Parallel Physically Based Path-tracing and Shading Part 1 of 2

CIS565 Fall 2012
University of Pennsylvania
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Agenda

- Part 1 (Today):
  - Quick introduction and theory review:
    - The Rendering Equation
    - Bidirectional reflection distribution functions
    - Pathtracing algorithm overview
  - Implementing parallel ray-tracing
    - Recursion versus iteration
    - Iterative ray-tracing
- Part 2 (Wednesday):
  - Distributed ray-tracing/Monte-carlo integration, more on BRDFs
  - Implementing parallel path-tracing
    - Path versus ray parallelization, ray compaction
    - Parallel computation, BRDF evaluation, and you!
  - Parallel approaches to spatial acceleration structures
    - Stack-less KD-tree construction and traversal
    - Bounding volume hierarchies

Path-tracing: Quick Introduction and Theory Review

The Rendering Equation

$$L_o(p,\omega_o) = L_e(p,\omega_o) + \int_\Omega \rho(p,\omega_i,\omega_o) L_i(p,\omega_i) \cos\theta \, d\omega_i$$

- Super high level meaning: [outgoing light] = [incoming light] + [emitted light] + [absorbed light]

$L_o(p,\omega_o)$ = Outgoing light

$L_e(p,\omega_o)$ = Emitted light

$\int_\Omega \; d\omega_i$ = Integrate over a hemisphere in the direction *w* over the given point *p*

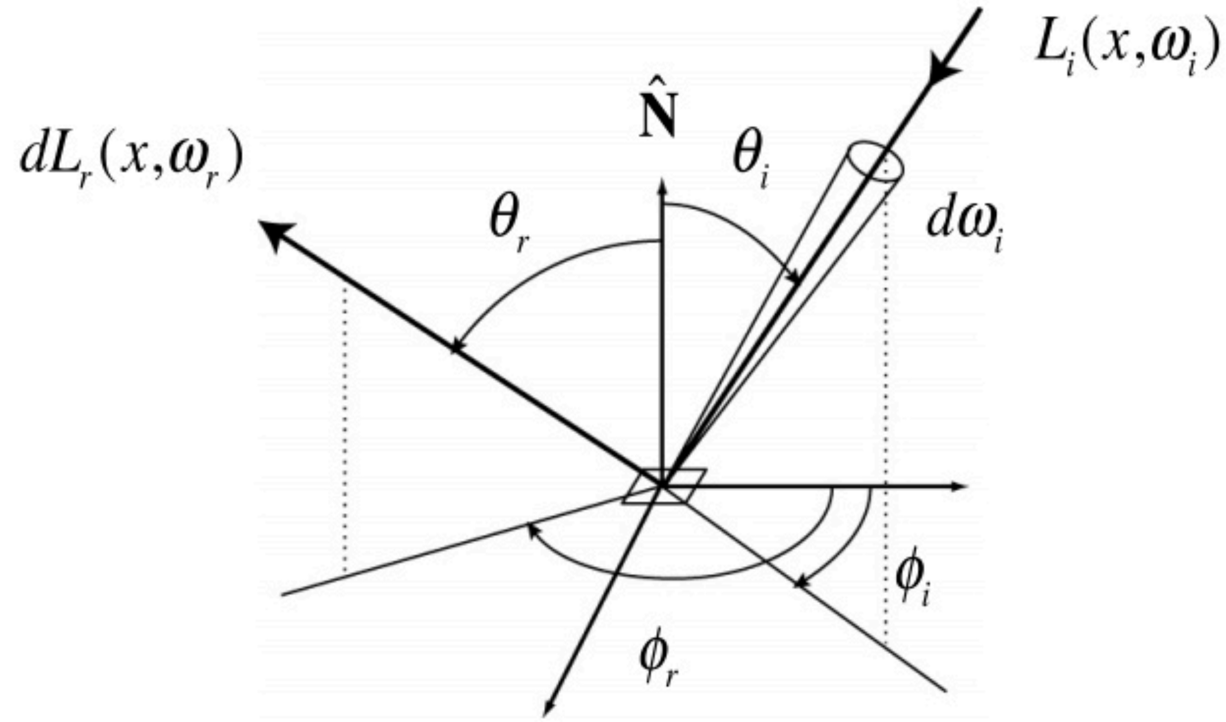
$\rho(p,\omega_i,\omega_o)$ = BRDF (Bidirectional Reflectance Distribution Function

$L_i(p,\omega_i)$ = Incoming Light

$\cos\theta$ = Attenuate incoming light based on the cosine of the angle between the normal *n* and the incoming light direction w_i

Bidirectional Reflectance Distribution Functions

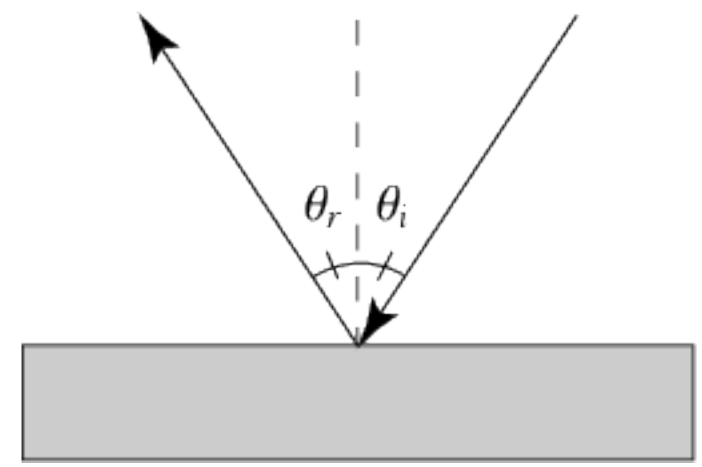
- Defines how light is reflected at a given opaque surface
- Can be extended with transmittance to produce the BSDF: Bidirectional Scattering Distribution Function
- Reflectance models:
  - Ideal Specular (think mirrors)
  - Ideal Diffuse
  - Specular/Glossy (won't cover today)
    - Phong Model
    - Microfacet Models
    - Torrance-Sparrow Model



$$f_r(\omega_i \to \omega_r) \equiv \frac{dL_r(\omega_i \to \omega_r)}{dE_i} \quad \left[\frac{1}{sr}\right]$$

Reflectance Models: Ideal Specular

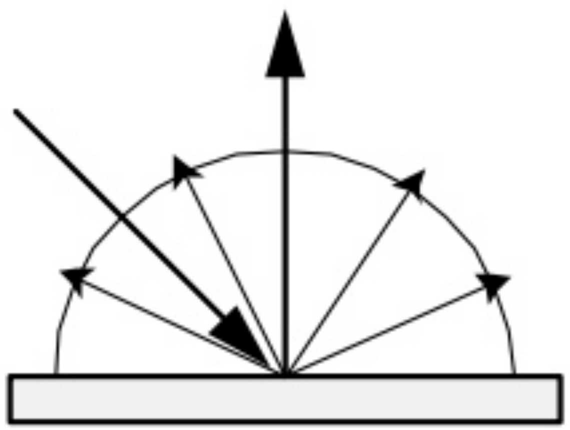
- Ideal specular reflection: incoming light and outgoing light make the same angle across the surface normal, so angle of incidence = angle of reflection

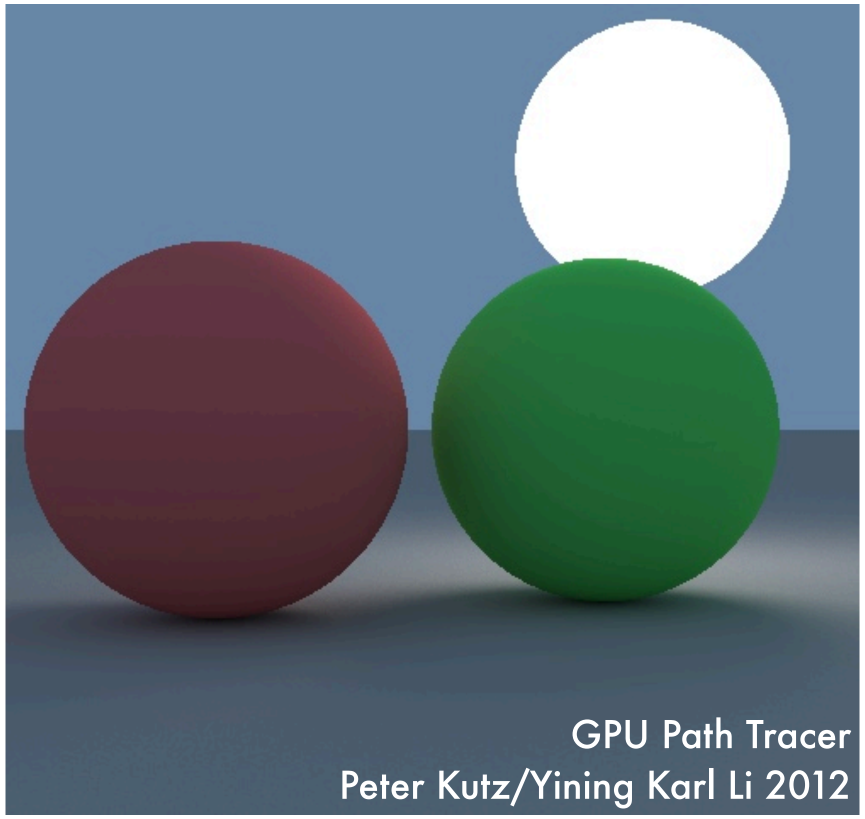


- Fresnel's law: defines the behavior of light when moving between mediums with different indices of refraction.
  - Can be approximated with Shlick's approximation.

Reflectance Models: Ideal Diffuse

- Ideal diffuse reflection: light is equally likely to be reflected in any output direction within a hemisphere oriented along the surface normal over a given point
- Think: wall paint.
- Theoretical models:
  - Micro-facet distribution
  - Subsurface reflection





