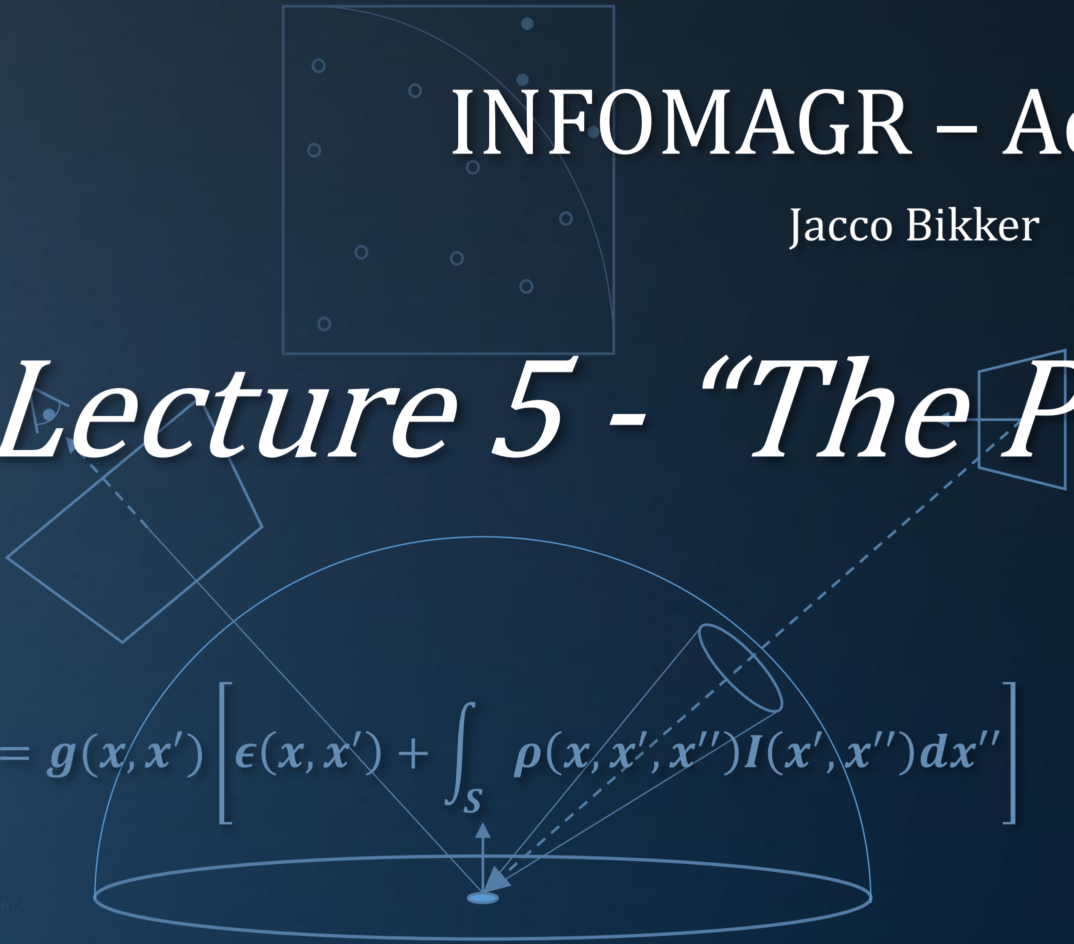
INFOMAGR – Advanced Graphics

Jacco Bikker - November 2021 - February 2022

Lecture 5 - “The Perfect BVH”

Welcome!



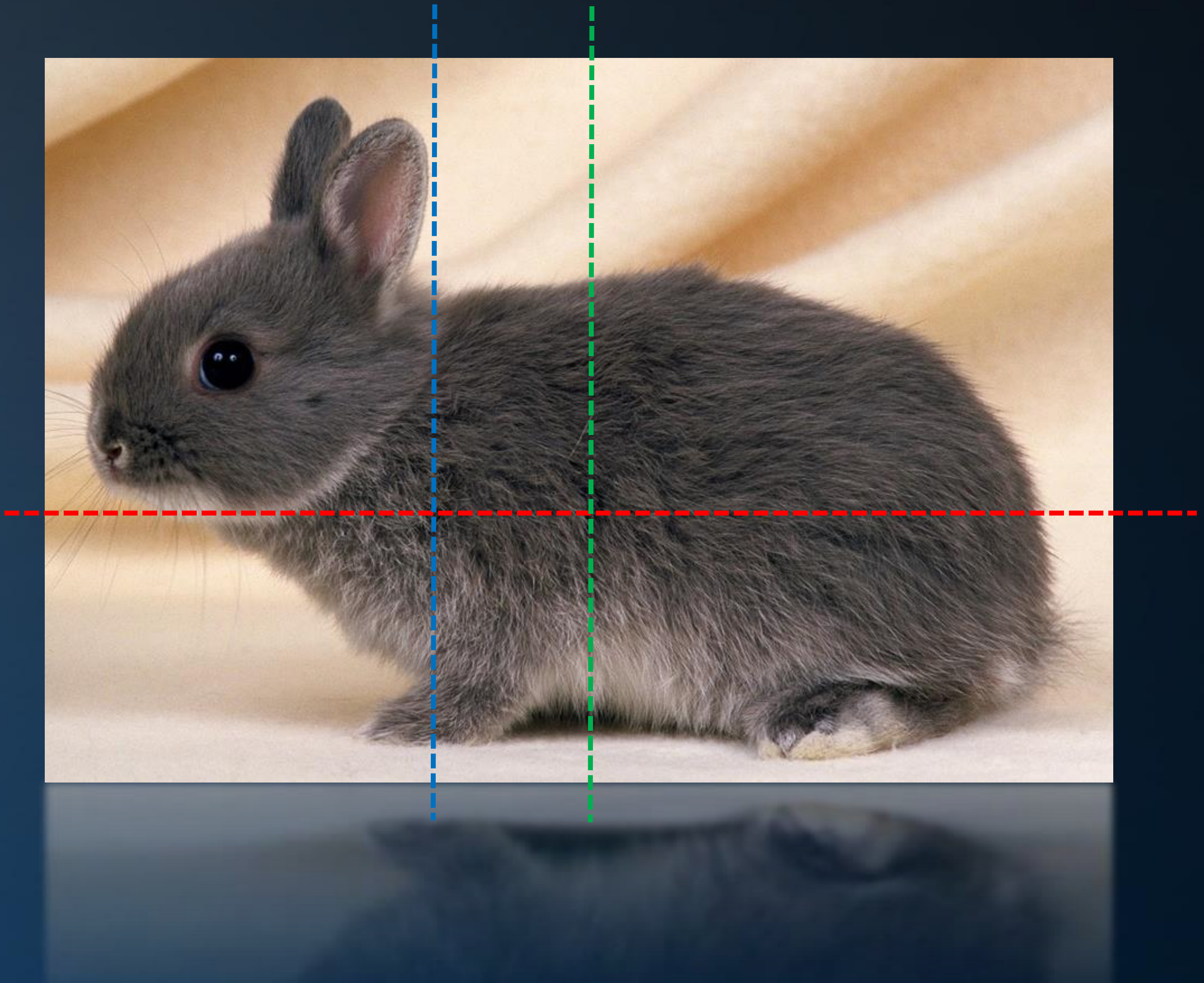
$$I(x,x') = g(x,x')\left[\epsilon(x,x') + \int_S \rho(x,x',x'')I(x',x'')dx''\right]$$

```
ics
& (depth < MAXDEPTH)

c = inside ? 1 : 1.2
nt = nt / nc, ddn = 
os2t = 1.0f - nnt * nnt
D, N );
0)

at a = nt - nc, b = nt
at Tr = 1 - (R0 + (1 - R0)
Tr) R = (D * nnt - N * (ddn

E * diffuse;
= true;

-
efl + refr)) && (depth < MAXDEPTH)

D, N );
refl * E * diffuse;
= true;


MAXDEPTH)

survive = SurvivalProbability( diffuse );
estimation - doing it properly, closely
df;
radiance = SampleLight( &rand, I, &L, &light
e.x + radiance.y + radiance.z) > 0) && (do

w = true;
at brdfPdf = EvaluateDiffuse( L, N ) * Psurvive;
at3 factor = diffuse * INVPI;
at weight = Mis2( directPdf, brdfPdf );
at cosThetaOut = dot( N, L );
E * ((weight * cosThetaOut) / directPdf) * (radiance

andom walk - done properly, closely following Smallvc
vive)

;
at3 brdf = SampleDiffuse( diffuse, N, r1, r2, &R, &pdf );
urvive;
pdf;
n = E * brdf * (dot( N, R ) / pdf);
sion = true;
```

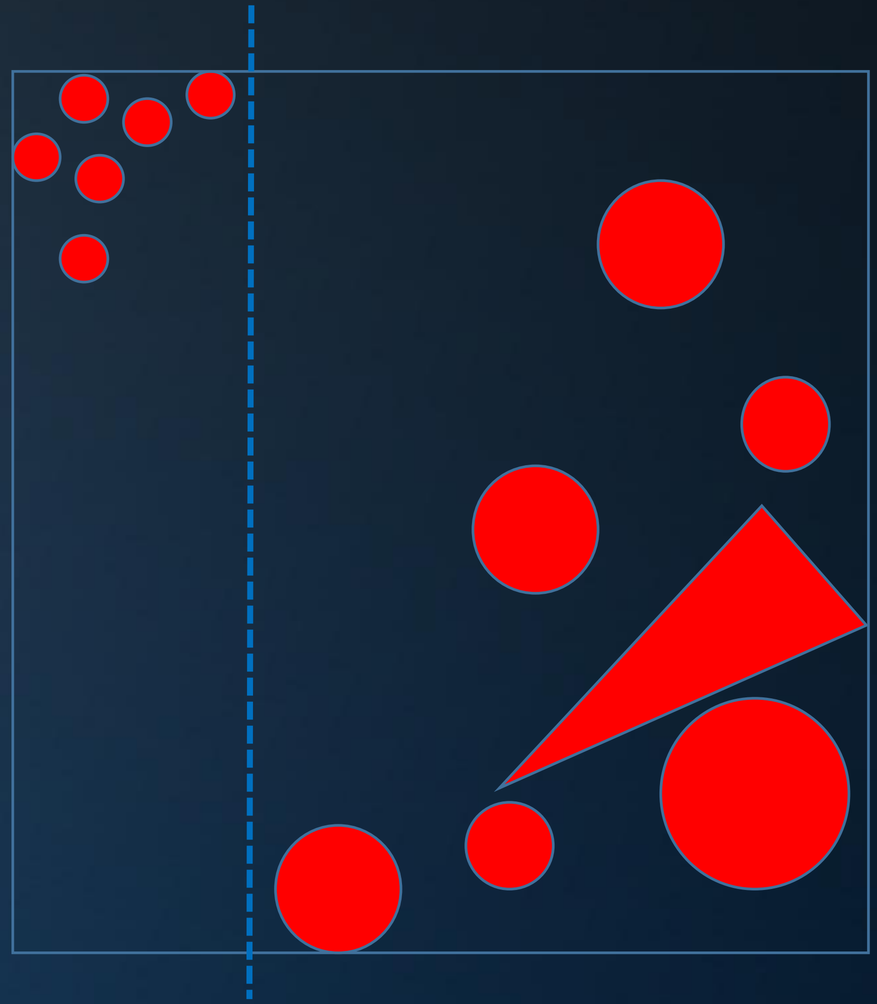
Today’s Agenda:

- Building Better BVHs
- Refitting
- Fast BVH Construction
- The Top-level BVH

Better BVHs



Better BVHs



Better BVHs

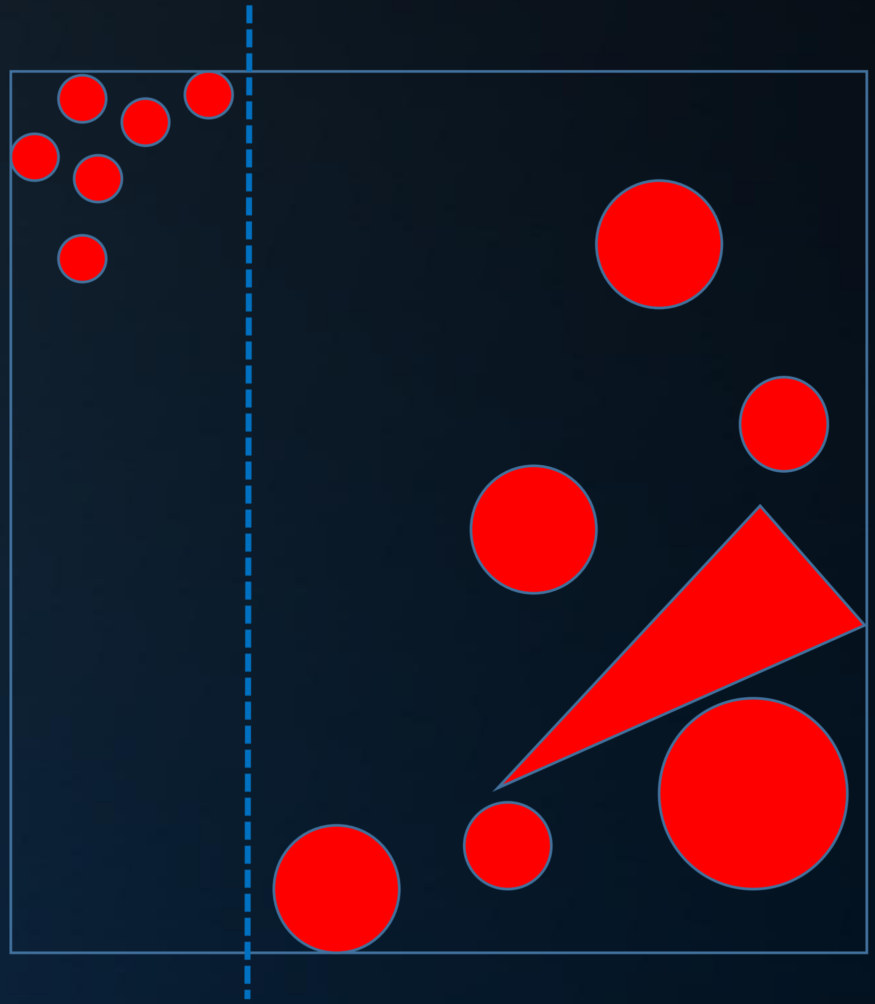
What Are We Trying To Solve?

A BVH is used to reduce the number of ray/primitive intersections.

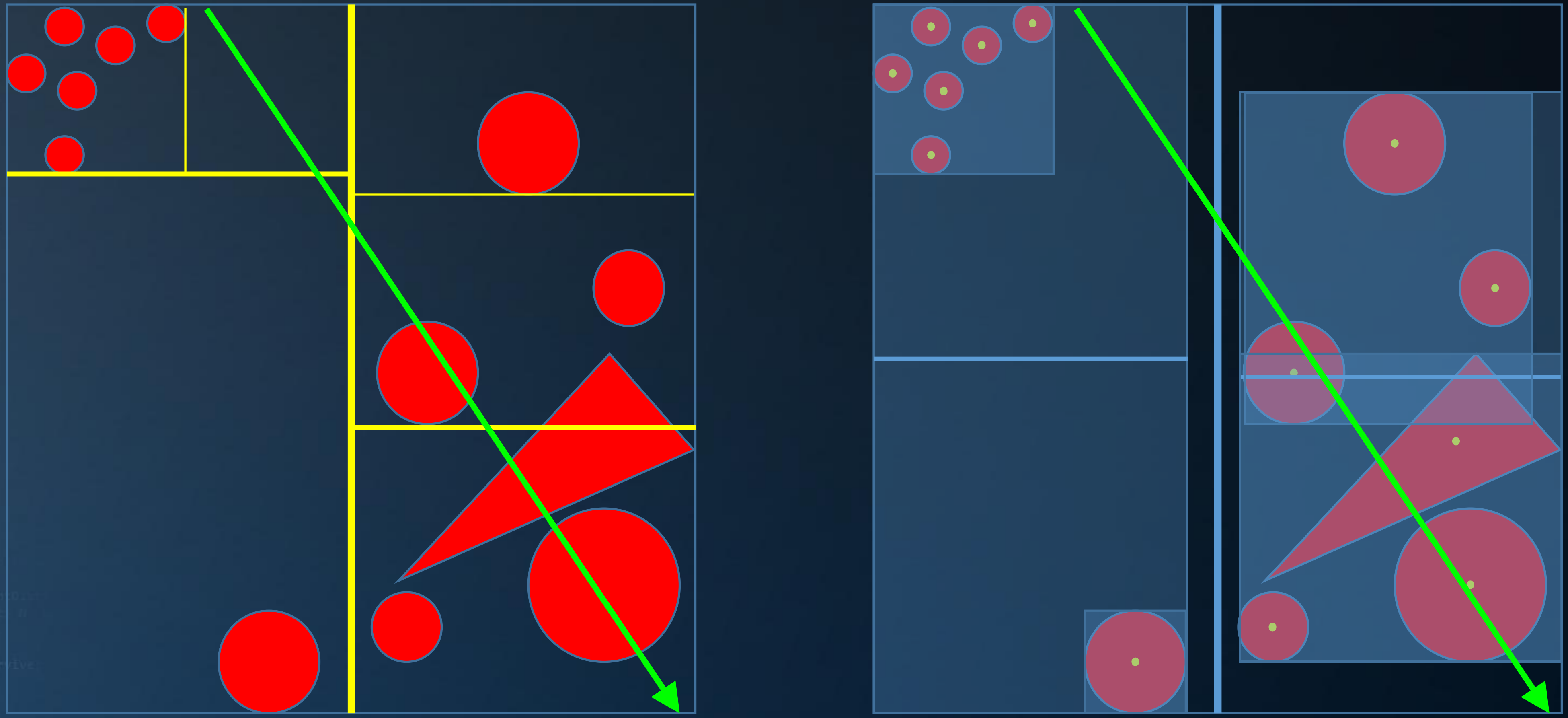
But: it introduces new intersections.

The ideal BVH minimizes:

- # of ray / primitive intersections
- # of ray / node intersections.



Better BVHs



Better BVHs

BVH versus kD-tree

The BVH better encapsulates geometry.

➔ This reduces the chance of a ray hitting a node.

➔ This is all about probabilities!

What is the probability of a ray hitting a random triangle?

What is the probability of a ray hitting a random node?

This probability is proportional to **surface area.**

Better BVHs

Route 1: 10% up-time, $1000 fine

Route 2: 100% up-time, $100 fine

Better BVHs

Optimal Split Plane Position

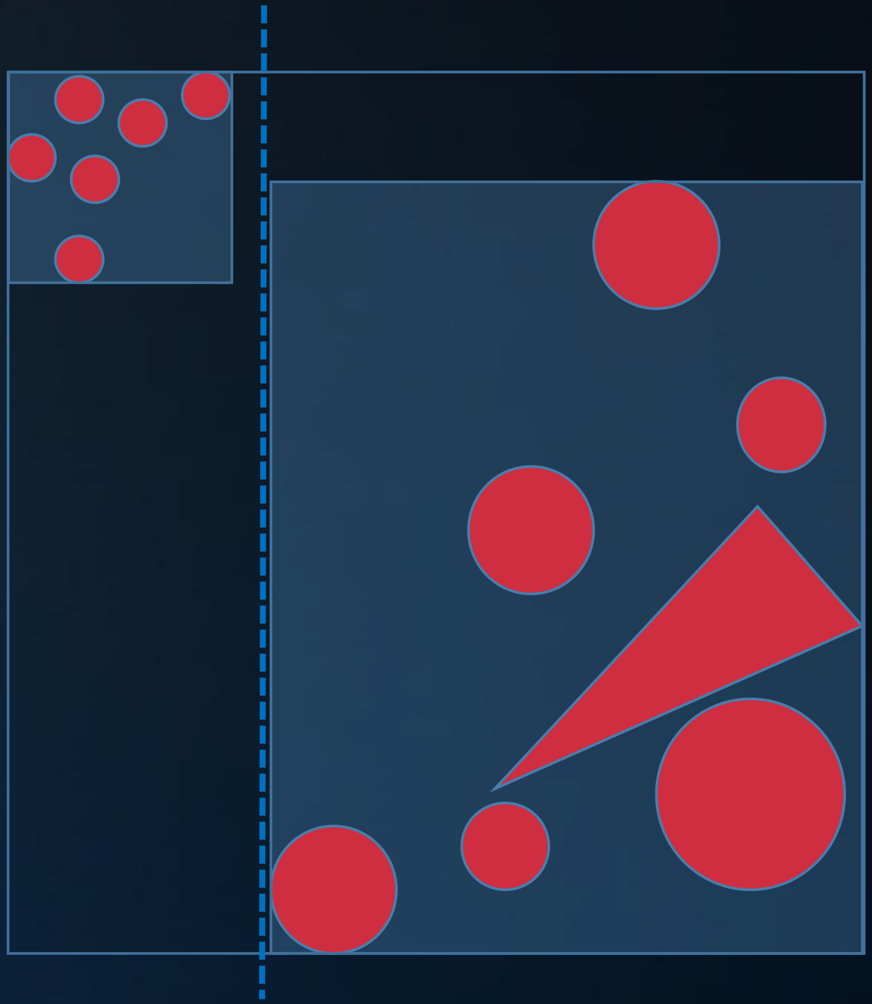
The ideal split minimizes the *expected cost* of a ray intersecting the resulting nodes.

This expected cost is based on:

- Number of primitives that will have to be intersected
- Probability of this happening

The cost of a split is thus:

$$A_{left} * N_{left} + A_{right} * N_{right}$$



Better BVHs

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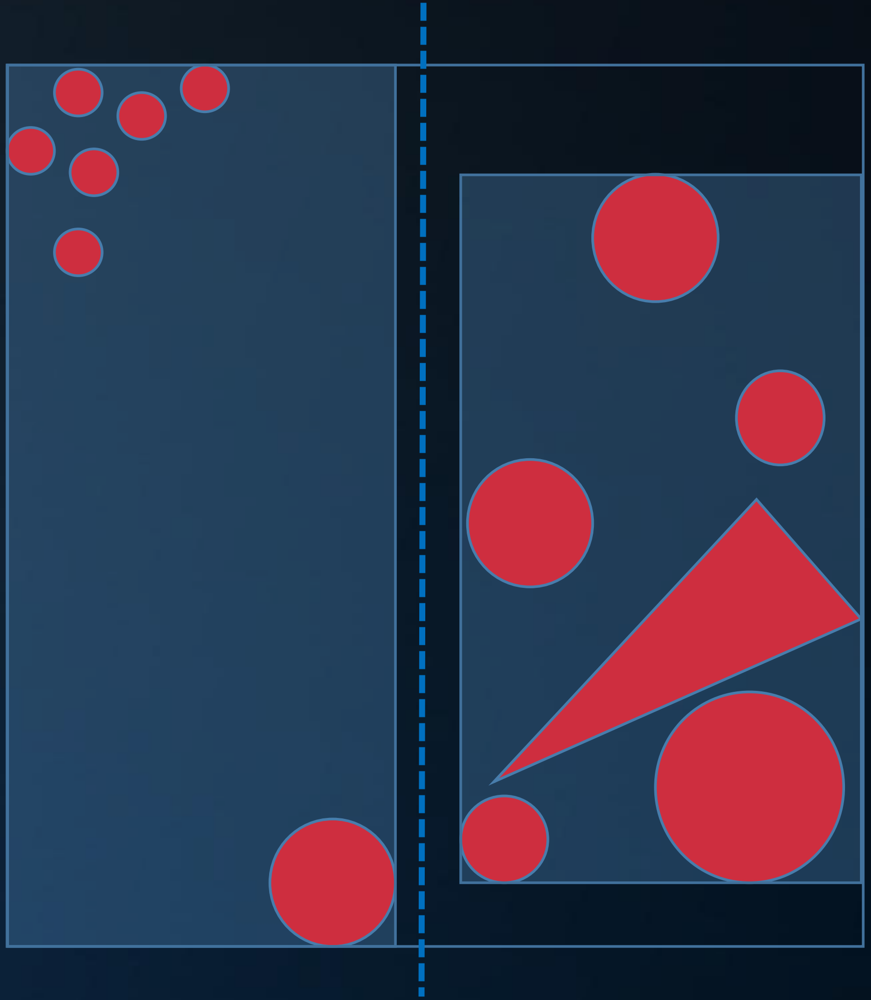


