EUROGRAPHICS 2016
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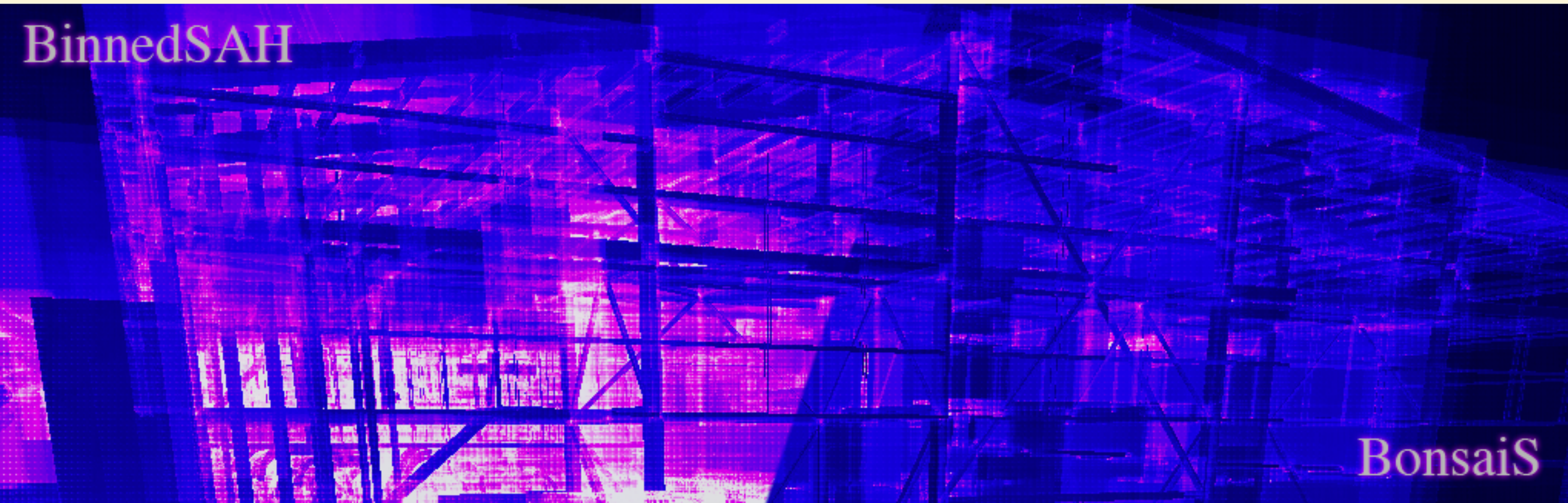
EUROPEAN ASSOCIATION FOR COMPUTER GRAPHICS

SAH guided spatial split partitioning for fast BVH construction

Per Ganestam and Michael Doggett
Lund University

Opportunistic triangle splitting for higher quality BVHs

- Bounding Volume Hierarchies (BVH) are a simple, compact 3D data structure commonly used in Ray Tracing
- Objective is fast construction, fast tracing, and minimal memory
- Traversal cost : Whiter pixels means higher cost



BVH construction

- Focus on a top down approach
- Recursively subdivide triangles
  - Decide where to divide
    - Surface Area Heuristic (SAH) measures cost
    - Sweep SAH is a greedy top down method
- Creating a binary tree

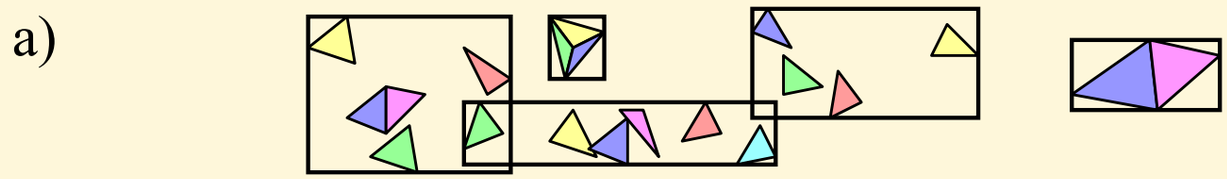
Surface Area Heuristic

$$C_i \sum_{n \in I} \frac{A(n)}{A(root)} + C_l \sum_{n \in L} \frac{A(n)}{A(root)} + C_t \sum_{n \in L} \frac{A(n)}{A(root)} N(n),$$

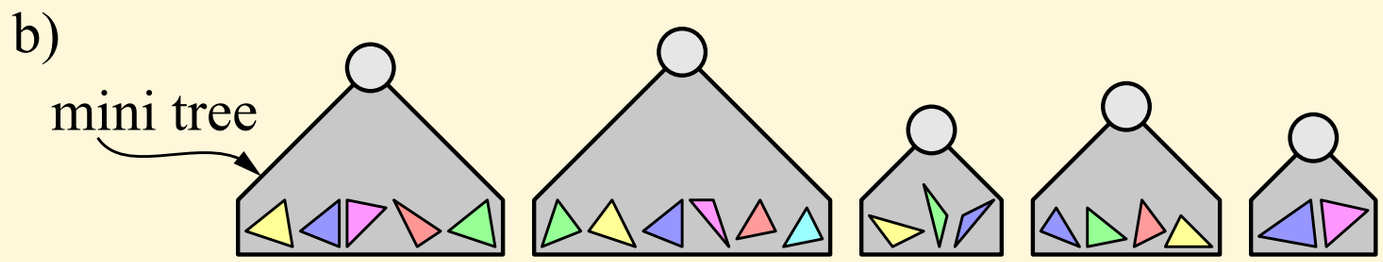
- *A(n)* is the surface area
- Find the ratio of current triangle's BB area to parent's
- Consider cost, *C*, of
  - intersection of internal, *i*, and leaf, *l*, nodes
  - *t*, traversal
- Which partitioning gives the lowest cost?

