Lecture 14:
Real-Time Ray Tracing

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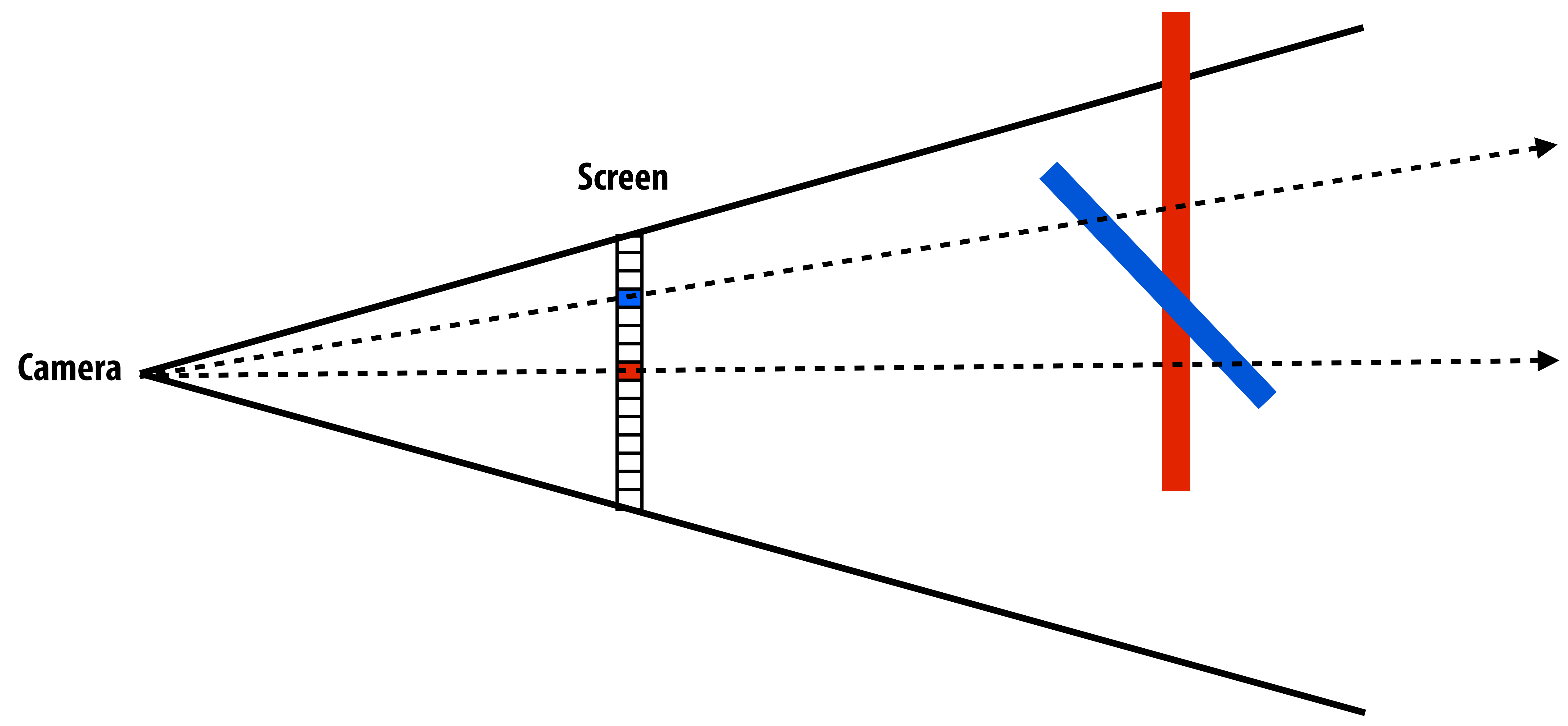
Recent push towards real-time ray tracing

Image credit: NVIDIA (this image can be rendered at "interactive rates" on NVIDIA Fermi: not real-time yet)

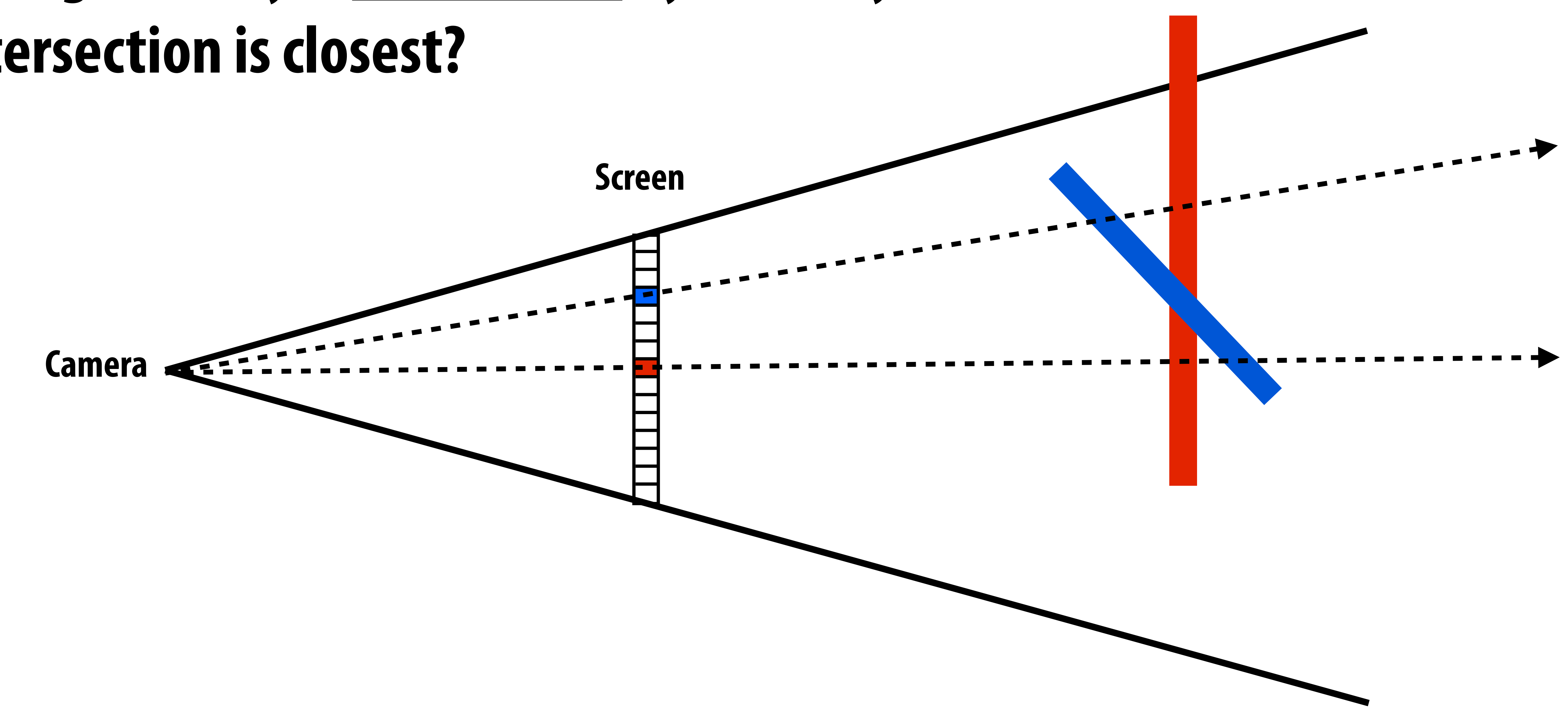
Visibility

- Determine which scene geometry contributes to the appearance of which screen pixels
- Can be thought of as a problem of computing interacting pairs
- Can be thought of as a search problem
  - Given polygon, find pixel(s) it contributes to
  - Given pixel, find triangle(s) that contribute to it



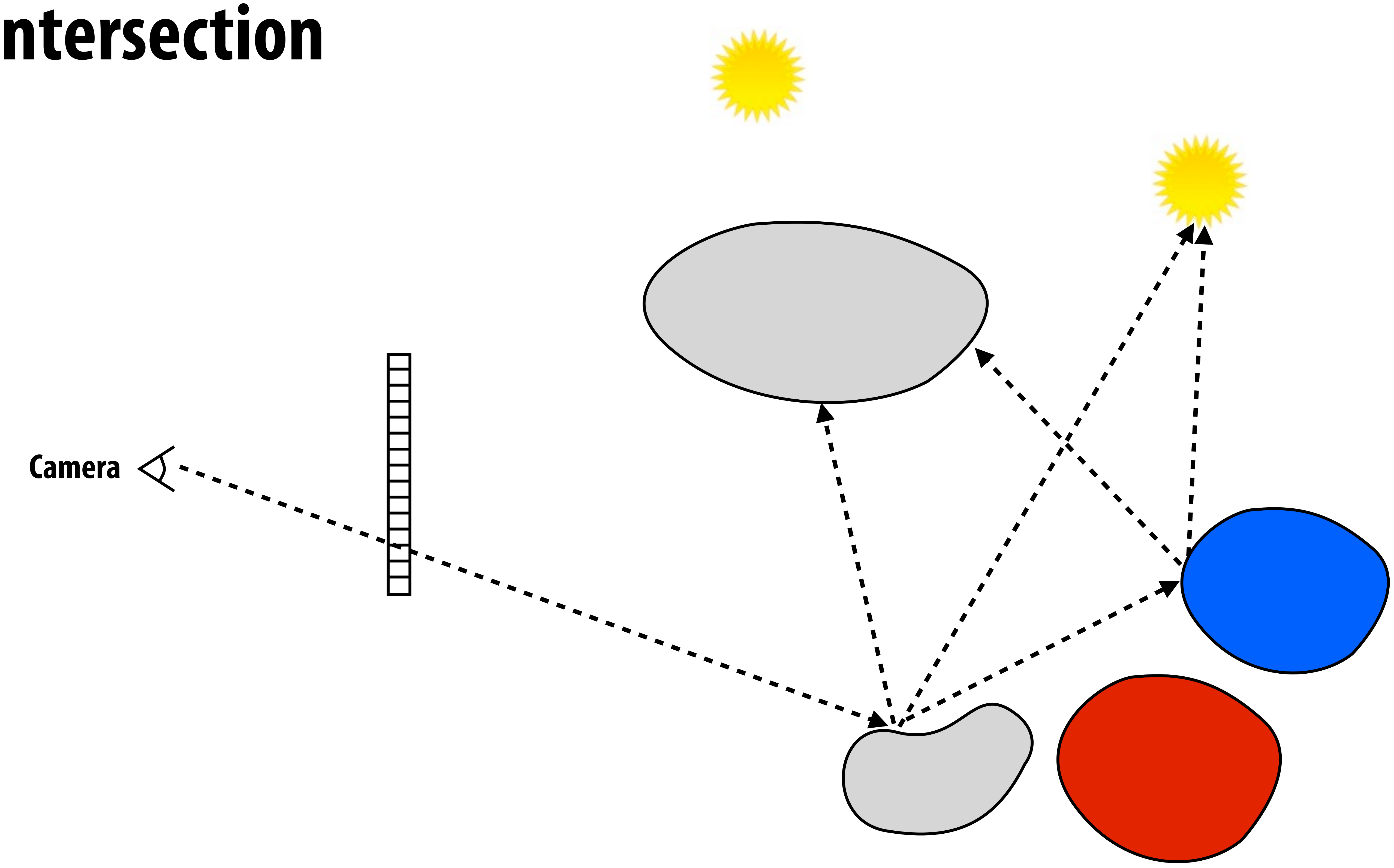
Visibility

- **Commonly solved via point sampling**
  - Rasterization:
    - What scene geometry covers each visibility sample?
    - Coverage (what triangles cover) + occlusion (closest covering triangle)
  - Ray tracing formulation:
    - Sample → ray in 3D
    - What scene geometry is intersected by each ray?
    - Which intersection is closest?



