GPU Ray-tracing using Irregular Grids

Arsène Pérard-Gayot, Javor Kalojanov, Philipp Slusallek

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Universität des Saarlandes
Intel Visual Computing Institute
Deutsches Forschungszentrum für Künstliche Intelligenz GmbH

Introduction
- Ray Tracing with Grids
- Challenges

Irregular Grids
- Construction (Part I)
- Traversal
- Construction (Part II)

Results

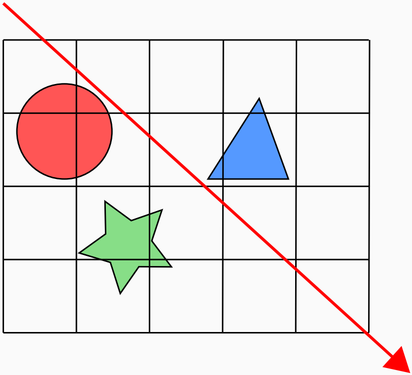
Introduction

Pros

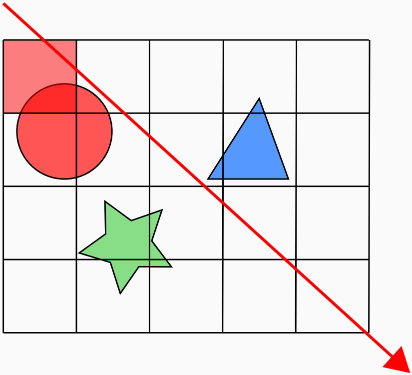
- Very fast parallel construction
- Ordered traversal, early exit
- Stackless traversal

Cons

- Empty space skipping: *Teapot in the Stadium*
- Cannot minimize both intersections and traversal steps



Introduction: Uniform Grid



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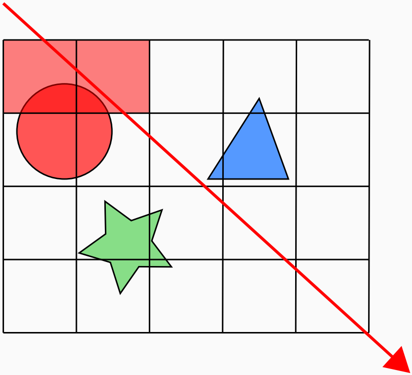

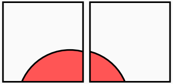

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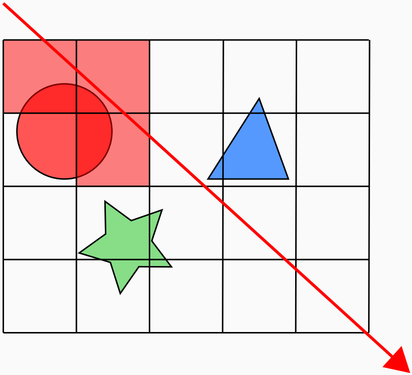

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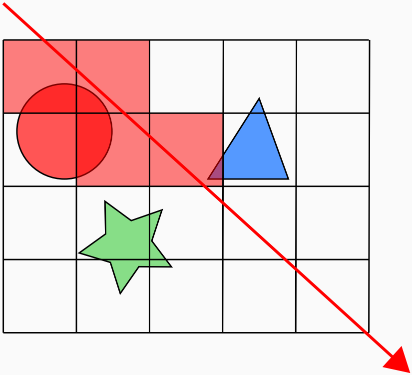

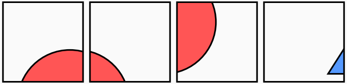

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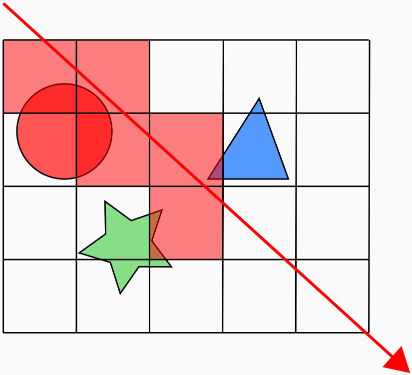

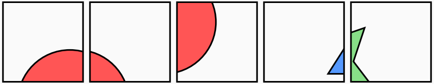

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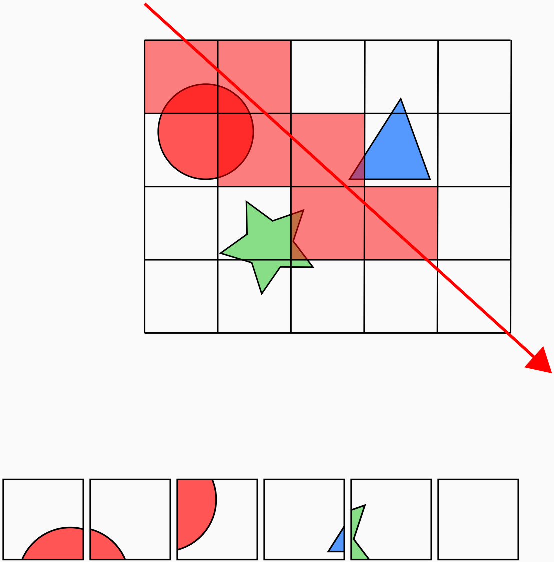

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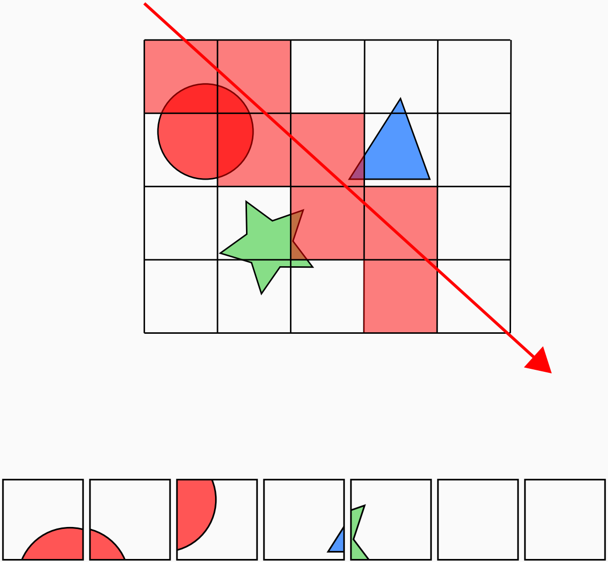

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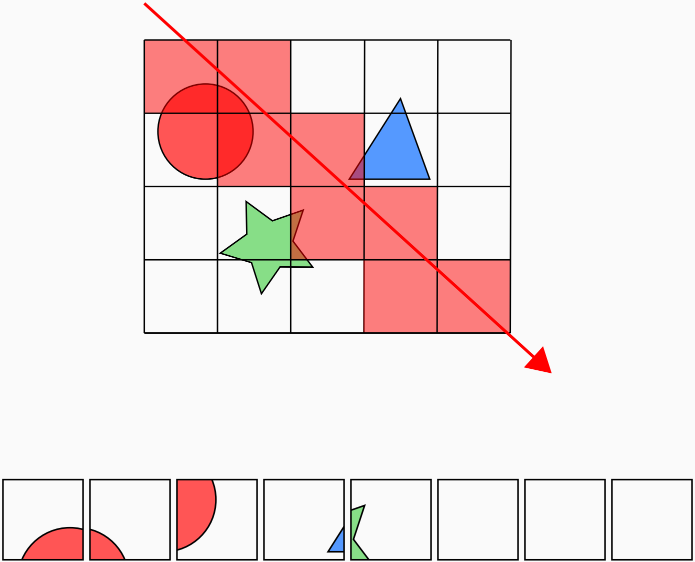

