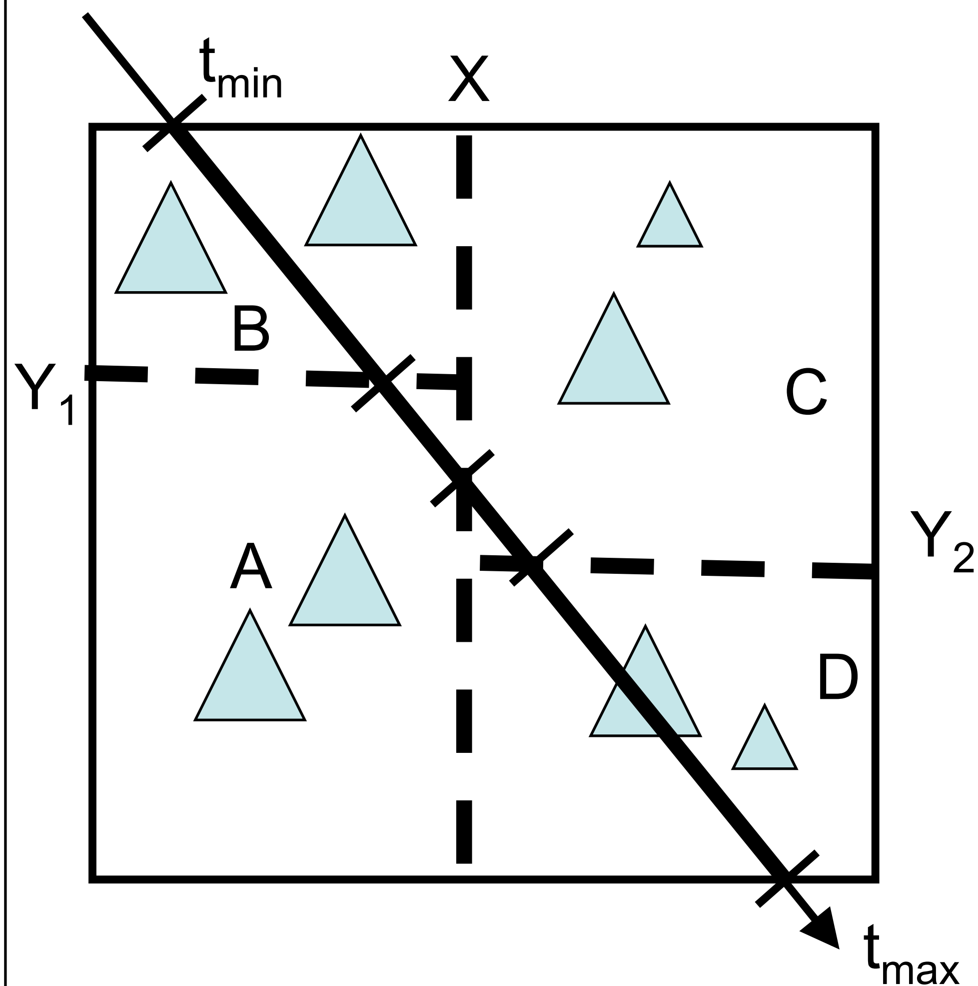
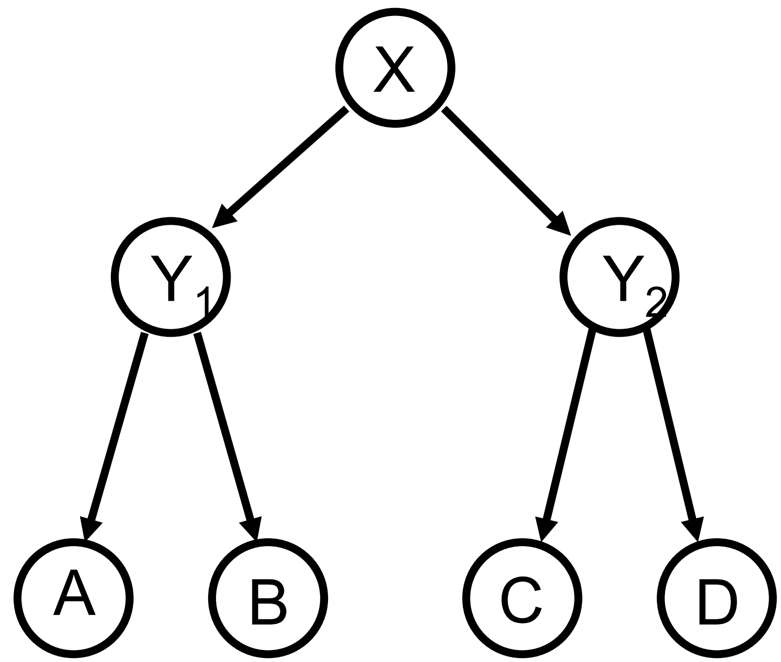
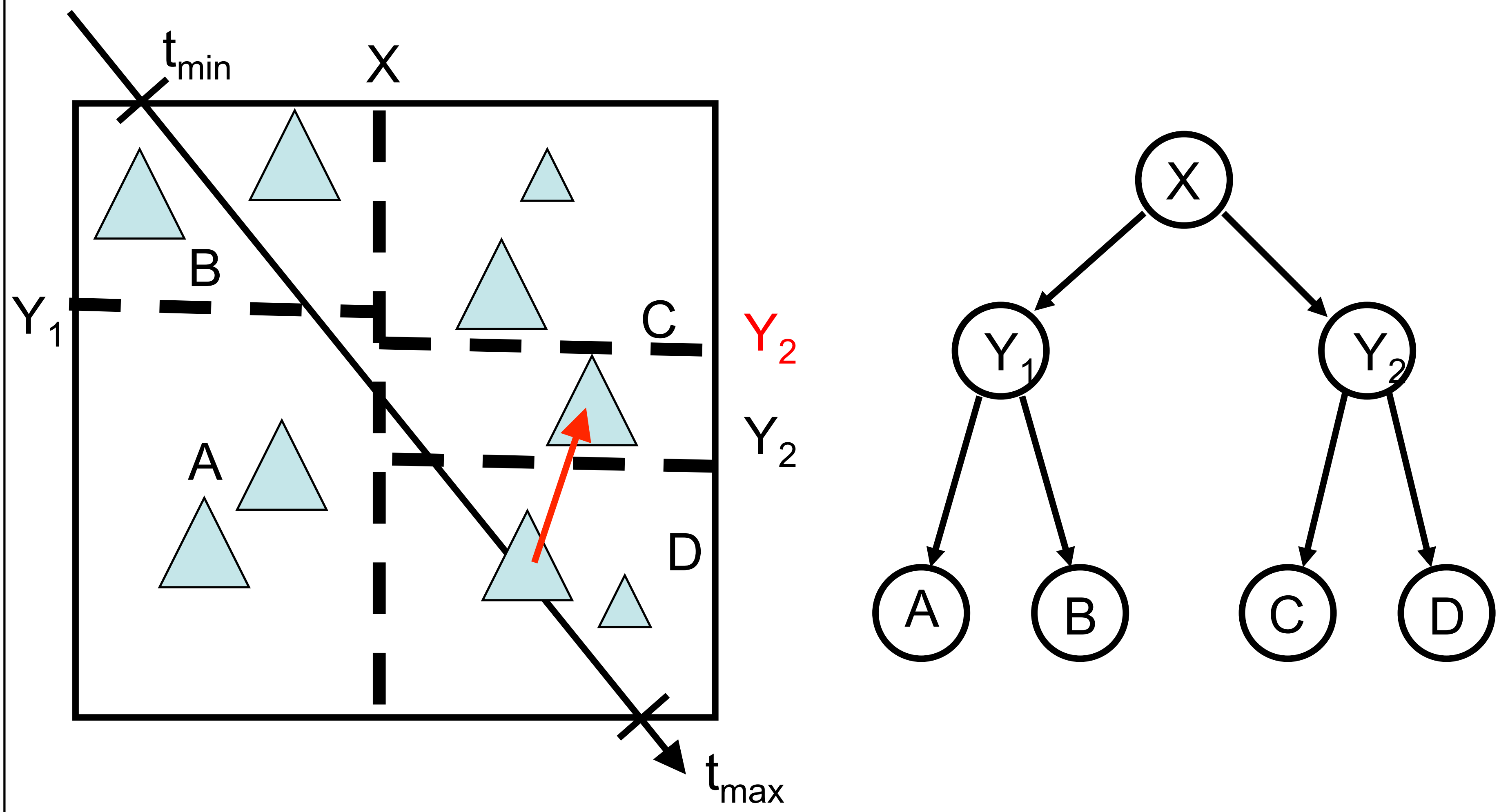
Acceleration Structure for Animated Scenes

