Lecture 16:

Architectural Support for Ray Tracing

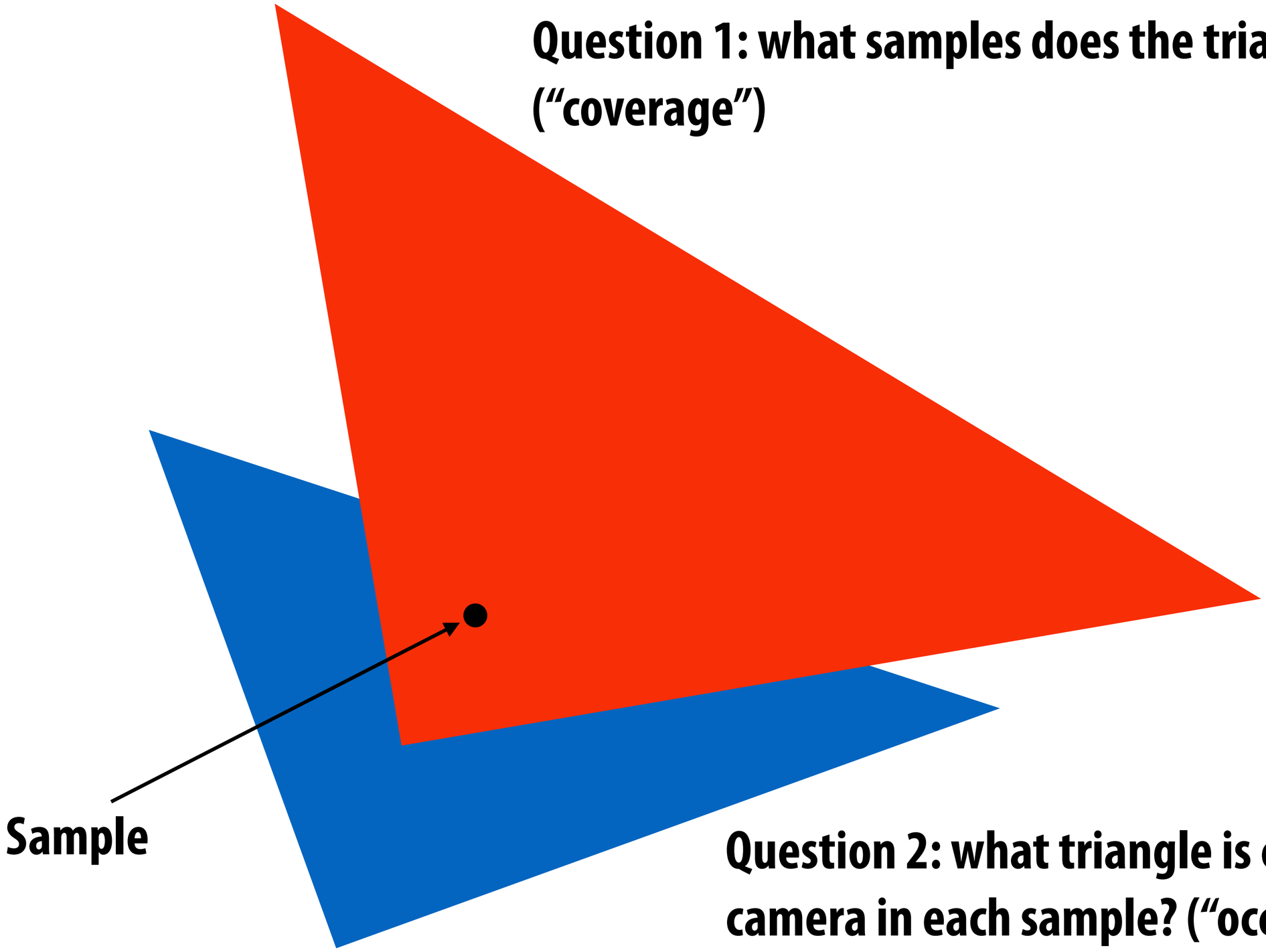
Visual Computing Systems
Stanford CS348K, Spring 2020

Ray Tracing for architects (in 15 minutes)

Take that Pete Shirley!

Rasterization and ray casting are two algorithms for solving the same problem: determining "visibility along rays"

Visibility problem



Question 1: what samples does the triangle overlap? (“coverage”)

Question 2: what triangle is closest to the camera in each sample? (“occlusion”)

Basic rasterization algorithm

Sample = 2D point

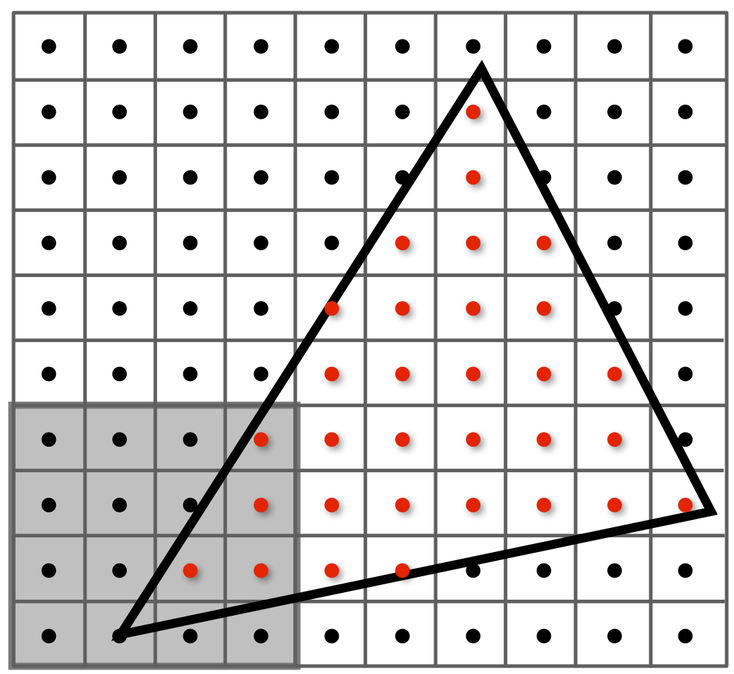
Coverage: 2D triangle/sample tests (does projected triangle cover 2D sample point)

Occlusion: depth buffer

```
initialize z_closest[] to INFINITY                  // store closest-surface-so-far for all samples
initialize color[]                                  // store scene color for all samples
for each triangle t in scene:                       // loop 1: triangles
    t_proj = project_triangle_to_screen(t)
    for each 2D sample s in frame buffer:           // loop 2: visibility samples
        if (t_proj covers s)
            compute color of triangle at sample     // run fragment shader
            if (depth of t at s is closer than z_closest[s])  // depth buffer check/update
                update z_closest[s] and color[s]
```

"Given a triangle, find the samples it covers"

(finding the samples is relatively easy since they are distributed uniformly on screen)

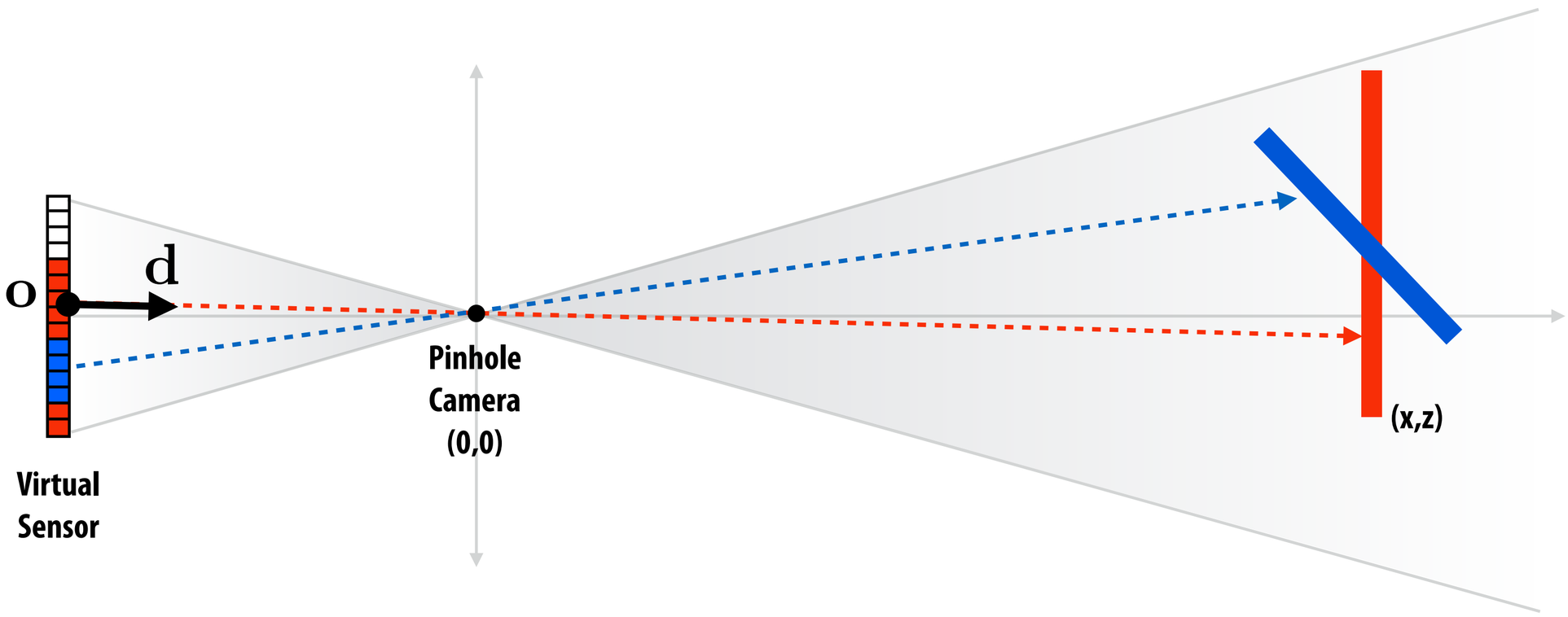


Recall: depth test logic

```
depth_test(frag_depth, frag_color, x, y) {

  if (tri_depth < depth_buffer[x][y]) {

    // triangle is closest object seen so far at this
    // sample point. Update depth and color buffers.

    depth_buffer[x][y] = tri_depth;  // update depth_buffer
    color[x][y] = frag_color;        // update color buffer
  }
}
```

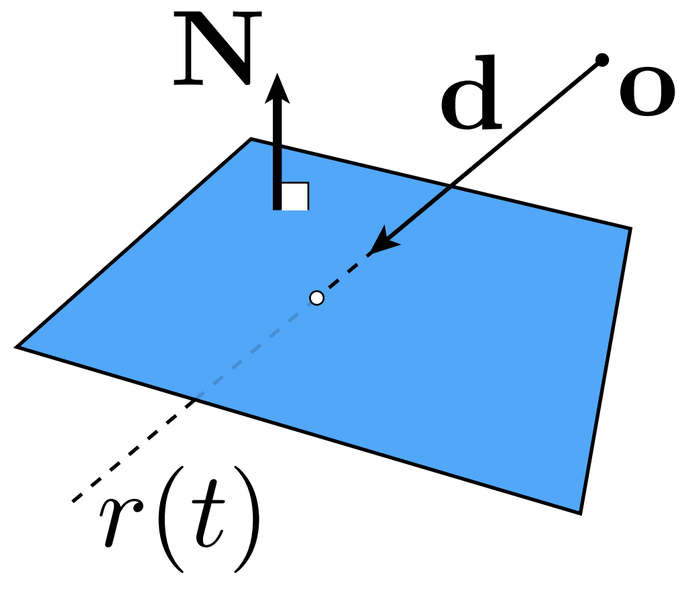
The visibility problem (described differently)

- **In terms of casting rays from a simulated camera:**
  - **What scene primitive is "hit" by a ray originating from a point on the virtual sensor and traveling through the aperture of the pinhole camera? (coverage)**
  - **What primitive is the first hit along that ray? (occlusion)**



Does a ray (in 3D) hit a triangle (in 3D)?

Ray-plane intersection



- Suppose we have a plane $\mathbf{N}^\mathsf{T}\mathbf{x} = c$
  - N - unit normal
  - c - offset
- How do we find intersection with ray r(t) = o + td?

- *Key idea:* again, replace the point x with the ray equation t:

$$\mathbf{N}^\mathsf{T}\mathbf{r}(t) = c$$

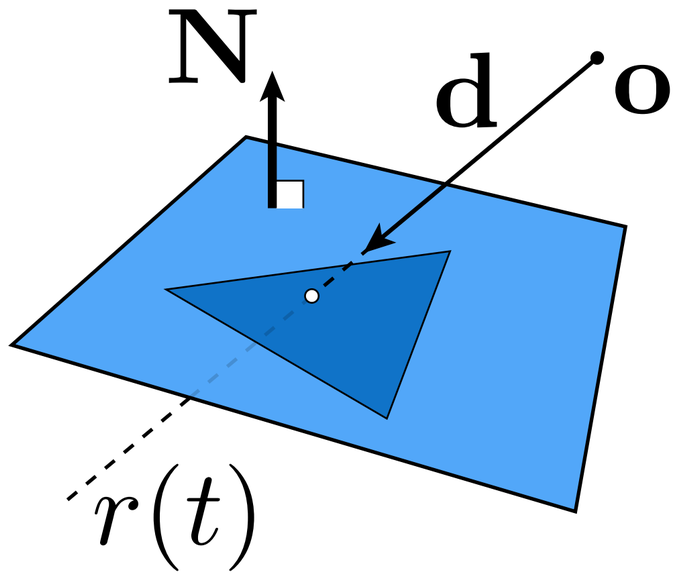
- Now solve for t:

$$\mathbf{N}^\mathsf{T}(\mathbf{o} + t\mathbf{d}) = c \qquad \Rightarrow t = \frac{c - \mathbf{N}^\mathsf{T}\mathbf{o}}{\mathbf{N}^\mathsf{T}\mathbf{d}}$$

