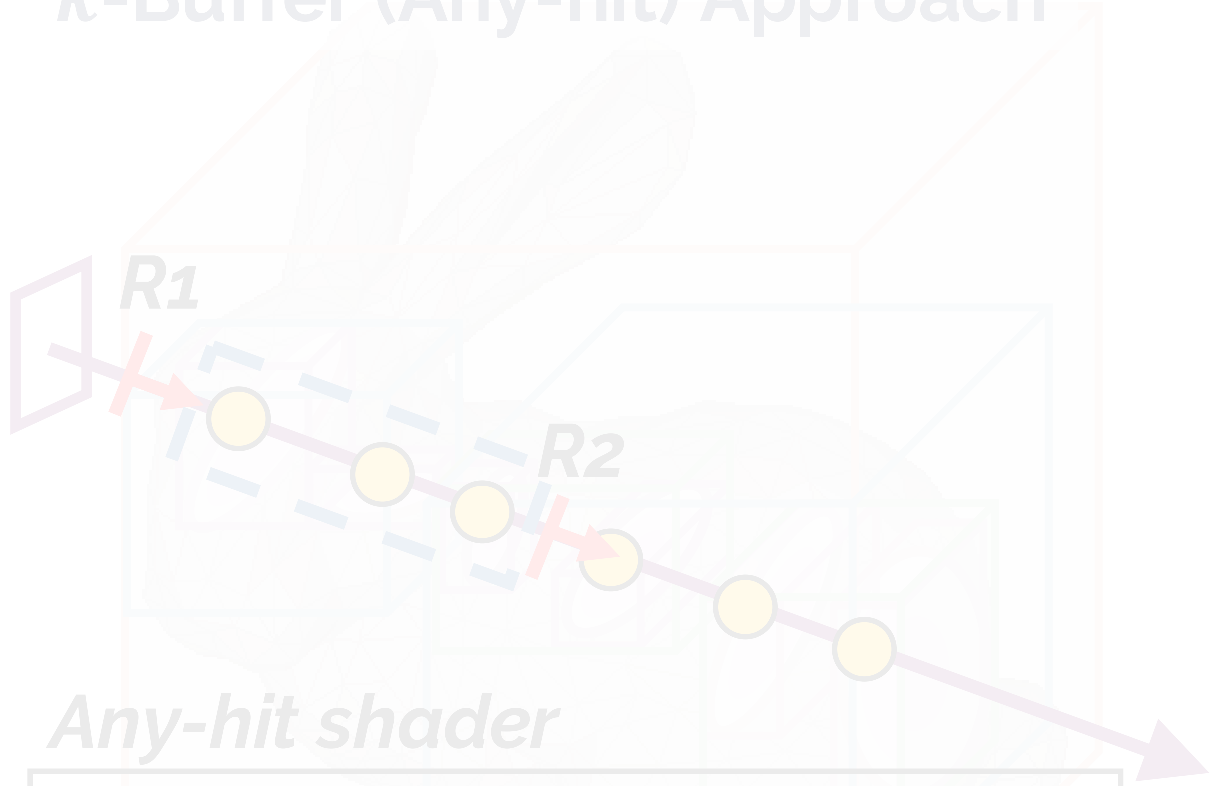
$1 \rightarrow 2 \rightarrow 3$

R2

$4 \rightarrow 5 \rightarrow 6$

Gaussian RT Optimizations & Limitations

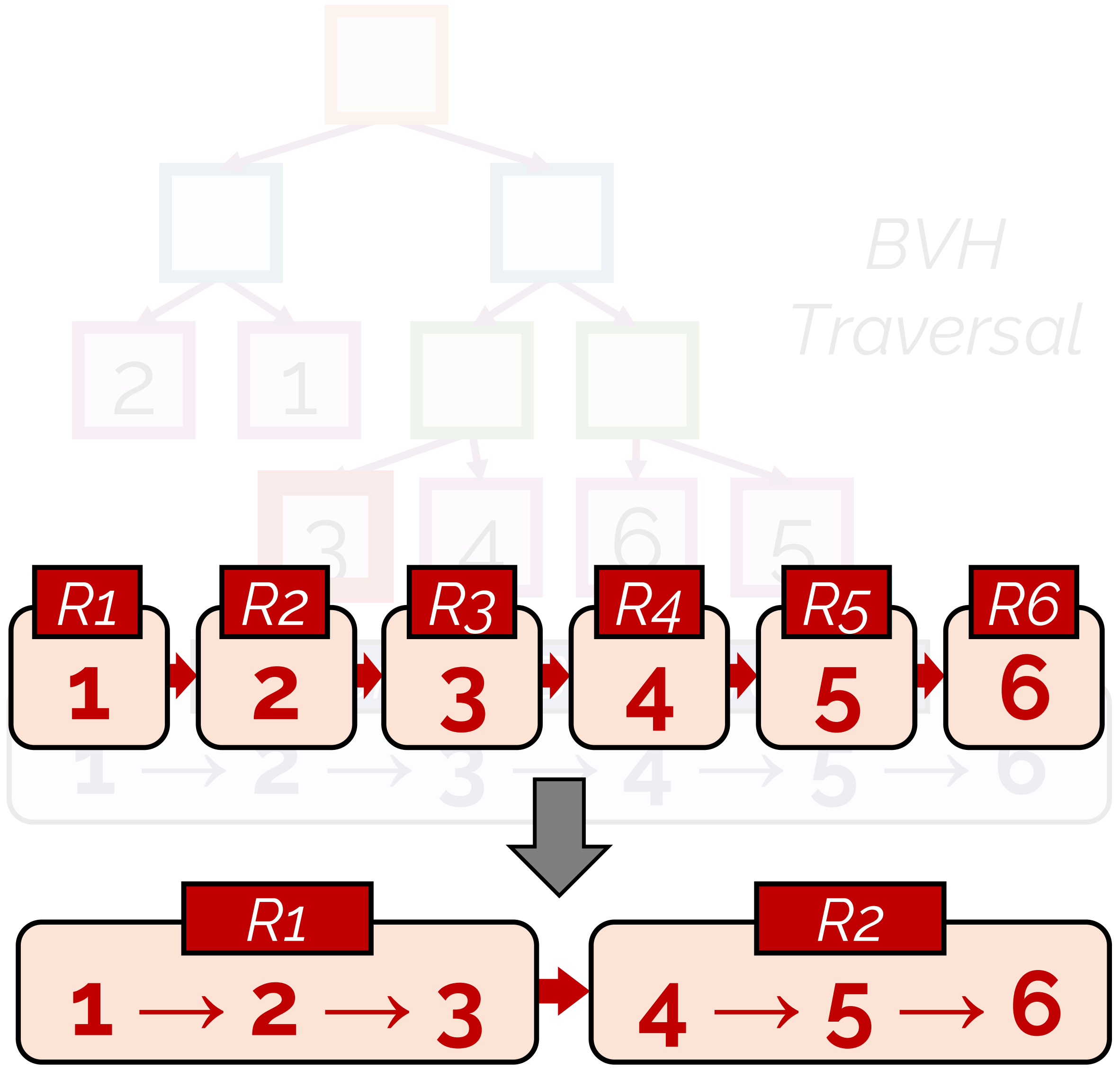
k-Buffer (Any-hit) Approach



Any-hit shader

Ray 1	1	2	3
Gaus. ID	1	2	3
Distance	1.4	3.7	5.2

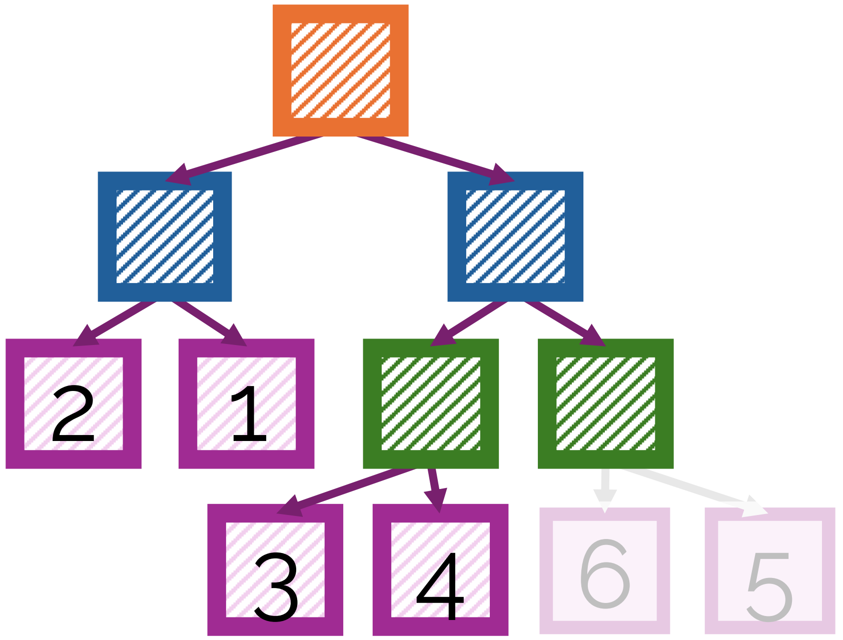
k-buffer ($k = 3$)



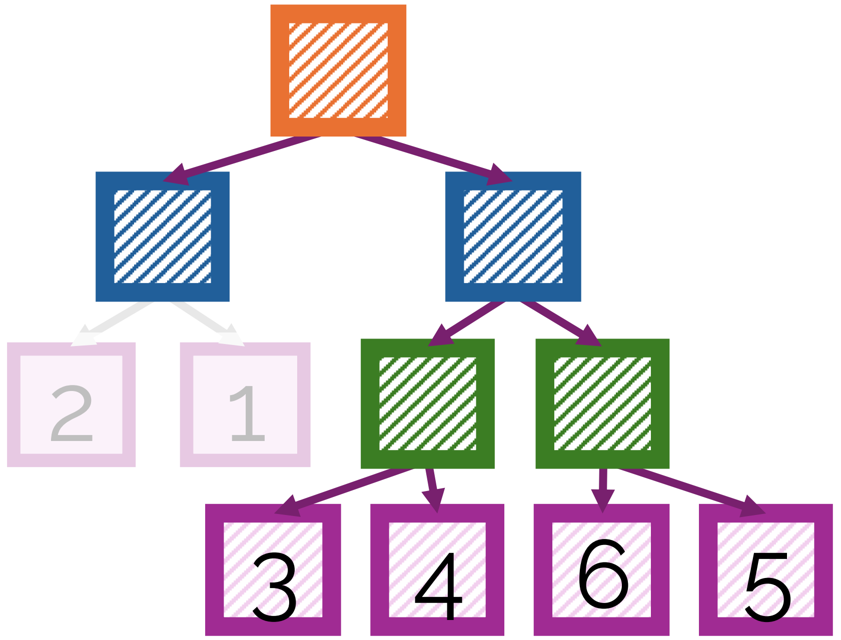
Gaussian RT Optimizations & Limitations

k-Buffer (Any-hit) Approach

Round 1



Round 2

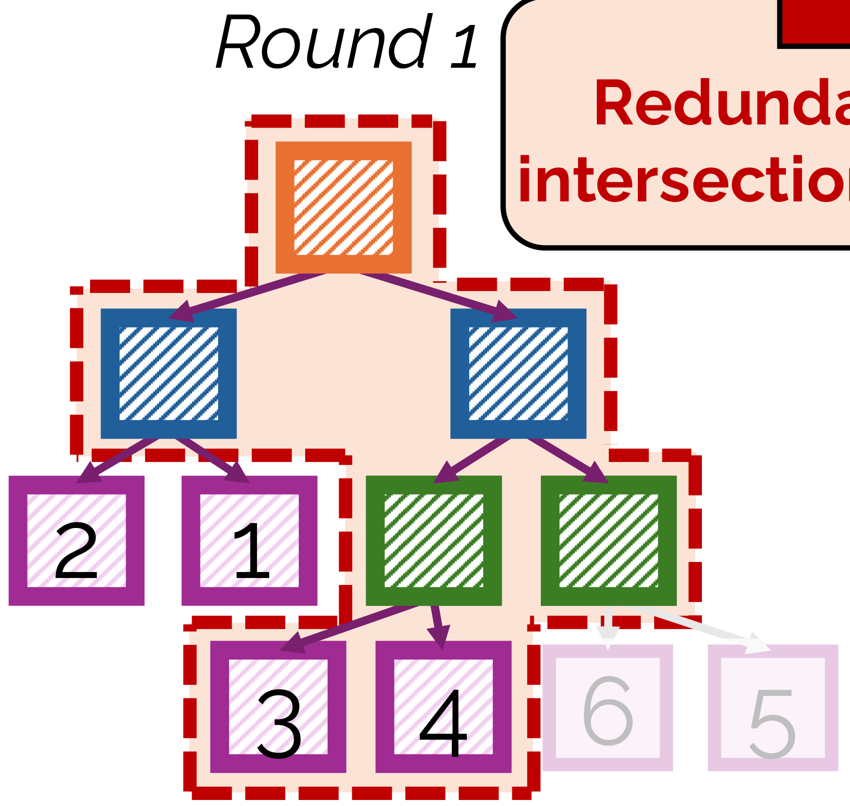


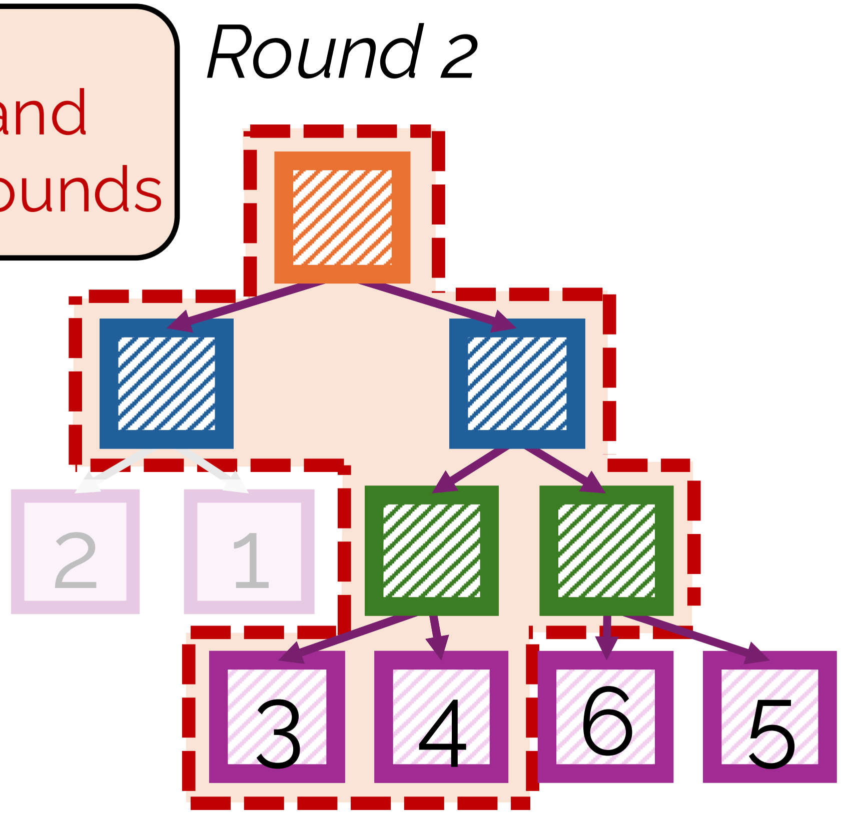
Gaussian RT Optimizations & Limitations

k-Buffer (Any-hit) Approach

Problem 2

Redundant node visits and **intersection tests** across rounds

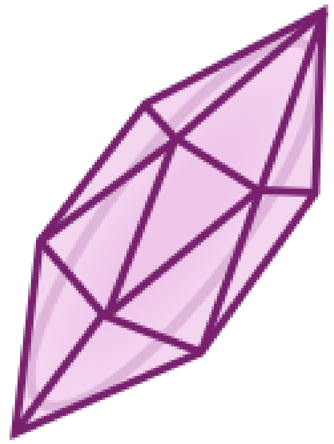




Gaussian RT Optimizations & Limitations

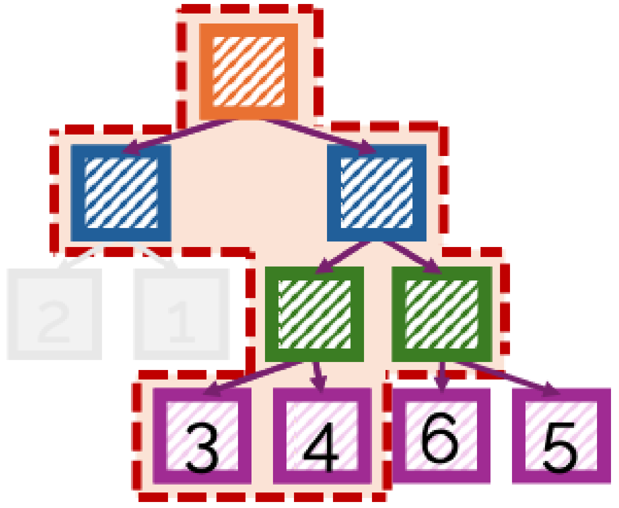
Problem 1

Bloated BVH size and
increased **memory footprint**



Problem 2

Redundant node visit and
intersection tests across rounds



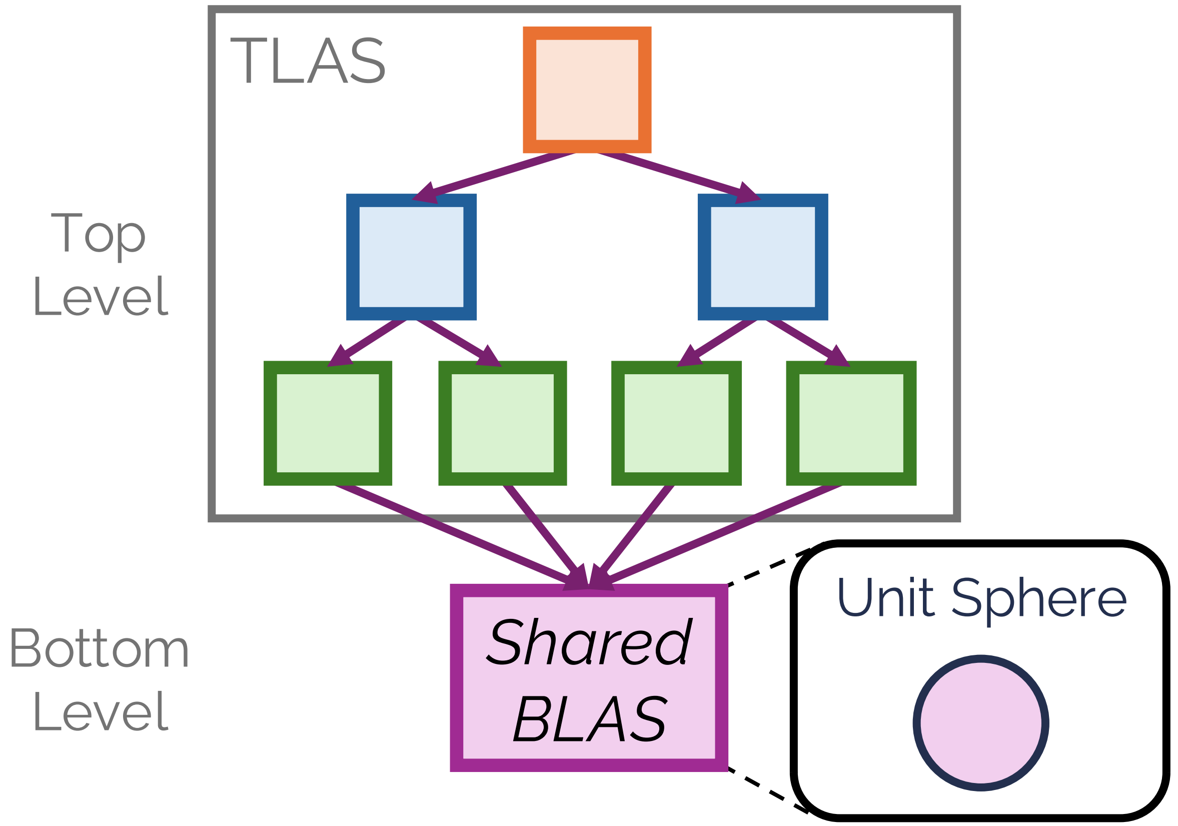
Outline

- **Background**
  - 3D Gaussian-based Rendering: Rasterization vs. Ray-tracing
  - Ray Tracing Accelerators in Modern GPUs
- **Gaussian RT Optimizations & Limitations**
- **GRTX: SW-HW Optimizations for Gaussian Ray Tracing**
  - GRTX-SW: Two-Level Acceleration Structure for Gaussian Primitives
  - GRTX-HW: HW Extension for Traversal Checkpointing and Replay
- **Evaluation**
- **Conclusion**

