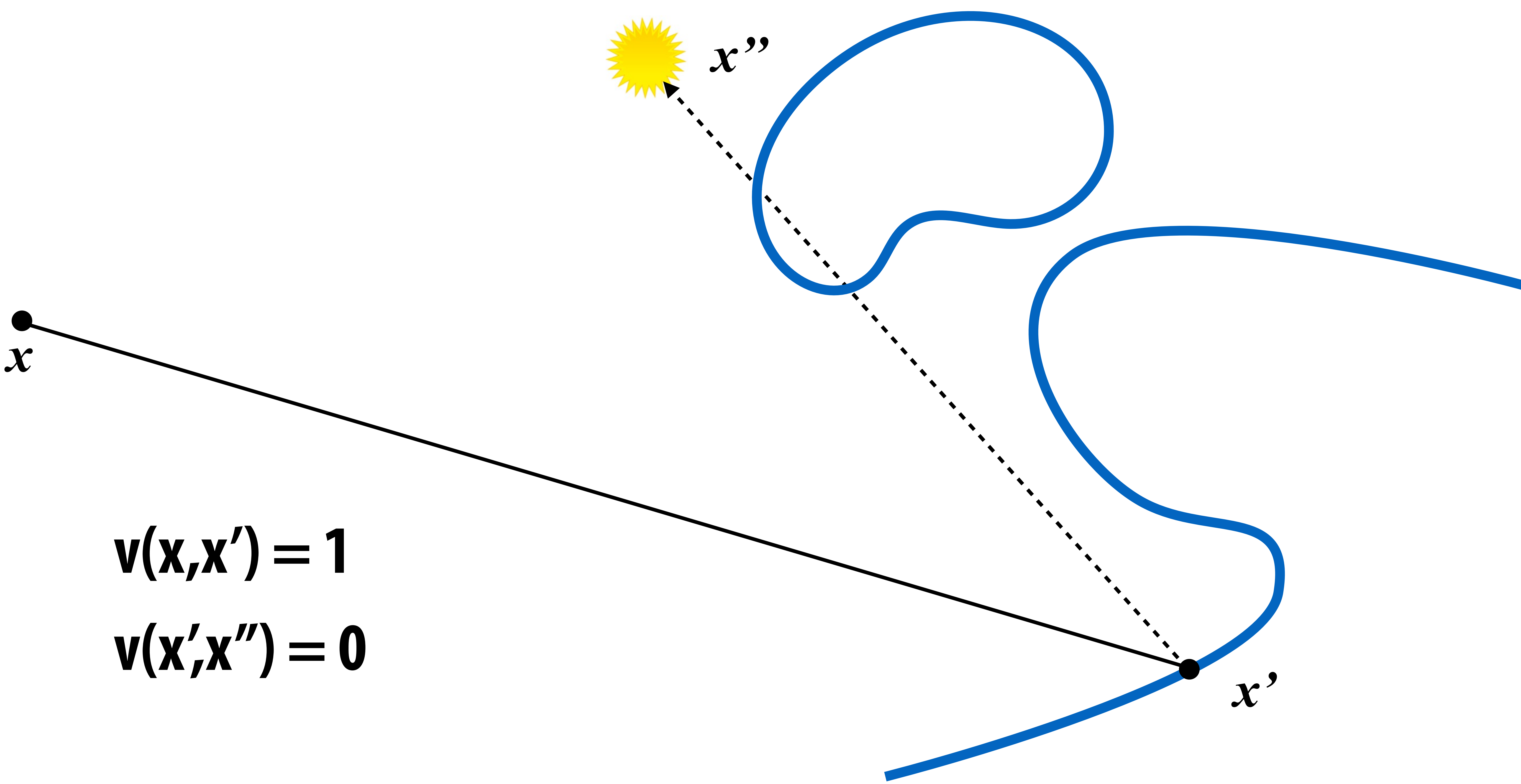
Lecture 16:

High-Performance Ray Tracing

Computer Graphics
CMU 15-462/15-662, Fall 2015

Ray tracing is a mechanism for answering "visibility" queries

$v(x_1,x_2) = 1$ if x_1 is visible from x_2, 0 otherwise



$v(x,x') = 1$

$v(x',x'') = 0$

Using rasterization to answer visibility queries

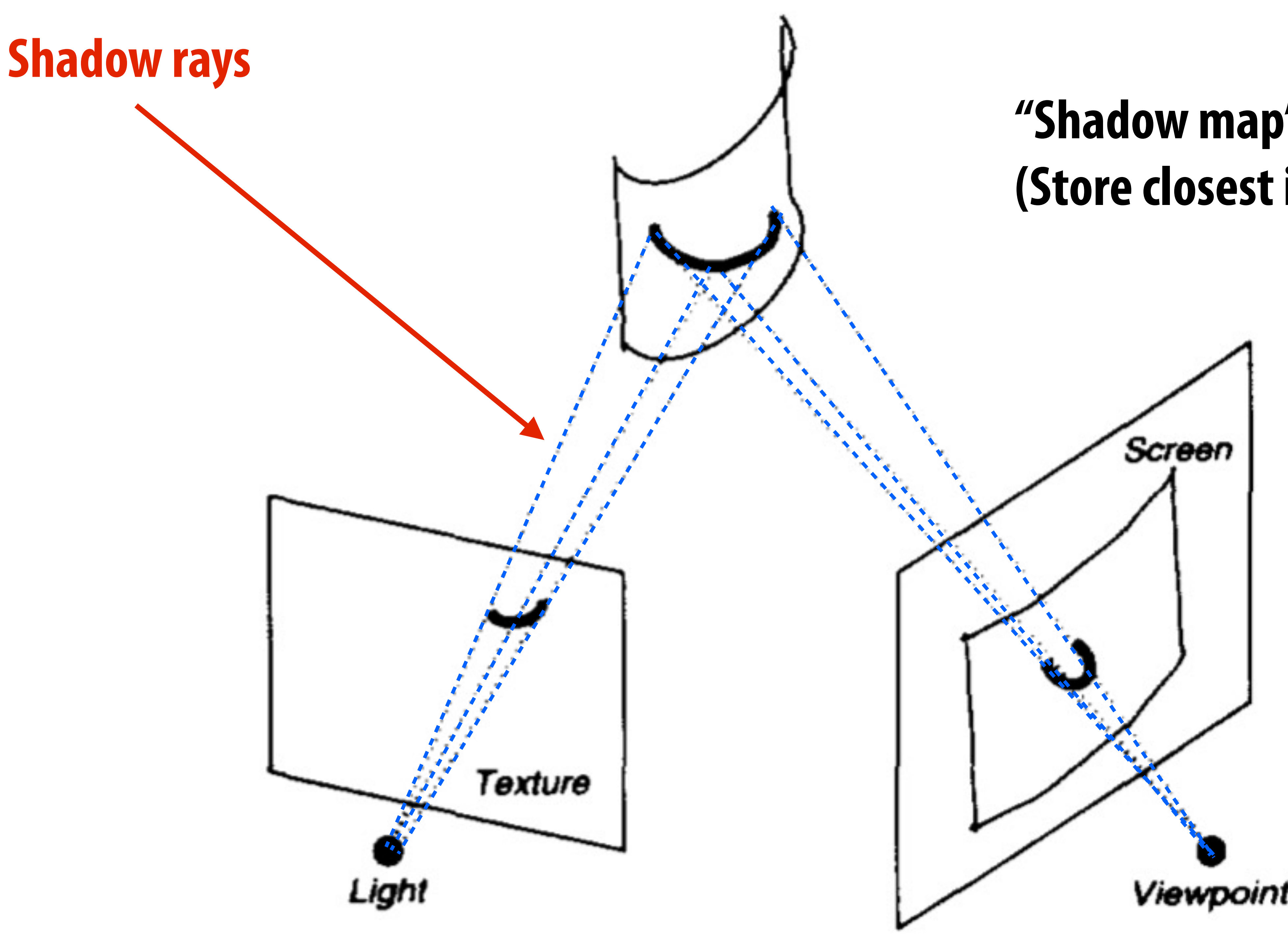
Another way to think about rasterization

- **Rasterization is an efficient algorithm for servicing large batches of visibility queries… for rays with specific properties**
  - Assumption 1: Rays have the same origin
  - Assumption 2: Rays are uniformly distributed over plane of projection (within specified field of view)

- **Assumptions → significant optimization opportunities**
  - Project triangles: reduce ray-triangle intersection to 2D point-in-polygon test
  - Projection to canonical view volume enables use of efficient fixed-point math, custom GPU hardware for rasterization

Shadow mapping: ray origin need not be the scene's camera position [Williams 78]

- Place ray origin at position of point light source
- Render scene to compute depth to closest object to light along uniformly distributed "shadow rays" (answer stored in depth buffer)
- Store precomputed shadow ray intersection results in a texture



"Shadow map" = depth map from perspective of a point light.
(Store closest intersection along each shadow ray in a texture map)

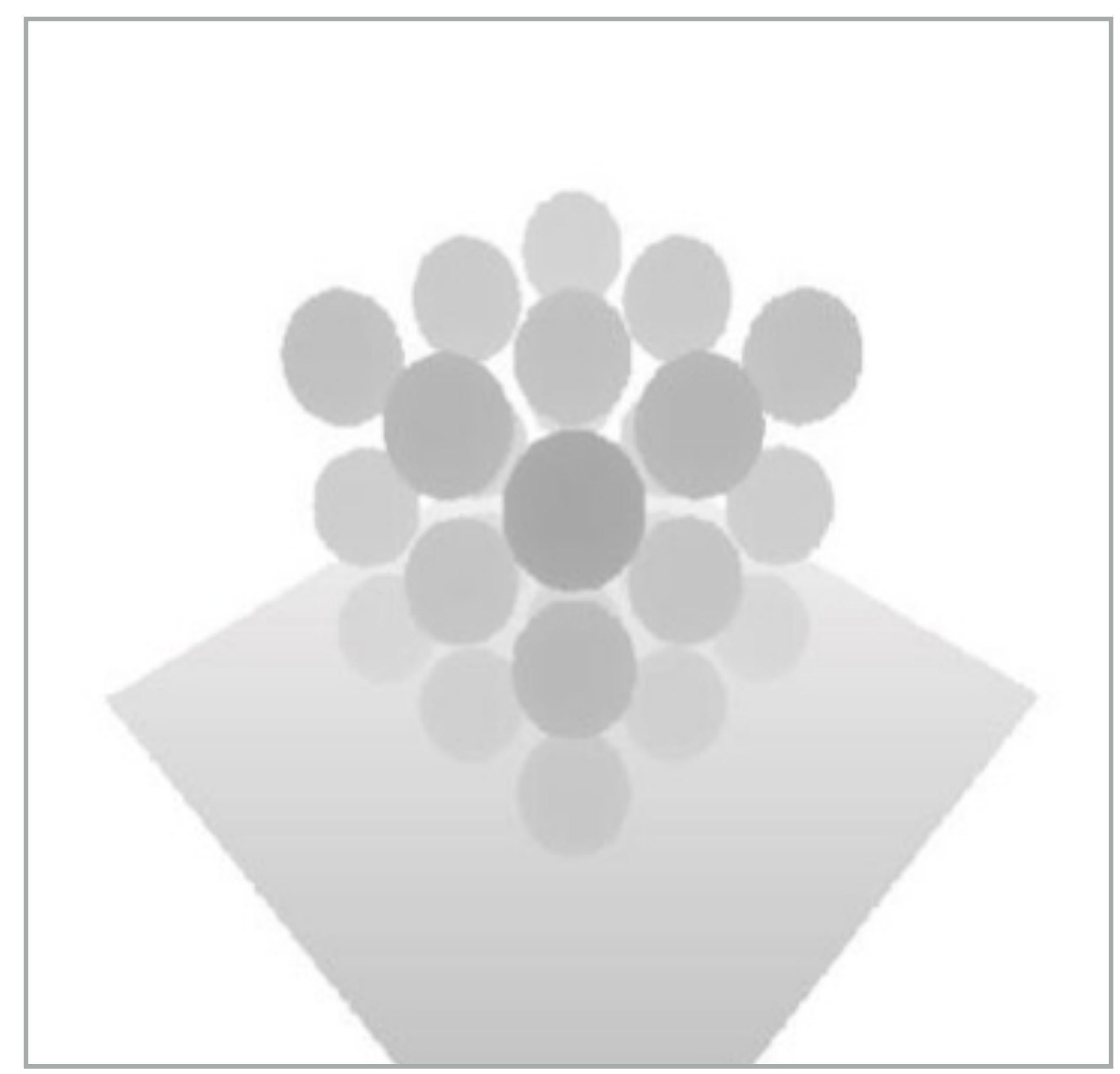
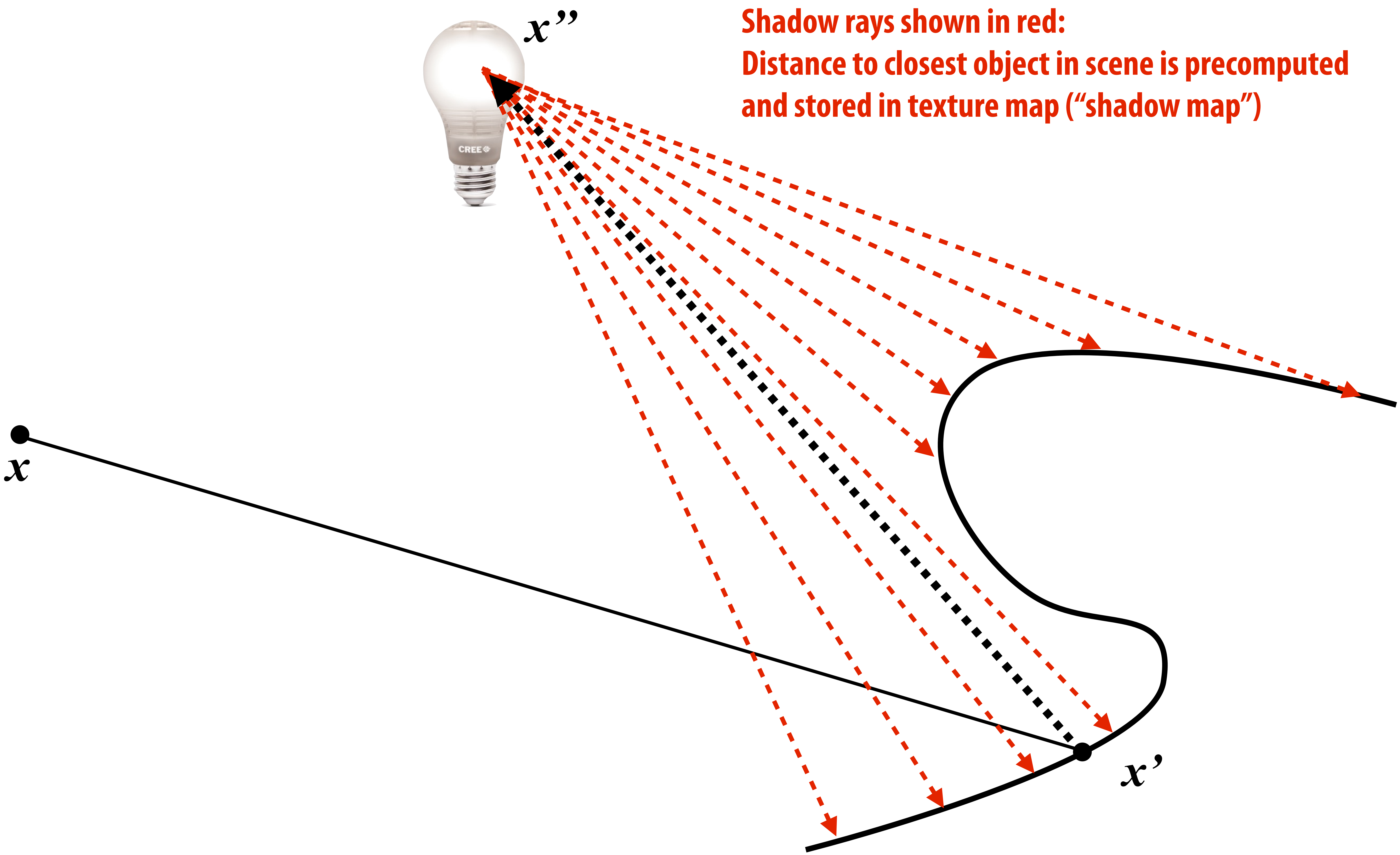
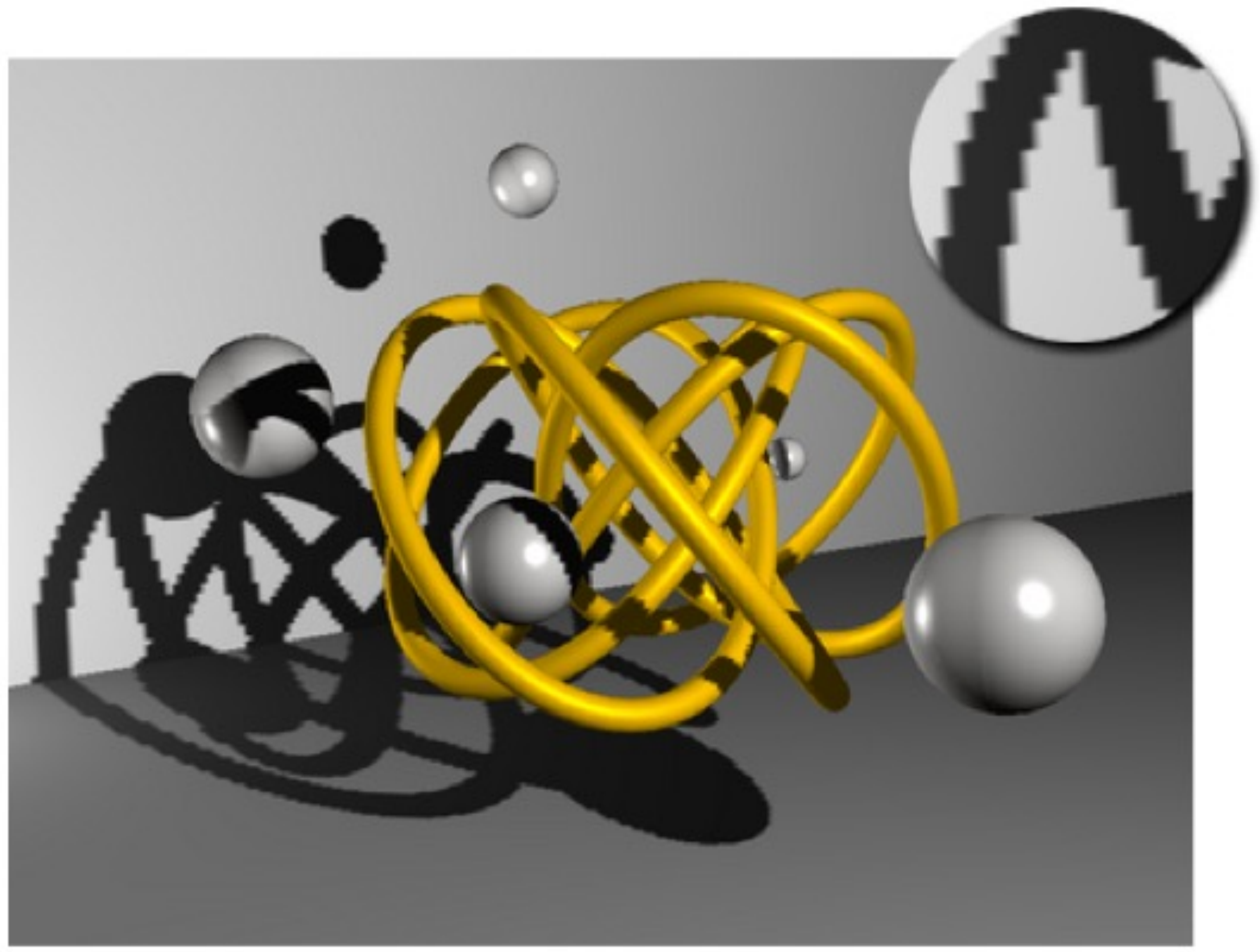