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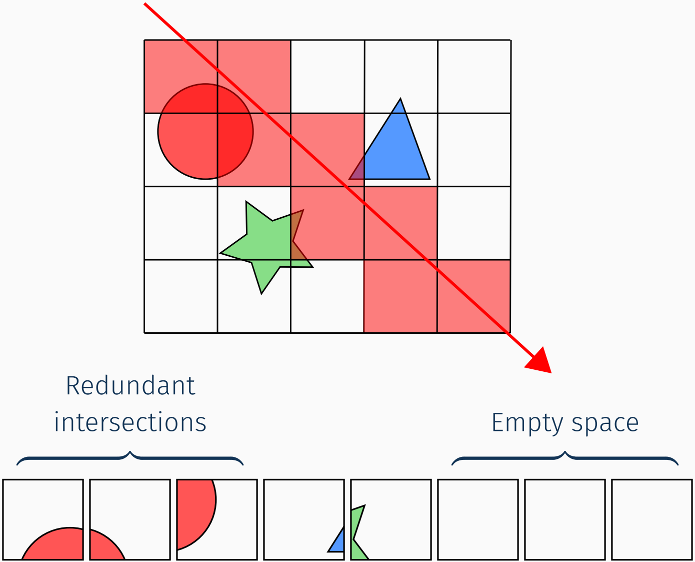

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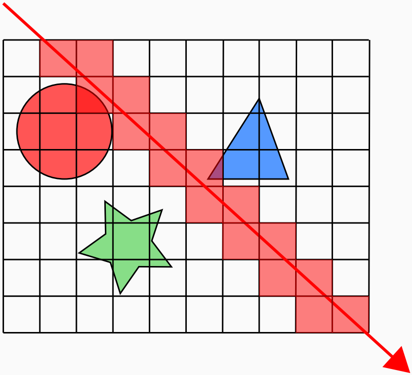
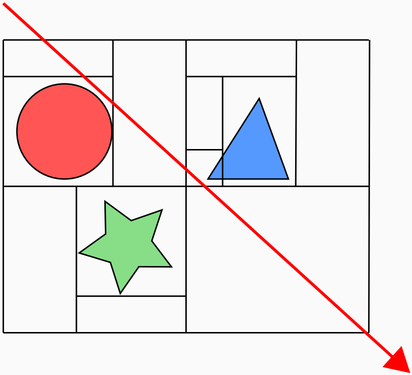


Increasing resolution

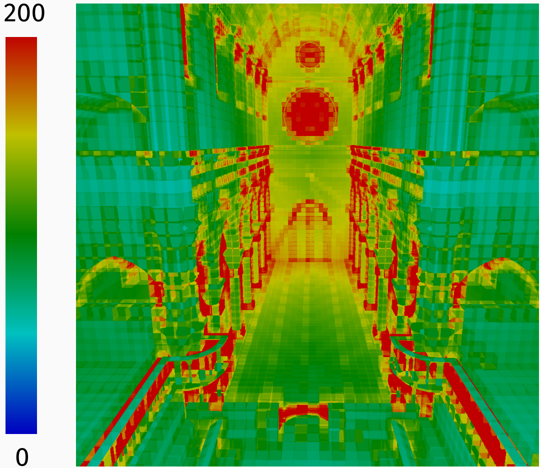
- Fewer intersections
- More traversal steps



Idea: Remove regularity

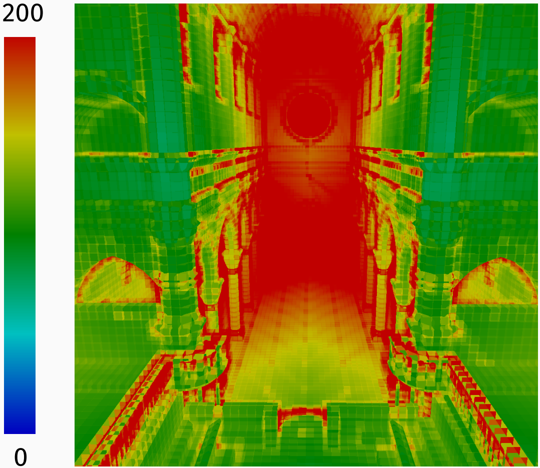
- Start with a dense subdivision
- Optimize cell shape to minimize traversal cost

Uniform Grid: Low Resolution



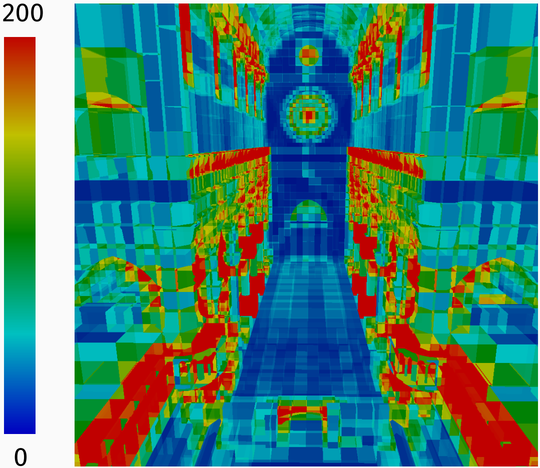
Traversal steps + Intersections

Uniform Grid: Medium Resolution



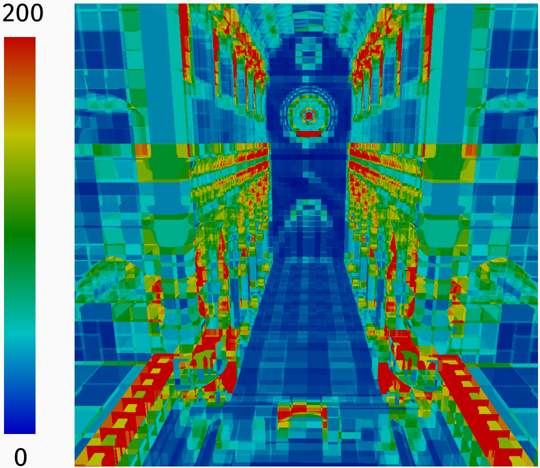
Traversal steps + Intersections

Irregular Grid: Low Resolution



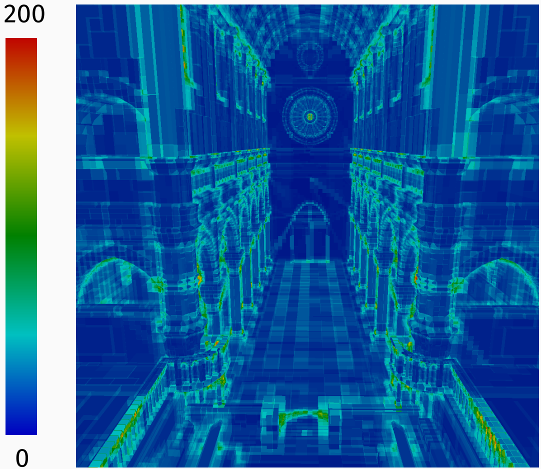
Traversal steps + Intersections

Irregular Grid: Medium Resolution



Traversal steps + Intersections

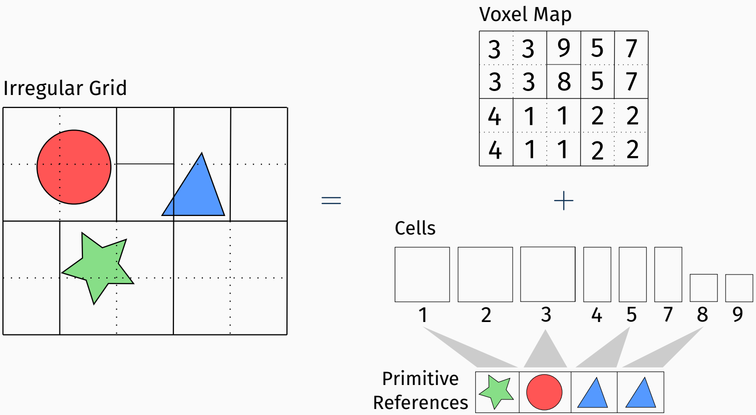
Irregular Grid: High Resolution



Traversal steps + Intersections

Irregular Grids

Data Structure

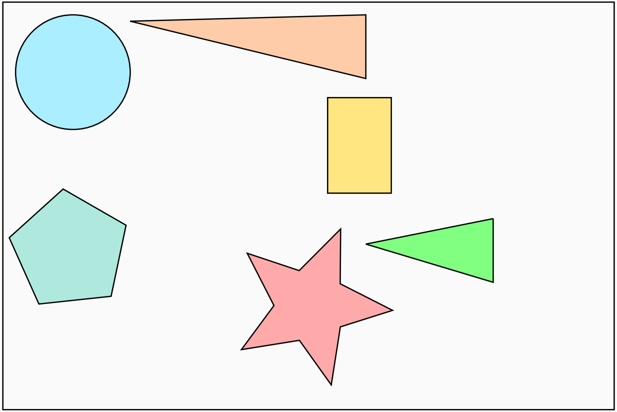


Construction (Part I)