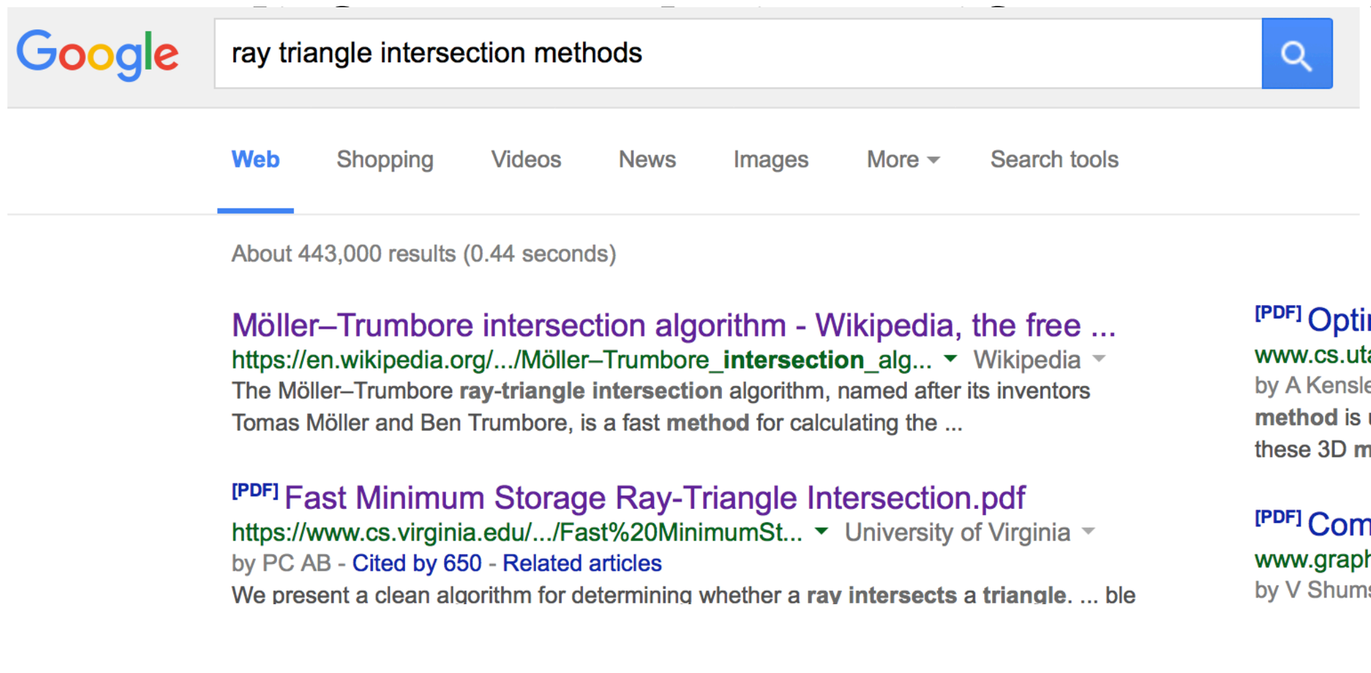
- And plug t back into ray equation:

$$r(t) = \mathbf{o} + \frac{c - \mathbf{N}^\mathsf{T}\mathbf{o}}{\mathbf{N}^\mathsf{T}\mathbf{d}}\mathbf{d}$$

Ray-triangle intersection



- **Algorithm:**
  - Compute ray-plane intersection
  - Q: What do we do now?
  - A: Compute barycentric coordinates of hit point?
  - If barycentric coordinates are all positive, point is in triangle
-



Basic ray casting algorithm

Sample = a ray in 3D

Coverage: 3D ray-triangle intersection tests (does ray "hit" triangle)

Occlusion: closest intersection along ray

```
initialize color[]                                  // store scene color for all samples
for each sample s in frame buffer:                  // loop 1: visibility samples (rays)
    r = ray from s on sensor through pinhole aperture
    r.closest_dist = INFINITY                         // only store closest-so-far for current ray
    r.closest_tri = NULL;
    for each triangle tri in scene:                   // loop 2: triangles
        if (intersects(r, tri)) {                     // 3D ray-triangle intersection test
            if (intersection distance along ray is closer than r.closest_dist)
                update r.closest_dist and r.closest_tri = tri;
        }
    color[s] = compute surface color of triangle r.tri at hit point  // hit shader
```

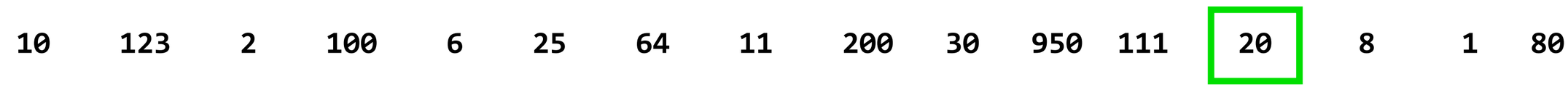
Compared to rasterization approach: just a reordering of the loops! (+ math in 3D)

"Given a ray, find the closest triangle it hits"

The brute force "for each triangle" loop is typically implemented using a search acceleration structure. (A rasterizer's "for each sample" inner loop is not just a loop over all screen samples either.)

A simpler problem

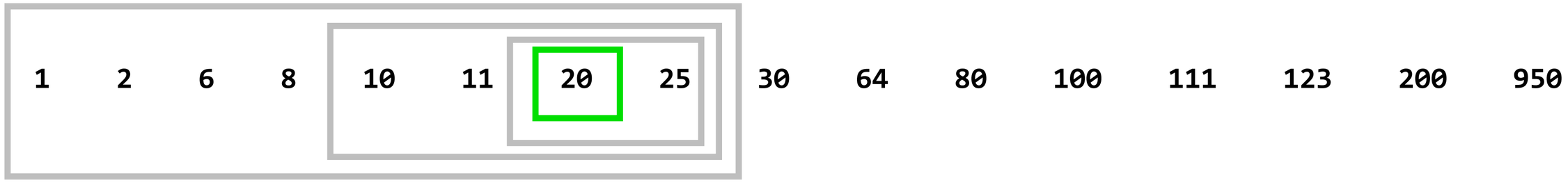
- Imagine I have a set of integers S
- Given an integer, say *k*=18, find the element of S closest to *k:*



What's the cost of finding *k* in terms of the size N of the set?

Can we do better?

Suppose we first *sort* the integers:



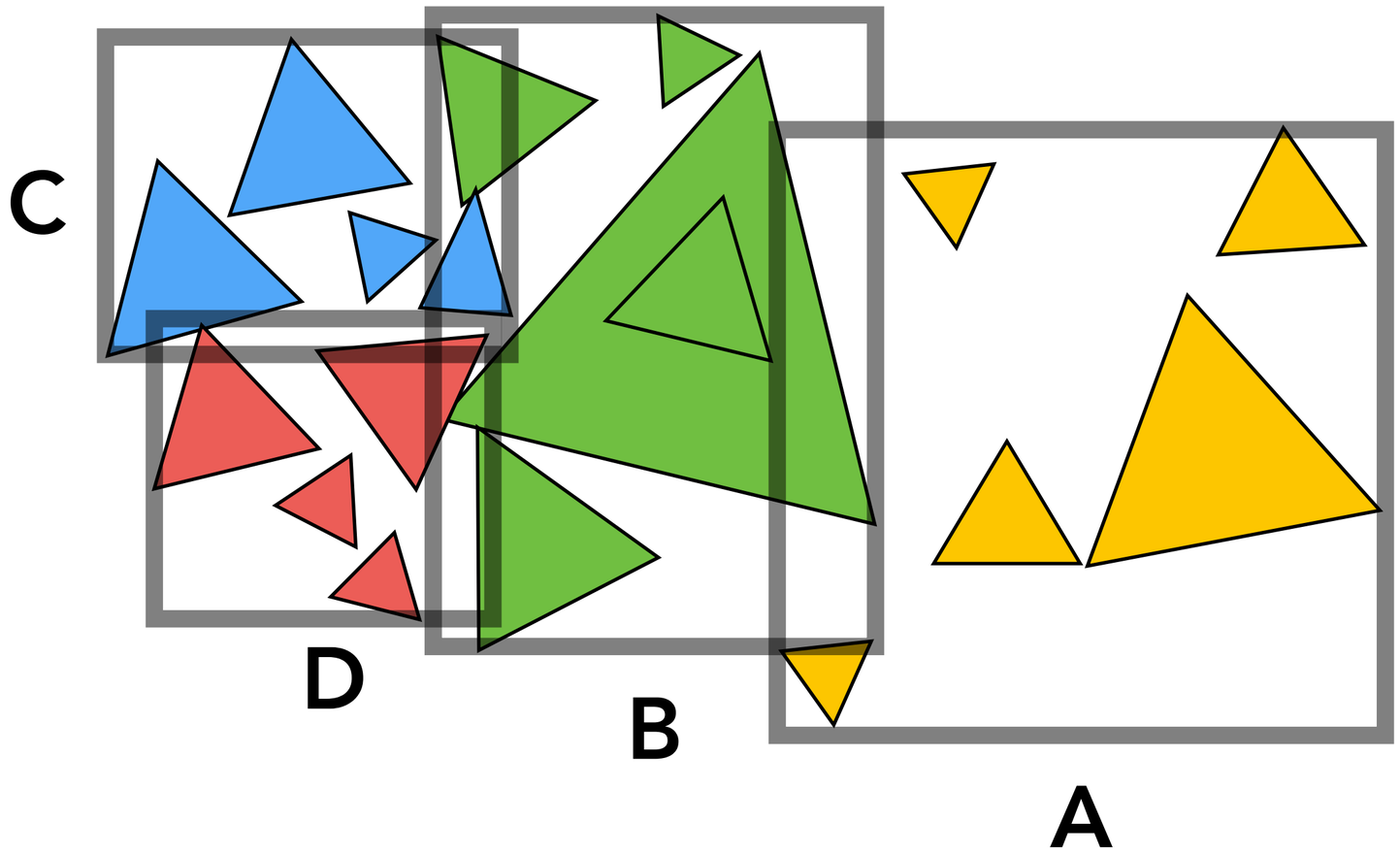
How much does it now cost to find k (*including sorting*)?

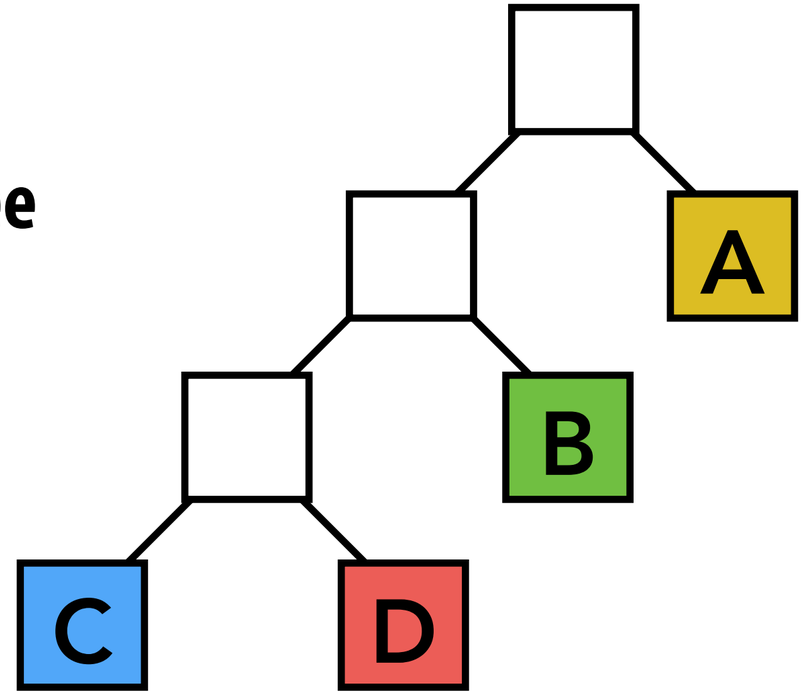
Cost for just ONE query: O(n log n) *worse* than before! :-(

Amortized cost over many queries: O(log n) . . . *much* better!

Bounding volume hierarchy (BVH)

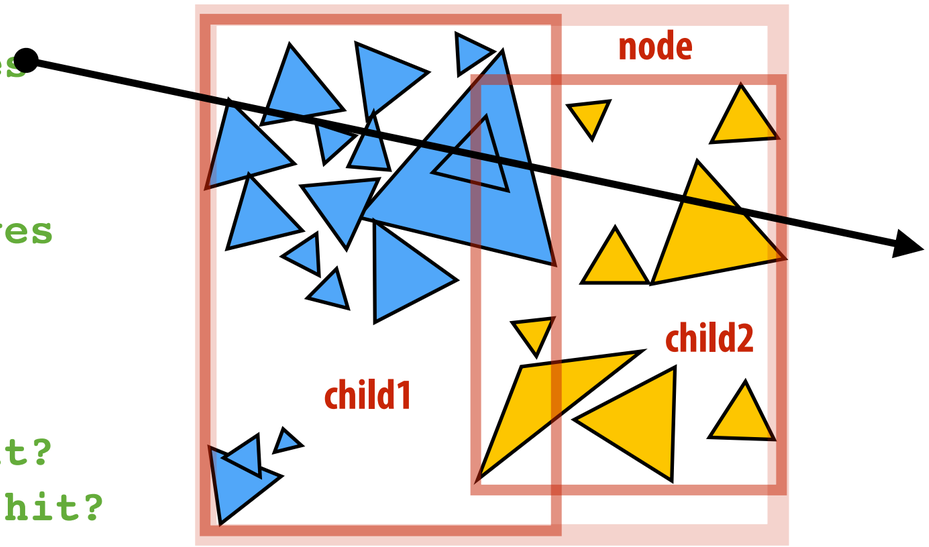
- **Leaf nodes:**
  - **Contain *small* list of primitives**
- **Interior nodes:**
  - **Proxy for a *large* subset of primitives**
  - **Stores bounding box for all primitives in subtree**





Ray-scene intersection using a BVH

```
struct BVHNode {
   bool leaf;  // true if node is a leaf
   BBox bbox;  // min/max coords of enclosed primitives
   BVHNode* child1; // "left" child (could be NULL)
   BVHNode* child2; // "right" child (could be NULL)
   Primitive* primList; // for leaves, stores primitives
};

struct HitInfo {
   Primitive* prim;  // which primitive did the ray hit?
   float dist;       // what is dist along ray to the hit?
};

void find_closest_hit(Ray* ray, BVHNode* node, HitInfo* closest) {
   HitInfo hit = intersect(ray, node->bbox);  // test ray against node's bounding box
   if (hit.prim == NULL || hit.dist > closest.dist))
      return; // don't update the hit record

   if (node->leaf) {
      for (each primitive p in node->primList) {
         hit = intersect(ray, p);
         if (hit.prim != NULL && hit.dist < closest.dist) {
            closest.prim = p;
            closest.dist = hit.dist;
         }
      }
   } else {
      find_closest_hit(ray, node->child1, closest);
      find_closest_hit(ray, node->child2, closest);
   }}
```



How could this occur?

