Real-time ray tracing (and opportunities for hardware acceleration)

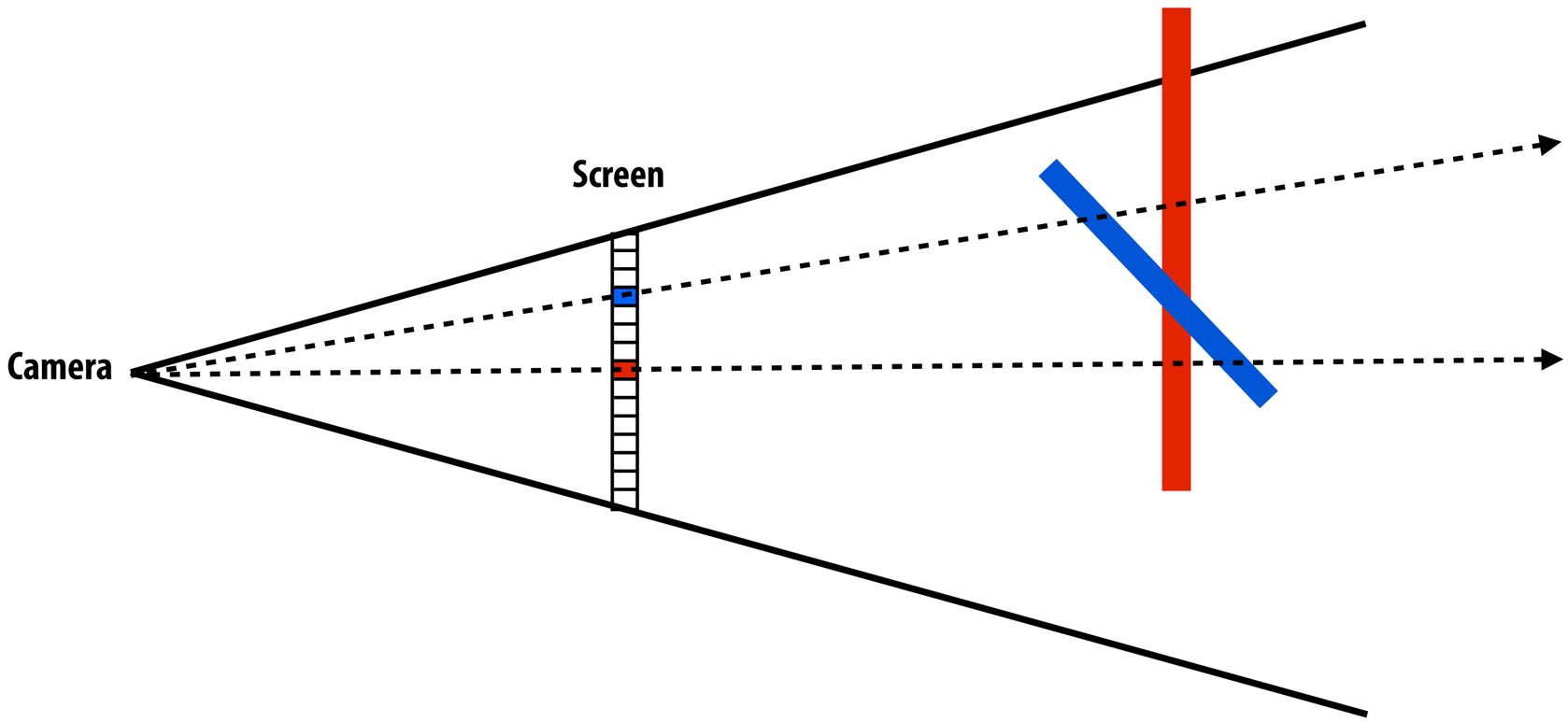
CMU 15-462, Fall 2013

Recent push towards real-time ray tracing

Image credit: NVIDIA (this ray traced image can be rendered at interactive rates on modern GPUs)

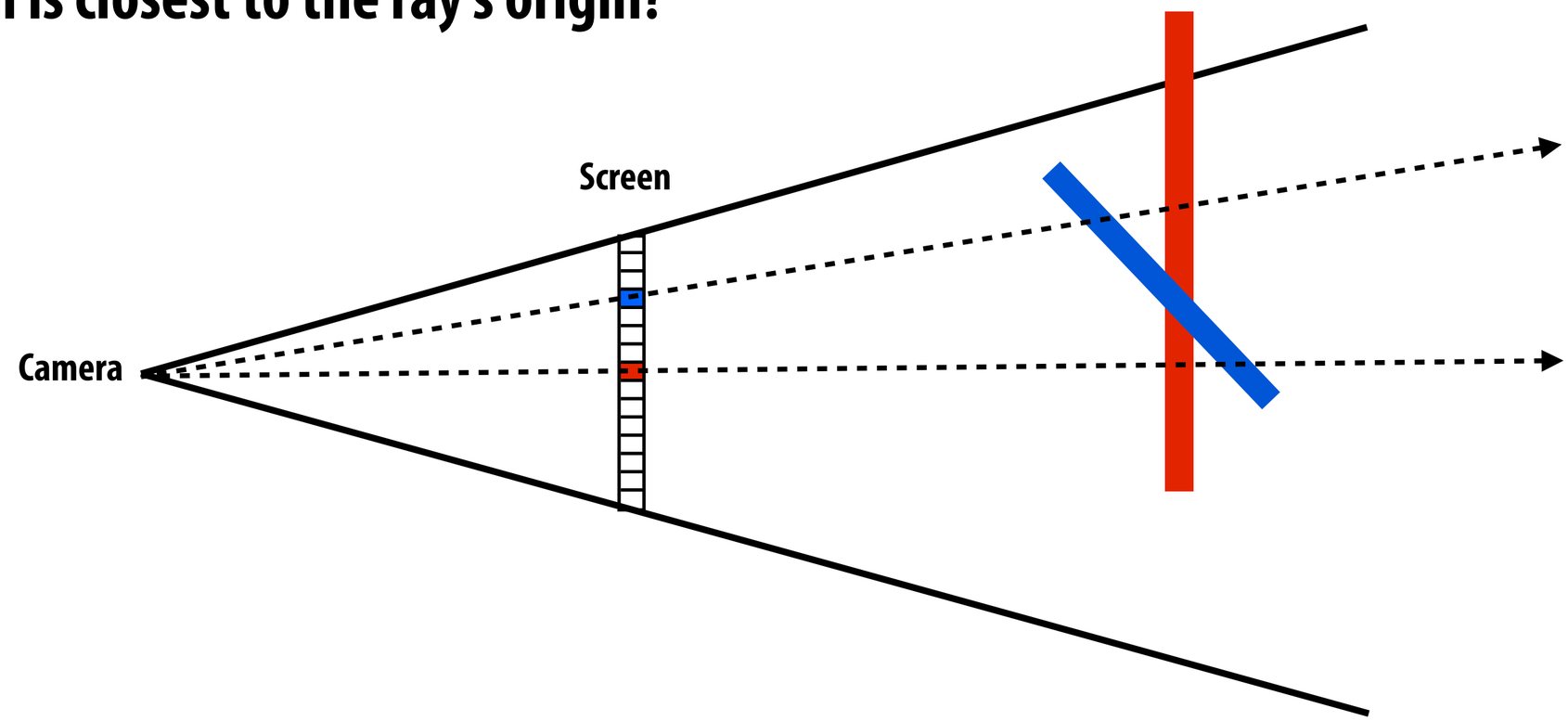
Review: visibility

- Problem: determine what scene geometry contributes to the appearance of which screen pixels
- Visibility can be thought of as a search problem
  - OpenGL rendering: given triangle, find samples (pixels) it contributes to
  - Today: given sample (a ray), find triangle(s) that contribute to it



Visibility as a search problem

- **Rasterization formulation:**
  - Sample = 2D point on screen
  - Coverage: What scene geometry, after projection into 2D, covers each visibility sample?
  - Occlusion: Which of the covering triangles is the closest?
- **Ray casting formulation:**
  - Sample = ray in 3D (ray = (origin, direction))
  - What scene geometry is intersected by each ray?
  - Which intersection is closest to the ray's origin?



Two naive visibility algorithms *

Naive "rasterizer":

```
initialize z_closest[] to INFINITY                  // store closest for all samples
for each triangle t in scene:                       // stream over triangles in outer loop
    t_proj = project_triangle(t)
    for each sample s in frame buffer:
        if (t_proj covers s)
            if (depth of t at s is closer than z_closest[s])
                update z_closest[s];
```

Naive "ray caster":

```
for each sample s in frame buffer:                  // stream over samples (rays) in outer loop
    ray = generate ray from camera through s out into scene
    ray_closest = INFINITY                          // store only closest point for current ray
    closest_tri = NULL;
    for each triangle t in scene:
        if (ray intersects t)
            if (intersection point is closer than ray_closest)
                update ray_closest;
                closest_tri = t;
```

*** As we will discuss, as optimizations get added the difference between these two approaches blurs**

Recall: the rendering equation

[Kajiya 86]

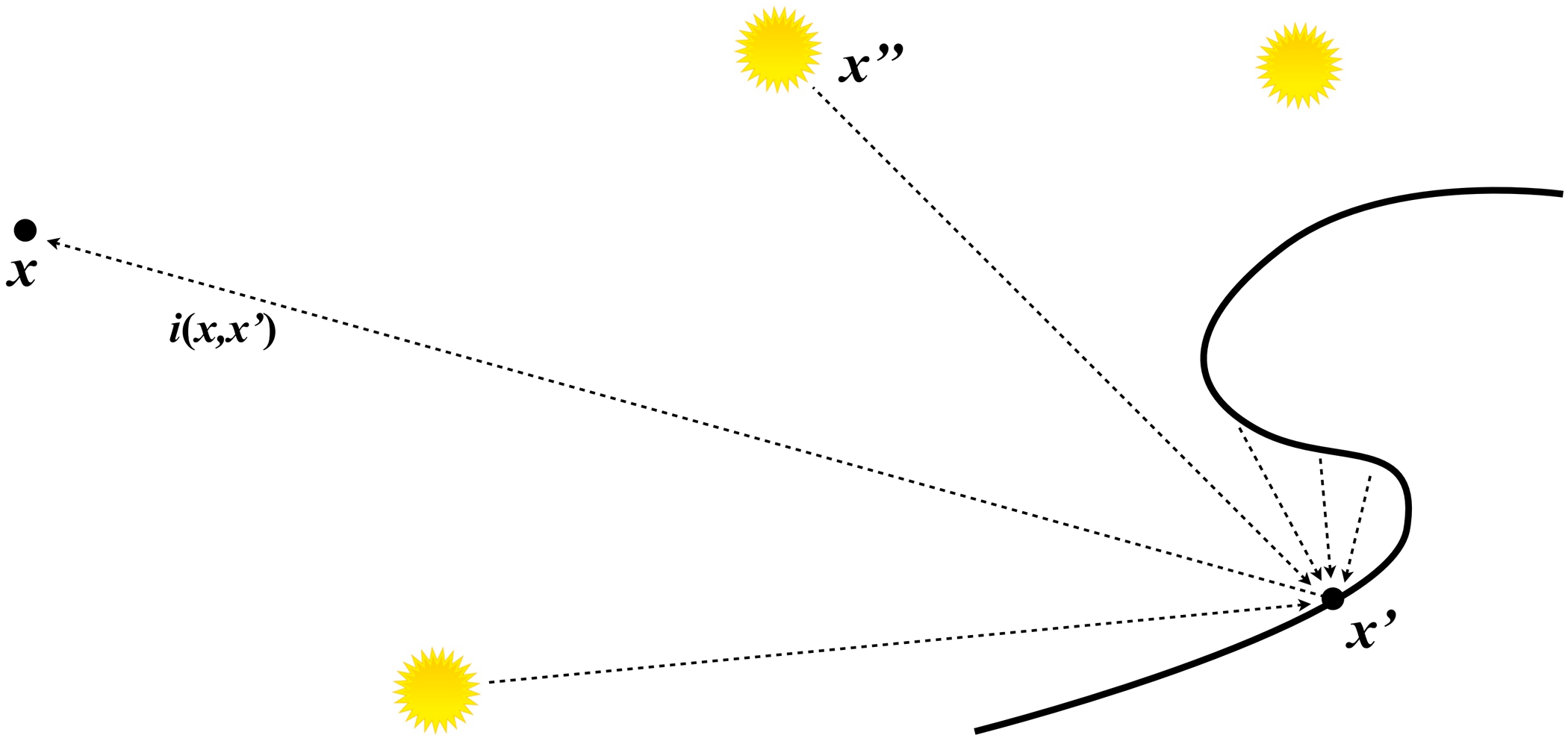
$$i(x,x') = v(x,x')\left[l(x,x') + \int r(x,x',x'')i(x',x'')\,dx''\right]$$

$i(x,x')$ = Radiance (energy along a ray) from point x′ in direction of point x

$v(x,x')$ = Binary visibility function (1 if ray from x′ reaches x, 0 otherwise)

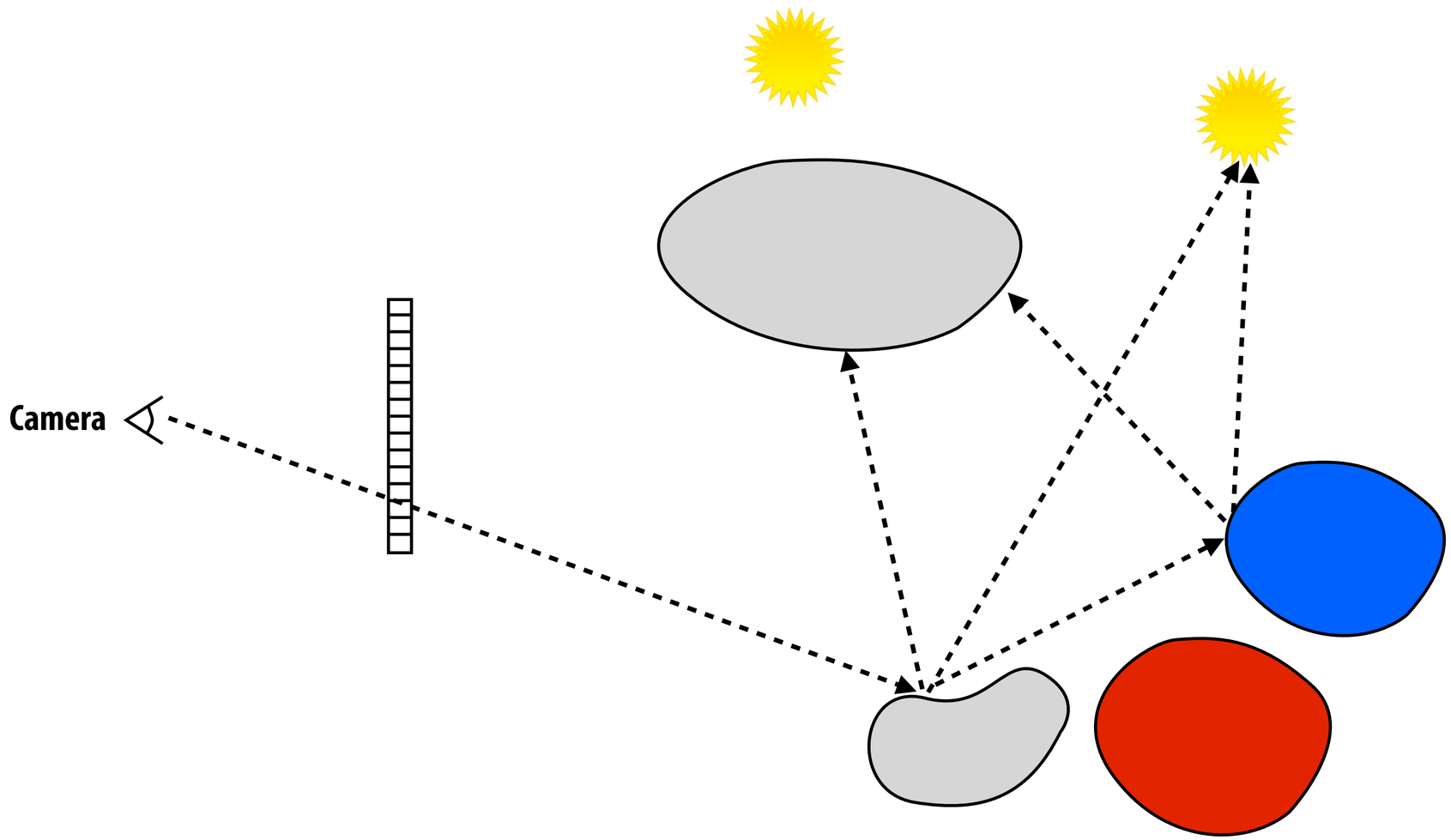
$l(x,x')$ = Radiance emitted from x′ in direction of x (if x′ is an emitter)

$r(x,x',x'')$ = BRDF: fraction of energy arriving at x′ from x″ that is reflected in direction of x

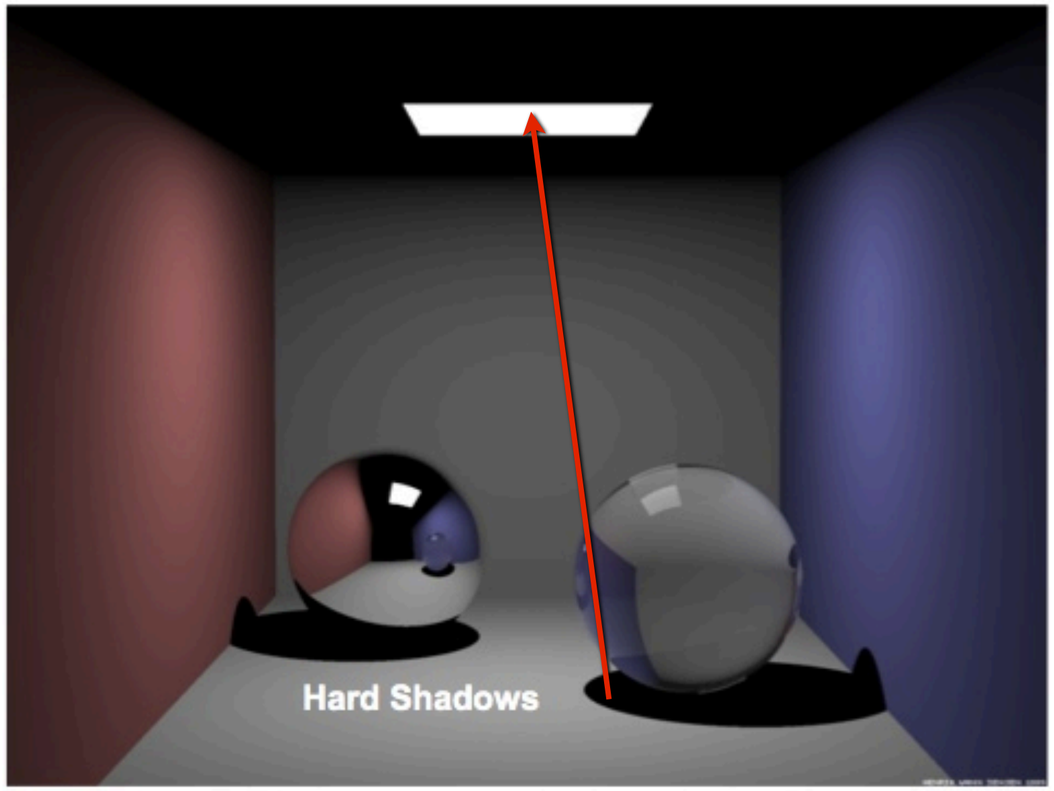


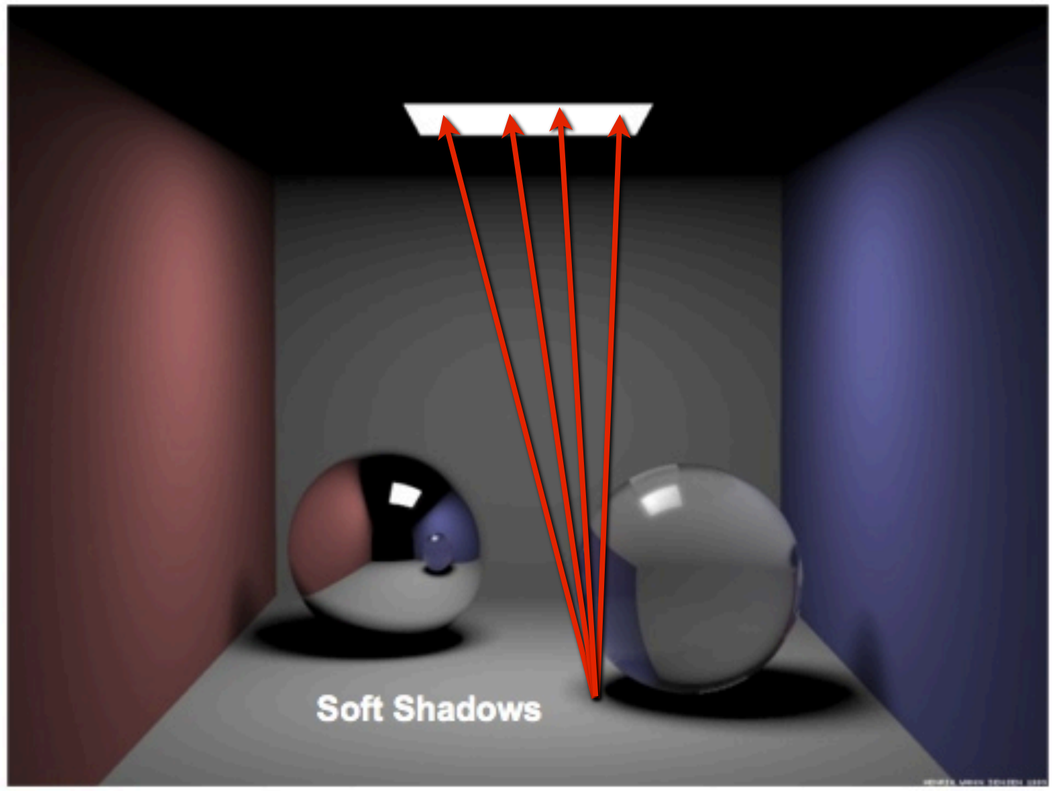
Trace a ray to compute visibility between two scene points (key component of evaluating rendering equation)