Ray tracing

- Perform ray-scene visibility queries
- Given ray (origin, direction), find what scene object(s) are intersected ("hit") by ray, optionally determine point of intersection



Sampling light paths

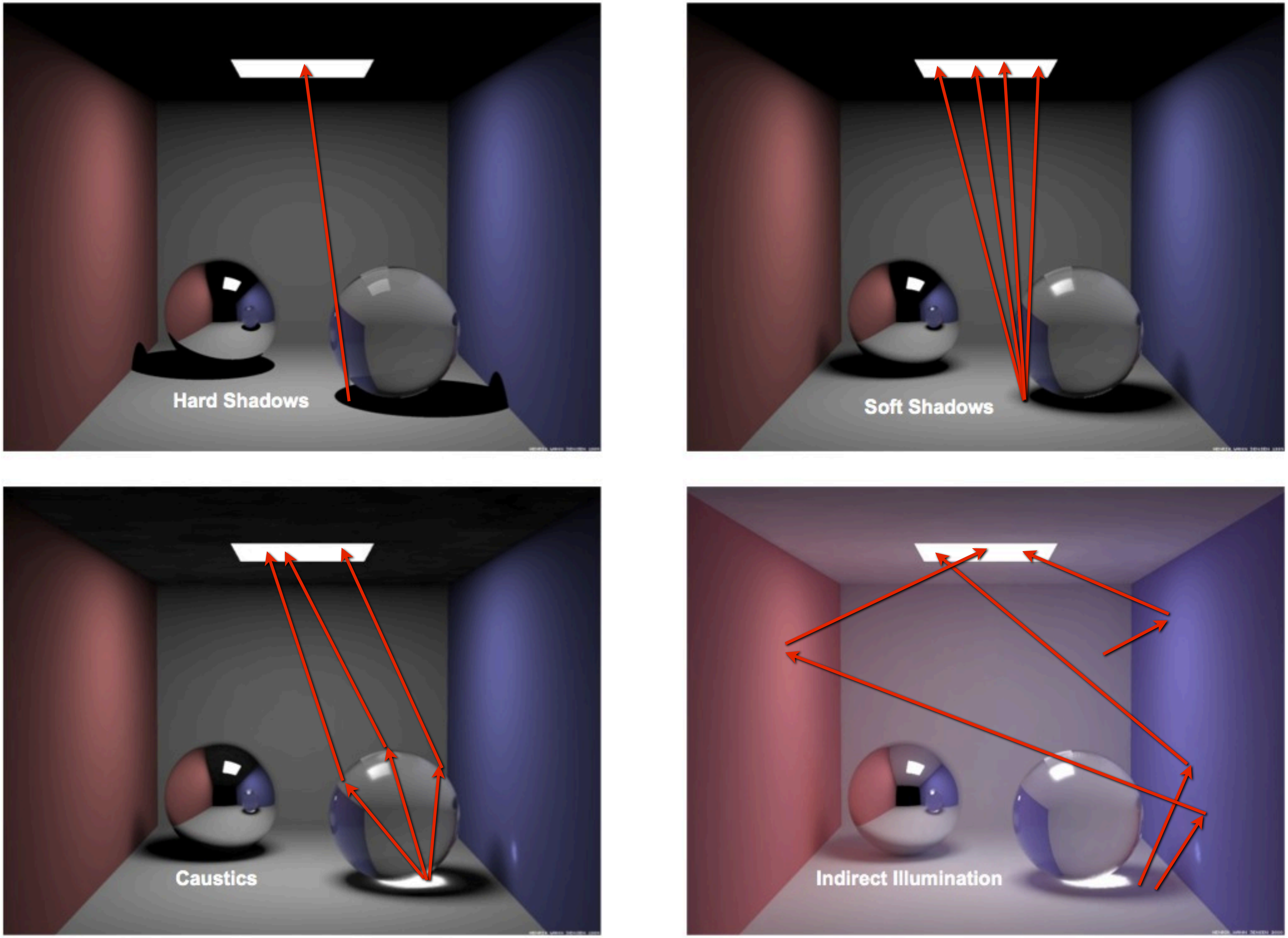
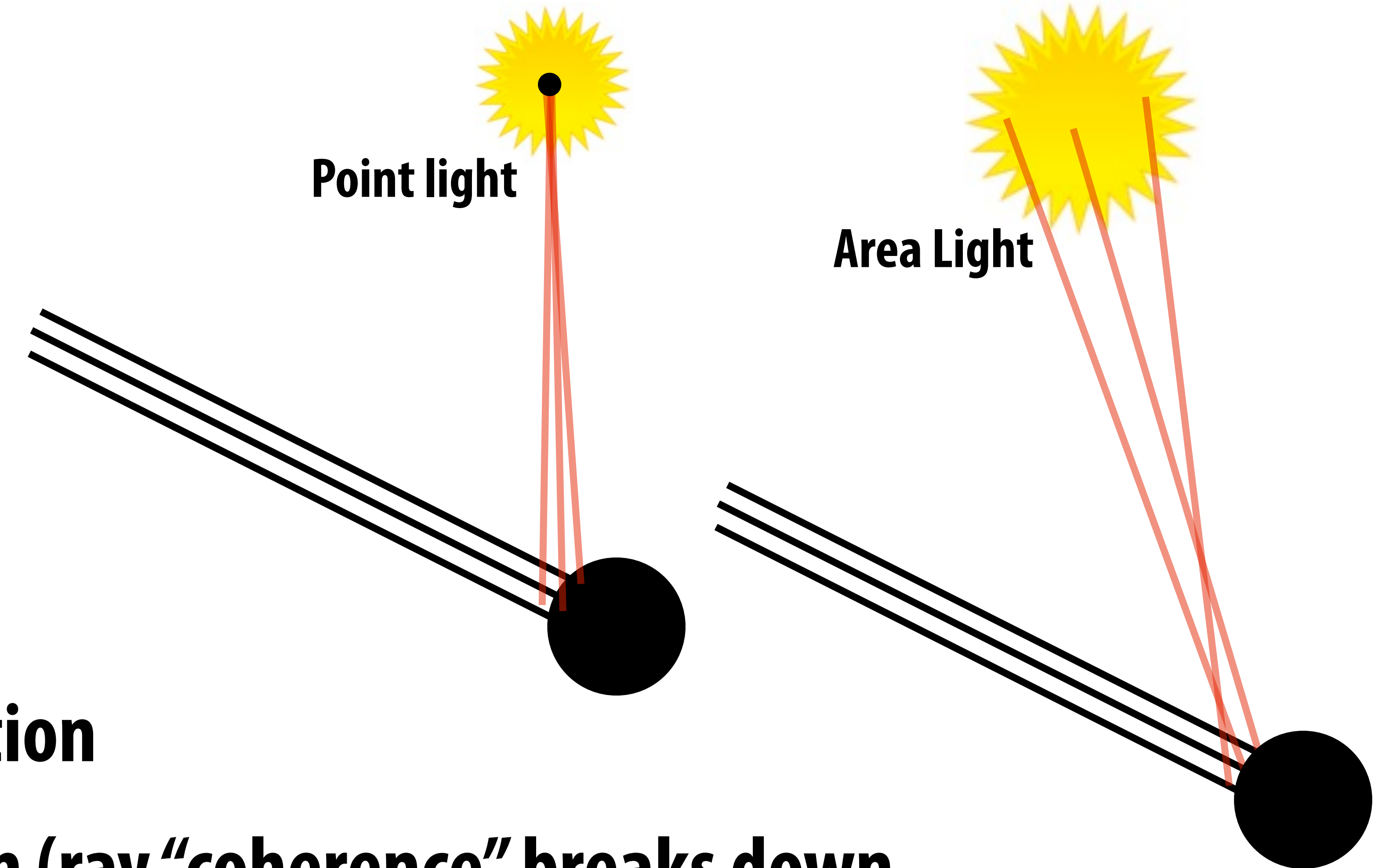


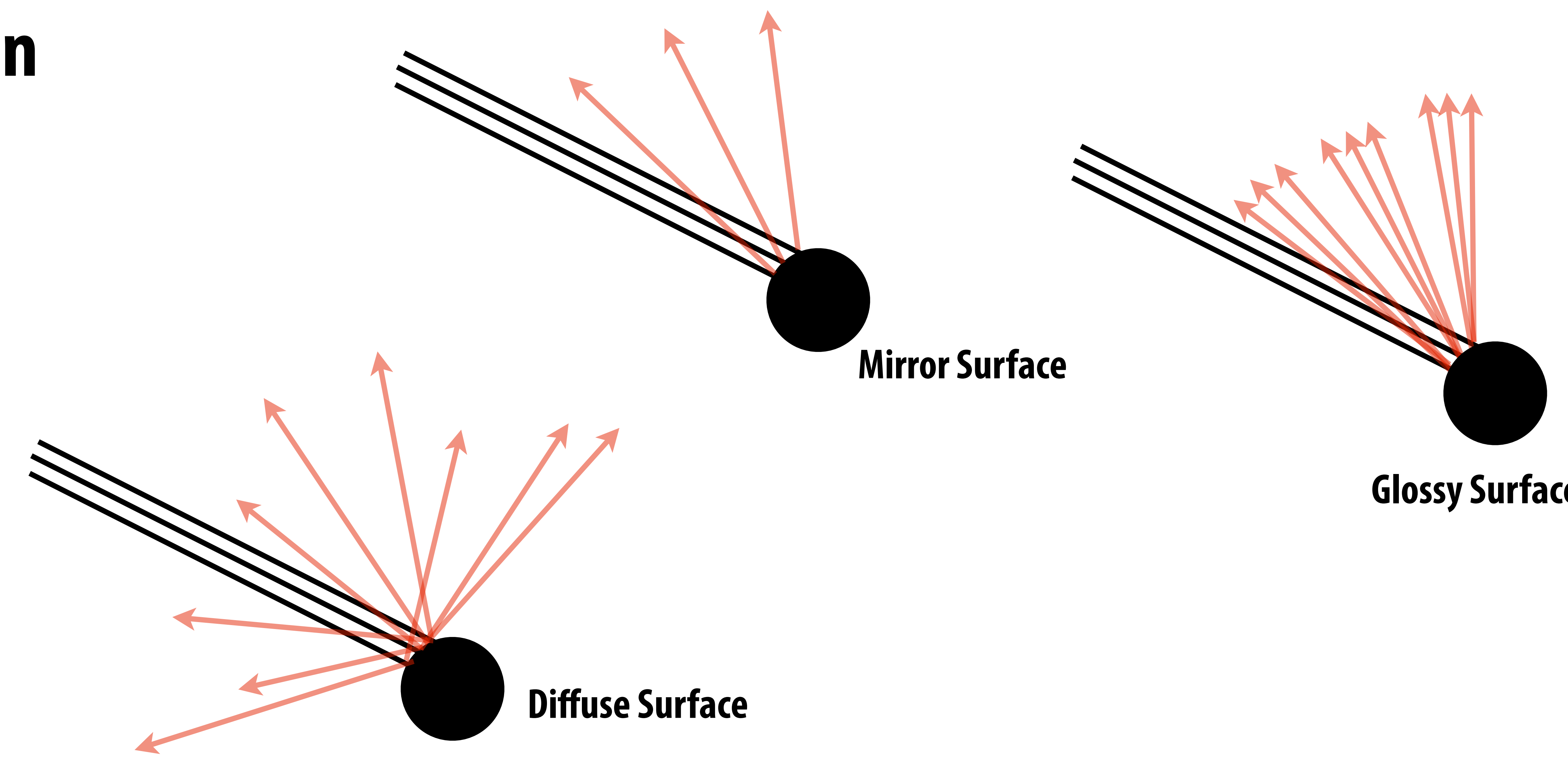
Image credit: Wann Jensen, Hanrahan

Types of rays

- **Camera (a.k.a., eye rays, primary rays)**
  - Common origin, similar direction
- **Shadow**
  - Point source: common destination, similar direction
  - Area source: similar destination, similar direction (ray "coherence" breaks down as light source increases in size: e.g., consider entire sky as an area light source)



- **Indirect illumination**
  - Mirror surface
  - Glossy surface
  - Diffuse surface



Recall: rasterization

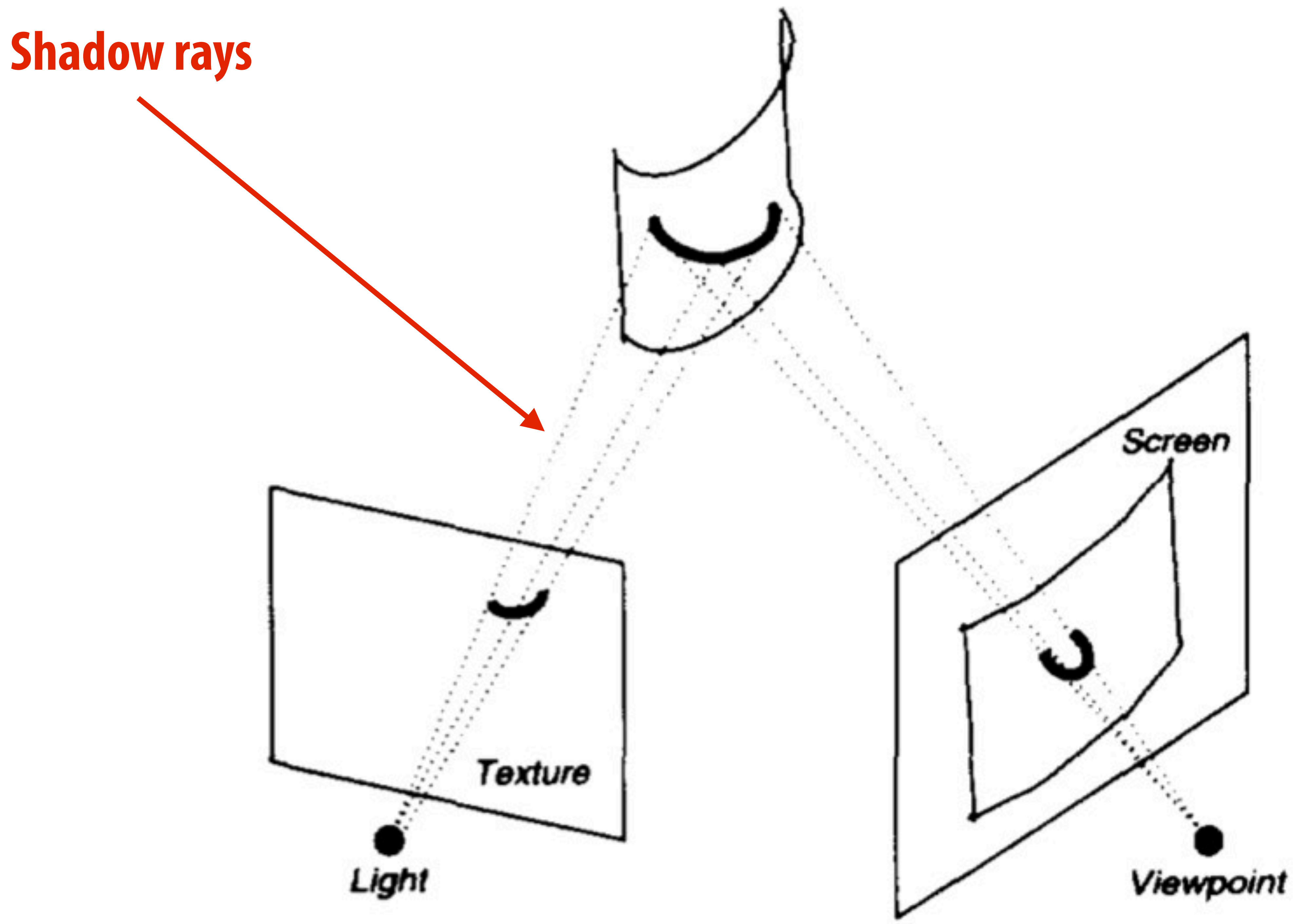
- **Rasterization is an optimized visibility algorithm**
  - Assumption 1: Rays have the same origin **
  - Assumption 2: Rays are uniformly distributed (within field of view)