Better BVHs

Optimal Split Plane Position

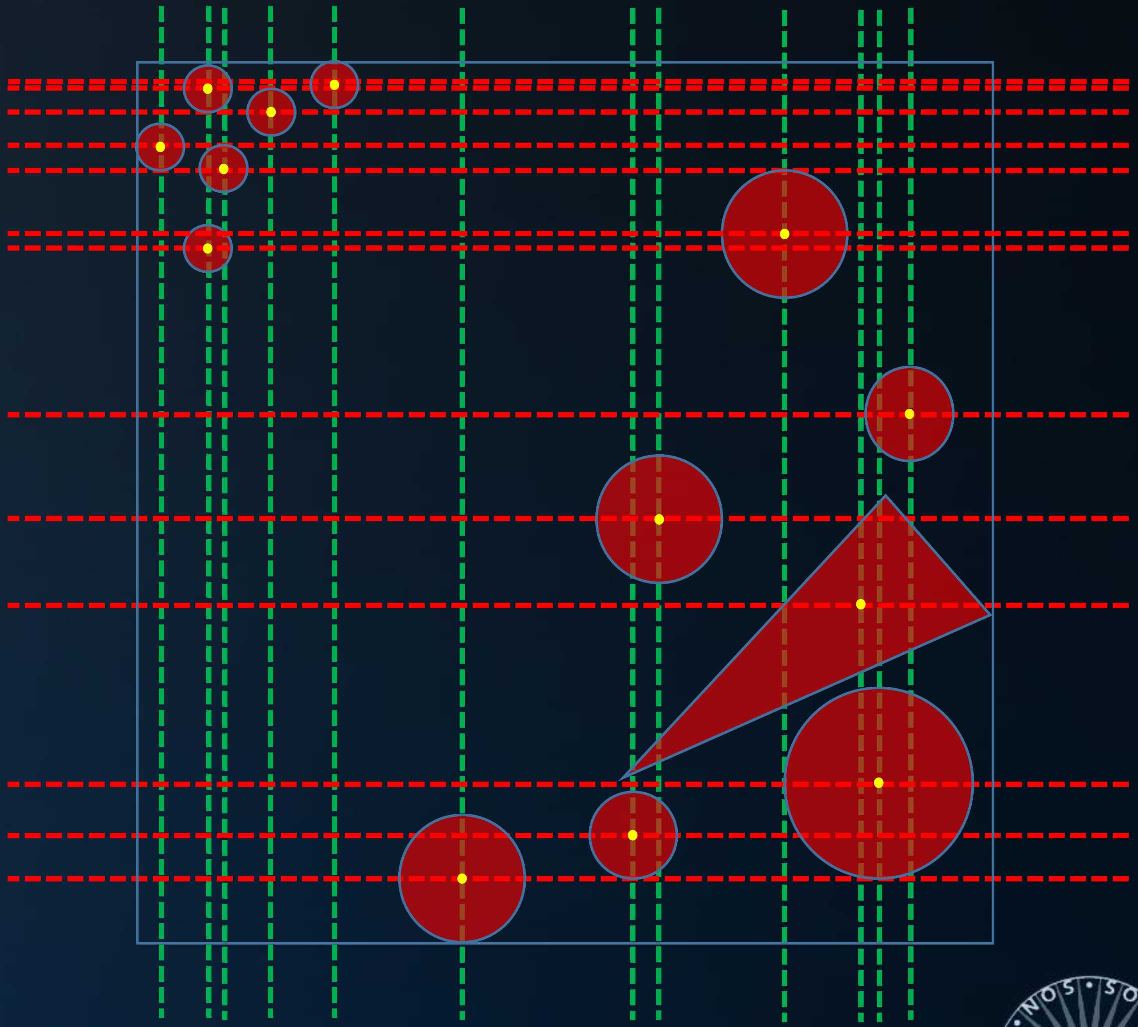
Which positions do we consider?

Object subdivision may happen over x, y or z axis.

The cost function is constant between primitive centroids.

➔ For N primitives: $3(N-1)$ possible locations

➔ For a 2-level tree: $(3(N-1))^2$ configurations



Better BVHs

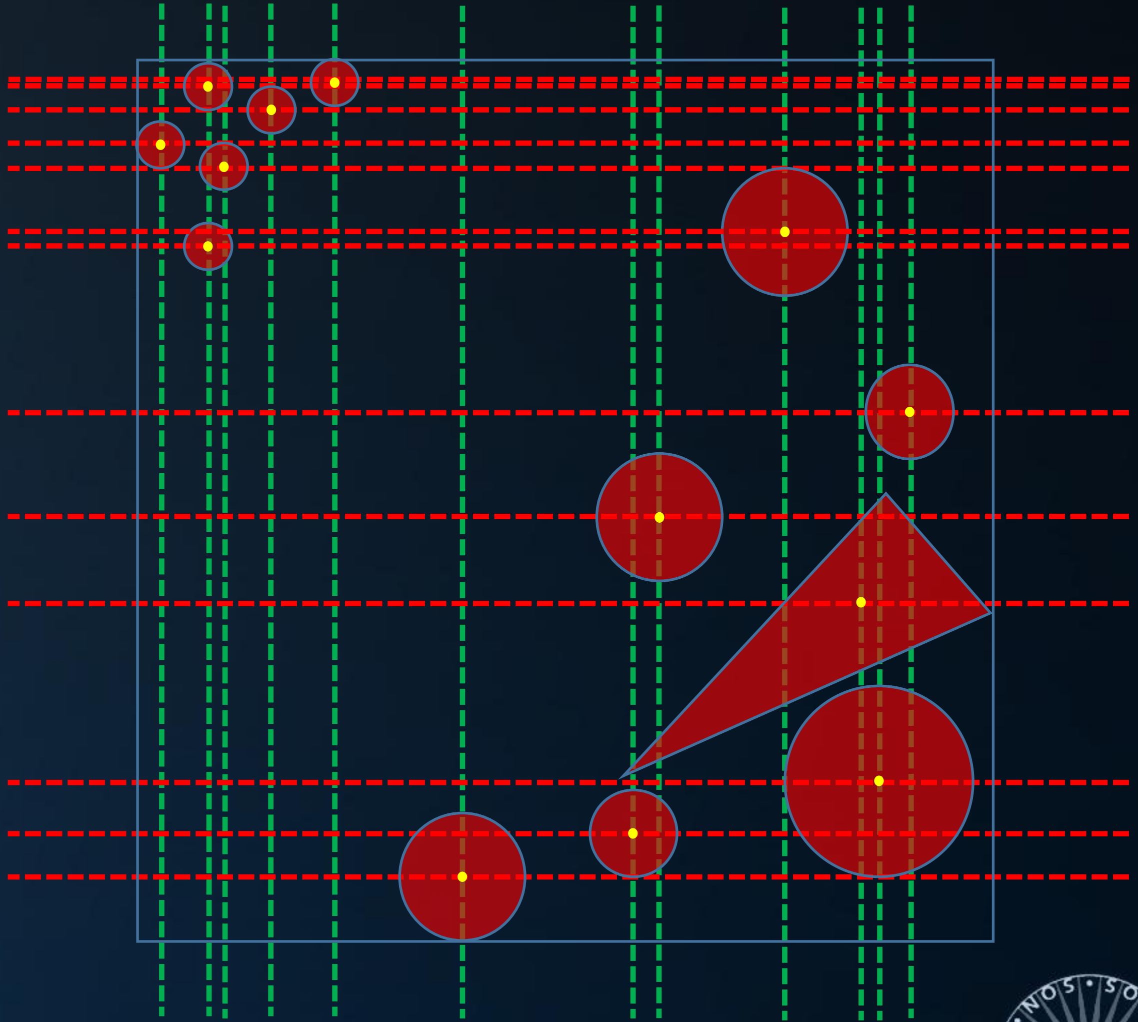
SAH and Termination

A split is ‘not worth it’ if it doesn’t yield a cost lower than the cost of the parent node, i.e.:

$$A_{left} * N_{left} + A_{right} * N_{right} \geq A * N$$

This provides us with a natural and optimal termination criterion.

(and it solves the problem of the Bad Artist)



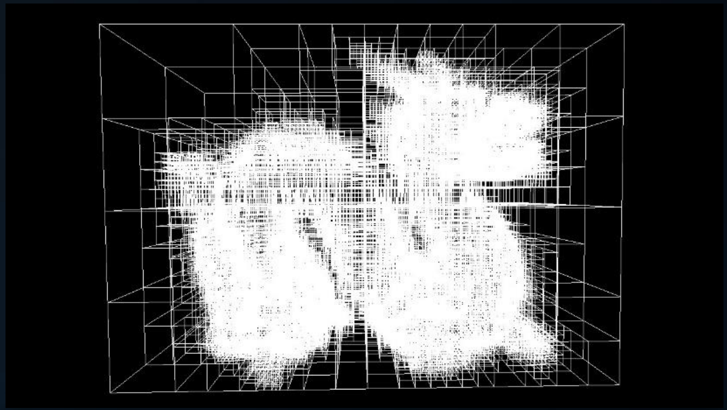
Better BVHs

Optimal Split Plane Position

The *surface area heuristic* (SAH) is applied in a greedy manner*.

*: Heuristics for Ray Tracing using Space Subdivision, MacDonald & Booth, 1990.

Better BVHs



Optimal Split Plane Position

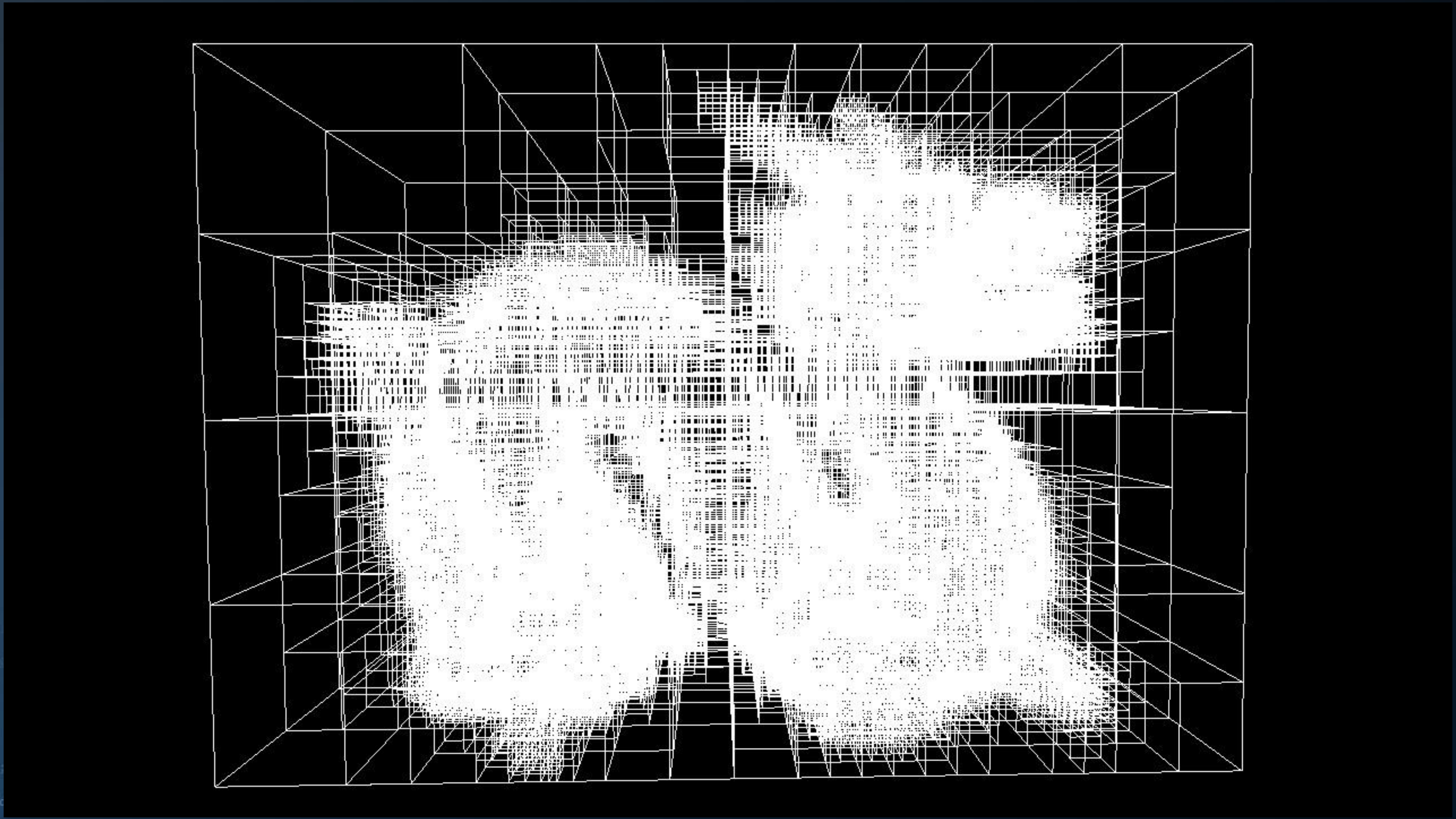
Comparing naïve versus SAH:

- SAH will cut #intersections in half;
- expect ~2x better performance.