Initialization

- Initial grid
- Two-level construction:
  1. A *coarse* uniform grid
  2. An octree in each of the grid cells
- Adaptive: More effort where the geometry is complex
- Dense: Up to 2^{15} resolution in each second-level cell

Initialization



Construction (Part I)

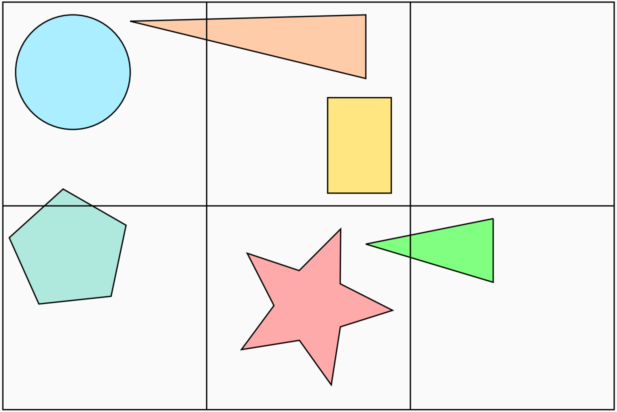
Initialization

- User-defined λ_1 controls top-level resolution
- With scene volume V and number of objects N [Cle+83]:

$$R_{\{x,y,z\}} = d_{\{x,y,z\}} \sqrt[3]{\frac{\lambda_1 N}{V}}$$

- Tries to make cells cubic

Initialization



Construction (Part I)

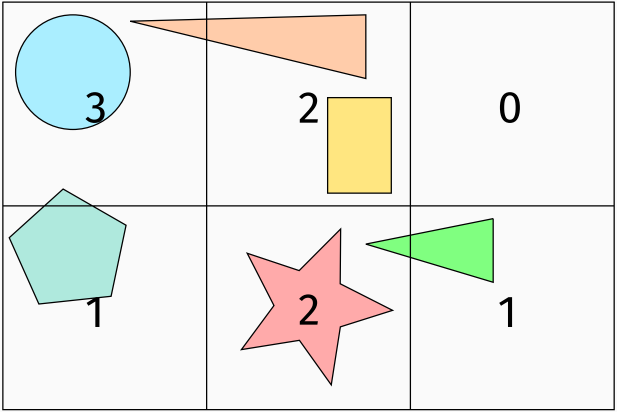
Initialization

- Octree depth computed independently in each cell
- Same formula, but: λ_2, local number of objects & volume
- Clamp resolution to a power of two:

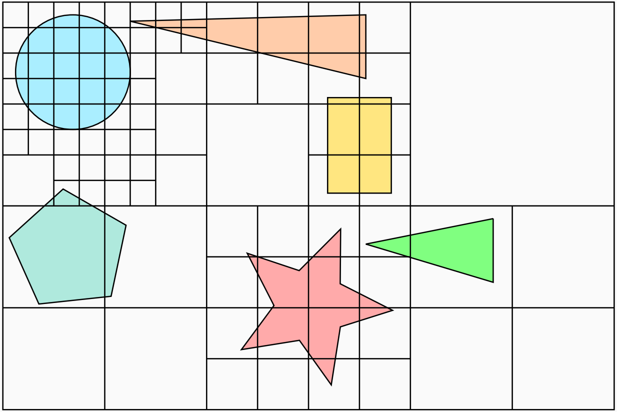
$$D = \lceil log_2(max(R_x, R_y, R_z)) \rceil$$

- Compact: only $log_2(log_2(R_{max}))$ bits needed
  - 4 bits = max. resolution of $2^{15} \times 2^{15} \times 2^{15}$

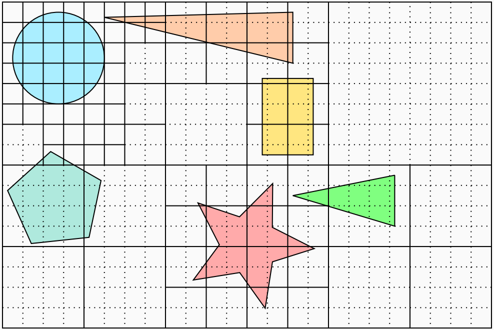
Initialization



Initialization



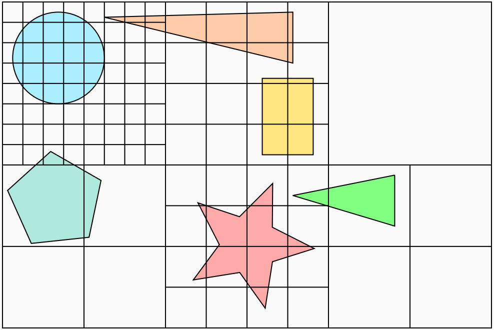
Construction (Part I): Virtual Grid



Property

Cells are aligned on a virtual grid of resolution $R_{x,y,z}\,2^{D}$

Construction (Part I): Voxel Map



Voxel map as a two level grid

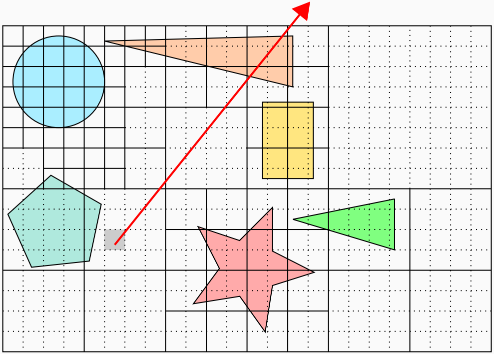
Memory efficient/Fast lookup

Traversal

- The data structure is not optimal
- But it can already be used for traversal

Ideas

- Maintain position on the virtual grid
- Recompute increment along the ray at each step



1. Locate ray origin
2. Loop
   - 2.1 Intersect primitives
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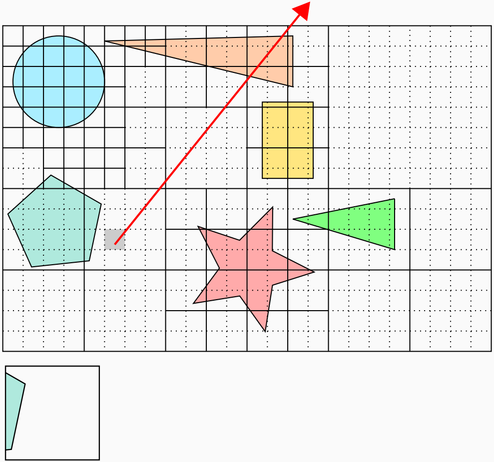
   - 2.4 Move to next cell

Interlude: Traversal



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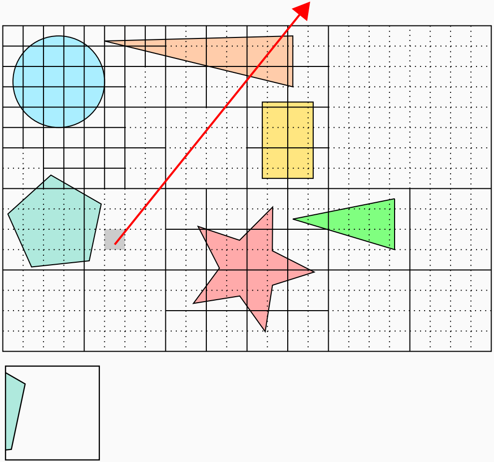

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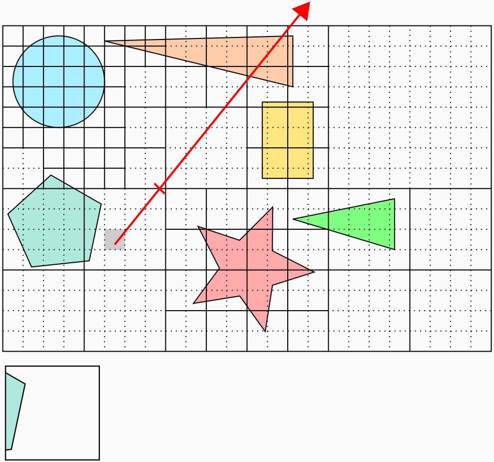

