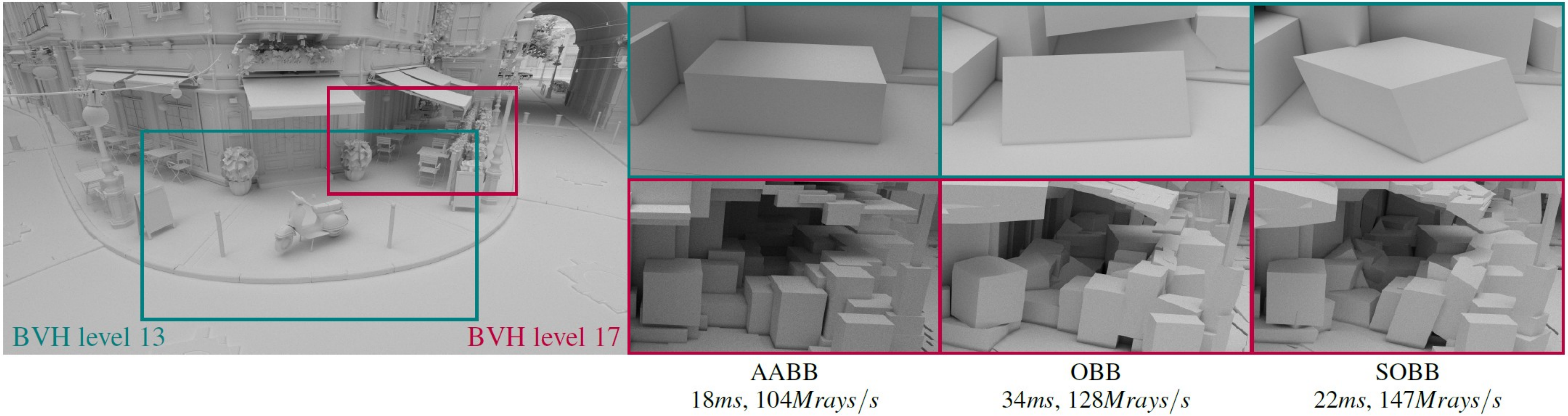
SOBB: Skewed Oriented Bounding Boxes for Ray Tracing

M. Kácerik and J. Bittner

(Czech Technical University, Prague)

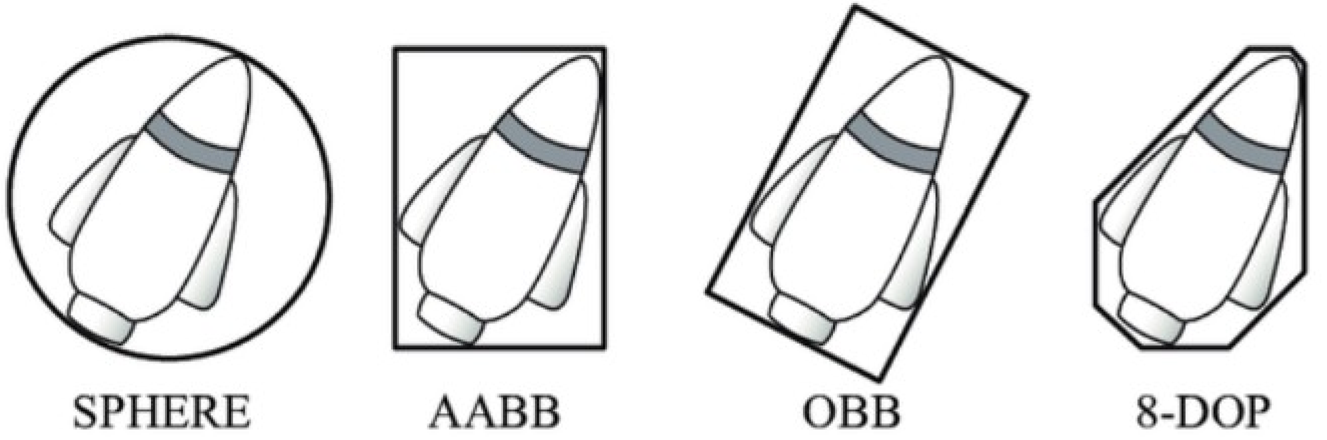


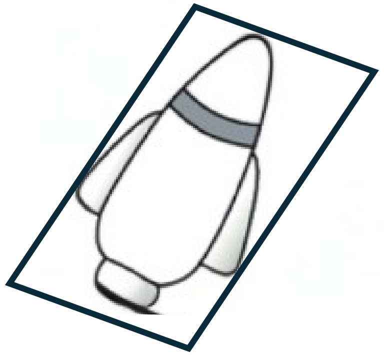
Idea

- To accelerate raytracing, Bounding Volume Hierarchies (BVH) are used, with axis-aligned bounding boxes (AABB)
  - Oriented Bounding Boxes (OBB) and
  - Discrete Orientation Polytope (DOP) have been used

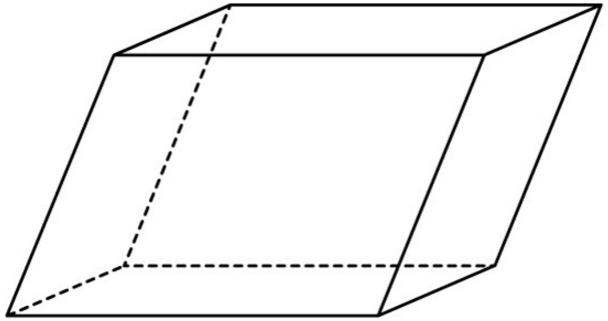
  - What if we use Skewed Oriented Bounding Boxes (parallelepipeds) ?

