# Implementing a practical rendering system using GLSL

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University of Tokyo

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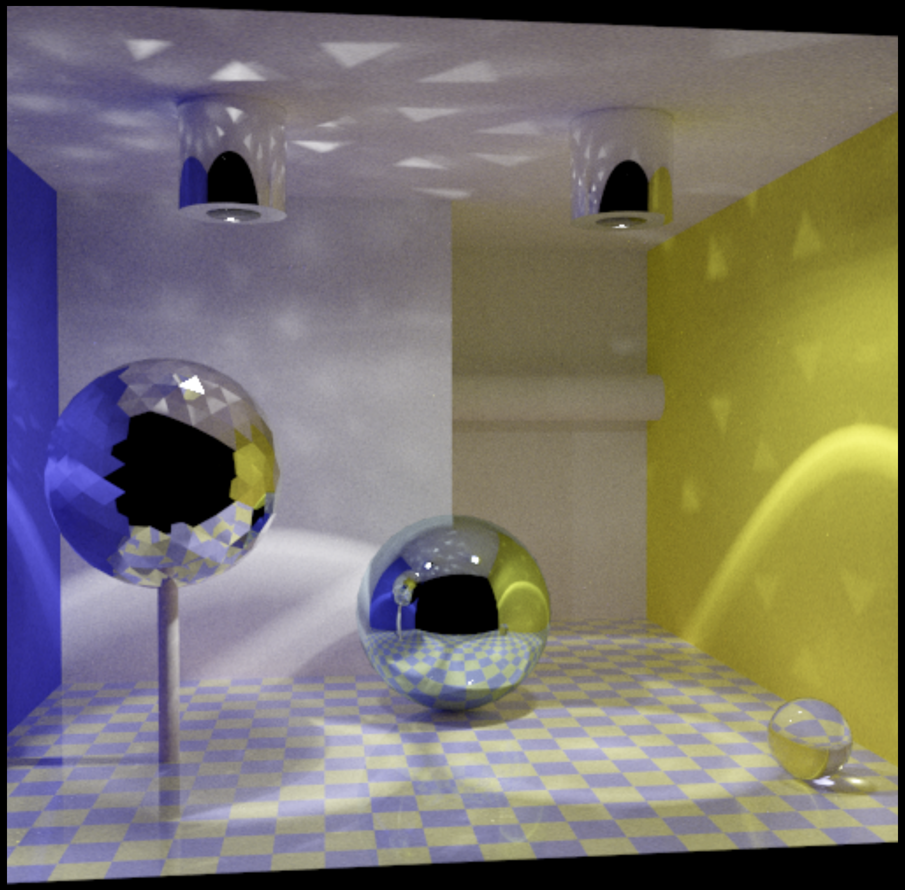
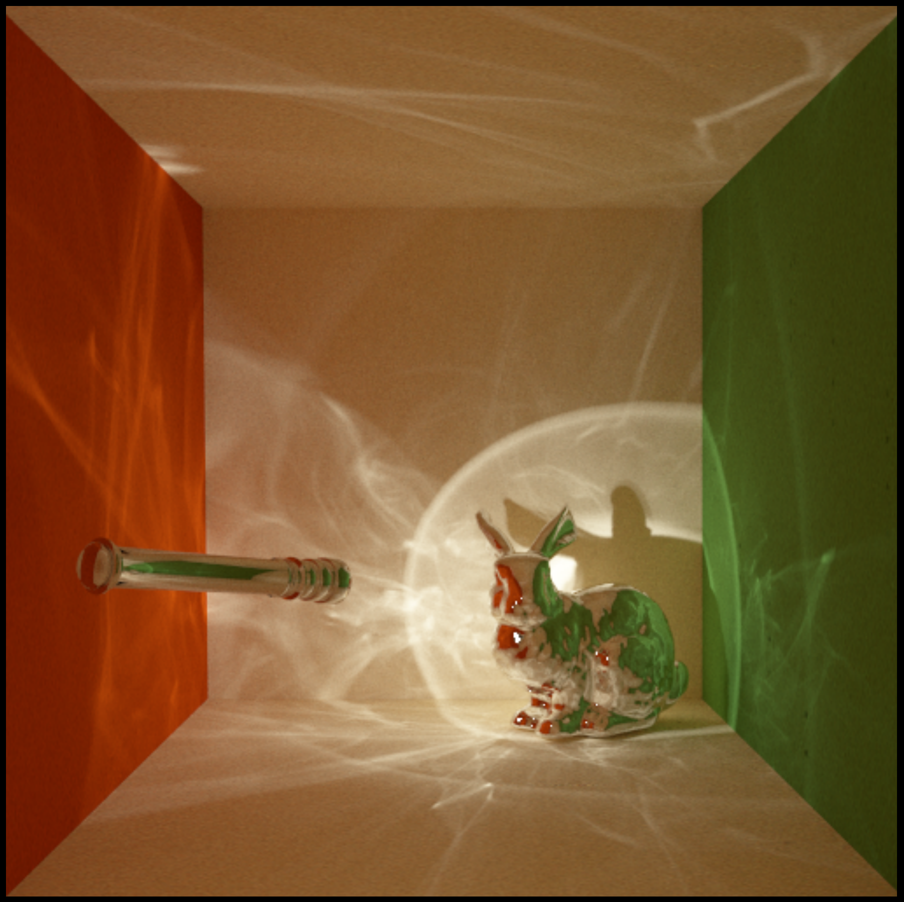
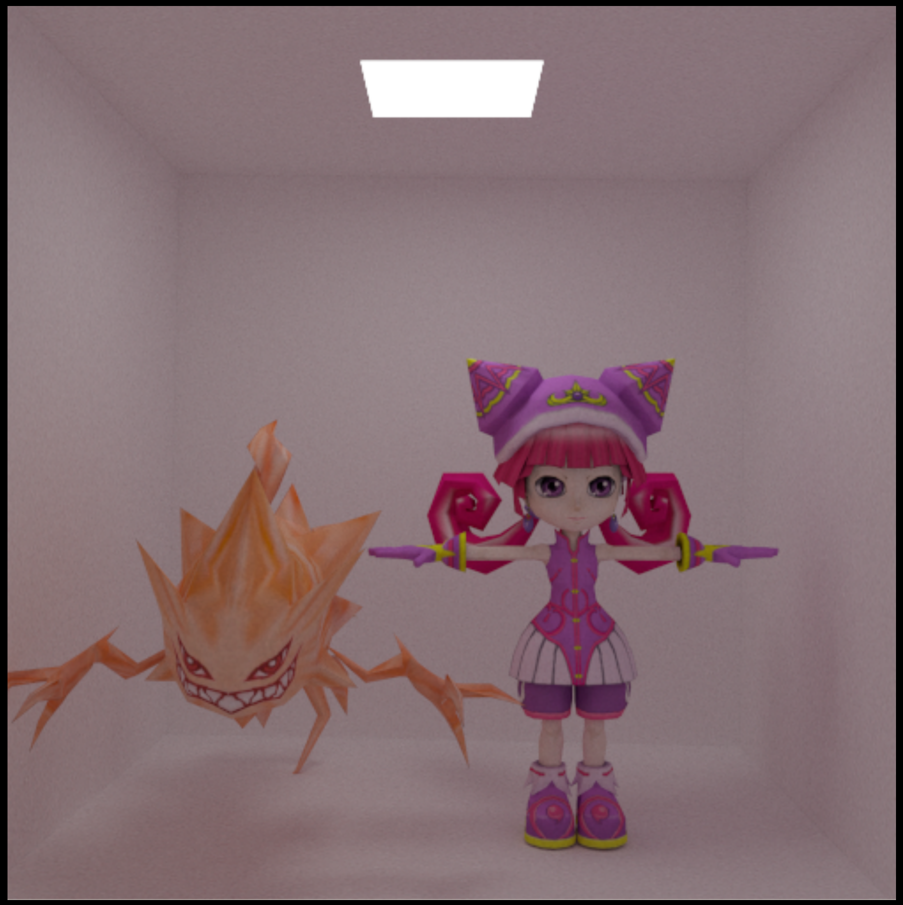
# Aim of this seminar

**Sharing my experience of writing a practical rendering system on a GPU only with GLSL**

Approx. 100M photon paths in 1 min @ GeForce GTX 680

# Disclaimer

Not all of my comments in this seminar
are fully validated by scientific experiments.

Take them with a grain of salt!

# Why GLSL?

- Cross-platform (both OS and GPU)
- Battle-tested
- Easy to write
- Automatic support for multiple GPUs

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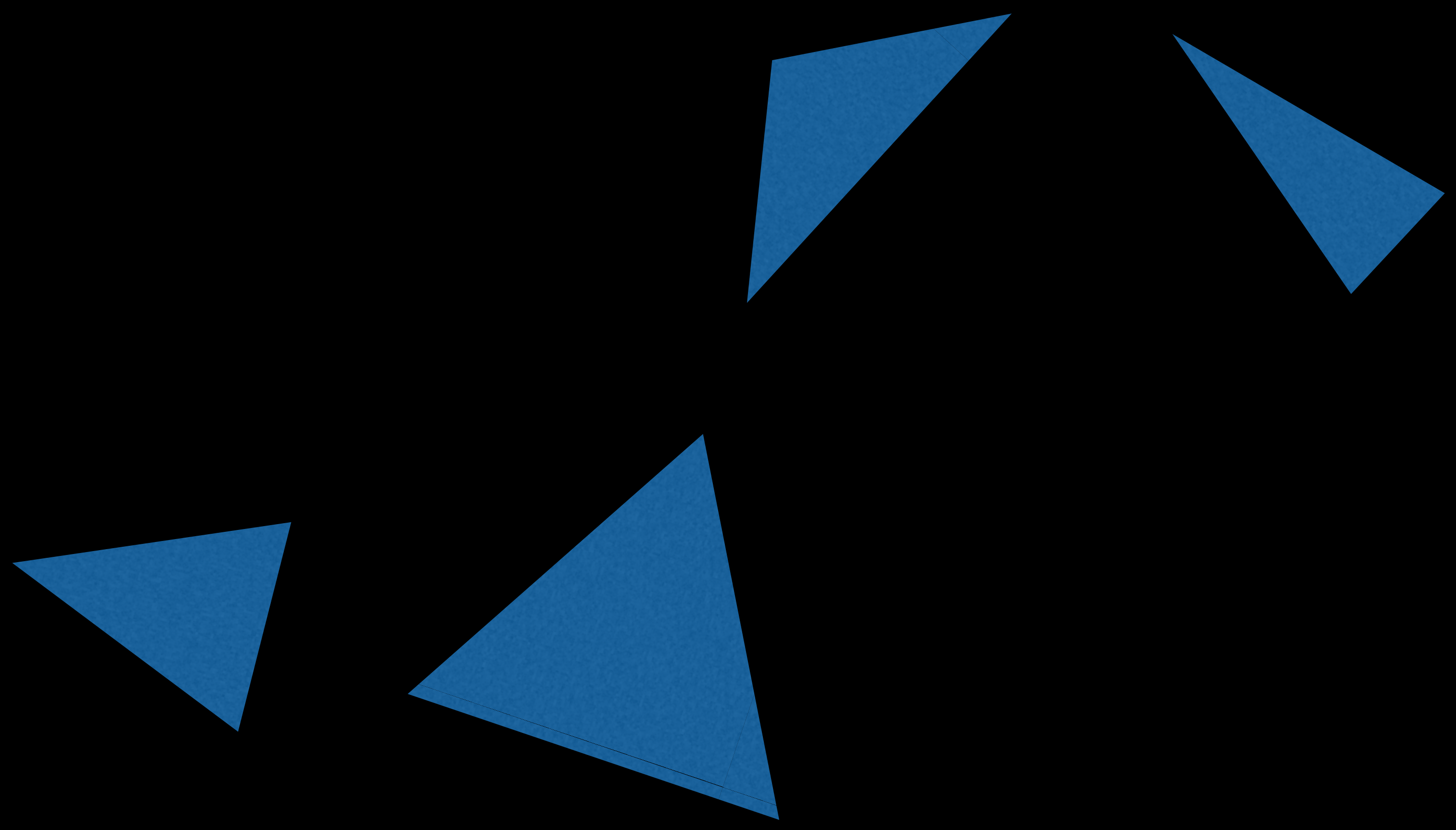
- Cross-platform (both OS and GPU)
- Battle-tested
- Easy to write
- Automatic support for multiple GPUs
- **Fun**

# Key features

- Bounding volume hierarchy (BVH)
    - Efficient ray tracing of lots of objects
    - Triangles only
- Stochastic progressive photon mapping (SPPM)
    - Physically accurate global illumination
    - Textures and basic materials

# Bounding volume hierarchy

- In a practical system, we have **lots** of triangles
- Data structure to avoid touching every triangle



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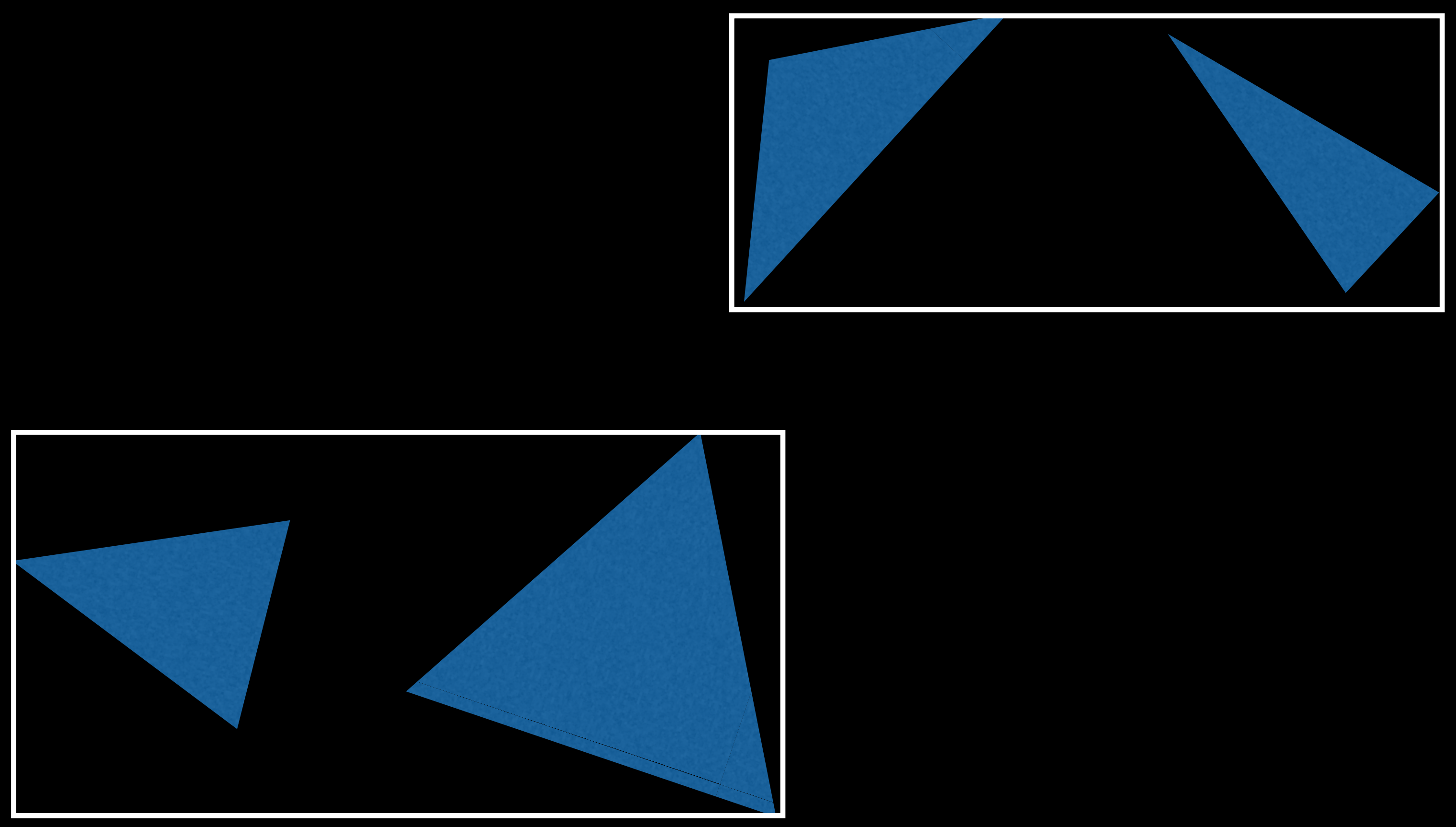

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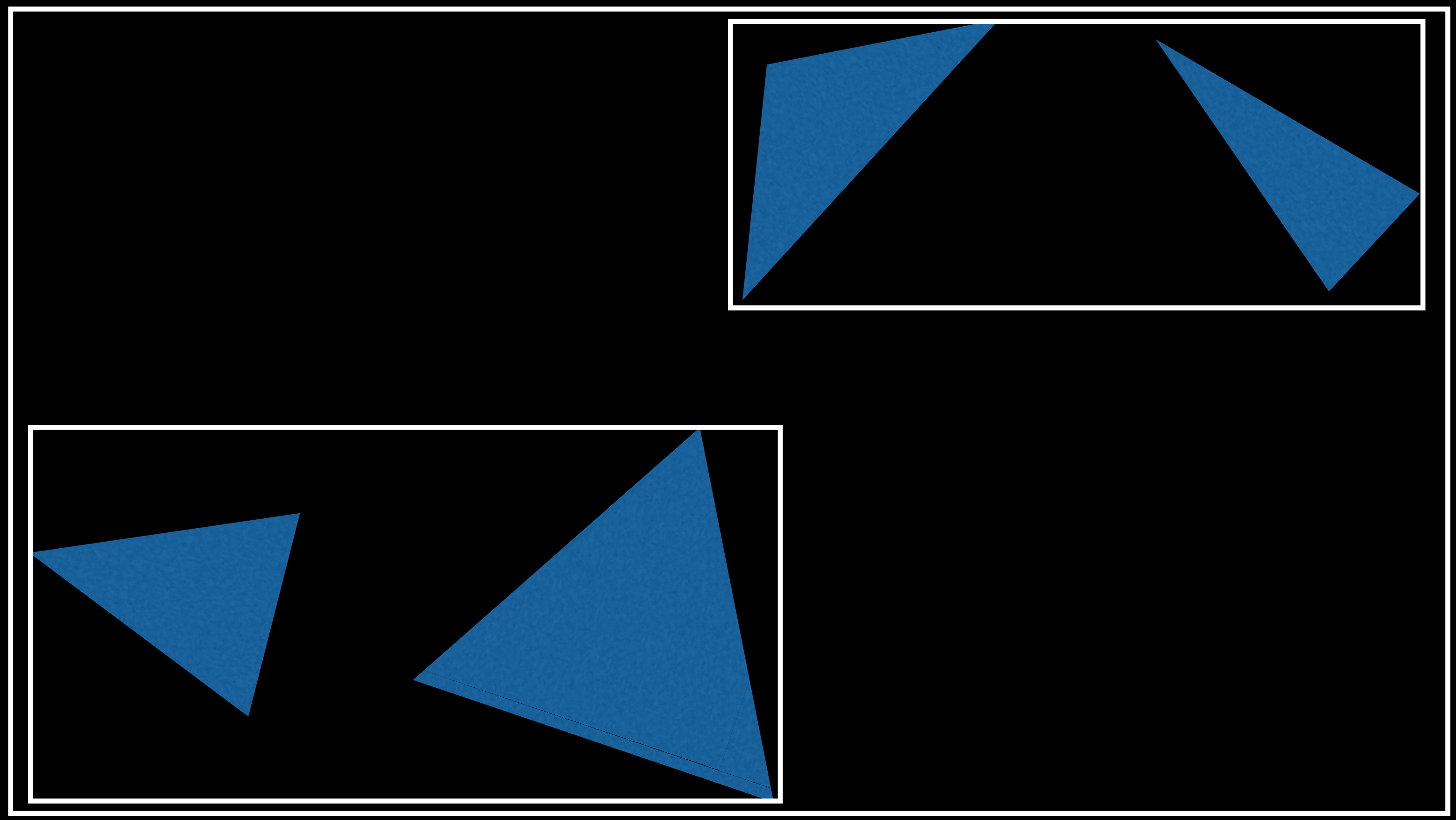

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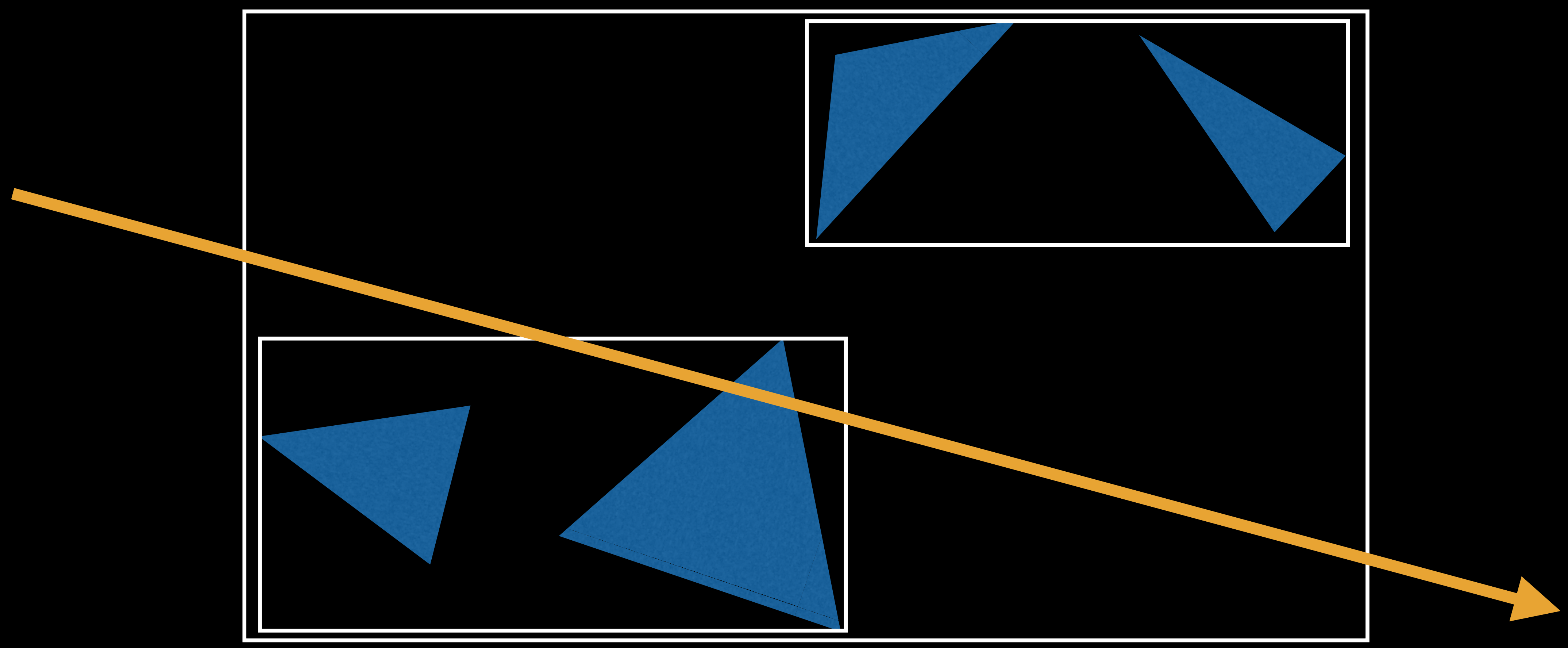

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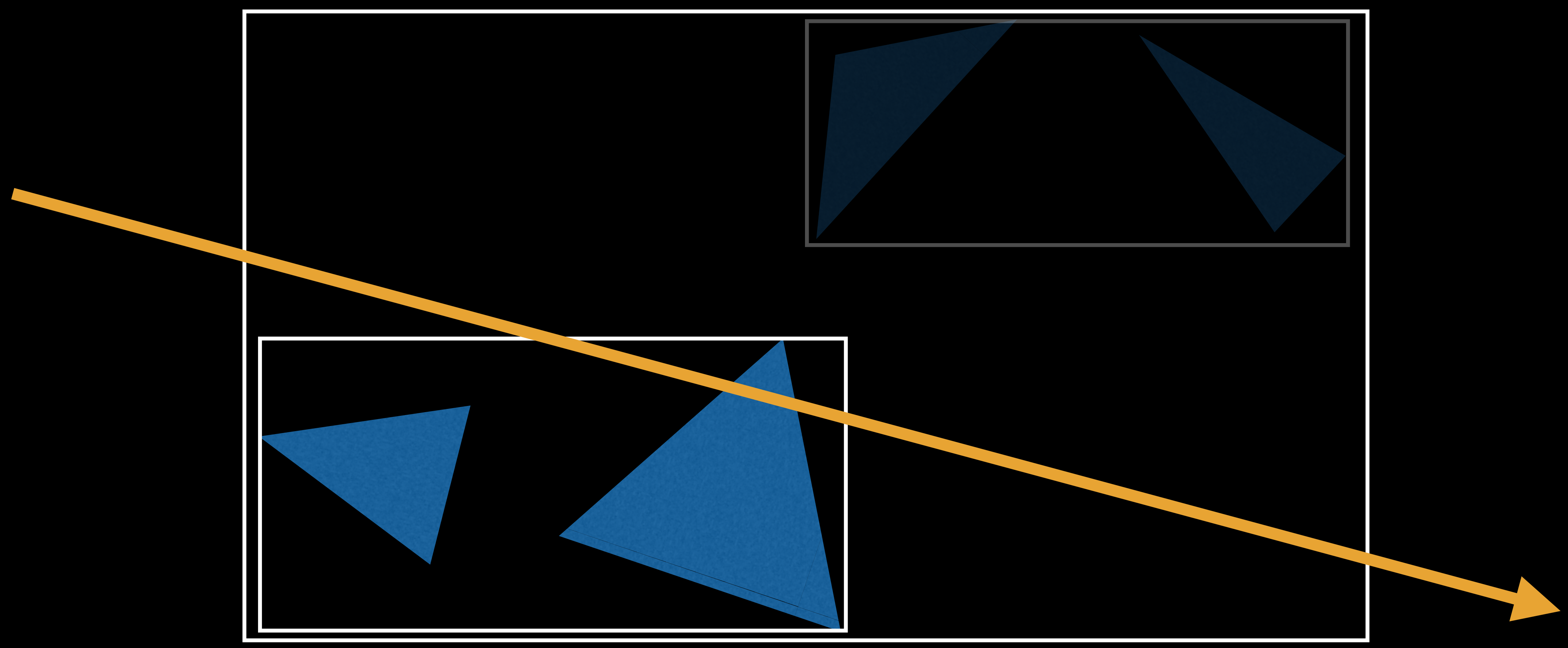
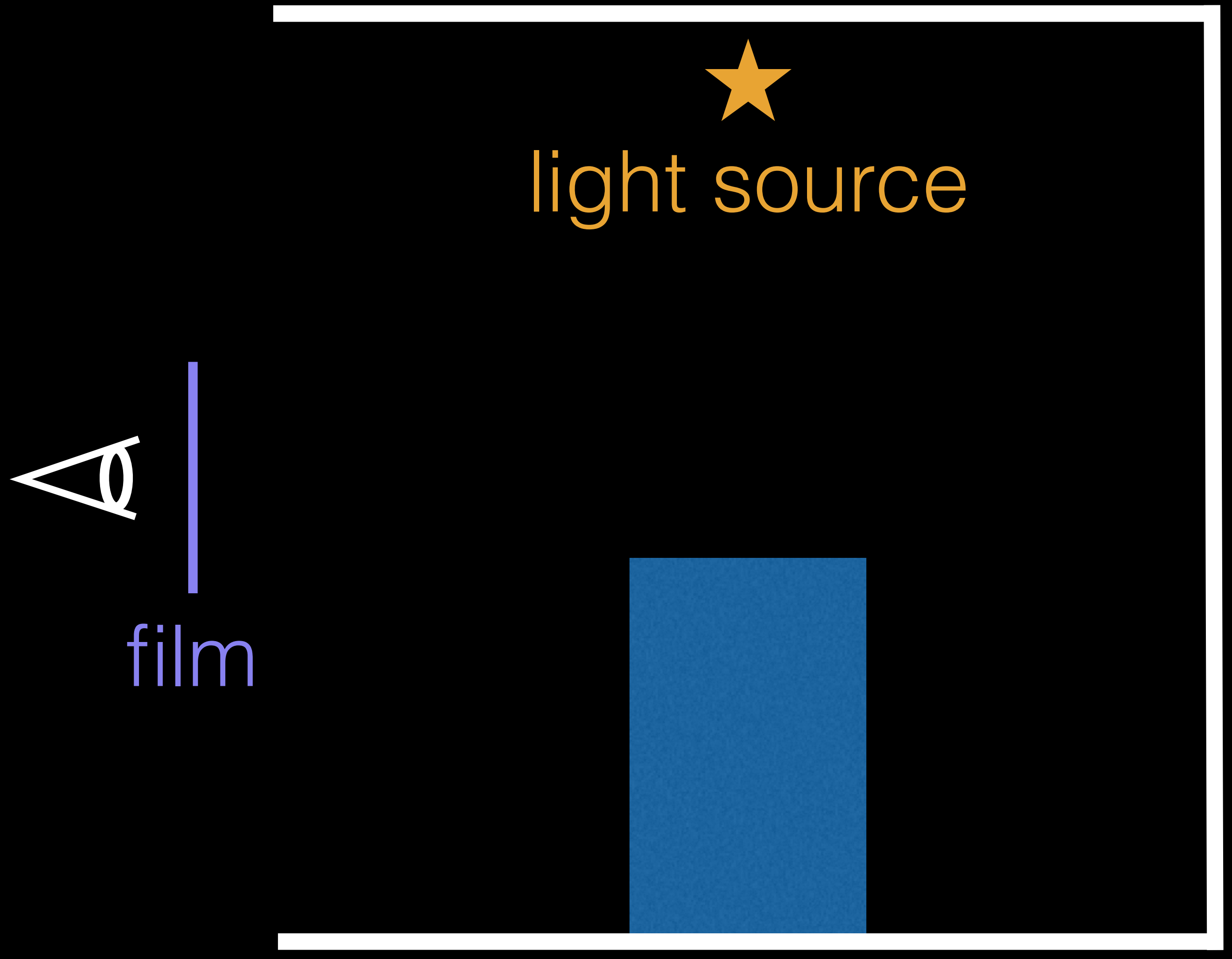


# Stochastic PPM

- Global illumination algorithm developed by myself
- Consists of three steps
  - Photon tracing
  - Eye ray tracing
  - Density estimation

"Stochastic Progressive Photon Mapping" T. Hachisuka and H. W. Jensen
ACM Transactions on Graphics (SIGGRAPH Asia 2009)

# Stochastic PPM



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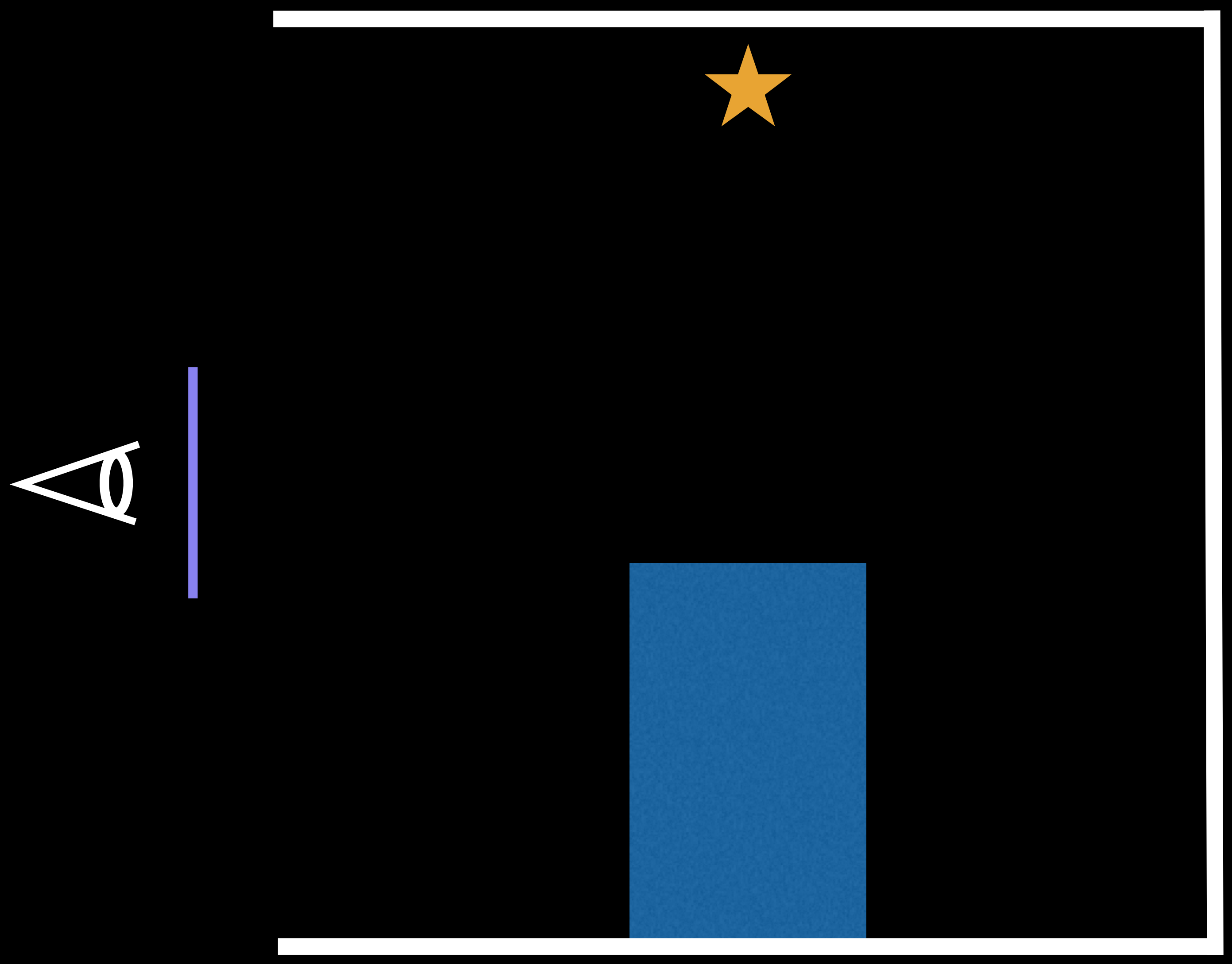
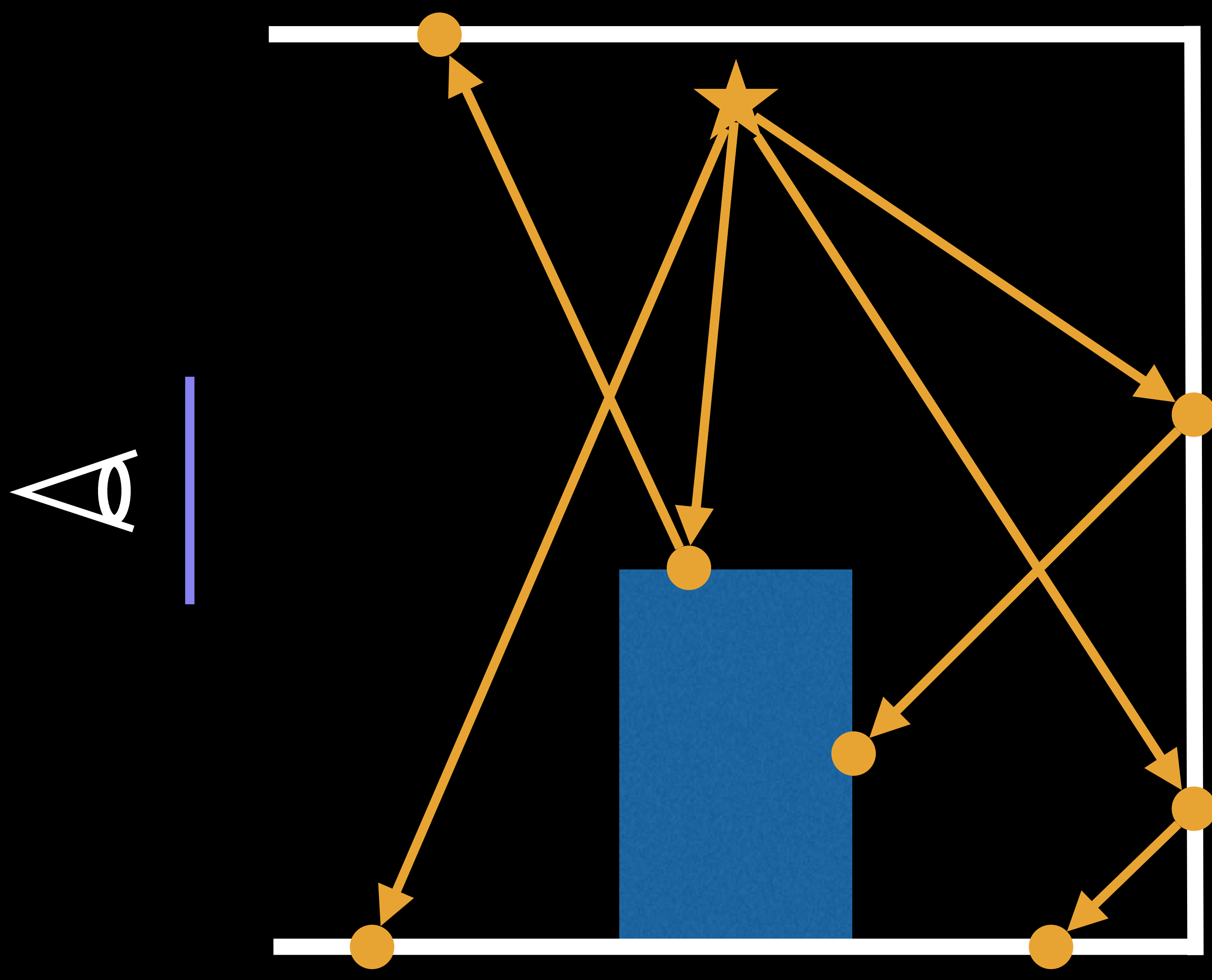


# Stochastic PPM

**Photon tracing**



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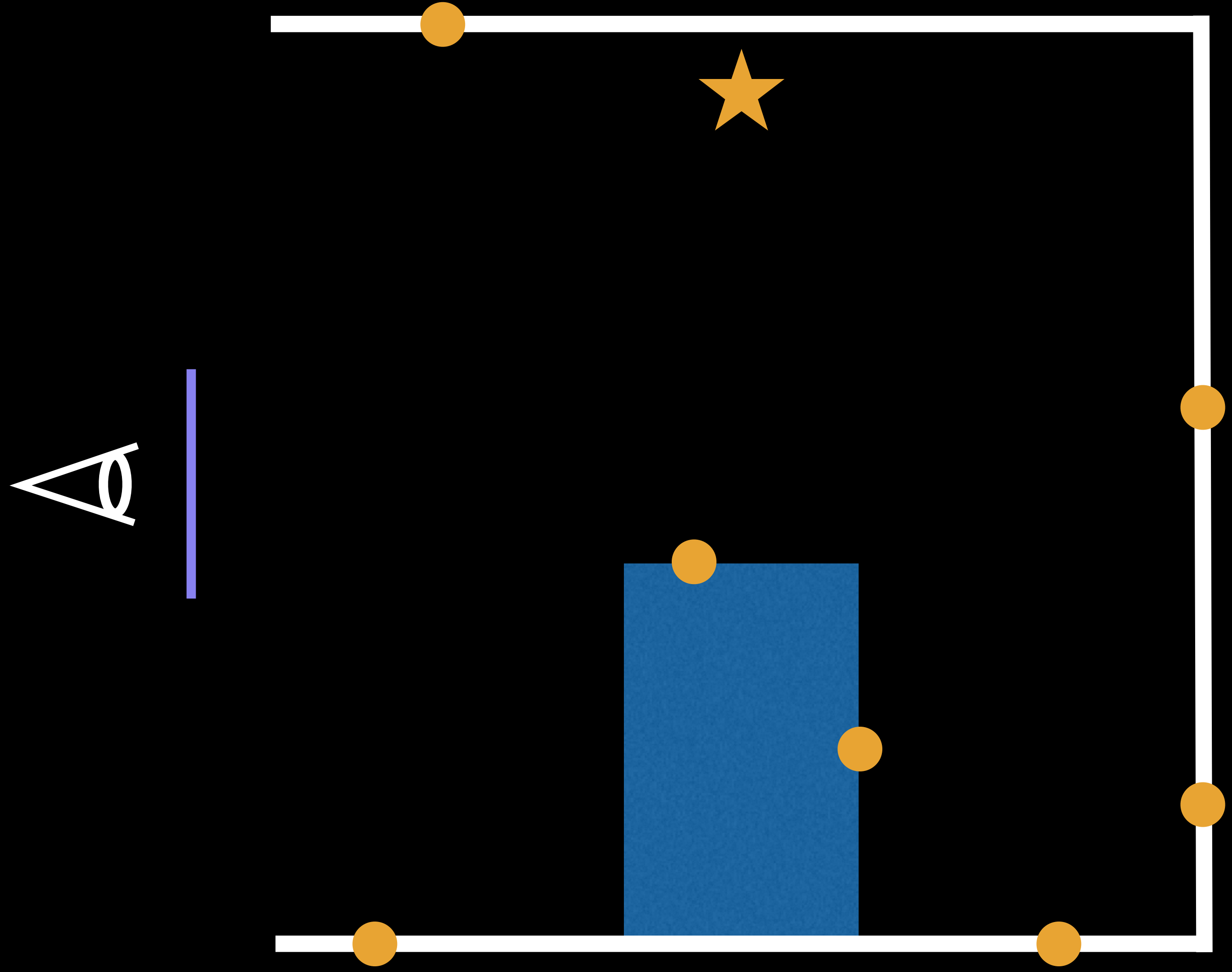
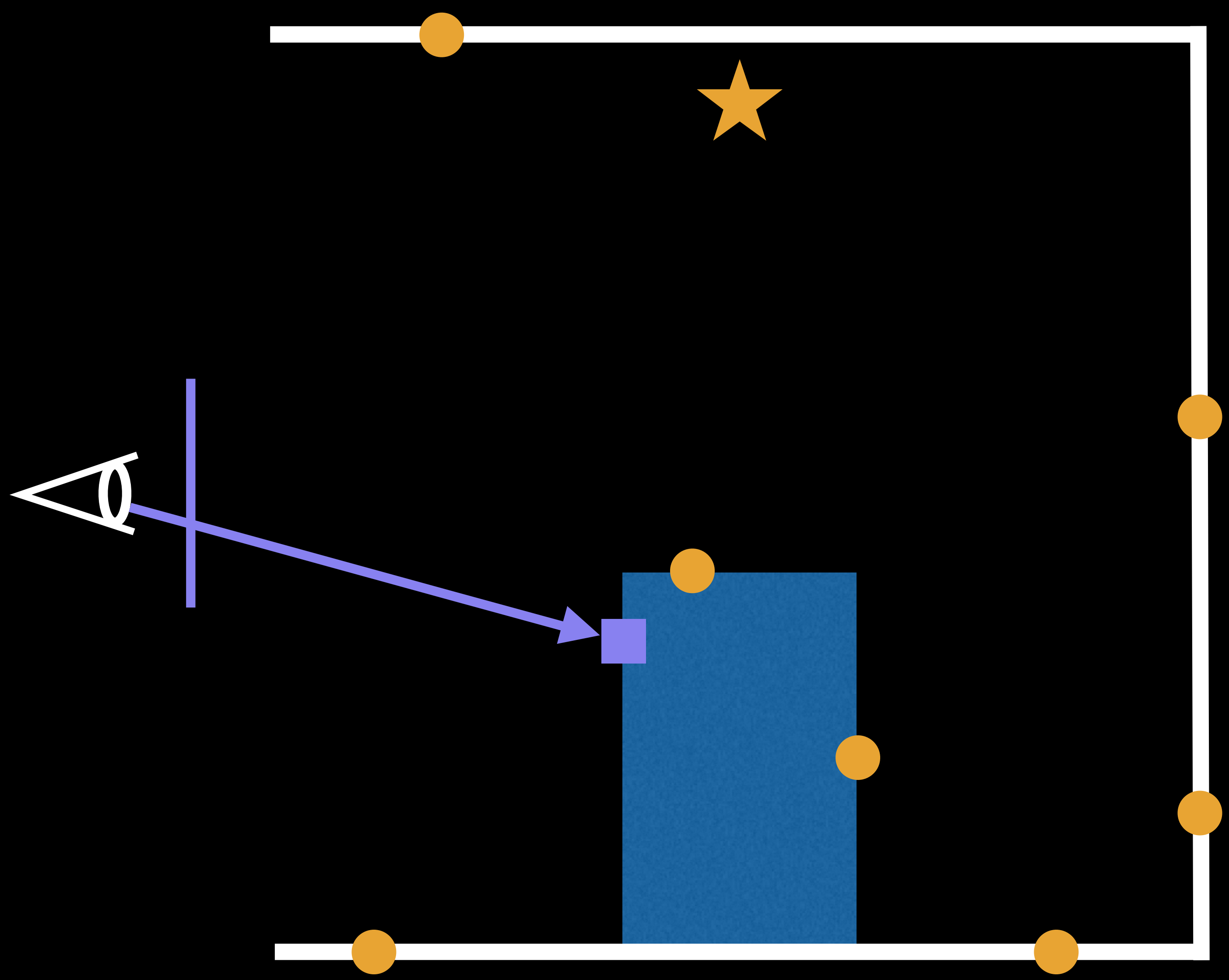