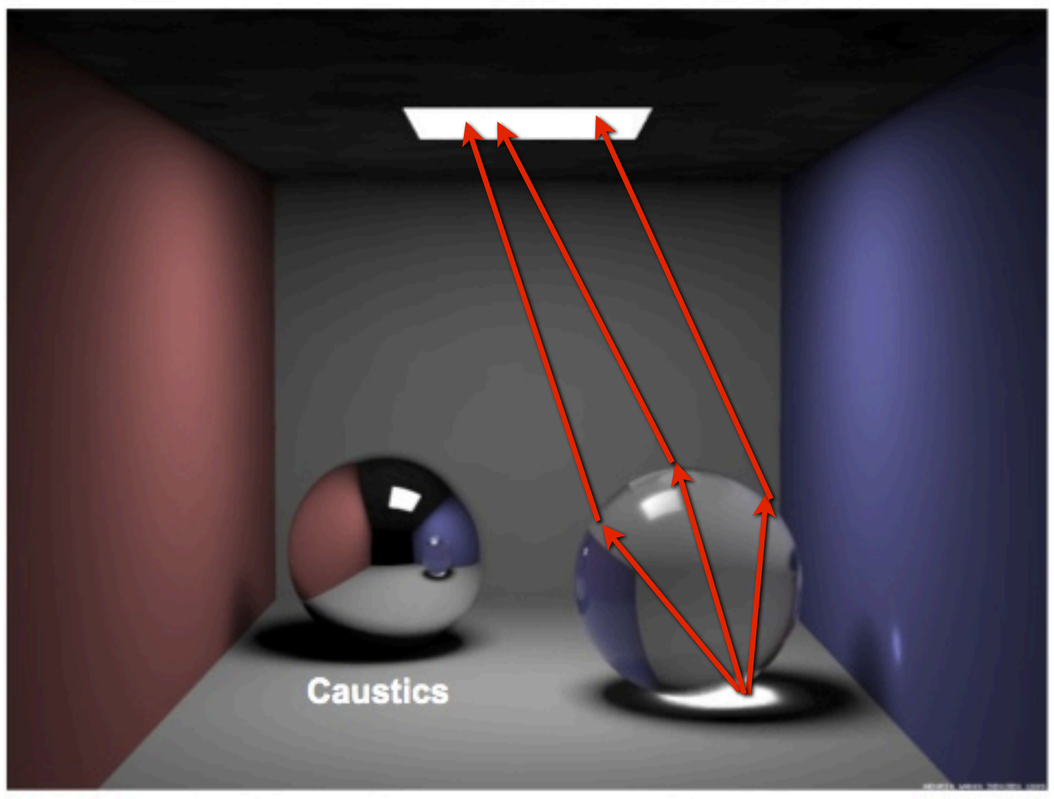
- Compute $v(x, x')$ (is there visibility along ray from x to x′)
- Compute hit = trace(x, x') (what surface was the first one hit by ray from x to x′)



Sampling light paths







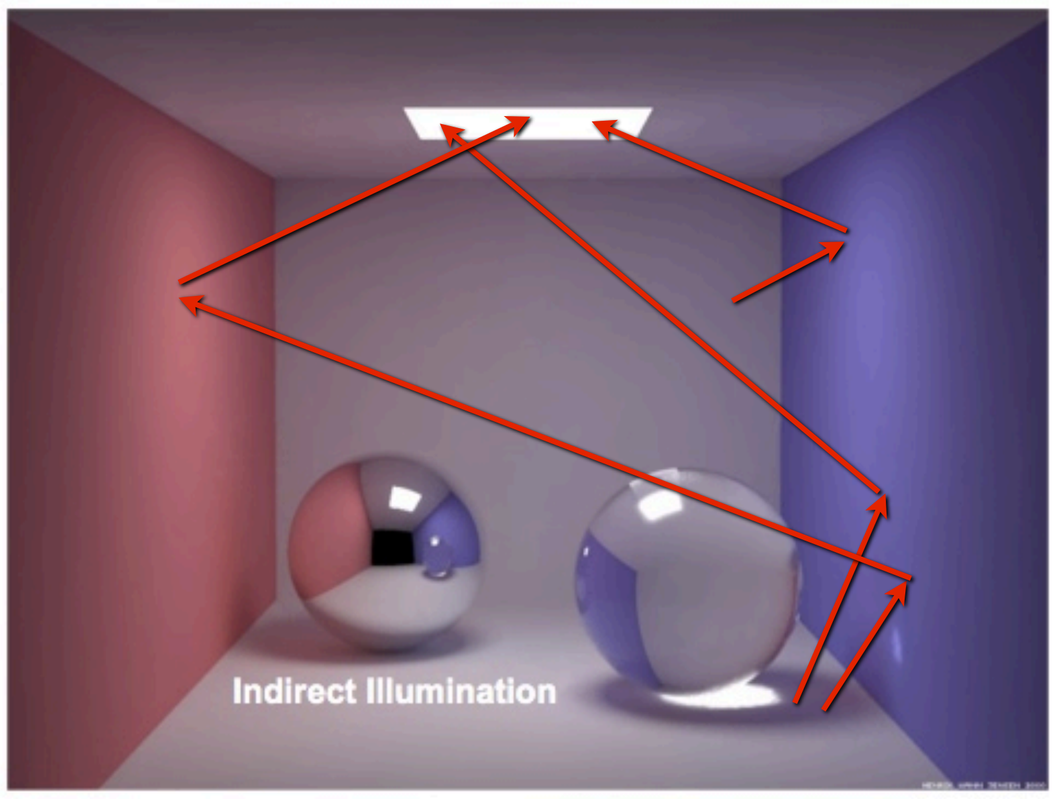
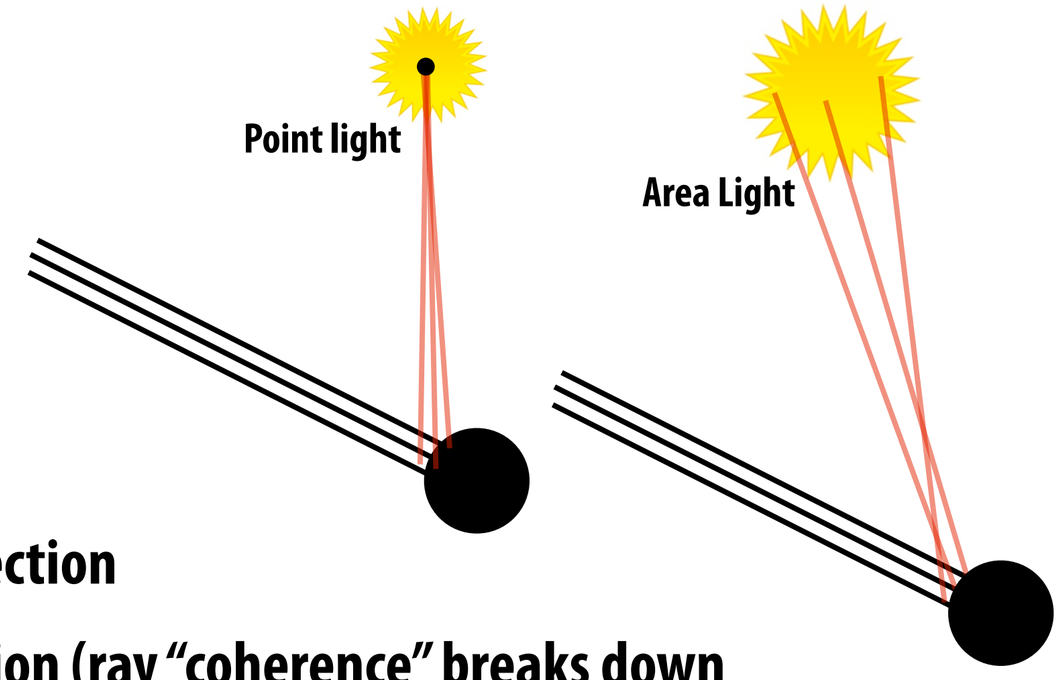


Image credit: Wann Jensen, Hanrahan

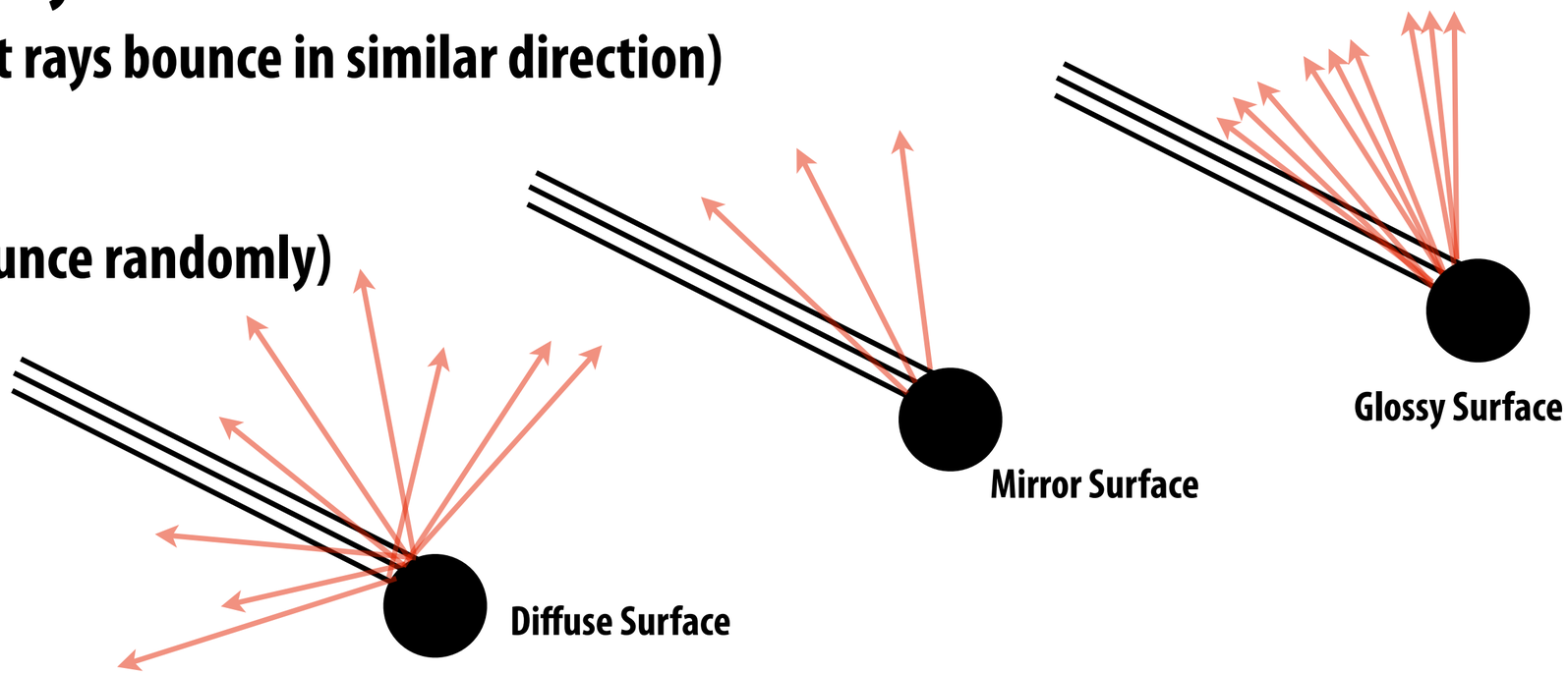
Tracing rays used in many contexts

- **Camera rays (a.k.a., eye rays, primary rays)**
  - Common origin, similar direction



- **Shadow rays**
  - Point light source: common destination, similar direction
  - Area light 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 rays**
  - Mirror surface (coherent rays bounce in similar direction)
  - Glossy surface
  - Diffuse surface (rays bounce randomly)



Another way to think about rasterization

- Rasterization is an optimized visibility algorithm for batches of rays with specific properties
  - Assumption 1: Rays have the same origin
  - Assumption 2: Rays are uniformly distributed (within field of view)

1. Same origin/known field-of-view: project triangles to reduce ray-triangle intersection to 2D point-in-polygon test
   - Simplifies math (2D point-in-triangle test rather than 3D intersection)
   - Fixed-point math (clipping used to ensures precision bounds)

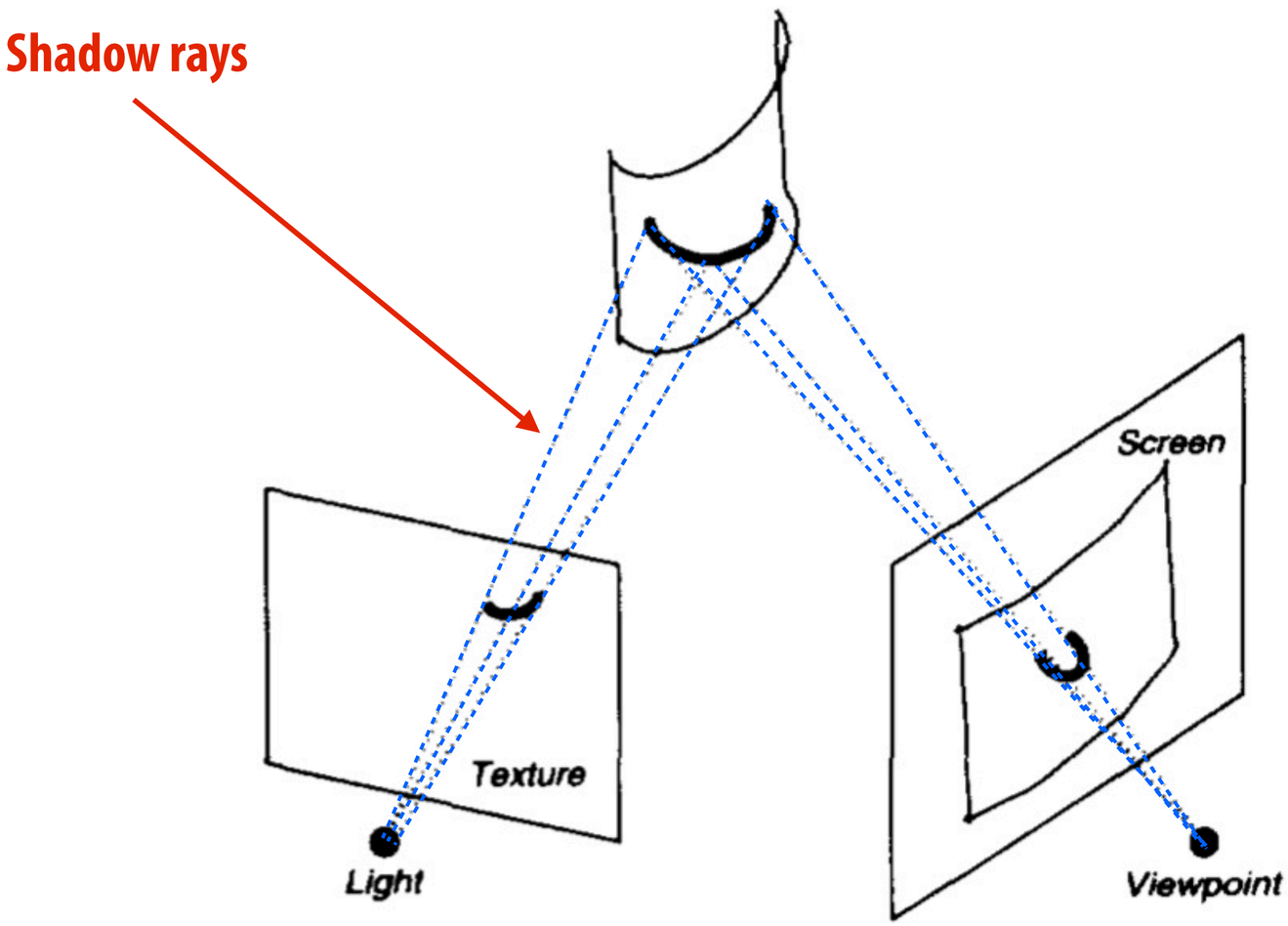
Rasterization: ray origin need not be camera position

Example: shadow mapping

- **Place ray origin at position of light source**

Shadow map: render scene with camera at light position to compute depth along uniformly distributed "shadow rays"