Workload: basic rasterization vs. basic ray casting

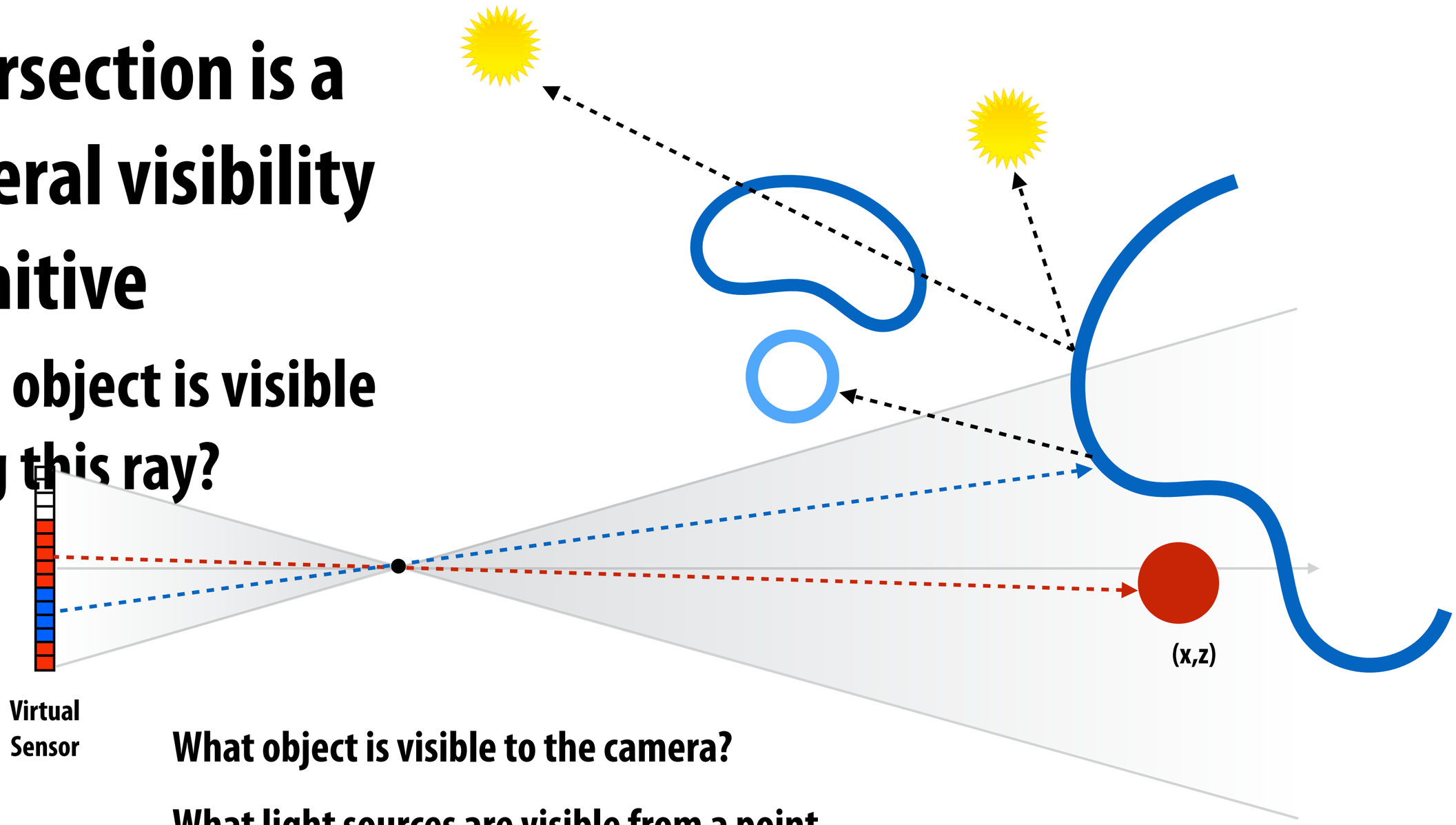
- **Basic rasterization:**
  - *Stream over triangles* in order (never have to store in entire scene in memory, naturally supports unbounded size scenes)
    - Do not need random access to triangle data
  - Must keep depth buffer in memory
    - Need *random access to a regular, fixed-size data structure (color/depth buffer)*

- **Ray casting:**
  - *Stream over screen samples* (rays)
    - No need to store closest depth so far for the entire screen (just current ray)
  - Must store acceleration structure for scene in memory *(unpredictable access to irregular search tree)*

Generality of ray-scene queries

Ray-scene intersection is a general visibility primitive

What object is visible along this ray?



What object is visible to the camera?

What light sources are visible from a point on a surface (Is a surface in shadow?)

What reflection is visible on a surface?