# Stochastic PPM

**Eye ray tracing**



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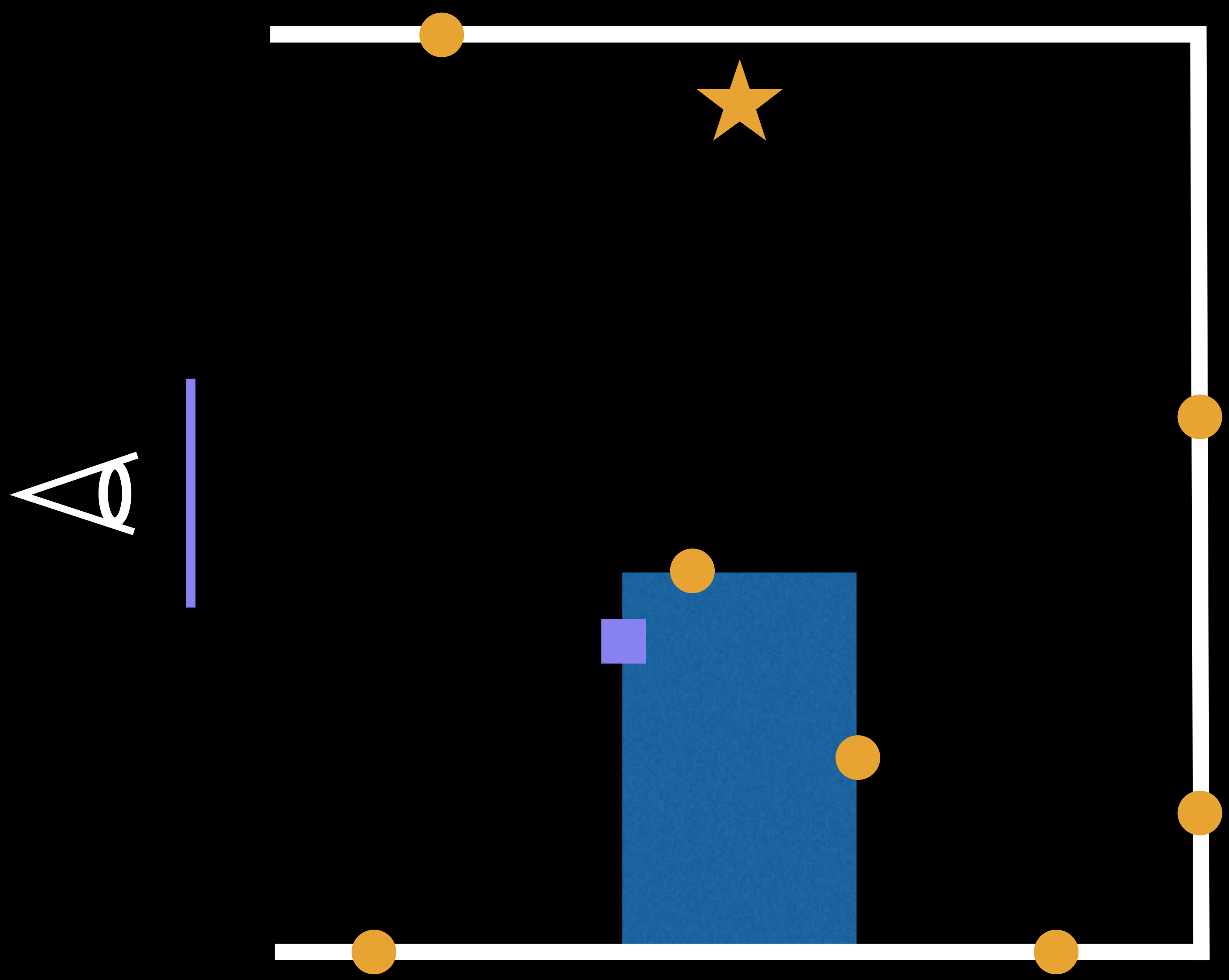
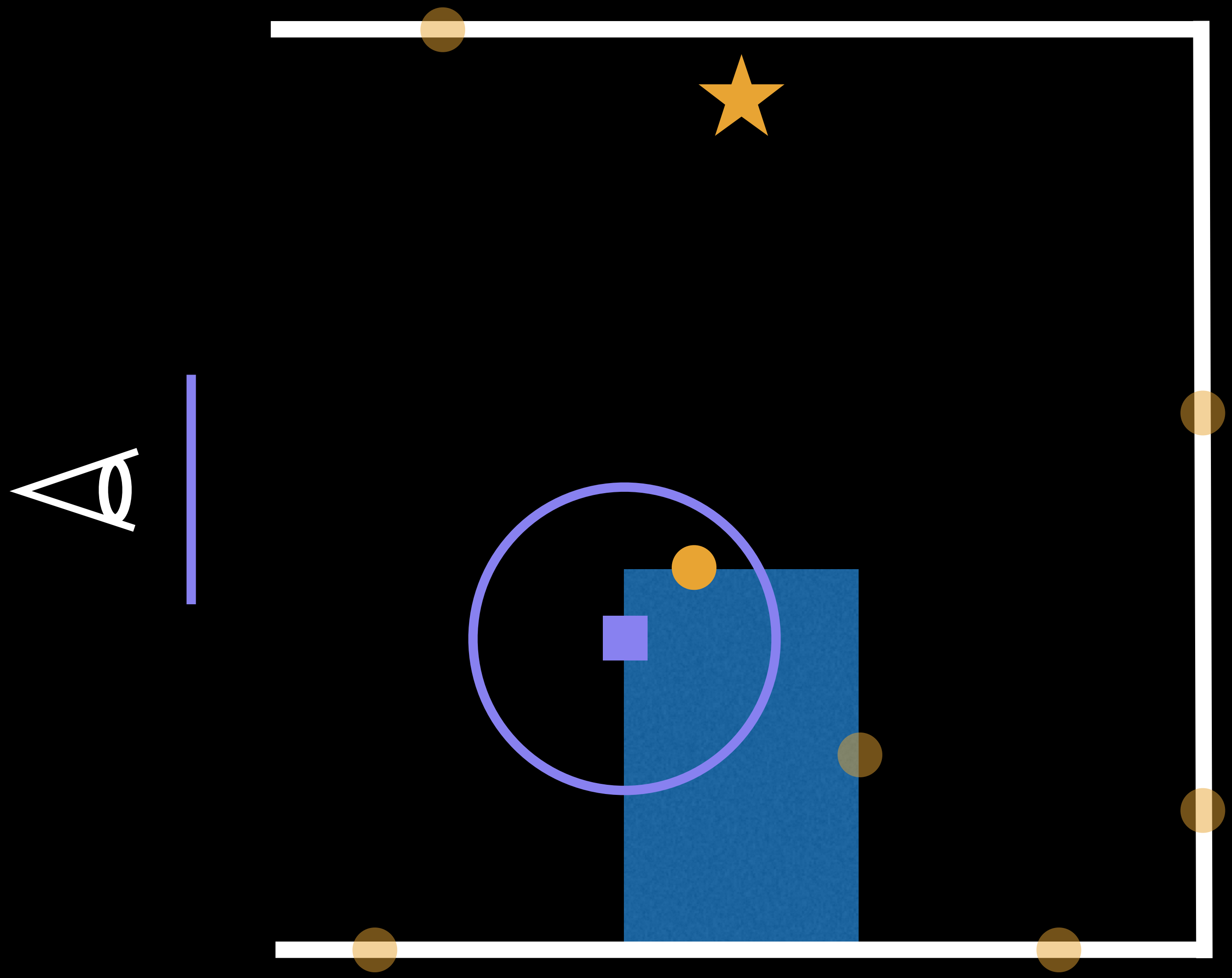
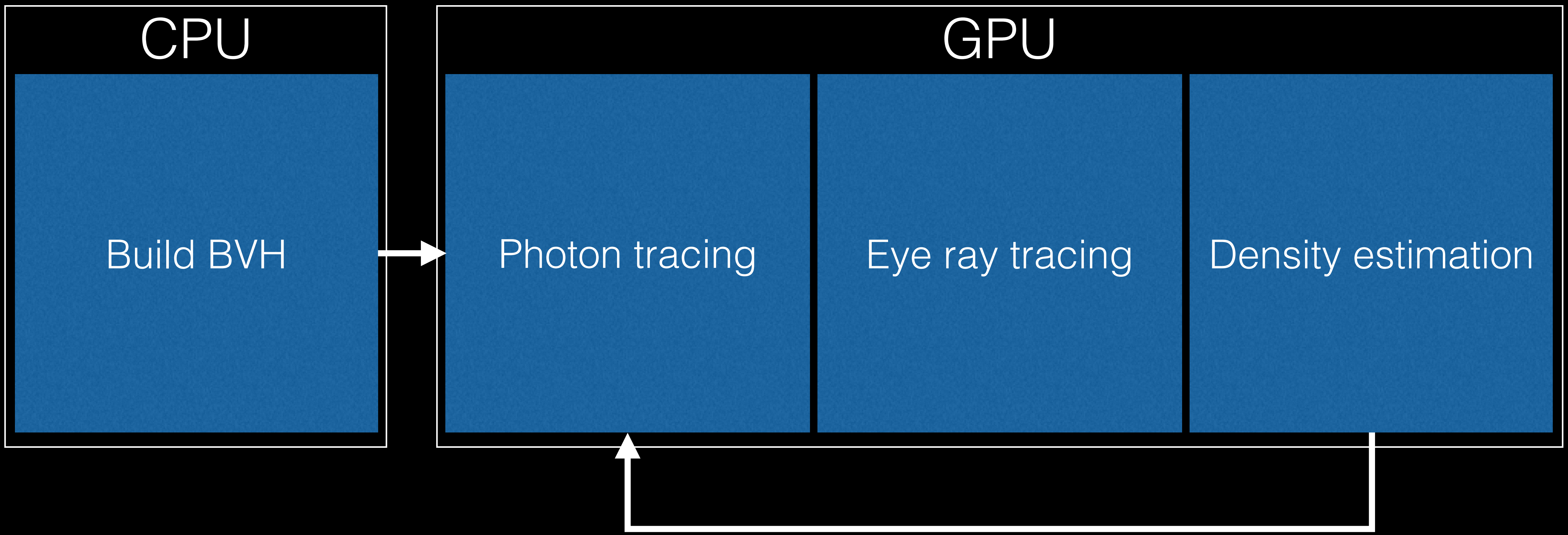


# Stochastic PPM

**Density estimation**




CPU
Build BVH
GPU
Photon tracing
Eye ray tracing
Density estimation

# Design principles

- Make all the tasks in rendering to
  - Have a high degree of parallelism
  - Have a uniform workload distribution
  - Use no local memory

  … so that they run efficiently on GPUs

- I did not aim for a “production-quality” system

# Bounding Volume Hierarchy

# Challenges

- Standard BVH traversal uses stack
  - Stack is implemented via local memory on GPUs
  - Contradicts with the design principles!

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**We want stackless traversal!**

# Why stackless?

- Modern GPUs can do stack-based traversal [Aila 09]
  - Straightforward to implement
  - Efficient (due to dynamic traversal order)

**Why bother implementing stackless traversal?**

# Why stackless?

**Size of local memory can limit the parallelism**

- Modern GPUs have around 32kB local memory
- Stack-based traversal consumes around 512 B

32kB / 512 B = 64 rays in parallel

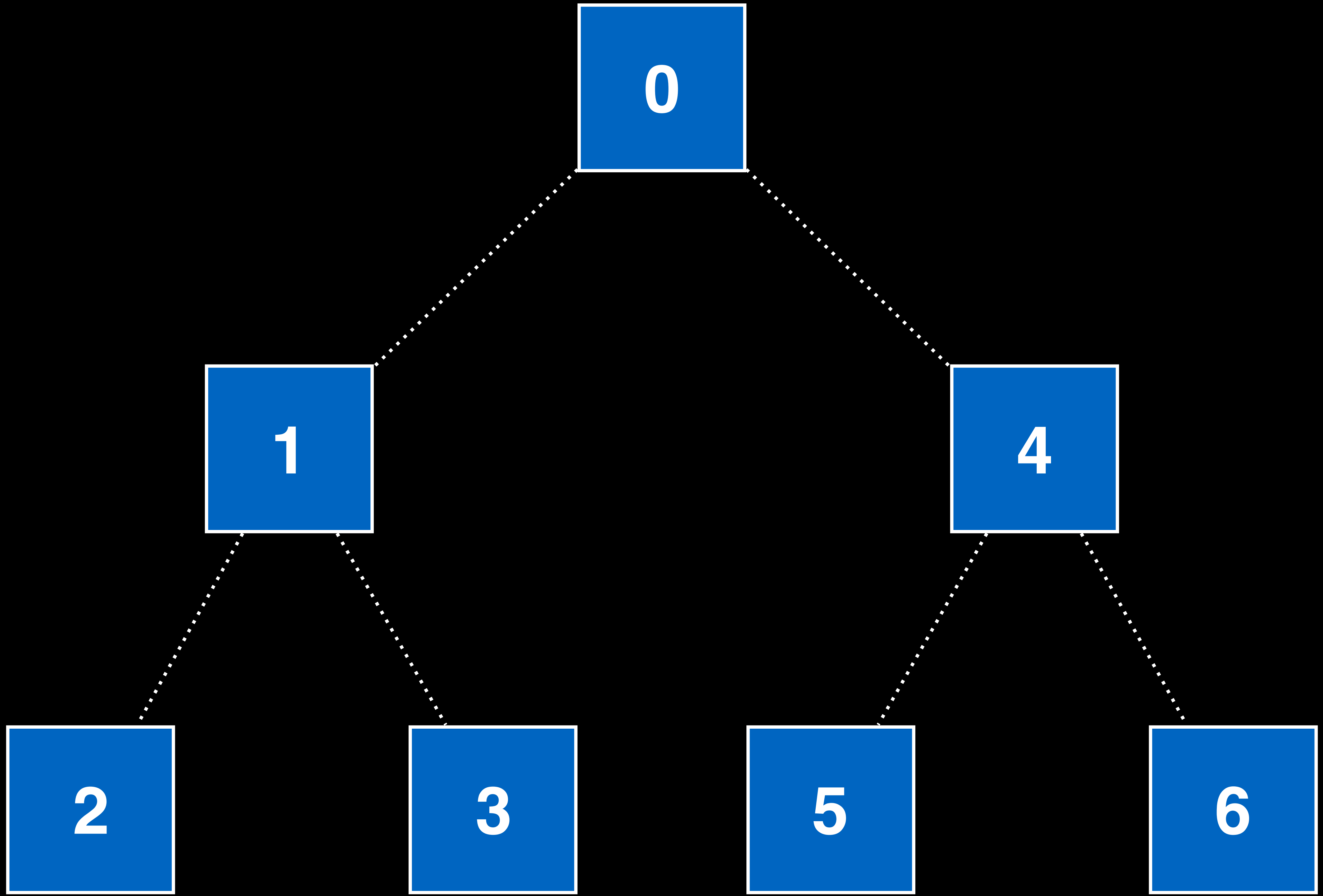
# Threaded BVH

- Precompute “hit” and “miss” links
  - Also known as skip pointers [Smits 98]

- Allows stackless traversal

- Order of traversal of child nodes is fixed

# Threaded BVH



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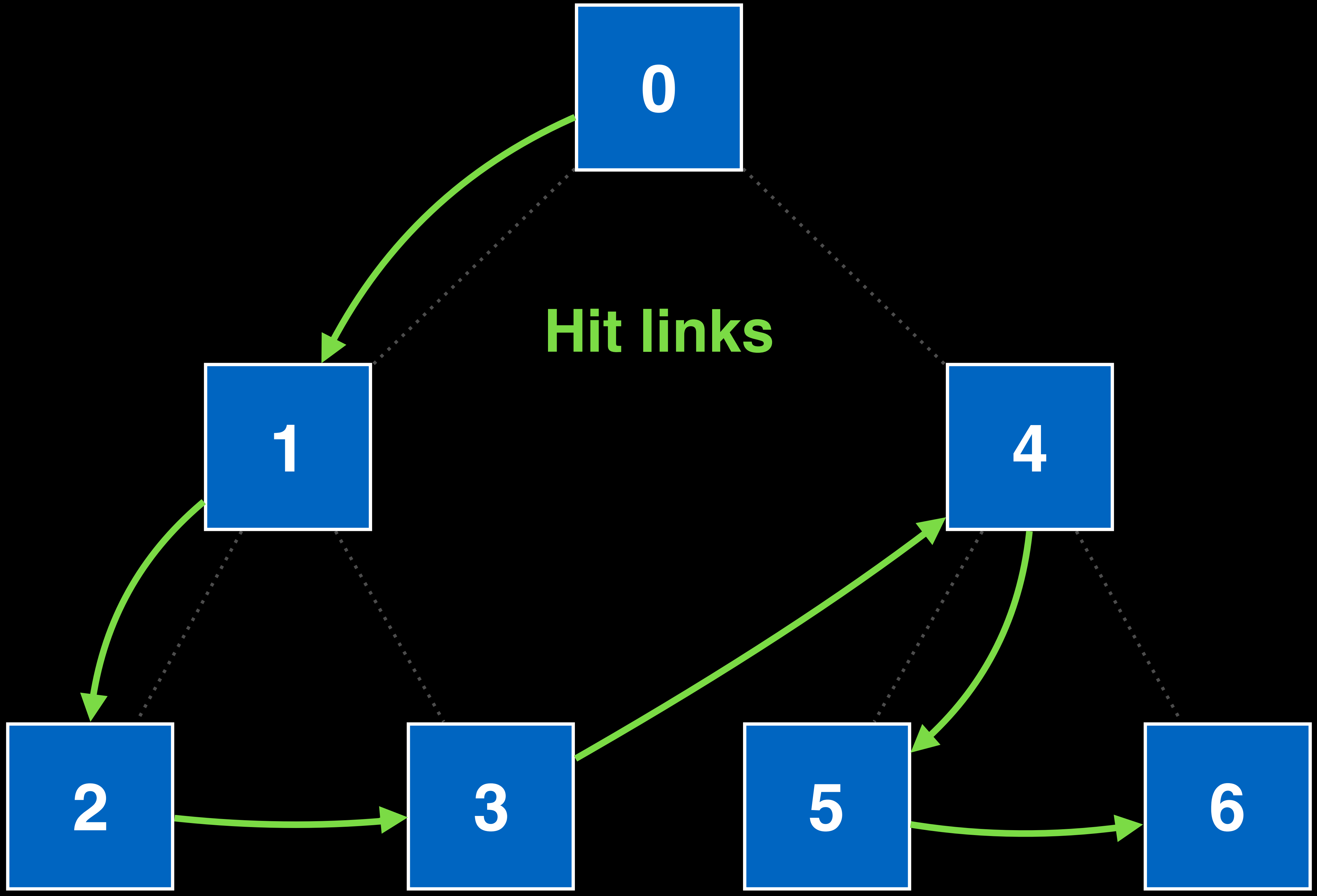

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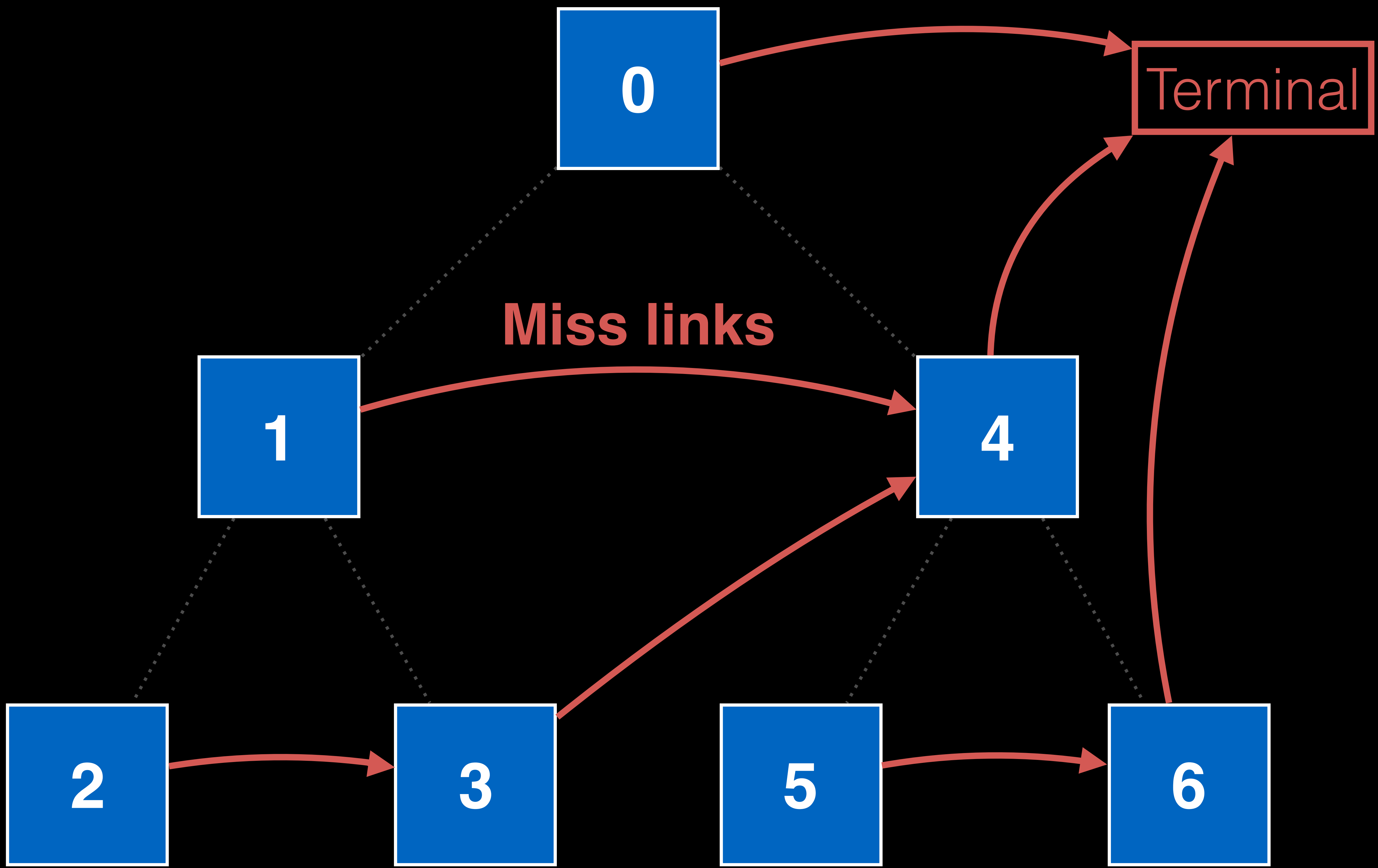

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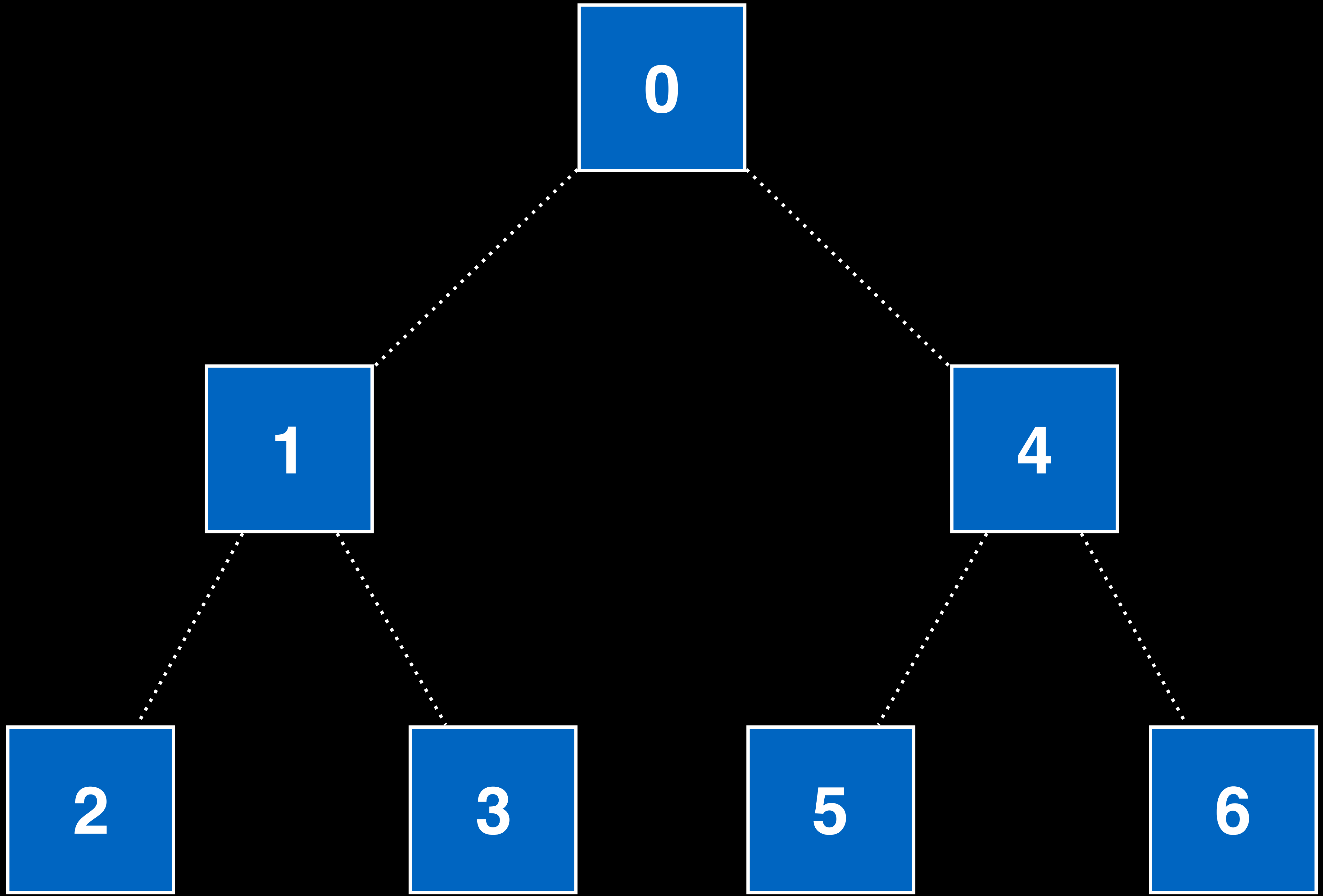

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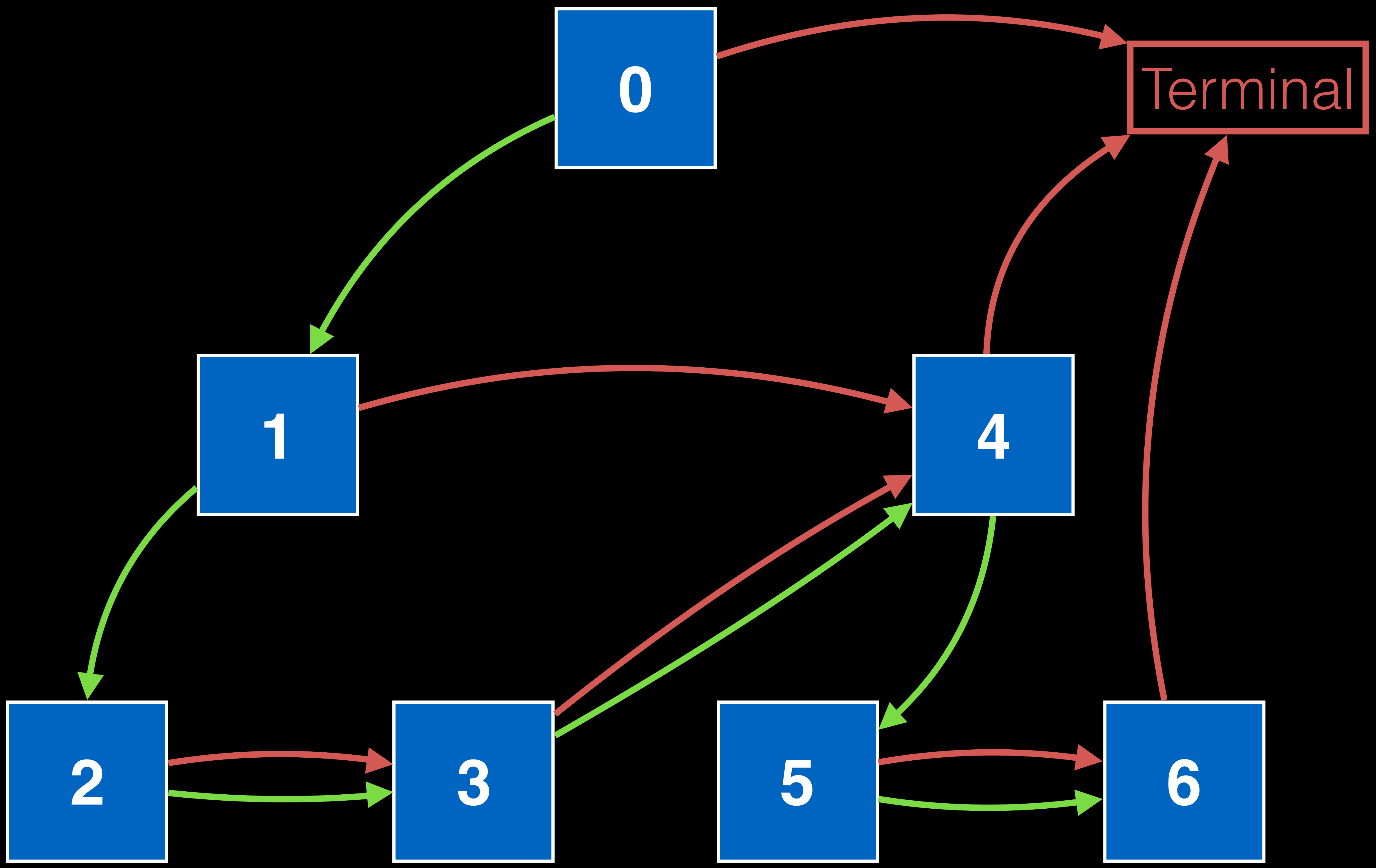

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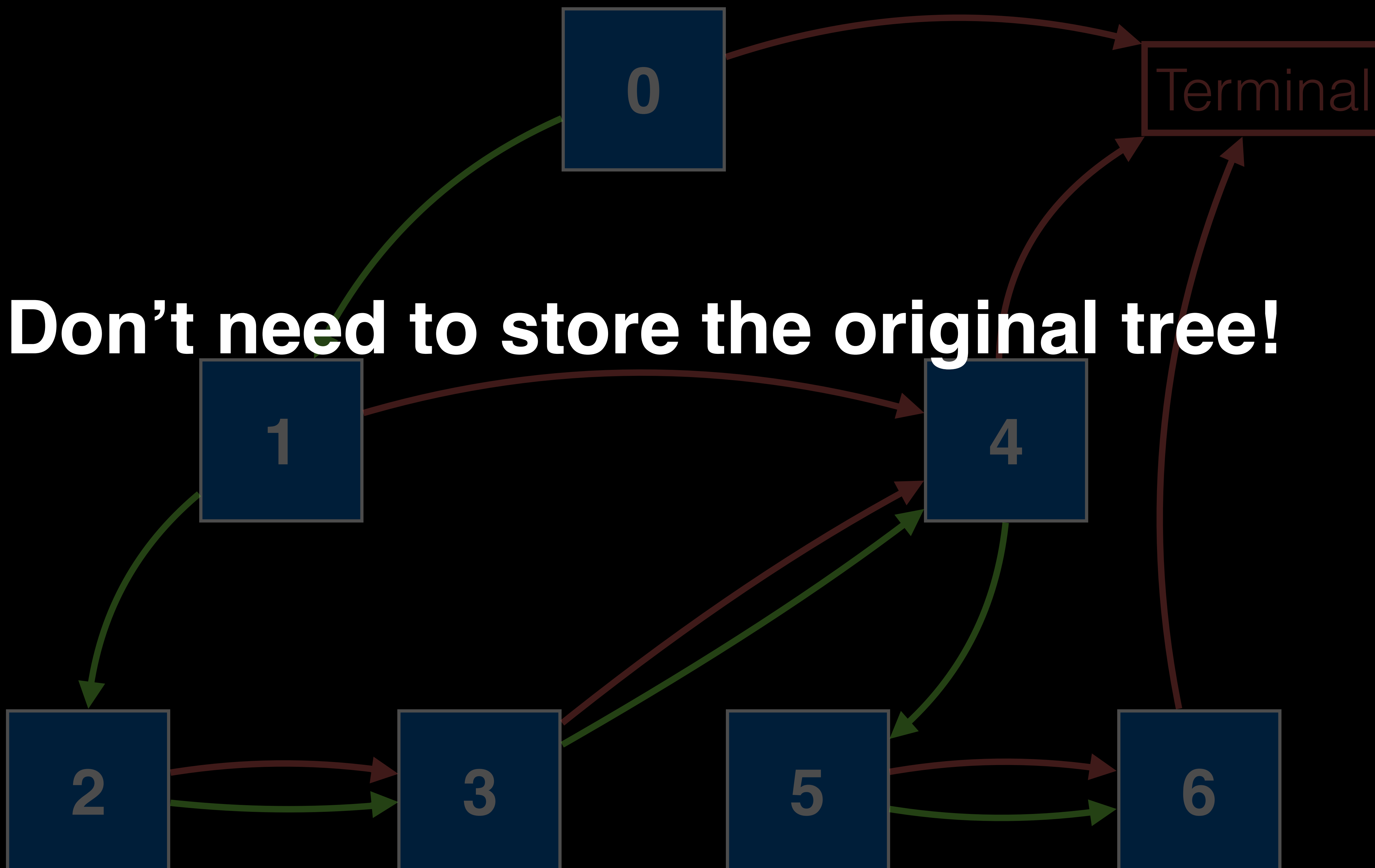



**Don’t need to store the original tree!**

# Hit and miss links

- Hit links
  - Always the next node in the array
- Miss links
  - Internal, left: sibling node
  - Internal, right: parent's sibling node (until it exists)
  - Leaf: same as hit links

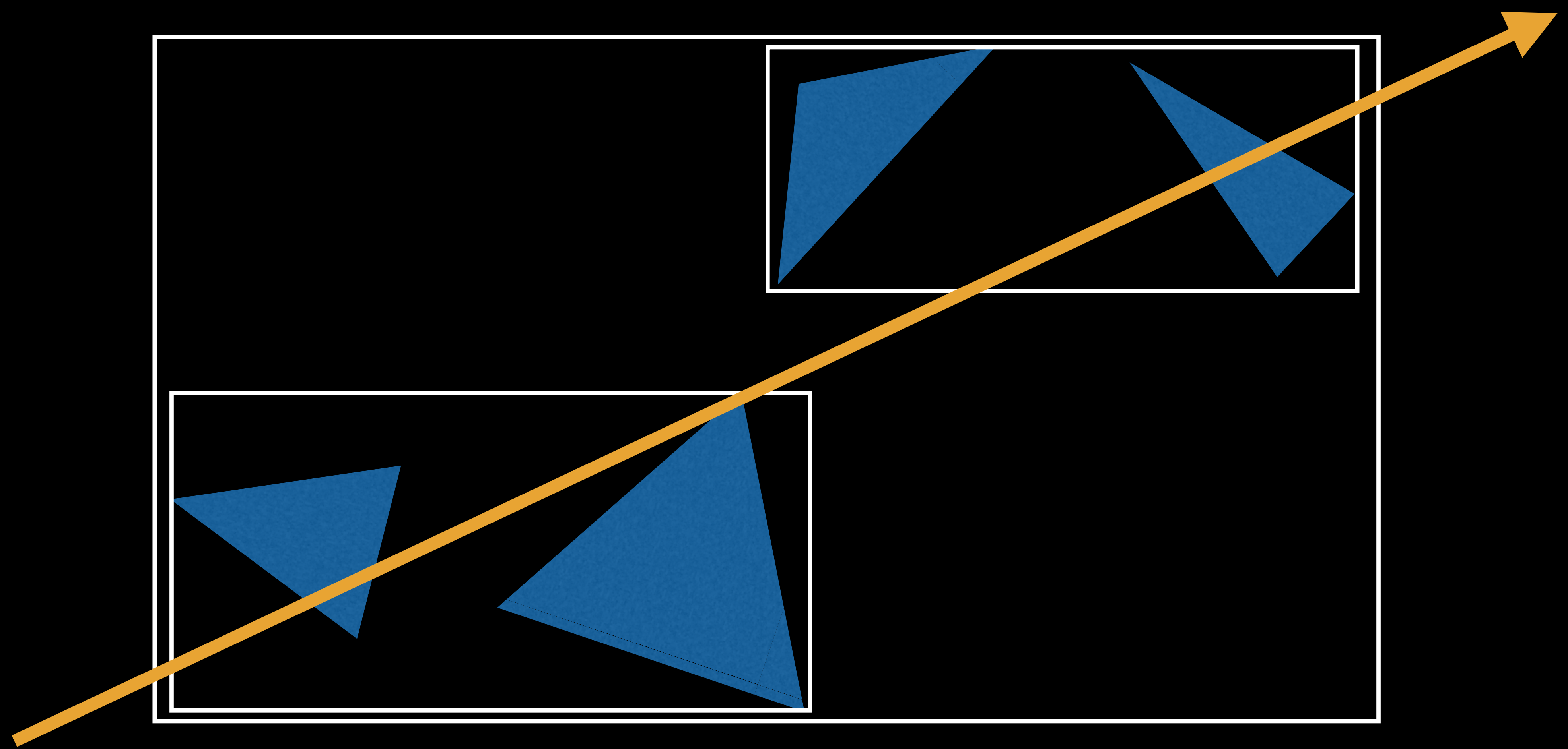
# Traversal

- Extremely **simple**! (no stack, no bitwise ops.)

```
node = root;
while (node != null) {
   if (intersect(node.bonding, ray)) {
      if (node.leaf) {
         hit_point = intersect(node.triangles, ray);
      }
      node = node.hit;
   } else {
      node = node.miss;
   }
}
```

# Challenges

- Traversal order is fixed
  - Want to visit the closest node first



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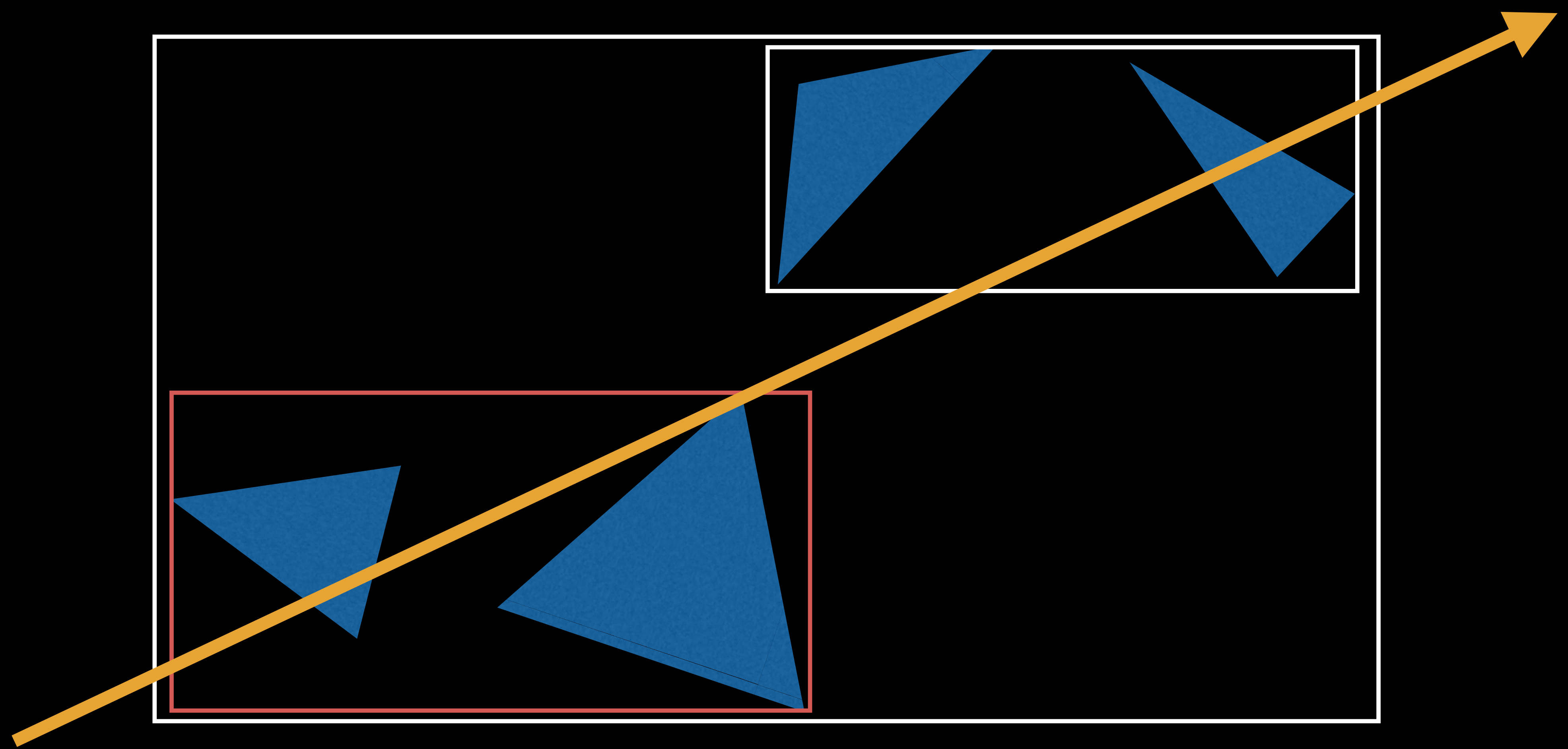

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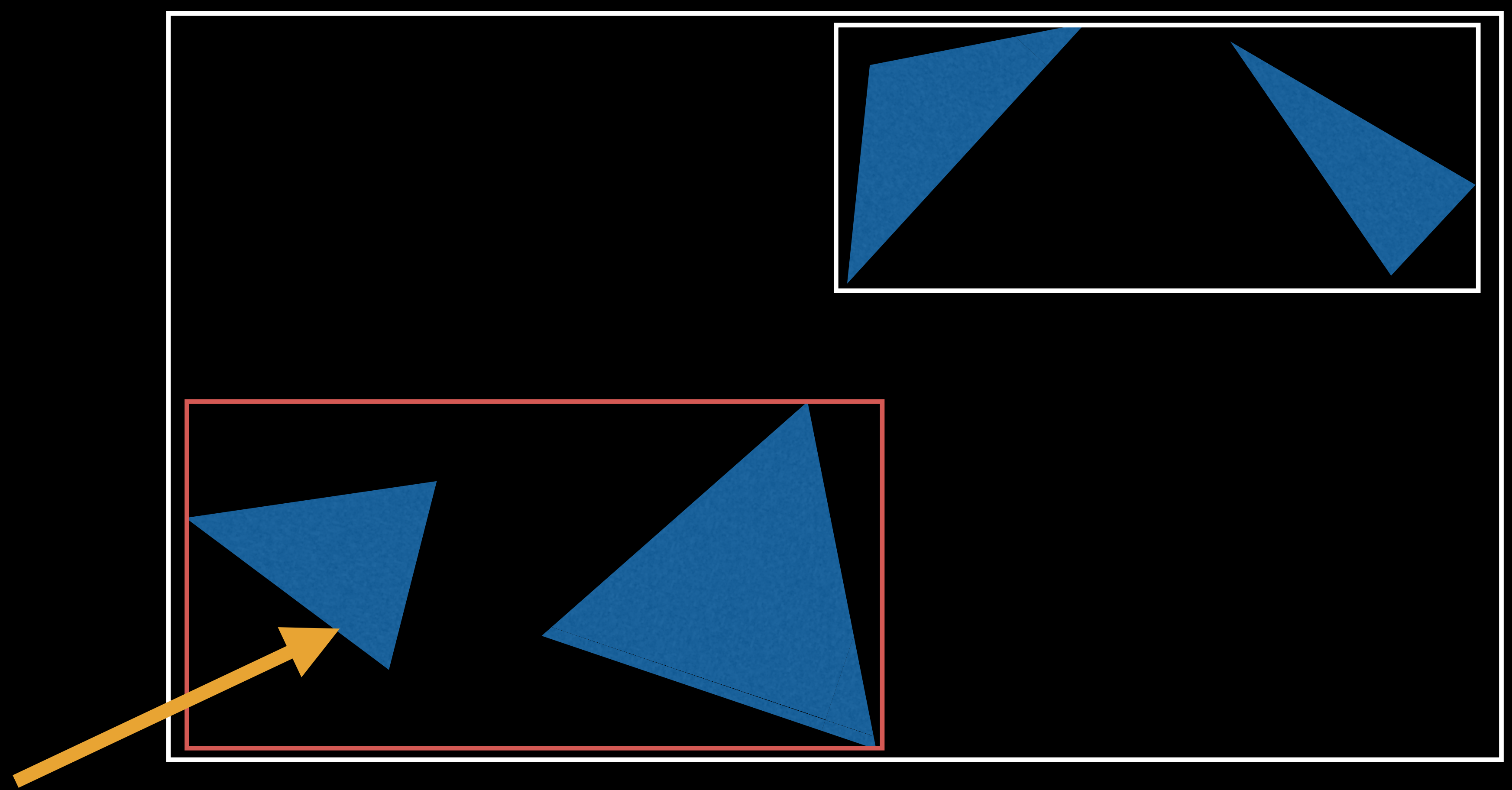