GRTX Overview

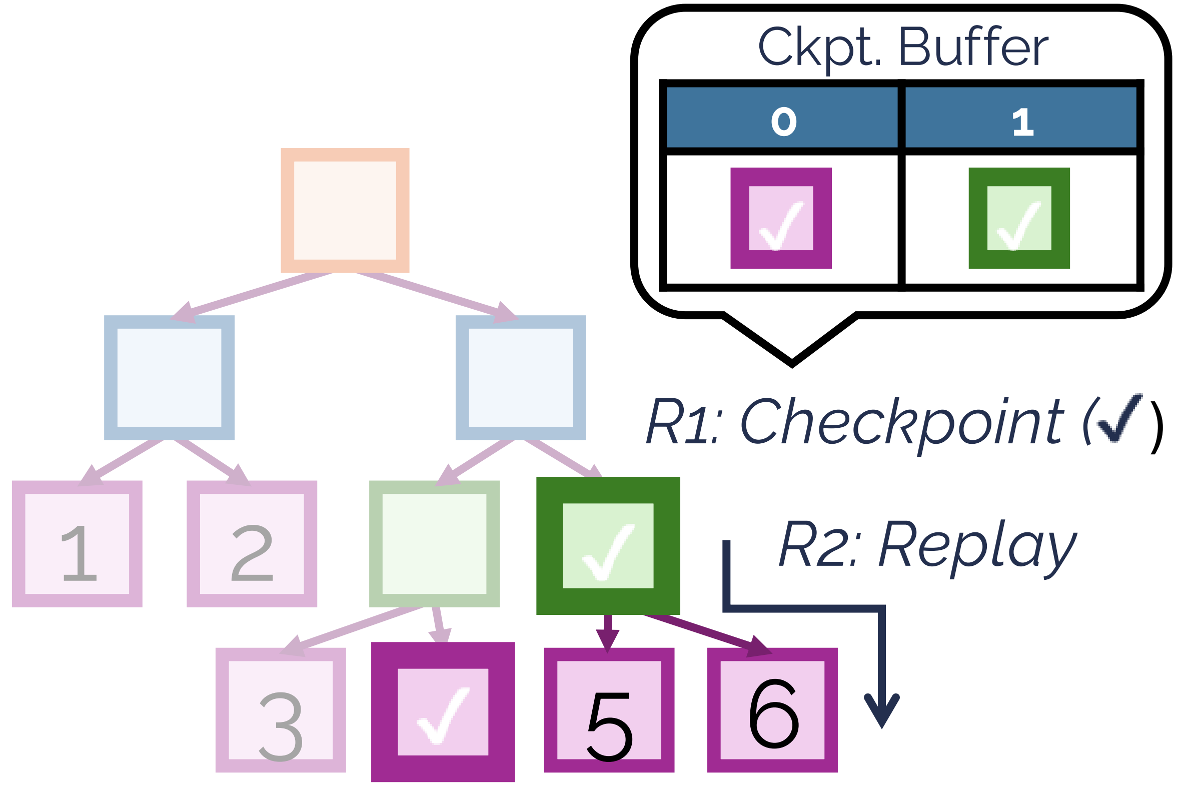
GRTX-SW

Two-level BVH with
a **single shared BLAS** for Gaussian



GRTX-HW

Hardware extension for
traversal checkpointing & replay



GRTX Overview

GRTX-SW

Two-level BVH with
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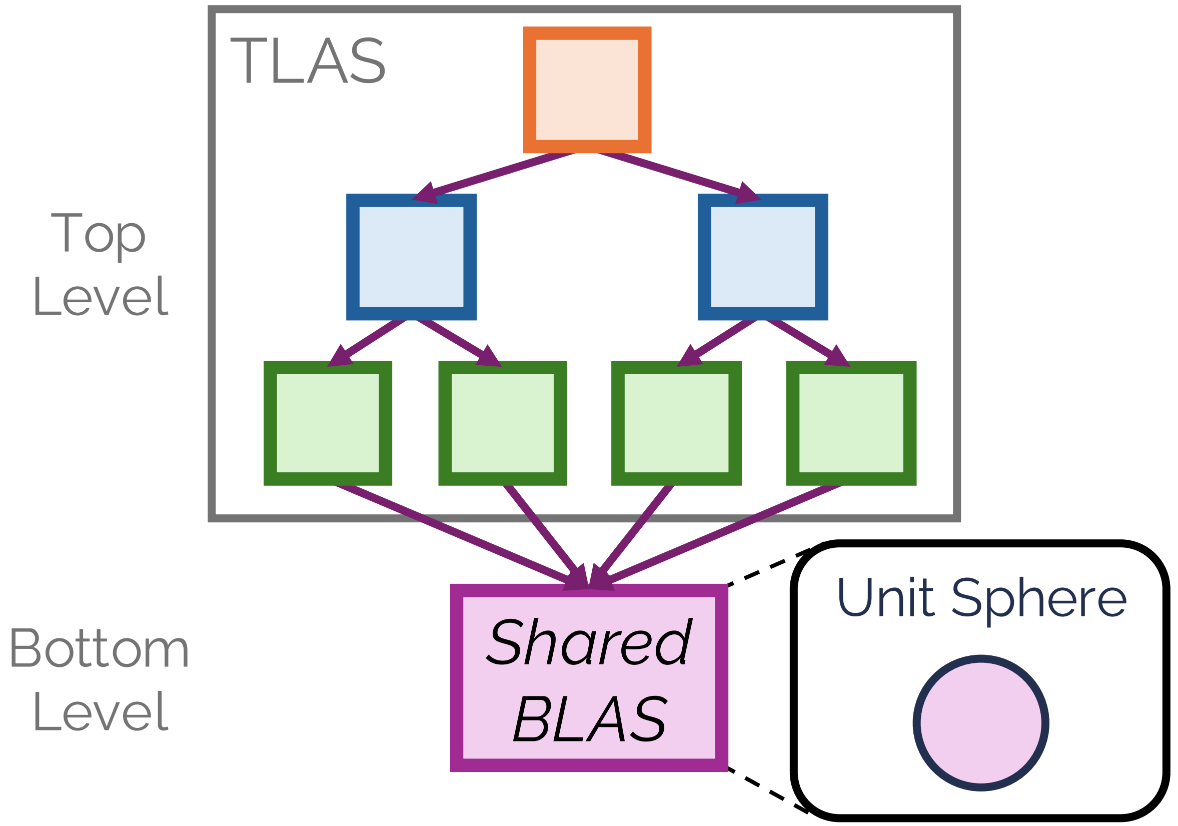

GRTX-HW

Hardware extension for
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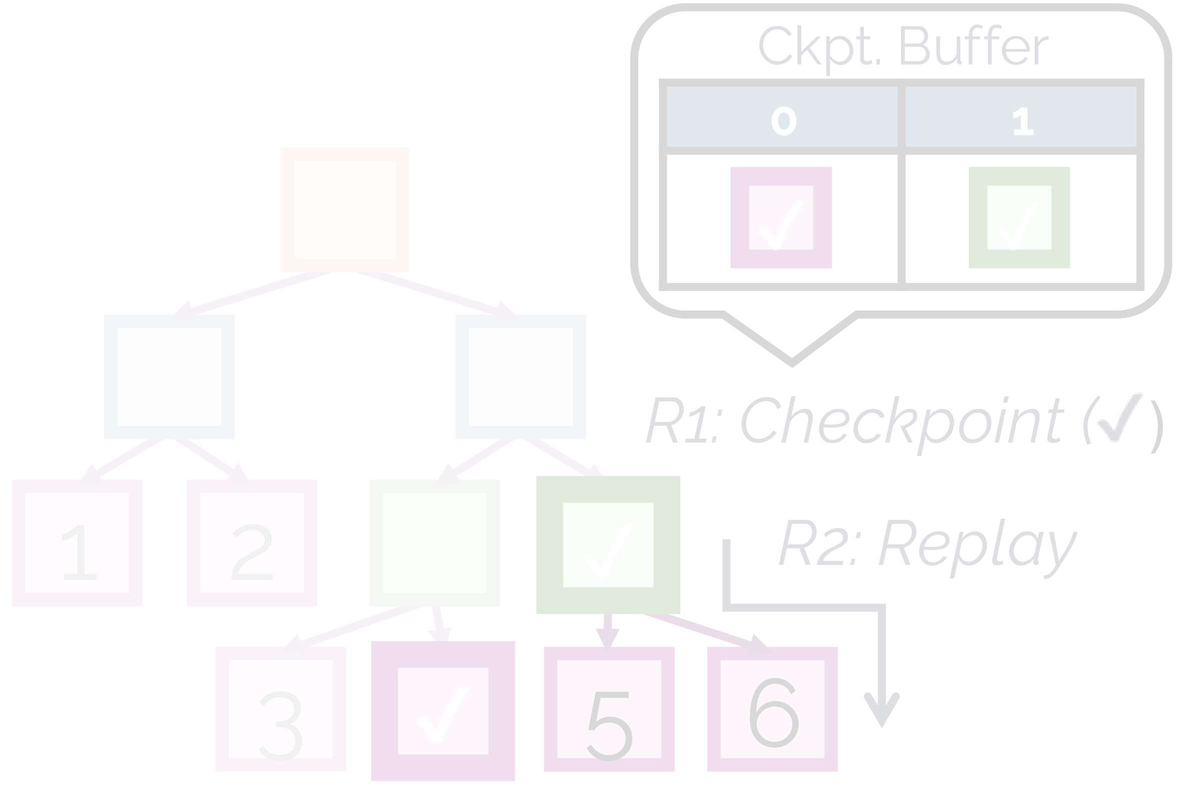

GRTX Overview

GRTX-SW

Two-level BVH with
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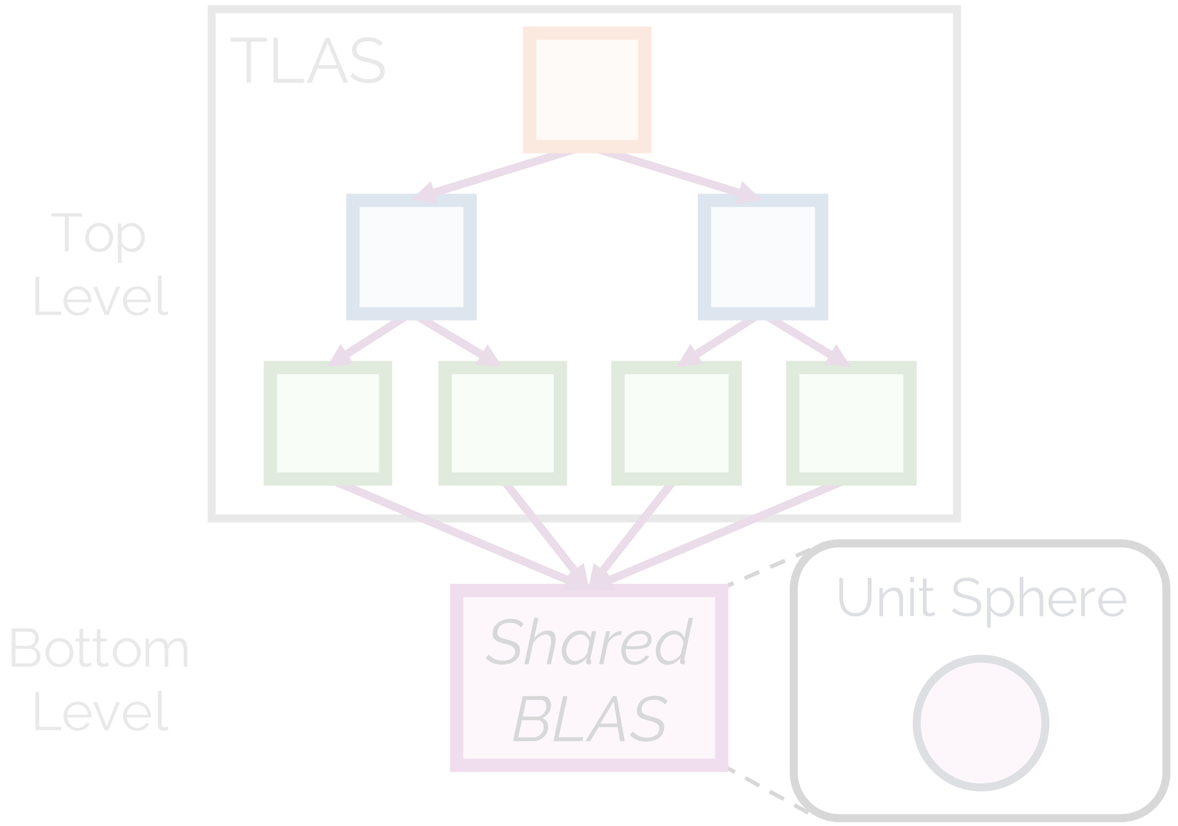

GRTX-HW

Hardware extension for
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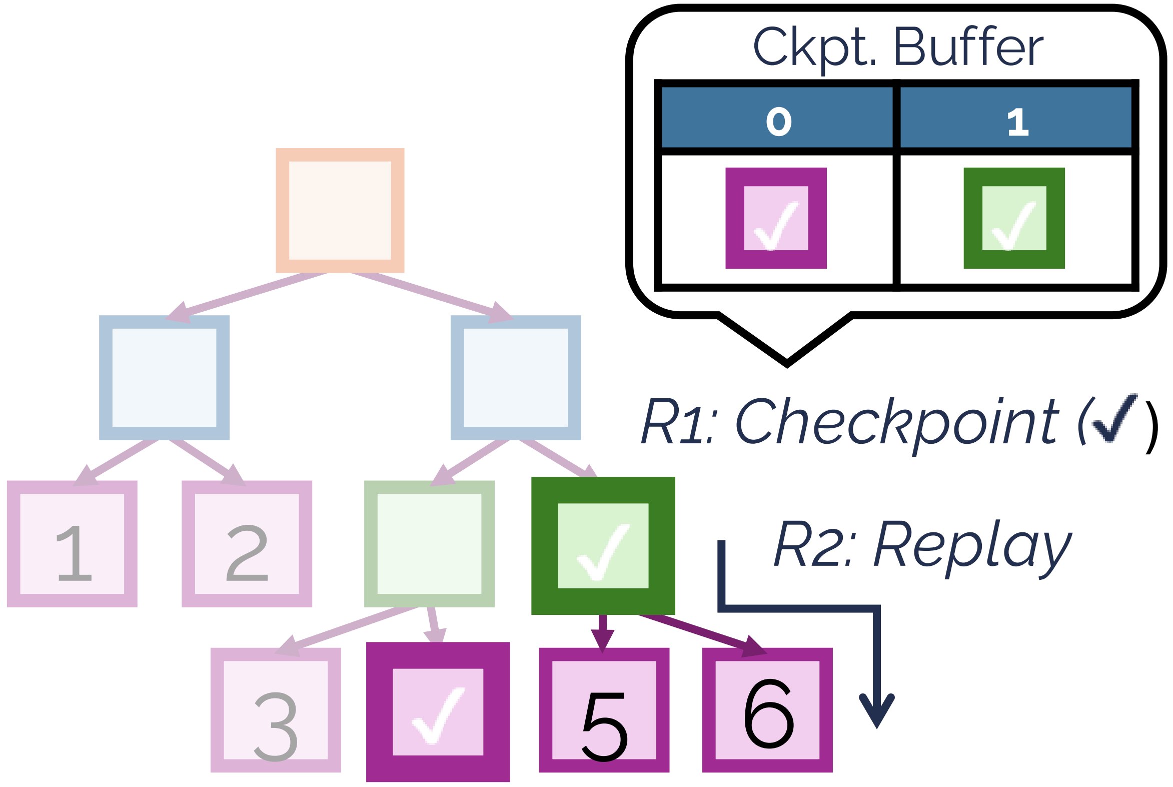
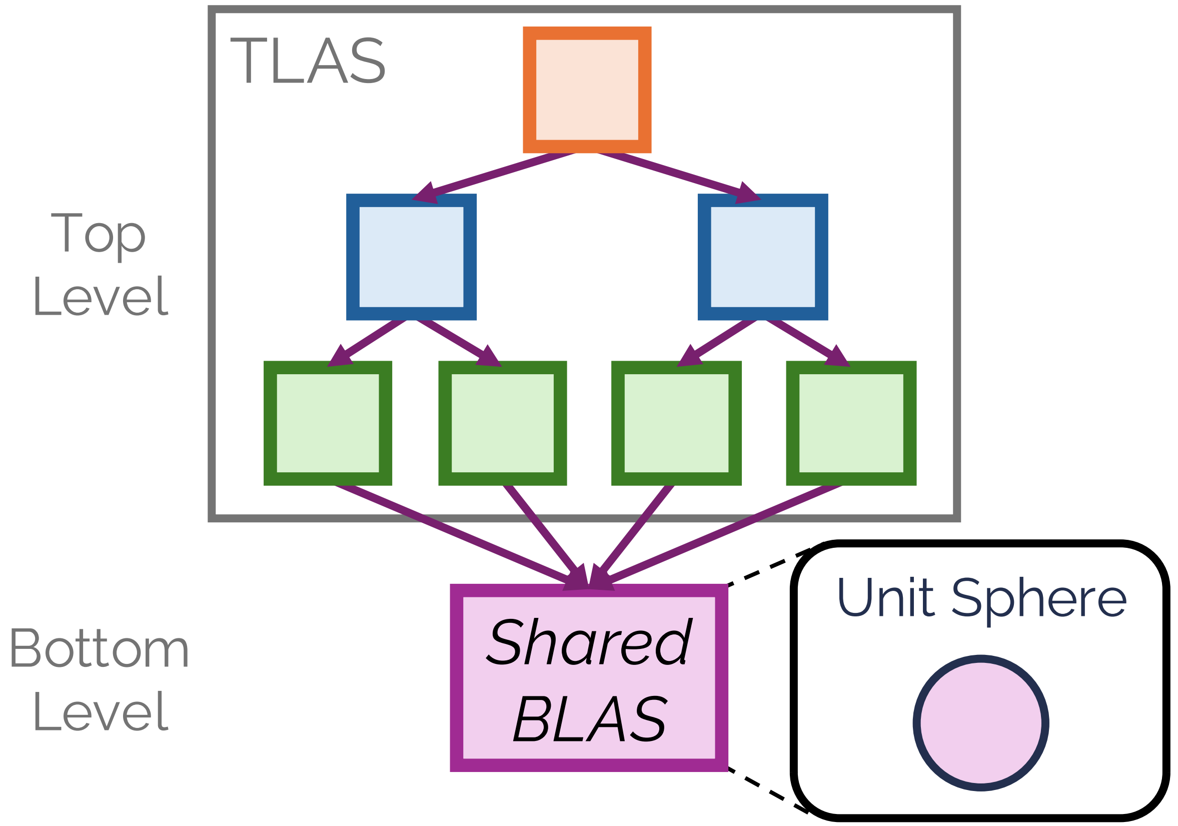