KD-Tree for Animated Scene

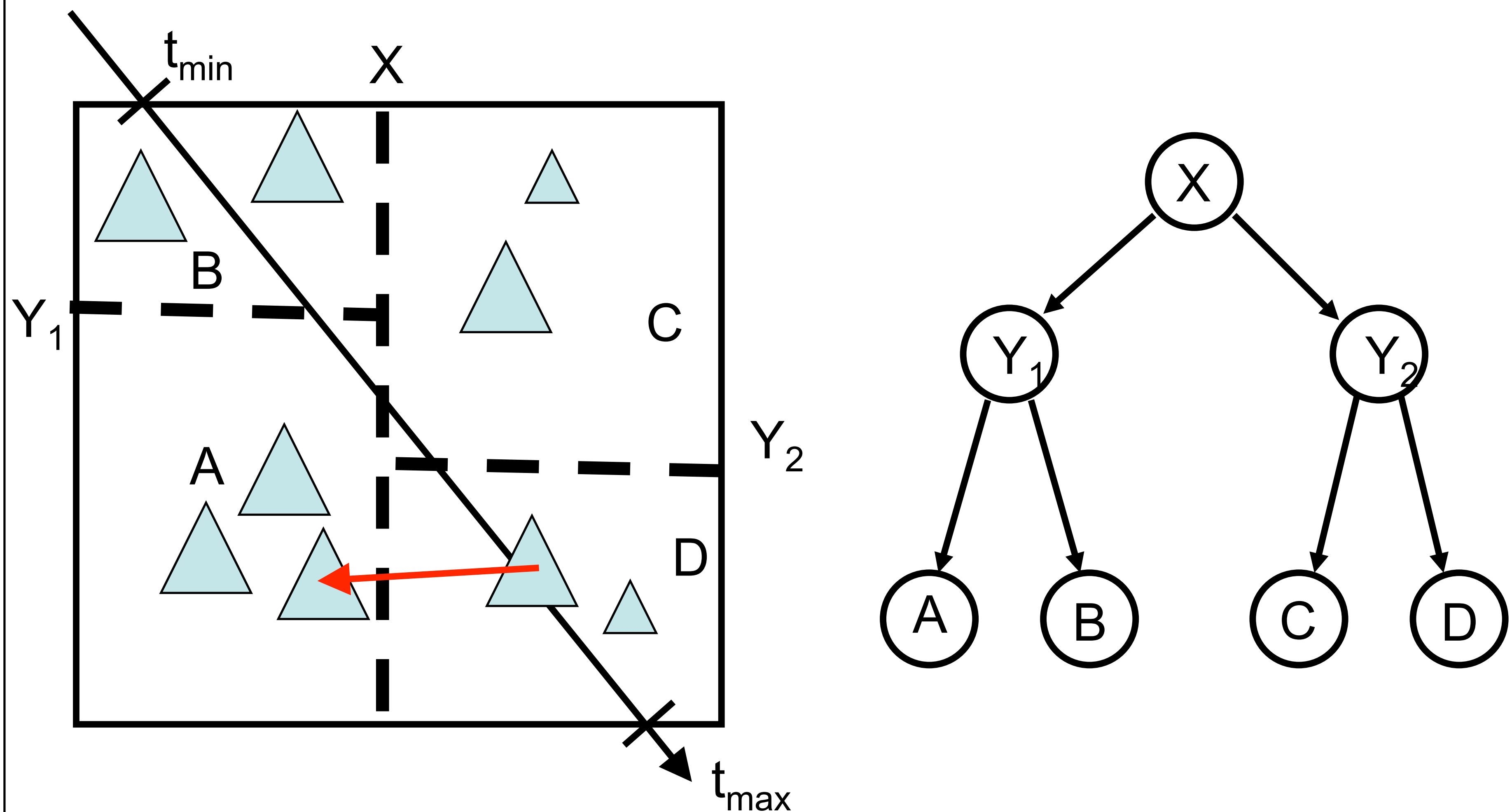




KD-Tree for Animated Scene



Another Case



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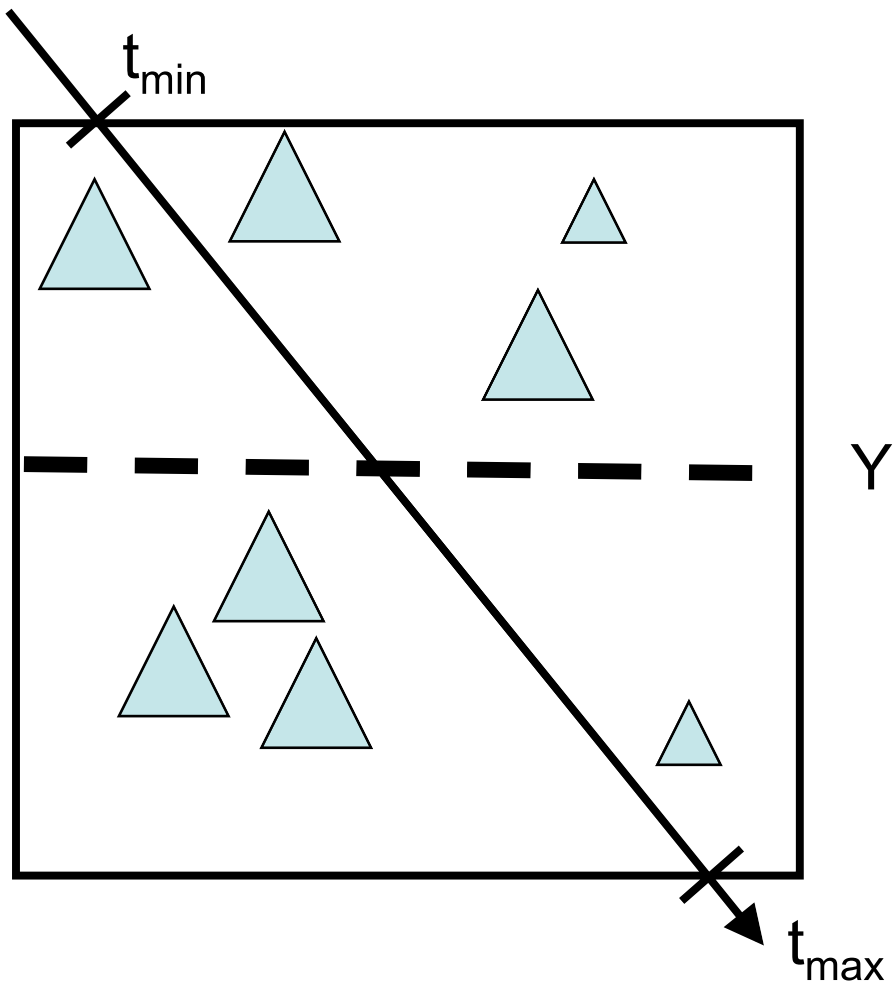
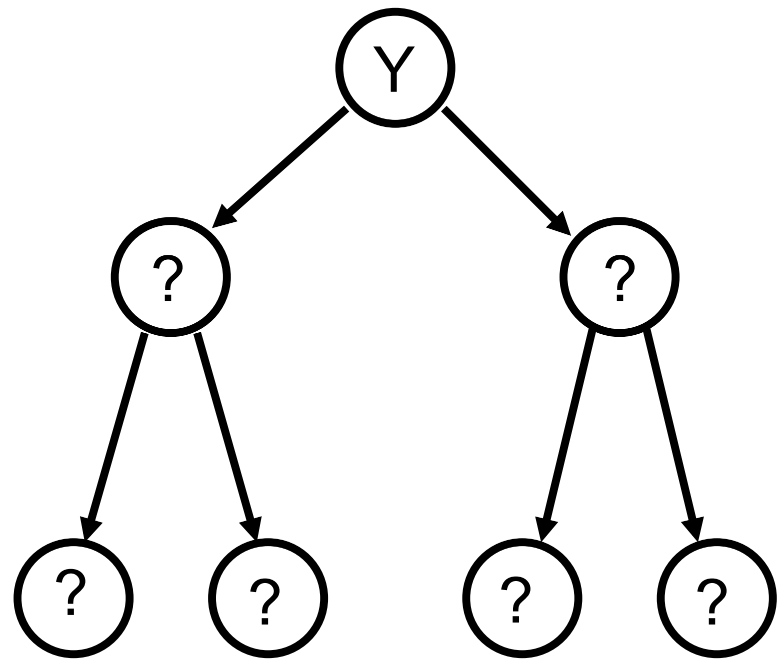


A large tree structure change.
A totally new tree!



Solution

- **Solution 1: Rebuild kd-tree each frame**
  - Rebuild kd-tree in a lazy manner, approximate SAH (Surface Area Heuristics) *[Hunt et al. 06]*
  - Can just move objects bounding boxes around and transform rays (for hierarchical movement) *[Wald et al. 03]*
  - Motion decomposition, fuzzy kd-trees *[Günther et al. 06]*
- **Solution 2: use different hierarchical structure**

Hierarchical Representations for Dynamic Ray Tracing

- **Bounding volume hierarchies (BVHs)**
  - *[Wald et al. 06b, Boulos et al. 06, **Lauterbach et al. 06**]*
- **Grids**
  - ***[Wald et al. 06a]***

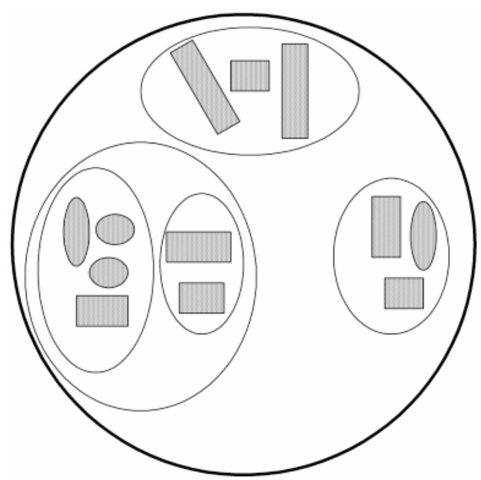
Ray Tracing Dynamic Scenes Using BVHs

[Lauterbach et al. 06]

Dinesh Manocha, Christian Lauterbach
University of North Carolina at Chapel Hill

Bounding Volume Hierarchies: BVHs

- Tree of bounding volumes (sphere, AABB, OBB, k-DOP, spherical shells, etc.)
- Each bounding volume encloses “nearby” primitives
- Parent node primitives are union of children node primitives



Spatial partitioning vs. Object Hierarchies

- **Spatial partitioning:**
  - space is subdivided into disjoint regions (e.g. grid, kd-tree, octree, ...)
- **Object hierarchy:**
  - groups or clusters of objects/primitives are subdivided (BVH, s-kd-tree)

Spatial partitioning vs. Object Hierarchies

- **Implications for ray tracing**
  - Spatial partitioning: Objects referenced in multiple nodes (overlap in object space)
  - BVH Hierarchies: Nodes can overlap each other (overlap in 3D space)
- **Spatial partitioning allows easier front-to -back ordering**

BVHs for intersection tests

- **Widely used for intersection computations**
  - Ray tracing
  - Visibility culling: view frustum and occlusion culling
  - Collision and proximity computations
  - Other applications

BVH based RT algorithm

- **Pretty simple:**
  - Start from root
  - If ray intersects AABB, try all children, too:
    - is inner node: recurse on both children
    - is leaf node: intersect with primitive(s)
- **Naïve implementation far slower than kd-tree!**

Why are BVHs slower?

- **Intersection test more costly**
  - Up to 6 ray-plane intersections for AABB (slabs test)
  - Just 1 for kd-tree
- **No front-to-back ordering**
  - Cannot stop after finding first hit
- **Nodes take more space**
  - 32 bytes vs. 8 bytes

On the other hand…

- **AABBs can provide tighter fit automatically**
  - No empty leafs, tree does not need to be as deep
  - Primitives only referenced once
  - ⇒less nodes in hierarchy
- **#nodes known in advance (*2n-1)***
  - (if 1 primitive/leaf)

More Importantly …

- AABBs can provide tighter fit automatically
  - No empty leafs, tree does not need to be as deep
  - Primitives only referenced once
  - ⇒less nodes in hierarchy
- #nodes known in advance (*2n-1)*
  - (if 1 primitive/leaf)
- **Can be updated easily!**

Hierarchy updates

- **What does updating mean?**
  - Underlying geometry changes
  - Update will ensure correctness of hierarchy without rebuilding it
- **Should be faster than rebuild**