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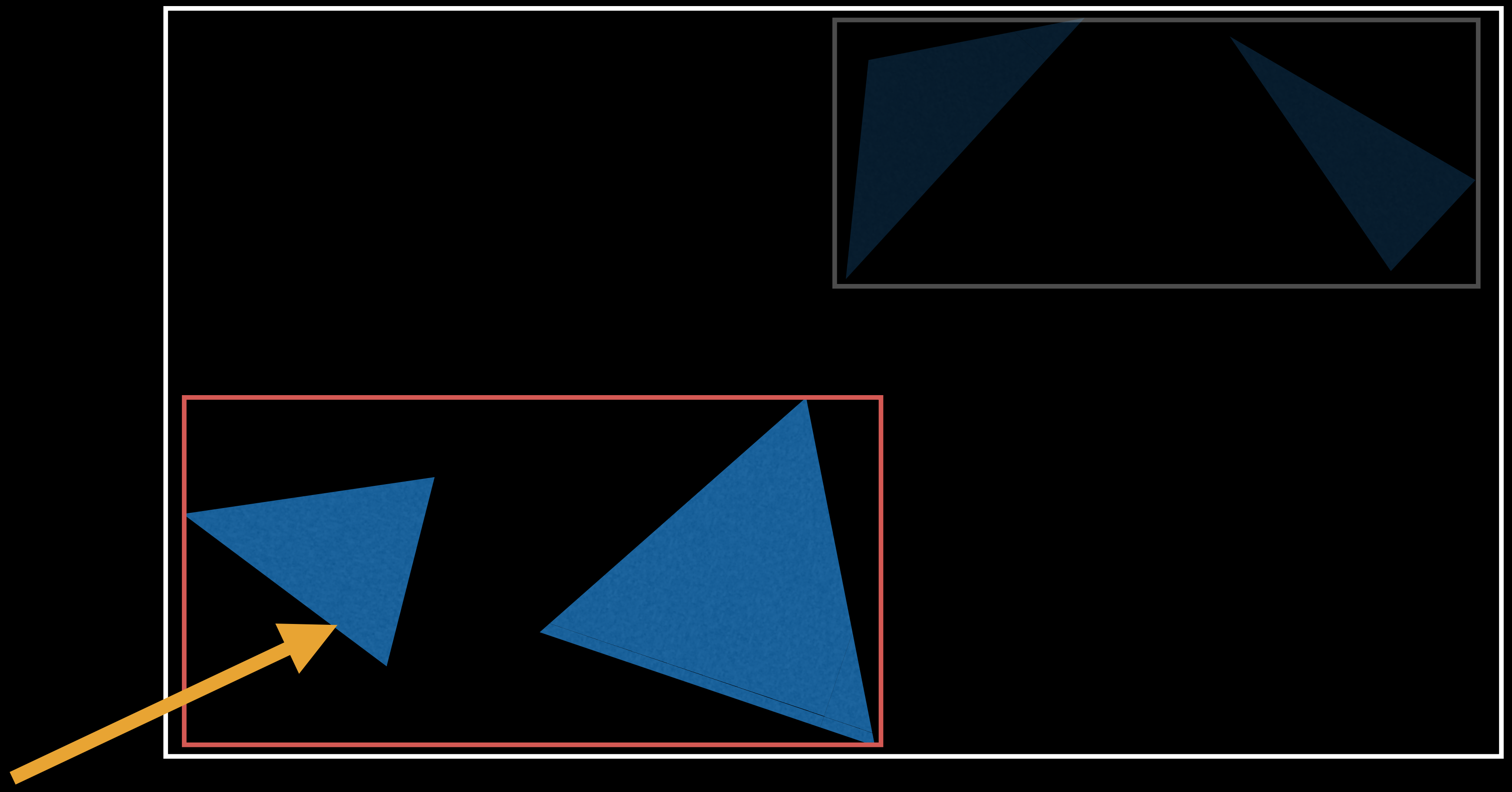

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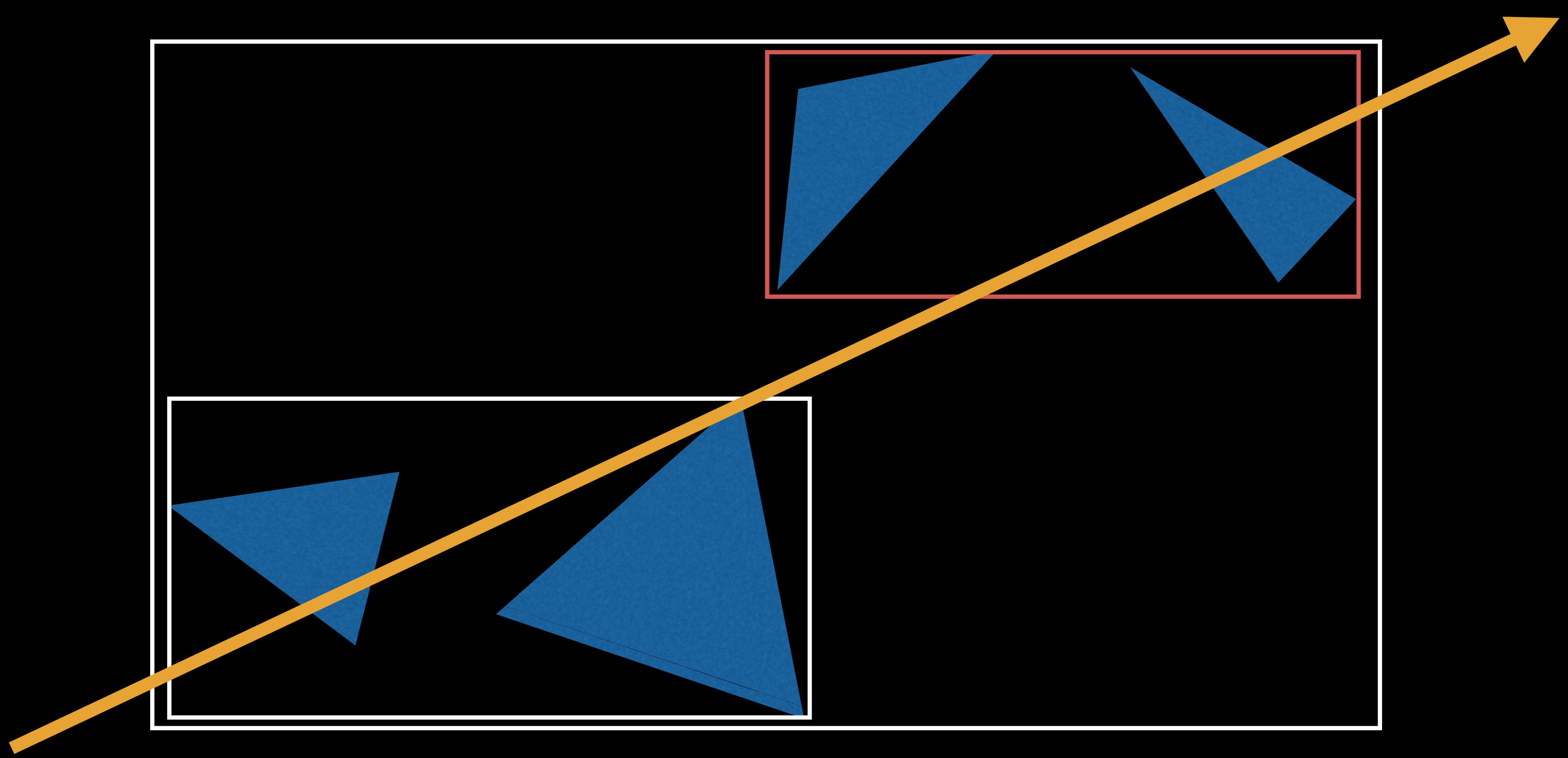

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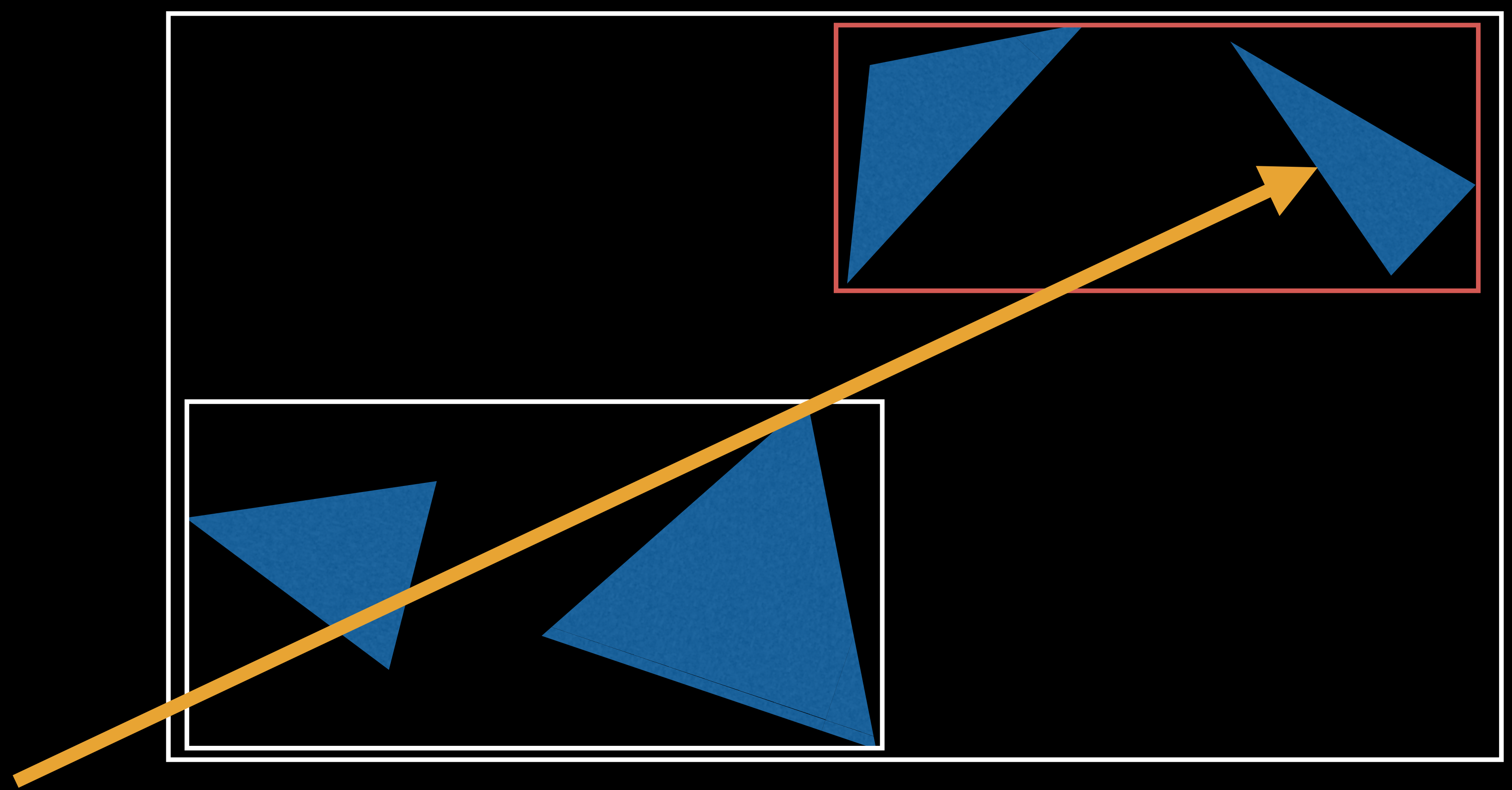

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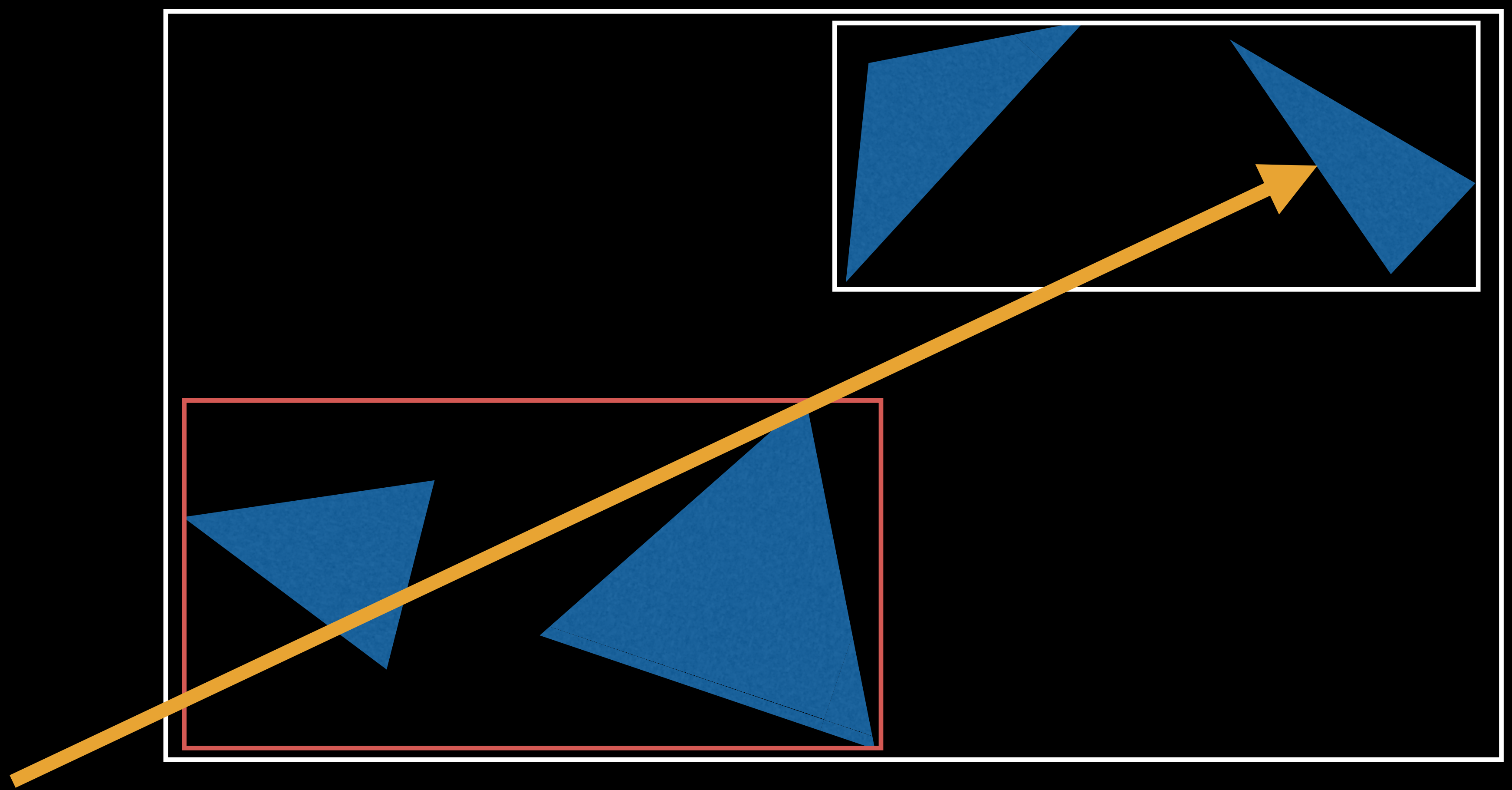
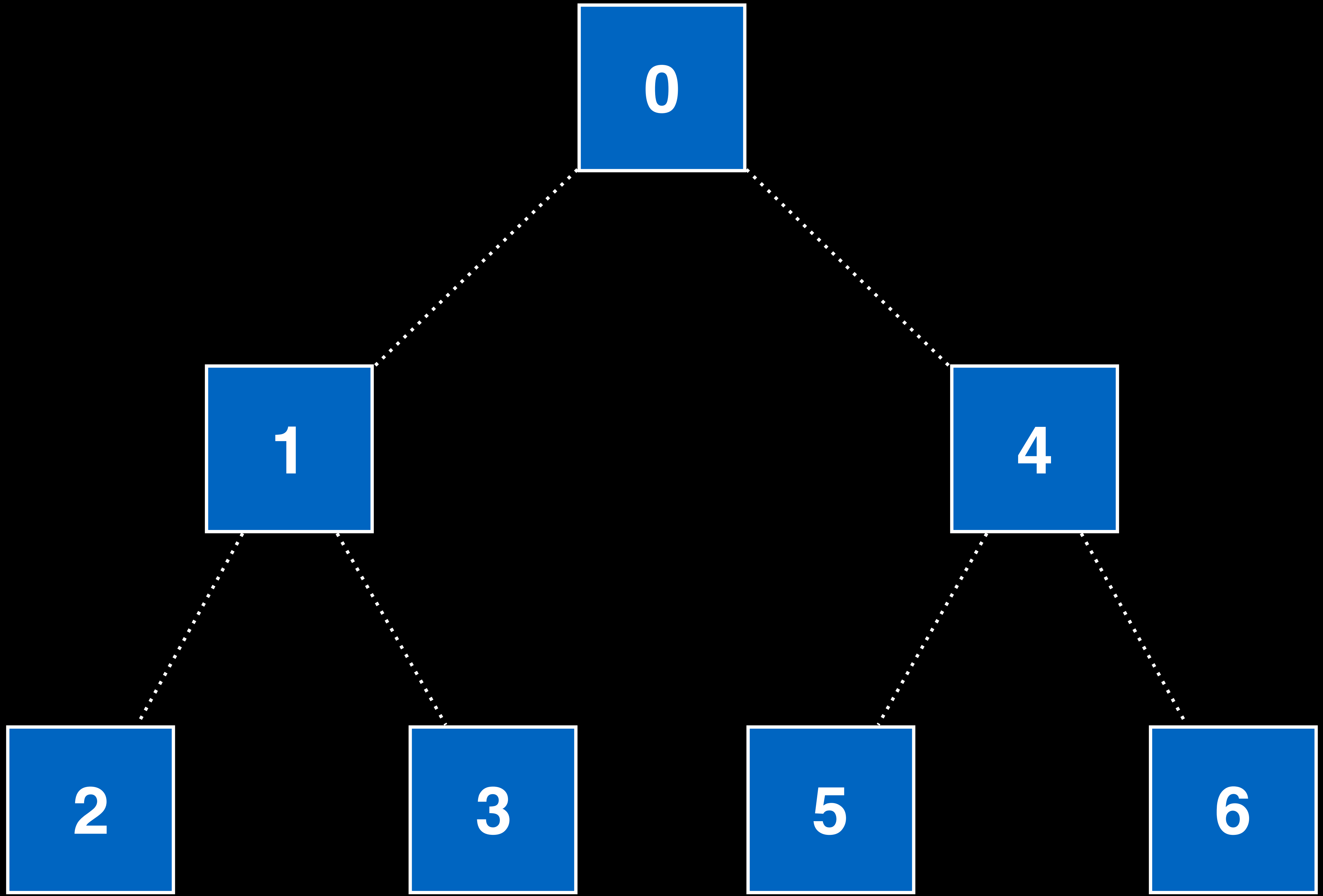
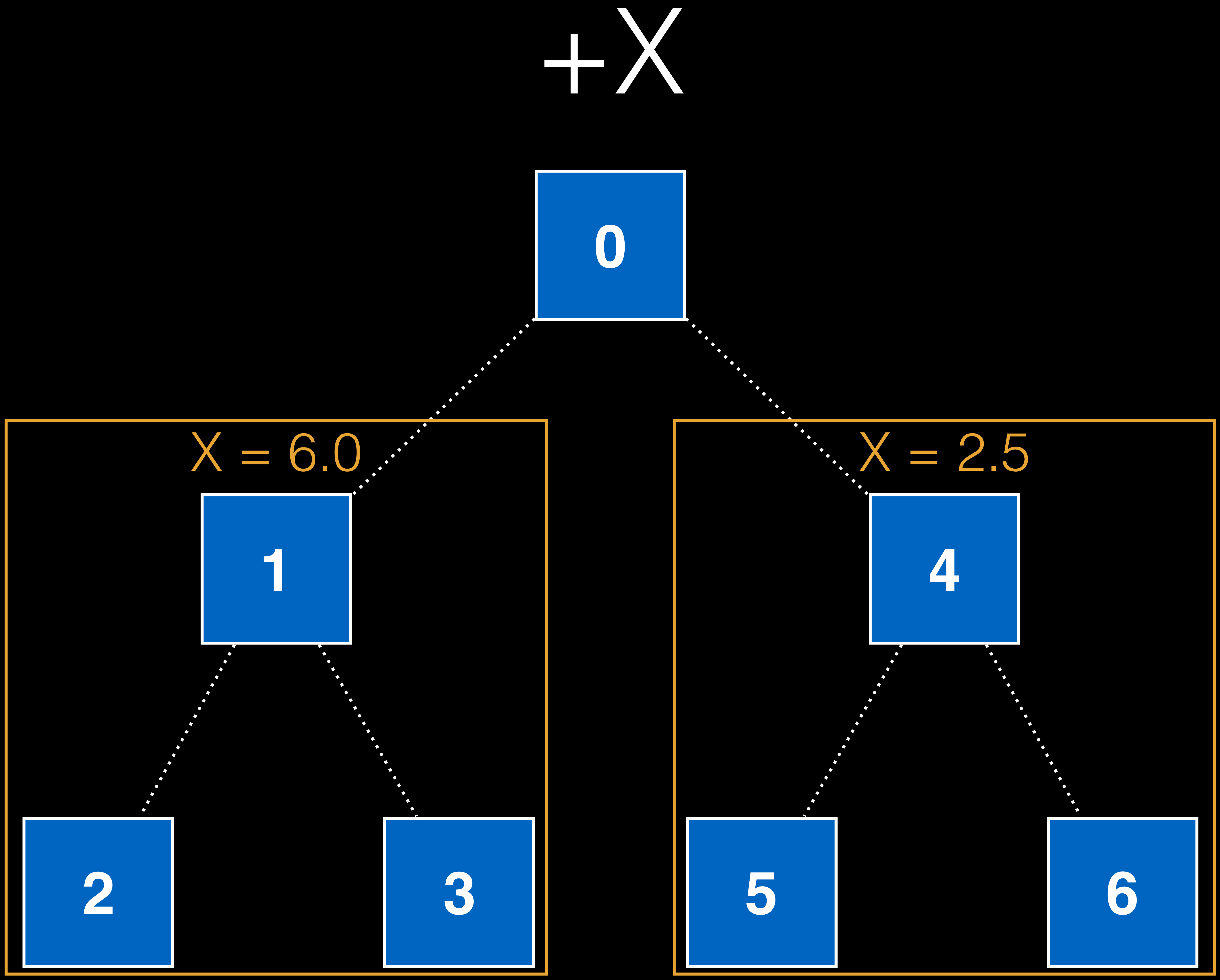


# Multiple-threaded BVH (MTBVH)

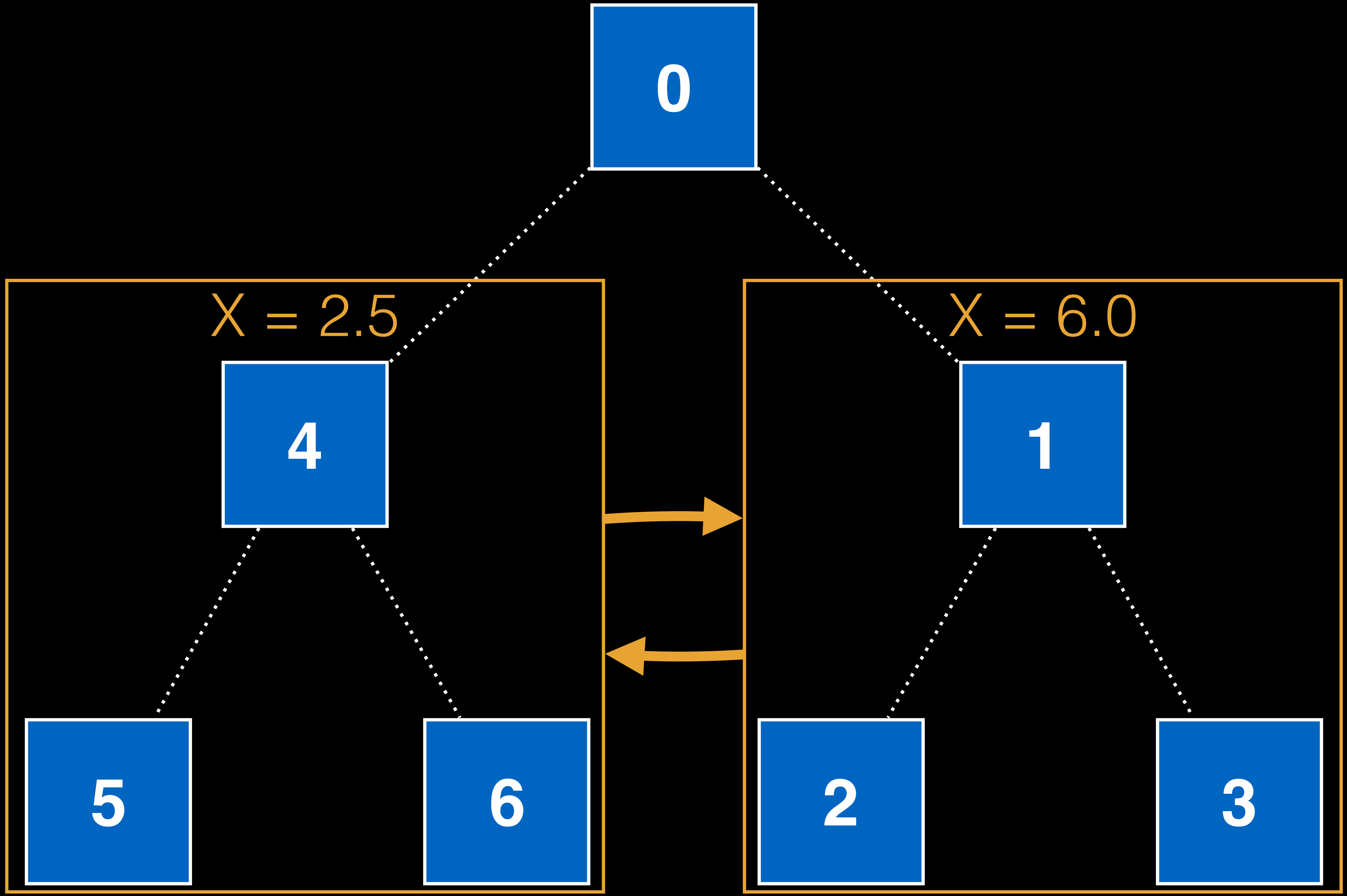
- Prepare threaded BVHs for six major directions
  - +X -X +Y -Y +Z -Z
- Need to add only “hit” and “miss” links
  - Bounding boxes data is shared
- Classify ray directions via 1x1 cube maps
- Unpublished novel idea as far as I know :->

# +X

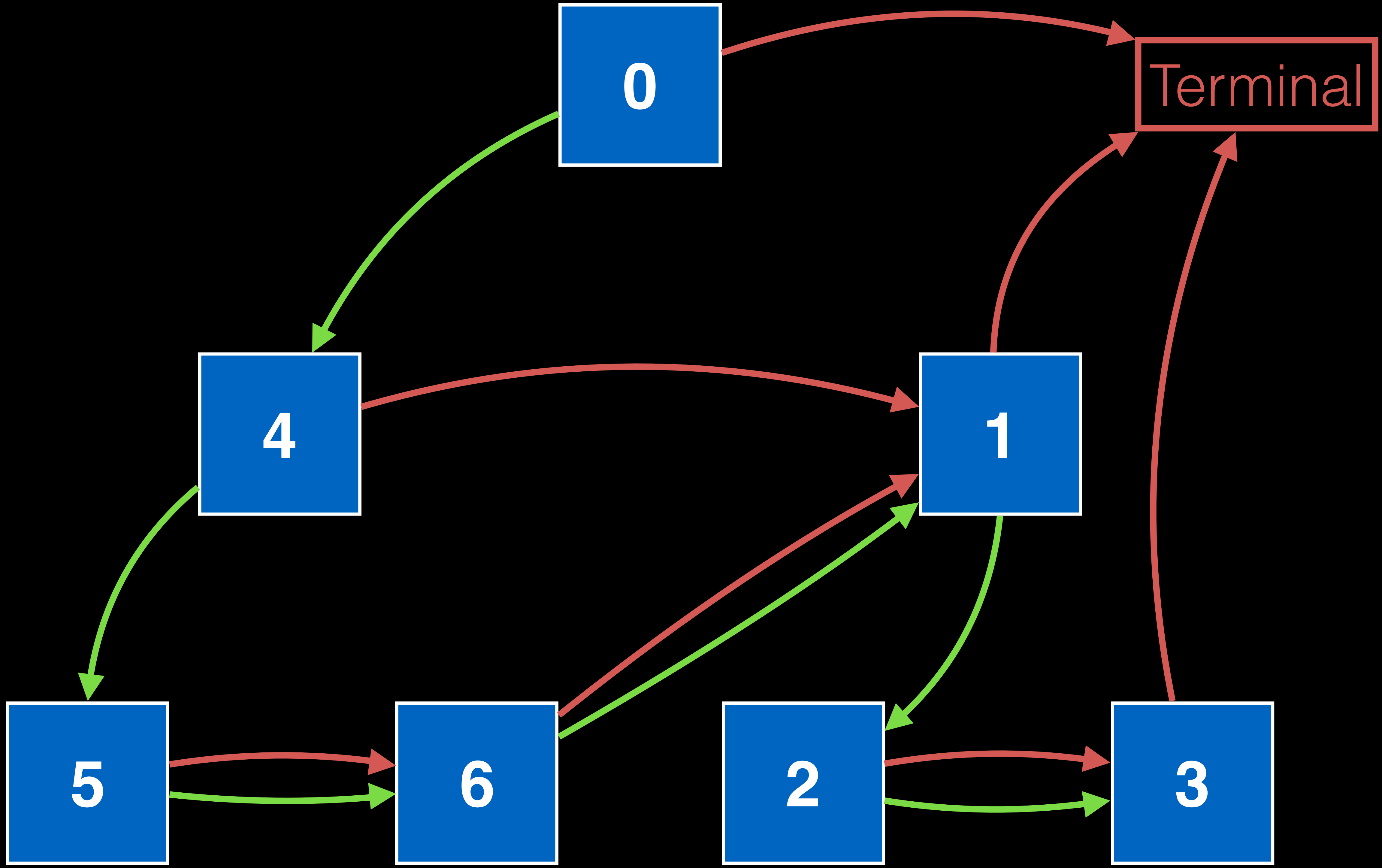


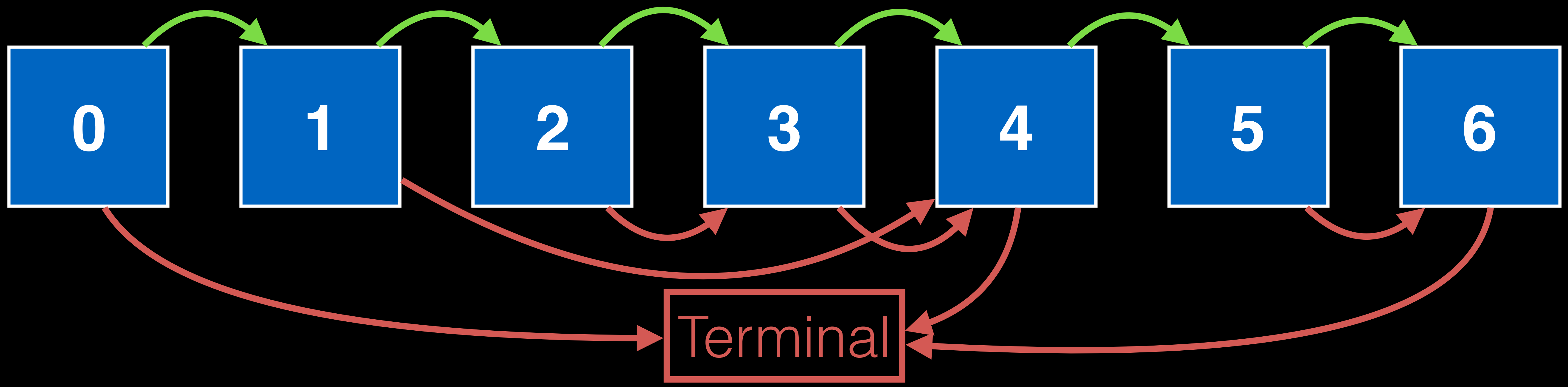

+X
0
X = 6.0
1
2
3
X = 2.5
4
5
6

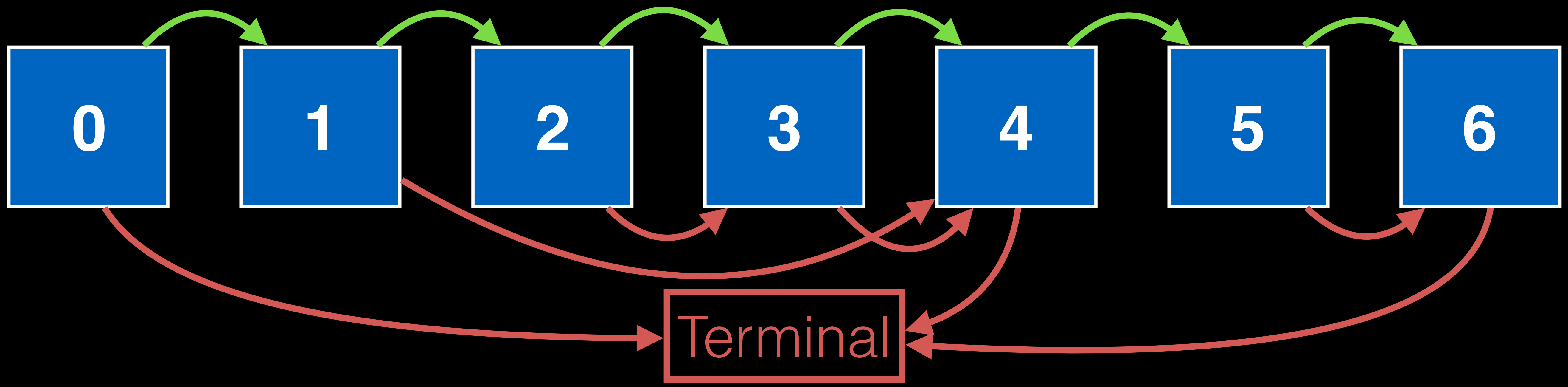
# +X



# +X




0
1
2
3
4
5
6
Terminal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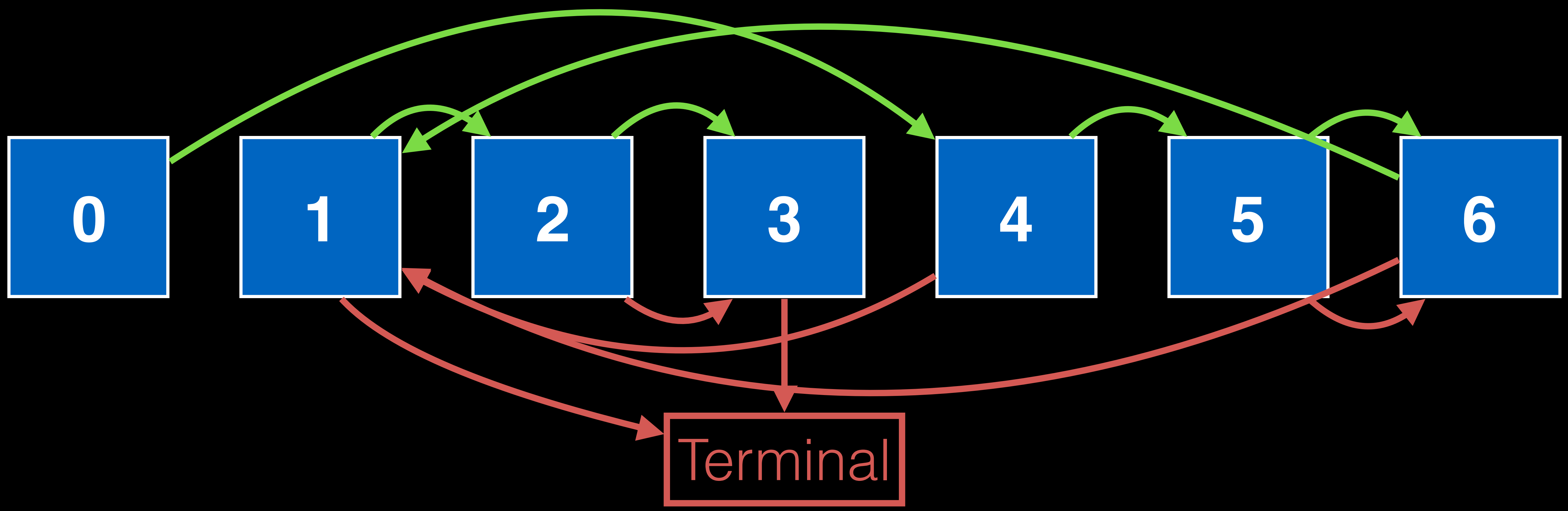
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3
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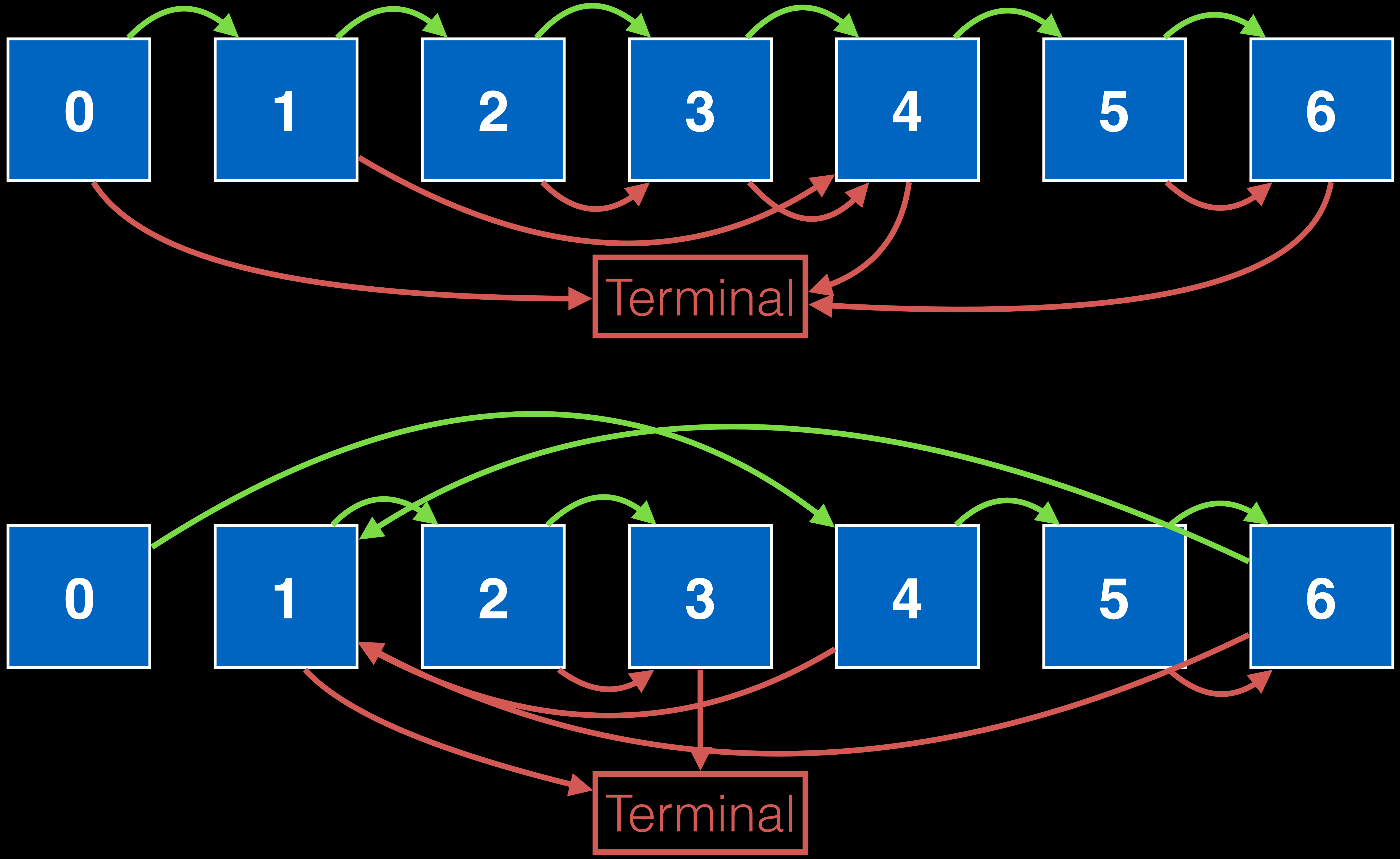
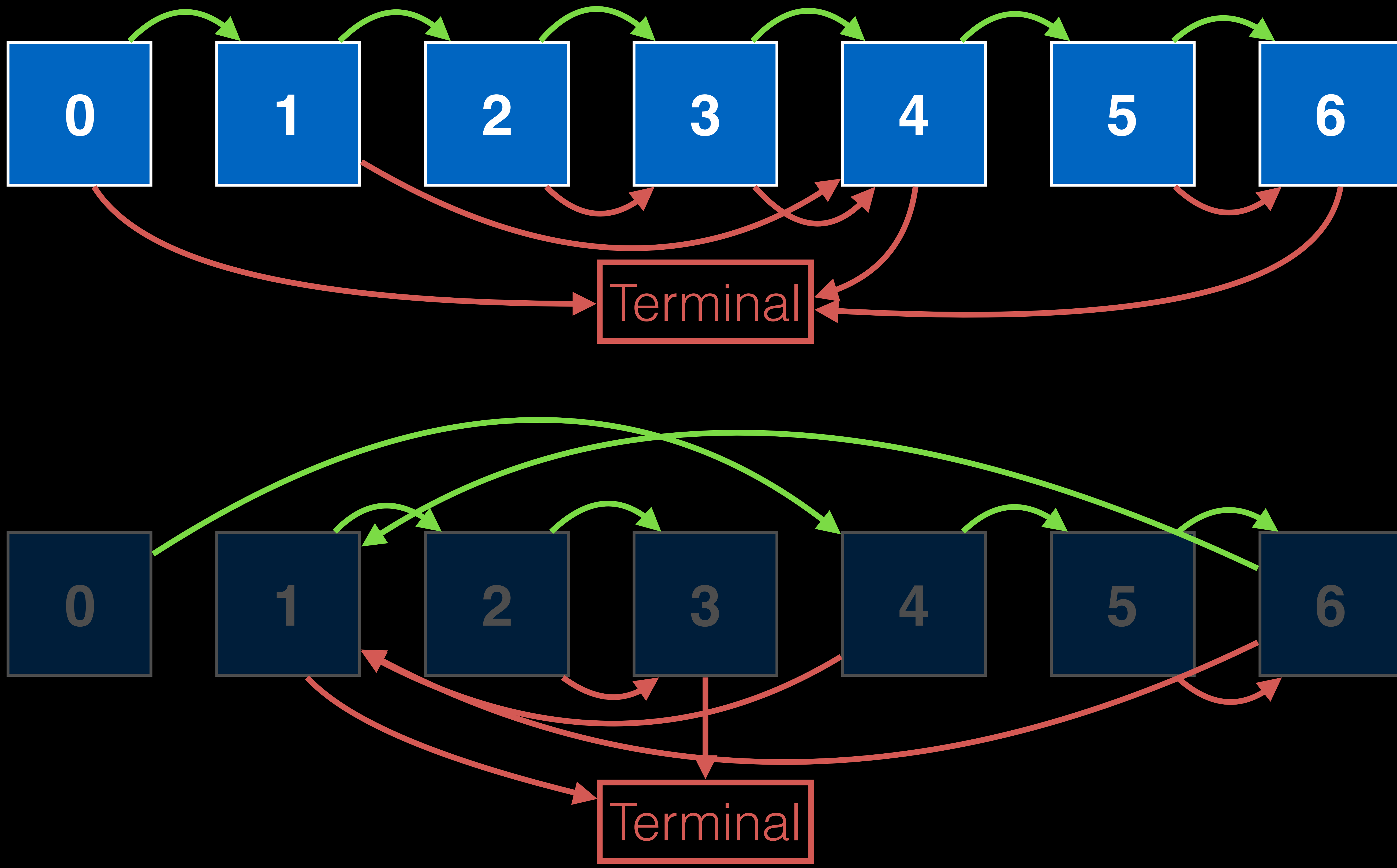