Direct illumination + reflection + transparency

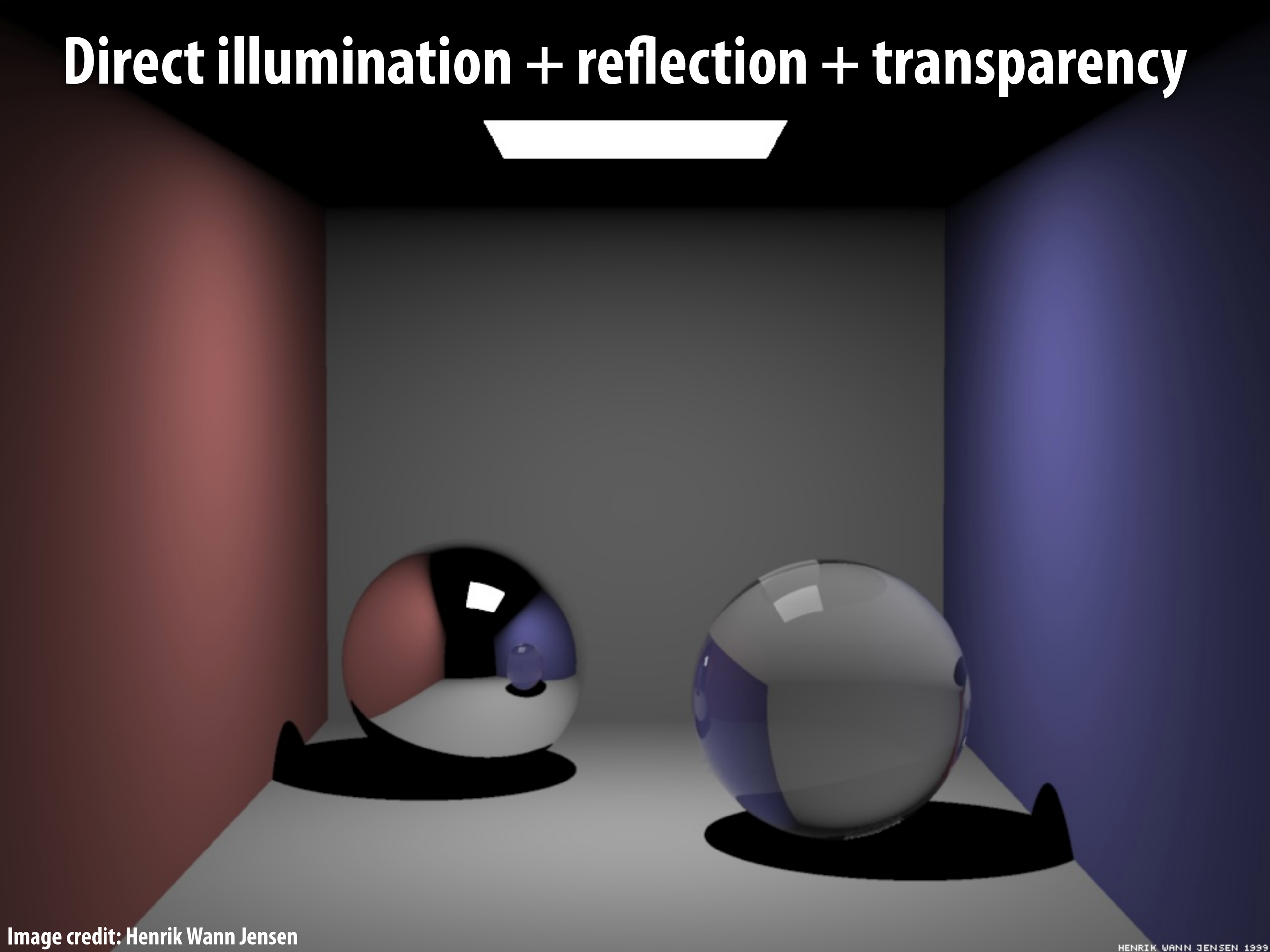


Image credit: Henrik Wann Jensen

Global illumination solution

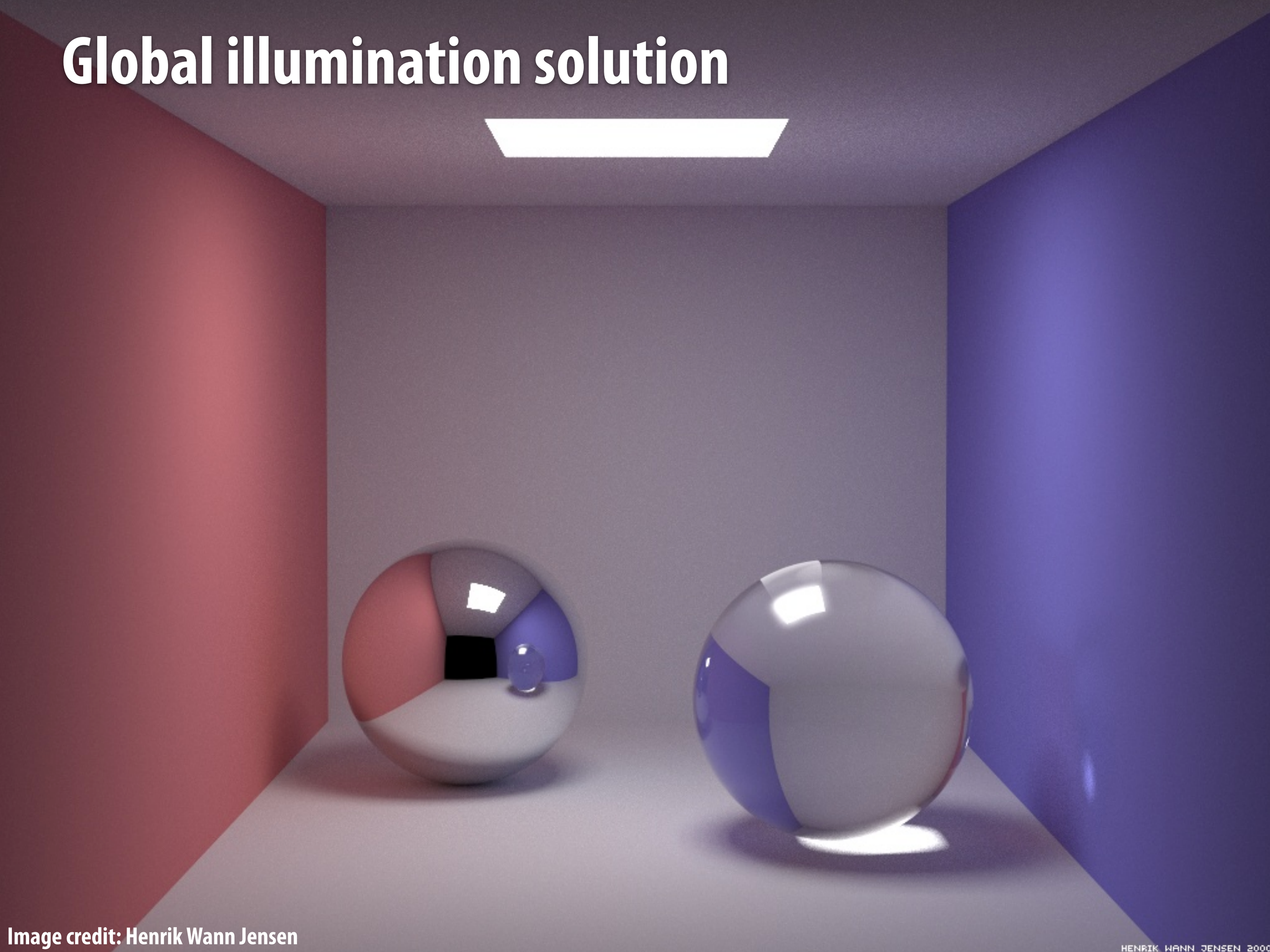


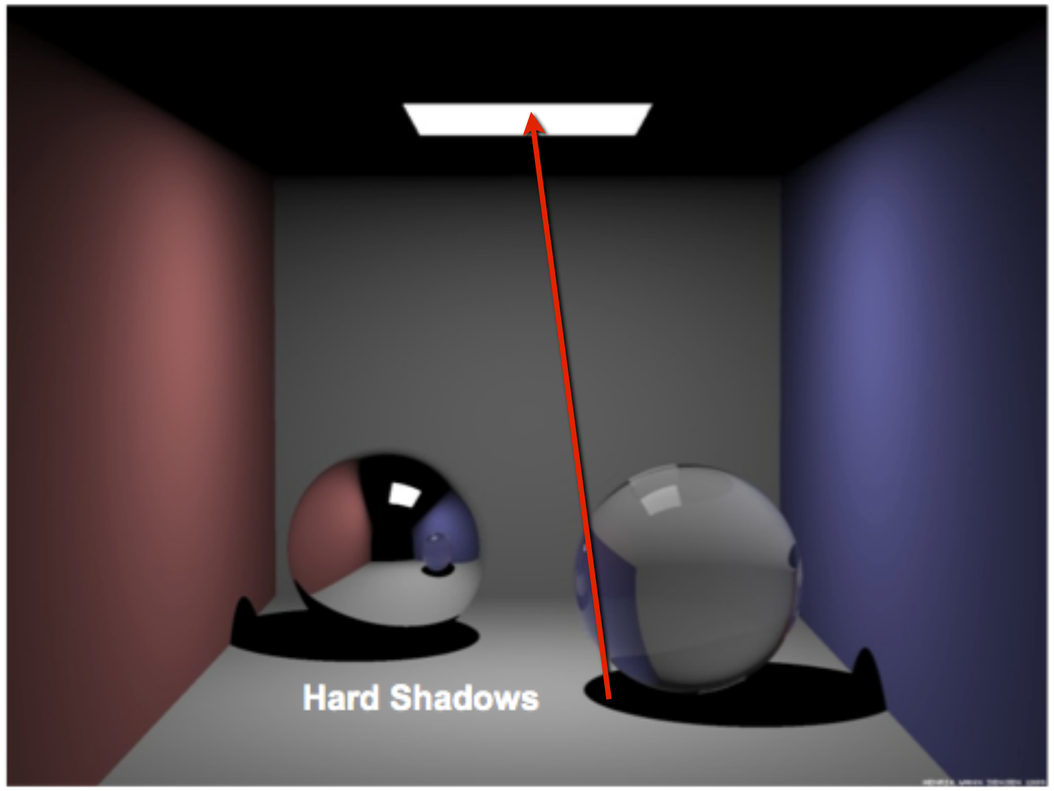
Image credit: Henrik Wann Jensen

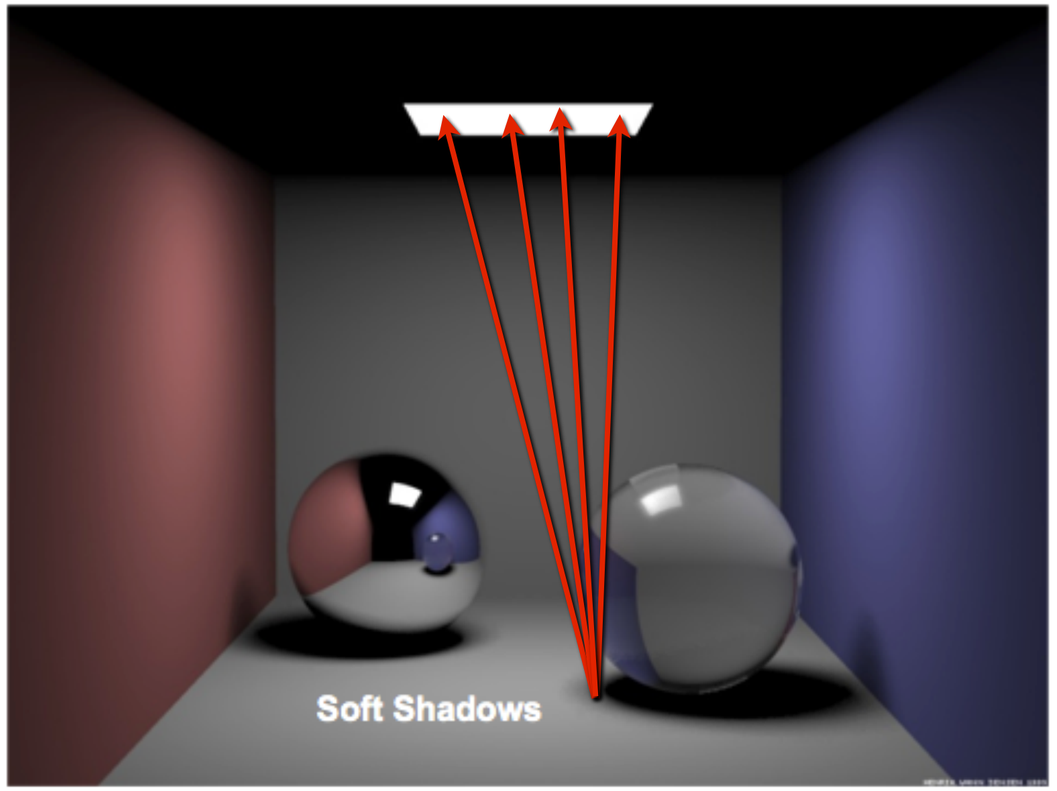
Direct illumination

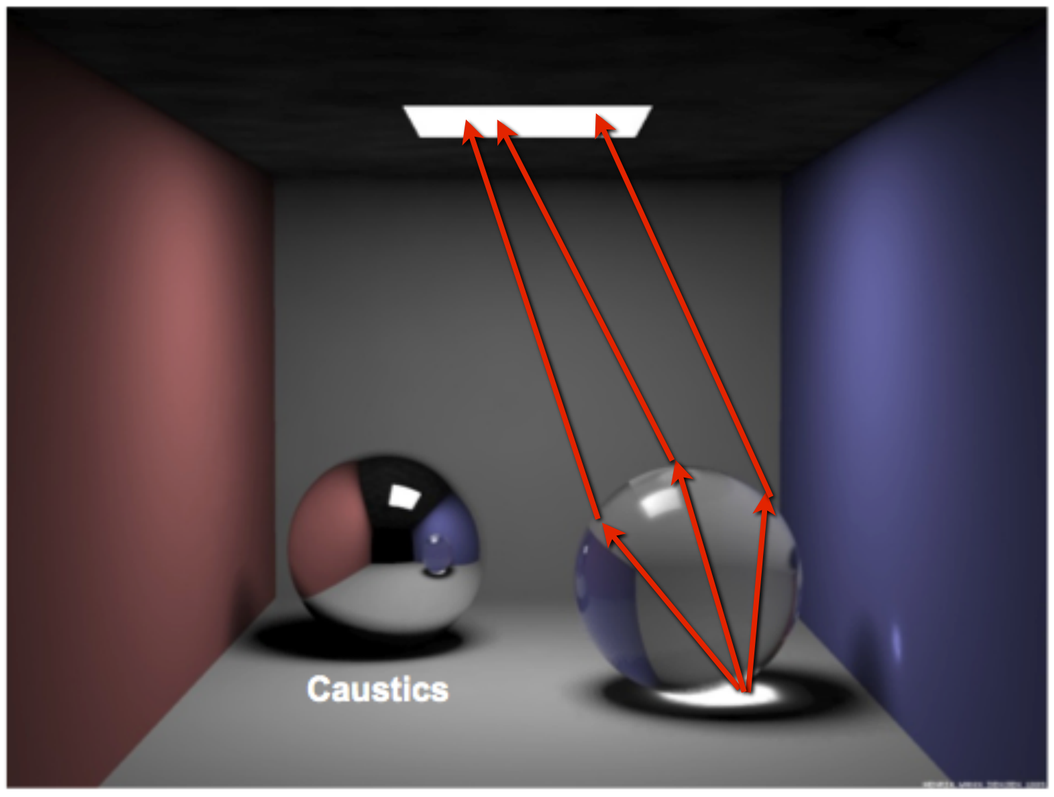
One-bounce global illumination

Sixteen-bounce global illumination

Sampling light paths







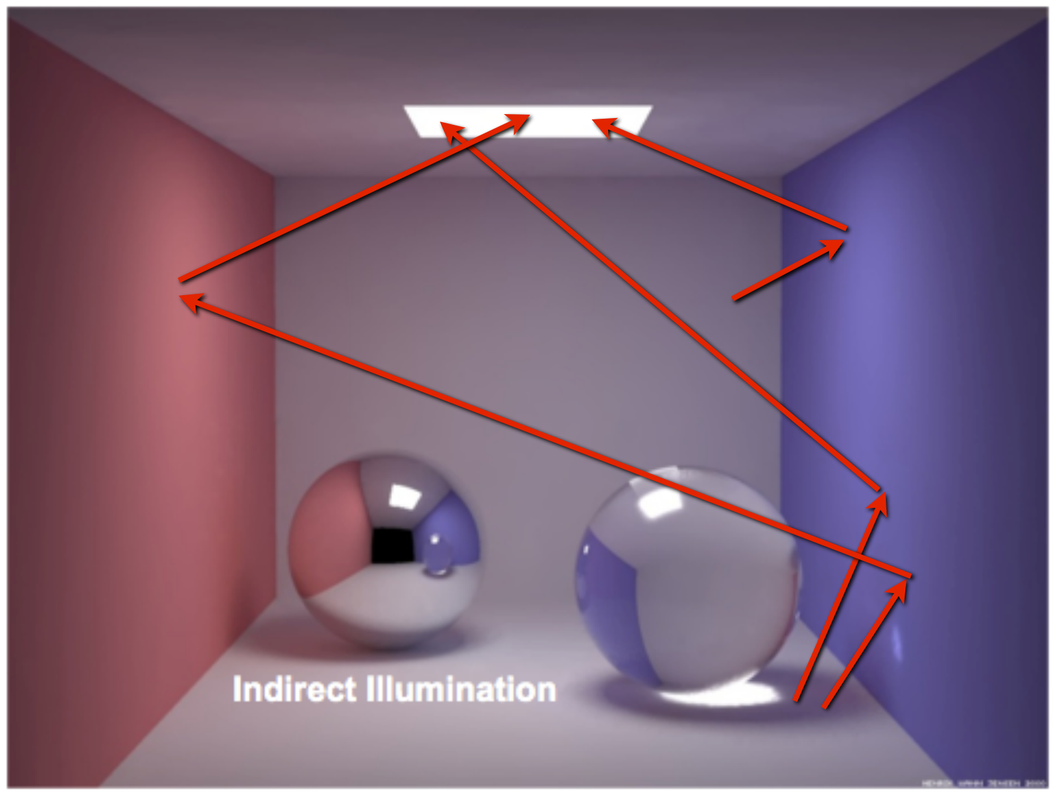
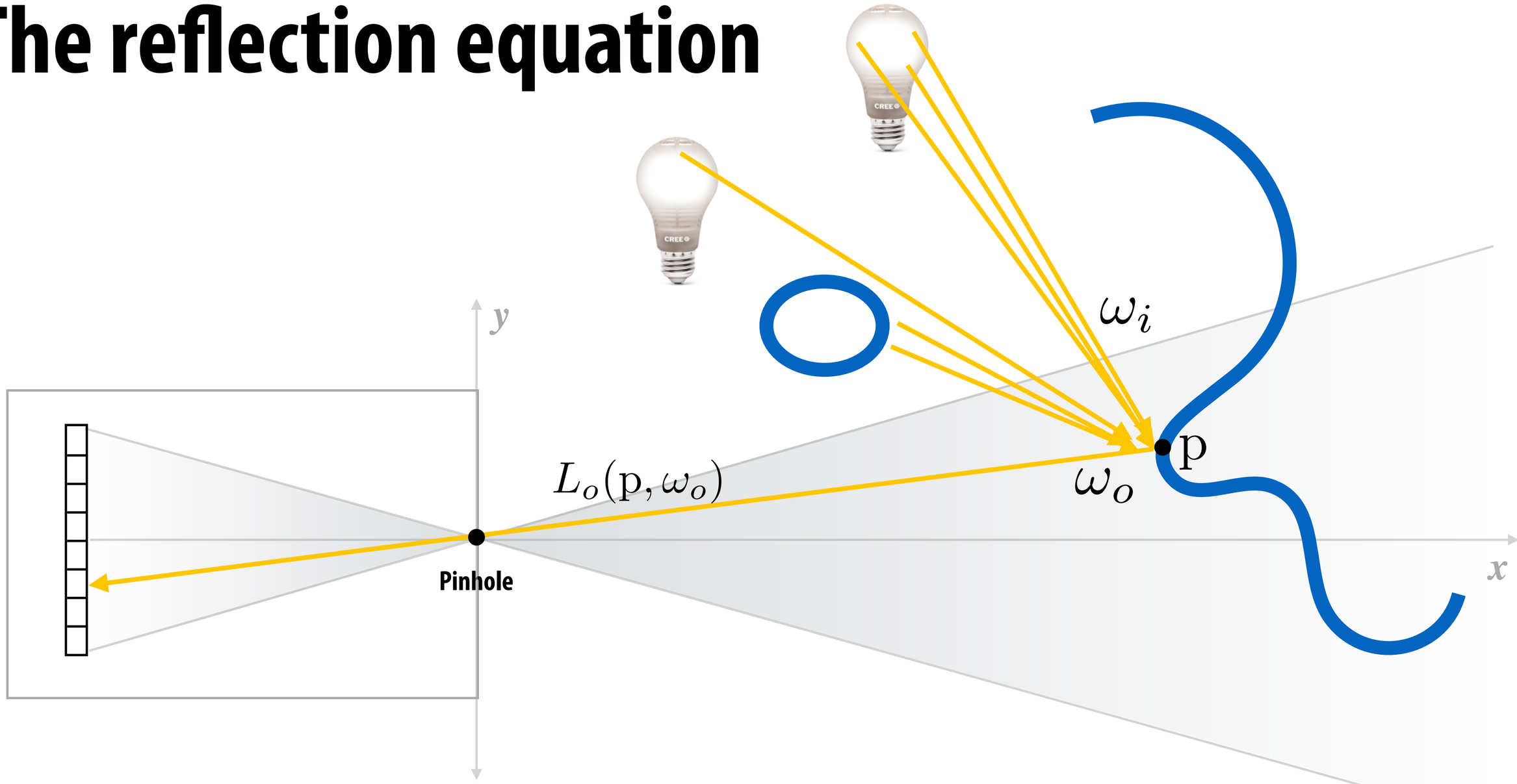