Dynamic Scenes: updating BVHs

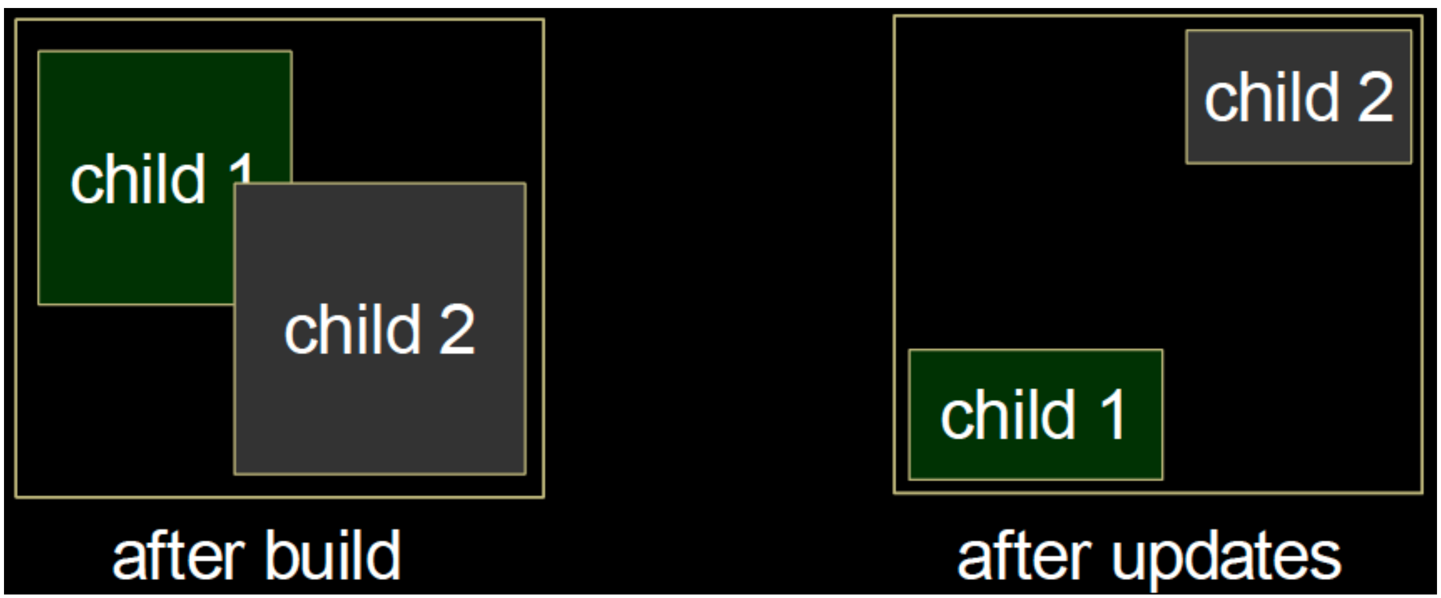
- **Post-order traversal of BVH**
  - Update children's AABB, then update own
  - At leaf level, update from primitives
  - Also update additional information such as axis
- **O(n) time**
  - Usually a few ms for small scenes
  - May become too long for large models!

Dynamic scenes: BVH degradation

- **Quality of BVH may decrease over animation**
  - Update does not change tree topology
  - Rebuild may be necessary
  - How to detect?
- **In worst-case scene:**
  - Performance dropping an order of magnitude over 20 animation frames
  - Not as bad for normal scenes, though

Quality degradation

- Use heuristic to detect degradation
- Assume performance lower when BVHs contain lots of empty space:



Rebuild heuristic

- **How to measure quality?**
  - Use ratio of surface area parent to children
    - SA(parent) / (SA(child1) + SA(child2))
    - Save on rebuild for each node (4 bytes/node)
  - On each update: compare to initial value
  - Sum up differences and normalize
  - If above threshold: initiate rebuild
    - ~30-40% work well in practice

Results

Video

Ray Tracing Animated Scenes using Coherent Grid Traversal

[Wald et al. 06a]

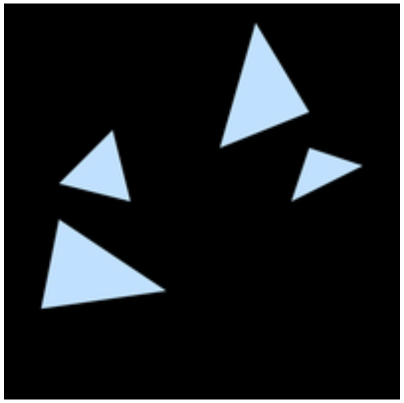
I Wald, T Ize, A Kensler, A Knoll, S Parker
SCI Institute, University of Utah

Coherent Grid Traversal

- A new traversal techniques for uniform grids
- … that makes packet/frustum traversal compatible with grids
- … thus achieves performance competitive with fastest kd-trees
- … and which allows for per-frame rebuilds (dynamic scenes)

What's so special about grids?

- Since 70'ies: Lots of different RT data structures



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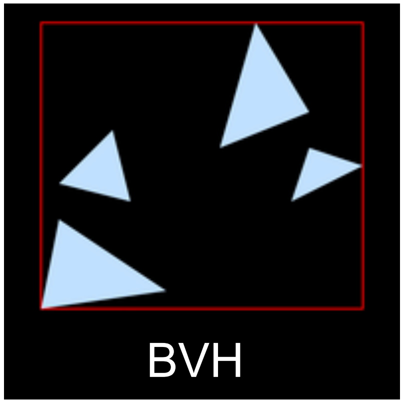

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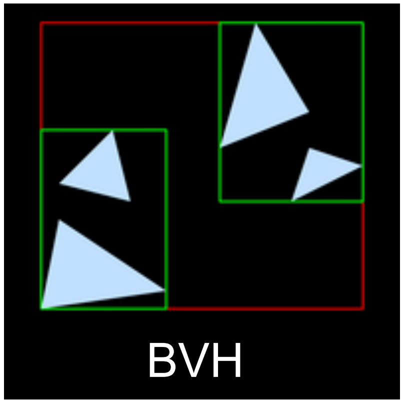

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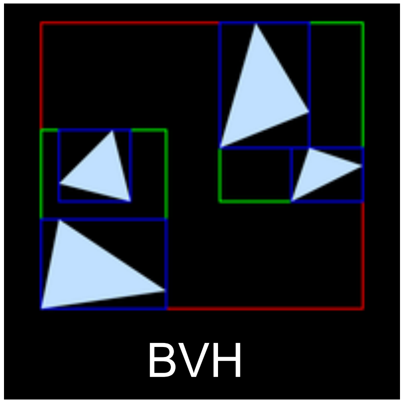

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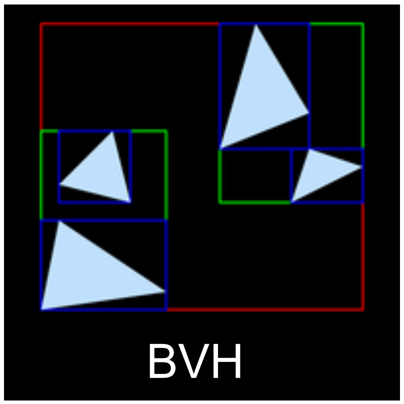

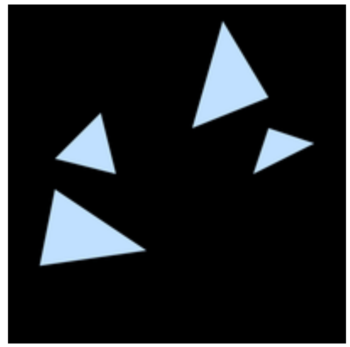

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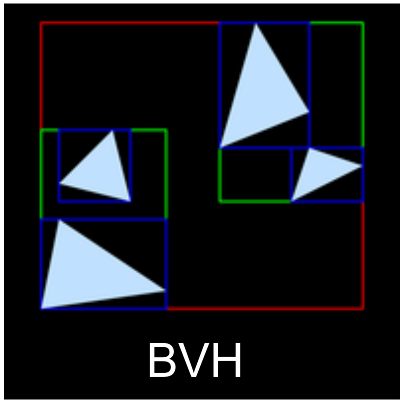

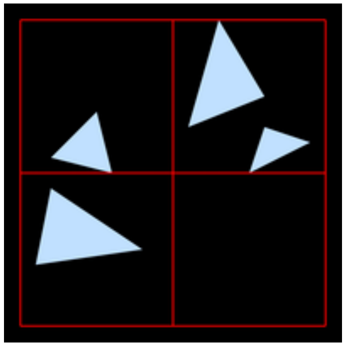

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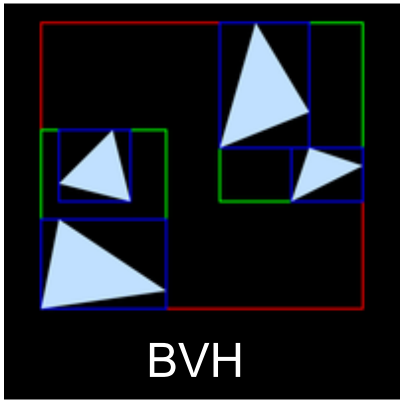

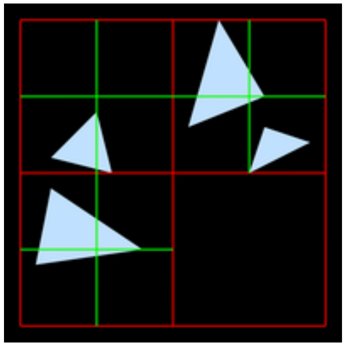

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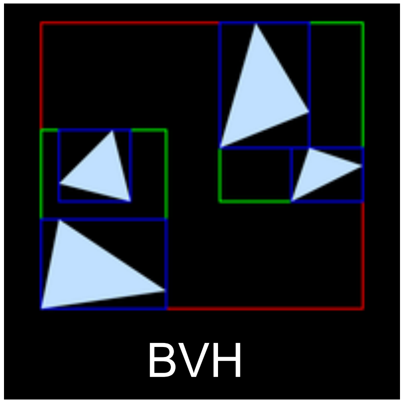

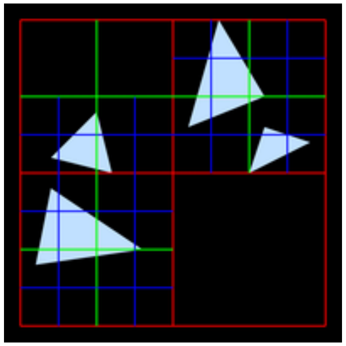

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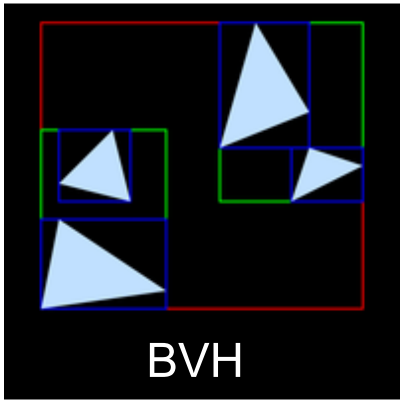