- **Store precomputed shadow ray intersection results in texture map**



Shadow map: texture stores closest intersection along each shadow ray

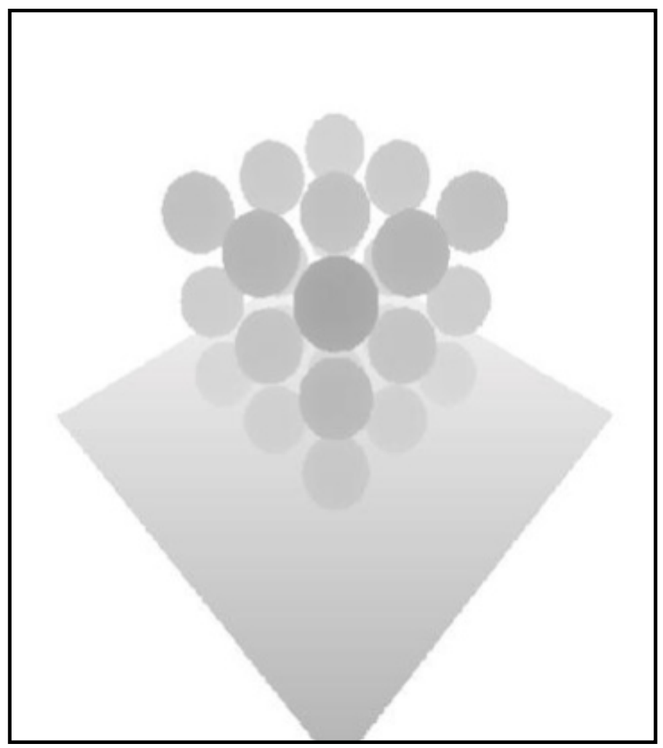
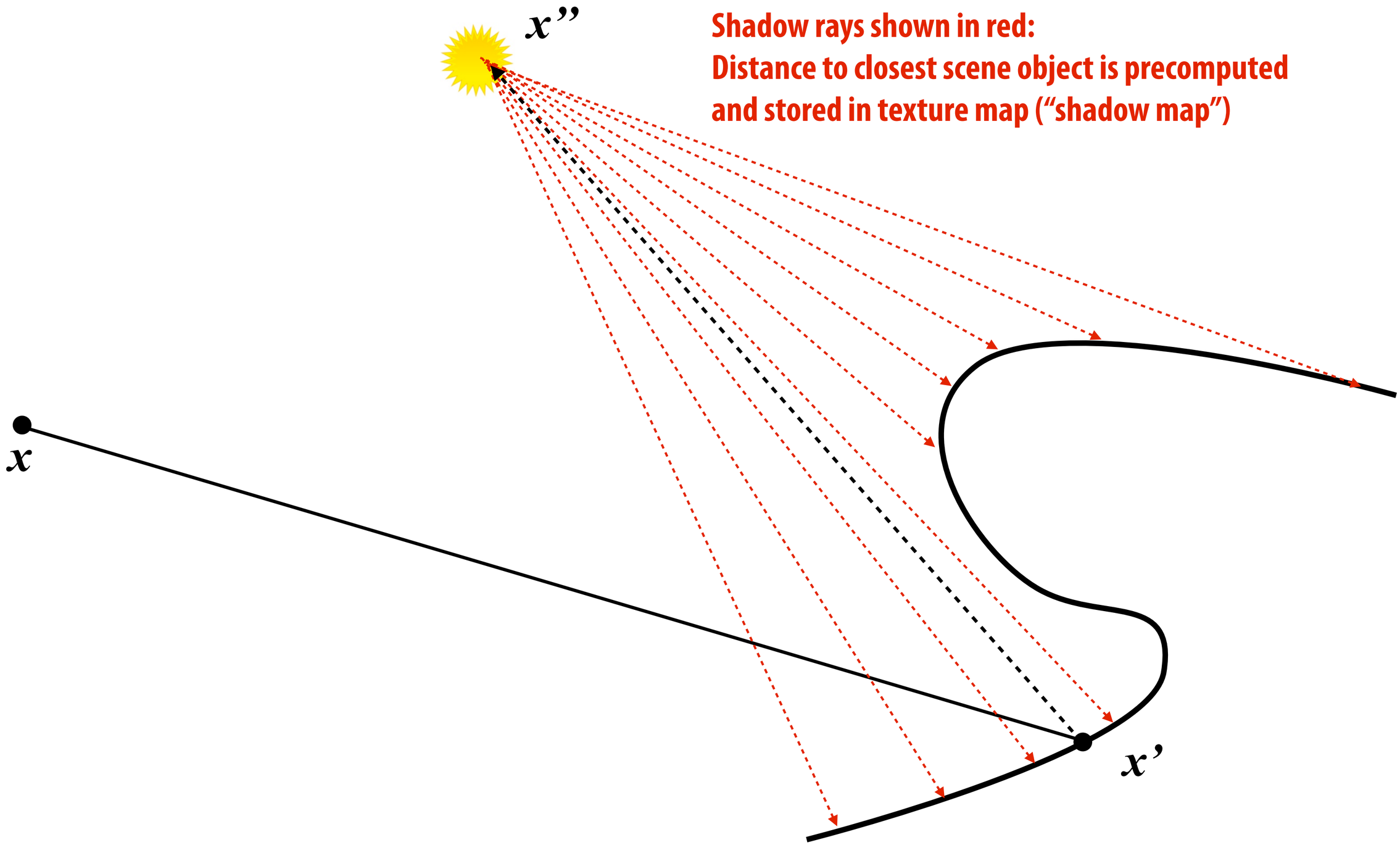
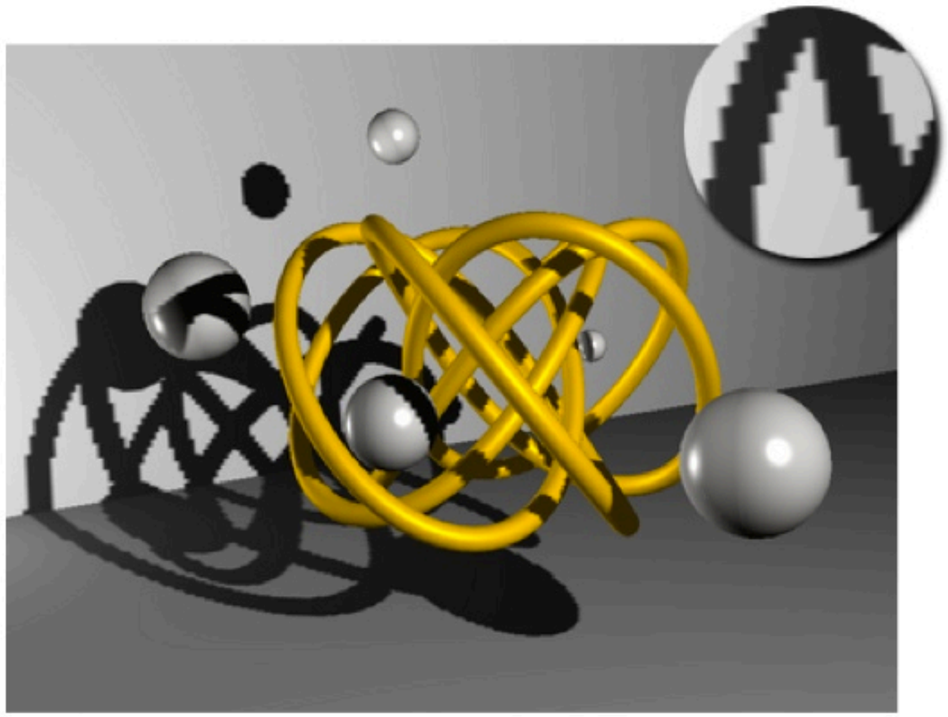


Image credits: Segal et al. 92, Cass Everitt

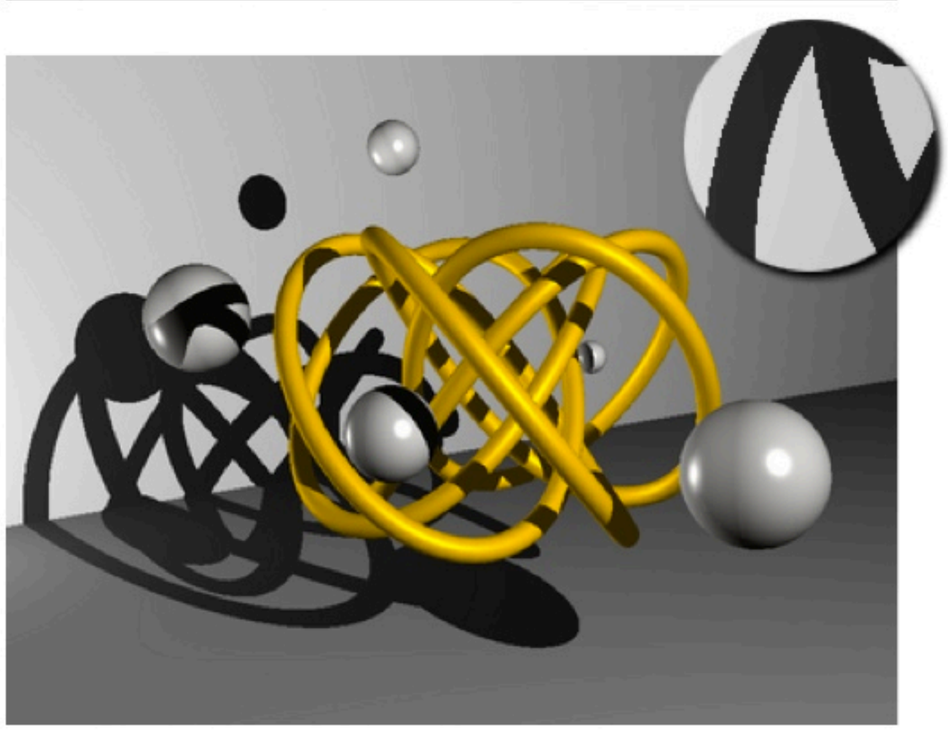
Shadow map used to approximate v(x′,x″) when shading fragment at x′



Shadow aliasing due to shadow map undersampling



Shadows computed using shadow map



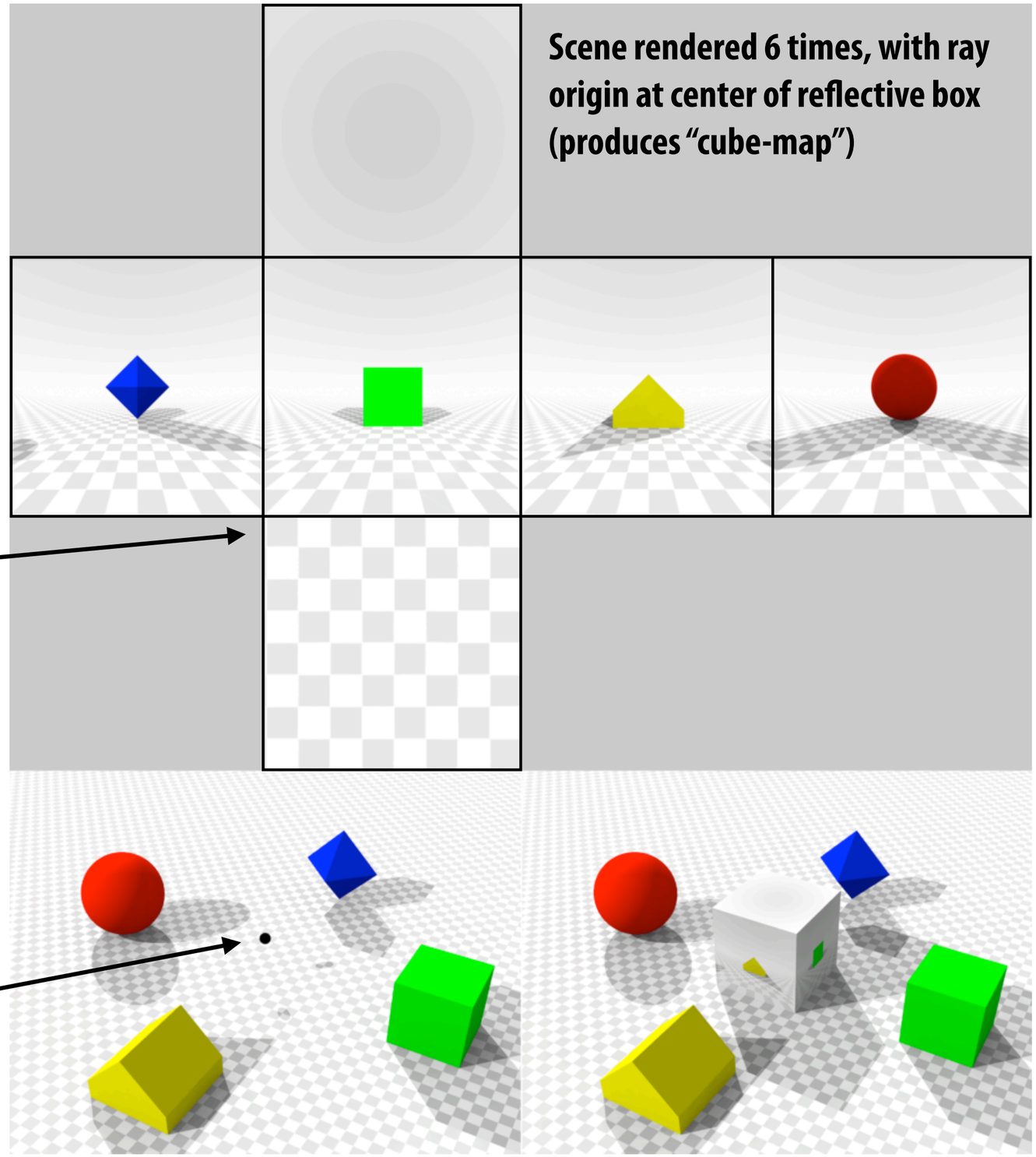
Correct hard shadows
(result from computing v(x′,x″) directly using ray tracing

Image credit: Johnson et al. TOG 2005

Rasterization: ray origin need not be camera position

Environment mapping:
place ray origin at reflective object

Yields approximation to true reflection results. Why?



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

Summary: rasterization as a visibility algorithm

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

1. Same origin+known field of view: projection of triangles reduces ray-triangle intersection to cheap/efficient 2D point-in-polygon test
   - GPUs have specialized fixed-function hardware for this computation

2. Uniform sample distribution: given polygon, it is easy (a.k.a. efficient) to "find" samples covered by polygon
   - Frame buffer: constant time sample lookup, update, edit
   - Sample search leverages 2D screen coherence: no need for complex acceleration structures to accelerate a search over samples (hierarchy implicit in the samples)

Rasterization: performance

- Stream over scene geometry (regular/predictable data access), but arbitrarily access frame-buffer sample data
  - Unpredictable access to sample data is manageable

- Z-buffered occlusion
  - Fixed number of samples (determined by screen resolution)
  - Known sample data structure
  - Implication: fixed-function hardware to accelerate computation

- Scales to high scene complexity
  - Stream over geometry: so required memory footprint in graphics pipeline is independent of scene size

Why real-time ray tracing?

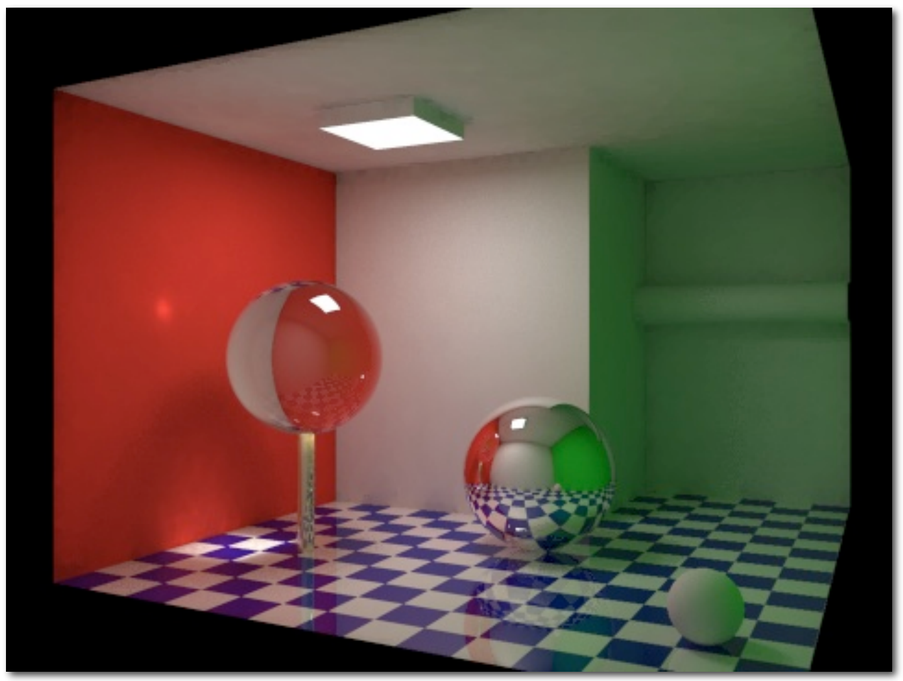
Potential real-time ray tracing motivations

VR may demand more flexible control over what pixels are drawn. (e.g., row-based display rather than frame-based, higher resolution where eye is looking)

Reduce content creation and game engine development time: single general solution rather a specialized technique for each effect.

Many of shadowed lights (pain to manage hundreds of shadow maps)

Accurate reflections from curved surfaces

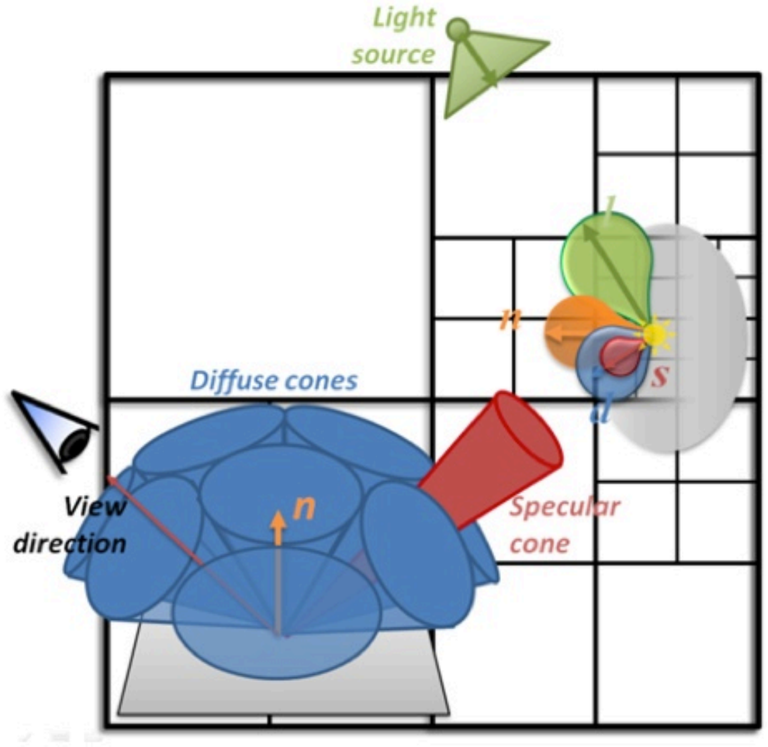


Other indirect illumination?