Image credit: Wann Jensen, Hanrahan

The reflection equation

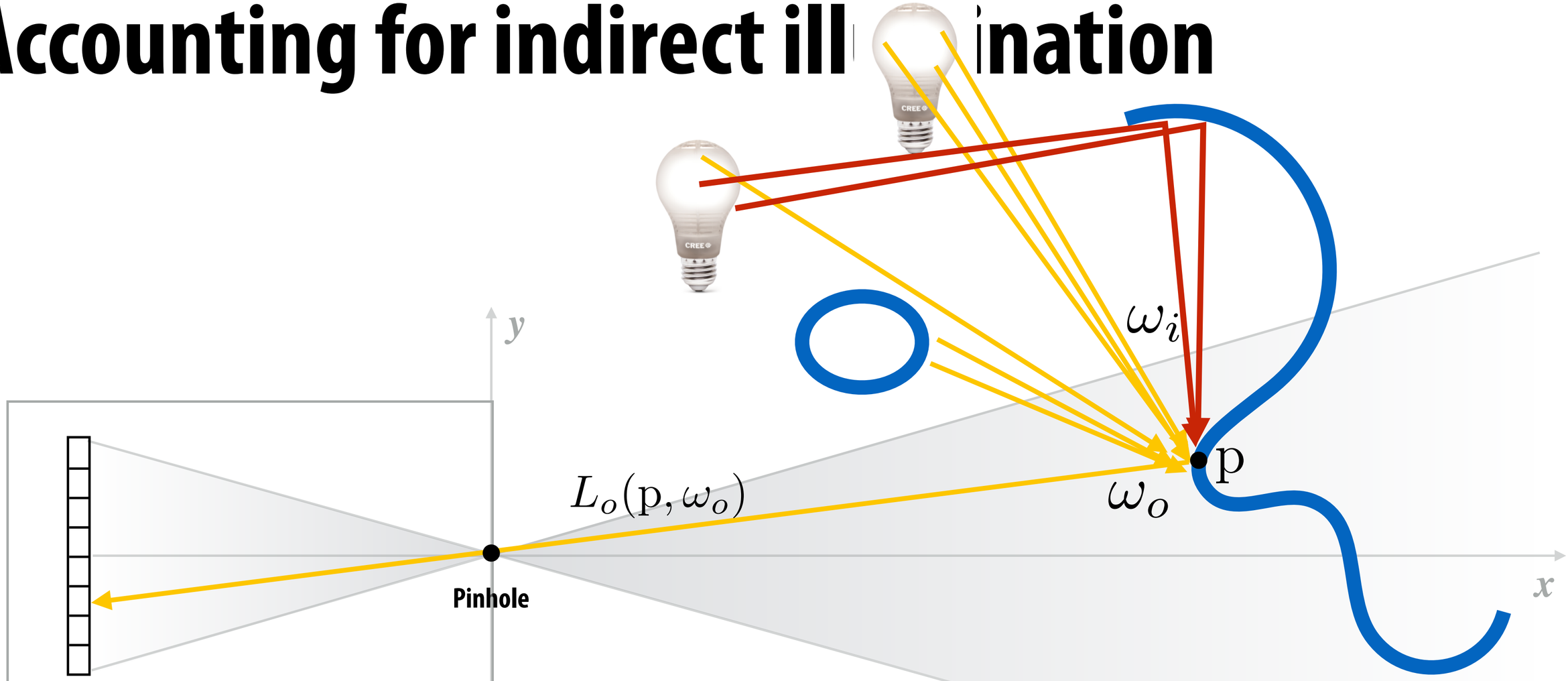


$$L_o(\mathrm{p}, \omega_o) = L_e(\mathrm{p}, \omega_o) + \int_{H^2} f_r(\mathrm{p}, \omega_i \rightarrow \omega_o)\, L_i(\mathrm{p}, \omega_i)\, \cos\theta_i \, \mathrm{d}\omega_i$$

1 area light sample
(high variance in irradiance estimate)

16 area light samples
(lower variance in irradiance estimate)

Accounting for indirect illumination



$$L_o(\mathrm{p}, \omega_o) = L_e(\mathrm{p}, \omega_o) + \int_{H^2} f_r(\mathrm{p}, \omega_i \rightarrow \omega_o)\, L_i(\mathrm{p}, \omega_i)\, \cos\theta_i \, \mathrm{d}\omega_i$$

Incoming light energy from direction ω_i may be due to light reflected off another surface in the scene (not an emitter)

Path tracing pseudocode

```
Color pathtrace(Ray ray) {
  Intersection isect = scene.intersect(ray);
  Vector2D wo = -ray.d;
  Vector2D wi;
  float pdf;
  generate_direction_sample(isect.brdf, wo, &wi, &pdf); // random direction to sample indirect
  Color f = isect.brdf.f(wo, wi);
  float terminateProbability = 1.f - f.rho();     // termination probability based on reflectance.
                                                  // Lower reflectance = high chance of terminating

  Lo = estimate_direct_lighting(isect, wo);       // reflectance in outgoing direction
  if (RandomFloat() >= terminateProbability)
     Lo += ((f * pathtrace(Ray(isect.P, wi)) * Dot(wi, isect.N) / (pdf * (1-terminateProbability)));
  return Lo;
}
```

One sample per pixel

32 samples per pixel

1024 samples per pixel

Ray tracing performance challenges

3D ray-triangle math is more expensive than point-in-triangle math of rasterization

Ray-scene intersection requires traversal through bounding volume hierarchy acceleration structure

- **Unpredictable data access**
- **Rays are essentially randomly oriented after enough bounces**

To simulate advanced effects in a ray tracer, renderer must trace many rays per pixel to reduce variance (noise) that results from numerical integration (via Monte Carlo sampling)

Ray tracing architectures

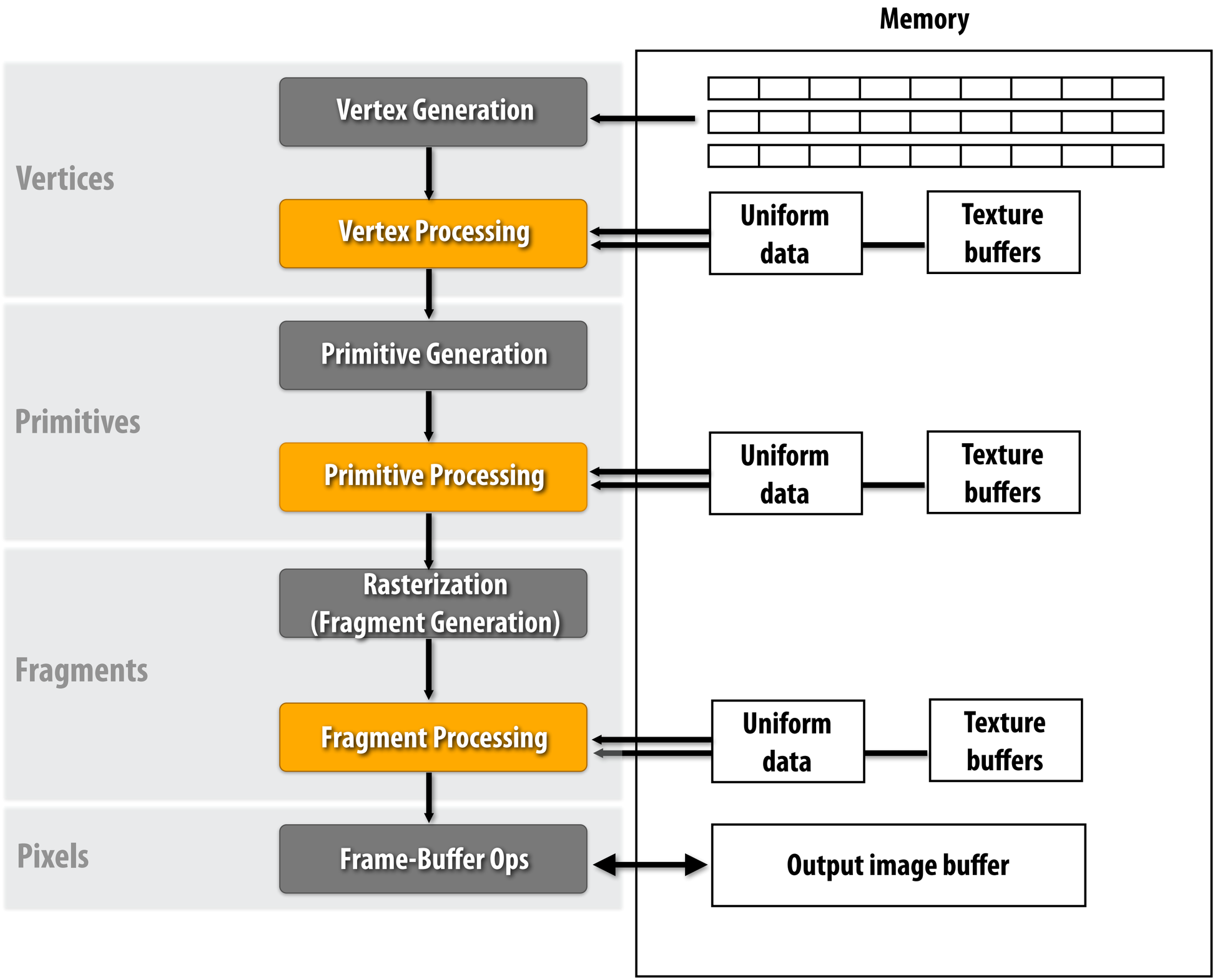
Keep in mind

- An application developer has always been able to write a ray tracer in CUDA

- So the ability to use a GPU to perform ray tracing is not new

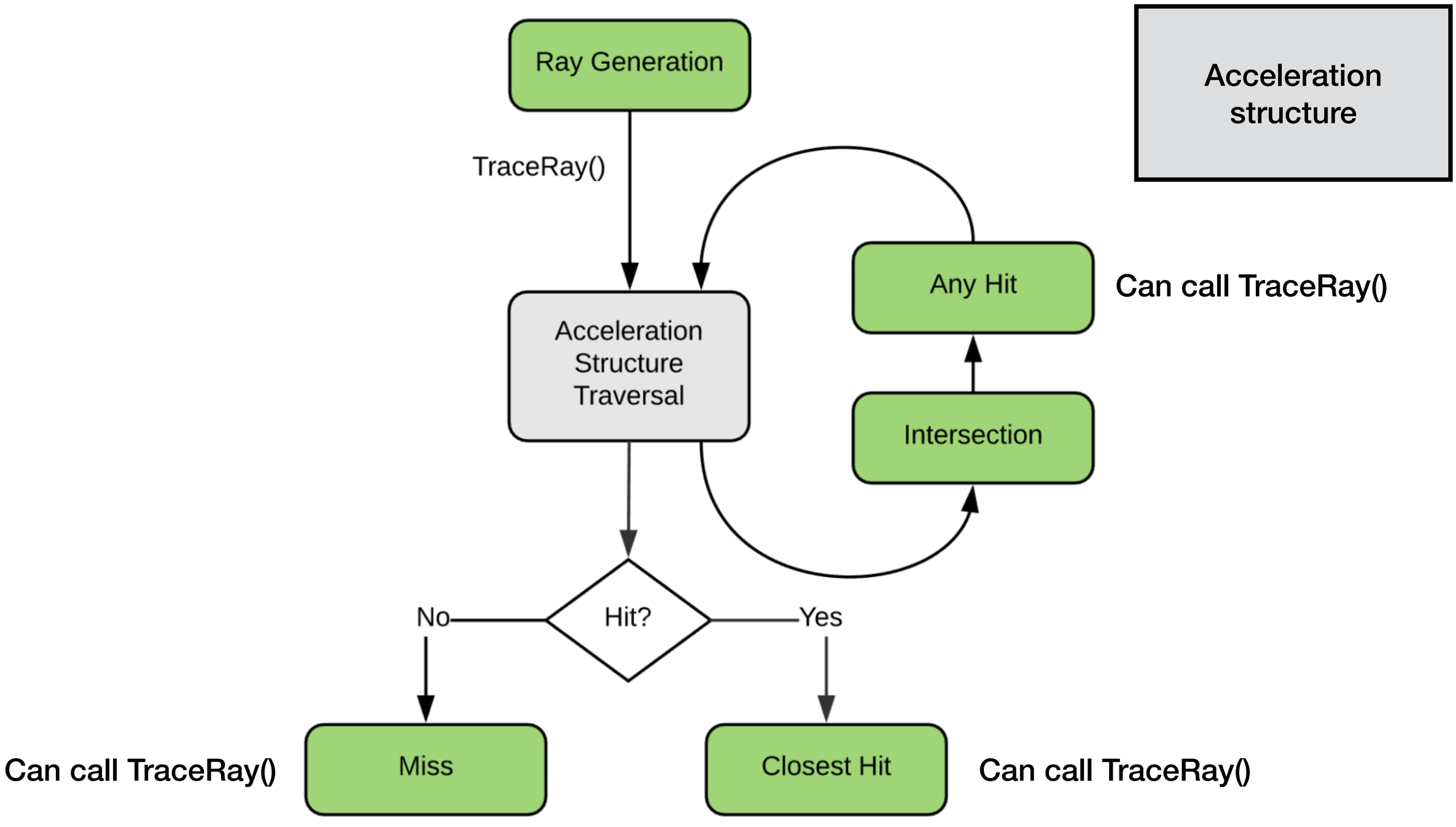
- But by establishing a new architecture for ray tracing, GPU vendors give themselves the opportunity to accelerate/optimize implementations

