Lecture 17:

Modern Rendering Techniques Using the Graphics Pipeline

Interactive Computer Graphics

Stanford CS248, Winter 2019

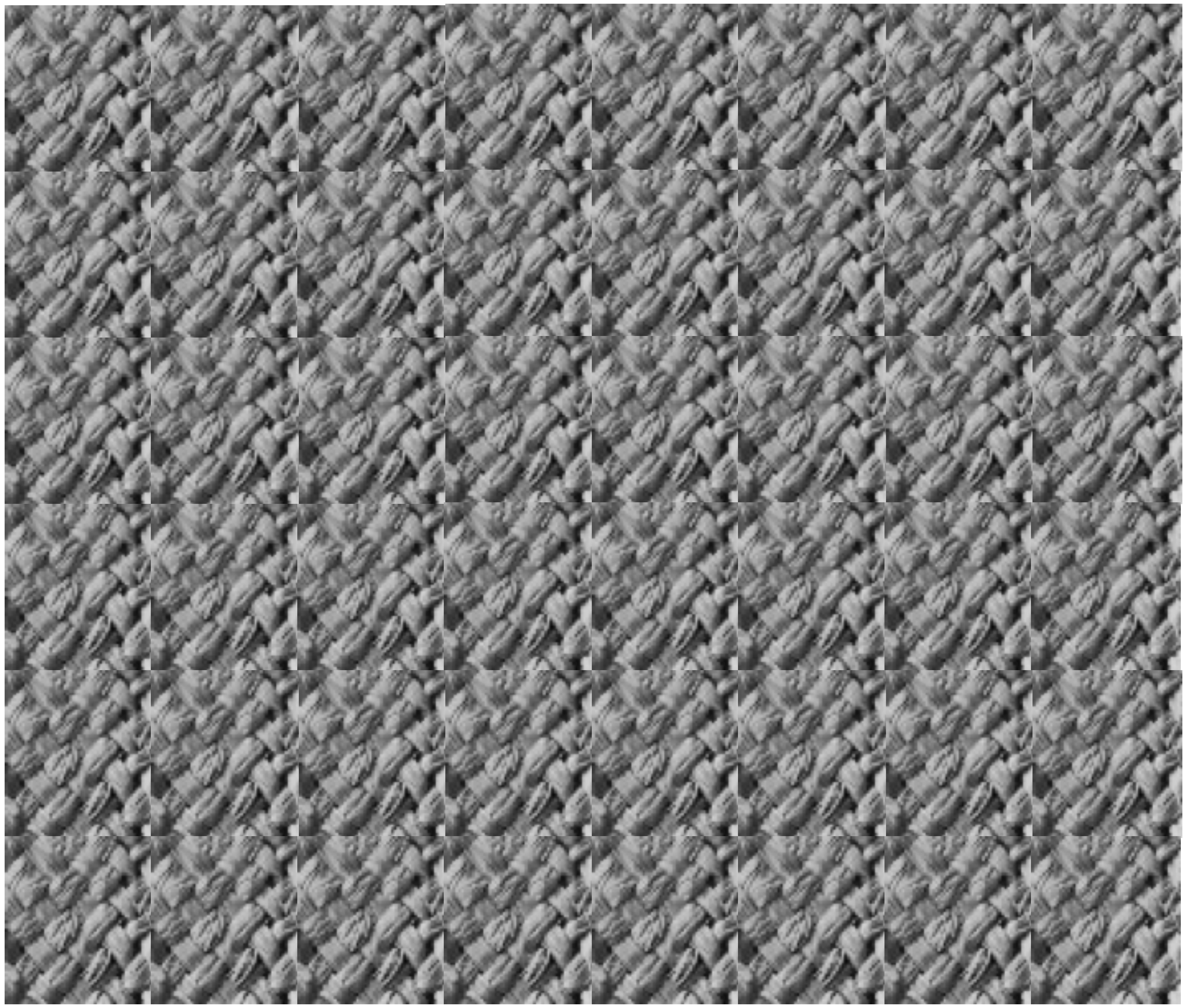
Left over from last time…

Data-driven texture synthesis

- Input: low resolution texture image
- Want: high resolution texture that appears "like" the input

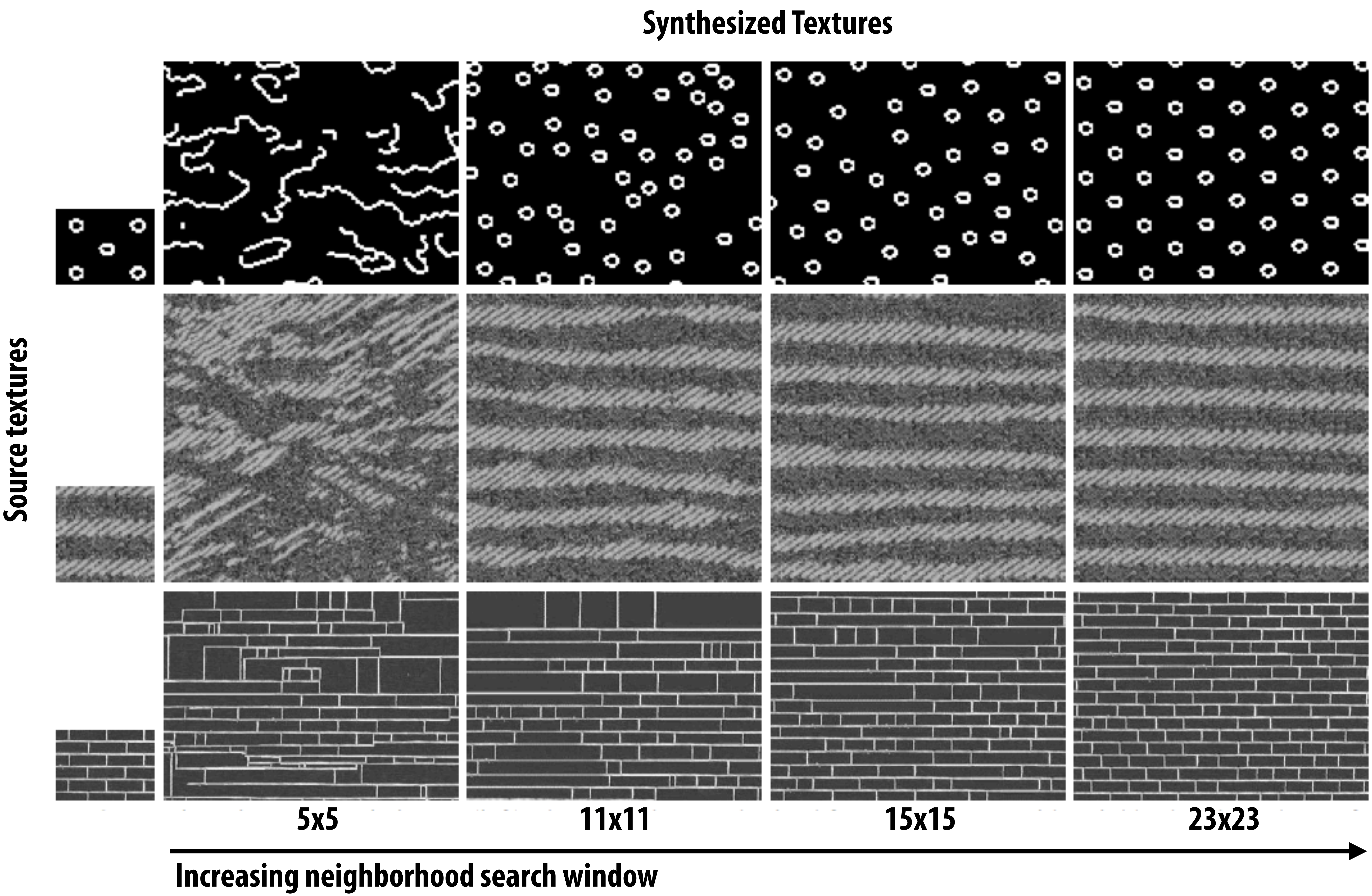
Source texture (low resolution)

High resolution texture generated by tiling



Non-parametric texture synthesis

[Efros and Leung 99]