Image credits: Segal et al. 92, Cass Everitt

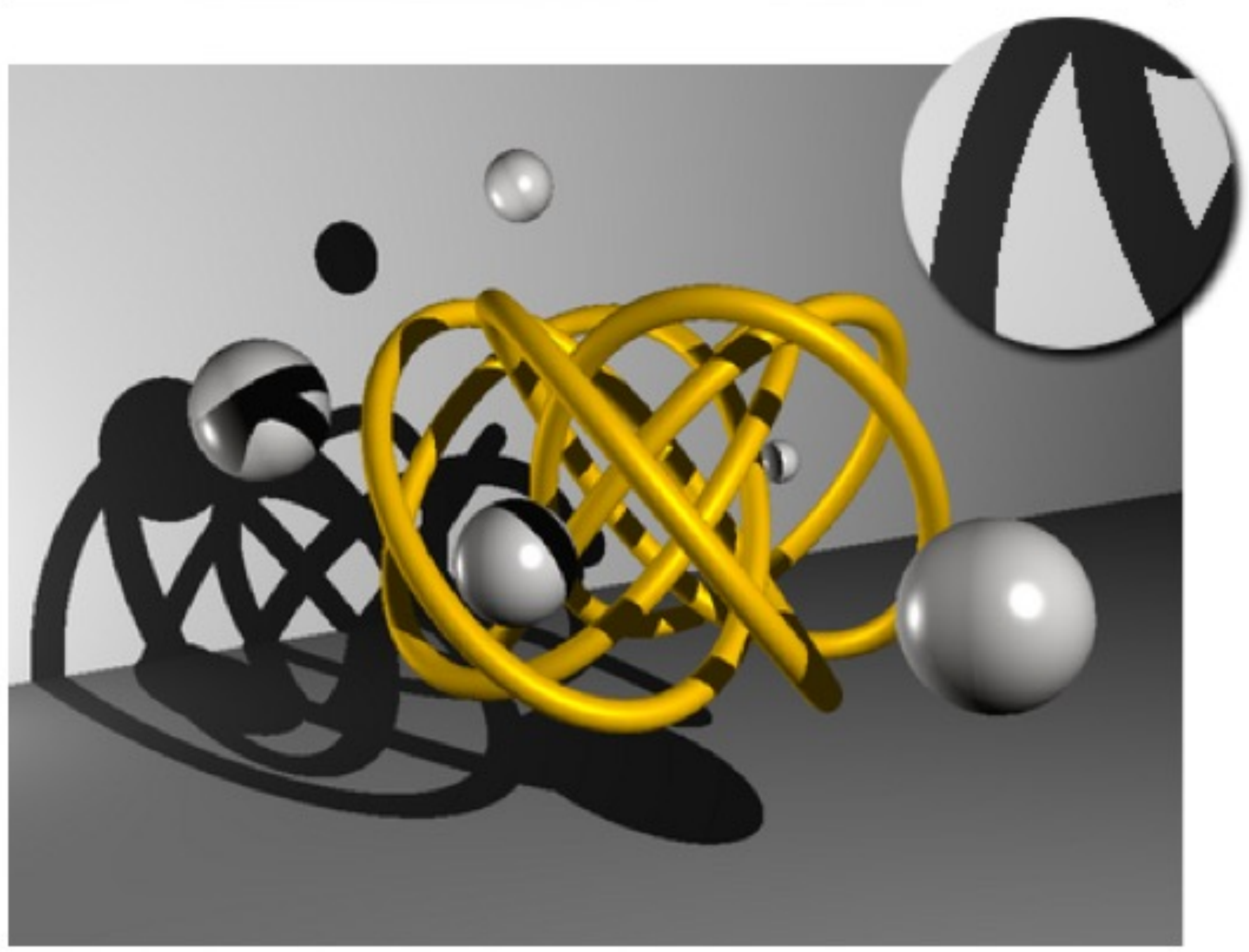
Result of shadow texture lookup approximates v(x',x") when shading fragment at x'



Shadow aliasing due to undersampling



Shadows computed using shadow map
(shadow map resolution is too low)



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

Image credit: Johnson et al. TOG 2005

Environment mapping

Place ray origin at location of reflective object.

Yields <u>approximation</u> to true reflection results. Why?

Cube map:
stores results of approximate mirror reflection rays

Center of projection

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

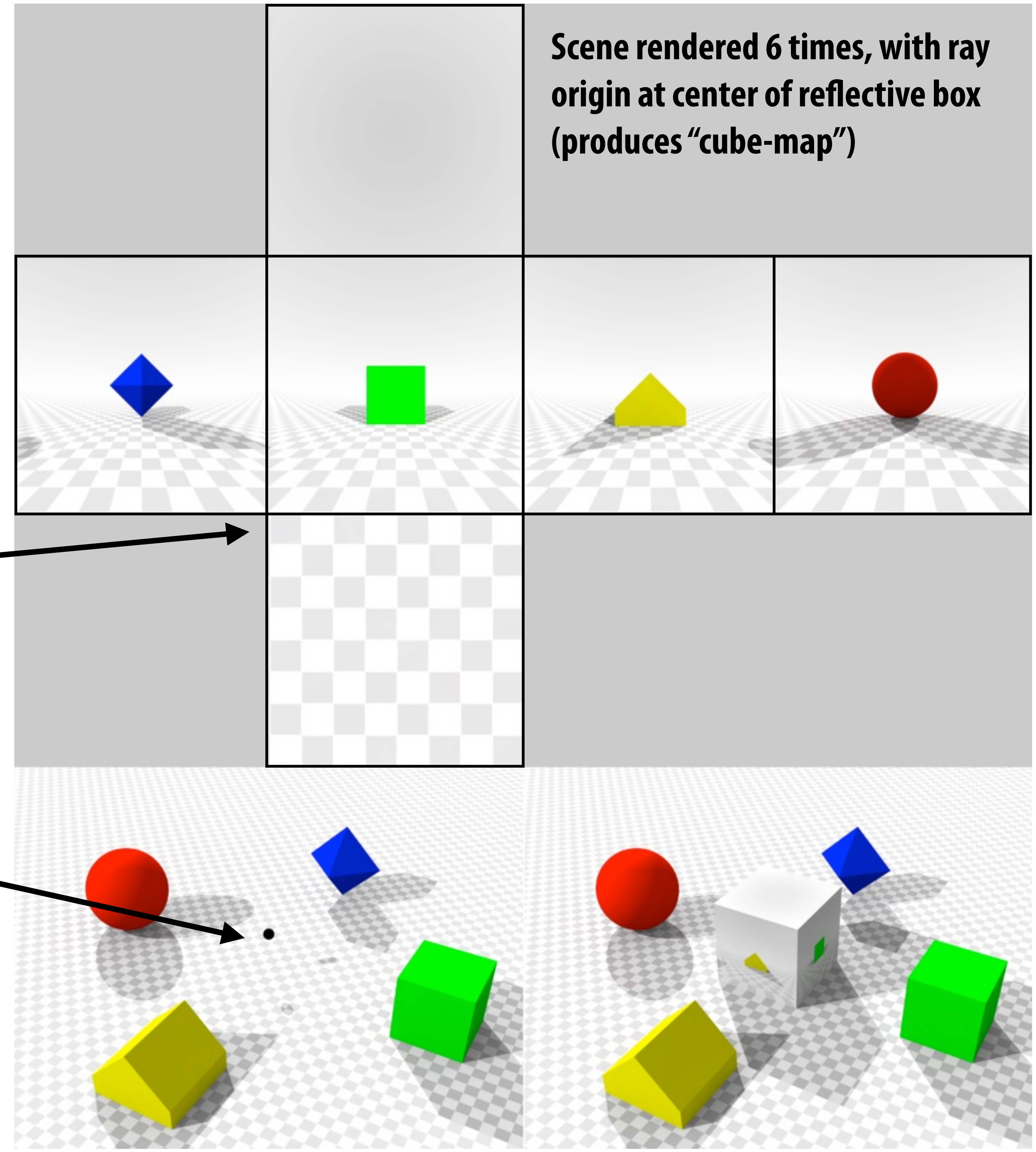
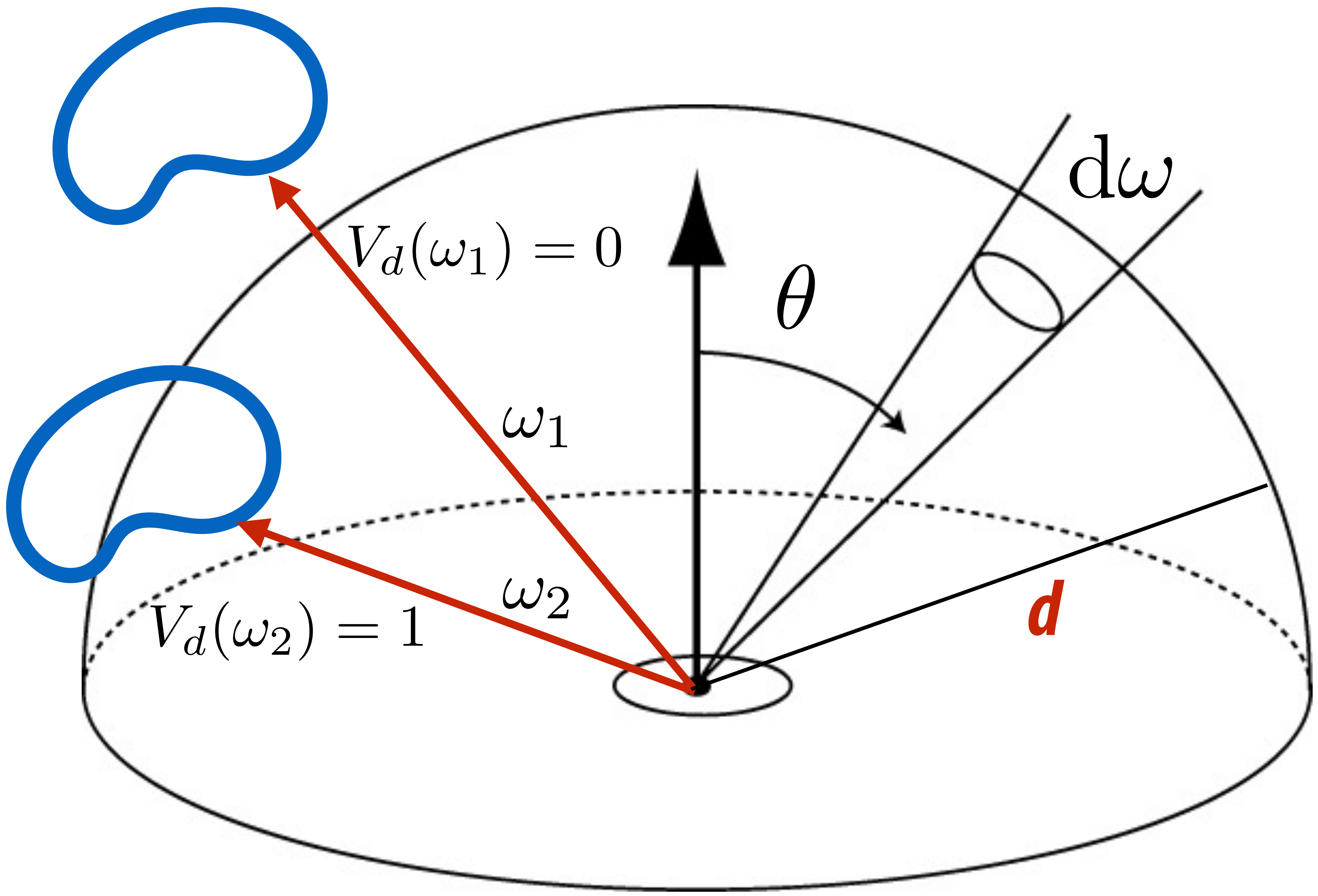


Image credit: http://en.wikipedia.org/wiki/Cube_mapping

Ambient occlusion

Ambient occlusion

Idea: precompute "amount of hemisphere" that is occluded from a point, attenuate direct environment lighting by this amount.



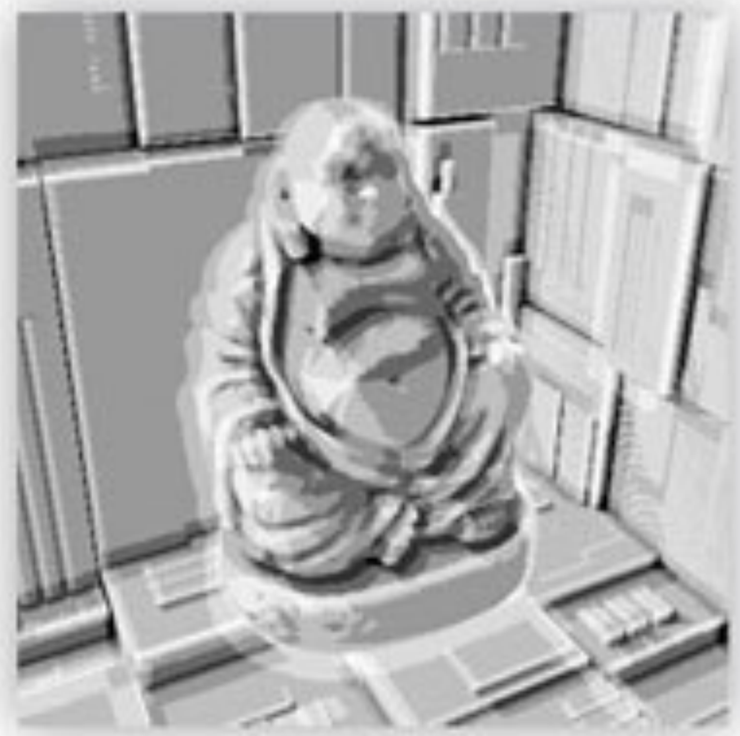
$$E(\mathrm{p}) = \int_{H^2} V(\omega)\, L_i(\mathrm{p}, \omega) \cos\theta \, \mathrm{d}\omega$$

$$\approx \int_{H^2} V_d(\omega)\, \mathrm{d}\omega \int_{H^2} L_i(\mathrm{p}, \omega) \cos\theta \, \mathrm{d}\omega$$

$$\approx O \int_{H^2} L_i(\mathrm{p}, \omega) \cos\theta \, \mathrm{d}\omega$$

Occlusion term: does ray from *p* in direction *w* hit any scene object within distance *d*

"Screen-space" ambient occlusion in games



low sample 'banding'