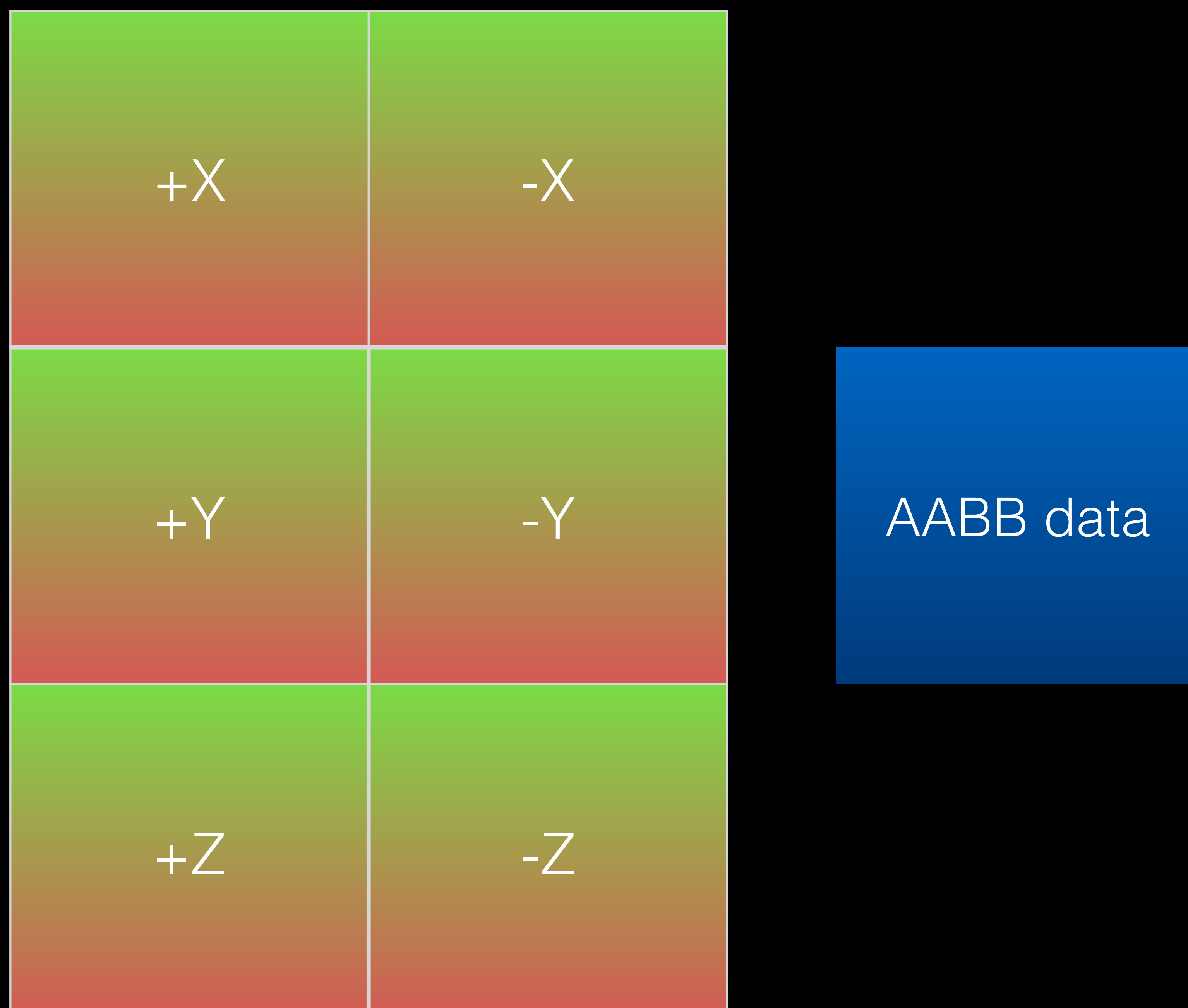

six different directions




- 
- six different directions
- 

# Data layout

- Put all six sets of hit and miss links into one texture



# Data layout

- Threading (vec4 × 1)
  - `vec4(hit.uv, miss.uv)`
  - Store -1.0 to indicate the terminal
- AABB (vec4 × 2)
  - `vec4(min.xyz, triangle.u), vec4(max.xyz, triangle.v)`
  - Store -1.0 for w to indicate internal nodes

# MTBVH traversal

- Still extremely **simple** (only one change)!

```
node = cubemap(root_tex, ray.direction);
while (node != null) {
   if (intersect(node.bonding, ray)) {
      if (node.leaf) {
         hit_point = intersect(node.triangles, ray);
      }
      node = node.hit;
   } else {
      node = node.miss;
   }
}
```

# Ray-triangle intersection

- There are many different approaches
- Best algorithm for CPUs is not the best for GPUs
  - Different computation/data transfer ratio and cost of conditional branches
  - Some “optimisation” can backfire!
  - Modified Möller-Trumbore algorithm works well

# Ray-triangle intersection

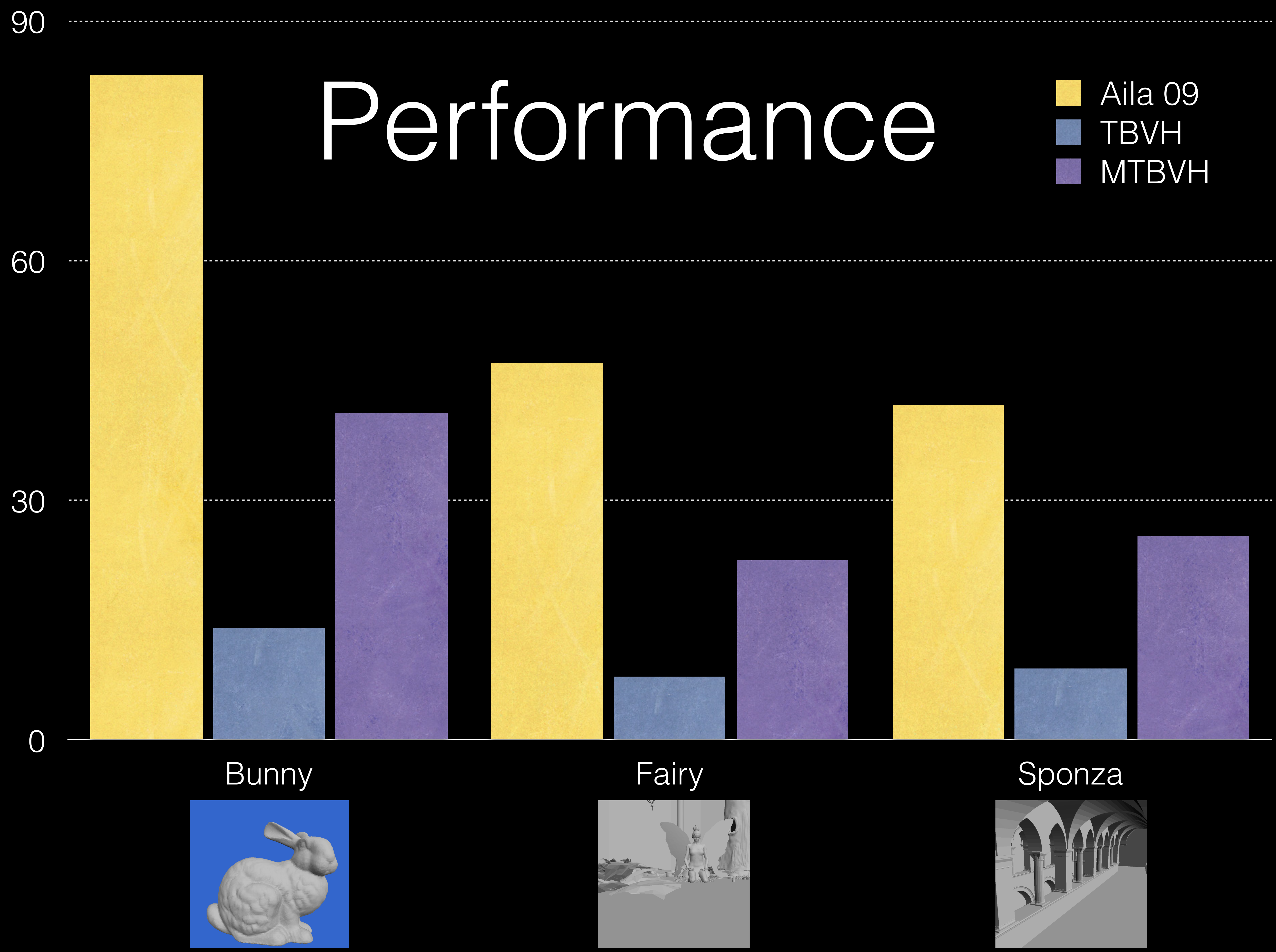
```
vec3 p0 = V0;
vec3 e0 = V1 - V0;
vec3 e1 = V2 - V0;
vec3 pv = cross(ray.direction, e1);
float det = dot(e0, pv);
vec3 tv = ray.origin - p0;
vec3 qv = cross(tv, e0);

vec4 uvt;
uvt.x = dot(tv, pv);
uvt.y = dot(ray.direction, qv);
uvt.z = dot(e1, qv);
uvt.xyz = uvt.xyz / det;
uvt.w = 1.0 - uvt.x - uvt.y;
if (all(greaterThanEqual(uvt, vec4(0.0))) && (uvt.z < hit.a)) {
    hit = vec4(triangle_id.uv, material_id, uvt.z);
}
```

# Packing vertex data

- Each vertex is packed into two vec4 data
  - Normal can be reconstructed via sign(z)
  - Material id is redundantly copied three times

| | | | | |
|---|---|---|---|---|
| **vec4_0** | position.x | position.y | position.z | texcoord.u |
| **vec4_1** | normal.x | normal.y | sign(normal.z) * material_id | texcoord.v |

# Performance




M rays/sec @ GeForce GT 630

# Performance

- 2.5 ~ 3.0 times faster than threaded BVH
- Roughly 0.5 of highly optimized SVBH traversal kernel for NVIDIA GPUs [Aila 09]
  - Not too bad for cross-platform code in my opinion
  - Threading (x 6 times) is very fast
- Can use SBVH with this algorithm as well
  - Potentially fill the rest of the performance gap

# Memory overhead

- Original threaded BVH
  - Triangle: 8 floats × 3 vertex
  - Bounding box: 4 floats × 2 (min & max)
  - Hit/miss links: 4 floats
- Total: 36 floats

# Memory overhead

- Multiple-threaded BVH
  - Triangle: 8 floats × 3 vertex
  - Bounding box: 4 floats × 2 (min & max)
  - Hit/miss links: 4 floats × 6 directions
- Total: 56 floats

# Memory overhead

- Multiple-threaded BVH
  - Triangle: 8 floats × 3 vertex
  - Bounding box: 4 floats × 2 (min & max)
  - Hit/miss links: 4 floats × 6 directions
- Total: 56 floats

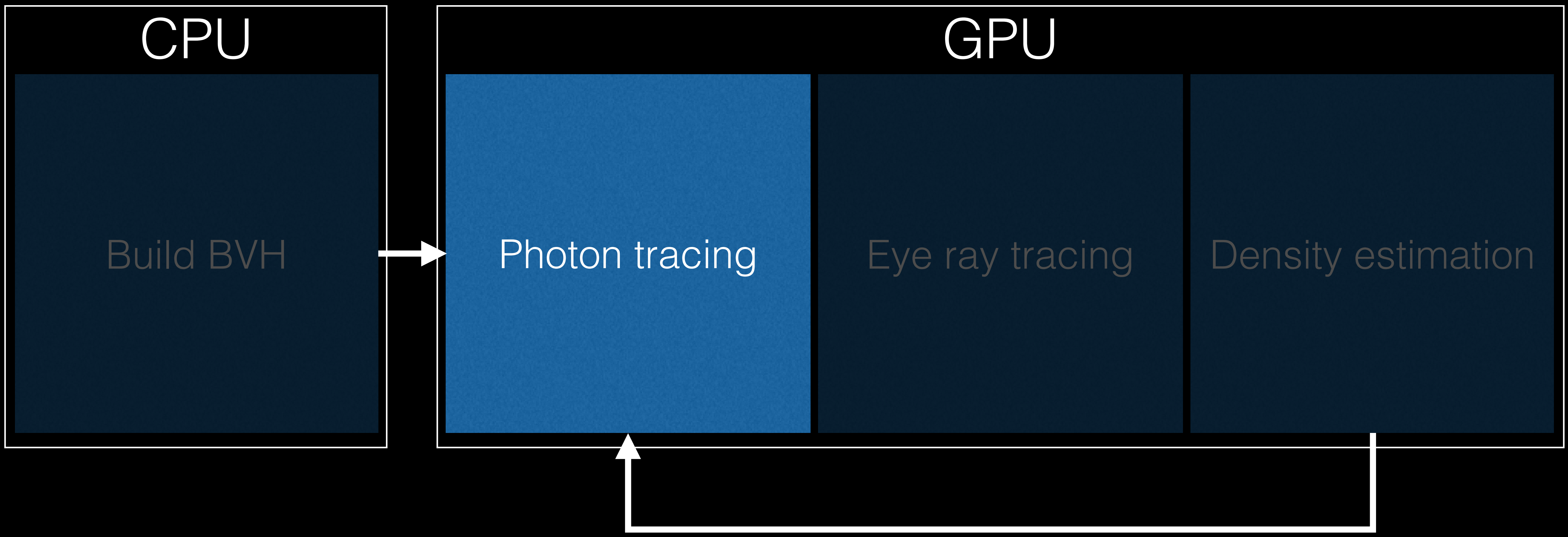
**(only) 1.5 times of the original**

# Other stackless traversals

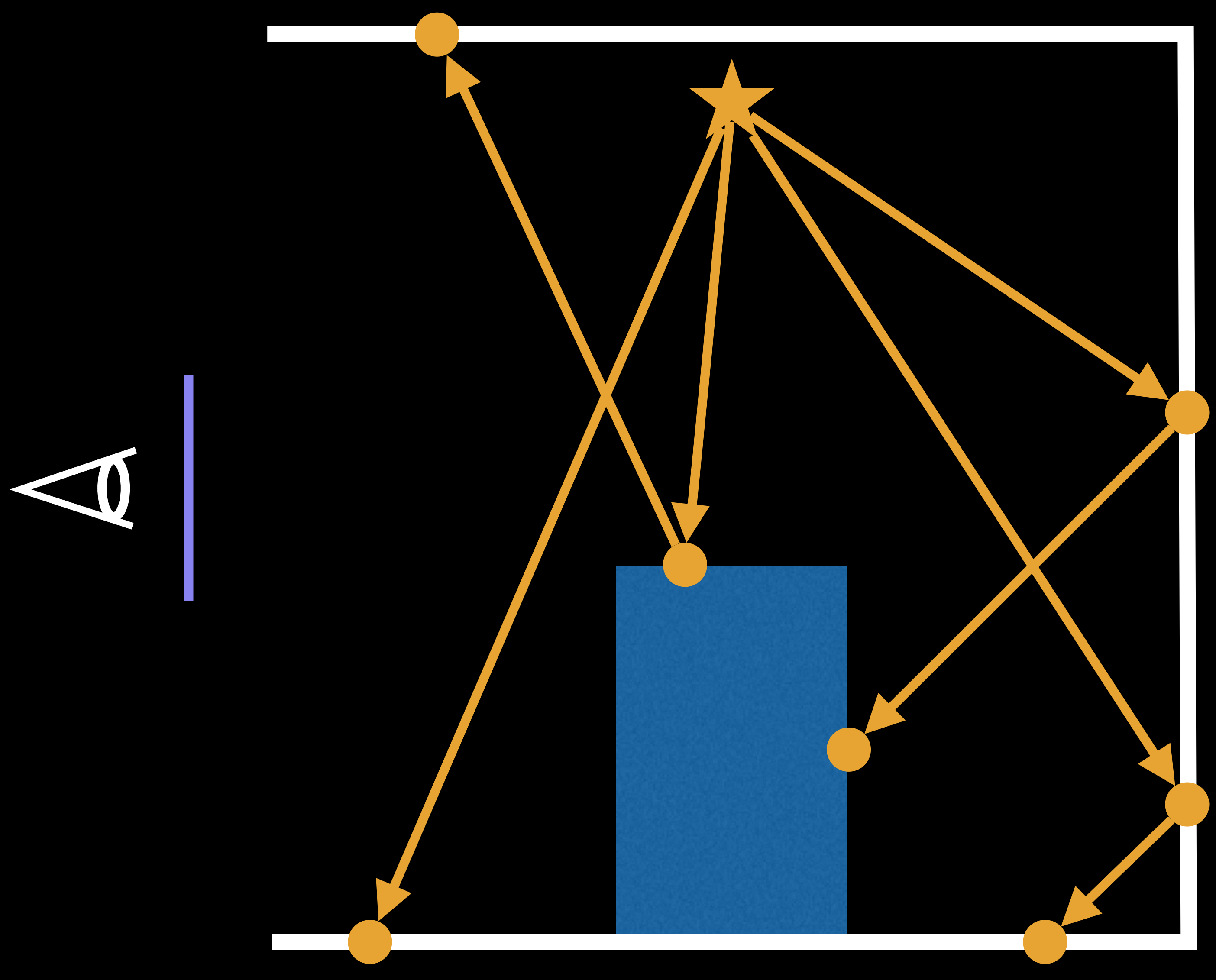
- There are many different approaches
  - Bitwise operation [Barringer13, Afra13…]
  - Restarting [Foley05, Laine10, Hapala11…]
- Multiple-threaded BVH seems faster in my tests
  - Traversal algorithm is extremely simple
  - 1.5 times memory overhead is acceptable IMHO

# Dynamic scenes

- Threaded BVH can be constructed entirely on GPUs
  - Just like linear BVH (sorting + indexing)
  - Hit/miss links can be constructed on the fly, too

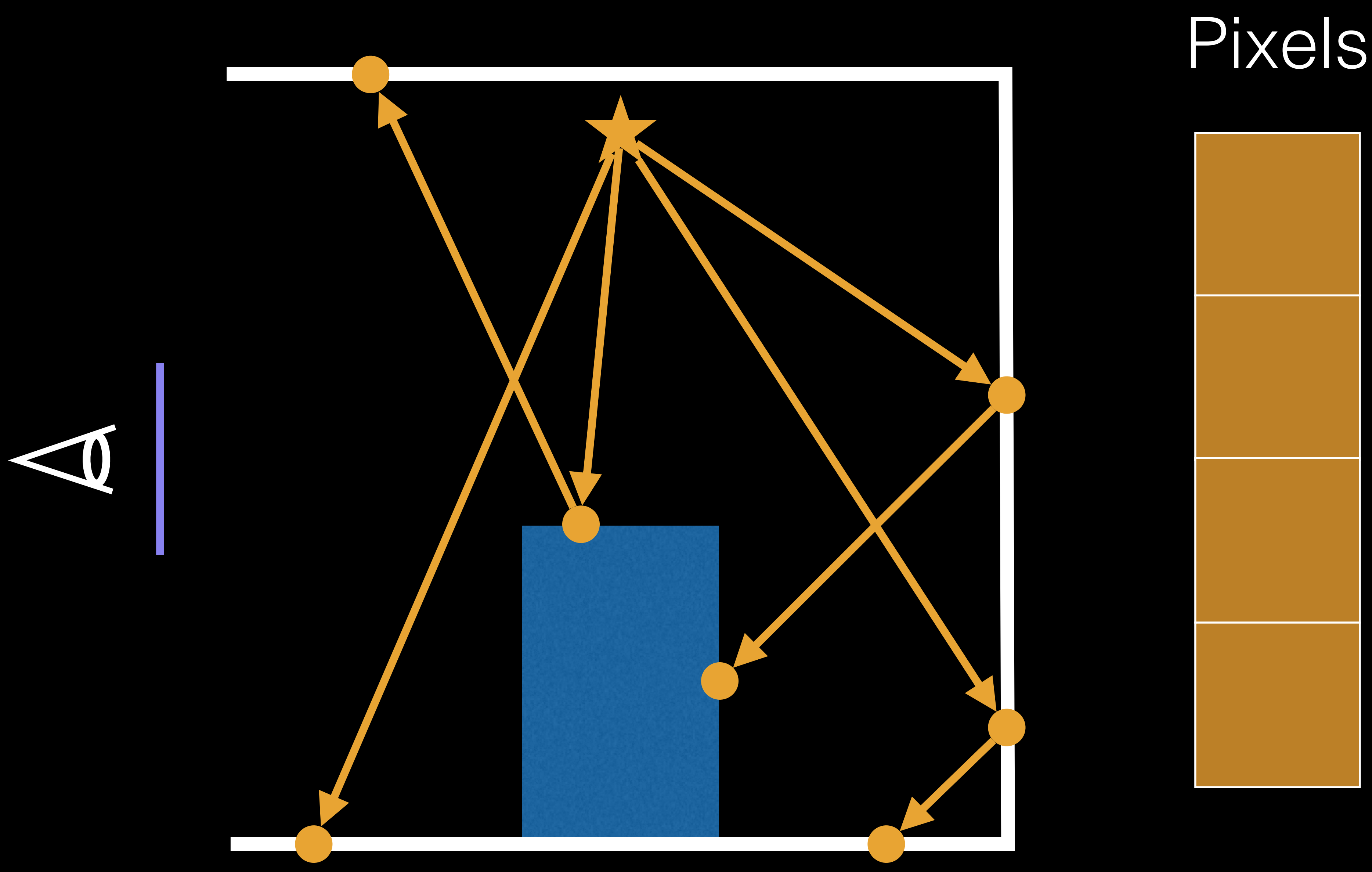

CPU
GPU
Build BVH
Photon tracing
Eye ray tracing
Density estimation

# Photon tracing



# Photon tracing on GPUs

- One pixel = one photon path



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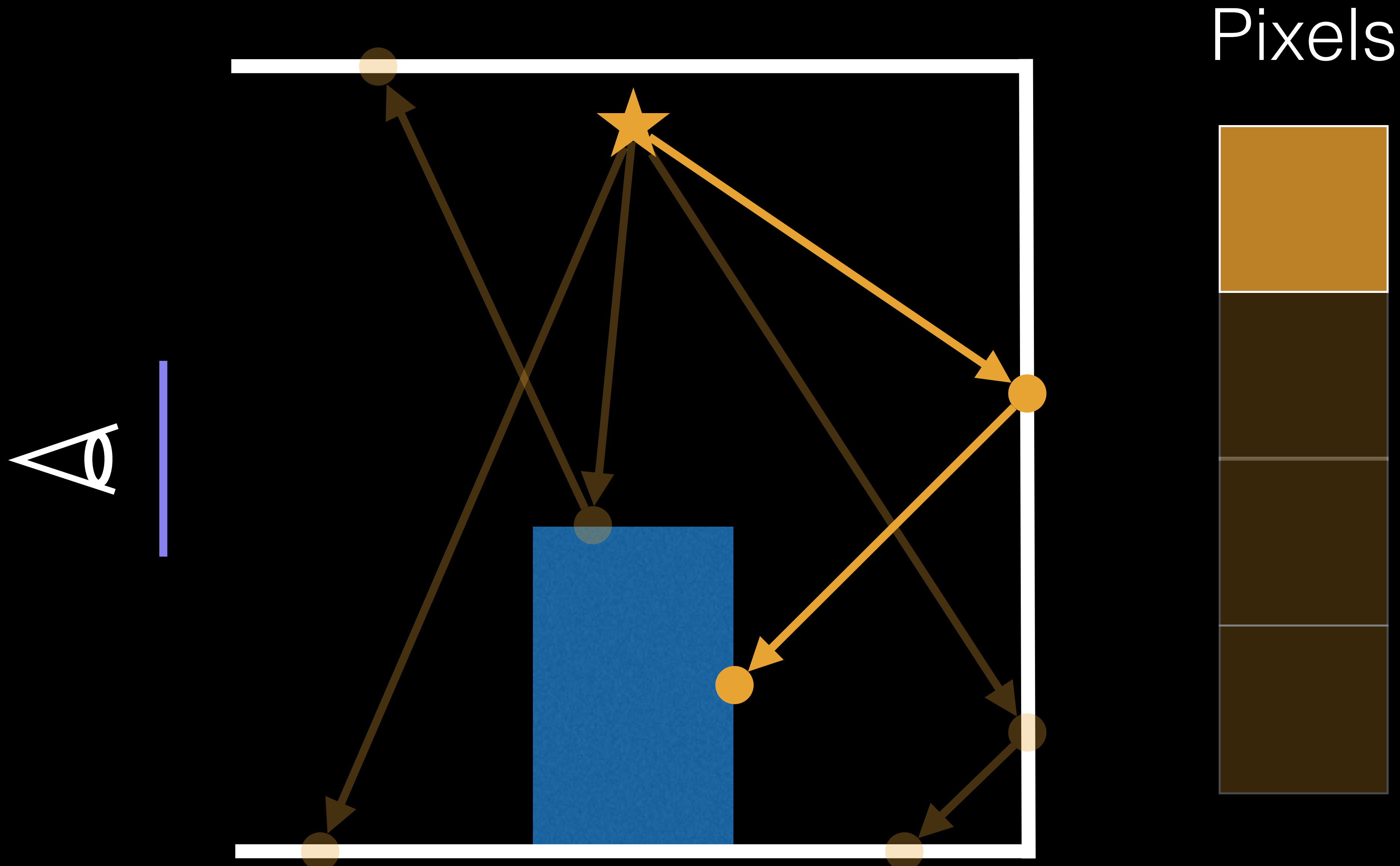

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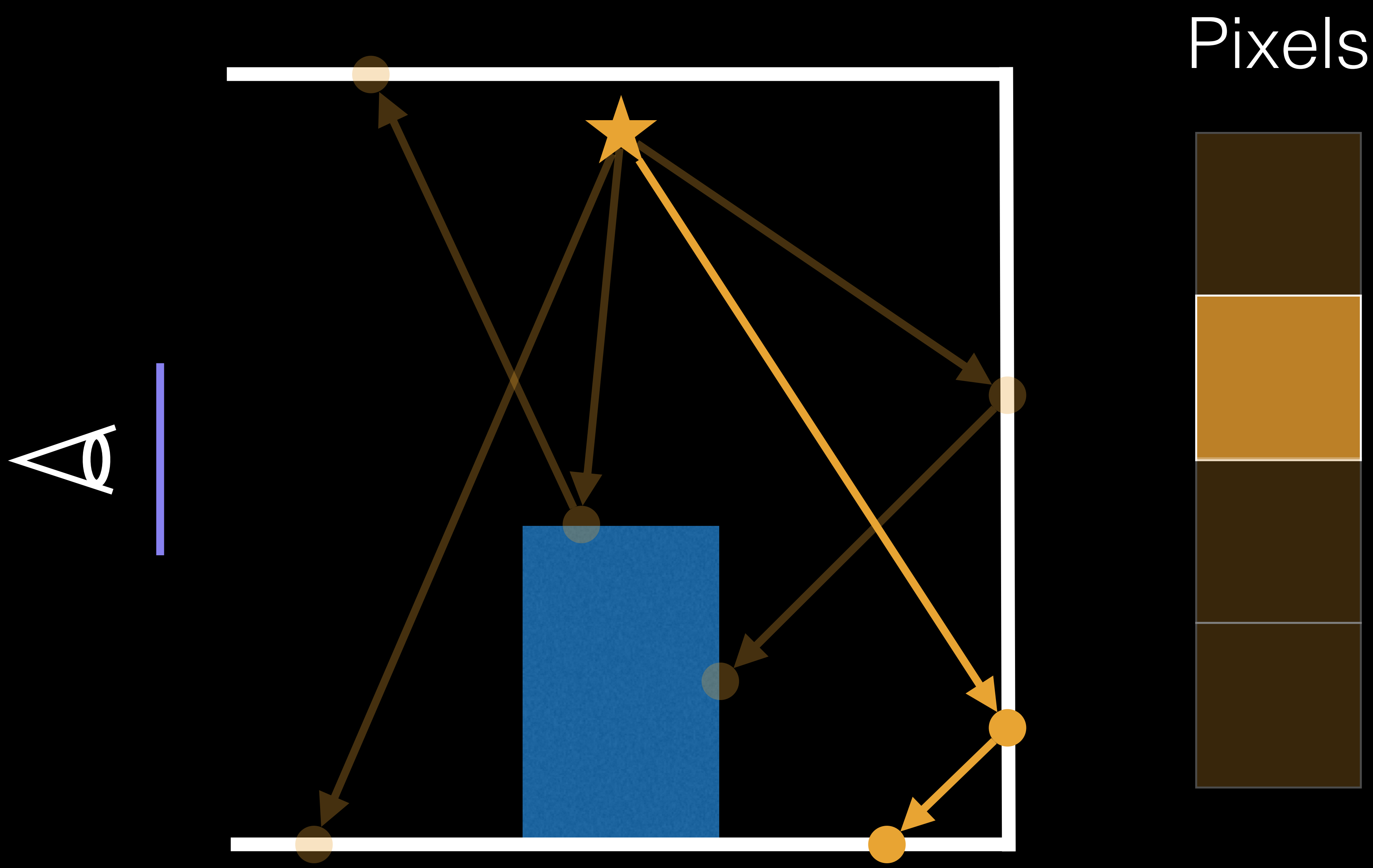

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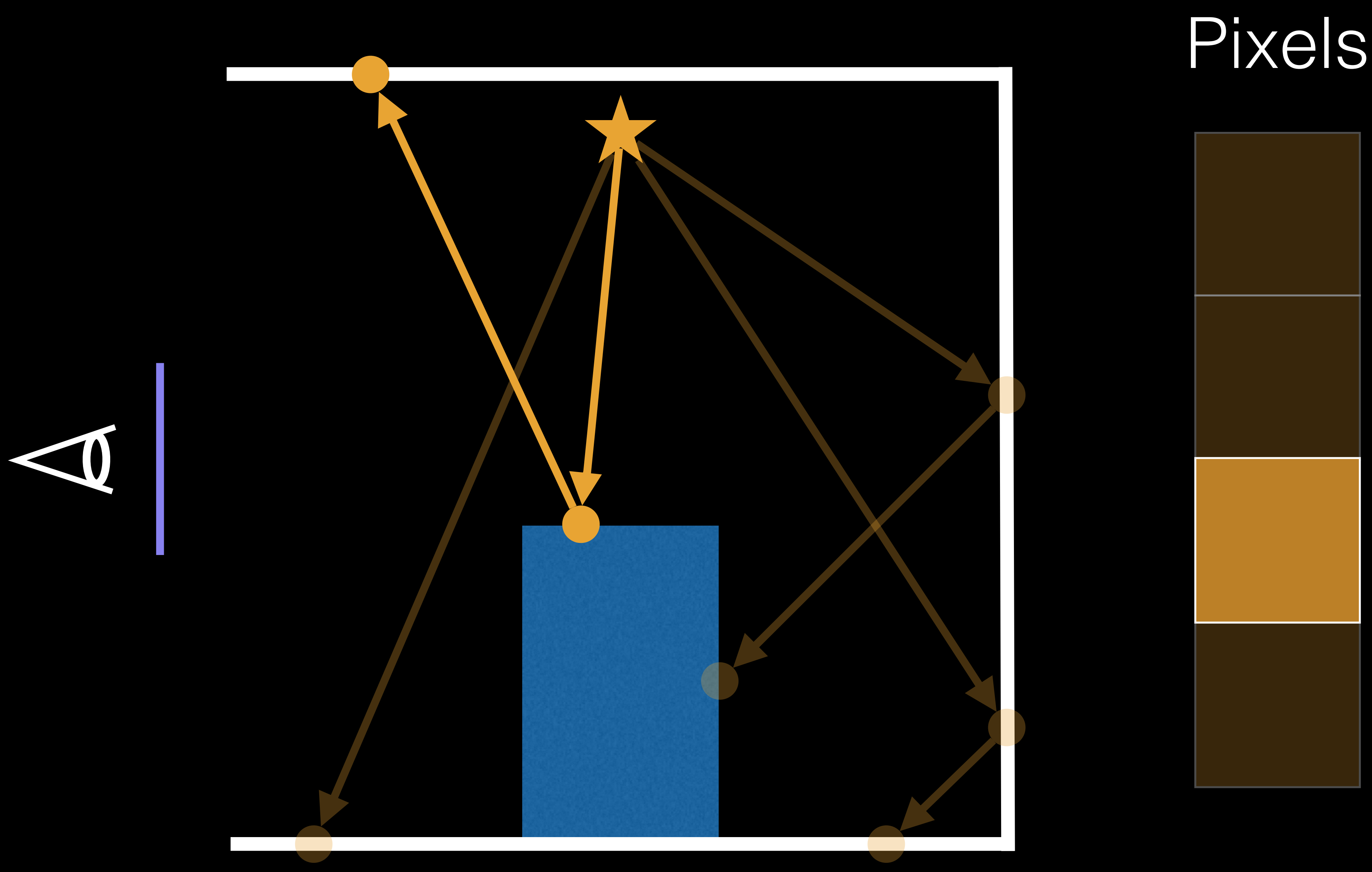

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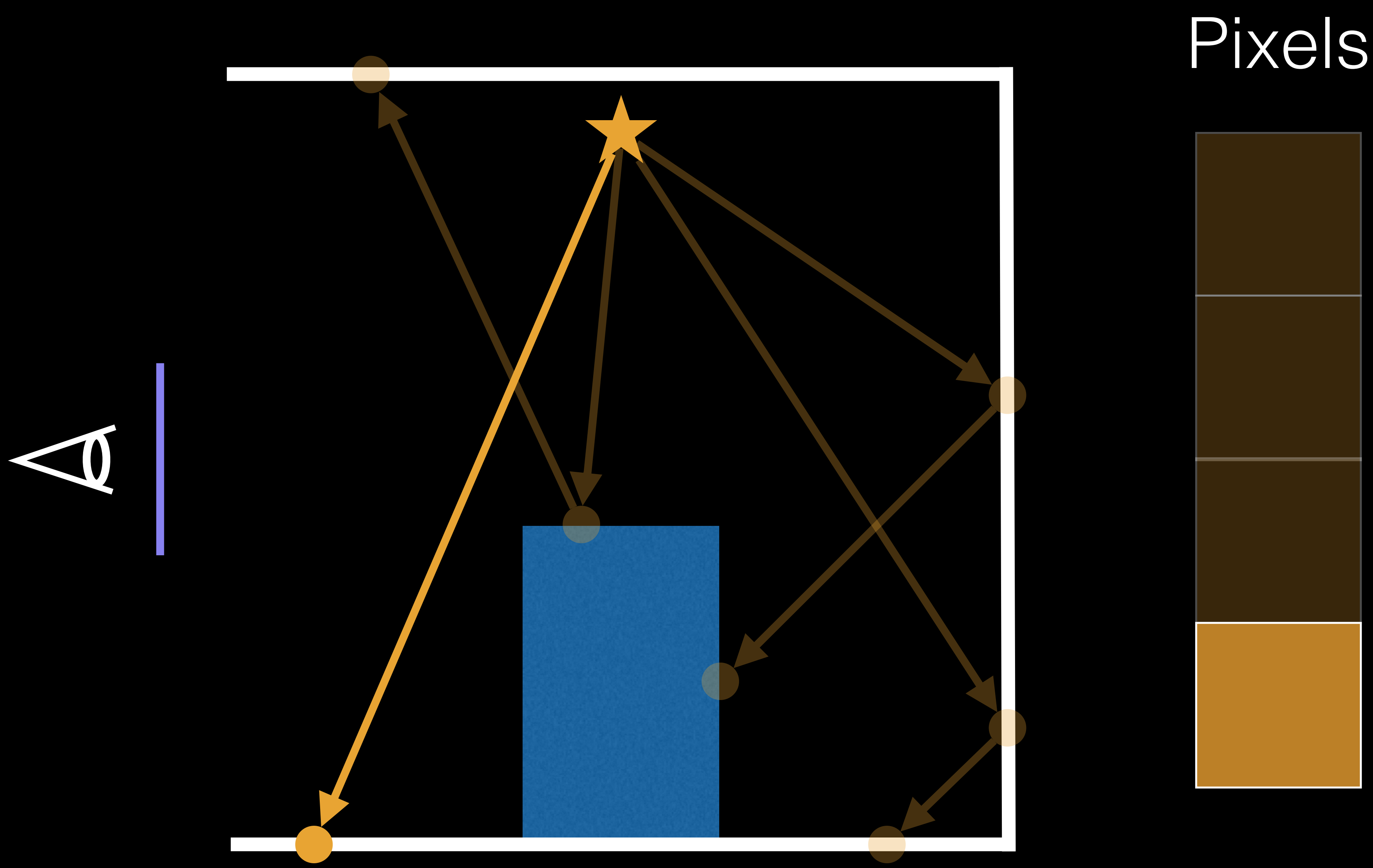
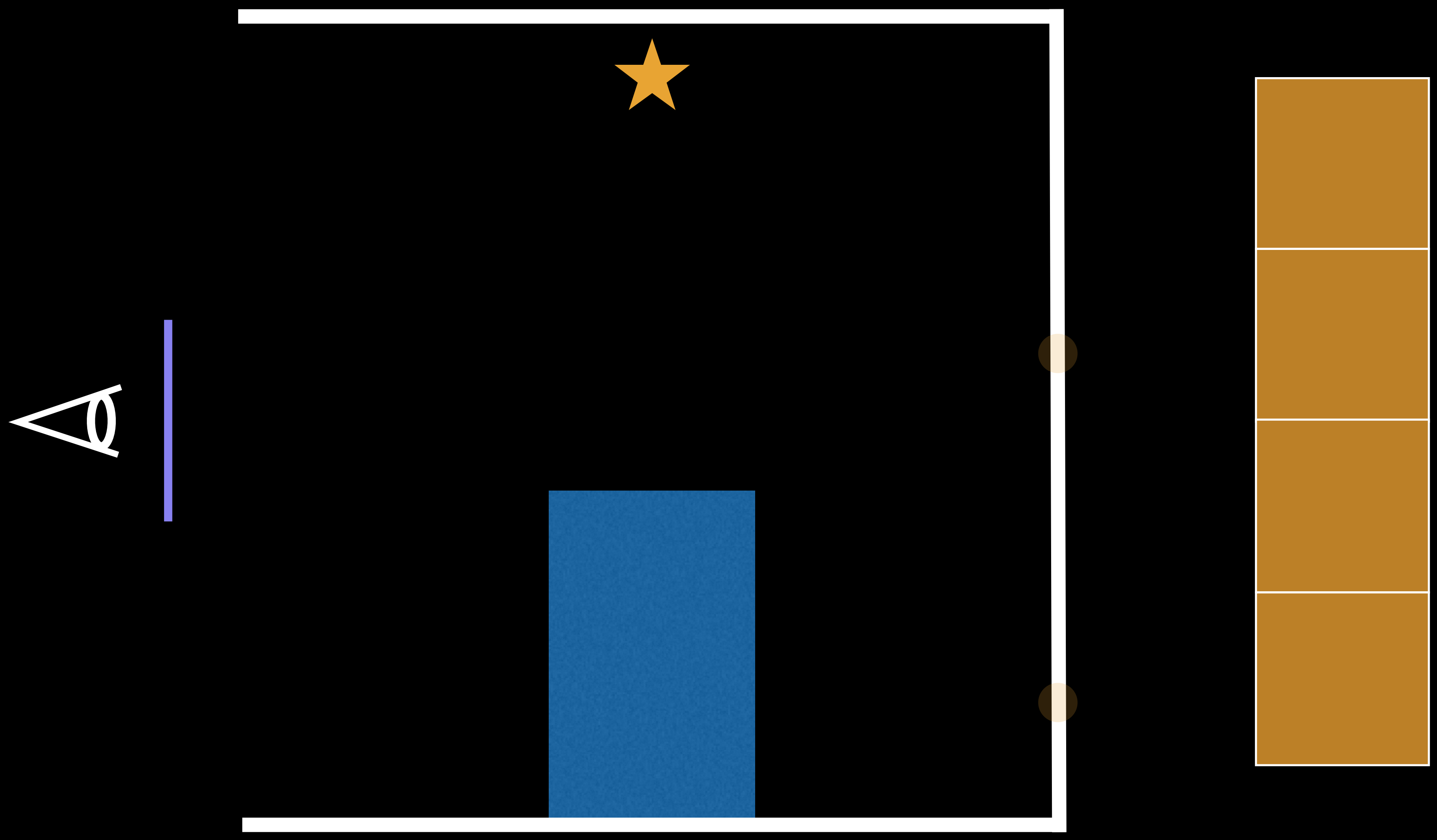


# Challenges

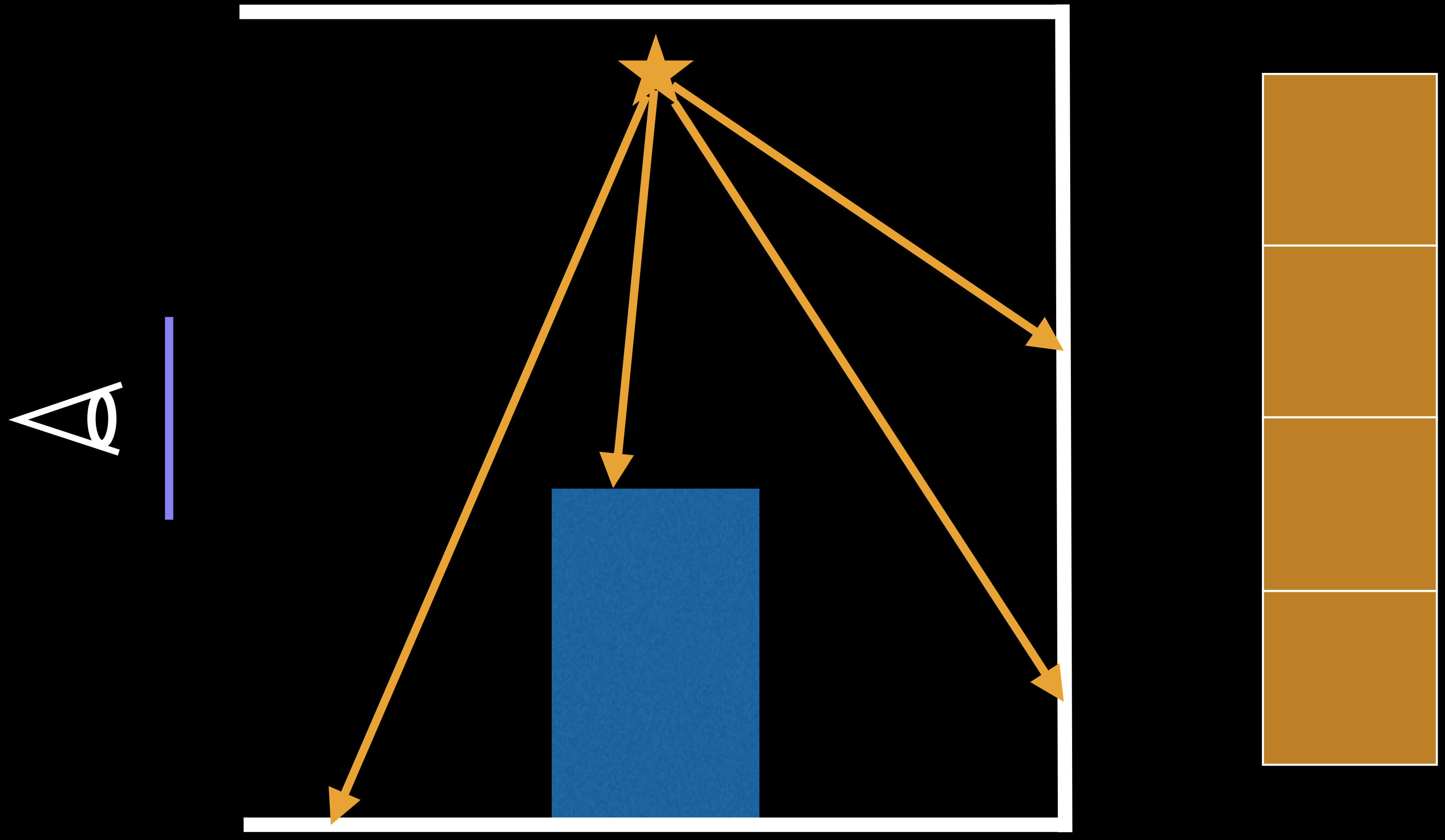
- The number of bounces can vary a lot
  - Don’t want to wait until long ones terminate
  - Need make a list of photons
- Need high quality random numbers in parallel
  - Only with floating-point number operations
  - “Noise” function won’t work