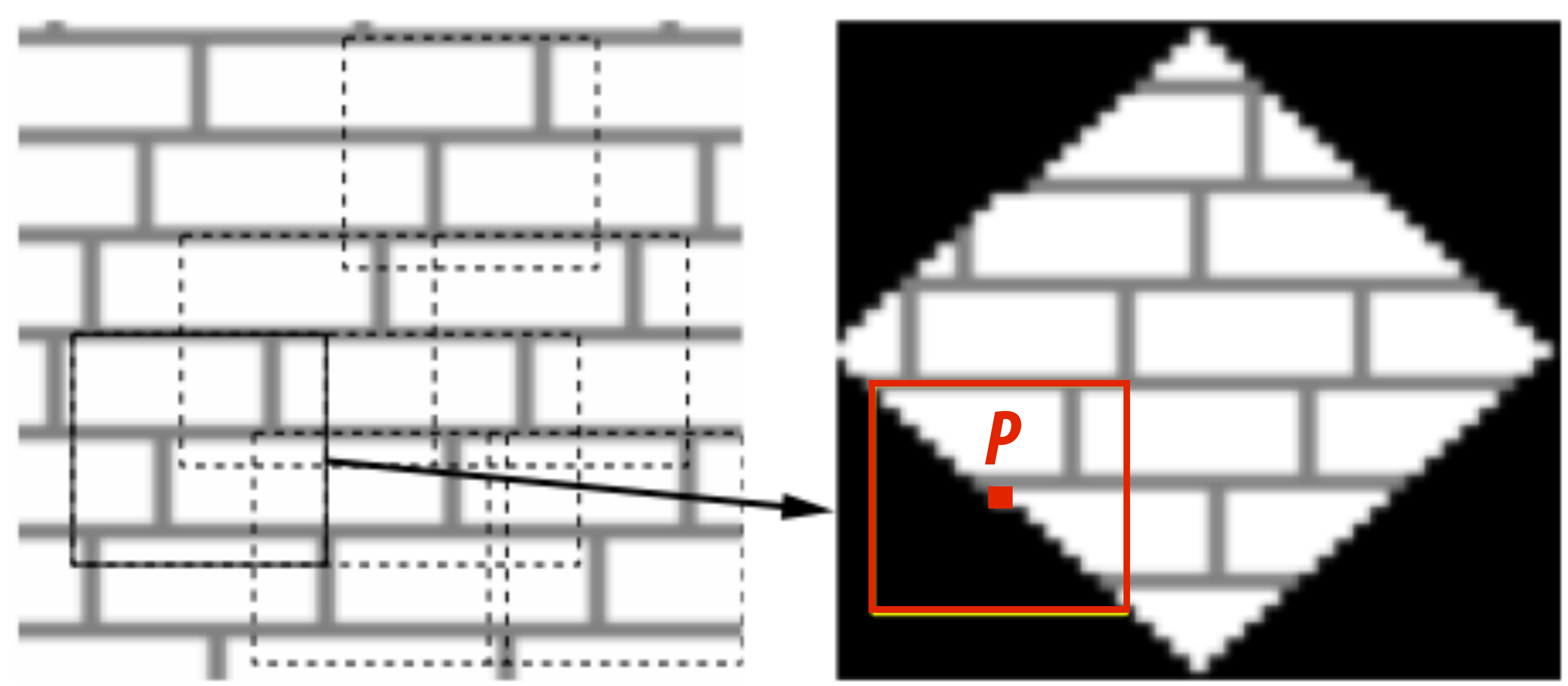
Algorithm: non-parametric texture synthesis

Main idea: given NxN neighborhood *w*(*p*) around unknown pixel *p*, want probability distribution function for value of p, given *w*(*p*).

```
For each pixel p to synthesize:
    1. Find other patches in the image that are similar to the
       NxN neighborhood around p

    2. Center pixel of patches are candidates for p

    3. Randomly sample from candidates weighted by distance d
```



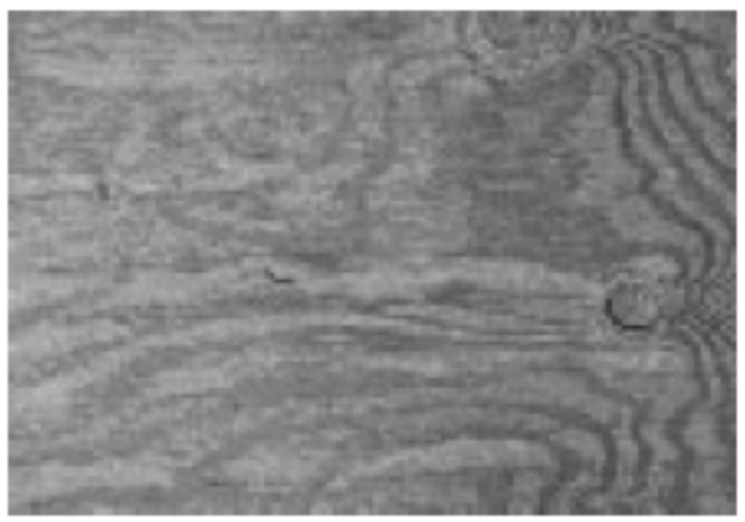
[Efros and Leung 99]

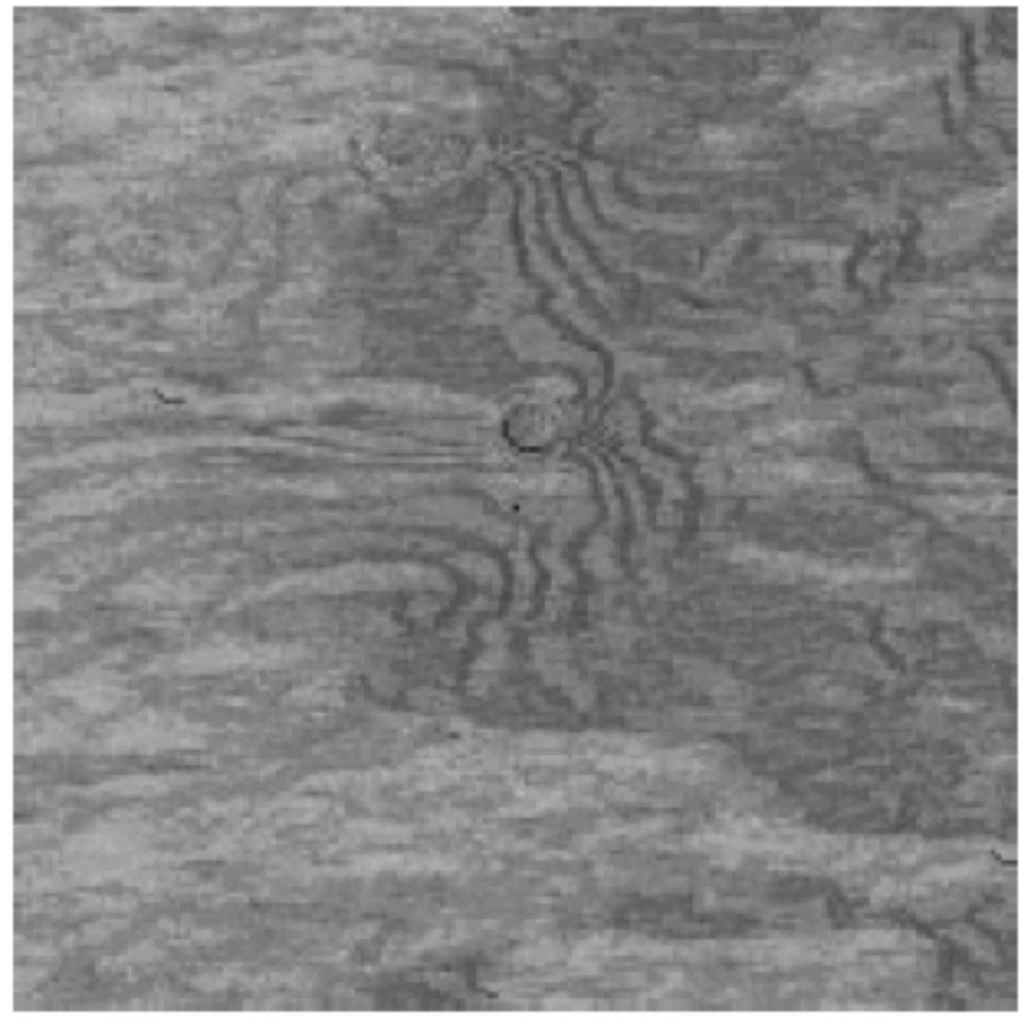
More texture synthesis examples

[Efros and Leung 99]

Source textures

Synthesized Textures





Naive tiling solution

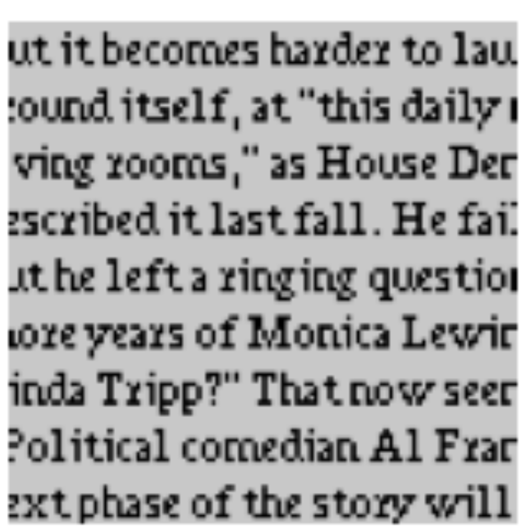


Image completion example

Image credit: [Barnes et al. 2009]

Original Image

Masked Region

Completion Result

Problem: low performance

- Large patch windows + full image search = slow
  - Large windows: preserve structure
  - Full-image search: highly relevant examples are rare
- Must repeat search process for all pixels
- Possible accelerations
  - Limit search window
  - Use acceleration structure for search (e.g., k-d tree)
  - Dimensionality reduction of patches + approximate nearest neighbor search
  - Exploit image coherence

PatchMatch

[Barnes et al. 2009]

- A randomized algorithm for rapidly finding correspondences between image patches

- Problem definition:
  - Given images A and B, for each overlapping patch in image A, compute the offset to the nearest neighbor patch in image B
  - Overlapping patches: each patch defined by its center pixel (ignoring boundary conditions, each MxN image consists of MxN patches)
  - PatchMatch computes "nearest neighbor field" (NNF)
    - NNF is function $f\colon A \rightarrow \mathbb{R}^2$ (maps patches in A to patches in B)
    - Example: if patch *b* in image B is NN of patch *a* in image A, then *f*(a) = b

PatchMatch idea #1

- **Law of large numbers: a non-trivial fraction of a large field of random offset assignments are likely to be good guesses**
- **Initialize *f* with random values**