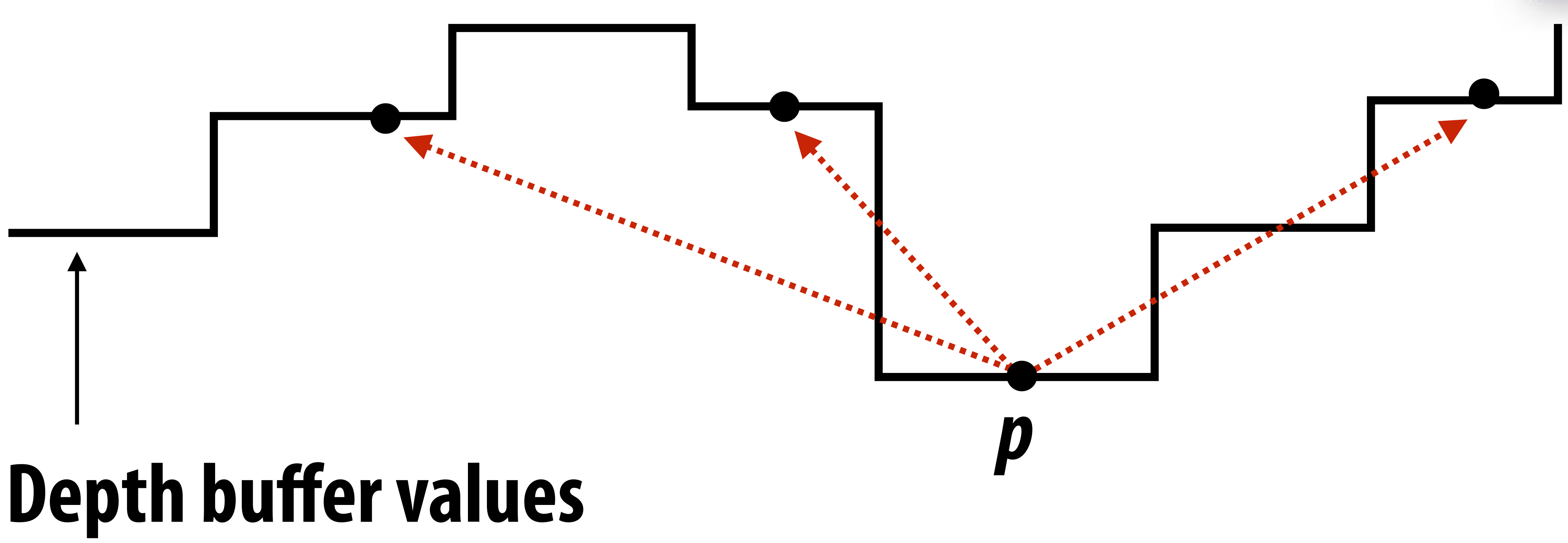
random rotation = noise

+ blur = acceptable

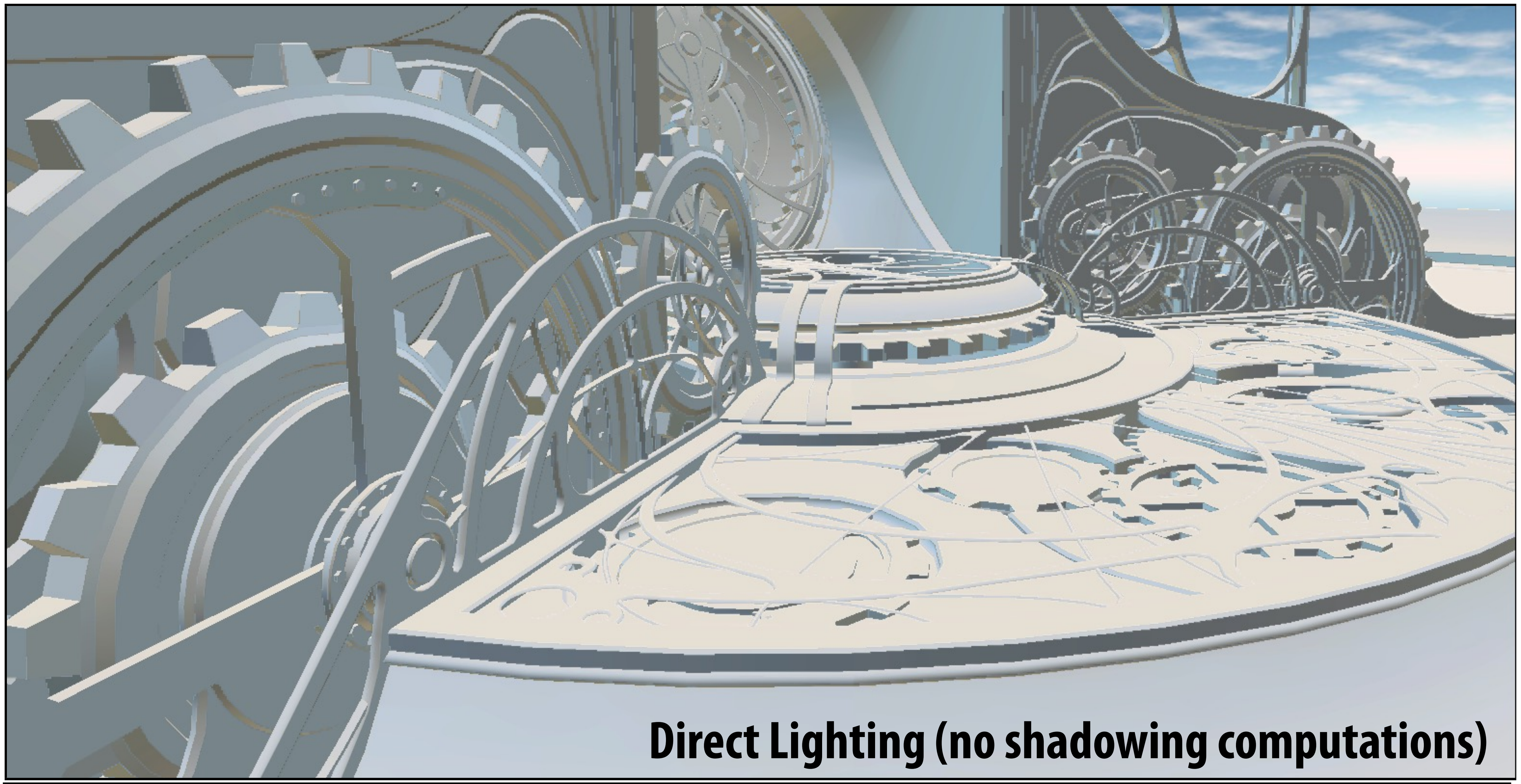
1. Render scene to depth buffer
2. For each pixel *p* ("ray trace" the depth buffer to estimate occlusion of hemisphere - use a few samples per pixel)
3. Blur the the occlusion map to reduce noise
4. Shade pixels, darken direct environment lighting by occlusion amount

without ambient occlusion

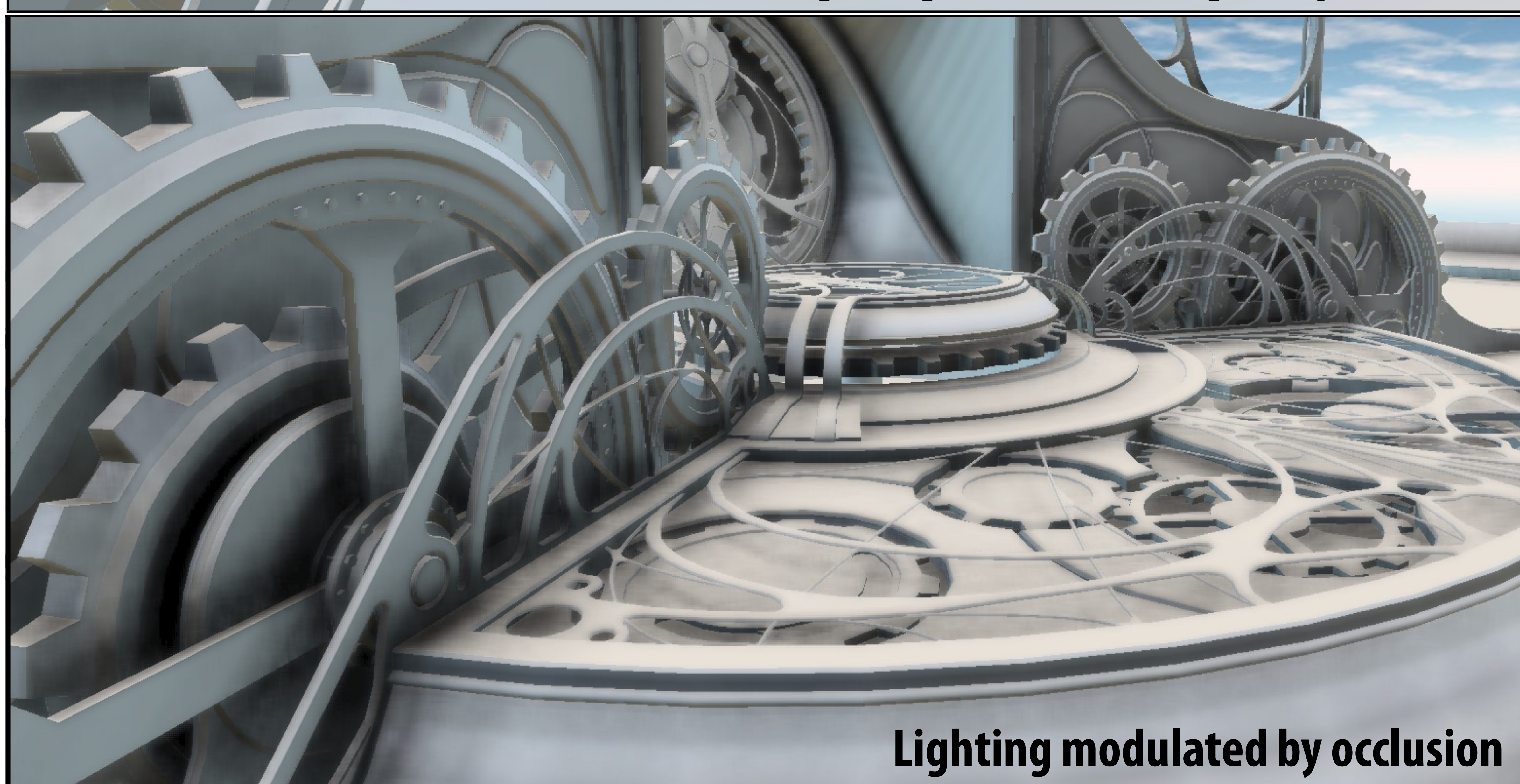
with ambient occlusion



Ambient occlusion

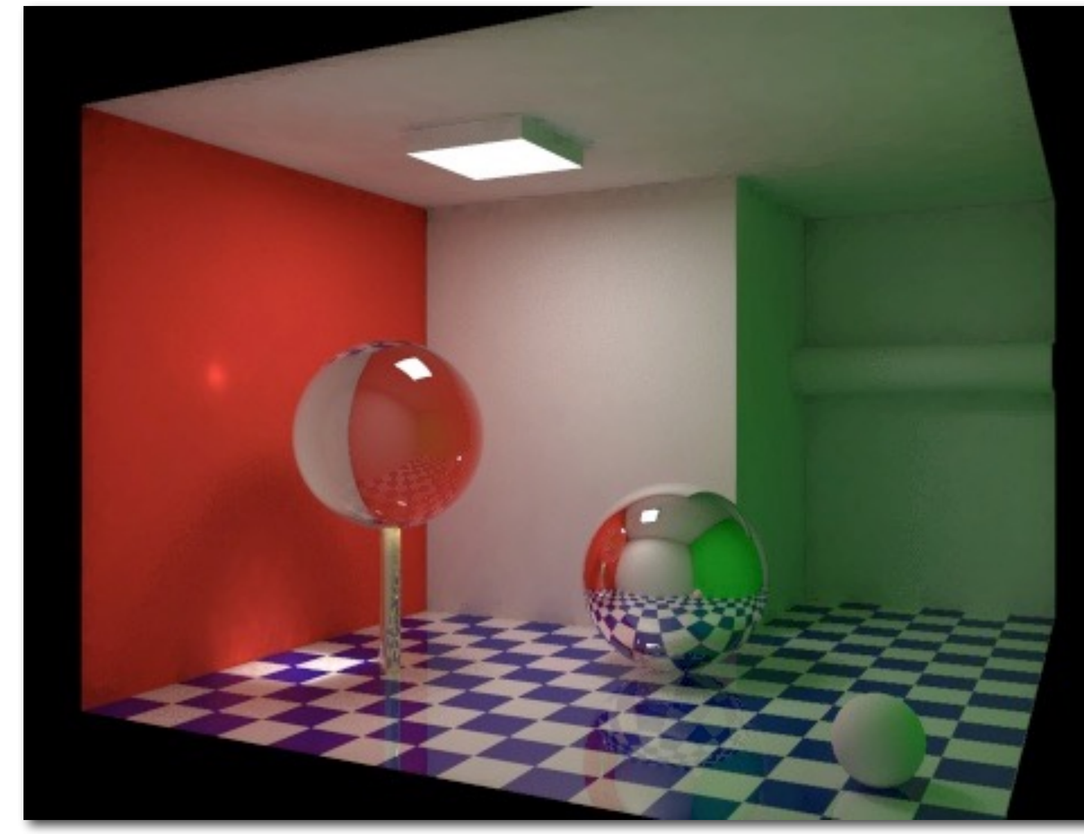


Direct Lighting (no shadowing computations)



Lighting modulated by occlusion

Motivations for real-time ray tracing



Estimate indirect illumination effects
(But unclear if ray tracing is best real-time solution for low frequency effects… more to come)

Many shadowed lights (big pain to manage many shadow maps)

Accurate reflections from curved surfaces

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

Less parameter tweaking (e.g., choosing shadow map texture size)

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, correct for distortion of optics)

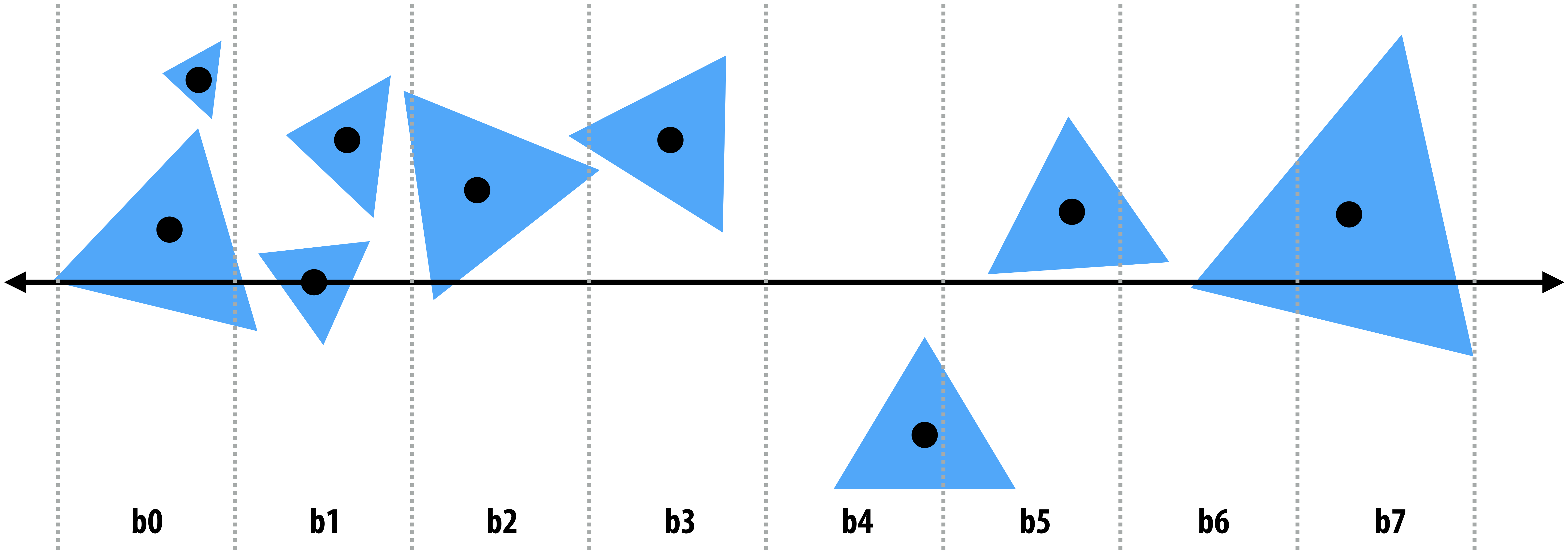
Efficient ray tracing

Imagine I give you a 16-core CPU

How would you parallelize your ray tracer to render this picture?

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

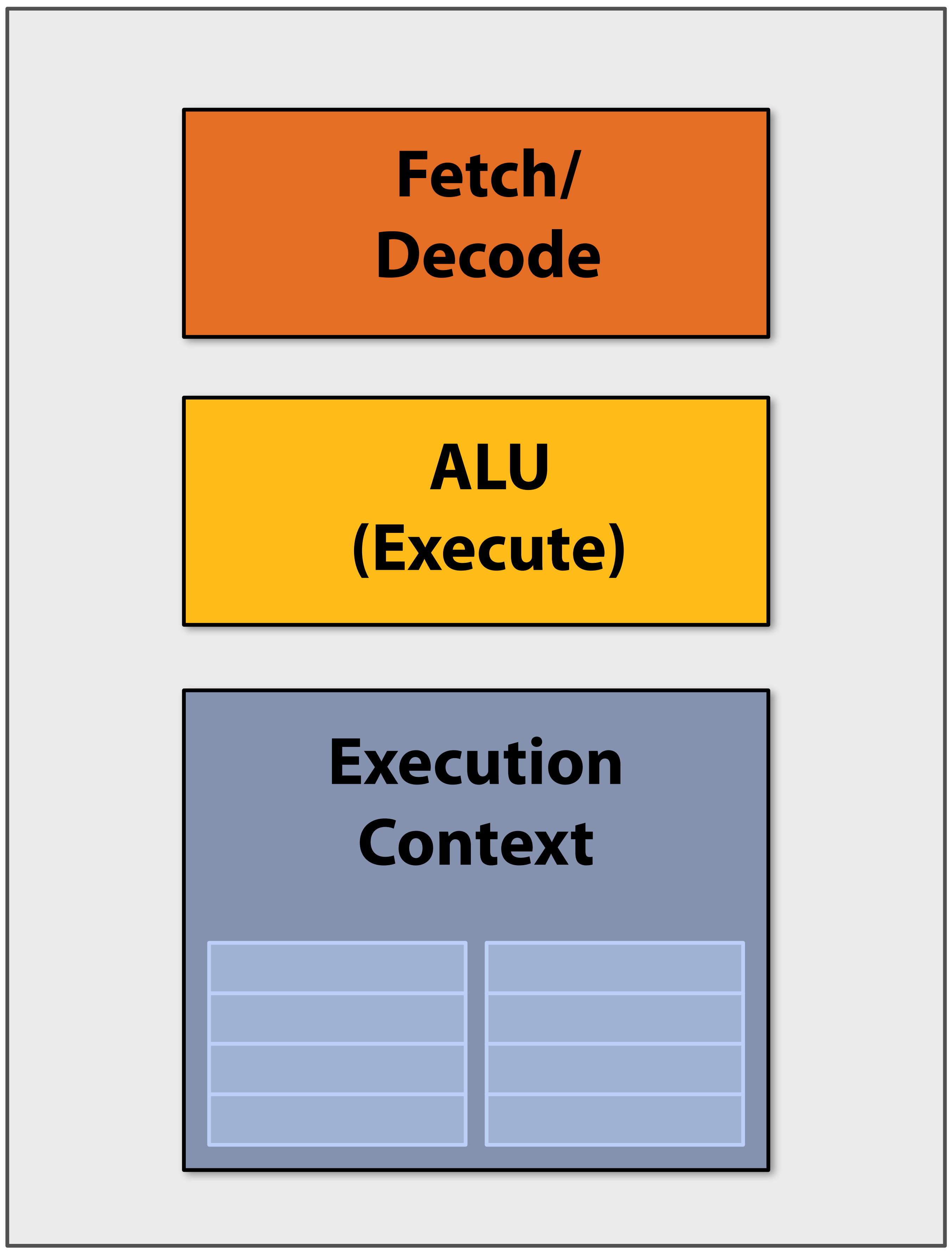
What about building a BVH in parallel?




```
Partition(node)
   For each axis: x,y,z:
      initialize buckets
      For each primitive p in node:
         b = compute_bucket(p.centroid)
         b.bbox.union(p.bbox);
         b.prim_count++;
      For each of the B-1 possible partitioning planes evaluate SAH
   Execute lowest cost partitioning found (or make node a leaf)
```

Modern computer architecture 101

What does a processor do?