Bounding volumes:





2d SOBB



3d:
Parallepiped

Why ?

- AABB is simple, but it is a loose fit for geometry

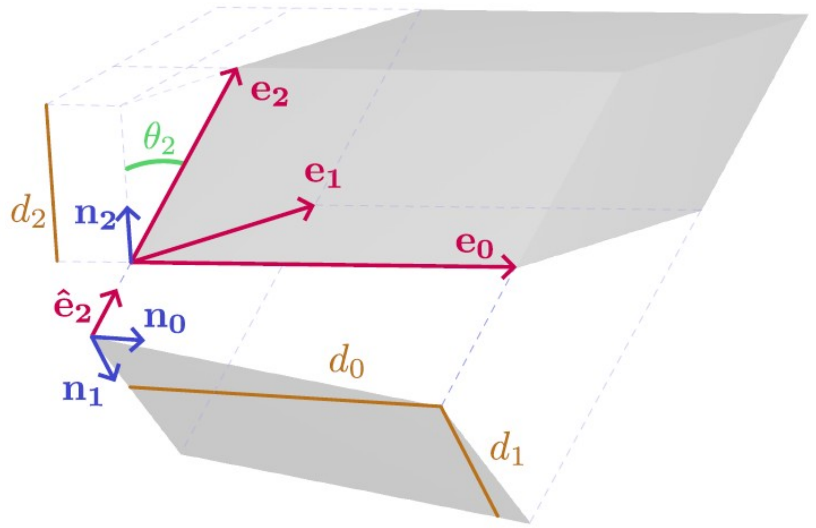
- More complex shapes are more expensive to build BVH with

Representation of parallepiped

- Edge-based: (e1, e2, e3)

- Slab-based: intersection of 3 slab
  - Slab: normal, and distance between 2 parallel planes
  - (n0, n1, n2, d0, d1, d2)

  - Slabs are easy to intersect with rays!



Surface area

- Easy in edge-based representation

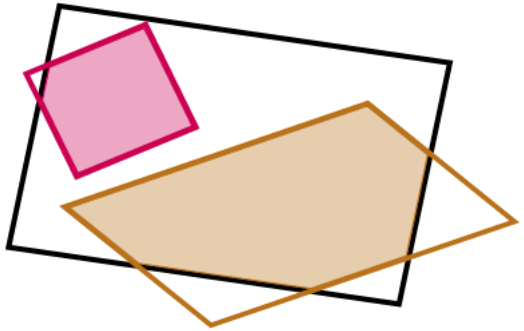
$$A_{pp}(\mathbf{e_0},\mathbf{e_1},\mathbf{e_2}) = 2(A^0_{pg}(\mathbf{e_0},\mathbf{e_1}) + A^1_{pg}(\mathbf{e_1},\mathbf{e_2}) + A^2_{pg}(\mathbf{e_2},\mathbf{e_0}))$$
$$= 2(|\mathbf{e_0}\times\mathbf{e_1}| + |\mathbf{e_1}\times\mathbf{e_2}| + |\mathbf{e_2}\times\mathbf{e_0}|).$$

- Harder with slabs

$$A_{pp}(\mathbf{n_0},\mathbf{n_1},\mathbf{n_2},d_0,d_1,d_2) = 2\left(\frac{d_0d_1 + d_1d_2 + d_2d_0}{\left|\det\begin{bmatrix}\mathbf{n_0} & \mathbf{n_1} & \mathbf{n_2}\end{bmatrix}\right|}\right)$$

Building the BVH

- Start with AABB hierarchy
- Bottom-up traversal:
  - Fit high-dimensional k-DOP (k/2 pairs of parallel planes) on the node
  - Explore the space of SOBB available and choose the best candidate



A parent node can clip its children

Choosing the best SOBB candidate

- O(k^3) strategy (brute force): iterate over all triplet generated by k-DOP
  - Pick the SOBB with the **smallest surface area**
  - Best possible SOBB with this construction method\
- O(k^2) strategy: select a basis vector, and iterate for the 2 others
  - We can select the normal of the narrowest slab in the k-DOP
- O(k) strategy:
  - Select the normal of the narrowest slab
  - Choose second axis to minimize the area* of the parallelogram formed
  - Iterate to choose the last axis