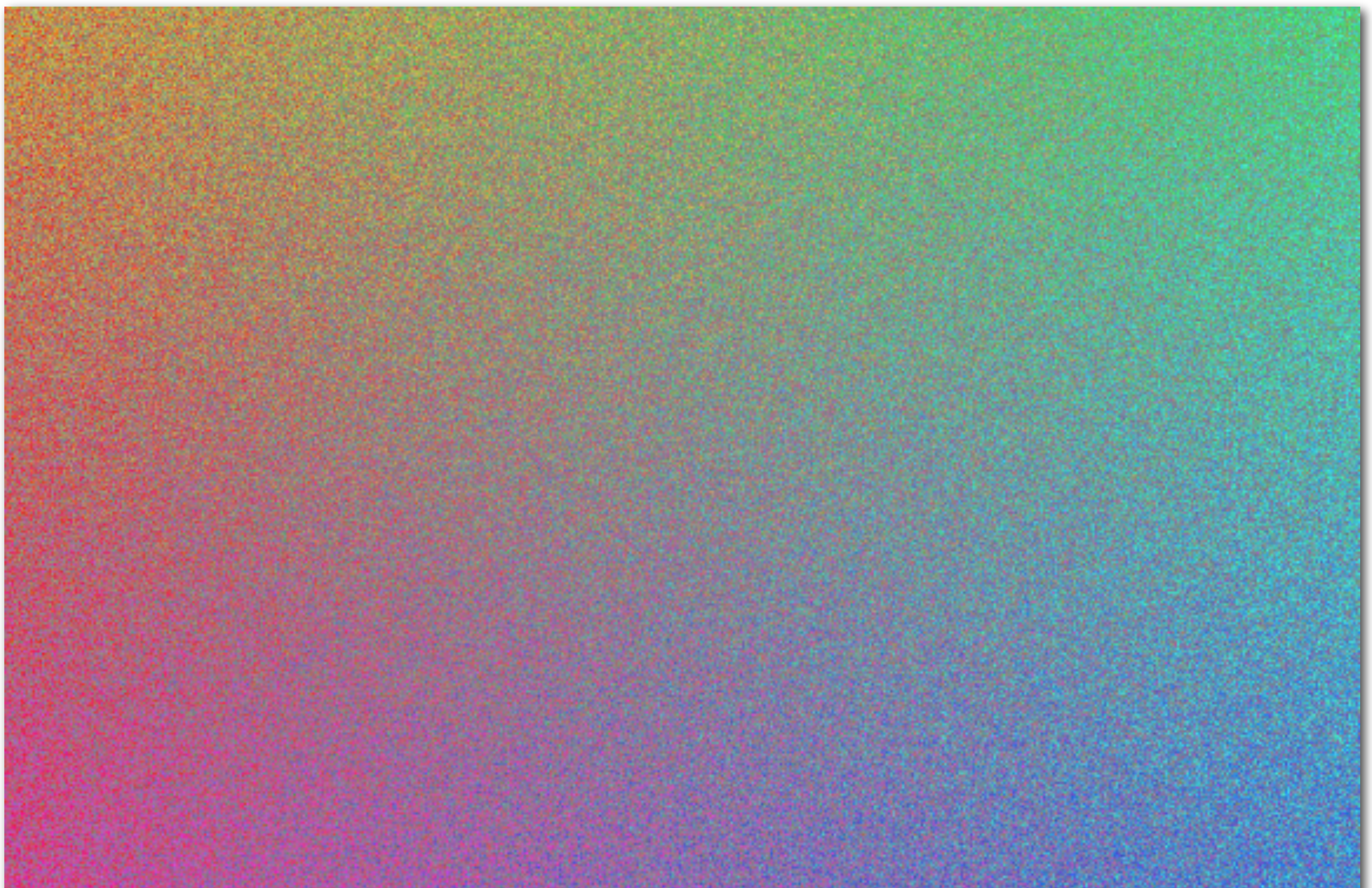


Image credit: [Barnes et al. 2009]

Visualization of *f*:

Saturation = magnitude of match offset (gray indicates matching patch in B is at same pixel location as match patch in A)

Hue = direction of offset
offset X = red-cyan axis
offset Y = blue-yellow axis

PatchMatch idea #2: spatial coherence

- High coherence of nearest neighbors in natural images
- Nearest neighbor of patch at (x,y) should be a strong hint for where to find nearest neighbor of patch at (x+1,y)

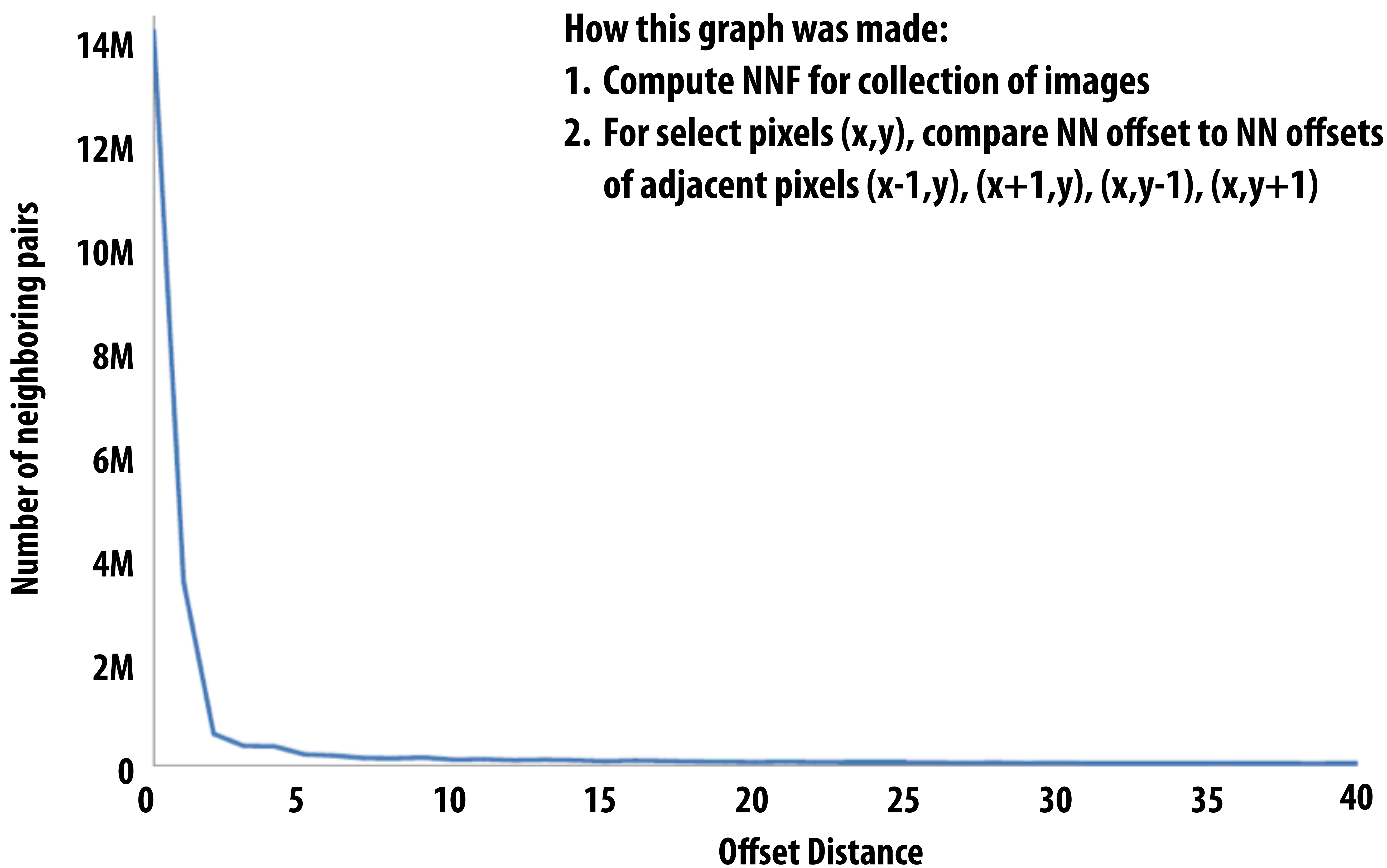


Image credit: [Barnes et al. 2009]

Propagation: improving the NNF estimate

- The NNF estimate provides a "best-so-far" NN for each patch in A
  - NN patch: $f(a)$
  - NN distance = $d(a,b)$ (where $b=f(a)$)

- Try to improve NNF estimate by exploiting spatial coherence with left and top neighbor:
  - Let $a=(x,y)$, then candidate matches for a are:
    - $f(x\text{-}1, y) + (1,0)$
    - $f(x, y\text{-}1) + (0,1)$
  - If candidate patch is better match than $f(a)$, then replace $f(a)$ with candidate
    - Replace $f(a)$ with candidate patch if $d(a, f(x,y\text{-}1)+(0,1)) < d(a, f(a))$

