Lecture 14:

Modern Real-Time Rendering Techniques

Computer Graphics: Rendering, Geometry, and Image Manipulation
Stanford CS248A, Winter 2024


Screenshot: Red Dead Redemption

Screenshot: Far Cry 5

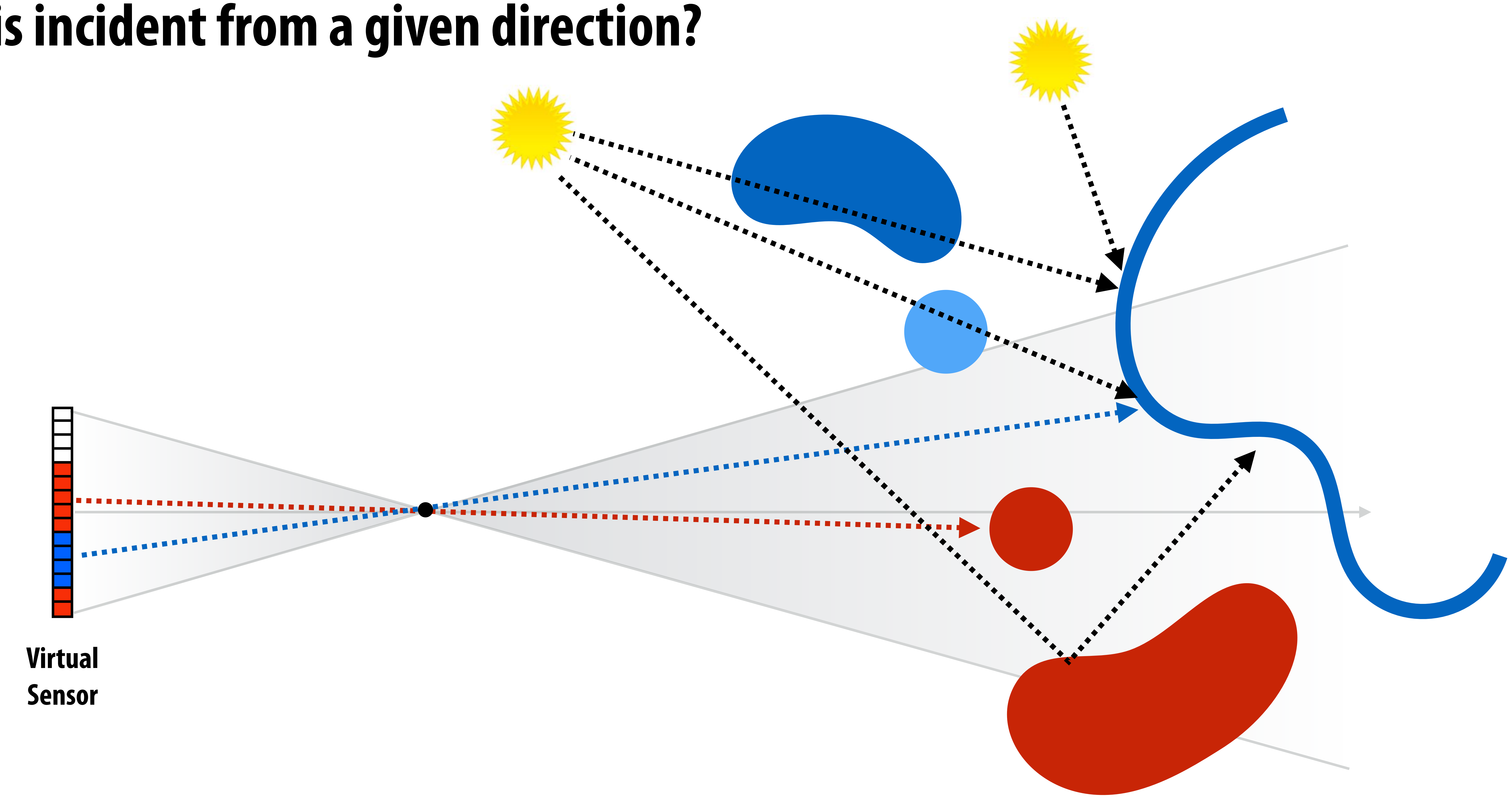
Screenshot: Battlefield V

Last couple of lectures: ray-scene queries

What object is visible to the camera?

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

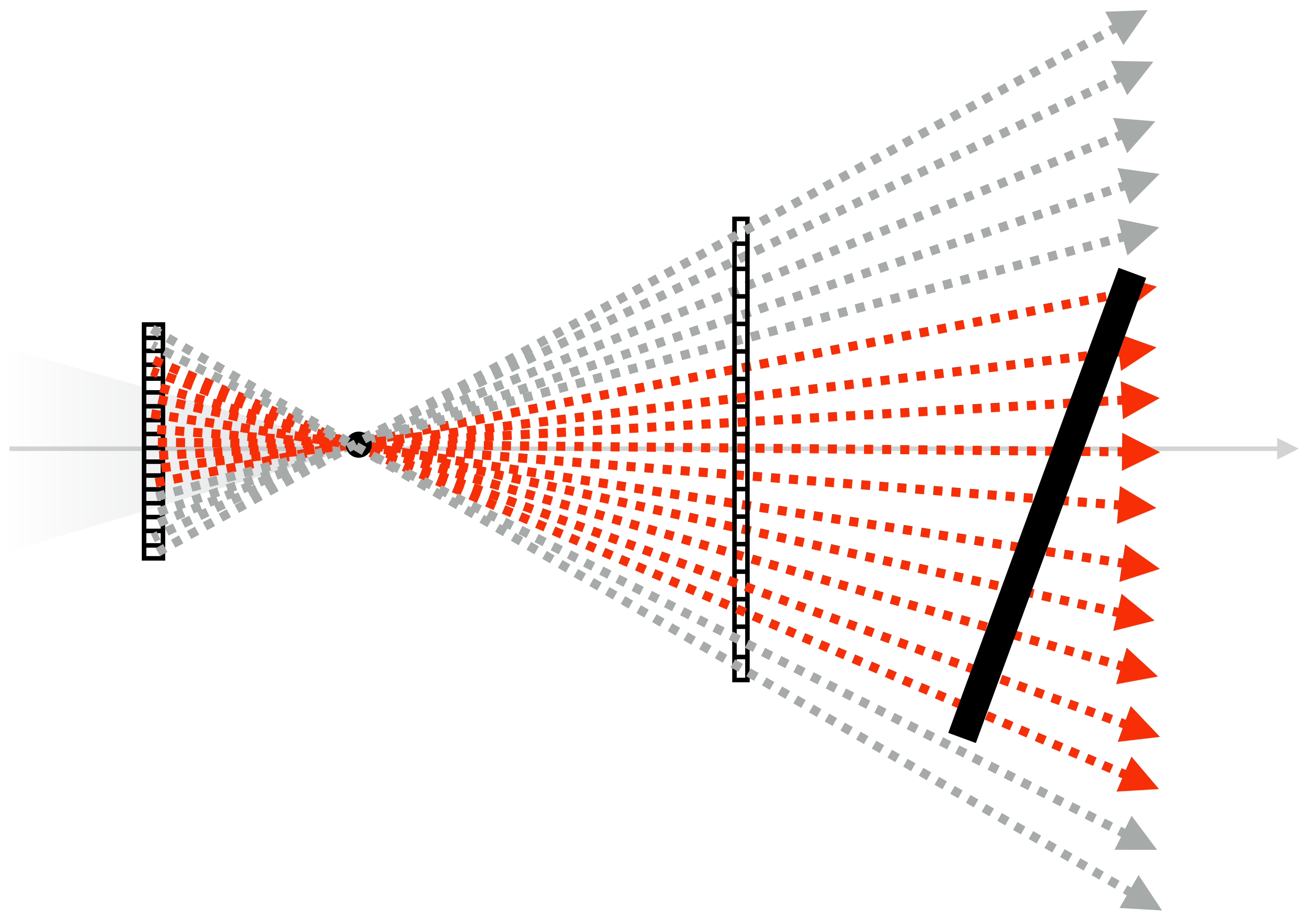
How much radiance is incident from a given direction?

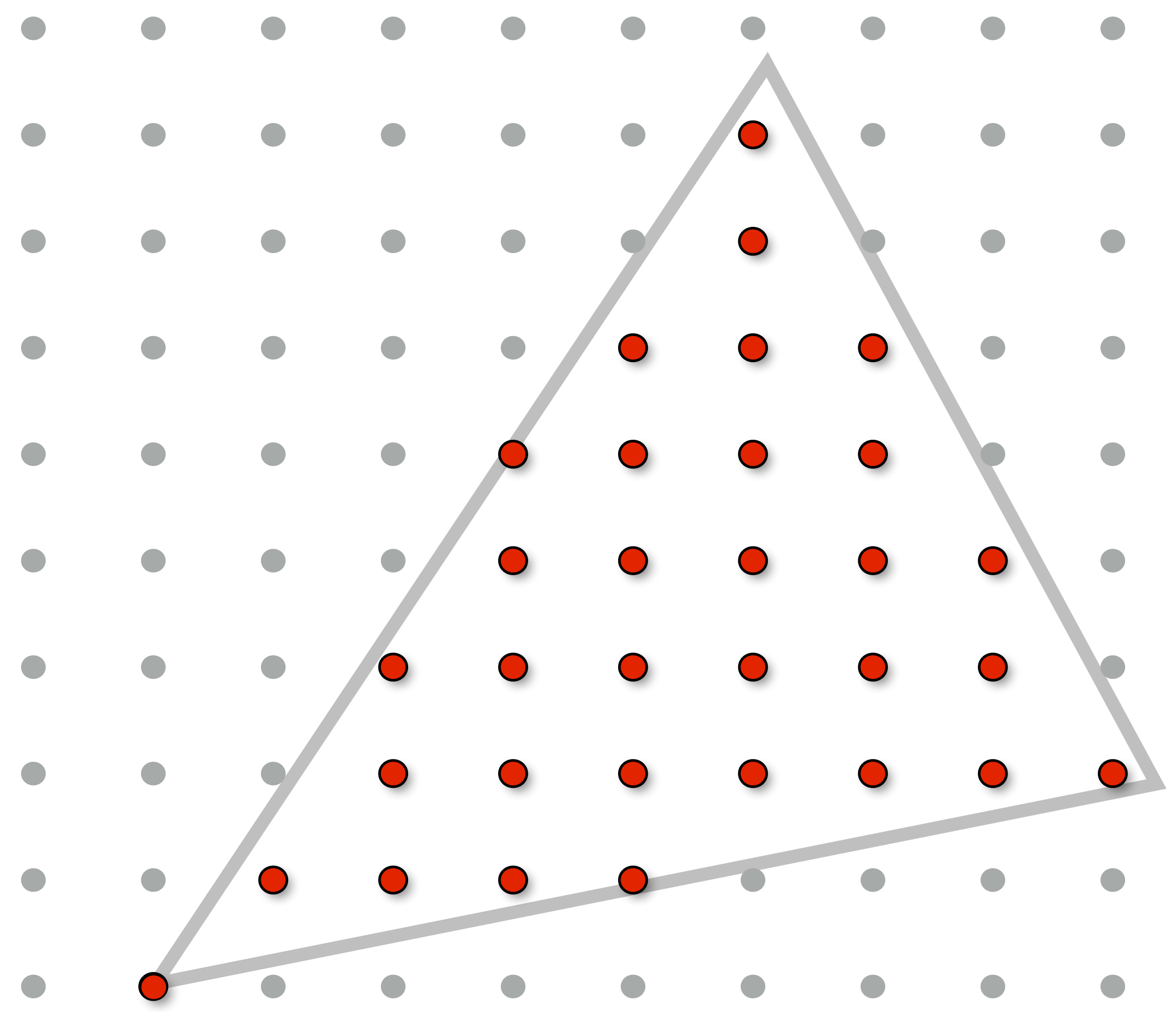


Rasterization: algorithm for “camera ray”- scene queries

- Rasterization is a efficient implementation of ray casting where:
  - Ray-scene intersection is computed for a batch of rays
  - All rays in the batch originate from same origin
  - Rays are distributed uniformly in plane of projection

  Note: rasterization does not yield uniform distribution in angle… angle between rays is smaller away from view direction than it is in the center of the view because equal steps in Y are not equal steps in angle.





Review: basic rasterization algorithm

Sample = 2D point

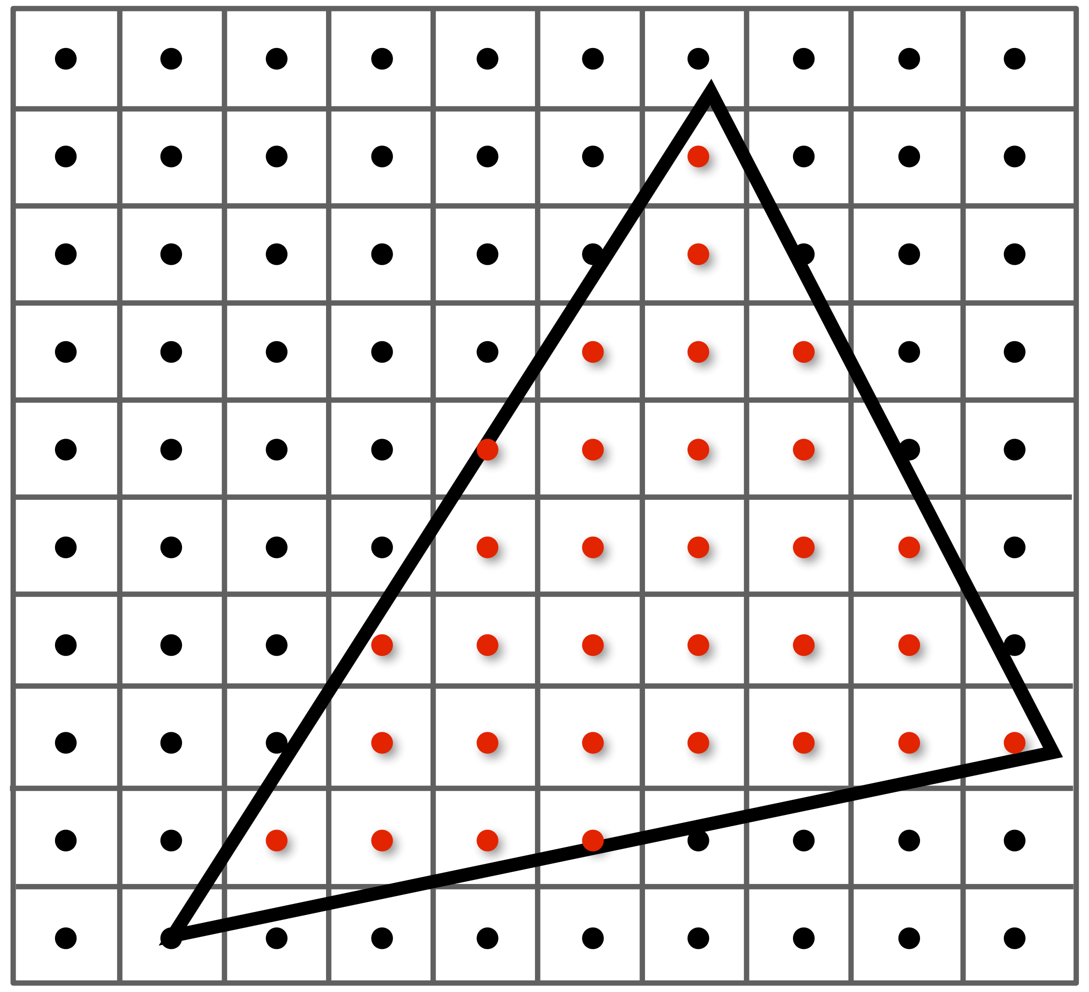
Coverage: 2D triangle/sample tests (does projected triangle cover 2D sample point)

Occlusion: depth buffer

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

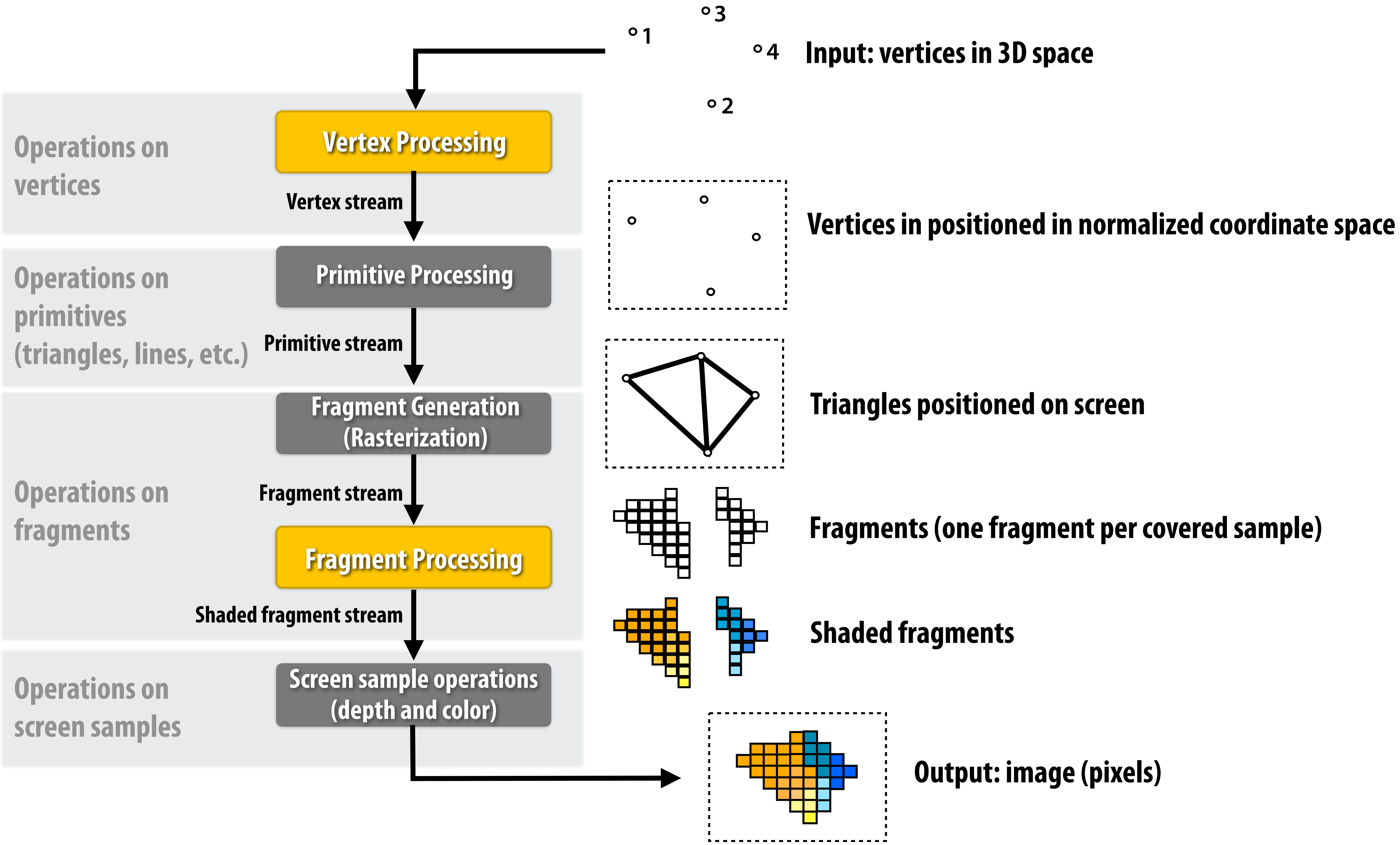
"Given a triangle, find the samples it covers"

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



Review: OpenGL/Direct3D graphics pipeline

* Several stages of the modern OpenGL pipeline are omitted



Review: basic ray casting algorithm

Sample = a ray in 3D

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

Occlusion: closest intersection along ray

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

And as you know now, a performant raytracer will use an acceleration structure like a BVH.

Compared to rasterization approach: just a reordering of the loops!

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

Theme of this part of the lecture

A surprising number of advanced lighting effects can be *approximated* using the basic primitives of the rasterization pipeline, without the need to actually ray trace the scene geometry. We are going to approximate the use of ray tracing with:

- **Rasterization**
- **Texture mapping**
- **Depth buffer for occlusion**

These techniques have been the basis of high quality real-time rendering for decades.