(unclear if ray tracing is best real-time solution for low frequency effects)

Indirect illumination via voxel cone tracing

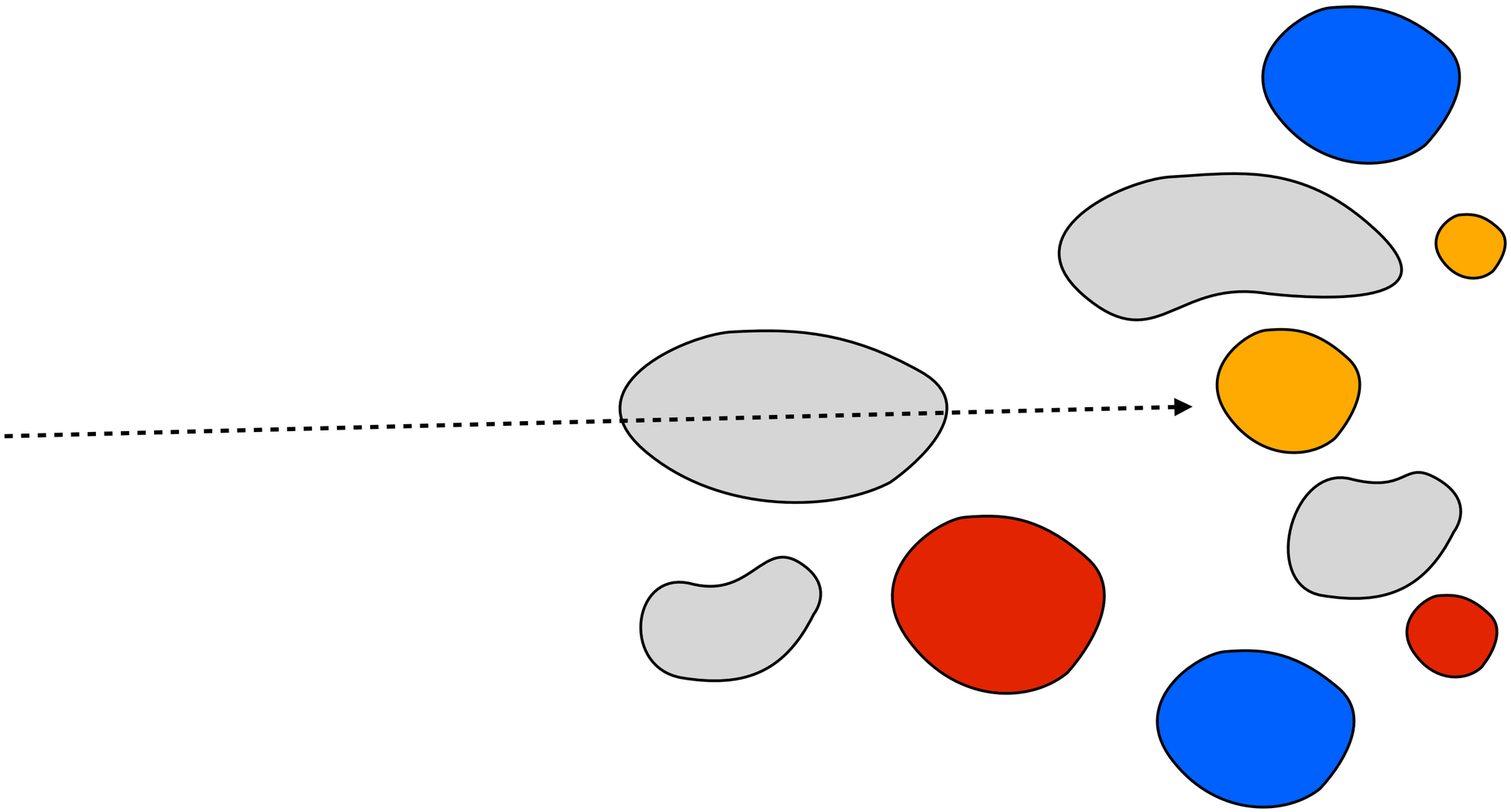
- Indirect illumination is low frequency
- Algorithm:
  1. Voxelize scene into multi-resolution voxel grid: sparse-voxel-octree (rasterization)
  2. For each light, rasterize scene from light source, deposit light in visible voxels (rasterization)
  3. Rasterize scene, for each fragment trace a few (~5) cones through octree, accumulating indirect lighting



Efficient ray tracing

Problem

Given ray, find first intersection with scene geometry **

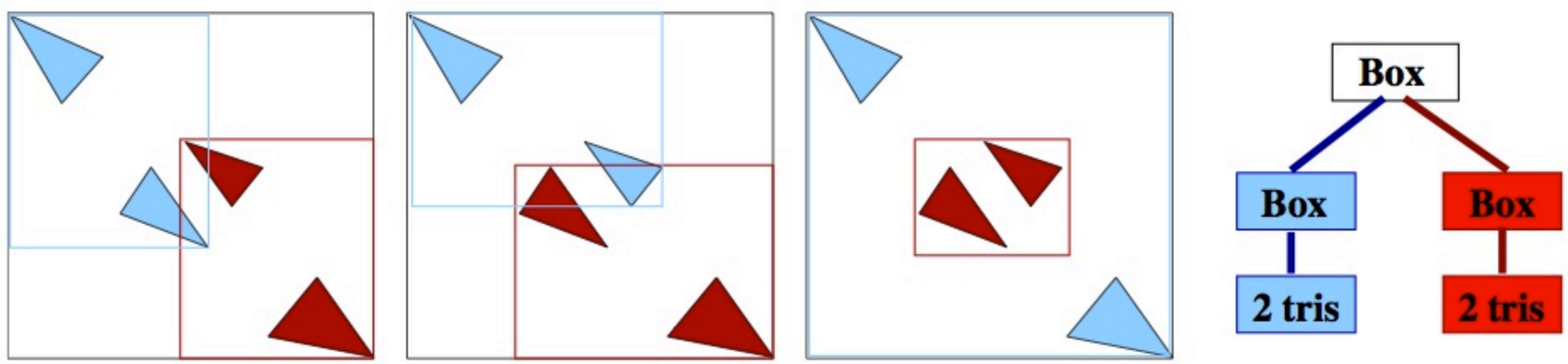


** A simpler, but common, query is to determine only if <u>any</u> intersection exists

Accelerating ray-scene intersection

- Preprocess scene to accelerate ray-scene visibility queries
  - 1D analogy: sort integers in a list to enable efficient binary search
  - Database analogy: build an index (e.g., B-tree)

- Popular acceleration structure for ray tracing: bounding volume hierarchy (BVH)
  - Group objects with spatial proximity into tree nodes
  - Adapts to non-uniform density of scene objects
  - Note: many other acceleration structures: K-D trees, octrees, uniform grids



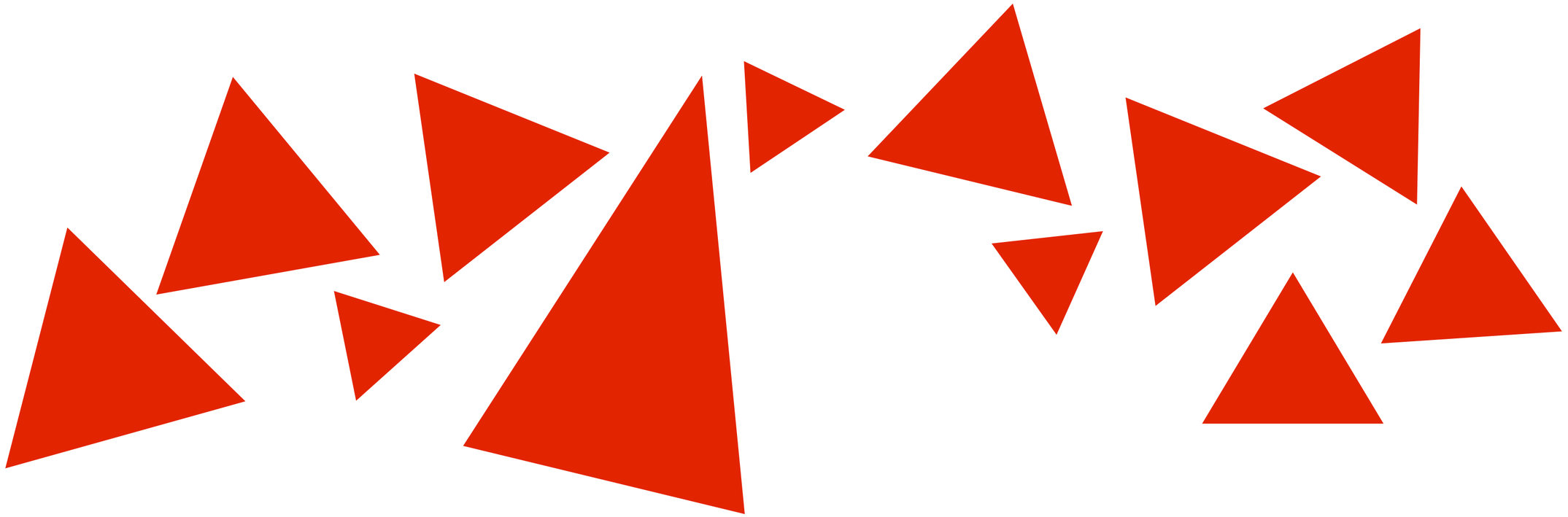
Three different bounding volume hierarchies for the same scene

Image credit: Wald et al. TOG 2004

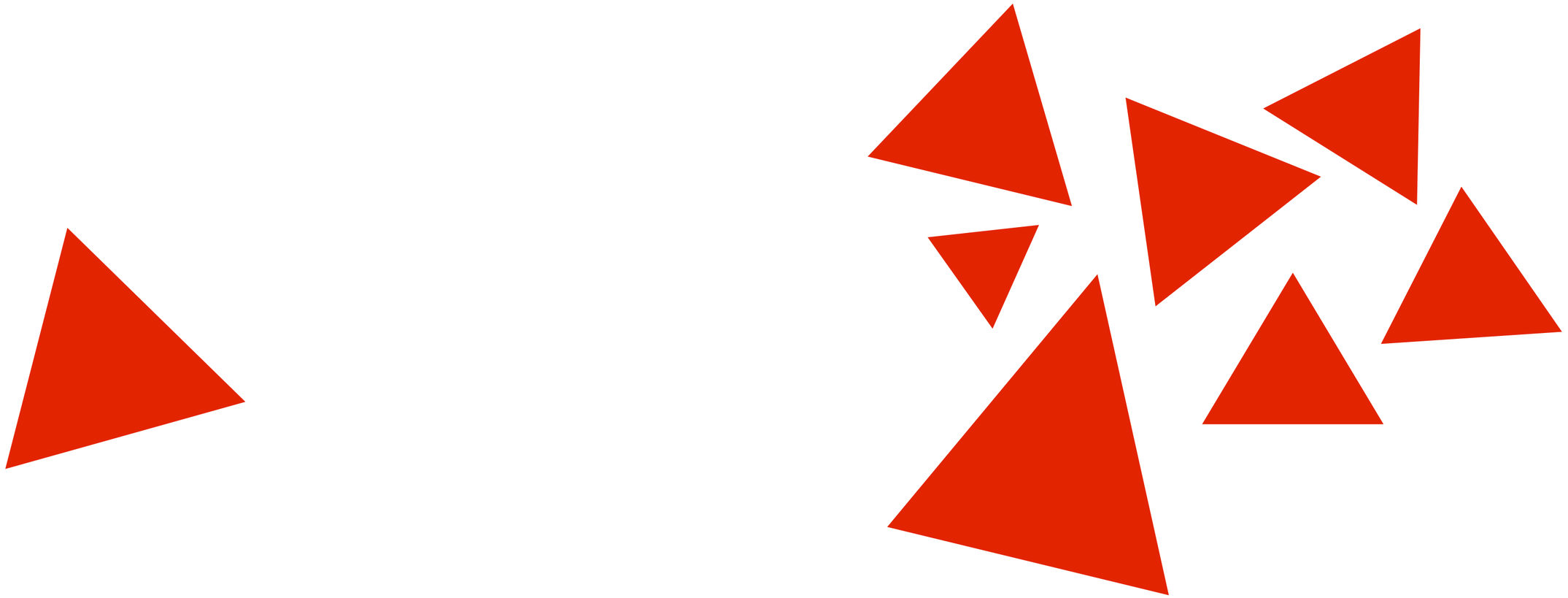
Simple ray tracer (using a BVH)

```
// 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);
   }
}
```

How to build a BVH?



How to build a BVH?



Surface area heuristic

[Goldsmith and Salmon 87]

- **Goal: minimize <u>expected cost</u> to trace rays through BVH**

  `cost of leaf node` = C_I x # primitives in node

  `cost of interior node` = $C_T + (P_L * C_L) + (P_R * C_R)$

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

  $P_{L/R}$ = probability of ray intersecting left/right child subtree

  $C_{L/R}$ = cost of intersecting ray with left/right child subtree

- **Assumptions made by the surface area heuristic:**
  - Rays are uniformly distributed (uniform distribution of origin and direction) but originate from outside node bounding box
    - Then P_i is surface area of child node bbox / surface area of parent node bbox
  - Costs of child subtrees typically estimated to be C_I x # primitives
    - C_I = cost to intersect ray with primitive
    - Works best in practice (open problem why this is so)

Basic top-down BVH build

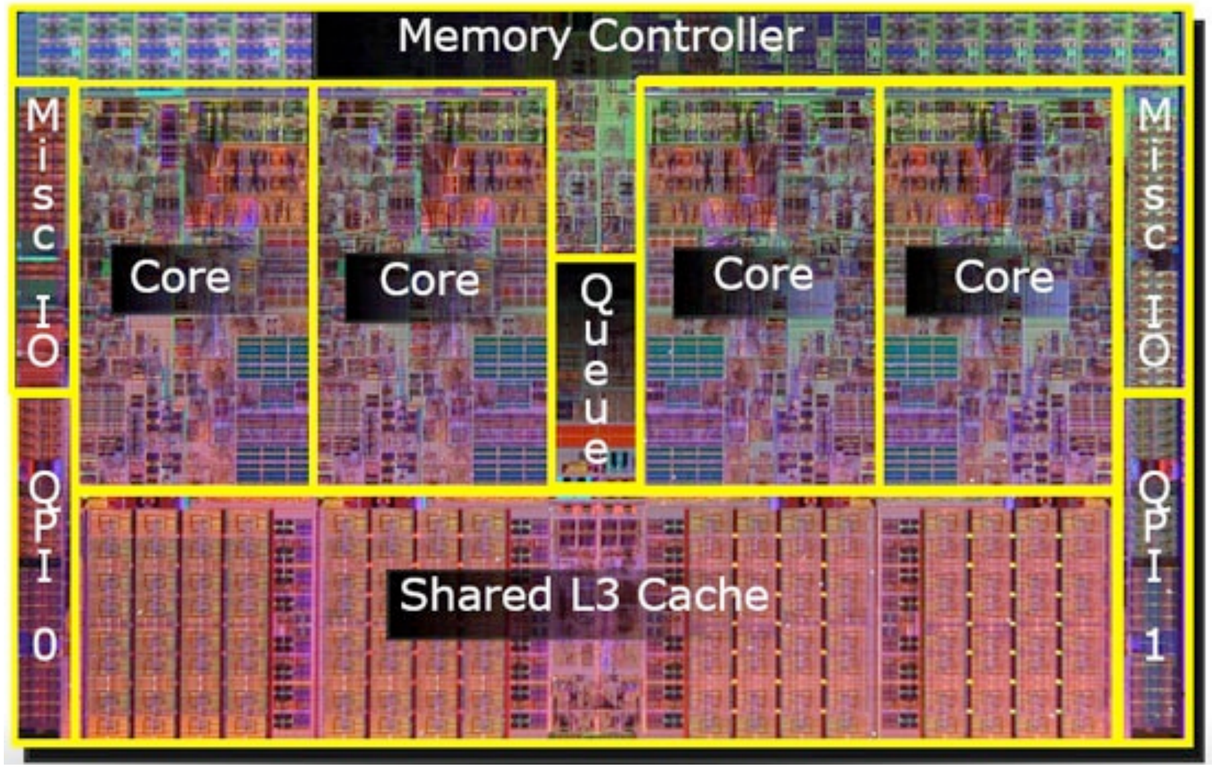
- Too costly to attempt to evaluate all possible primitive partitions
- Common approximation technique: top-down "binned" sweep
  - Partition coordinate axes uniformly into bins
  - Only attempt partitions at bin boundaries
  - Once partition is found, recurse on resulting sets to construct left/right subtrees

```
FIND_PARTITION(prims)
  min_score = INFINITY
  for each axis (X, Y, Z) {
    Partition axis uniformly into N bins   // in practice N=16 or 32
    for each primitive in prims:
       place primitive into bin based on primitive's centroid
       (Accumulate total count of primitives in bin and aggregate surface area)
    for (i=0; i<N+1; i++) {
      score = evaluate SAH by partitioning according to contents of bins 0-i and bins i-32
      if (score < min_score)
        min_score = score;  // this is best partition so far
    }
}
```

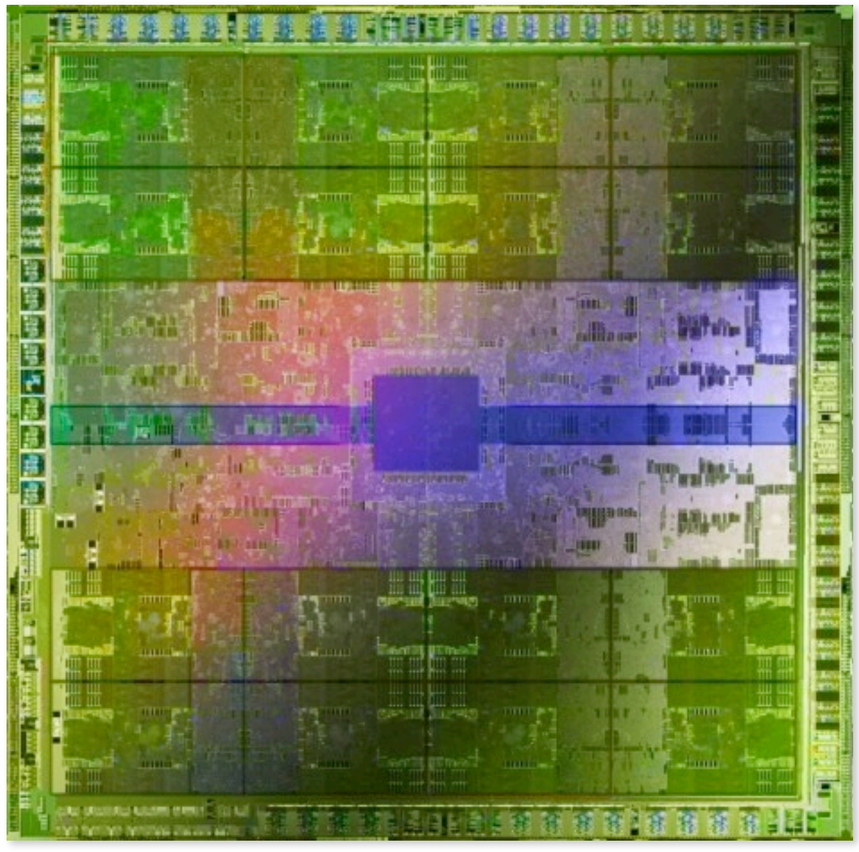
Accelerating ray-scene queries using a BVH