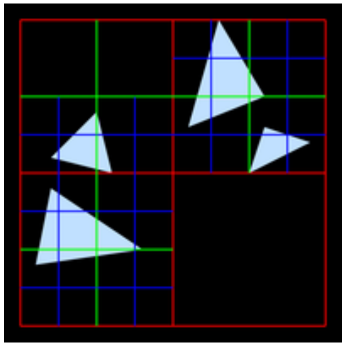

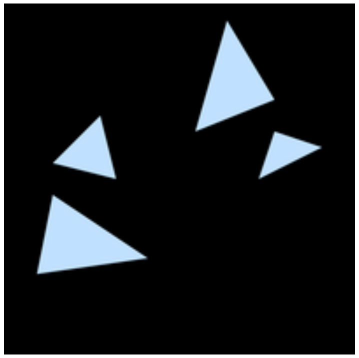

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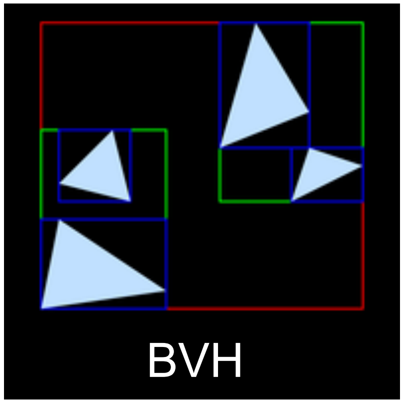

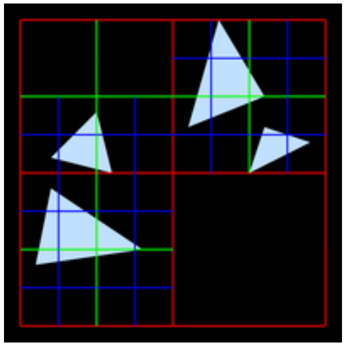

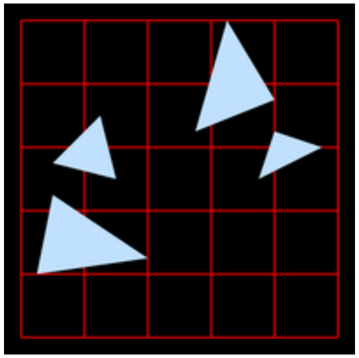

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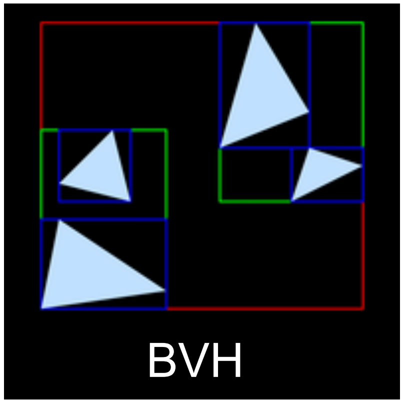

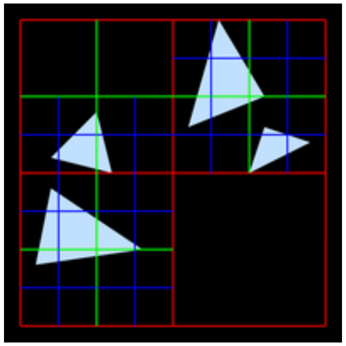

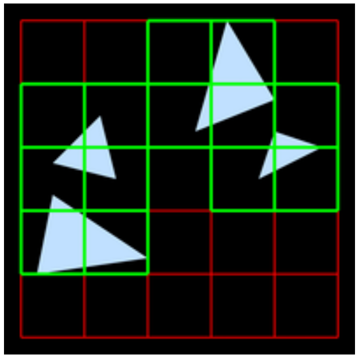

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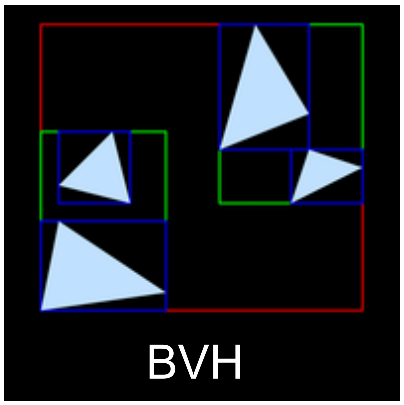

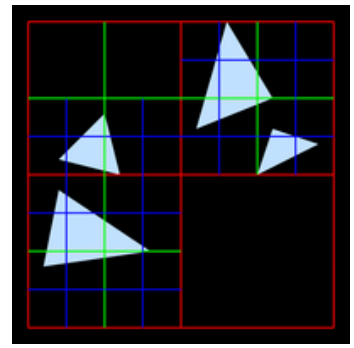

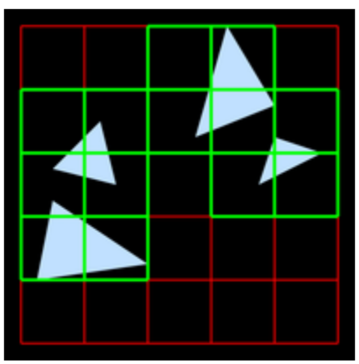

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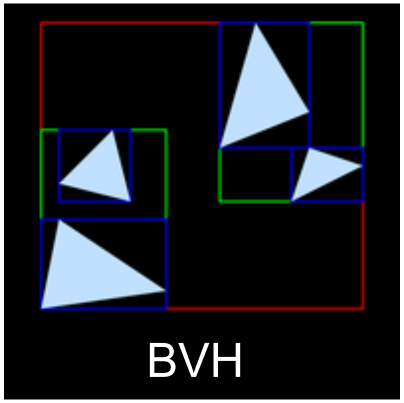

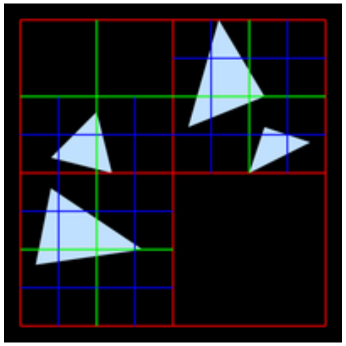

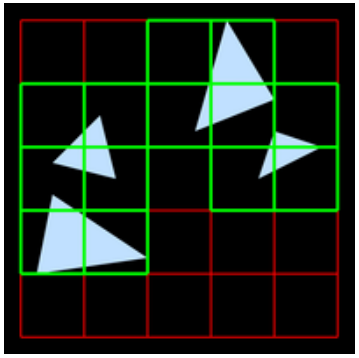

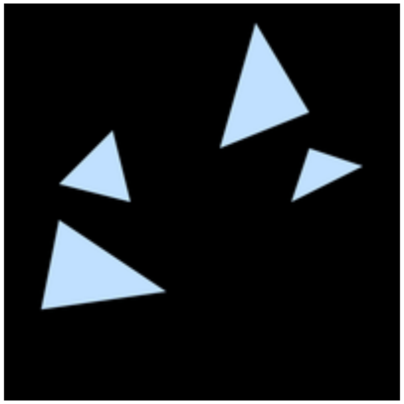

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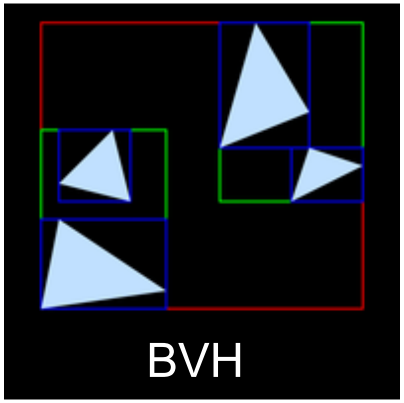

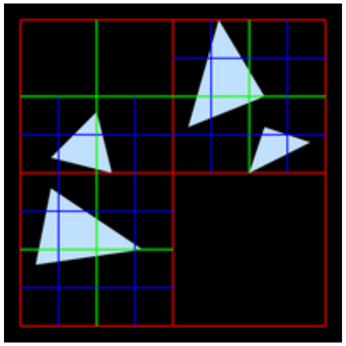

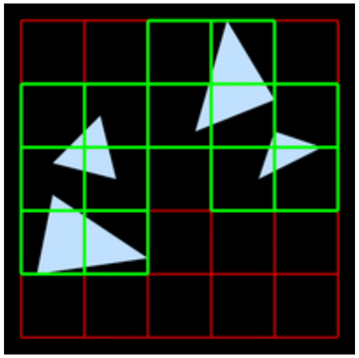

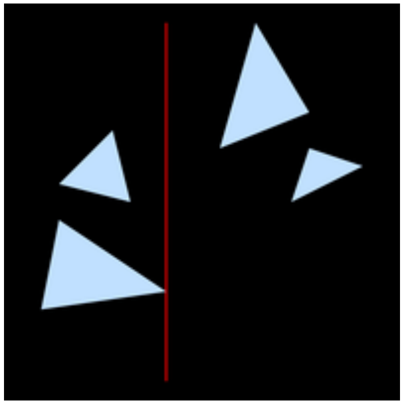

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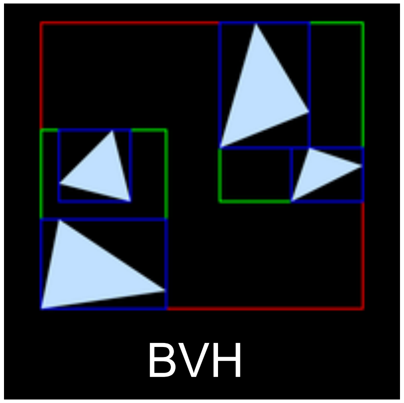

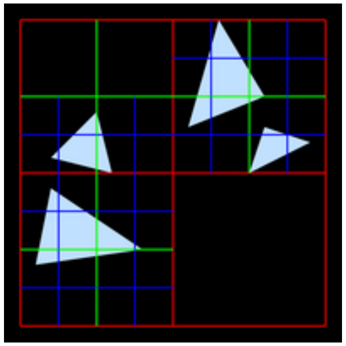

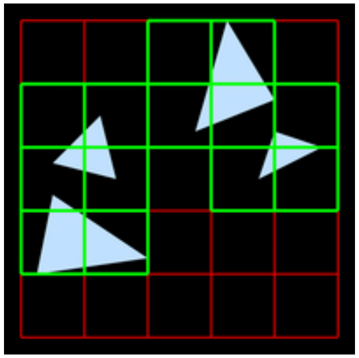

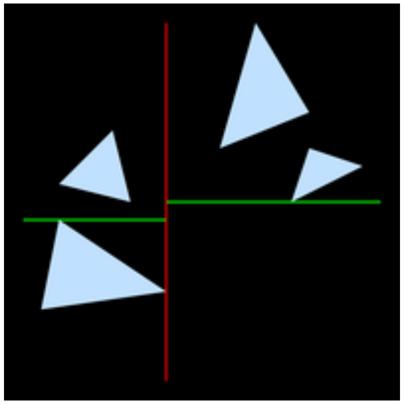

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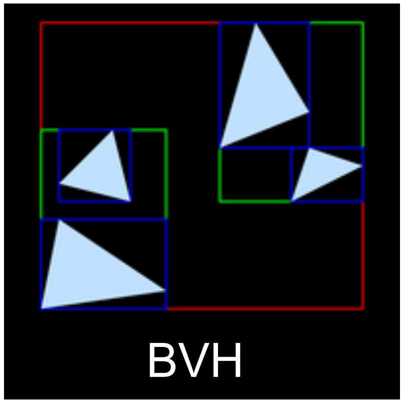