# Photon tracing on GPUs



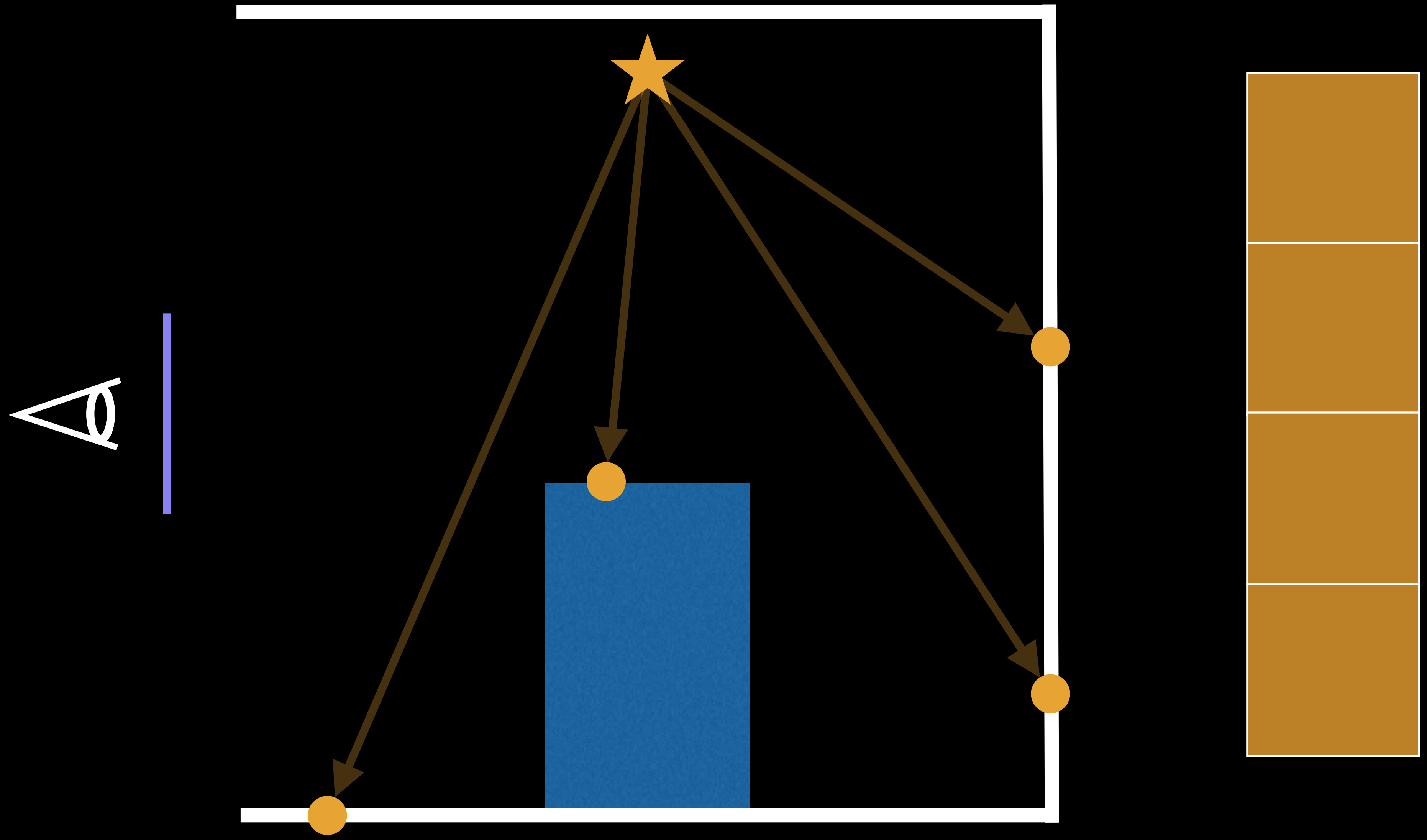
# Photon tracing on GPUs

**Ray tracing from a light source**

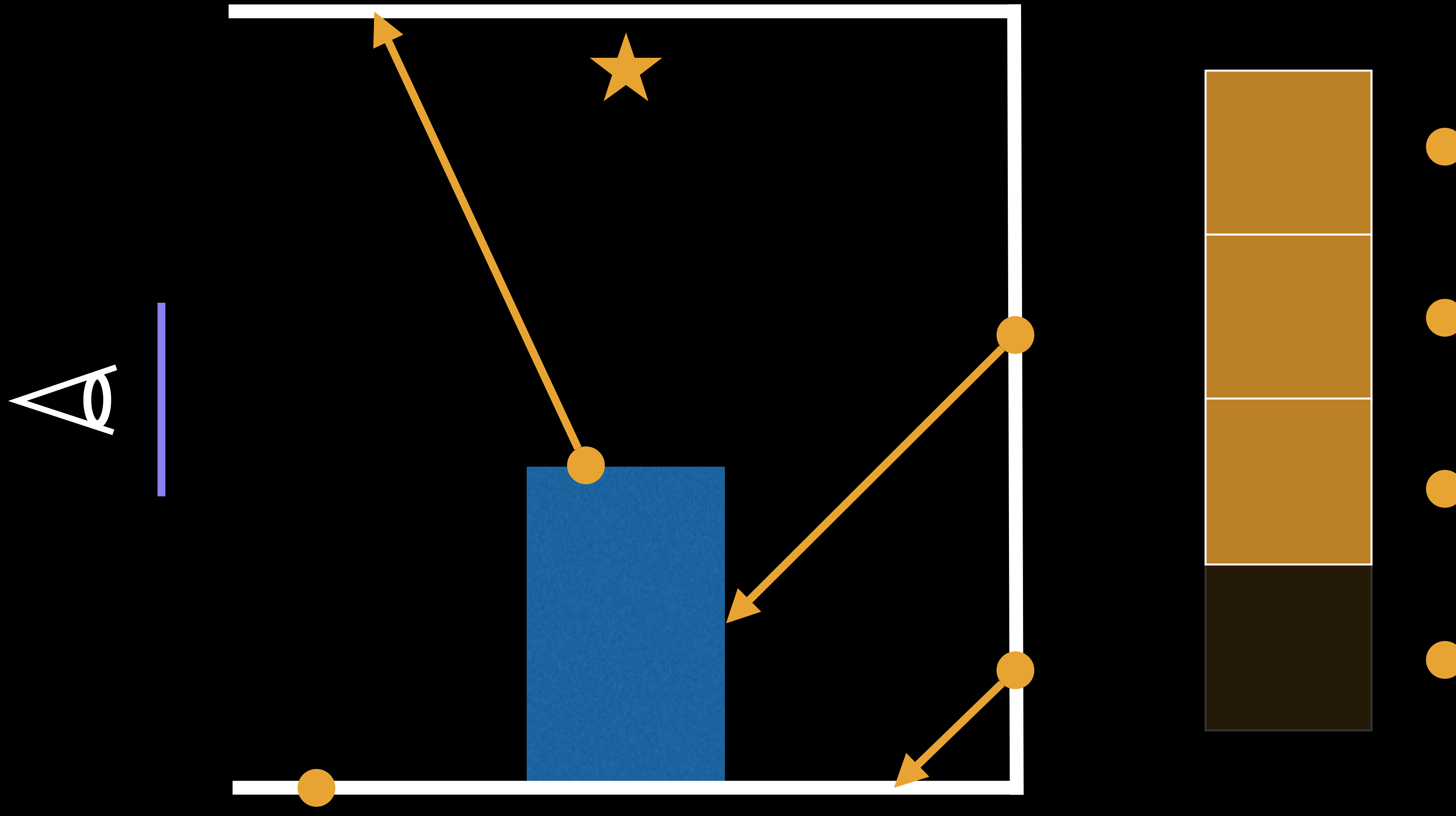


# Photon tracing on GPUs

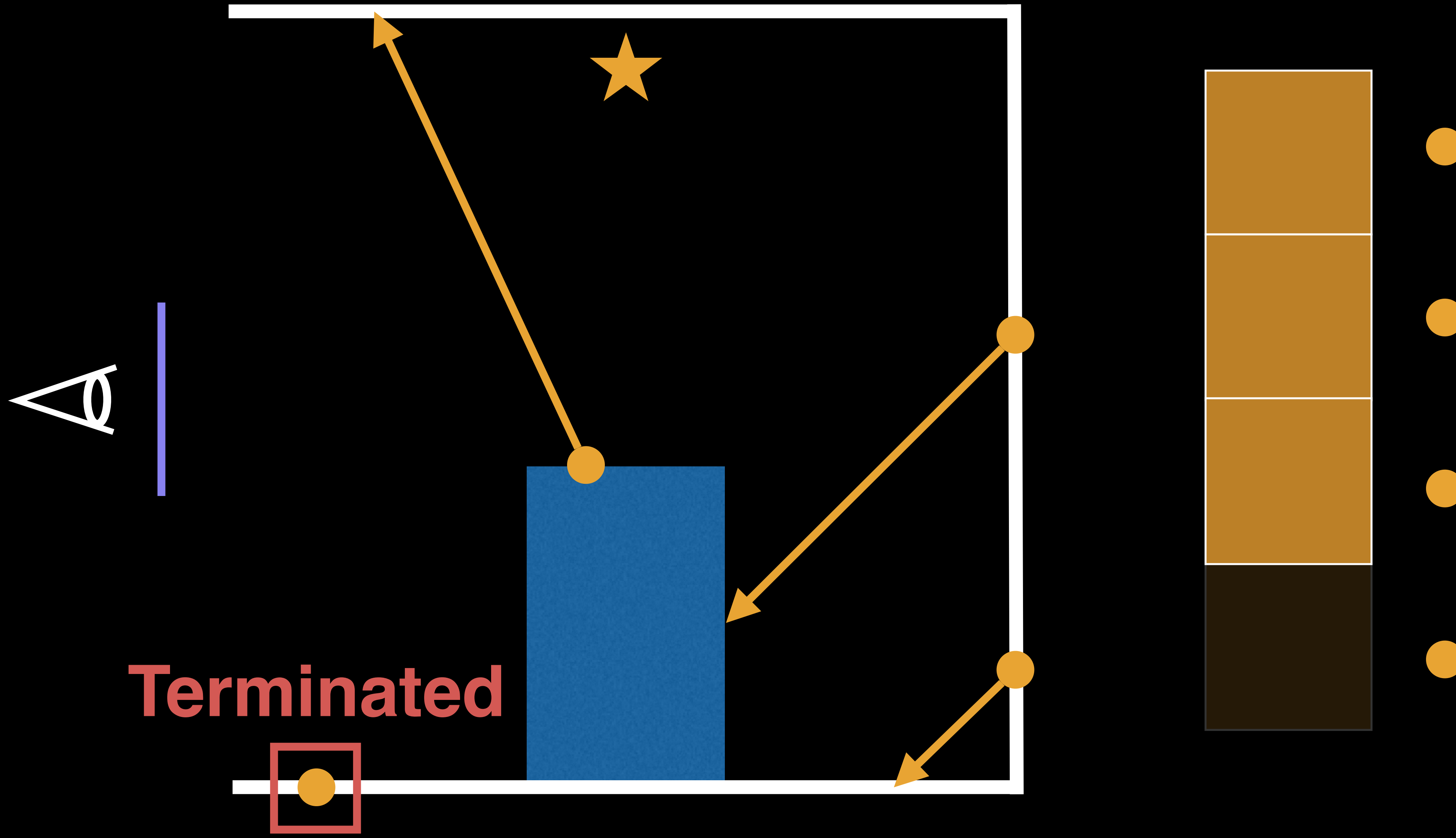
**Hit points = photons**



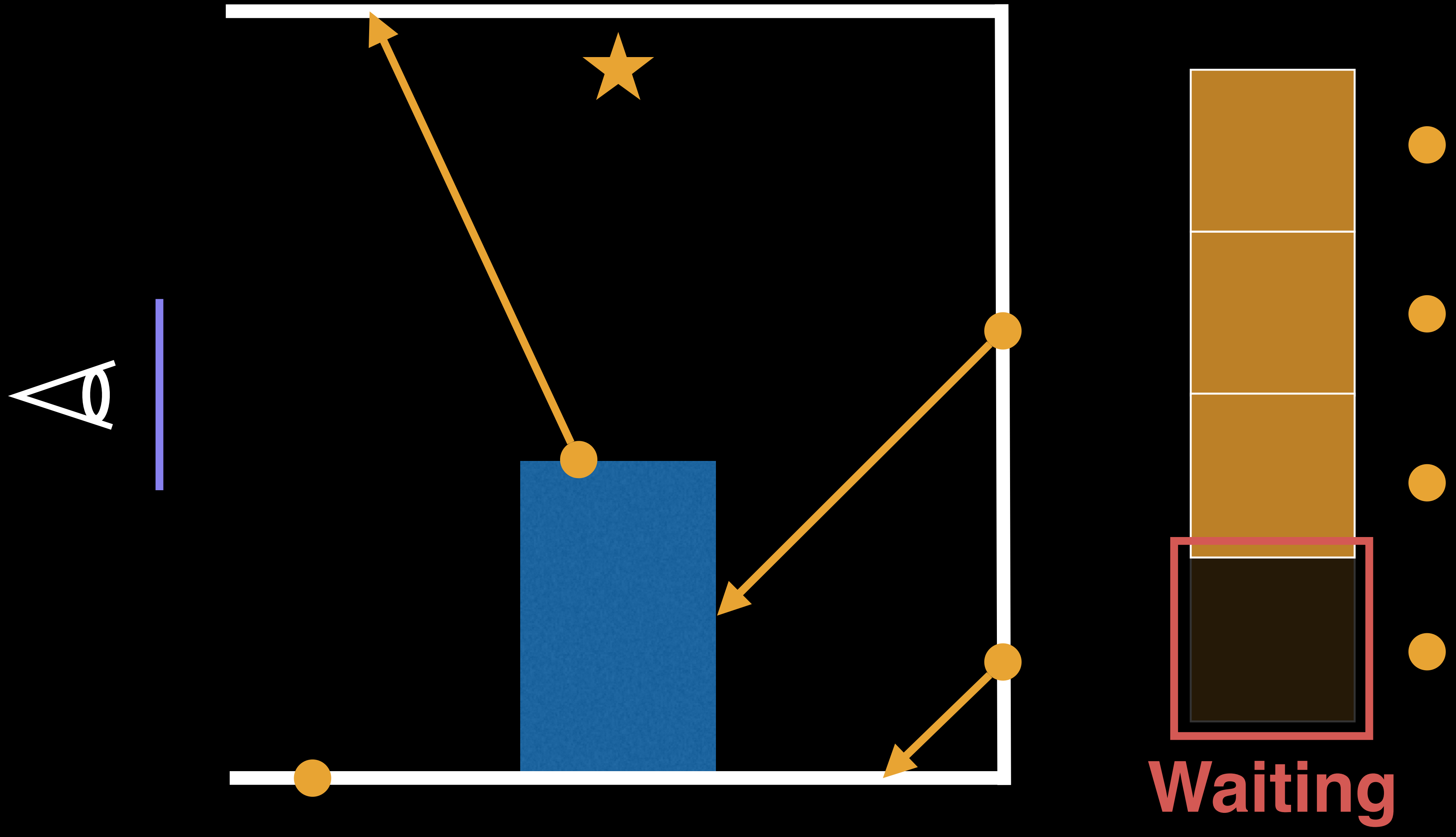
# Photon tracing on GPUs



# Photon tracing on GPUs

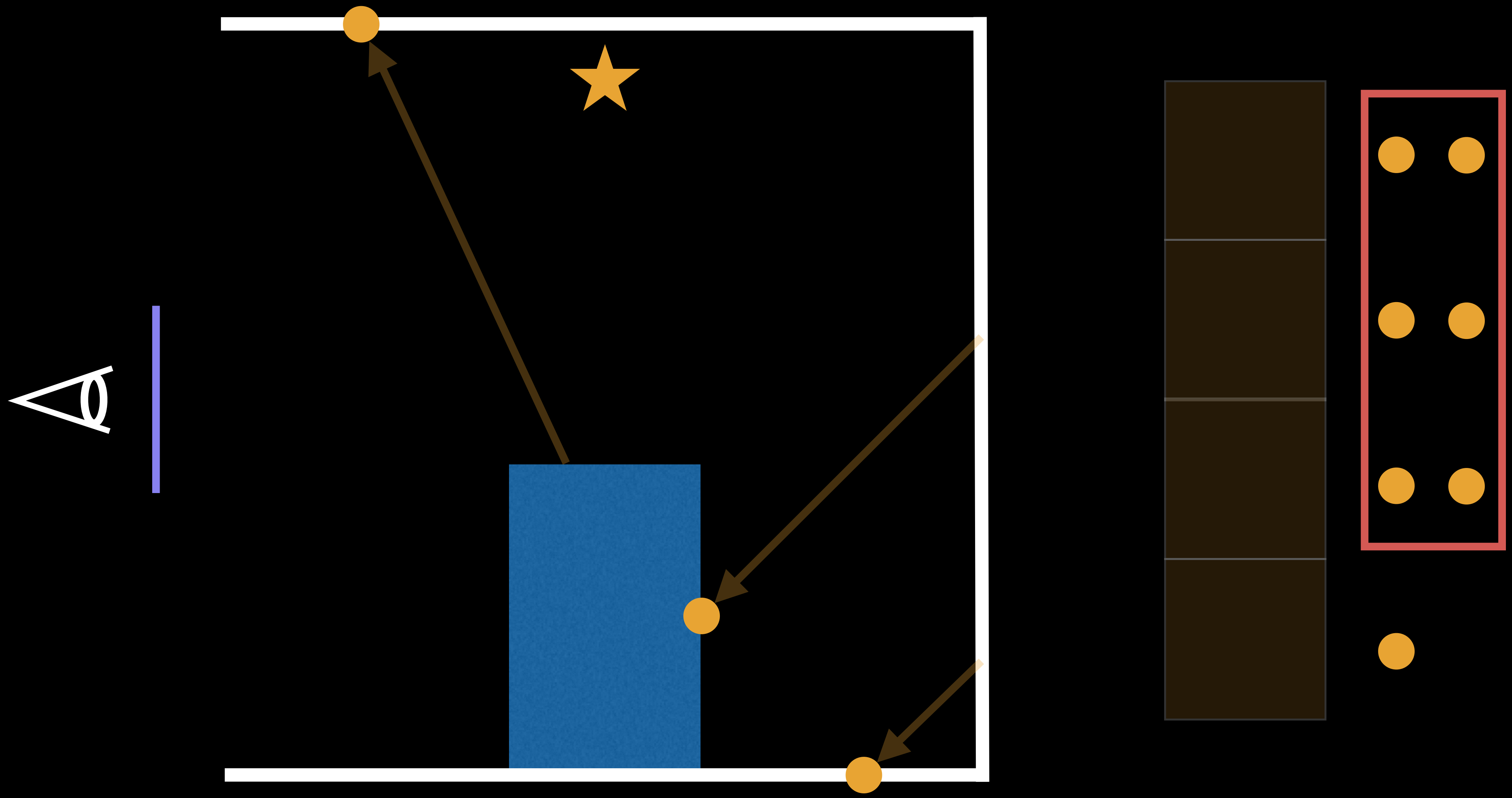


# Photon tracing on GPUs



# Photon tracing on GPUs

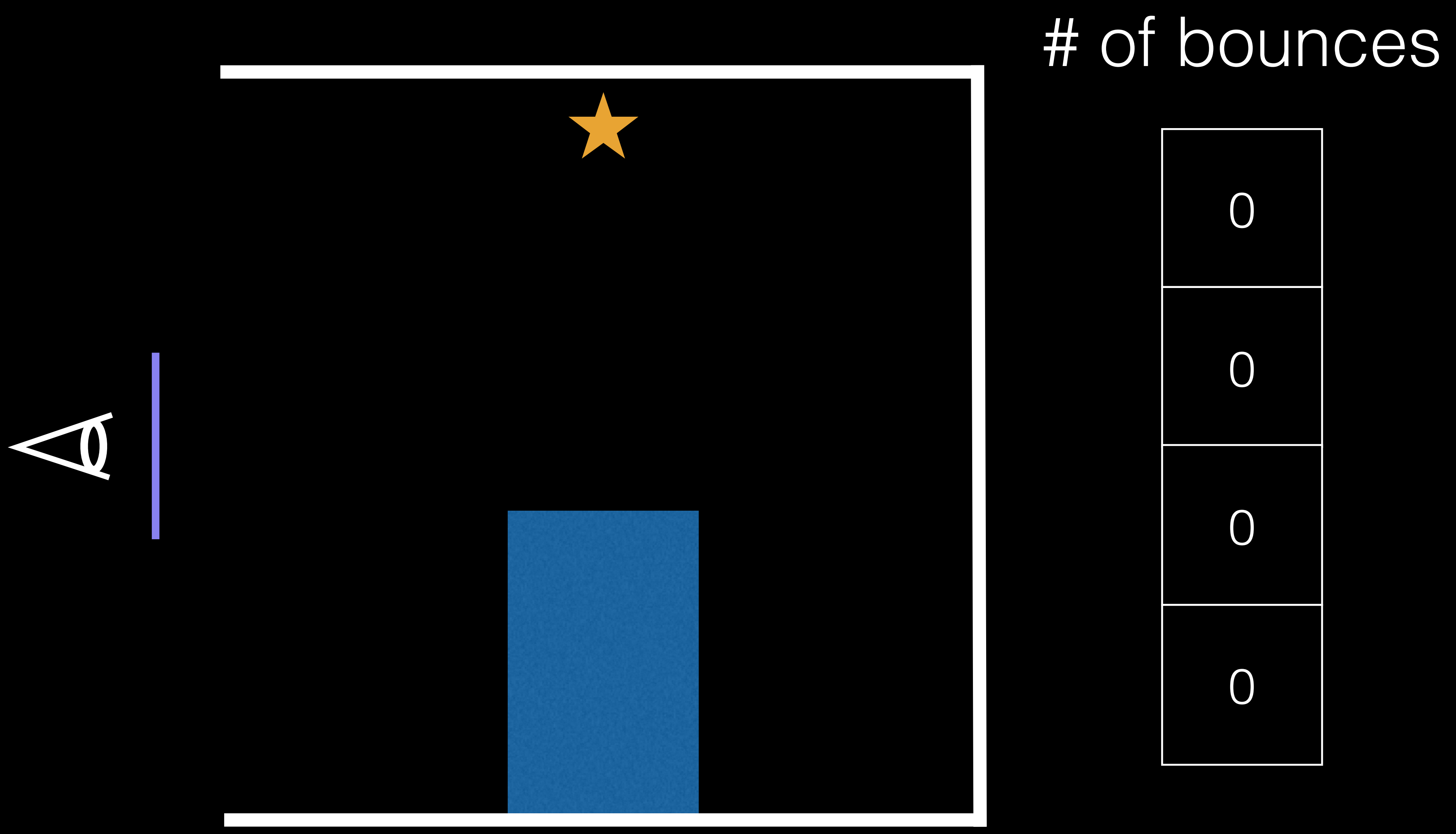
**Multiple photons per pixel**



# Asynchronous path regeneration

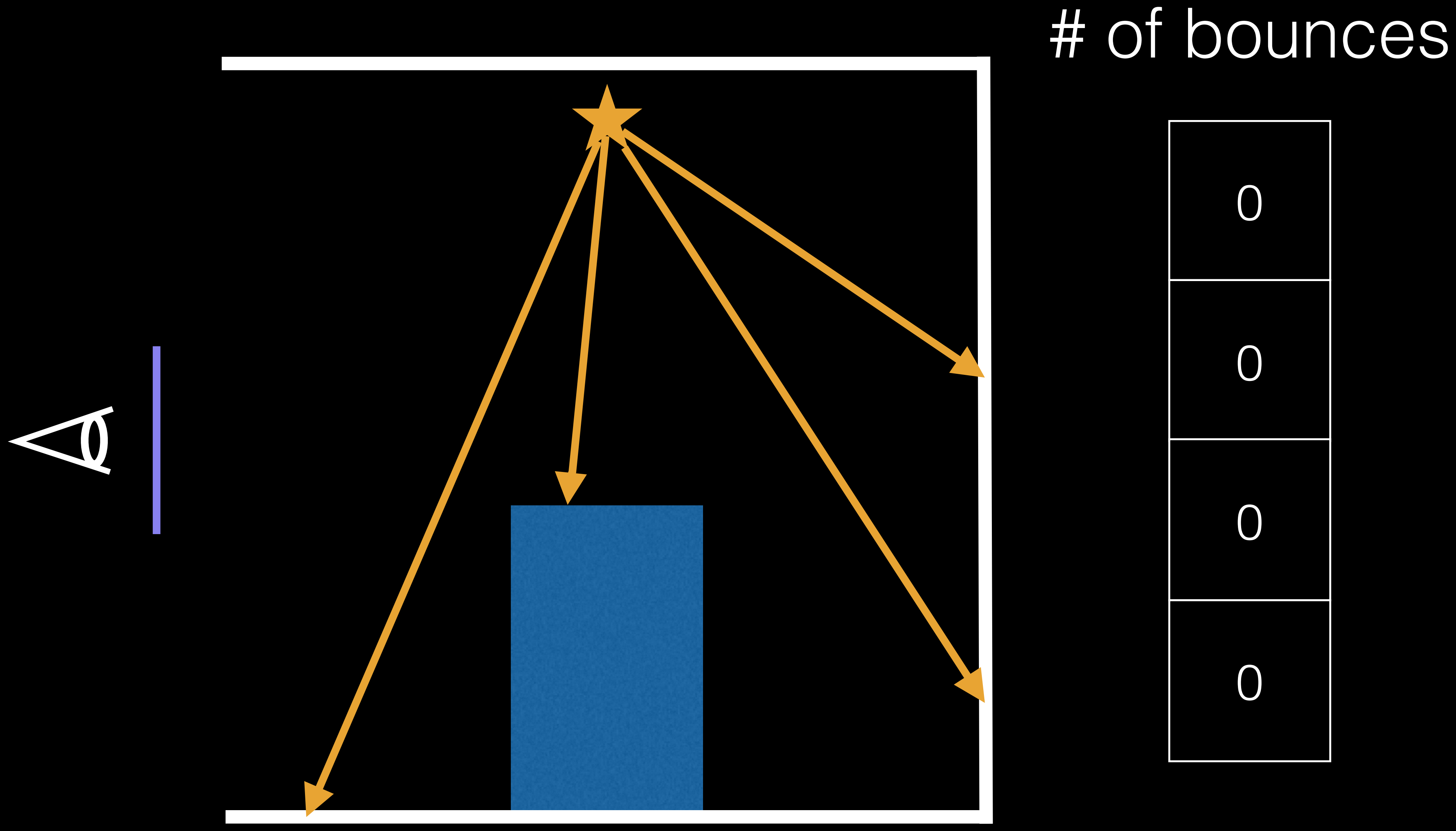
- Each photon pass = only one bounce
- Photon paths are asynchronously regenerated
    - As soon as it's terminated, sample a new one
    - Count the number of photon paths via reduction
    - Similar to the idea by Novak et al. [2010]