Recall: traditional graphics pipeline arch

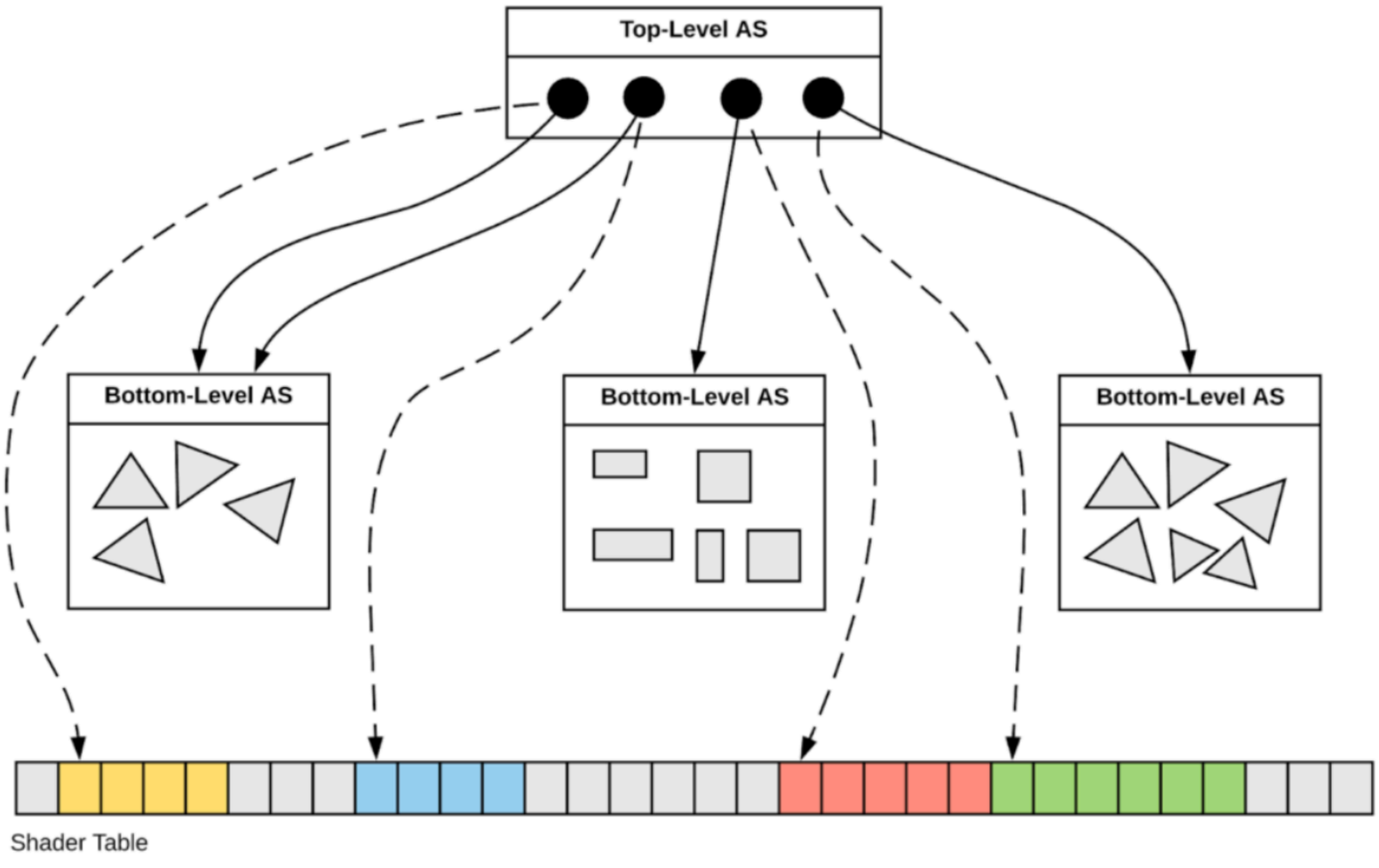


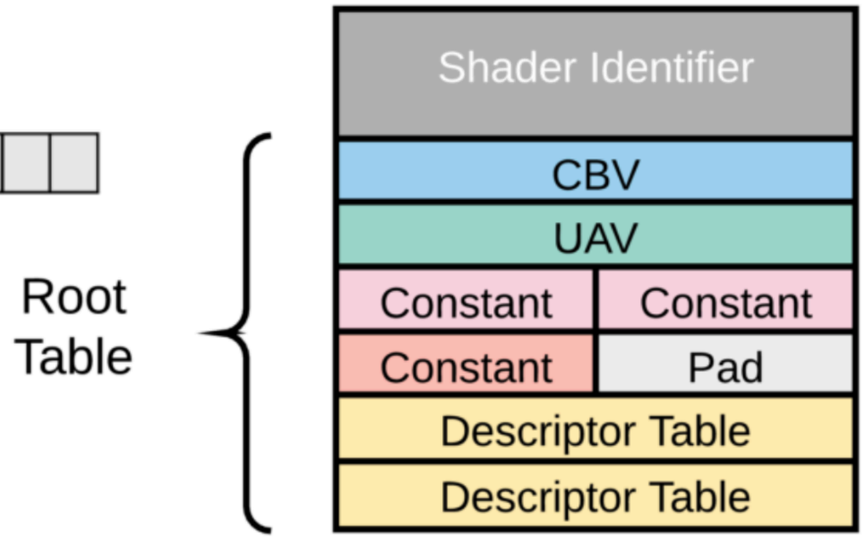
Ray tracing architecture (RTX)

- **TraceRay() is a blocking function that can be called by shaders**



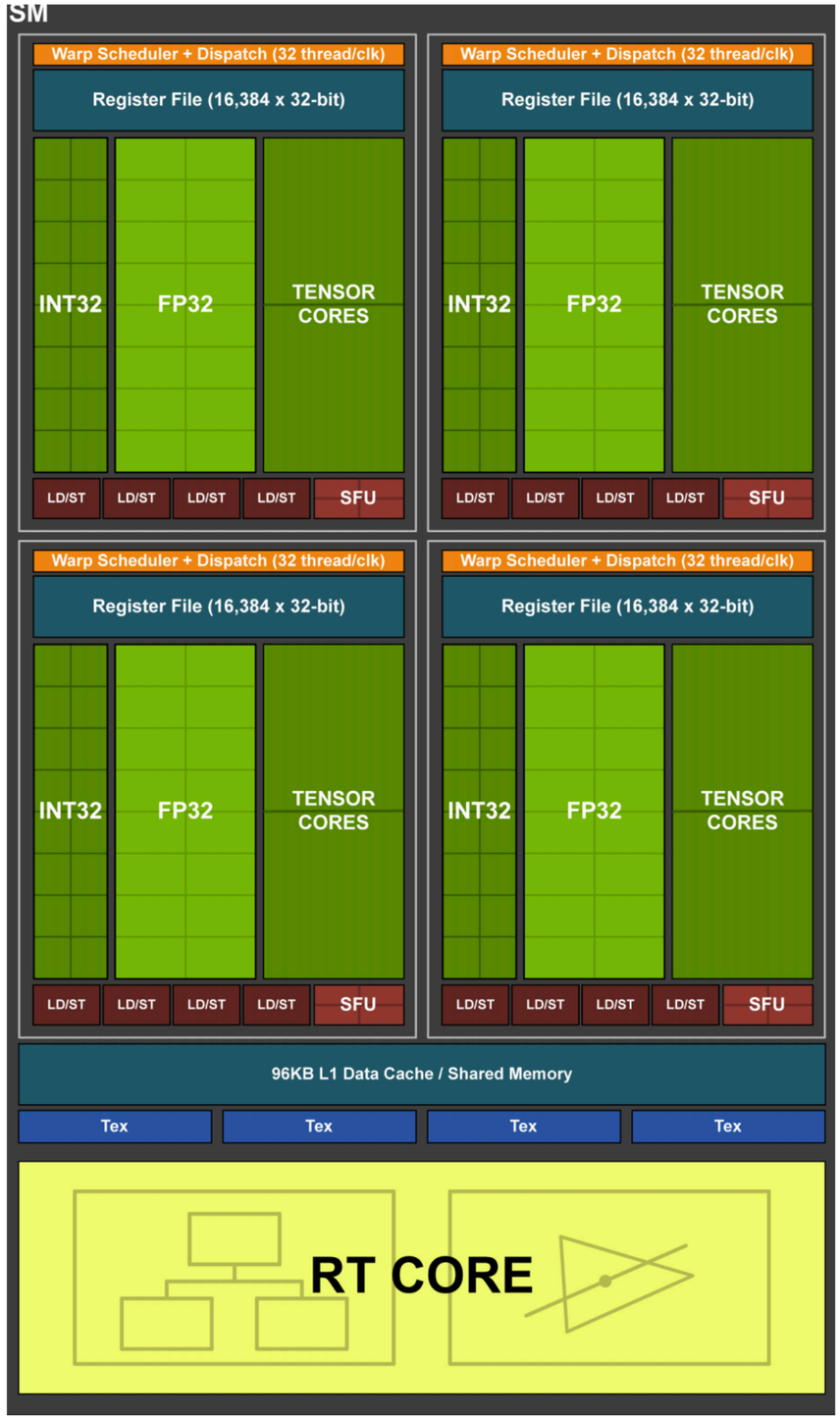
Ray tracing architecture maintains BVH acceleration structure for all scene objects and "shader table" (which shader to run for each object in scene)





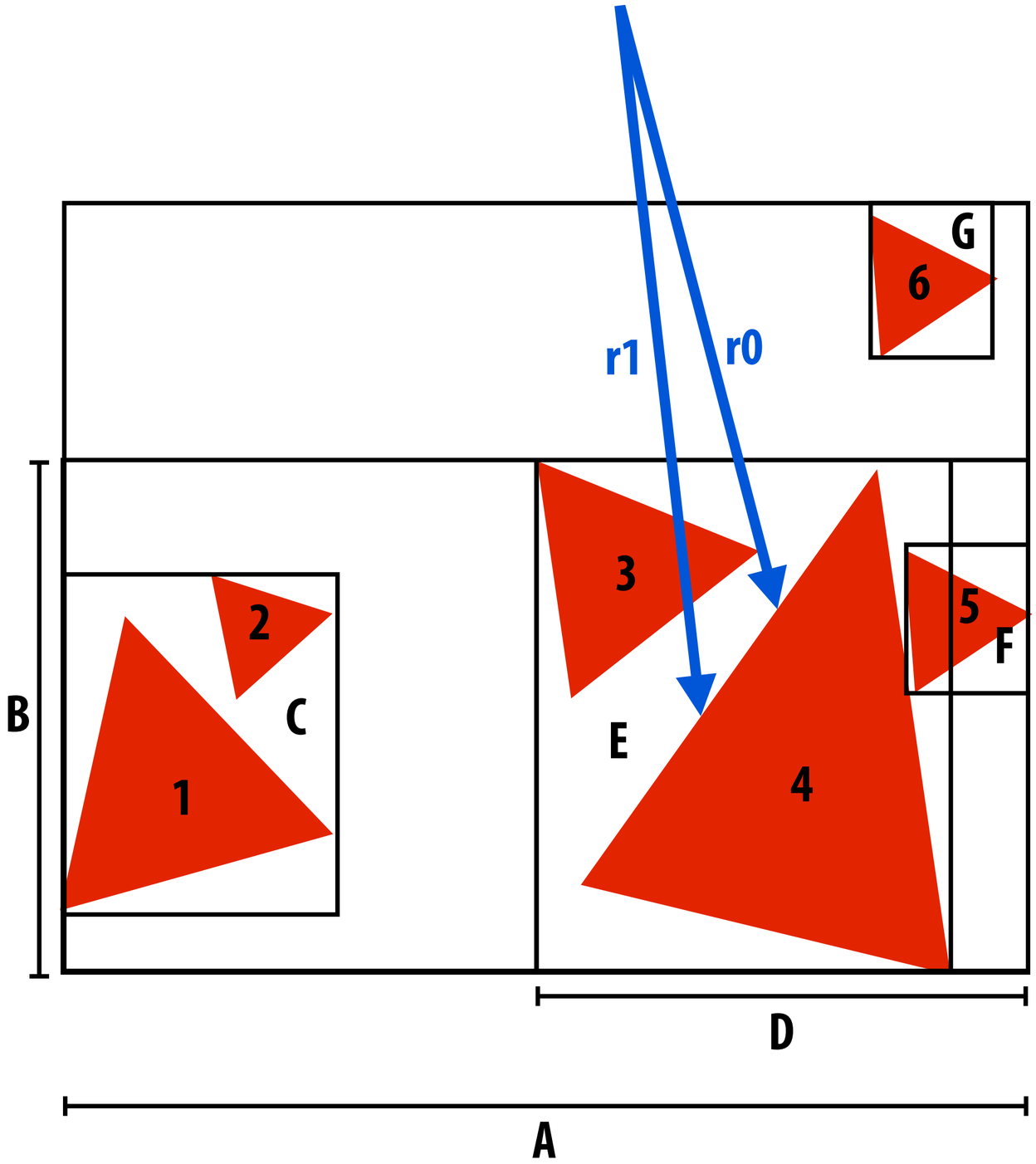
RT acceleration in NVIDIA Turing GPUs

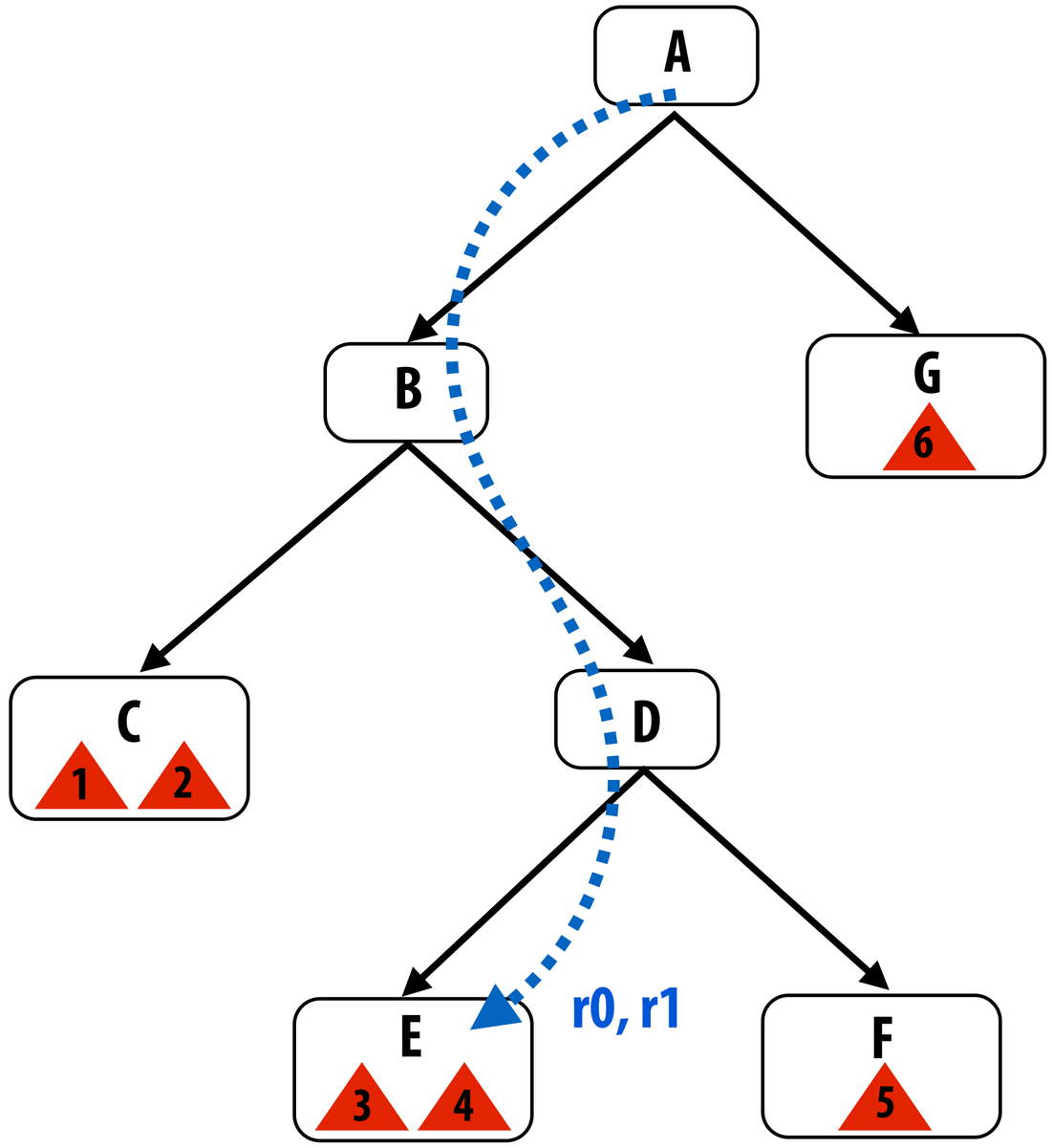
- **Custom processing elements for:**
  - **ray-triangle intersection**
  - **ray-box intersection / BVH traversal**