GRTX Overview

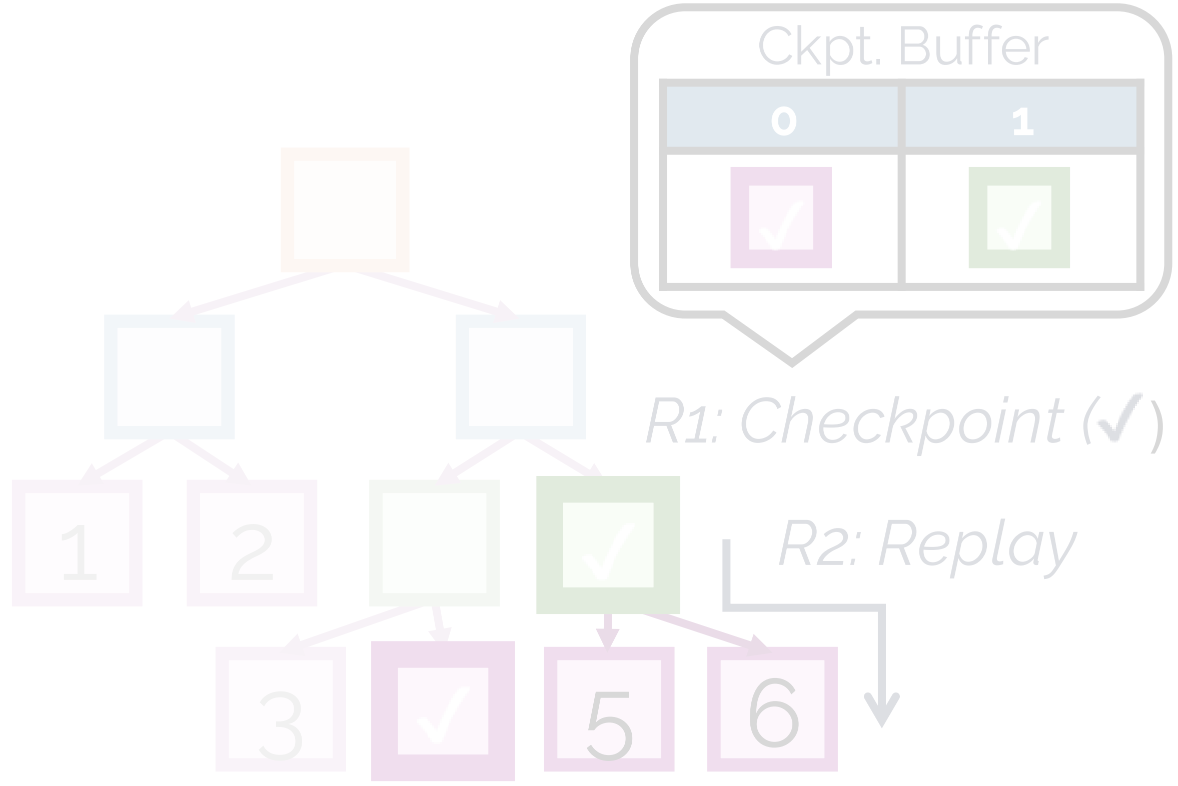
GRTX-SW

Two-level BVH with
a **single shared BLAS** for Gaussian

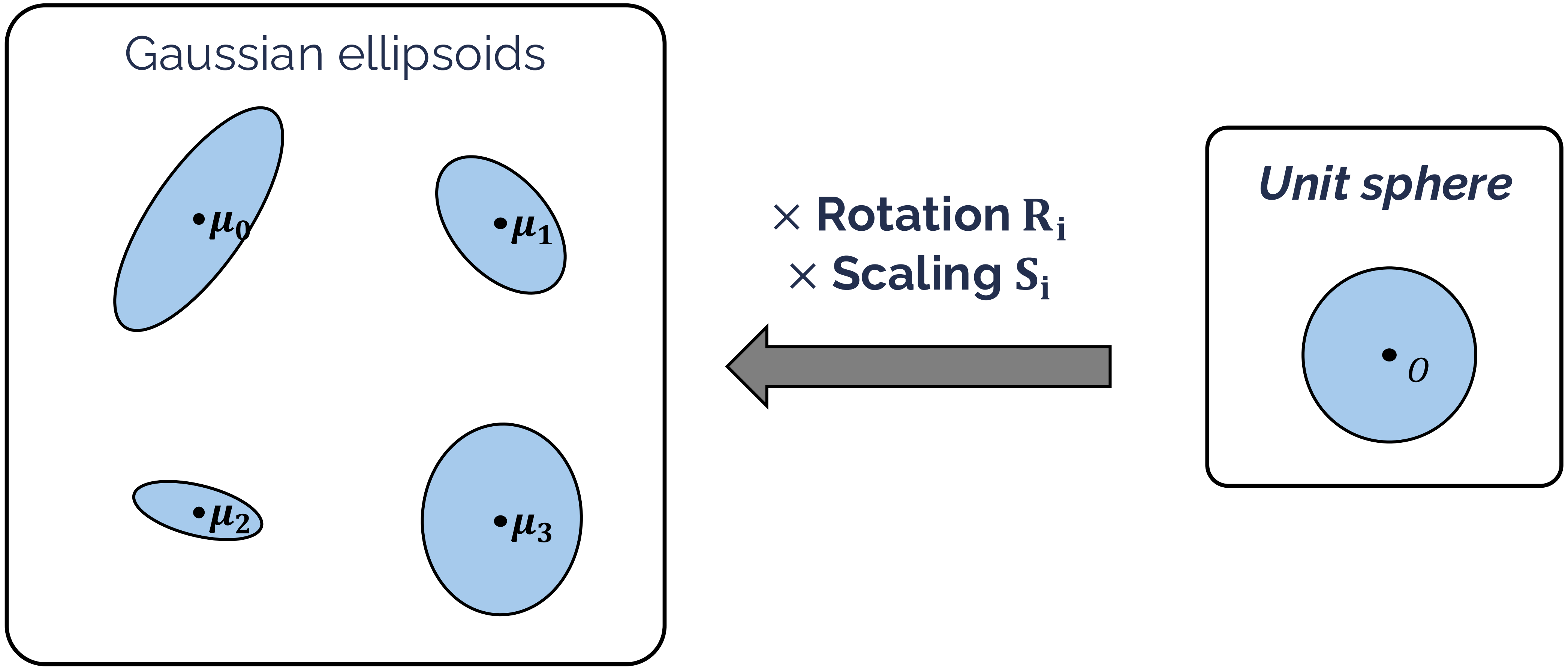


GRTX-HW

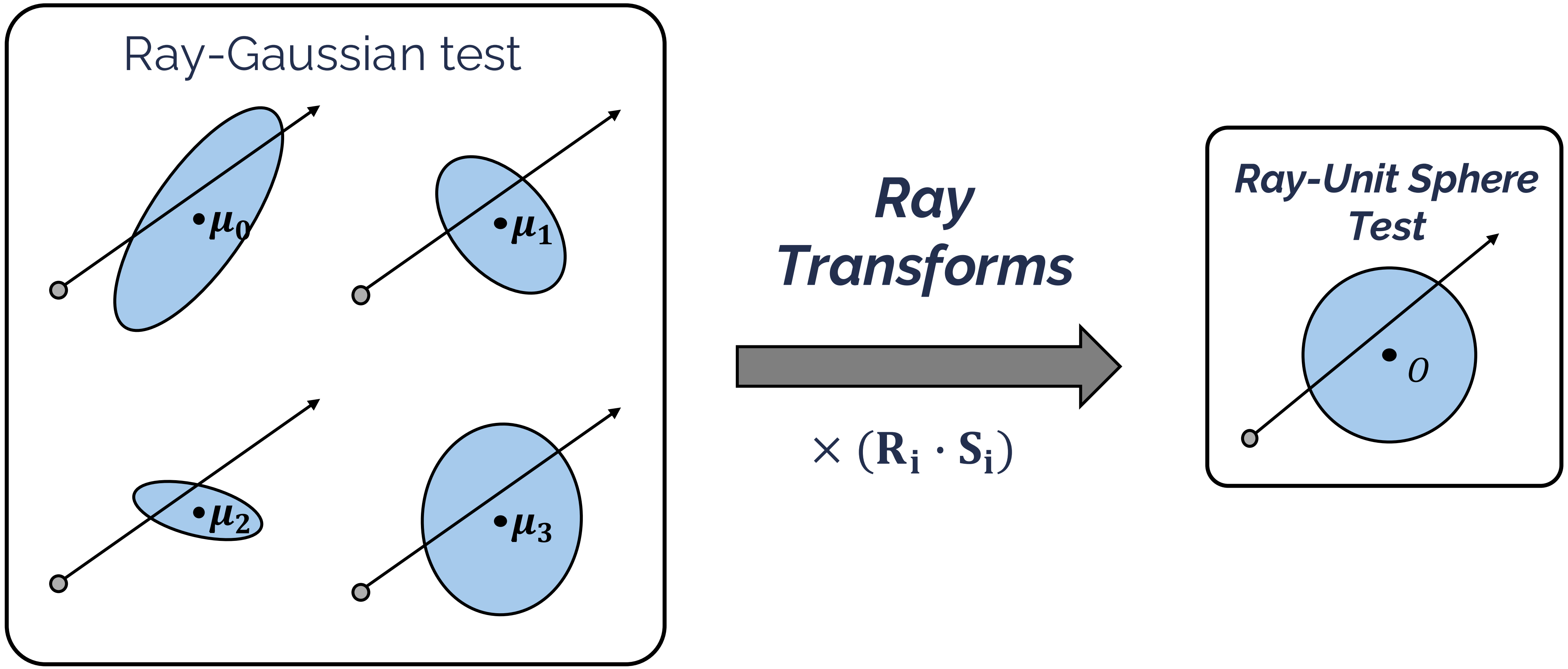
Hardware extension for
traversal checkpointing & replay



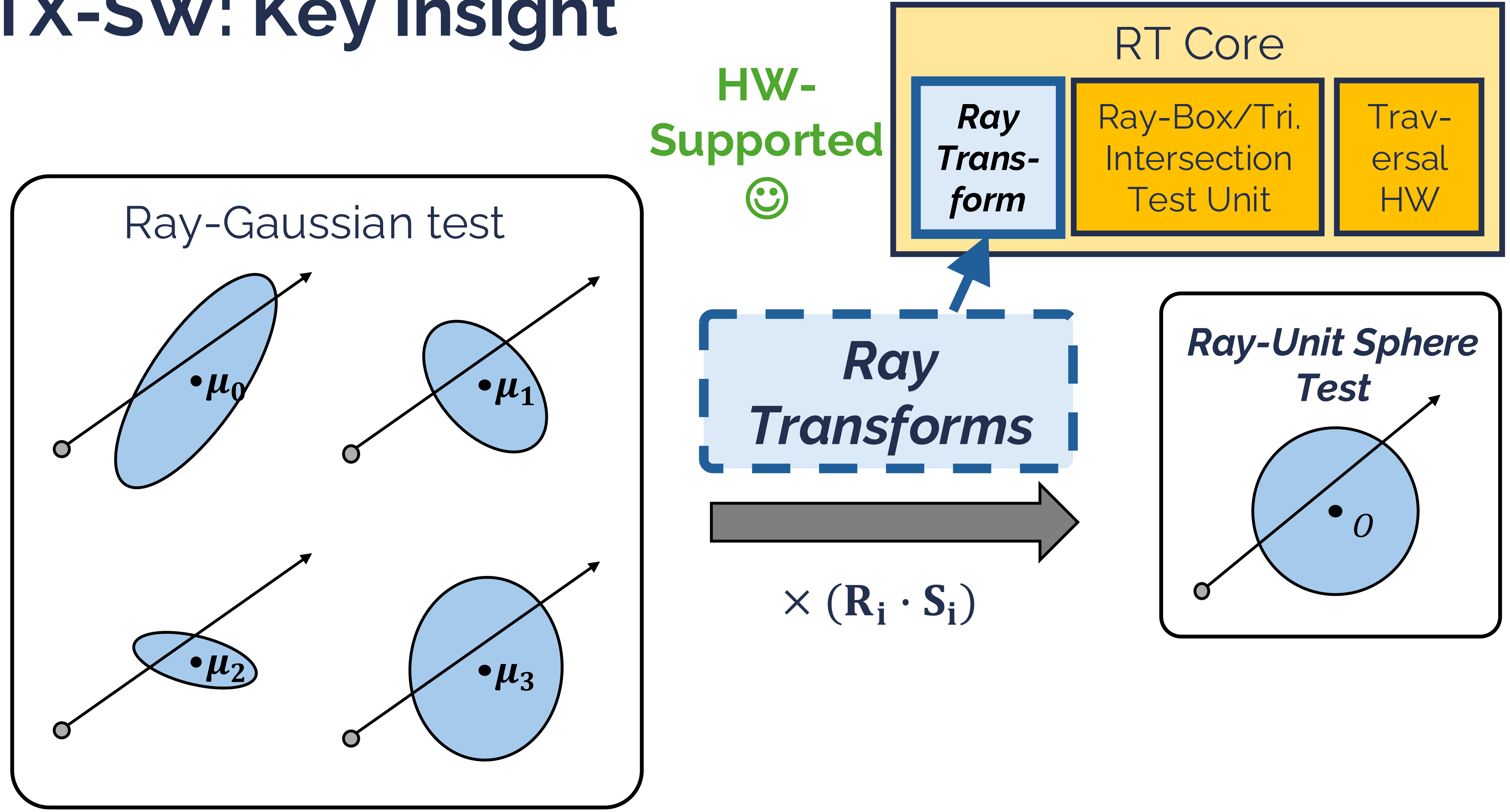
GRTX-SW: Key Insight


Gaussian ellipsoids
μ_0
μ_1
μ_2
μ_3
$\times$ Rotation $\mathbf{R_i}$
$\times$ Scaling $\mathbf{S_i}$
Unit sphere
O

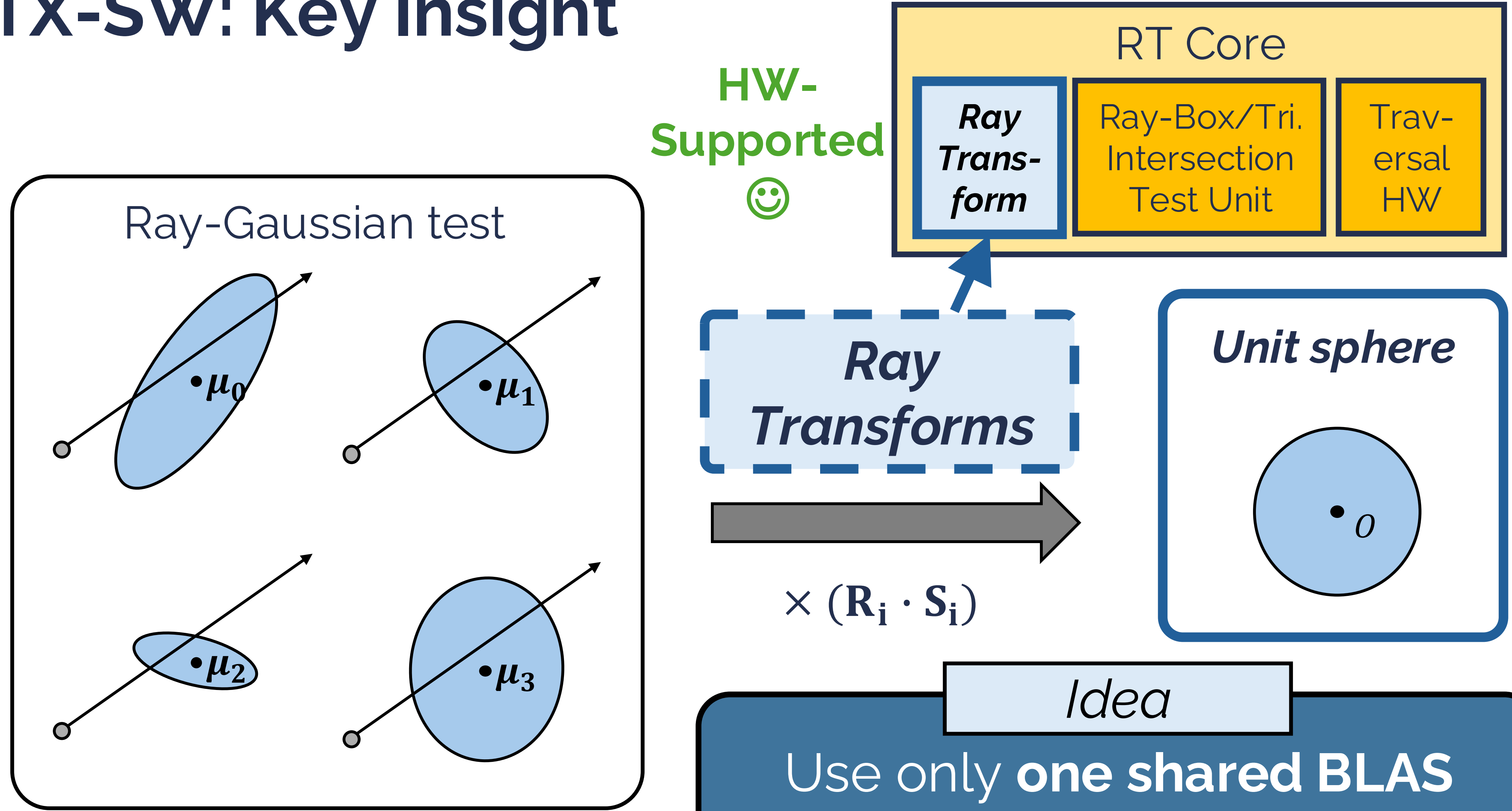
GRTX-SW: Key Insight



GRTX-SW: Key Insight



GRTX-SW: Key Insight

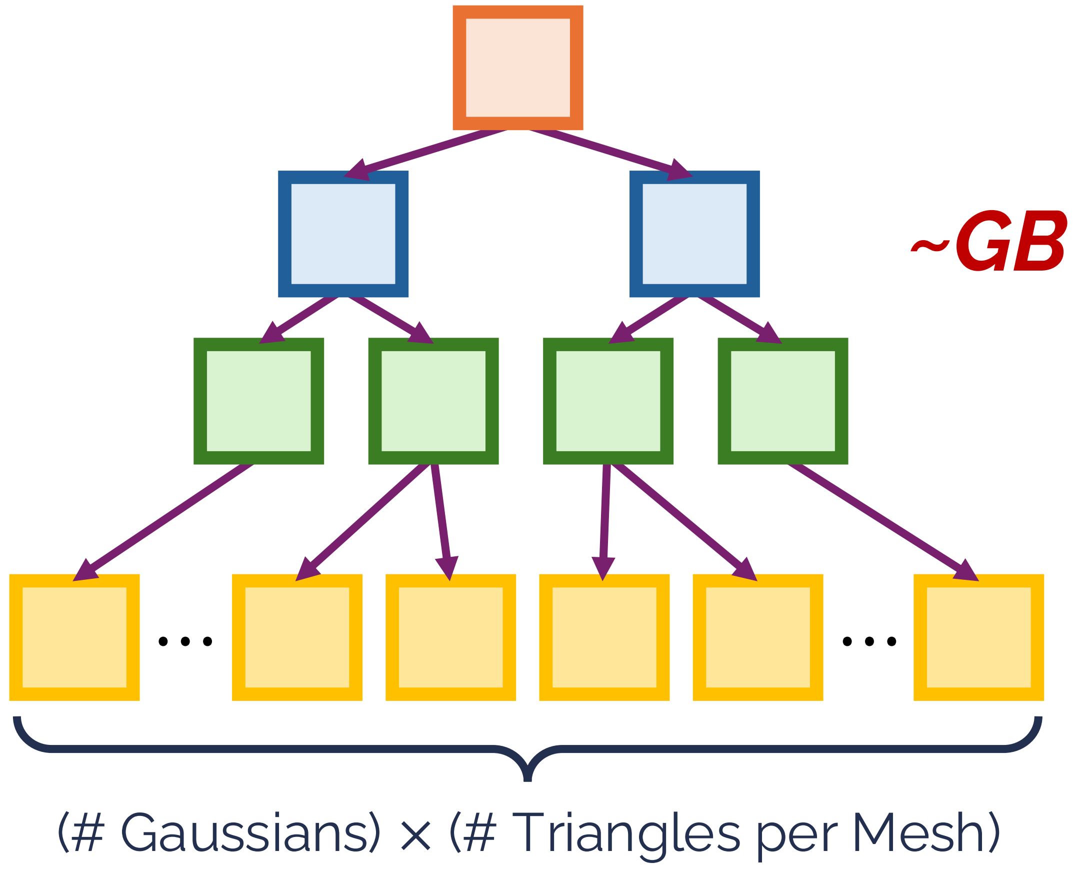


Idea

Use only **one shared BLAS** across all Gaussians

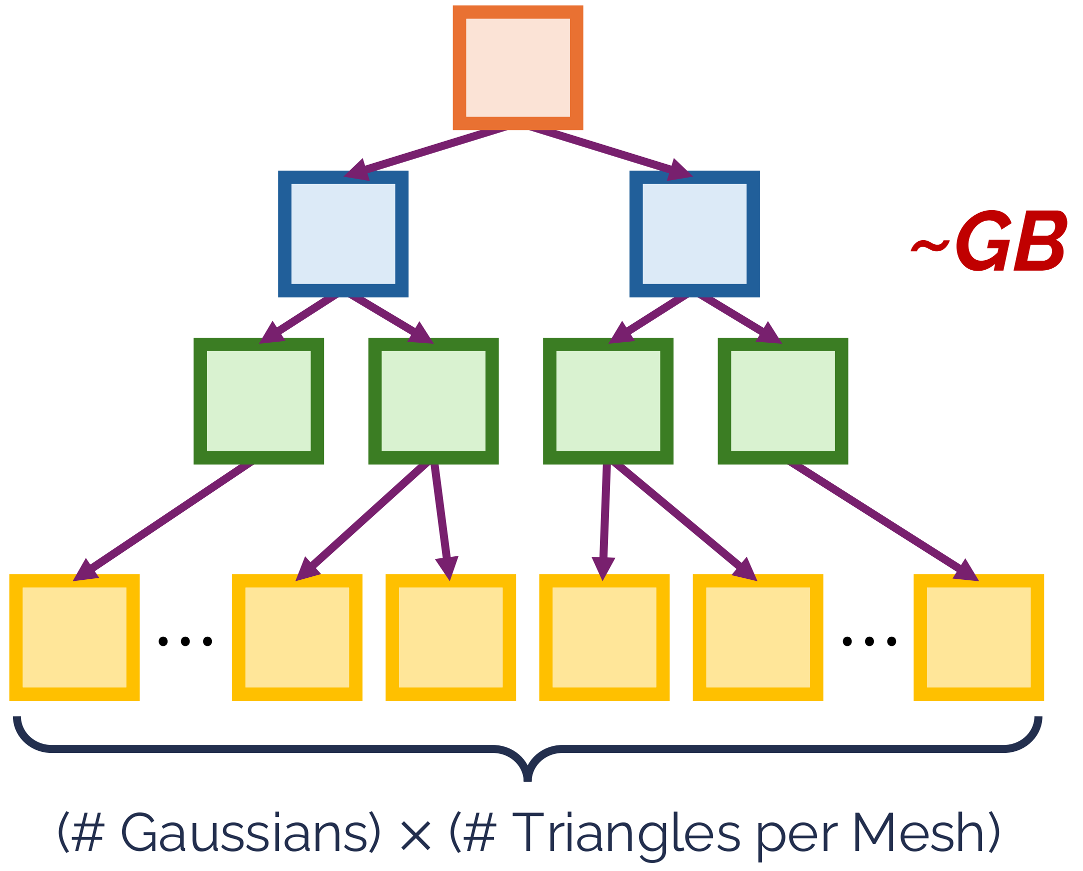
GRTX-SW: Two-Level BVH with a Shared BLAS