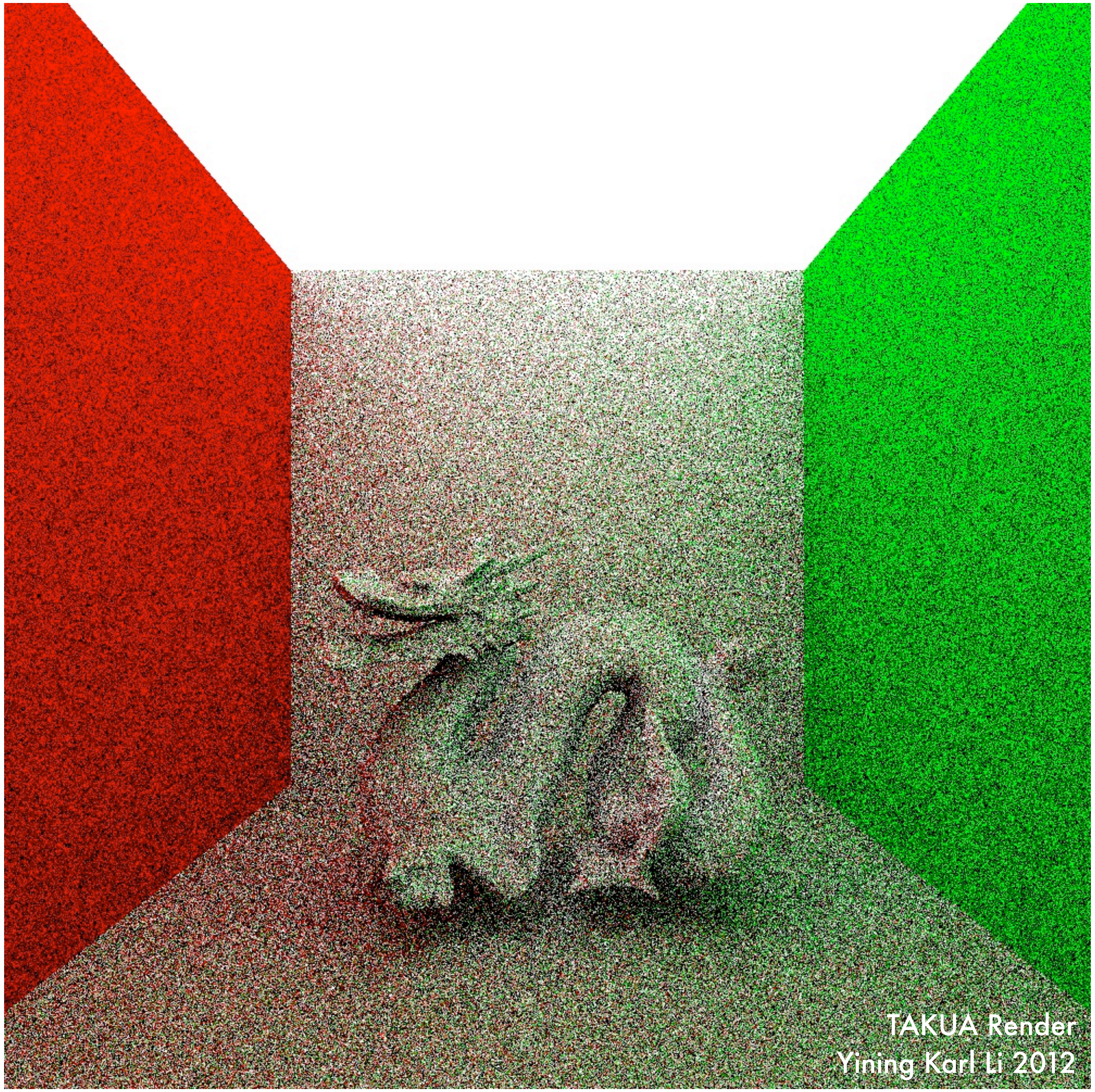
Path-tracing Algorithm

- Solves the rendering equation, which was first proposed by James Kajiya in 1986.
- Generalizes ray tracing to produce accurate, unbiased images with full global illumination. Path tracing allows for effects like soft shadows, DOF, antialiasing for free.
- Potentially extremely slow on the CPU and has only become a feasible technique in recent years due to faster and faster hardware.

The Third and the Seventh
Alex Roman

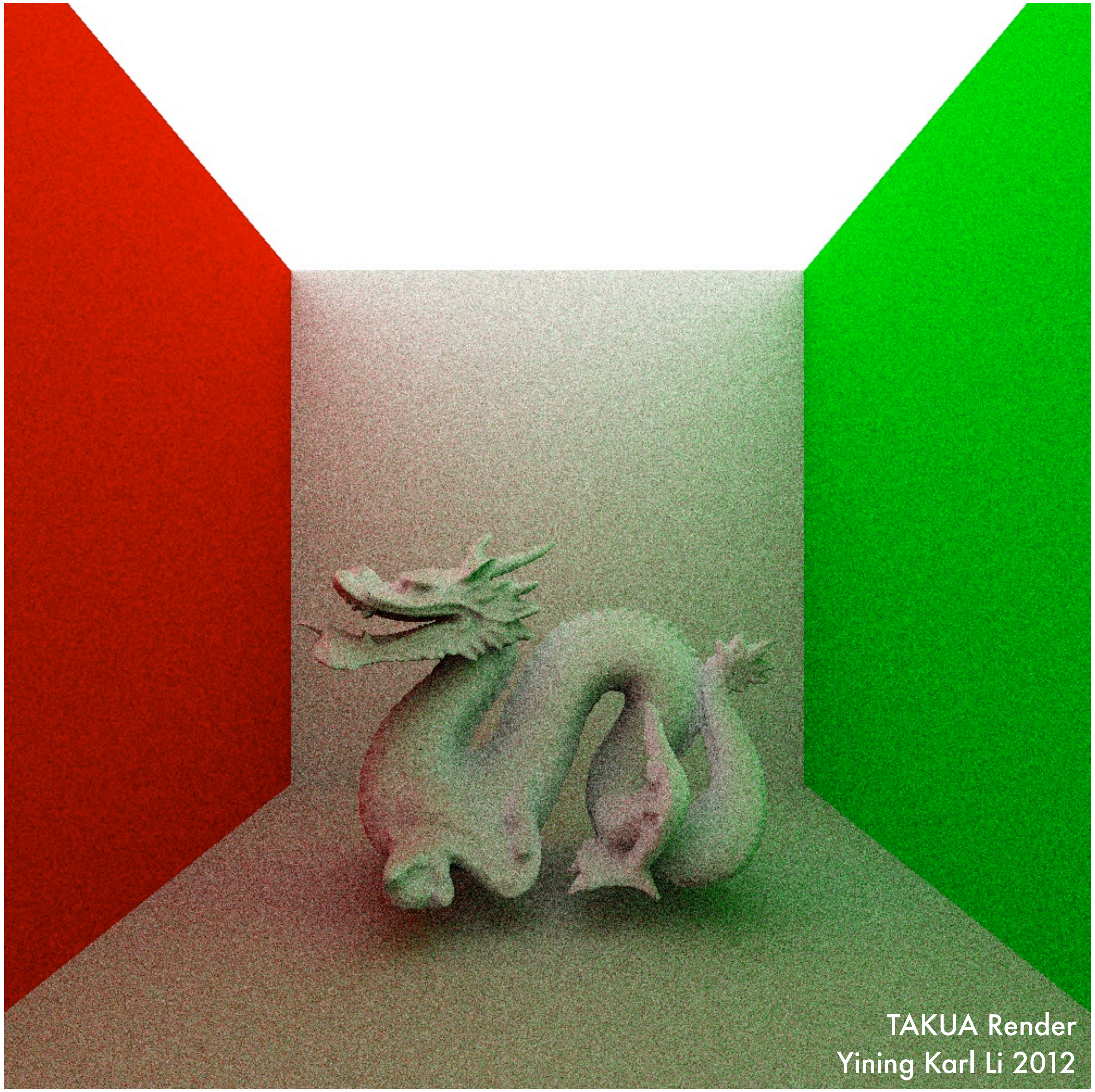
Path-tracing Algorithm

- 1. For each pixel, shoot a ray into the scene
- 2. For each ray, trace until the ray hits a surface. Upon hitting a surface, sample the emittance and BRDF for the surface and then send the ray in a new random direction
- 3. Continue bouncing each ray around until a recursion depth is reached
- 4. Repeat steps 1-3 over and over and continuously accumulate the result until a final image begins to converge



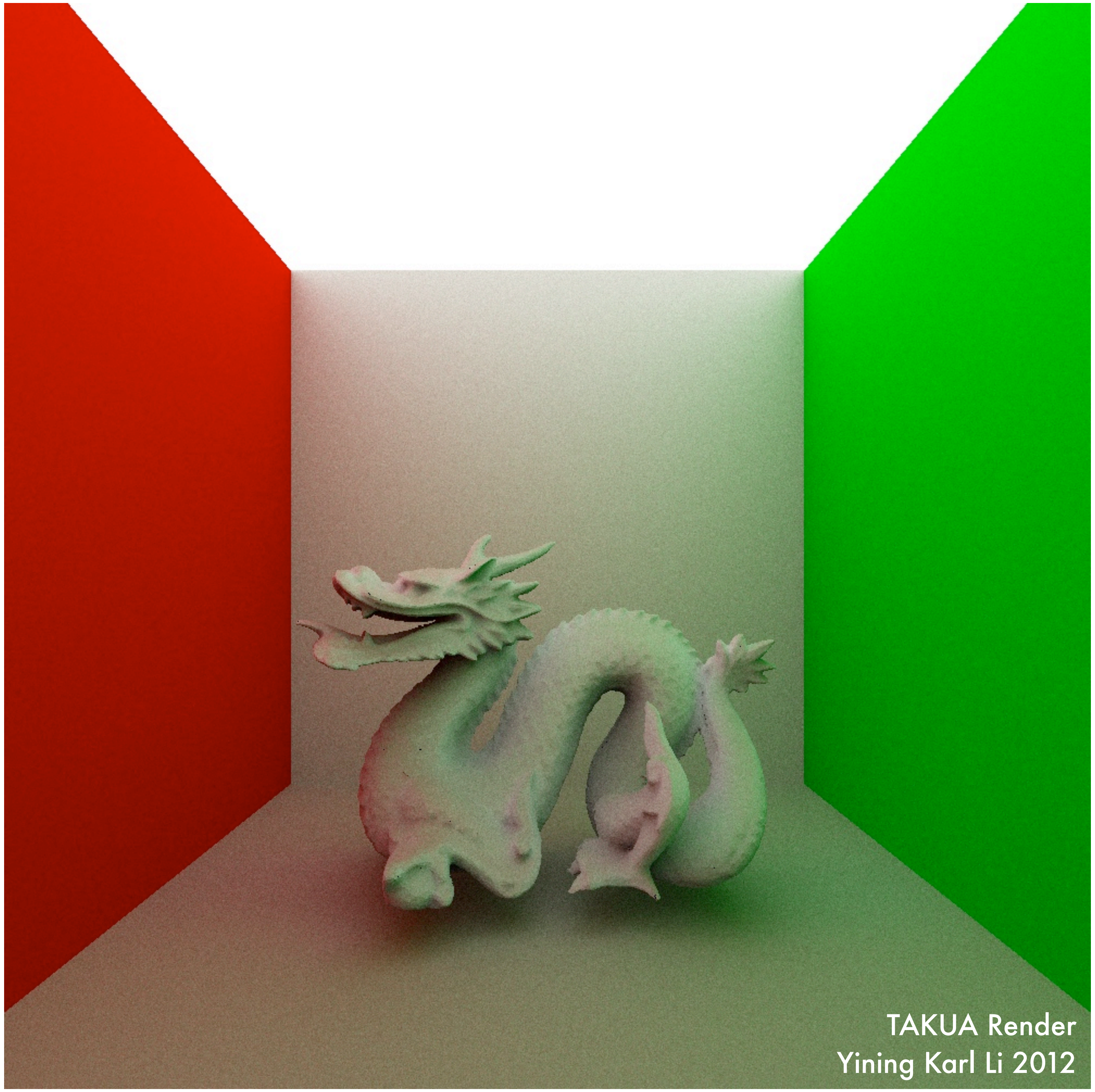
1 Iteration

The random "Monte Carlo" method that path tracers use means that they can take some time to converge to a final image



20 Iterations

The random “Monte Carlo” method that path tracers use means that they can take some time to converge to a final image



250 Iterations

The random “Monte Carlo” method that path tracers use means that they can take some time to converge to a final image

Path-tracing: GPU Motivation

- Even with a naive implementation, GPU path tracing can converge fast enough to be interactive! Contrast with CPU implementations, which can take dozens of minutes to hours to converge.

- Even more performance can be extracted through the use of spatial acceleration structures such as stack-less KD-trees or BVH.