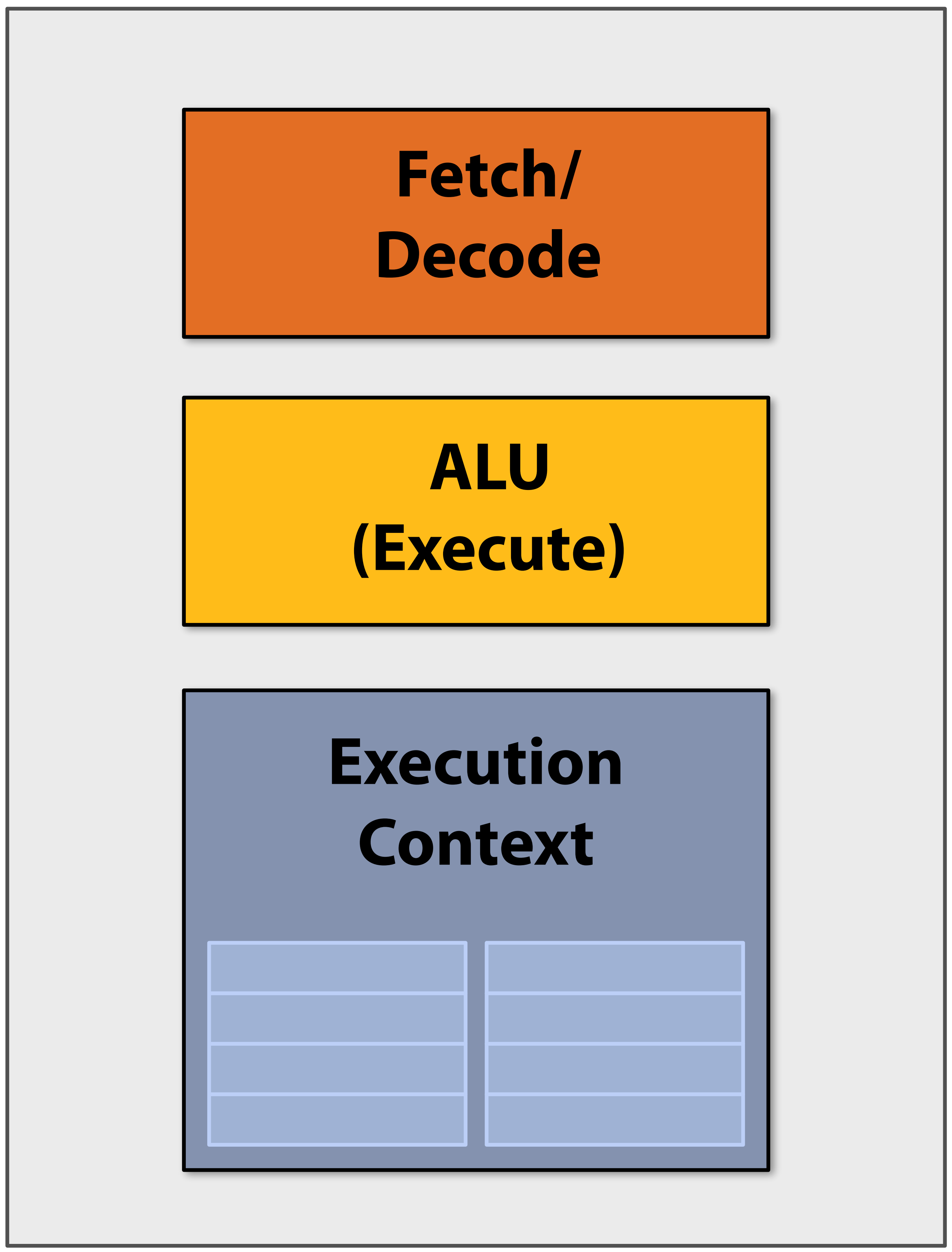

```
input
```

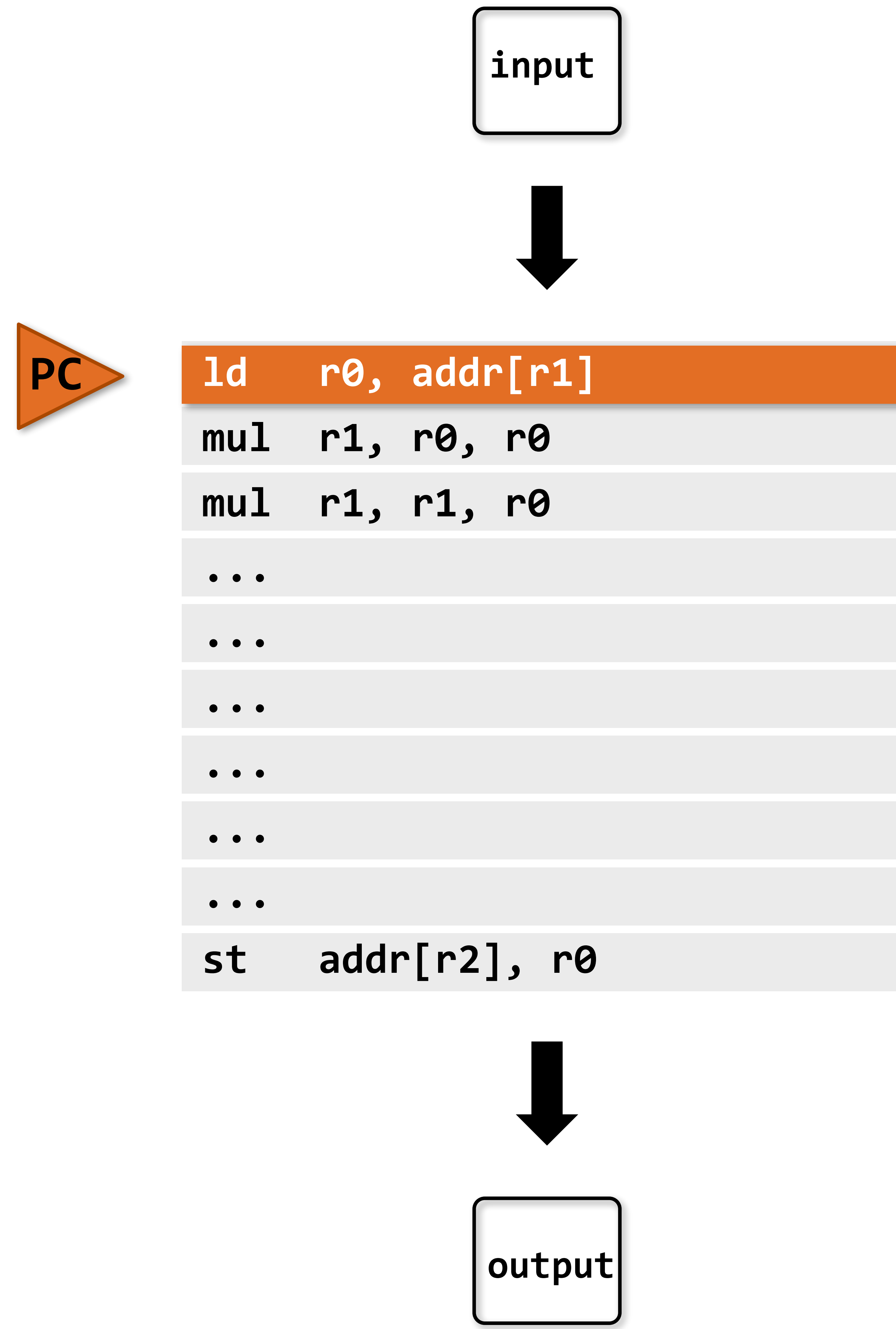
```
ld   r0, addr[r1]
mul  r1, r0, r0
mul  r1, r1, r0
...
...
...
...
...
...
st   addr[r2], r0
```

```
output
```

A processor executes an instruction stream

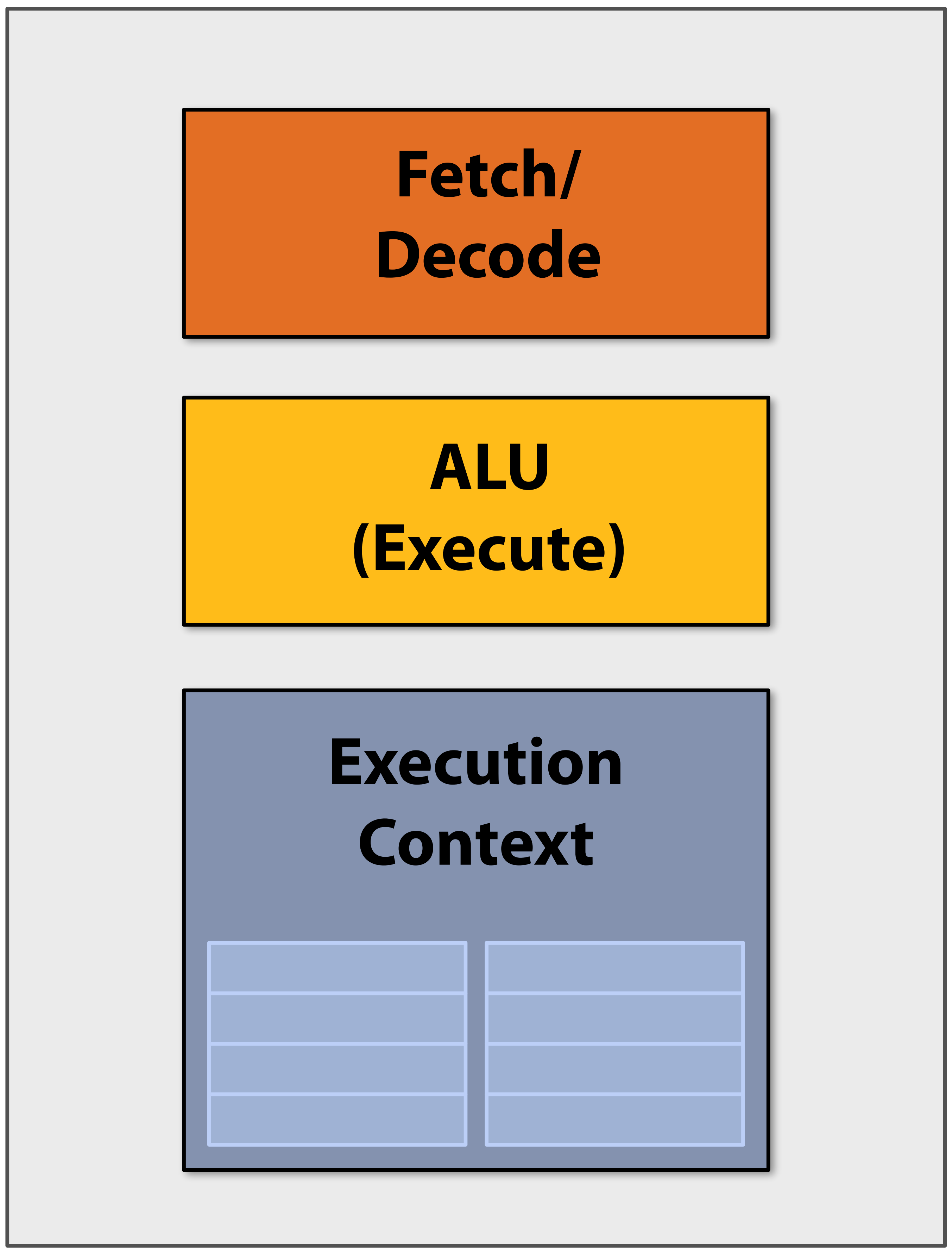
My very simple processor: executes one instruction per clock