Bonsai BVH construction algorithm

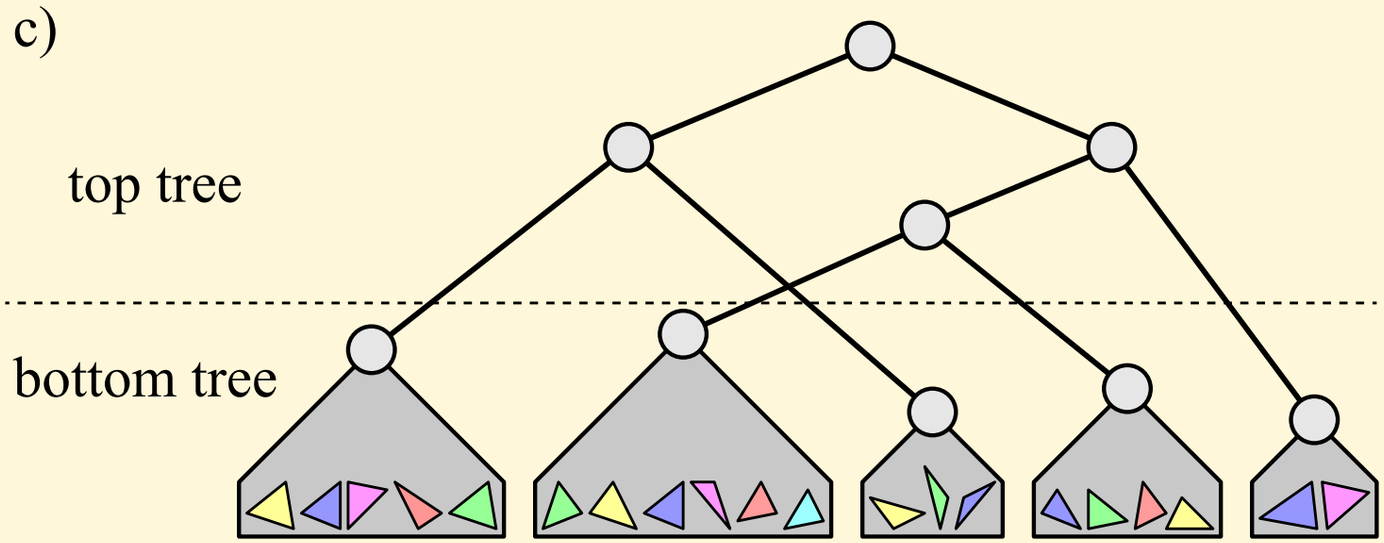
Partitioning



Built in parallel

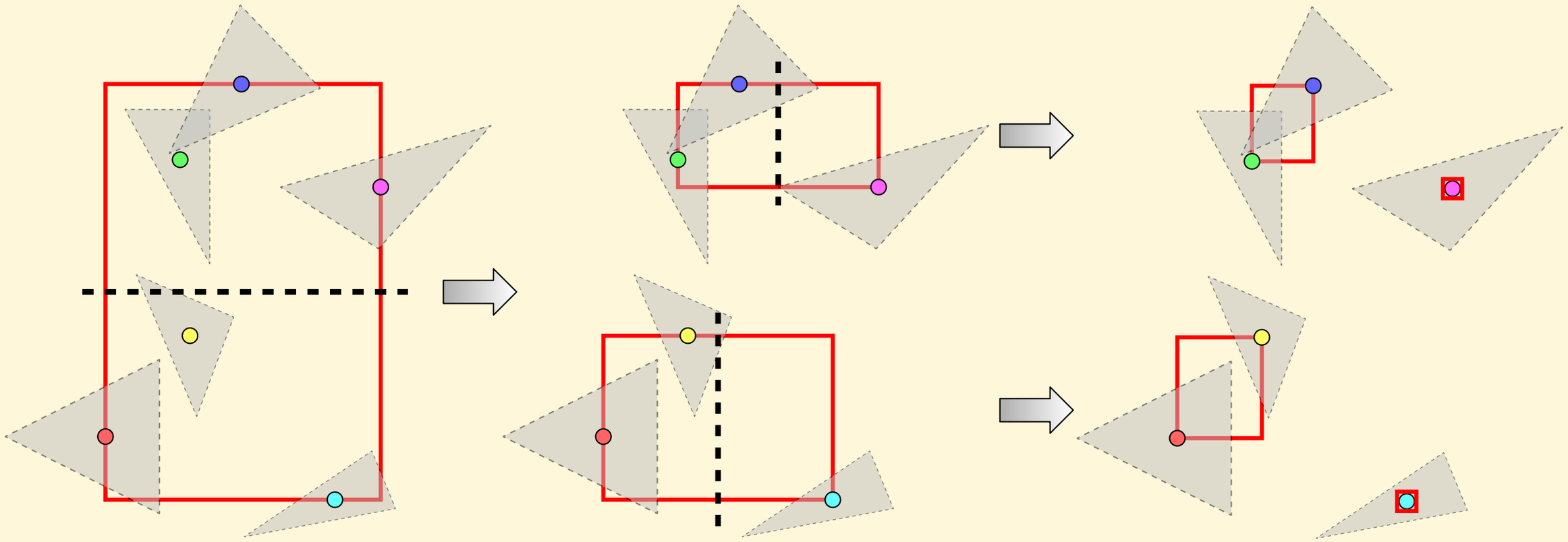


Built using Sweep



- From "**Bonsai: Rapid Bounding Volume Hierarchy Generation using Mini Trees**", *Ganestam, Barringer, Doggett, and Akenine-Möller*, JCGT, Sep. 2015