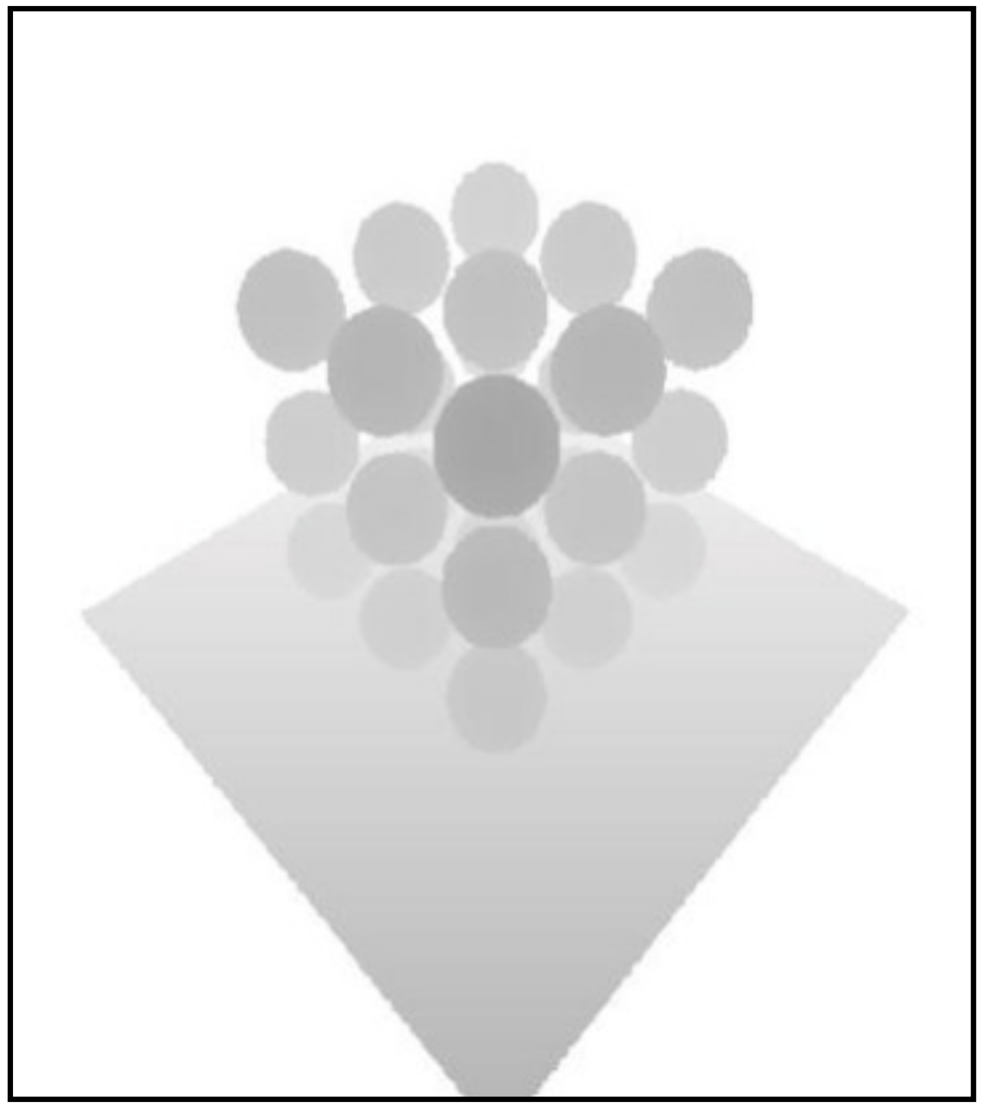
1. **Same origin: project triangles to reduce ray-triangle intersection to 2D point-in-polygon test**
   - Simplifies math
   - Fixed-point math (clipping used to ensures precision bounds)