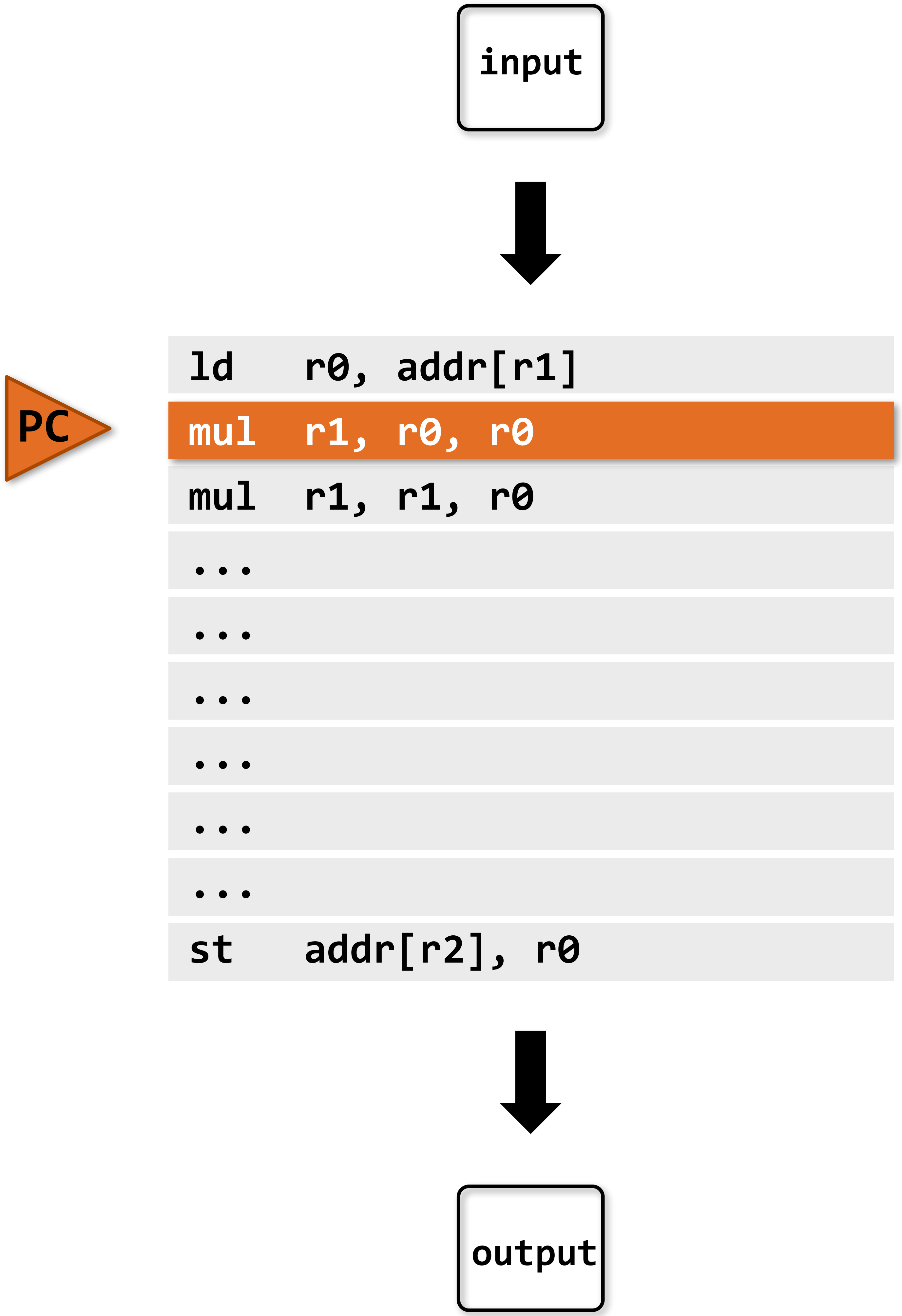




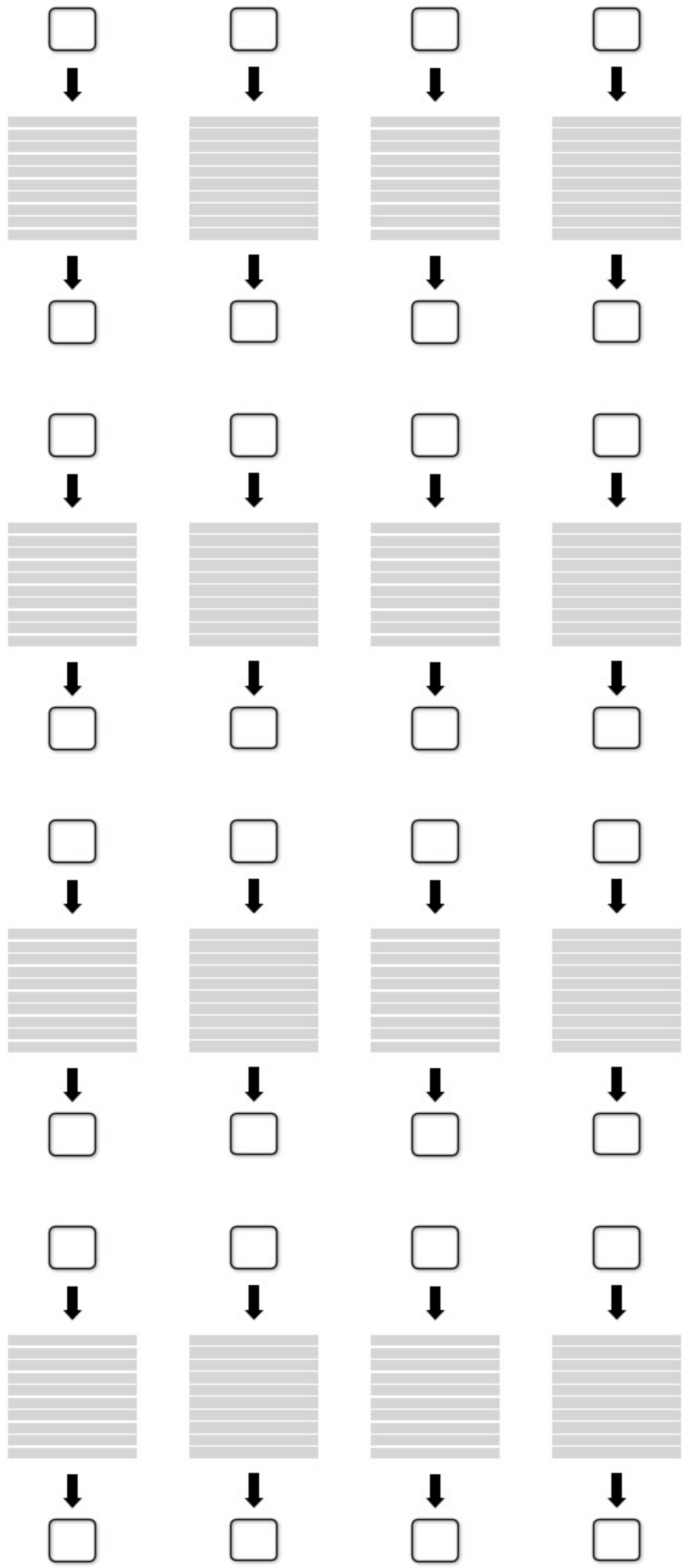
Execute program

My very simple processor: executes one instruction per clock

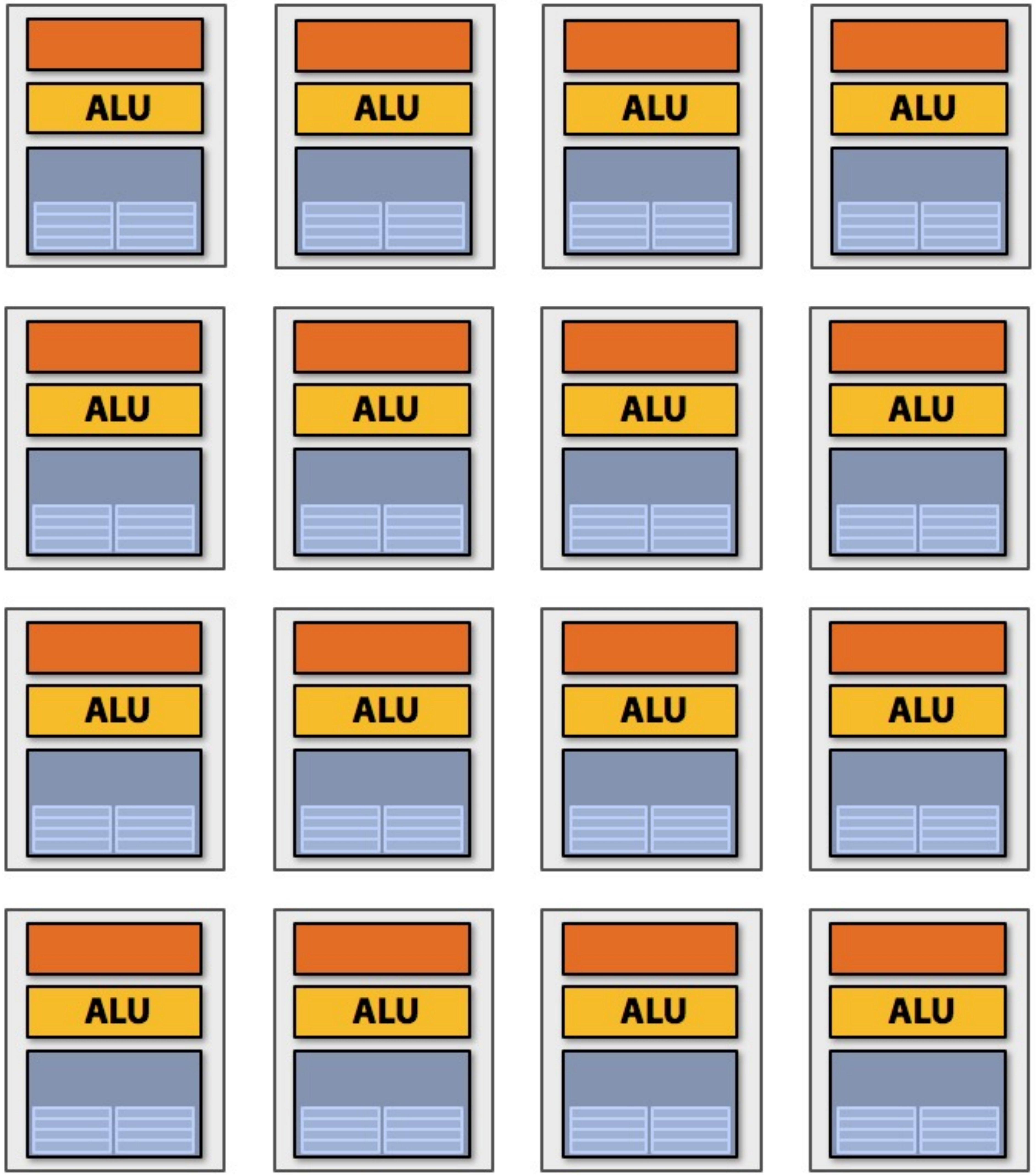




Sixteen cores: process 16 tasks in parallel



Sixteen tasks processed at once

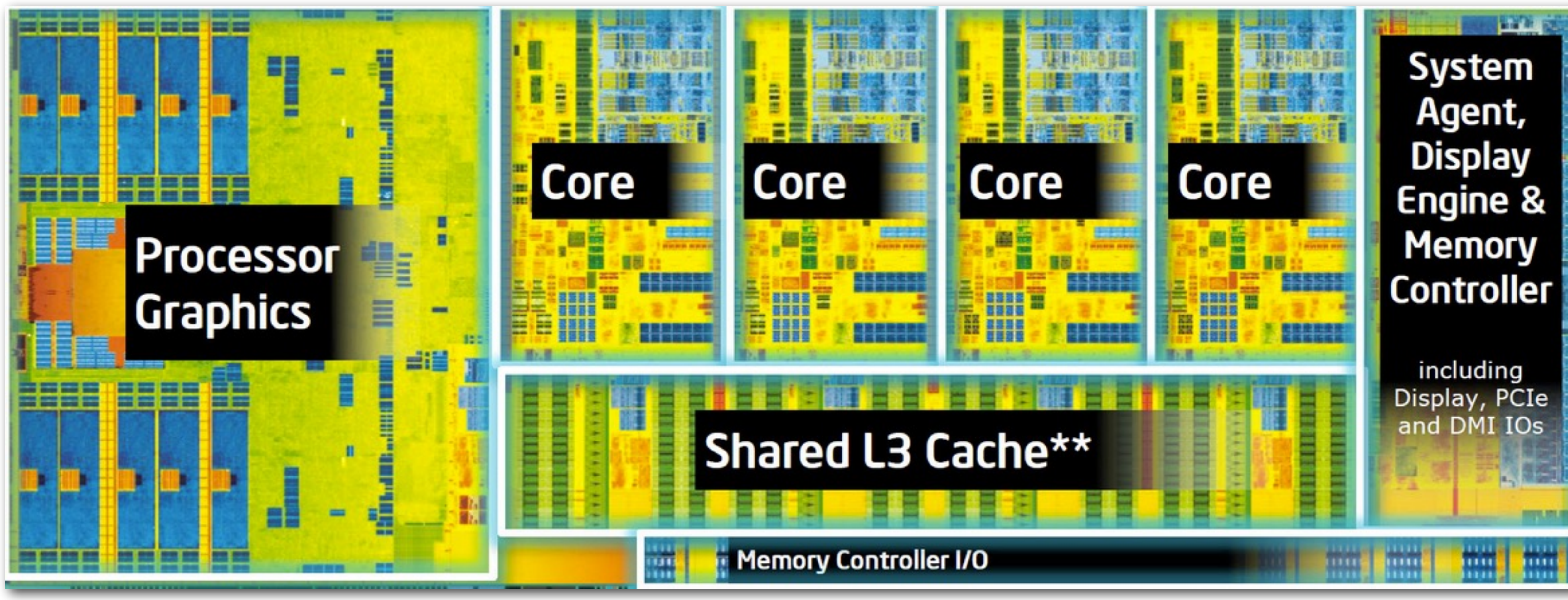


Sixteen cores

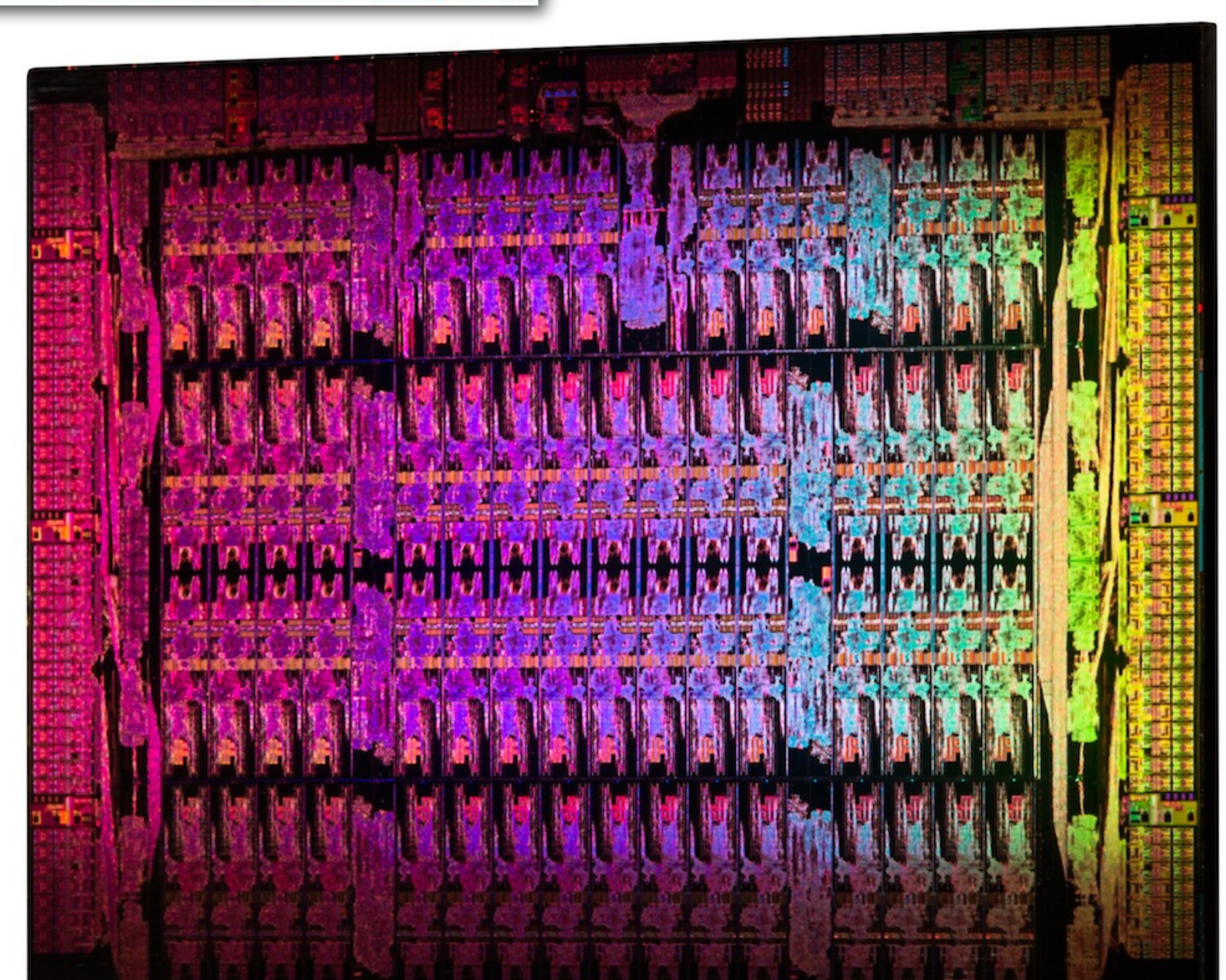
An efficient ray tracer implementation must use all the cores on a modern processor (this is quite easy)