Bonsai Partitioning using triangle mid-points

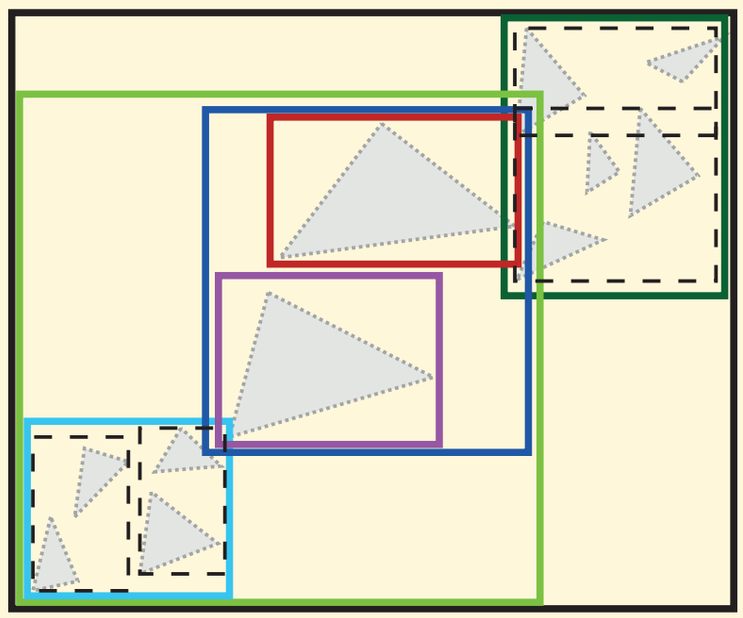


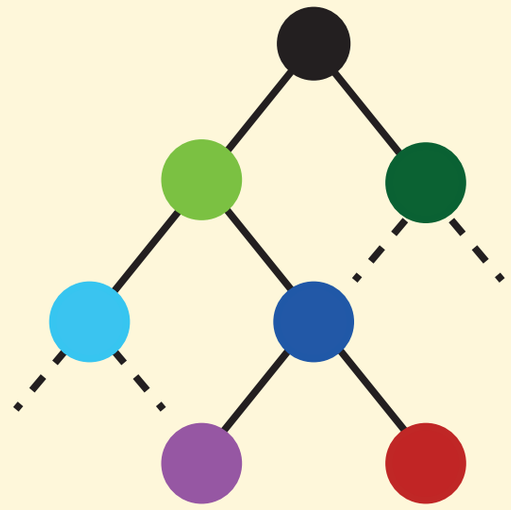
- Guarantees no empty partitions

Bonsai algorithm with pruning

- For mini-trees with large bounds
- Delete node and promote children

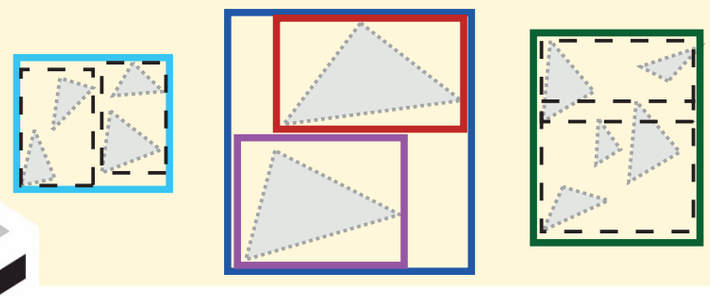
Before pruning



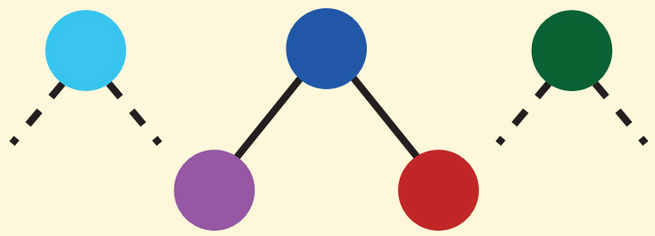


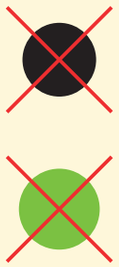
Original mini tree

After pruning



New mini trees





Deleted nodes

Triangle Splitting

- Problem : Big and small triangles don’t mix well
- Split clipping splits the bounding box
- Previous algorithms split before construction
  - Early Split Clipping [EG07] and EVH [DHK08]
  - Can result in more triangles and poor splits
  - Also adds to the overall construction time
- Some algorithms need per scene parameters
- **Our solution : SAH Spatial Split Partitioning**

SAH Spatial Split Partitioning

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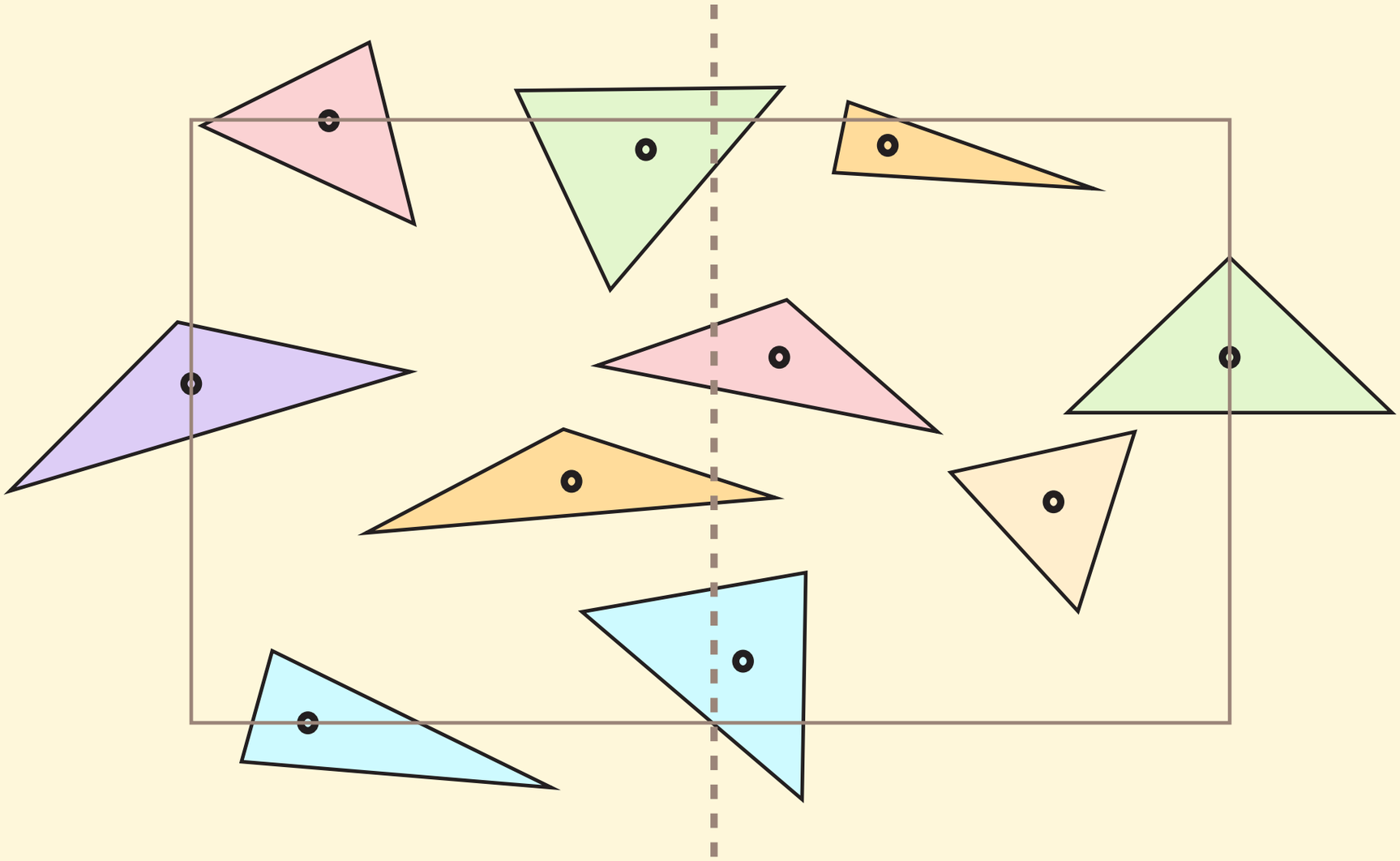
SAH Spatial Split Partitioning