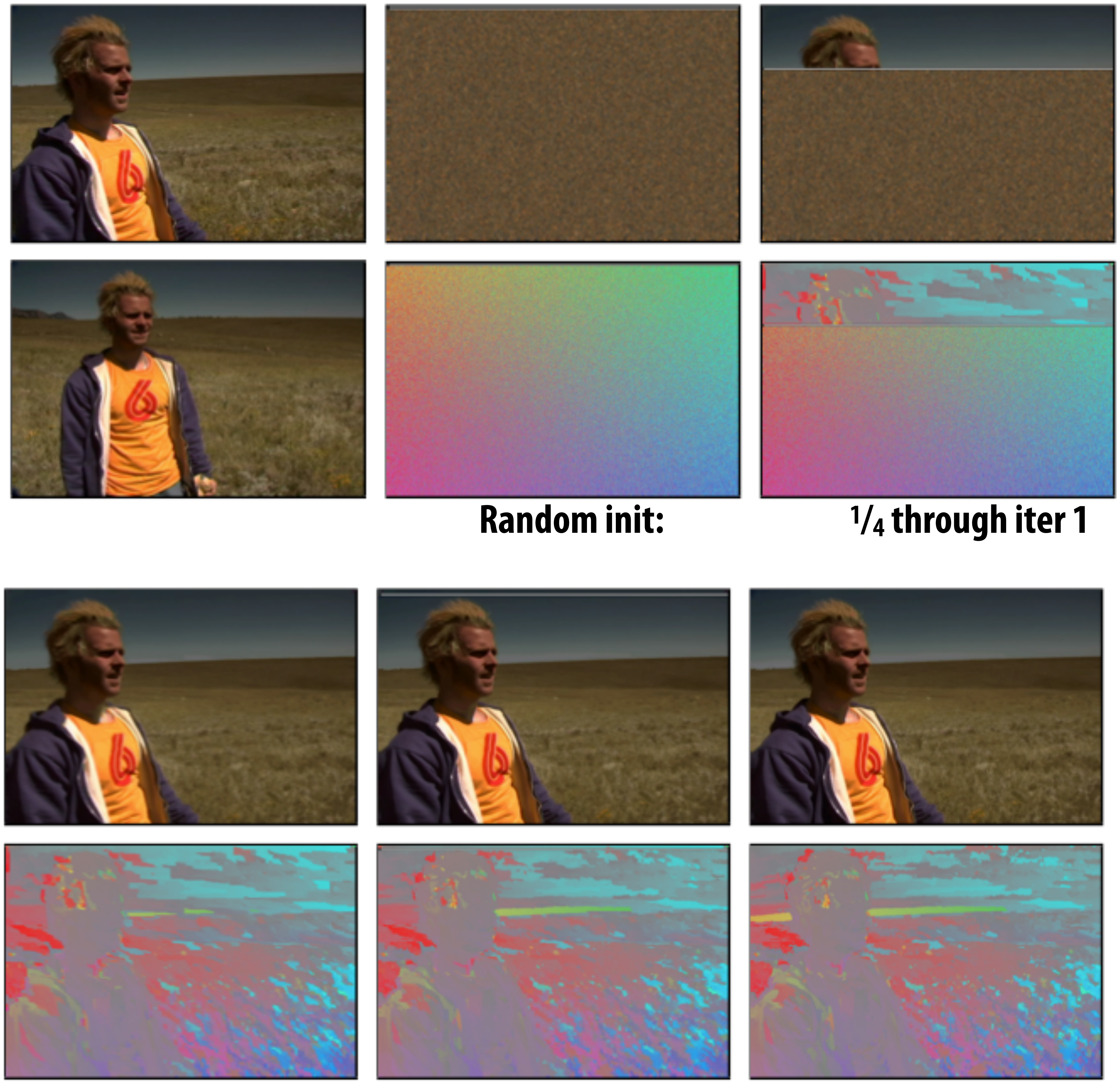
- Next iteration, use bottom and right neighbors as candidates

PatchMatch iterative improvement

Experiment:
Reconstruct A using patches from B

Image A

Image B (source of patches)



Random init:

¼ through iter 1

End of iter 1

Iter 2

Iter 5

Image credit: [Barnes et al. 2009]

Random search: avoiding local minima

- Propagation can cause PatchMatch to get stuck in local minima

- Sample random sequence of candidates from exponential distribution
  - Let ***a***=(***x***,***y***), then candidate matches for ***a*** are: $(x,y) + w\alpha^i R^i$
  - R^i is uniform random offset in [-1,1]x[-1,1]
  - w is maximum search radius (e.g., width of entire image)
  - α is typically 1/2
  - Check all candidates where $w\alpha^i \geq 1$

Example applications

Photoshop's Content Aware Fill

Object Manipulation

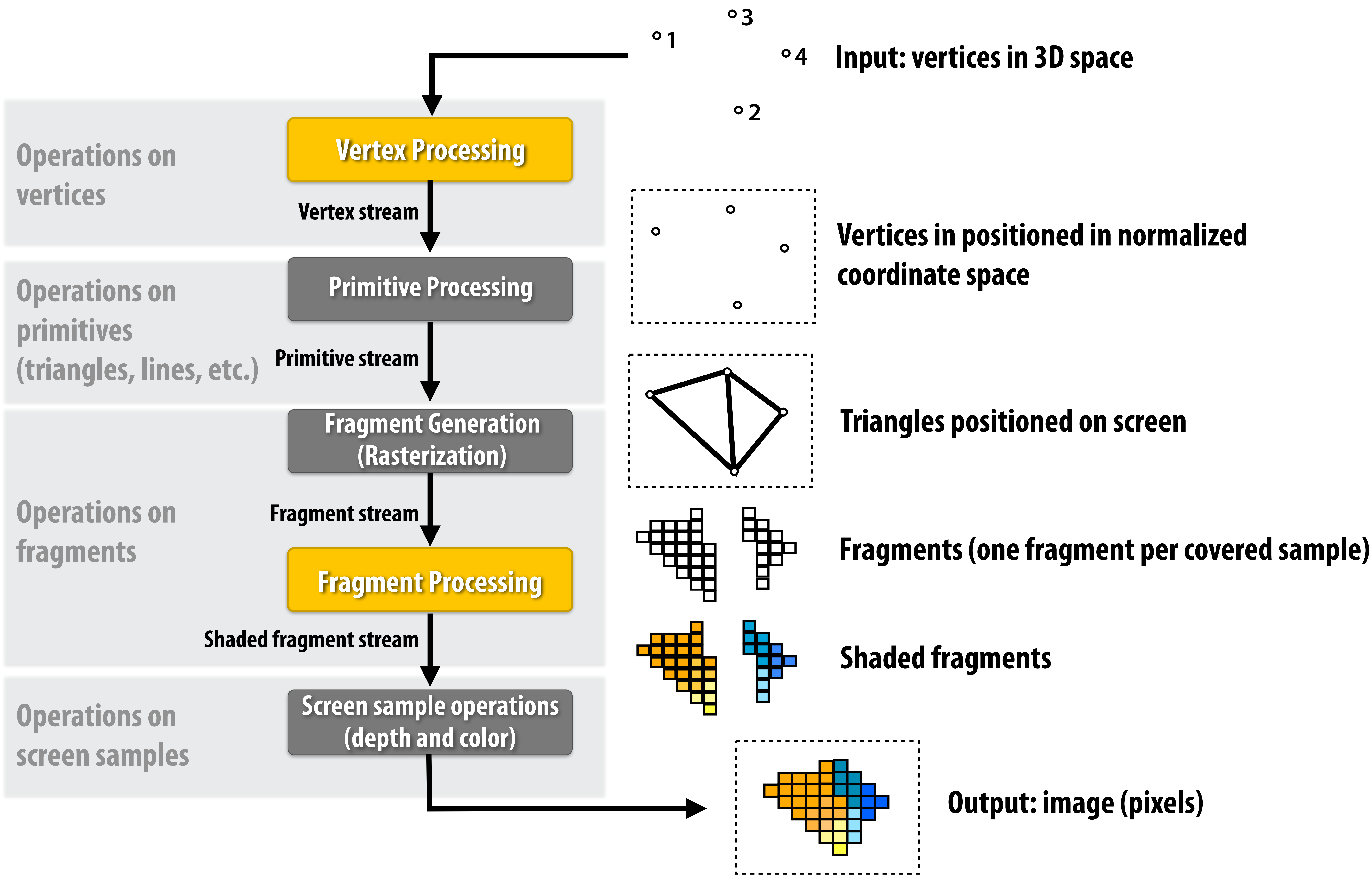
Building segment marked by user

Building scaled up, preserving texture

Image credits: [Barnes et al. 2009]

Back to today's lecture…

Recall: OpenGL/Direct3D graphics pipeline



Theme of this part of the lecture:

A surprising number of advanced lighting effects can be efficiently approximated using the basic primitives of rasterization pipeline, without the need to actually ray trace the scene geometry:

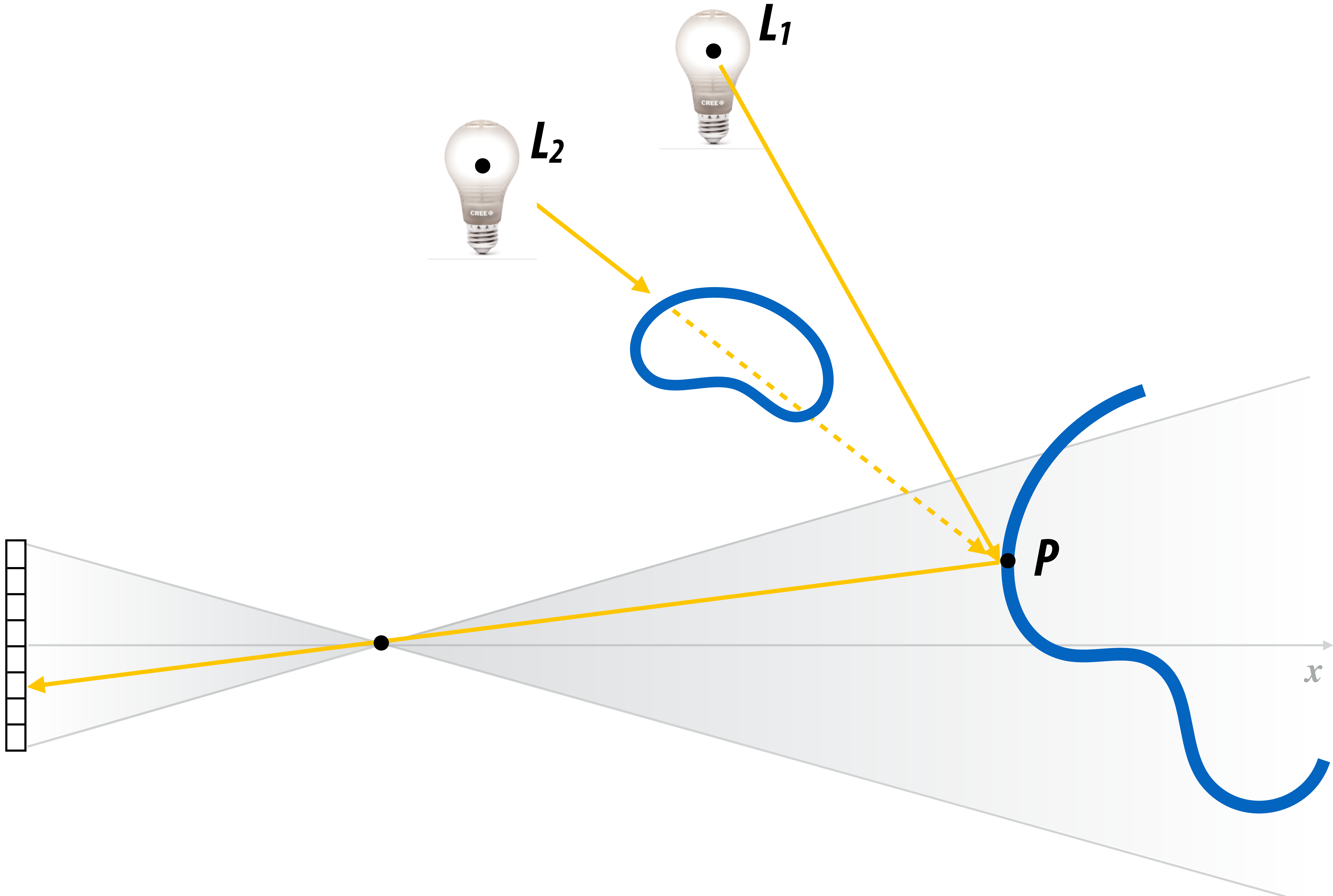
- Rasterization
- Texture mapping
- Depth buffer for occlusion

Shadows

Shadows

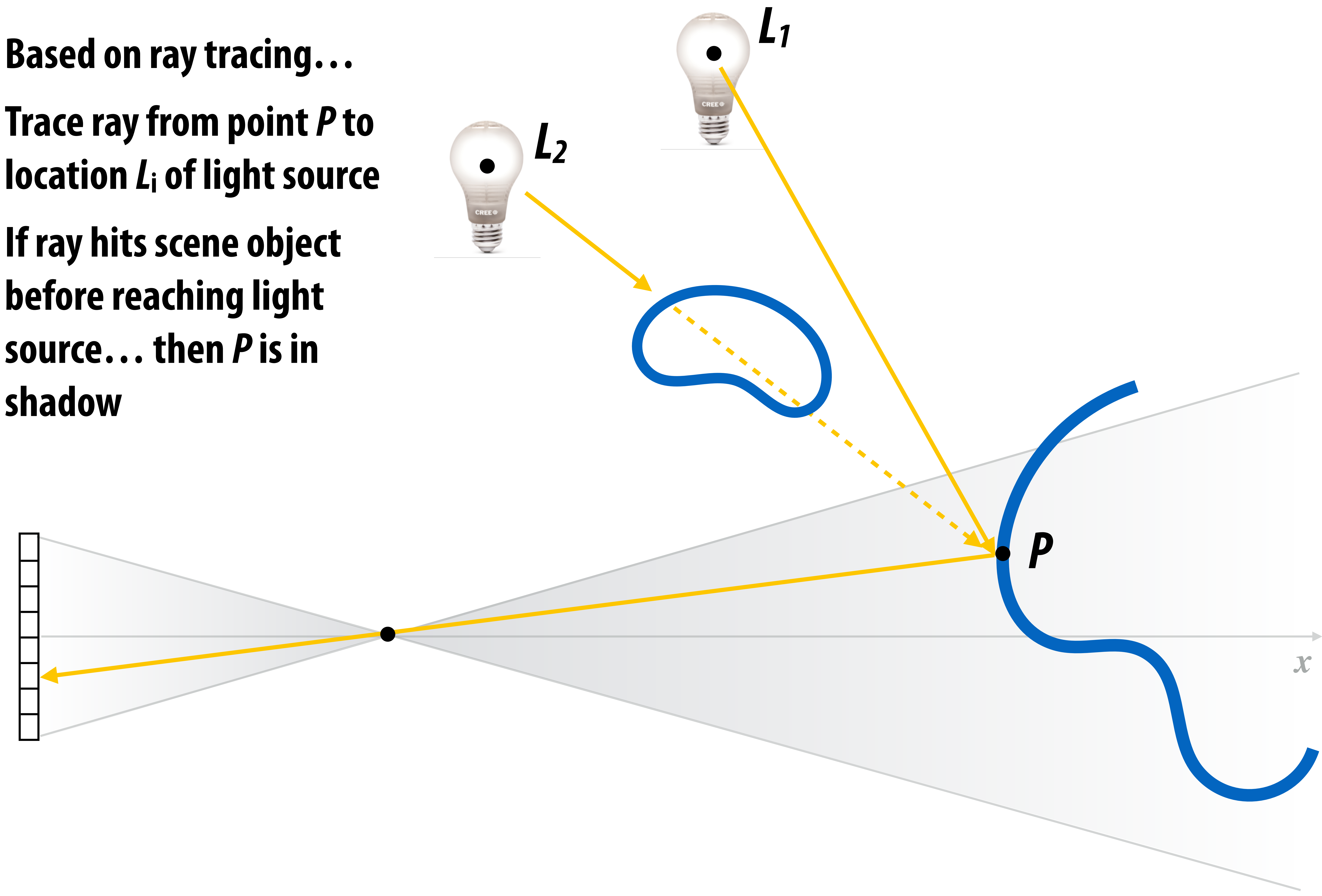
Image credit: Grand Theft Auto V

How to compute if a surface is in shadow?



Review: How to compute if a surface is in shadow?

- Based on ray tracing…
- Trace ray from point P to location L_i of light source
- If ray hits scene object before reaching light source… then P is in shadow

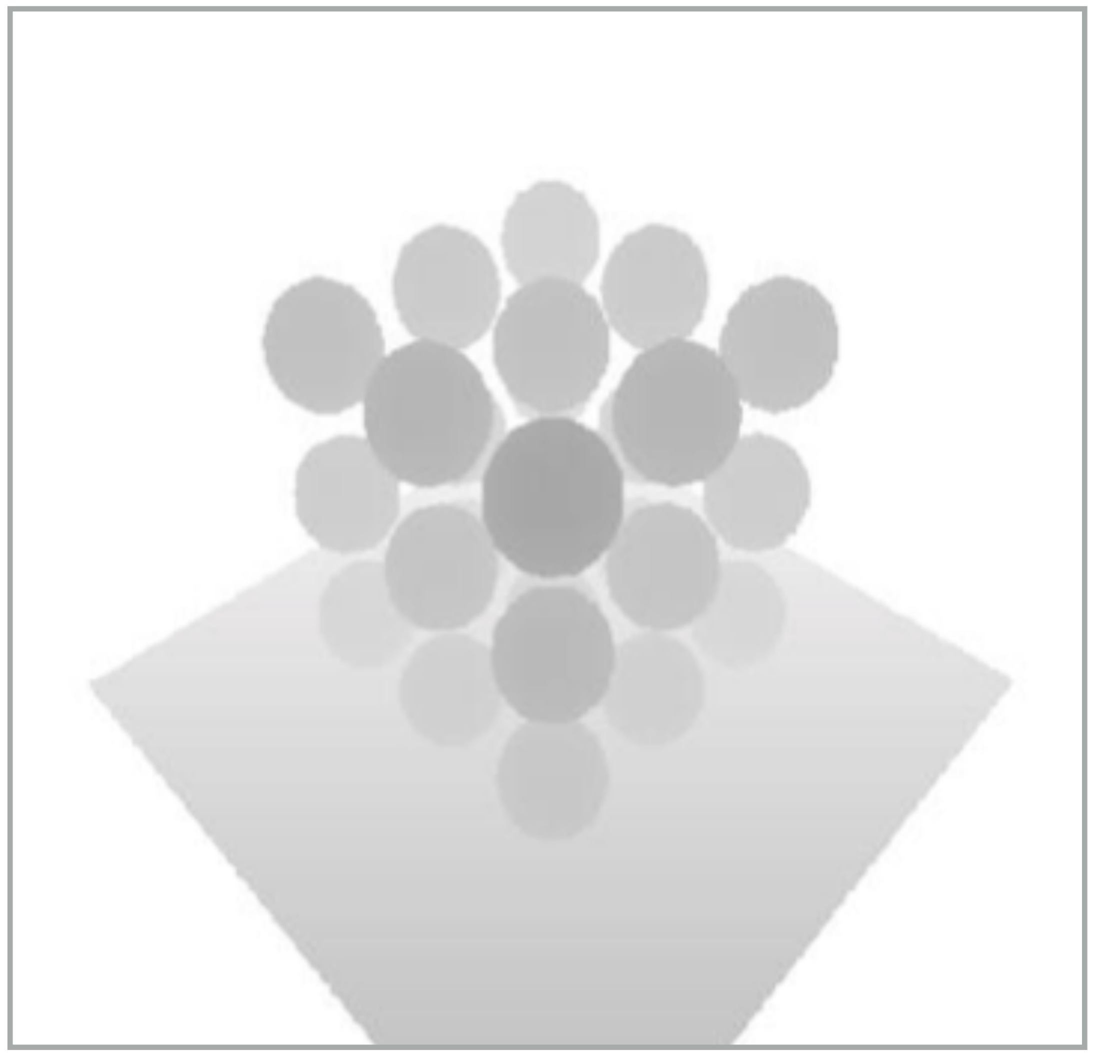


Shadow mapping version (recall Assignment 3)