Some parallel processing basics

Multi-core processor examples

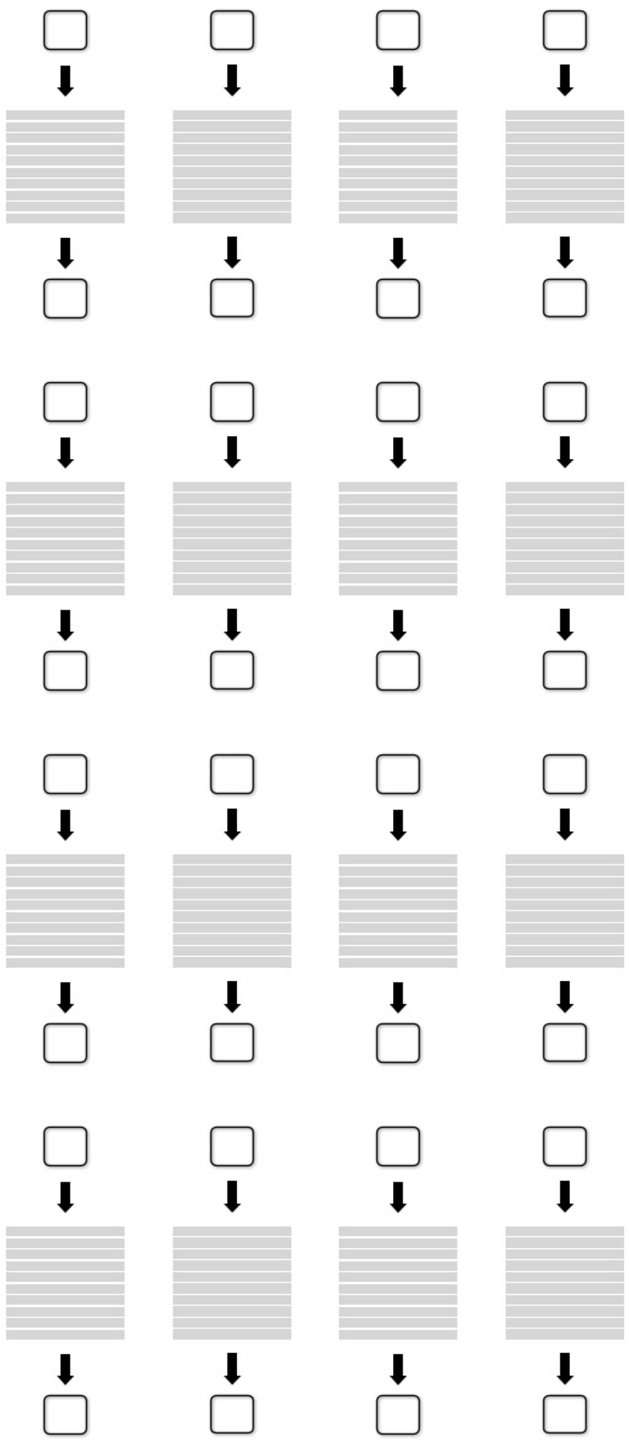


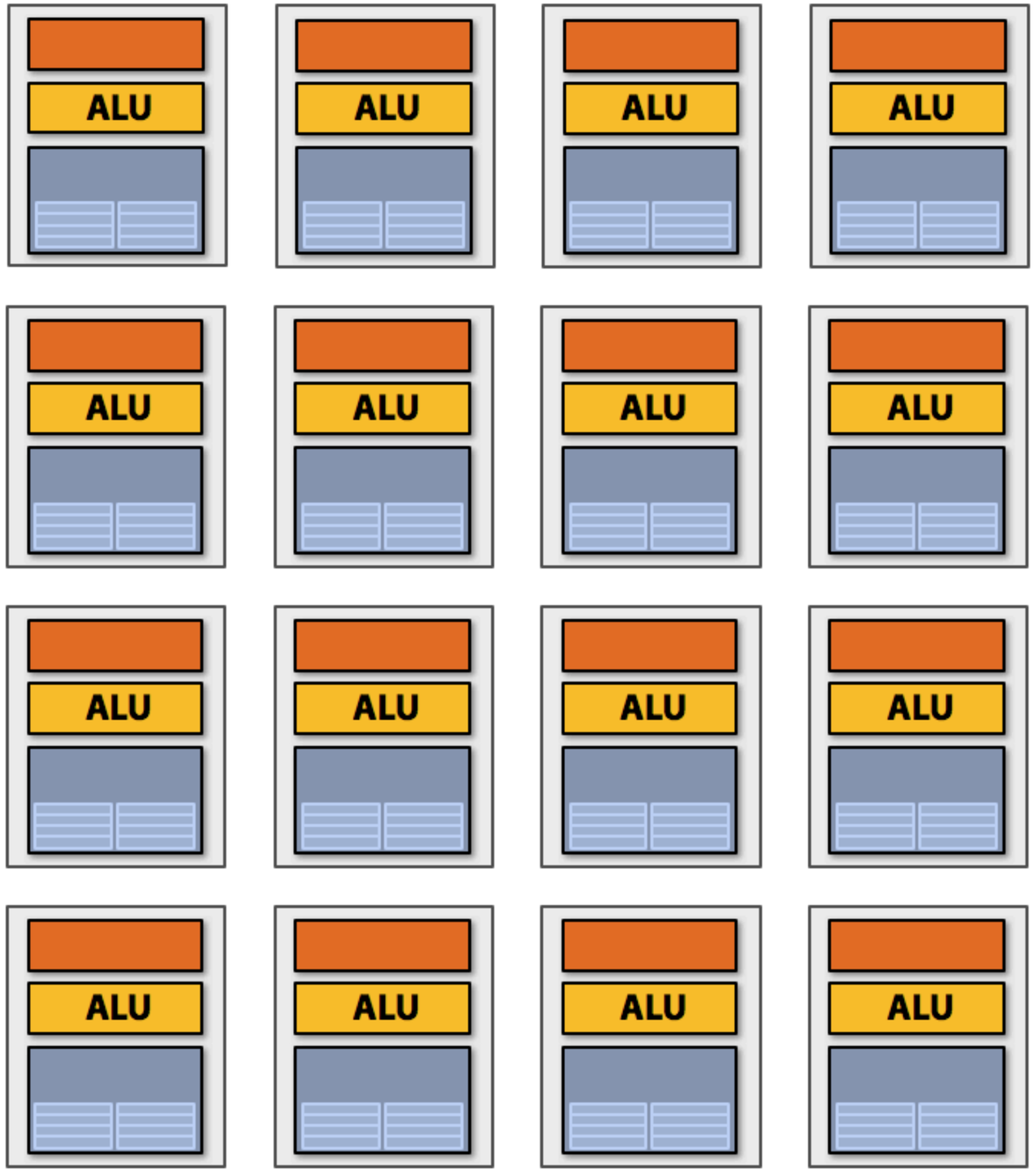
Intel Core i7 quad-core CPU (2010)



NVIDIA Tesla GPU (2009)
16 "SM" cores

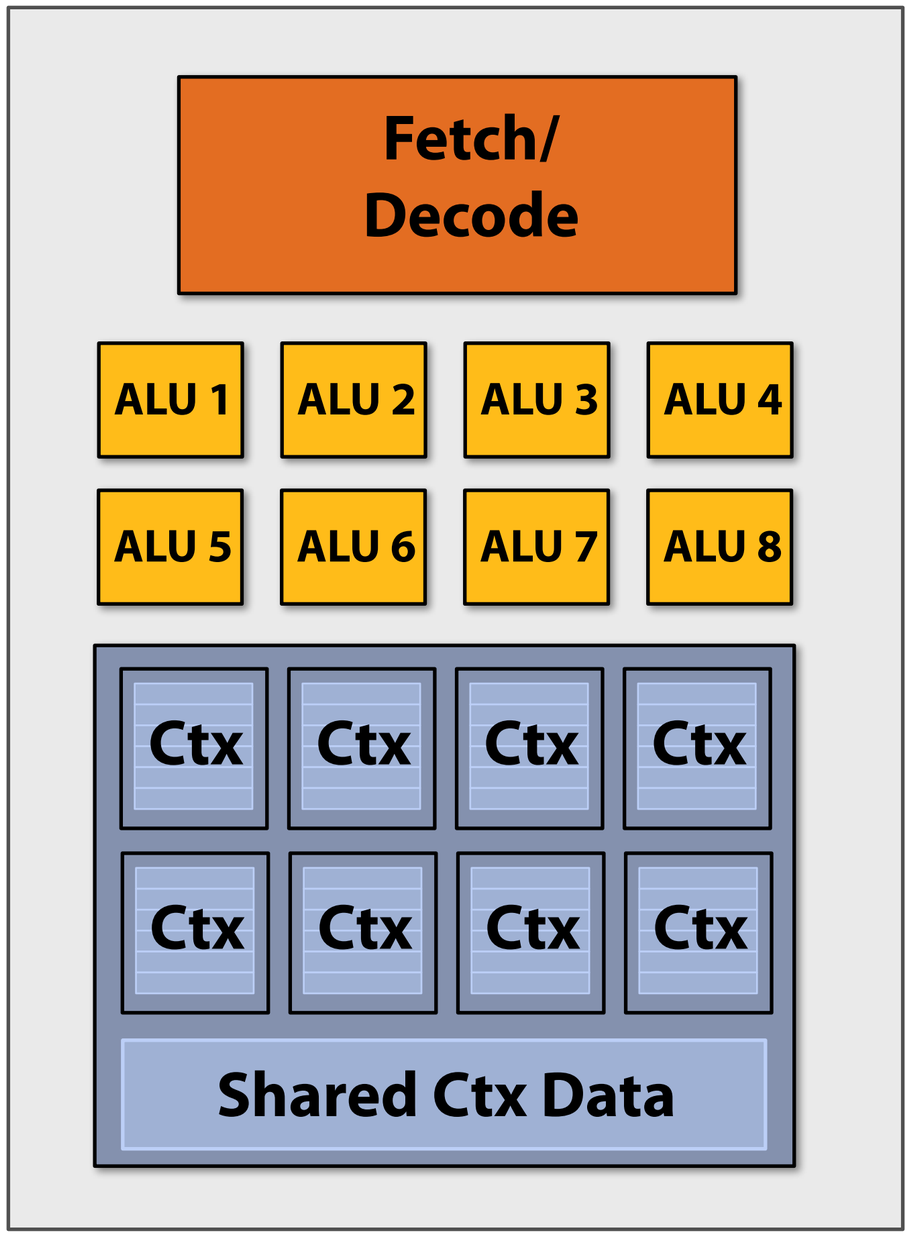
Sixteen cores: compute sixteen elements in parallel





Sixteen cores, sixteen simultaneous instruction streams

SIMD processing



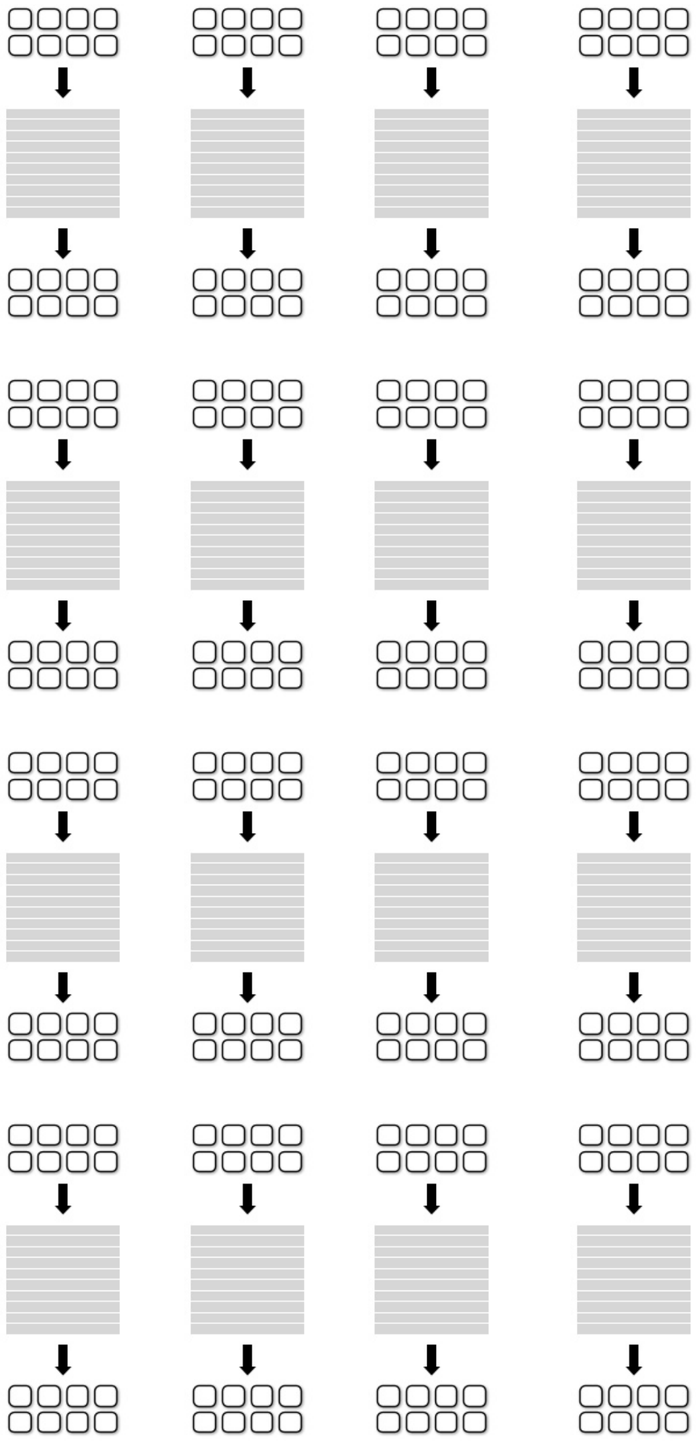
SIMD = Single instruction, multiple data

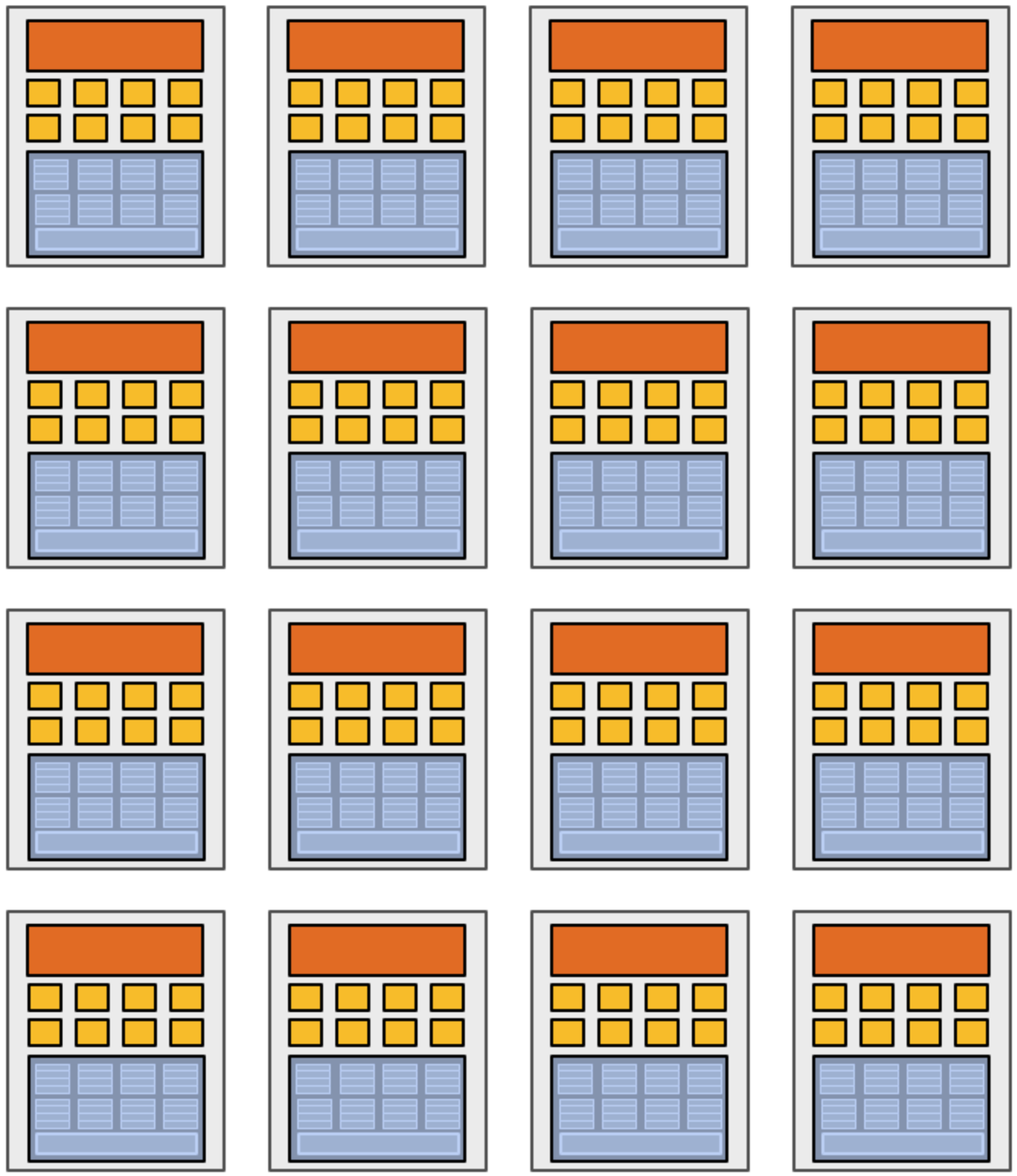
Same instruction executed in parallel on all ALUs on different pieces of data

Modern CPUs:
SSE instructions 4 operations in parallel
AVX instructions 8 operations in parallel
(similar to illustration at right)

Modern GPUs:
16-64 operations in parallel

16, 8-wide SIMD cores: 128 operations in parallel





16 independent CPU cores, 8-wide SIMD, 128 total ALUs

Example program

Compute $\sin(x)$ using Taylor expansion: $\sin(x) = x - x^3/3! + x^5/5! - x^7/7! + \ldots$

for each element of an array of N floating-point numbers

```
void sinx(int N, int terms, float* x, float* result)
{
   for (int i=0; i<N; i++)
   {
      float value = x[i];
      float numer = x[i] * x[i] * x[i];
      int denom = 6;  // 3!
      int sign = -1;

      for (int j=1; j<=terms; j++)
      {
         value += sign * numer / denom
         numer *= x[i] * x[i];
         denom *= (2*j+2) * (2*j+3);
         sign *= -1;
      }

      result[i] = value;
   }
}
```

Vector program (using AVX intrinsics)

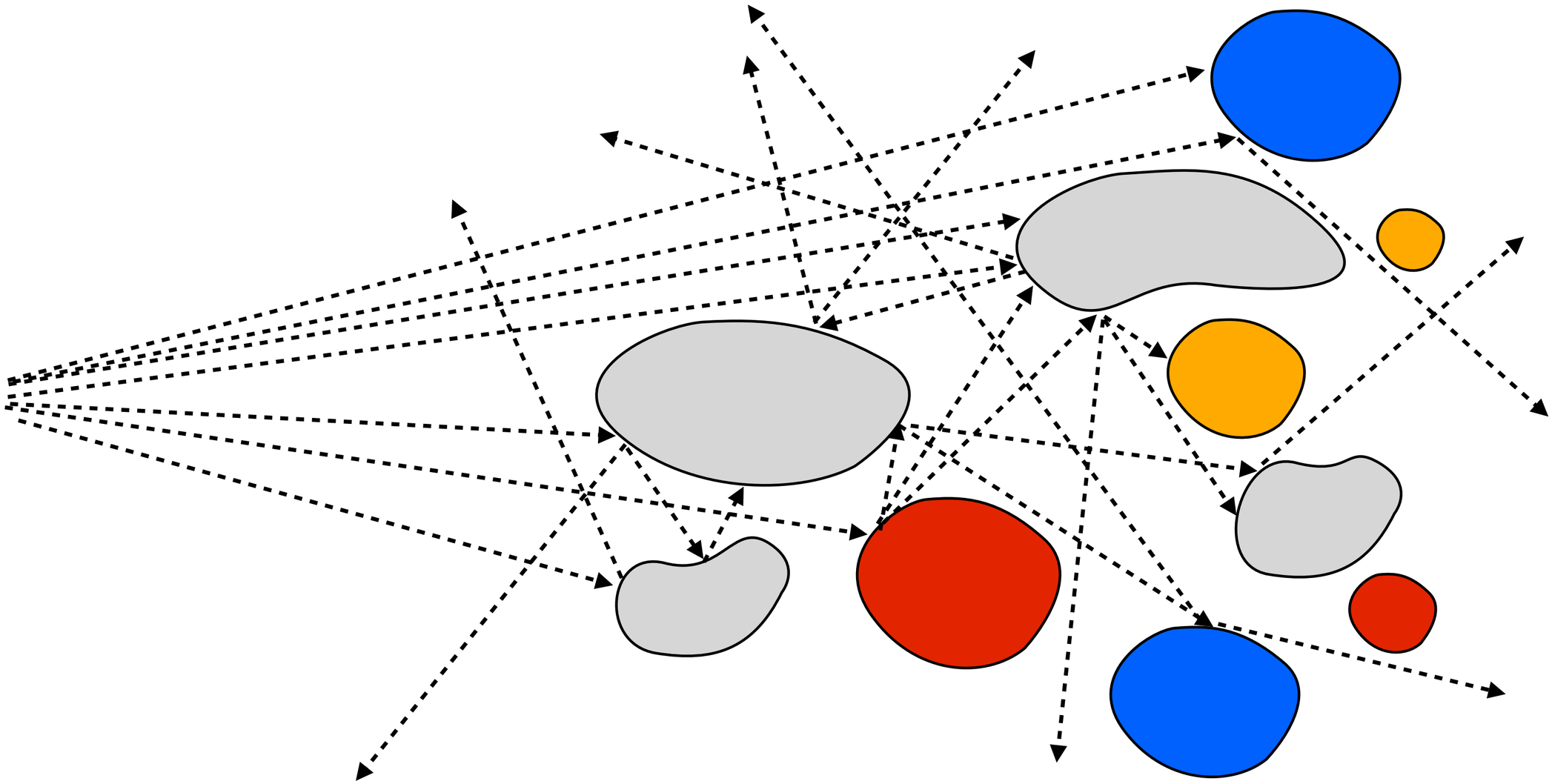
Intrinsics available to C programmers

```
#include <immintrin.h>
void sinx(int N, int terms, float* x, float* result)
{
   for (int i=0; i<N; i+=8)
   {
       __m256 origx = _mm256_load_ps(&x[i]);
      __m256 value = origx;
      __m256 numer = _mm256_mul_ps(origx, _mm256_mul_ps(origx, origx));
      __m256 denom = _mm256_broadcast_ss(6); // 3!
      int sign = -1;

      for (int j=1; j<=terms; j++)
      {
         // value += sign * numer / numer
         __m256 tmp = _mm256_div_ps(_mm256_mul_ps(_mm256_set1ps(sign), numer), denom);
         value = _mm256_add_ps(value, tmp);

         numer = _mm256_mul_ps(numer, _mm256_mul_ps(origx, origx));
         denom = _mm256_mul_ps(denom, _mm256_broadcast_ss((2*j+2) * (2*j+3)));
         sign *= -1;
      }
      _mm256_store_ps(&result[i], value);
   }
}
```

Accelerating ray-scene queries using a BVH

High-throughput ray tracing

Find intersection of millions of rays with scene geometry



High-throughput ray tracing

- **Want work efficient algorithms (do less)**
  - High-quality acceleration structures (minimize ray-box, ray-primitive tests)
  - Smart traversal algorithms (early termination, etc.)