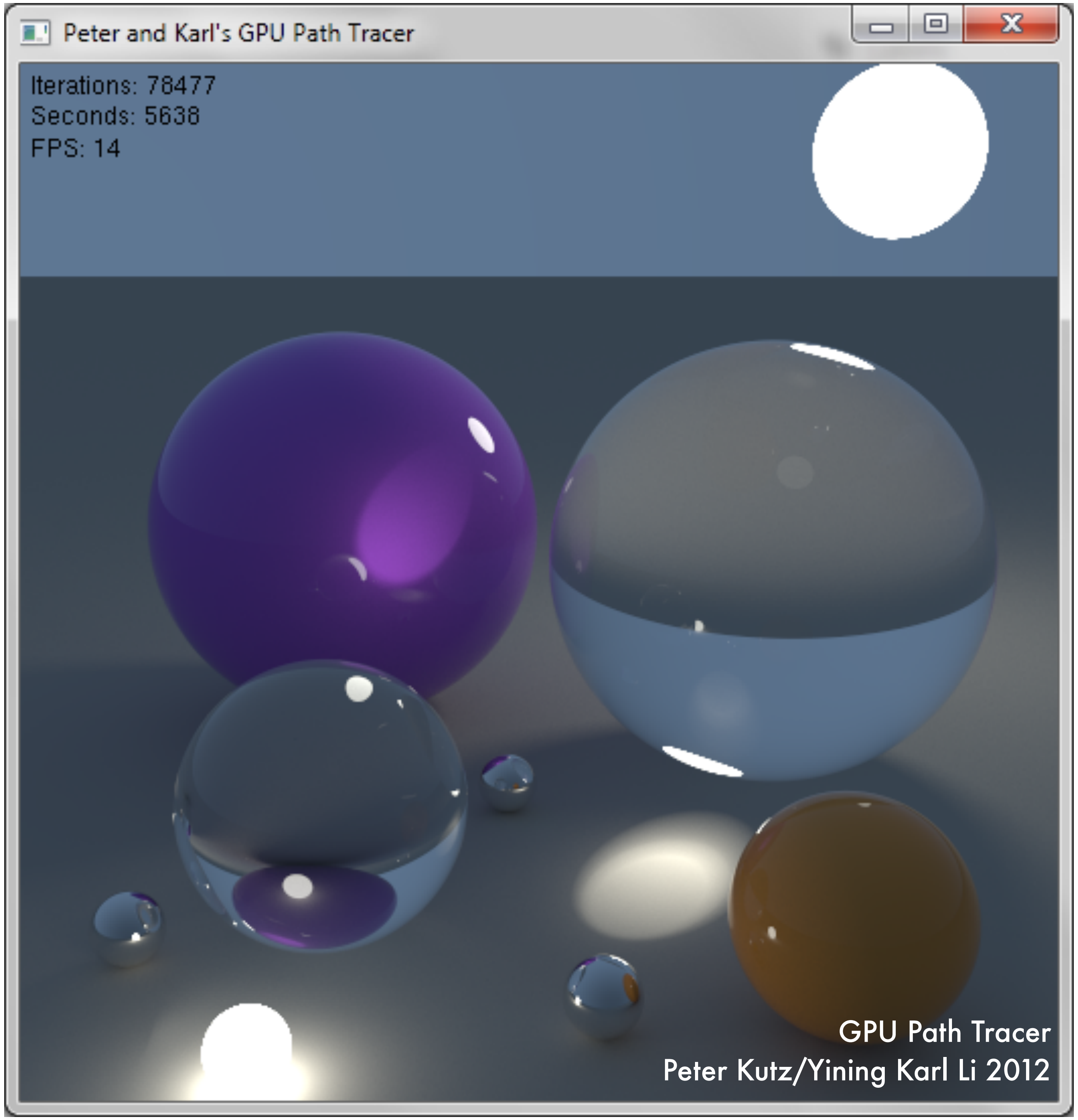
- Single biggest constraint is memory: path tracing requires keeping everything in a scene in memory at once, which is not an issue on the CPU with 16 Gb RAM available, but can become a problem on the GPU with typically <1.5 Gb RAM available

Current Commercial GPU Path-tracers

- Brigade Render by OTOY
- Arion Render by RandomControl
- Octane Render by Refractive Software

CUDA Path-tracing Demos

- Peter and Karl's GPU Path Tracer: https://vimeo.com/41109177
- BRIGADE Renderer: http://www.youtube.com/watch?feature=player_embedded&v=FJLy-ci-RyY



Parallel Ray-tracing: A stepping stone to path-tracing

Basic Ray-tracing Algorithm

- 1. For each pixel, shoot a ray into the scene
- 2. For each ray, trace until the ray hits a surface.
- 3. For each intersection, cast a shadow feeler ray to each light source to see if each light source is visible and shade the current pixel accordingly
- 4. If the surface is diffuse, stop. If the surface is reflective, shoot a new ray reflected across the normal from the incident ray
- 5. Repeat steps 1-4 over and over until a maximum tracing depth has been reached or until the ray hits a light or a diffuse surface

Recursive Ray-tracing

- The most obvious way to implement basic raytracing is through a purely recursive approach:

```
color3 rayTrace(int depth, ray r, vector<geom> objects, vector<lights> light_sources){

   [determine closest intersected object j, intersection normal n, intersection point p]

   color = black

   if(object j is reflective){
      reflected_r = reflect_ray(r, normal, p);
      reflected_color = rayTrace(depth+1, reflected_r, objects, light_sources);
      color = reflected_Color;
   }

   for each light l in light_sources{
      if shadow_ray(p, l)==true{
         light_contribution = calculate_light_contribution(p,l,n,j);
         color += light_contribution;
      }
   }

   return color;
}
```

Parallelizing Ray-tracing

- Ray-tracing is an embarrassingly parallel problem!
  - Tracing each pixel in the image is computationally independent from all other pixels
  - Tracing a single pixel is not a terribly computationally intense task, there's simply a lot of tracing that needs to happen
- Solution: parallelize along pixels!
  - Launch one thread per pixel, trace hundreds to thousands of pixels in mass parallel!

Parallelizing Ray-tracing

Wait, we have a problem...

CUDA does not support recursion!*

*Except on Fermi and newer

Iterative Ray-tracing

- Iterative ray-tracing: a slightly less intuitive ray-tracing algorithm that does not need recursion!
- Analogy: think breadth first search versus depth first search
- Recursive model:

Trace all ray bounces in first ray path

Iterative Ray-tracing

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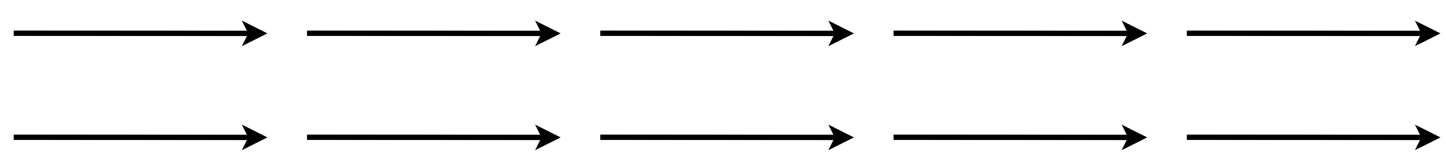

Trace all ray bounces in second ray path

Iterative Ray-tracing

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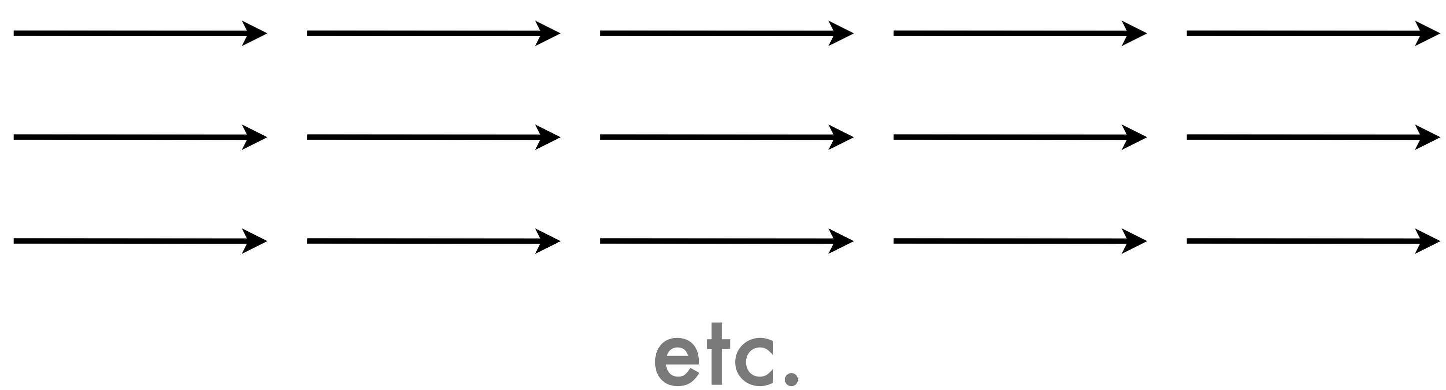
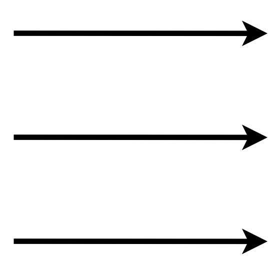
- Analogy: think breadth first search versus depth first search
- Recursive model:



Trace all ray bounces in third ray path

Iterative Ray-tracing

- Iterative ray-tracing: a slightly less intuitive ray-tracing algorithm that does not need recursion!
- Analogy: think breadth first search versus depth first search
- Iterative model:



Trace first ray
bounce in all
ray paths

Iterative Ray-tracing

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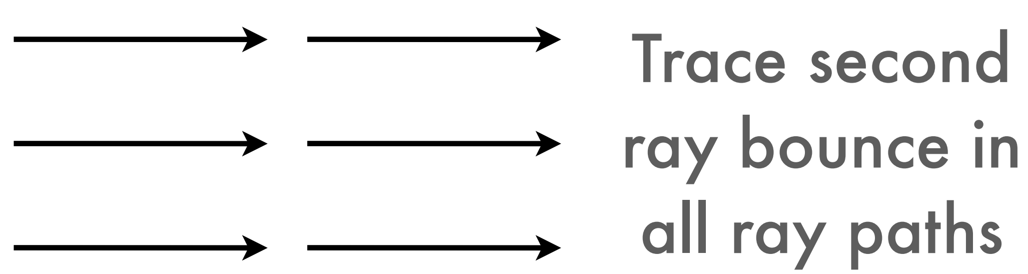

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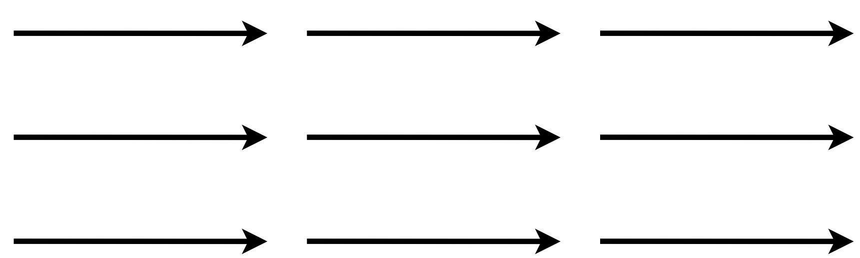


Trace third ray bounce in all ray paths, and so on and so forth

Iterative Ray-tracing

- Implement ray-tracing as a while or for loop and cache the current ray for use in the next iteration of the loop:

```
color3 rayTrace(int depth, ray r, vector<geom> objects, vector<lights> light_sources){
   ray currentRay = r;
   color = black;

   for(int i=0; i<depth; i++){

      [determine closest intersected object j, intersection normal n, intersection point
      p]

      if(object j is reflective){
         reflected_r = reflect_ray(r, normal, p);
      }
      for each light l in light_sources{
         if shadow_ray(p, l)==true{
            color += color * calculate_light_contribution(p,l,n,j);
         }
      }
   }
   return color;
}
```

Parallelizing Ray-tracing

So we can just implement that entire interative ray-tracing algorithm in a CUDA kernal and we're done, right?