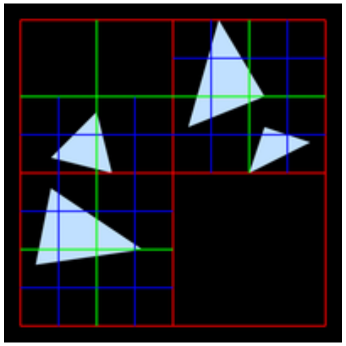

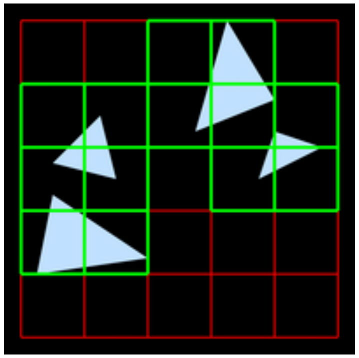

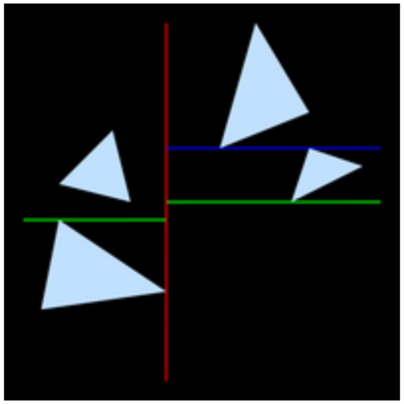

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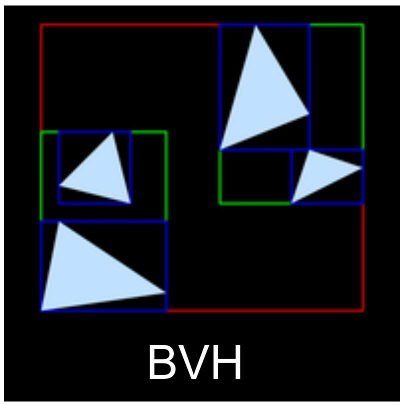
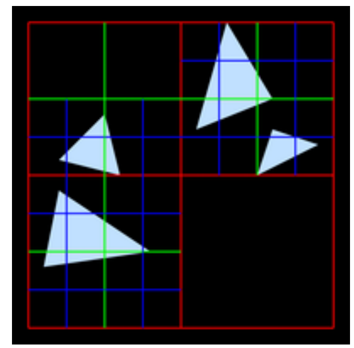
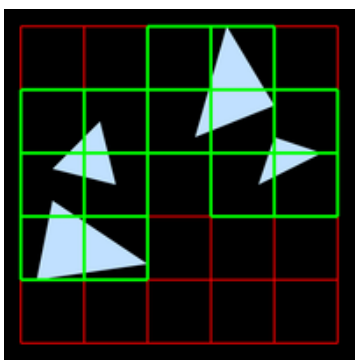
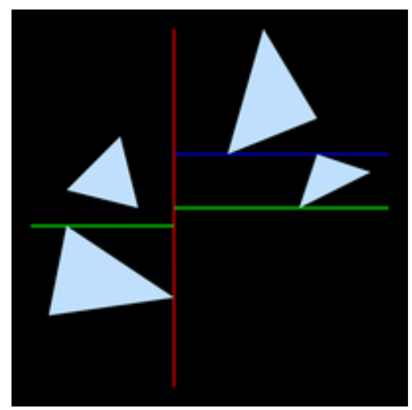








→ Of all these, grid is only that is *not* hierarchical !

What's so special about grids?

- **Grid is not hierarchical…**
  - → Much simpler to build (similar to 3D -rasterization, very fast)
    - Build-times in the paper: 2.2M "Soda Hall" in 110 ms
  - → Ideally suited for handling dynamic scenes
    - Full rebuild every frame, no restrictions at all !

What is so special about dynamic scenes ?

- **All of the recent advancements of RT are for kd-trees !**
  - Pre-2000: Tie between grids and kd-trees…
  - [Wald '01]: New concept → "coherent ray tracing" (for kd-tree)
    - Trace "packets" of coherent rays → 10x faster than single rays
  - [Woop '05]: First RT hardware prototype → RPU (for kd-tree)
  - [Reshetov '05]: New concept → "multilevel ray tracing" (kd-tree)
    - Trace packets using bounding frusta → another 10x faster than CRT !
- **But: (good) kd-trees are (too) costly to build…**

Ray Tracing & Dynamic Scenes

- **SIGGRAPH ‘05: Dynamic Scenes huge problem**
  - Ray tracing has become very fast (MLRT: ~100fps)
  - If ray tracing is to ever replace rasterization, it must support dynamic scenes (games…)
  - But: All our fast RT algos are for kd-trees…
  - … and kd-trees can’t do dynamic scenes …

Ray Tracing & Dynamic Scenes

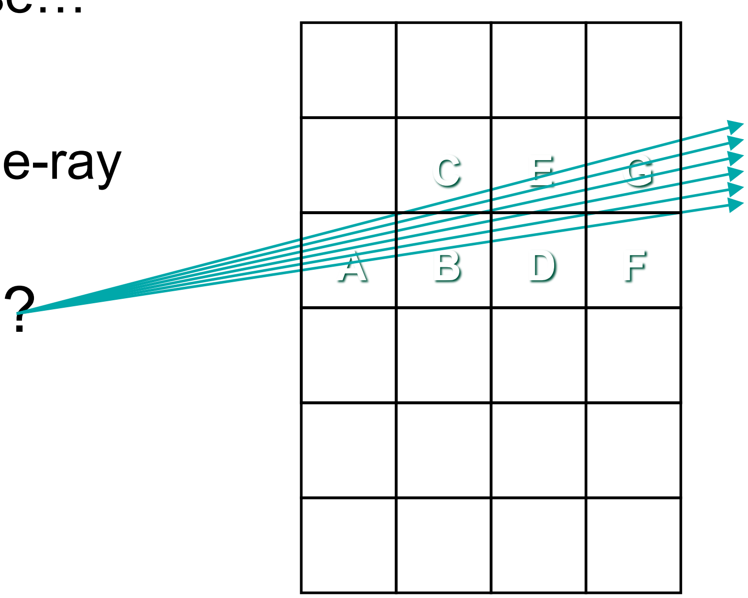
- **SIGGRAPH '05: Dynamic Scenes huge problem**
- **Since then, lots of research**
  - Lazy kd-tree construction (Razor [Stoll, Mark '06])
  - Fast BVH and kd-tree construction (yet unpublished)
  - Motion decomposition [Günther et al. '06]
  - Dynamic BVHs [Wald et al. '06, Lauterbach et al. '06]
  - Hybrid BVH/kd-trees [Woop '06, Havran '06, Wachter '06, …]
  - Coherent Grid Traversal [Wald et al. '06]

Using grids for dynamics – Where's the problem ?

- **2005: Grid too slow to traverse (vs kd-tree)…**
- **Fact: Fast RT needs "packets" & "frusta" concepts**
  - Traverse multiple packets over same node of DS
- **Rather simple for hierarchical data structures…**
  - Test both children in turn for overlap w/ packet
  - If child overlaps: traverse it, else: skip it.
    - (it's as simple as that)
- **… but not for grids**

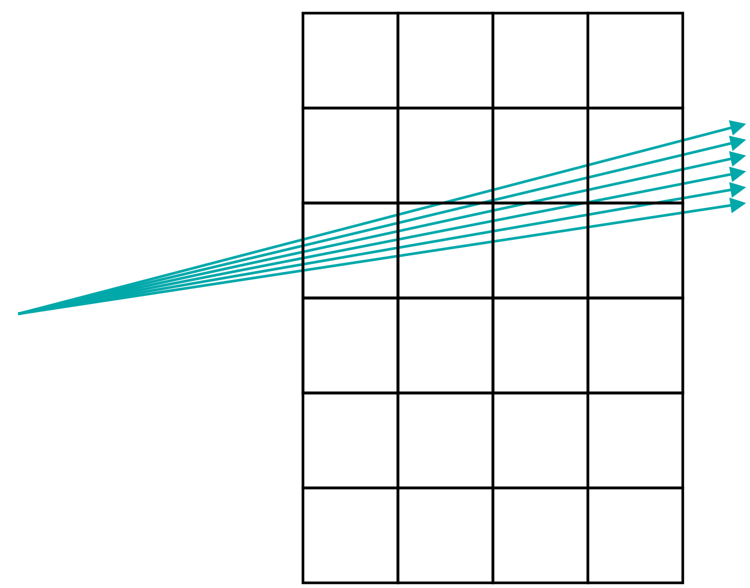
Grids and Packets – Where's the problem ?

- **Packets & grids: "Non-trivial task"**
  - In which order to test the nodes ? ABCD or ABDC ?
  - What to do when packet diverges?
    - 3DDDA etc break in that case…
  - Split diverging packet ?
    - Quickly degenerates to single-ray traversal…
  - Fix by re-merging packets ?
    - Non-trivial & costly …



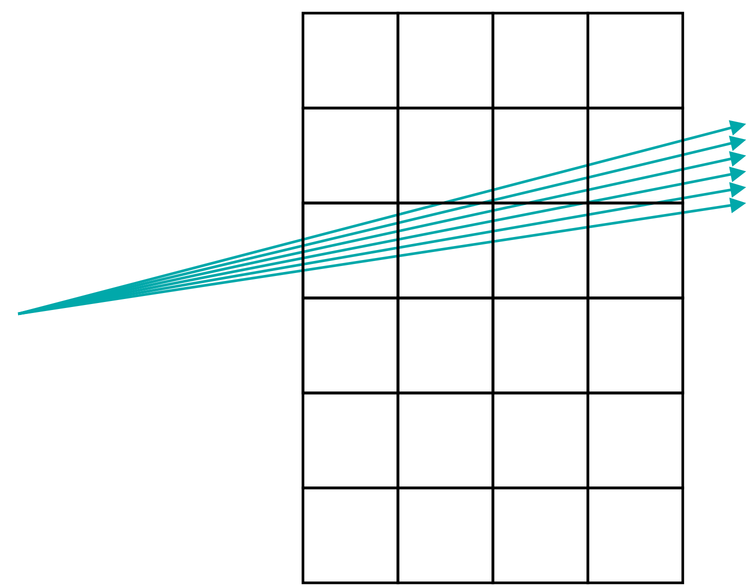
Coherent Grid Traversal

- **First: Transform all rays into "canonical grid space"**
  - i.e., [0,0,0]-[Nx,Ny,Nz]



Coherent Grid Traversal

- Idea: Consider only frustum, not "set of rays"