[Williams 78]

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

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



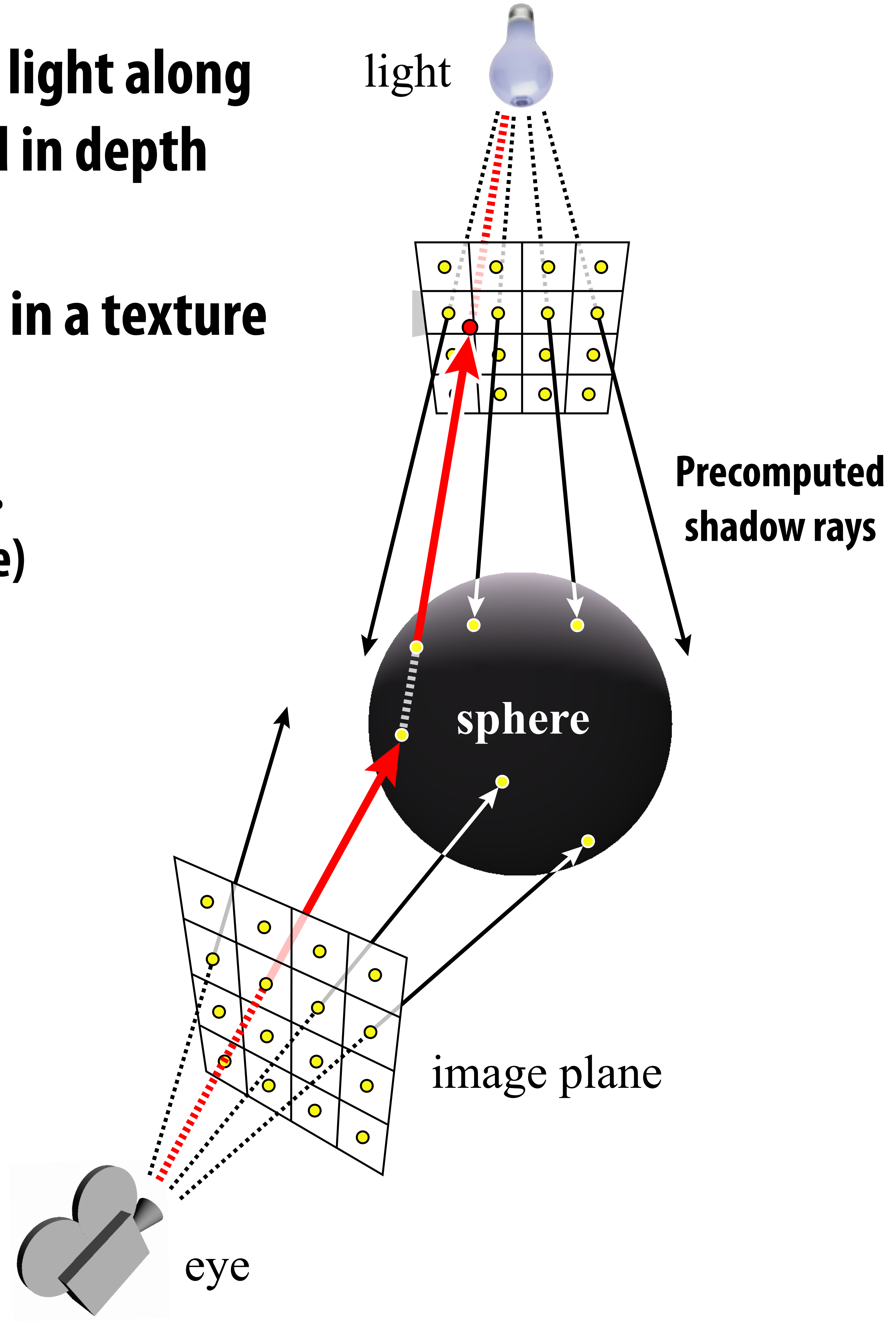
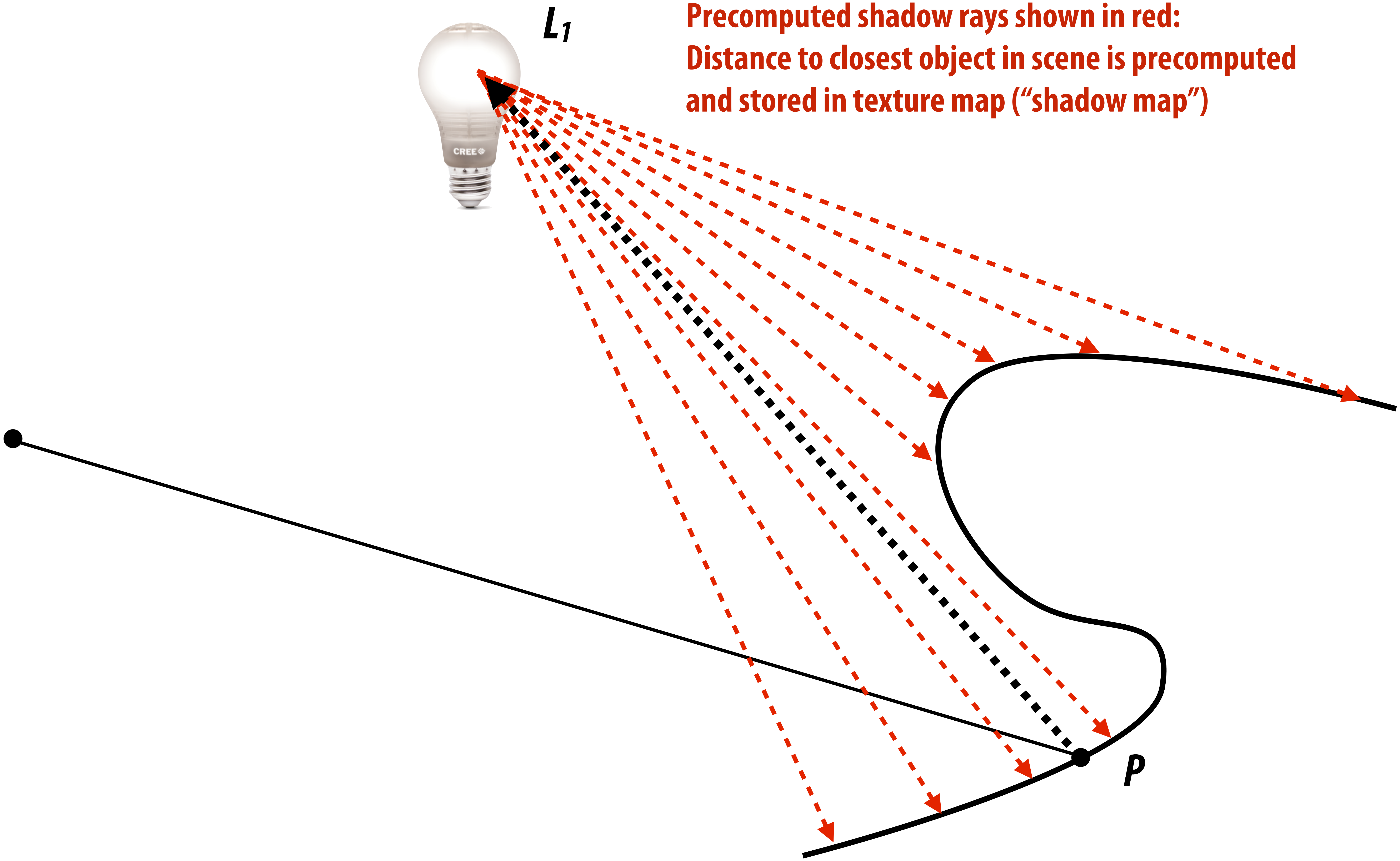