** Assumption relaxed if rasterizer simulates defocus blur (e.g., Reyes)

Rasterization: ray origin need not be camera position

Shadow mapping: place origin at shadowed light source

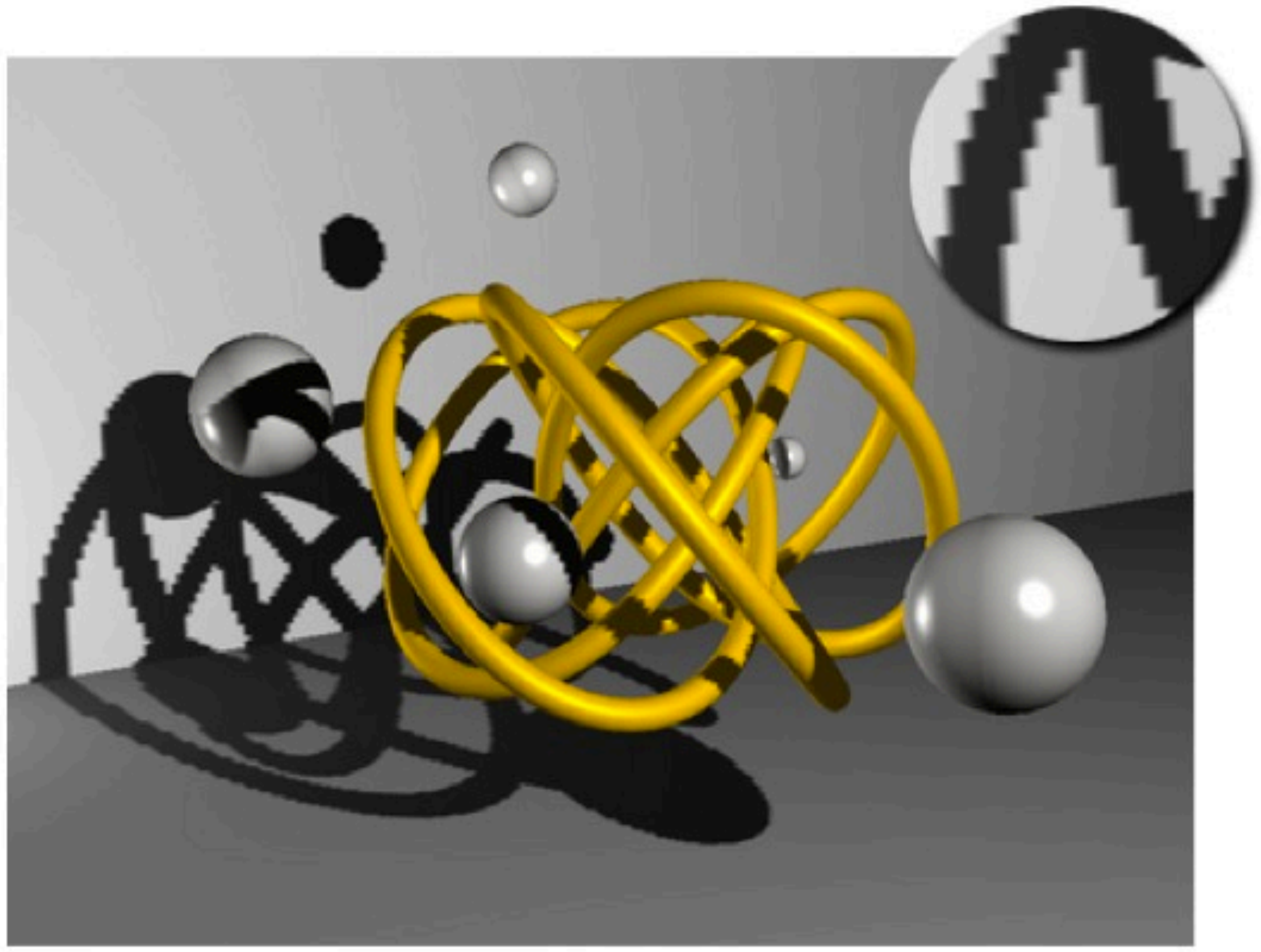




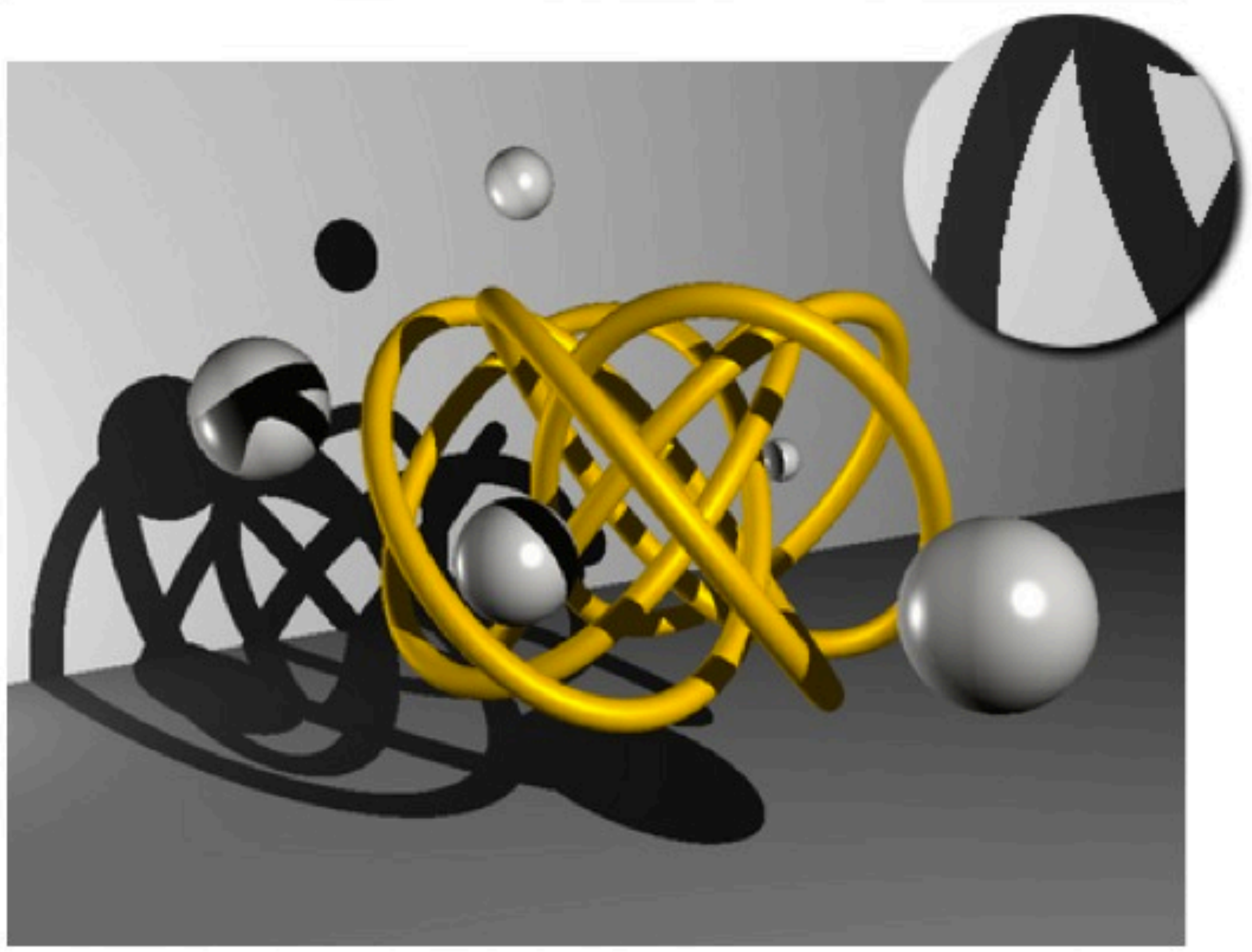
Shadow map: stores shadow ray results

Image credits: Segal et al. 92, Cass Everitt

Shadow map undersampling



Shadows computed using shadow map



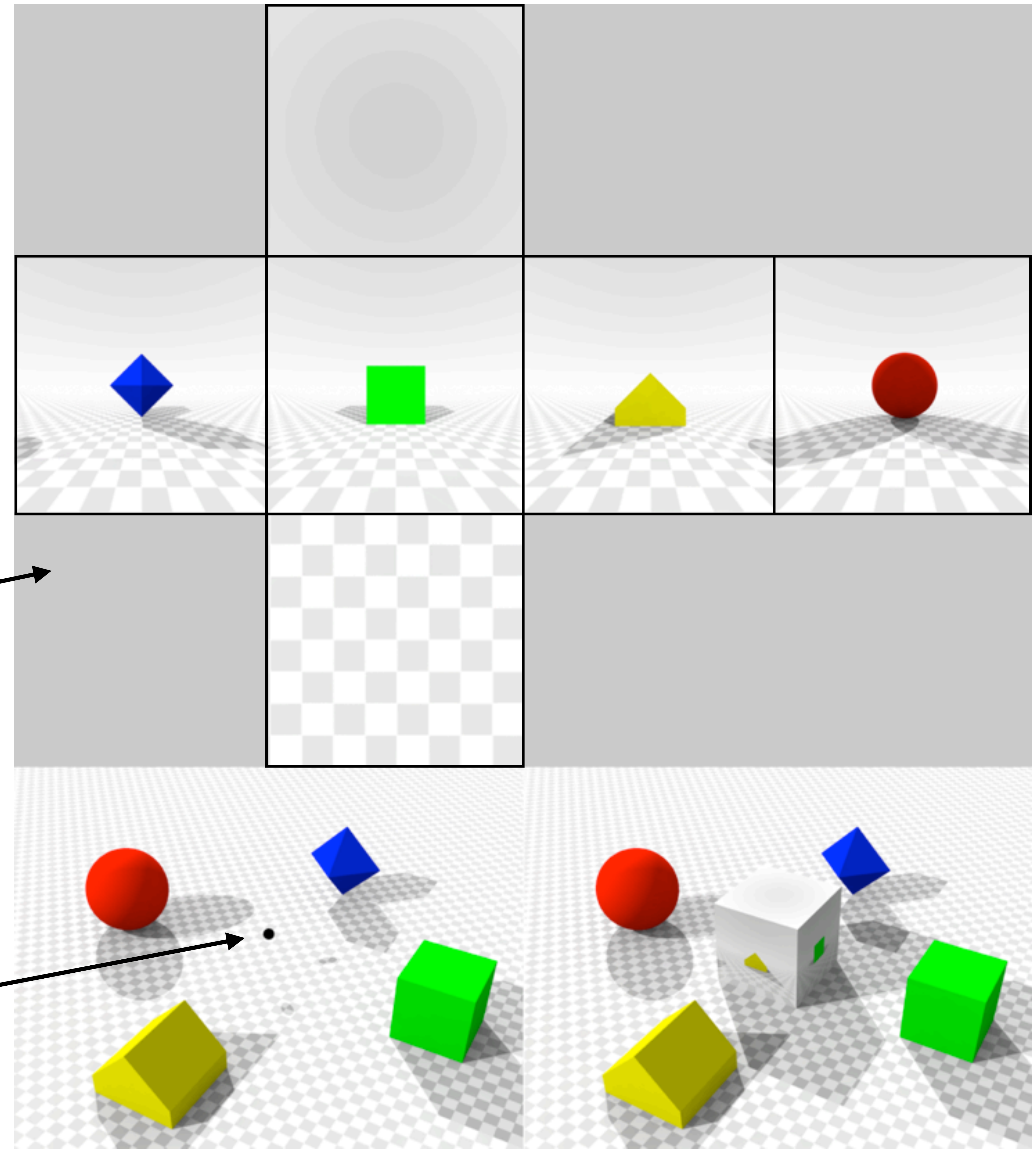
Correct hard shadows

Image credit: Johnson et al. TOG 2005

Rasterization: ray origin need not be camera position

Environment mapping:
place ray origin at reflective object

Scene rendered 6 times, with ray origin at center of reflective box
(produces cube-map)



Cube map:
stores results of approximate mirror reflection rays

(Question: how can a glossy surface be rendered using the cube-map)

Center of projection

Image credit: http://en.wikipedia.org/wiki/Cube_mapping

Rasterization

- **Rasterization is an optimized visibility algorithm**
  - Assumption 1: Rays have the same origin
  - Assumption 2: Rays are uniformly distributed within field of view

1. **Same origin: project triangles to reduce ray-triangle intersection to <u>cheap/efficient</u> 2D point in polygon test**

2. **Uniform sample distribution: given polygon, easy (a.k.a. fast/efficient) to "find" samples covered by polygon**
   - Regular frame buffer: constant time sample lookup, update, edit
   - Search leverages 2D screen coherence: amortize operations over tile of samples
   - No need for complex acceleration structures to accelerate a search over samples (hierarchy implicit in the samples)

Rasterization: performance

- Frame-buffer: fixed number of samples (determined by screen resolution, sampling rate) and common sample representation
    - Efficient to find samples covered by polygon (highly optimized fixed-function implementations of both coverage computation and frame-buffer update)

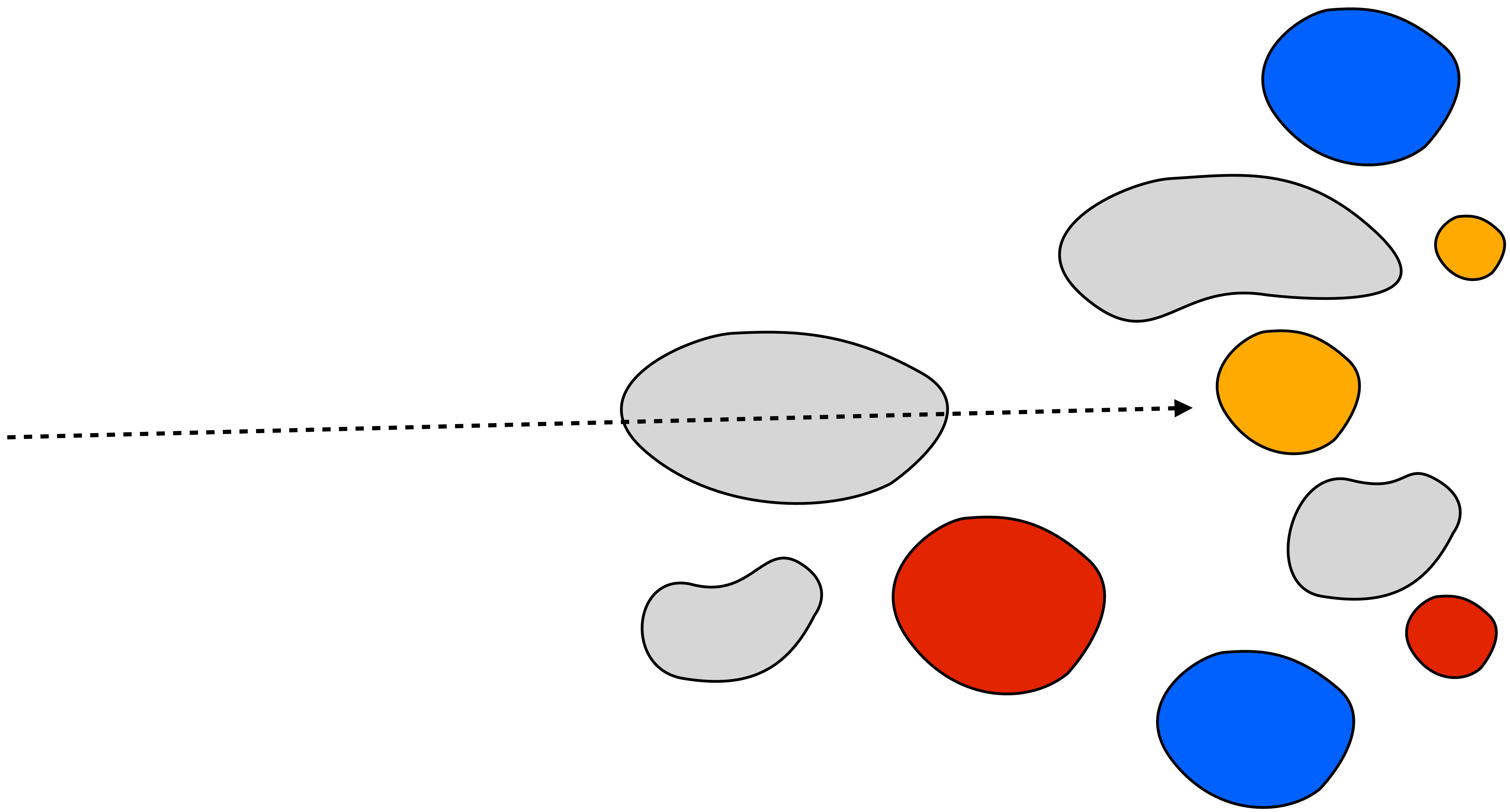
- Approach: <u>stream</u> over geometry (regular/predictable), directly access frame-buffer samples
    - Unpredictable access to samples, but manageable (see properties above, and previous lectures about pipeline sorting and color/z-buffer caching/compression)

- Scales to high scene complexity

Review: Ray Tracing 101

Problem

Given ray, find first intersection with scene geometry **



** Simpler, but common query: determine if <u>any</u> intersection exists

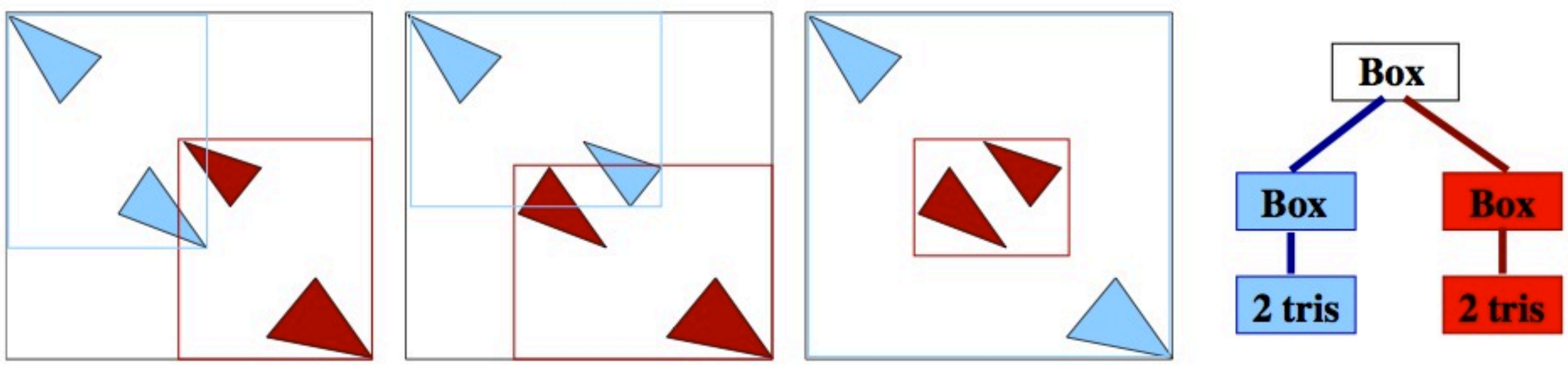
Acceleration structures

Preprocess scene to build data structure to accelerate ray-scene visibility queries

e.g., bounding volume hierarchy (BVH)

Idea: nodes group objects with spatial proximity

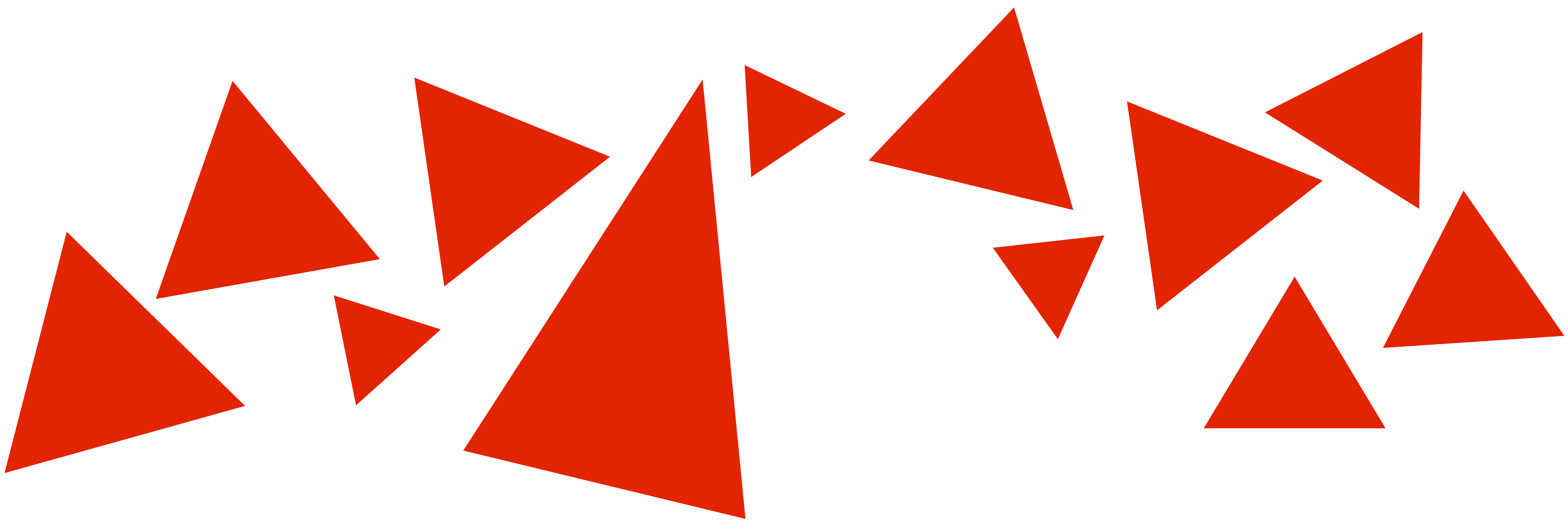
Adapts to non-uniform density of scene objects