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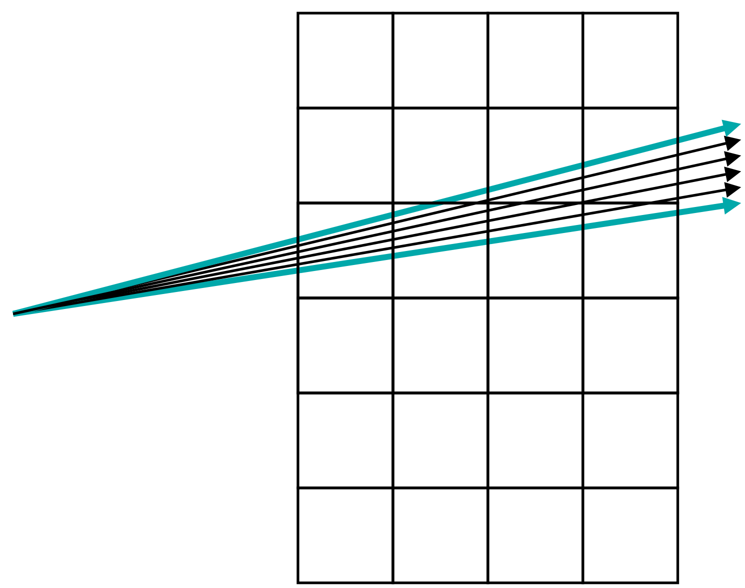
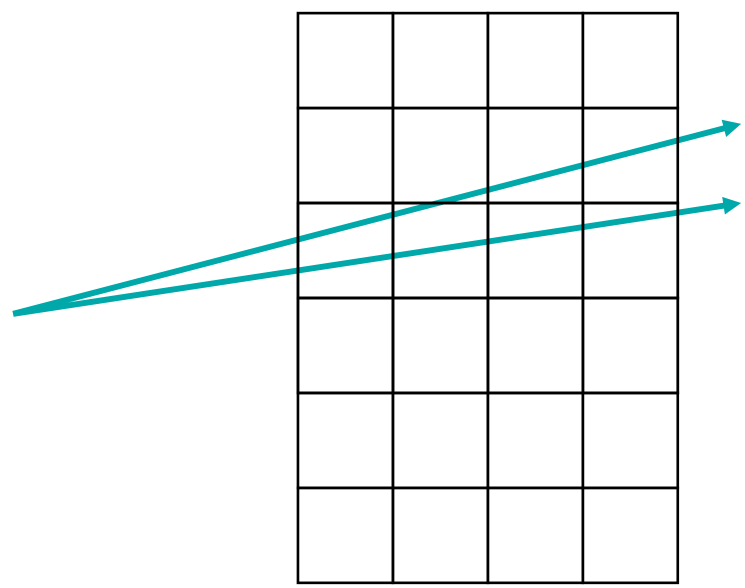


Coherent Grid Traversal

- **Idea: Consider only frustum, not "set of rays"**
  - Traverse "slice by slice" instead of "cell to cell"
    - Pick "major traversal axis" (e.g., max component of 1st ray)



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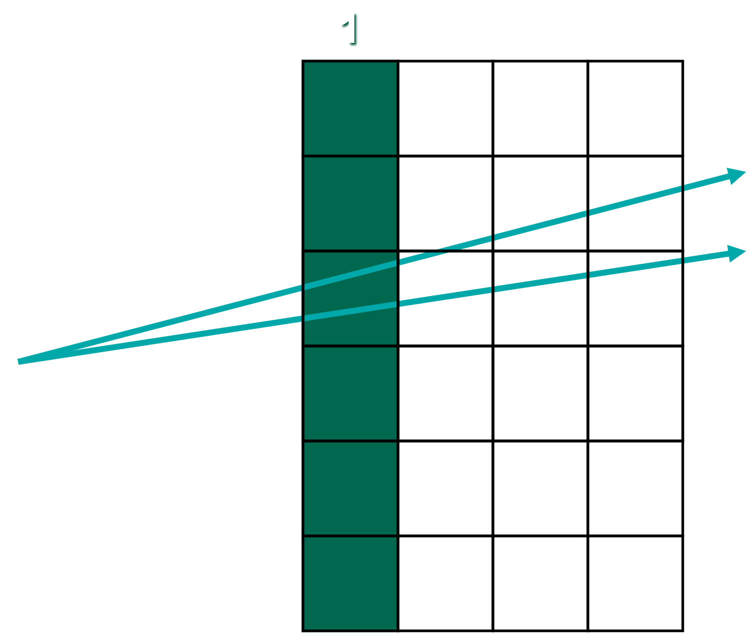

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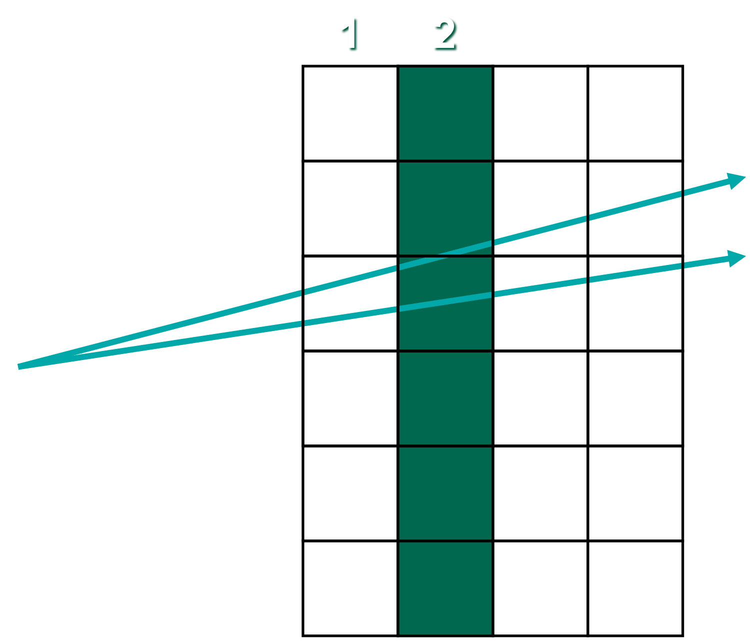

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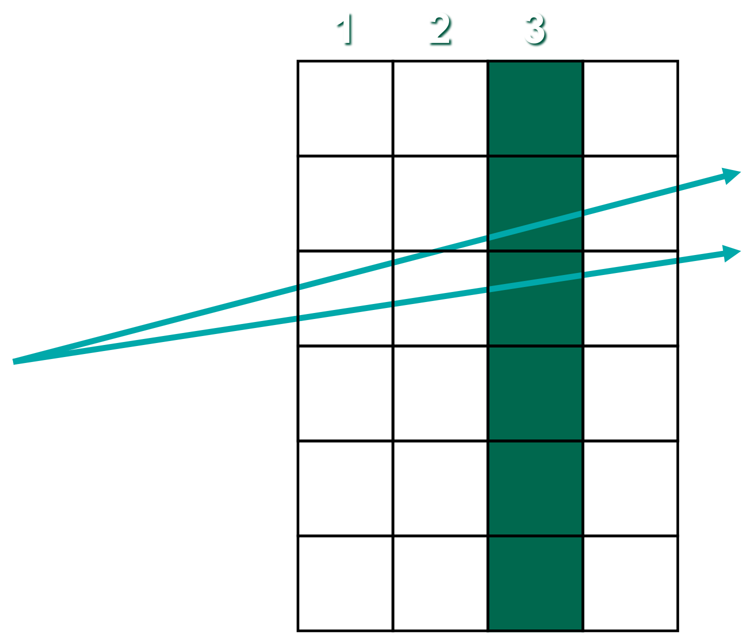

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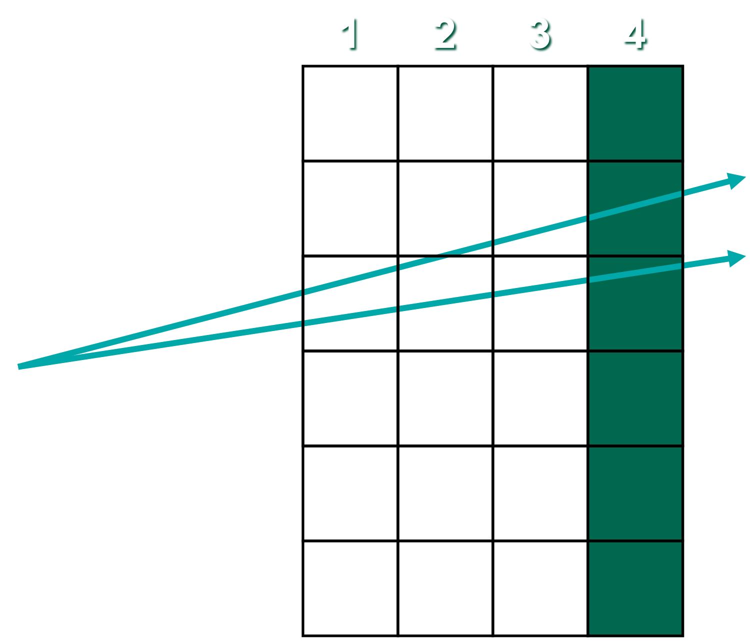

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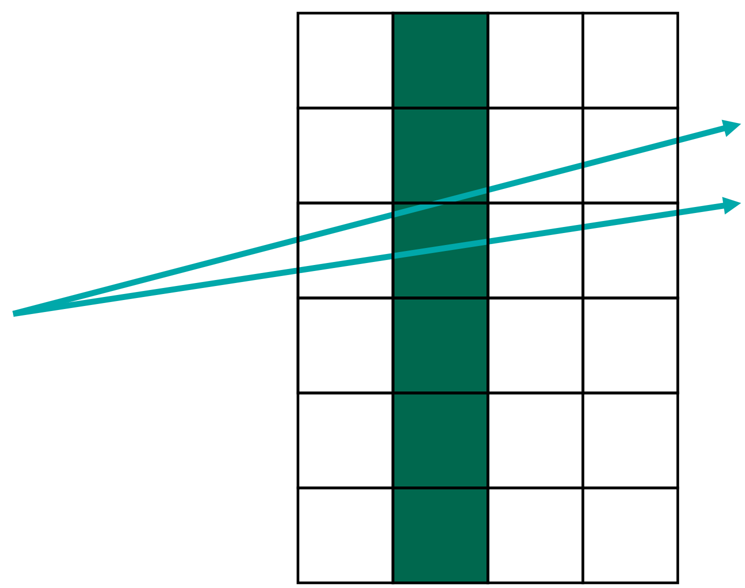
  - For each slice, compute frustum/slice overlap