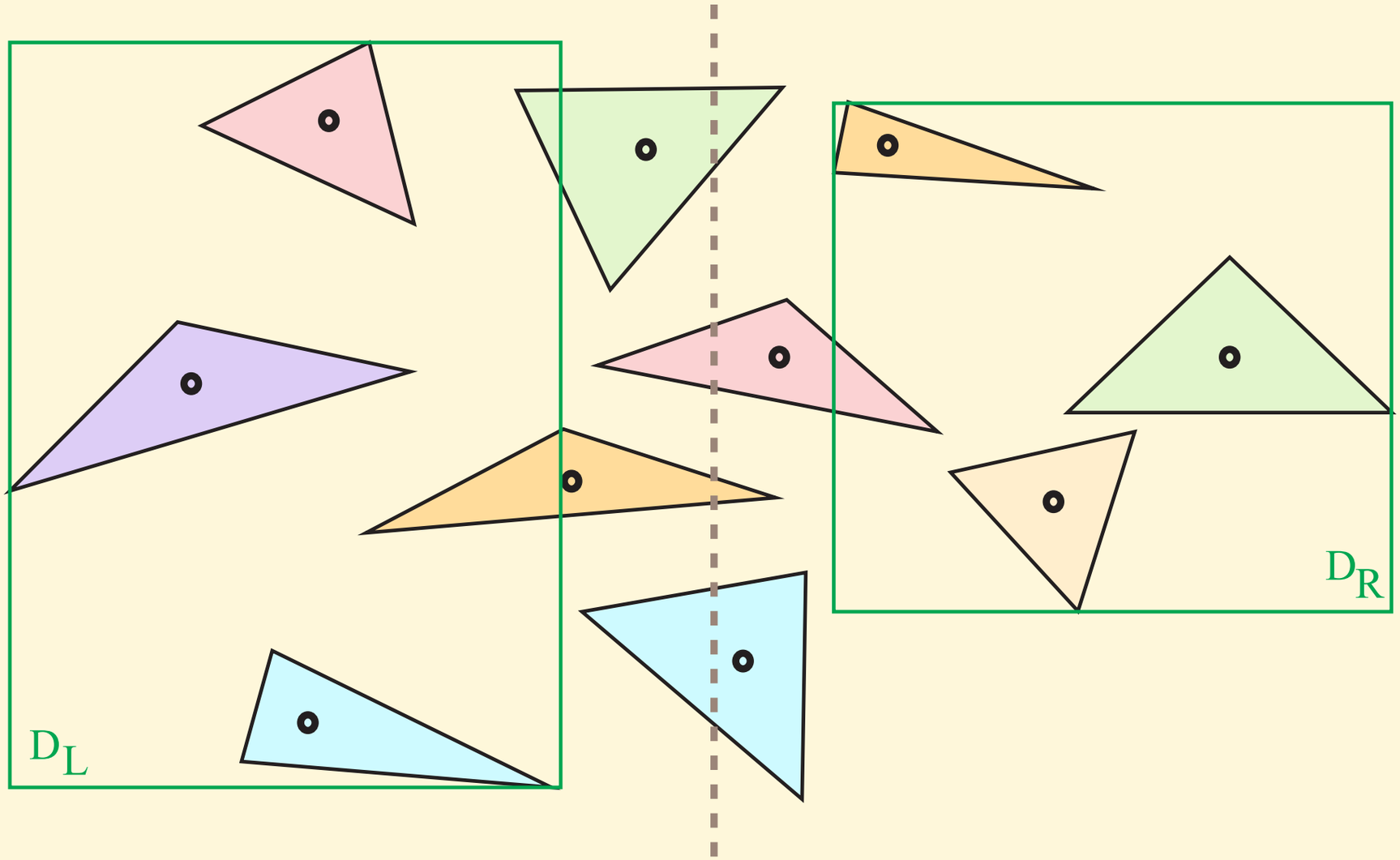
- Split triangles while partitioning
- Create triangle sets
- Only split triangles when SAH cost is lower than not splitting

SAH Spatial Split Partitioning



- Brown box is mid-point bounds and used to find split plane

SAH Spatial Split Partitioning

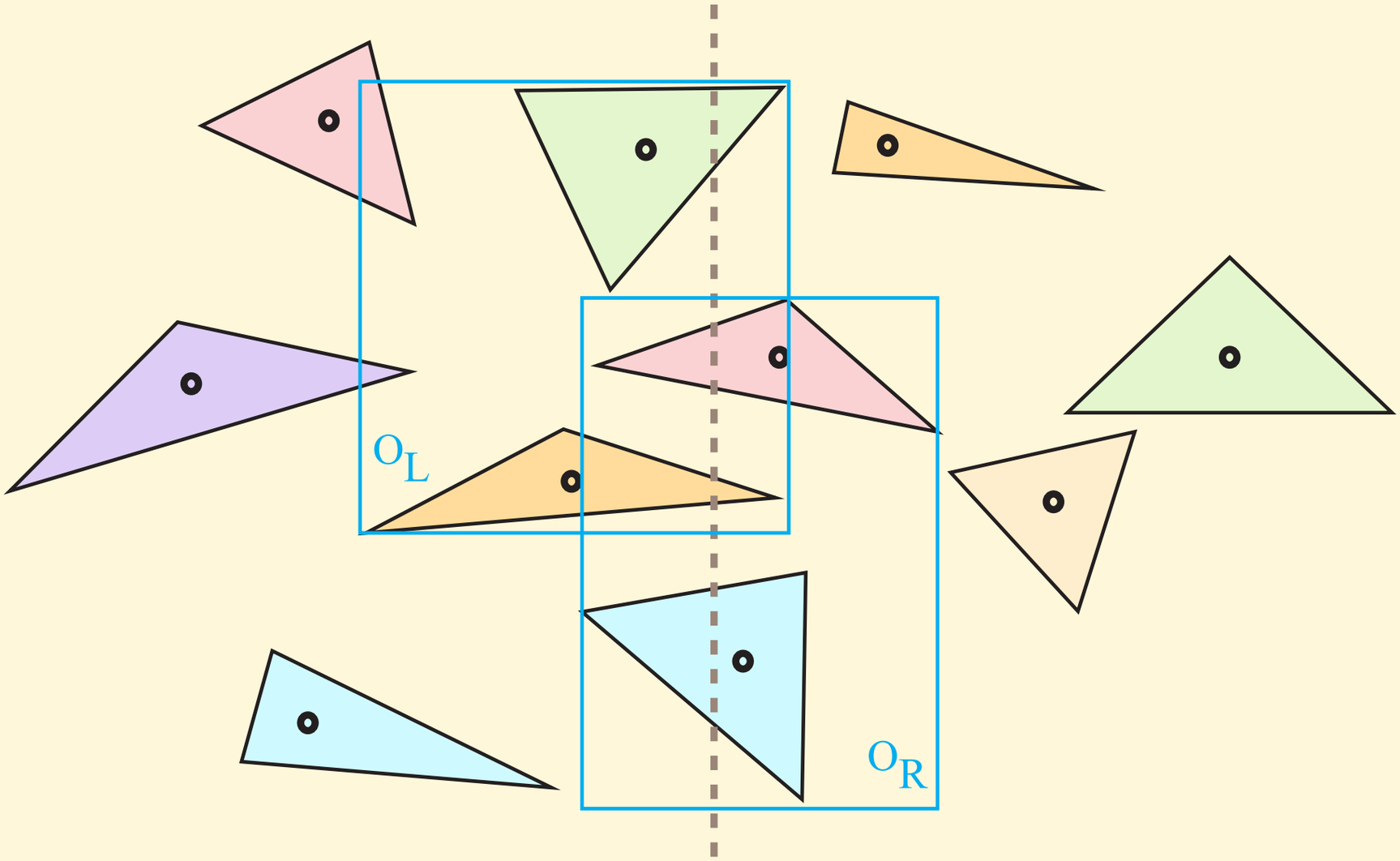


Triangle Sets

- Disjoint set
  - D_L, D_R

- Brown box is mid-point bounds and used to find split plane

SAH Spatial Split Partitioning



Triangle Sets

- Disjoint set
  - D_L, D_R
- Overlap sets
  - O_L, O_R

- Brown box is mid-point bounds and used to find split plane
- Overlap sets have triangles that overlap the split plane