*Area of the projection on the plane formed by the 2 axes

Memory layouts

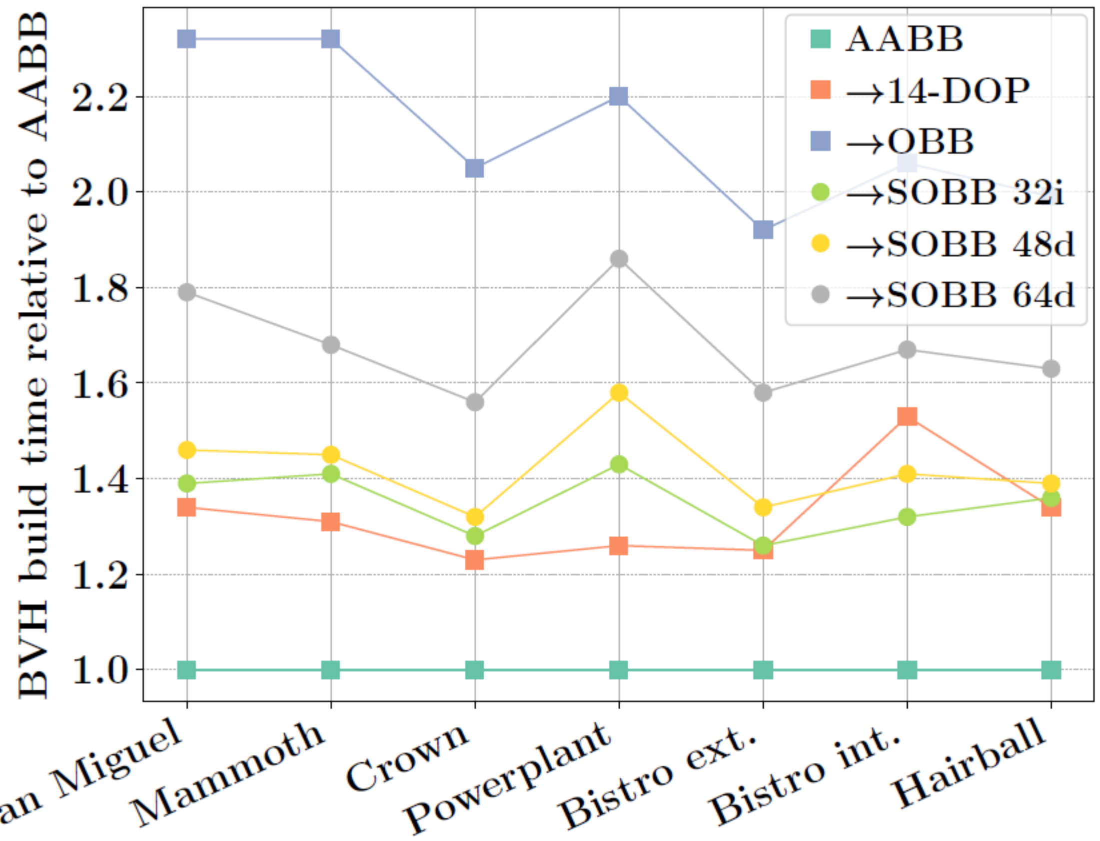
- 4 floats per slabs: 12 floats (48 bytes)

$$\rho = \frac{1}{\max(p_{max} - p_{min}, \epsilon)}$$

$$\mathbf{s} = \rho \cdot \begin{bmatrix} n_x & n_y & n_z & p_{min} \end{bmatrix}^T$$

- Normal directions are discretized: 26 bytes
  - 24 bytes for pmin and pmax
  - 2 bytes to store the normal index (up to k = 64)