# 1st pass



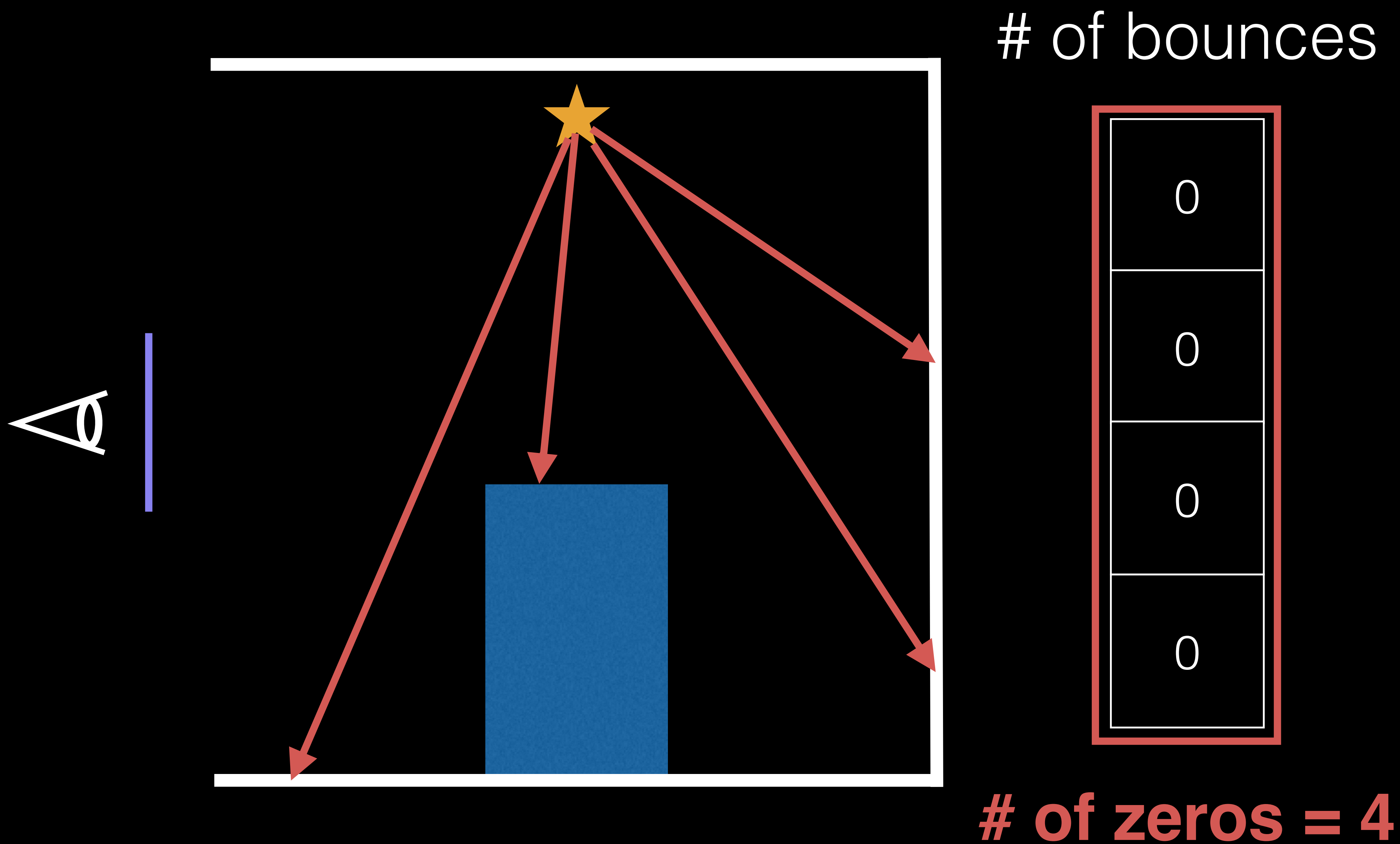
# 1st pass

**0th bounce = gen. a new path**

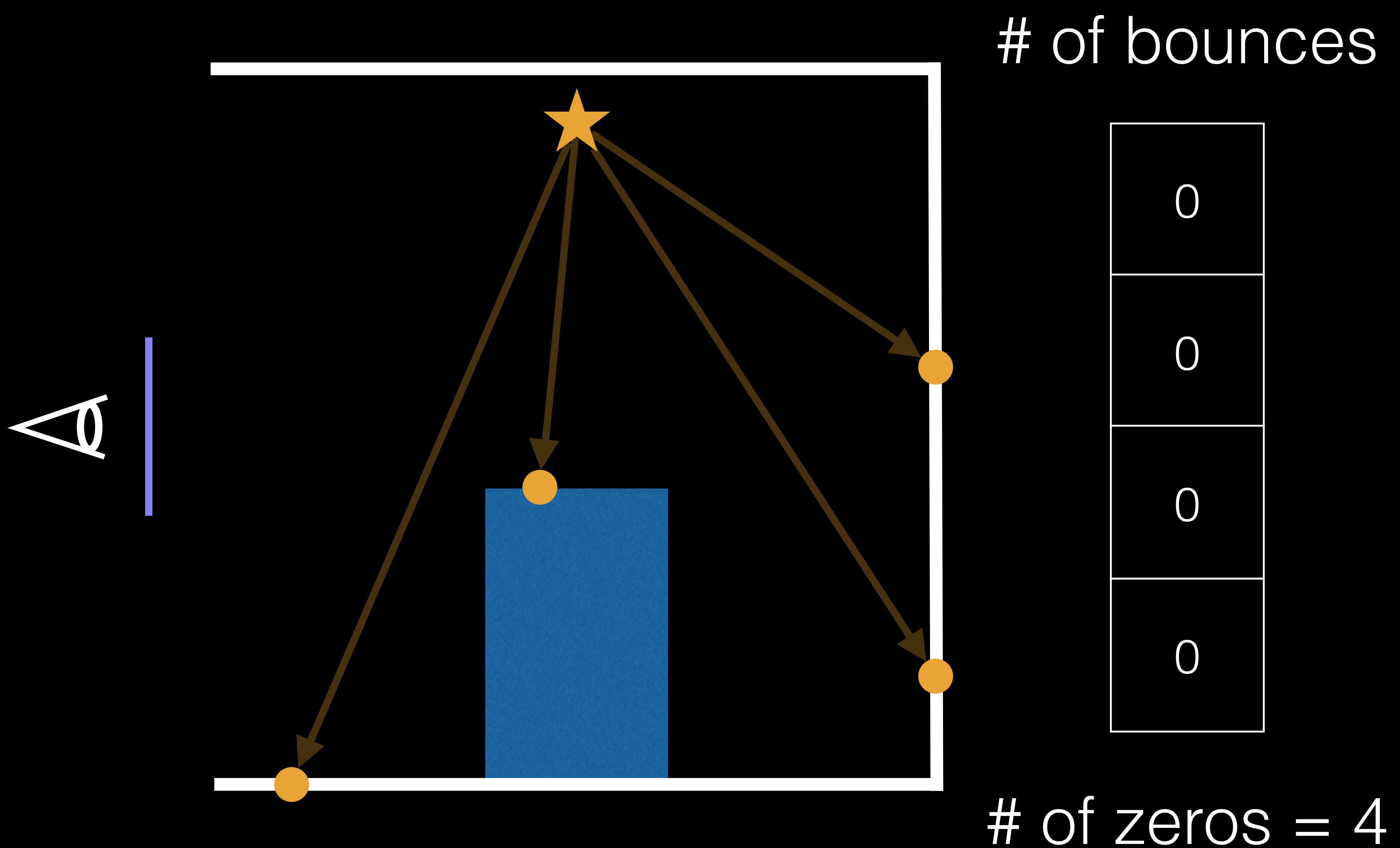


# 1st pass

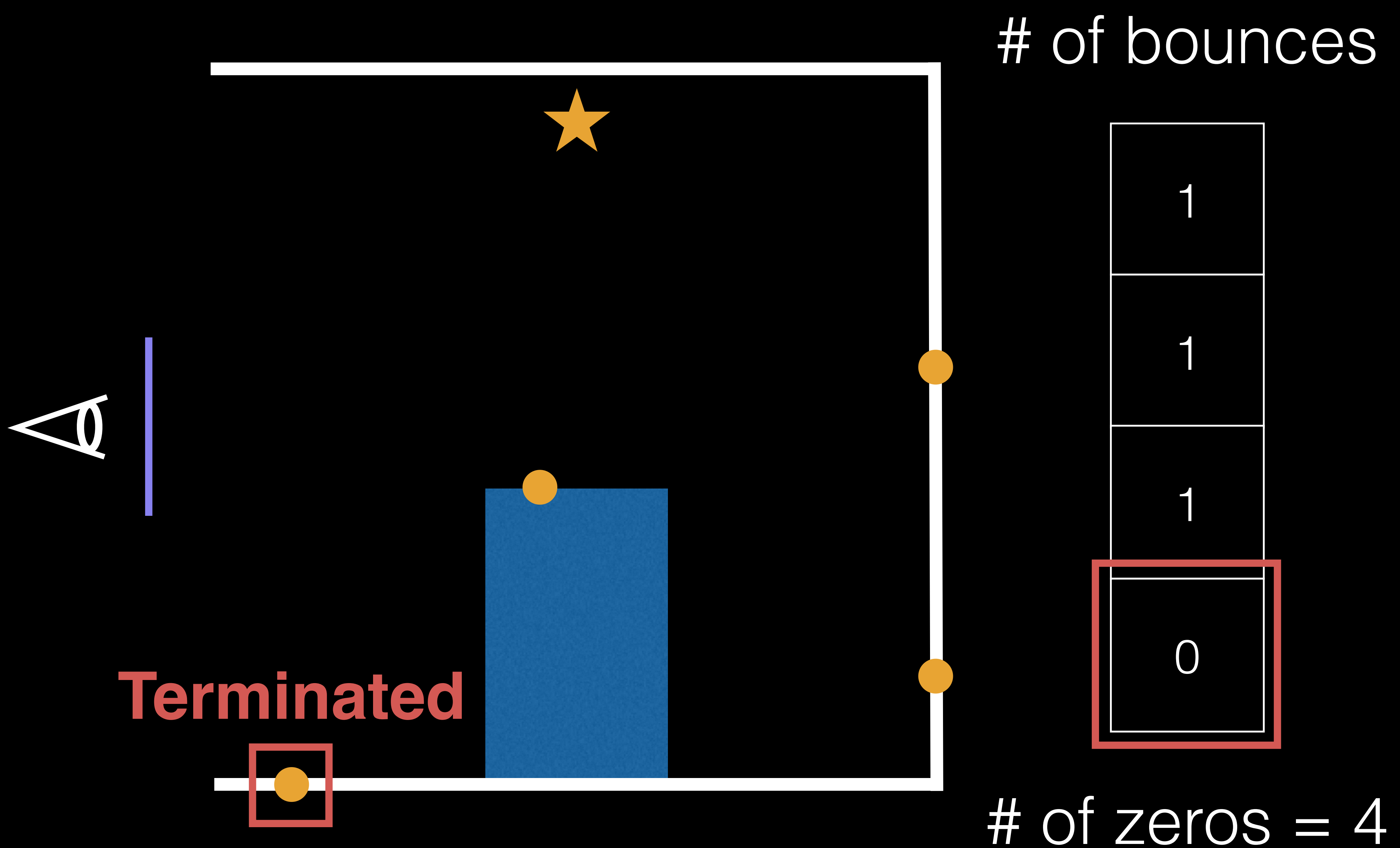
**0th bounce = gen. a new path**



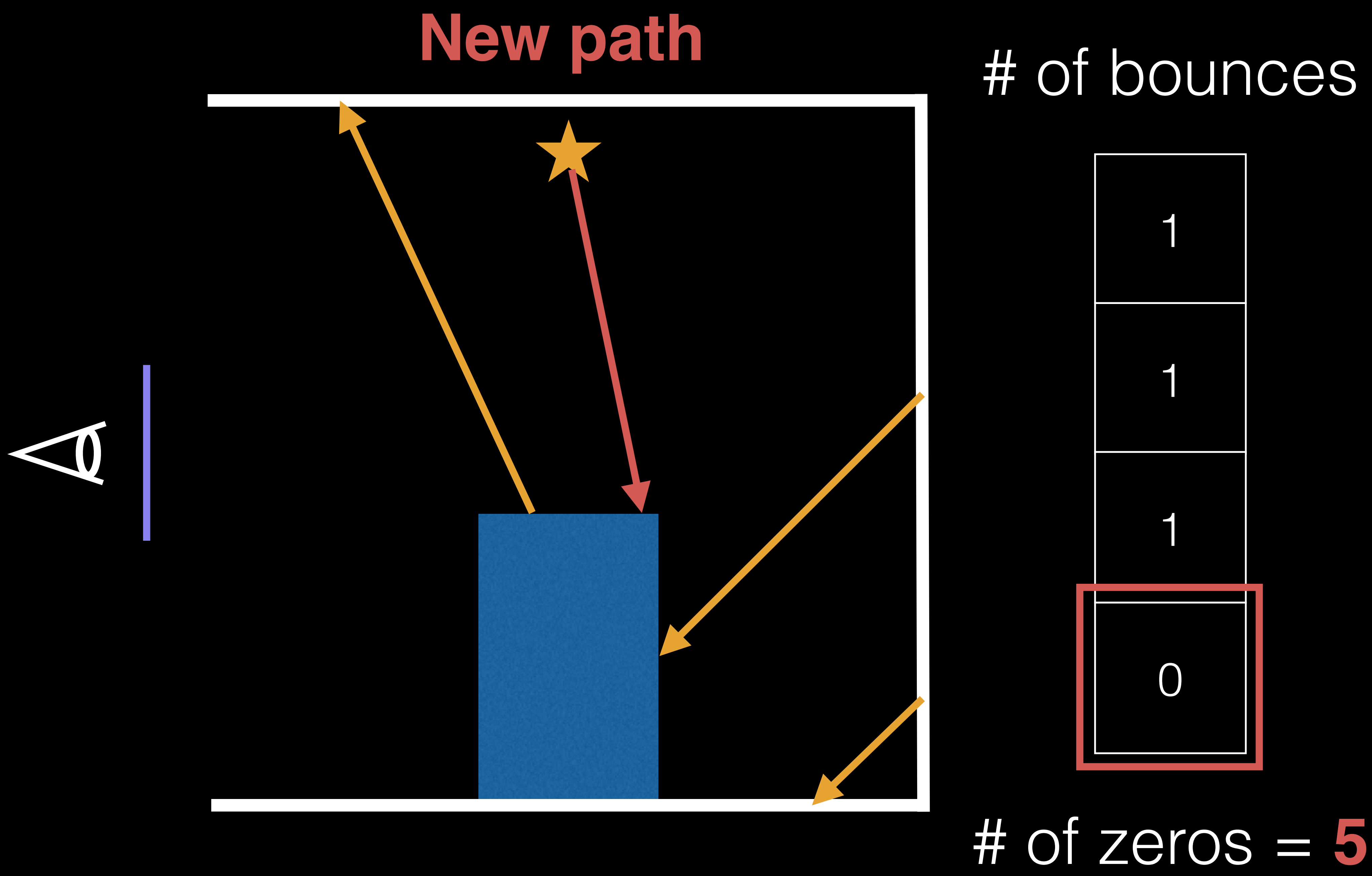
# 1st pass



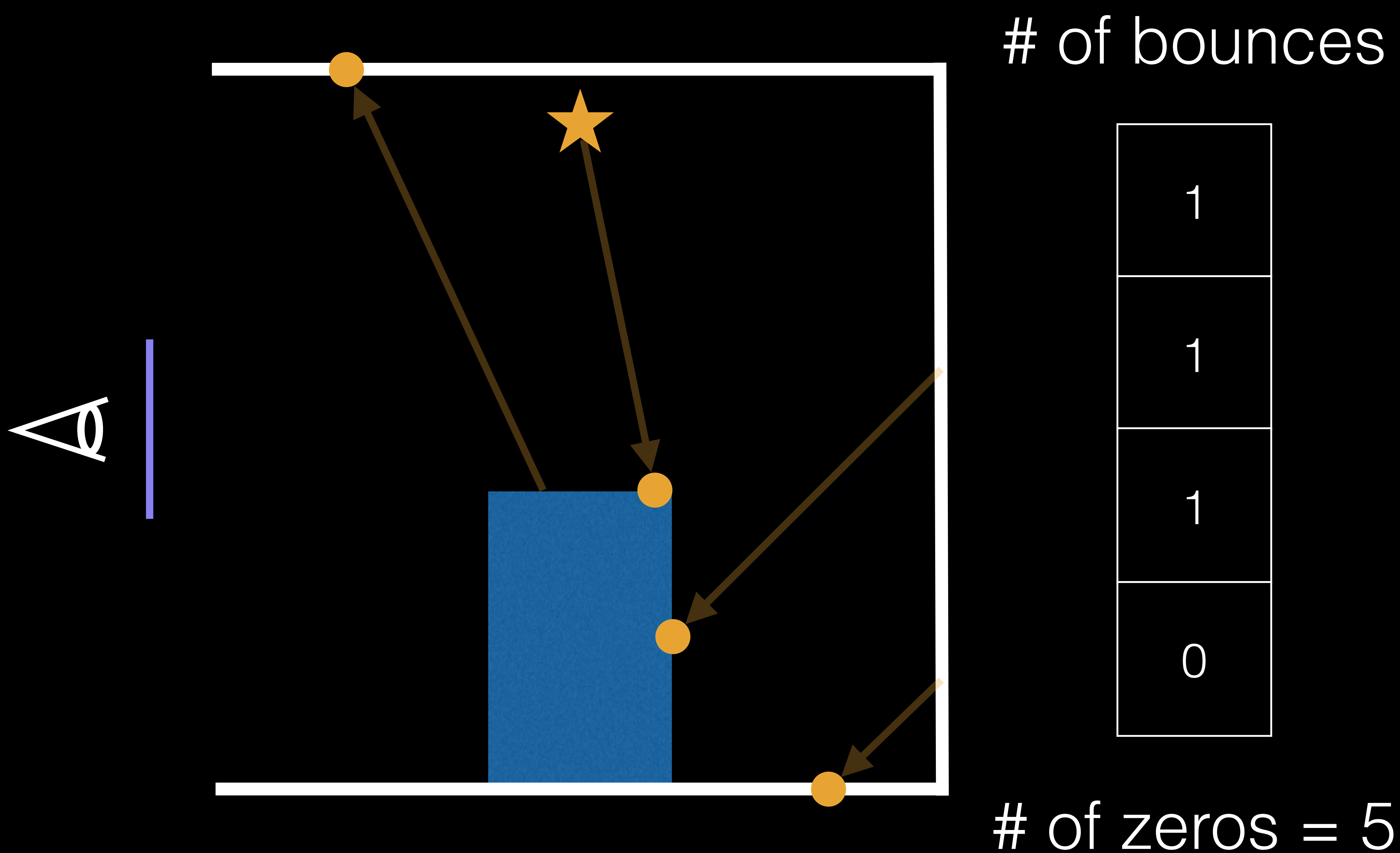
# 1st pass



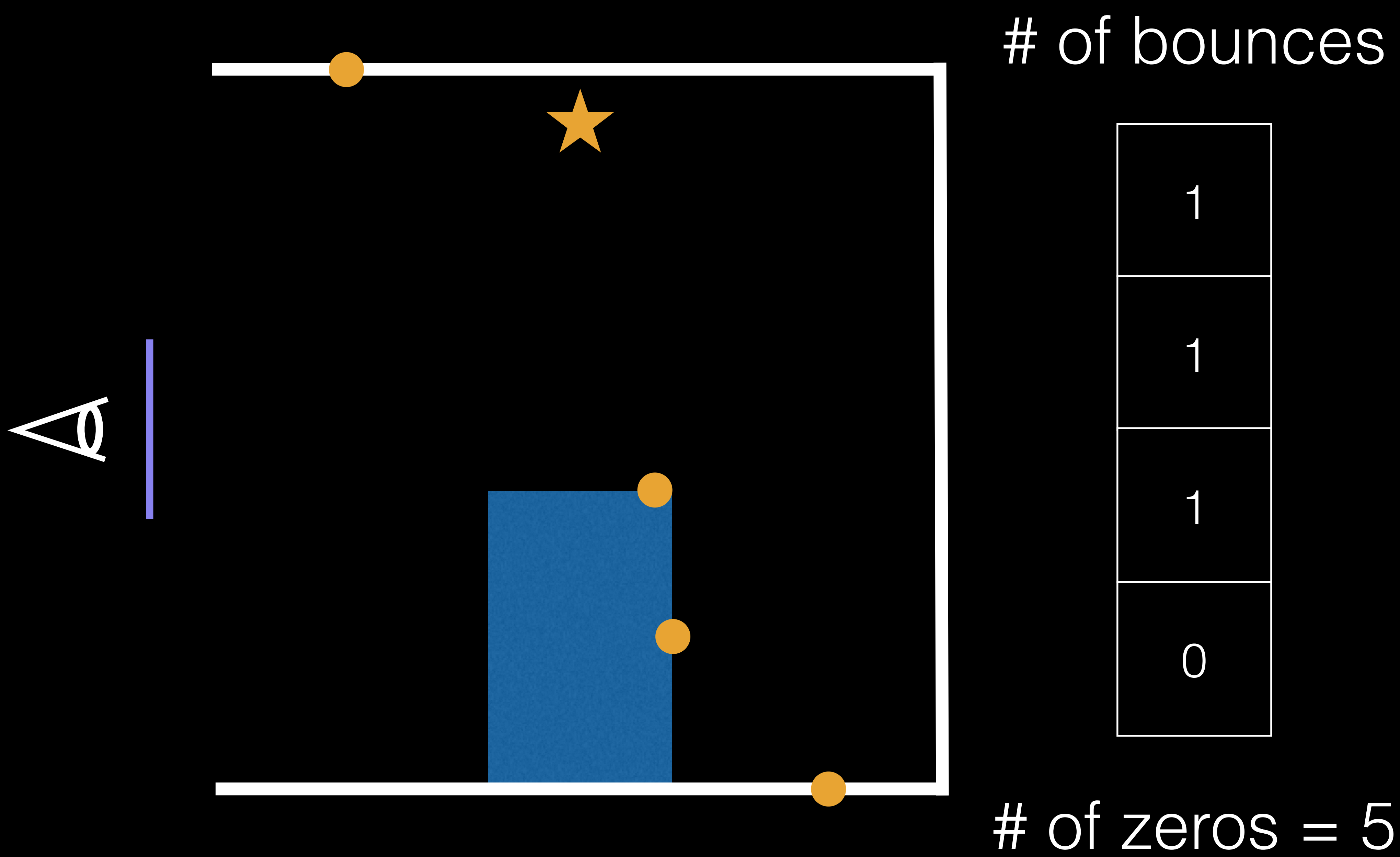
# 2nd pass



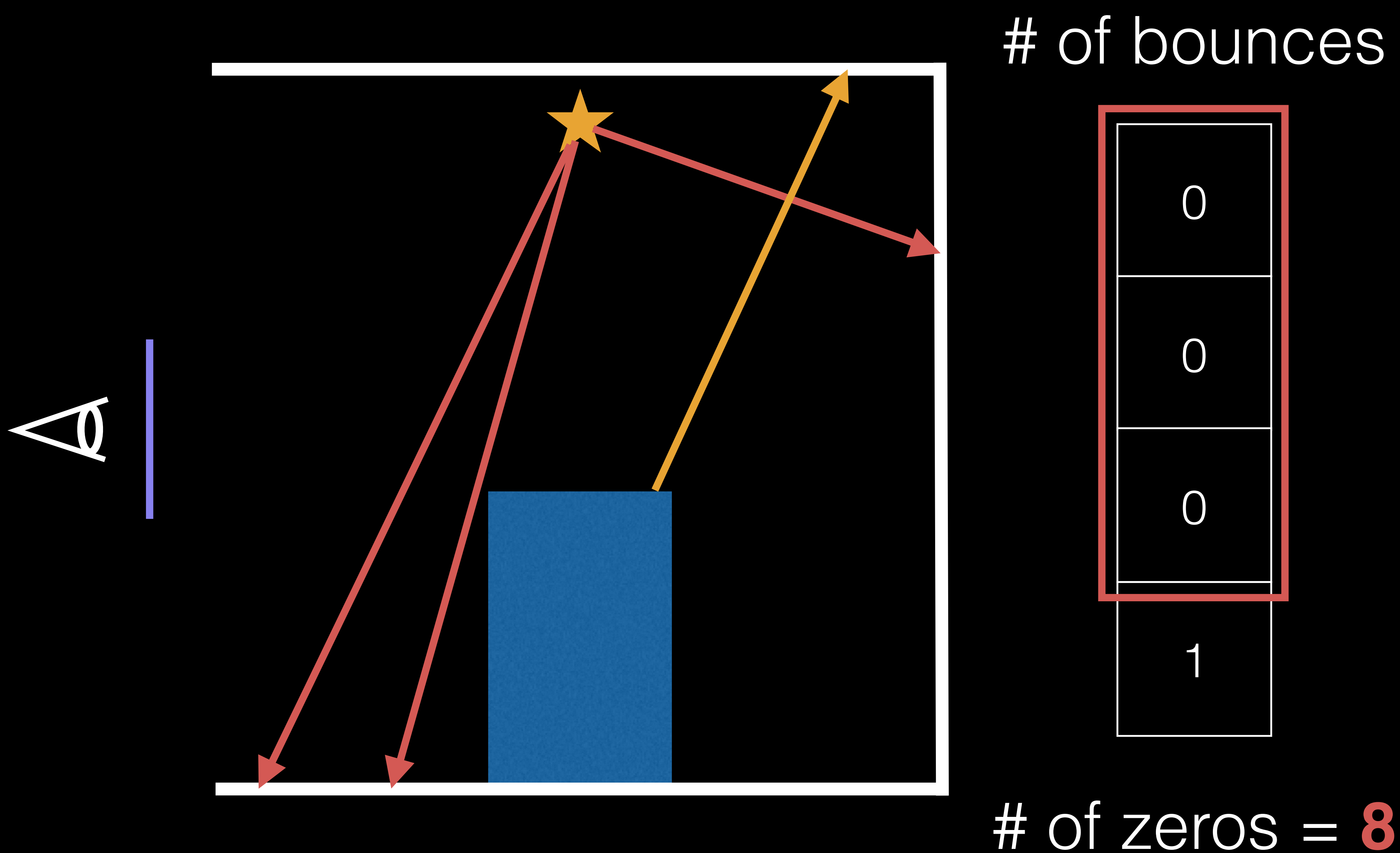
# 2nd pass



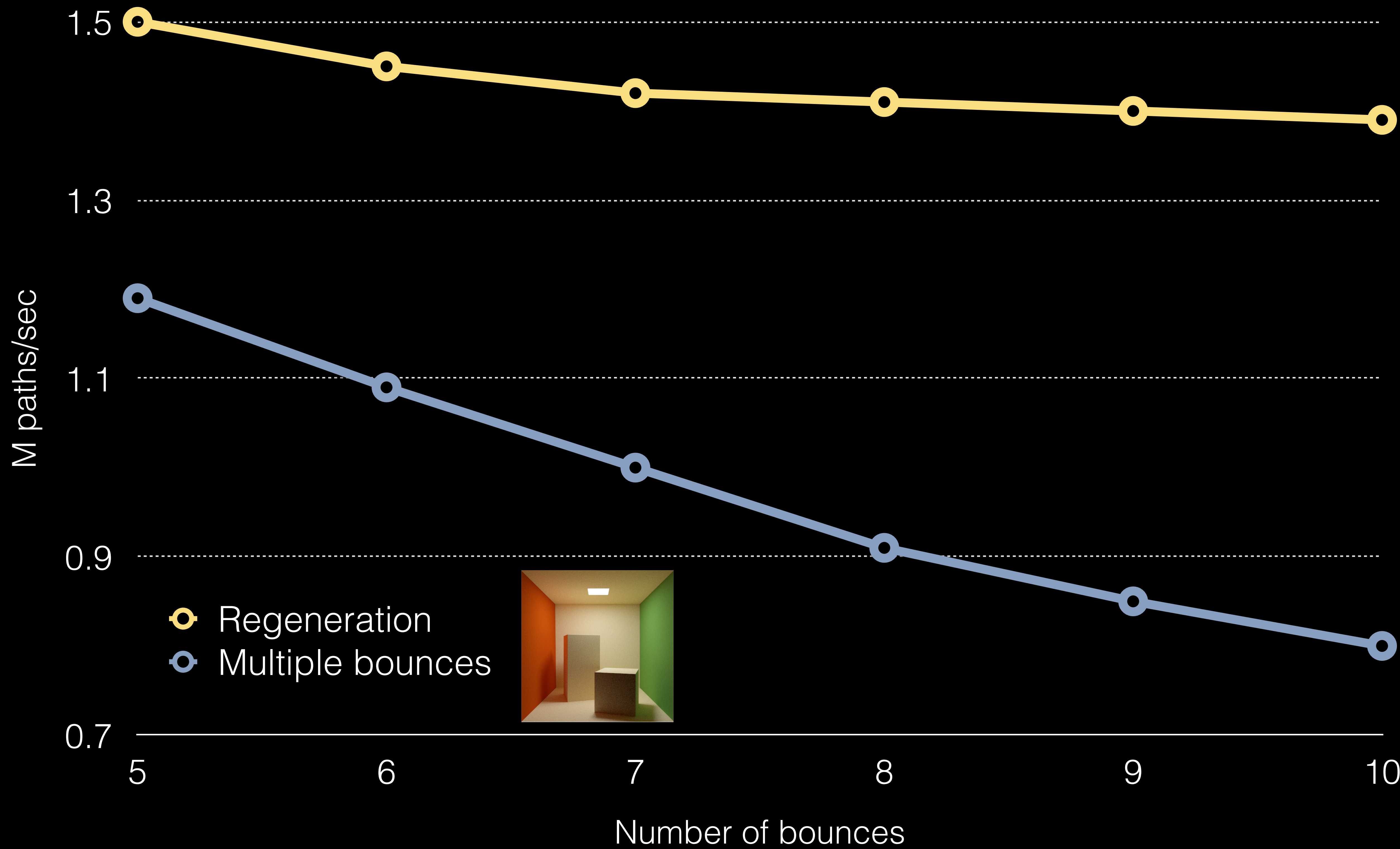
# 2nd pass



# 3rd pass

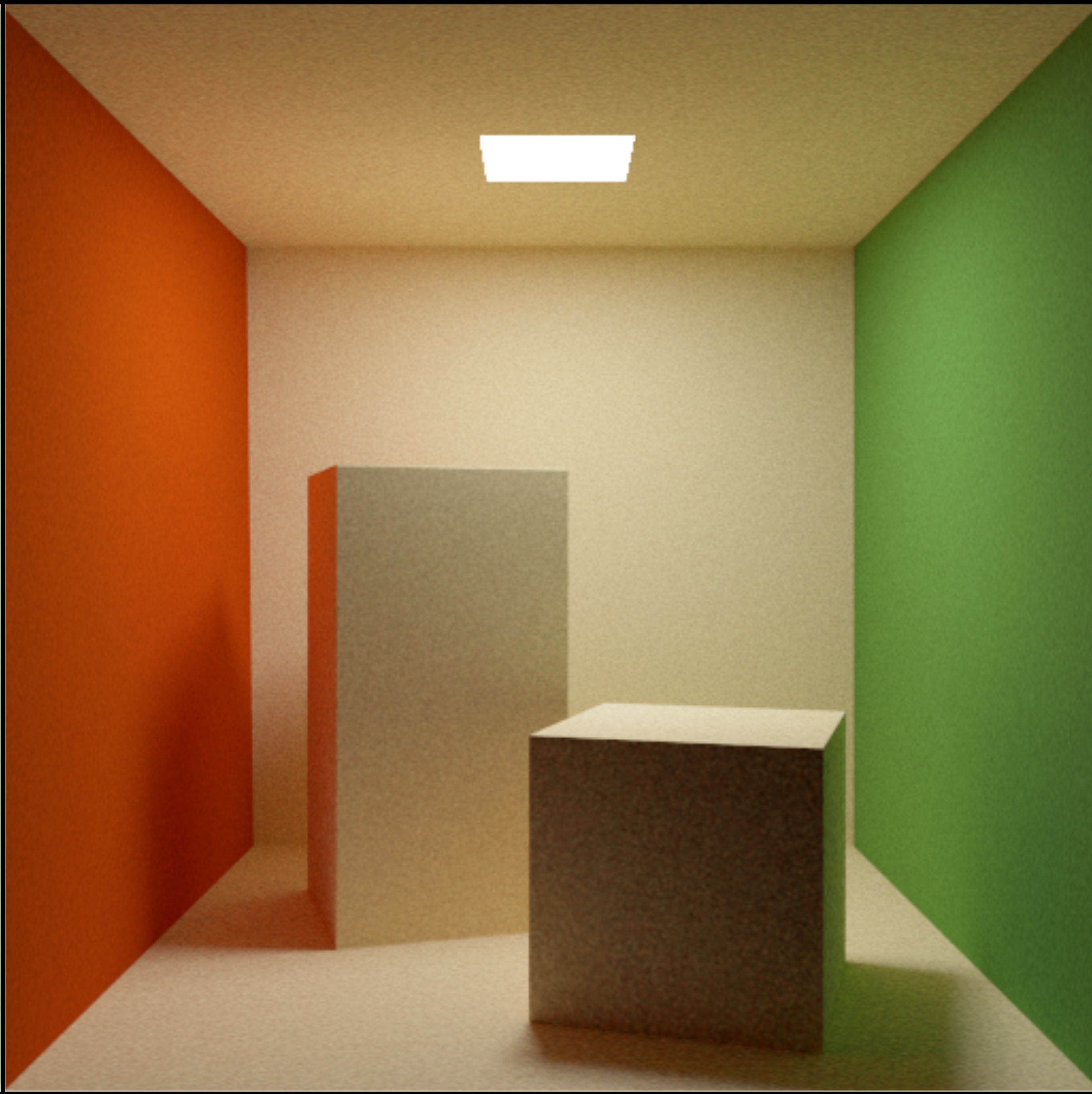


# Performance



# Random number generator

Famous fract(sin(…)) PRNG



Good PRNG

# Random number generator

- Photon mapping is a statistical computation
  - “Noise function” is not random enough
  - Low quality random numbers = artifacts
- Legacy GLSL does not support integer operations
  - Existing good PRNGs use integer operations
- Need lots of good random numbers in parallel

# Random number generator

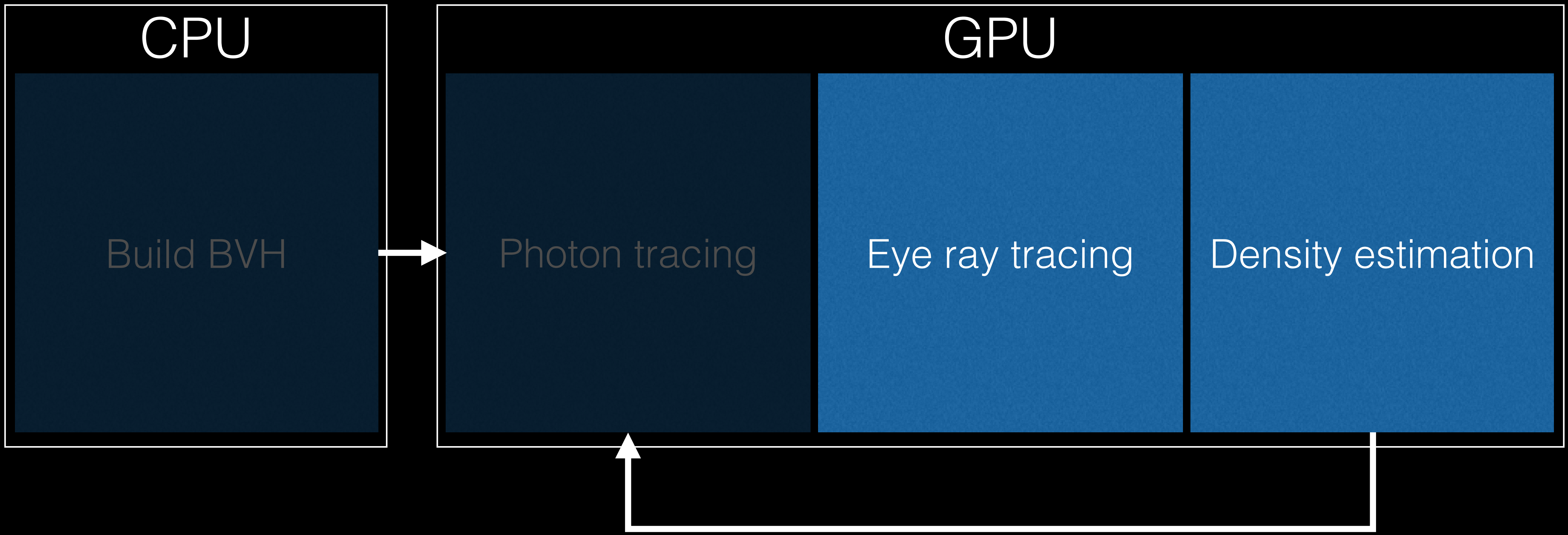
- Modification of PRNG of unknown origin (post on an old GPGPU forum), but works surprisingly well and very fast

```
float GPURnd(inout vec4 state)
{
    const vec4 q = vec4(   1225.0,    1585.0,    2457.0,    2098.0);
    const vec4 r = vec4(   1112.0,     367.0,      92.0,     265.0);
    const vec4 a = vec4(   3423.0,    2646.0,    1707.0,    1999.0);
    const vec4 m = vec4(4194287.0, 4194277.0, 4194191.0, 4194167.0);

    vec4 beta = floor(state / q);
    vec4 p = a * (state - beta * q) - beta * r;
    beta = (sign(-p) + vec4(1.0)) * vec4(0.5) * m;
    state = (p + beta);

    return fract(dot(state / m, vec4(1.0, -1.0, 1.0, -1.0)));
}
```

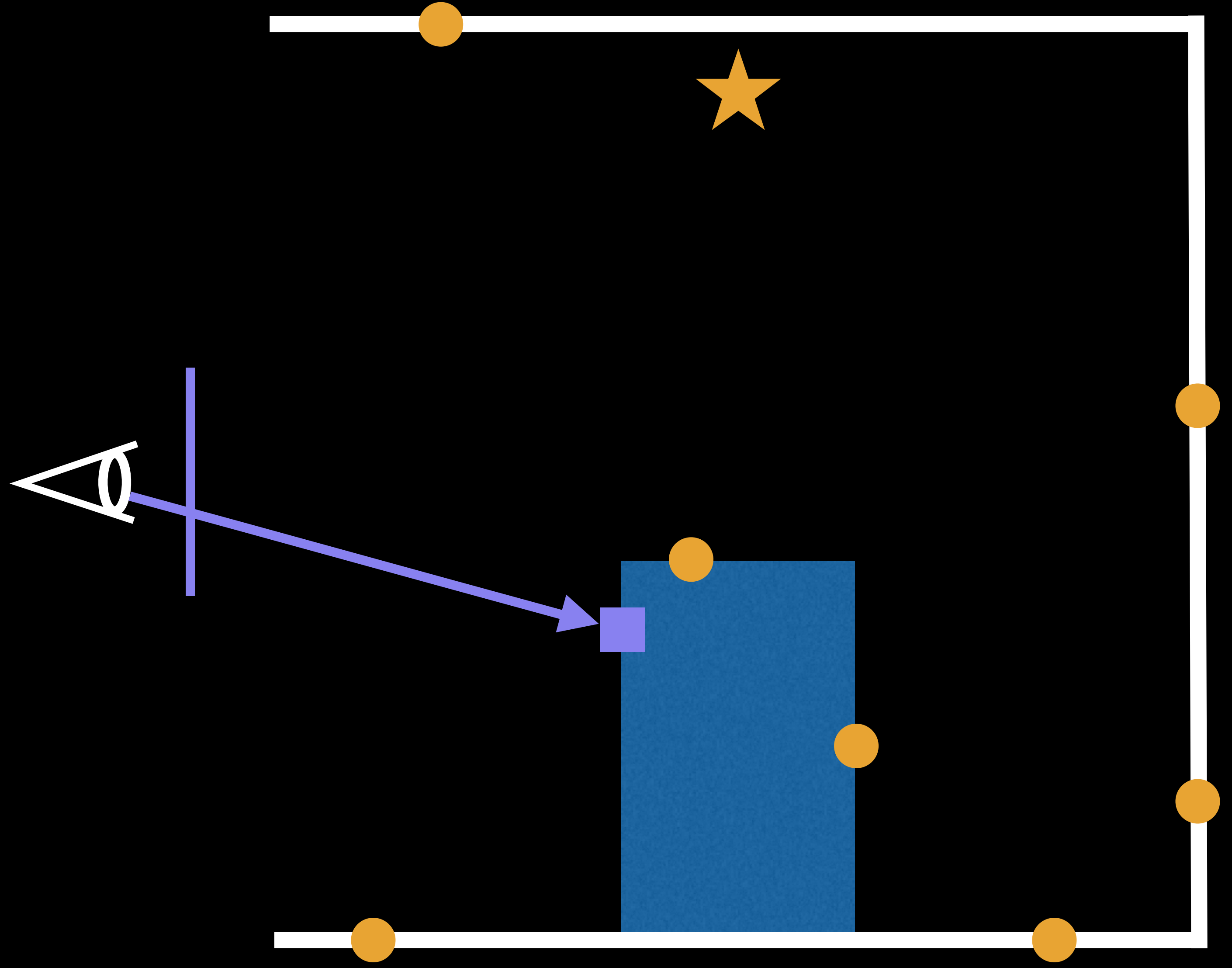
# Other PRNGs

- LCG: works fine only if you do some simple stuff
- Crypto-hash: works well, but somewhat slower
- (GPU) Mersenne twister: works well, but too slow
- xorshift: not very suitable for parallel PRNGs

- My choices: crypto-hash or the one in prev. slide


CPU
GPU
Build BVH
Photon tracing
Eye ray tracing
Density estimation

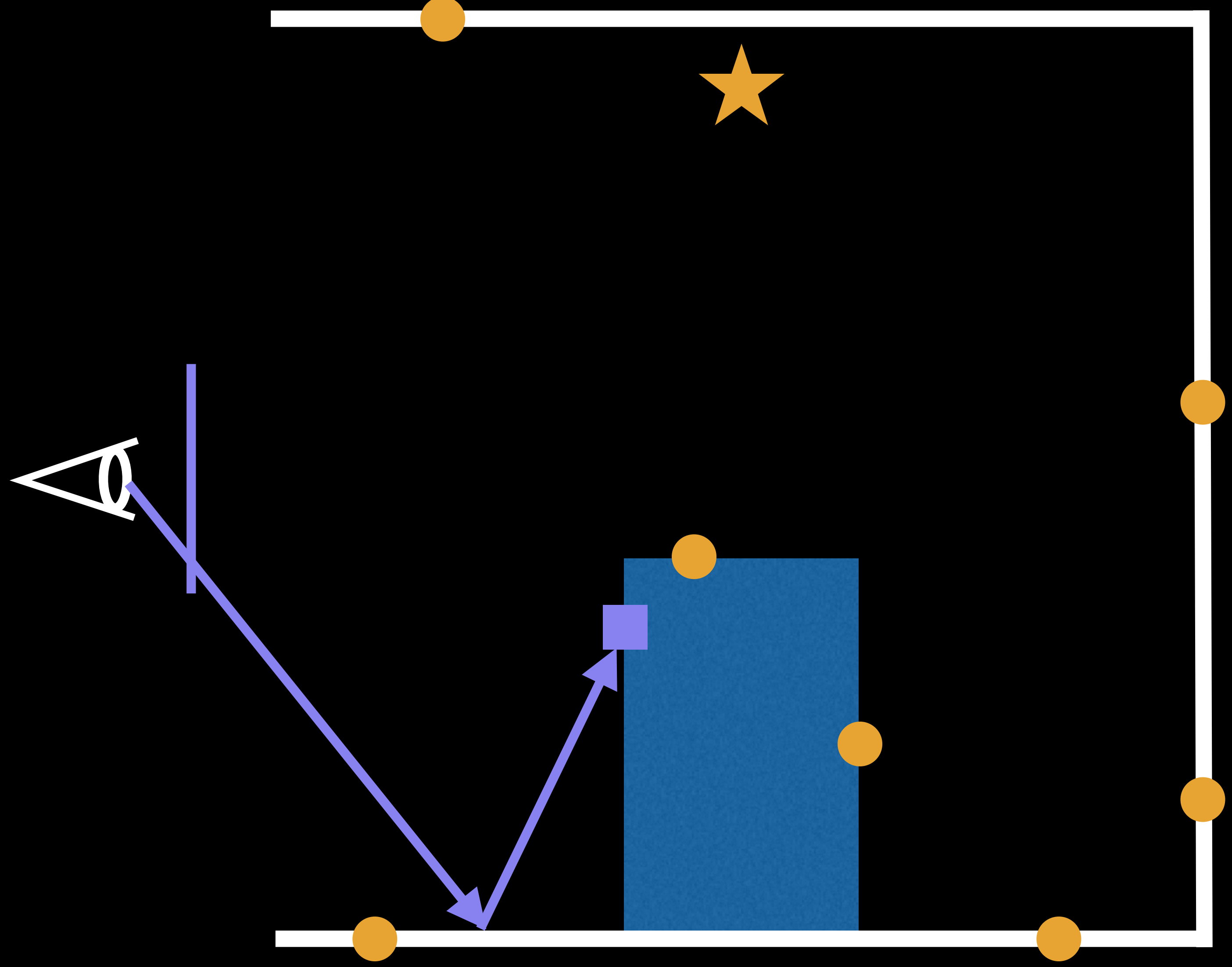
# Eye ray tracing



# Eye ray tracing

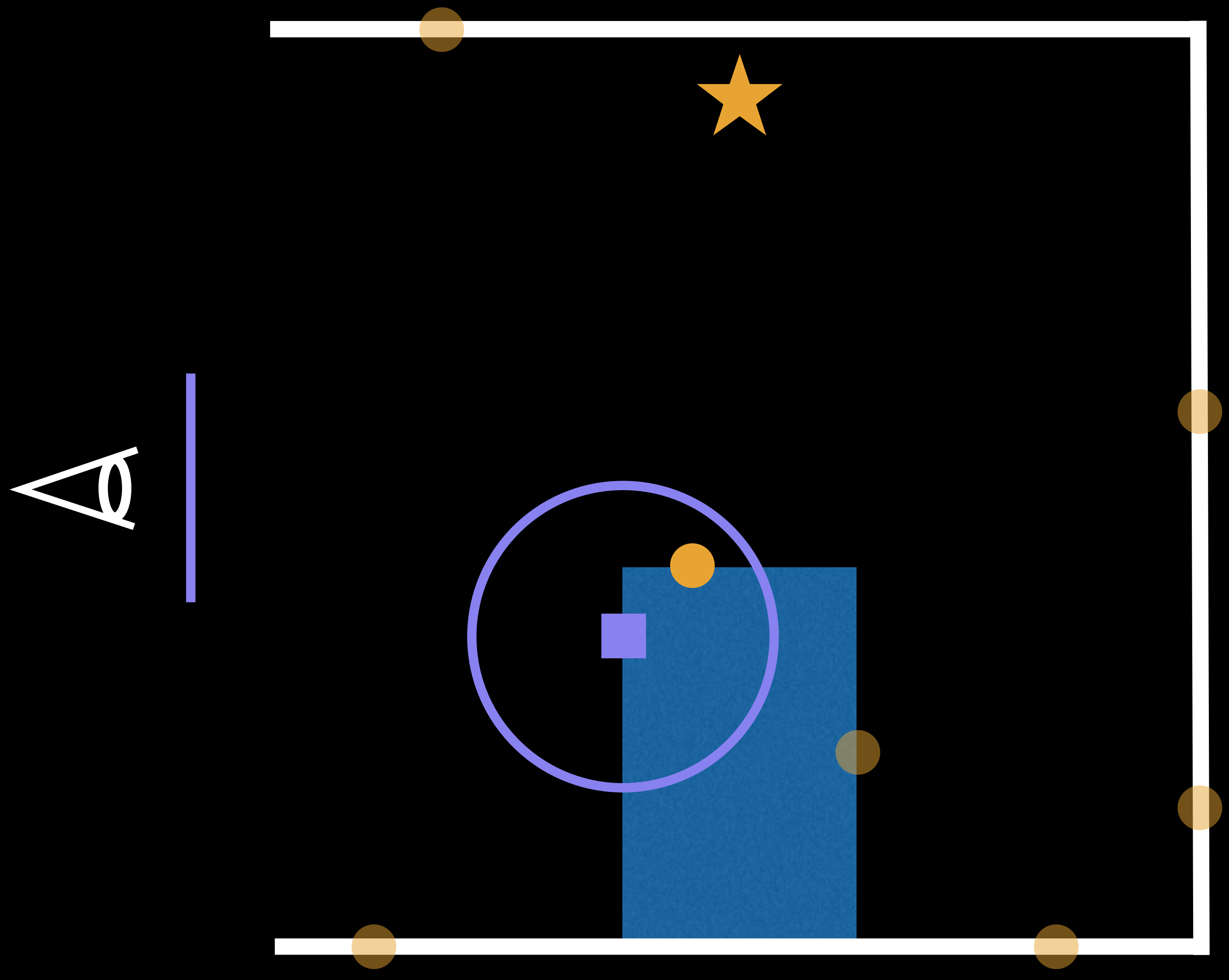
- Almost the same as photon but one difference
  - Trace a path until it hits a “non-specular” surface
  - Single pass = multiple bounces
  - No asynchronous path regeneration (run it once per multiple photon passes to balance the loads)
- Store the result for the density estimation step

# Eye ray tracing



# Density estimation

- Find nearby photons around the eye ray hit point



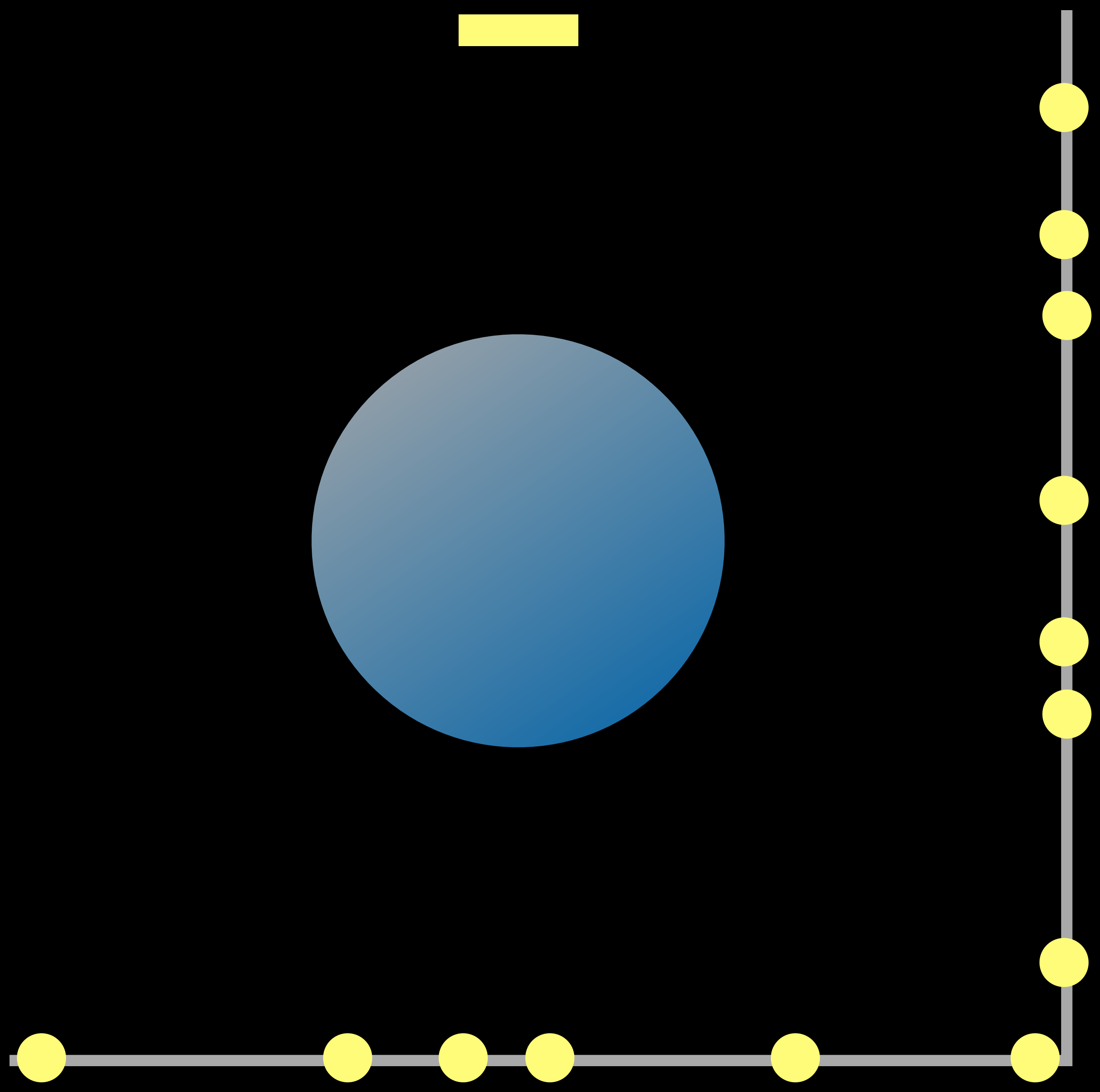
# Challenges

- Brute-force search is too slow (O(N) for N photons)
- Photons are newly generated at each pass
  - Cannot use a fixed data structure like BVHs
- More nearby photons = more computation
  - Highly non-uniform workload distribution

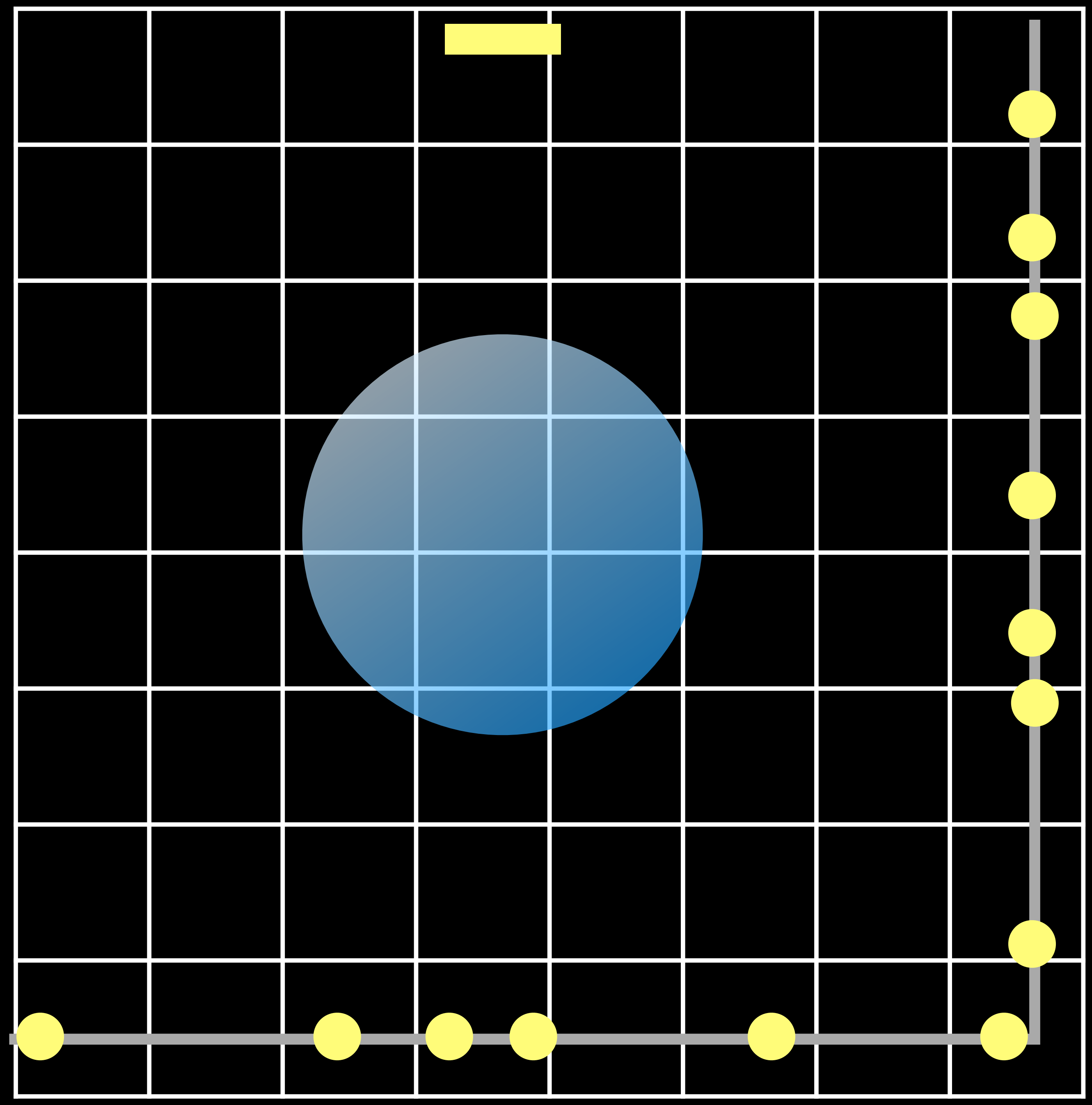
# Spatial hashing

- Multidimensional extension of regular hashing
- Two phase
  - Construct a hash table
  - Query the hash table