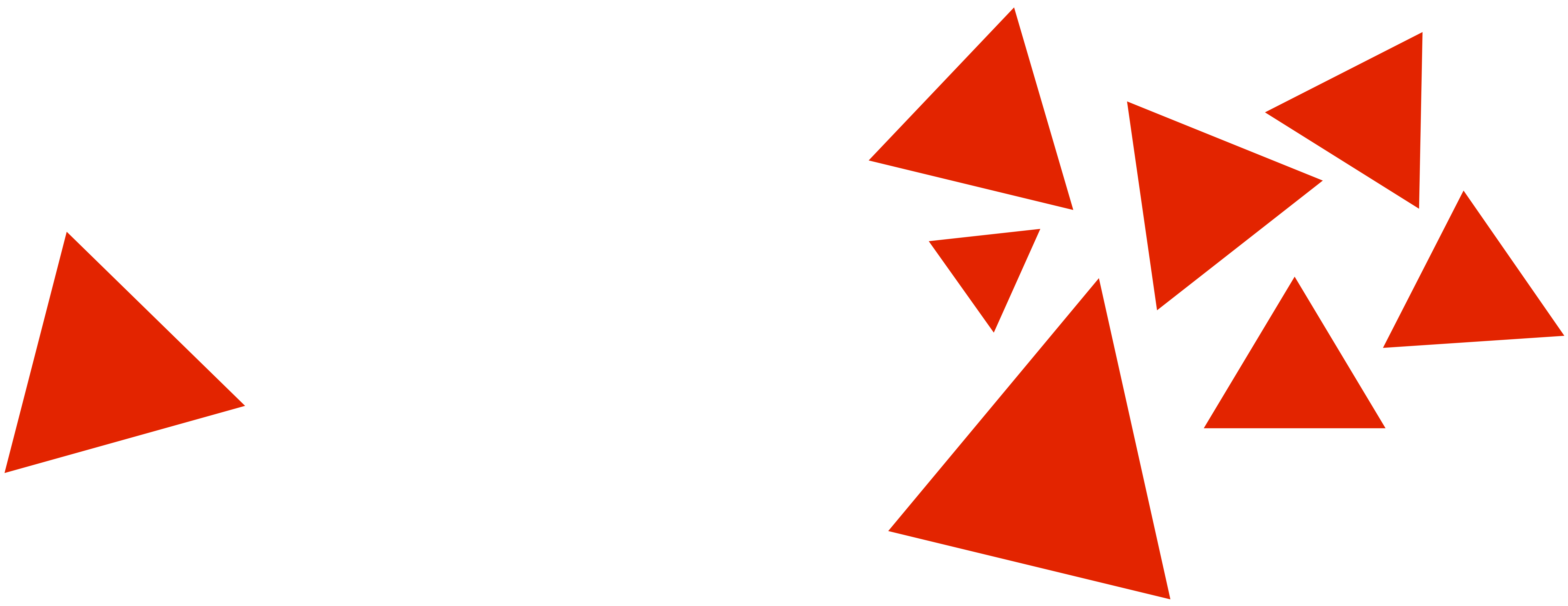
Three different bounding volume hierarchies for the same scene

Image credit: Wald et al. TOG 2004

How to build a BVH?



How to build a BVH?



Surface area heuristic

[Goldsmith and Salmon 87]

- **Current best practice**

- **Minimize cost function:**

  $cost = C_T + (P_L * C_L) + (P_R * C_R)$

  C_T = cost of performing a tree node traversal (ray-box test)

  P_L / P_R = probability of ray intersecting left/right child

  C_L / C_R = cost of intersecting ray with left/right child

- **Assumptions:**
  - Rays are uniformly distributed (uniform distribution of origin and direction) but originate from outside node bounding box
  - Costs of children typically set to be C_I * # primitives

Simple ray tracer (using BVH)

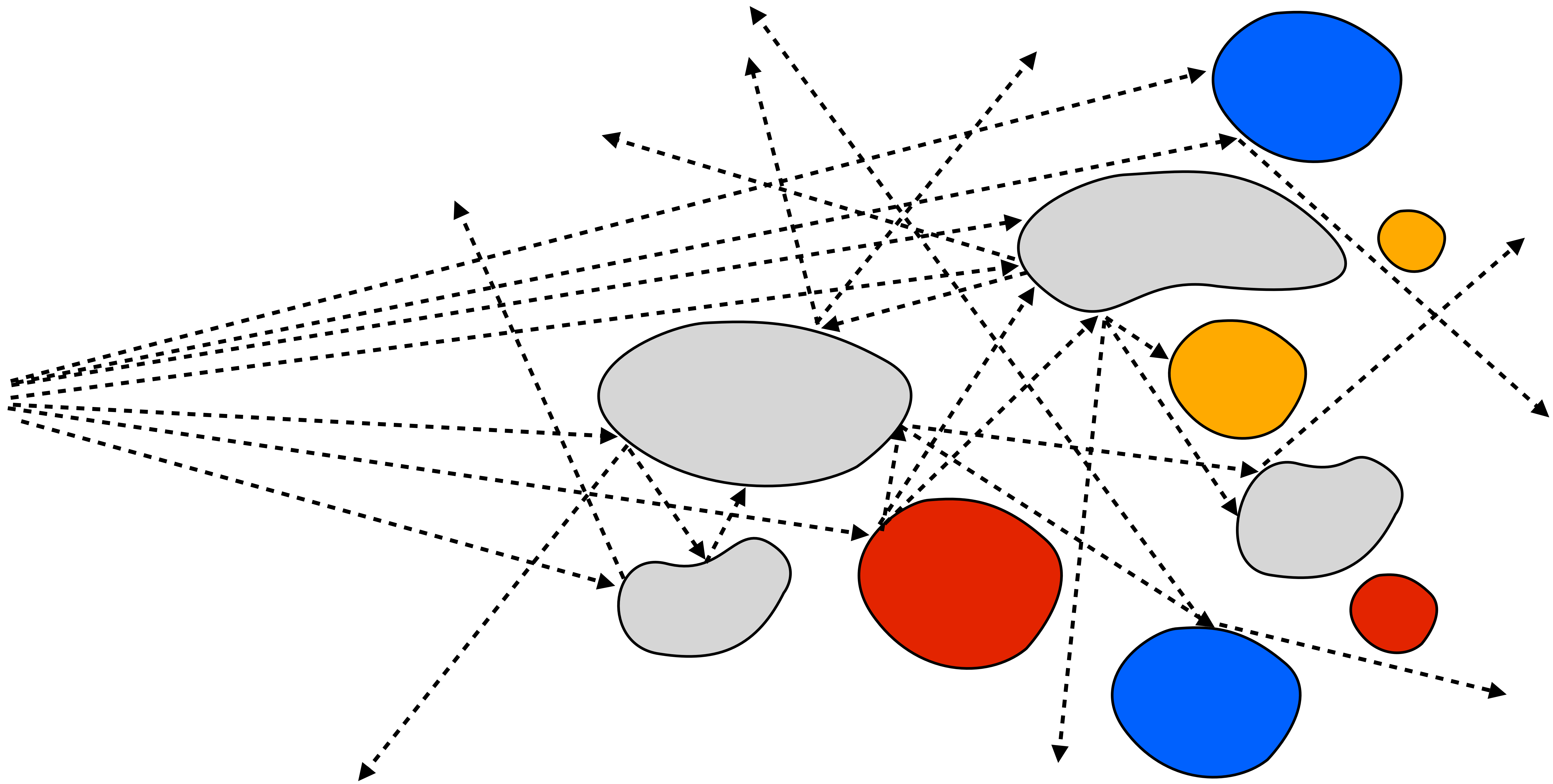
```
// stores information about closest hit found so far
struct ClosestHitInfo {
   Primitive primitive;
   float distance;
};

trace(Ray ray, BVHNode node, ClosestHitInfo hitInfo)
{
   if (!intersect(ray, node.bbox) || (closest point on box is farther than hitInfo.distance))
      return;

   if (node.leaf) {
      for (each primitive in node) {
         (hit, distance) = intersect(ray, primitive);
         if (hit && distance < hitInfo.distance) {
            hitInfo.primitive = primitive;
            hitInfo.distance = distance;
         }
      }
   } else {
     trace(ray, node.leftChild, hitInfo);
     trace(ray, node.rightChild, hitInfo);
   }
}
```

Making Ray Tracing Run Fast

Simplifications in today's discussion:
Will not discuss how to make acceleration structure build fast (active research topic)
Scene acceleration structure is read-only: no on-demand build, no on-demand tessellation

High-throughput ray tracing

Find intersection of millions of rays with scene geometry



High-throughput ray tracing

- **Work efficiency of algorithms**
  - High quality acceleration structures (minimize ray-box, ray-primitive tests)
  - Smart traversal algorithms (early termination, etc.)
- **Parallelism: multi-core, SIMD execution efficiency**
- **Bandwidth efficiency (caching, memory access characteristics)**

Same issues we've talked about all class!

Tension between employing most work-efficient algorithms, and using available execution and bandwidth resources well.

Parallelize across rays

- Simultaneously intersect multiple rays with scene

- Method 1: SPMD style
  - Each program instance intersects one ray against scene BVH (programmer writes single ray algorithm)
  - Recall previous homework assignment (1D ray tracing)
    - SIMD efficient when program instances execute same instructions
    - Bandwidth efficient when rays in a SIMD block ("warp") visit same BVH nodes
    - Will discuss further after reading Aila et al. 2009