- **Implementations for existing parallel hardware (CPUs/GPUs):**
  - High multi-core, SIMD execution efficiency
  - Help from fixed-function processing?

- **Bandwidth-efficient implementations:**
  - How to minimize bandwidth requirements so that processes are not bottlenecked by reading data from memory?

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

Parallelize ray-box, ray-triangle intersection

- Given one ray and one bounding box, there are opportunities for SIMD processing
  - Can use 3 of 4 SSE vector lanes (e.g., xyz work, point-multiple-plane tests, etc.)

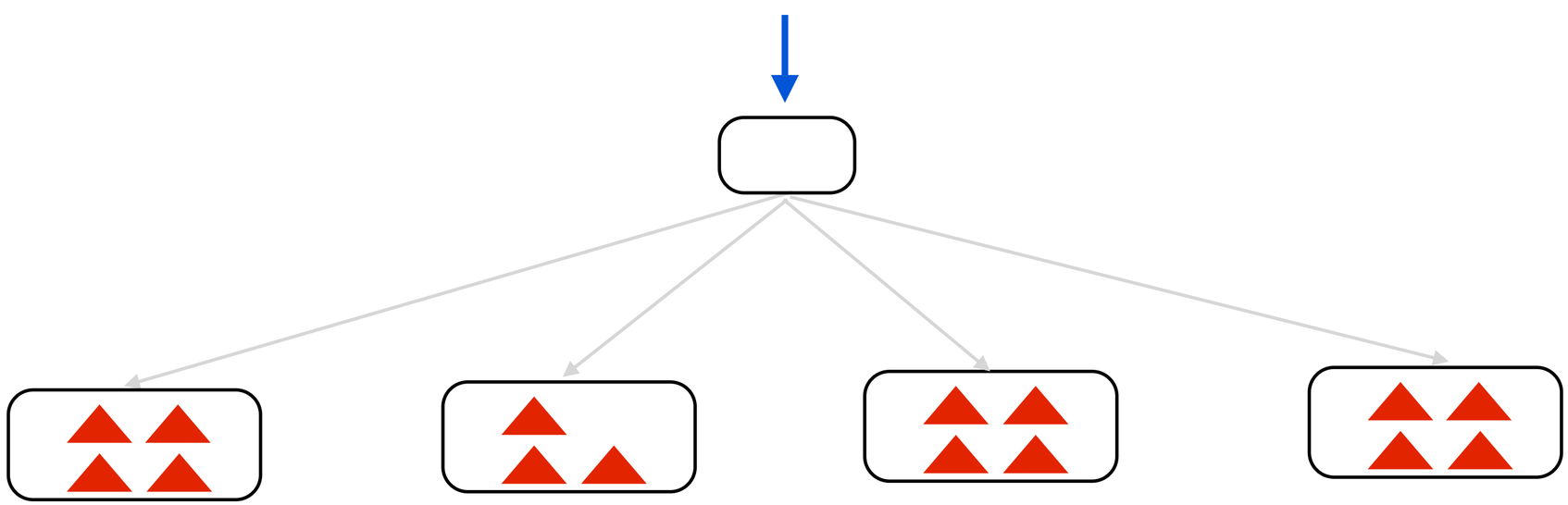
- Similar SIMD parallelism in ray-triangle test at BVH leaf

- If leaf nodes contain multiple triangles, can parallelize ray-triangle intersection across these triangles

Parallelize over BVH child nodes

[Wald et al. 2008]

- Idea: use wider-branching BVH (test single ray against multiple child node bboxes in parallel)
  - BVH with branching factor 4 has similar work efficiency to branching factor 2
  - BVH with branching factor 8 or 16 is significantly less work efficient (diminished benefit of leveraging SIMD execution)



Parallelize across rays

- Simultaneously intersect multiple rays with scene

- Trivial solution: each core processes one ray in parallel
  - Parallelism across cores

- More complicated: each core processes multiple rays in parallel
  - Today we will discuss implementation called “packet tracing”
  - Code is explicitly written to trace N rays at a time, not 1 ray

Simple ray tracer (using a 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);
   }
}
```

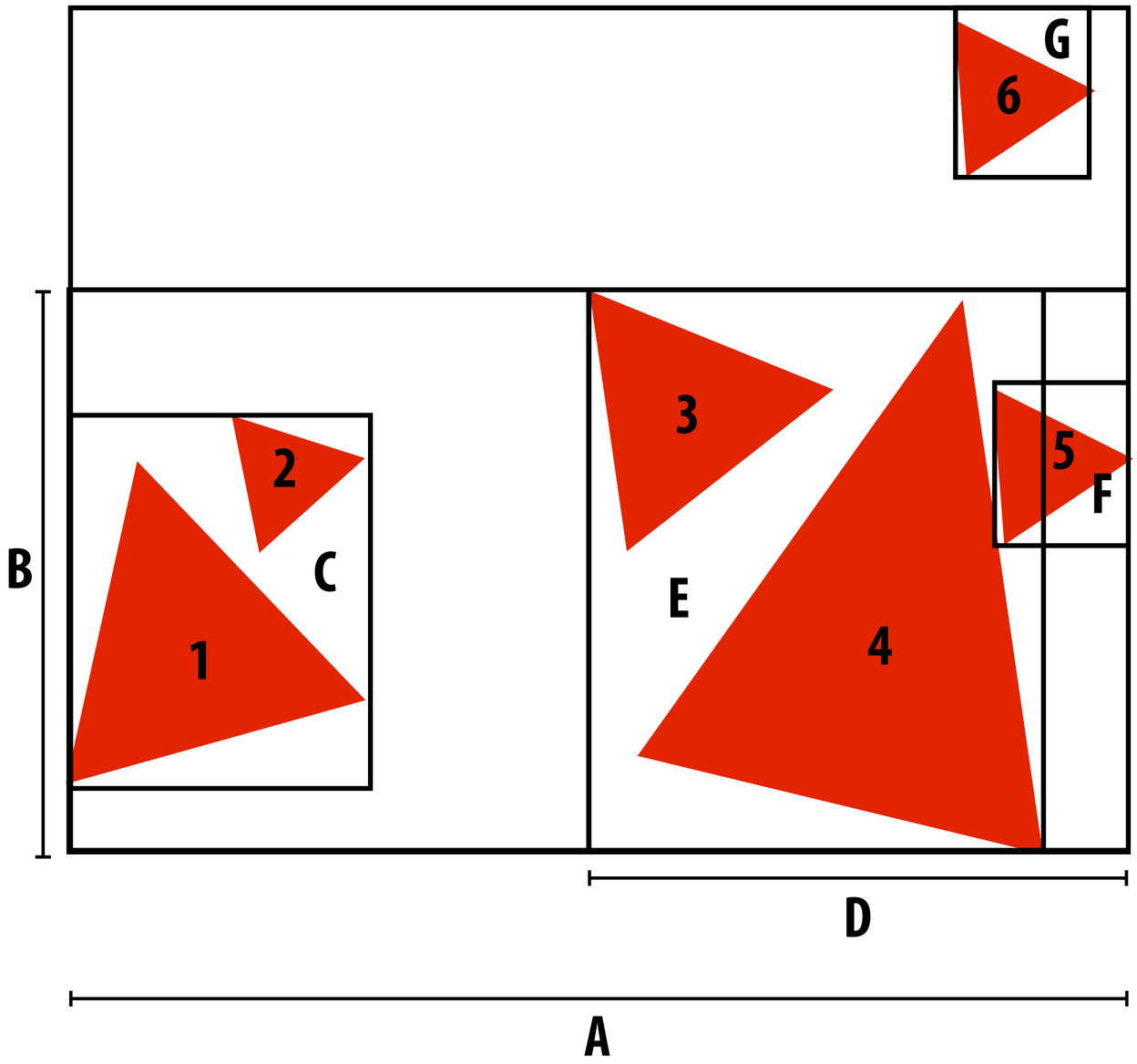
Ray packet tracing

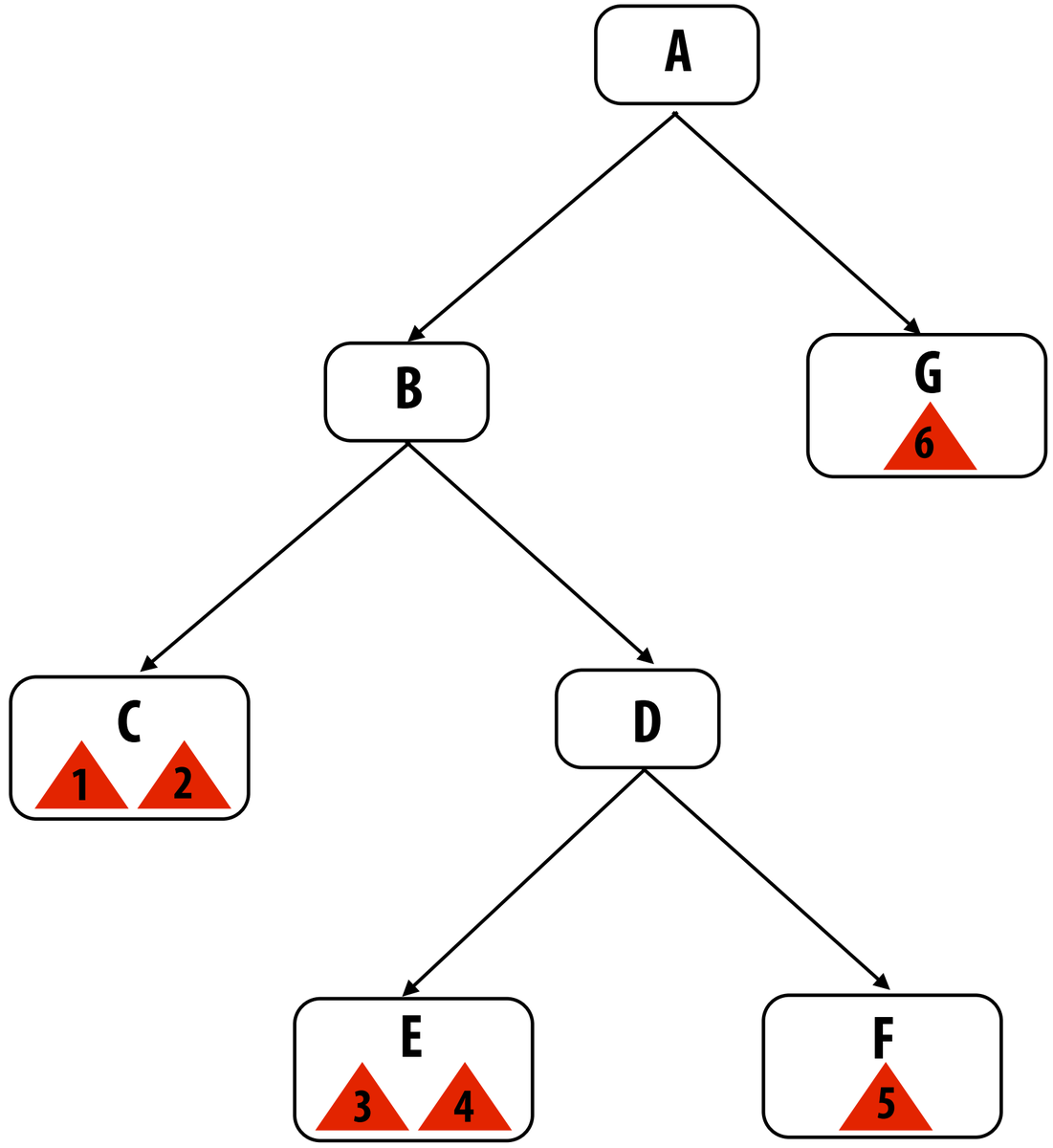
[Wald et al. 2001]

Program explicitly intersects a collection of rays against BVH at once

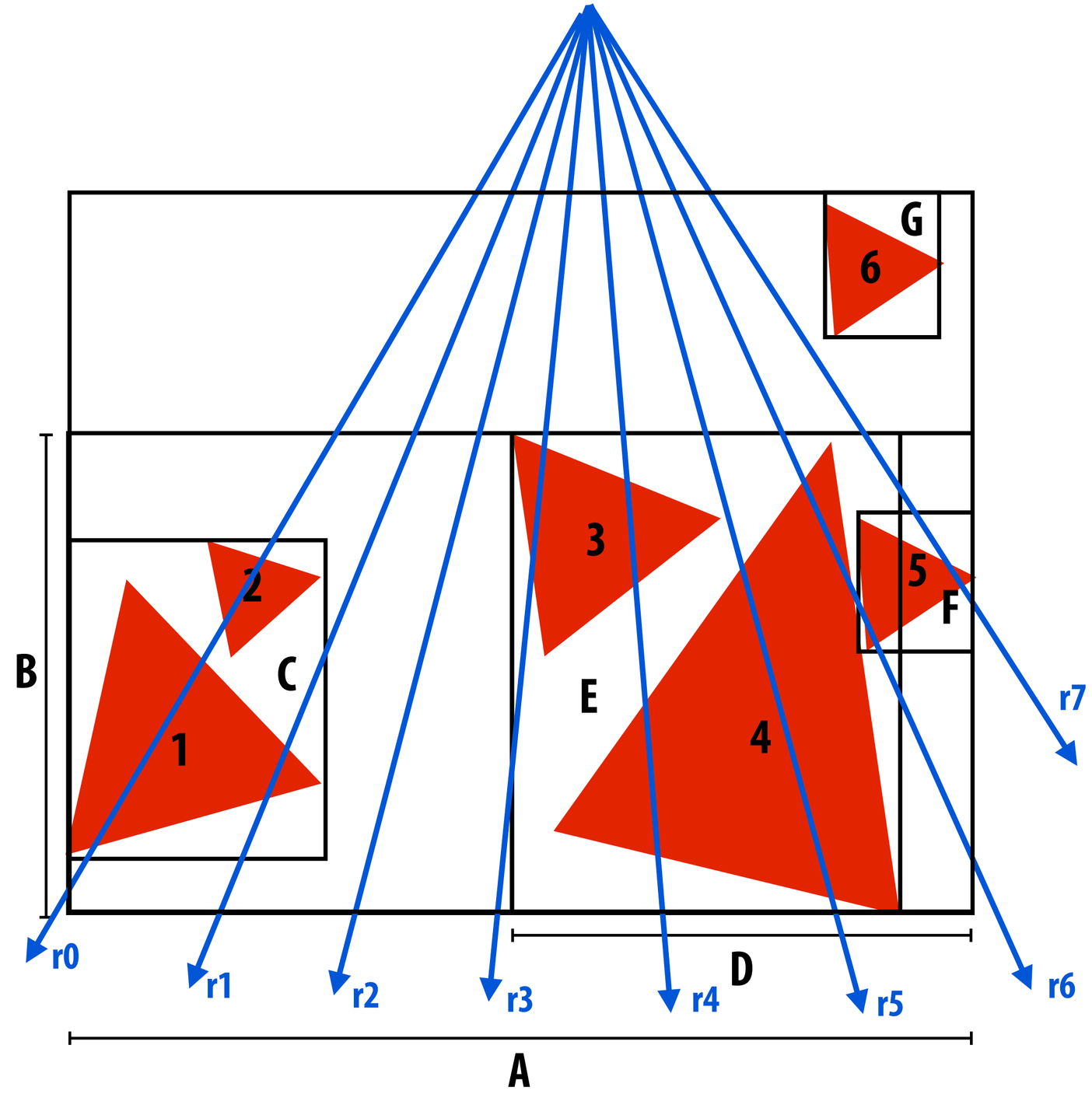
```
RayPacket
{
    Ray rays[PACKET_SIZE];
    bool active[PACKET_SIZE];
};