Since ray tracing performance is not fast enough to be used in real-time applications.

Although this is changing…

Shadows

How much light is REFLECTED from p toward p_0

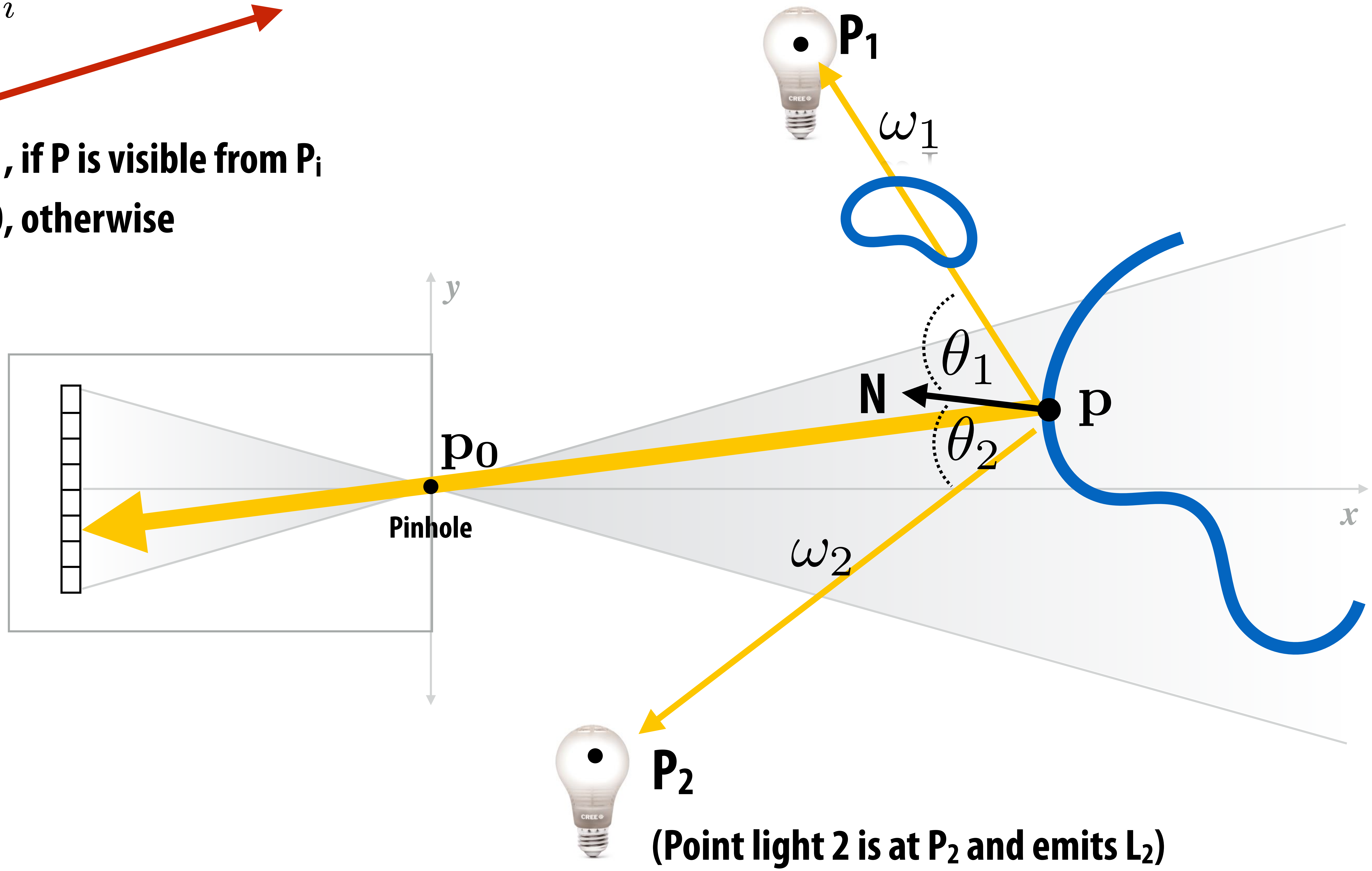
$$L(\mathbf{p}, \omega_o) = \sum_i f(\mathbf{p}, \omega_i, \omega_o) V(\mathbf{p}, \mathbf{p_i})\, L_i \,\cos\theta_i$$

Visibility term:

$V(\mathbf{p}, \mathbf{p_i})$ 1, if P is visible from P_i

0, otherwise

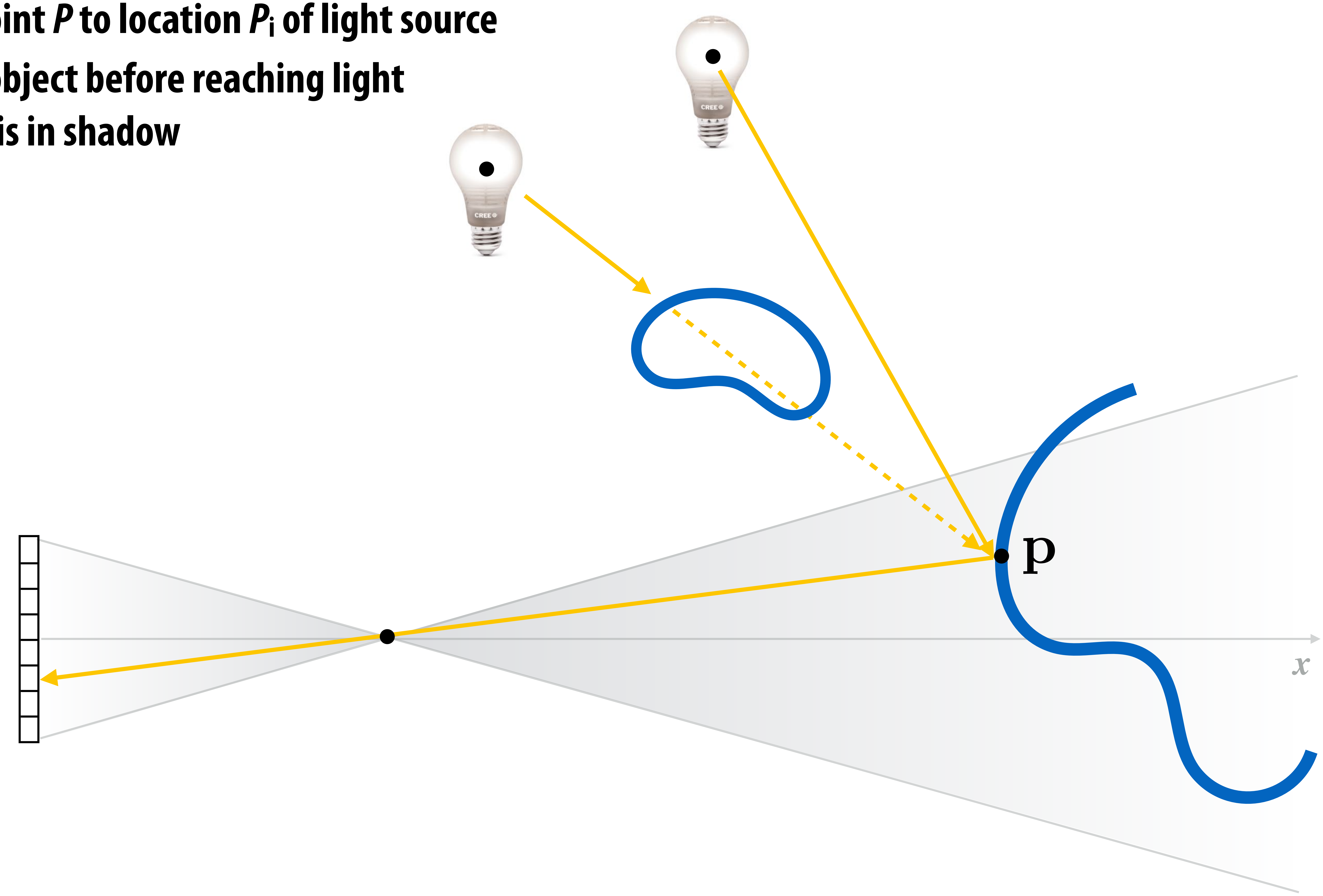
(Point light 1 is at P_1 and emits L_1)



(Point light 2 is at P_2 and emits L_2)

Review: How to compute $V(\mathrm{p}, \mathrm{p_i})$ using ray tracing

- Trace ray from point *P* to location P_i of light source
- If ray hits scene object before reaching light source… then *P* is in shadow



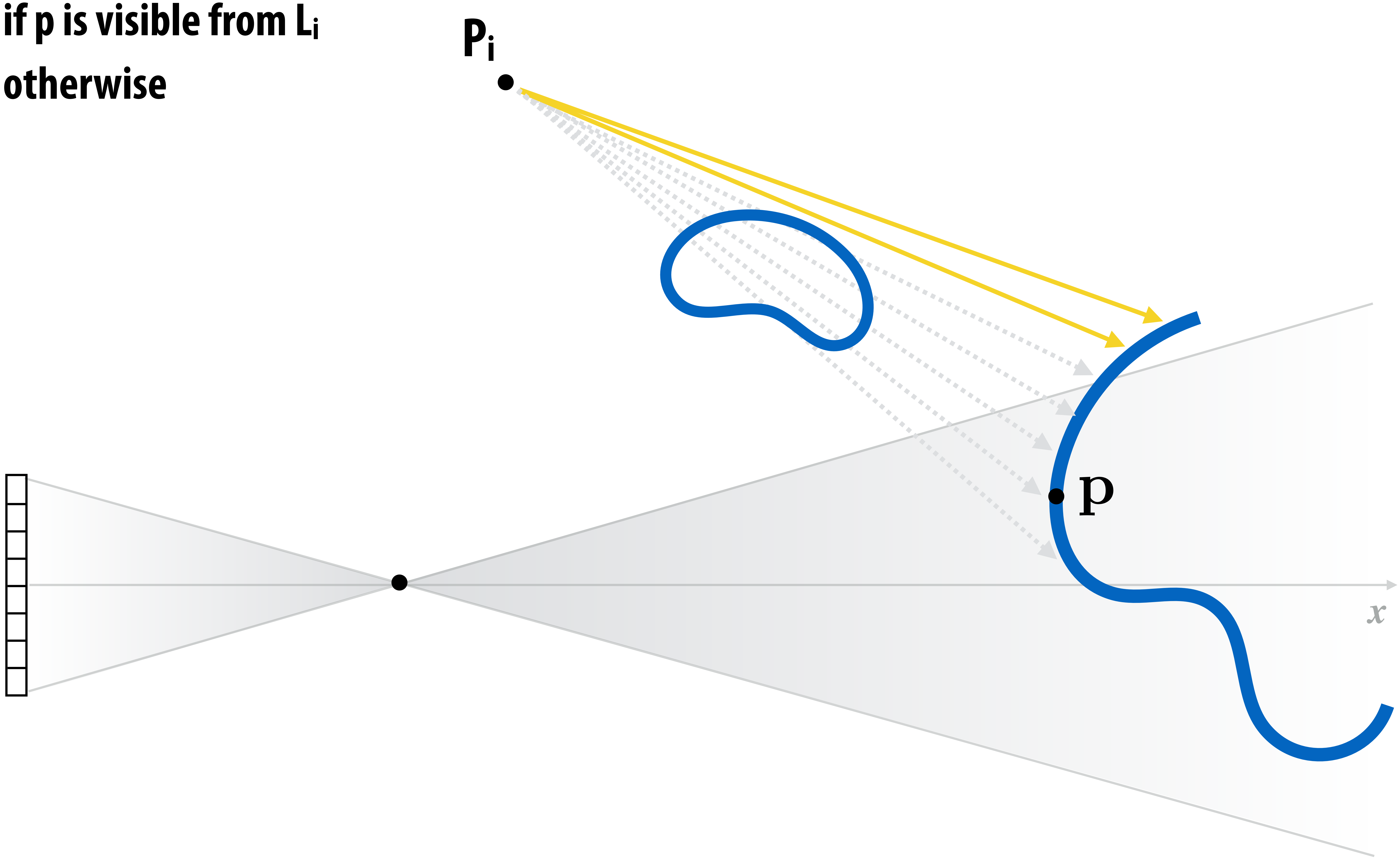
Convince yourself this algorithm produces "hard shadows" like these (what you'd see on a sunny day)

Image credit: Grand Theft Auto V

Or this…

Point lights generate "hard shadows"
(Either a point is in shadow or it's not)

$$V(\mathbf{p}, \mathbf{p_i}) = \begin{cases} 1, \text{ if p is visible from } L_i \\ 0, \text{ otherwise} \end{cases}$$

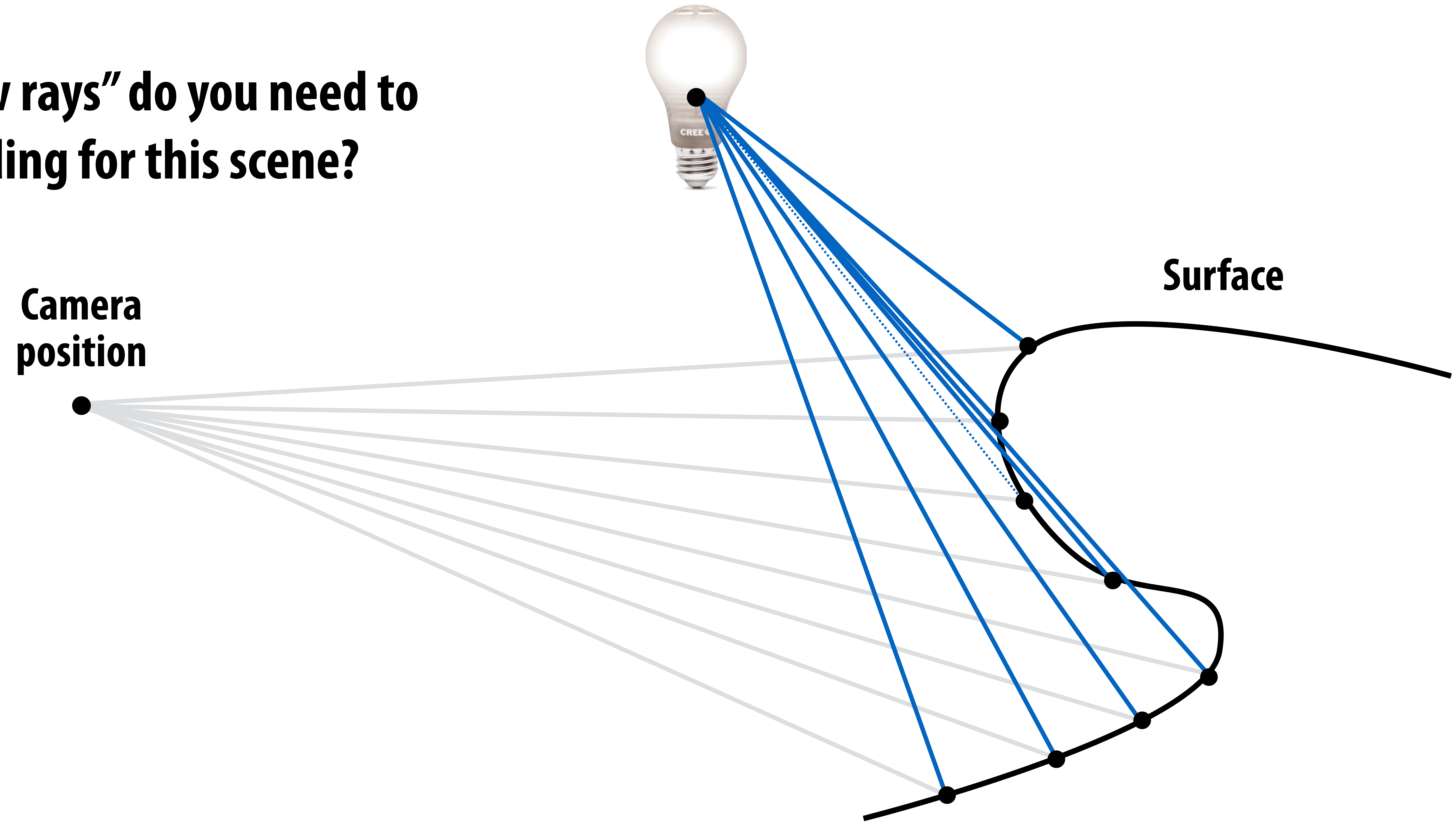


What if you didn't have a ray tracer, just a rasterizer?

We want to shade these points

(aka "fragments" in rasterization pipeline)

What "shadow rays" do you need to compute shading for this scene?



Shadow mapping

[Williams 78]

1. *Place camera at position of the scene's point light source*
2. Render scene to compute depth of closest object to light along a uniformly spaced set of "shadow rays" (note: answer is stored in depth buffer after rendering)
3. Store precomputed shadow ray intersection results in a texture map