Prior Approaches

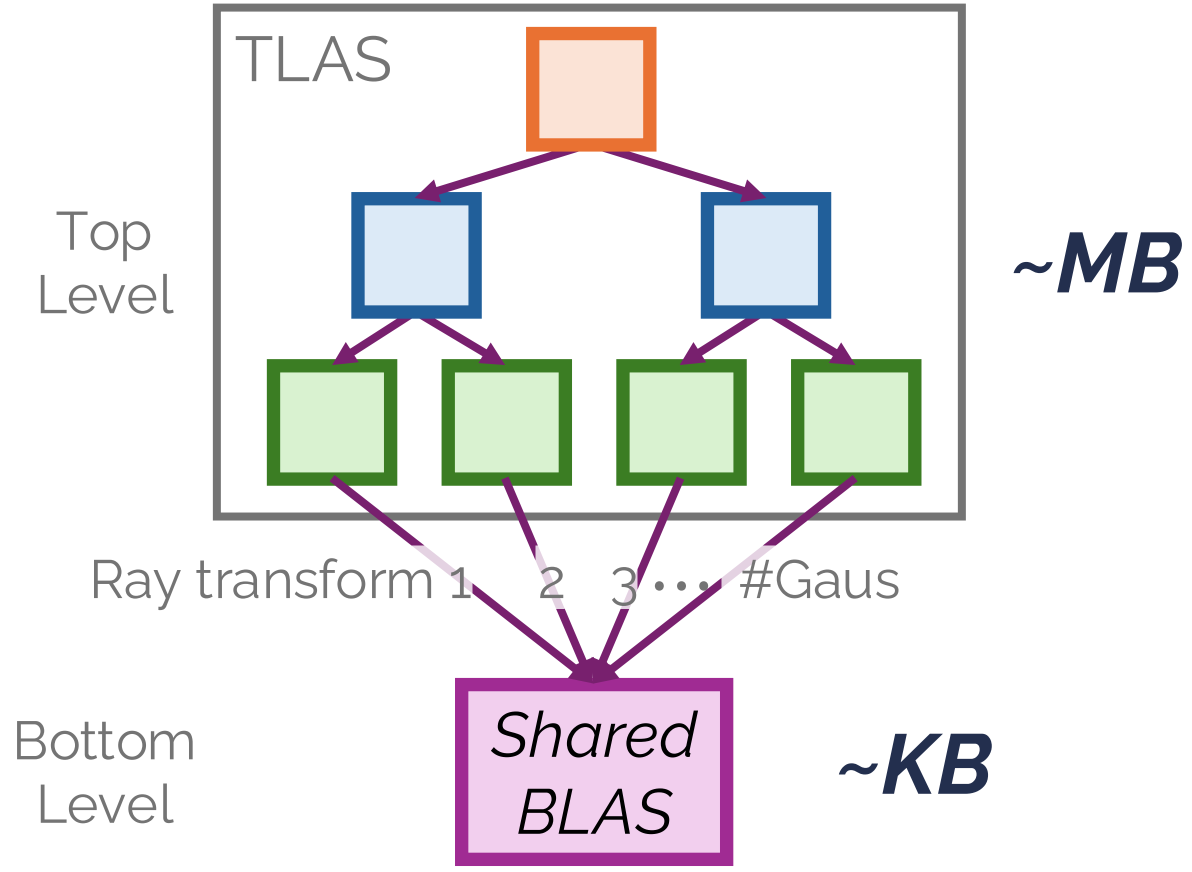


GRTX-SW: Two-Level BVH with a Shared BLAS

Prior Approaches

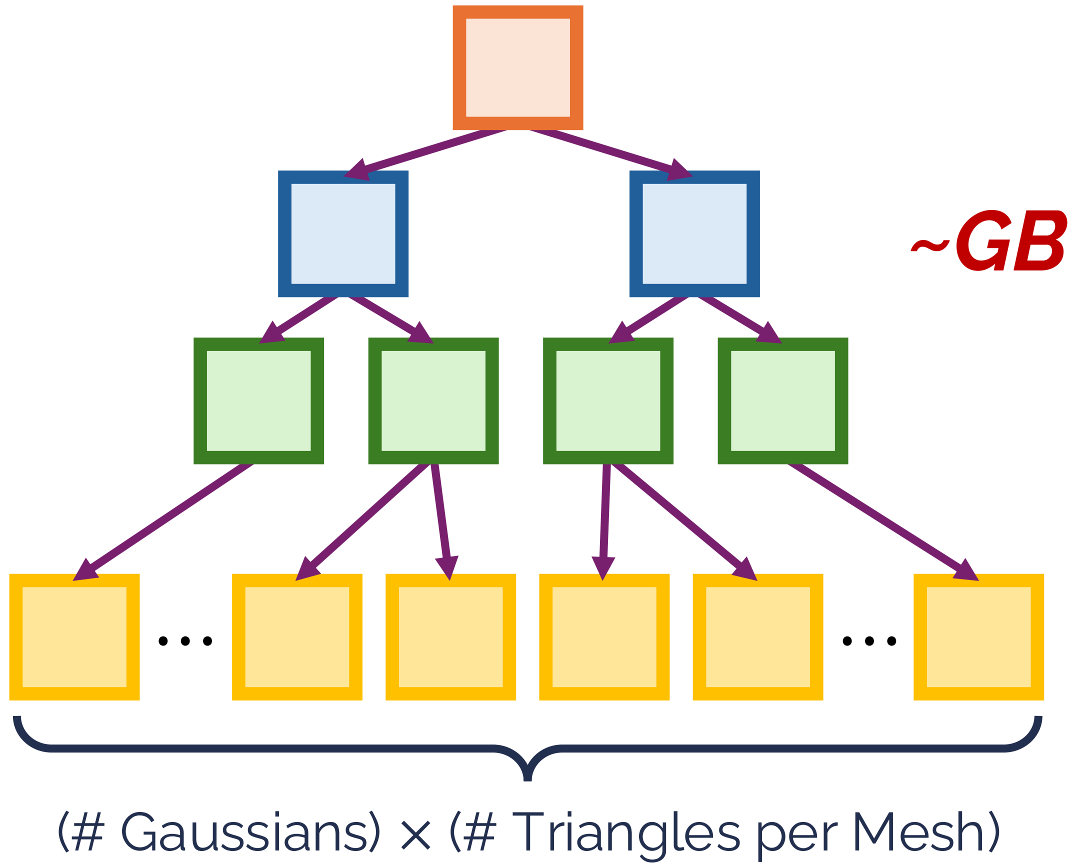


GRTX-SW

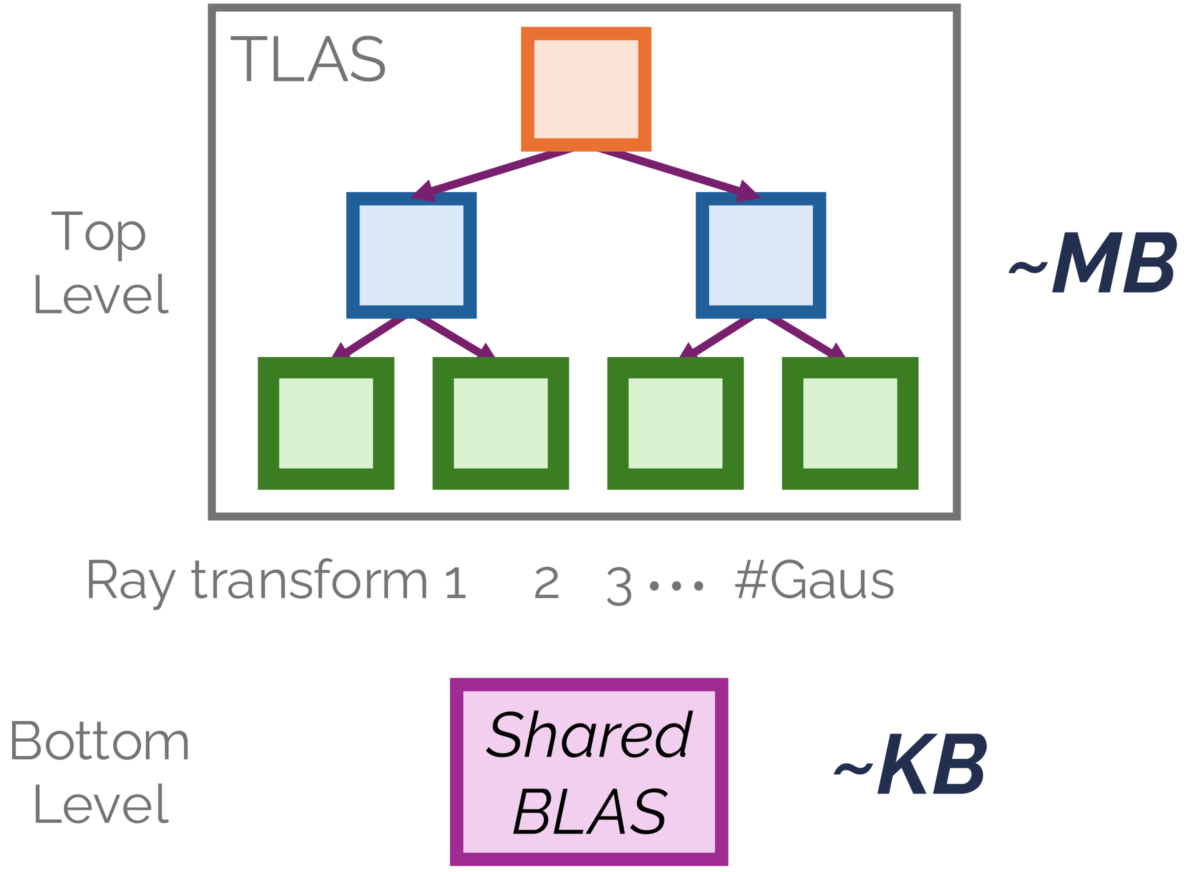


GRTX-SW: Two-Level BVH with a Shared BLAS

Prior Approaches

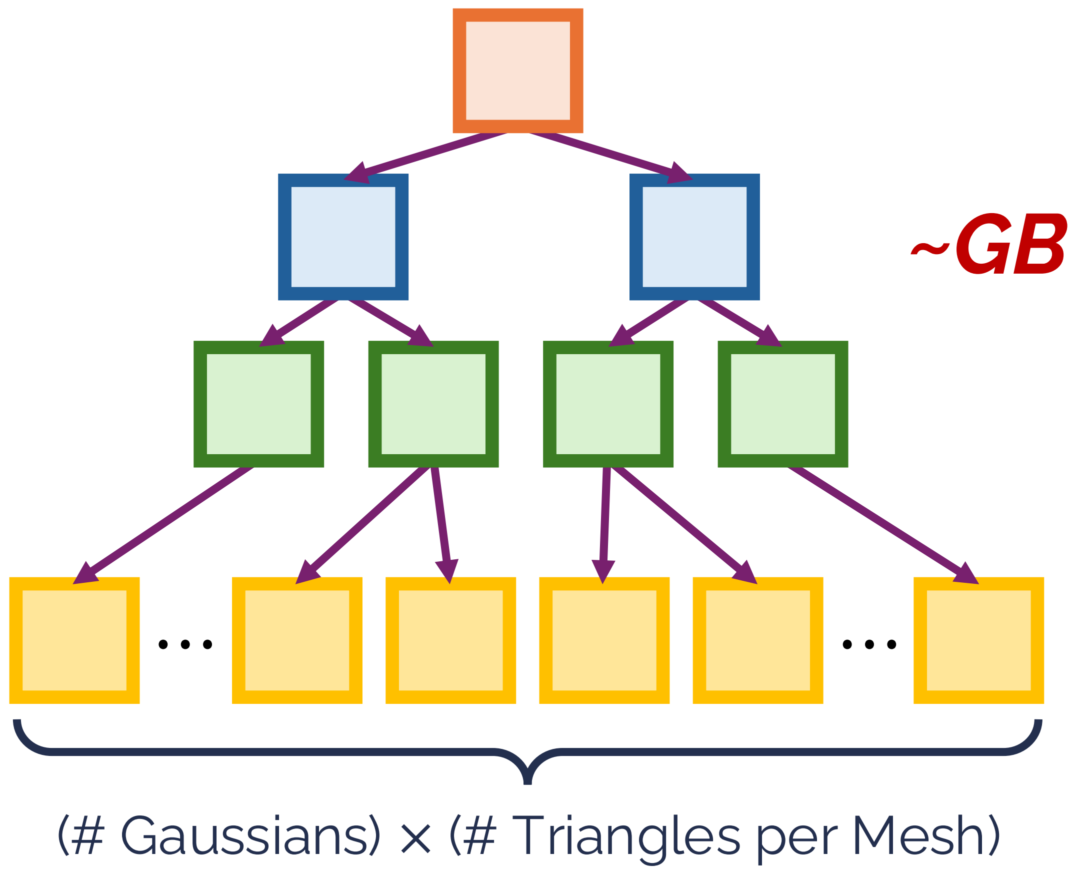


GRTX-SW

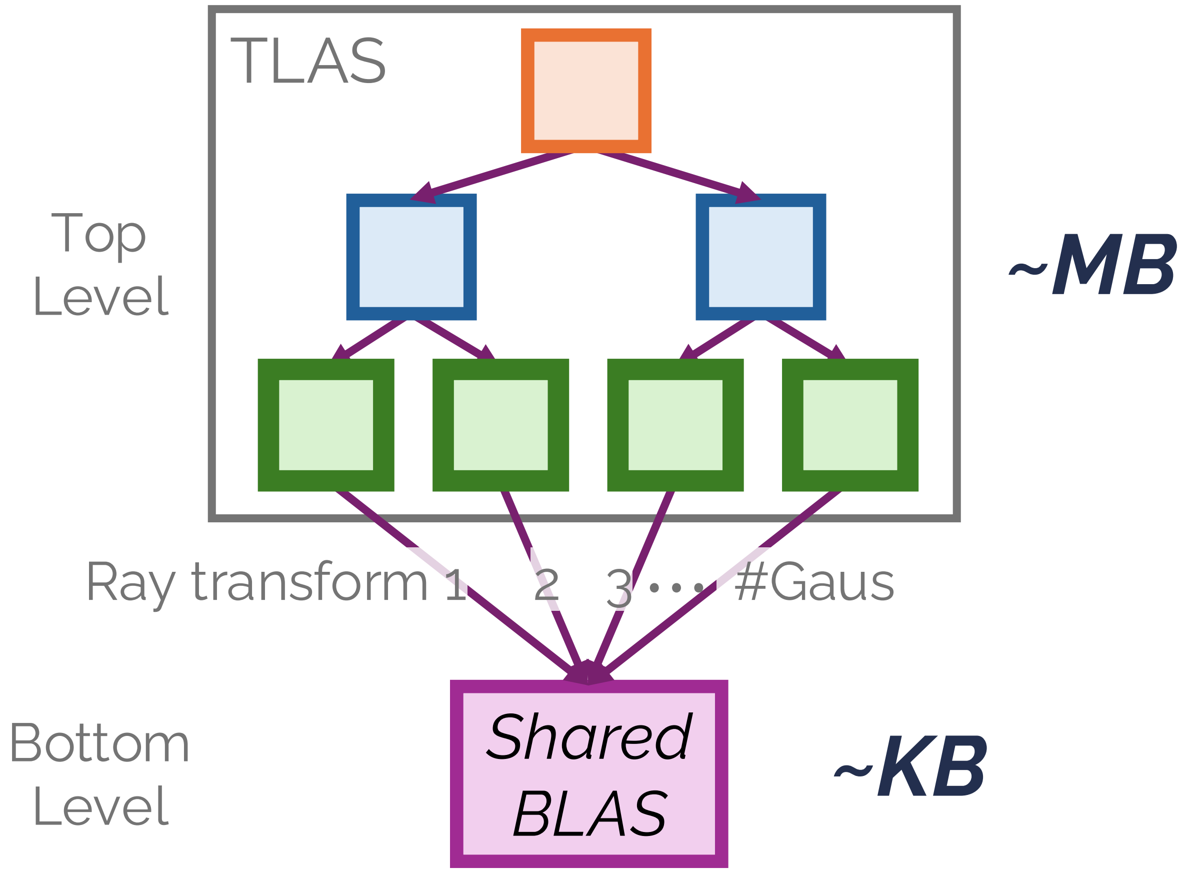


GRTX-SW: Two-Level BVH with a Shared BLAS

Prior Approaches



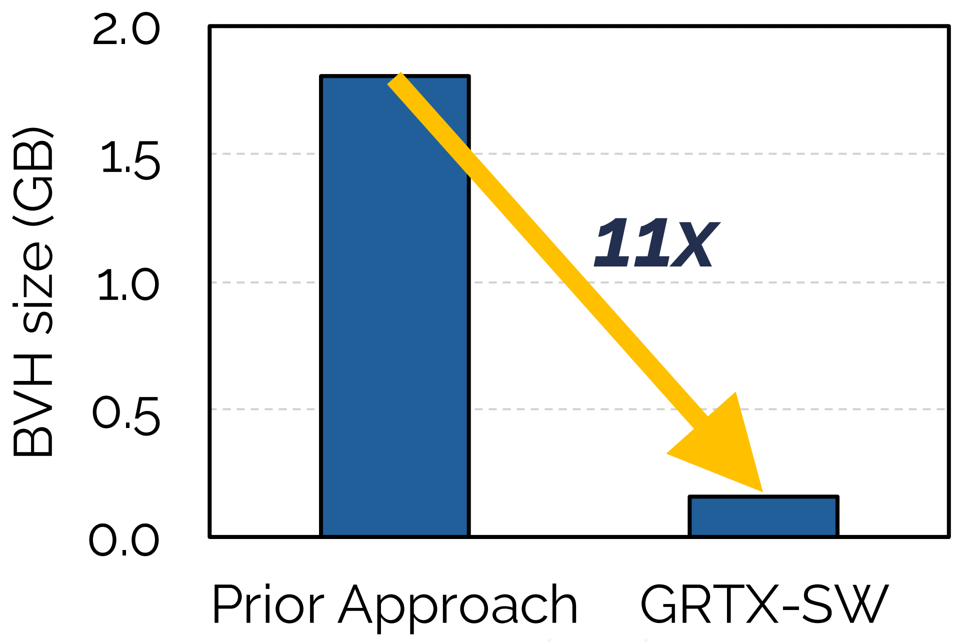
GRTX-SW

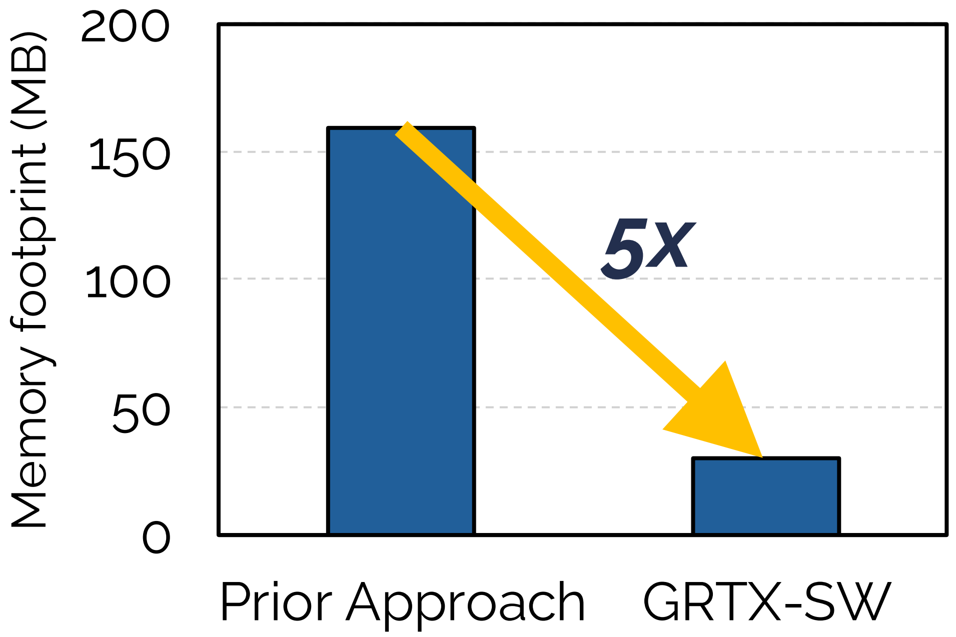