SAH & kD-trees:

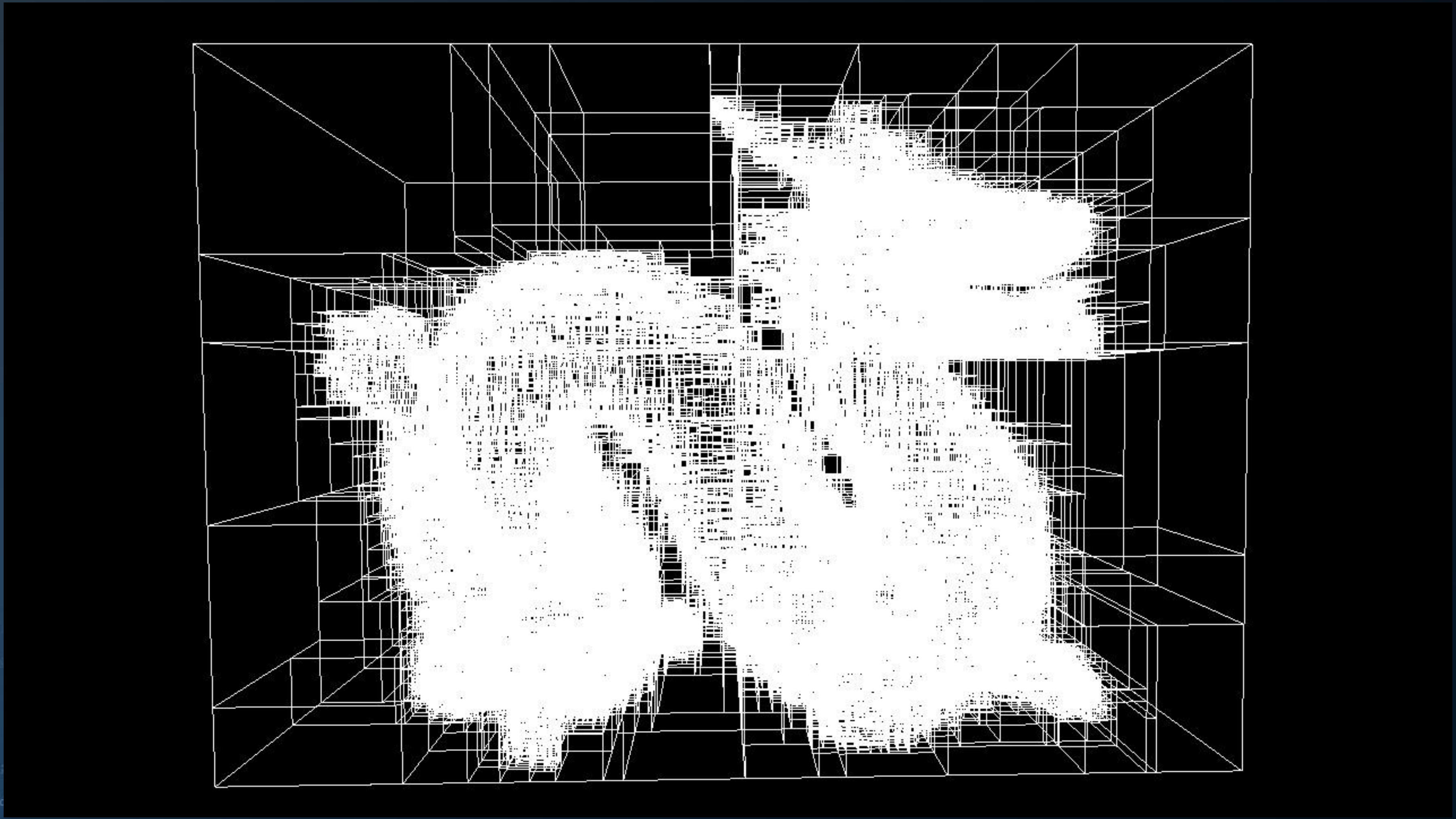
- Same scheme applies.