- Method 2: ray packets

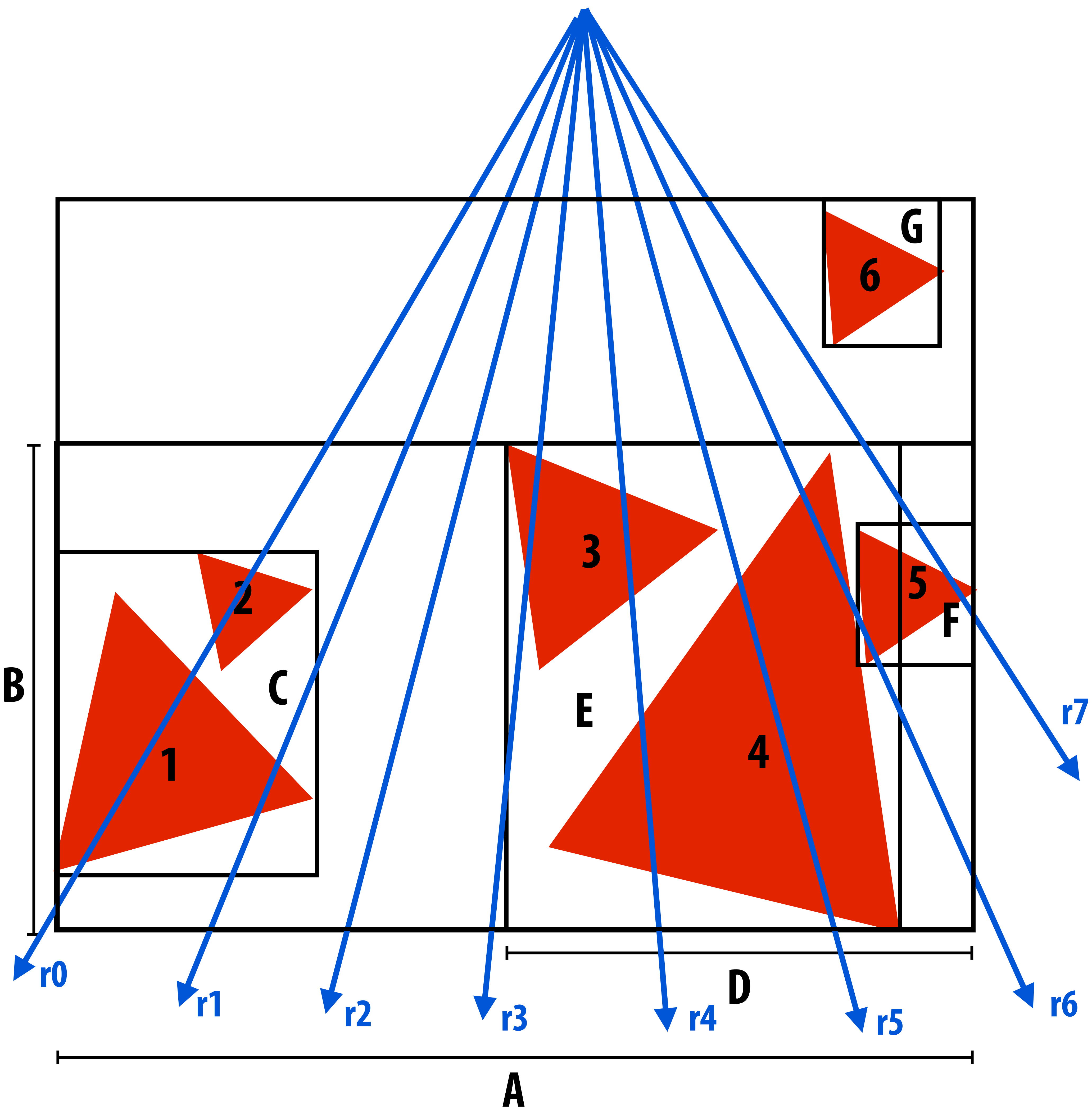
Ray packet tracing

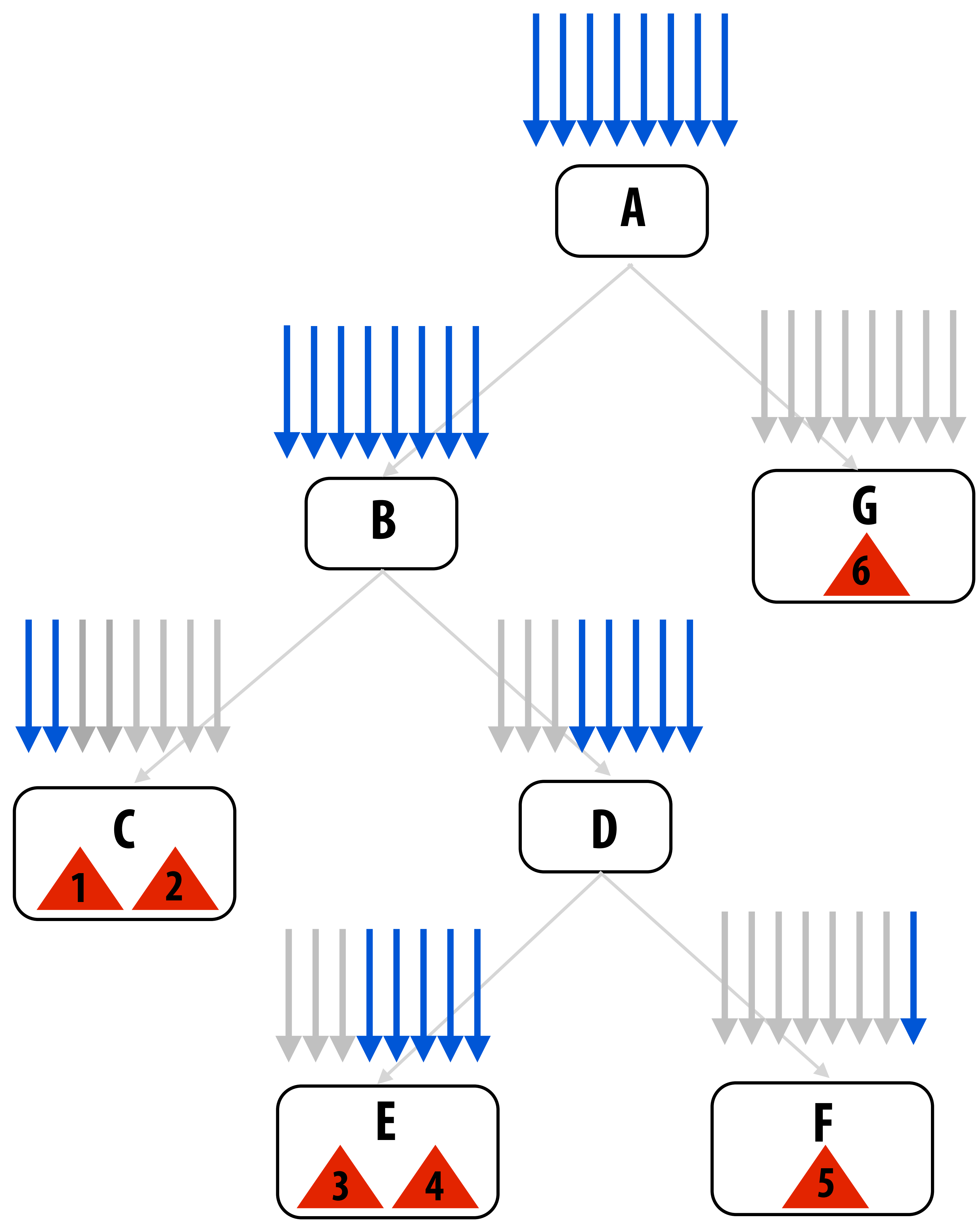
[Wald et al. 2001]

Program explicitly intersects a collection of rays against BVH at once

```
RayPacket
{
    Ray rays[PACKET_SIZE];
    bool active[PACKET_SIZE];
};

trace(RayPacket rays, BVHNode node, ClosestHitInfo packetHitInfo)
{
   if (!ANY_ACTIVE_intersect(rays, node.bbox) ||
       (closest point on box (for all active rays) is farther than hitInfo.distance))
      return;

   update packet active mask

   if (node.leaf) {
      for (each primitive in node) {
         for (each ACTIVE ray r in packet) {
            (hit, distance) = intersect(ray, primitive);
            if (hit && distance < hitInfo.distance) {
               hitInfo[r].primitive = primitive;
               hitInfo[r].distance = distance;
            }
         }
      }
   } else {
     trace(rays, node.leftChild, hitInfo);
     trace(rays, node.rightChild, hitInfo);
   }
}
```

Ray packet tracing





Advantages of packets

- SIMD execution
  - One vector lane per ray
- Amortize fetch: all rays in packet visit node at same time
  - Load BVH node once for all rays in packet
  - Note: value to making packets much bigger than SIMD width!
  - Contrast with SPMD approach
- Amortize work (packets are hierarchies over rays)
  - Use interval arithmetic to conservatively test entire set of rays against node bbox (e.g., think of a packet as a beam)
  - Further optimizations possible when all rays share origin
  - Note: value to making packets much bigger than SIMD width!

Disadvantages of packets

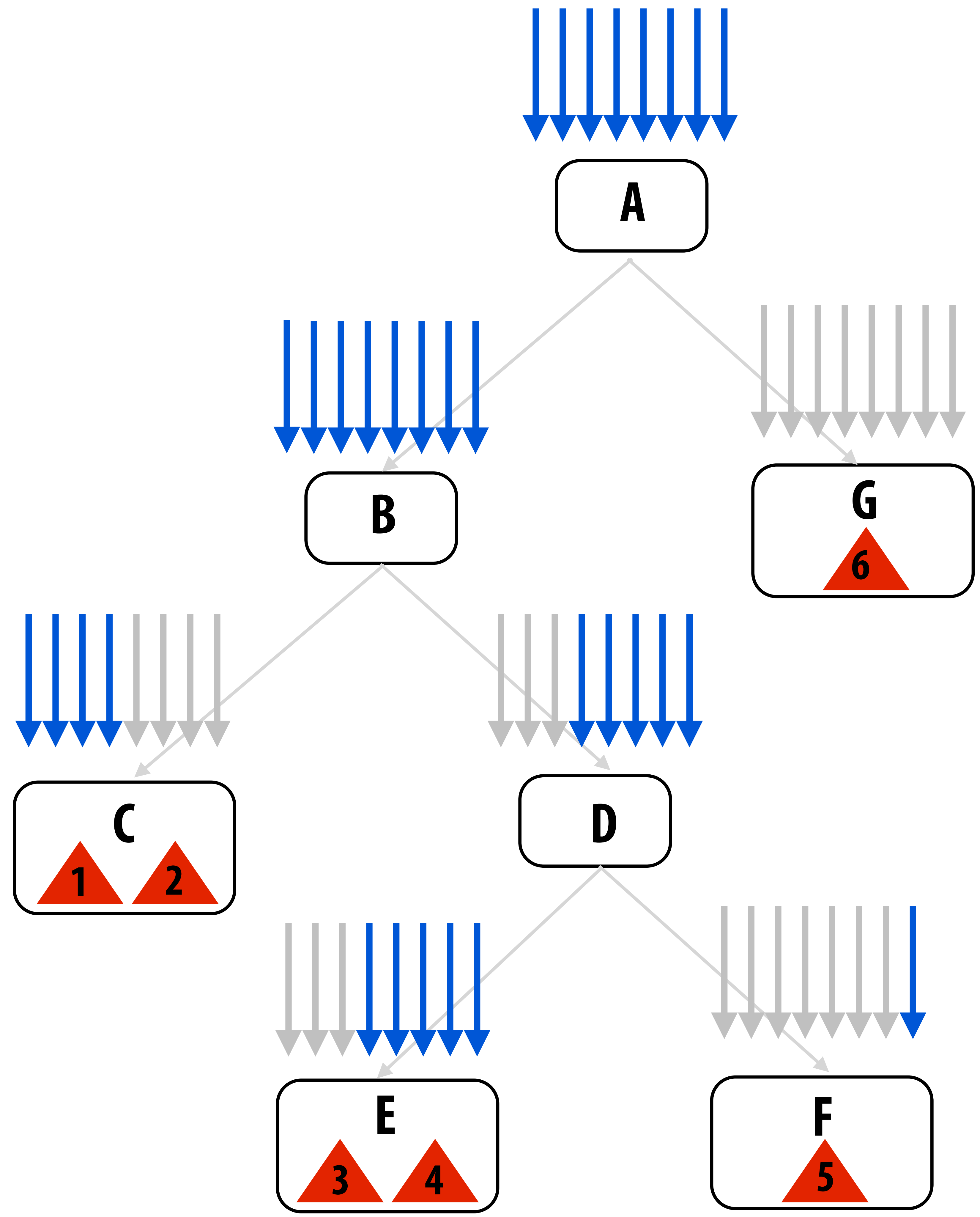
- If any ray must visit a node, it drags all rays in the packet along with it

  (note contrast with SPMD version: each ray only visits BVH nodes it is required to)

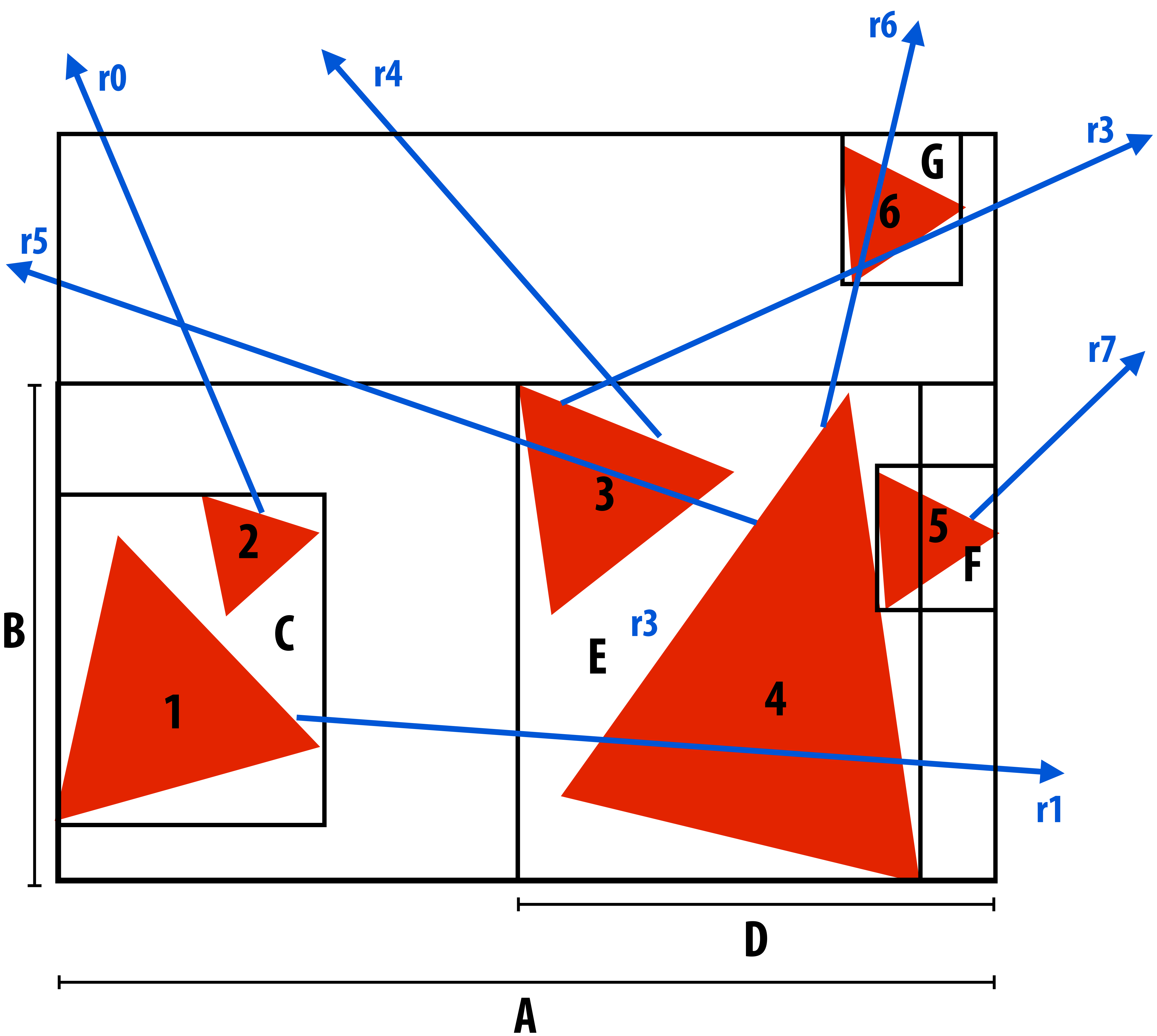
- Loss of efficiency: node traversal, intersection, etc. amortized over less than a packet's worth of rays