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

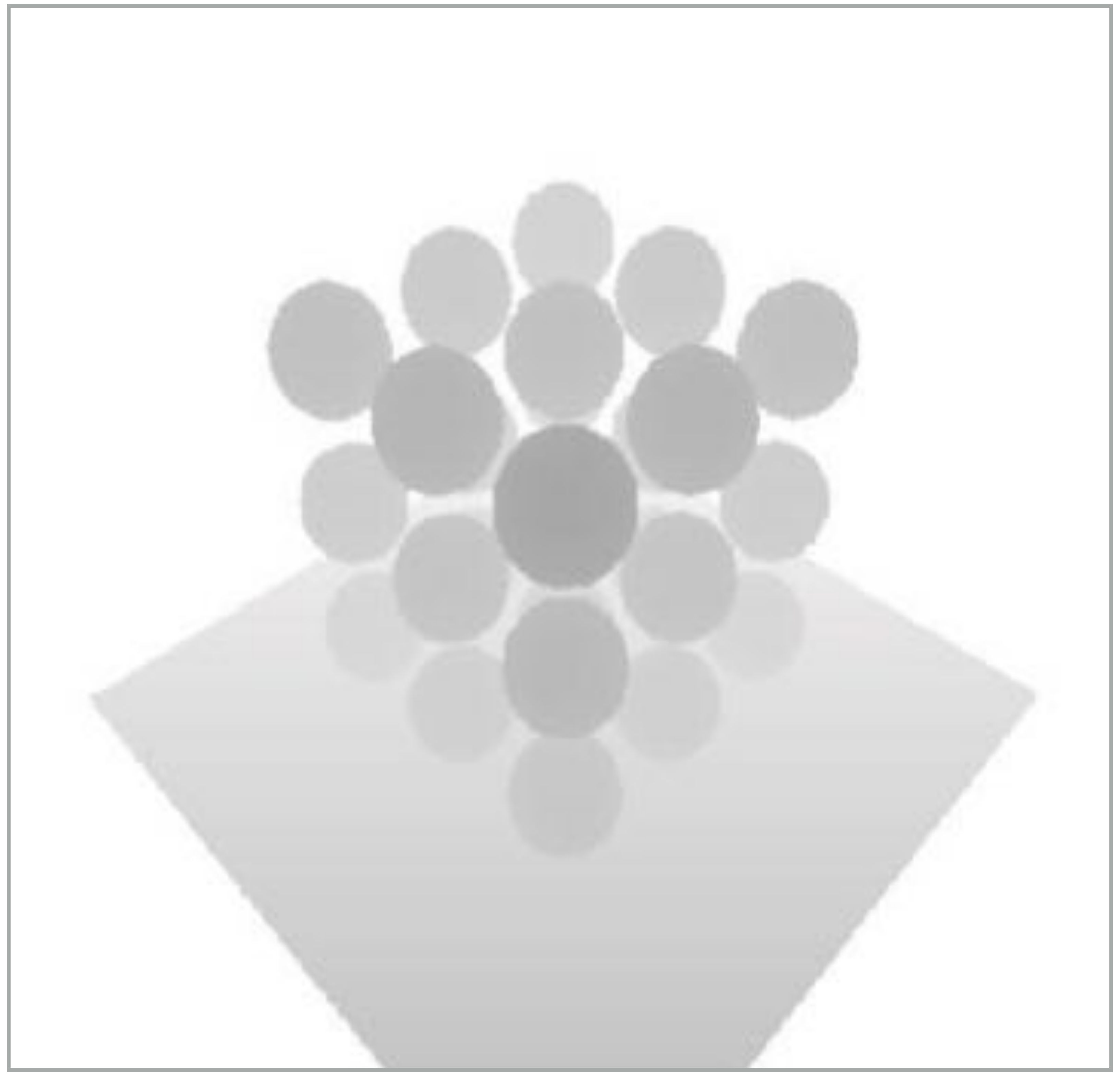
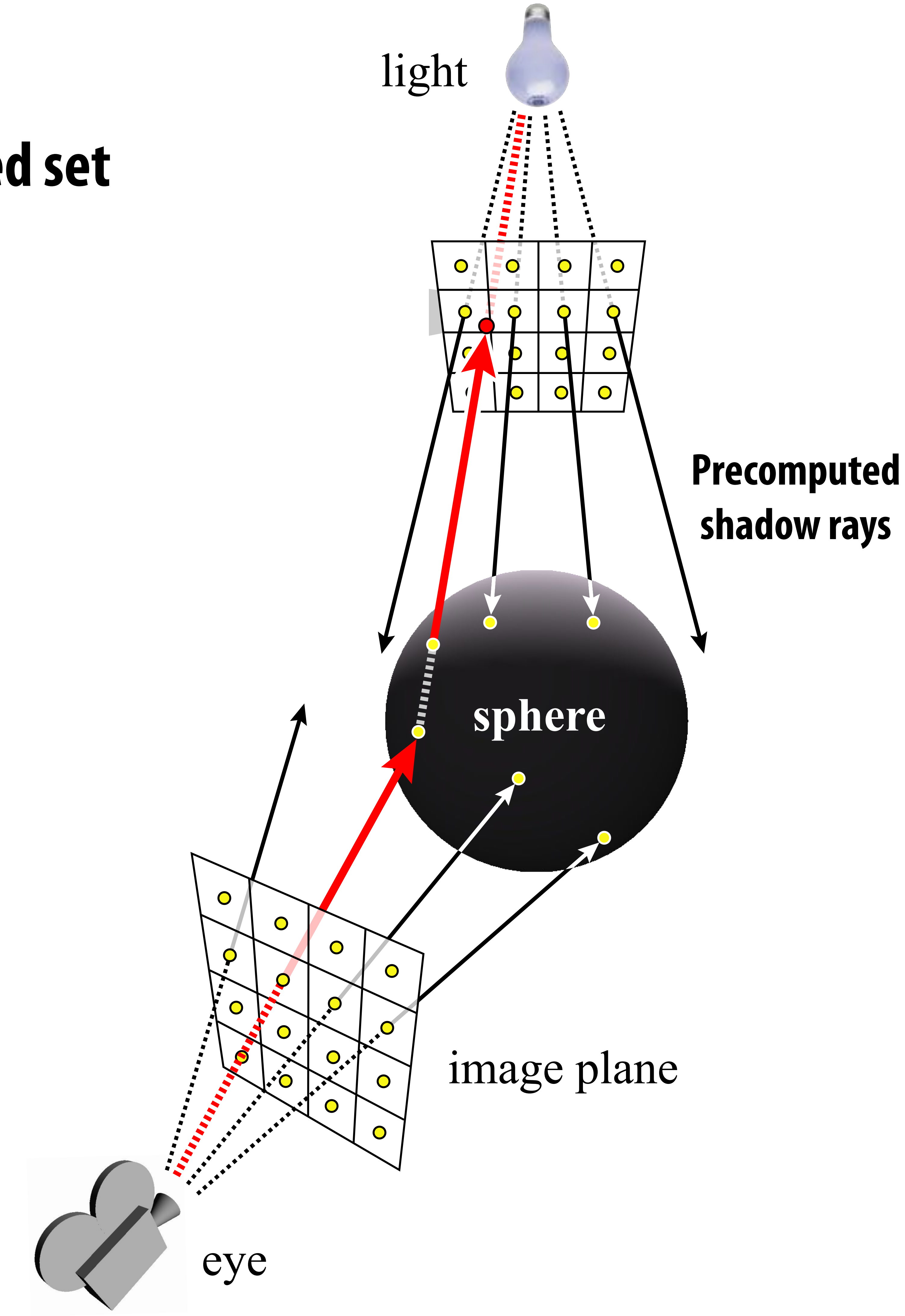
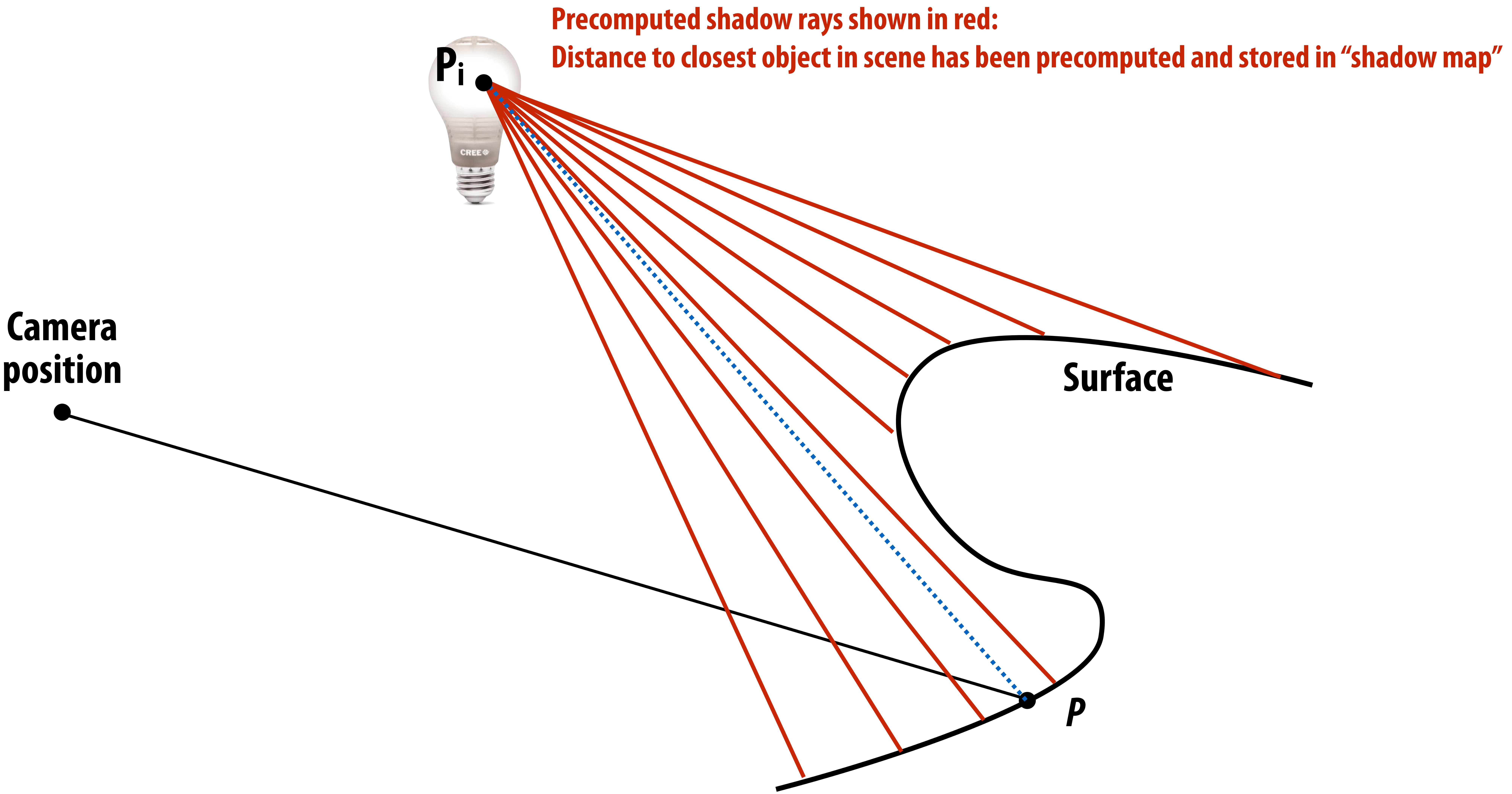


Image credits: Segal et al. 92, NVIDIA

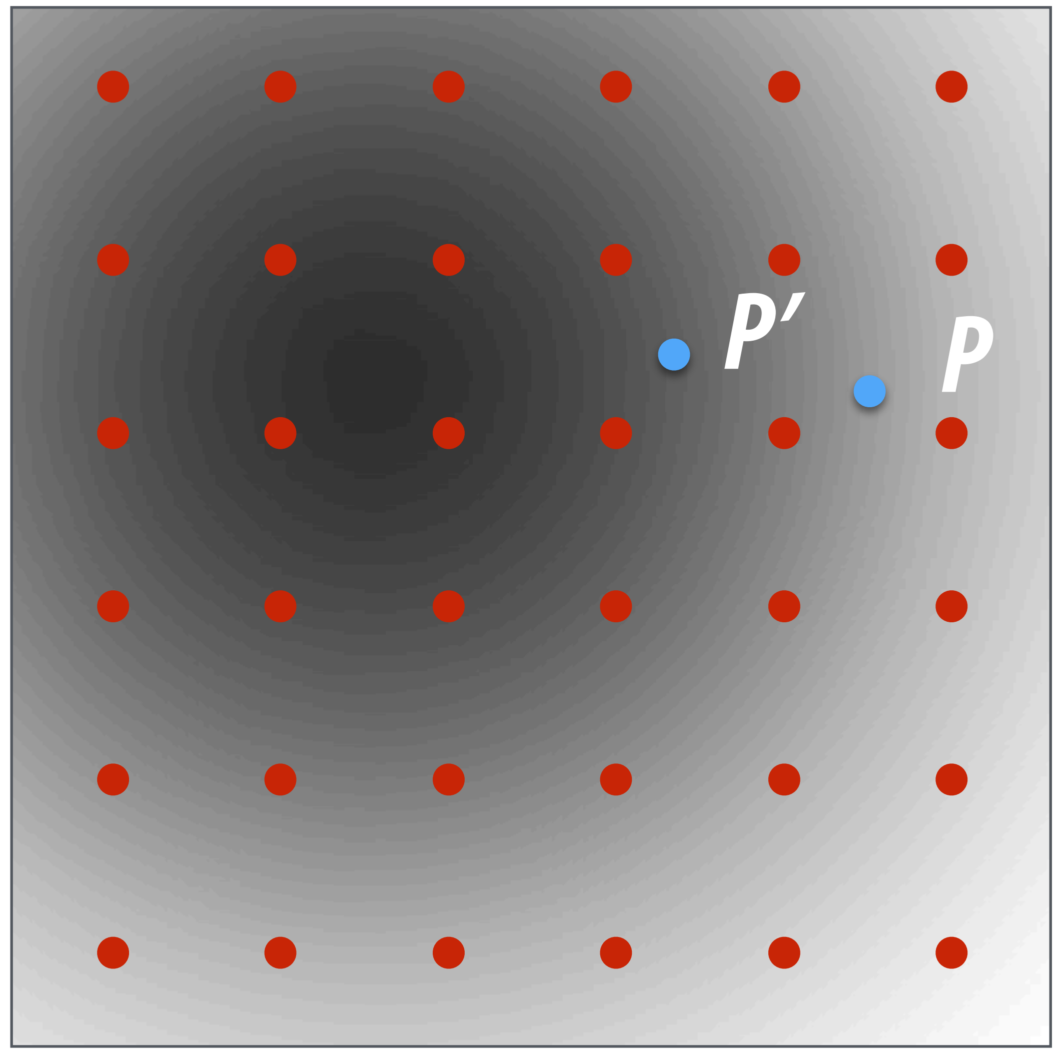


Result of shadow texture lookup approximates visibility result when shading fragment at *P*

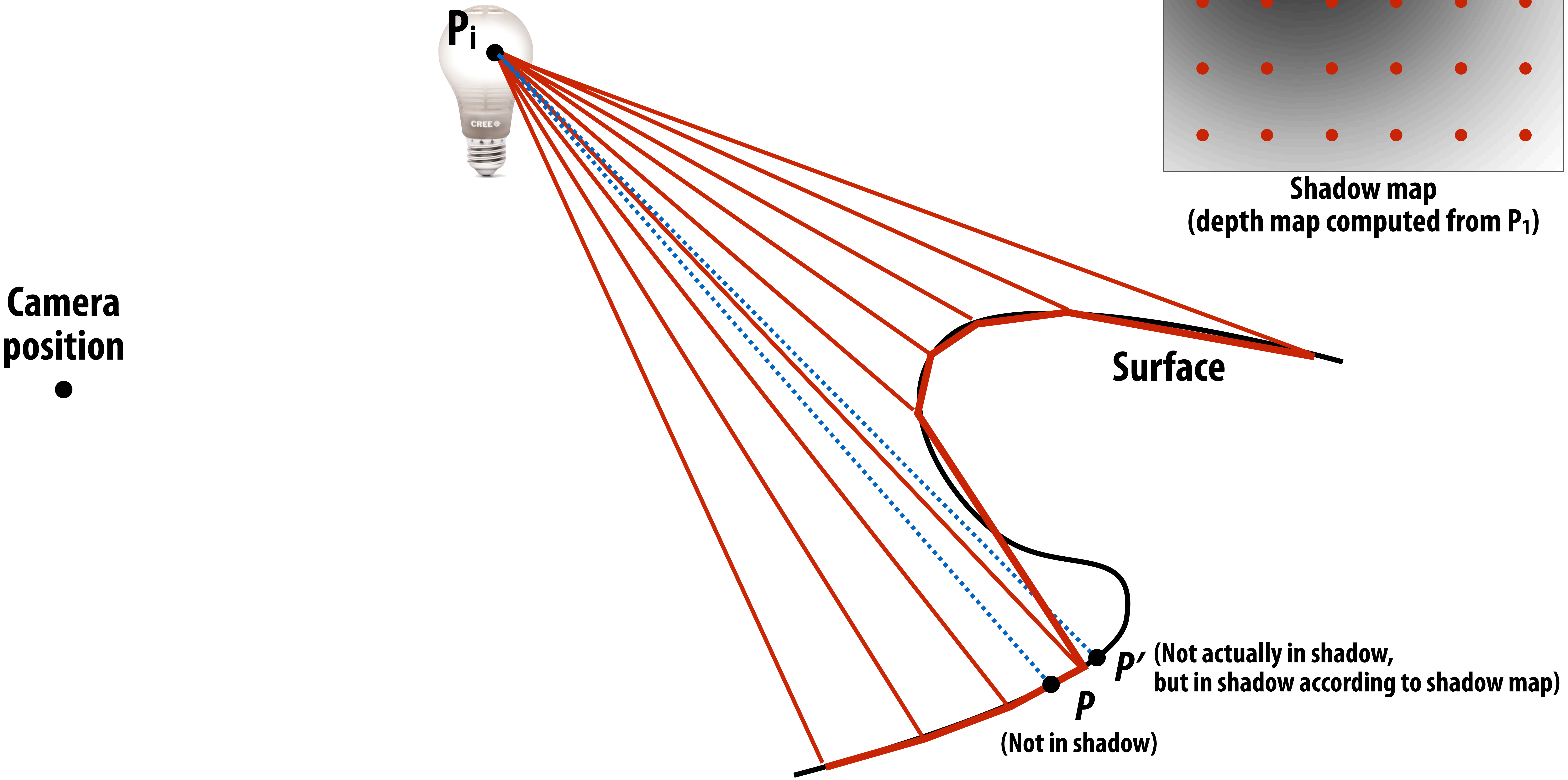


Interpolation error

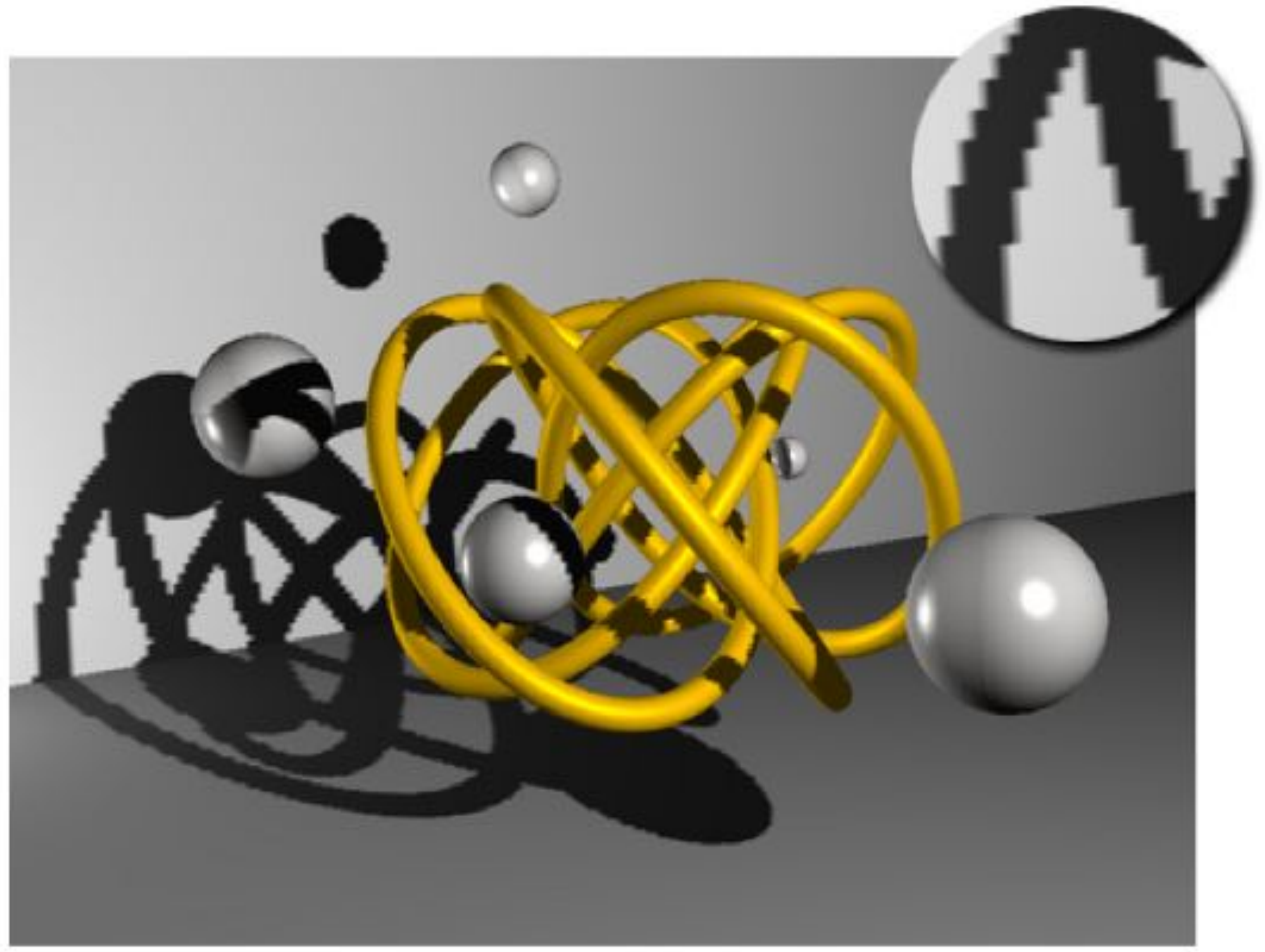
Bilinear interpolation of shadow map values (red line) only approximates distance to closest surface point in all directions from the camera