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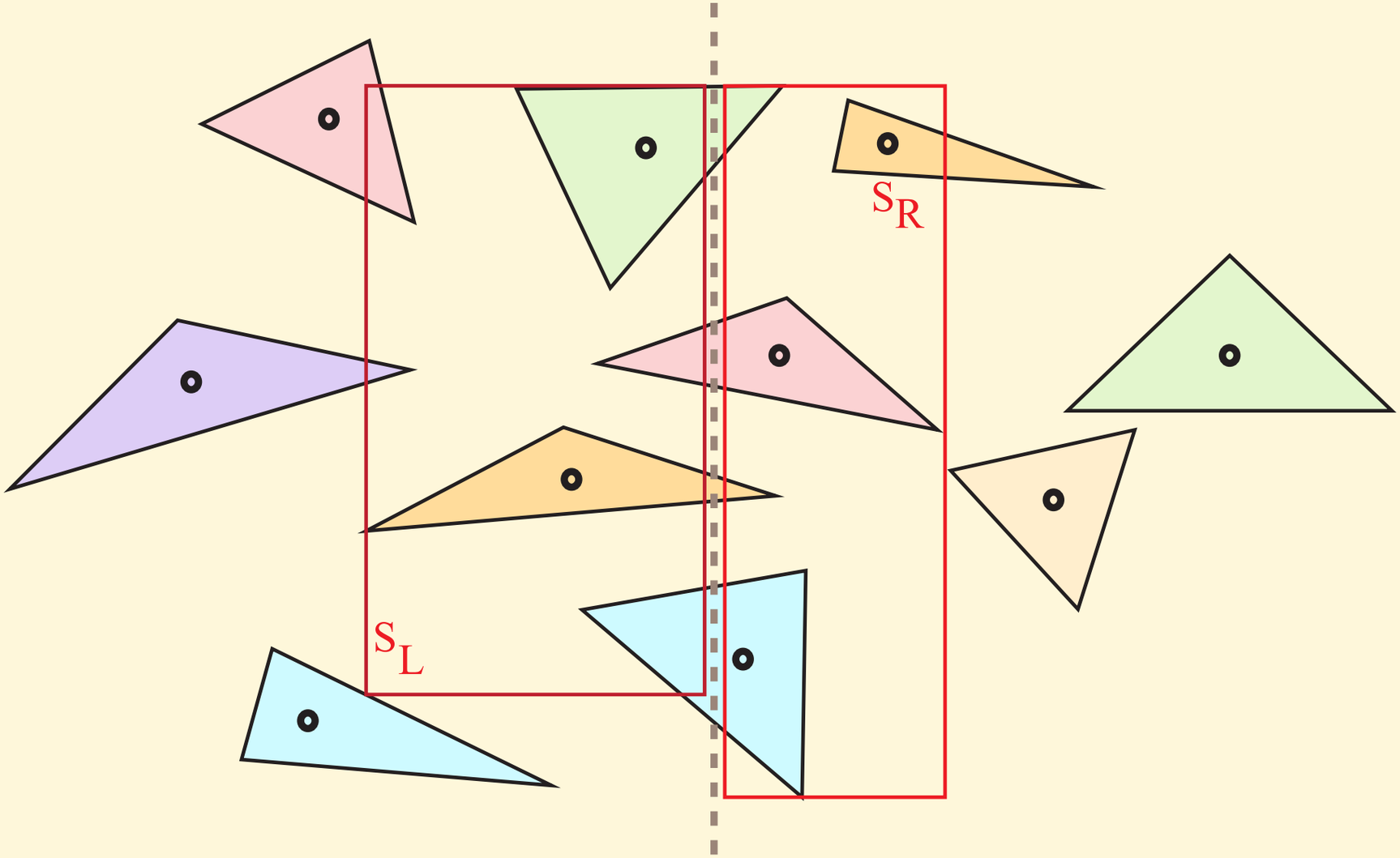


Triangle Sets

- Disjoint set
  - D_L, D_R
- Overlap sets
  - O_L, O_R
- Split sets
  - S_L, S_R

- Brown box is mid-point bounds and used to find split plane
- Overlap sets have triangles that overlap the split plane
- Split sets contain all overlap triangles

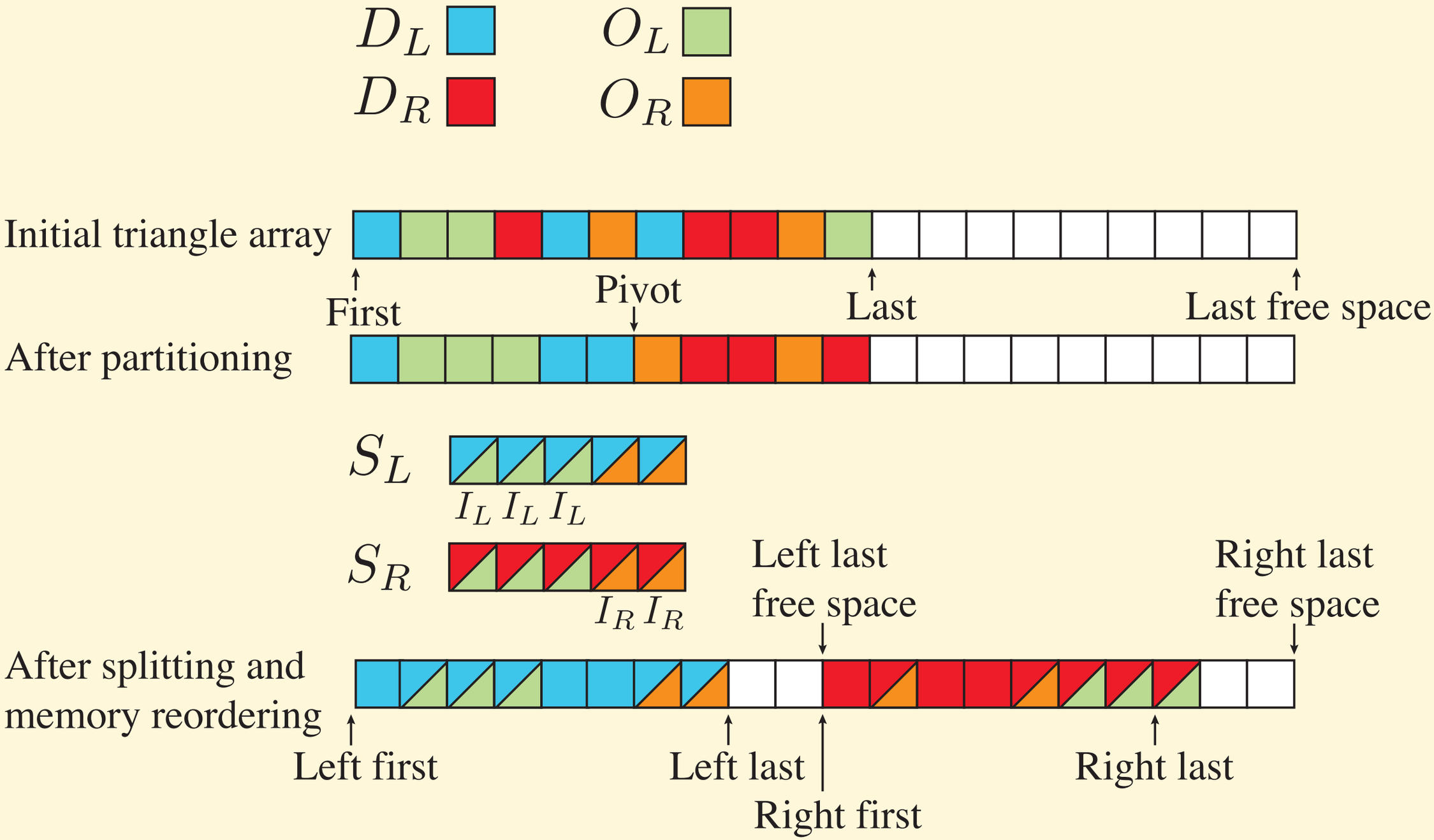
SAH Spatial Split Partitioning algorithm