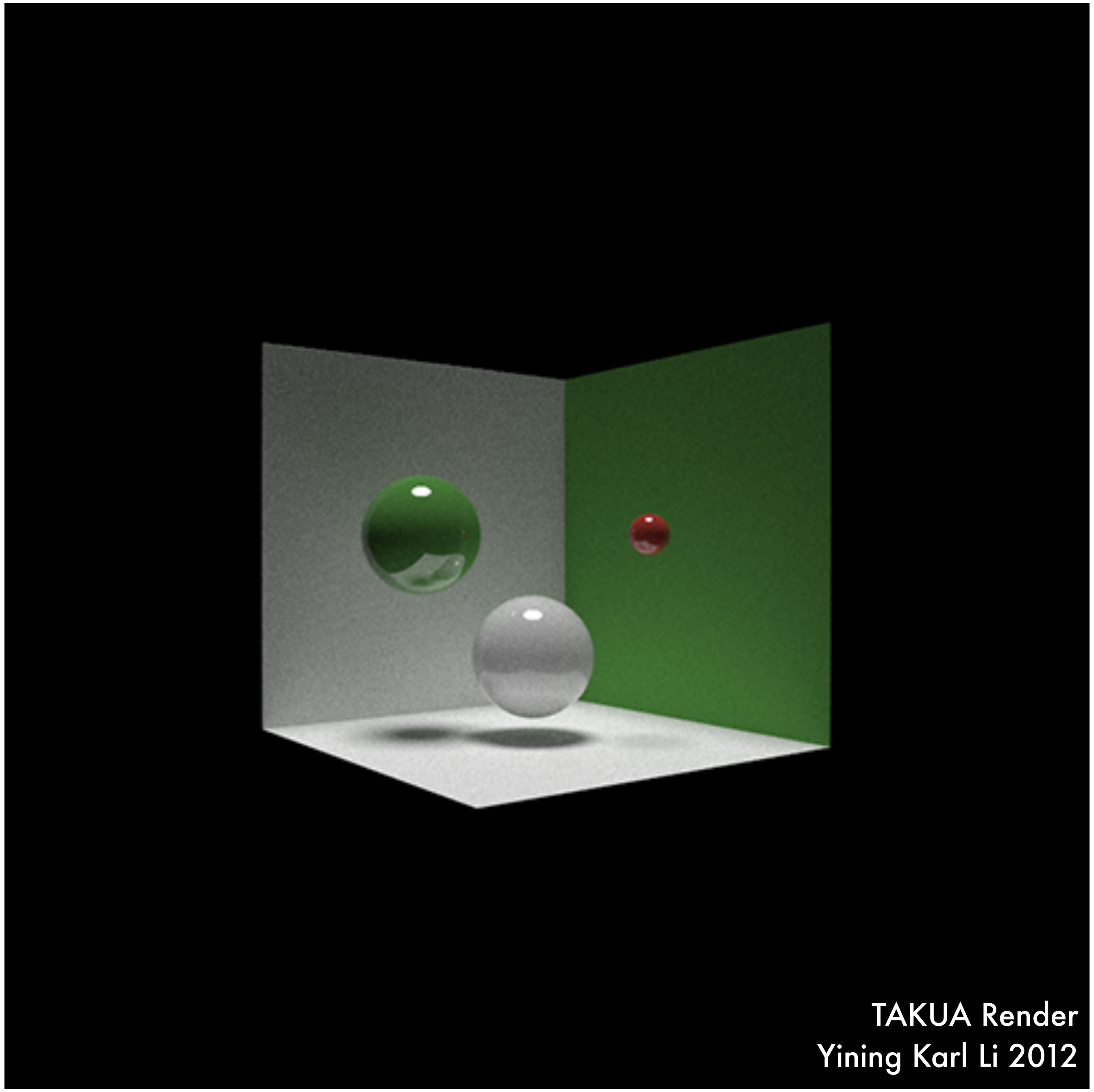
Parallelizing Ray-tracing

So we can just implement that entire interative ray-tracing algorithm in a CUDA kernal and we're done, right?

Well yes, BUT...

Parallel Ray-Tracing Quirks: Wasted Cycles

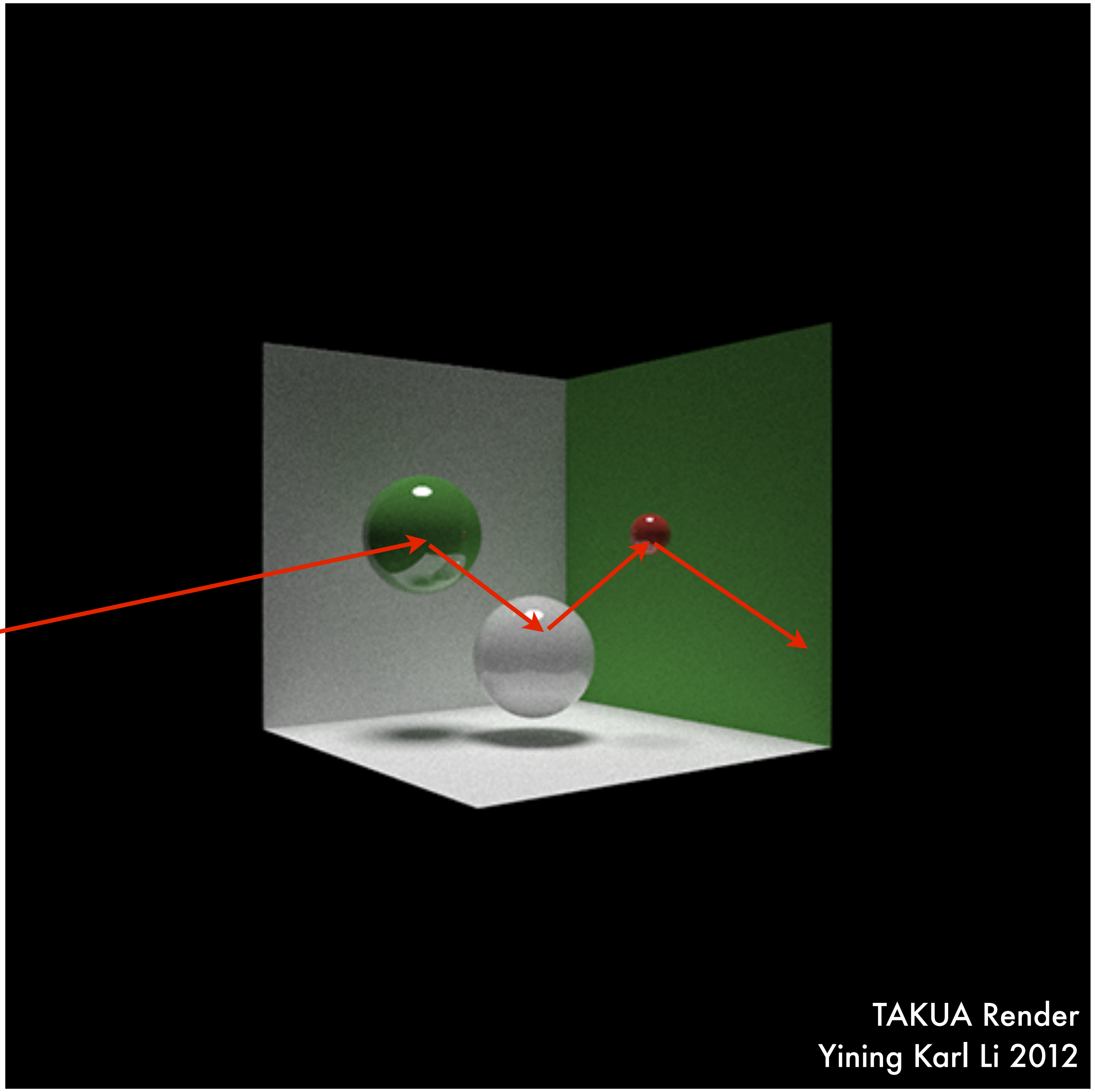
- How many bounces does each ray path make before terminating?



Parallel Ray-Tracing Quirks: Wasted Cycles

- How many bounces does each ray path make before terminating?

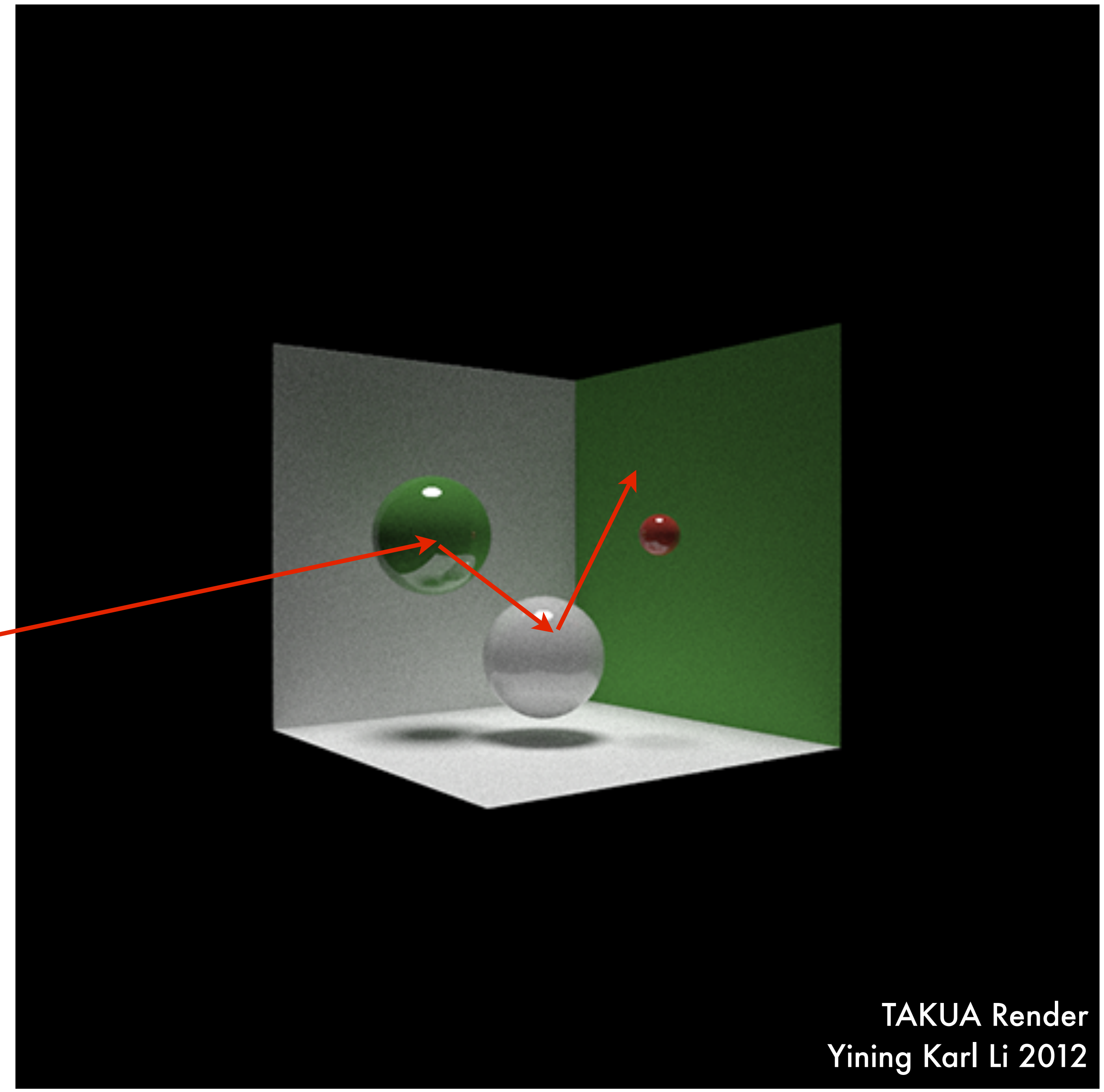
4 bounces?