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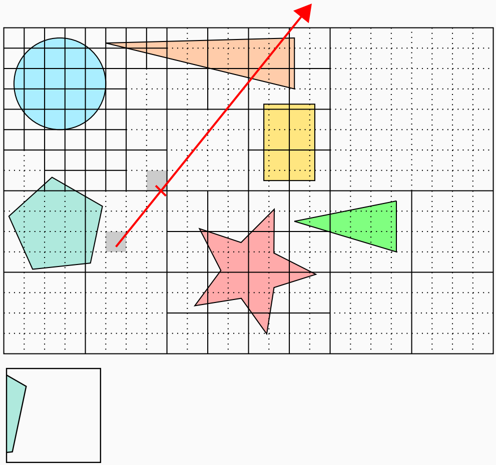

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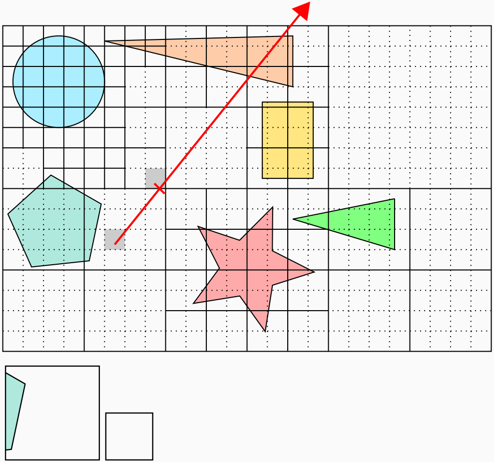

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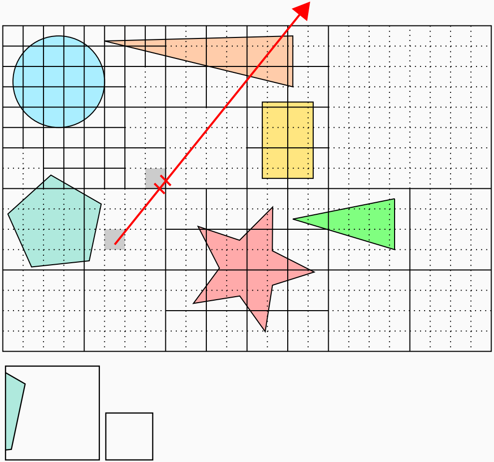

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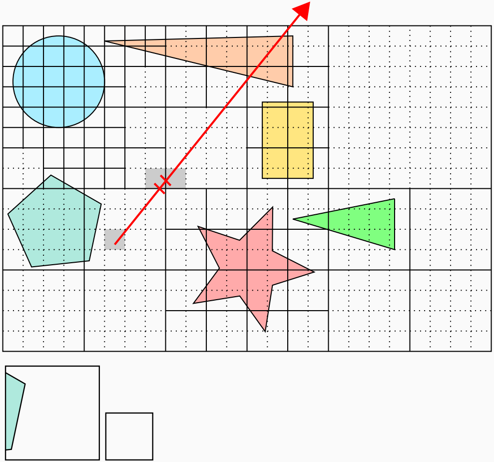

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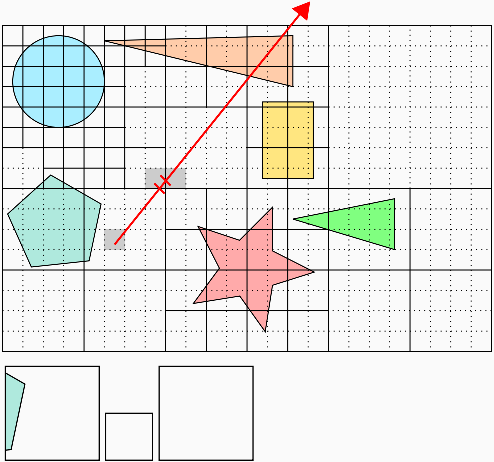

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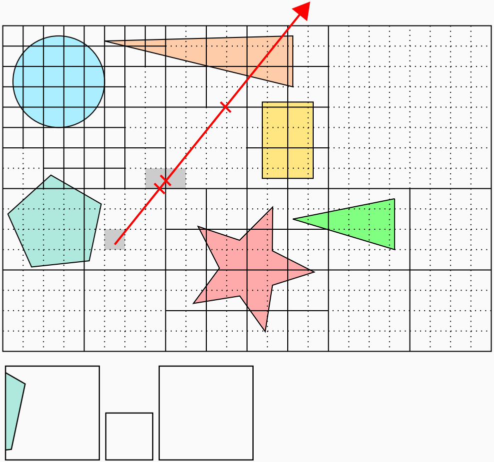

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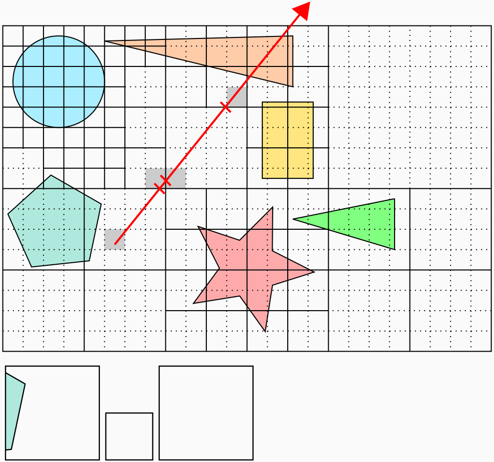

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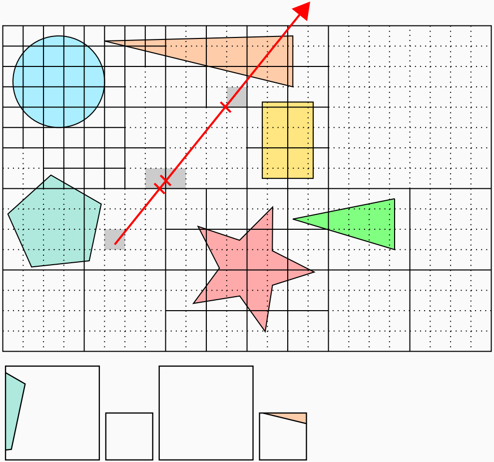

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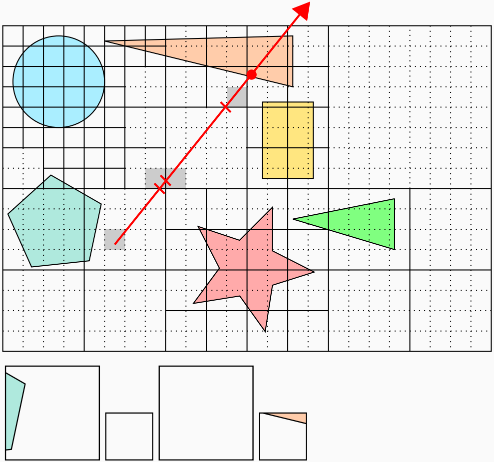

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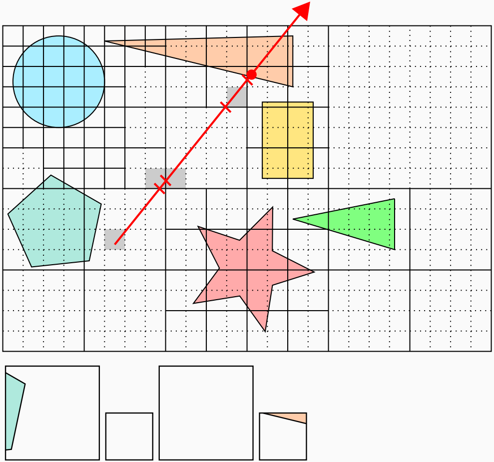

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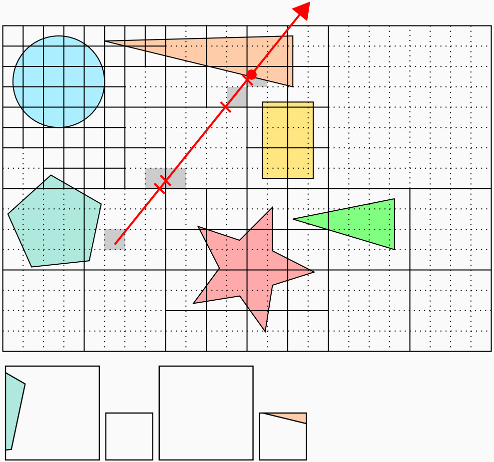