- Recursively partition using mid-point and SAH cost
  - Take lowest cost of split vs. not split
  - Until mini trees are between 512 and 8K triangles (based on overall scene size)
- Mini trees processed using Sweep SAH

Efficient memory allocation

- Problem : Using separate arrays and merging
- Solution : In place, memory growing
- Memory is allocated for all triangles + 20%
- One half of split triangle overwritten in-place
  - and the other half added to the other side
- What empty space is left is rebalanced
- If split triangles don’t fit
  - Allocate more memory for right set + 20%

Efficient memory allocation

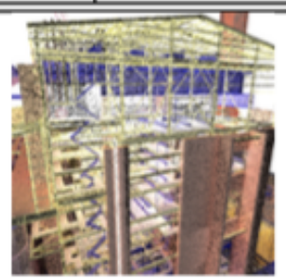
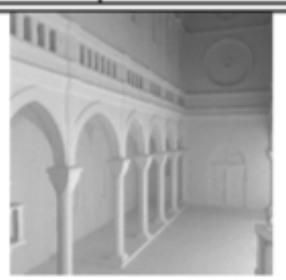


Results

- Implemented in Intel's Embree Ray Tracer, version 2.7.1
- Results generated on laptop **CPU** (MacBook Pro) with AVX2 support
- Consider both build and tracing times
- Compare to algorithms
    - Without splitting
        - SweepSAH
        - Bonsai
        - BinnedSAH (included in Embree)
    - With splitting
        - BonsaiS (Proposed algorithm)
        - SweepPre (Proposed algorithm as a pre splitting pass for Sweep)
        - BinnedPre (Pre-split algorithm in Embree)
        - BinnedS (Spatial split algorithm in Embree, based on SBVH [SFD09])

Results

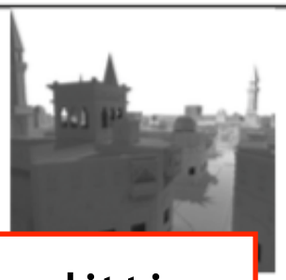
	 Arabic City	 Crown	 Dragon	 Fairy Forest	 Italian City	 Kalabsha
Triangles	416,236	4,868,924	7,349,978	174,117	382,029	4,542,705
	Build / Trace	Build / Trace	Build / Trace	Build / Trace	Build / Trace	Build / Trace
SweepSAH	254 / 295 [100%]	4680 / 325 [100%]	7595 / 129 [100%]	117 / 299 [100%]	240 / 300 [100%]	4910 / 551 [100%]
Bonsai	34 / 291 [99%]	469 / 331 [102%]	664 / 131 [102%]	16 / 299 [100%]	31 / 292 [97%]	451 / 554 [101%]
BinnedSAH	33 / 302 [102%]	447 / 322 [99%]	**674** / **126 [98%]**	**14** / **296 [99%]**	31 / 297 [99%]	459 / 555 [101%]
SweepPre	**374** / **243 [82%]**	5414 / 322 [99%]	8087 / 134 [104%]	147 / 301 [100%]	322 / 239 [80%]	6098 / 550 [100%]
BonsaiS	53 / 247 [84%]	**535** / **316 [97%]**	827 / 132 [102%]	24 / **297 [99%]**	**47** / **231 [77%]**	**765** / **513 [93%]**
BinnedPre	91 / 267 [91%]	980 / 317 [98%]	1577 / 134 [104%]	40 / 305 [102%]	77 / 254 [85%]	811 / 572 [104%]
BinnedS	404 / **237 [80%]**	4130 / **304 [94%]**	2205 / **124 [96%]**	129 / **289 [97%]**	316 / **229 [76%]**	4646 / **505 [92%]**

	 Mini	 Power Plant	 Sala	 San Miguel	 Sibenik	 Sponza
Triangles	912,411	12,759,246	400,637	7,880,512	79,380	262,267
	Build / Trace	Build / Trace	Build / Trace	Build / Trace	Build / Trace	Build / Trace
SweepSAH	719 / 593 [100%]	14347 / 617 [100%]	283 / 298 [100%]	8208 / 394 [100%]	49 / 222 [100%]	178 / 1210 [100%]
Bonsai	74 / 581 [98%]	1261 / 606 [98%]	34 / 298 [100%]	711 / 363 [92%]	9 / 225 [101%]	22 / 1137 [94%]
BinnedSAH	83 / 592 [100%]	1311 / 700 [113%]	35 / 332 [111%]	798 / 386 [98%]	7 / 222 [100%]	22 / 1393 [115%]
SweepPre	952 / **548 [92%]**	17603 / 469 [76%]	359 / 296 [100%]	9301 / 359 [91%]	53 / 222 [100%]	213 / 1224 [101%]
BonsaiS	**106** / **538 [91%]**	**1881** / **437 [71%]**	**47** / **286 [96%]**	**835** / **339 [86%]**	**11** / **218 [98%]**	**29** / **1057 [87%]**
BinnedPre	166 / 617 [104%]	3625 / 606 [98%]	90 / 339 [114%]	2168 / 388 [98%]	14 / 229 [103%]	56 / 1244 [103%]
BinnedS	739 / 572 [96%]	13835 / **441 [71%]**	342 / **292 [98%]**	7118 / **341 [87%]**	53 / **213 [96%]**	168 / **1113 [92%]**

All measurements in ms

Results

Without splitting



Crown
4,868,924

Dragon
7,349,978

Fairy Forest
174,117

Italian City
382,029

Kalabsha
4,542,705

	Build	Trace	Build	Trace	Build	Trace	Build	Trace	Build	Trace	Build	Trace
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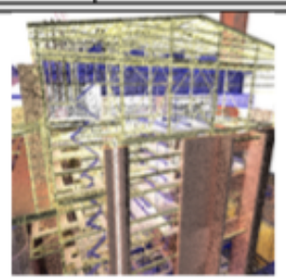
BinnedPre	91	267 [91%]	980	317 [98%]	1577	134 [104%]	40	305 [102%]	77	254 [85%]	811	572 [104%]
BinnedS	404	**237 [80%]**	4130	**304 [94%]**	2205	**124 [96%]**	129	**289 [97%]**	316	**229 [76%]**	4646	**505 [92%]**