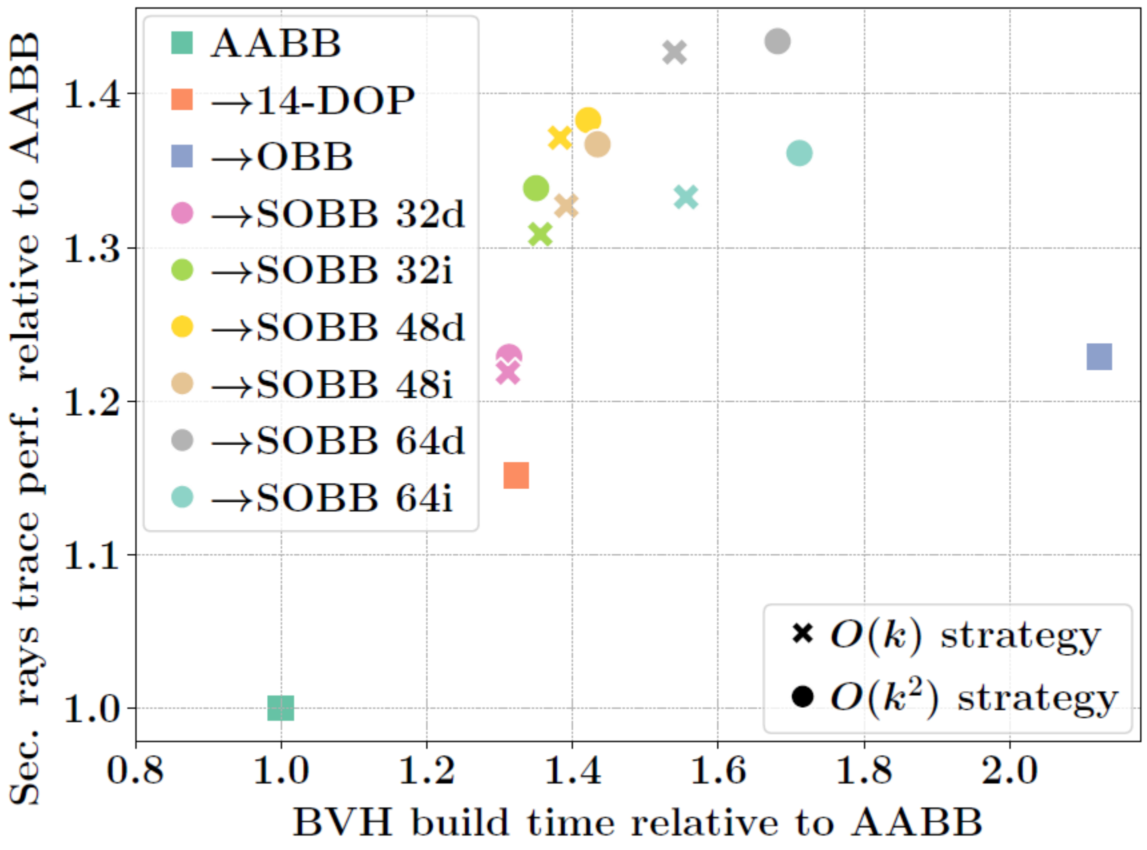
Build Time



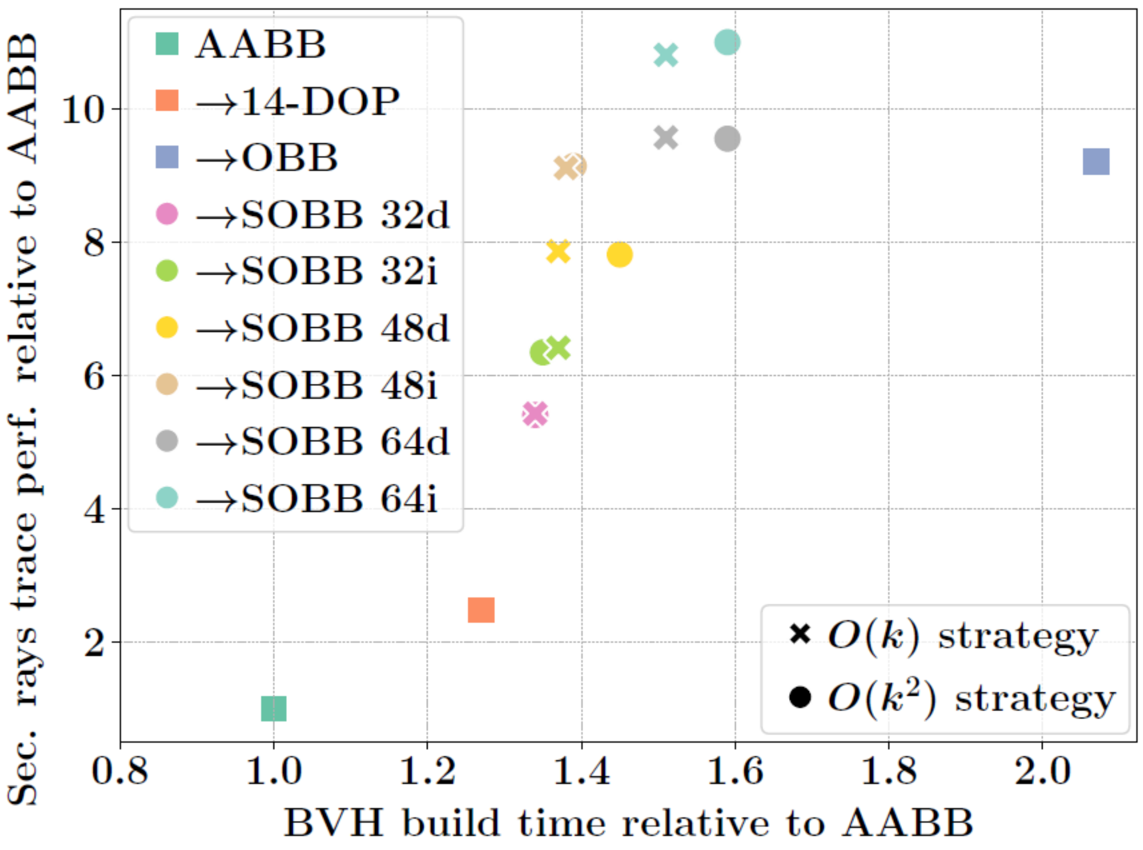
BVH build time relative to AABB
2.2
2.0
1.8
1.6
1.4
1.2
1.0
AABB
→14-DOP
→OBB
→SOBB 32i
→SOBB 48d
→SOBB 64d
San Miguel
Mammoth
Crown
Powerplant
Bistro ext.
Bistro int.
Hairball