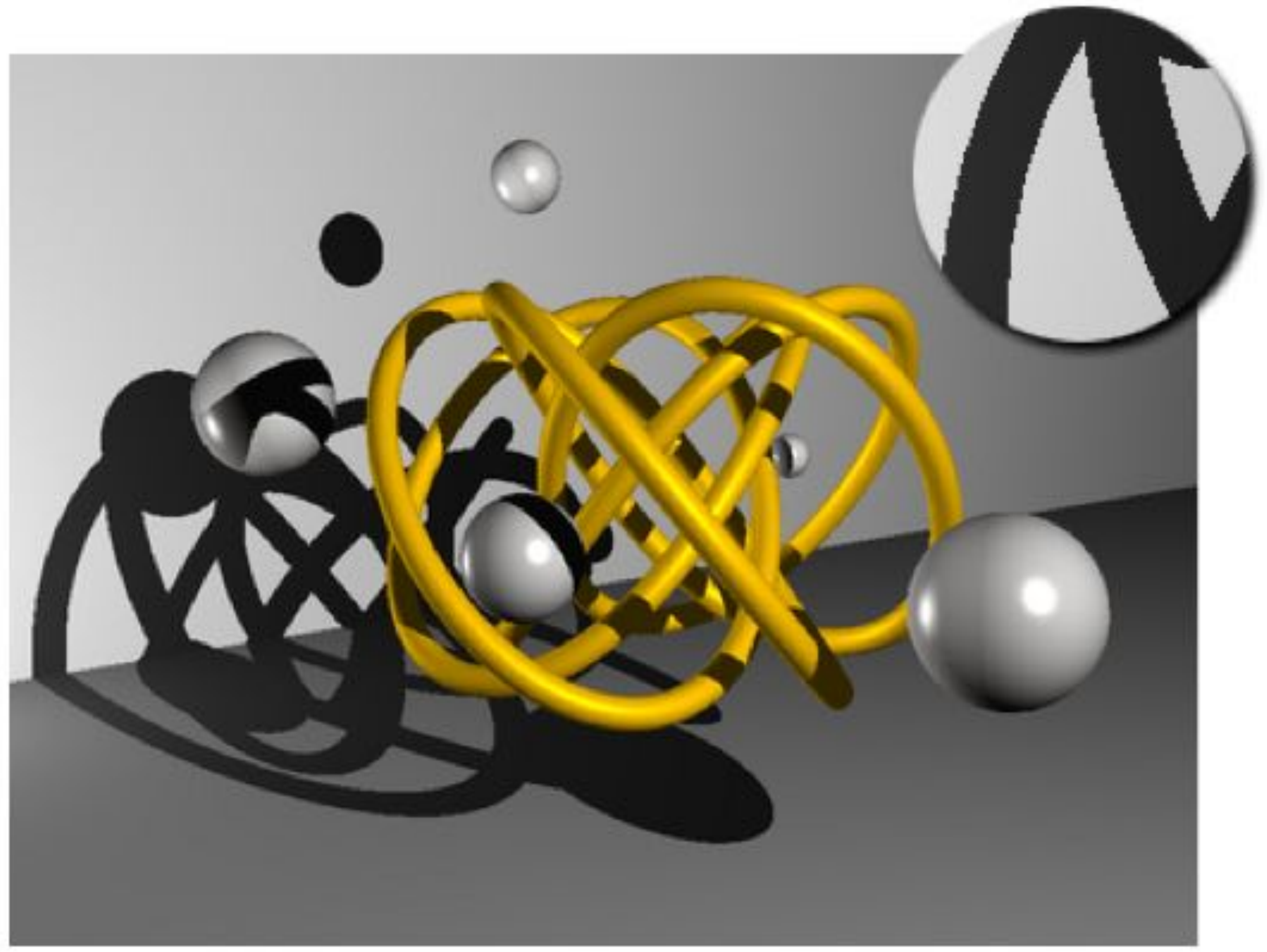
Shadow map
(depth map computed from P_1)



Shadow aliasing due to shadow map undersampling

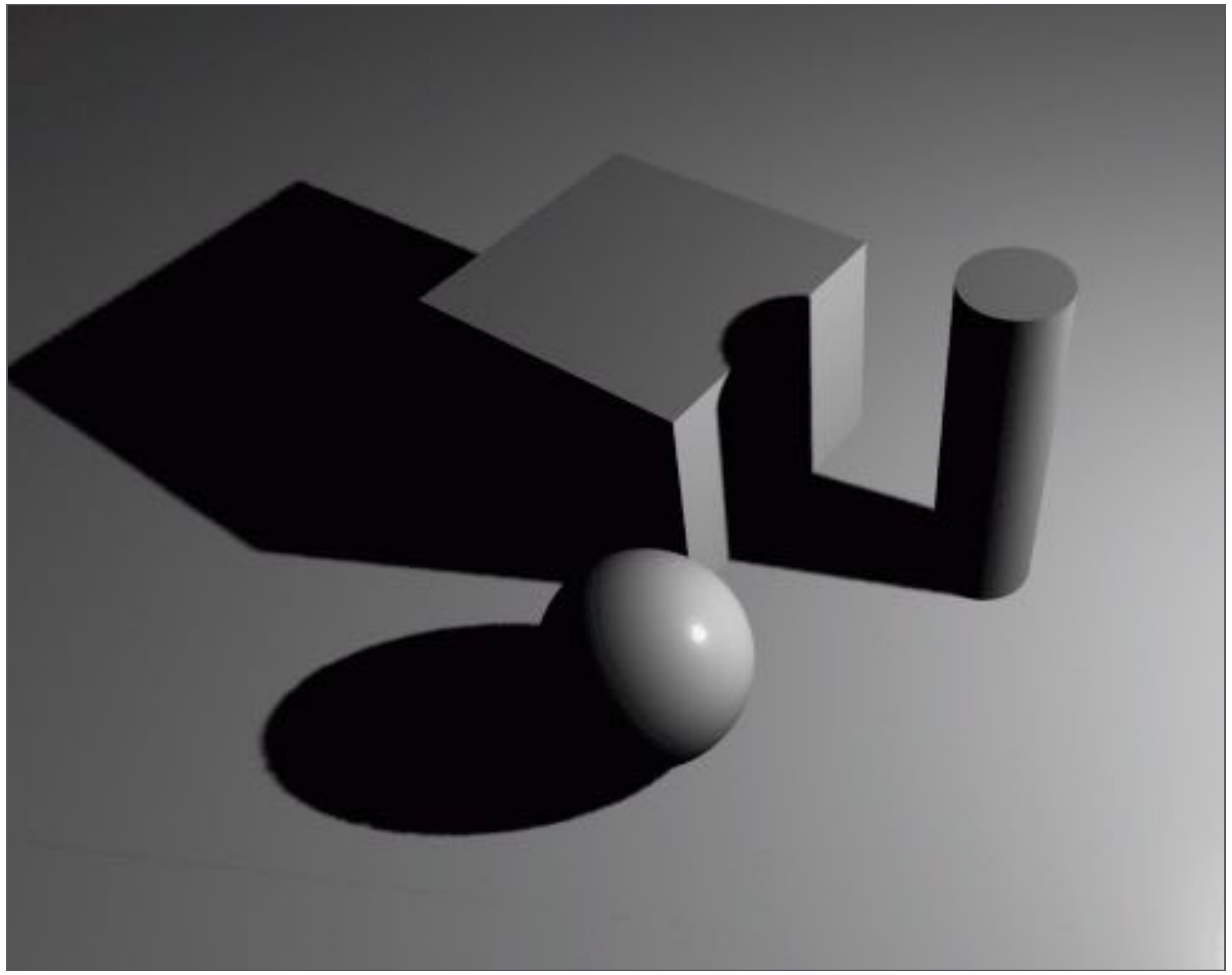


Shadows computed using shadow map

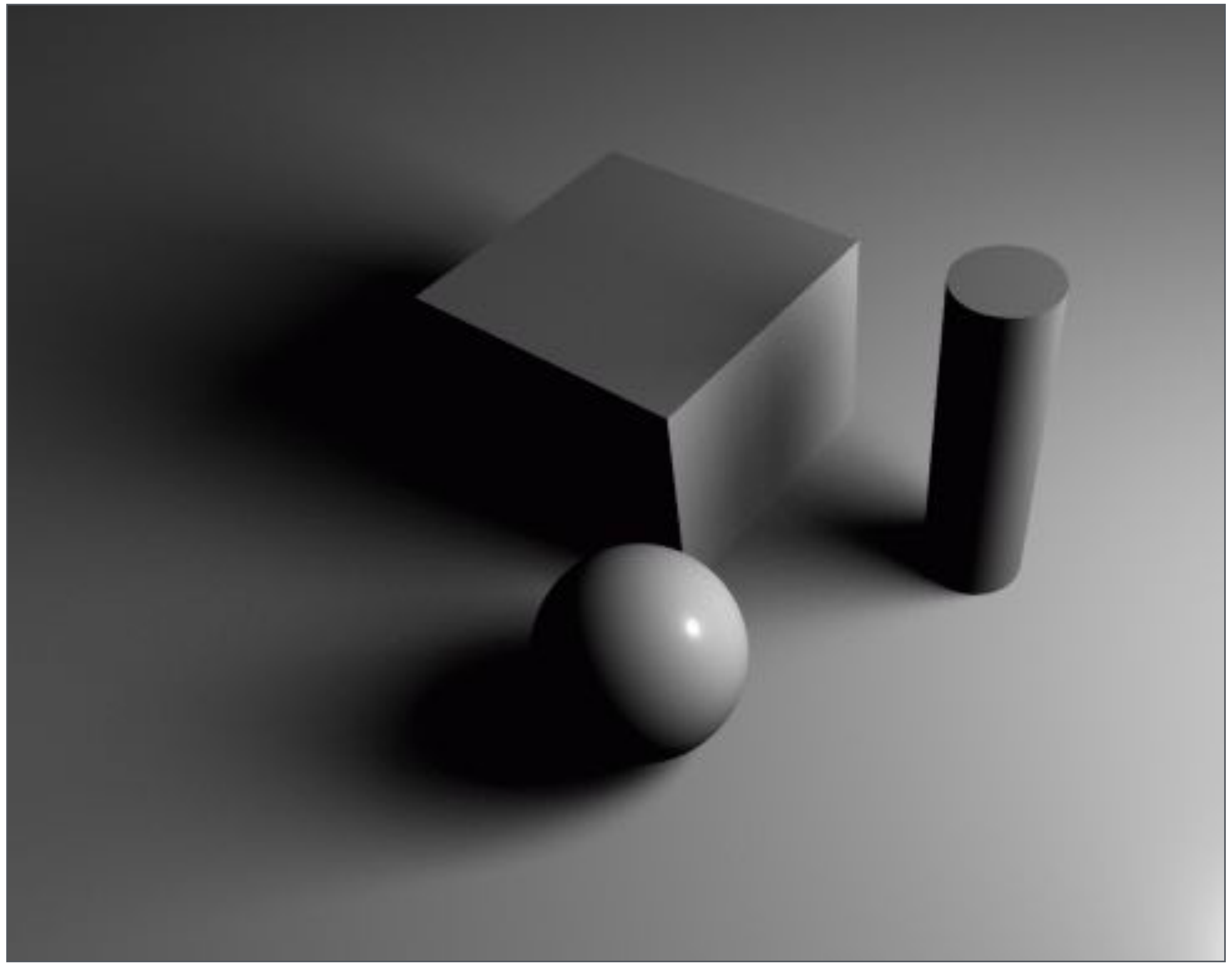


Correct hard shadows
(result from computing visibility along ray between surface point and light directly using ray tracing)

Soft shadows



Hard shadows
(created by point light source)



Soft shadows
(created by ???)

Image credit: Pixar

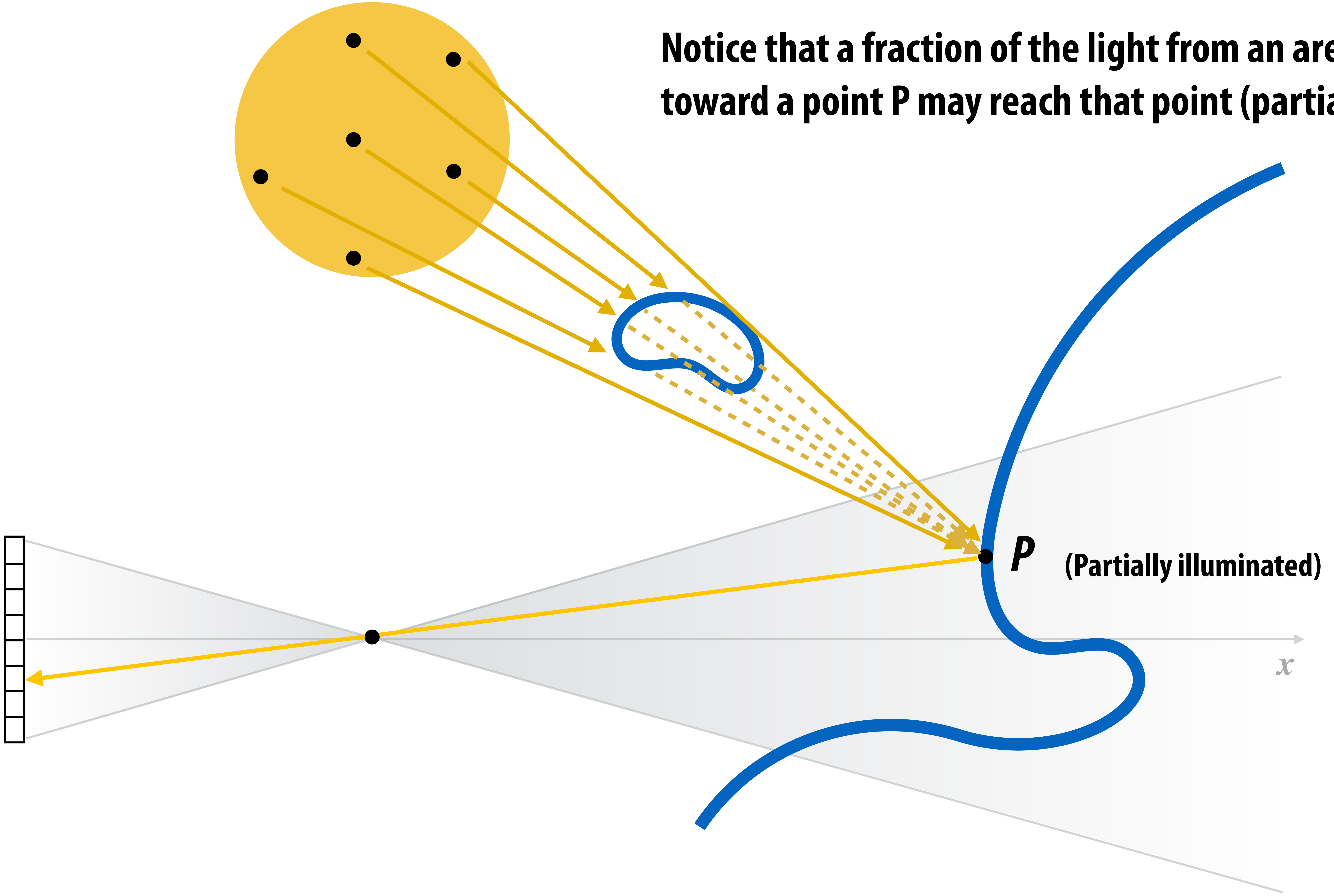

Area light
Soft shadow
boundary
Credit: Jaime Velasco (https://all3dp.com/2/blender-lighting-simply-explained/)

Area light

Credit: Jaime Velasco (https://all3dp.com/2/blender-lighting-simply-explained/)

Shadow cast by an area light (via ray tracing)

Notice that a fraction of the light from an area light toward a point P may reach that point (partial occlusion)

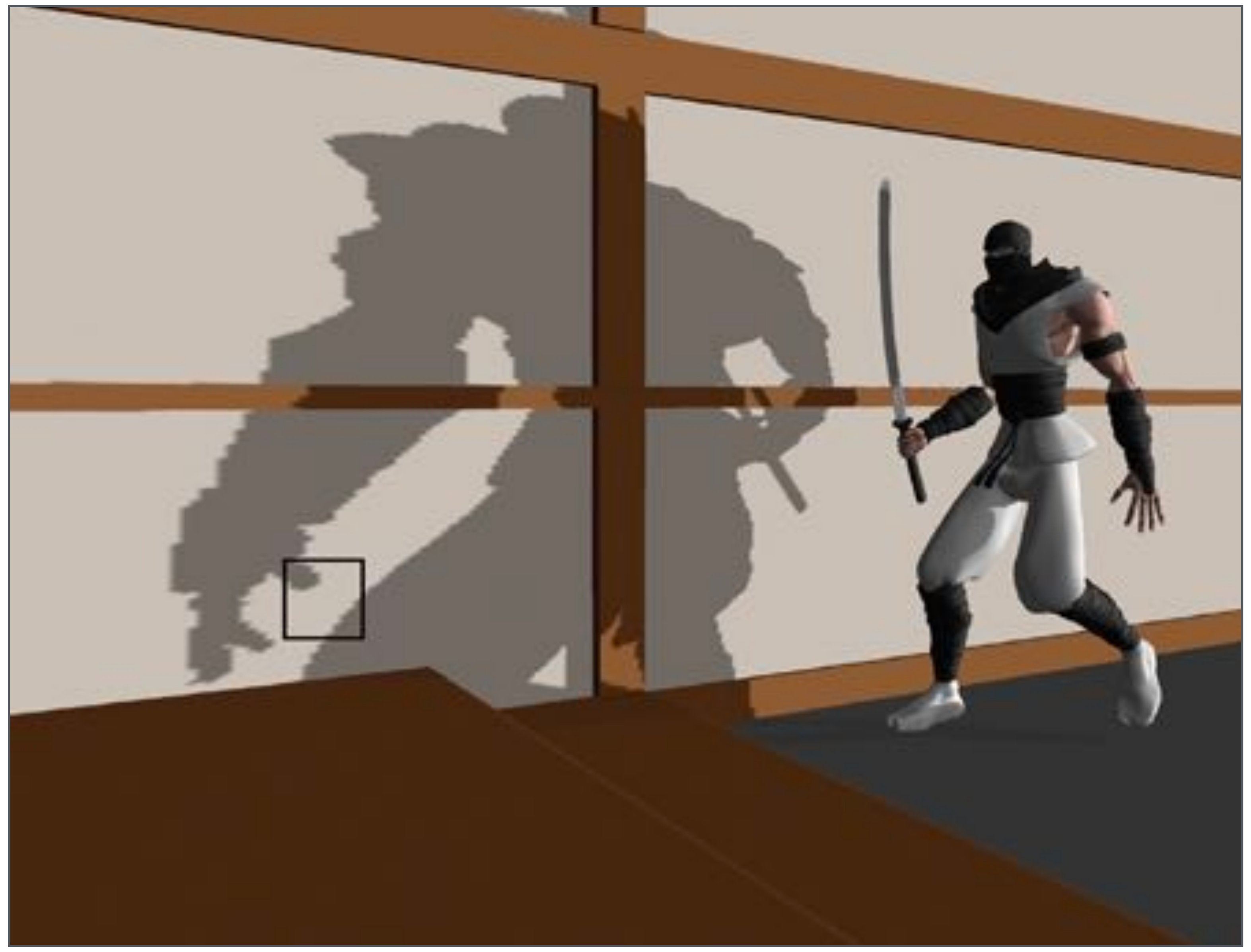


Percentage closer filtering (PCF) — hack!