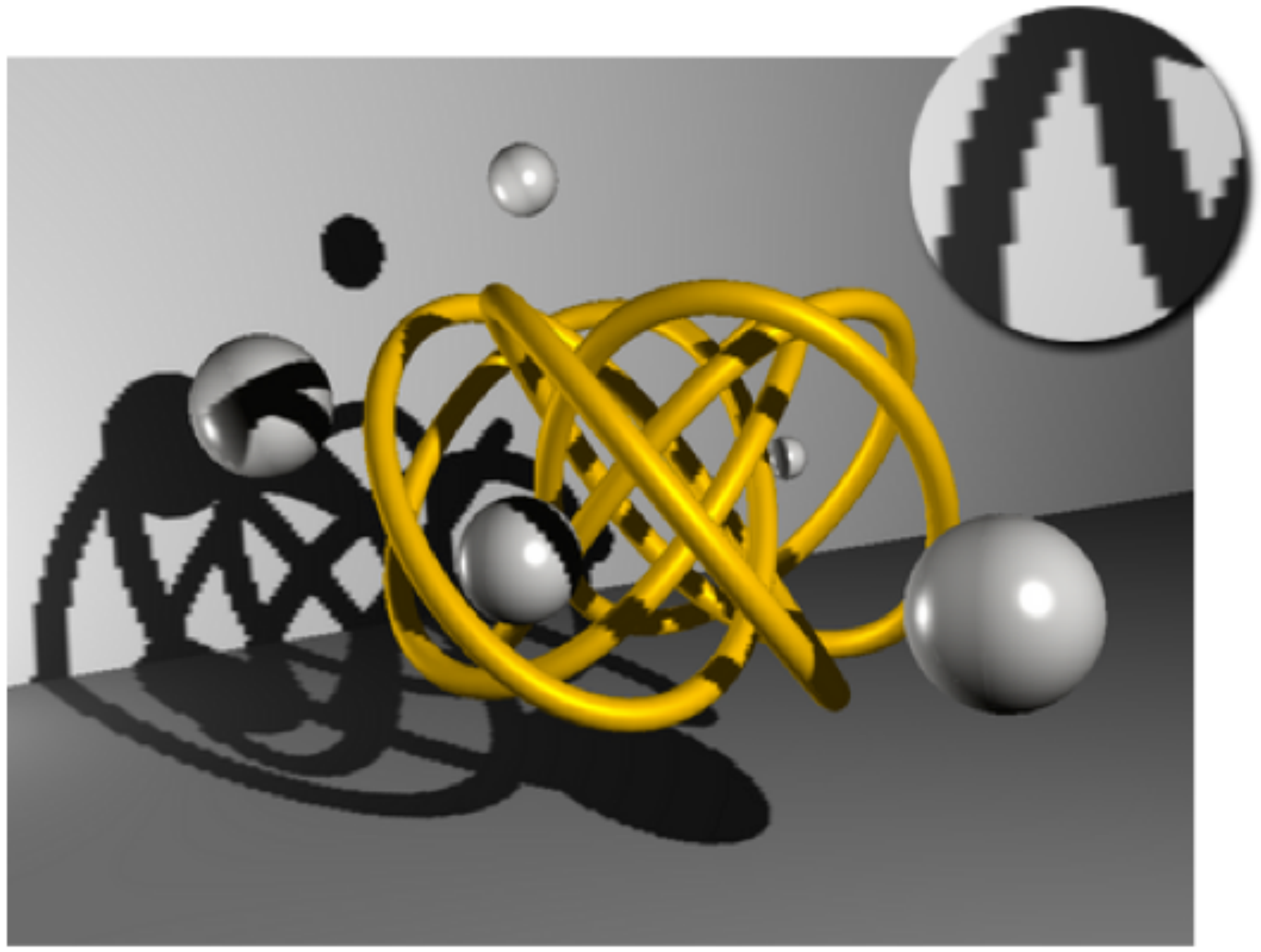
Image credits: Segal et al. 92, NVIDIA

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

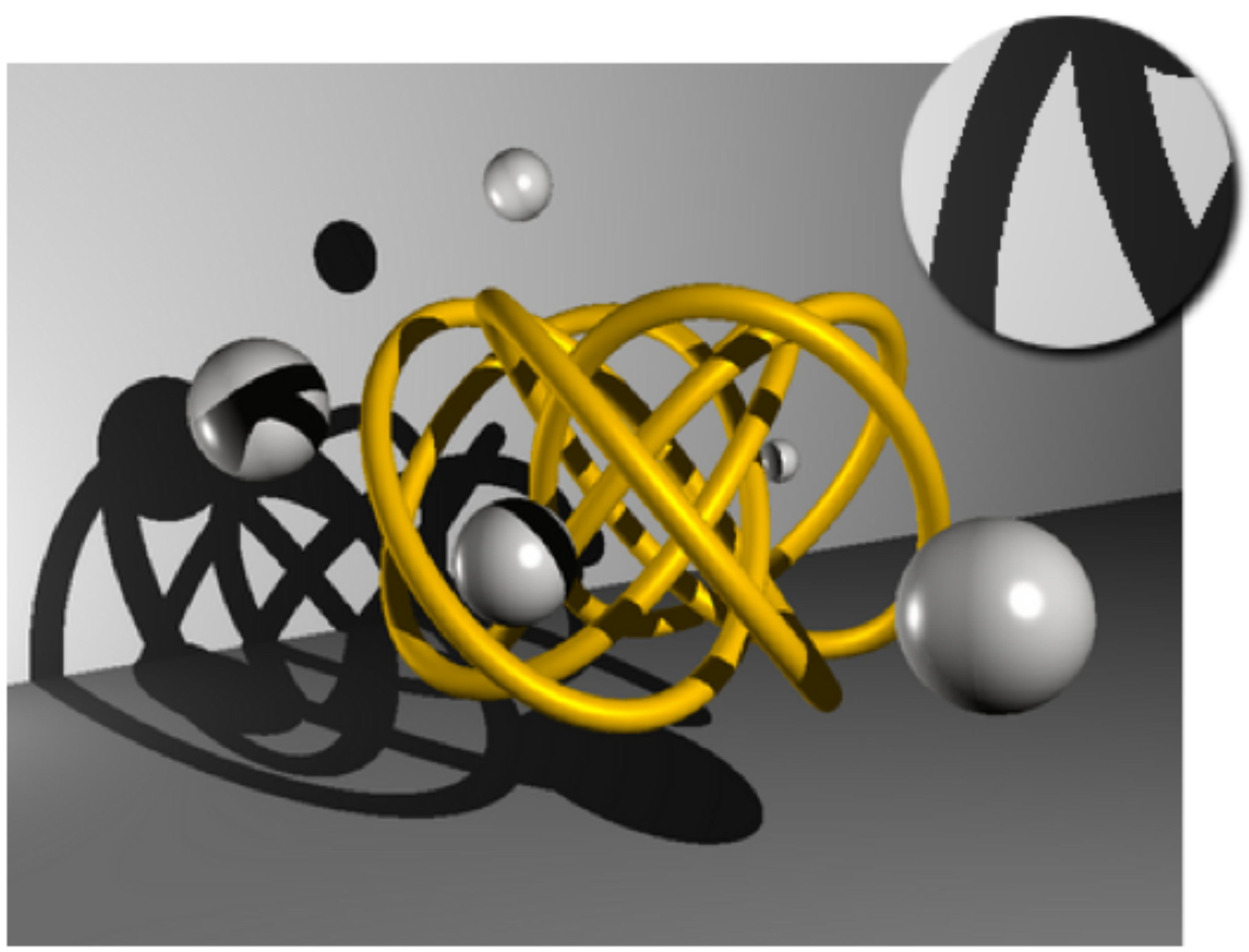


Precompuited shadow rays shown in red:
Distance to closest object in scene is precomputed and stored in texture map ("shadow map")