Multi-core processors

Intel Core i7 (Haswell): quad-core CPU



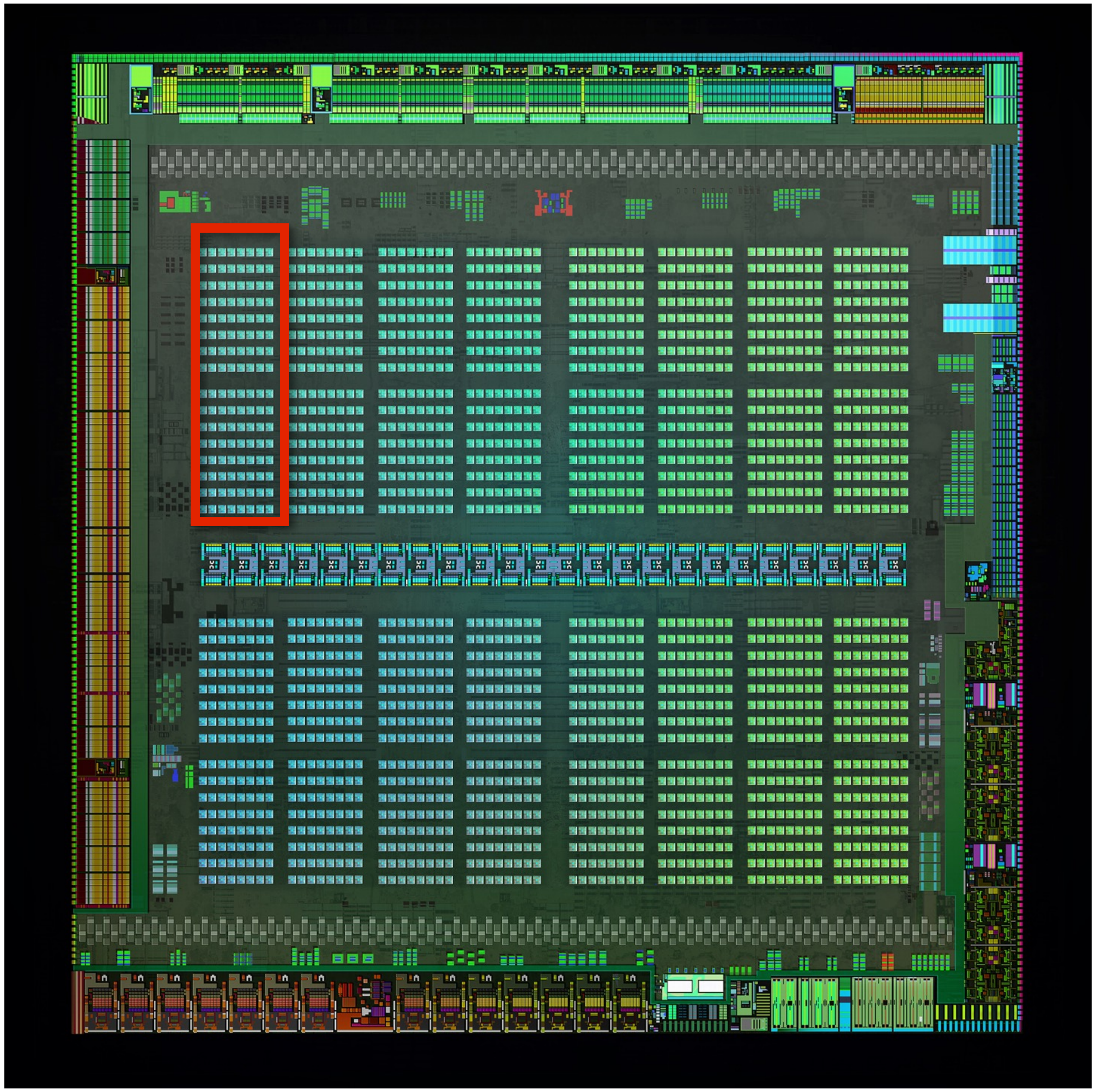
Intel Xeon Phi: 60 core CPU



Multi-core processors

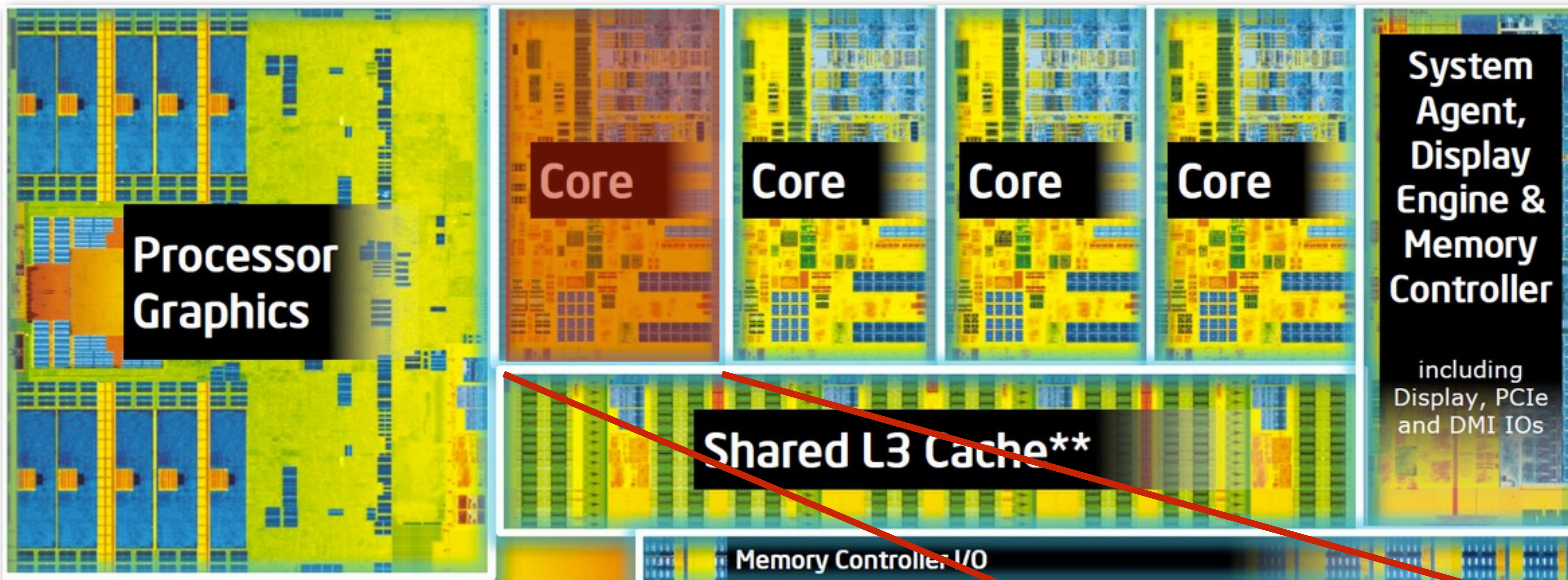
NVIDIA

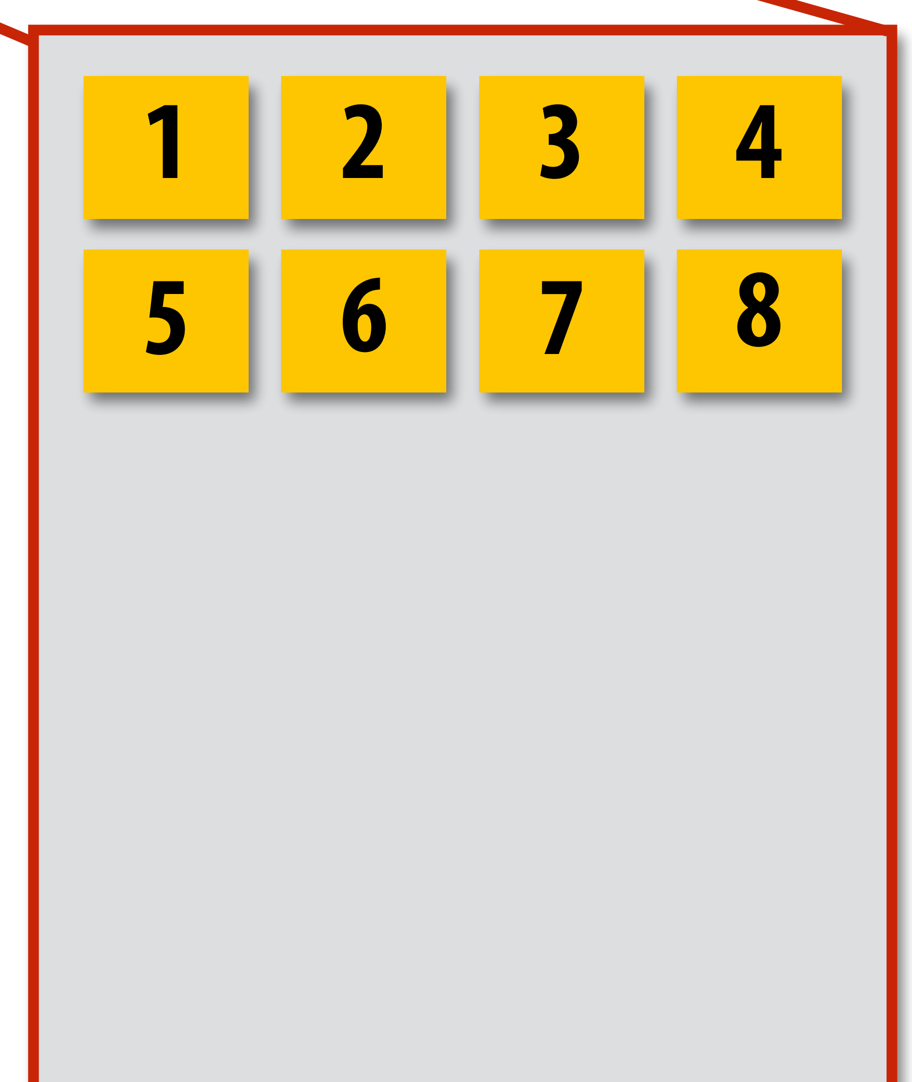
GeForce GTX 980 (Maxwell) GPU



SIMD processing

Single instruction, multiple data





Each core can execute the same instruction simultaneously on multiple pieces of data:

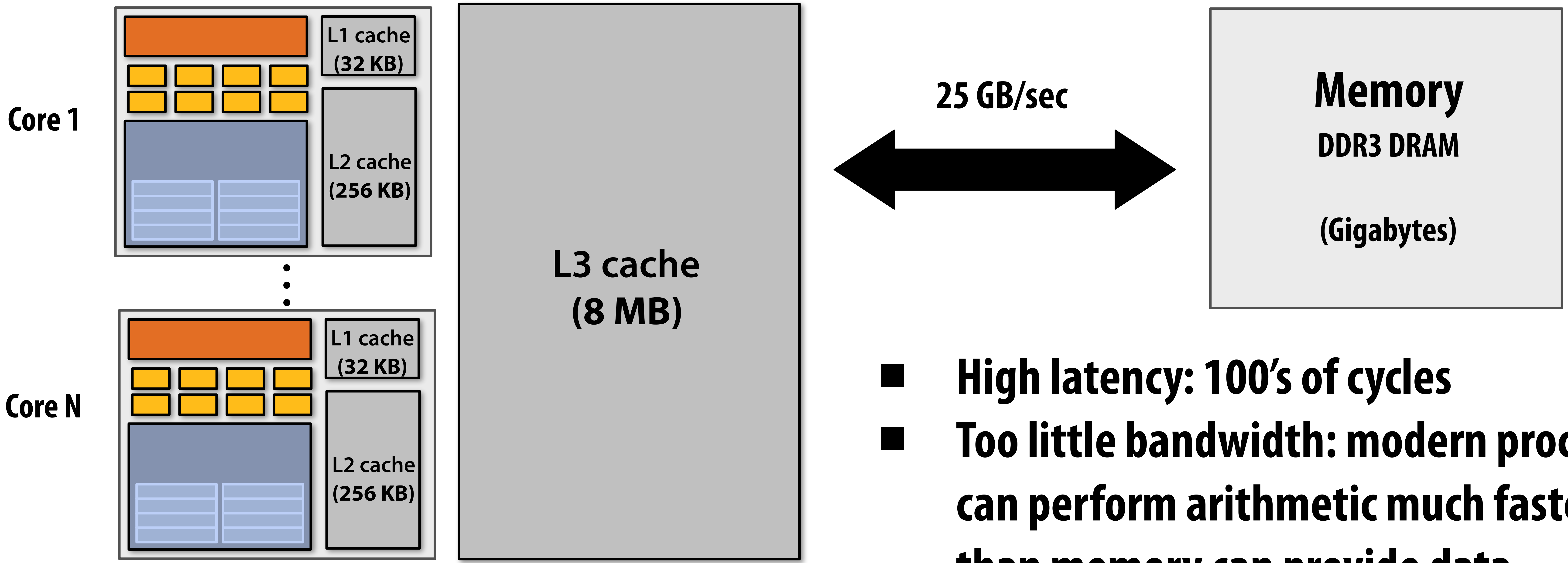
e.g., add vector A to vector B (length 8)
32-bit addition performed in parallel for each vector element.

An efficient ray tracer implementation must also utilize the SIMD execution capabilities of modern processors

CPUs: up to a factor of 8

GPUs: up to a factor of 32

Accessing memory has high cost



- **High latency: 100's of cycles**
- **Too little bandwidth: modern processors can perform arithmetic much faster than memory can provide data.**

Product	**Peak flops (fp)**	**DRAM Bandwidth (compute/BW ratio)**
NVIDIA Tesla K40 (2014, high-end discrete GPU)	4.4 TF (fp32)	288 GB/sec (8.75 flops/byte)
NVIDIA Tegra X1 (2015, high-end mobile GPU)	512 GF (fp32) 1 TF (fp16)	25.6 GB/sec (10 flops/byte)
Imagination PowerVR GX6450 (2014, iPhone 6)	115.2 GF (fp32)	12.4 GB/sec (9.2 flops/byte)
Imagination PowerVR GT7900 (2015, high-end mobile GPU)	384 GF (fp32) 768 GF (fp16)	TBD since processor is not in shipping SoCs
Intel Integrated HD 350 GPU (2014, integrated desktop GPU)	384 GF (fp32)	34.1 GB/sec (11.2 flops/byte)
Xbox 360 (2005)	240 GF (fp32)	32.1 GB/sec (7.5 flops/byte)

An efficient ray tracer implementation must be careful to reduce memory access costs as much as possible.

Rules of the game

- Many individual processor cores
  - Run tasks in parallel
- SIMD instruction capability
  - Single instruction carried out on multiple elements of an array in parallel (8-wide on modern GPUs, 16-wide on Xeon Phi, 8-to-32-wide on modern GPUs)
- Accessing memory is expensive
  - Processor must wait for data to arrive
  - Role of CPU caches is to reduce wait time (want good locality)

Efficient ray traversal algorithms

High-throughput ray tracing

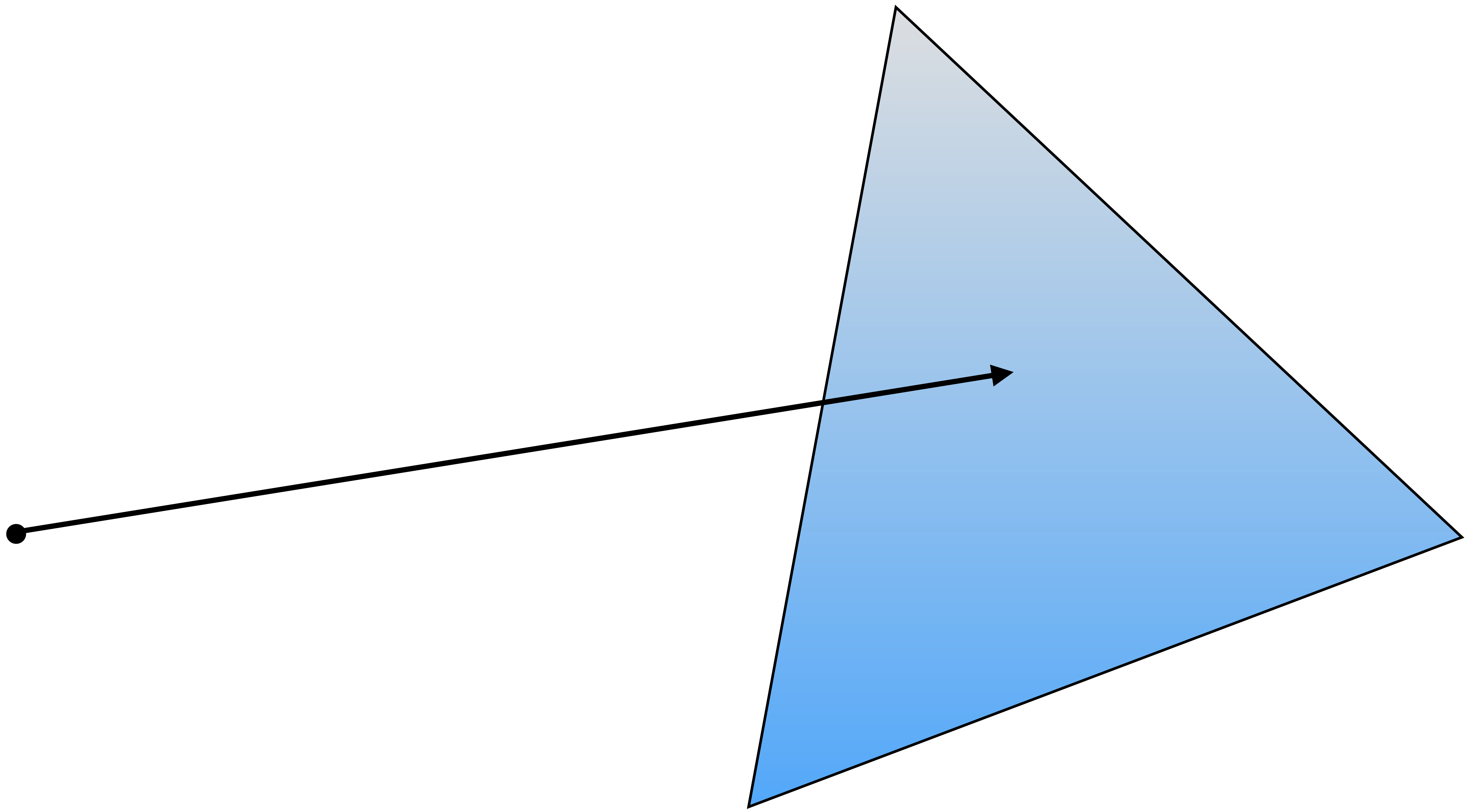
- **Want work-efficient algorithms (do less)**
  - High-quality acceleration structures (minimize ray-box, ray-primitive tests)
  - Smart traversal algorithms (early termination, etc.)

Discussed in earlier lecture

- **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?

Parallelizing ray-triangle tests?



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.)

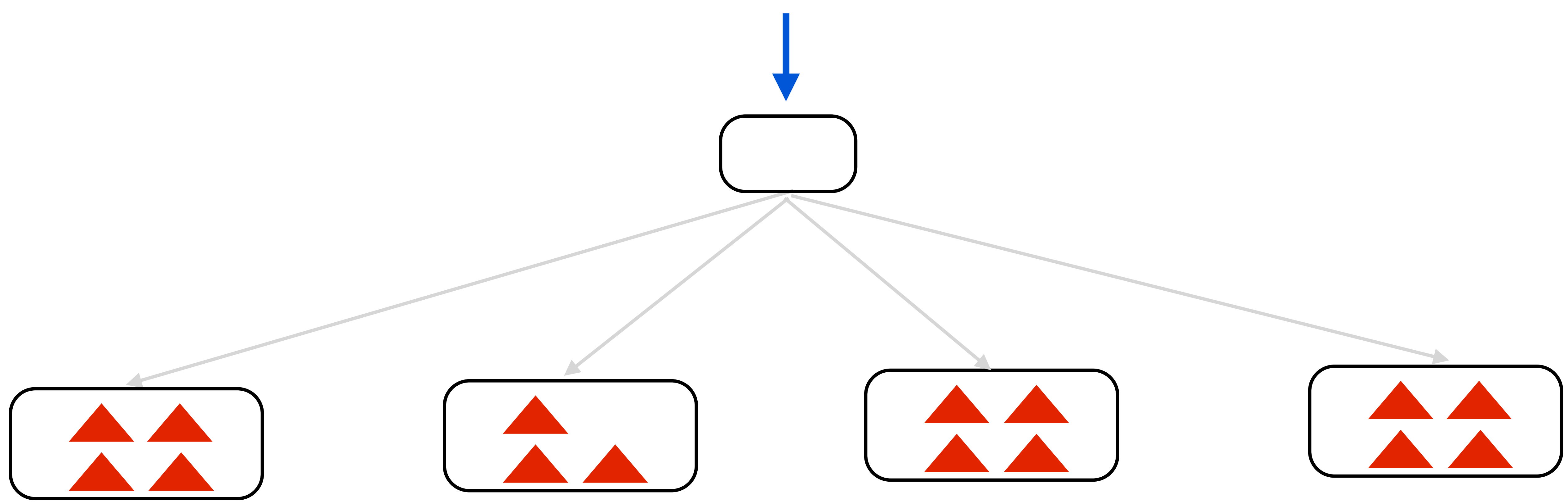
- Similar SIMD parallelism in ray-triangle test at BVH leaf