GRTX-SW: Two-Level BVH with a Shared BLAS

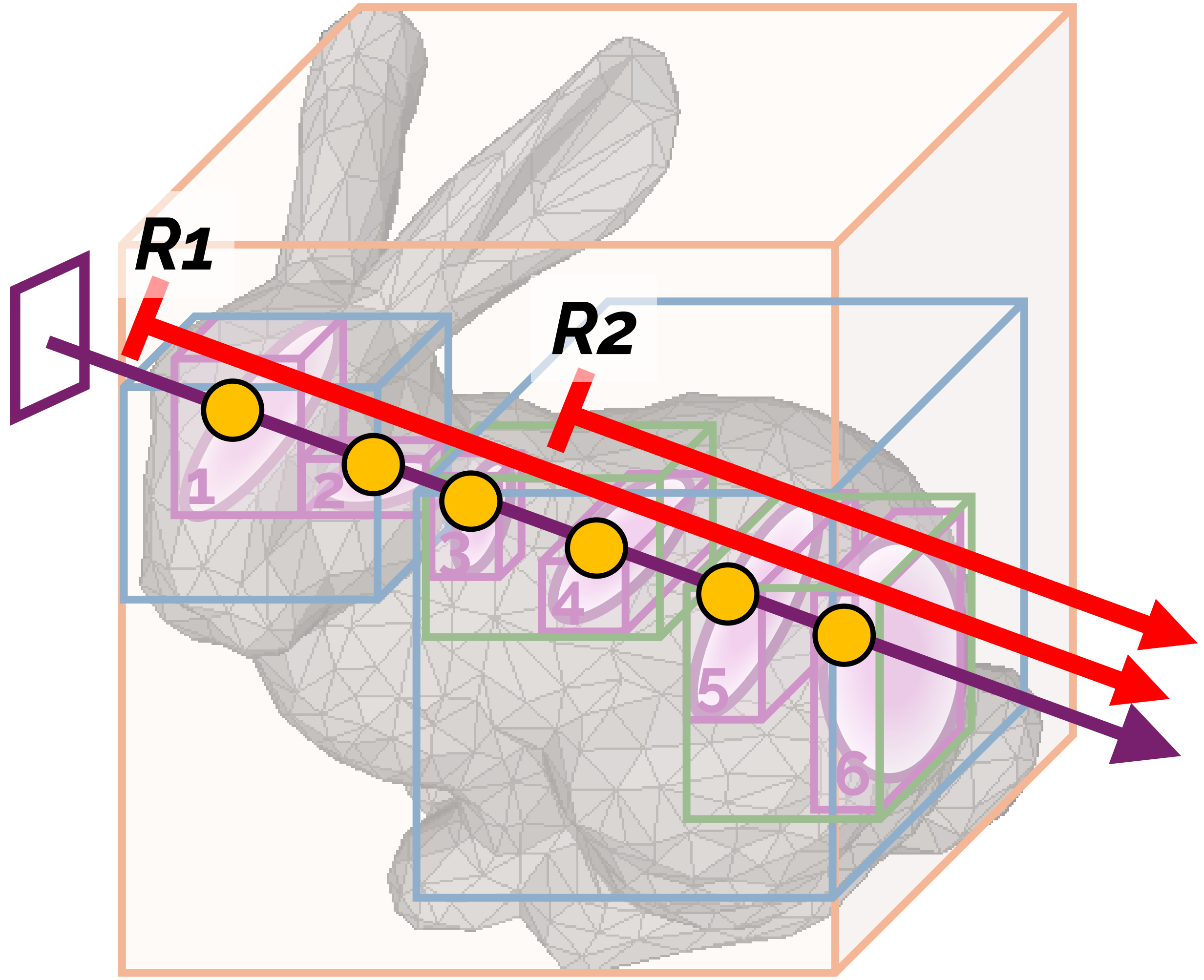
Advantage

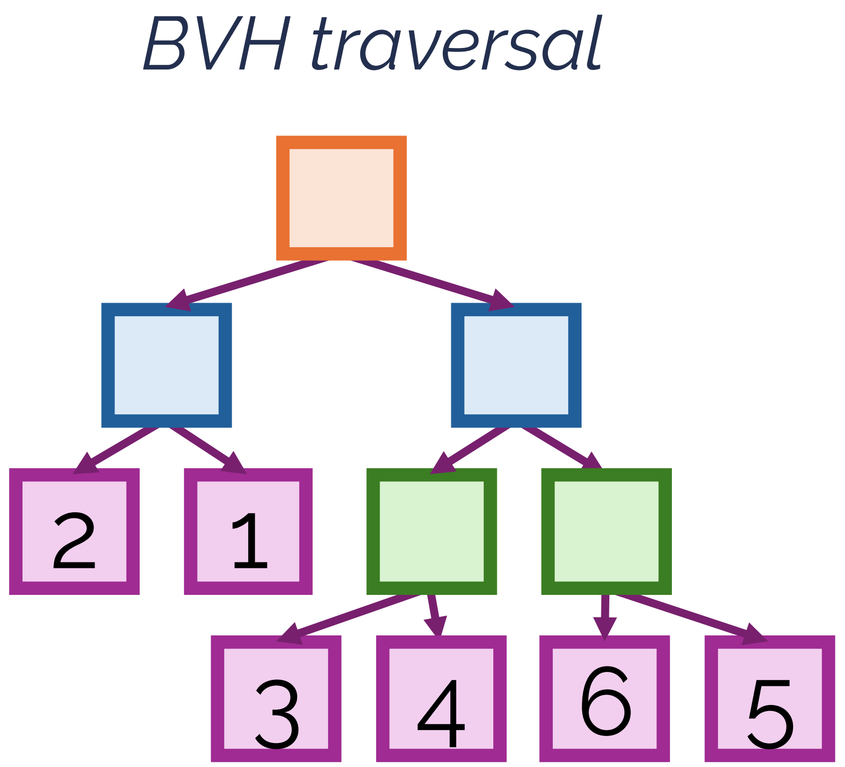
Reduce BVH size & BVH memory footprint



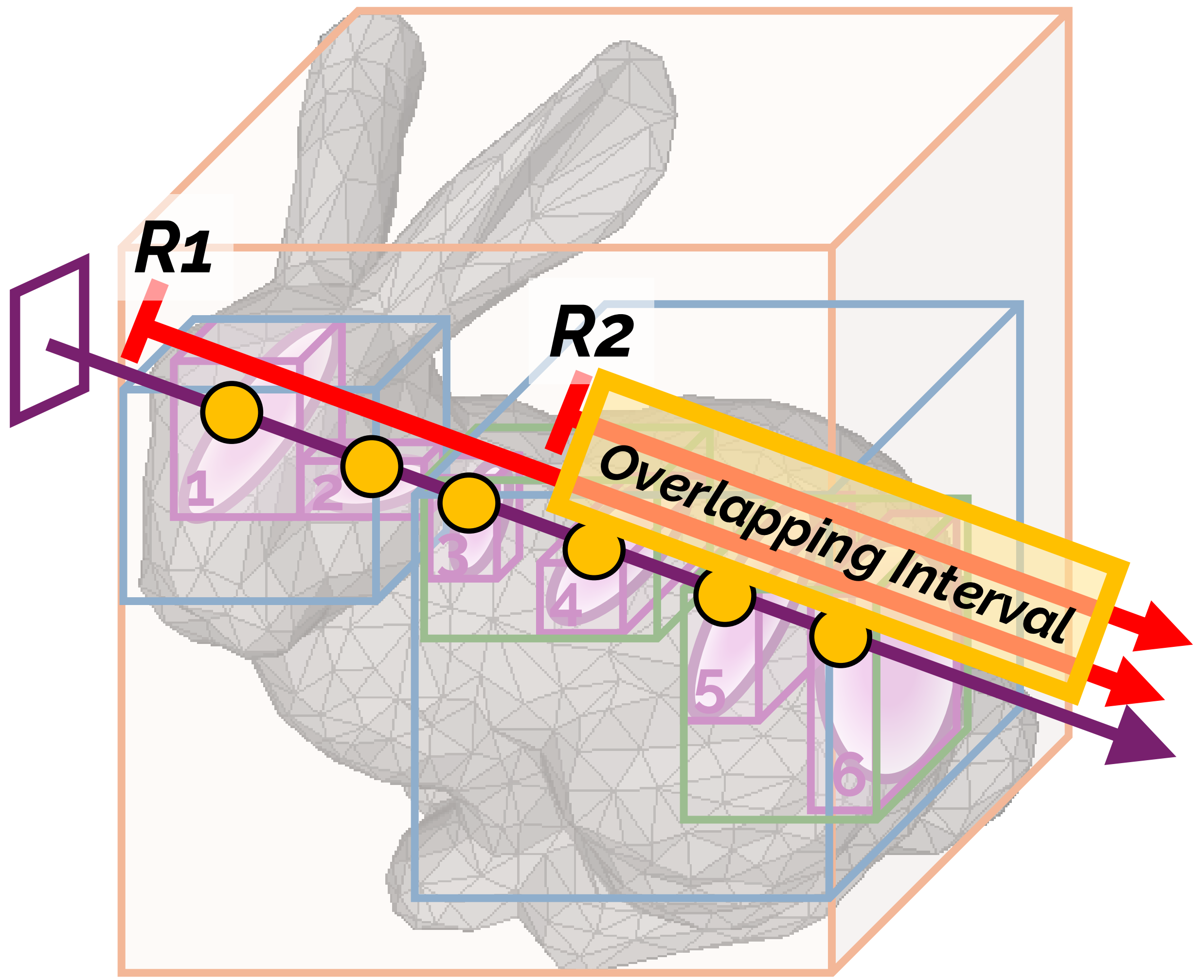


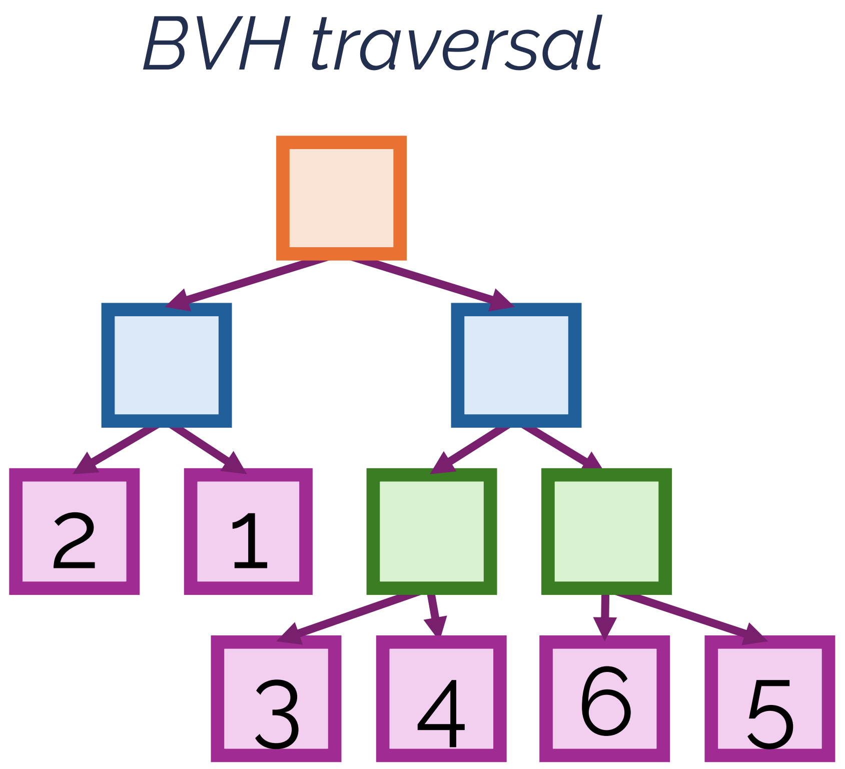
GRTX-HW: Traversal Checkpointing & Replay



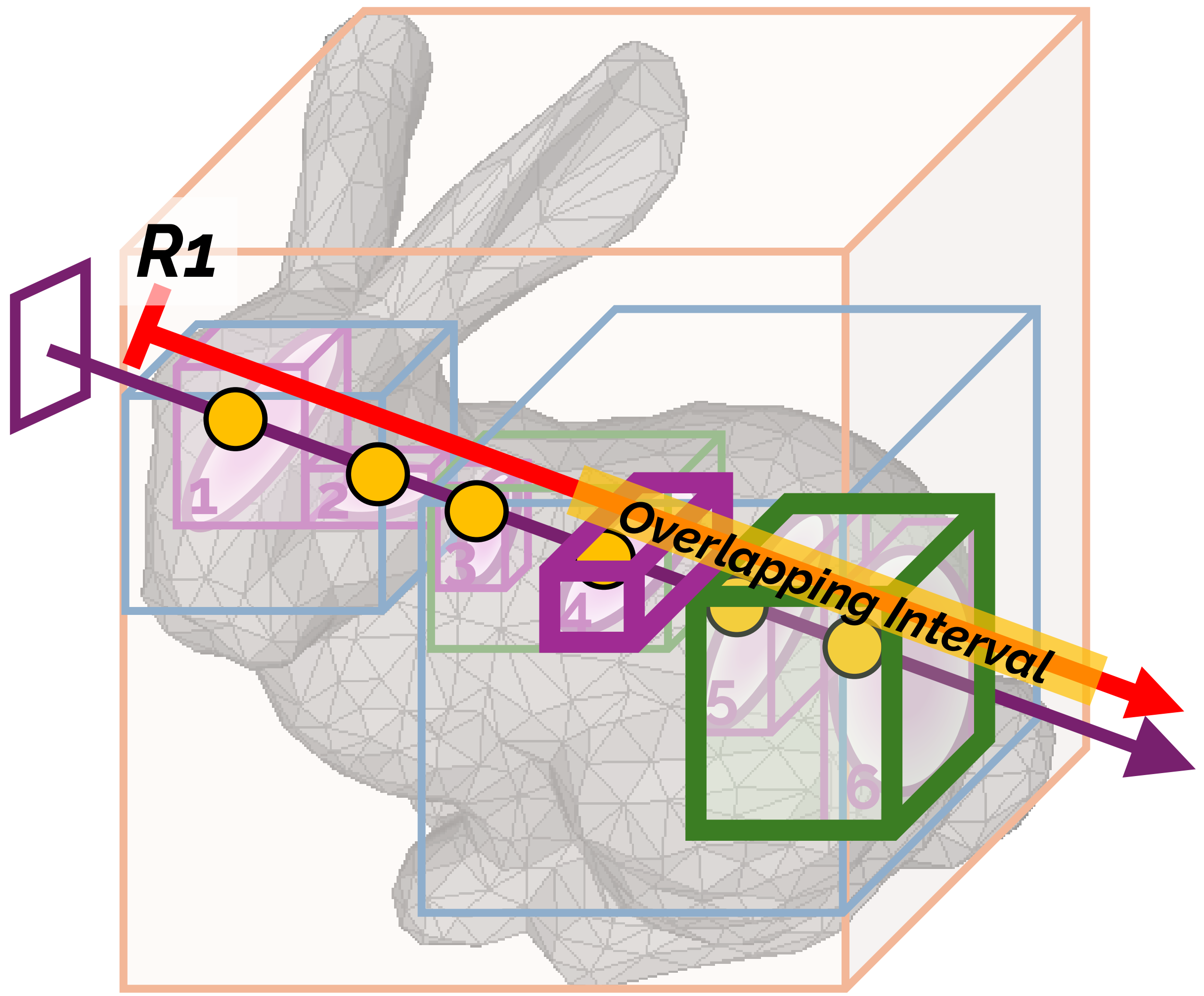


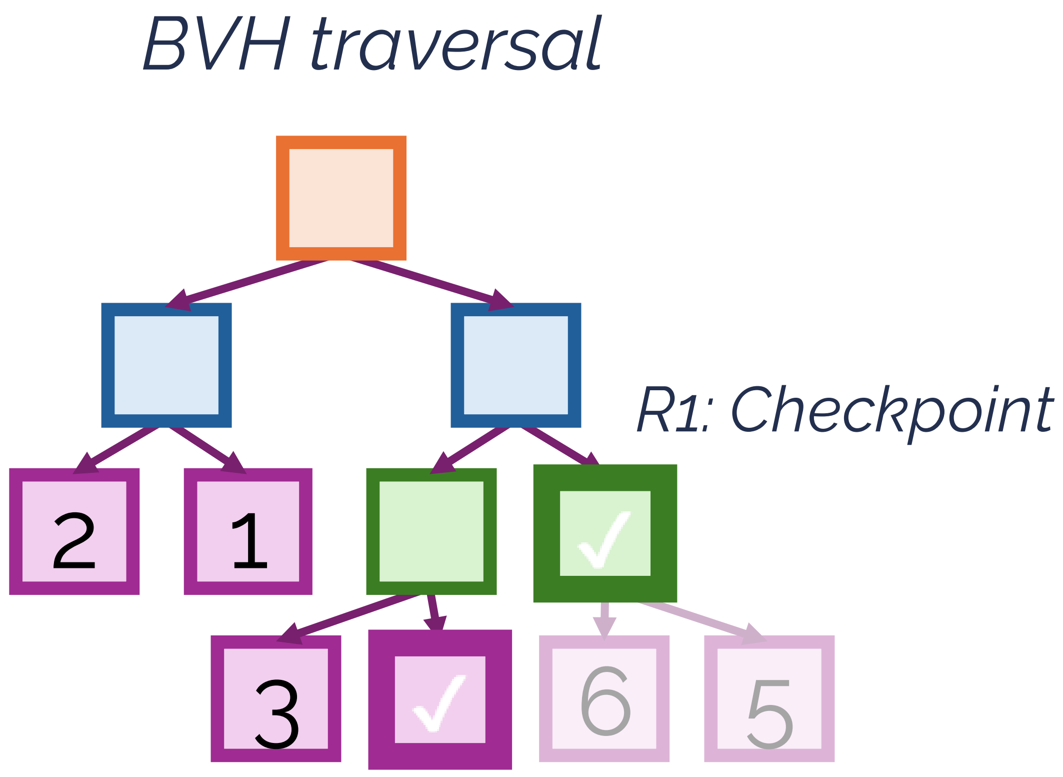
GRTX-HW: Traversal Checkpointing & Replay



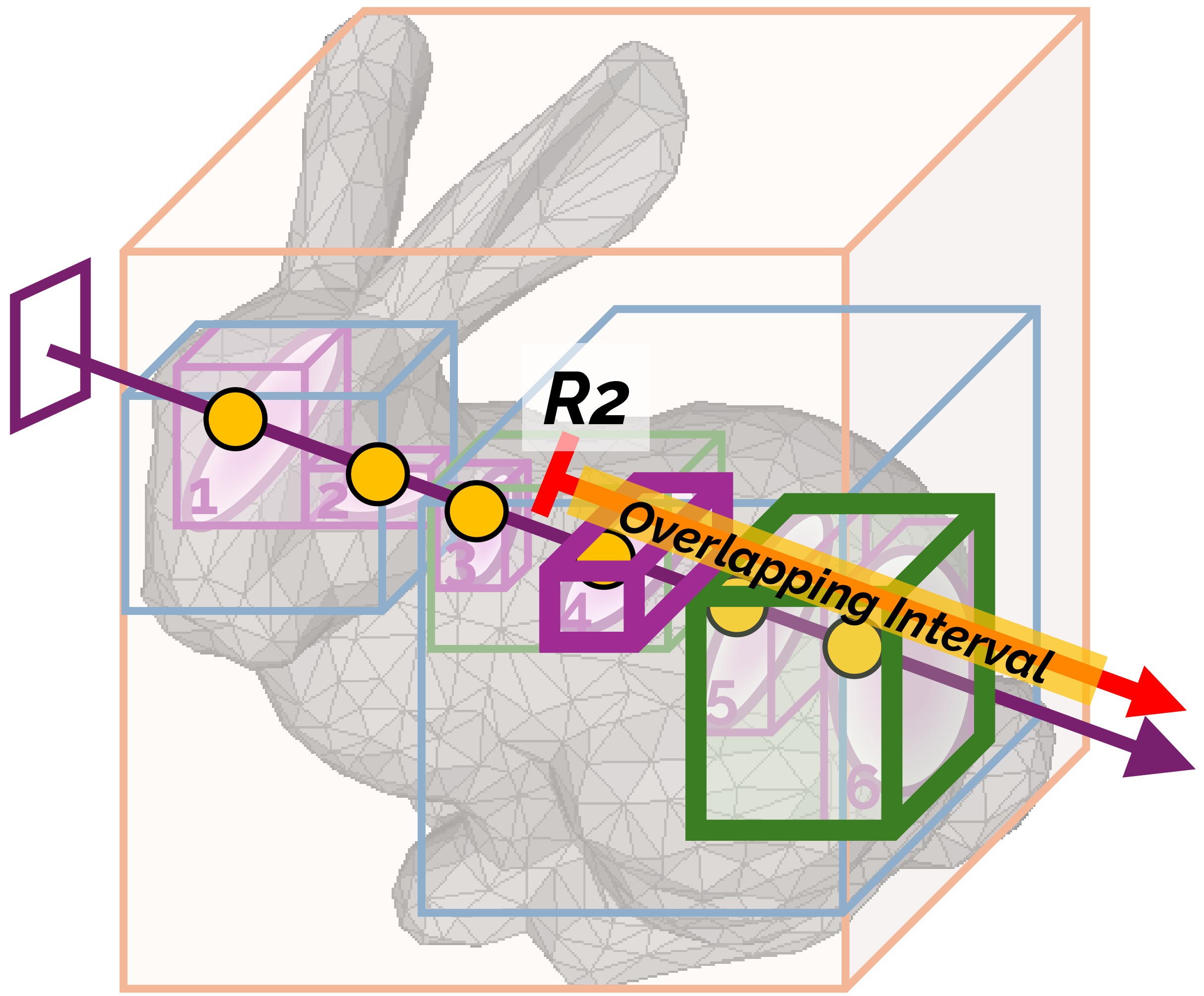


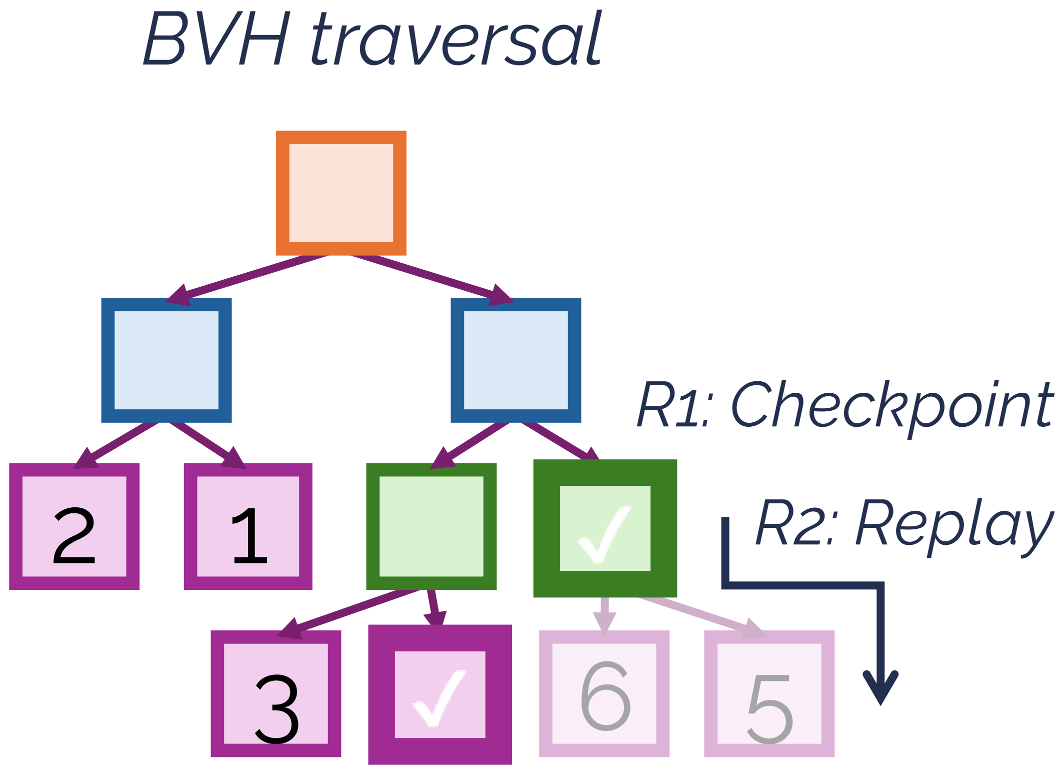
GRTX-HW: Traversal Checkpointing & Replay