Better BVHs



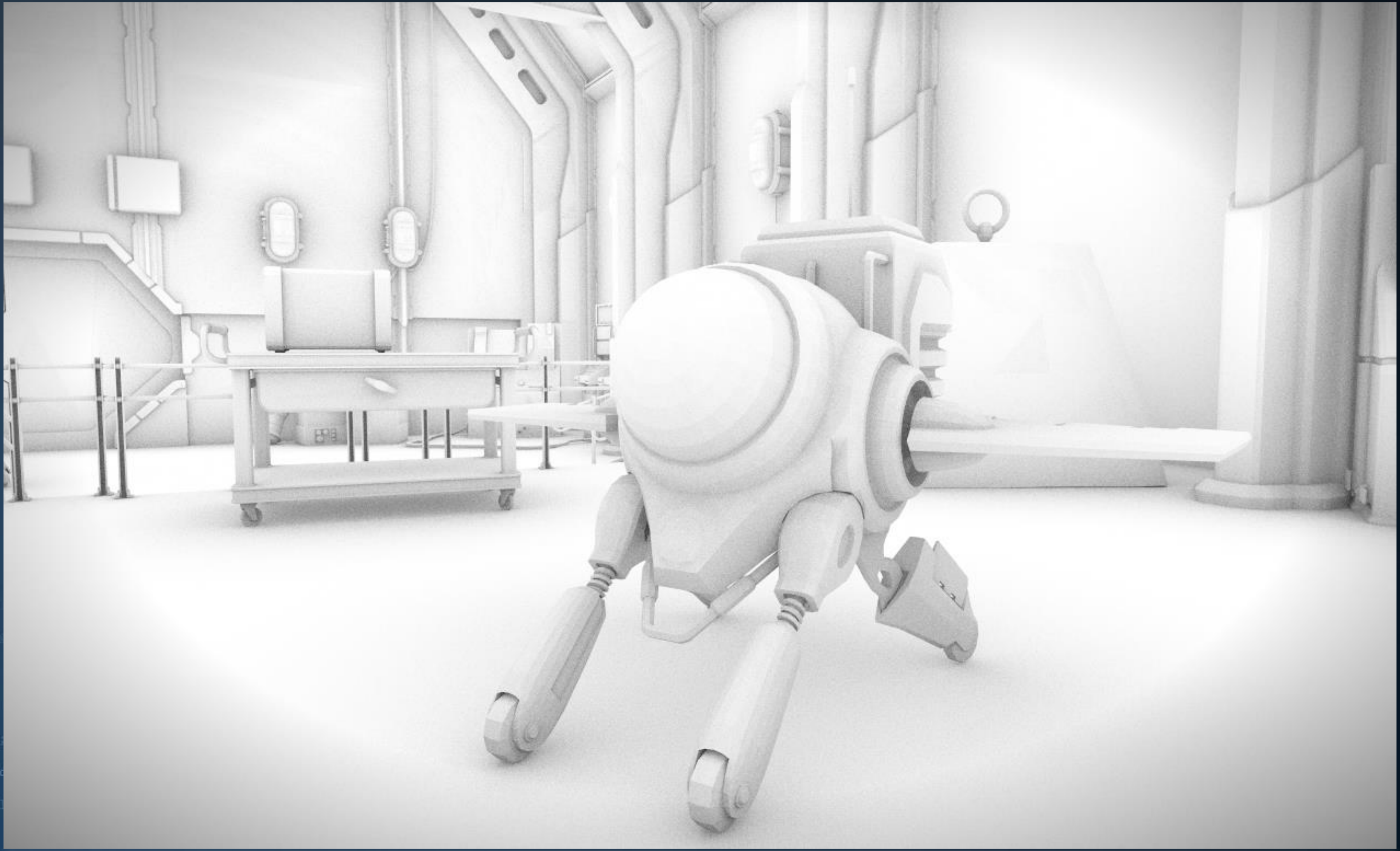
Median Split

Better BVHs

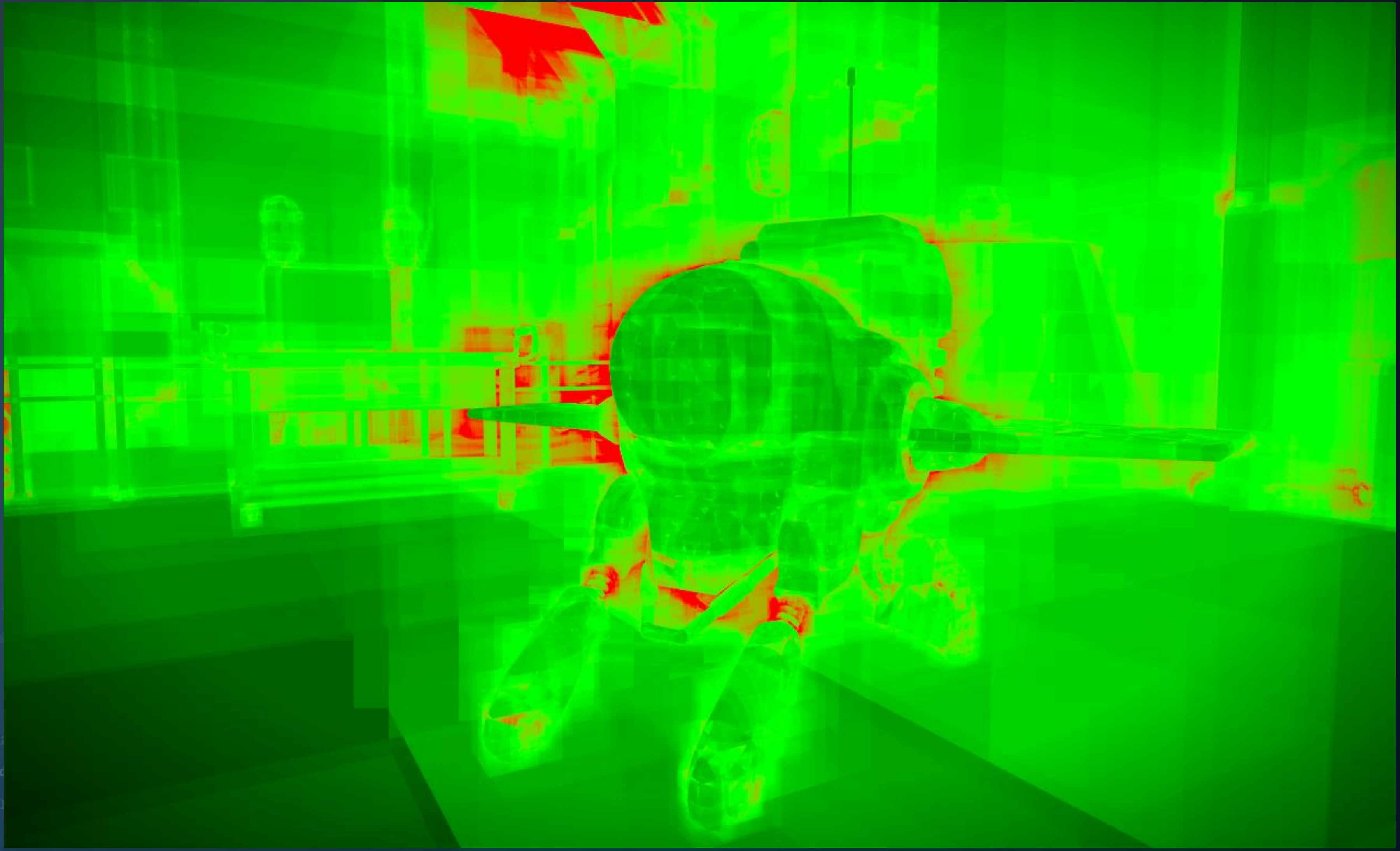


Surface Area Heuristic

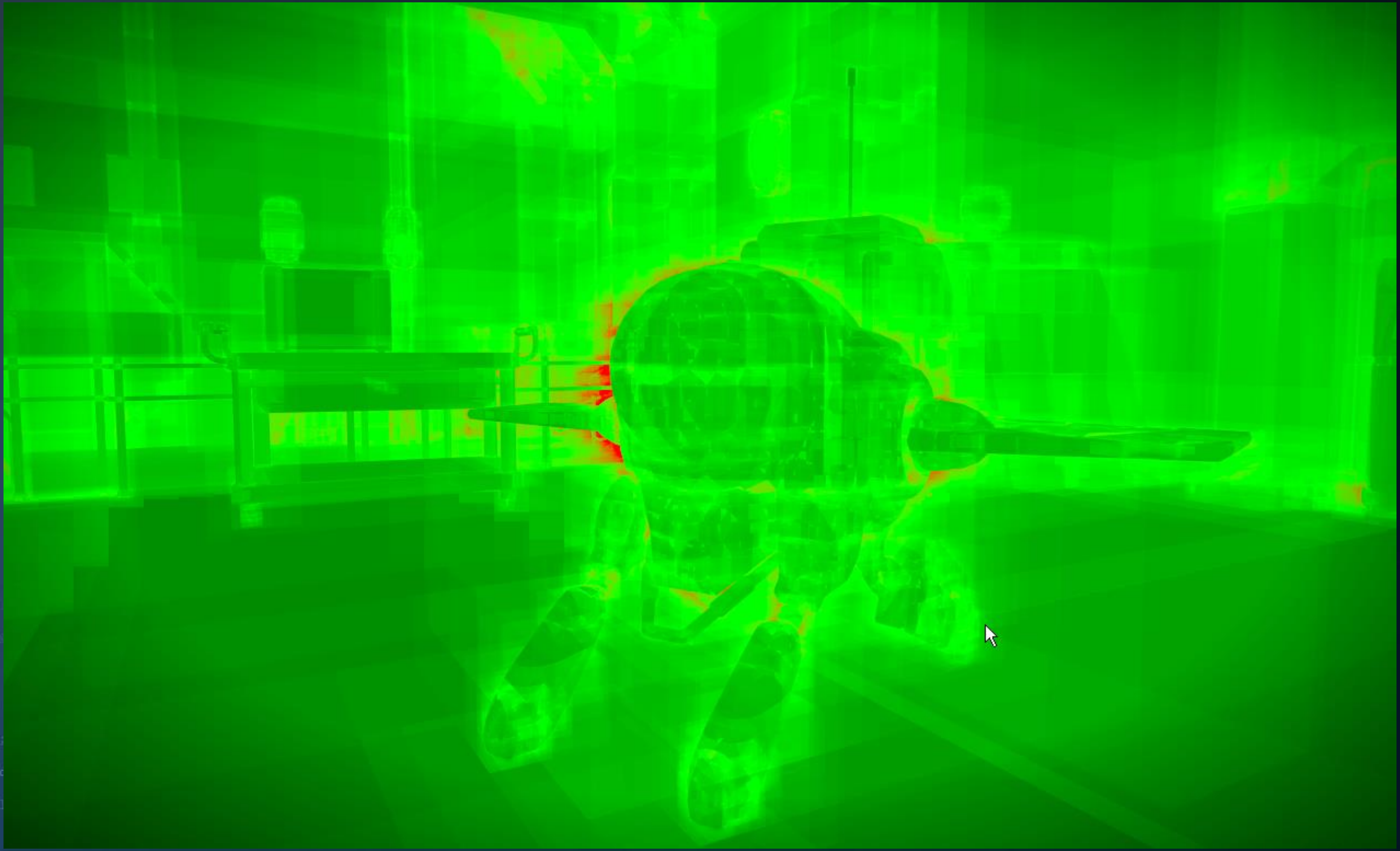
Better BVHs



Better BVHs



Better BVHs



Today’s Agenda:

- Building Better BVHs
- Refitting
- Fast BVH Construction
- The Top-level BVH

Refitting

Summary of BVH Characteristics

A BVH provides significant freedom compared to e.g. a kD-tree:

- No need for a 1-to-1 relation between bounding boxes and primitives
- Bounding boxes may overlap
- Bounding boxes can be altered, as long as they fit in their parent box
- A BVH can be very bad but still valid

Some consequences / opportunities:

- We can rebuild part of a BVH
- We can combine two BVHs into one
- We can *refit* a BVH

Refitting

Refitting

Q: What happens to the BVH of a tree model, if we make it bend in the wind?

A: Likely, only bounds will change; the topology of the BVH will be the same (or at least similar) in each frame.

Refitting:

Updating the bounding boxes stored in a BVH to match changed primitive coordinates.

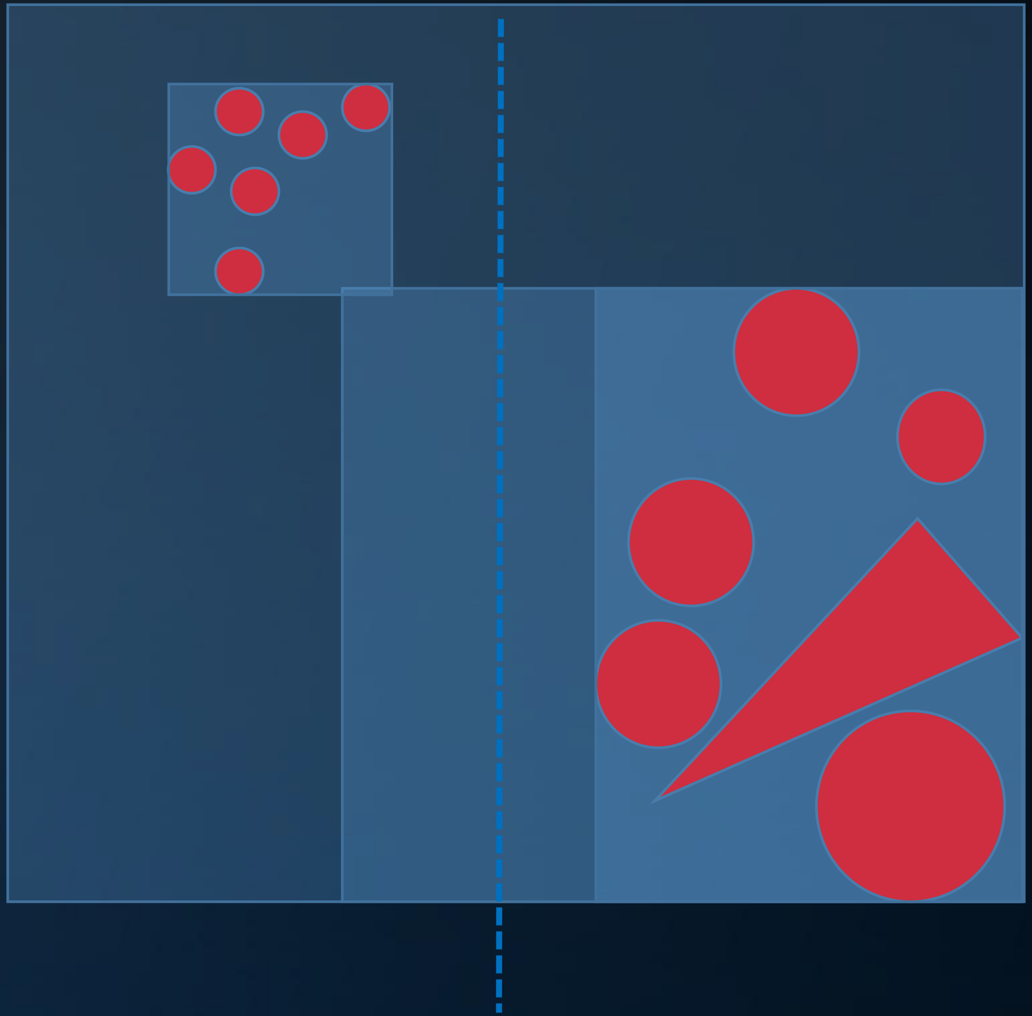
Refitting

Refitting

Updating the bounding boxes stored in a BVH to match changed primitive coordinates.

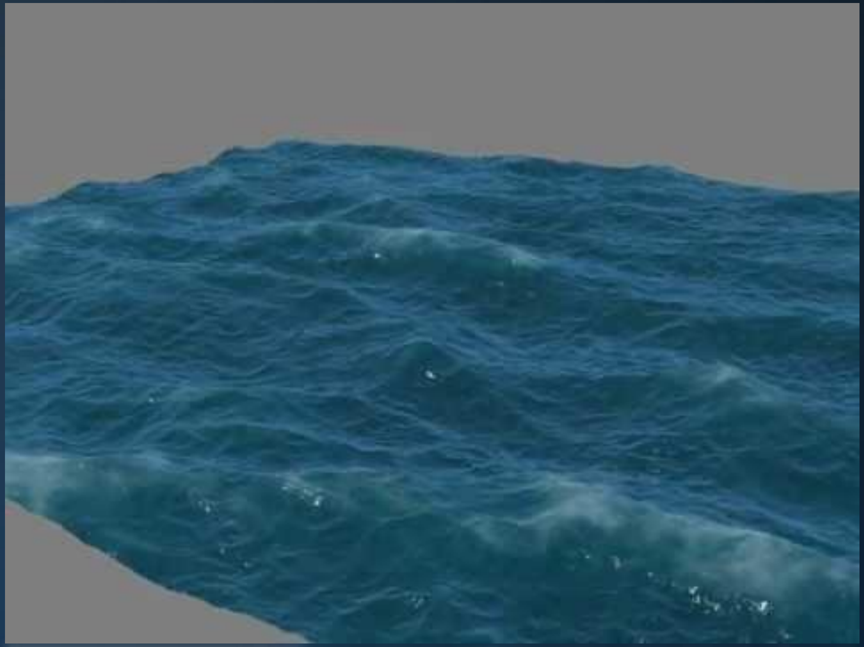
Algorithm:

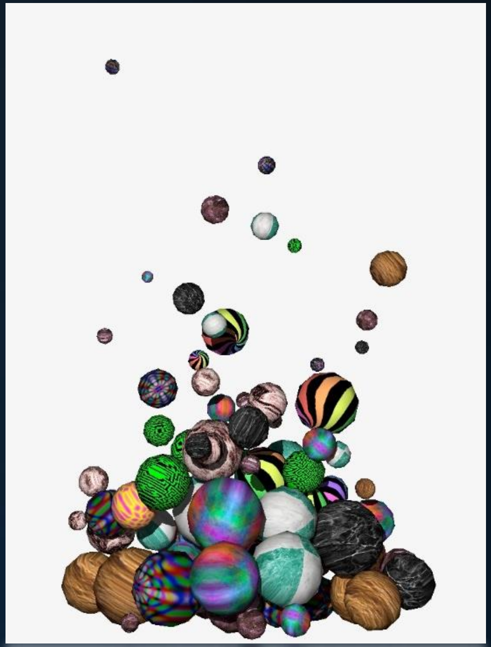
1. For each leaf, calculate the bounds over the primitives it represents
2. Update parent bounds



Refitting

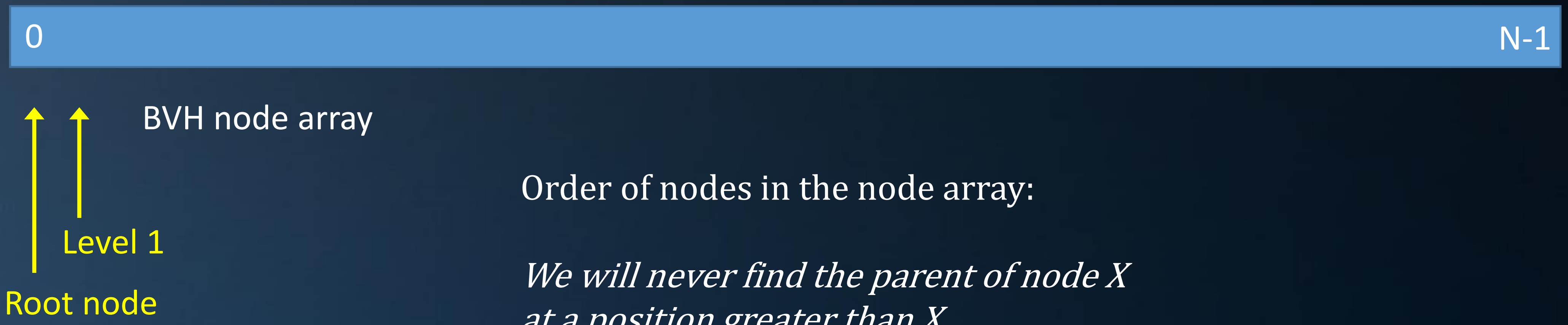
Refitting - Suitability





Refitting

Refitting – Practical



Order of nodes in the node array:

We will never find the parent of node X at a position greater than X.