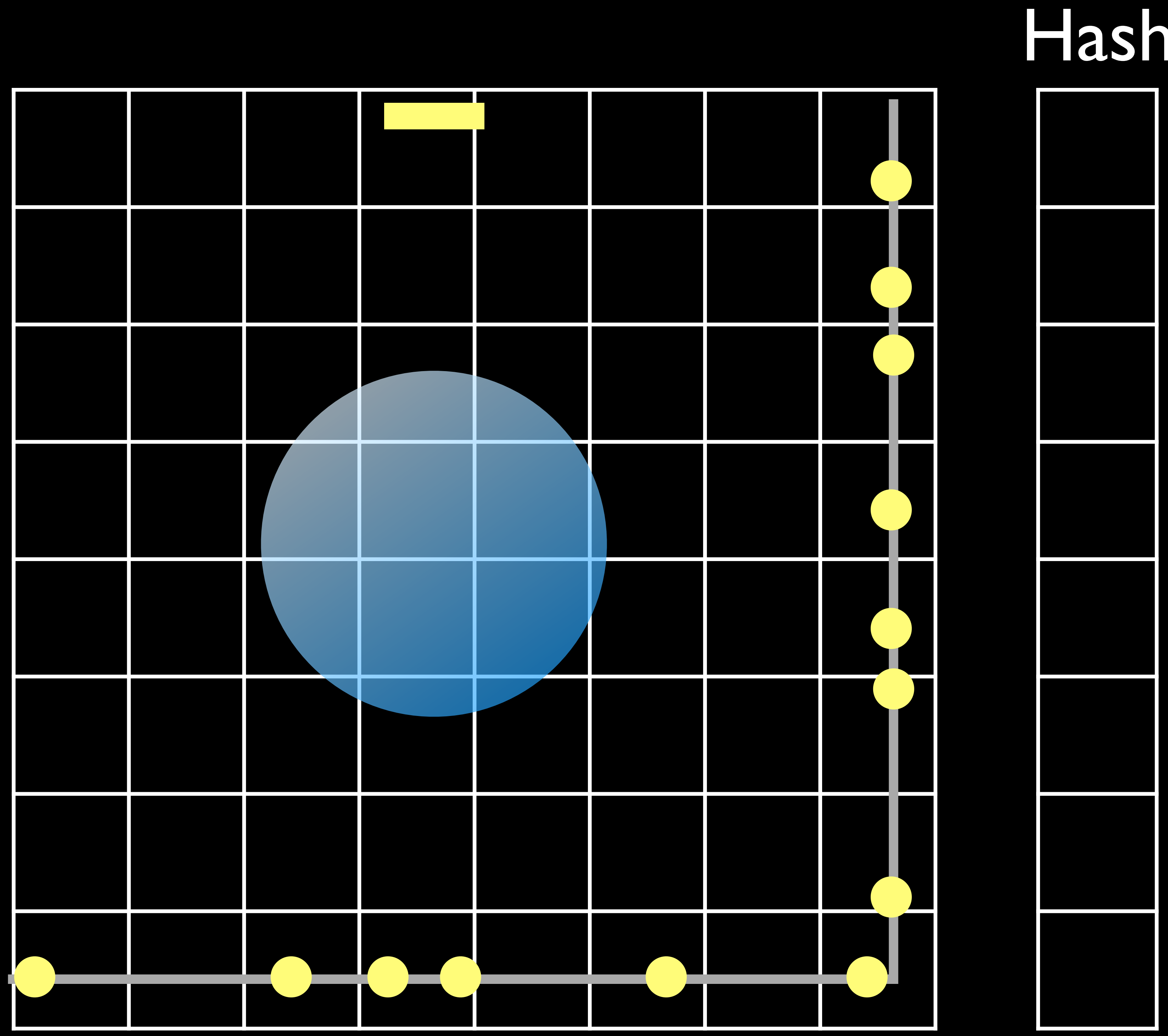
# Construction



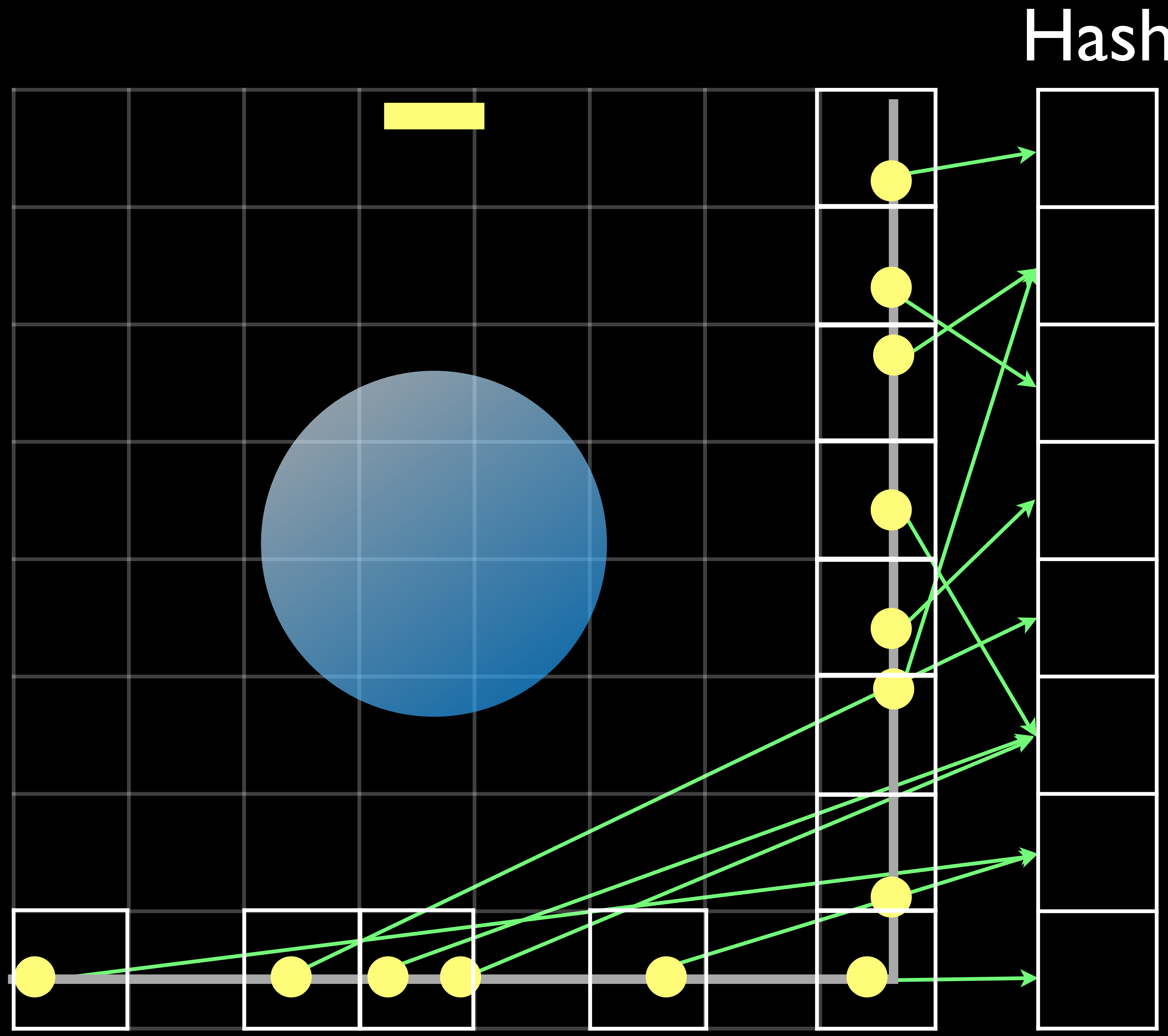
# Construction



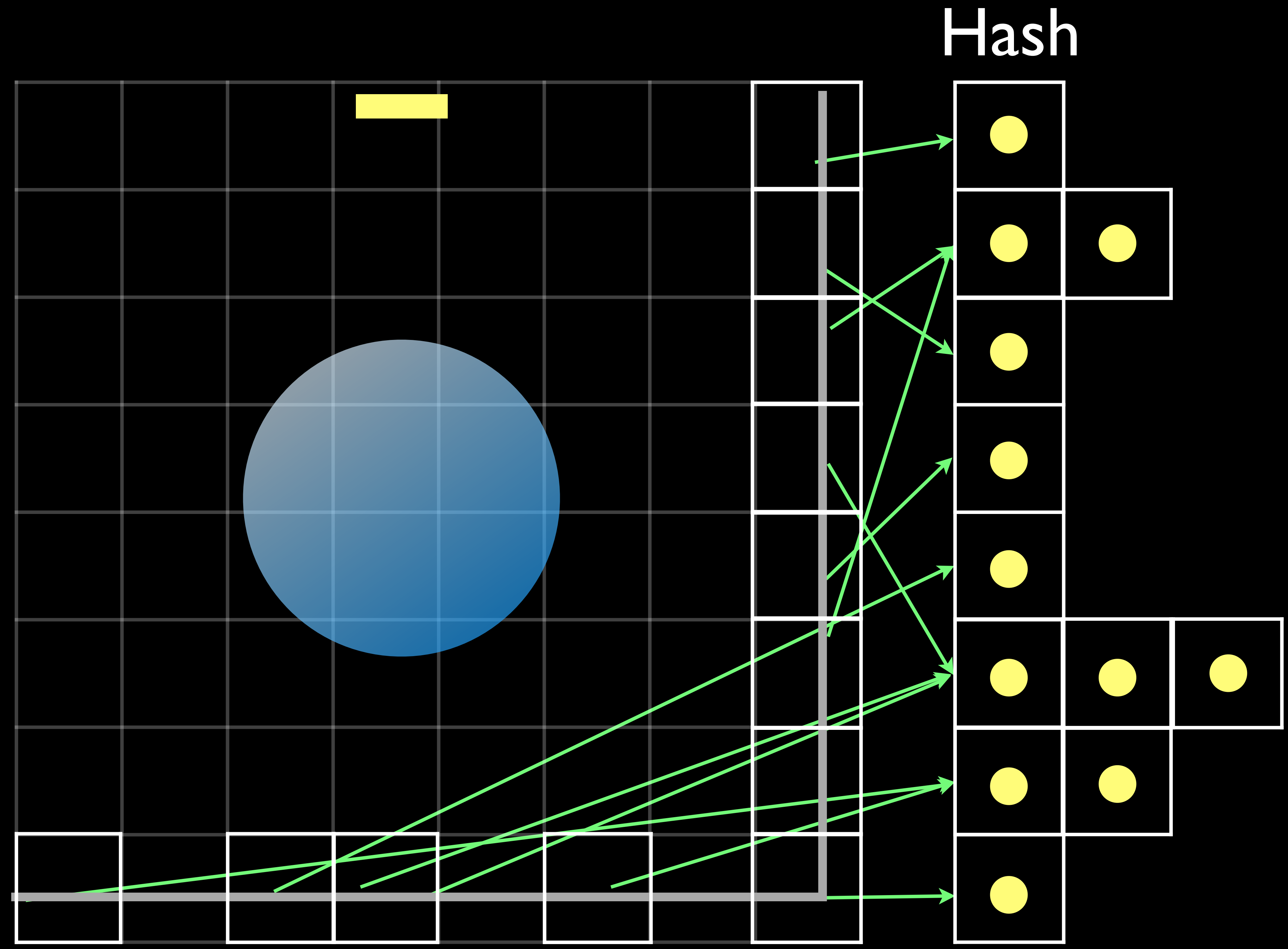
# Construction



# Construction

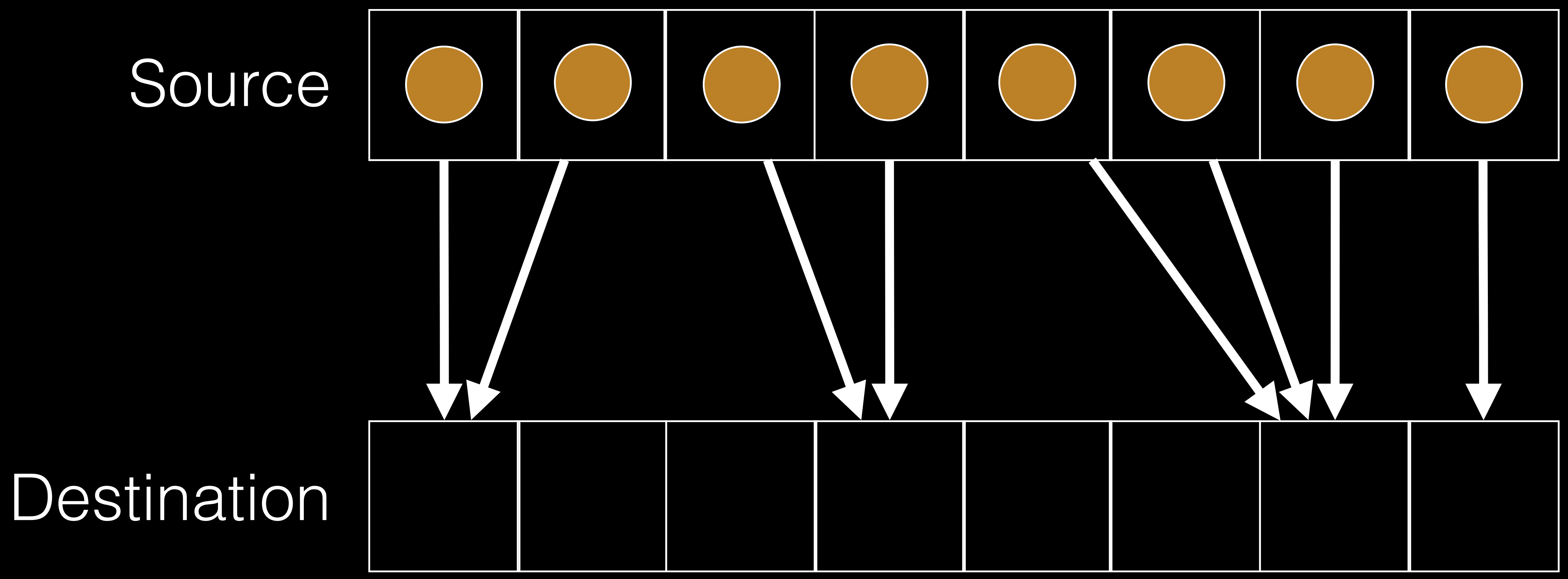


# Construction



# Random writes using points

- Drawing one vertex per pixel
  - Write into a specific pixel, not the same pixel



# Hash function

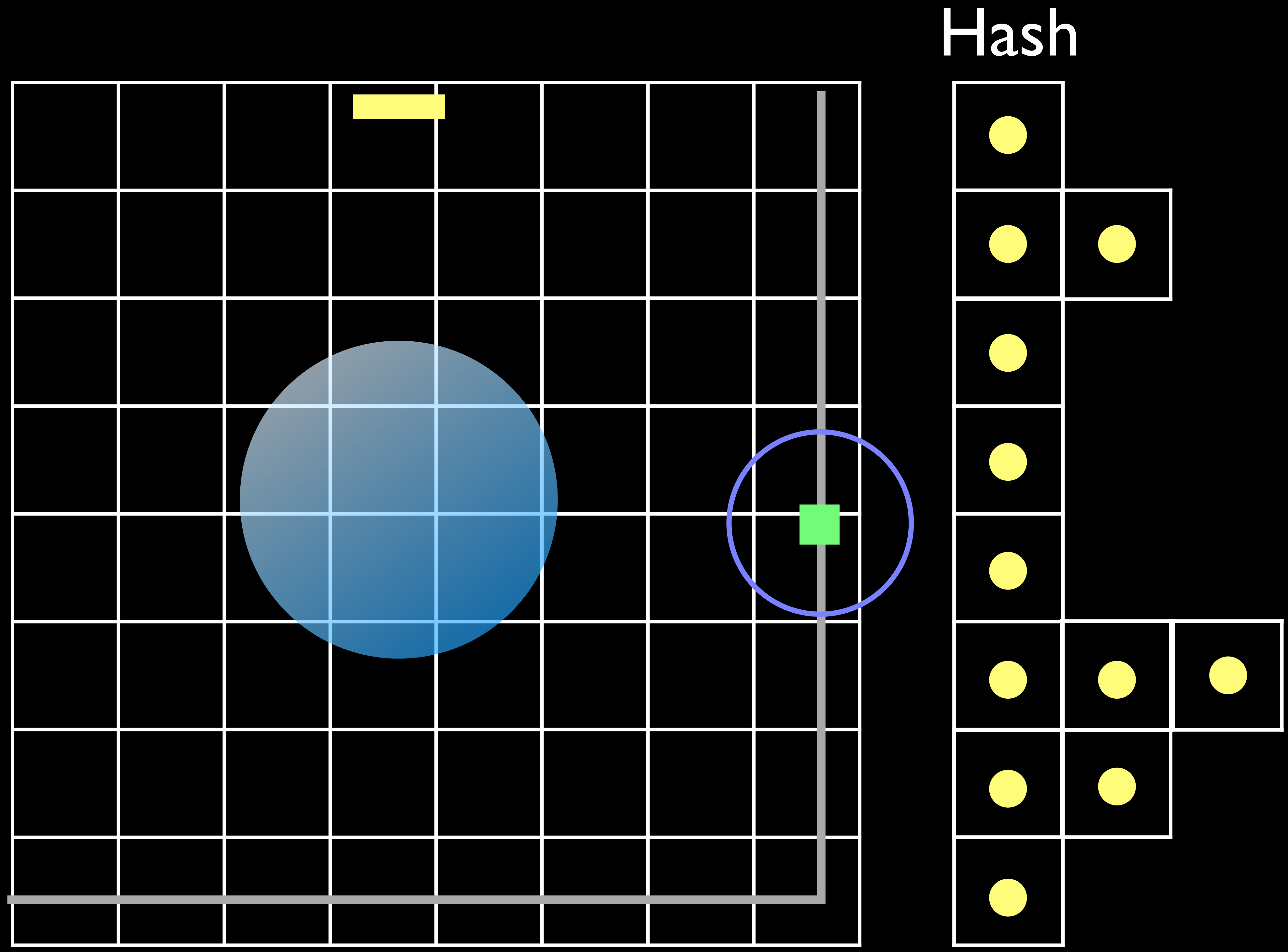
- Utilize the PRNG (works fairly well)

```
vec4 n = vec4(idx, (idx.x + idx.y + idx.z) / 3.0) * 4194304.0;
float hash = GPURnd(n);
```

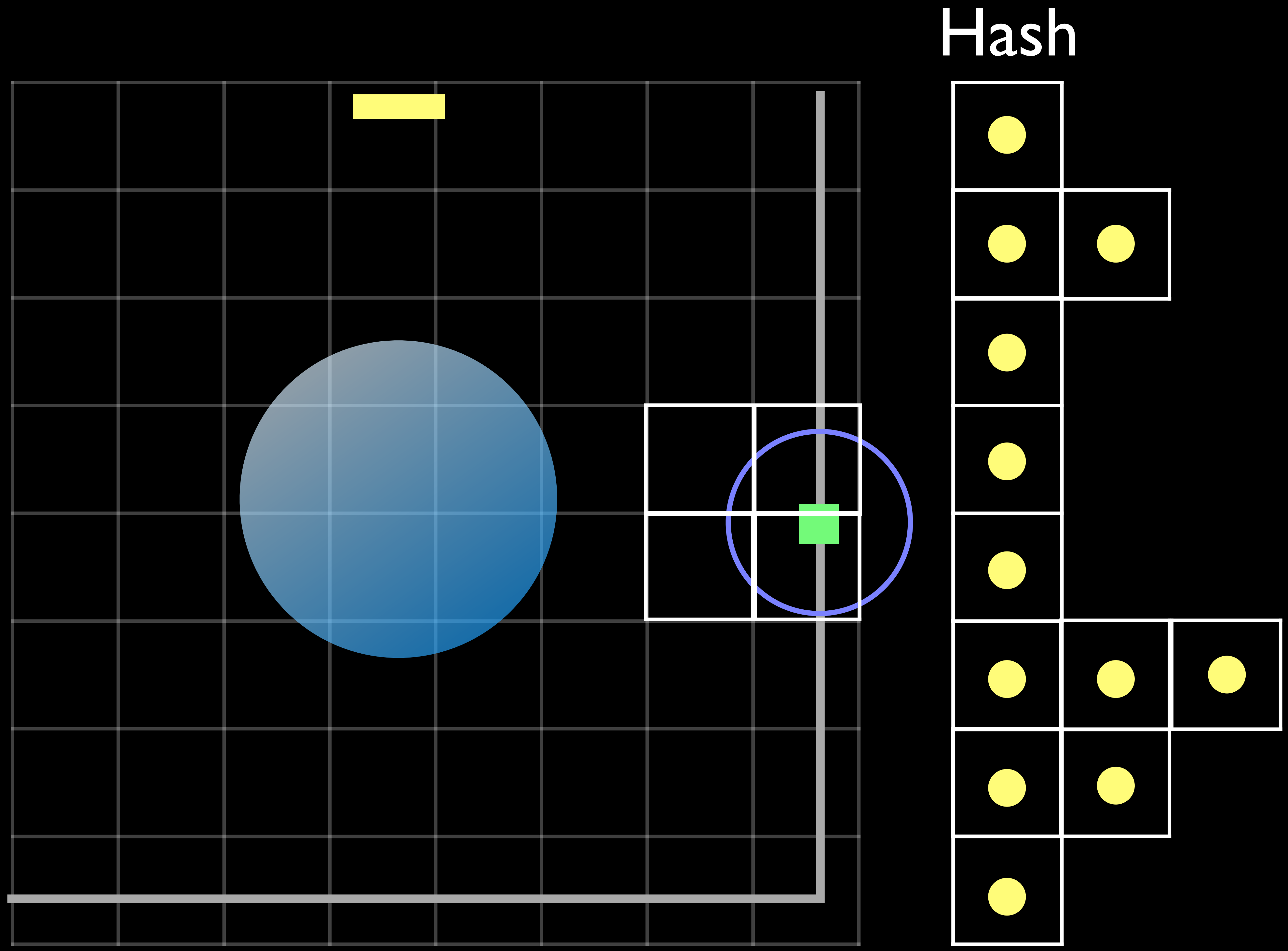
- S-box via textures (works very well, but slow)

- Some standard integer hash functions
(they can fail for spatial hashing - be careful)

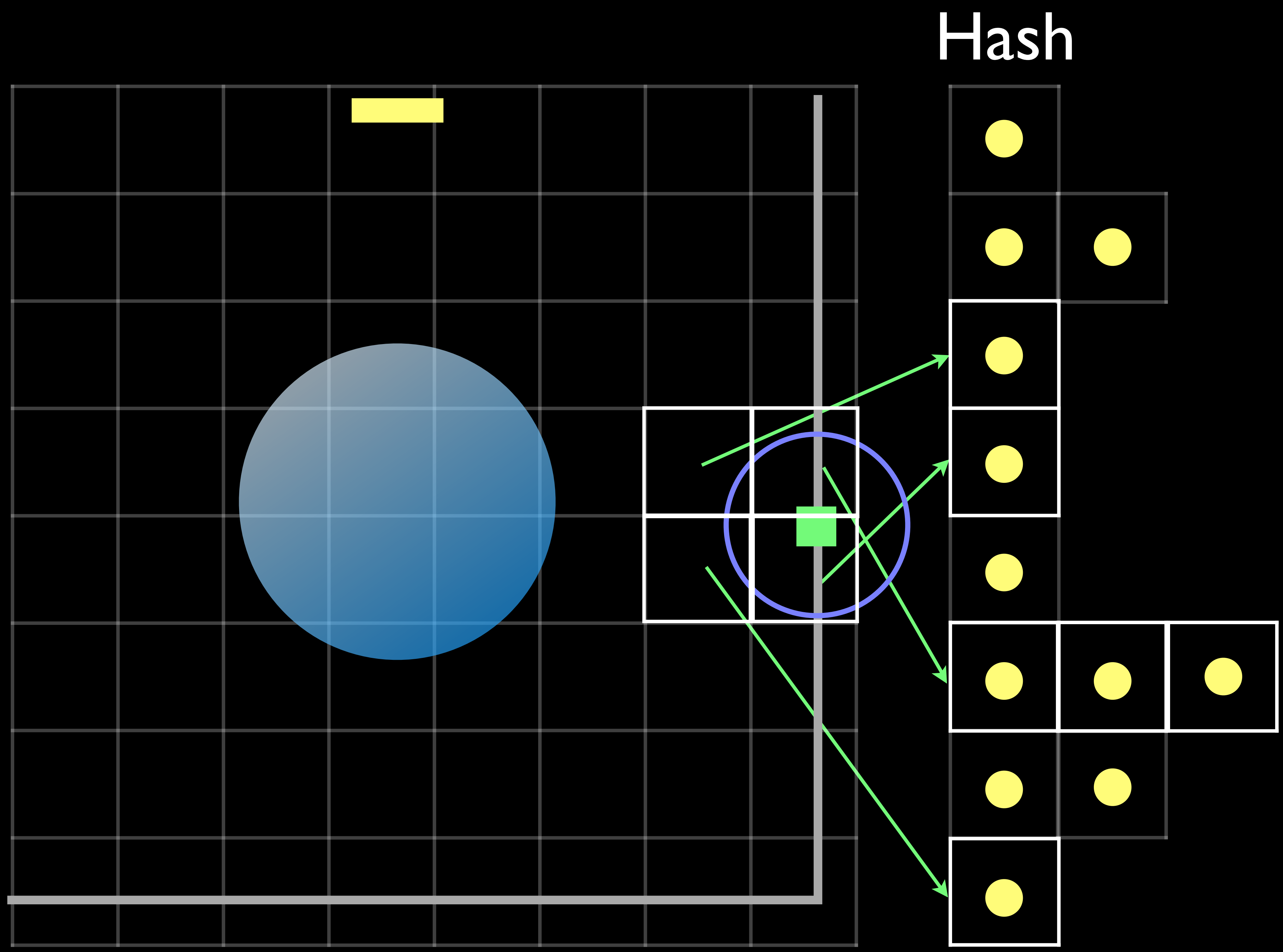
# Query



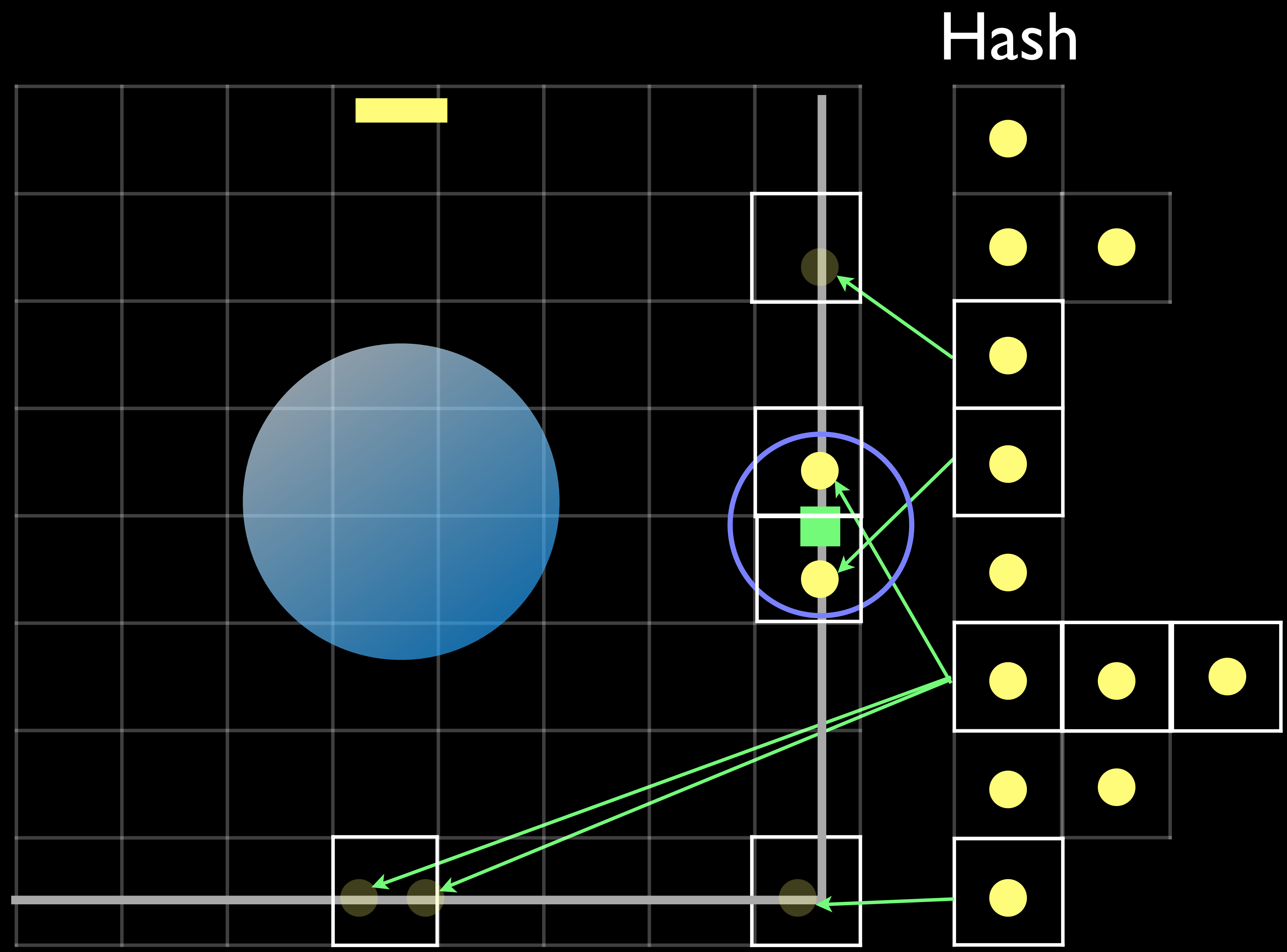
# Query



# Query



# Query



# Problems

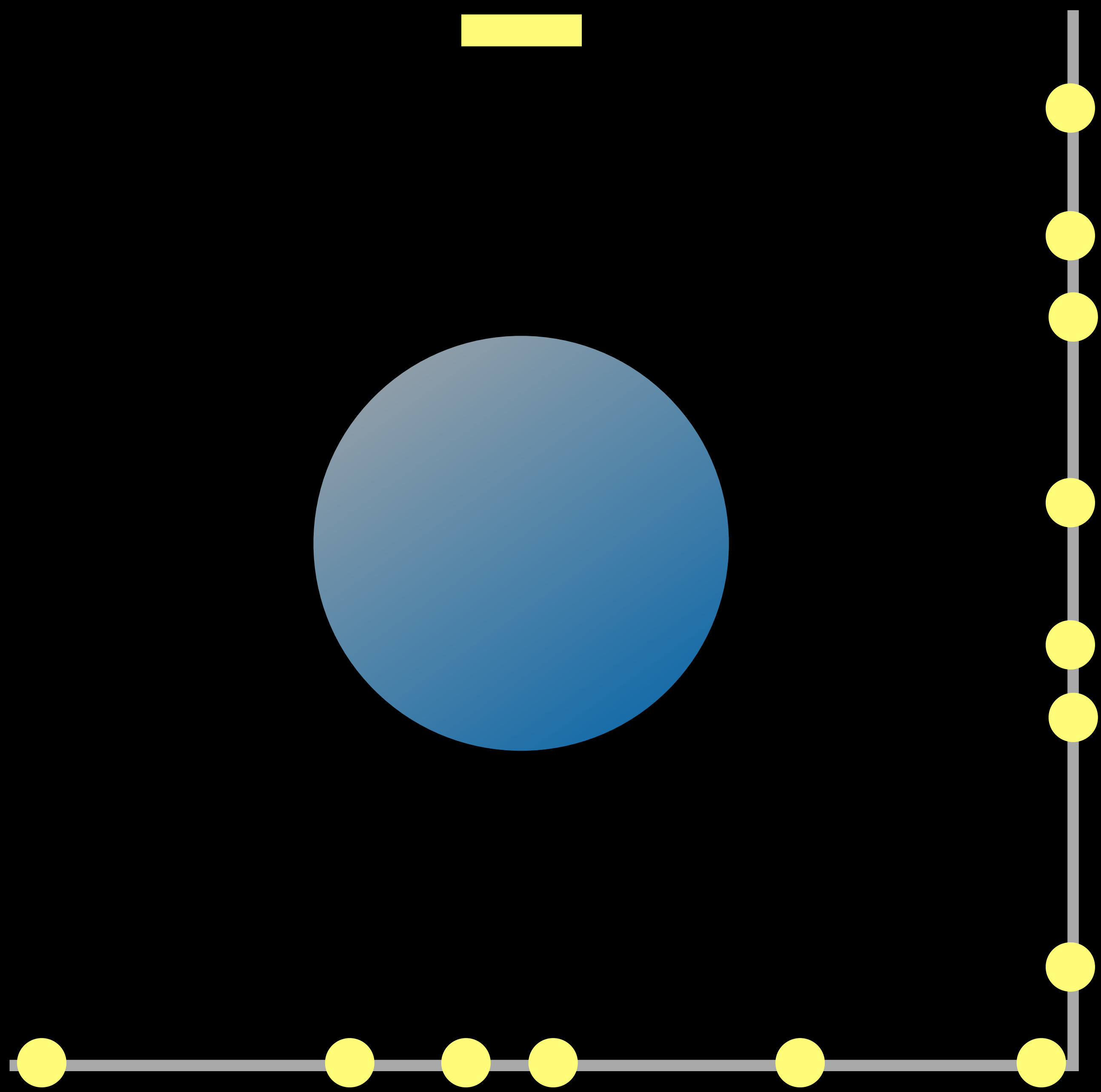
- Need to make a list when hash collision occurs
  - Not GPU friendly data structure
- Some hashed lists can contain lots of photons
  - Very non-uniform workload distribution

# Stochastic spatial hashing

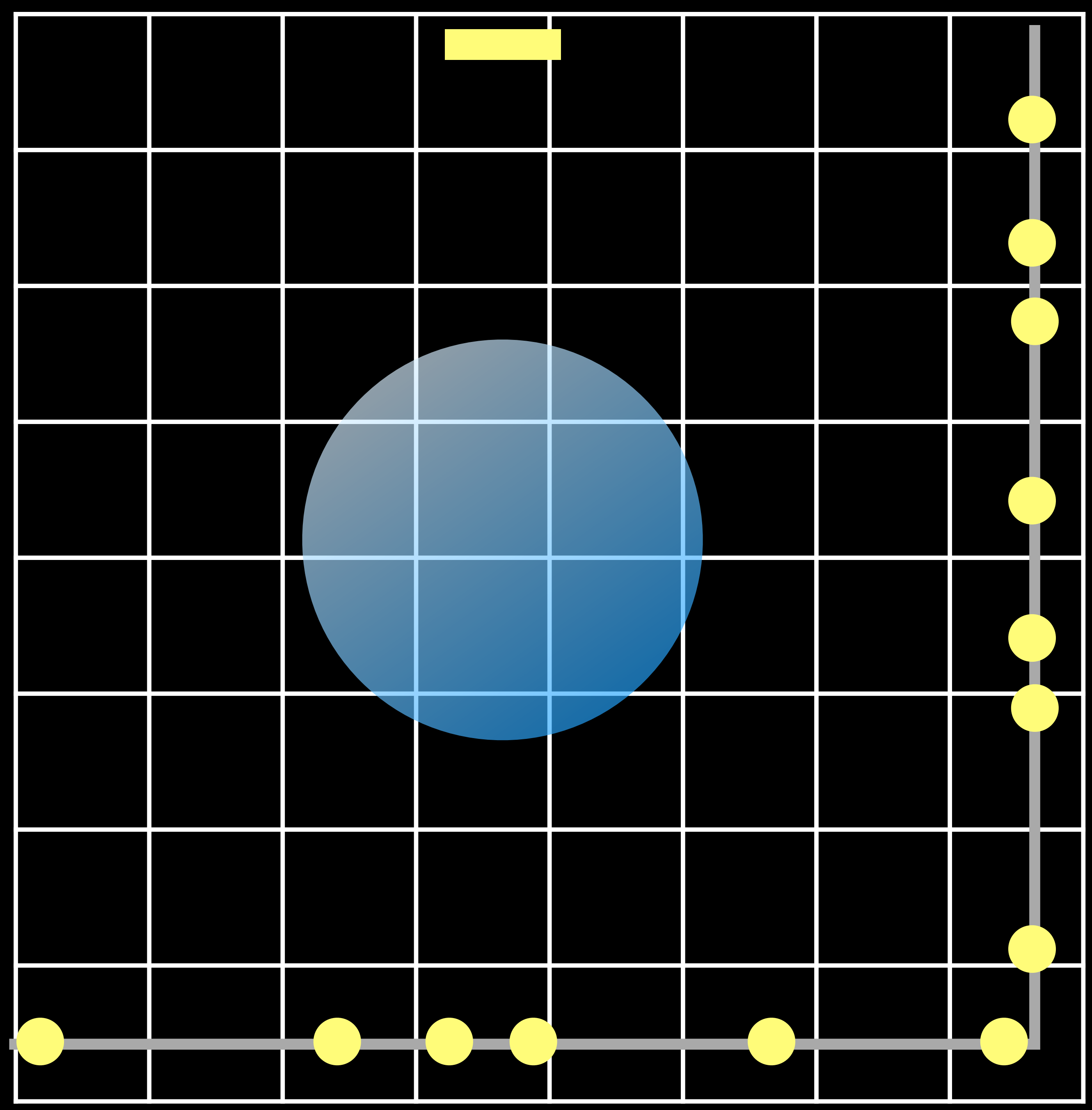
Randomly keep only one photon

"Parallel Progressive Photon Mapping on GPUs" T. Hachisuka and H. W. Jensen
SIGGRAPH Asia 2010 Technical Sketches