Parallel Ray-Tracing Quirks: Wasted Cycles

- How many bounces does each ray path make before terminating?

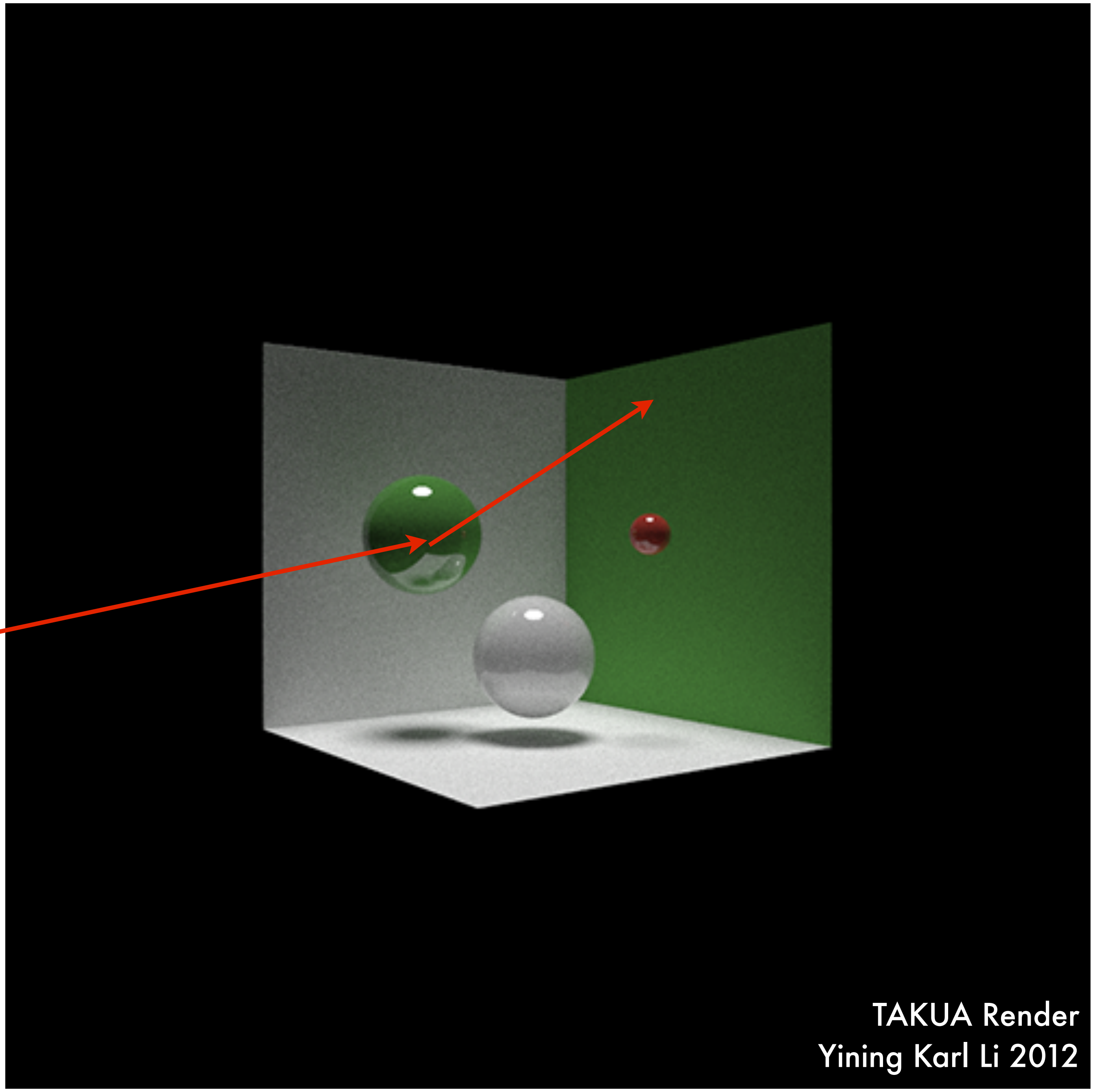
3 bounces?



Parallel Ray-Tracing Quirks: Wasted Cycles

- How many bounces does each ray path make before terminating?

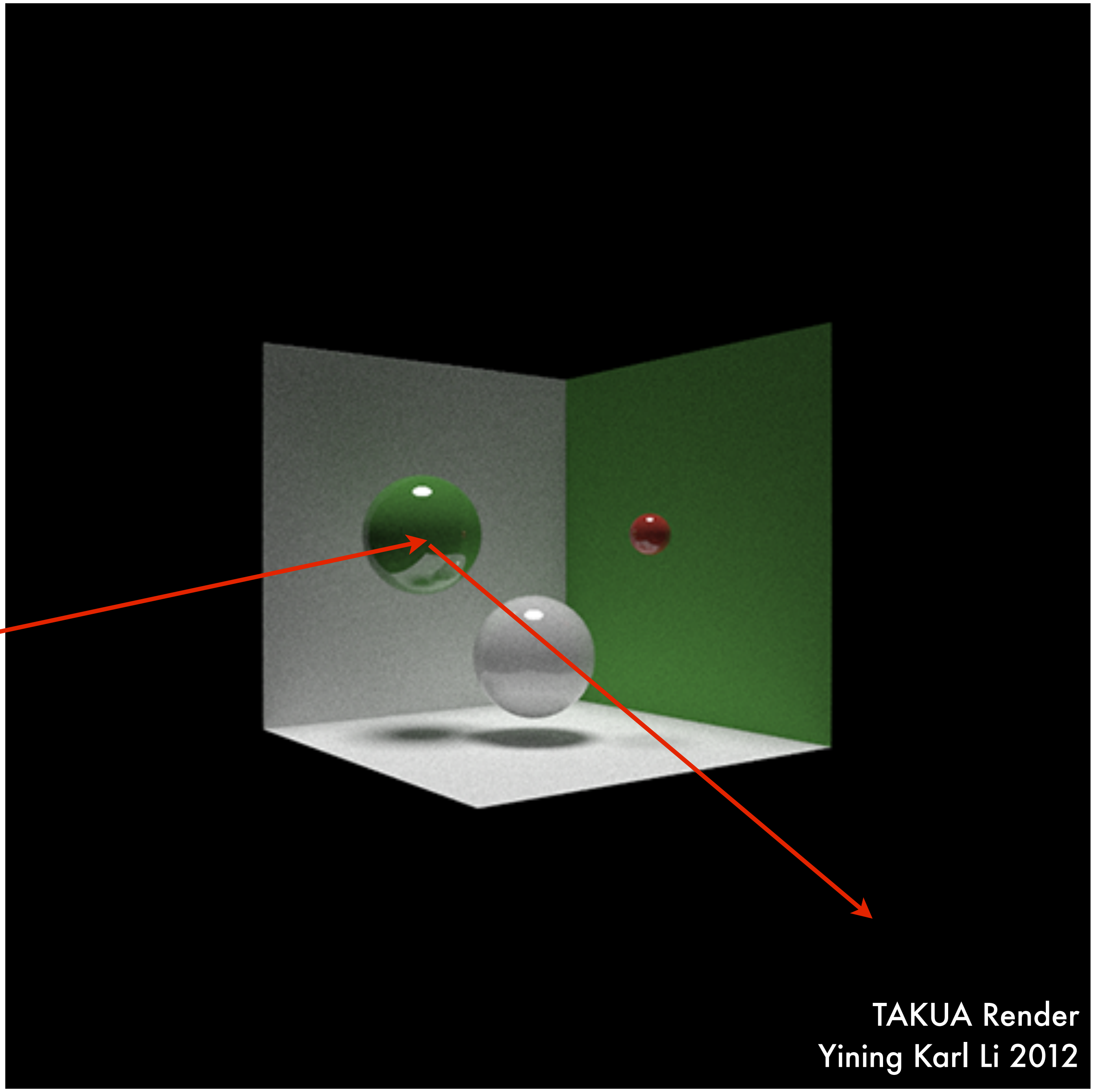
2 bounces?



Parallel Ray-Tracing Quirks: Wasted Cycles

- How many bounces does each ray path make before terminating?

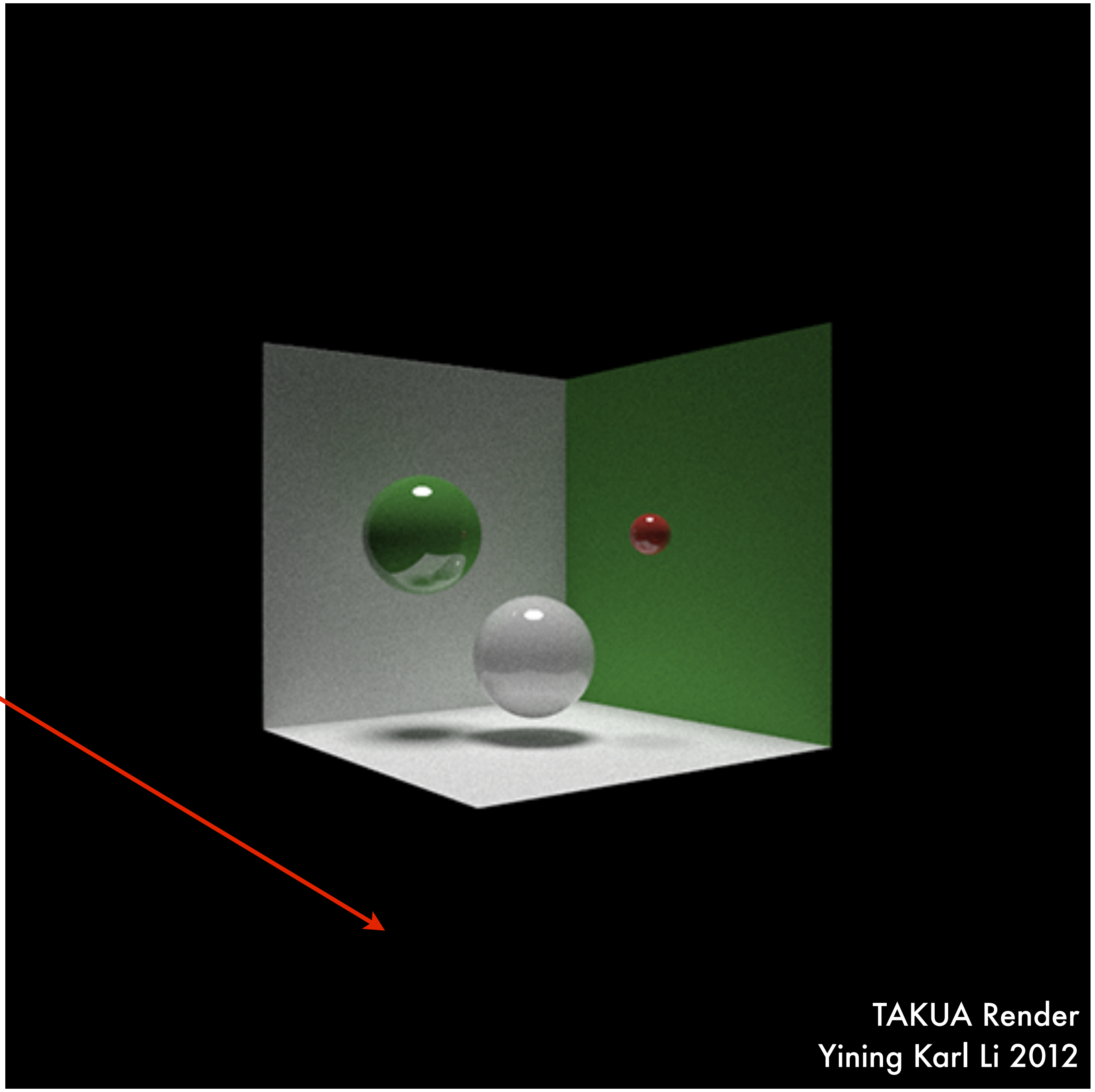
1 bounce?