Therefore:

```
for( int i = N-1; i >= 0; i-- )
   nodeArray[i].AdjustBounds();
```

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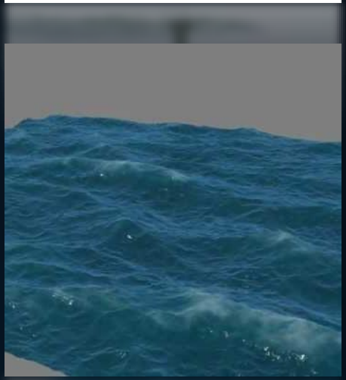
Binning



Rapid BVH Construction

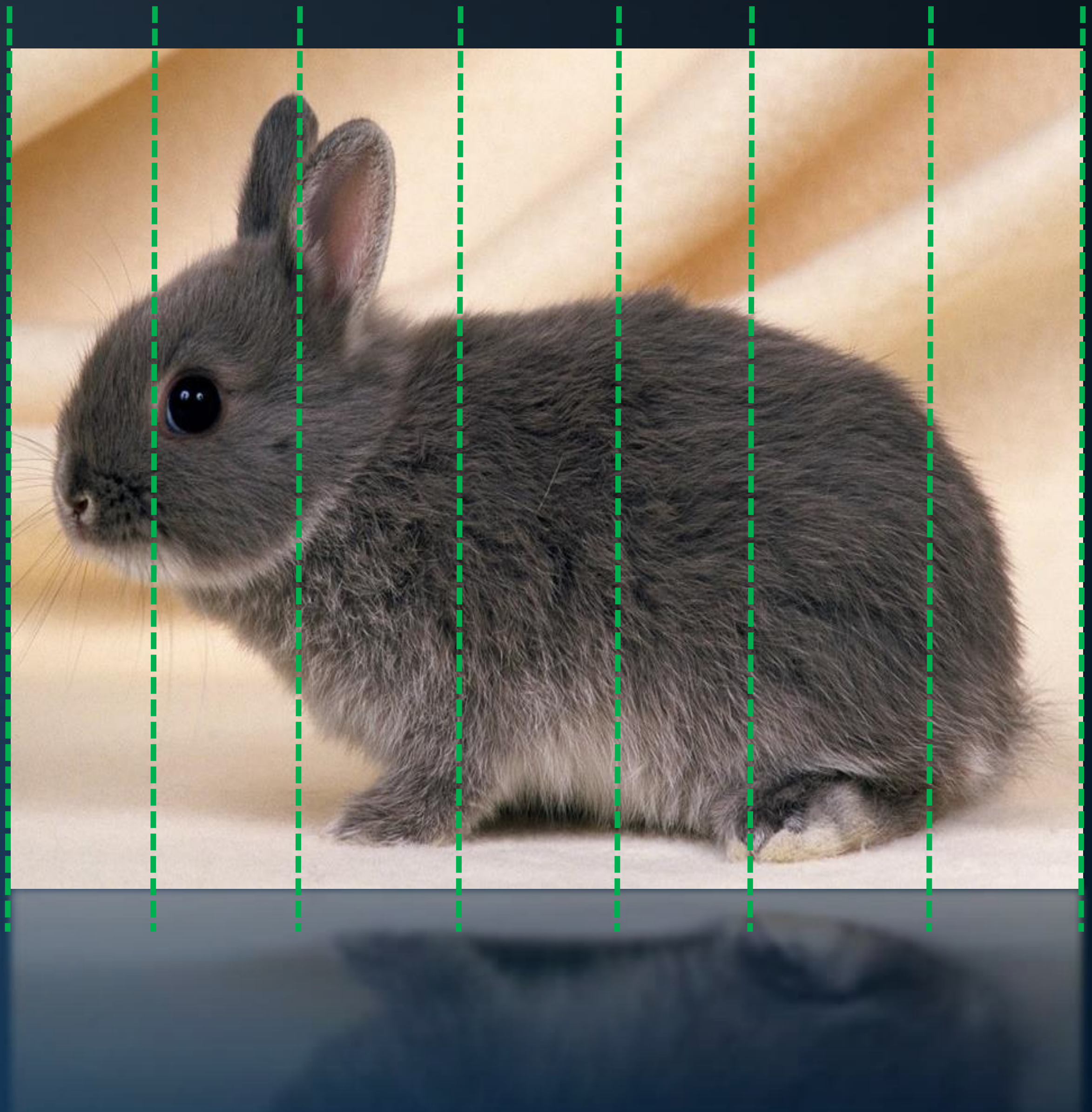
Refitting allows us to update hundreds of thousands of primitives in real-time. But what if topology changes significantly?

Rebuilding a BVH requires $3NlogN$ split plane evaluations.

Options:

1. Do not use SAH (significantly lower quality BVH)
2. Do not evaluate all 3 axes (minor degradation of BVH quality)
3. Make split plane selection independent of N

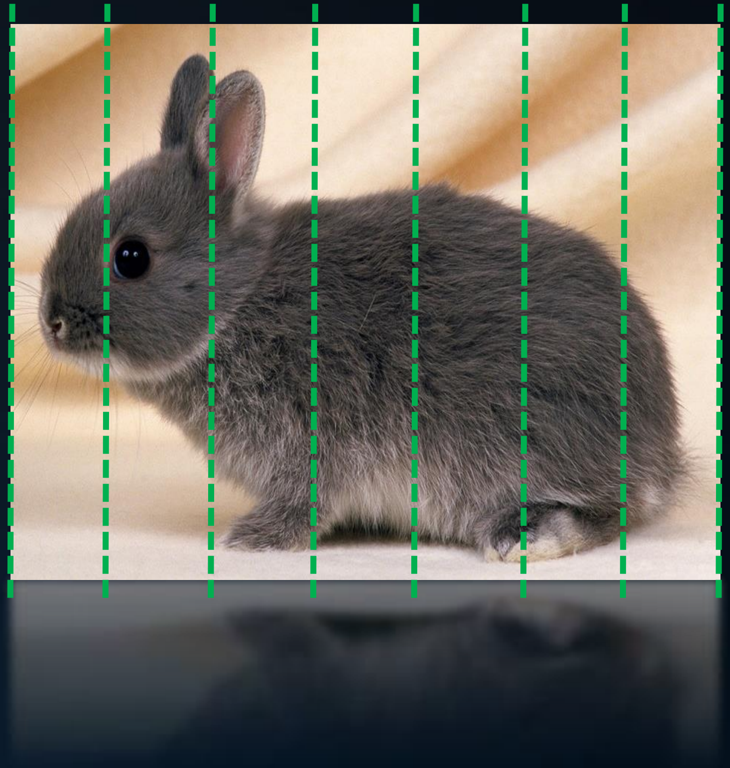
Binning



Binning

Binned BVH Construction*

Binned construction:
Evaluate SAH at N discrete intervals.



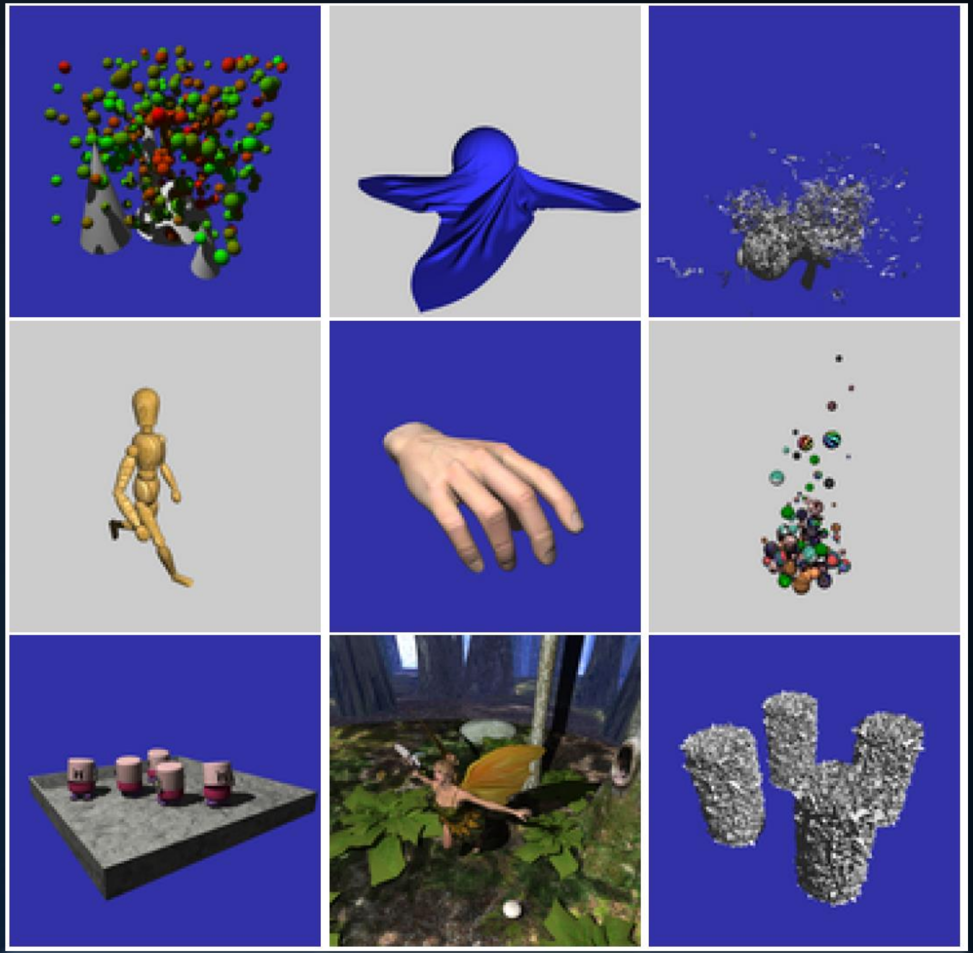
*: On fast Construction of SAH-based Bounding Volume Hierarchies, Wald, 2007

Binning

Binned BVH Construction

Performance evaluation:

472ms 7.88M triangles (12 cores @ 2Ghz)*.



*: Parallel BVH Construction using Progressive Hierarchical Refinement, Henrich et al., 2016.