Raytracing performance

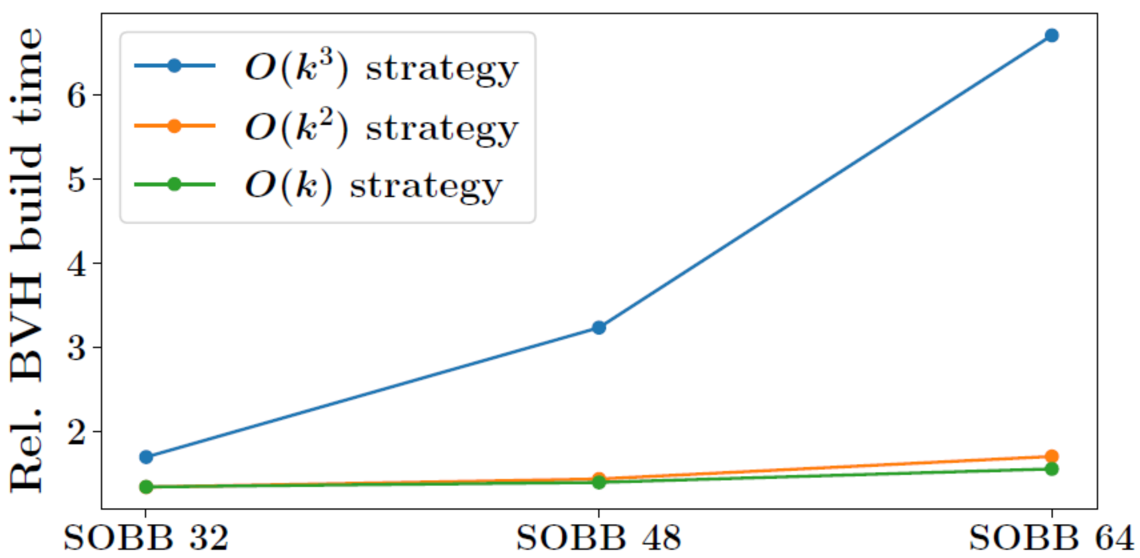
On average

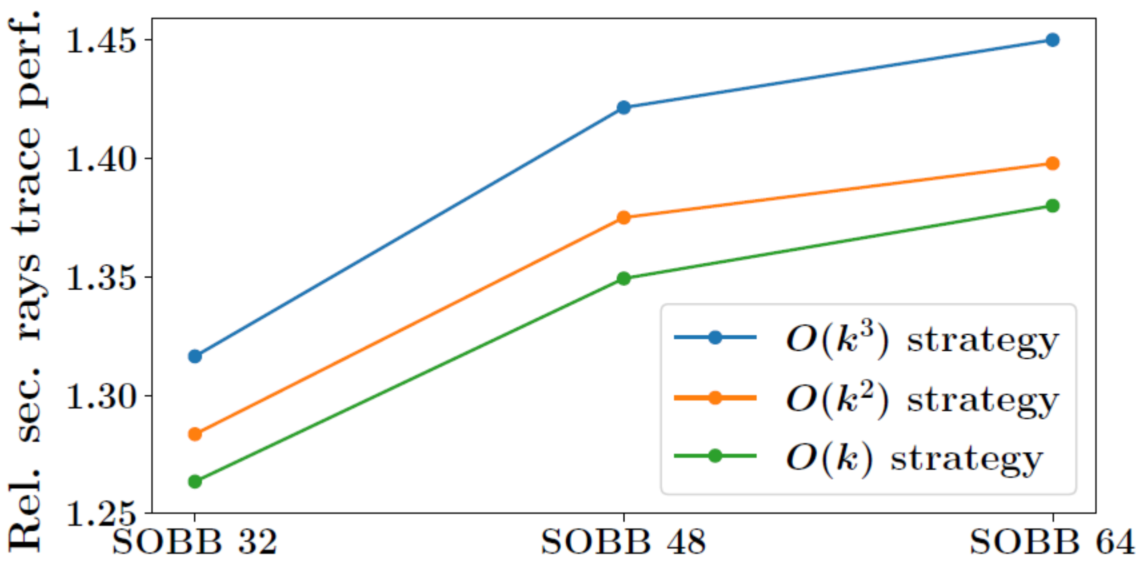


On “Sheep” scene



Raytracing performance





Raytracing Performance

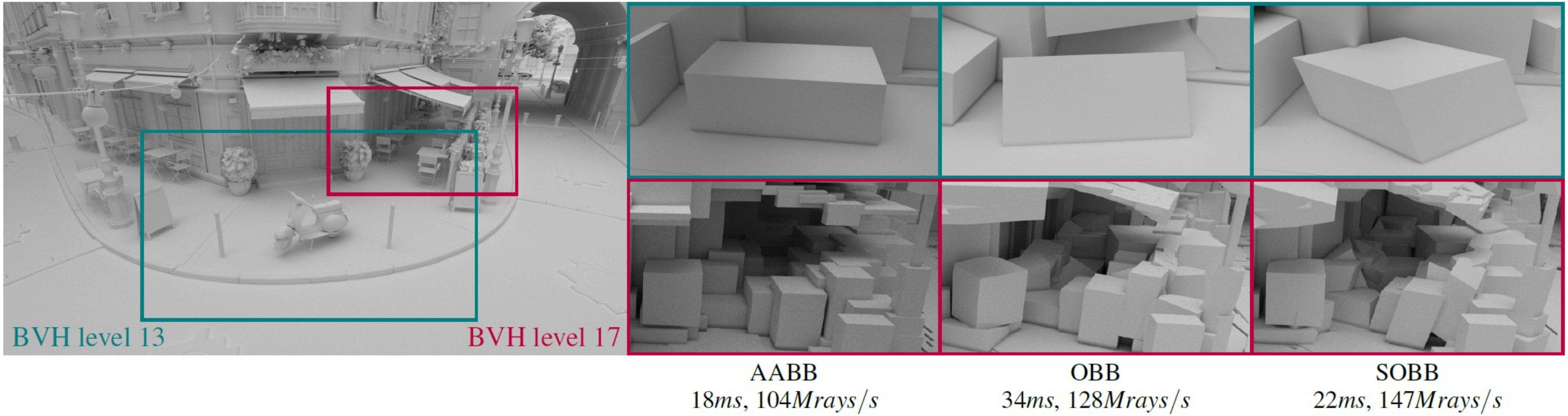
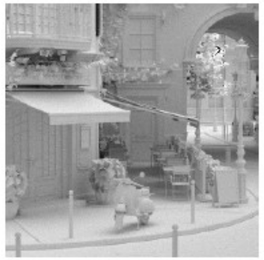
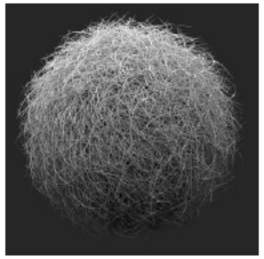