- 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

- Today: we'll discuss one approach: ray packets
  - 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);
   }
}
```

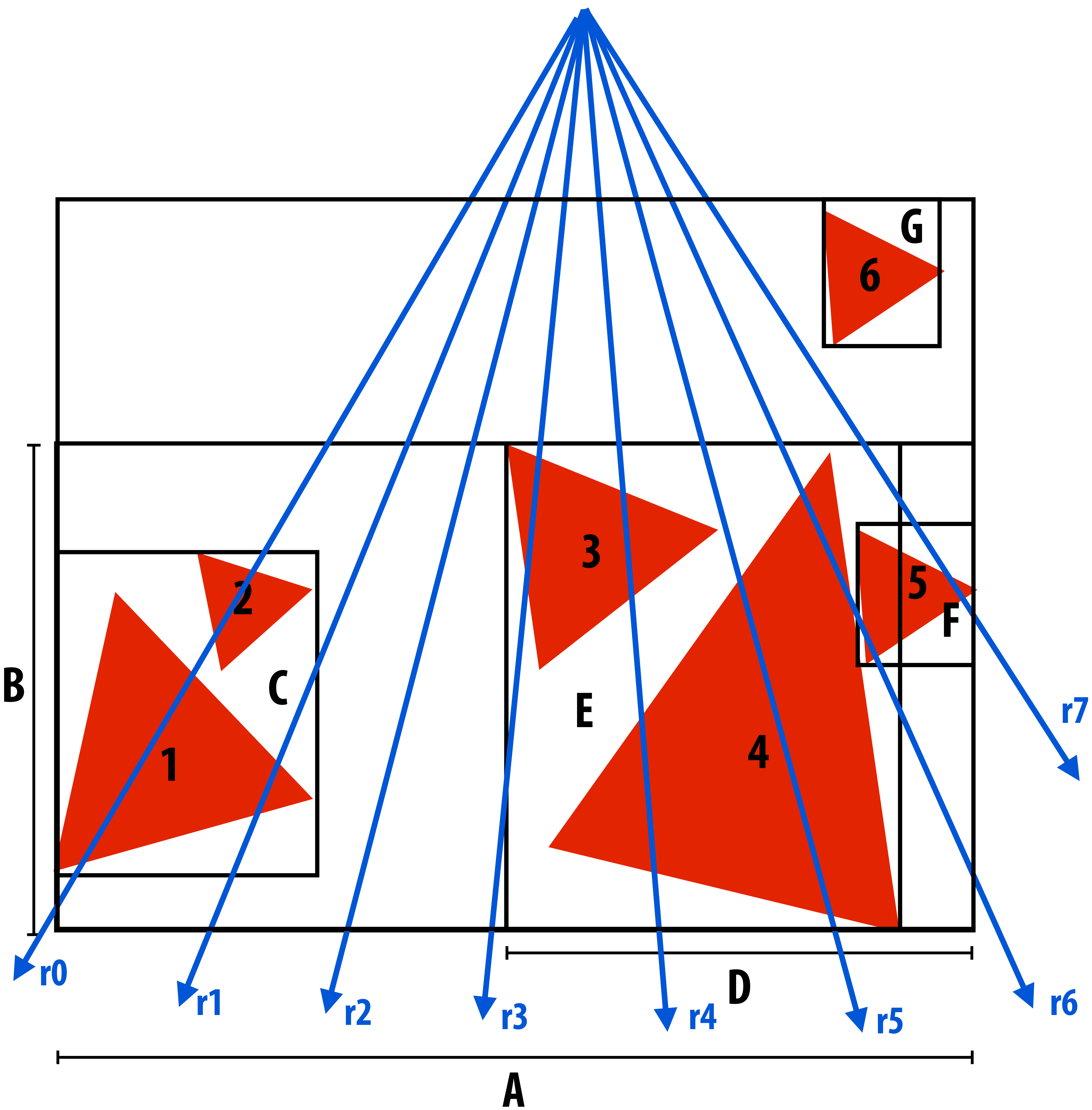
Ray packet tracing

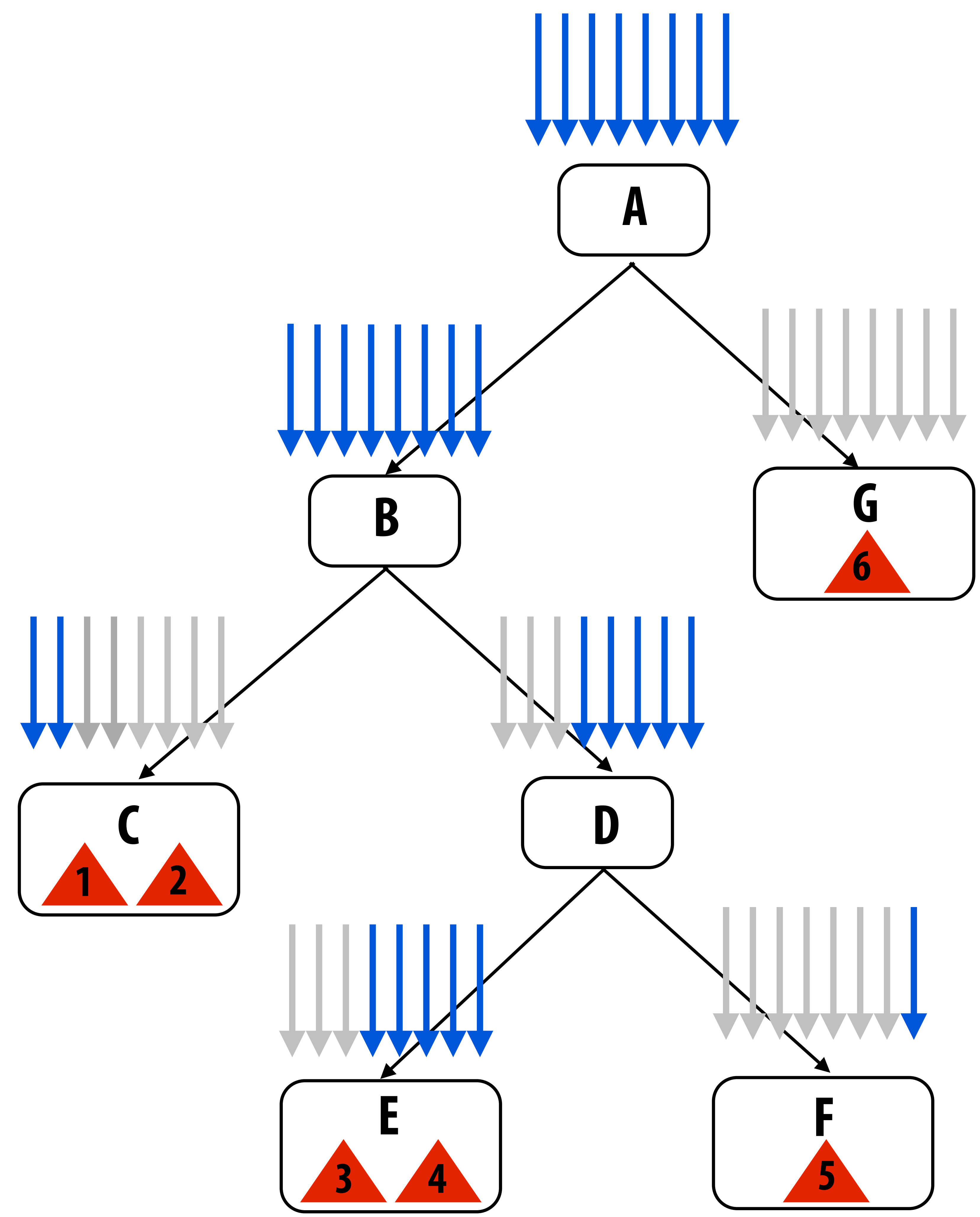
[Wald et al. 2001]

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





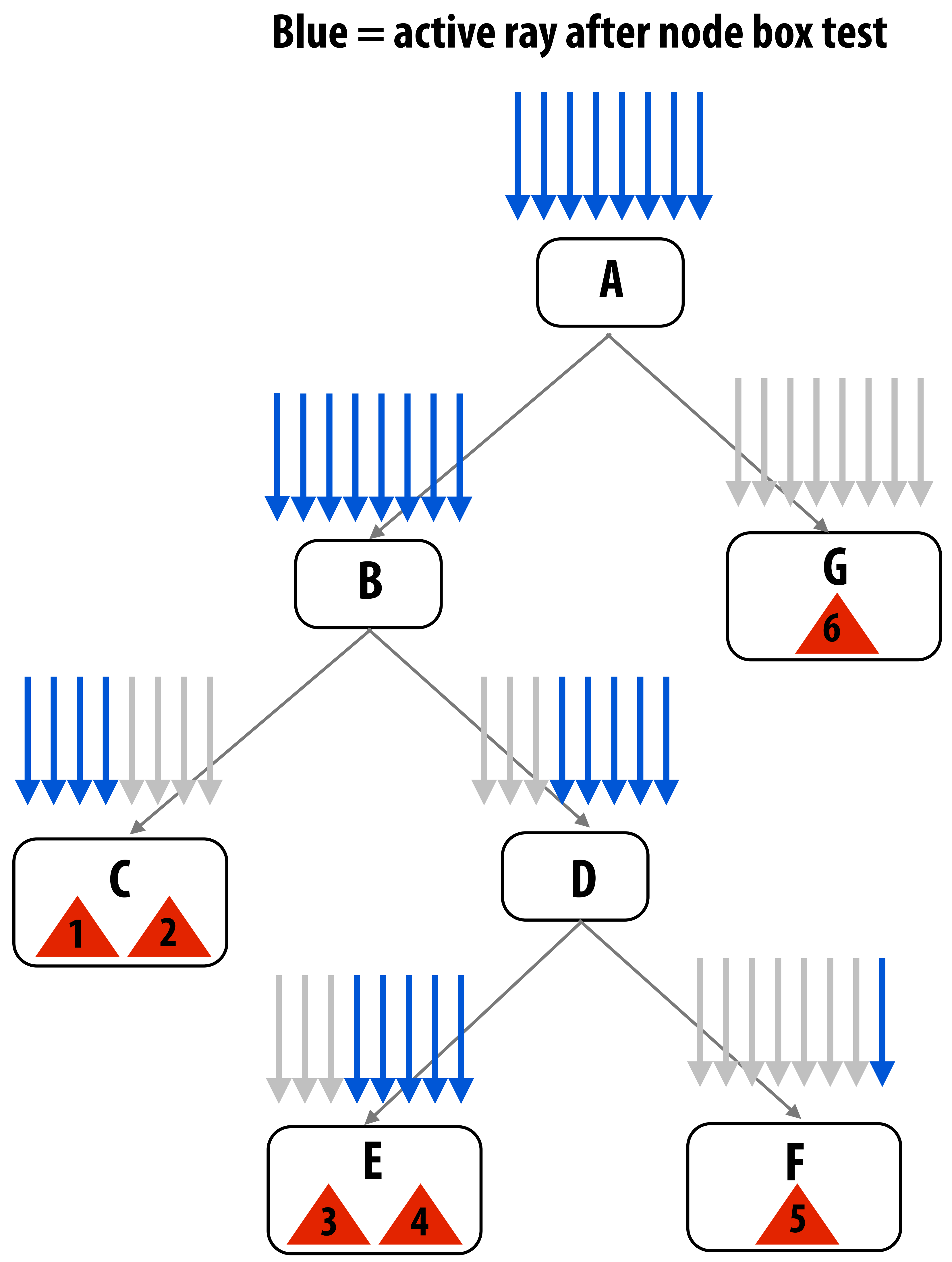
Note: r6 does not pass node F box test due to closest-so-far check, and thus does not visit F

Advantages of packets

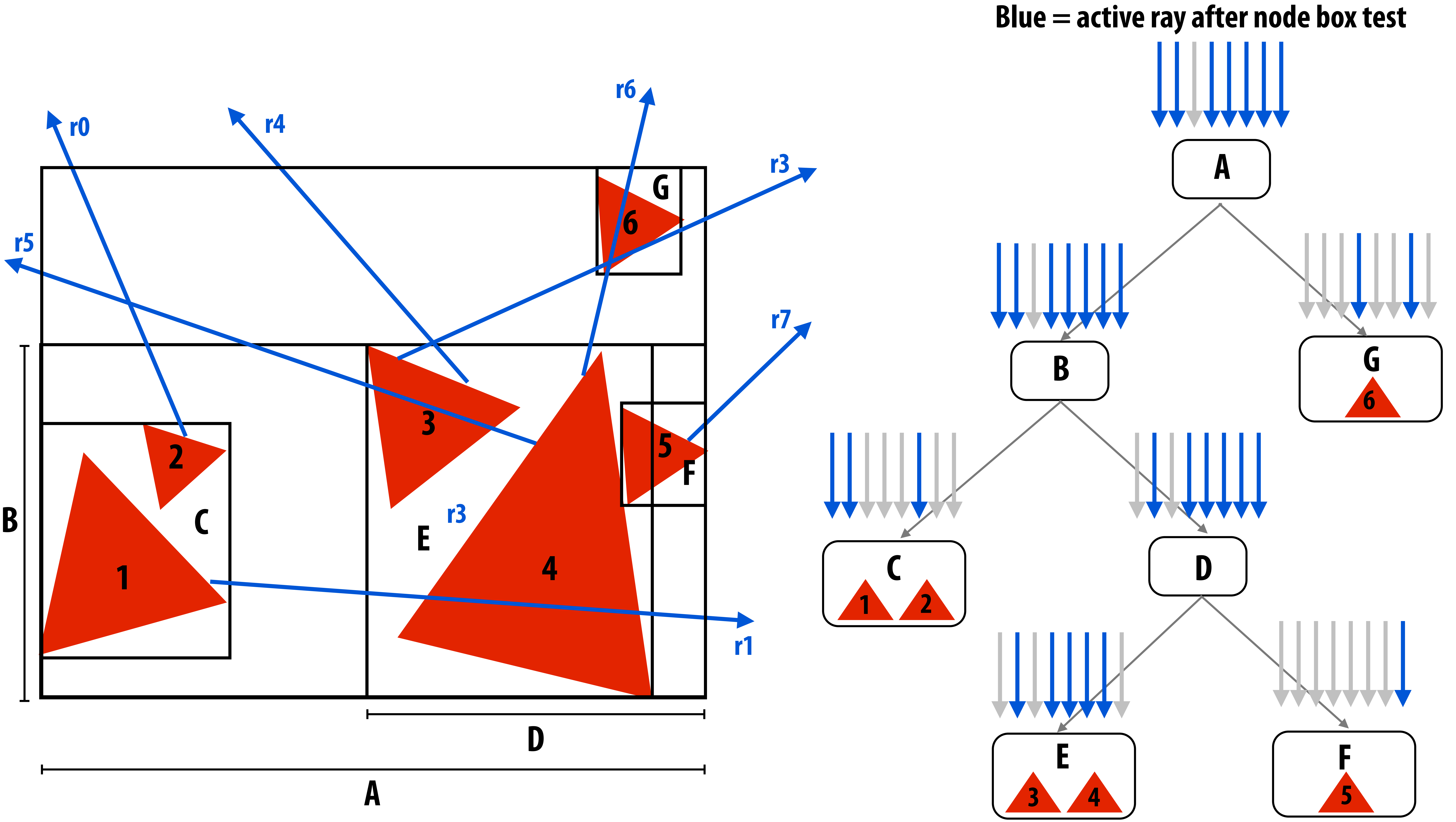
- Enable wide SIMD execution
  - One vector lane per ray
- Amortize BVH data fetch: all rays in packet visit node at same time
  - Load BVH node once for all rays in packet (not once per ray)
  - Note: there is value to making packets bigger than SIMD width! (e.g., size = 64)
- Amortize work (packets 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 arithmetic 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)
- Loss of efficiency: node traversal, intersection, etc. amortized over less than a packet's worth of rays
- Not all SIMD lanes doing useful work

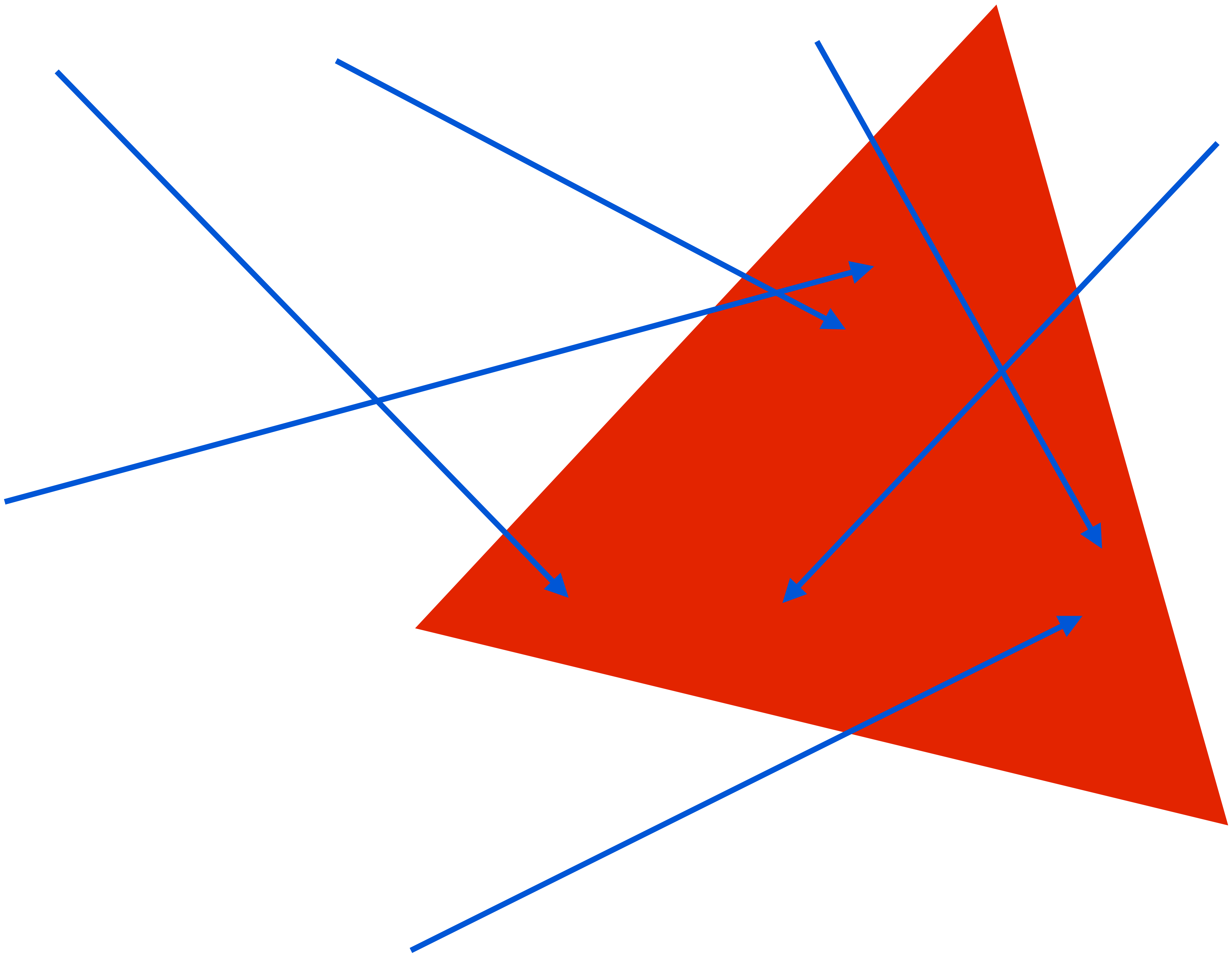


Ray packet tracing: incoherent rays



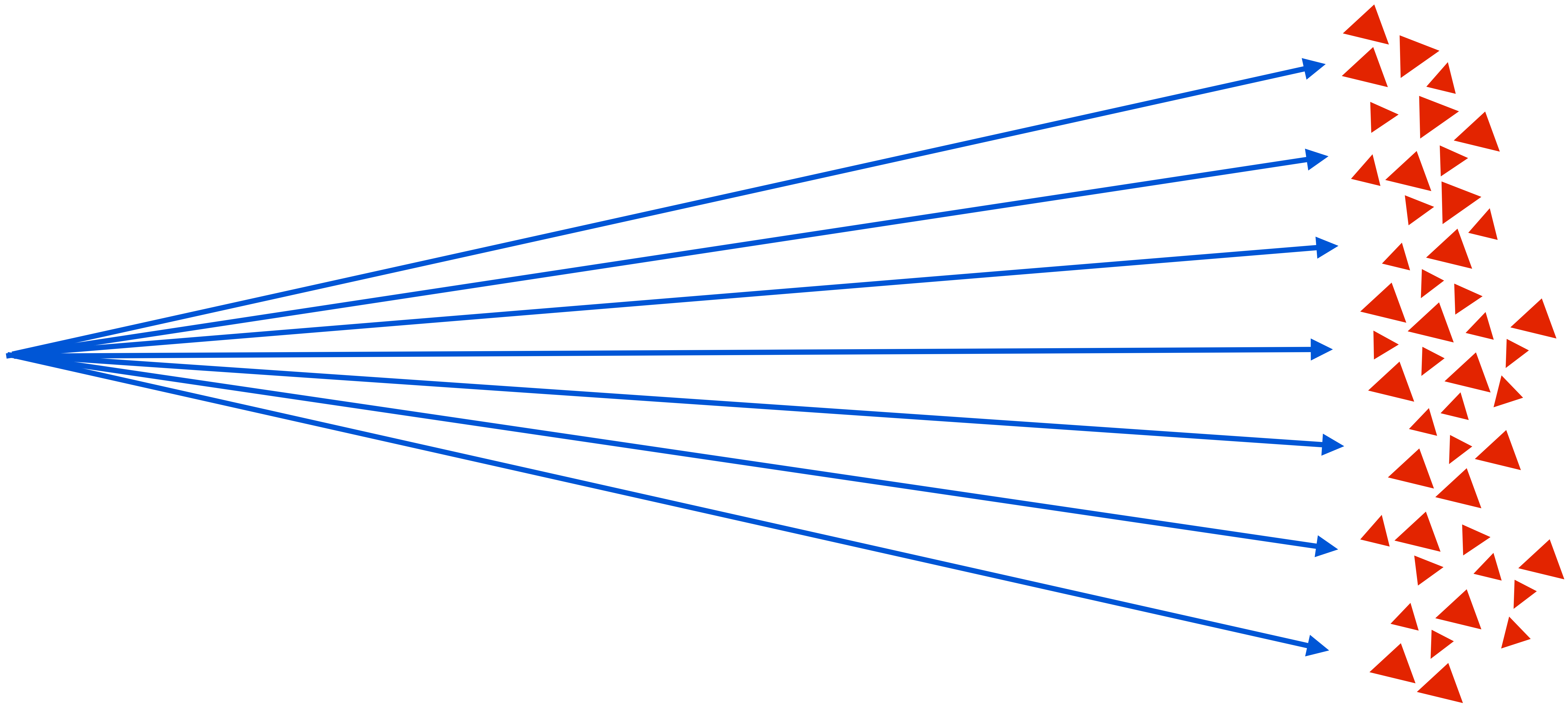
When rays are incoherent, benefit of packets can decrease significantly. This example: packet visits all tree nodes. (So all eight rays visit all tree nodes! No culling benefit!)

Incoherence is a property of both 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 both 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)

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

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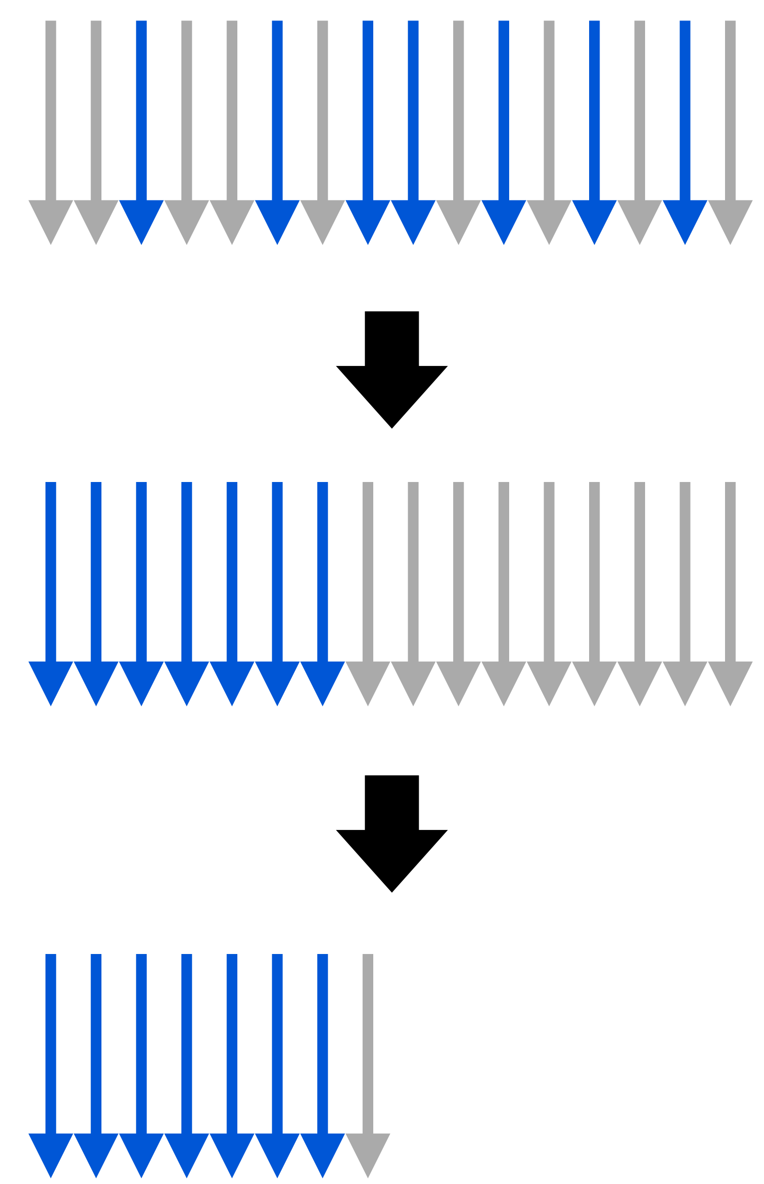
Example: consider 8-wide SIMD processor and 16-ray packets
(2 SIMD instructions required to perform each operation on all rays in packet)

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



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

- Switch to single ray (intra-ray SIMD) when packet utilization drops below threshold [Benthin et al. 2011]
  - For wide SIMD machine, a branching-factor-4 BVH works well for both packet traversal 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