Today's Agenda:

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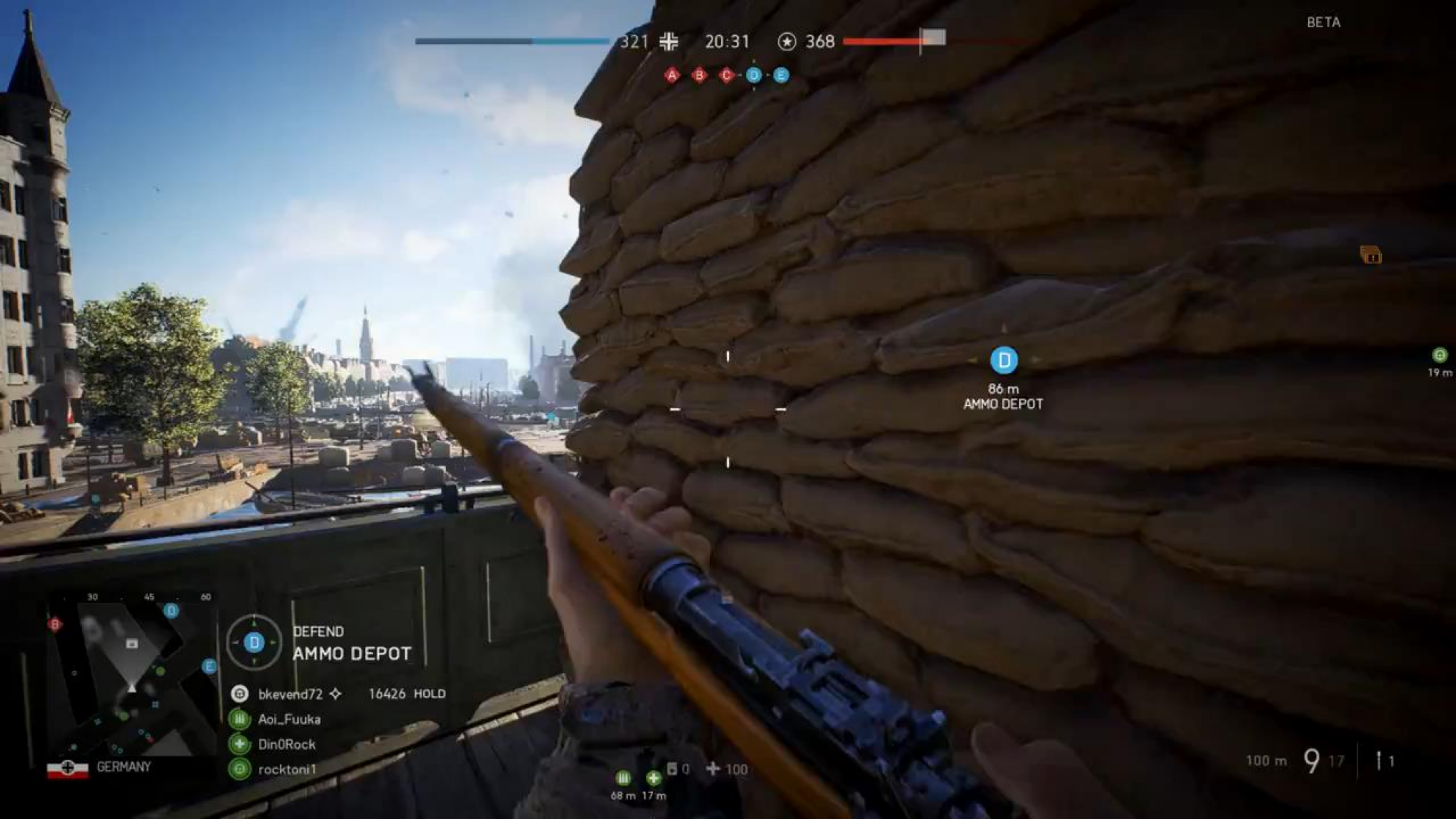
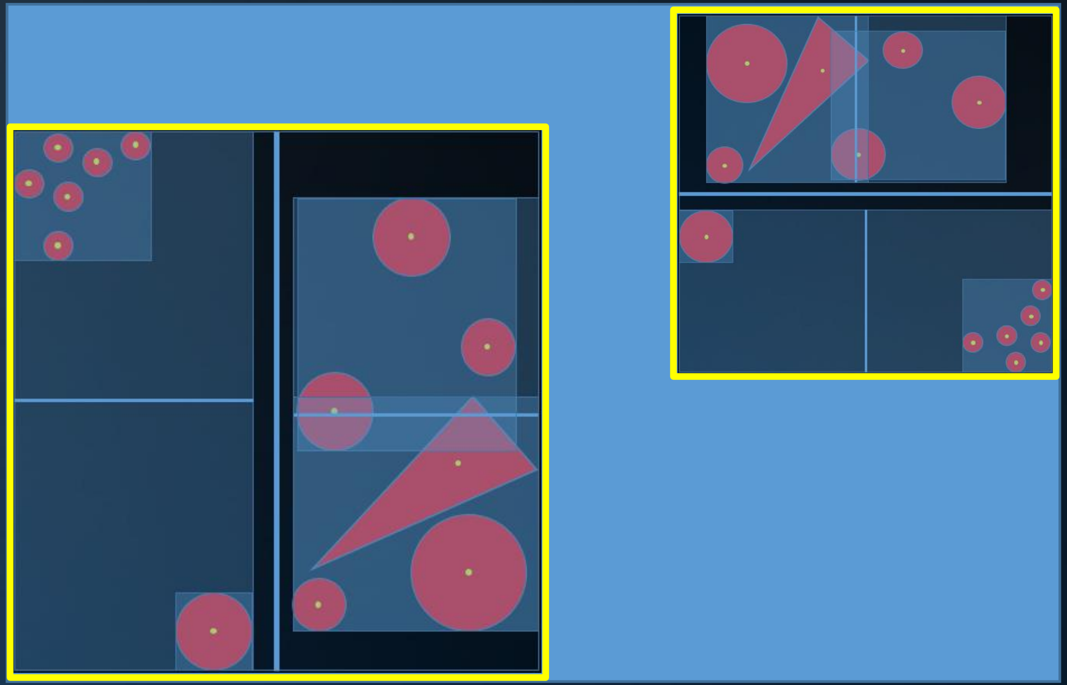
Top-level BVH

Top-level BVH


BETA
321
20:31
368
A B C D E
D
86 m
AMMO DEPOT
19 m
30 45 60
B D E
GERMANY
DEFEND
AMMO DEPOT
bkevend72
16426 HOLD
Aoi_Fuuka
Din0Rock
rocktoni1
0
100
68 m 17 m
100 m
9
17
1

Top-level BVH

Combining BVHs

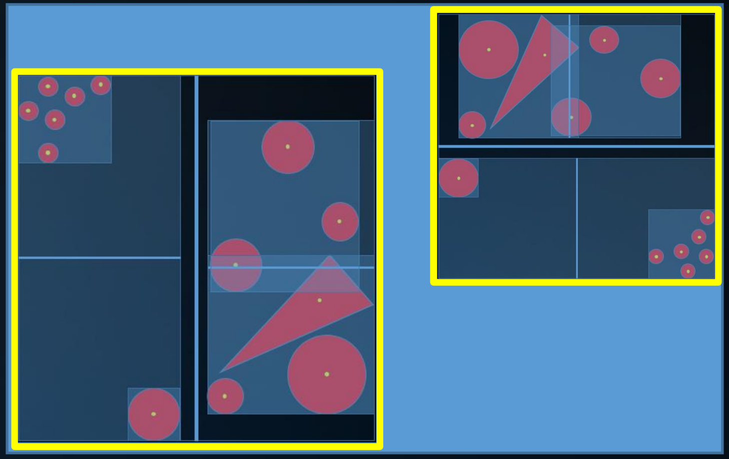


Top-level BVH

Combining BVHs

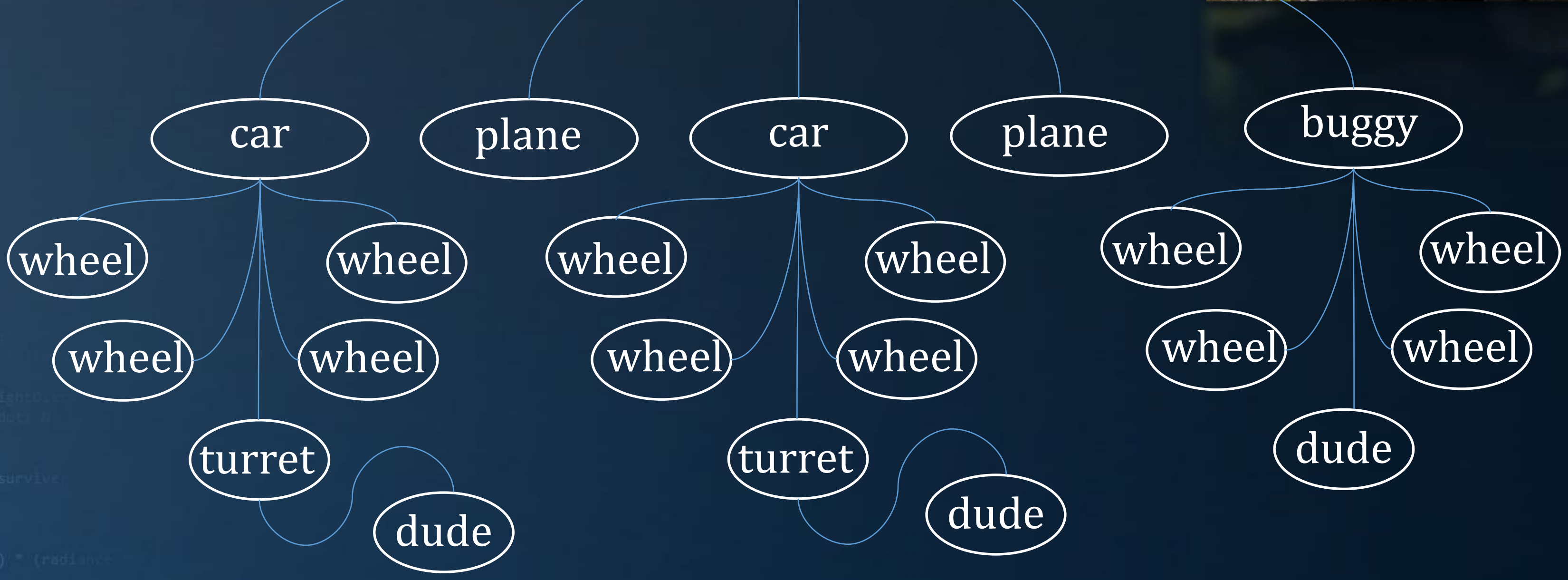
Two BVHs can be combined into a single BVH, by simply adding a new root node pointing to the two BVHs.

- This works regardless of the method used to build each BVH
- This can be applied repeatedly to combine many BVHs



Top-level BVH

Scene Graph



world

car
wheel
wheel
wheel
wheel
turret
dude

plane

car
wheel
wheel
wheel
wheel
turret
dude

plane

buggy
wheel
wheel
wheel
wheel
dude

Top-level BVH

Scene Graph

If our application uses a scene graph, we can construct a BVH for each scene graph node.

The BVH for each node is built using an appropriate construction algorithm:

- High-quality SBVH for static scenery (offline)
- Fast binned SAH BVHs for dynamic scenery

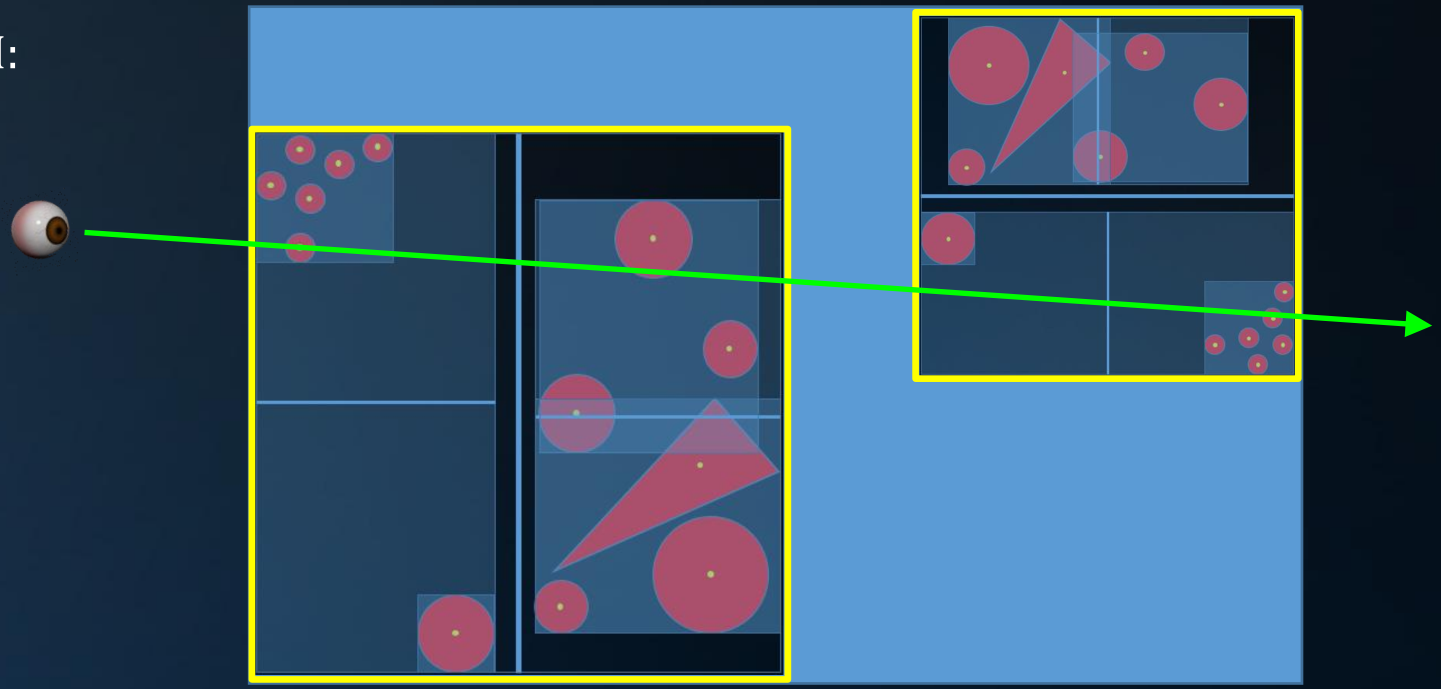
The extra nodes used to combine these BVHs into a single BVH are known as the *Top-level BVH* .