Figure 1: *The comparison of the BVH using AABB, OBB, and SOBB as bounding volumes on the Bistro exterior scene (2.8 million triangles). From left to right: sample view of the scene, visualization of the AABB, OBB, and SOBB bounding volumes for levels 13 (top row) and 17 (bottom row) of the BVH. The numbers below the images show the build times for the BVH and the trace speeds for secondary rays.*

Scene [#triangles]	Method	Build time [ms]		Overhead [ms]		Area int. nodes		Area leaf nodes		Primary MRps		Secondary MRps	
San Miguel [10.0M]	AABB	42.7	(1.00)	-	-	41.3	(1.00)	6.1	(1.00)	**835.4**	**(1.00)**	155.8	(1.00)
	AABB→*14*-DOP	57.1	(1.34)	14.4	(0.26)	**32.7**	**(0.79)**	4.7	(0.76)	757.7	(0.91)	143.9	(0.92)
	AABB→OBB	99.1	(2.32)	56.4	(1.00)	38.4	(0.93)	**4.5**	**(0.74)**	525.4	(0.63)	124.5	(0.80)
	AABB→SOBB 32d	58.1	(1.36)	15.4	(0.27)	38.5	(0.93)	4.9	(0.80)	438.8	(0.53)	149.0	(0.96)
	AABB→SOBB 32i	59.4	(1.39)	16.7	(0.30)	38.5	(0.93)	4.9	(0.80)	476.3	(0.57)	**157.9**	**(1.01)**
	AABB→SOBB 48d	62.5	(1.46)	19.8	(0.35)	38.1	(0.92)	4.7	(0.77)	456.7	(0.55)	153.8	(0.99)
	AABB→SOBB 48i	63.1	(1.48)	20.4	(0.36)	38.1	(0.92)	4.7	(0.77)	489.8	(0.59)	153.6	(0.99)
	AABB→SOBB 64d	76.3	(1.79)	33.6	(0.60)	37.9	(0.92)	4.7	(0.76)	461.4	(0.55)	156.0	(1.00)
	AABB→SOBB 64i	74.7	(1.75)	32.0	(0.57)	37.9	(0.92)	4.7	(0.76)	488.3	(0.58)	149.6	(0.96)
Mammoth [8.8M]	AABB	40.9	(1.00)	-	-	32.5	(1.00)	2.2	(1.00)	1092.7	(1.00)	183.6	(1.00)
	AABB→*14*-DOP	53.5	(1.31)	12.6	(0.23)	**23.4**	**(0.72)**	1.4	(0.65)	1073.8	(0.98)	179.3	(0.98)
	AABB→OBB	94.9	(2.32)	54.0	(1.00)	26.3	(0.81)	**1.2**	**(0.55)**	1128.7	(1.03)	192.0	(1.05)
	AABB→SOBB 32d	57.4	(1.40)	16.5	(0.31)	28.1	(0.87)	1.5	(0.68)	1165.8	(1.07)	197.0	(1.07)
	AABB→SOBB 32i	57.8	(1.41)	16.9	(0.31)	28.1	(0.87)	1.5	(0.68)	1018.6	(0.93)	**216.3**	**(1.18)**
	AABB→SOBB 48d	59.2	(1.45)	18.3	(0.34)	27.3	(0.84)	1.4	(0.63)	1255.5	(1.15)	206.1	(1.12)