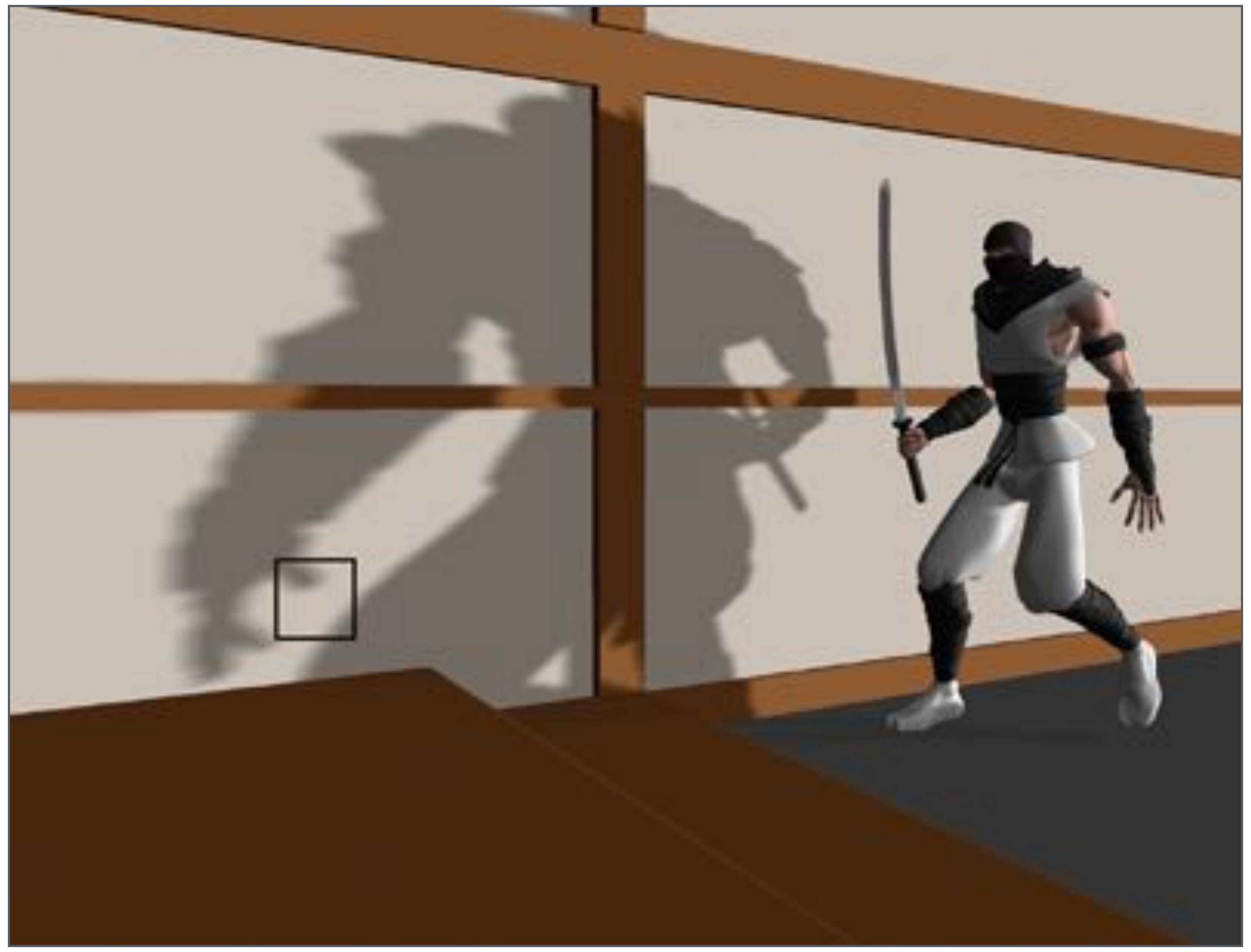
- Instead of sampling shadow map once, perform multiple lookups around desired texture coordinate
- Tabulate fraction of lookups that are in shadow, modulate light intensity accordingly

shadow map values
(consider case where distance from light to surface is 0.5)

0	0	0	0	0	0	0	0	1
0	0	0	0	0	0	1	1	1
0	0	0	0	0	1	1	1	1
0	0	0	0	0	1	1	1	1
0	0	0	0	1	1	1	1	1
0	0	0	0	1	1	1	1	1
1	1	1	1	1	1	1	1	1



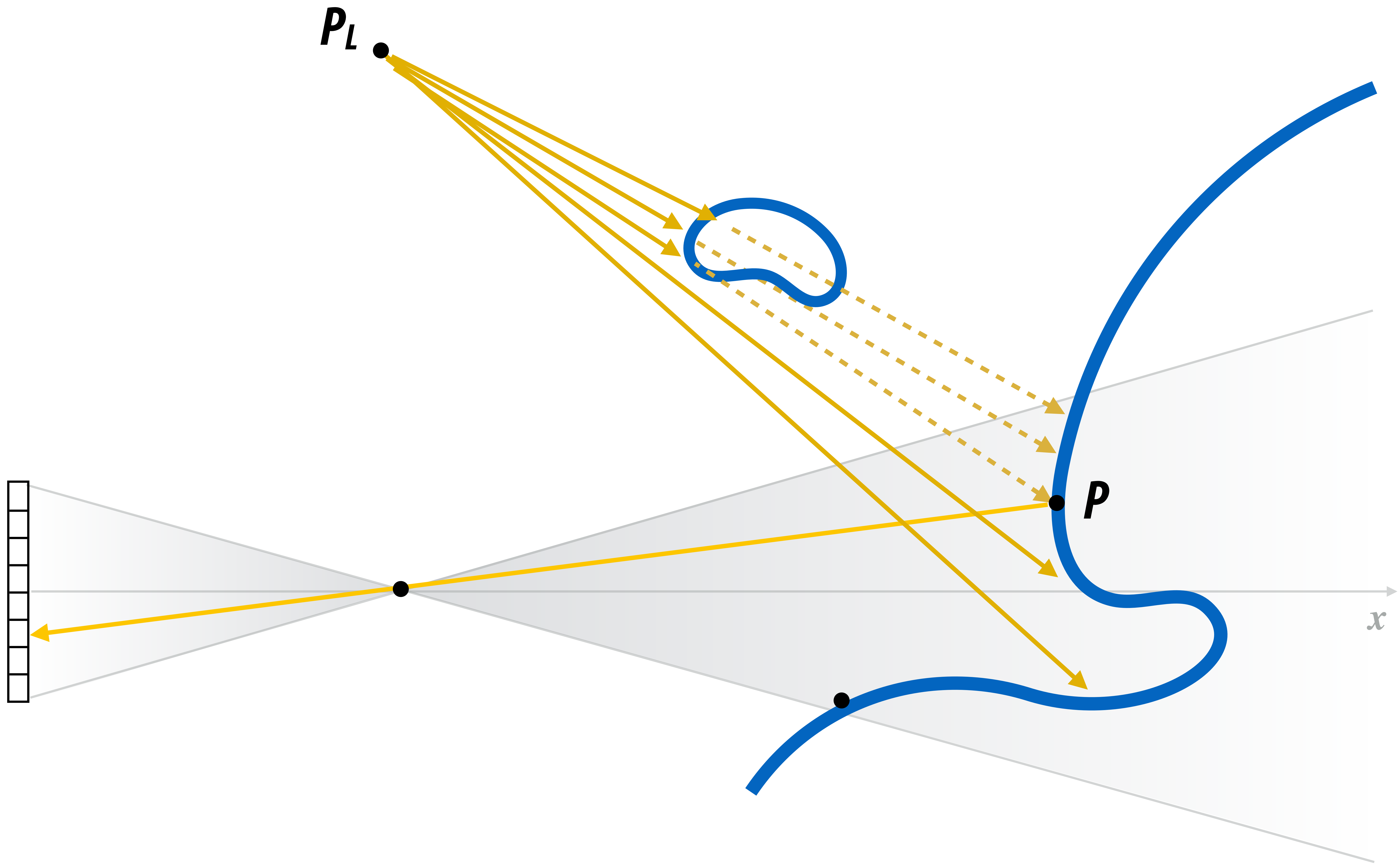
Hard shadows
(one lookup per fragment)



PCF shadows
(16 lookups per fragment)

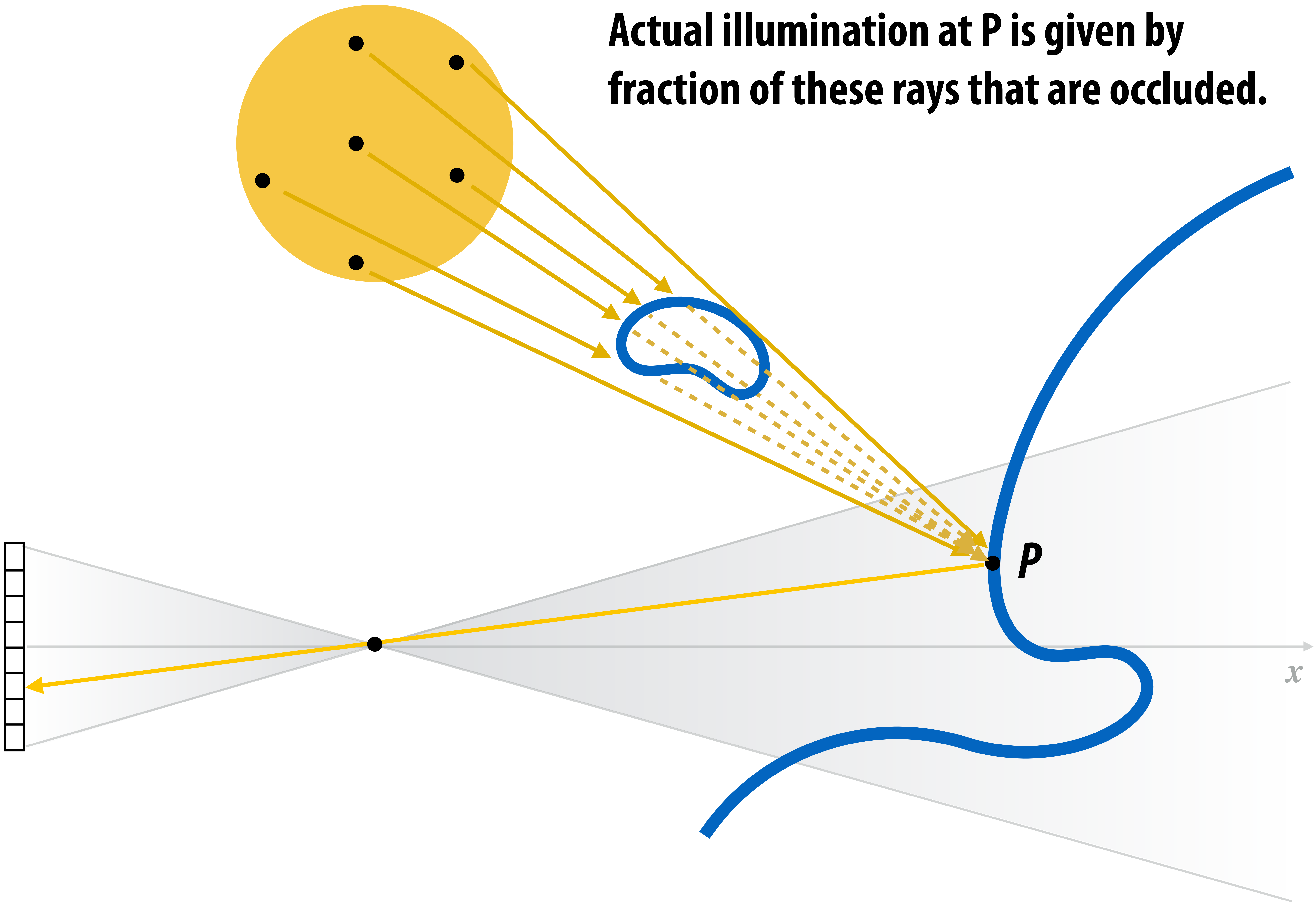
What PCF computes

The fraction of these rays that are shorter than $|P-P_L|$



Shadow cast by an area light

Actual illumination at P is given by fraction of these rays that are occluded.



Q. Why isn't the surface in shadow completely black?

Answer: Assumption that some amount of "ambient light" (light scattered from off surfaces) hits every surface. Here… ambient light is just a constant.

Image credit: Grand Theft Auto V

Image credit: Brennan Shacklett

Ambient occlusion

This scene contains an environment light source that has equal illumination from all directions. (e.g., an overcast day)

All surfaces are diffuse reflectors.

Without accounting for shadows, all surfaces should be the same color.

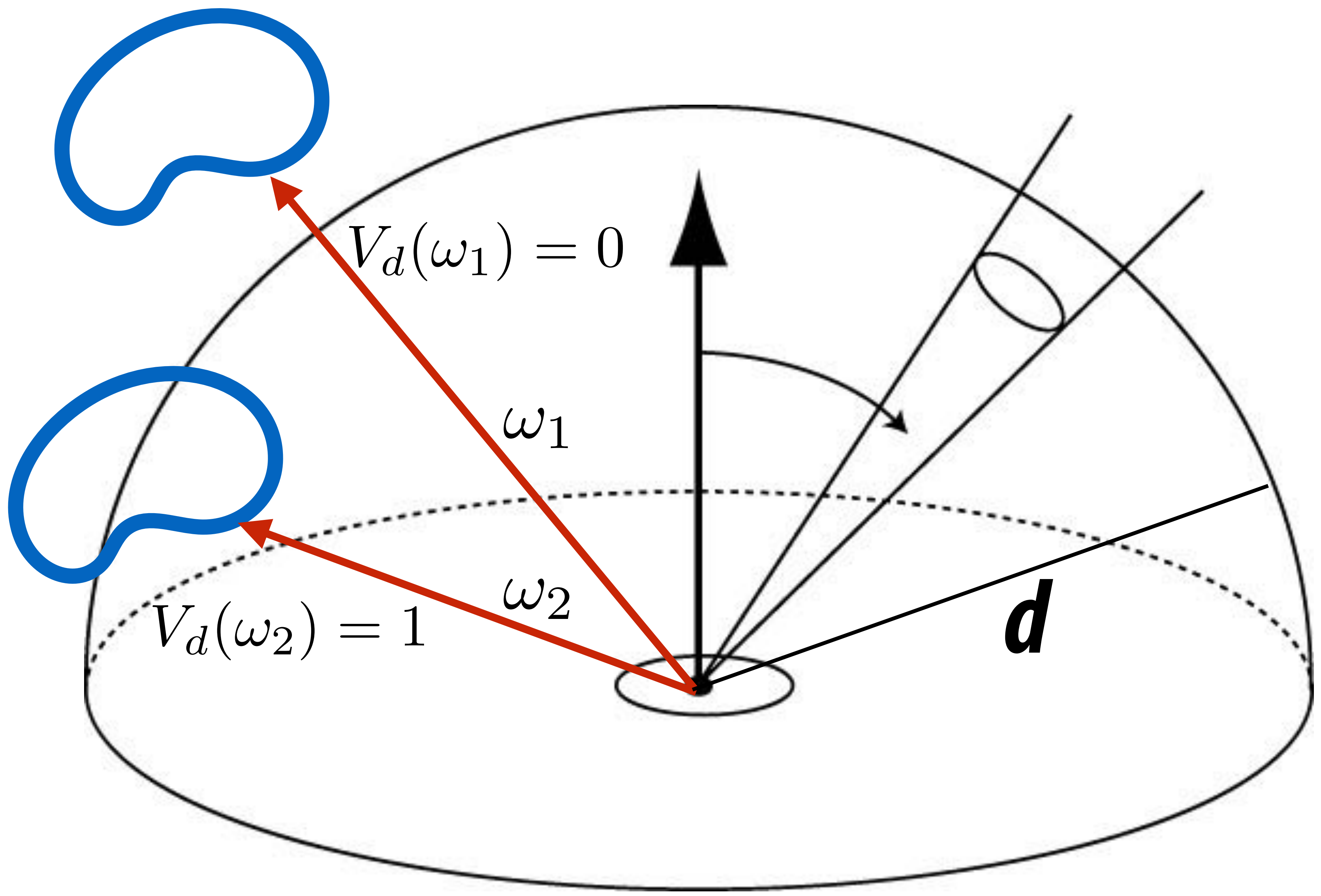
Hack: ambient obscurance

Idea:

Precompute "fraction of hemisphere" that is occluded within distance *d* from a point (via a ray tracer)

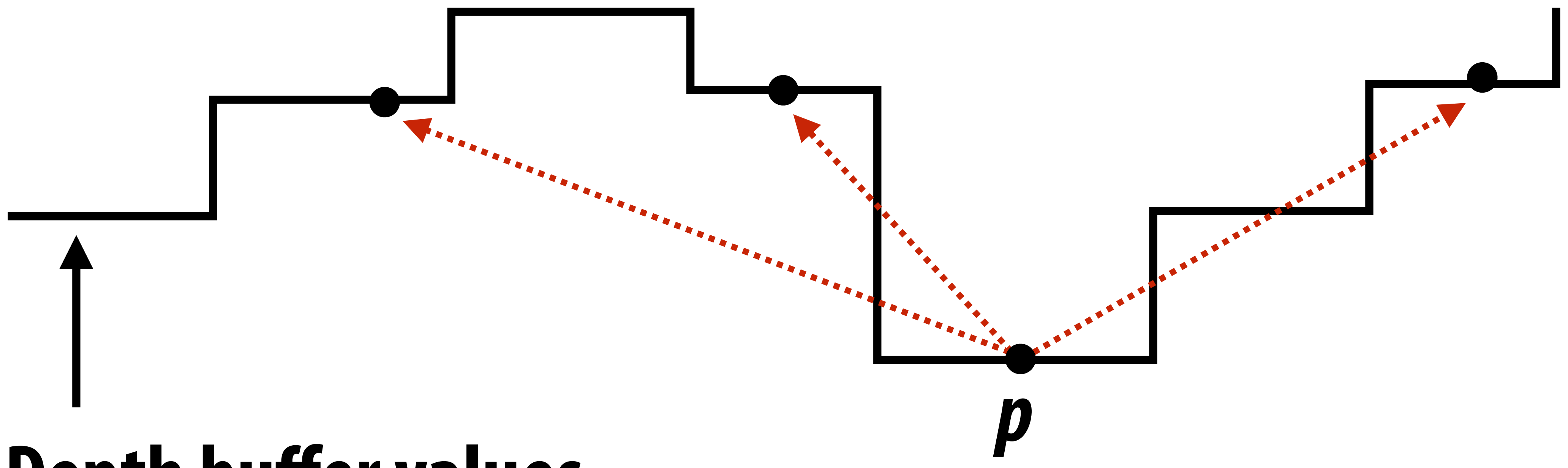
Store this fraction in a texture map

When shading, attenuate environment lighting by this fraction



"Screen-space" ambient occlusion in games

1. Render scene to depth buffer
2. For each pixel *p*, "ray trace" the depth buffer to estimate local occlusion of hemisphere - use a few samples per pixel
3. Blur the the per-pixel occlusion results to reduce noise
4. When shading pixels, darken direct environment lighting by occlusion amount computed for the current pixel