Ray traversal "coherence"

r0 visits nodes: A, B, D, E…
r1 visits nodes: A, B, D, E…

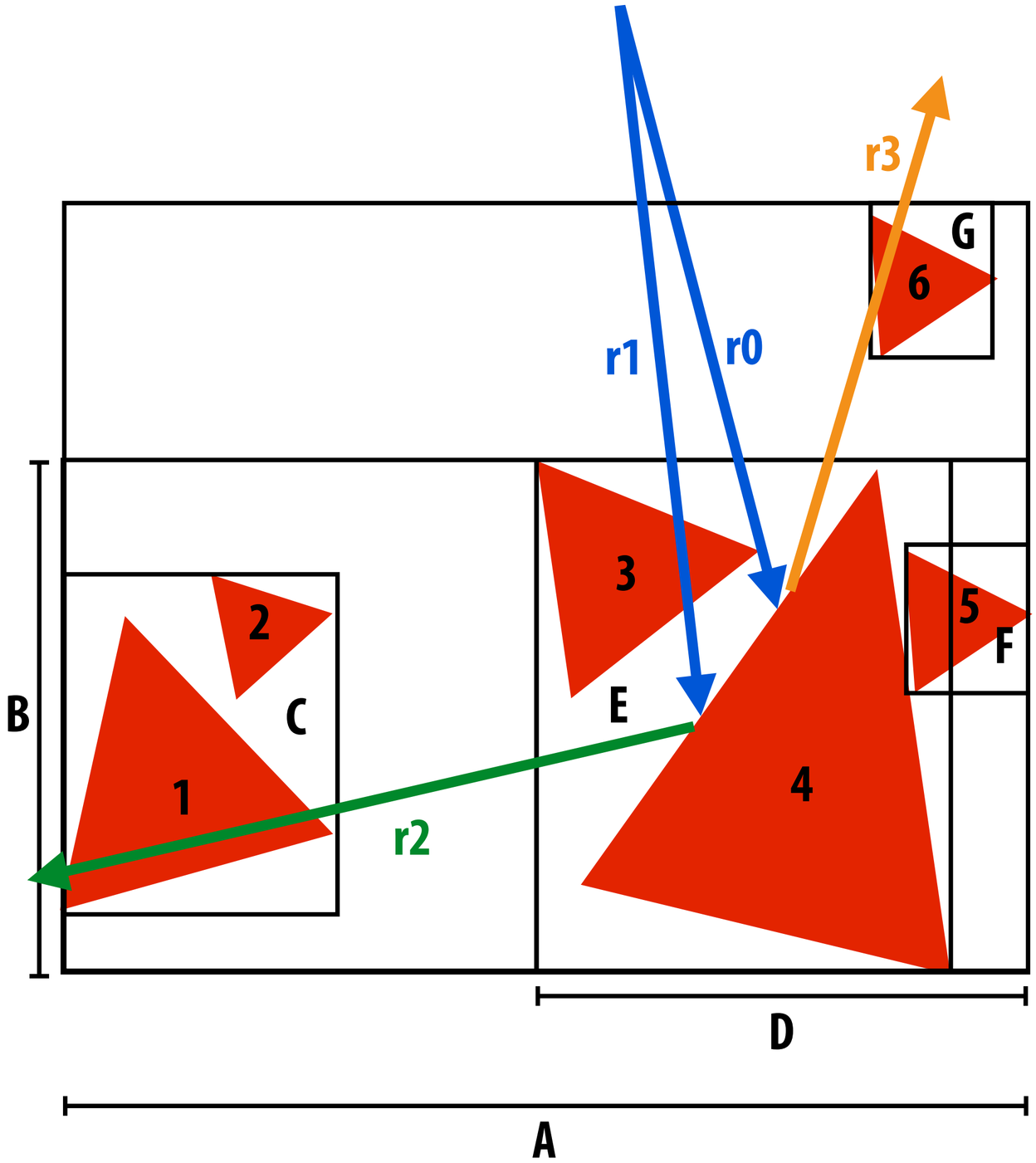


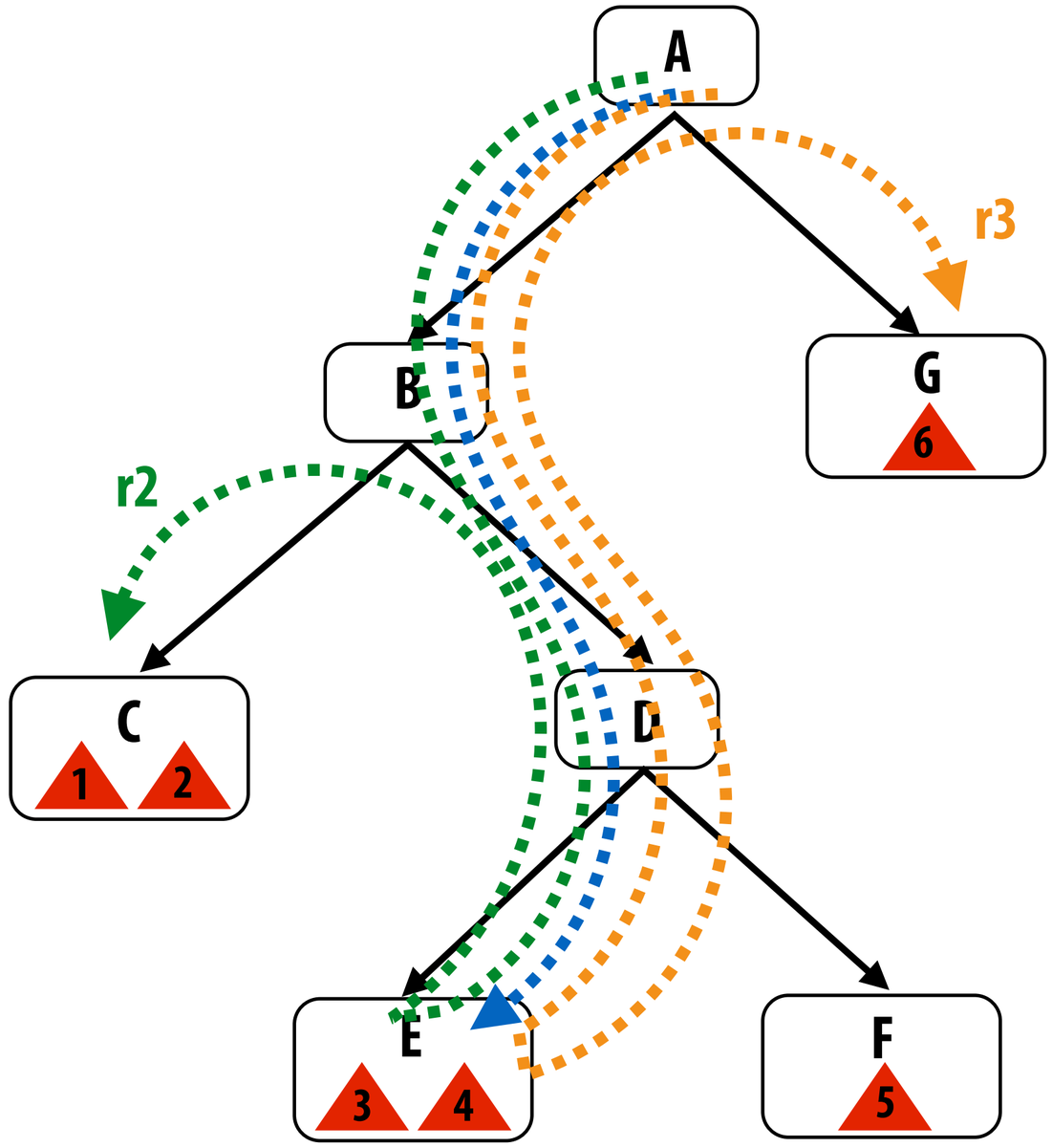


Bandwidth reduction: BVH nodes (and triangles) loaded into cache for computing scene intersection with r0 are cache hits for r1

Ray traversal "divergence"

r0 visits nodes: A, B, D, E…
r1 visits nodes: A, B, D, E…
r2 visits nodes: A, B, D, E, C…
r3 visits nodes: A, B, D, E, G…

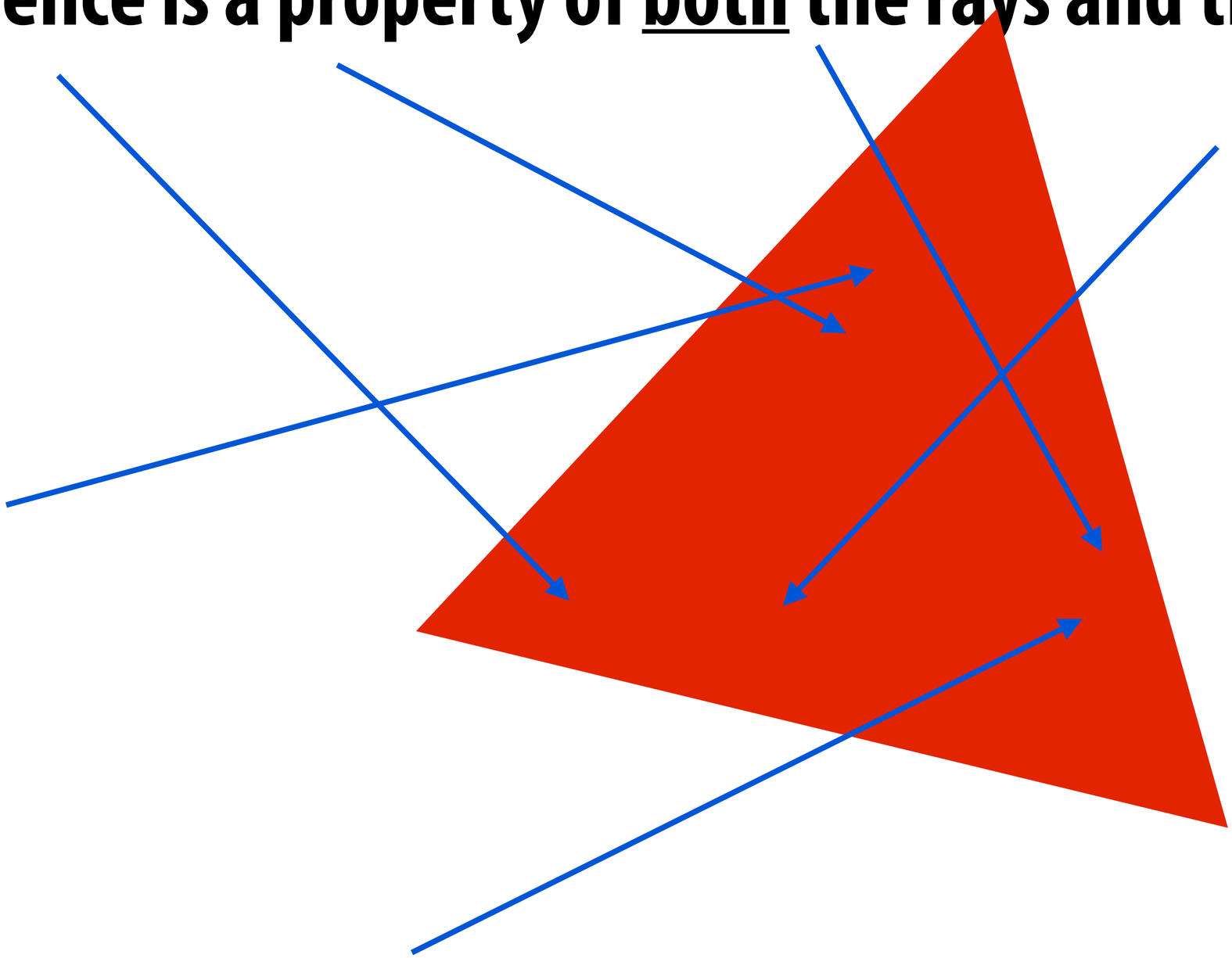




R2 and R3 require different BVH nodes and triangles

Incoherent rays

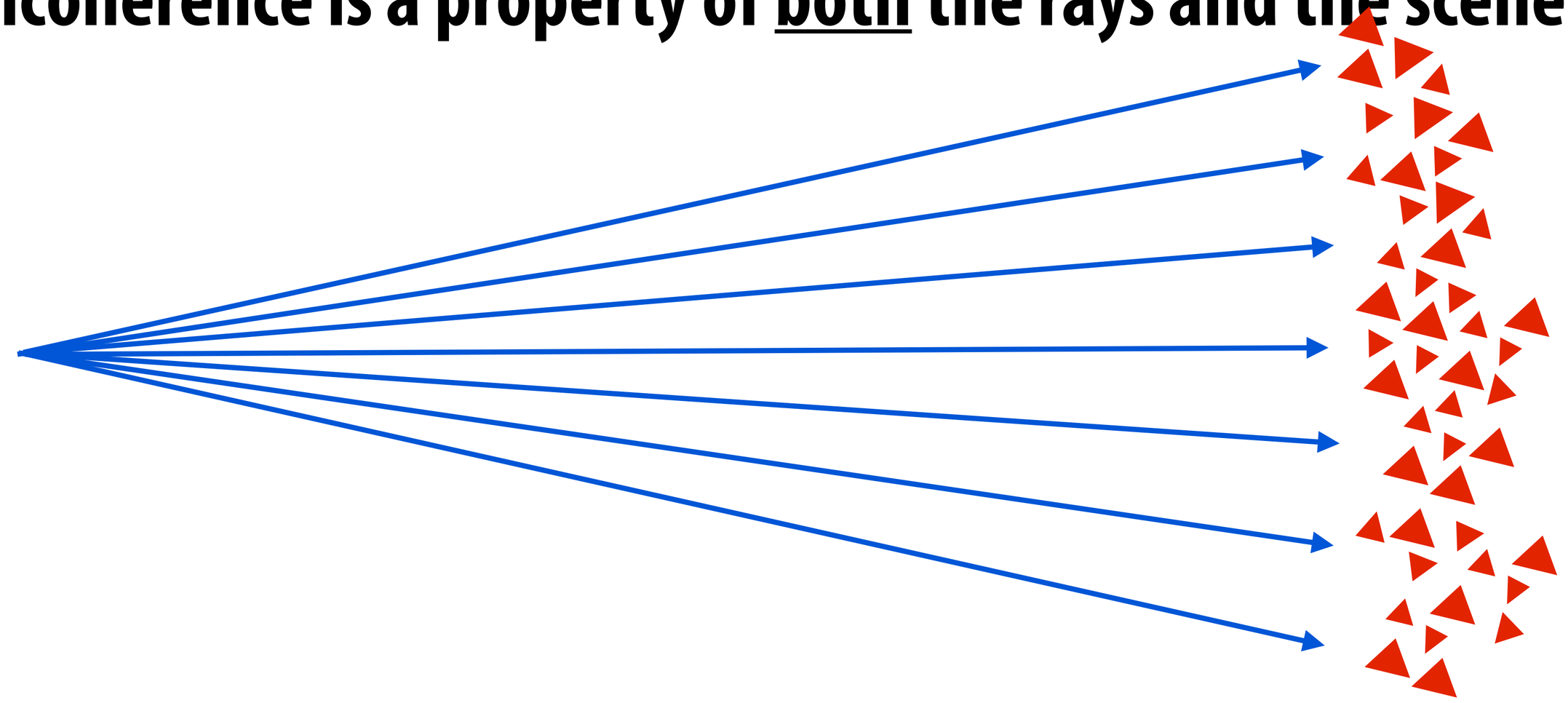
Incoherence is a property of <u>both</u> the rays and the scene



Random rays are "coherent" with respect to the BVH if the scene is one big triangle!