	AABB→SOBB 48i	59.4	(1.45)	18.5	(0.34)	27.3	(0.84)	1.4	(0.63)	1023.1	(0.94)	212.6	(1.16)
	AABB→SOBB 64d	68.7	(1.68)	27.8	(0.51)	26.8	(0.82)	1.3	(0.60)	**1293.1**	**(1.18)**	213.0	(1.16)
	AABB→SOBB 64i	68.6	(1.68)	27.7	(0.51)	26.8	(0.82)	1.3	(0.60)	1023.1	(0.94)	208.1	(1.13)
Crown [3.5M]	AABB	18.7	(1.00)	-	-	15.0	(1.00)	1.7	(1.00)	**1640.8**	**(1.00)**	181.7	(1.00)
	AABB→*14*-DOP	22.9	(1.23)	4.2	(0.21)	**11.1**	**(0.74)**	1.2	(0.72)	1475.8	(0.90)	198.0	(1.09)
	AABB→OBB	38.3	(2.05)	19.6	(1.00)	12.1	(0.81)	**0.8**	**(0.50)**	989.0	(0.60)	199.1	(1.10)
	AABB→SOBB 32d	23.3	(1.25)	4.6	(0.23)	13.0	(0.86)	1.2	(0.71)	1145.6	(0.70)	208.2	(1.15)
	AABB→SOBB 32i	24.0	(1.28)	5.3	(0.27)	13.0	(0.86)	1.2	(0.71)	965.7	(0.59)	**225.3**	**(1.24)**
	AABB→SOBB 48d	24.7	(1.32)	6.0	(0.31)	12.4	(0.83)	1.0	(0.61)	1139.3	(0.69)	217.9	(1.20)
	AABB→SOBB 48i	25.0	(1.34)	6.3	(0.32)	12.4	(0.83)	1.0	(0.61)	955.2	(0.58)	213.5	(1.17)
	AABB→SOBB 64d	29.2	(1.56)	10.5	(0.54)	12.3	(0.82)	1.0	(0.59)	1149.5	(0.70)	220.4	(1.21)
	AABB→SOBB 64i	29.5	(1.58)	10.8	(0.55)	12.3	(0.82)	1.0	(0.59)	951.5	(0.58)	206.5	(1.14)
Powerplant [12.8M]	AABB	47.2	(1.00)	-	-	17.4	(1.00)	3.0	(1.00)	**831.2**	**(1.00)**	122.1	(1.00)
	AABB→*14*-DOP	59.3	(1.26)	12.1	(0.21)	**14.1**	**(0.81)**	2.0	(0.67)	824.3	(0.99)	147.1	(1.21)
	AABB→OBB	103.8	(2.20)	56.6	(1.00)	15.5	(0.89)	**1.3**	**(0.43)**	557.8	(0.67)	129.4	(1.06)
	AABB→SOBB 32d	63.7	(1.35)	16.5	(0.29)	15.6	(0.90)	1.6	(0.55)	688.0	(0.83)	158.5	(1.30)
	AABB→SOBB 32i	67.6	(1.43)	20.4	(0.36)	15.6	(0.90)	1.6	(0.55)	535.0	(0.64)	157.2	(1.29)
	AABB→SOBB 48d	74.4	(1.58)	27.2	(0.48)	15.5	(0.89)	1.5	(0.51)	742.9	(0.89)	166.6	(1.36)
	AABB→SOBB 48i	71.9	(1.52)	24.7	(0.44)	15.5	(0.89)	1.5	(0.51)	549.8	(0.66)	160.4	(1.31)
	AABB→SOBB 64d	88.0	(1.86)	40.8	(0.72)	15.4	(0.89)	1.5	(0.49)	727.1	(0.87)	**171.0**	**(1.40)**
	AABB→SOBB 64i	90.1	(1.91)	42.9	(0.76)	15.4	(0.89)	1.5	(0.49)	560.5	(0.67)	162.4	(1.33)