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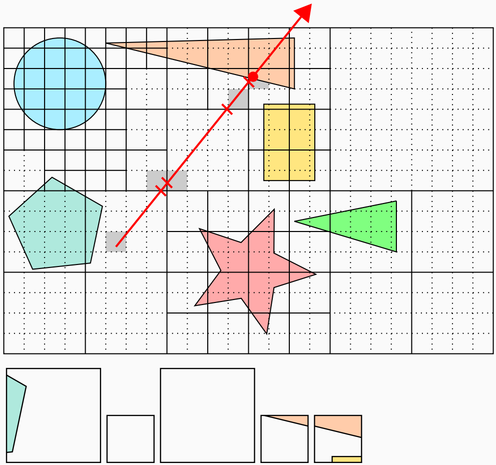

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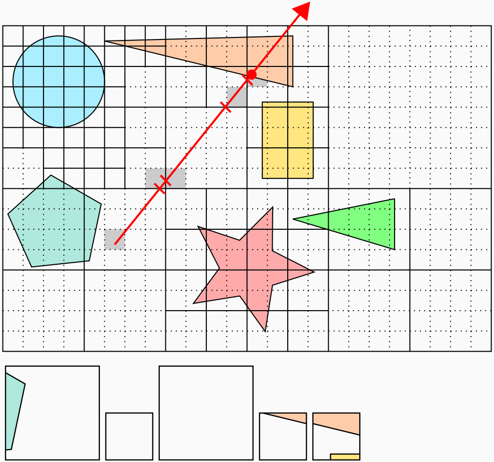

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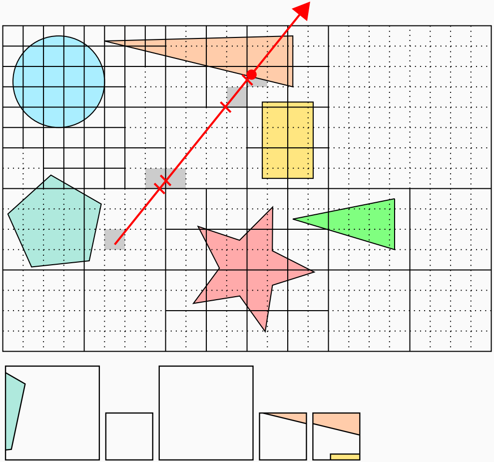

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Contruction (Part II)

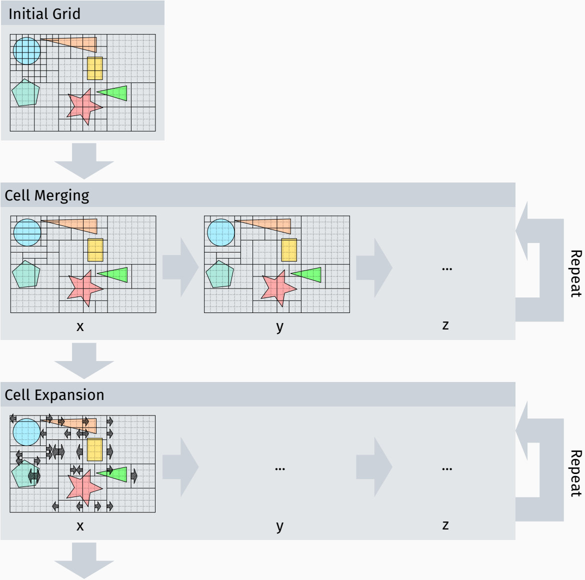
Traversal Performance

- Poor empty space skipping $\Longrightarrow$ memory latency
- Redundant intersections $\Longrightarrow$ instr./memory latency

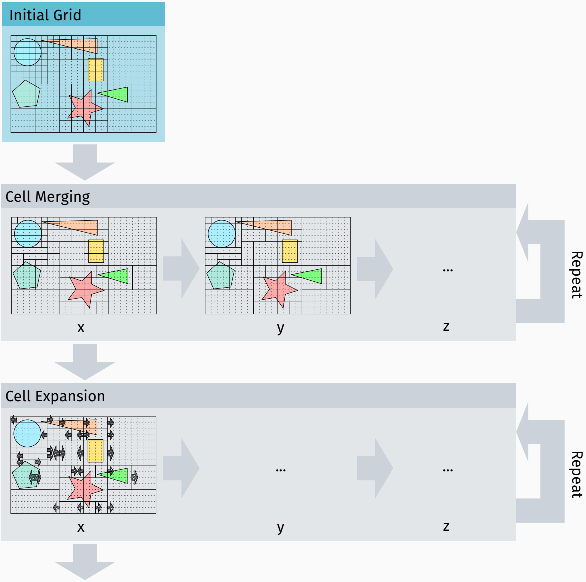
Cell Merging and Expansion

- Local (greedy) optimizations
- Examine cells and their neighborhoods
- Keep optimizations simple and parallelizable

CONTRUCTION (PART II): OPTIMIZATION PASSES



Contruction (Part II): Optimization Passes



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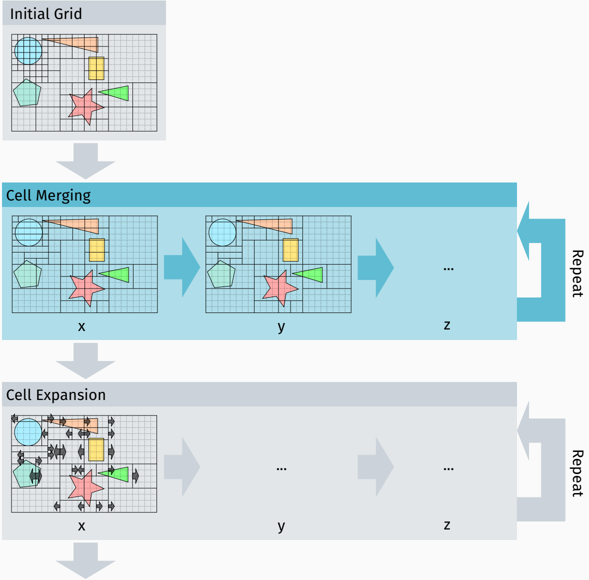
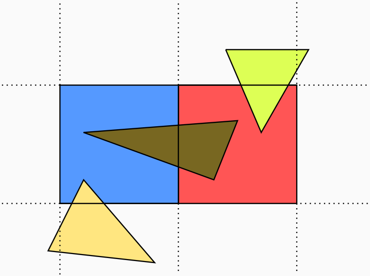


Contruction (Part II): Cell Merging



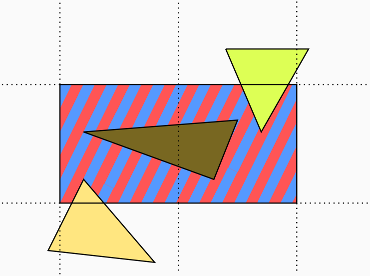
Cell Merging

- Merge each cell with its neighbor if the SAH decreases:

$$|\mathcal{R}(A)|\,\mathcal{SA}(A) + |\mathcal{R}(B)|\,\mathcal{SA}(B) \geq |\mathcal{R}(A \cup B)|\,\mathcal{SA}(A \cup B) - \mathcal{C}_t$$

- For empty and non-empty cells

Contruction (Part II): Cell Merging



Limitations

- Only consider the union of 2 aligned cells
- Union must be a box

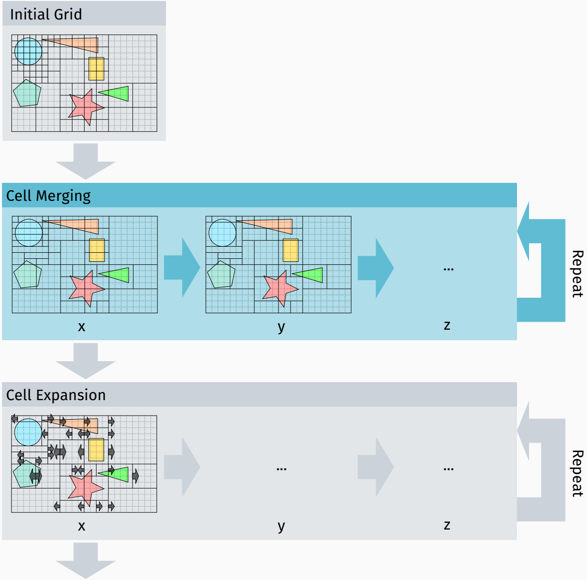
Stopping criterion

- Keep merging until:

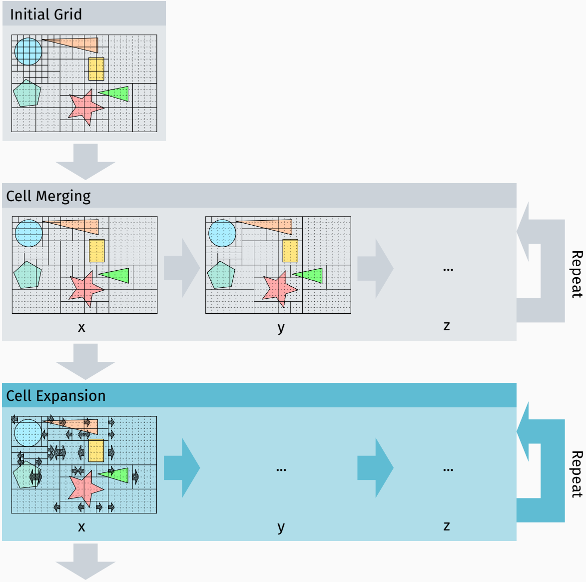
$$N_{after} \geq \alpha N_{before}$$

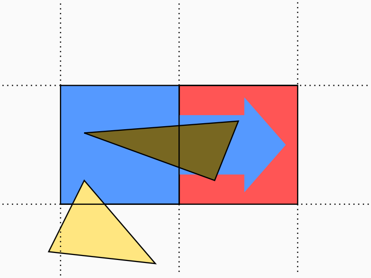
  - N_{after}/N_{before}: number of cells after/before merging
  - $\alpha = 0.995$

Contruction (Part II): Optimization Passes



Contruction (Part II): Optimization Passes



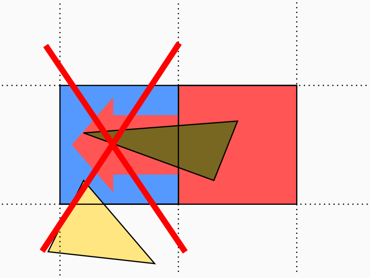


Cell Expansion

- Expand the exit boundaries of the cells
- Must maintain correctness of traversal:

$$\mathcal{R}(B) \subset \mathcal{R}(A)$$

Contruction (Part II): Cell Expansion

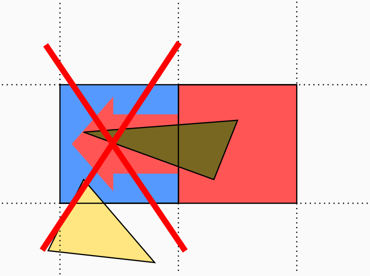


Cell Expansion

- Expand the exit boundaries of the cells
- Must maintain correctness of traversal:

$$\mathcal{R}(A) \not\subset \mathcal{R}(B)$$

Contruction (Part II): Cell Expansion

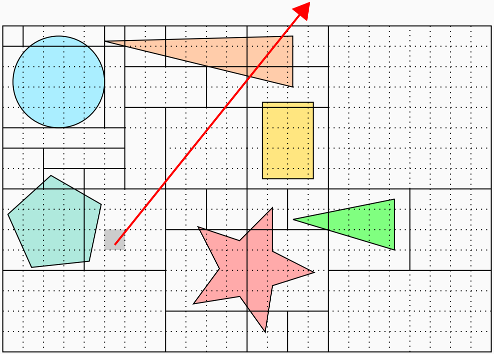


Limitations

- Must examine every neighbor on the box face
- Binary decision, no partial expansion

Stopping criterion

- Fixed number of expansion passes:
  - 3 for static scenes,
  - 1 for dynamic scenes.



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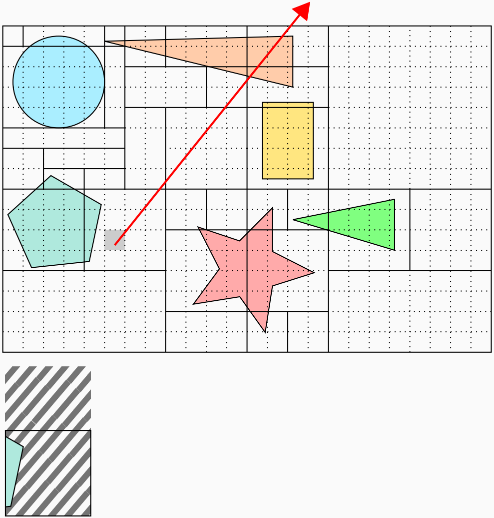
Contruction (Part II): Impact on Traversal



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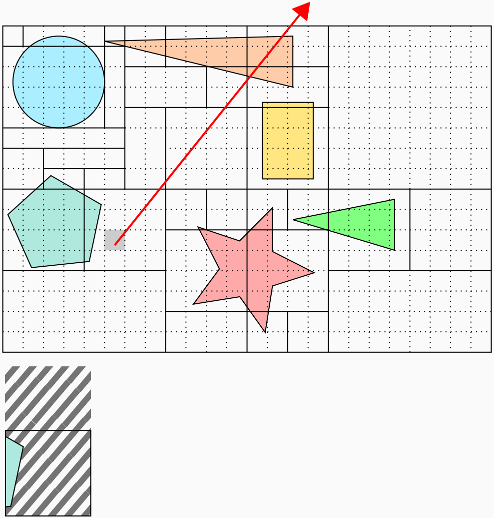
CONTRUCTION (PART II): IMPACT ON TRAVERSAL



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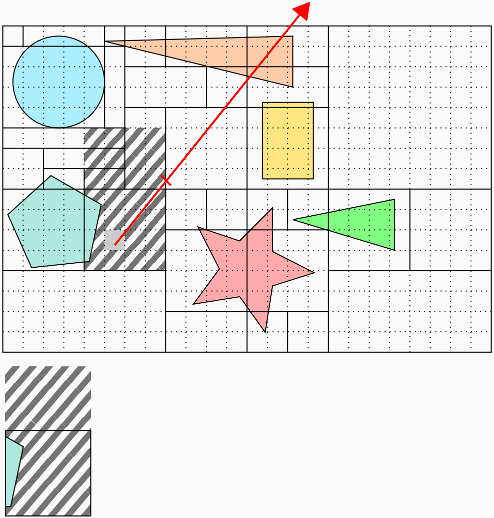

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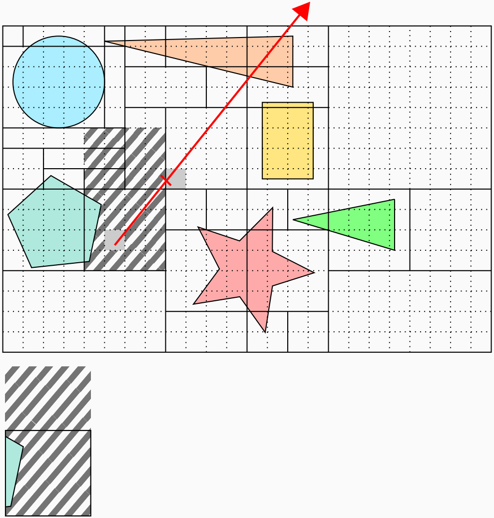

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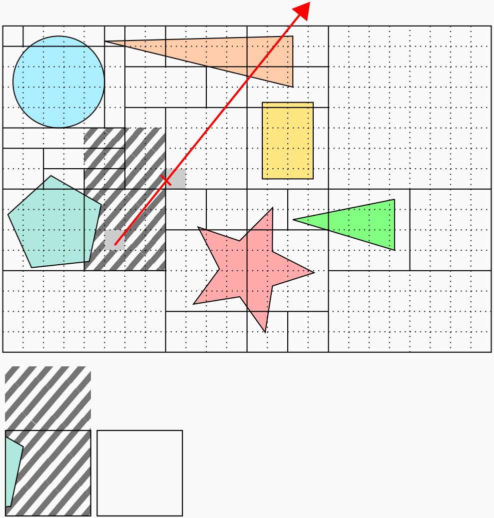