Incoherent rays

Incoherence is a property of <u>both</u> the rays and the scene



Camera rays become "incoherent" with respect to lower nodes in the BVH if a scene is overly detailed

(Side note: this suggests the importance of choosing the right geometric level of detail)

Ray incoherence

Nearby rays may hit different surfaces, with different shaders

Consider implications for SIMD processing

Recall difference in ordering

Rasterizer:

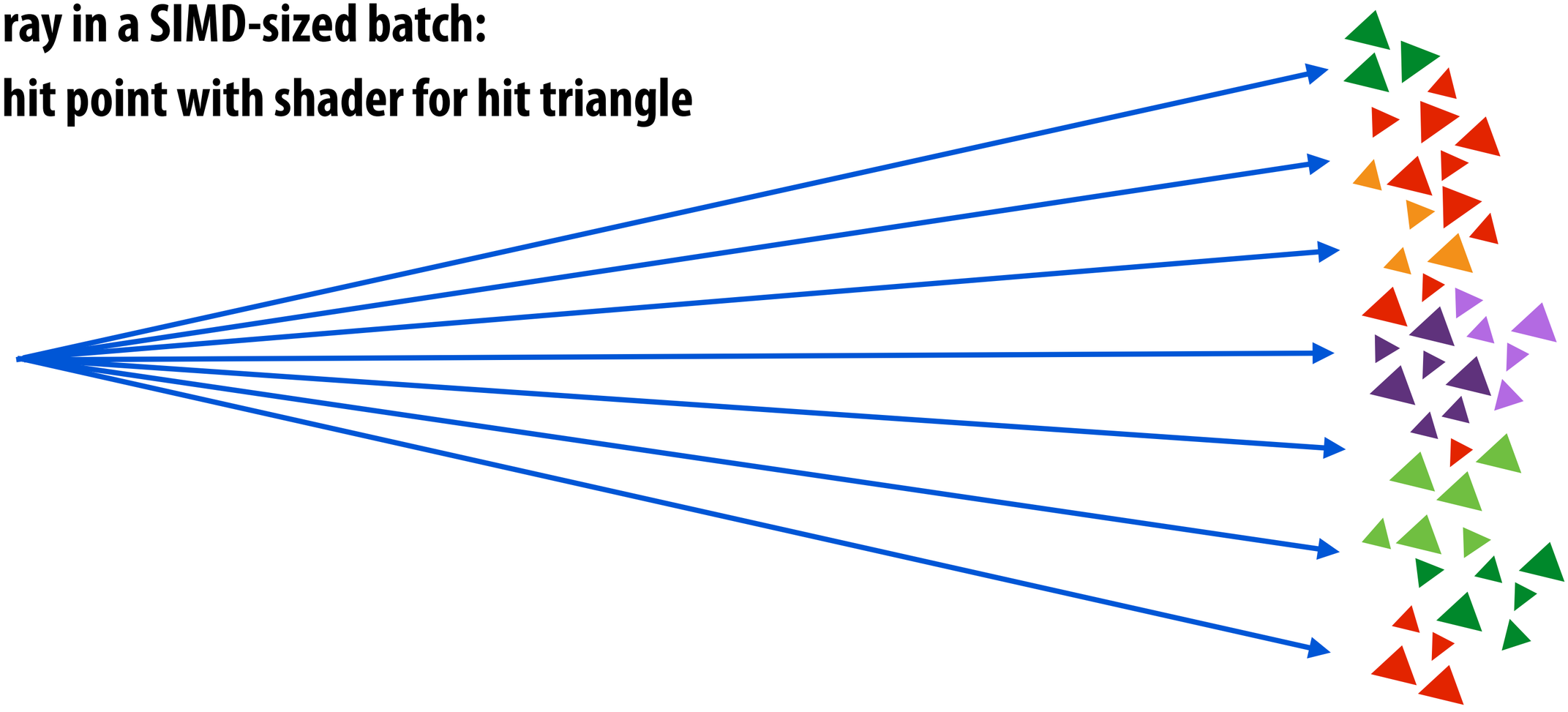
For each triangle

shade SIMD batch of pixels in parallel (with same shader)

Ray tracer:

For each ray in a SIMD-sized batch:

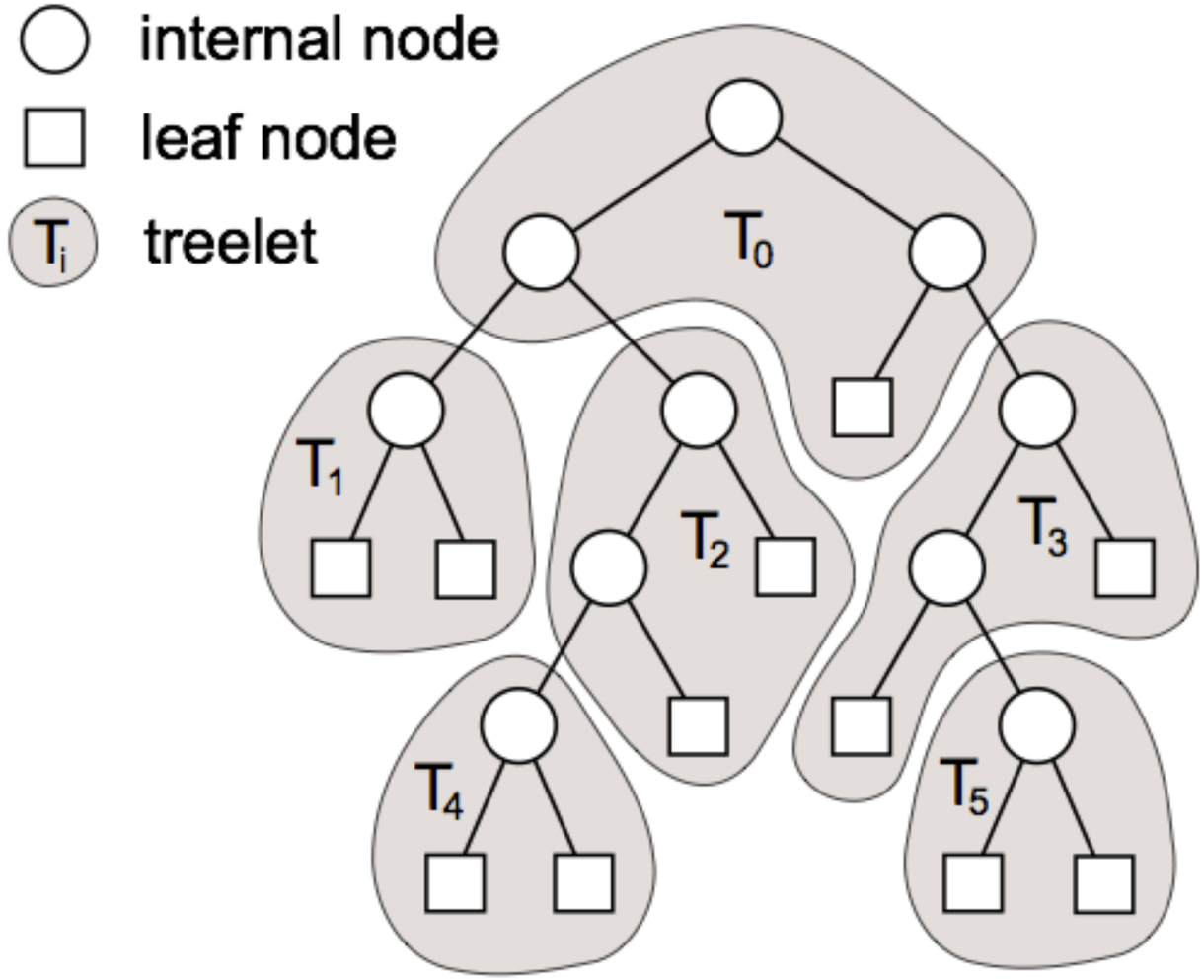
shade hit point with shader for hit triangle



Global ray reordering

[Pharr 1997, Navratil 07, Alia 10]

Idea: dynamically batch up rays that must traverse the same part of the scene. Process these rays together to increase locality in BVH access



Partition BVH into treelets
(treelets sized for L1 or L2 cache)

1. **When ray (enters treelet, add rays to per-treelet queue**

2. **When treelet queue is sufficiently large, intersect enqueued rays with treelet**
   (amortize load of treeless data across all enqueued rays)

Buffering overhead to global ray reordering: must store per-ray "stack" (need not be entire call stack, but must contain traversal history) for many rays.

Per-treelet ray queues sized to fit in caches (or in dedicated ray buffer SRAM)

Denoising ray traced images

32 samples per pixel

Deep learning-based denoising

- Idea: Use image-to-image transfer methods based on deep learning to convert cheap to compute (but noisy) ray traced images into higher quality images that look like they were produced by shooting many rays per pixel

Denoising examples

Image credit: Intel Open Image Denoise : https://openimagedenoise.github.io/

Denoising examples

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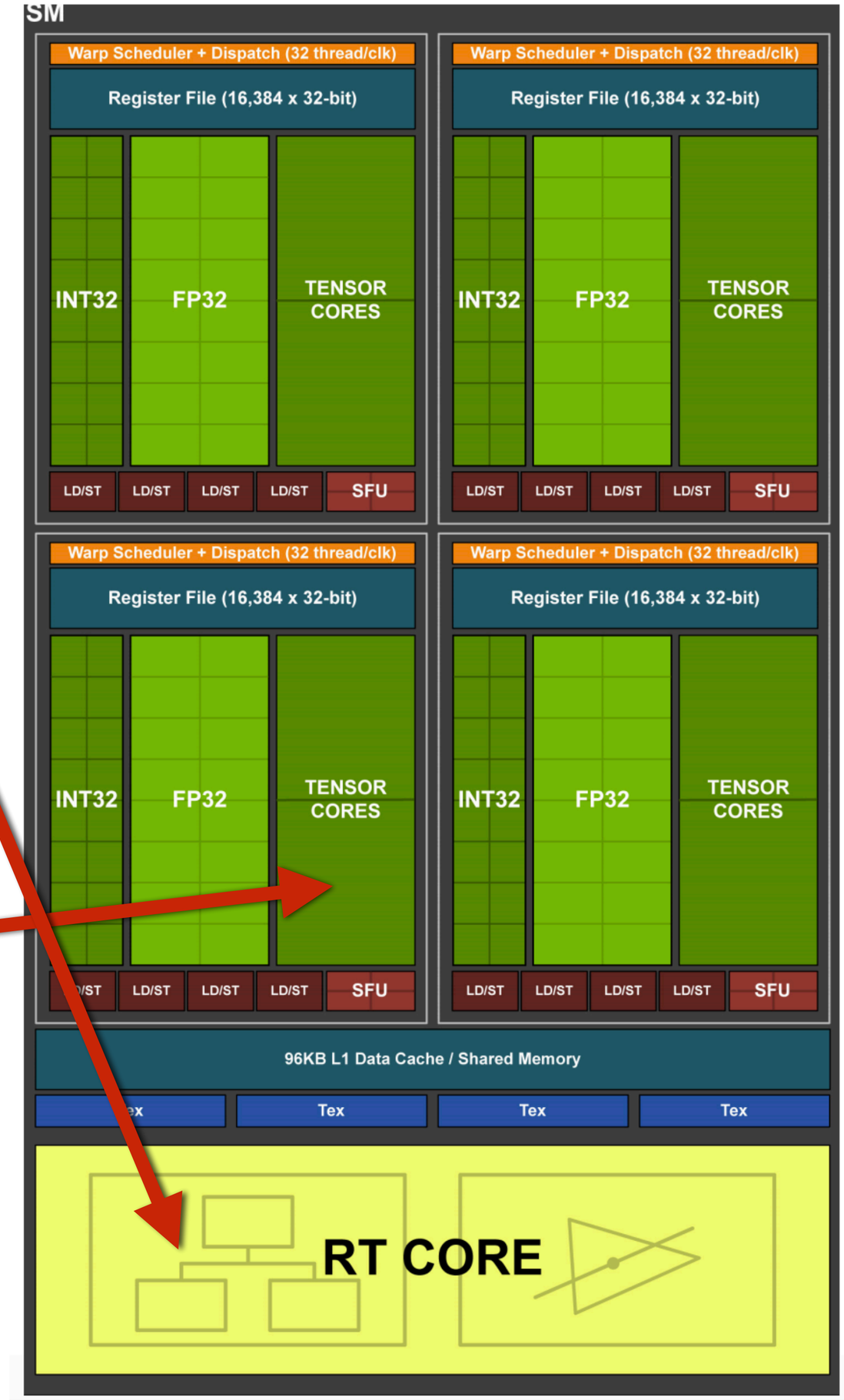
Surprising synergies

- New GPU hardware for ray-tracing operations

- But ray tracing still too expensive for noise-free images in real-time

- Tensor core: specialized hardware for accelerated DNN computations

  (that can be used to perform sophisticated denoising)



Technologies that are making real-time ray tracing possible

- Better algorithms: fast parallel BVH construction and traversal algorithms (many SIGGRAPH/HPG papers circa 2010-2013)
- GPU hardware evaluation:
  - HW acceleration of ray-triangle insect, BVH traversal
  - Increasingly flexible aspects of traditional GPU pipeline (bindless textures/resources)
- DNN-based image denoising
  - Can make plausible images using small number of rays per pixel
  - Make use of DNN hardware acceleration