Scene [#triangles]	Method	Build time [ms]		Overhead [ms]		Area int. nodes		Area leaf nodes		Primary MRps		Secondary MRps	
Bistro ext. [2.8M]	AABB	17.7	(1.00)	-	-	39.4	(1.00)	10.5	(1.00)	**877.1**	**(1.00)**	103.5	(1.00)
	AABB→*14*-DOP	22.2	(1.25)	4.5	(0.27)	**28.8**	**(0.73)**	6.6	(0.63)	839.0	(0.96)	125.9	(1.22)
	AABB→OBB	34.1	(1.92)	16.4	(1.00)	29.7	(0.75)	**3.3**	**(0.32)**	633.9	(0.72)	127.9	(1.24)
	AABB→SOBB 32d	22.0	(1.24)	4.3	(0.26)	30.5	(0.77)	5.1	(0.49)	603.0	(0.69)	119.8	(1.16)
	AABB→SOBB 32i	22.4	(1.26)	4.7	(0.29)	30.5	(0.77)	5.1	(0.49)	510.4	(0.58)	146.8	(1.42)
	AABB→SOBB 48d	23.8	(1.34)	6.1	(0.37)	30.2	(0.77)	4.5	(0.43)	669.6	(0.76)	132.5	(1.28)
	AABB→SOBB 48i	24.4	(1.37)	6.7	(0.41)	30.2	(0.77)	4.5	(0.43)	538.9	(0.61)	148.2	(1.43)
	AABB→SOBB 64d	28.0	(1.58)	10.3	(0.63)	29.6	(0.75)	4.2	(0.40)	673.9	(0.77)	135.1	(1.31)
	AABB→SOBB 64i	28.4	(1.60)	10.7	(0.65)	29.6	(0.75)	4.2	(0.40)	572.9	(0.65)	**149.6**	**(1.45)**
Bistro int. [1.0M]	AABB	6.1	(1.00)	-	-	46.1	(1.00)	18.4	(1.00)	**1128.1**	**(1.00)**	144.6	(1.00)
	AABB→*14*-DOP	9.4	(1.53)	3.3	(0.51)	34.0	(0.74)	12.4	(0.67)	1073.7	(0.95)	162.1	(1.12)
	AABB→OBB	12.6	(2.06)	6.5	(1.00)	**28.8**	**(0.62)**	**3.5**	**(0.19)**	765.8	(0.68)	229.4	(1.59)
	AABB→SOBB 32d	7.8	(1.27)	1.7	(0.26)	36.4	(0.79)	9.6	(0.52)	793.6	(0.70)	189.6	(1.31)
	AABB→SOBB 32i	8.1	(1.32)	2.0	(0.31)	36.4	(0.79)	9.6	(0.52)	702.0	(0.62)	172.7	(1.19)
	AABB→SOBB 48d	8.7	(1.41)	2.6	(0.40)	31.0	(0.67)	4.9	(0.26)	796.0	(0.71)	280.2	(1.94)
	AABB→SOBB 48i	9.1	(1.49)	3.0	(0.46)	31.0	(0.67)	4.9	(0.26)	710.7	(0.63)	211.4	(1.46)
	AABB→SOBB 64d	10.2	(1.67)	4.1	(0.63)	30.4	(0.66)	4.6	(0.25)	815.9	(0.72)	**292.1**	**(2.02)**
	AABB→SOBB 64i	11.2	(1.83)	5.1	(0.78)	30.4	(0.66)	4.6	(0.25)	739.2	(0.66)	208.3	(1.44)
Hairball [2.9M]	AABB	13.2	(1.00)	-	-	221.8	(1.00)	44.9	(1.00)	171.2	(1.00)	48.2	(1.00)
	AABB→*14*-DOP	17.7	(1.34)	4.5	(0.34)	**156.8**	**(0.71)**	25.2	(0.56)	253.0	(1.48)	73.0	(1.52)
	AABB→OBB	26.3	(1.99)	13.1	(1.00)	186.4	(0.84)	**12.5**	**(0.28)**	299.5	(1.75)	84.7	(1.76)
	AABB→SOBB 32d	17.5	(1.32)	4.3	(0.33)	194.8	(0.88)	21.7	(0.48)	266.7	(1.56)	79.7	(1.65)
	AABB→SOBB 32i	18.0	(1.36)	4.8	(0.37)	194.8	(0.88)	21.7	(0.48)	235.5	(1.38)	98.1	(2.04)
	AABB→SOBB 48d	18.3	(1.39)	5.1	(0.39)	189.6	(0.85)	19.3	(0.43)	303.5	(1.77)	86.0	(1.79)
	AABB→SOBB 48i	18.4	(1.39)	5.2	(0.40)	189.6	(0.85)	19.3	(0.43)	266.6	(1.56)	98.7	(2.05)
	AABB→SOBB 64d	21.6	(1.63)	8.4	(0.64)	186.4	(0.84)	17.9	(0.40)	**336.2**	**(1.96)**	93.2	(1.94)
	AABB→SOBB 64i	21.6	(1.63)	8.4	(0.64)	186.4	(0.84)	17.9	(0.40)	286.2	(1.67)	**100.1**	**(2.08)**
Sheep [10.7M]	AABB	57.3	(1.00)	-	-	1298.4	(1.00)	1029.4	(1.00)	13.5	(1.00)	2.8	(1.00)
	AABB→*14*-DOP	73.0	(1.27)	15.7	(0.26)	739.4	(0.57)	544.9	(0.53)	28.4	(2.10)	7.0	(2.48)
	AABB→OBB	117.8	(2.07)	60.5	(1.00)	**412.5**	**(0.32)**	190.2	(0.18)	84.3	(6.26)	25.8	(9.22)
	AABB→SOBB 32d	77.0	(1.34)	19.7	(0.33)	531.1	(0.41)	250.5	(0.24)	44.6	(3.31)	15.2	(5.41)
	AABB→SOBB 32i	77.5	(1.35)	20.2	(0.33)	531.1	(0.41)	250.5	(0.24)	47.9	(3.54)	17.9	(6.35)
	AABB→SOBB 48d	82.9	(1.45)	25.6	(0.42)	459.3	(0.35)	181.3	(0.18)	85.0	(6.29)	22.0	(7.82)
	AABB→SOBB 48i	79.8	(1.39)	22.5	(0.37)	459.3	(0.35)	181.3	(0.18)	84.6	(6.27)	25.7	(9.15)
	AABB→SOBB 64d	90.9	(1.59)	33.6	(0.56)	424.8	(0.33)	**149.1**	**(0.14)**	**86.2**	**(6.39)**	26.9	(9.56)
	AABB→SOBB 64i	90.8	(1.59)	33.5	(0.55)	424.8	(0.33)	**149.1**	**(0.14)**	80.5	(5.96)	**31.0**	**(11.01)**

Discussion

- How close is the structure to optimum ?
  - SOBB 128 / SOBB 256
- Build AABB, then k-DOP hierarchies before getting to SOBB
  - With a different construction method, could the BVH be shallower than with AABB?