Top-level BVH

Rigid Motion

Applying rigid motion to a BVH:

1. Refit the top-level BVH
2. Refit the affected BVH



Top-level BVH

Rigid Motion

Applying rigid motion to a BVH:

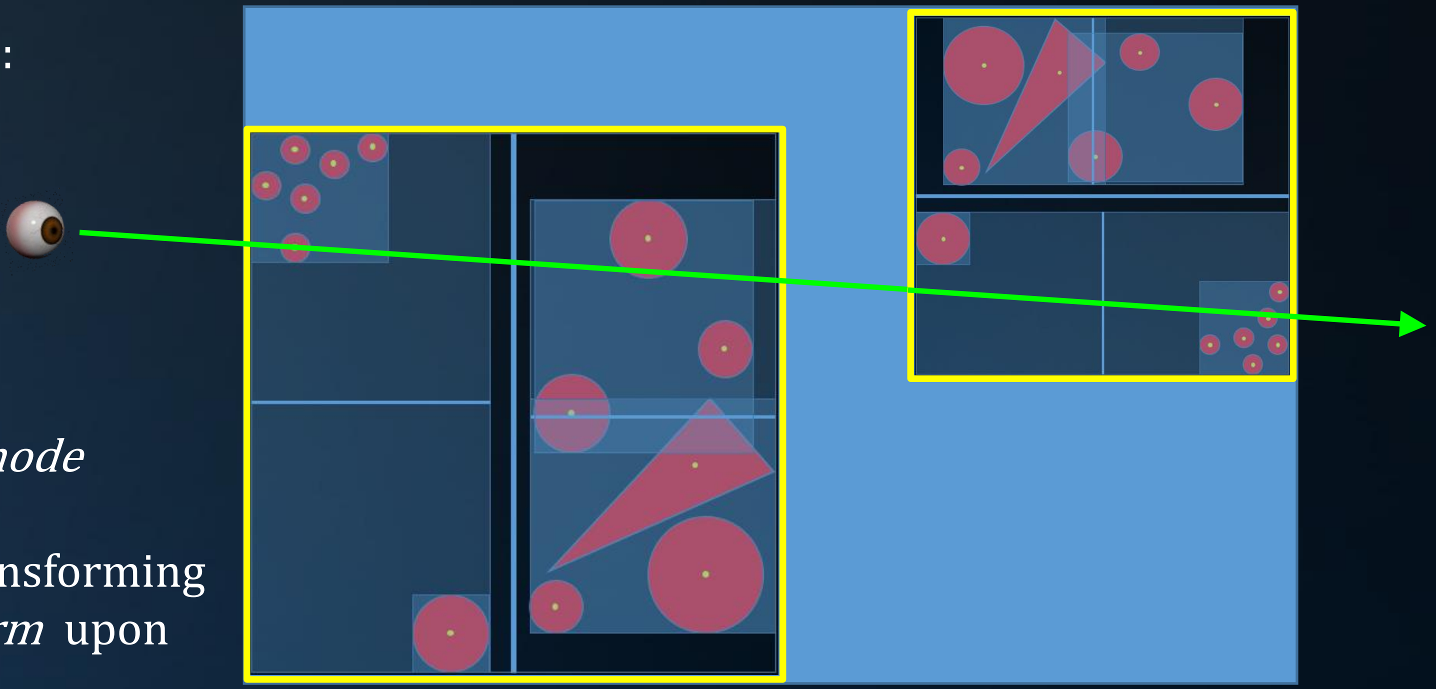
1. Refit the top-level BVH
2. Refit the affected BVH

or:

2. Transform the ray, not the node

Rigid motion is achieved by transforming the rays by the *inverse transform* upon entering the sub-BVH.

(this obviously does not only apply to translation)



Top-level BVH

The Top-level BVH - Construction

Input: *list of axis aligned bounding boxes for transformed scene graph nodes*

Algorithm:

1. Find the two elements in the list for which the AABB has the smallest surface area
2. Create a parent node for these elements
3. Replace the two elements in the list by the parent node
4. Repeat until one element remains in the list.

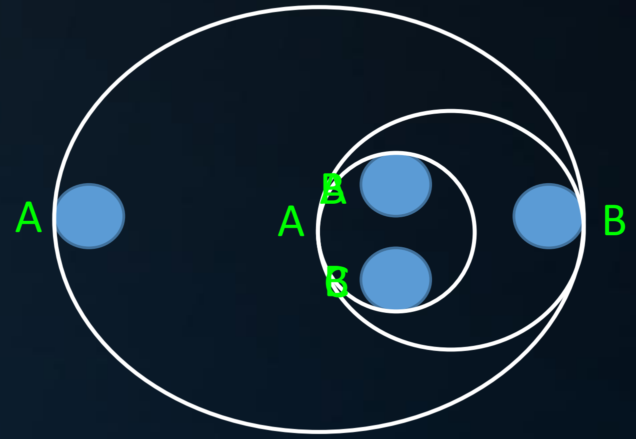
Note: algorithmic complexity is $O(N^3)$.

Top-level BVH

The Top-level BVH – Faster Construction*

Algorithm:

```
Node A = list.GetFirst();
Node B = list.FindBestMatch( A );
while (list.size() > 1)
{
    Node C = list.FindBestMatch( B );
    if (A == C)
    {
        list.Remove( A );
        list.Remove( B );
        A = new Node( A, B );
        list.Add( A );
        B = list.FindBestMatch( A );
    }
    else A = B, B = C;
}
```



*: Fast Agglomerative Clustering for Rendering, Walter et al., 2008

Top-level BVH

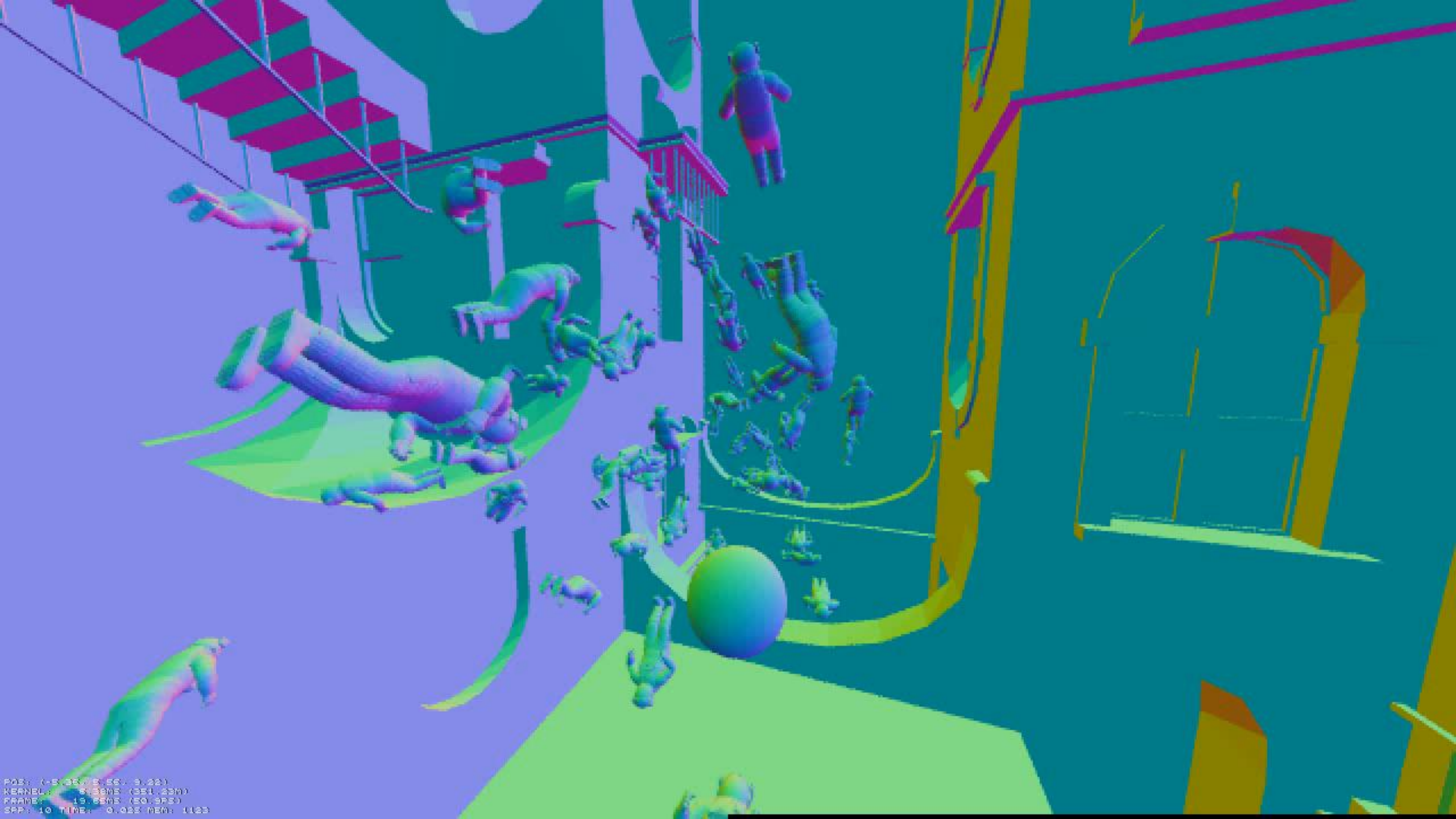
The Top-level BVH – Traversal

The leafs of the top-level BVH contain the sub-BVHs.

When a ray intersects such a leaf, it is transformed by the inverted transform matrix of the sub-BVH. After this, it traverses the sub-BVH.

Once the sub-BVH has been traversed, we transform the ray again, this time by the transform matrix of the sub-BVH.

For efficiency, we store the inverted matrix with the sub-BVH root.



```
POS: (-5.36, 5.56, 9.22)
KERNEL:     6.38MS (351.23M)
FRAME:     19.65MS (50.9FPS)
SPP: 10 TIME:  0.02S MEM: 1123
```

Top-level BVH

The Top-level BVH – Summary

The top-level BVH enables complex animated scenes:

- for static objects, it contains high-quality sub-BVHs;
- for objects undergoing rigid motion, it also contains high-quality sub-BVHs, with a transform matrix and its inverse;
- for deforming objects, it contains sub-BVHs that can be refitted;
- for arbitrary animations, it contains lower quality sub-BVHs.

Combined, this allows for efficient maintenance of a global BVH.

INFOMAGR – Advanced Graphics

Jacco Bikker - November 2021 - February 2022

END of “The Perfect BVH”

next lecture: “Path Tracing”