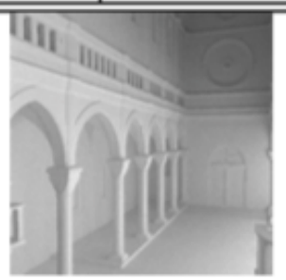
Mini
912,411



Power Plant
12,759,246

Sala
400,637

San Miguel
7,880,512



Sibenik
79,380

Sponza
262,267

Triangles

	Build	Trace	Build	Trace	Build	Trace	Build	Trace	Build	Trace	Build	Trace
SweepSAH	719	593 [100%]	14347	617 [100%]	283	298 [100%]	8208	394 [100%]	49	222 [100%]	178	1210 [100%]
Bonsai	74	581 [98%]	1261	606 [98%]	34	298 [100%]	711	363 [92%]	9	225 [101%]	22	1137 [94%]
BinnedSAH	83	592 [100%]	1311	700 [113%]	35	332 [111%]	798	386 [98%]	7	222 [100%]	22	1393 [115%]
SweepPre	952	**548 [92%]**	17603	469 [76%]	359	296 [100%]	9301	359 [91%]	53	222 [100%]	213	1224 [101%]
BonsaiS	**106**	**538 [91%]**	**1881**	**437 [71%]**	**47**	**286 [96%]**	**835**	**339 [86%]**	**11**	**218 [98%]**	**29**	**1057 [87%]**
BinnedPre	166	617 [104%]	3625	606 [98%]	90	339 [114%]	2168	388 [98%]	14	229 [103%]	56	1244 [103%]
BinnedS	739	572 [96%]	13835	**441 [71%]**	342	**292 [98%]**	7118	**341 [87%]**	53	**213 [96%]**	168	**1113 [92%]**

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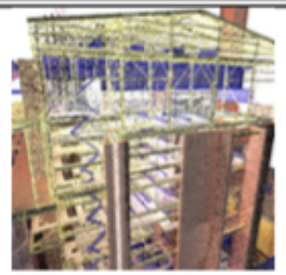
With splitting

	 Mini	 Power Plant	 Sala	 San Miguel	 Sibenik	 Sponza
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BonsaiS is one of 2 best tracing 10/12 times

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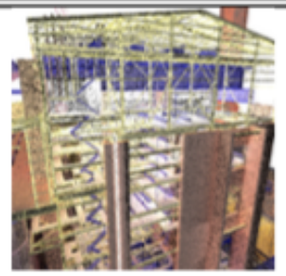
	 Mini		 Power Plant		 Sala		 San Miguel		 Sibenik		 Sponza	
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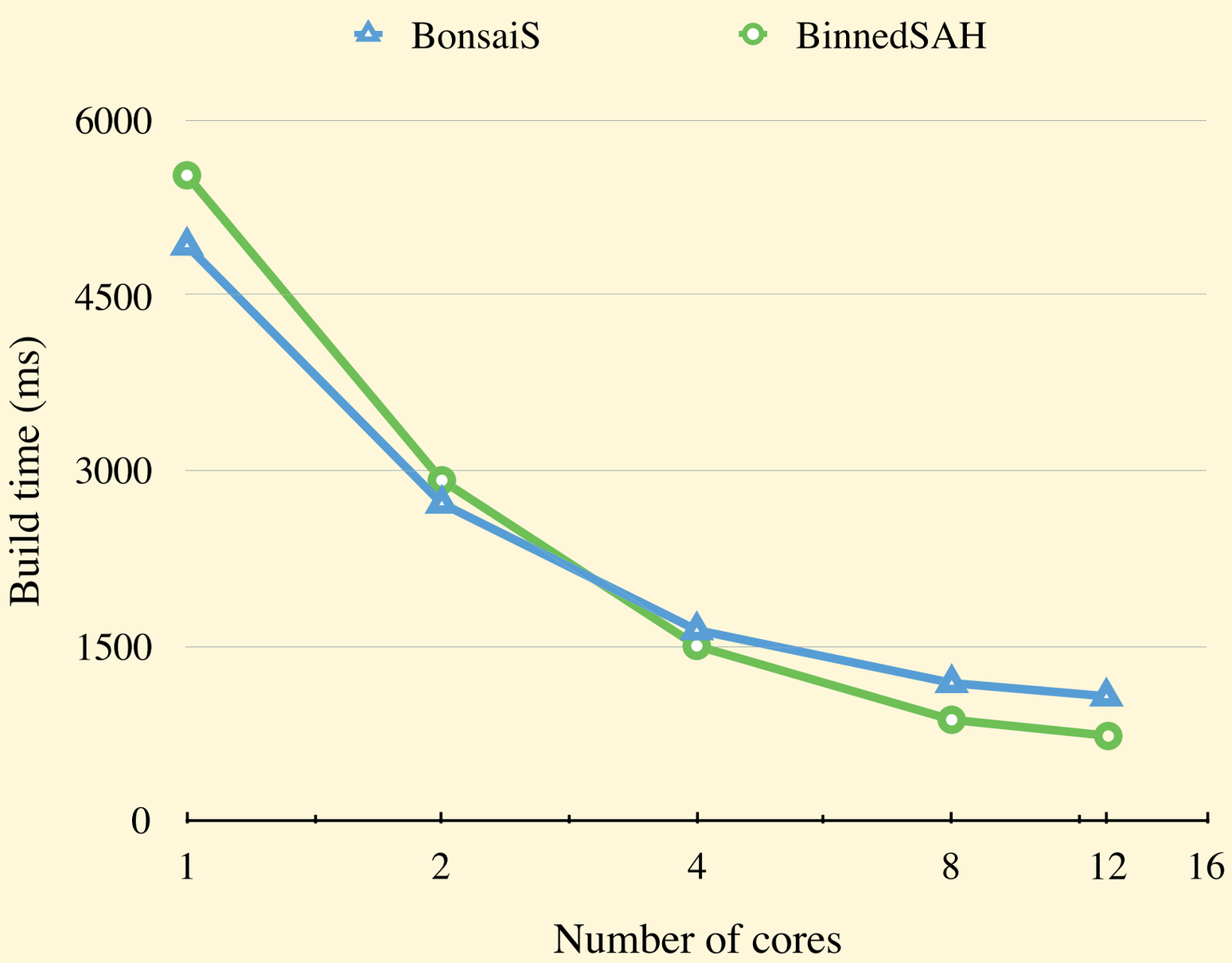
SweepPre	952	**548 [92%]**	17603	469 [76%]	359	296 [100%]	9301	359 [91%]	53	222 [100%]	213	1224 [101%]
BonsaiS	**106**	**538 [91%]**	**1881**	**437 [71%]**	**47**	**286 [96%]**	**835**	**339 [86%]**	**11**	**218 [98%]**	**29**	**1057 [87%]**
BinnedPre	166	617 [104%]	3625	606 [98%]	90	339 [114%]	2168	388 [98%]	14	229 [103%]	56	1244 [103%]
BinnedS	739	572 [96%]	13835	**441 [71%]**	342	**292 [98%]**	7118	**341 [87%]**	53	**213 [96%]**	168	**1113 [92%]**

Results

- For 4 scenes BonsaiS traces faster than BinnedS (considered to be the HQ builder)
- SweepPre is twice in the top two tracers
  - and is typically between BinnedS and BinnedPre (Embree builders)
- BinnedS always improves tracing performance of BinnedSAH, but at much longer build times
- BinnedS allocated 34x more memory compared to BonsaiS (measured with Valgrind)
- For Arabic City BonsaiS allocated 735MB, BinnedS 25GB