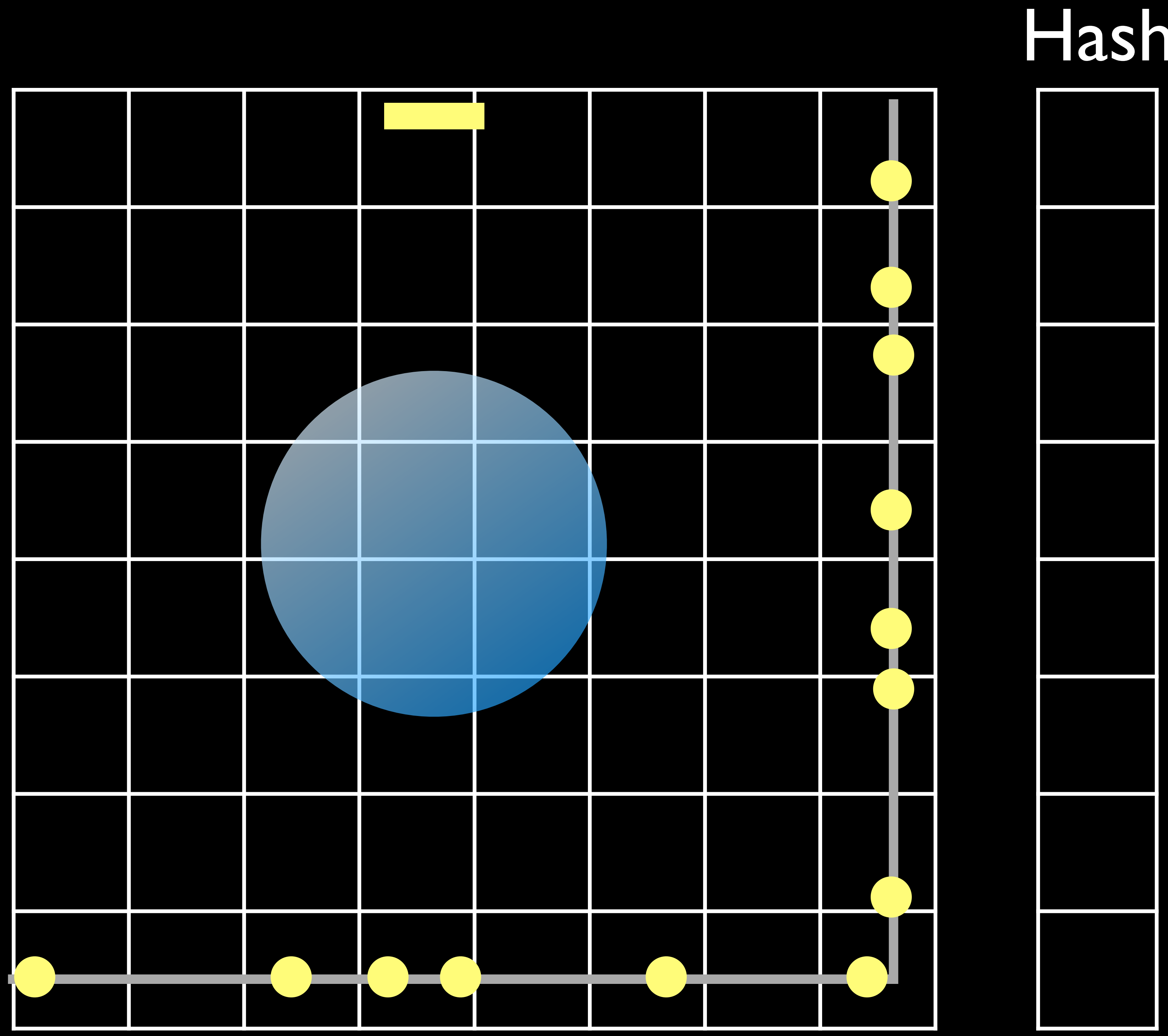
# Construction



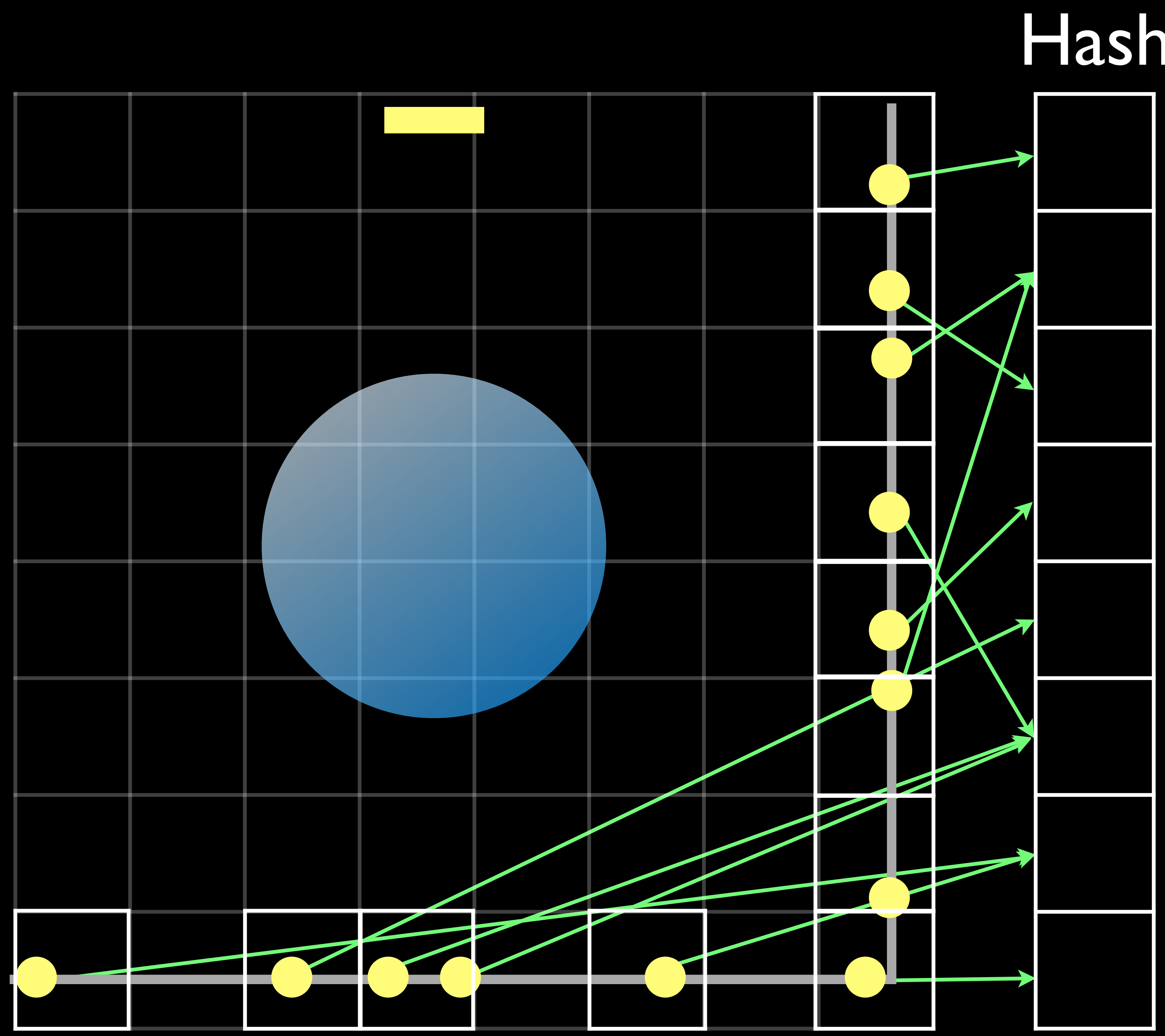
# Construction



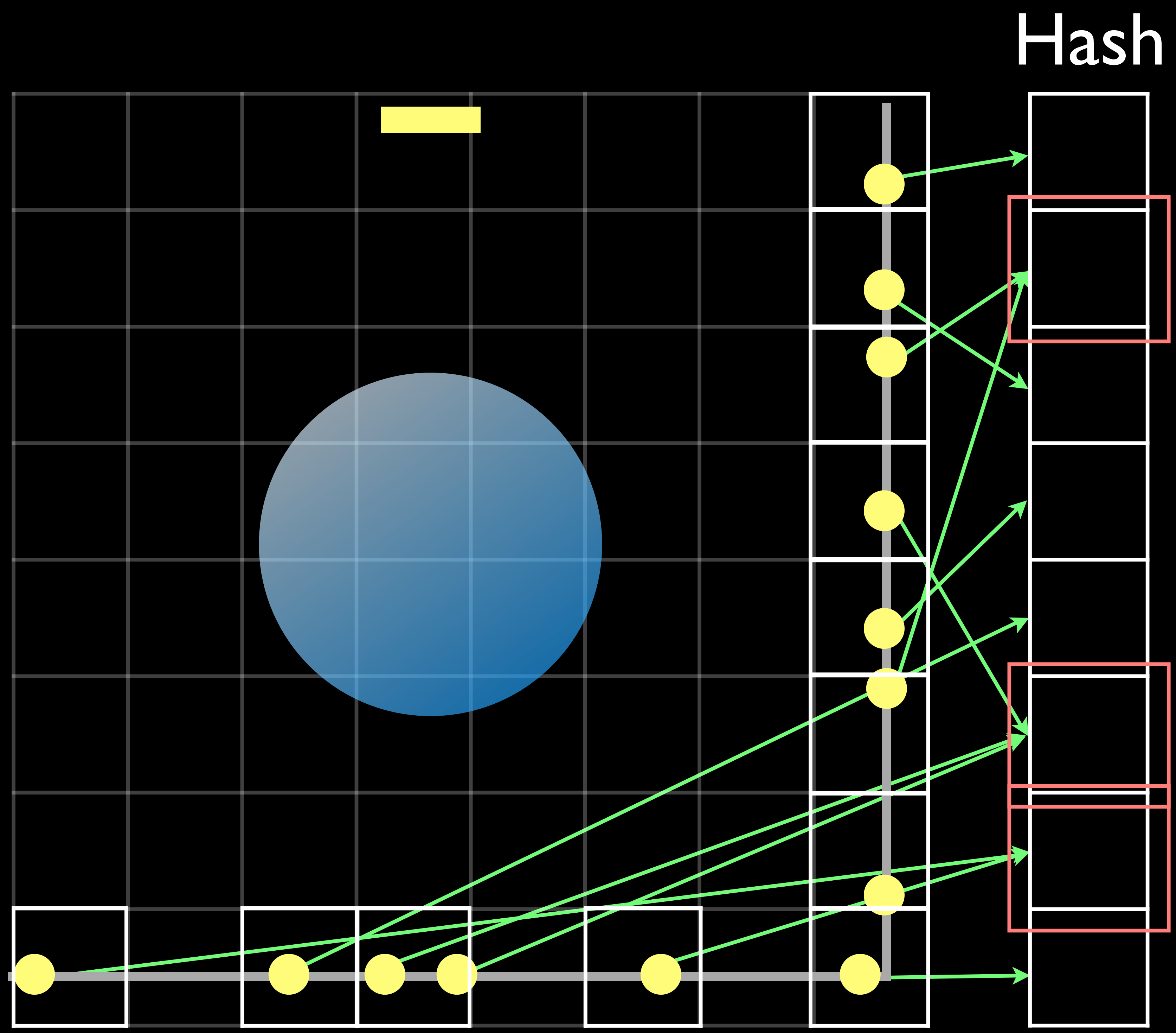
# Construction



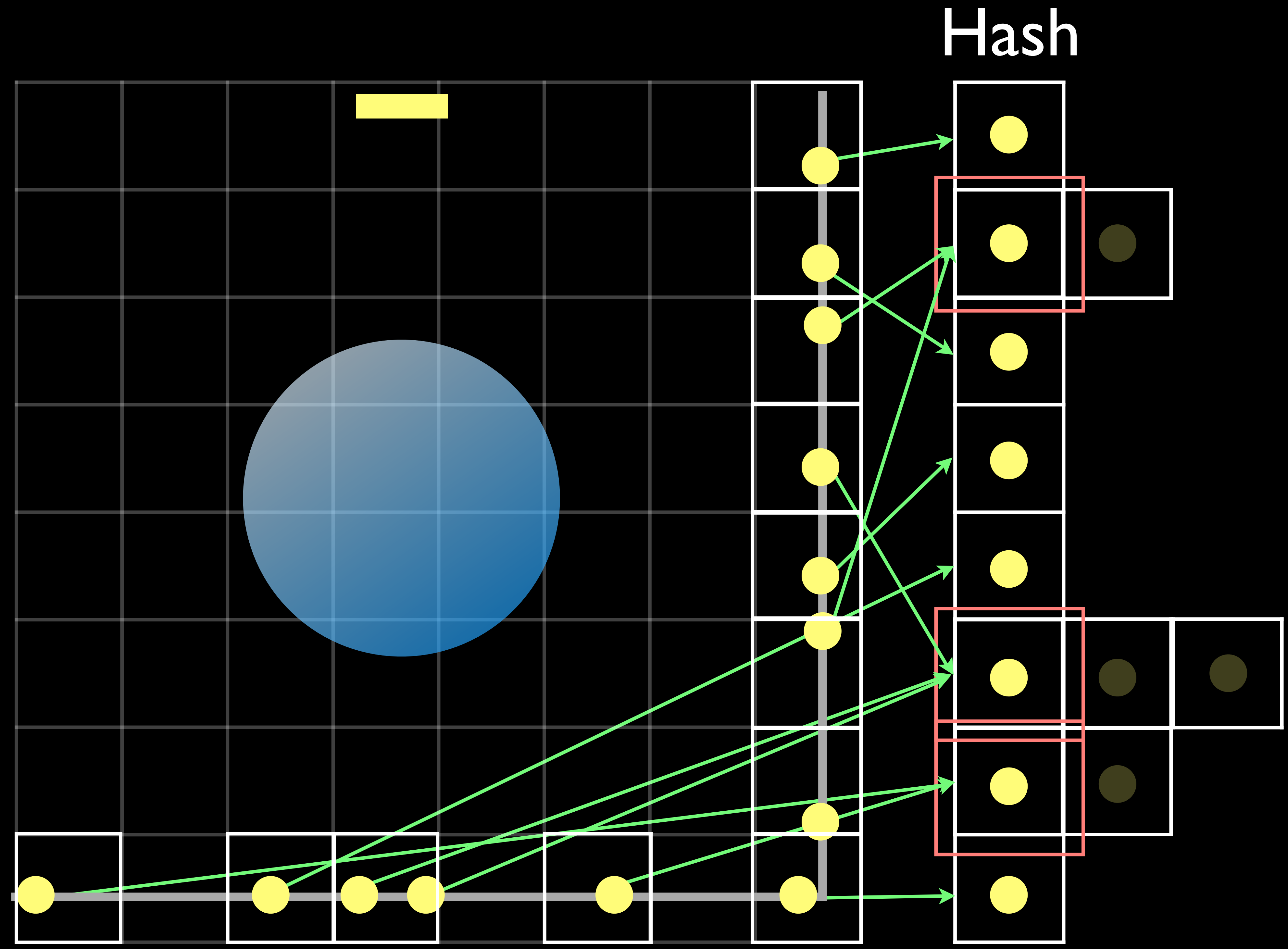
# Construction



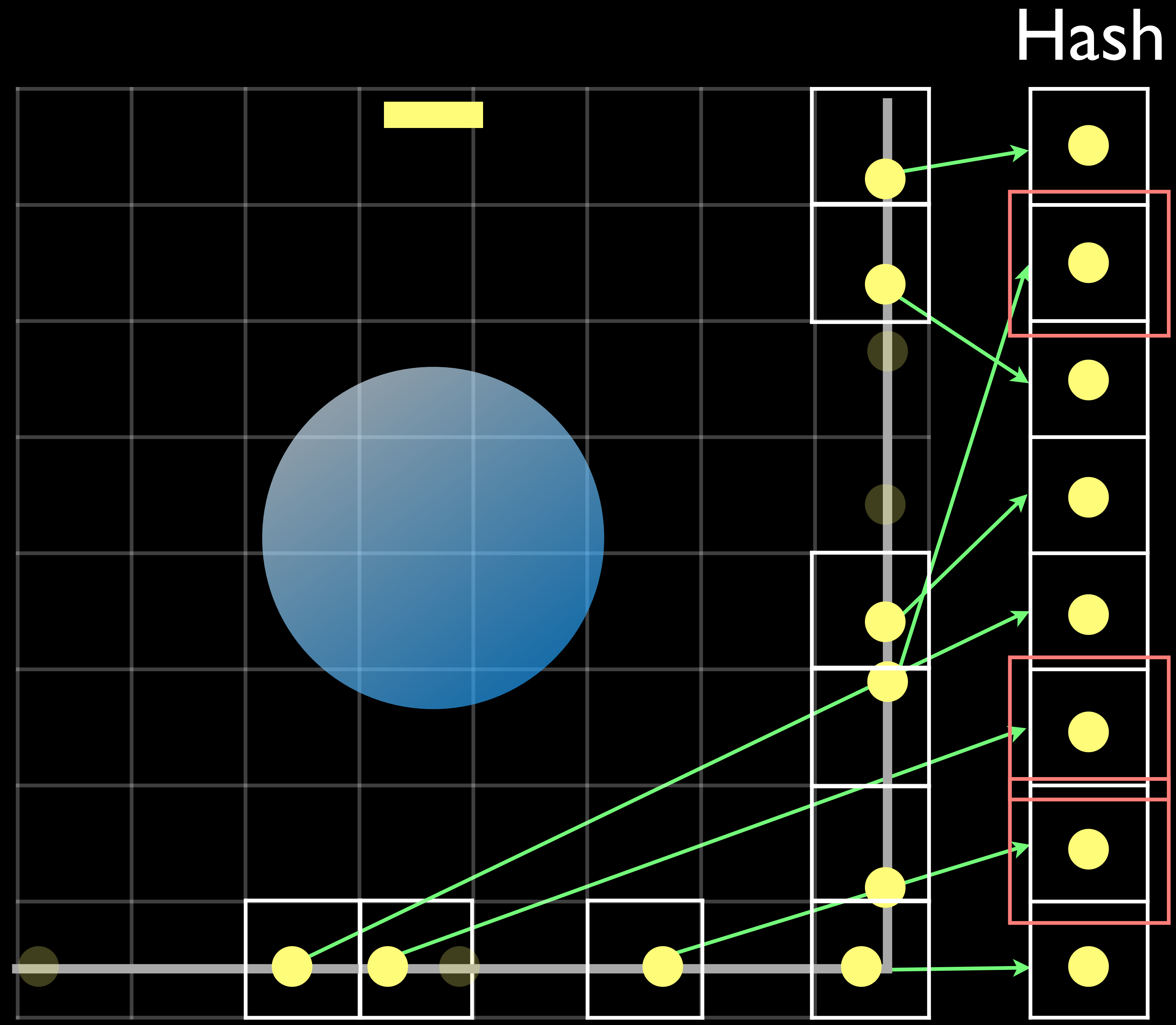
# Construction



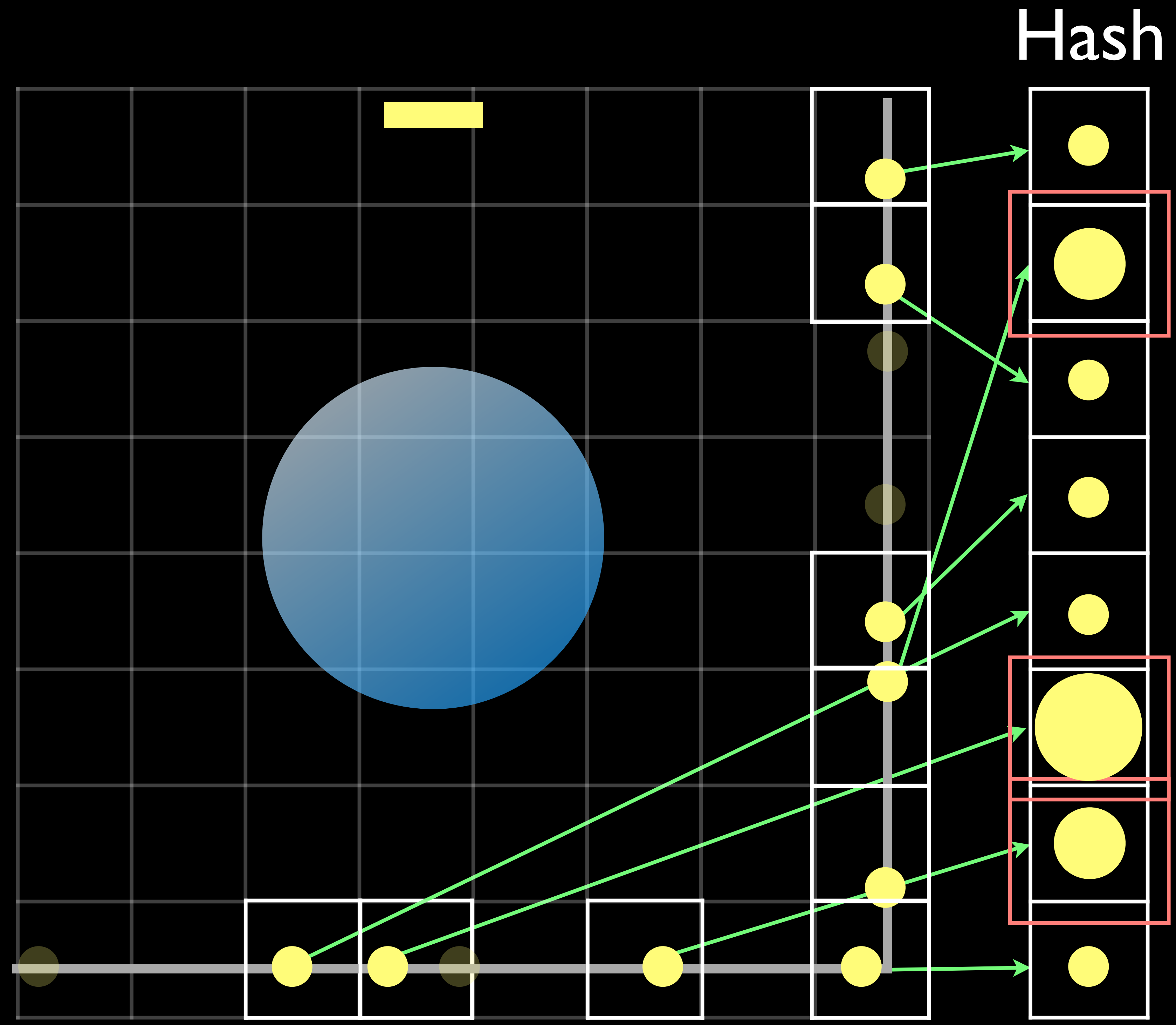
# Construction



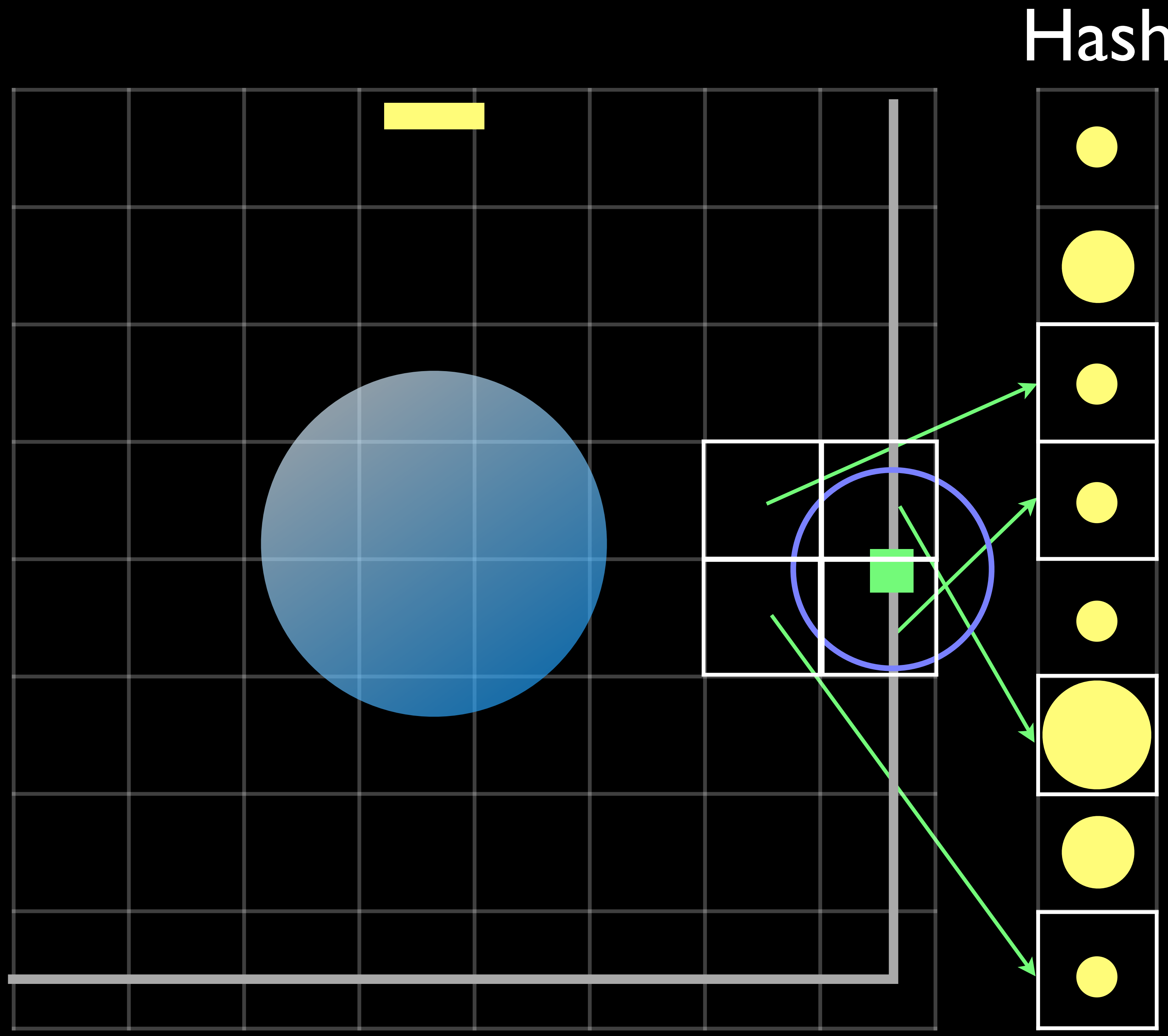
# Construction



# Construction



# Query

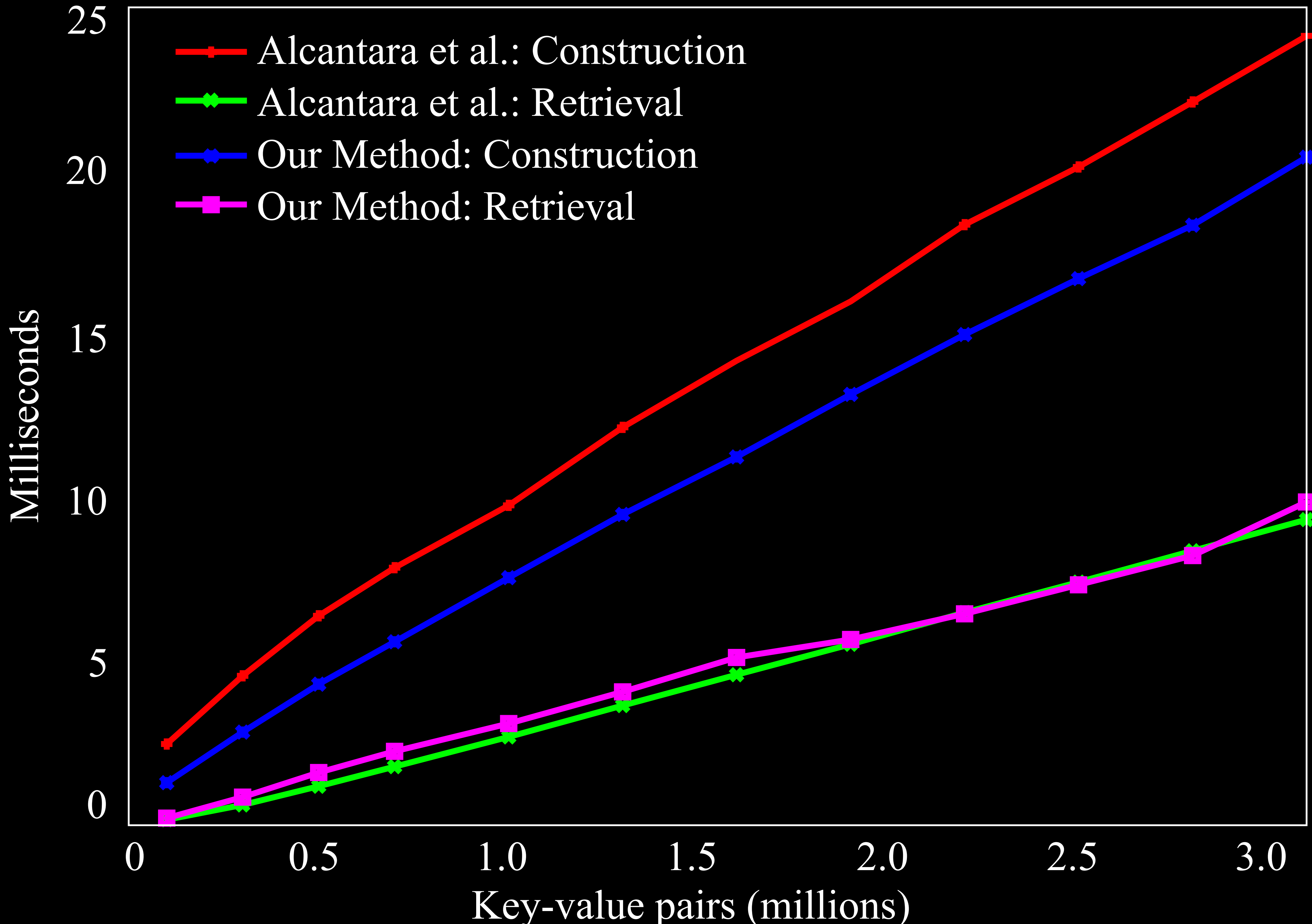


# Implementation

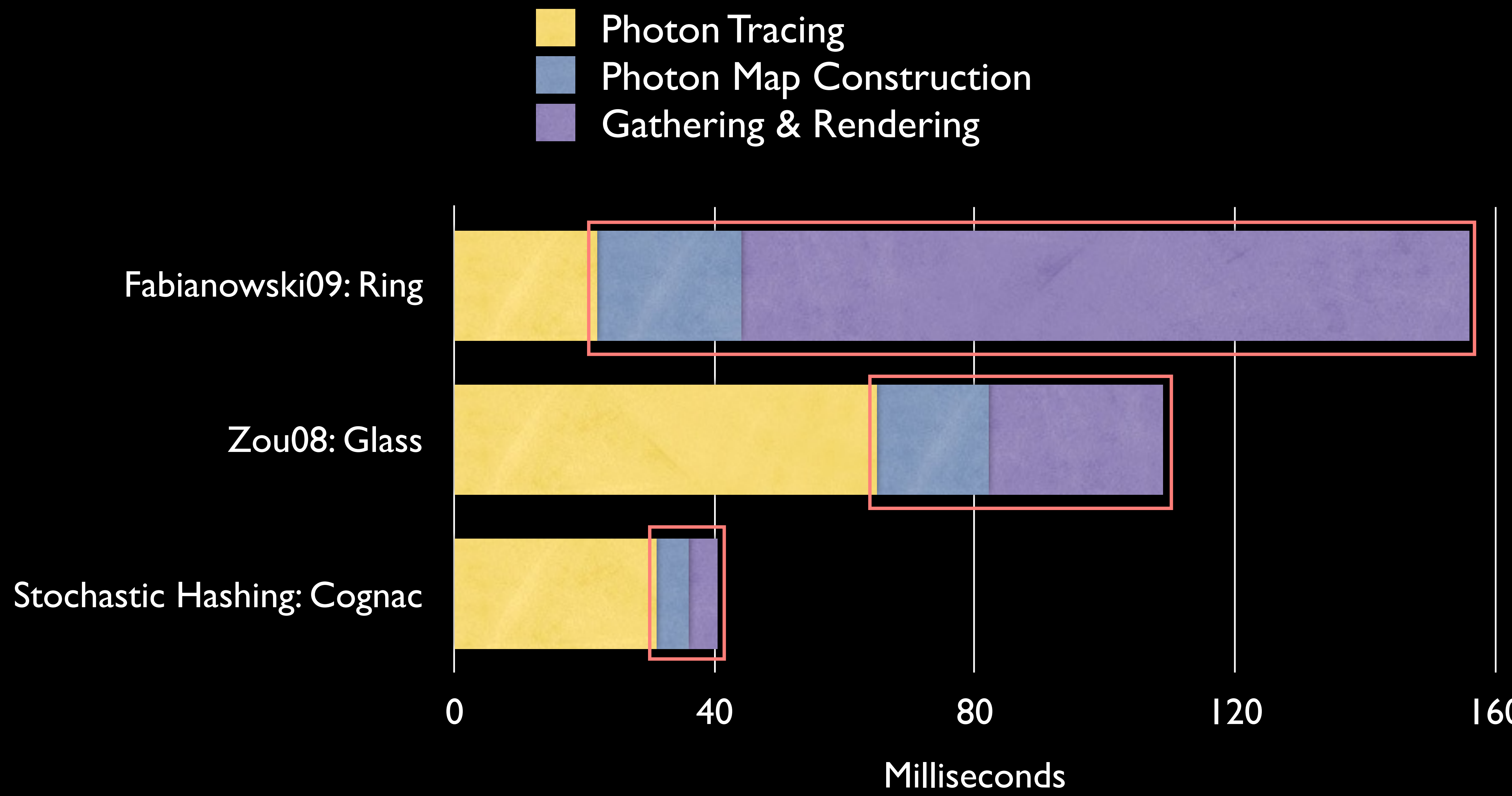
- Extremely simple!

```
For all photons in parallel
  HashIndex = Hash(Photon.Position)
  Table[HashIndex] = Photon
  AtomicInc(Count[HashIndex])
```

# Comparison with spatial hashing

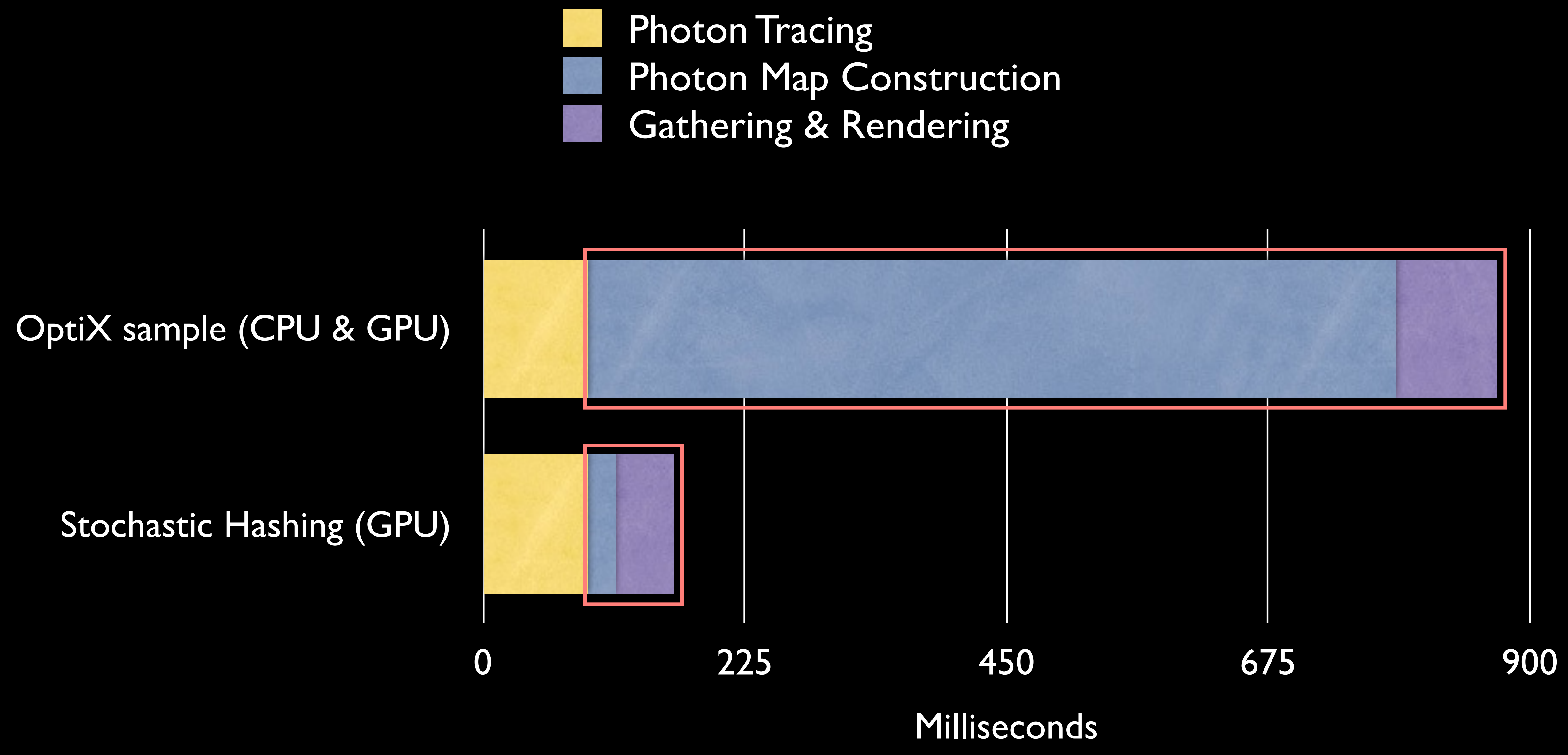


# Comparison with tree



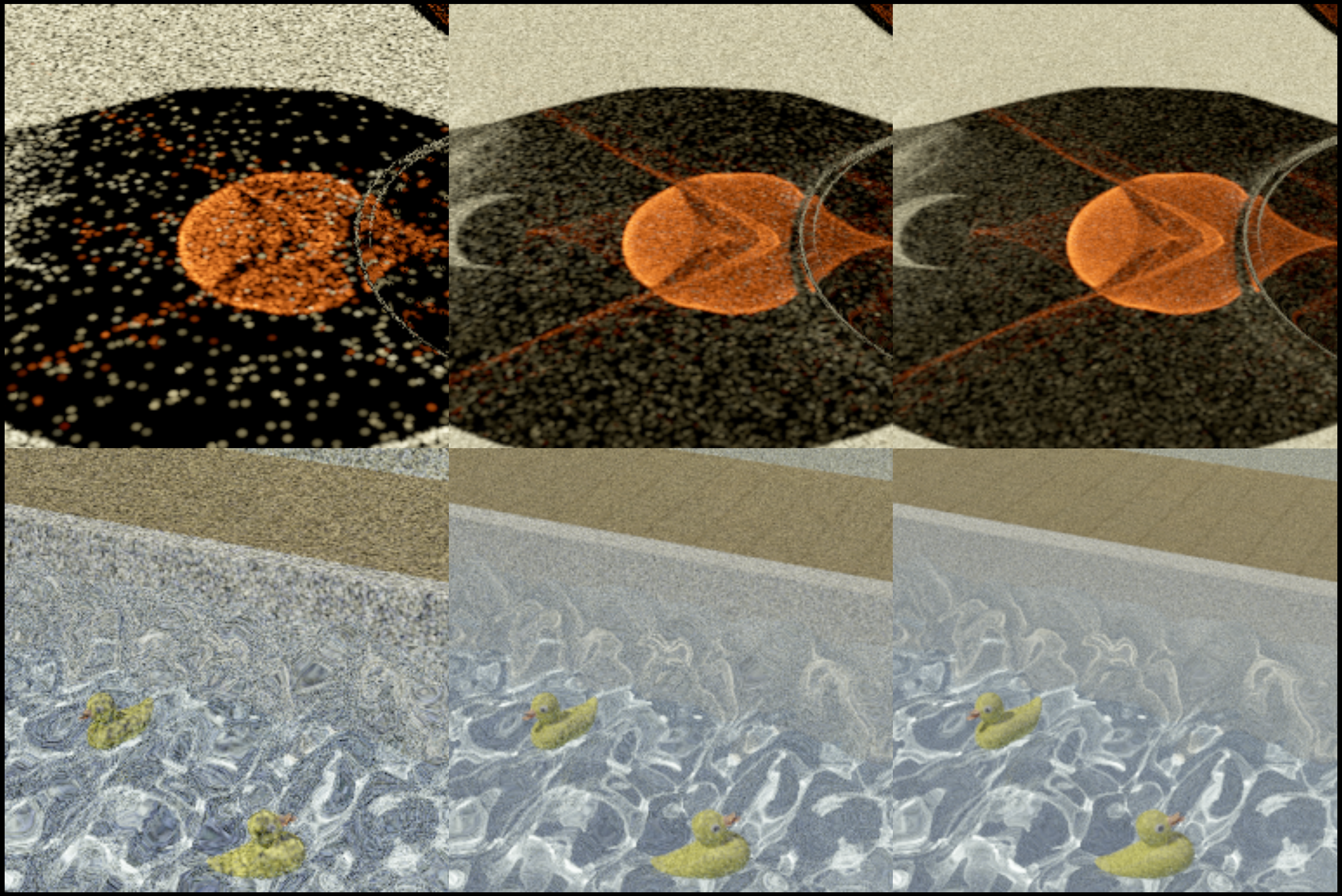

×3 ~ ×10 faster

# Comparison with CPU




Construction alone: ×30
Total: ×5

# Additional noise



1:64 table | 1:1 table | Full list

# Stochastic spatial hashing

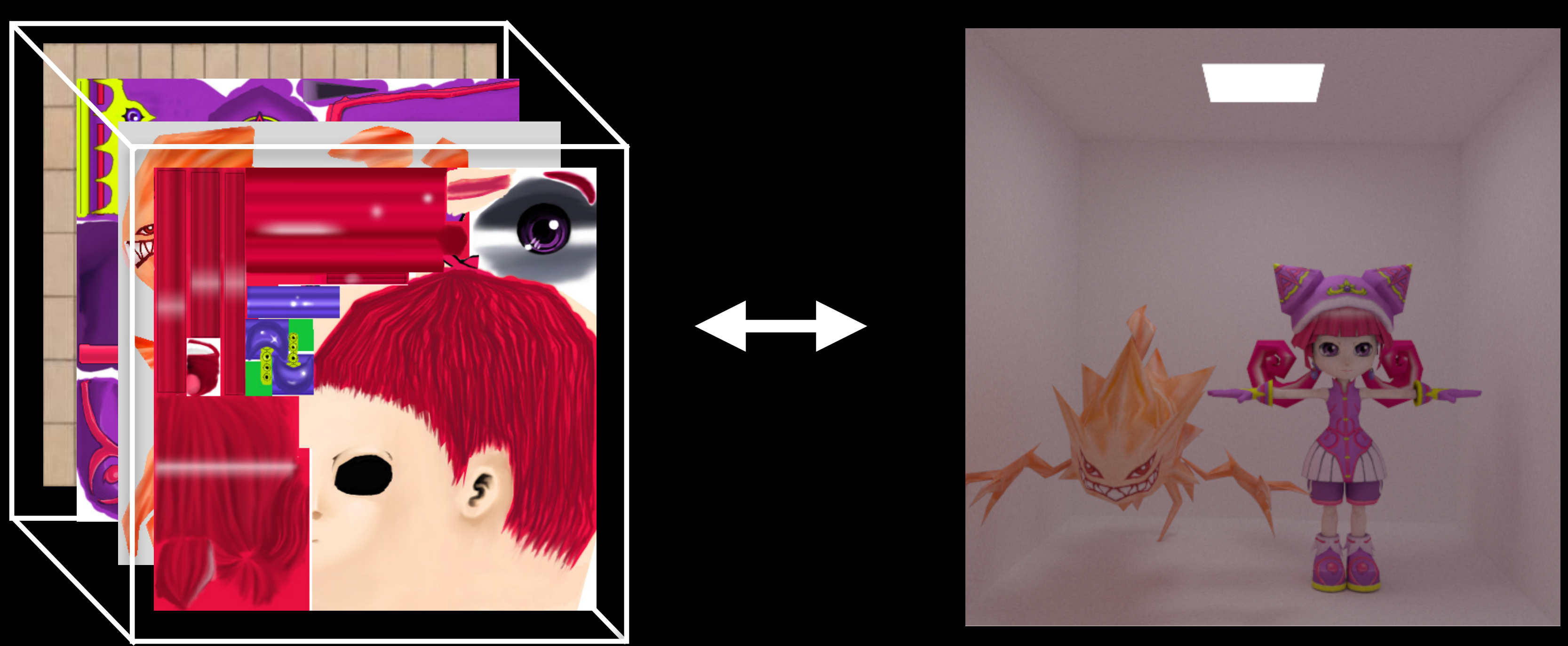
- Fundamentally avoids the two issues
  - No list construction is necessary
  - Hashed entry contains only one photon at most
  - Added bonus - very easy to implement

# Other Tips

# Texturing

- You don't want to have a separate GL texture for each
  - Slow & the number of textures is limited
- Store multiple textures as one volume texture

```
texture3D(textures, vec3(hit.texcoord.uv, hit.mat_id).rgb
```



# Data structure for materials

- "Über shader" fits well with the current system
- Three options to store material data
  - Texture - generally the slowest
  - Uniform - faster than texture, but limited
  - Embedded - need to compile shaders

# Lowering CPU usage

- Naive implementation causes 100% CPU usage
  - Due to the way OpenGL waits for next command
  - GPU renderer uses 100% CPU sounds stupid!

# Lowering CPU usage

- Use asynchronous occlusion query
  - Wait until we get the number of pixels drawn back
  - Use non-busy sleep (e.g., usleep)

```
int a = 0;
glBeginQuery(GL_TIME_ELAPSED_EXT, OcclusionQuery);
    // draw quad
glEndQuery(GL_TIME_ELAPSED_EXT);
do {
    glGetQueryObjectiv(OcclusionQuery, GL_QUERY_RESULT_AVAILABLE, &a);
    sleep(1);
} while(!a);
```

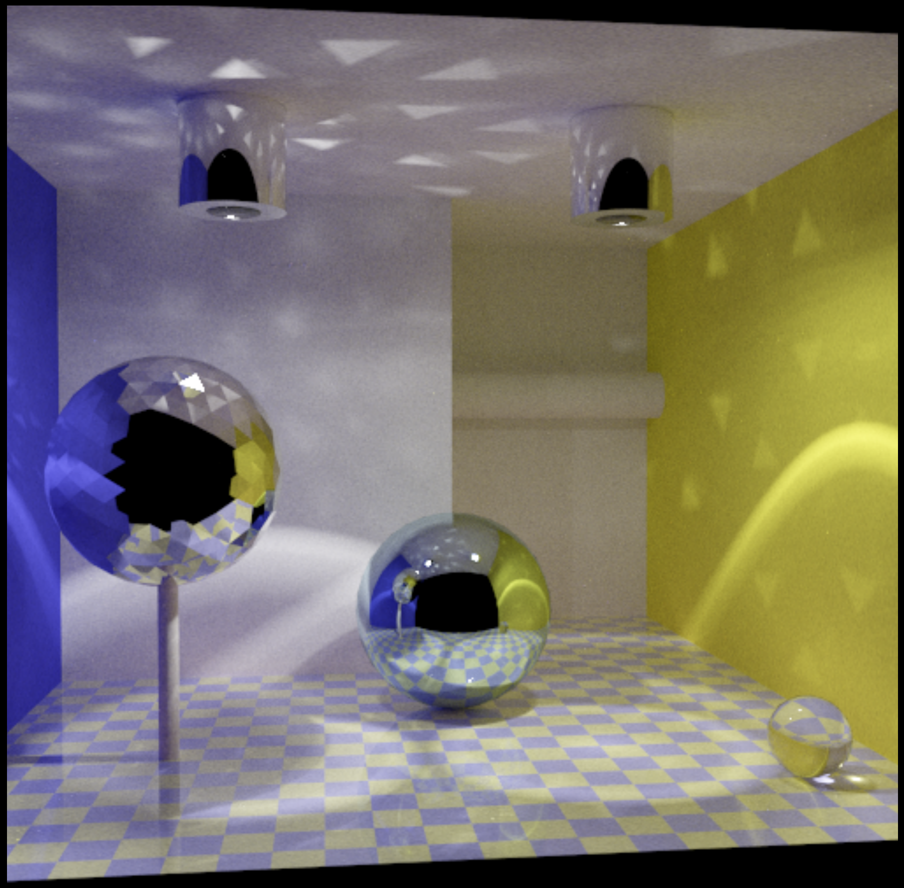
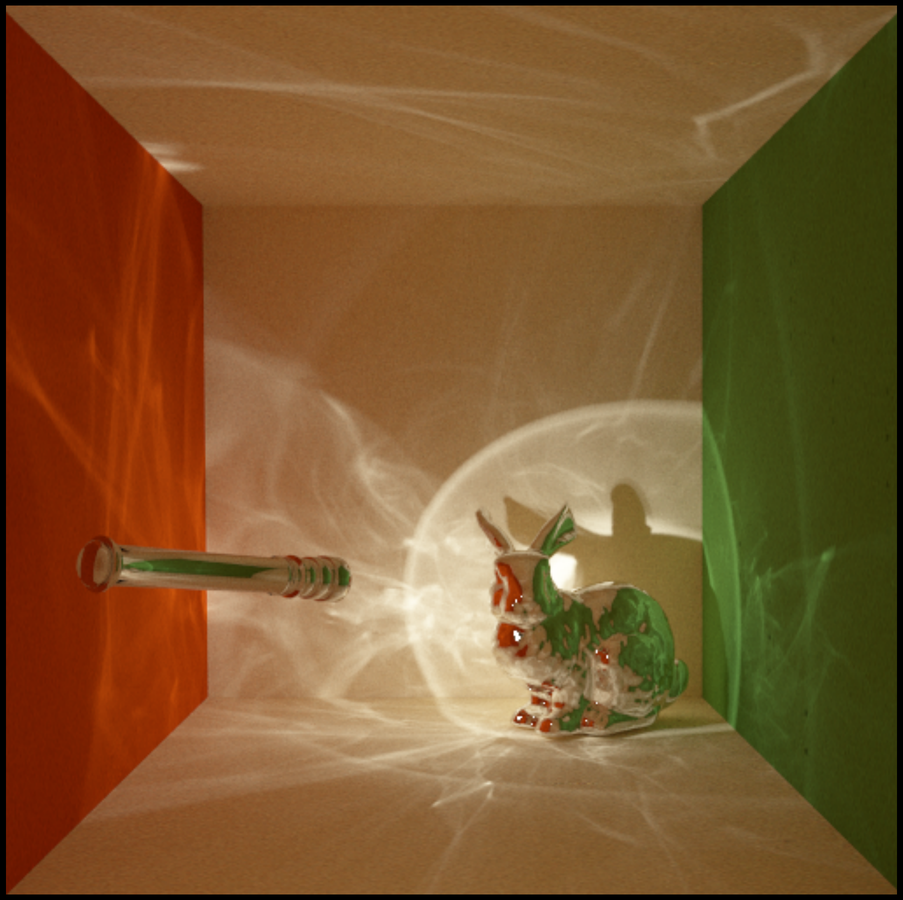
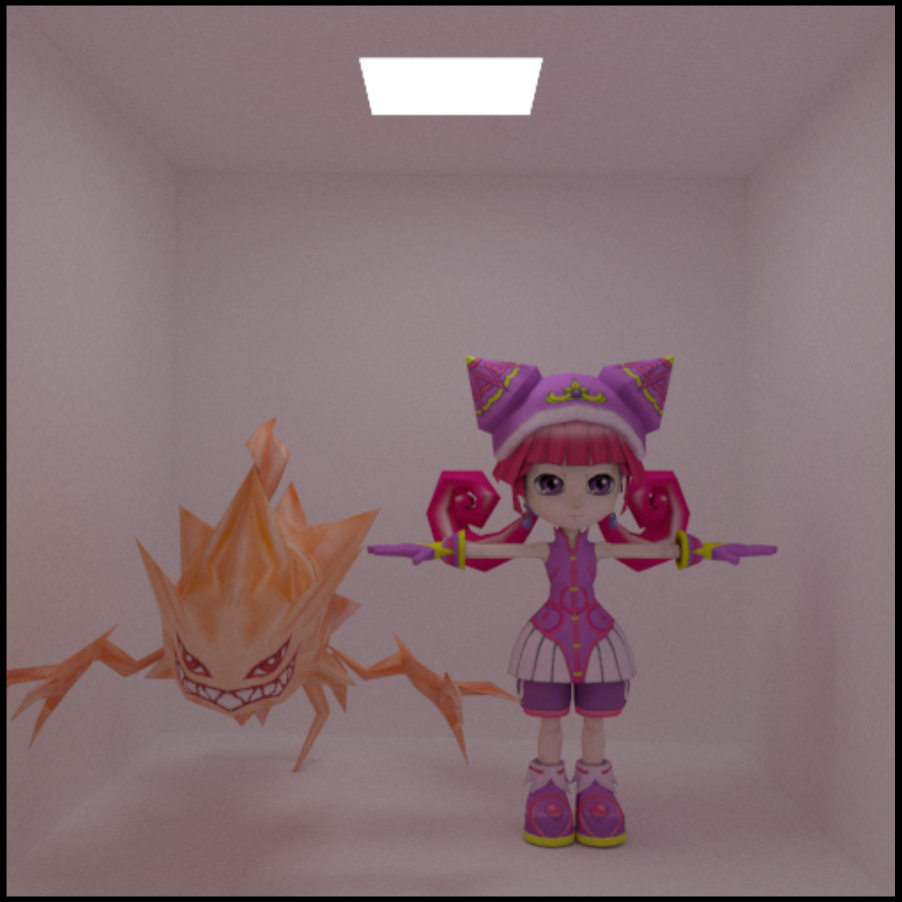
# 16bits vs 32bits

- GLSL can easily use 16bits floats
- Surprising(?) fact: 16bits is often times enough!
  - As long as you convert everything into 16bits
  - Perhaps not true for very large scenes
  - Usually slightly faster than 32bits

# Cross-platform issues

- OpenCL and GLSL are cross-platform, in theory
  - This is the reason to use “legacy” GLSL
  - Battle-tested GLSL versions are stable enough
  - My code works on Intel’s, NVIDIA’s, and AMD’s
- Some annoyance only in rare cases
  - “mod” produces wrong results (use floor and arithmetics)
  - conditional while loop does not work (use break instead)

# Live demo

Approx. 100M photon paths in 1 min @ GeForce GTX 680

# Conclusions

- Fully functional rendering system using GLSL
  - Multiple-threaded BVH
  - Asynchronous path generation
  - PRNG using only floating-point numbers
  - Stochastic hashing