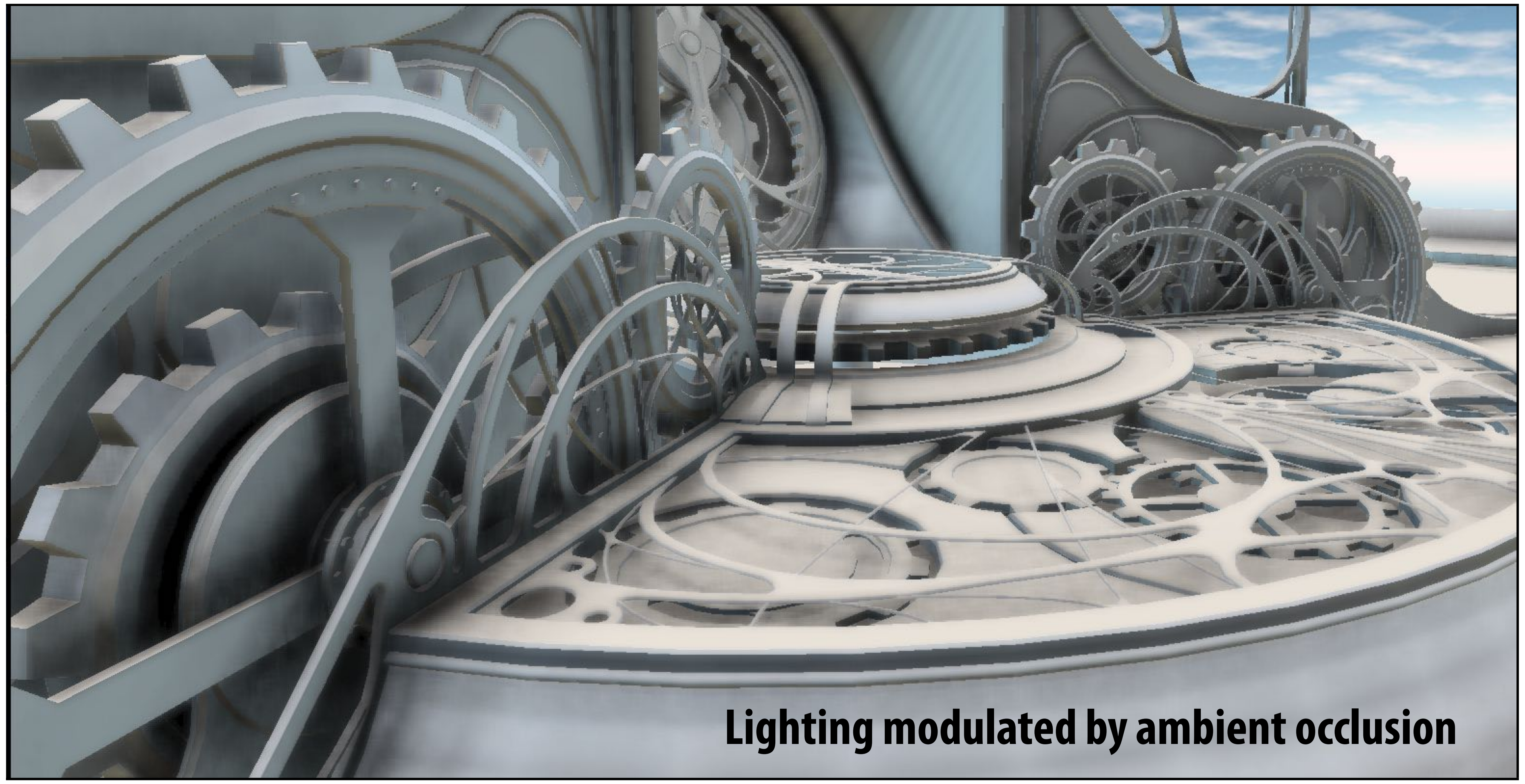


Depth buffer values

without ambient occlusion

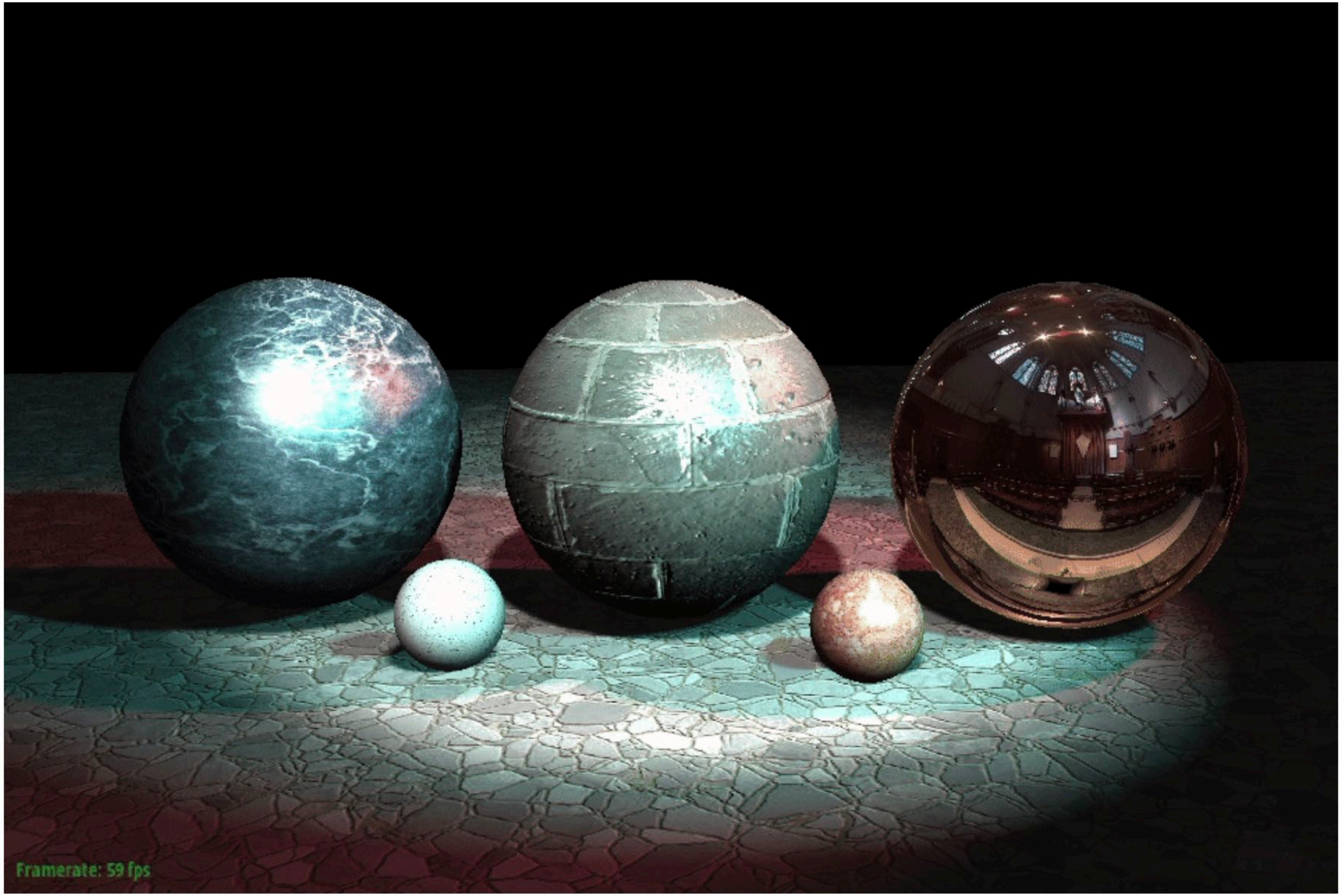
with ambient occlusion

Ambient occlusion



Reflections

What is wrong with this picture?

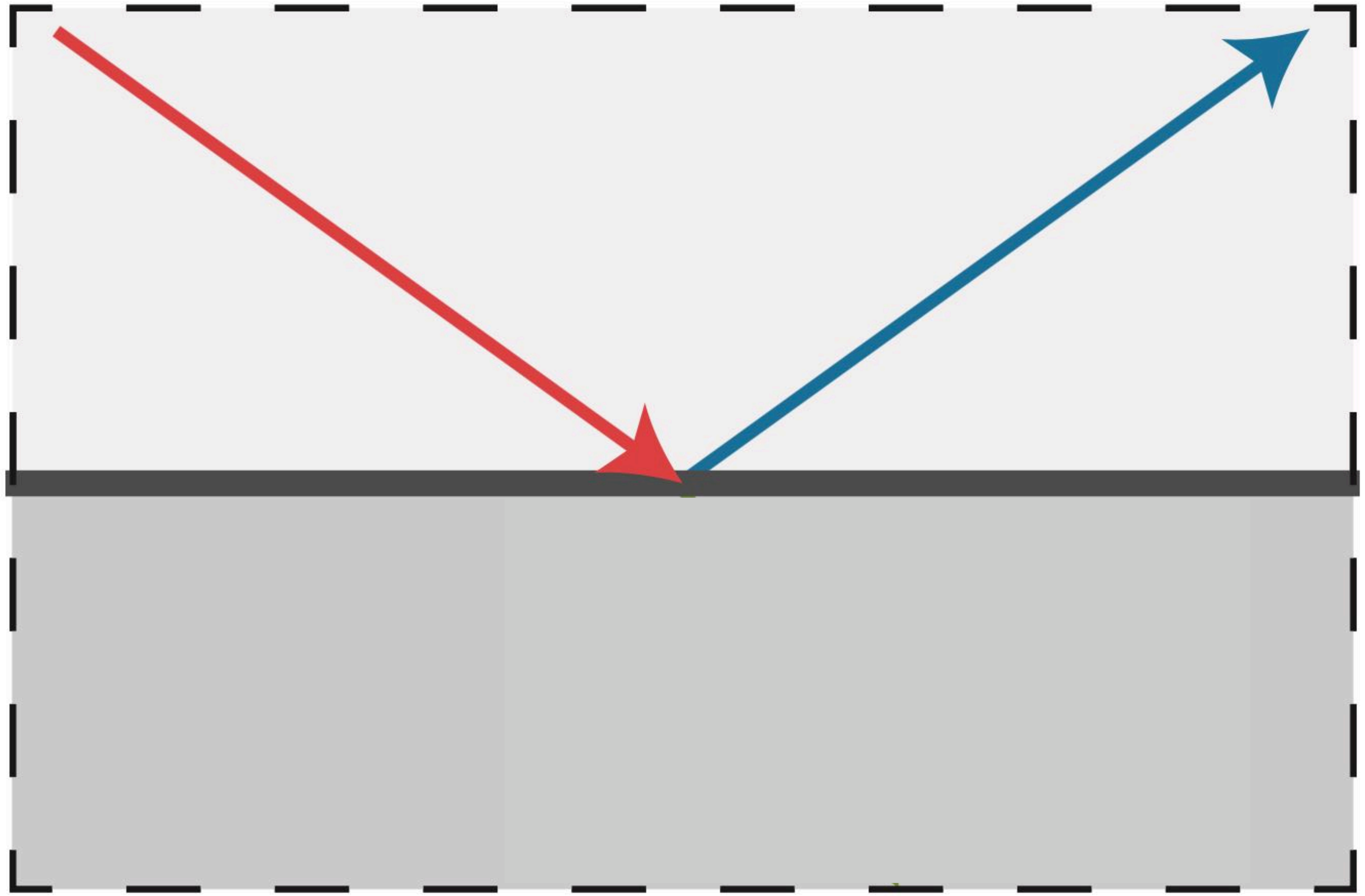


Reflections

Image credit: NVIDIA

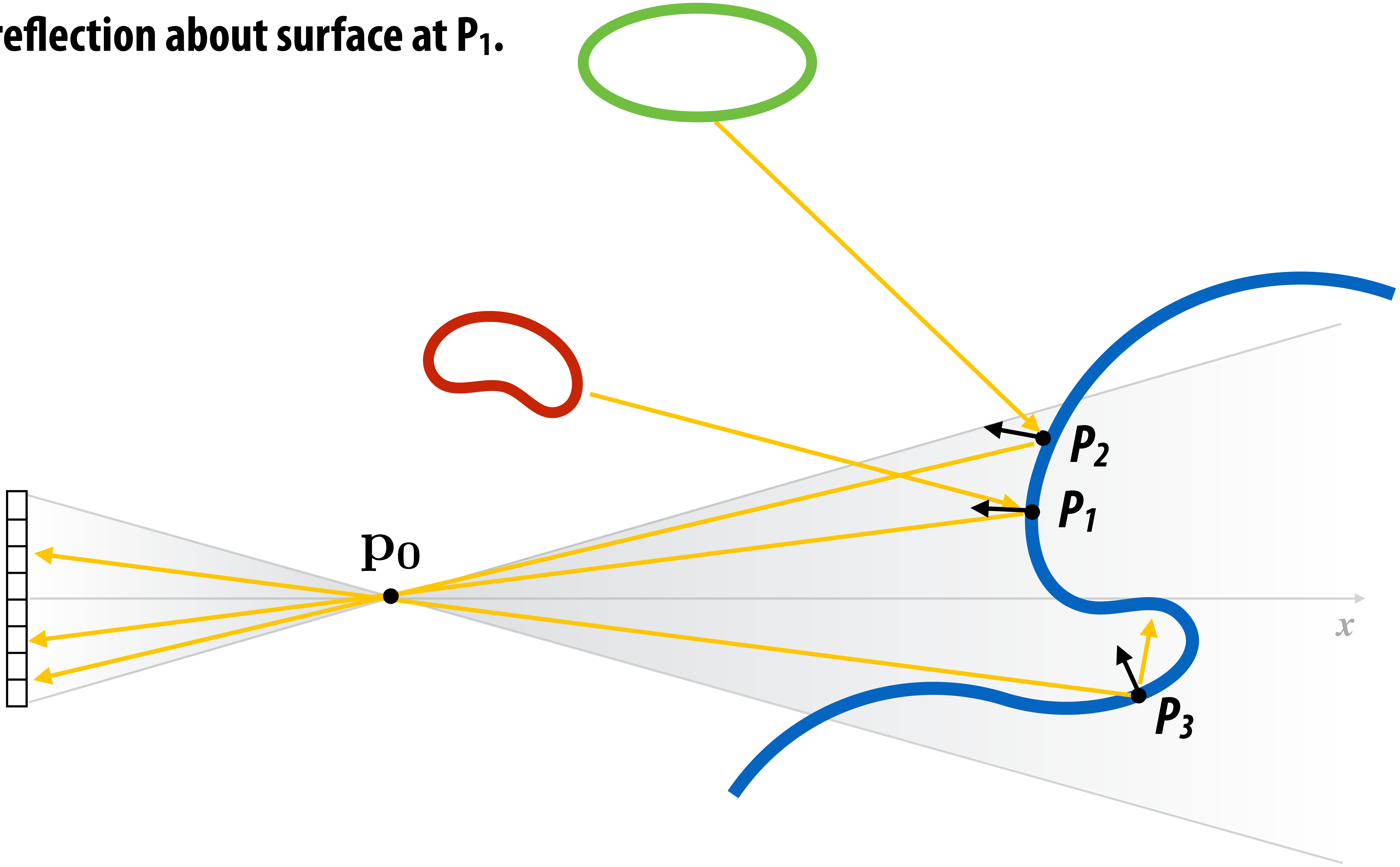
Reflections

Recall: perfect mirror material



Recall: perfect mirror reflection

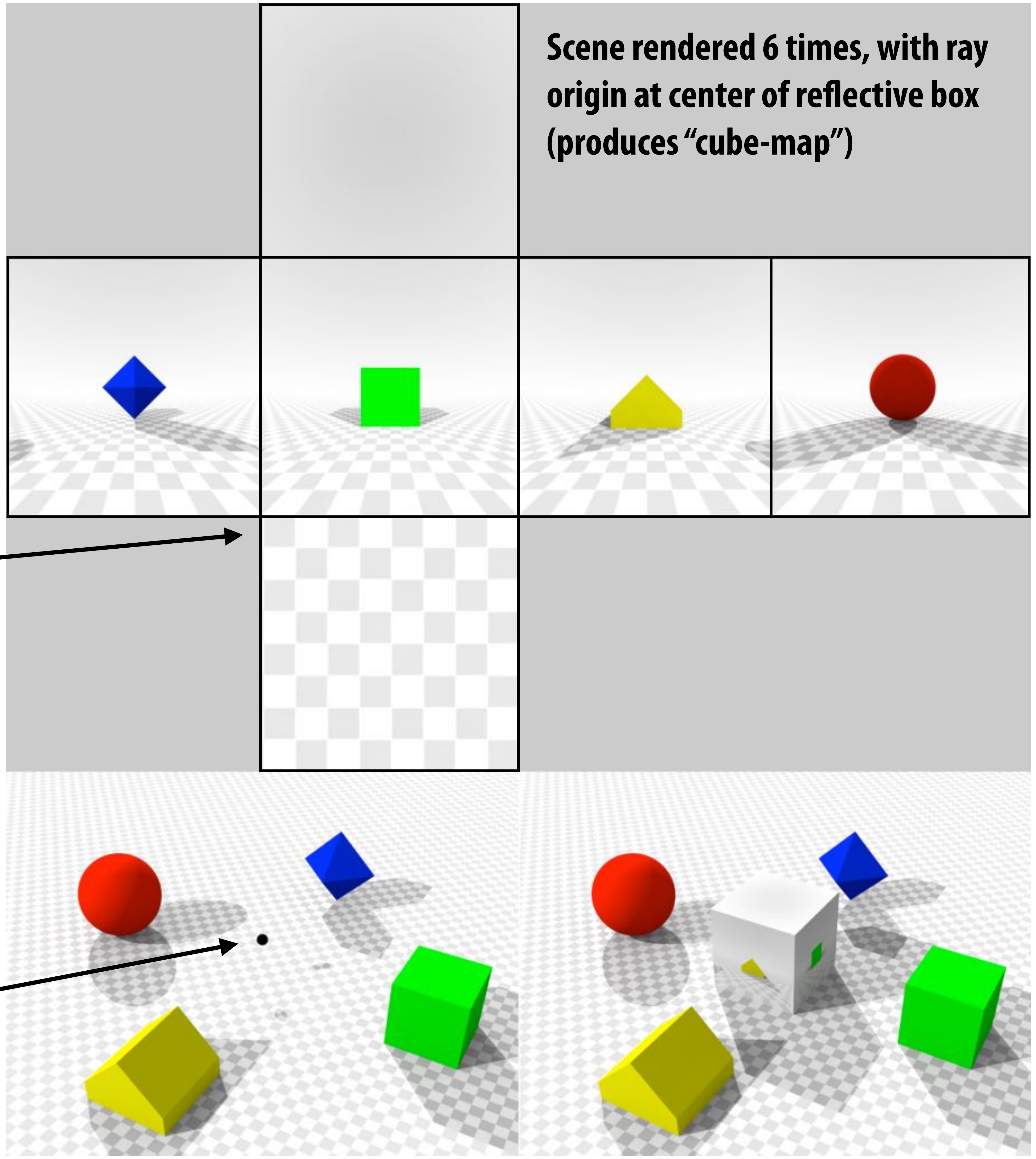
Light reflected from P_1 in direction of P_0 is incident on P_1 from reflection about surface at P_1.



Rasterization: “camera” position can be reflection point

Environment mapping:
place ray origin at reflective object

Yields <u>approximation</u> 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