Parallel Ray-Tracing Quirks: Wasted Cycles

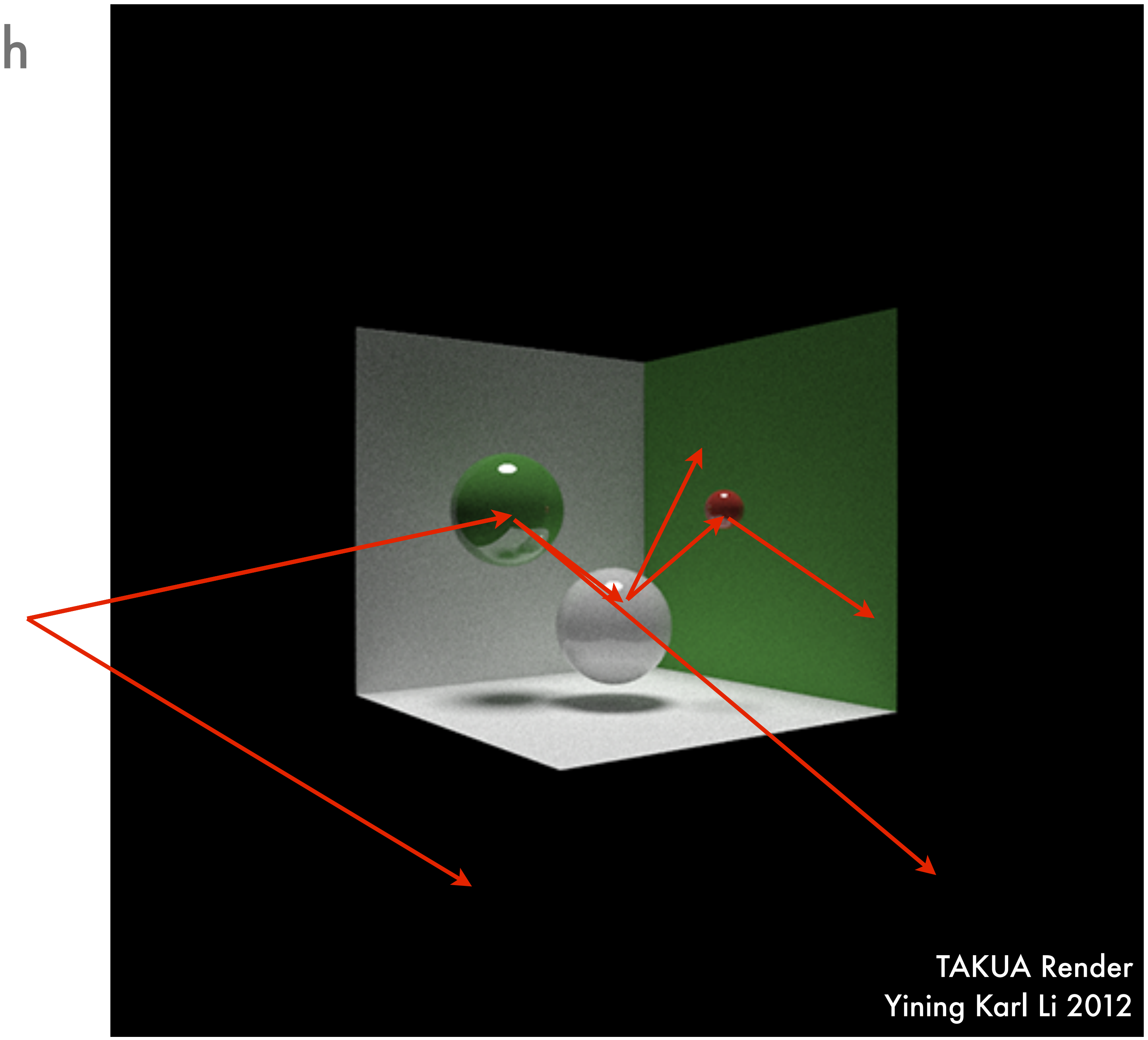
- How many bounces does each ray path make before terminating?

No bounces?



Parallel Ray-Tracing Quirks: Wasted Cycles

- How many bounces does each ray path make before terminating?
- We have no idea how many bounces each ray path may take!
- What does this uncertainty imply about parallelizing by pixels?



Parallel Ray-Tracing Quirks: Wasted Cycles

- Remember, in CUDA, we can only launch a finite number of blocks at a time, and must wait for blocks to complete before launching more.
- If some threads need to trace more bounces than others, then potentially a large number of threads will spend the majority of the time idling.
- Conclusion: parallelizing by pixels is one possible approach, but ultimately a naive one.

Thread 1	Thread 2	Thread 3	Thread 4	Thread 5	Thread 6
Bounce 1	Bounce 1	DONE	Bounce 1	Bounce 1	Bounce 1
Bounce 2	DONE		Bounce 2	DONE	DONE
Bounce 3			DONE		
Bounce 4					
DONE					

WASTED CYCLES

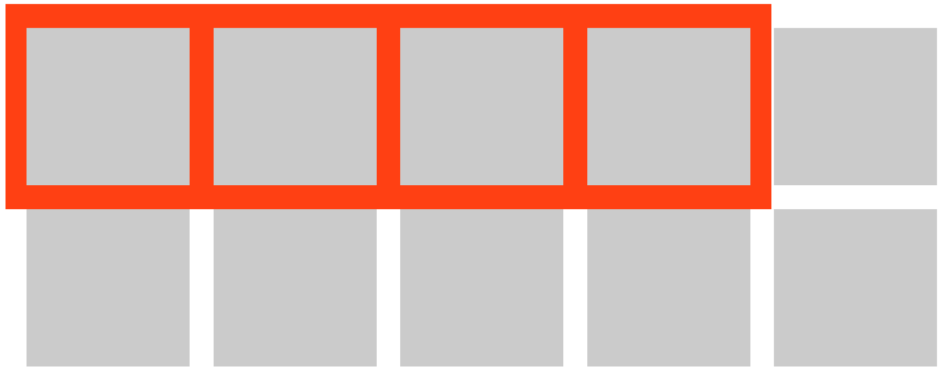
Ray Parallelization

- Solution: parallelize by rays, not pixels!
- Instead of a single kernel launch that traces an entire ray path, do multiple kernel launches that trace individual bounces!
  - 1. Construct pool of rays that need to be intersection tested
  - 2. Construct grid of colors and unaccumulated colors
  - 3. Launch a kernel that traces ONE bounce and records the next ray into the ray pool
  - 4. Remove terminated rays from the ray pool through string compaction type process
  - 5. Repeat

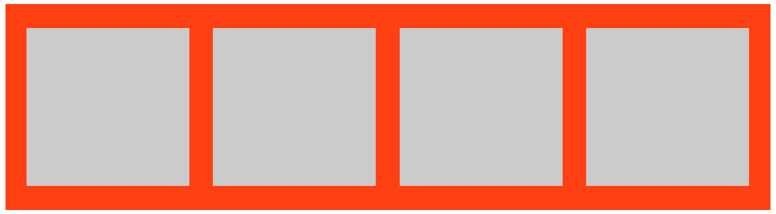
Ray Parallelization

- With each iteration of the ray-trace, we need less threads as rays terminate! As a result, each iteration requires fewer blocks, meaning each iteration executes faster than the previous iteration.

Iteration 1: 10 blocks executing in groups of 4 = 3 batches



Iteration 2: 4 blocks executing in groups of 4 = 1 batch



- Well, there are a few rare edge cases where this approach does not provide a performance boost. Can you think of any?

Ray Parallelization: Super Simple Example

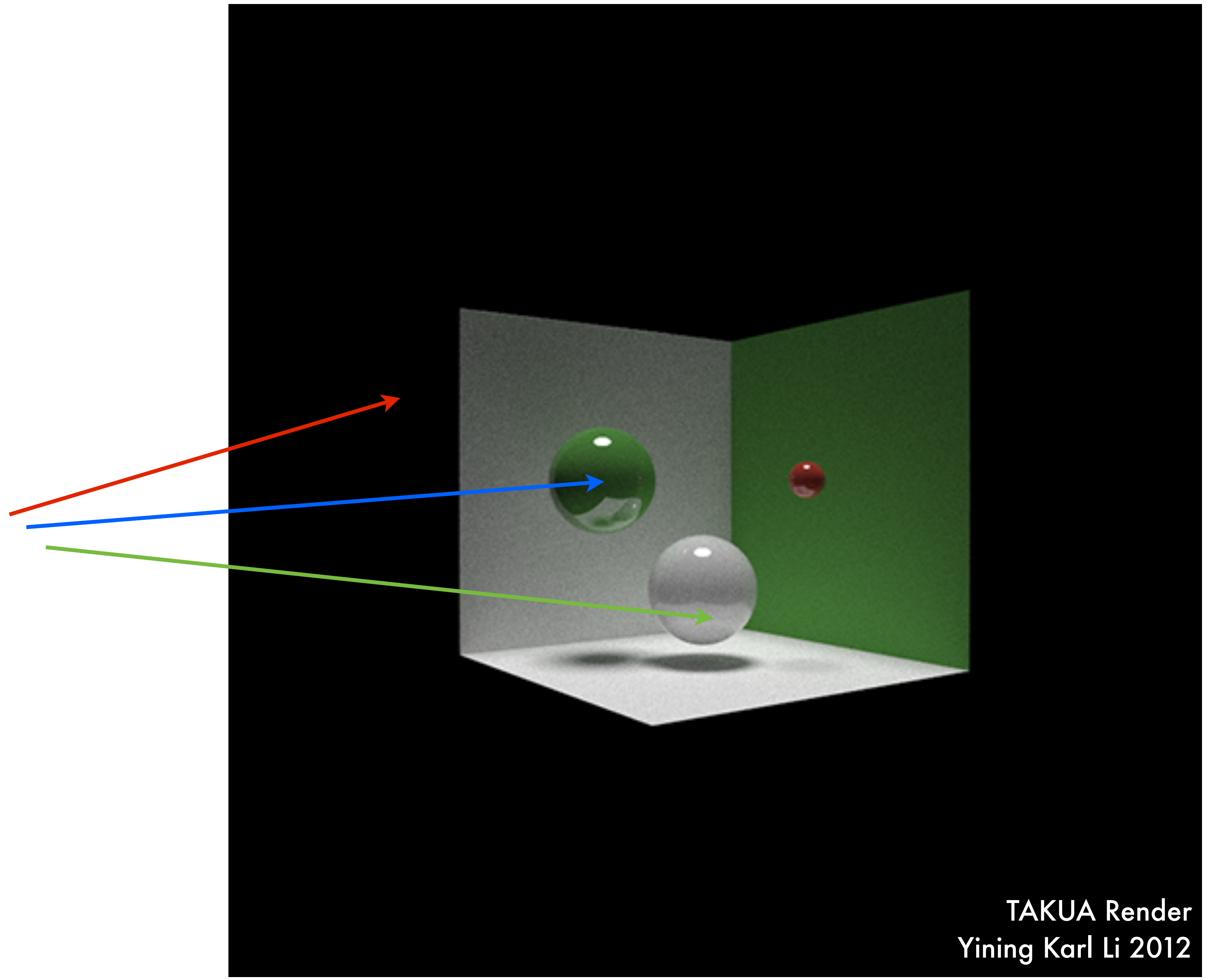
First Kernel Launch

Ray Pool:
Ray 1, Ray 2, Ray 3

Threads Needed:
3

Result:

Terminated Rays:
Ray 1



Ray Parallelization: Super Simple Example

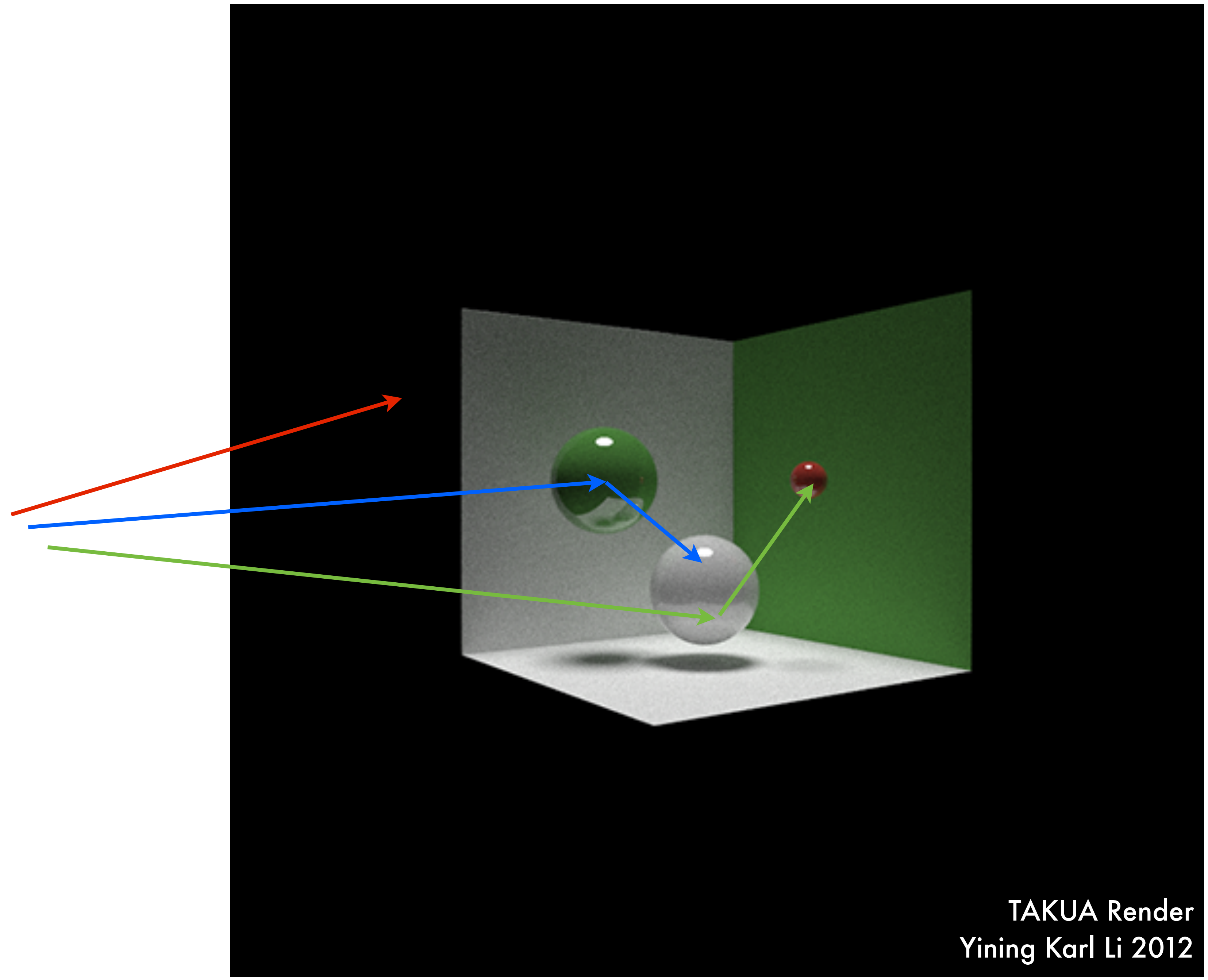
Second Kernel Launch

Ray Pool:
Ray 2, Ray 3

Threads Needed:
2

Result:

Terminated Rays:
Ray 1



Ray Parallelization: Super Simple Example

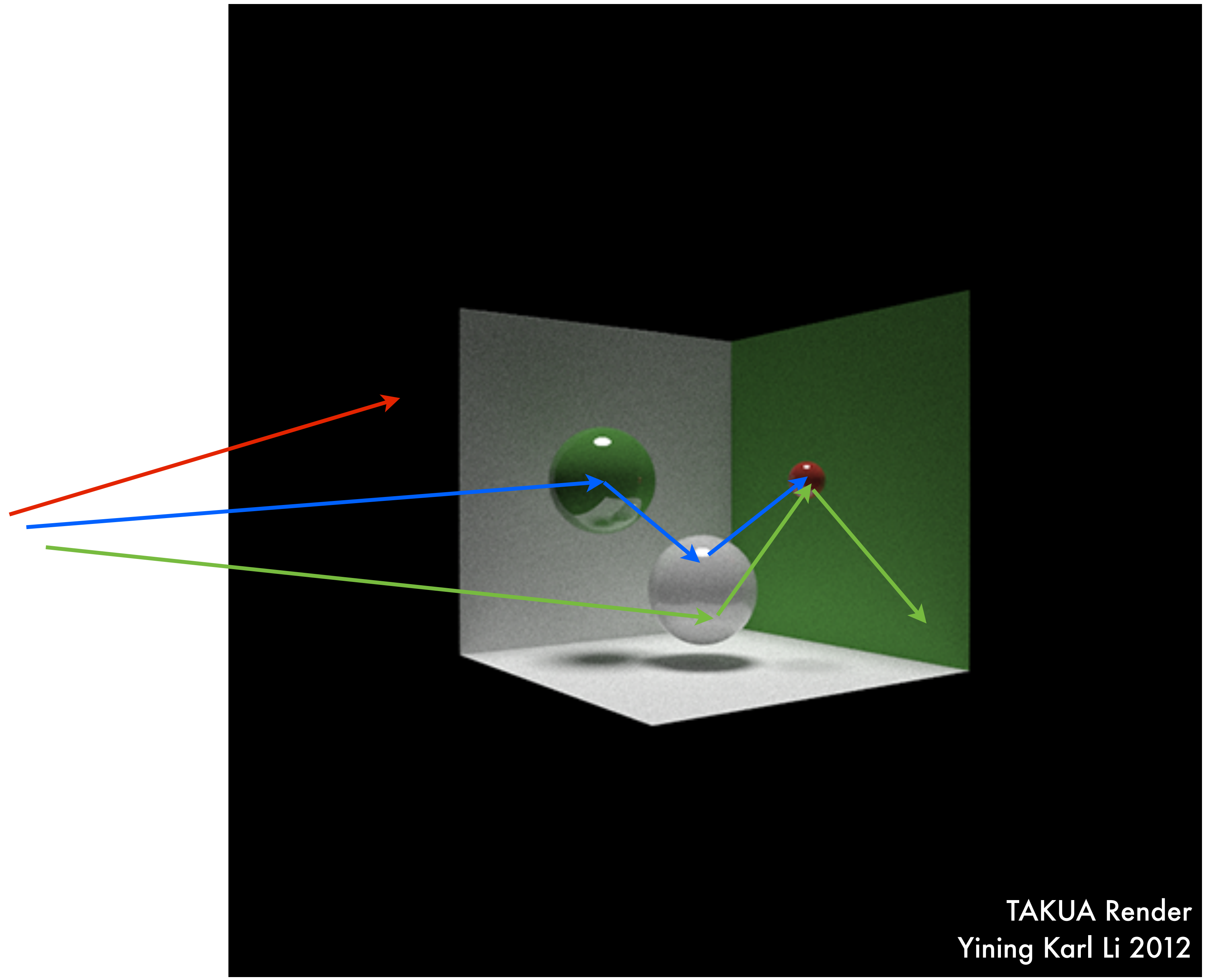
Third Kernel Launch

Ray Pool:
Ray 2, Ray 3

Threads Needed:
2

Result:

Terminated Rays:
Ray 1, Ray 3



Ray Parallelization: Super Simple Example

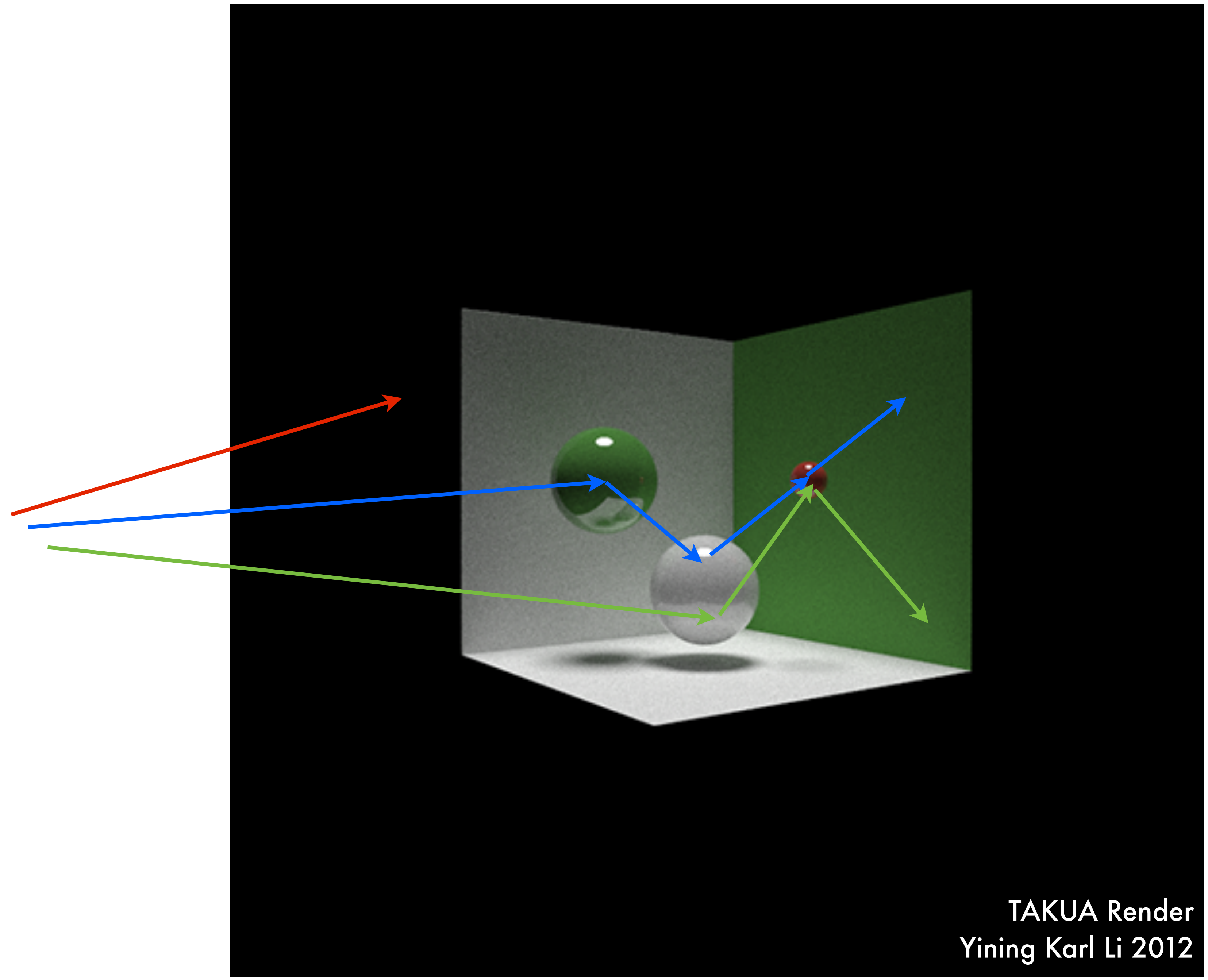
Fourth Kernel Launch

Ray Pool:
Ray 2

Threads Needed:
1

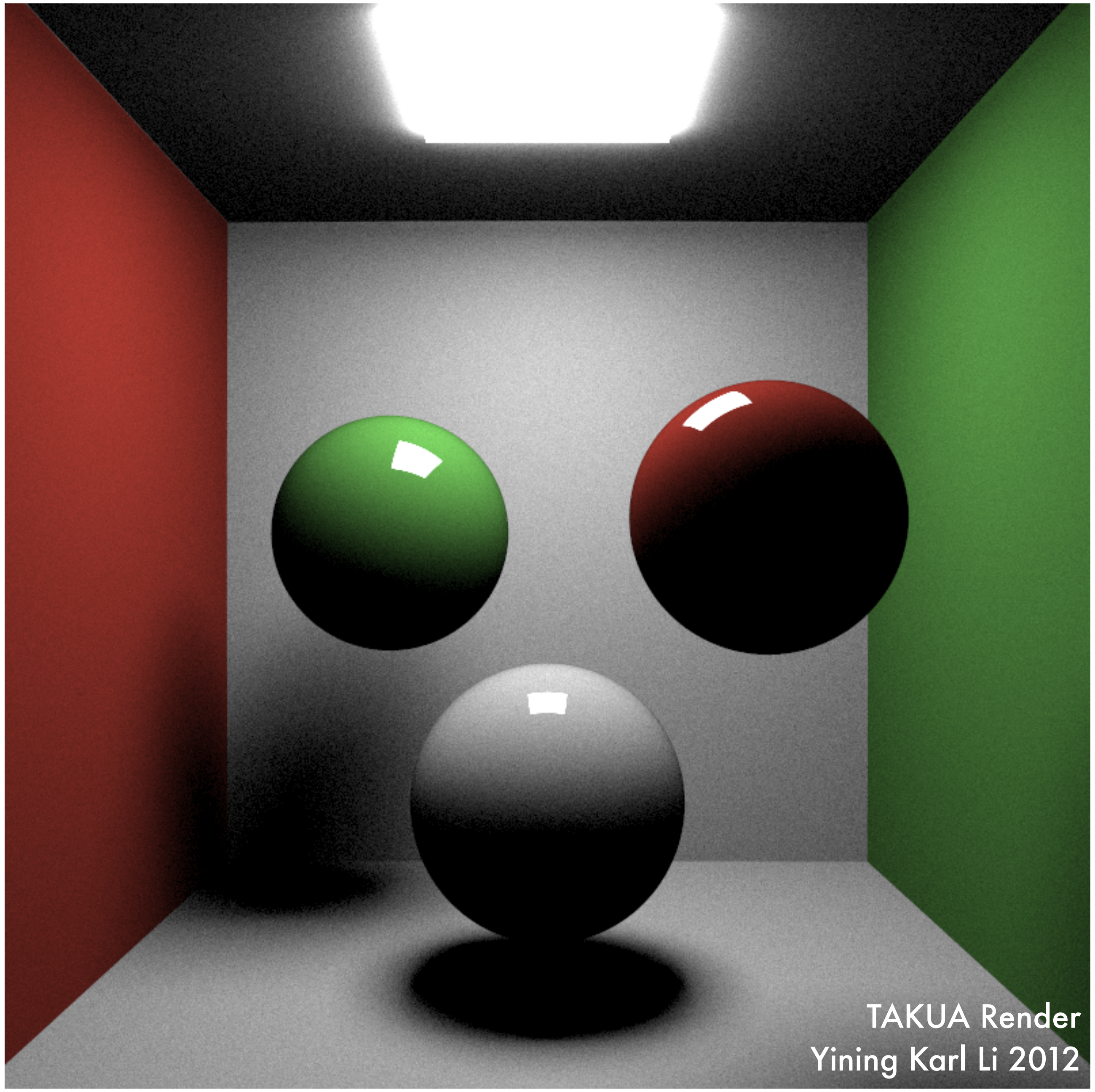
Result:

Terminated Rays:
Ray 1, Ray 3, Ray 2



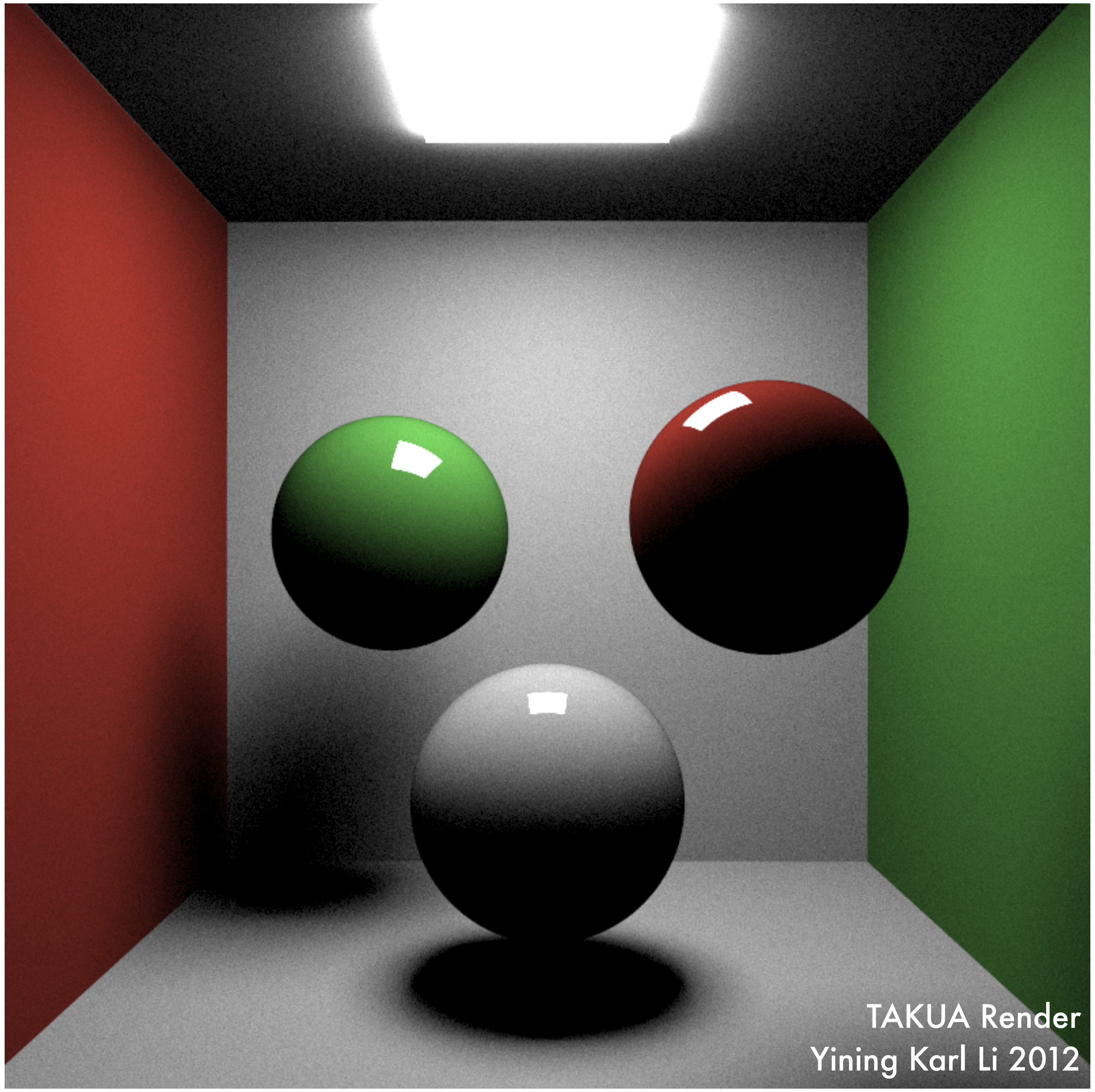
Parallel Ray-Tracing Quirks: Memory Management

- Assume we cudaMemcpy() all of our geometry and materials and other scene assets from host memory to device global memory.
- What happens in this scene on the first bounce?



Parallel Ray-Tracing Quirks: Memory Management

- Assume we cudaMemcpy() all of our geometry and materials and other scene assets from host memory to device global memory.
- What happens in this scene on the first bounce?
  - A lot of rays are hitting the same objects, meaning a lot of threads are concurrently trying to access the same places in global memory!



Parallel Ray-Tracing Quirks: Memory Management

- Possible Solutions:
  - In distributed raytracing scenarios: since the first bounce will always involve the same raycasts from the camera, cache the result of the first bounce and recycle the result .
    - "First bounce cache, second bounce thrash"
  - If the scene is sufficiently small, cache geometry data in shared memory.
    - Why might this be a bad idea in some cases?

References

- Tatarinov, Kharlamov, NVIDIA SIGGRAPH 2009 Alternative Rendering Pipelines Presentation: http://developer.download.nvidia.com/presentations/2009/SIGGRAPH/Alternative_rendering_pipelines.pdf
- [Kajiya86] Kajiya, "The Rendering Equation": http://dl.acm.org/citation.cfm?id=15902
- Sam Lapere's "Ray Tracey's Blog": http://raytracey.blogspot.de/
- [Pharr04] Matt Pharr, Greg Humphreys, "Physically Based Rendering": http://www.pbrt.org/
- Rory Driscoll's "CodeItNow" Blog: http://www.rorydriscoll.com/2008/08/24/lighting-the-rendering-equation/
- Stanford University's CS348B: Image Synthesis course materials: https://graphics.stanford.edu/wikis/cs348b-12