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);
   }
}
```

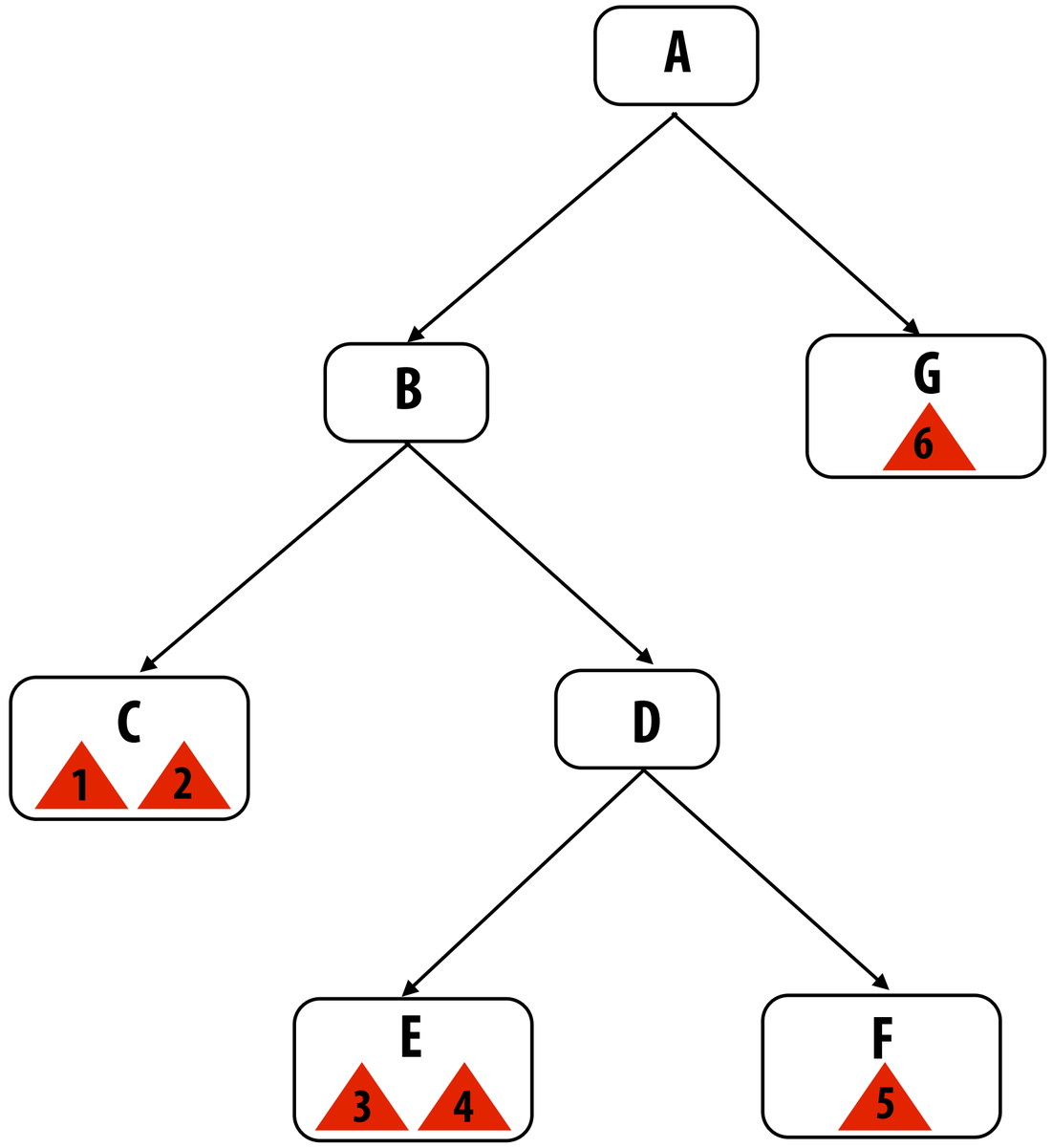
Ray packet tracing



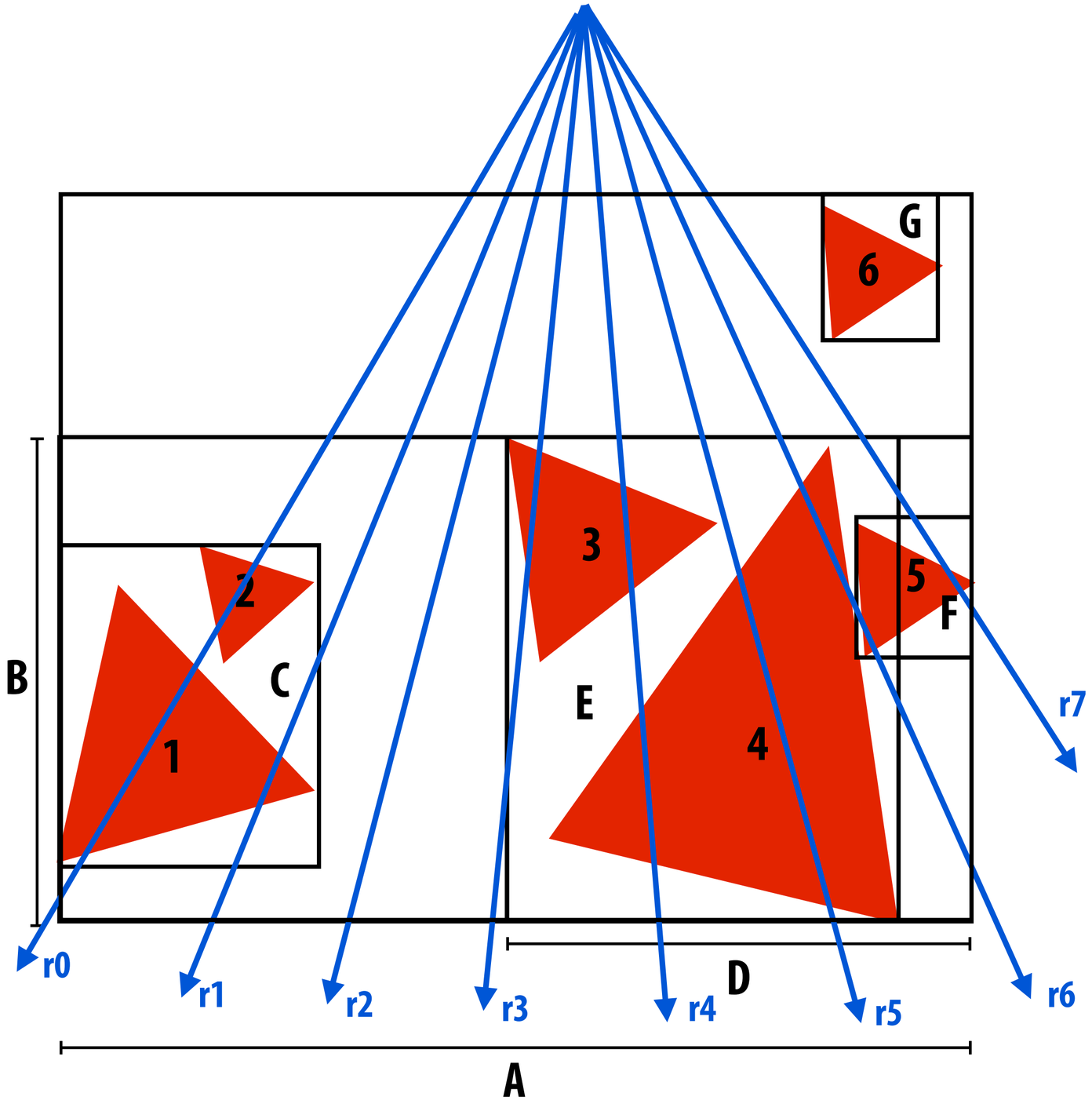


Ray packet tracing

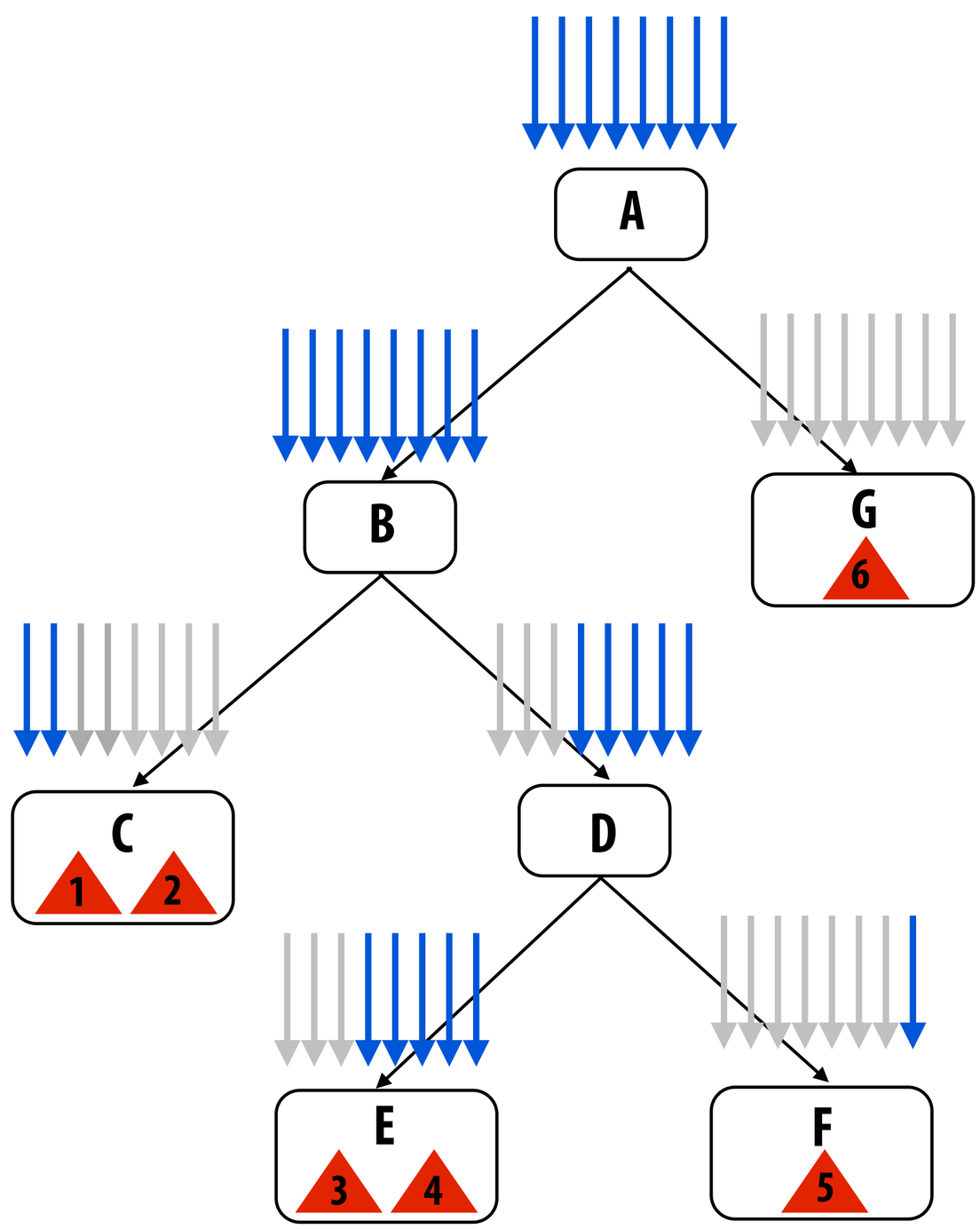




Ray packet tracing



Blue = active rays after node box test



Note: r6 does not pass node F box test due to closest-so-far check, and thus does not visit F

Advantages of packets

- Enable wide SIMD execution
  - One vector lane per ray
- Amortize BVH data fetch: all rays in packet visit node at same time
  - Load BVH node once for all rays in packet (not once per ray)
  - Note: there is value to making packets 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 math optimizations possible when all rays share origin
  - Note: there is value to making packets much bigger than SIMD width!

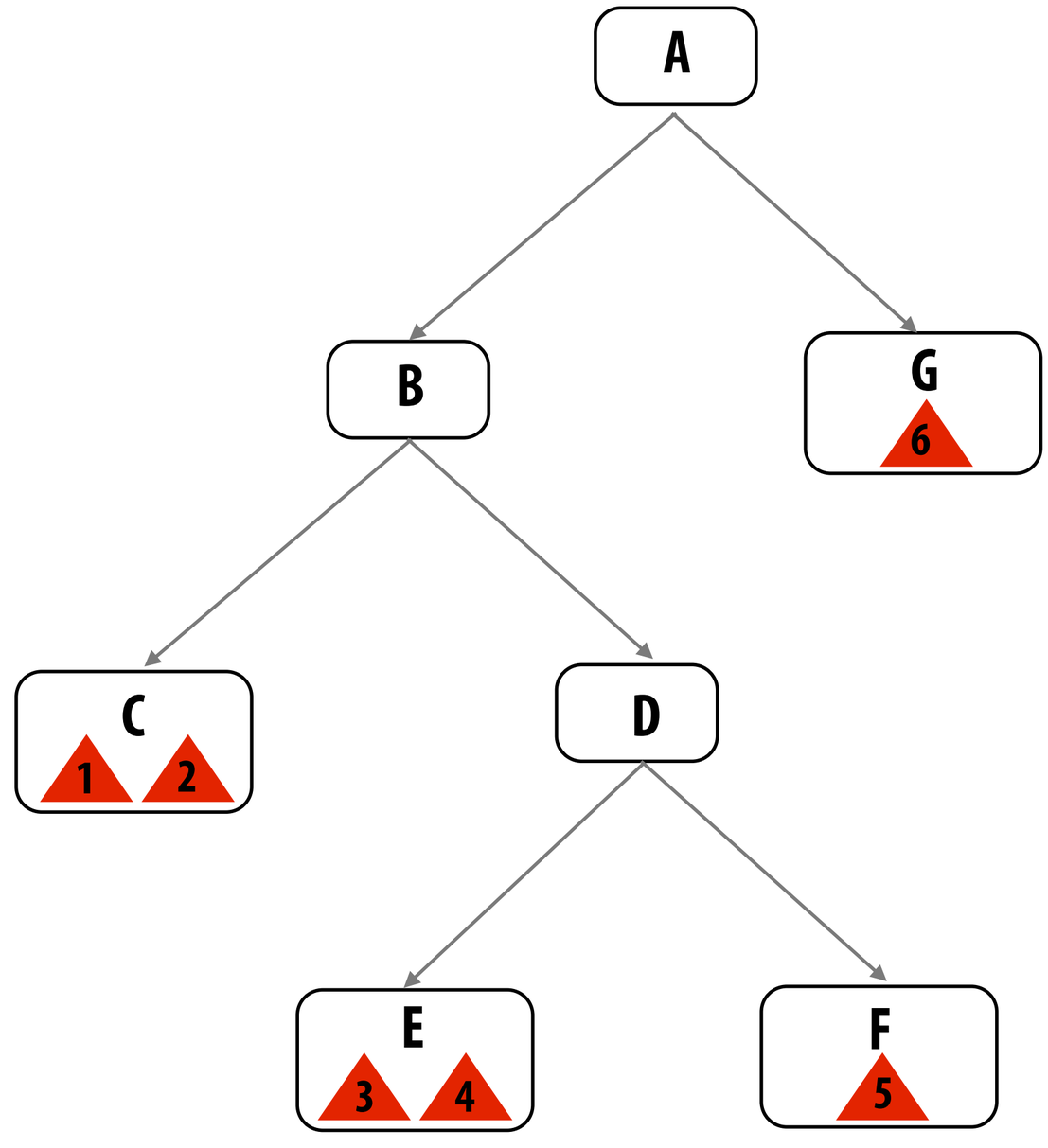
Disadvantages of packets

- 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).

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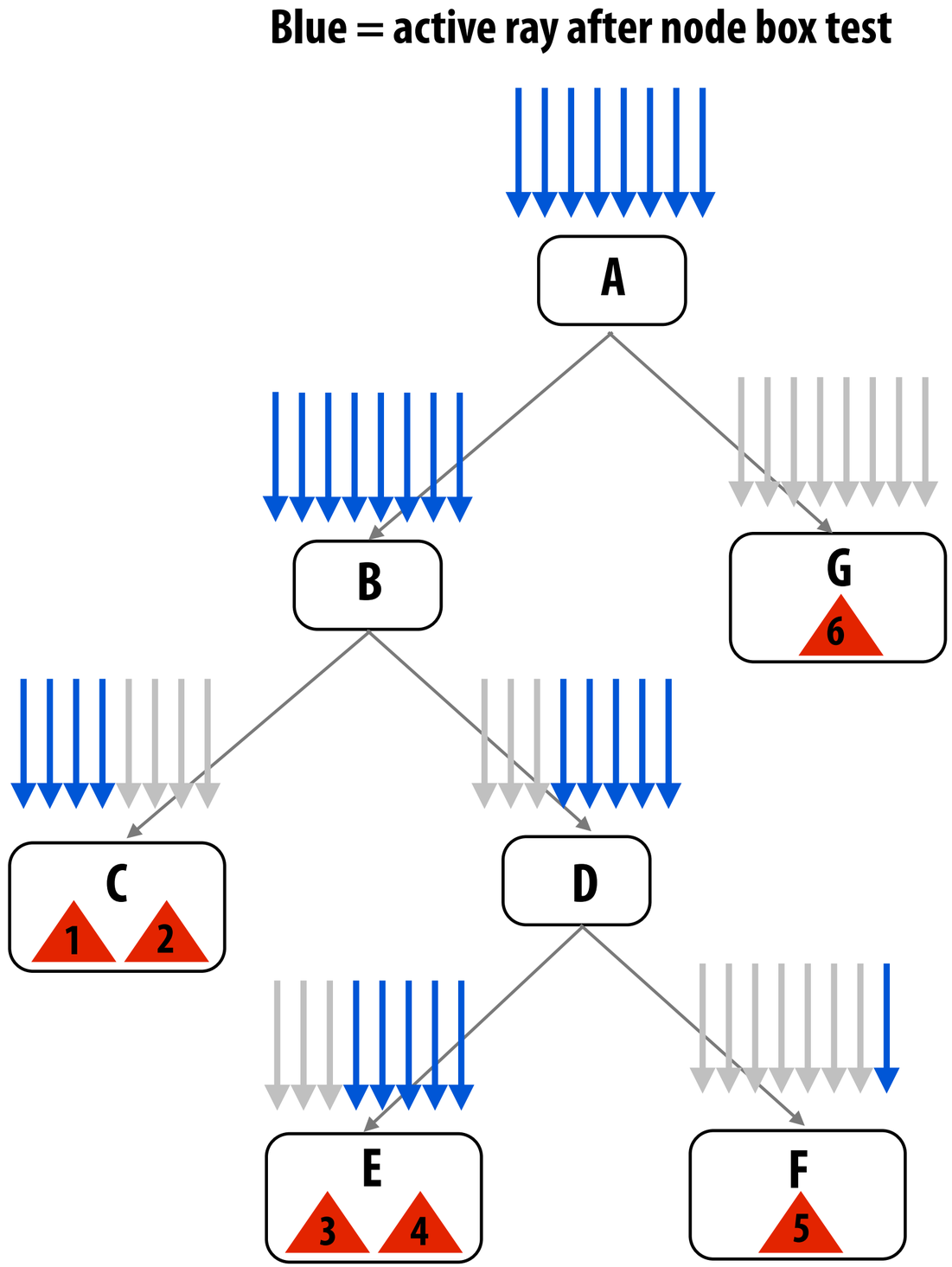
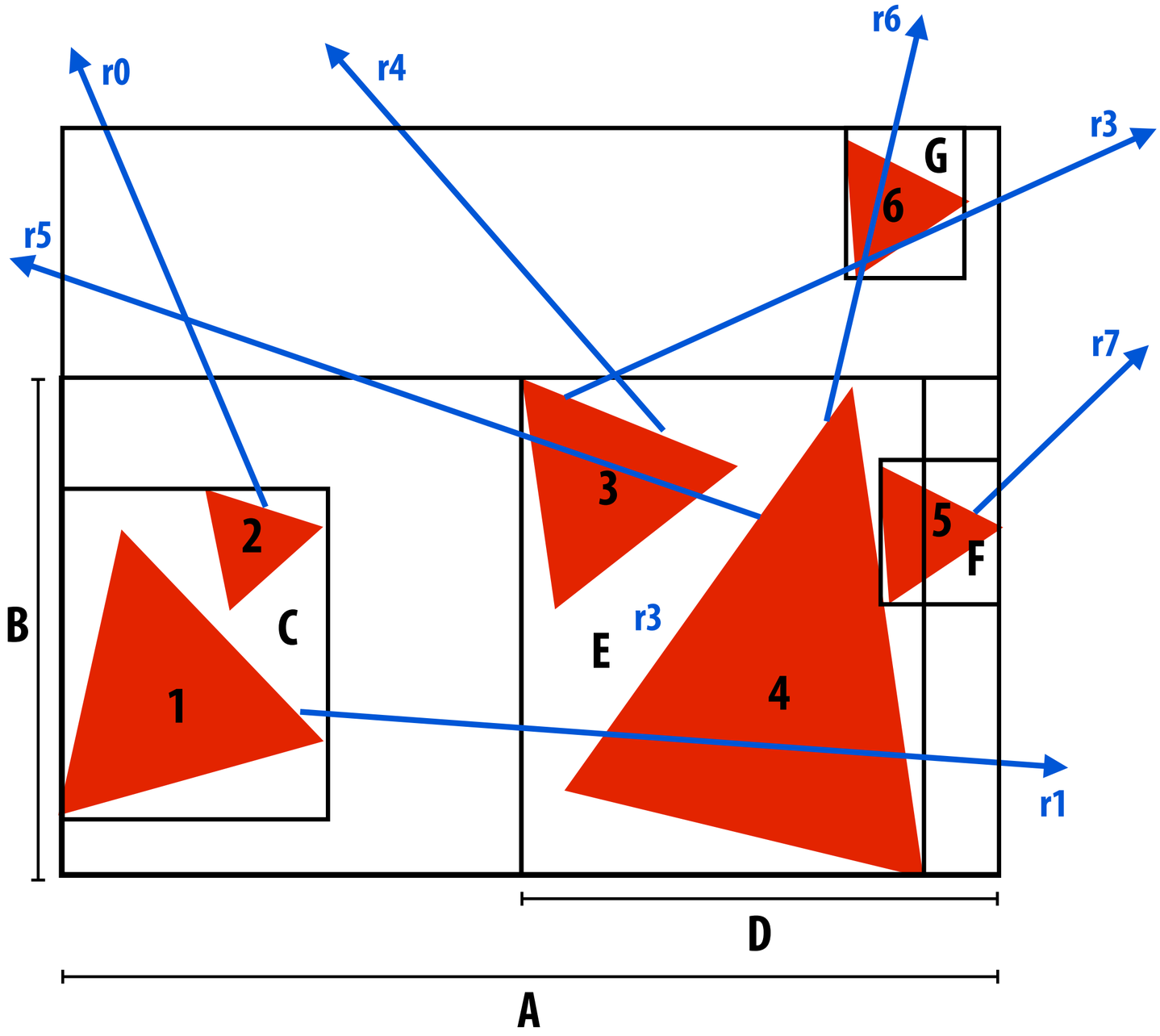
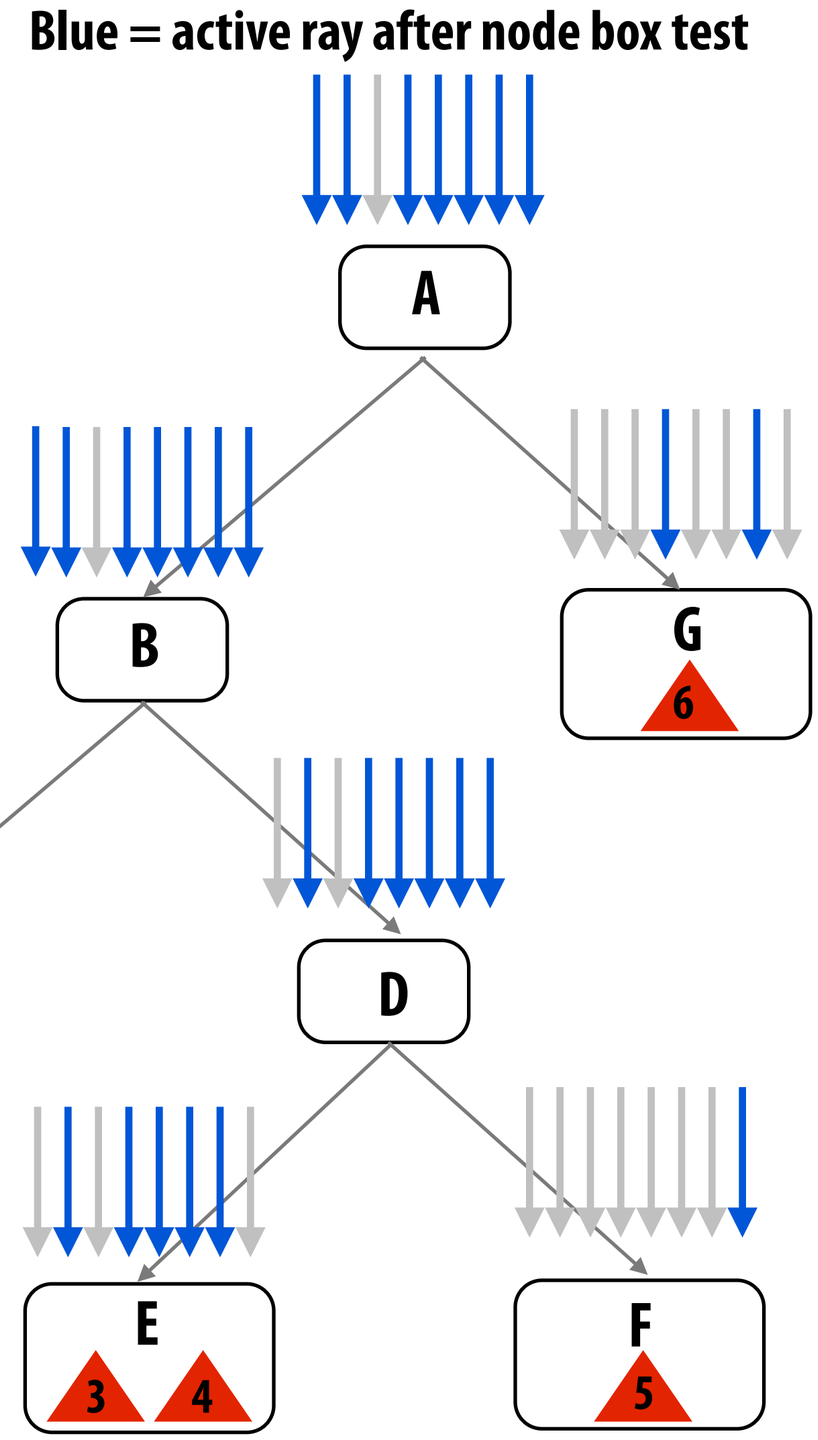


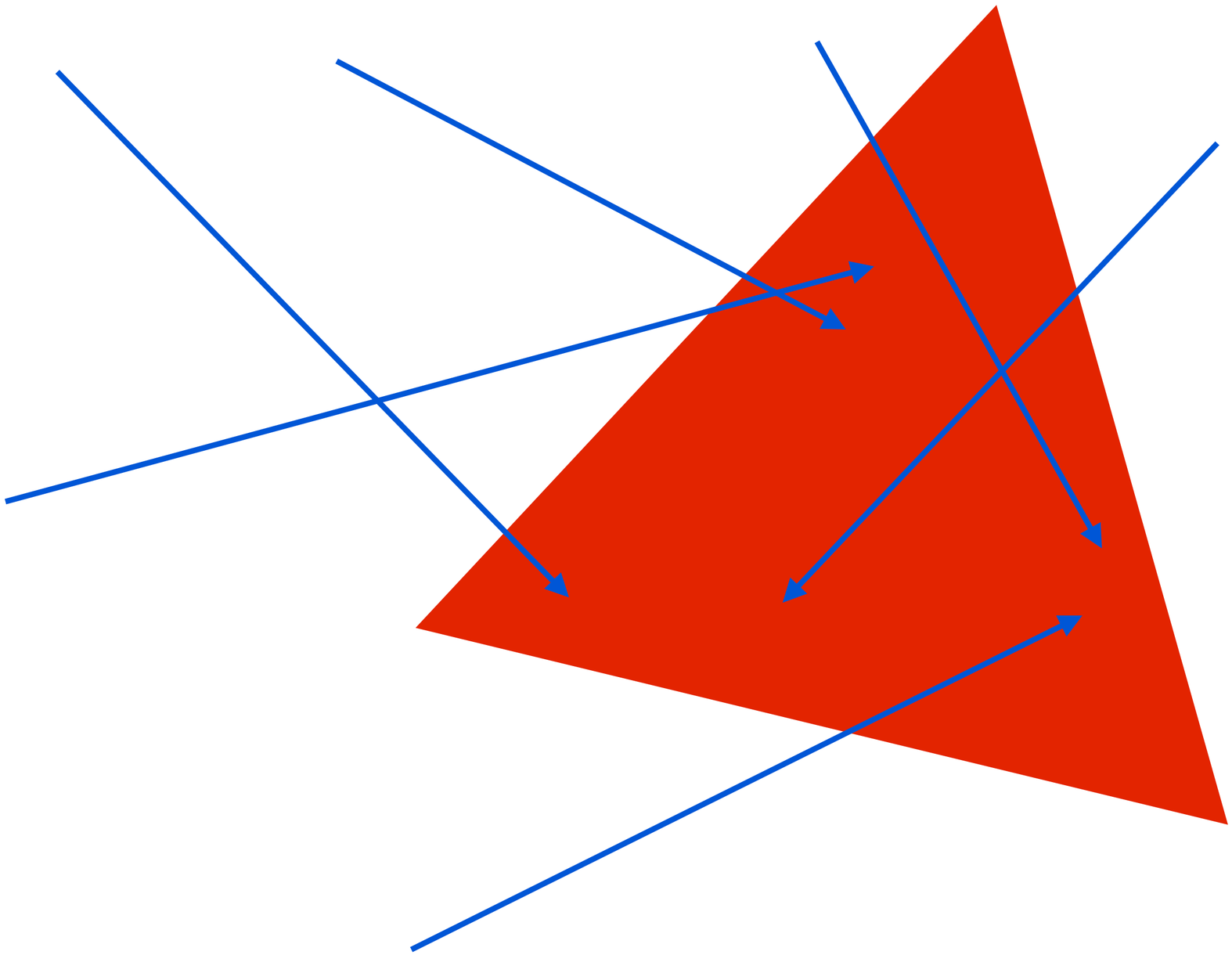
Ray packet tracing: incoherent rays





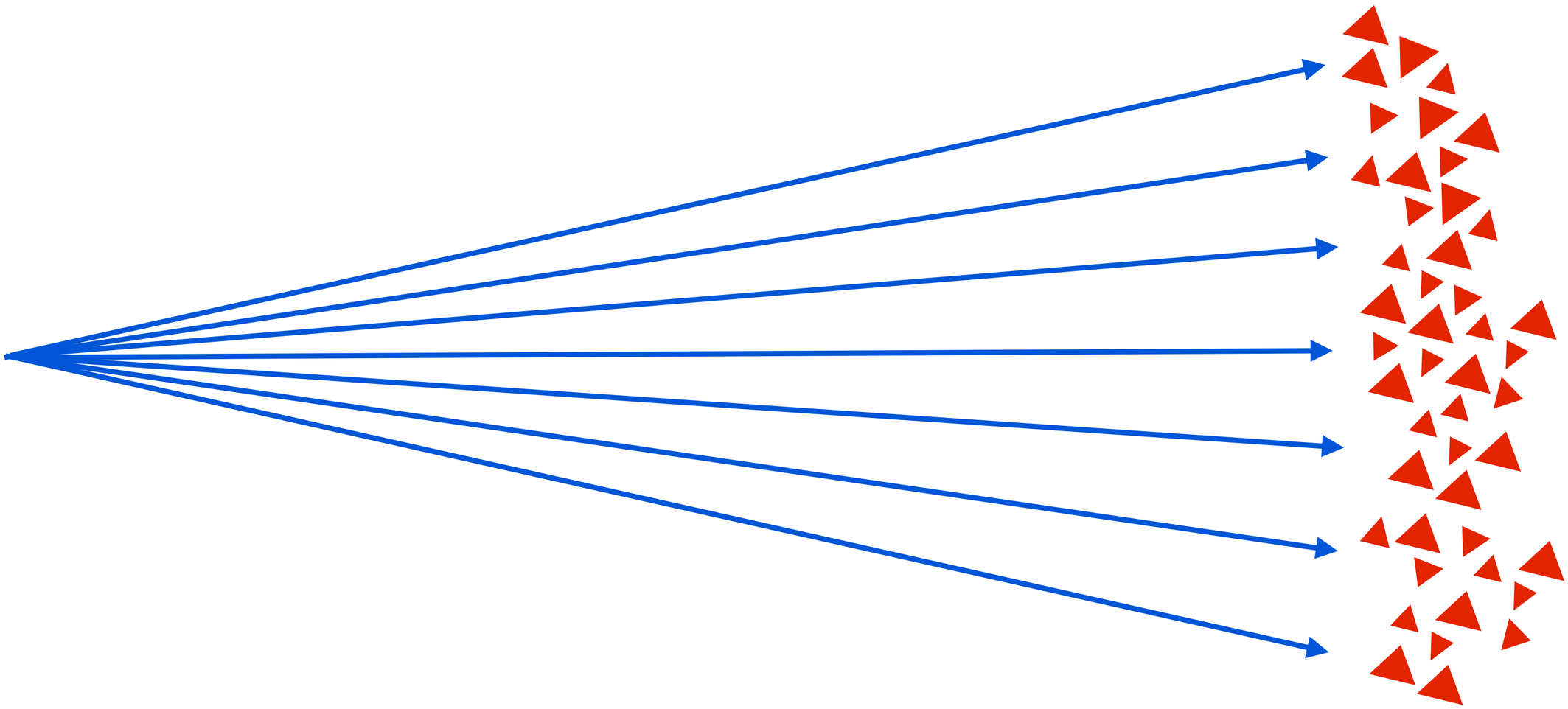
When rays are incoherent, benefit of packets can decrease significantly. This example: packet visits all tree nodes. (So all eight rays visit all tree nodes! No culling benefit!)

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**
- **Amortization benefits of smaller packets, but not large packets**

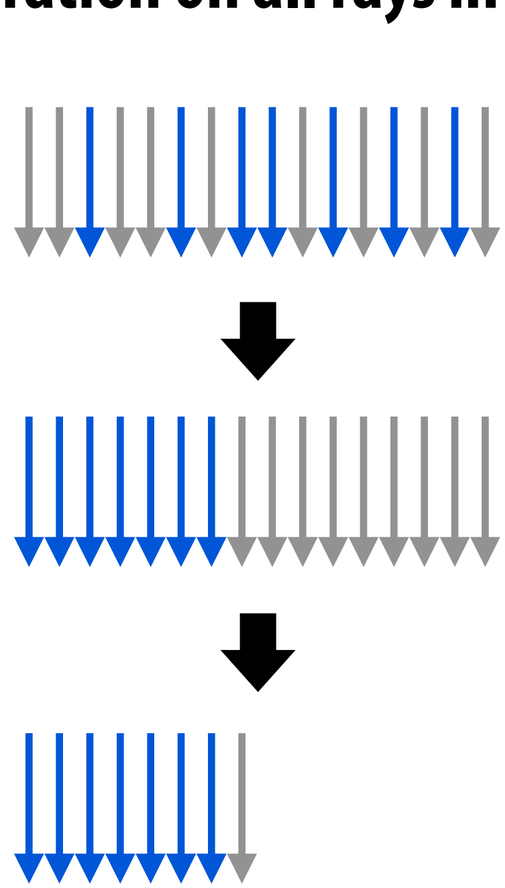
Example: consider 8-wide SIMD processor and 16-ray packets (2 SIMD instructions required to perform each operation on all rays in packet)

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

---

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
  - Diffuse bounces result in essentially random ray distribution
  - High resolution geometry encourages incoherence near leaves of tree

- In these situations there is little benefit to packets (can even decrease performance compared to single ray code)

Packet tracing best practices

- **Use large packets for eye/reflection/point light shadow rays or higher levels of BVH**

  [Wald et al. 2007]

  - **Ray coherence always high at the top of the tree**

  [Benthin et al. 2011]

- **Switch to single ray (intra-ray SIMD) when packet utilization drops below threshold**
  - **For wide SIMD machine, a single branching-factor 4 BVH works well for both packet and single ray traversal**
  - **Recall: intra-ray SIMD provides no work amortization or bandwidth reduction benefits**

- **Can use packet reordering to postpone time of switch**

  [Boulos et al. 2008]