GRTX-HW: Traversal Checkpointing & Replay

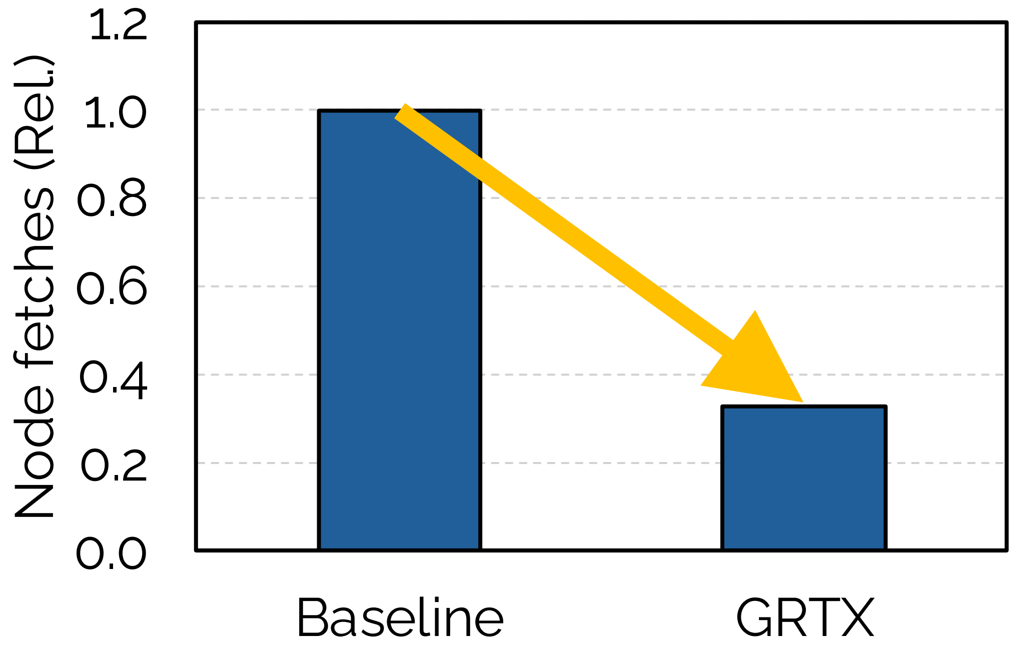


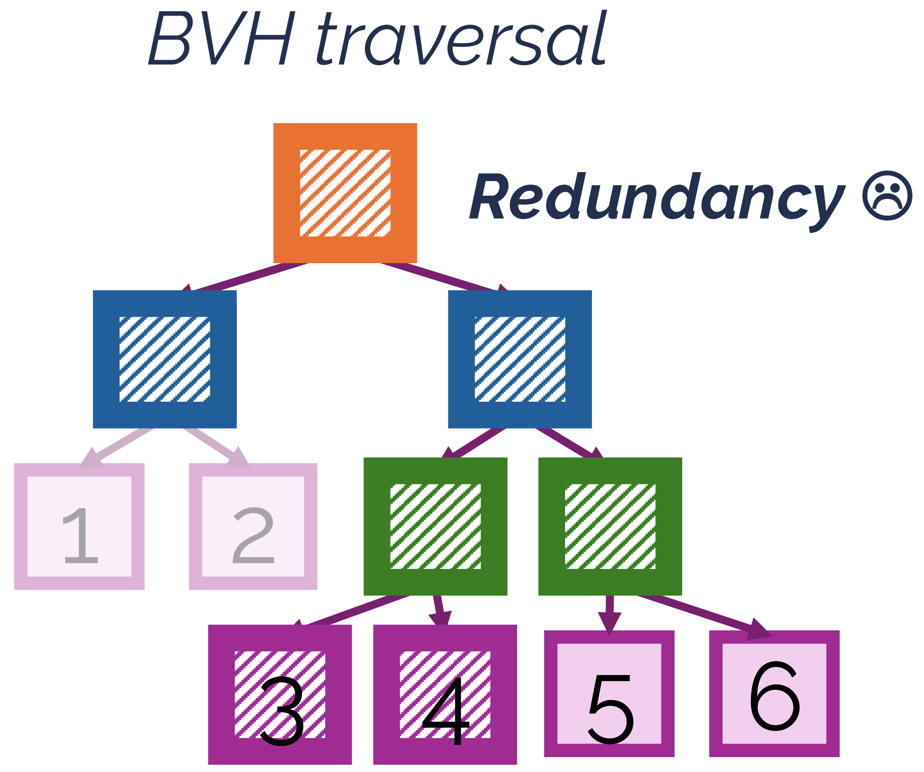


GRTX-HW: Traversal Checkpointing & Replay

Advantage

Eliminate redundant node visits & tests across rounds

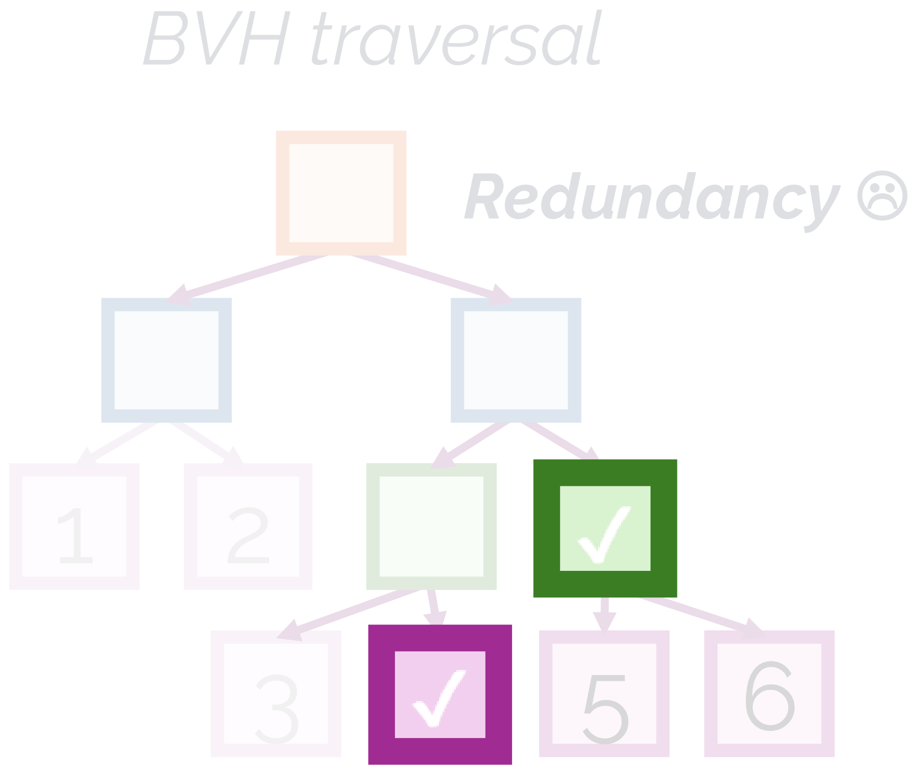




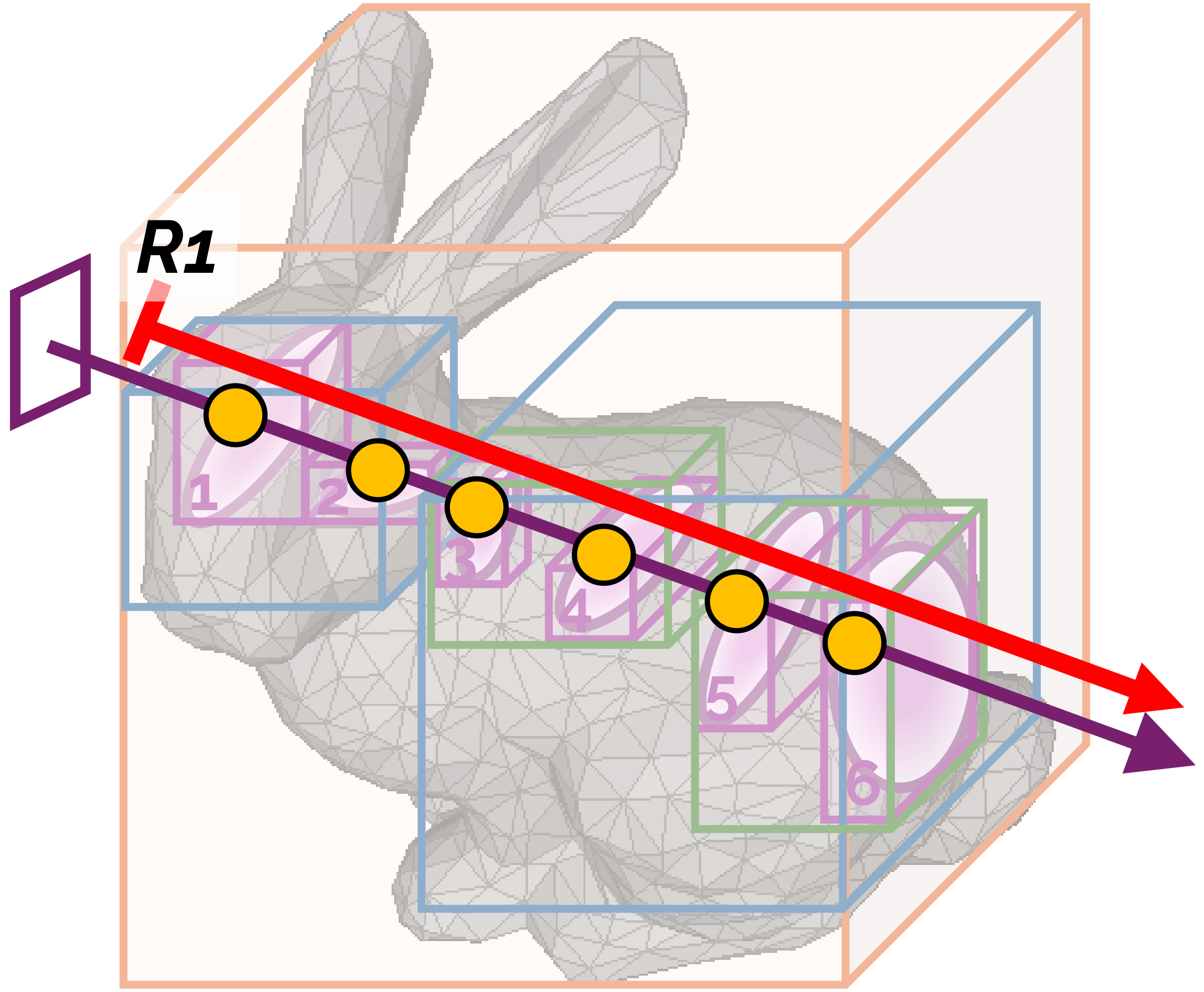
GRTX-HW: Traversal Checkpointing & Replay

Challange

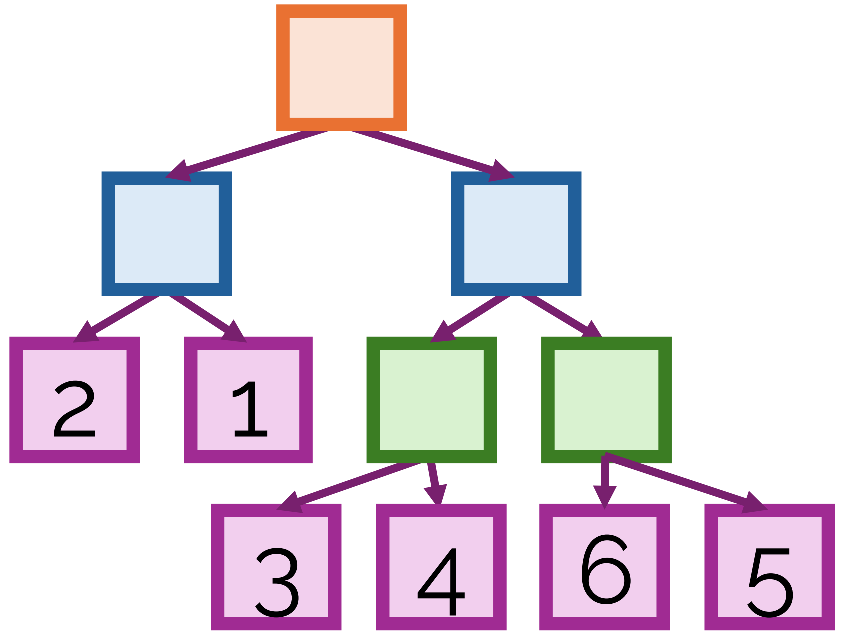
*Q: How can we **pinpoint** nodes that should be **checkpointed?***



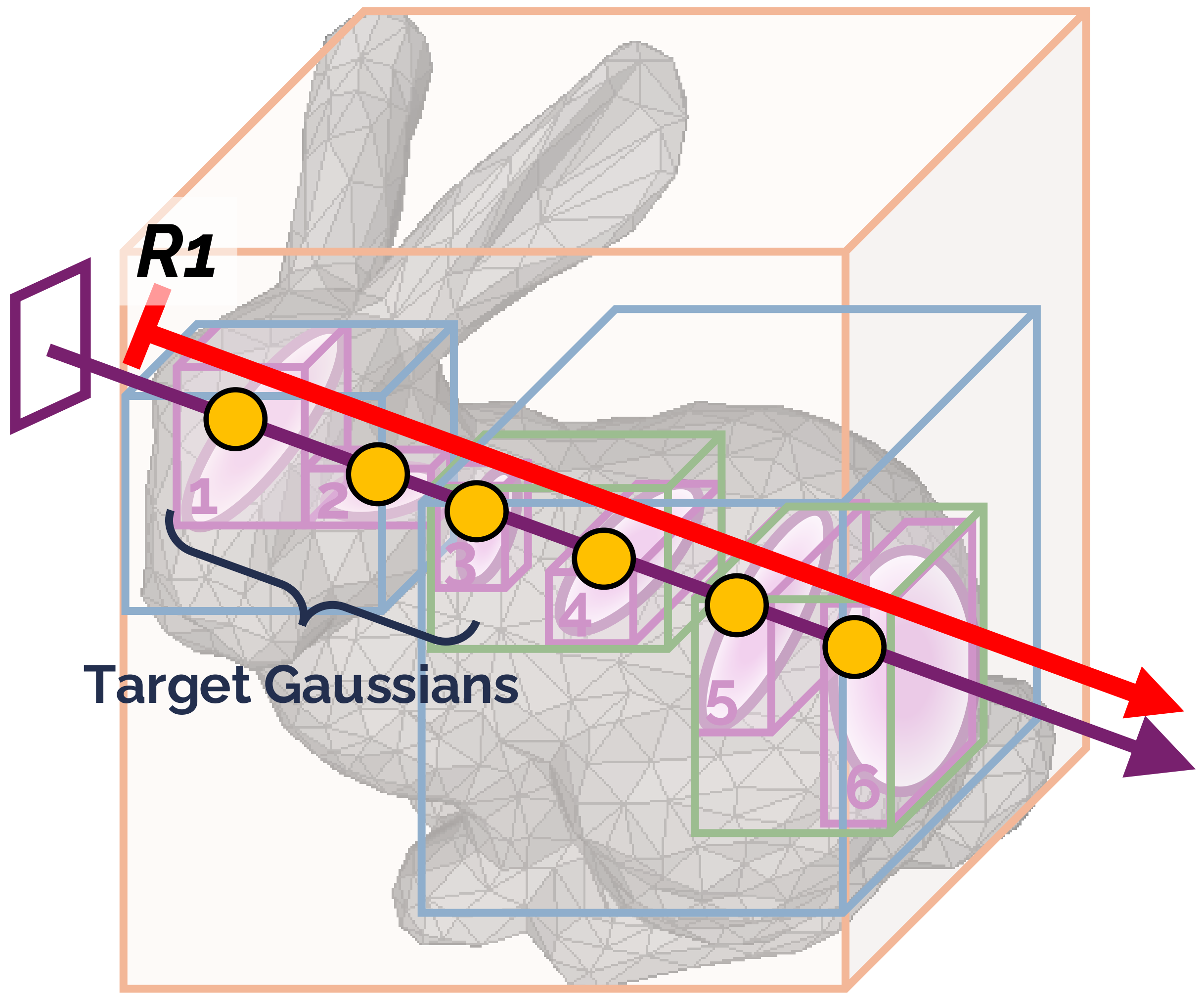
GRTX-HW: Traversal Checkpointing & Replay



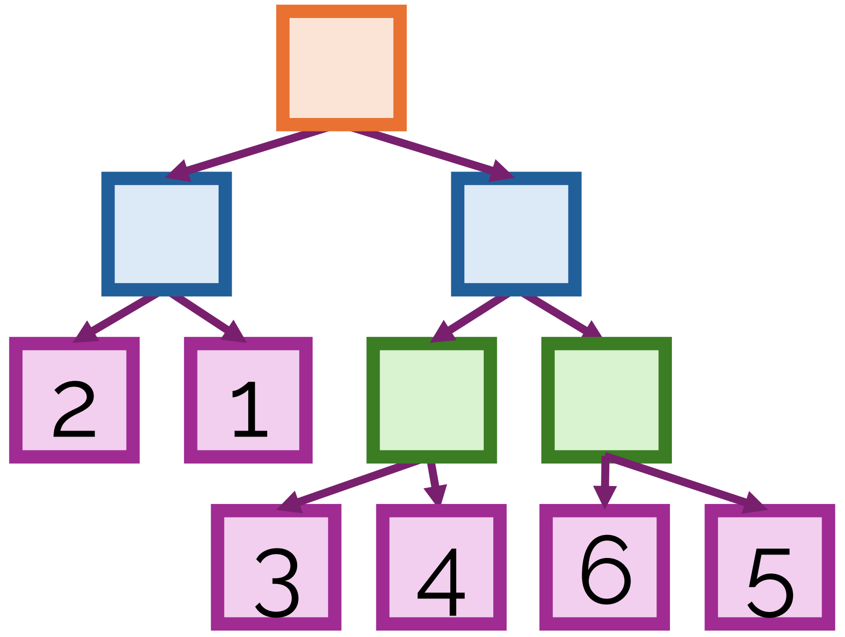
Round 1



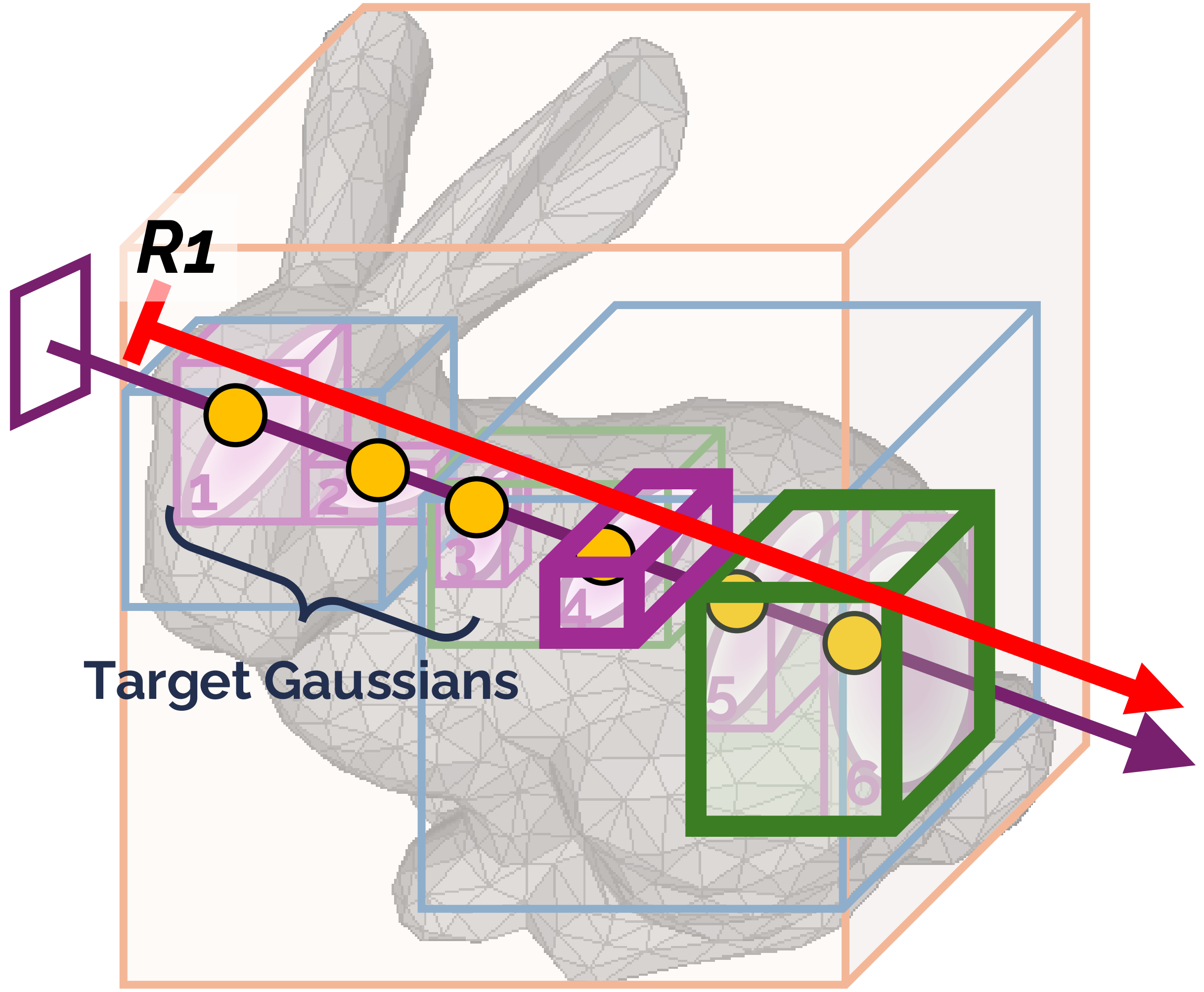
GRTX-HW: Traversal Checkpointing & Replay



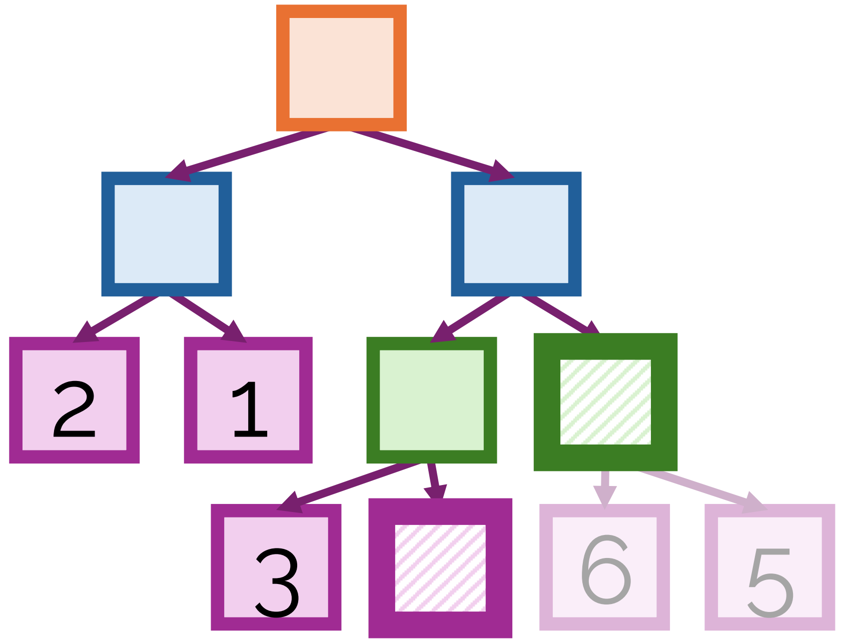
Round 1



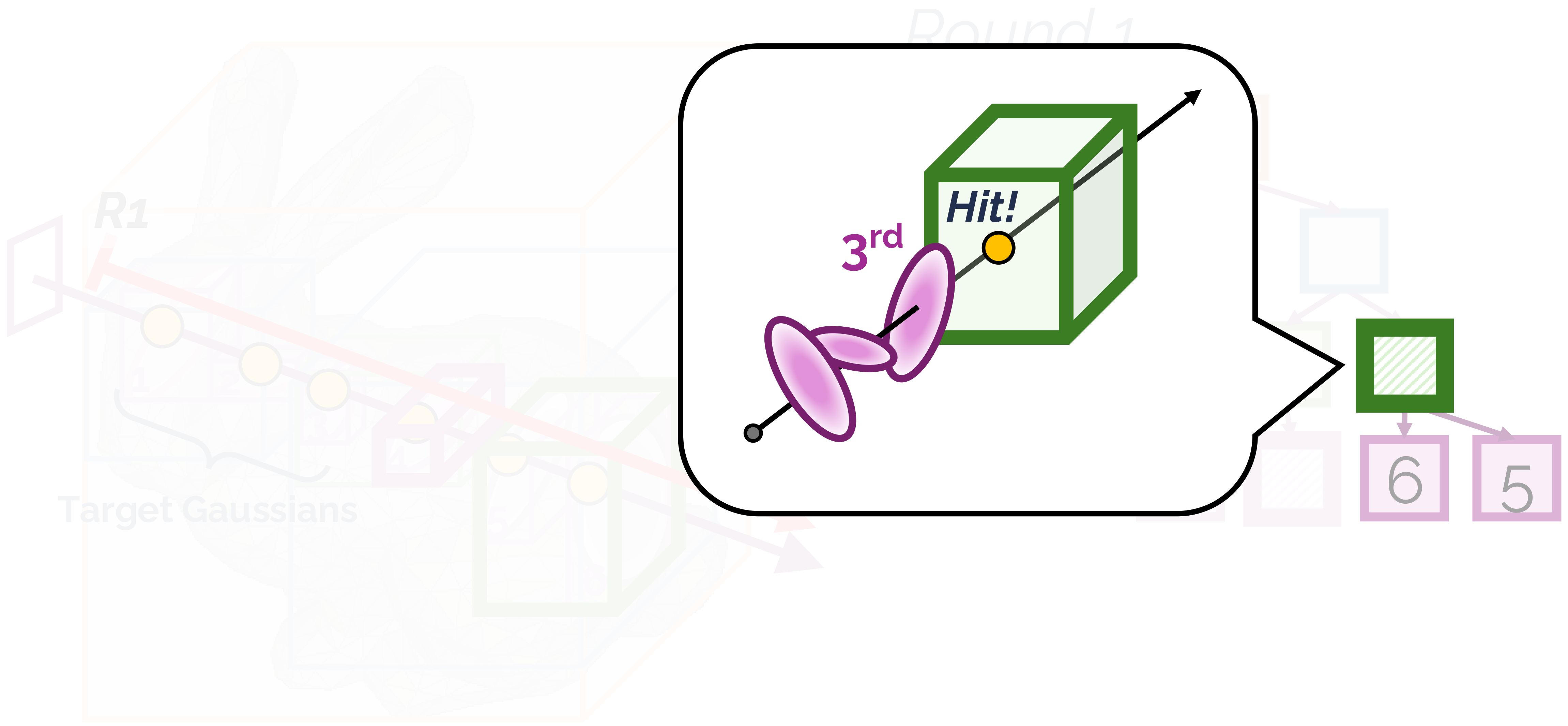
GRTX-HW: Traversal Checkpointing & Replay