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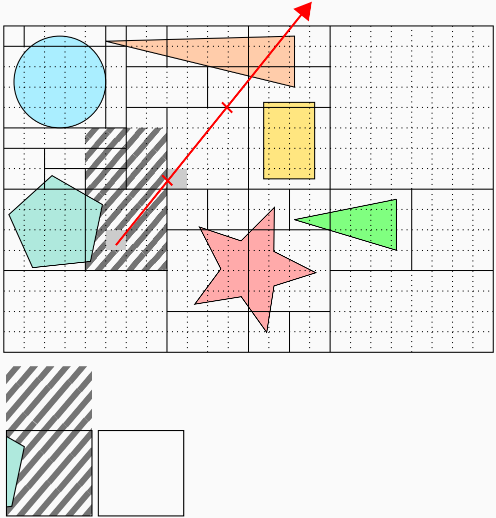

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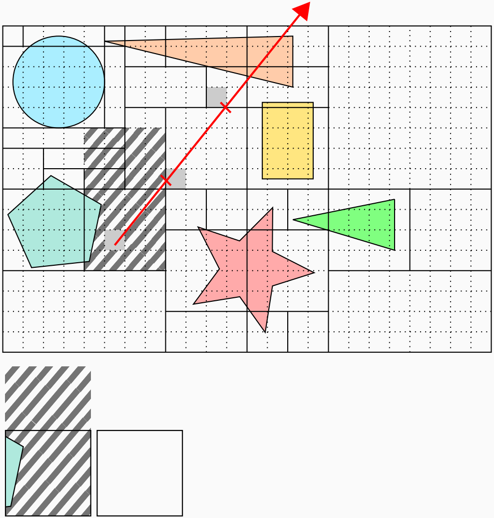

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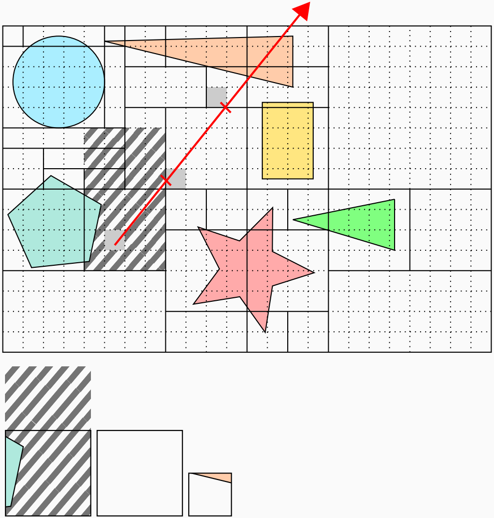

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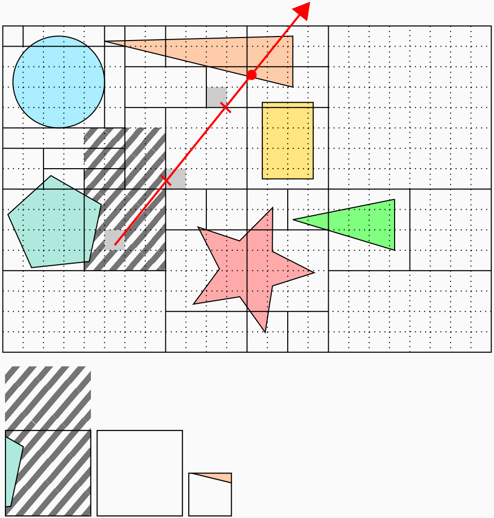

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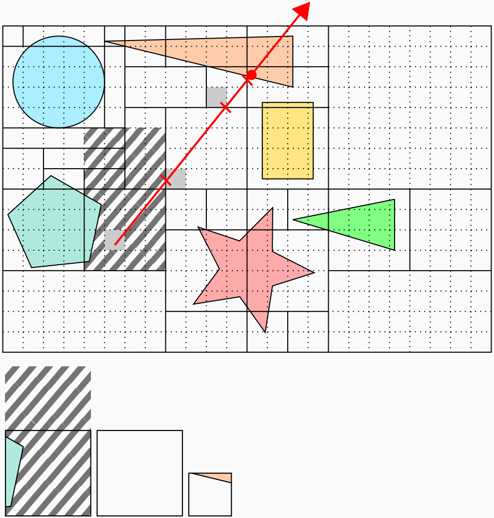

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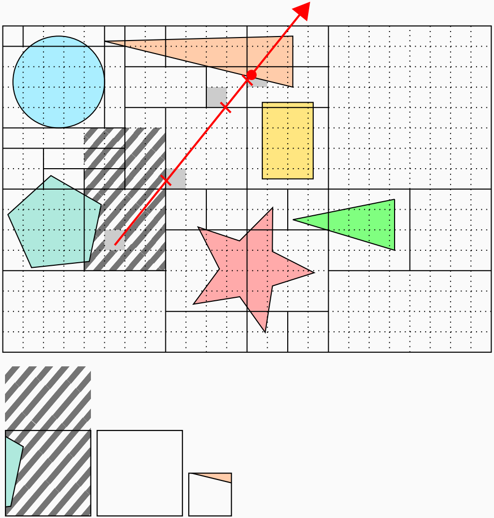

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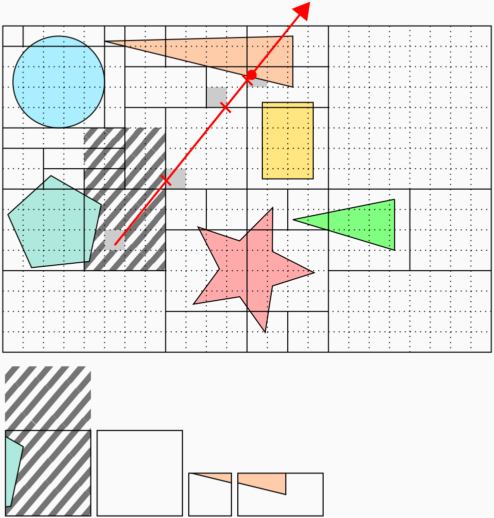

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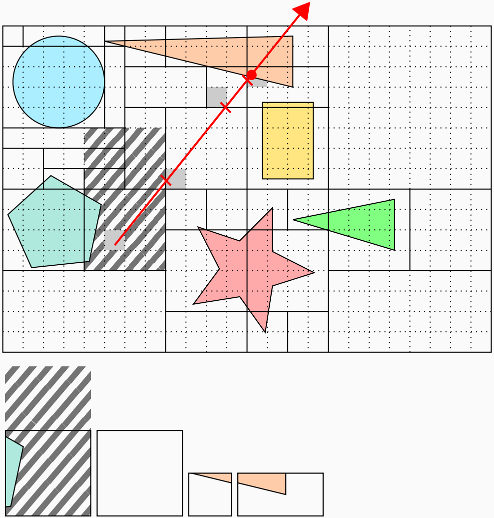

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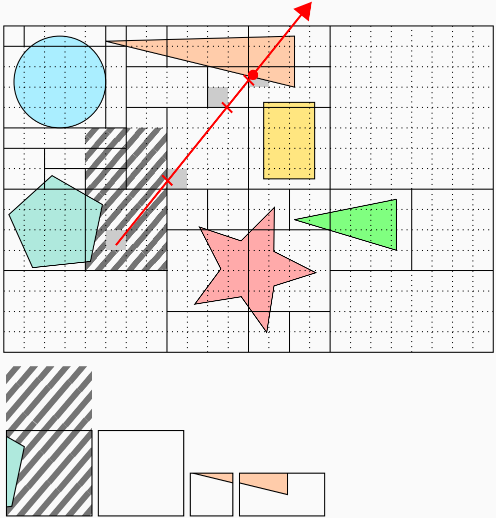

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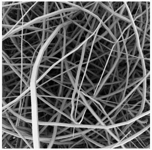
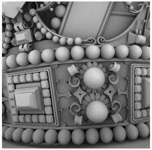
Results