  - **Reordering allows packets to provide benefit deeper into tree**
  - **Not often used in practice due to high implementation complexity**

Data access challenges

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

- Ray tracer data access
  - Frame-buffer access is minimal (once per ray)
  - But access to BVH nodes is frequent and unpredictable
    - Not predictable by definition (or the BVH is low quality)
    - Packets amortize cost of node fetches, but are less useful under divergent conditions.

- Incoherent ray traversal suffers from poor cache behavior
  - Rays require different BVH nodes during traversal
  - Ray-scene intersection becomes bandwidth bound for incoherent rays
    - E.g., soft shadows, sampling indirect illumination

Let's stop and think

- One strong argument for high performance ray tracing is to produce advanced effects that are difficult or inefficient to compute given the single point of projection and uniform sampling constraints of rasterization
  - e.g., soft shadows, diffuse interreflections

- But these phenomenon create situations of high ray divergence! (where packet- and SIMD-optimizations are less effective)

Emerging hardware for ray tracing

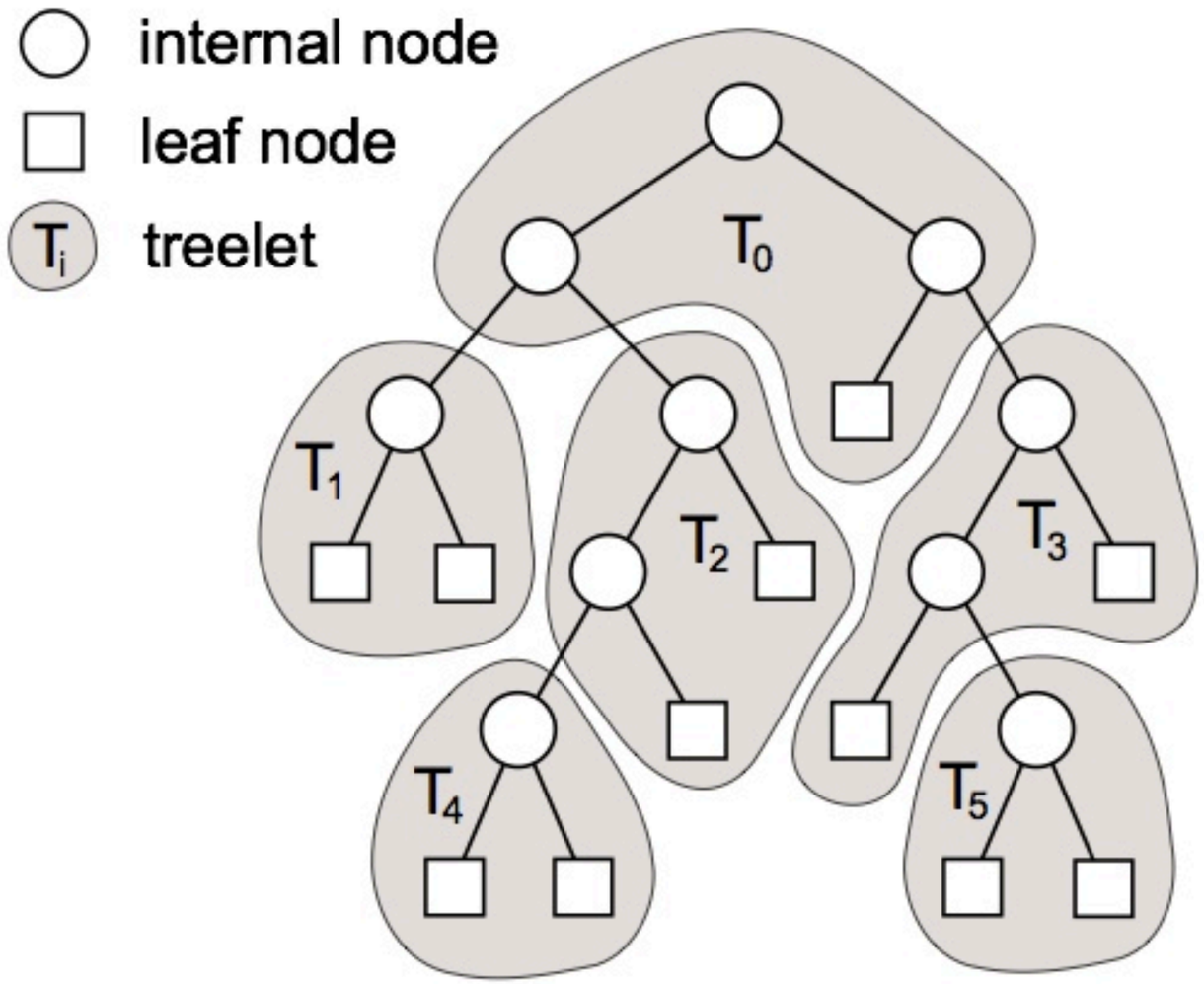
- **Modern implementations:**
  - Trace single rays, not ray packets (assume most rays are incoherent rays… if they weren't there problem is a reasonable rasterization-based solution)

- **Two areas of focus:**
  - Custom logic for accelerating ray-box and ray-triangle tests
  - MIMD designs: wide SIMD execution not beneficial
  - Support for efficiently reordering ray-tracing computations to maximize memory locality (ray scheduling)

Global ray reordering

[Pharr 1997, Navratil 07, Alia 10]

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



[Pharr 1997, Navratil 07, Alia 10]

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 large, intersect enqueued rays with treelet**
   (amortize treelet load over 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 constrained to fit in caches (or in dedicated ray buffer SRAM)

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**
   - Good recent work on parallel BVH builds
2. **On-demand geometry: tessellation**
   - Tesselate surface first time it is hit by a ray
   - Intersection modifies BVH (not so embarrassingly parallel anymore)
   - How to determine level-of-detail?
3. **Efficiently shading ray hits**
   - Shading remains at least 50% of execution time in modern ray tracers (making ray tracing infinitely fast yields only a 2X speedup!)
   - What to do when rays in a packet hits surfaces with different shaders?

Visibility summary

- Visibility problem: 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 (tiles, ray packets)
  - Hierarchy over geometry (BVHs)