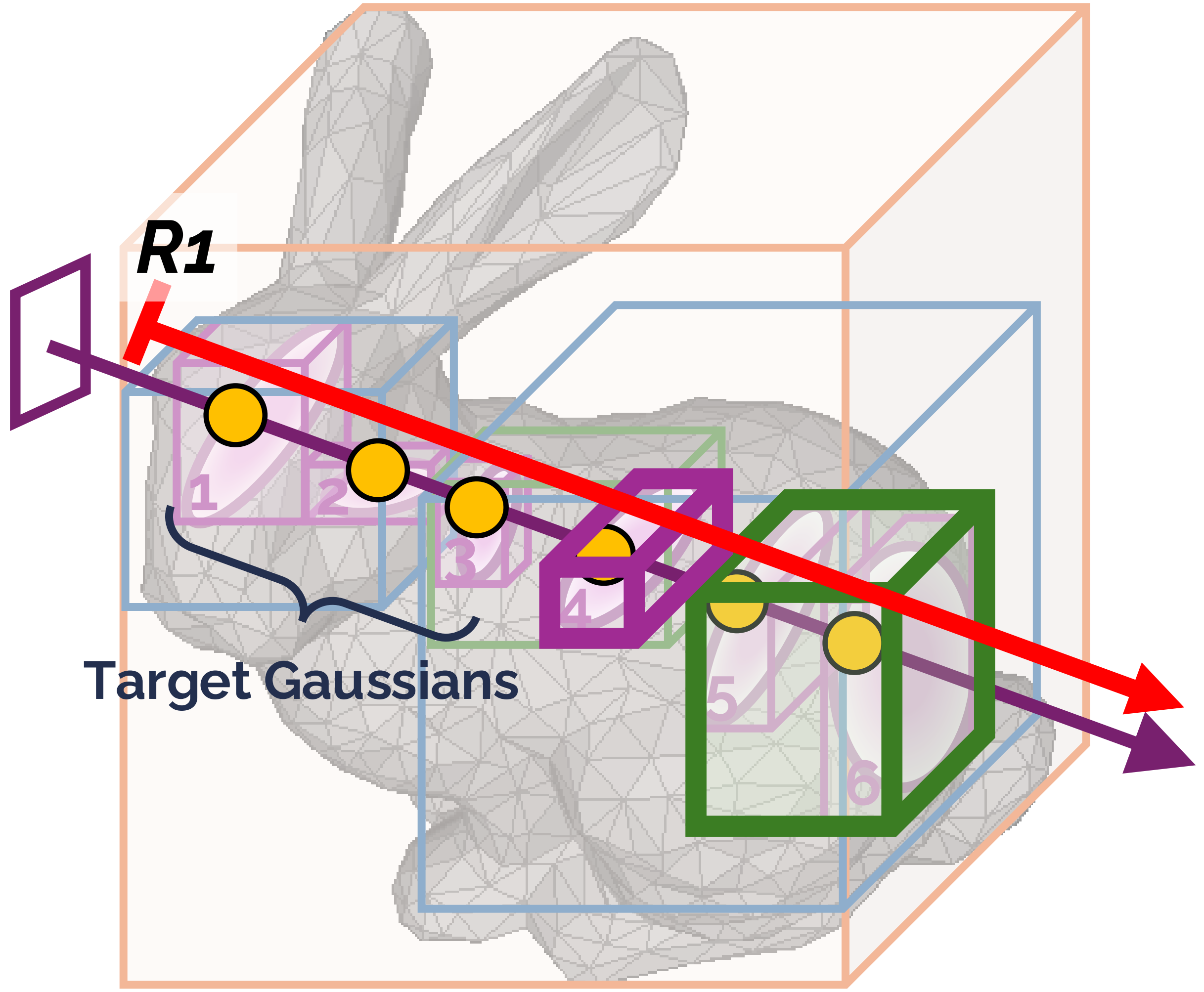
Round 1



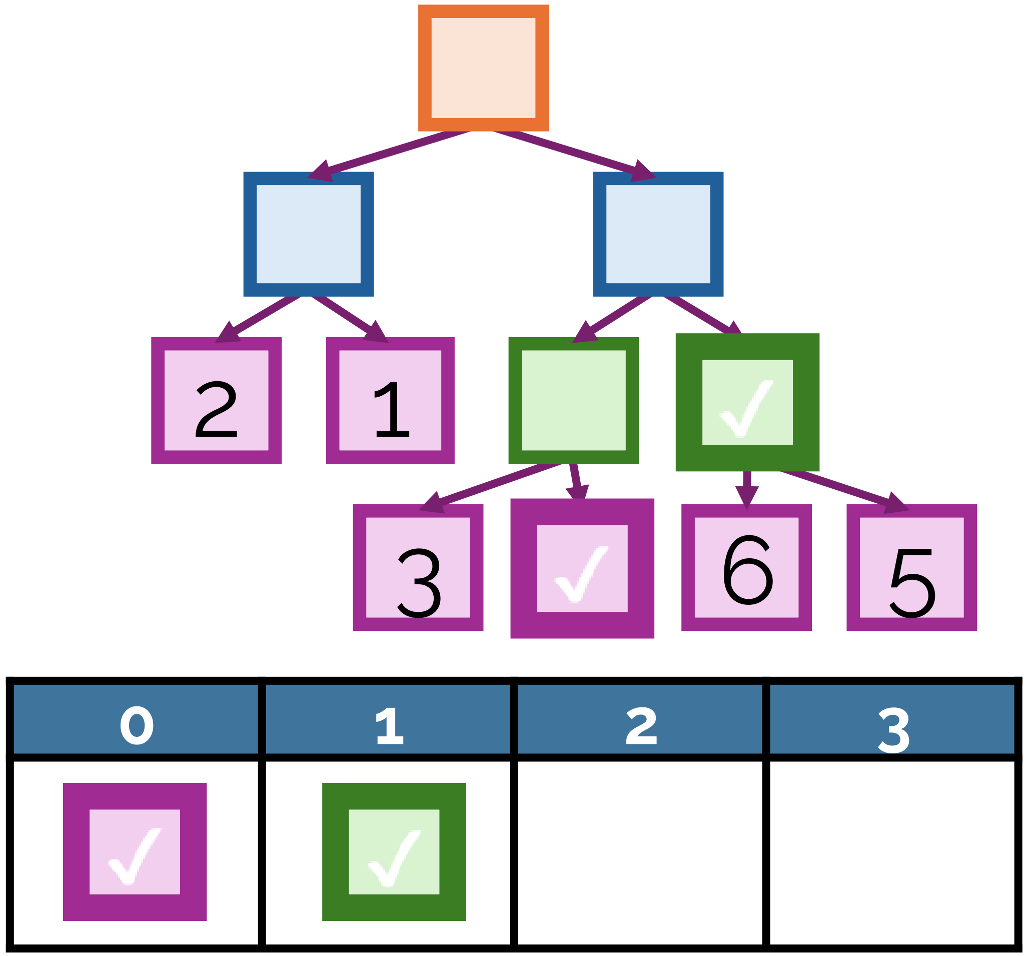
GRTX-HW: Traversal Checkpointing & Replay