- Not all SIMD lanes doing useful work

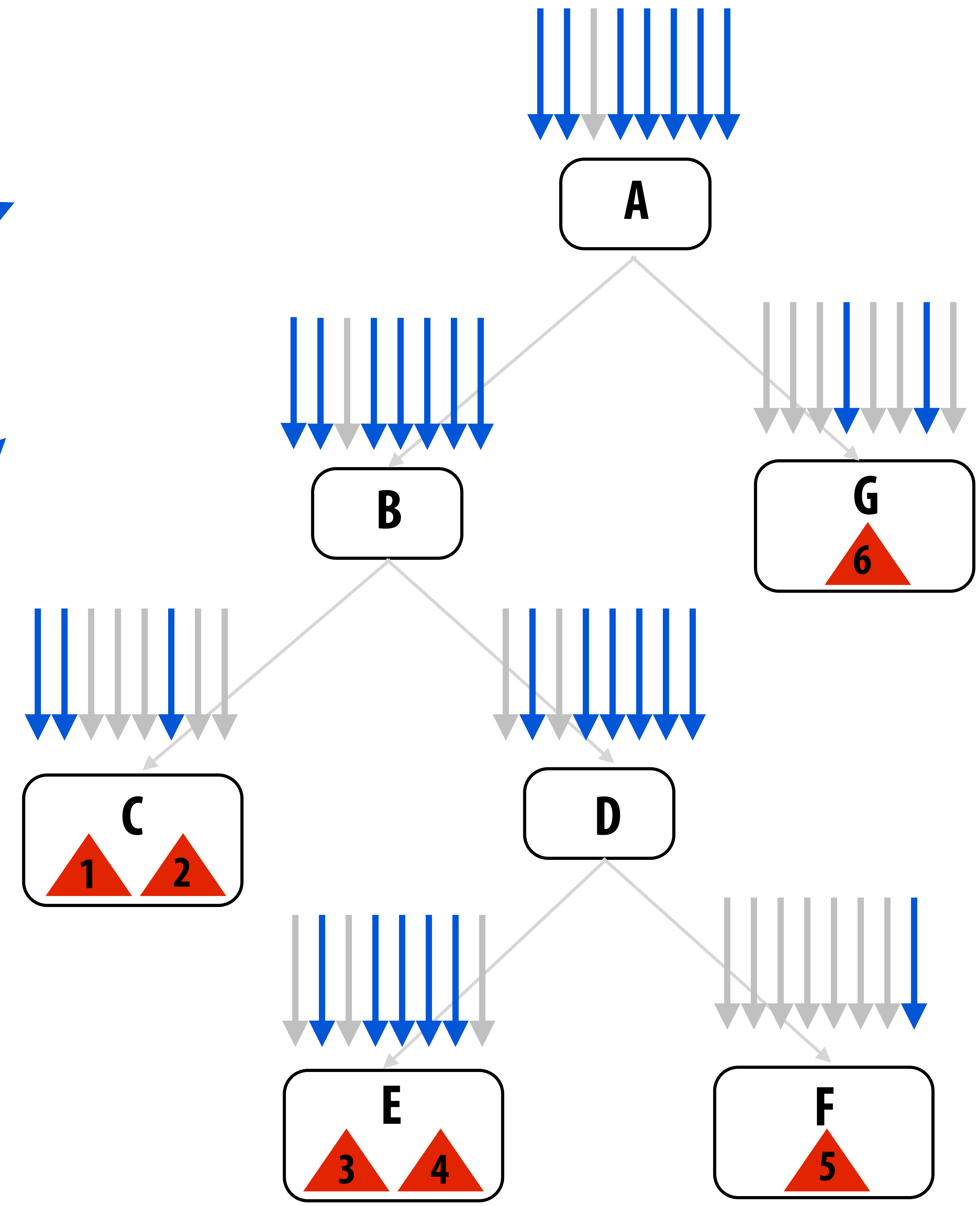
Both packet tracing and SPMD ray tracing suffer from decreased SIMD and cache efficiency when rays traverse the BVH differently... but take a moment to think about why (the reasons are different).



Ray packet tracing: incoherent rays

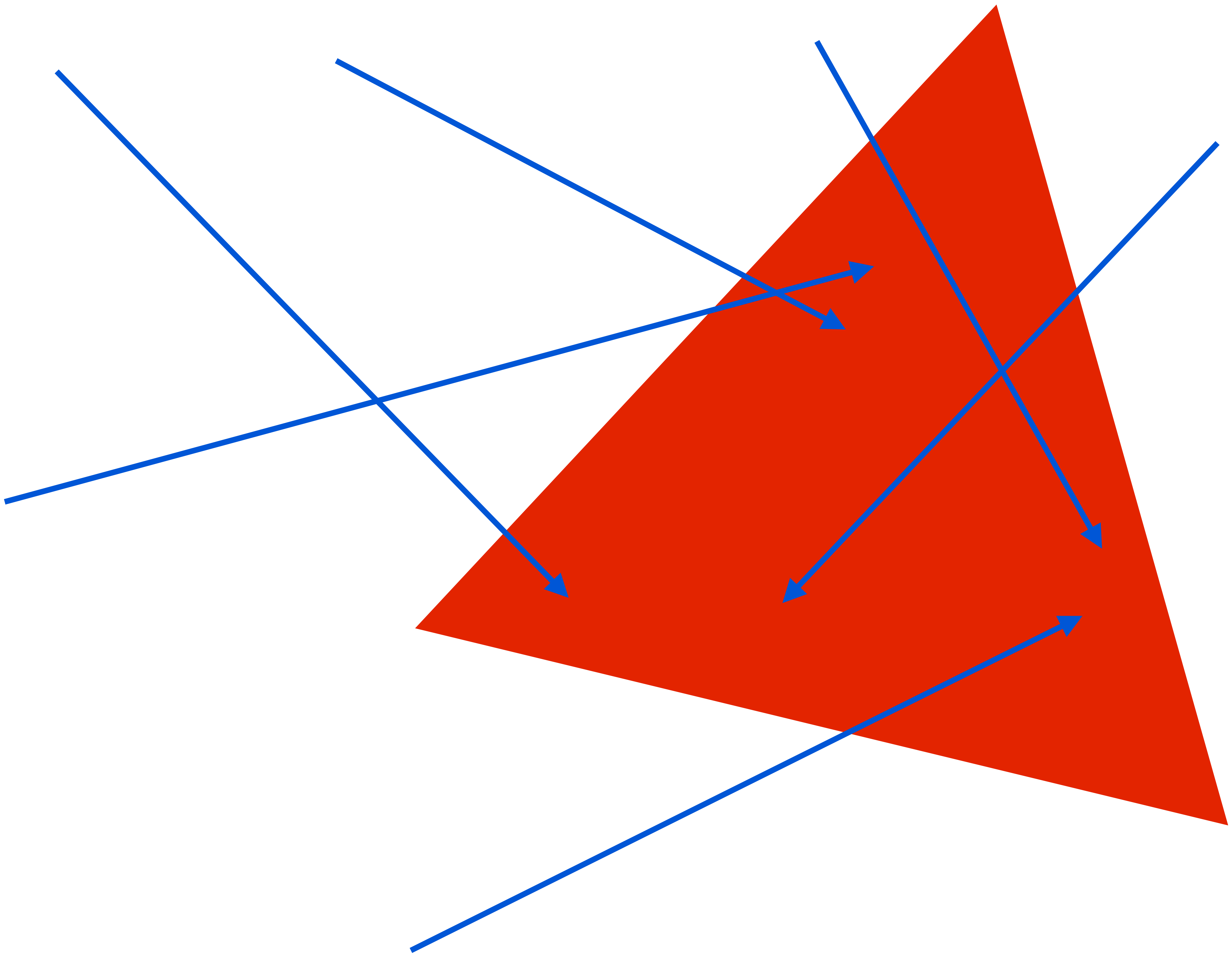


Blue = active ray after node box test



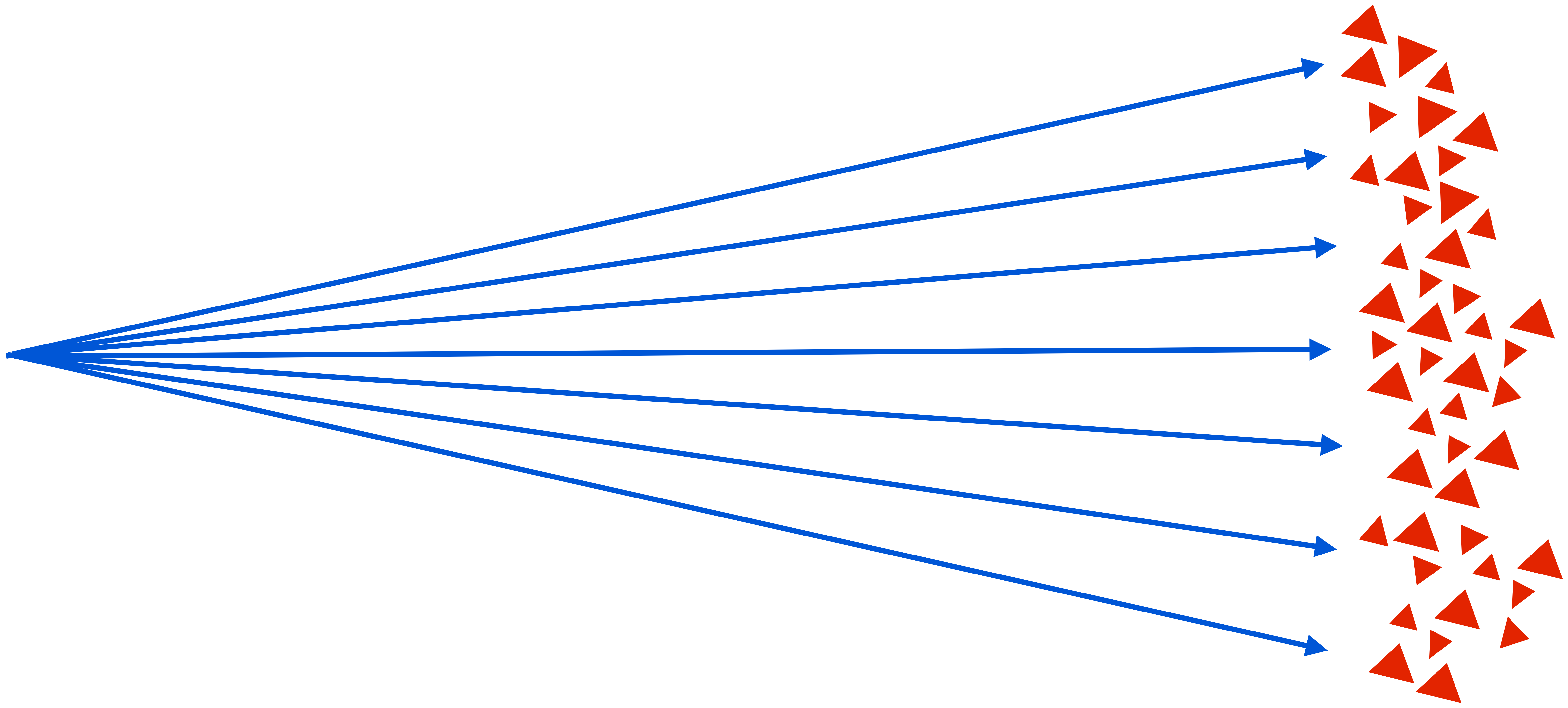
When rays are incoherent, benefit of packets can decrease significantly. This example: packet visits all tree nodes. (All rays visit all tree nodes)

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!