Parallel scaling



- Intel E5-2643V3 dual socket 12 core CPU
- Powerplant scene
- Per frame tracing performance on the 12 core CPU
  - BonsaiS 105ms
  - BinnedSAH 162ms

Conclusion

- Simple top down triangle splitting and BVH construction algorithm
- Integrated or preprocess triangle splitter
- Fast BVH construction and fast ray tracing

- Source code will be available in Embree and on paper web page

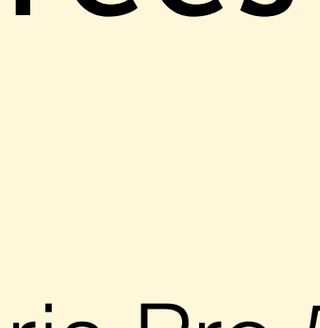
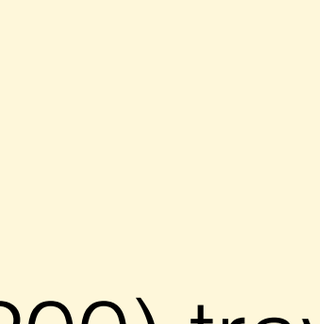
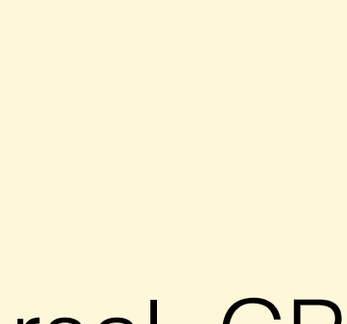
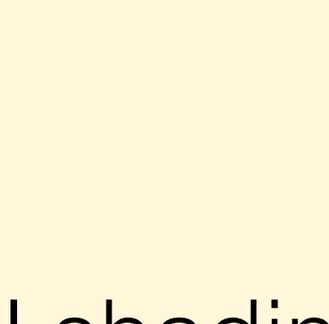
- **Acknowledgements** : Thanks to ELLIIT and the Intel Visual Computing Institute for funding.

Thanks for listening!

Bonus slides

Binary Trees

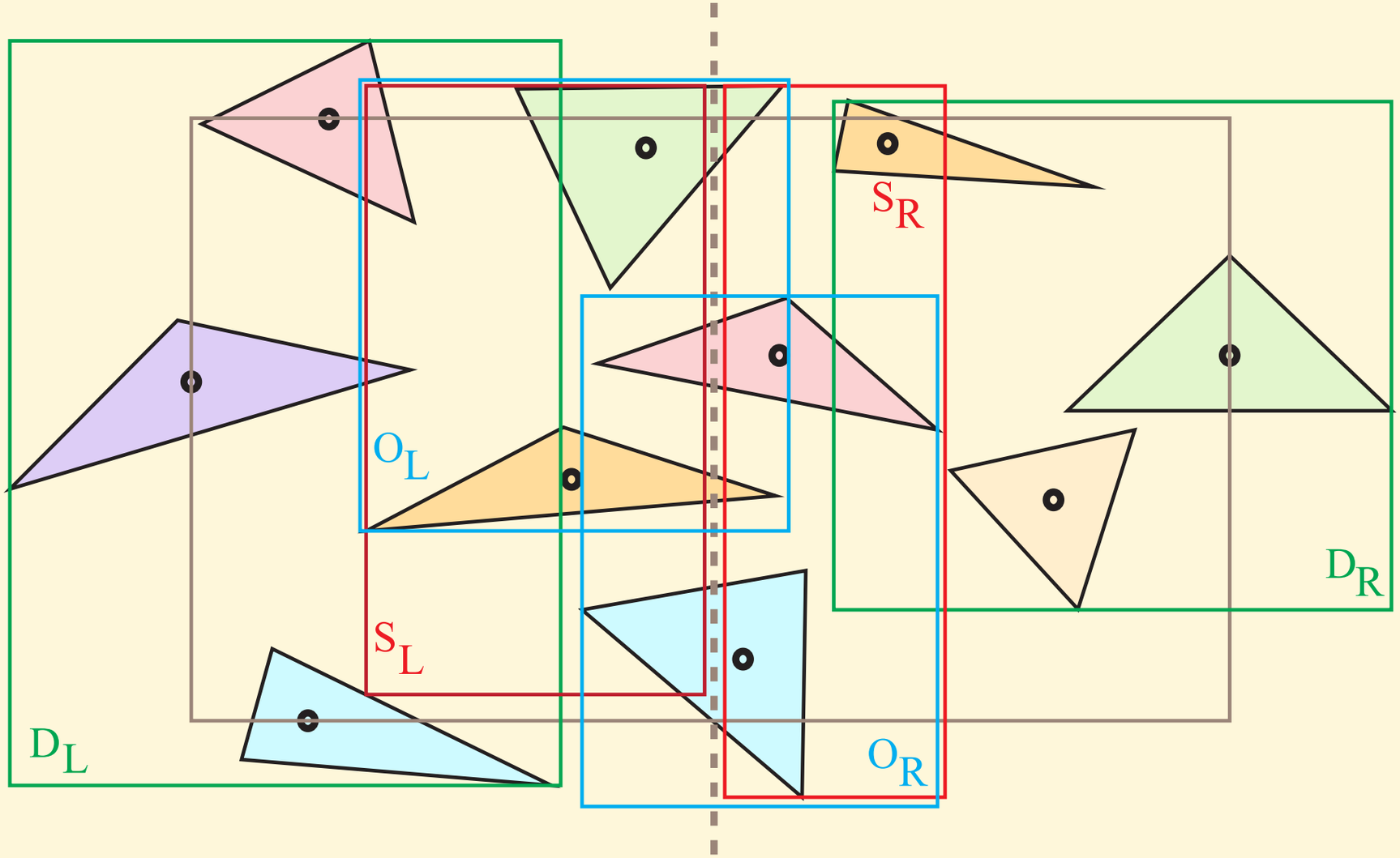
- GPU (Intel Iris Pro 5200) traversal, CPU shading
- BonsaiS improves tracing performance compared to SweepSAH for all scenes
- Similar tracing improvement to [KA13], but with fewer split triangles

	 Arabic City	 Crown	 Italian City	 Kalabsha	 San Miguel	Sponza
SweepSAH	240 [100%]	191 [100%]	129 [100%]	455 [100%]	667 [100%]	630 [100%]
BonsaiS	155 [65%]	183 [96%]	86 [67%]	330 [73%]	499 [75%]	380 [60%]

Triangle Counts and SAH costs

- BonsaiS creates fewer additional triangles than the two triangle split methods available in Embree
- BonsaiS can split far fewer triangles and get the same and faster tracing
- BonsaiS consistently produces lower SAH costs

SAH Spatial Split Partitioning



Triangle Sets

- Disjoint set
  - D_L, D_R
- Overlap sets
  - O_L, O_R
- Split sets
  - S_L, S_R

- Brown box is mid-point bounds and used to find split plane
- Overlap sets have triangles that overlap the split plane
- Split sets contain all overlap triangles