Environment map vs. ray traced reflections

Image credit: Control

https://www.techspot.com/article/1934-the-state-of-ray-tracing/

Environment map vs. ray traced reflections

Image credit: Control

https://www.techspot.com/article/1934-the-state-of-ray-tracing/

Indirect lighting

Indirect lighting

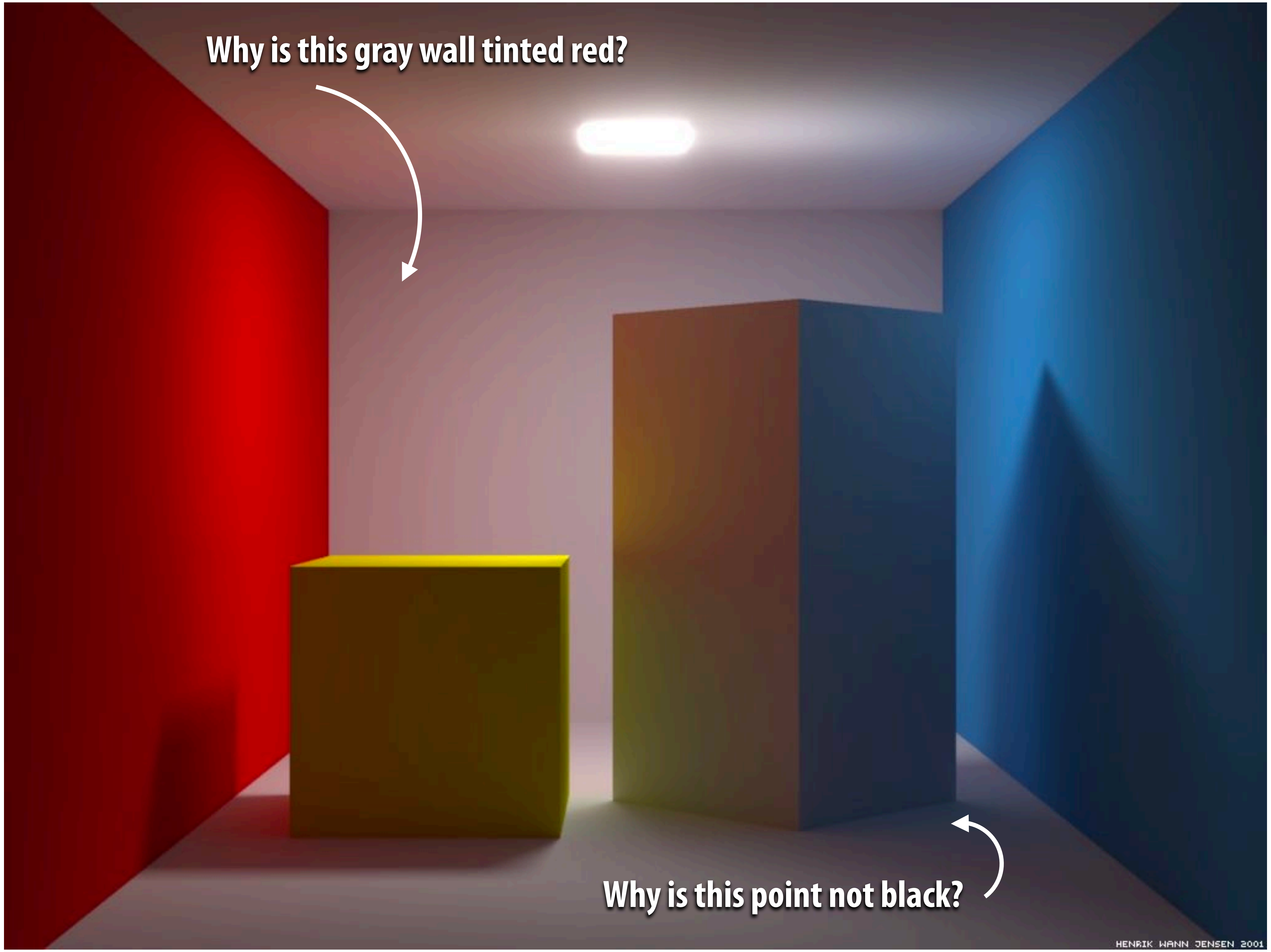
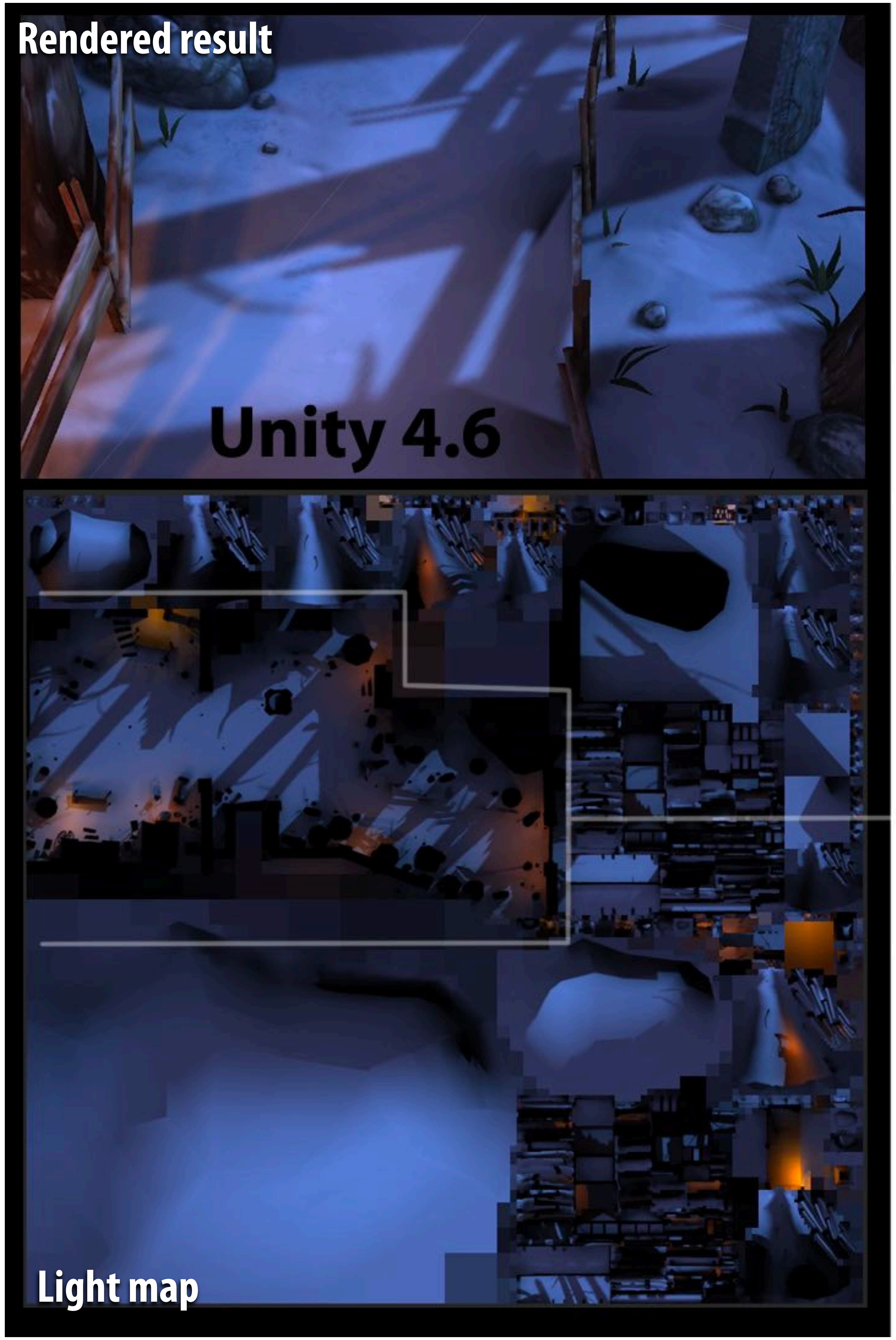


Image credit: Henrik Wann Jensen

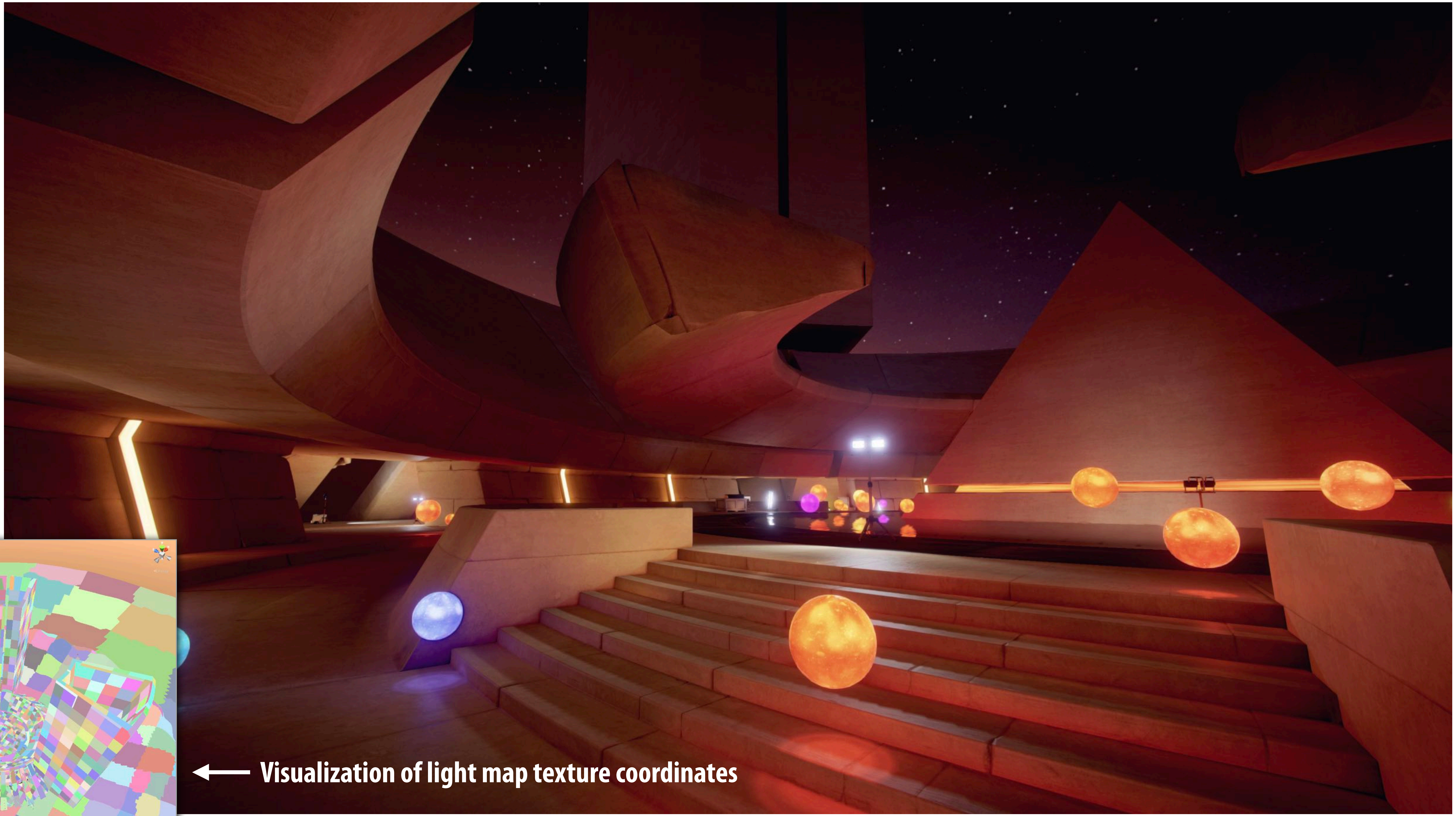
Precomputed lighting

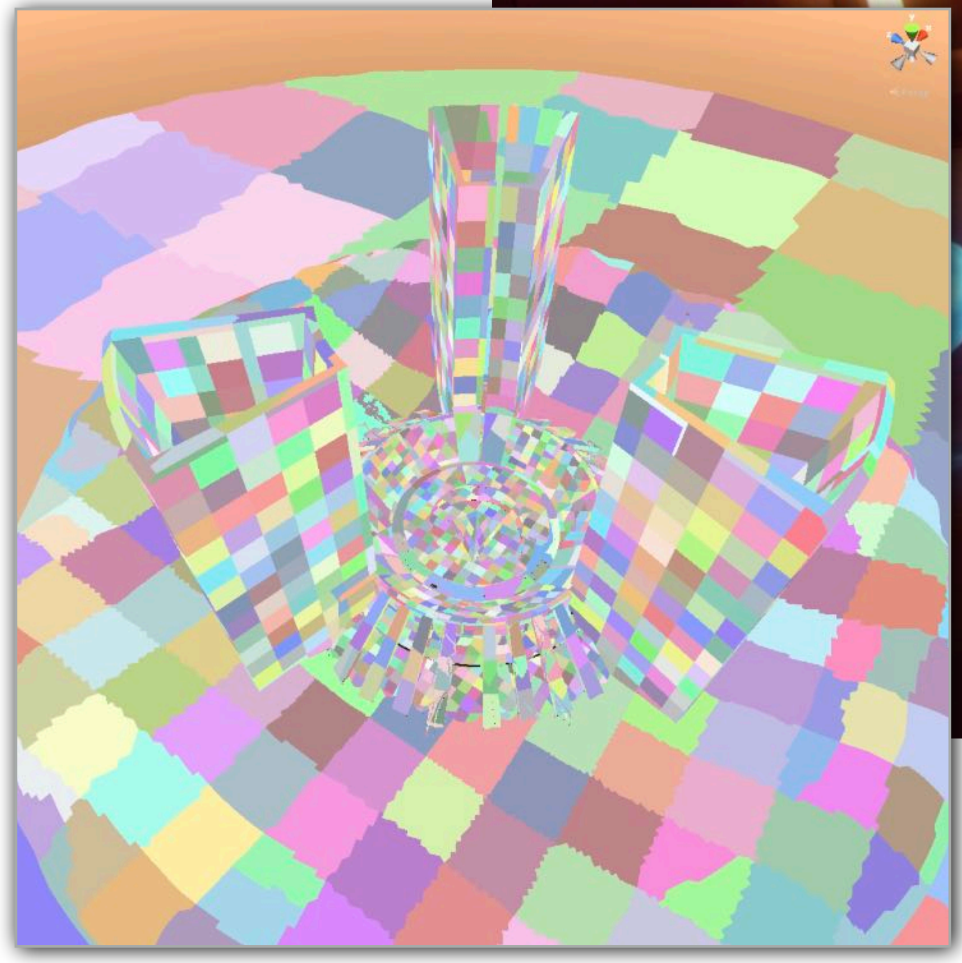
- Precompute accurate lighting for a scene offline using a ray tracer (possible for static lights)

- "Bake" results of lighting into texture map



Precomputed lighting in Unity Engine



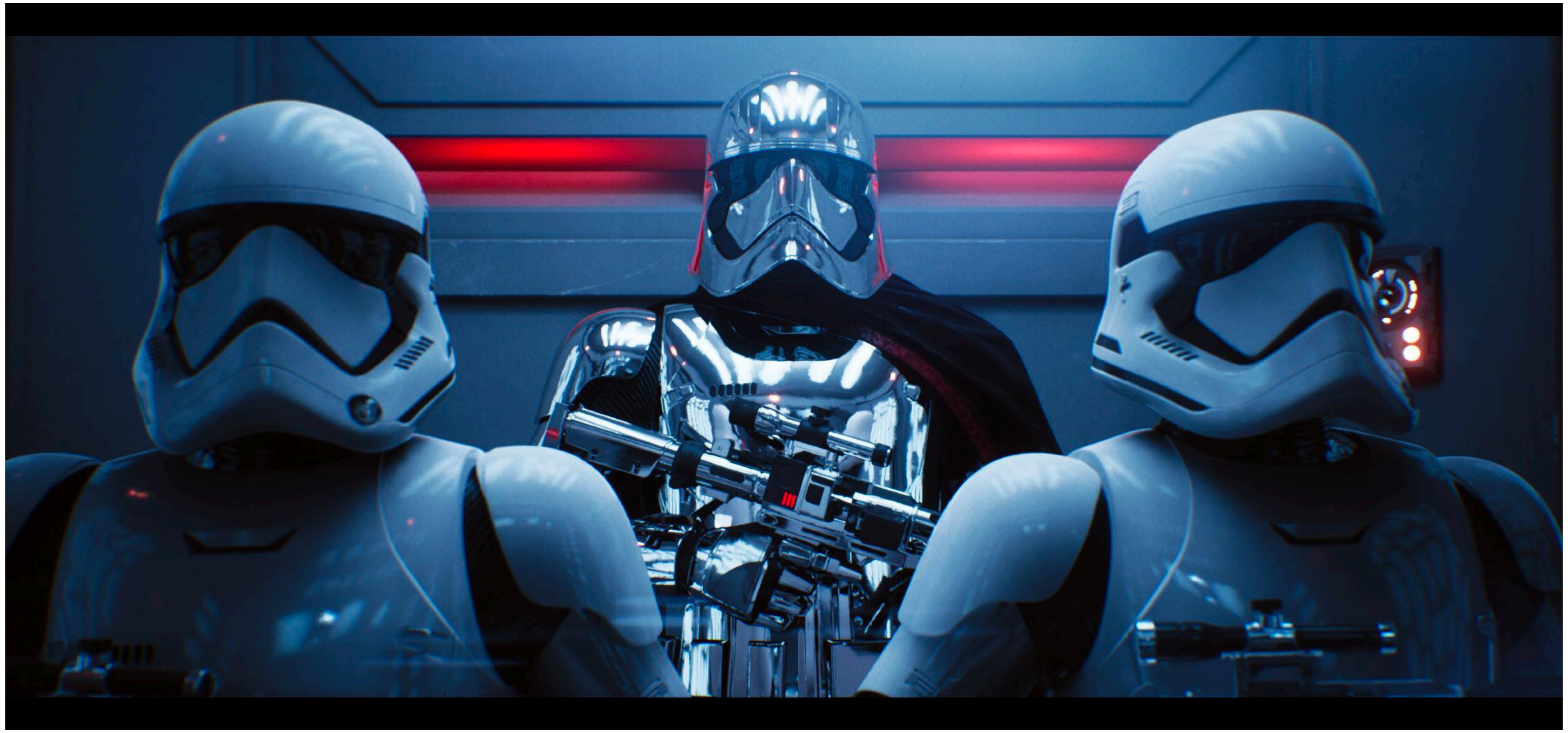


← Visualization of light map texture coordinates

Image credit: Unity / Alex Lovett

Growing interest in real-time ray tracing

- I've just shown you an array of different techniques for approximating different advanced lighting phenomenon using a rasterizer
- Challenges:
  - Different algorithm for each effect (code complexity)
  - Algorithms may not compose
  - They are only approximations to the physically correct solution ("hacks!")
- Traditionally, tracing rays to solve these problems was too costly for real-time use
  - That is rapidly changing…



This image was ray traced in real-time on a GPU

This image was rendered in real-time on a single high-end GPU

Real-time ray tracing challenge:

Need to shoot many rays per pixel to accurately simulate advanced lighting effects

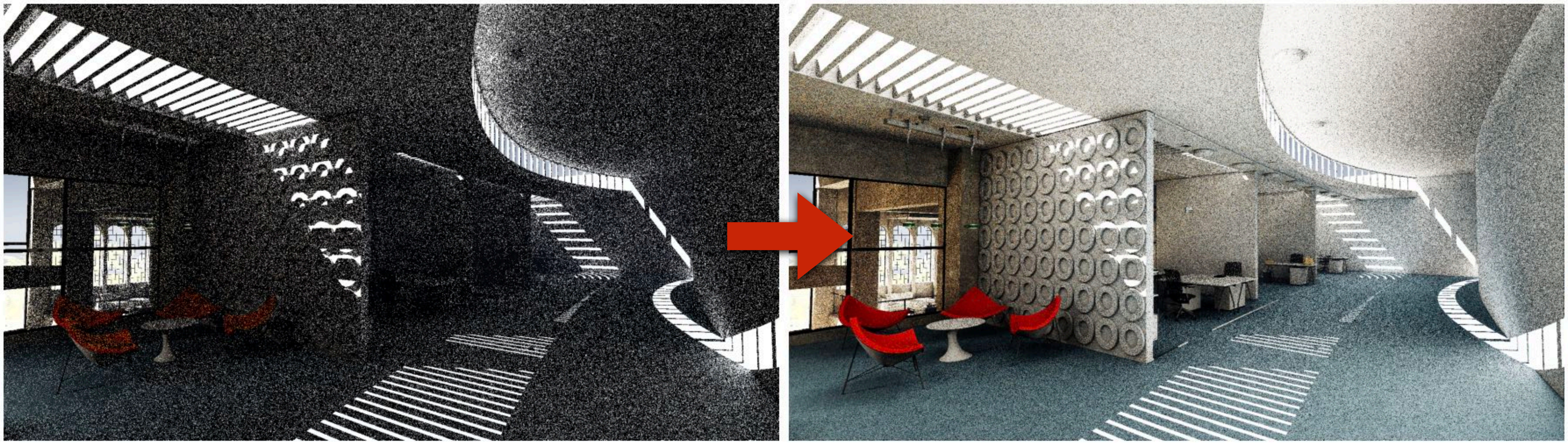
Want high-performance interactive rendering

😥

Innovation 1:
Hardware innovation: custom GPU hardware for RT

NVIDIA GeForce RTX 3080 GPU

Innovation 2: better importance sampling algorithms



Path traced: 1 path/pixel (8 ms/frame)

Path traced: 1 path/pixel using ReSTIR GI (8.9 ms/frame)

Key idea: cache good paths, reuse good paths found from from prior frames or for prior pixels in same frame

[Ouyang et al. 2021]

Innovation 3: Neural network based denoising

Idea: Use neural image-to-image transfer methods to convert cheaper to compute (but noisy) ray traced images into higher quality images that look like they were produced by tracing many rays per pixel

High quality image (via expensive global illumination)

Rendering of surface albedo (no illumination — very cheap)

Rendering of surface normals
(no illumination — very cheap)

Recall: numerical integration of light (via Monte Carlo sampling) suffers from high variance, resulting in images with "noise"

16 paths/pixel


64 paths/pixel


256 paths/pixel


1024 paths/pixel


4096 paths/pixel

Denoised results


16 paths/pixel


16 paths/pixel (denoised)

64 paths/pixel (denoised)


256 paths/pixel (denoised)


1024 paths/pixel (denoised)
VICTROLA


4096 paths/pixel (denoised)


4096 paths/pixel (NOT DENOISED)