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

(note importance of geometric level of detail)

Improving packet tracing with ray reordering

[Boulos et al. 2008]

Idea: when packet utilization drops below threshold, resort rays and continue with smaller packet

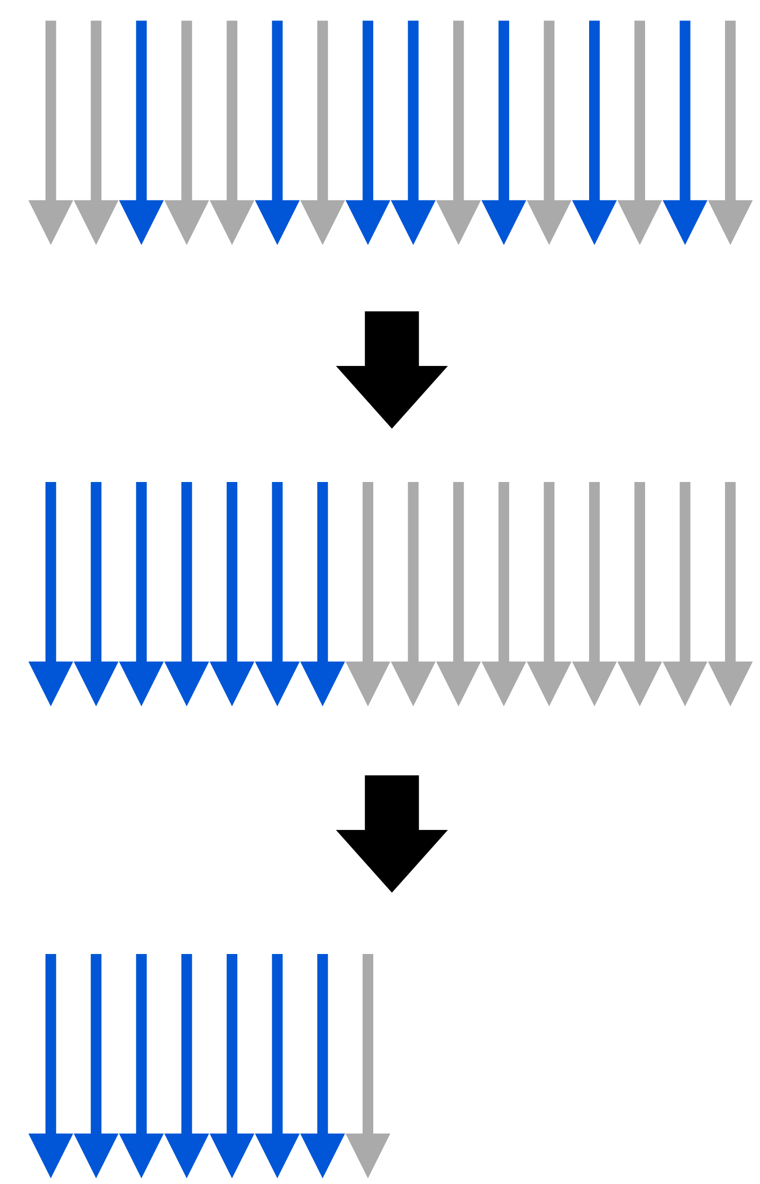
- Increases SIMD utilization
- Still loses amortization benefits of large packets

Example: 8-wide SIMD processor, 16-ray packets
(2 SIMD instructions required to perform operation on all rays in packet)

16-ray packet: 7 of 16 rays active

Reorder rays
Recompute intervals/bounds for active rays

Continue tracing with 8-ray packet:
7 of 8 rays active



Improving packet tracing with ray reordering

Idea: when packet utilization drops below threshold, resort rays and continue with smaller packet

- **Increases SIMD utilization**
- **Still loses amortization benefits of large packets**

Benefit of higher utilization/tighter packet bounds must overcome overhead of reordering operation

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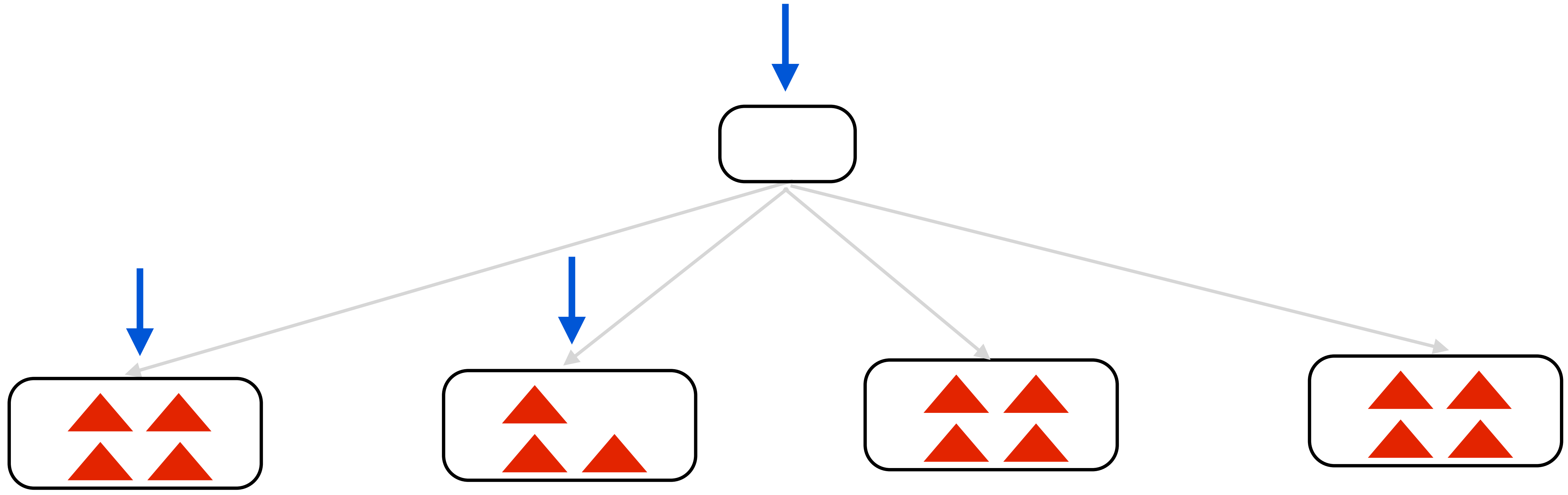
10-18% speedup over standard packet tracing for glossy reflection rays **[Boulos et al. 2008]**
25-50% speedup for 2-bounce diffuse interreflection rays
(4-wide SSE implementation)

Giving up on packets

- **Even with reordering, ray coherence during BVH traversal will diminish**
  - **Little benefit to packets (can decrease performance compared to single ray code)**

- **Idea: exploit SIMD execution within single ray-BVH intersection query**
  - **Interior: use wider-branching BVH**
    (test single ray against multiple node bboxes in parallel)
    - **Branching factor 4 has similar efficiency to branching factor 2** [Wald et al. 2008]
    - **Branching factor 16 exhibits significant reduction in efficiency**
  - **Leaf: test ray against multiple triangles in parallel**



Giving up on packets

- Even with reordering, ray coherence during BVH traversal will diminish
  - Little benefit to packets (can decrease performance compared to single ray code)

- Idea: exploit SIMD execution within <u>single</u> ray-BVH intersection query
  - Interior: use wider-branching BVH
  - Leaf: test ray against multiple triangles in parallel

- SIMD efficiency independent of ray coherence

- But no work/bandwidth reduction due to amortization across rays
  - Weren't getting much benefit from packets of incoherent rays anyway

Packet tracing best practices

- **Use large packets for higher levels of BVH** [Wald et al. 2007]
  - Ray coherence always high at the top of the tree
- **Switch to single ray (intra-ray SIMD) when packet utilization drops below threshold** [Benthin et al. 2011]
  - For wide SIMD machine, a single branching-factor 4 BVH works well for both packet and single ray traversal
- **Can use packet reordering to postpone time of switch** [Boulos et al. 2008]
  - Reordering allows packets to provide benefit deeper into tree

Scene data access

- **Recall data access in rasterization**
  - Stream through scene geometry
  - Allow arbitrary, direct access to frame-buffer samples (accelerated by highly specialized implementations)

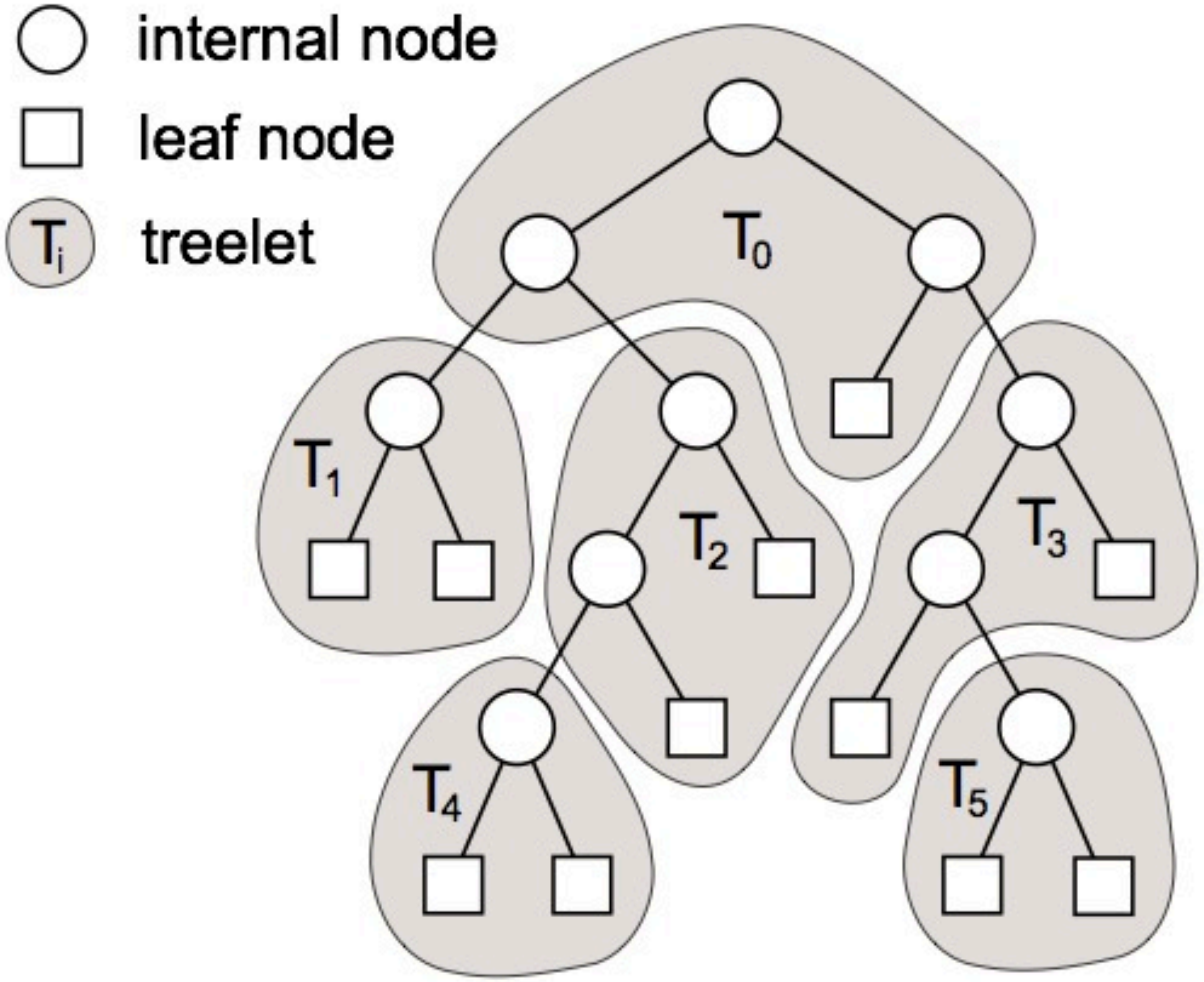
- **Ray tracer**
  - Frame-buffer access is minimal
  - But BVH traversal requires a lot of jumping through memory
    - Not predictable by definition (or you have a bad tree)
    - Packets amortize cost of node fetches

- **Incoherent ray traversal suffers from poor cache behavior**
  - Ray-scene intersection becomes bandwidth bound

Global ray reordering

[Phar 1997, Navratil 07, Alia 10]

Idea: batch up rays in the same part of the scene. Process these rays together to increase locality



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

1. **When ray (or packet) enters treelet, add rays to treelet queue**
2. **When treelet queue is sufficiently deep, intersect enqueued rays with treelet**

[Phar 1997, Navratil 07, Alia 10]
Lots of academic work + some industry attempts
Still not common in major ray tracing implementations

Summary

Not discussed today

A practical, efficient real-time ray tracing system will also need to solve these important challenges

1. **Building the BVH efficiently**
   - Rebuild or update each frame as scene changes?
2. **On-demand geometry: tessellation**
   - Intersection modifies BVH (not so embarrassingly parallel anymore)
   - How to determine level-of-detail?
3. **Efficiently shading ray hits**
   - What to do when rays in a packet hits surfaces with different shaders?

Summary

- Visibility: determine which scene geometry contributes to the appearance of which screen pixels
  - "Basic" rasterization: given polygon, find samples(s) it overlaps
  - "Basic" ray tracing: given ray, find triangle(s) that it intersects

- In practice, not as different as you might think

- Just different ways to solve the problem of finding interacting pairs between two hierarchies **
  - Hierarchy over point samples
  - Hierarchy over geometry

** A great analogy is collision detection (credit Tim Foley)

Consider performant, modern solutions for primary-ray visibility

- "Rasterizer"
  - Hierarchical rasterization (uniform grid over samples)
  - Hierarchical depth culling (quad-tree over samples)
  - Application scene graph, hierarchy over geometry
    - Modern games perform conservative coarse culling, only submit potentially visible geometry to the rendering pipeline

      (in practice, rasterization not linear in amount of geometry in scene)

- "Ray tracer"
  - BVH: hierarchy over geometry
  - Packets form hierarchy over samples (akin to frame buffer tiles). Breaking packets into small packets during traversal adds complexity to the hierarchy
  - Wide packet traversal, high-branching BVH: decrease work efficiency for better machine utilization

    (in practice, significant constants in front of that lg(N))

Trends: ray tracing in film

Image Credit: Blue Sky

Image Credit: Pixar (Cars)

- Reyes algorithm still predominant solution for primary ray visibility
- Reflections, indirect illumination, ambient occlusion, some shadows often computed via ray tracing
- Sony Pictures Imageworks now uses only ray tracing for all films
  - Arnold renderer has replaced Renderman at Sony
- Complex reasons motivate shift to ray tracing
  - More than just performance (artist time, production cost, etc.)

Image Credit: Sony (Cloudy With a Chance of Meatballs)

Readings

- For next time:
  - T. Aila and S. Laine, Understanding the Efficiency of Ray Traversal on GPUs. High Performance Graphics 2009

- Lots of supplemental ray tracing readings posted on the web site