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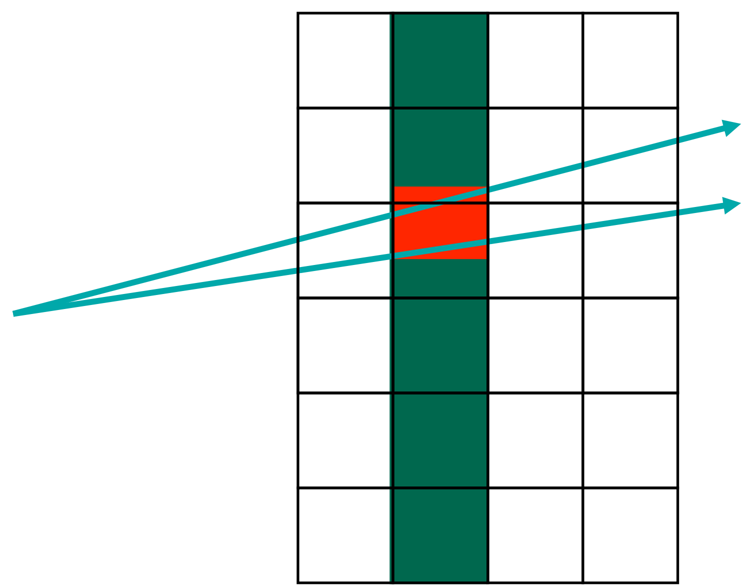

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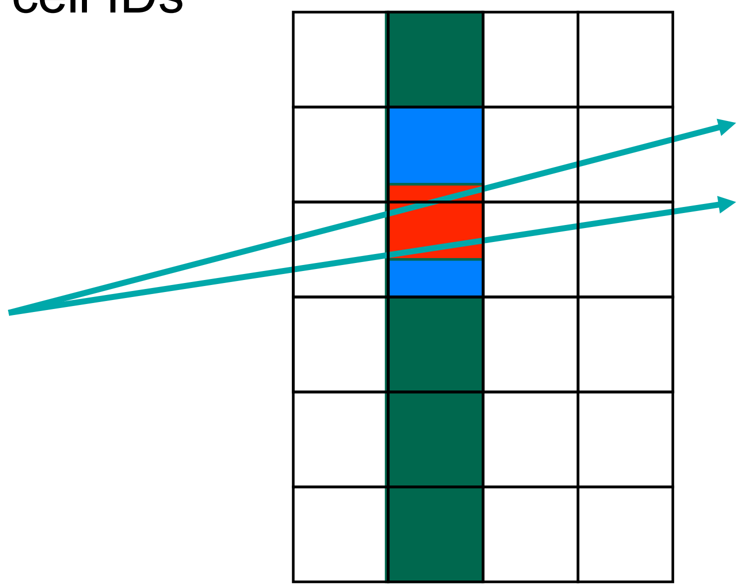

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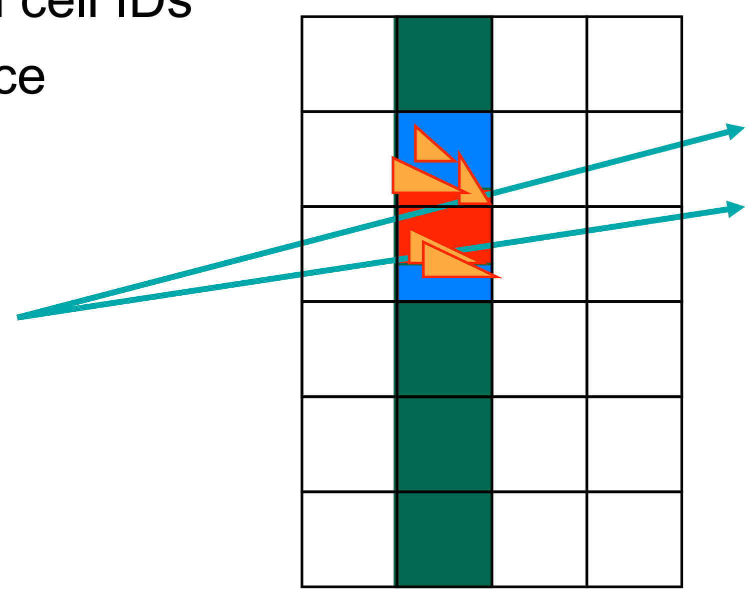

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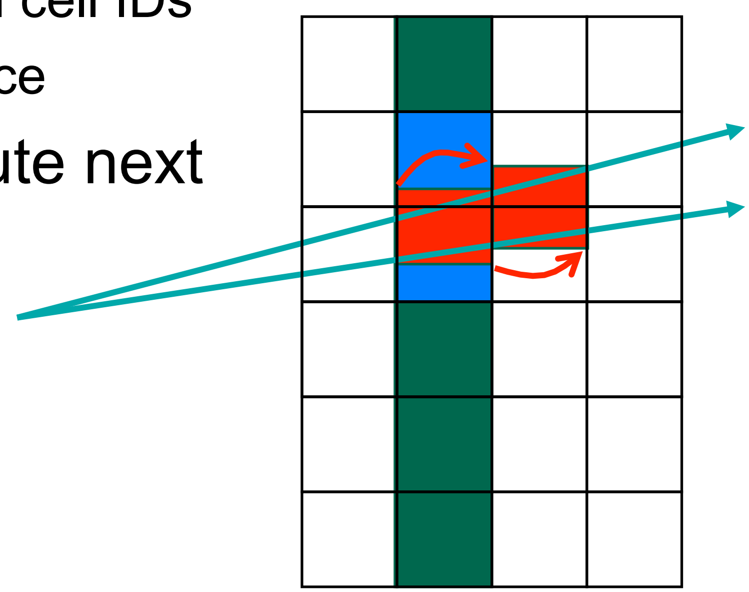
  - Loop: incrementally compute next slice's overlap box
    - 4 additions…



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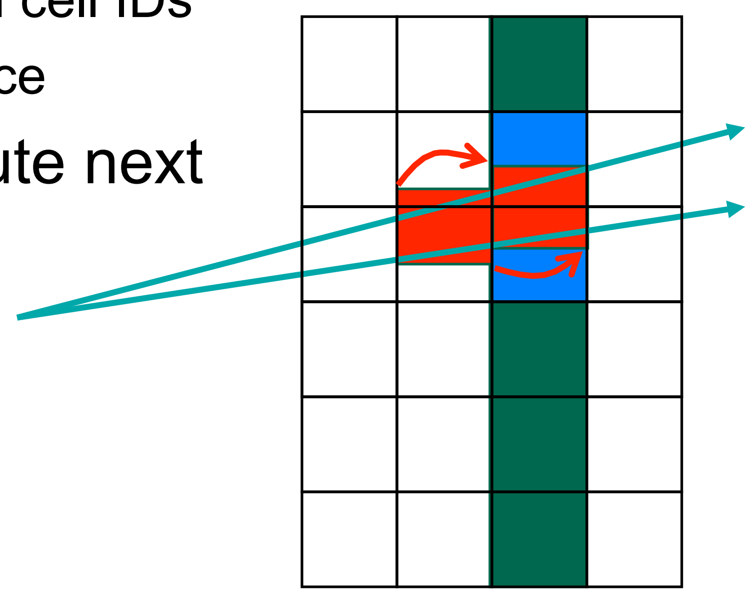
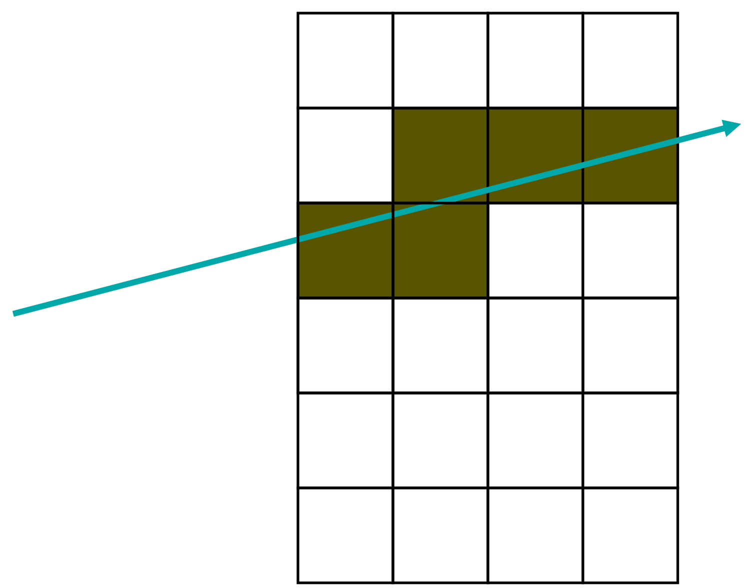


CGT features

- **Expensive setup phase**
  - Transform rays to canonical grid coordinate system
  - Determine major march direction (simple)
  - Compute min/max bounding planes (slopes and offsets)
  - Compute first and last slice to be traversed (full frustum clip)
- **But: Very simple traversal step**
  - Overlap box update: 4 float additions (1 SIMD instruction)
  - Get cell IDs: 4 float-to-int truncations (SIMD…)
  - Loop over overlapped cells (avg: 1.5-2 cells per slice)

Traversal fast, but …

- Grid usually less efficient than kd-tree



Traversal fast, but …

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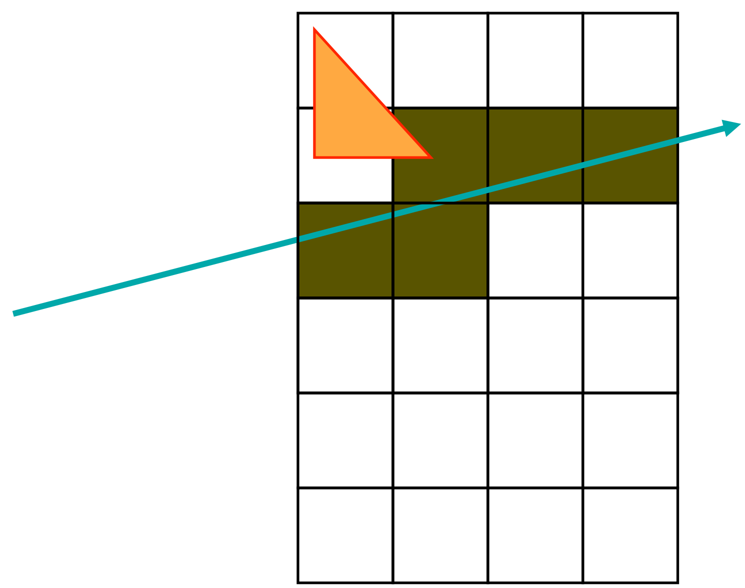
  - Cannot adapt to geometry as well → more intersections



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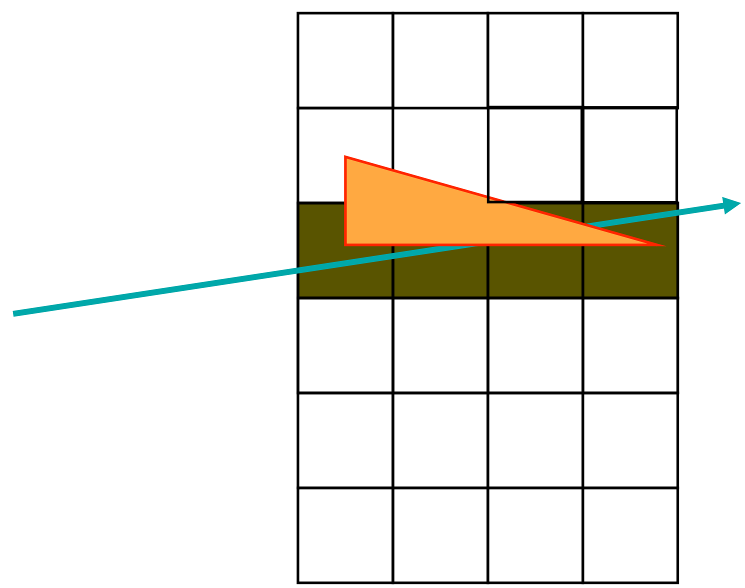