Summary

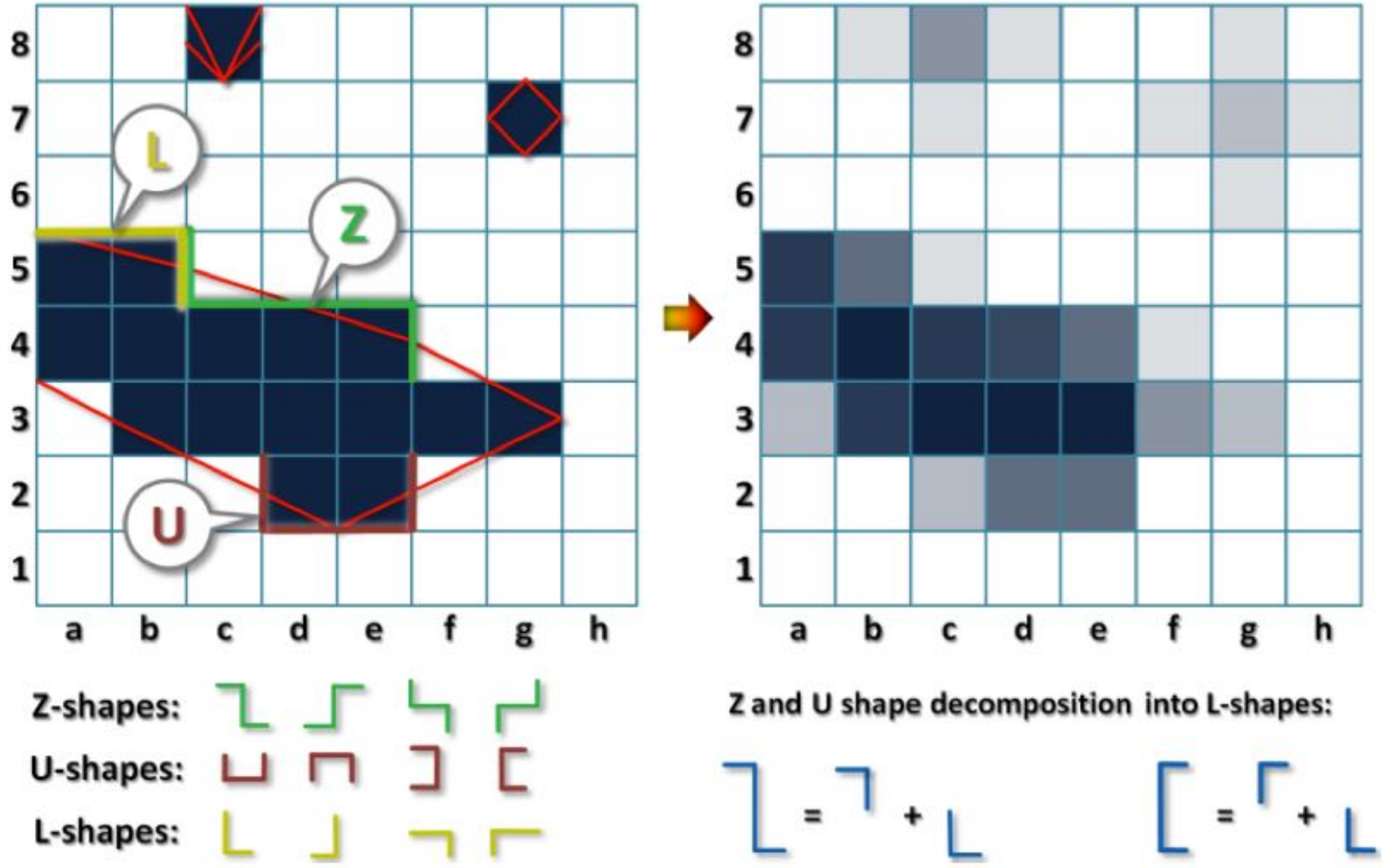
- Until very recently, it was too expensive to perform ray tracing in real-time graphics systems
- Many rasterization-based methods for approximating ray traced effects (shadows, reflections, etc).
- In the last five years, there's been a major shift toward using more ray tracing in real-time graphics systems
  - Brute force: new ray tracing hardware supported by graphics APIs (D3D12/Vulkan)
  - Algorithmic innovation: smarter ways to importance sample paths
  - Introduction of ML: use ML to convert noisy low sample count images to images that "look like" images that were ray traced at high sample counts

- Gradual introduction of ray tracing into shipping games

[Reshetov 09]

Morphological anti-aliasing (MLAA)

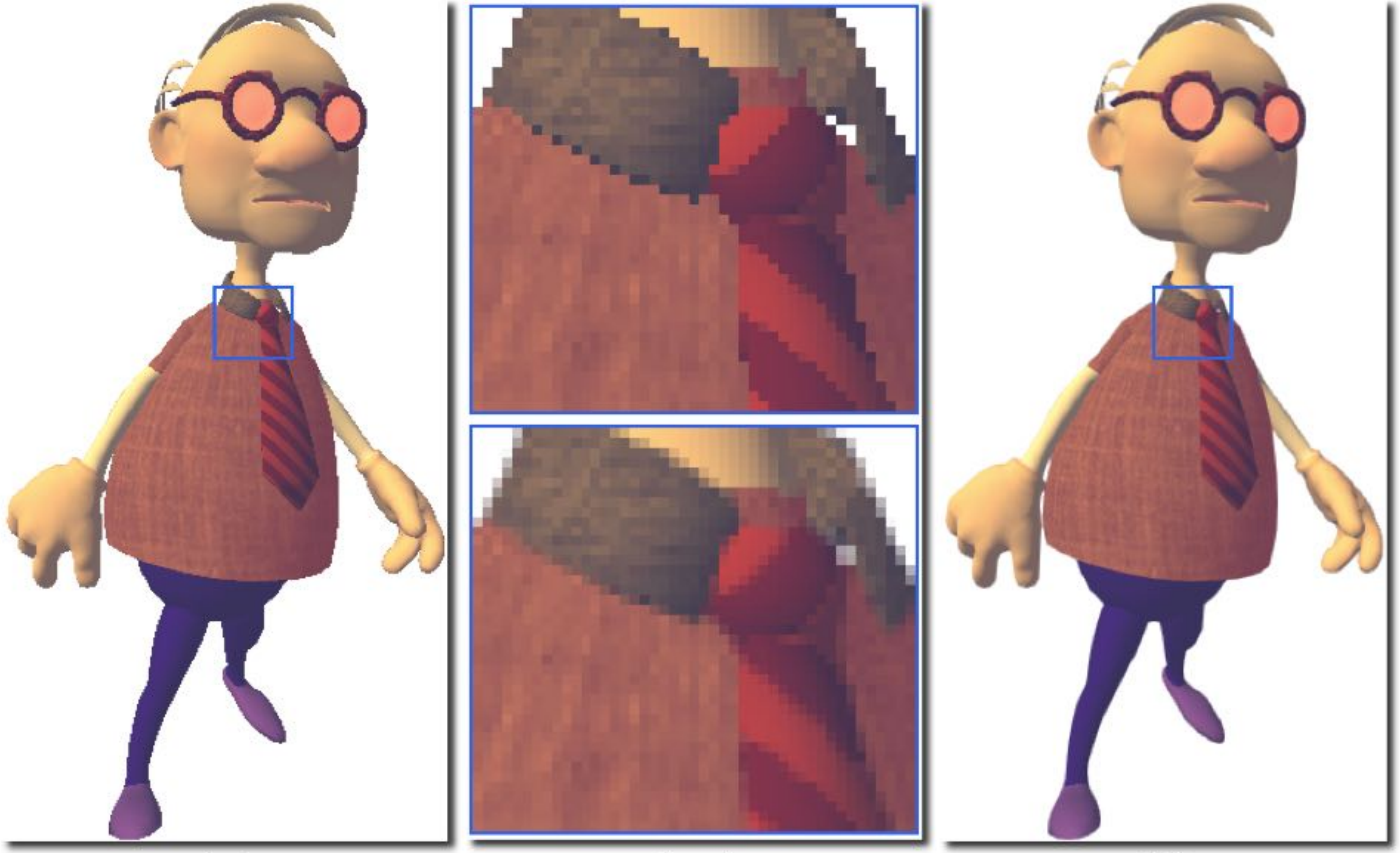
Detect careful designed patterns in rendered image
For detected patterns, blend neighboring pixels according to a few simple rules
("hallucinate" a smooth edge.. it's a hack!)



Note: modern interest in replacing MLAA patterns with DNN-based anti-aliasing.

Morphological anti-aliasing (MLAA)

[Reshetov 09]



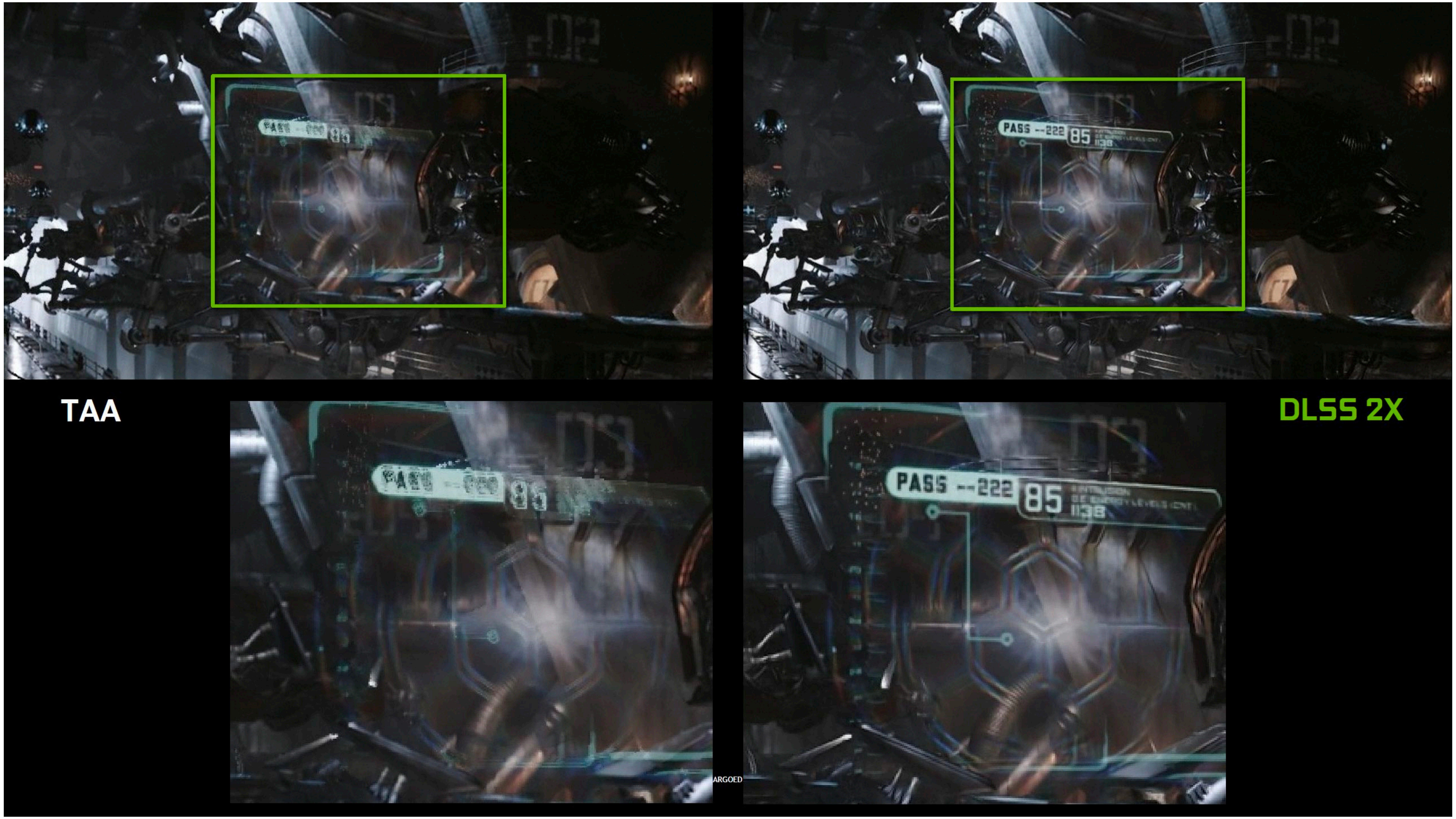
Aliased image
(one shading sample per pixel)

Zoomed views
(top: aliased, bottom: after MLAA)

After filtering using MLAA

Modern trend: learn anti-aliasing functions

Use modern image processing deep networks to reduce aliasing artifacts from rendered images.

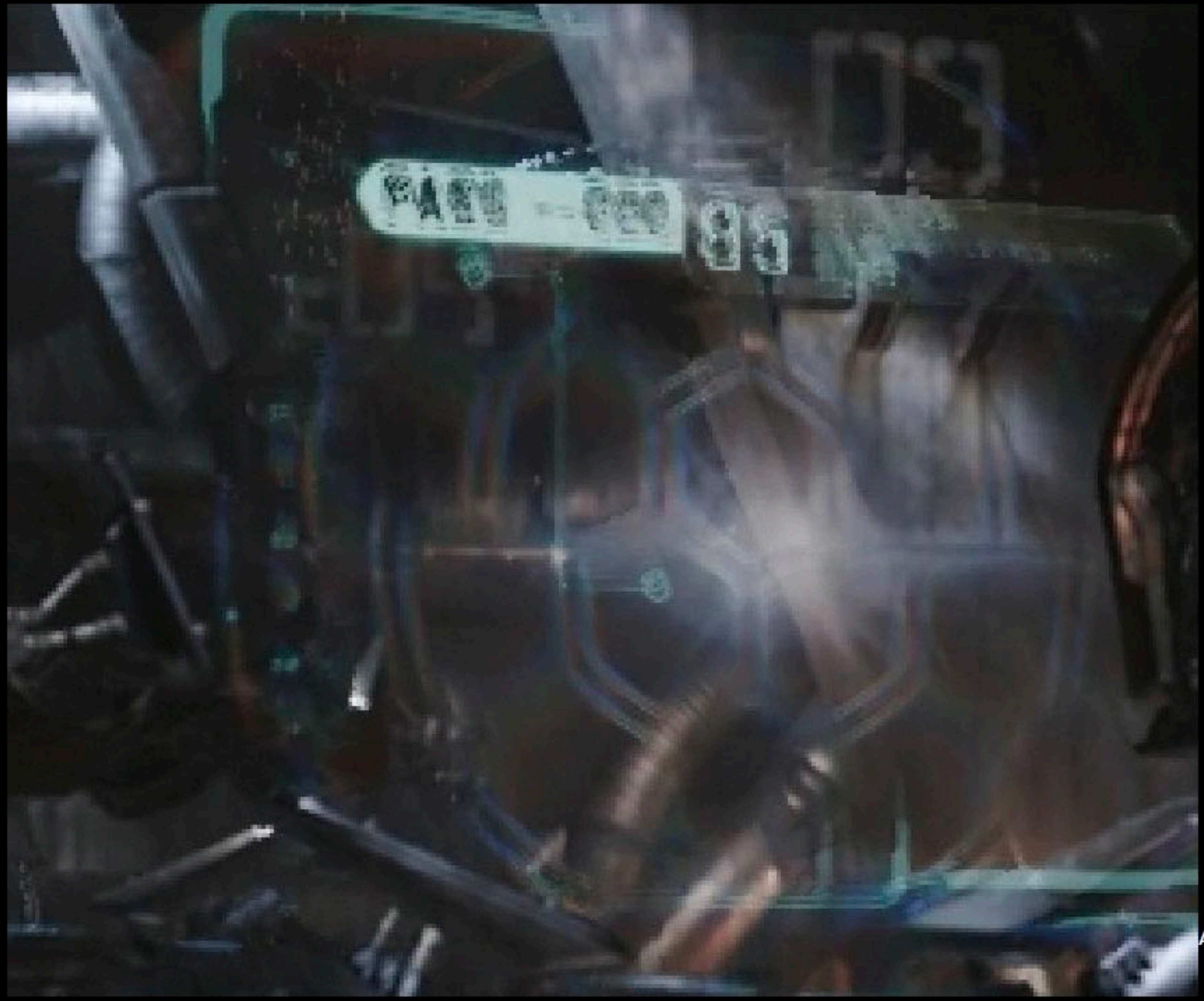


https://wccftech.com/nvidia-dlss-explained-nvidia-ngx/

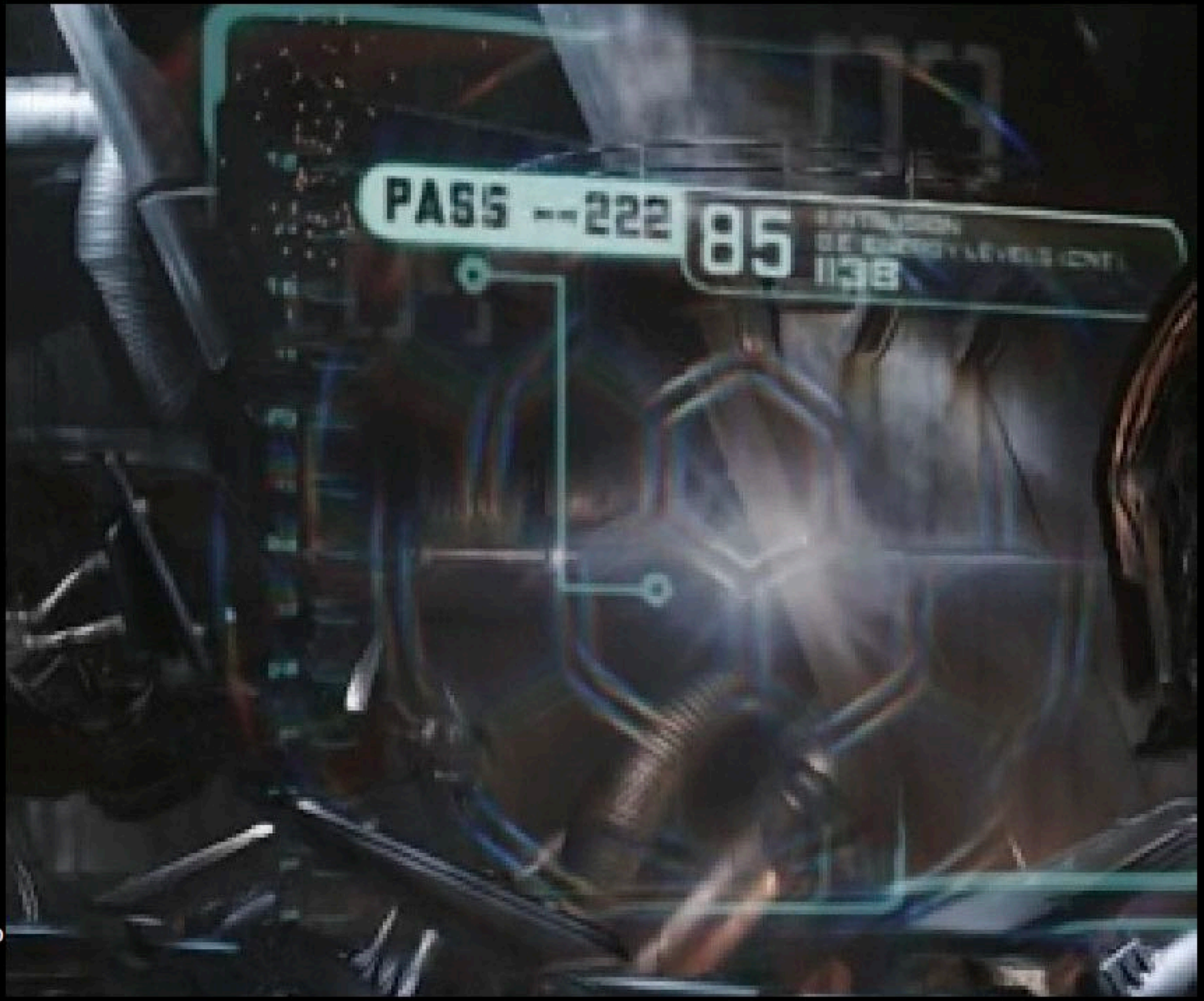
Learn anti-aliasing functions

Use modern image processing deep networks to reduce aliasing artifacts from rendered images.

Traditional Heuristic (TXAA)



Learned AA (DLSS)



https://wccftech.com/nvidia-dlss-explained-nvidia-ngx/

Summary: deferred shading

- Very popular technique in modern games
- Creative use of graphics pipeline
  - Create a G-buffer, not a final image
- Two major motivations
  - Convenience and simplicity of separating geometry processing logic/costs from shading costs
  - Potential for high performance under complex lighting and shading conditions
    - Shade only once per sample despite triangle overlap
    - Often more amenable to "screen-space shading techniques"
      - e.g., screen space ambient occlusion