Results: Source Code

GPU implementation

- `https://github.com/madmann91/hagrid`
- Parallel construction & traversal
- CUDA implementation
- MIT license

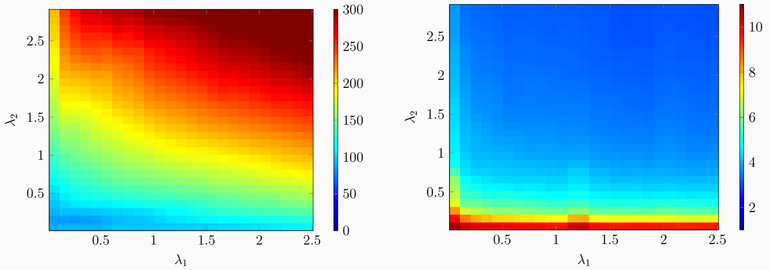
Parameters

- $(\lambda_1, \lambda_2) = (0.12, 2.4)$ for every scene
- Memory footprint $\approx$ SBVH [SFD09]
- Different viewpoints

Results: Static Scenes

Scene	#Tris	Build times (ms)	Primary (MRays/s) SBVH	Primary (MRays/s) Ours	AO (MRays/s) SBVH	AO (MRays/s) Ours	Random (MRays/s) SBVH	Random (MRays/s) Ours
Sponza	262K	26	409 265	653 +60% 473 +78%	270 187	386 +43% 234 +25%	166	274 +65%
Conference	283K	22	583 523	597 +2% 526 +1%	303 326	332 +10% 338 +4%	295	312 +6%
Hairball	2.9M	893	100 79	148 +48% 93 +18%	53 63	69 +30% 61 -3%	19	26 +37%
Crown	3.5M	203	232 181	296 +28% 191 +6%	108 112	120 +11% 125 +12%	221	238 +8%
San Miguel	7.9M	492	227 157	291 +28% 180 +15%	119 125	119 +0% 115 -8%	119	160 +34%

Results: Build Times vs. Traversal Performance



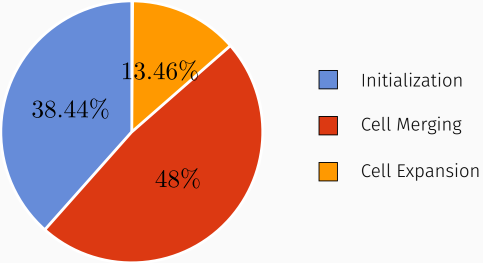
Build Times (ms) Traversal Times (ms)

Lower = Better

Varying parameters for *Crown*

- No local optimum $\neq$ two-level grid
- Increasing density $\implies$ increasing performance

Results: Construction Steps Performance



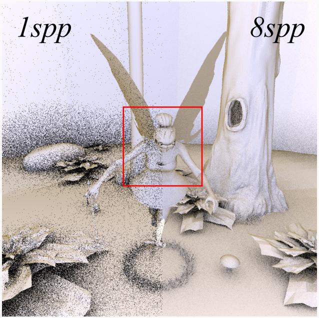
Time spent during construction

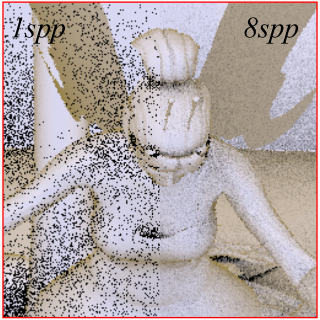
- Average over all static scenes
- Dominated by initialization & merging

Methodology

- Comparison with two-level grids [KBS11]
- Fixed time budget
- Two-level grids: choose optimal resolution
- Irregular grid:
    - Fixed ratio: $\lambda_1 : \lambda_2 = 1 : 8$.
    - Range: $\lambda_1 \in [0.01, 0.3]$, $\lambda_2 \in [0.08, 2.4]$
    - Start at minimum, increase until $T_{build} = 0.5\, T_{budget}$

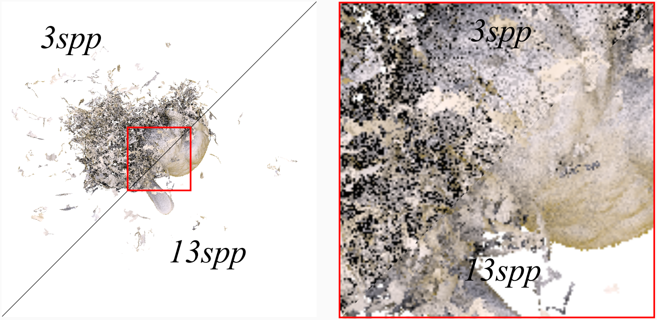
Results: Dynamic Scenes





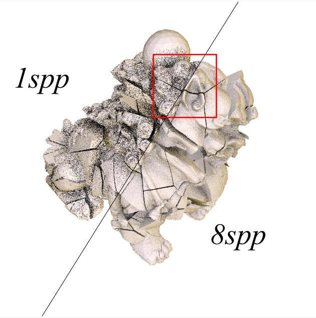
	10FPS (100ms)		20FPS (50ms)		30FPS (33ms)	
	2L Grid	Ours	2L Grid	Ours	2L Grid	Ours
λ_1, λ_2	0.2, 2.0	0.3, 2.4	0.2, 2.0	0.3, 2.4	0.2, 2.0	0.3, 2.4
AO spp	2	20	1	8	0	3

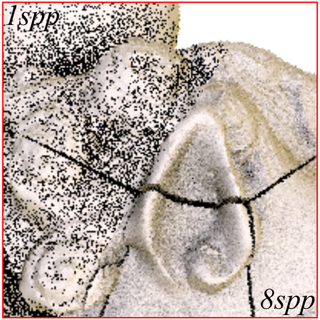
Results: Dynamic Scenes



	10FPS (100ms)		20FPS (50ms)		30FPS (33ms)	
	2L Grid	Ours	2L Grid	Ours	2L Grid	Ours
λ_1, λ_2	0.2, 2.0	0.3, 2.4	0.2, 2.0	0.3, 2.4	0.2, 2.0	0.3, 2.4
AO spp	21	57	8	24	3	13

Results: Dynamic Scenes





	10FPS (100ms)		20FPS (50ms)		30FPS (33ms)	
	2L Grid	Ours	2L Grid	Ours	2L Grid	Ours
λ_1, λ_2	0.03, 0.6	0.3, 2.4	0.03, 0.6	0.02, 0.16	0.03, 0.6	0.01, 0.08
AO spp	1	8	0	1	0	0

Results: Conclusion

Irregular grid properties

- Ordered, stackless traversal
- Same construction/traversal algorithm for:
  - Static scenes
  - Dynamic scenes
- Performance similar/superior to state-of-the-art

Future directions

- Exploring initial subdivision schemes
- Different voxel map structure
- More aggressive optimizations

Questions?

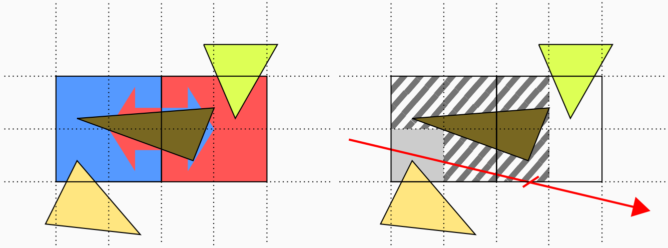
Backup: Related Work

Macro regions

Irregular grid
(uniform initialization)

Macro Regions [Dev89]

- Limited to empty space
- Based on uniform grids



Partial expansion

- Expand cells partially over their neighbors
- Test primitives inside neighbor for intersection
- Implemented in GitHub version
- Additional +10-20% over merge + basic expansion

References

J. G. Cleary et al. “Design and analysis of a parallel ray tracing computer”. In: *Graphics Interface ’83*. 1983, pp. 33–38.

Olivier Devillers. “The Macro-Regions: An Efficient Space Subdivision Structure for Ray Tracing”. In: *EG 1989-Technical Papers*. Eurographics Association, 1989.

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Martin Stich, Heiko Friedrich, and Andreas Dietrich. “Spatial splits in bounding volume hierarchies”. In: *In Proc. of High-Performance Graphics*. 2009, pp. 7–13.