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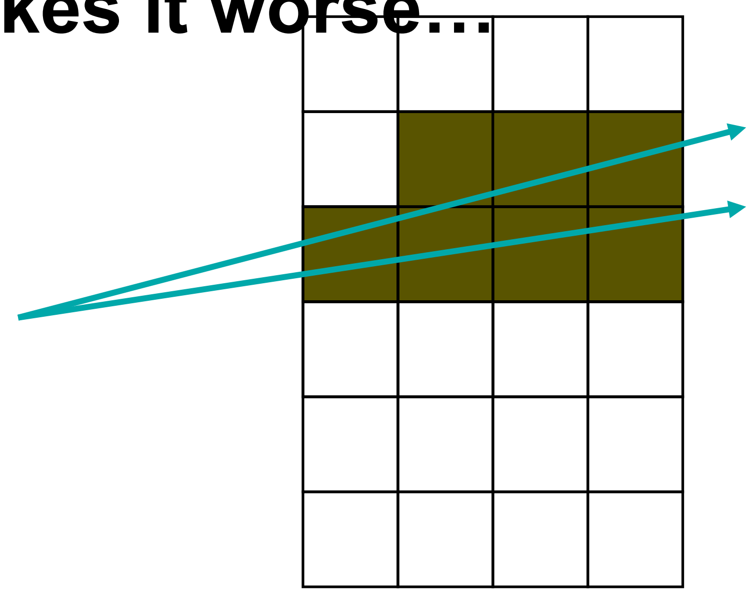

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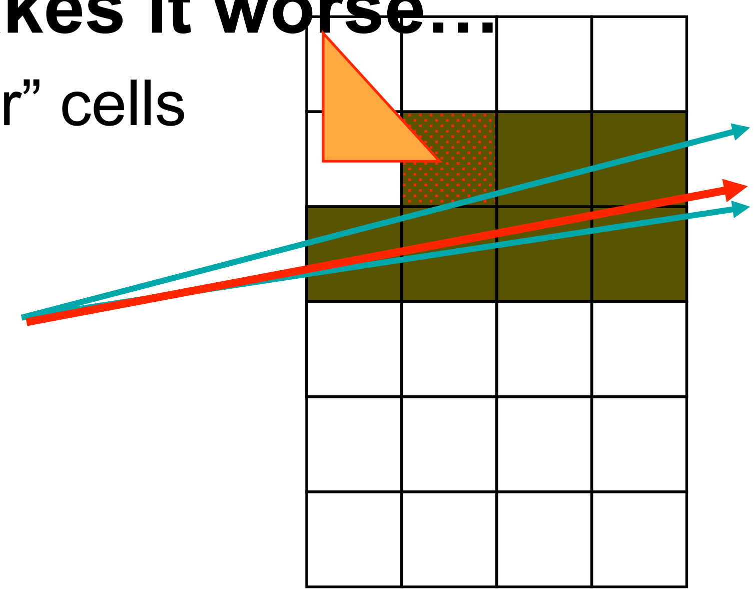

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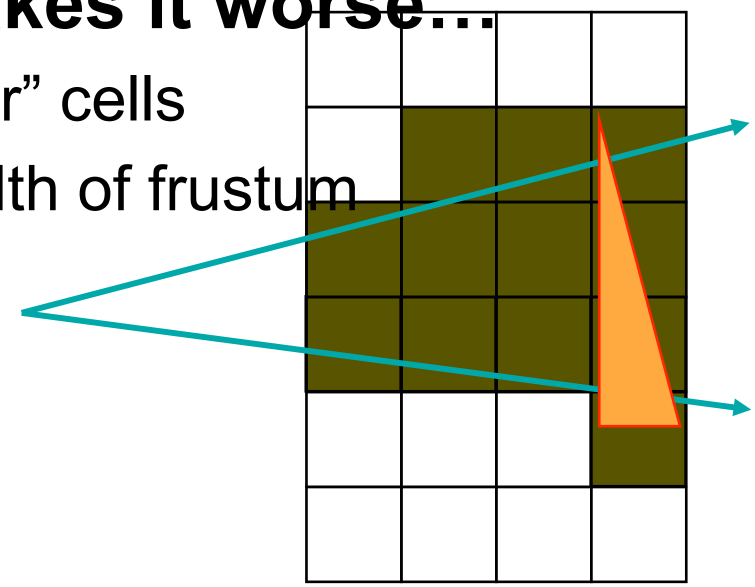
  - Re-isec aggravated by width of frustum



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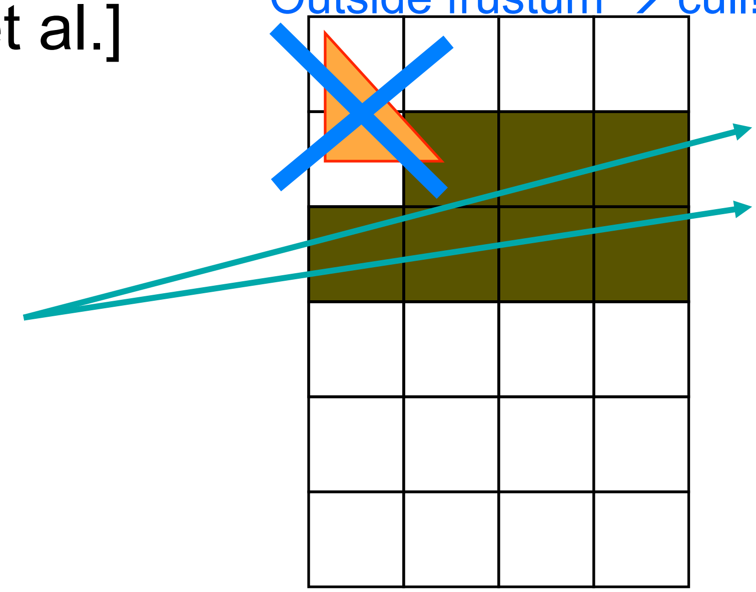
  - Bad culling → SIMD Frustum culling in Packet/Tri Isec [Dmitriev et al.]



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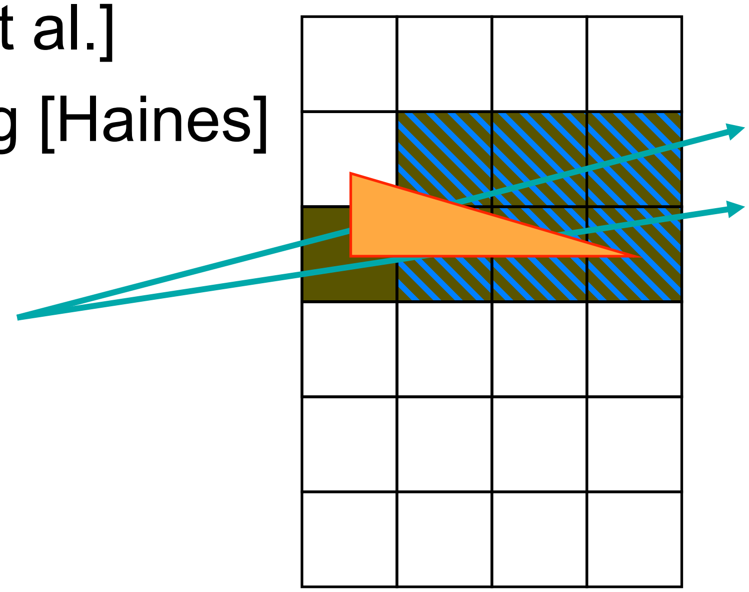
- First sight: Frustum makes it worse…
- But: Two easy fixes
  - Bad culling → SIMD Frustum culling in Packet/Tri Isec [Dmitriev et al.]
  - Re-intersection: Mailboxing [Haines]



CGT efficiency

- **Surprise: Mailboxing & Frustum culling very effective**
  - Both standard techniques, both limited success for kd-trees
  - Grid & Frustum: Exactly counter weak points of CGT …
    - “Hand”
      - Grid w/o FC & MB : 14 M ray-tri isecs
      - Grid with FC & MB: .9 M ray-tri isecs (14x less)
      - Kd-tree : .85M ray-tri isecs (5% less than grid)
  - And: cost indep of #rays → very cheap (amortize)

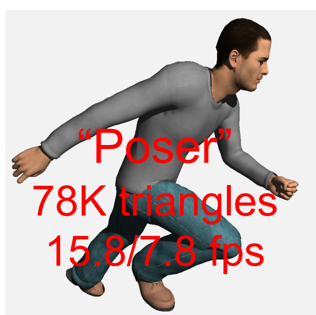
Results

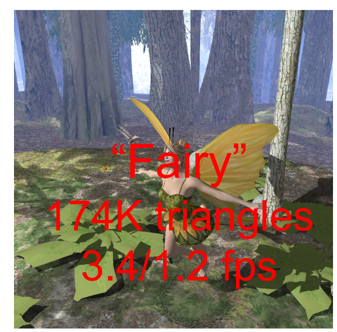
Impact of Method: Compare to single-ray & kd-tree

- **Comparison to single-ray grid**
  - Fast single-ray traverser, macrocell if advantageous, …
  - Speedup 6.5x to 20.9x, usually ~10x
- **Comparison to kd-tree**
  - To OpenRT: 2x-8x faster (2M Soda Hall: 4.5x)
  - To MLRT: ~3x slower (but much less optimized)
  - Tests performed on "kd-tree friendly" models

Overall Performance

- **Build time: Usually affordable even on single CPU…**
- **Traversal results (1024^2, dual 3.2 GHz Xeon PC)**
  - X/Y: X=raycast only; Y=raytrace+shade+texture+shadows





Discussion

- **Comparison to state-of-the-art BVH or kd-tree**
  - Somewhat harder to code and "get right" than, e.g., BVH
  - Usually somewhat slower (~1.5x-3x)
  - More susceptible to incoherence & teapot-in-stadium cases
    - Pure frustum tech.: Visits all cells in frustum even if not touched by any ray!
- **BUT:**
  - It works at all ! (Who'd have thought 12m ago ?)
  - ~10x faster than single-ray grid
  - Benefits better from additional coherence (4x AA at 2x cost)
  - "Maybe" better suited for regular data or special HW (Cell, GPUs)
  - Most flexible wrt dynamic → no limitation at all

Conclusion

- Have developed a new technique that
- Makes grid compatible with packets & frusta
- Is competitive with BVHs and kd-trees
- Most general in handling dynamic scenes

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