  - Not often used in practice due to high implementation complexity

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

Emerging hardware for ray tracing

- **Modern academic/announced industry implementations:**
  - Trace single rays, not ray packets (assume most rays are incoherent rays…)

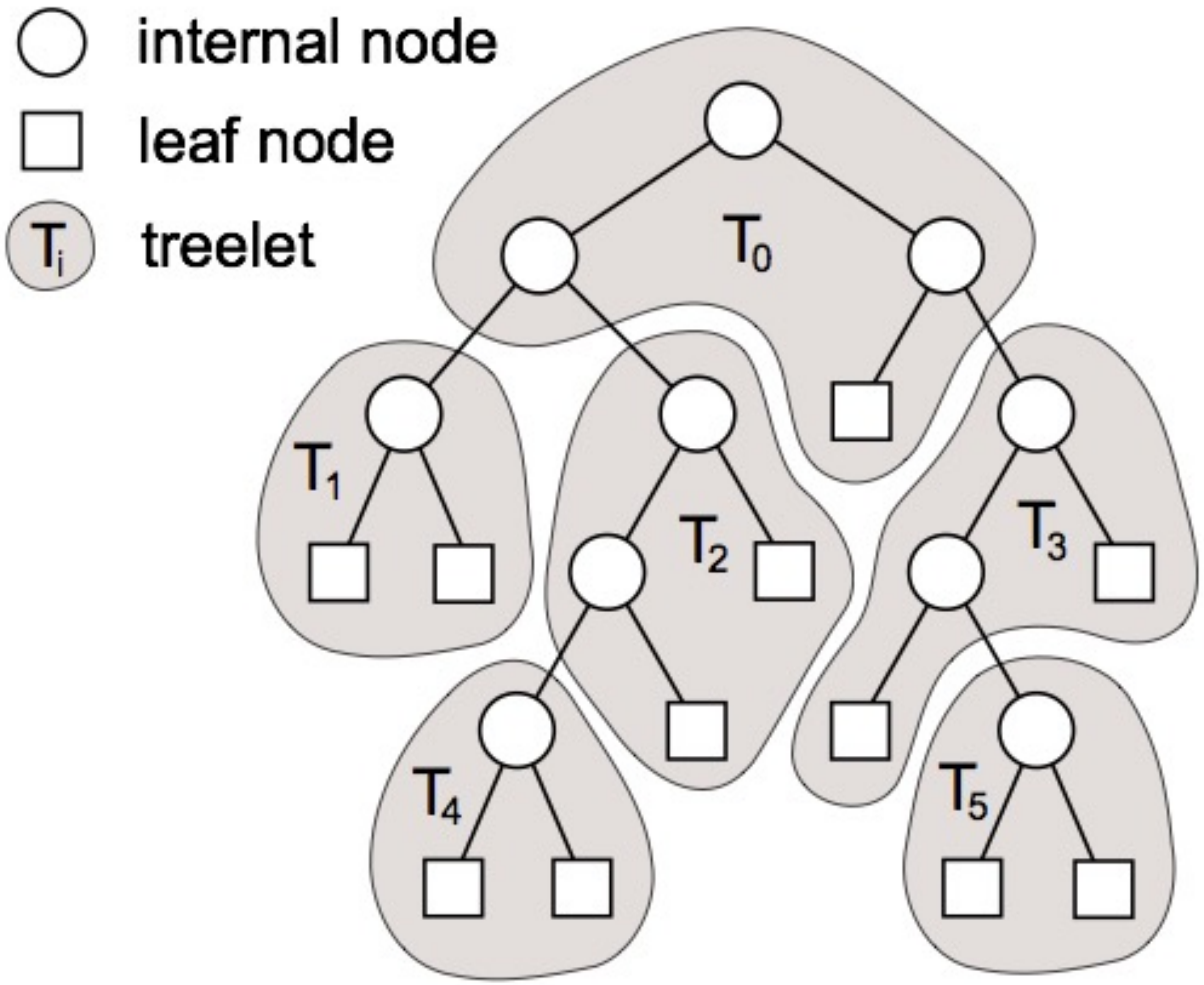
- **Two areas of focus:**
  - Custom logic for accelerating ray-box and ray-triangle tests
    - MIMD designs: wide SIMD execution not beneficial
  - Support for efficiently reordering ray-tracing computations to maximize memory locality (ray scheduling)

- **See "further reading" on web site for a list of references**

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 (or packet) enters treelet, add rays to treelet queue**

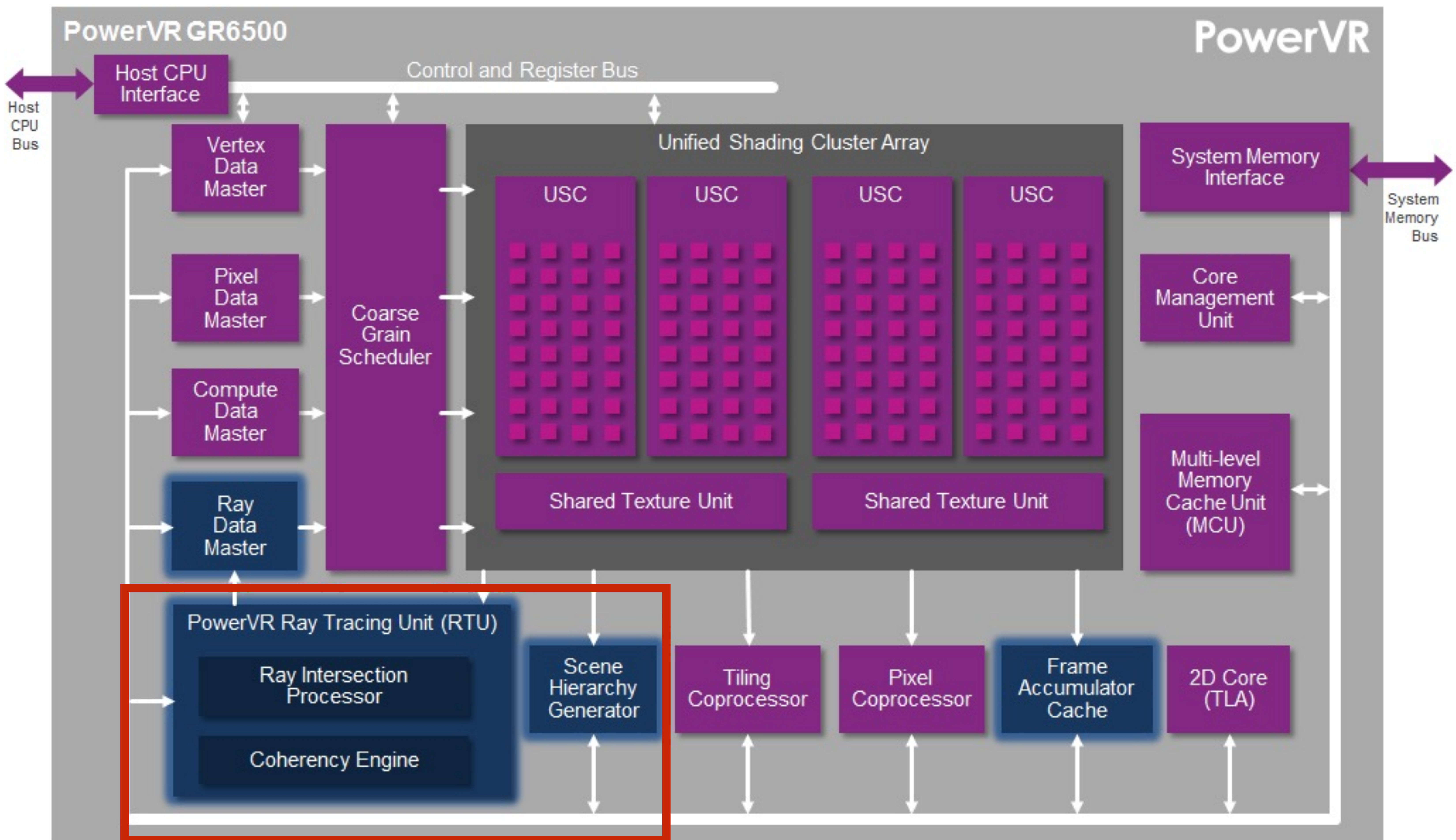
2. **When treelet queue is sufficiently large, intersect enqueued rays with treelet**
   (amortize treelet load over all enqueued rays)

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 sized to fit in caches (or in dedicated ray buffer SRAM)

[Pharr 1997, Navratil 07, Alia 10]

PowerVR GR6500 ray tracing GPU



Constructing High-Quality BVHs Quickly

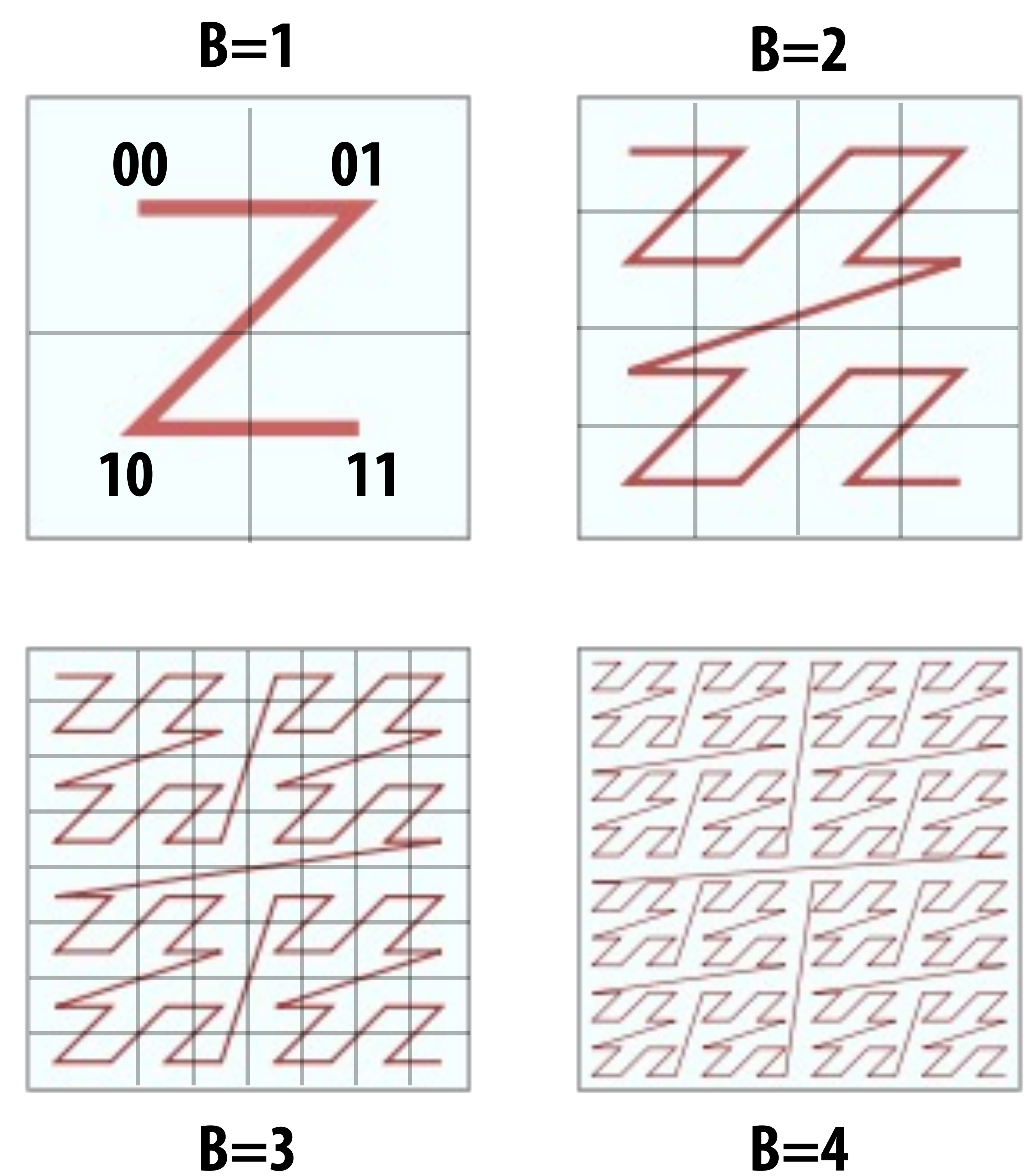
Building a "poor" BVH quickly

1. Discretize each dimension of scene into 2^B cells
2. Compute index of centroid of bounding box of each primitive:
   (c_i, c_j, c_k)
3. Interleave bits of c_i, c_j, c_k to get 3B bit-Morton code
4. Sort primitives by Morton code (primitives now ordered with high locality in 3D space: in a space-filling curve!)
   - O(N) radix sort

Simple, highly parallelizable BVH build:

```
Partition(int i, primitives):
  node.bbox = bbox(primitives)
  (left, right) = partition primitives by bit i
  if there are more bits:
     Partition(left, i+1);
     Partition(right, i+1);
  else:
     make a leaf node
```

2D Morton Order



Modern, fast BVH build schemes

- **Build "poor" BVH quickly using Morton Codes**
- **Use initial BVH to <u>accelerate</u> construction of high-quality BVH**
- **Example: [Kerras 2013]**

```
For all treelets of size < N in original "poor" BVH: (in parallel)
  try all possible trees, keep "optimal" topology that minimizes SAH for treeless
```