GRTX-HW: Traversal Checkpointing & Replay



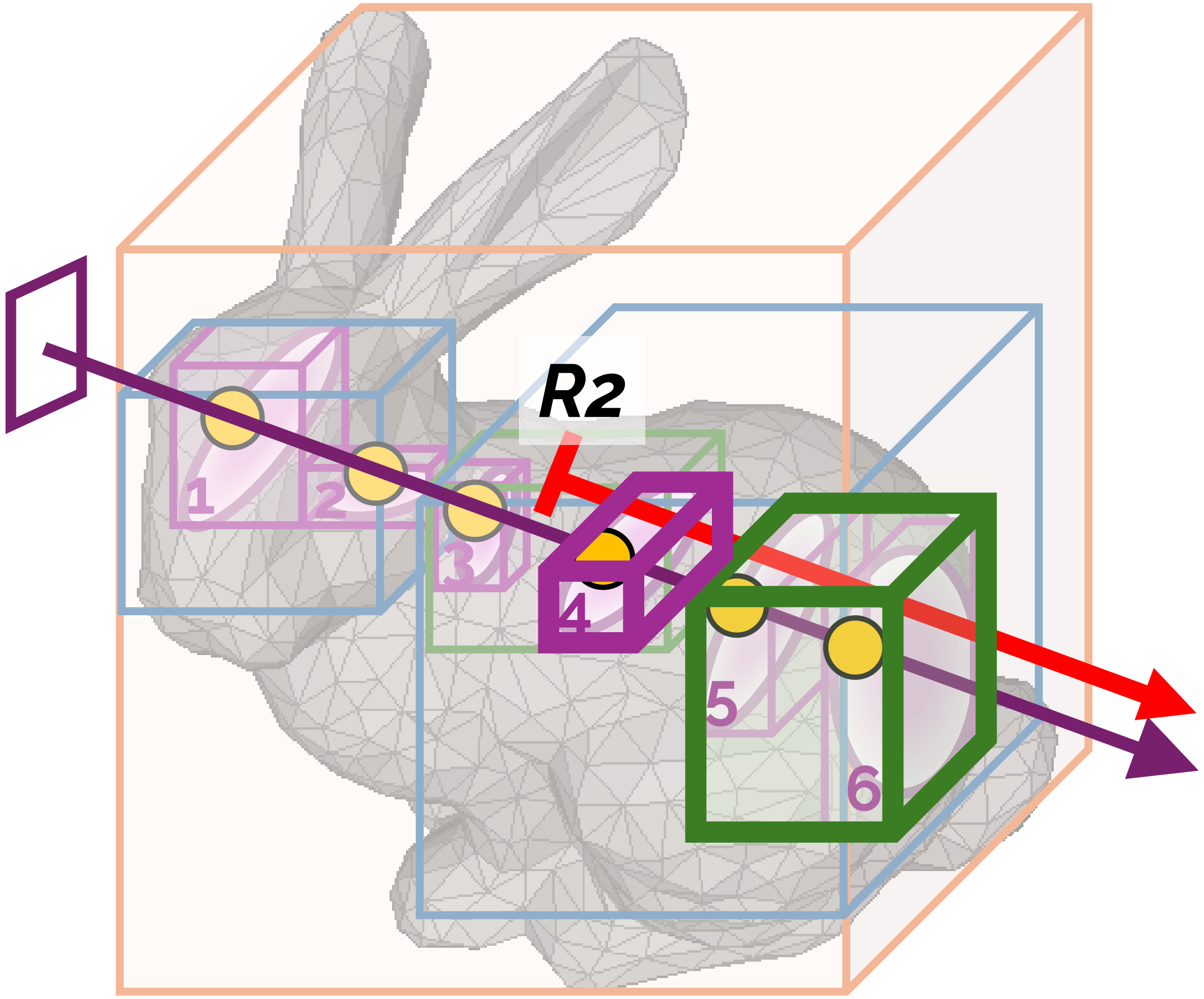
Round 1

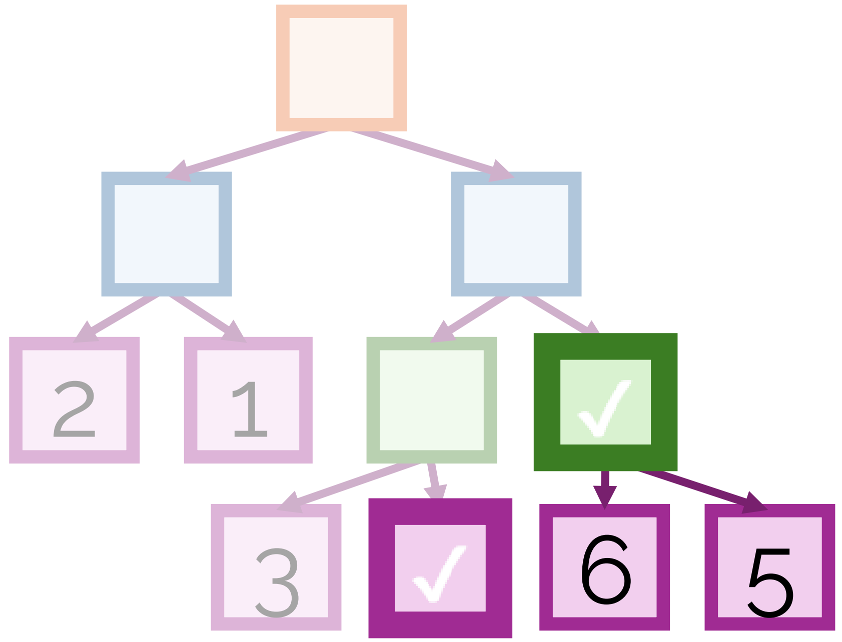


Checkpoint buffer

GRTX-HW: Traversal Checkpointing & Replay

Round 2

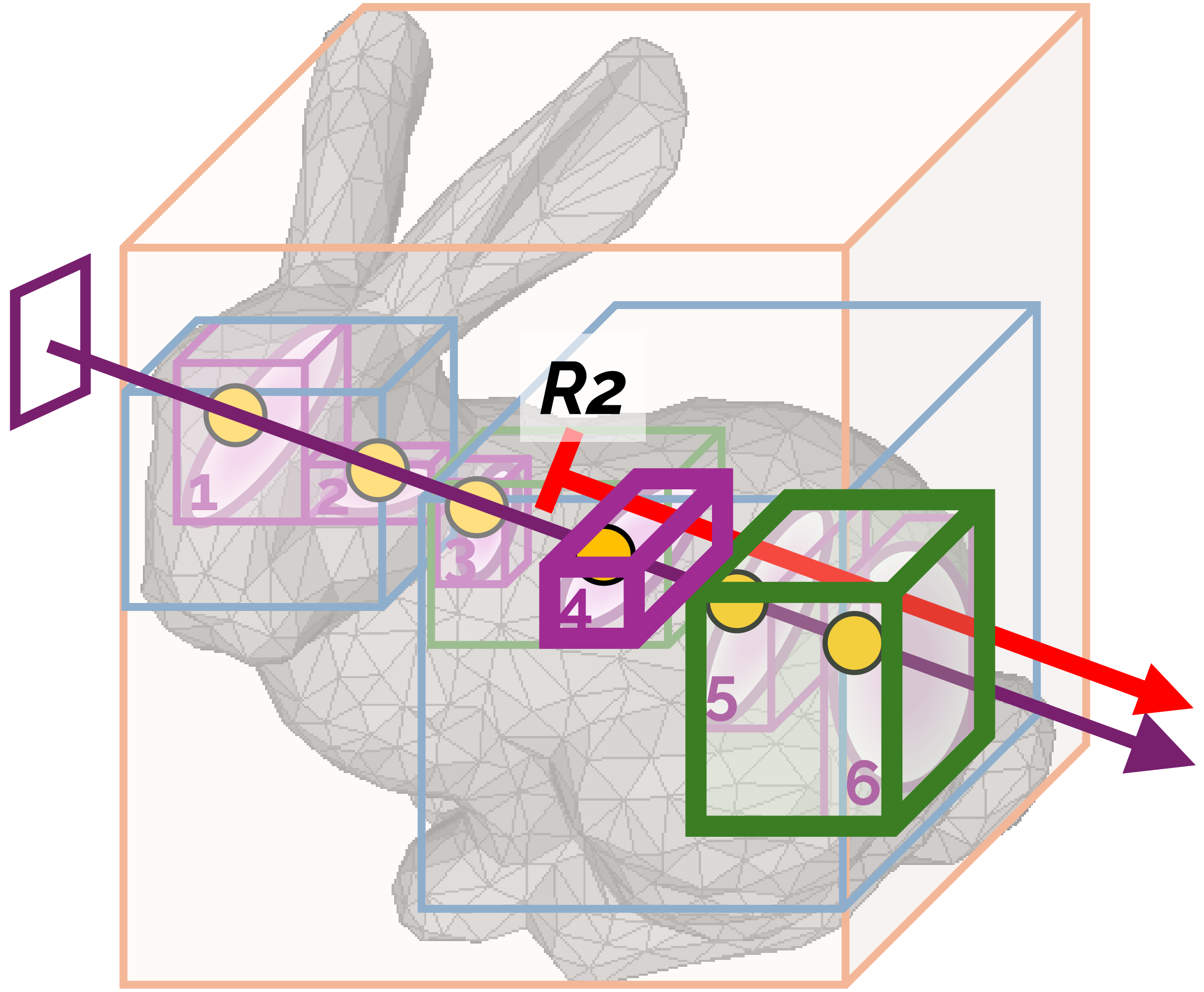




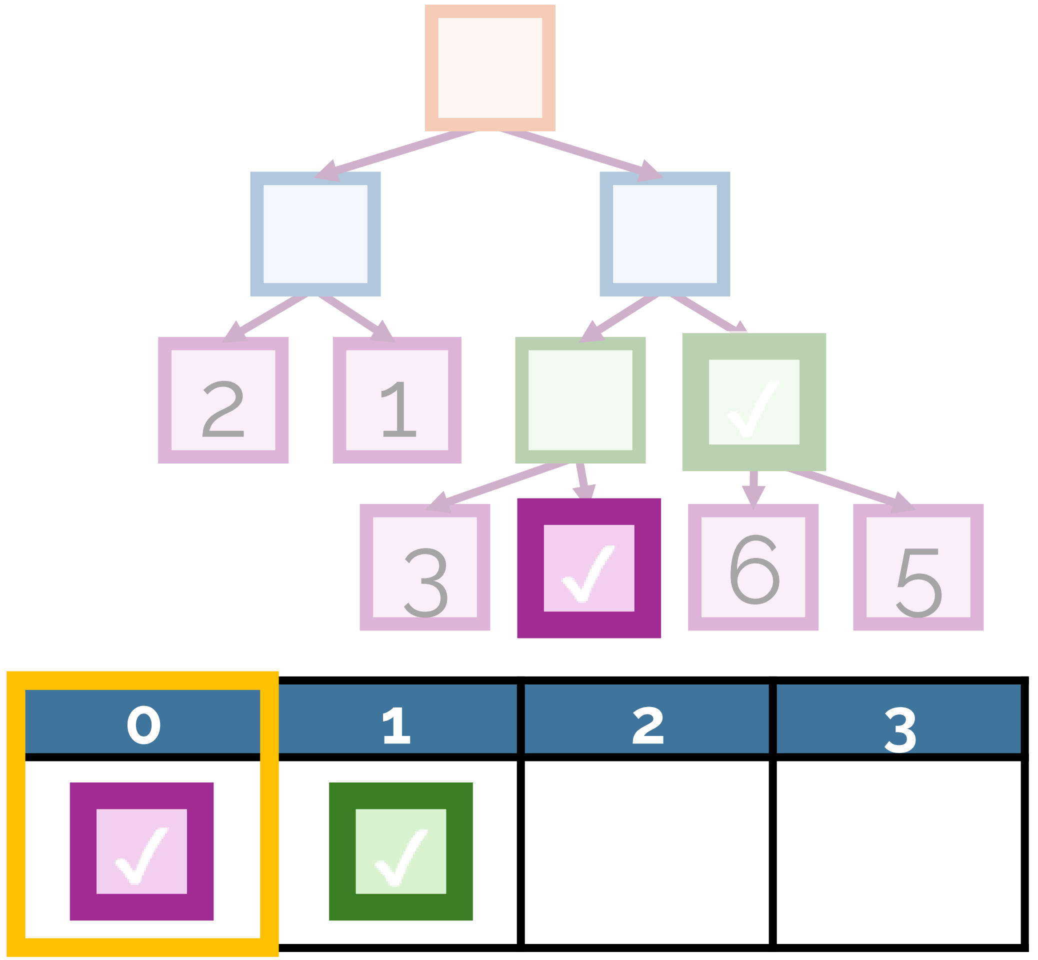
0	1	2	3
✓	✓		

Checkpoint buffer

GRTX-HW: Traversal Checkpointing & Replay

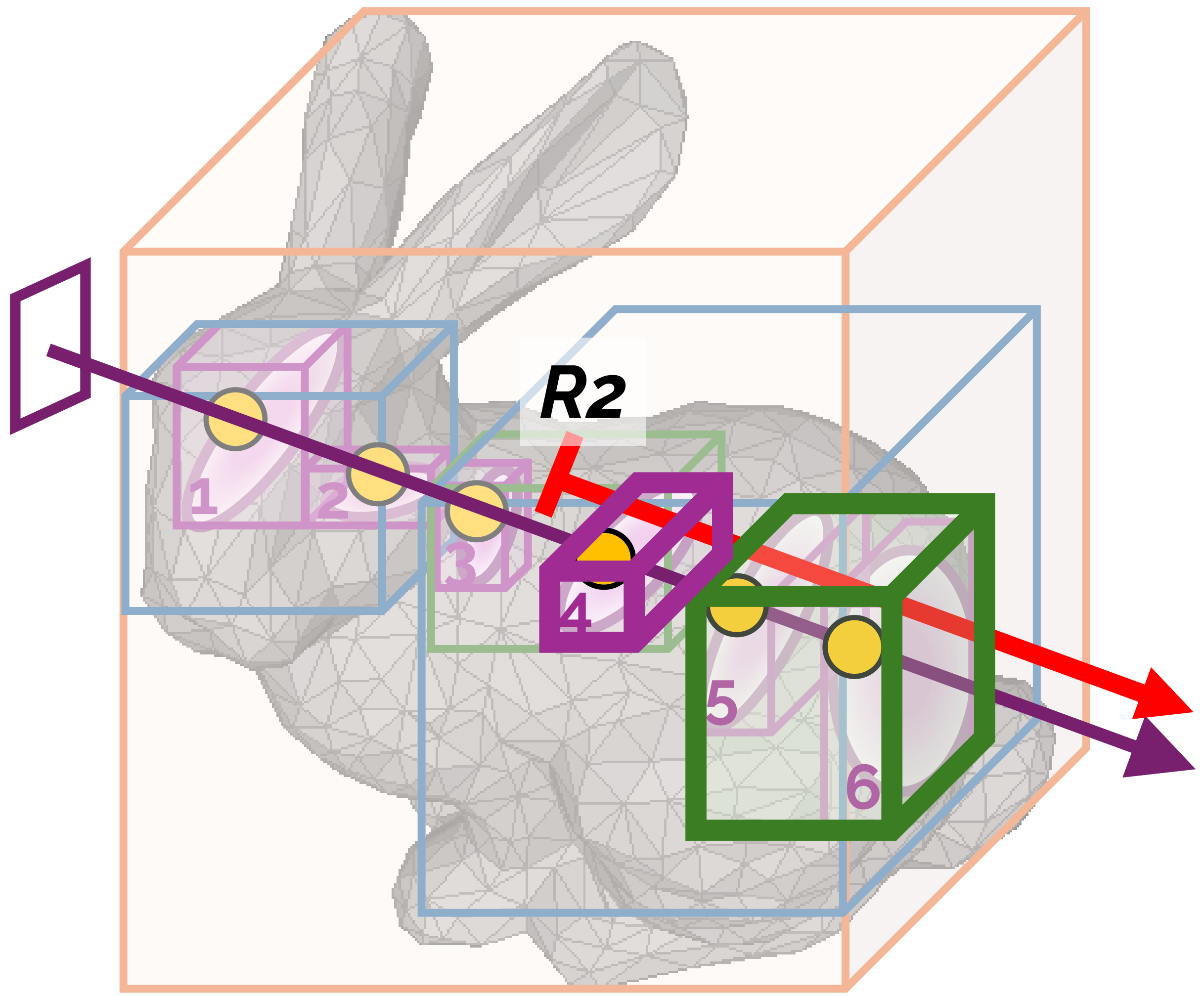


Round 2

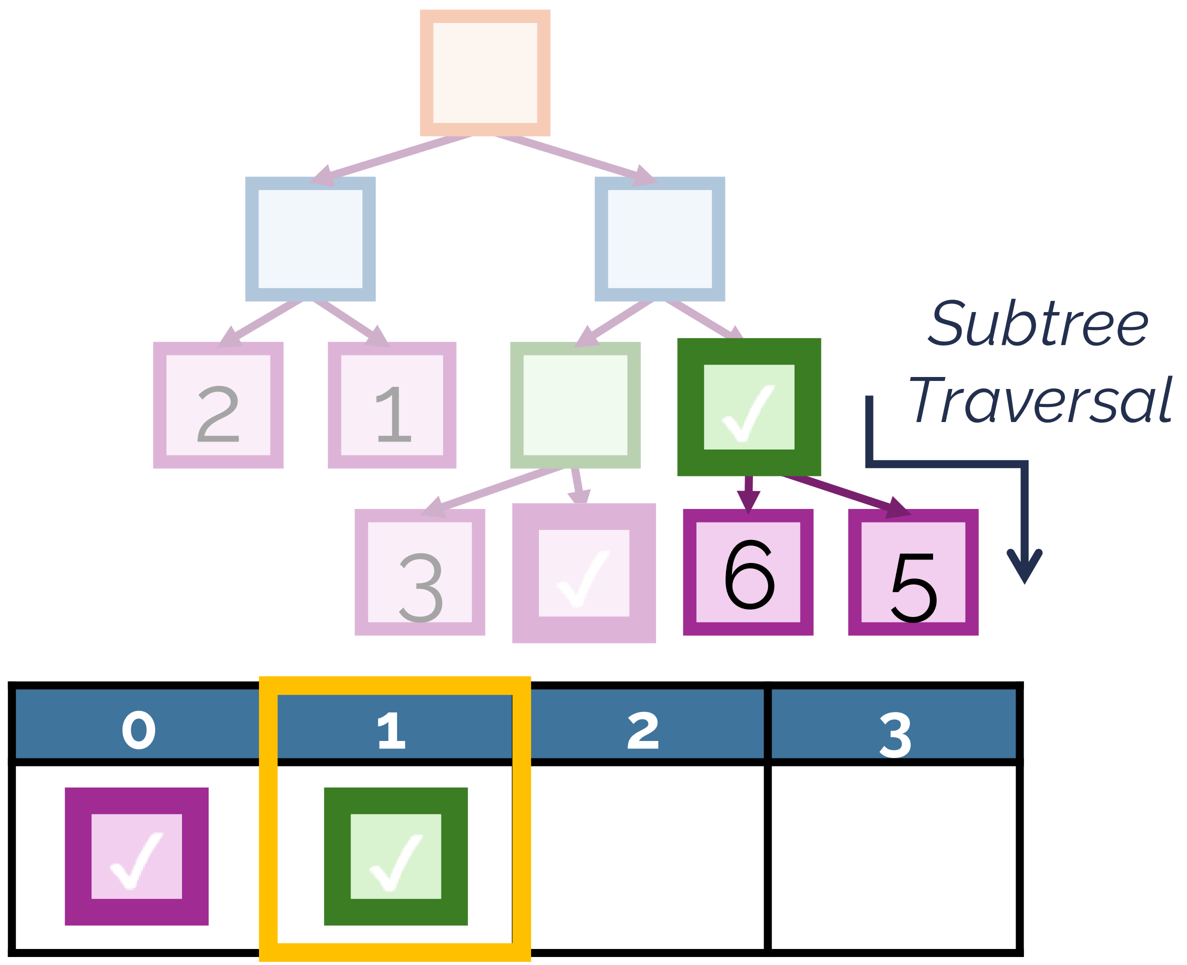


Checkpoint buffer

GRTX-HW: Traversal Checkpointing & Replay



Round 2



Checkpoint buffer

Outline

- **Background**
  - 3D Gaussian-based Rendering: Rasterization vs. Ray-tracing
  - Ray Tracing Accelerators in Modern GPUs
- **Gaussian RT Optimizations & Limitations**
- **GRTX: SW-HW Optimizations for Gaussian Ray Tracing**
  - GRTX-SW: Two-Level Acceleration Structure for Gaussian Primitives
  - GRTX-HW: Traversal Checkpointing and Replay
- **Evaluation**
- **Conclusion**

Experimental Setup

Performance Evaluation

- Vulkan-Sim (MICRO'22)
  - Cycle-level GPU simulator w/ ray-tracing accelerator modeling based on GPGPU-sim
  - With our **in-house ray tracing simulator** based on real-GPU analysis

Workloads

- Tanks & Temples: Train, Truck
- Mip-NeRF 360: Bonsai, Room
- Deep Blending: Drjohnson, Playroom

Baseline

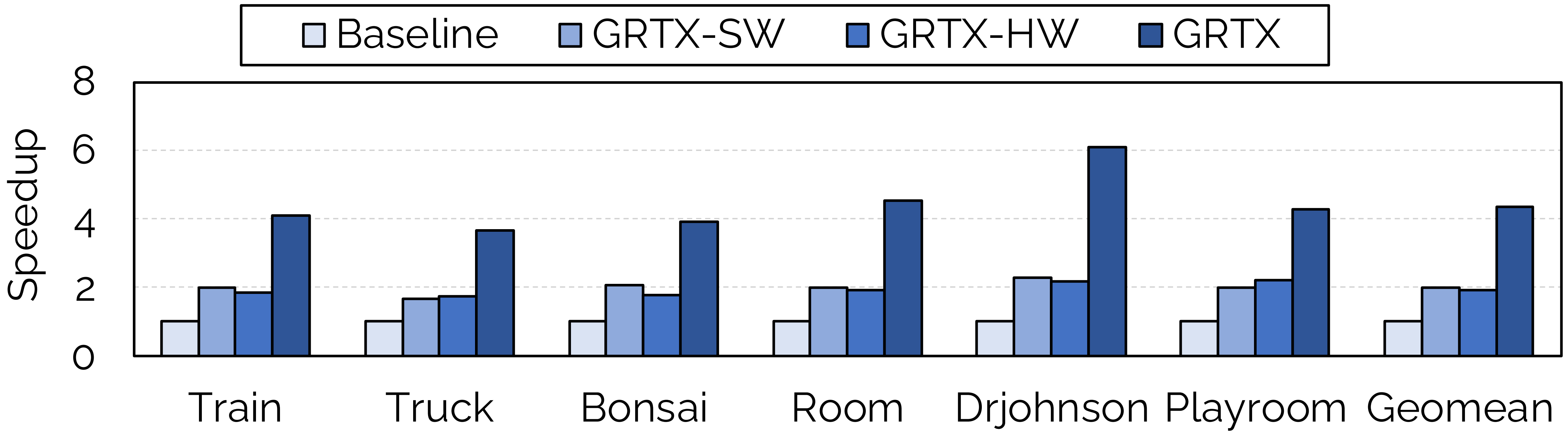
- Monolithic BVH w/ 20-faced polyhedron used in 3DGRT (NVIDIA) [1]

Baseline GPU Configuration

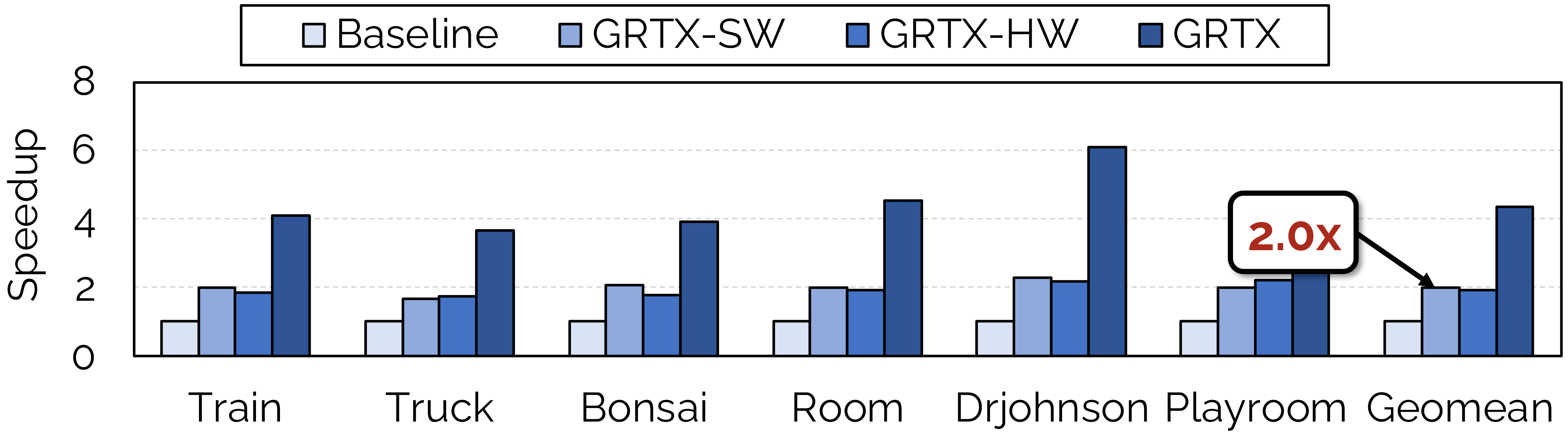
# GPC	1
# SMs	8
Core Frequency	1365 MHz
L1D Cache	128KB, 128B line (sectored)
L2 Cache	4MB, 128B line (sectored)
Memory Clock	3500MHz
# RT Units Per SM	1
Warp Buffer Size	8 (warps)

[1] Nicolas et al., 3D Gaussian Ray Tracing: Fast Tracing of Particle Scenes (SIGGRAPH Asia'24)

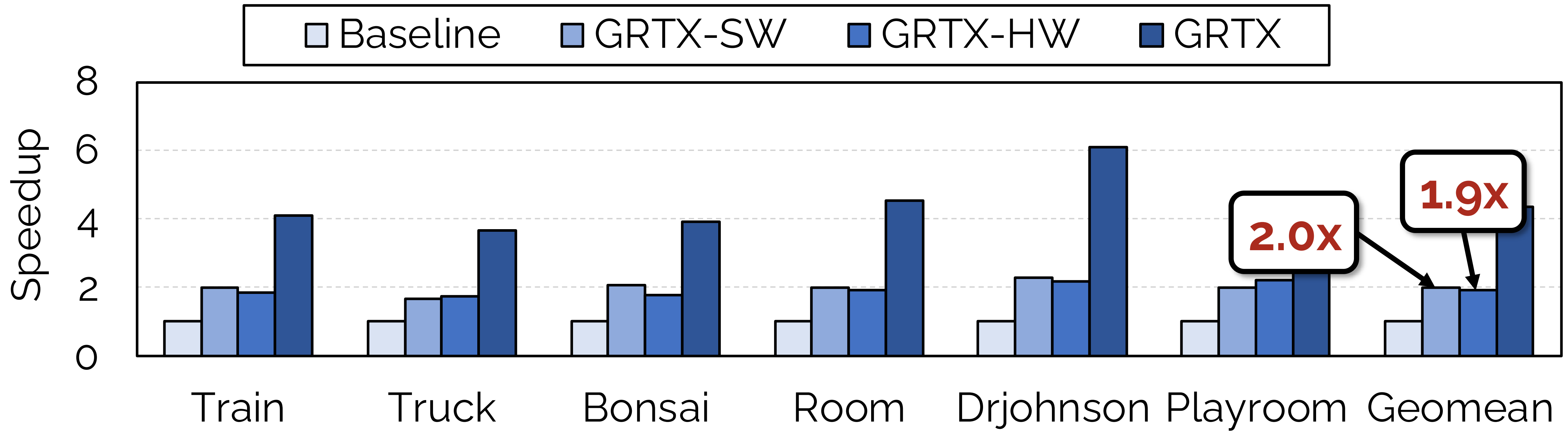
Performance



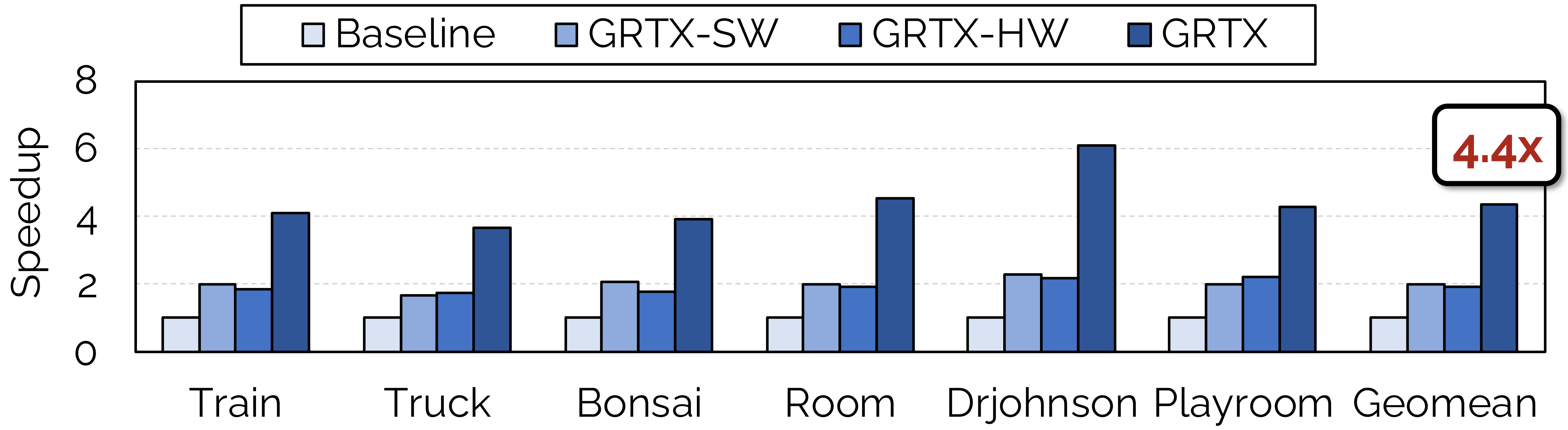
Performance



Performance



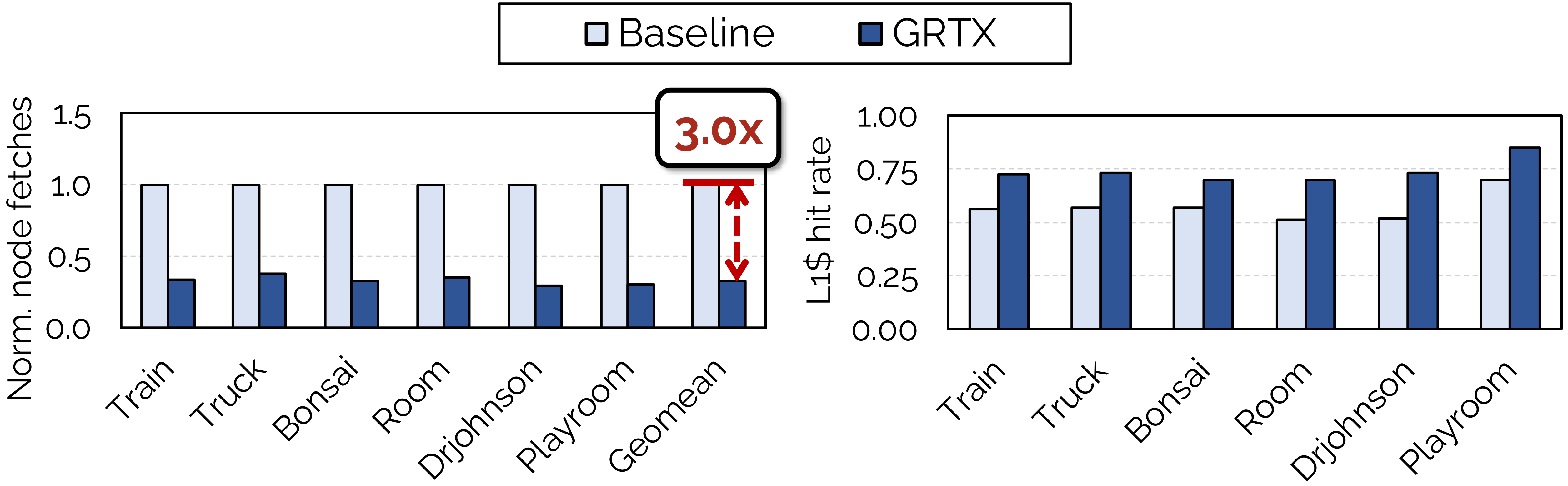
Performance



GRTX greatly improves rendering performance by 4.4x ☺

Source of Performance Gain

Number of Node Fetches & L1$ Hit Rate

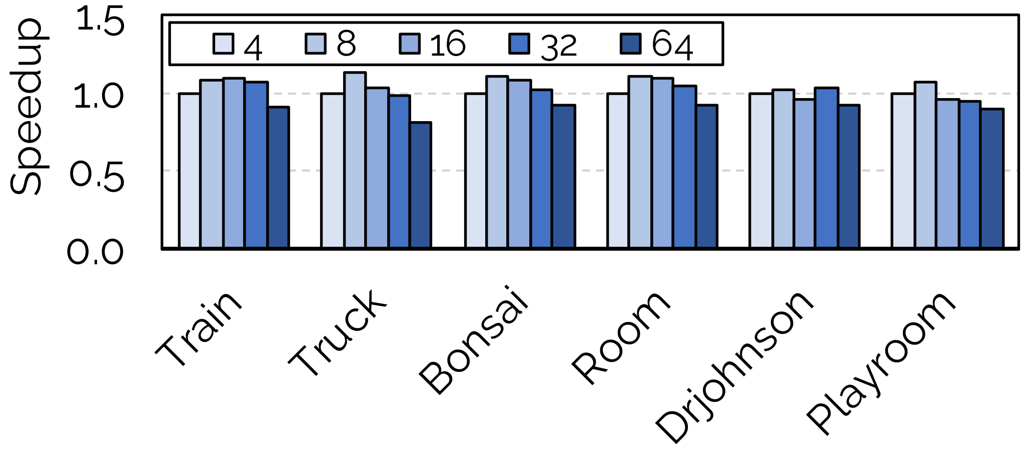


GRTX significantly **reduces the number of node fetches** while **increasing L1 cache hit rates**

More Details in Our Paper

- Support for dynamic and multi-object scenes
- GRTX-HW on secondary rays

- Sensitivity studies
  - k-buffer size
  - Varying resolutions and FoVs
- Cross-vendor applicability
- Others…



Conclusion

Problem

- Bloated BVH size and BVH memory footprint
- Redundant node visits and intersection tests across traversal rounds

Solution: **GRTX**, SW & HW optimizations for Gaussian ray-tracing

- **GRTX-SW**: Two-level BVH with a shared BLAS
- **GRTX-HW**: RT hardware extension with checkpointing and replay capabilities

Result

- GRTX shows **4.3x faster** ray-tracing performance over the baseline GPU with negligible hardware cost! ☺

Thank You!

GRTX

Efficient Ray Tracing for 3D Gaussian-Based Rendering

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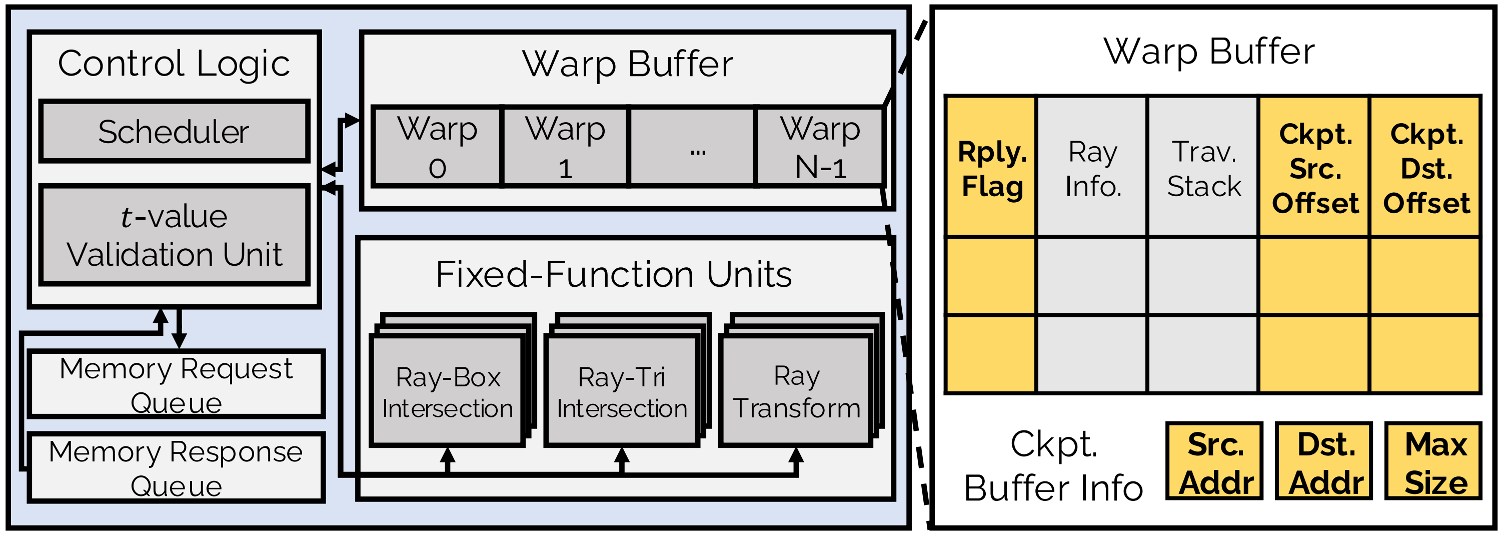
Control Logic
Scheduler
t-value Validation Unit
Memory Request Queue
Memory Response Queue
Warp Buffer
Warp 0
Warp 1
...
Warp N-1
Fixed-Function Units
Ray-Box Intersection
Ray-Tri Intersection
Ray Transform
Warp Buffer
Rply. Flag
Ray Info.
Trav. Stack
Ckpt. Src. Offset
Ckpt. Dst. Offset
Ckpt. Buffer Info
Src. Addr
Dst. Addr
Max Size