Shadow aliasing due to shadow map undersampling



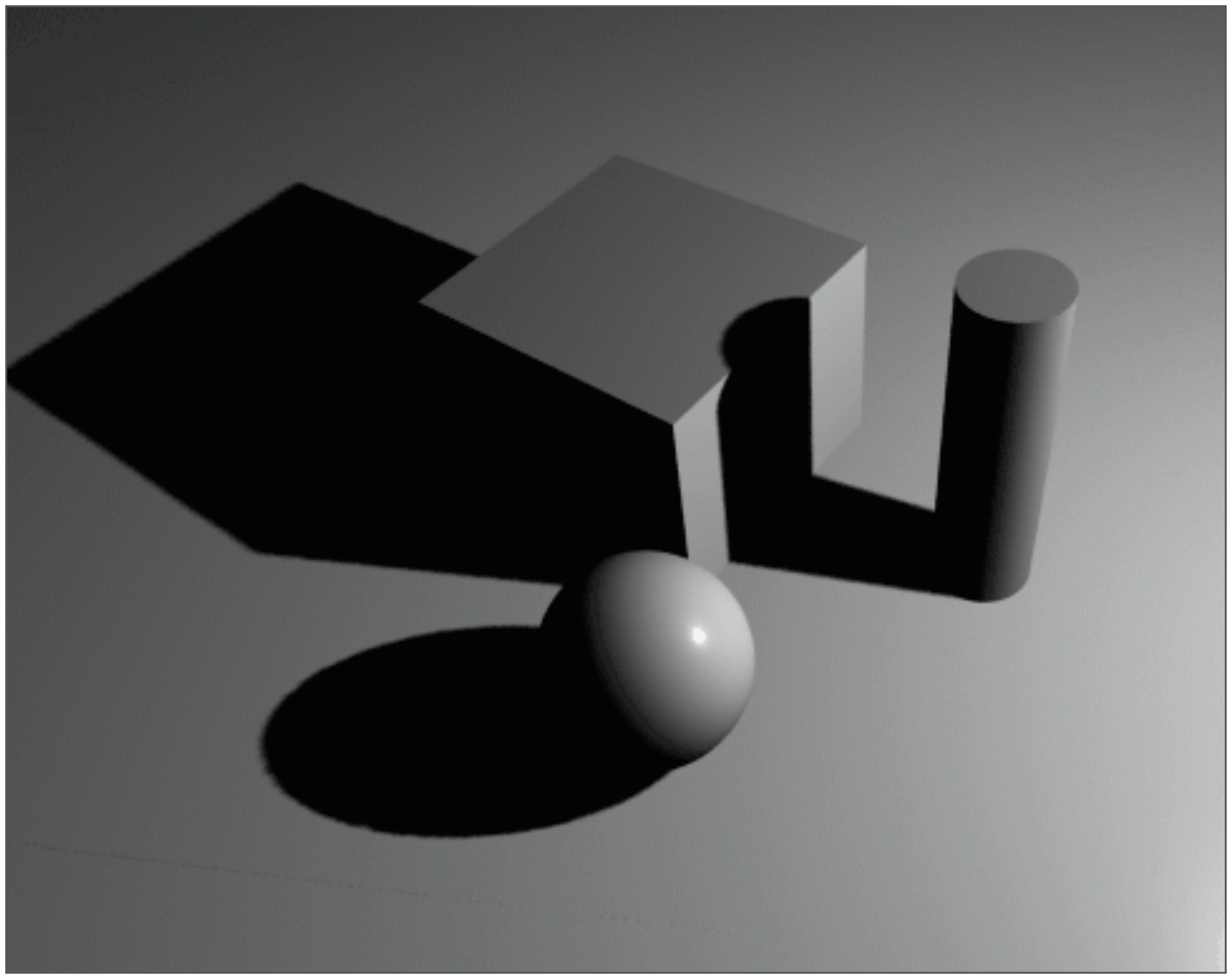
Shadows computed using shadow map



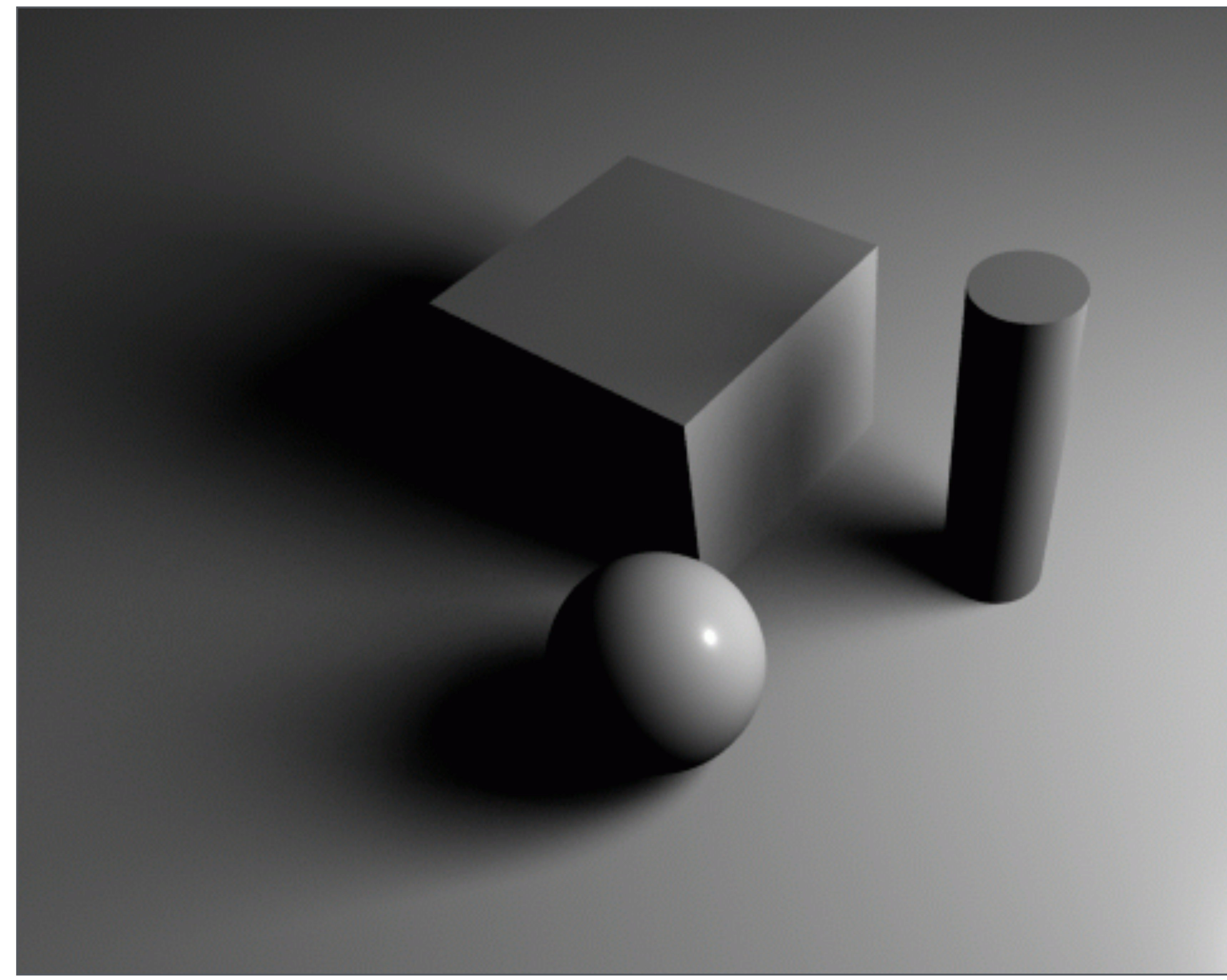
Correct hard shadows
(result from computing v(x′,x″) directly using ray tracing)

Image credit: Johnson et al. TOG 2005

Soft shadows



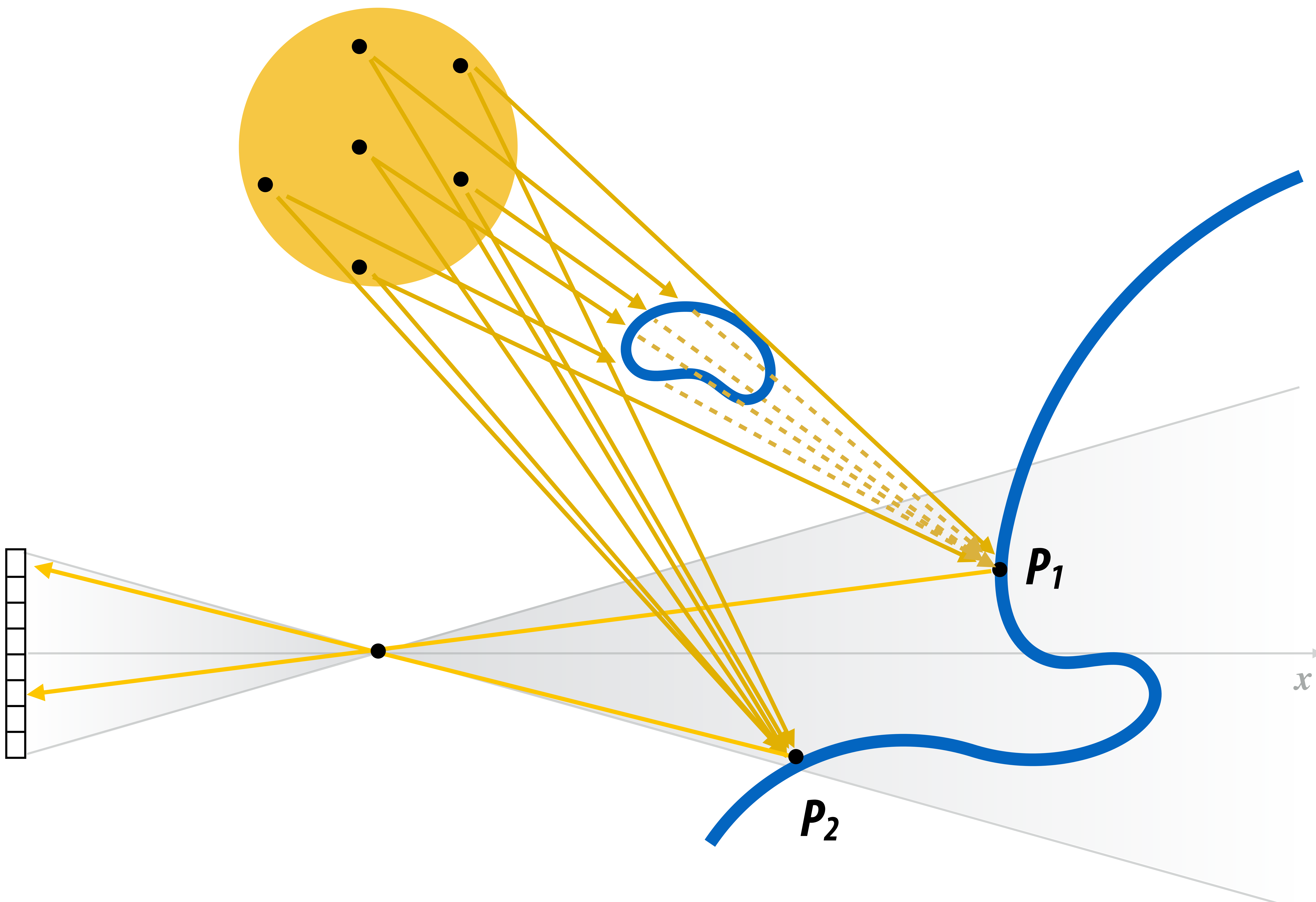
Hard shadows
(created by point light source)



Soft shadows
(created by ???)

Image credit: Pixar

Shadow cast by an area light



Percentage closer filtering (PCF) — hack!

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

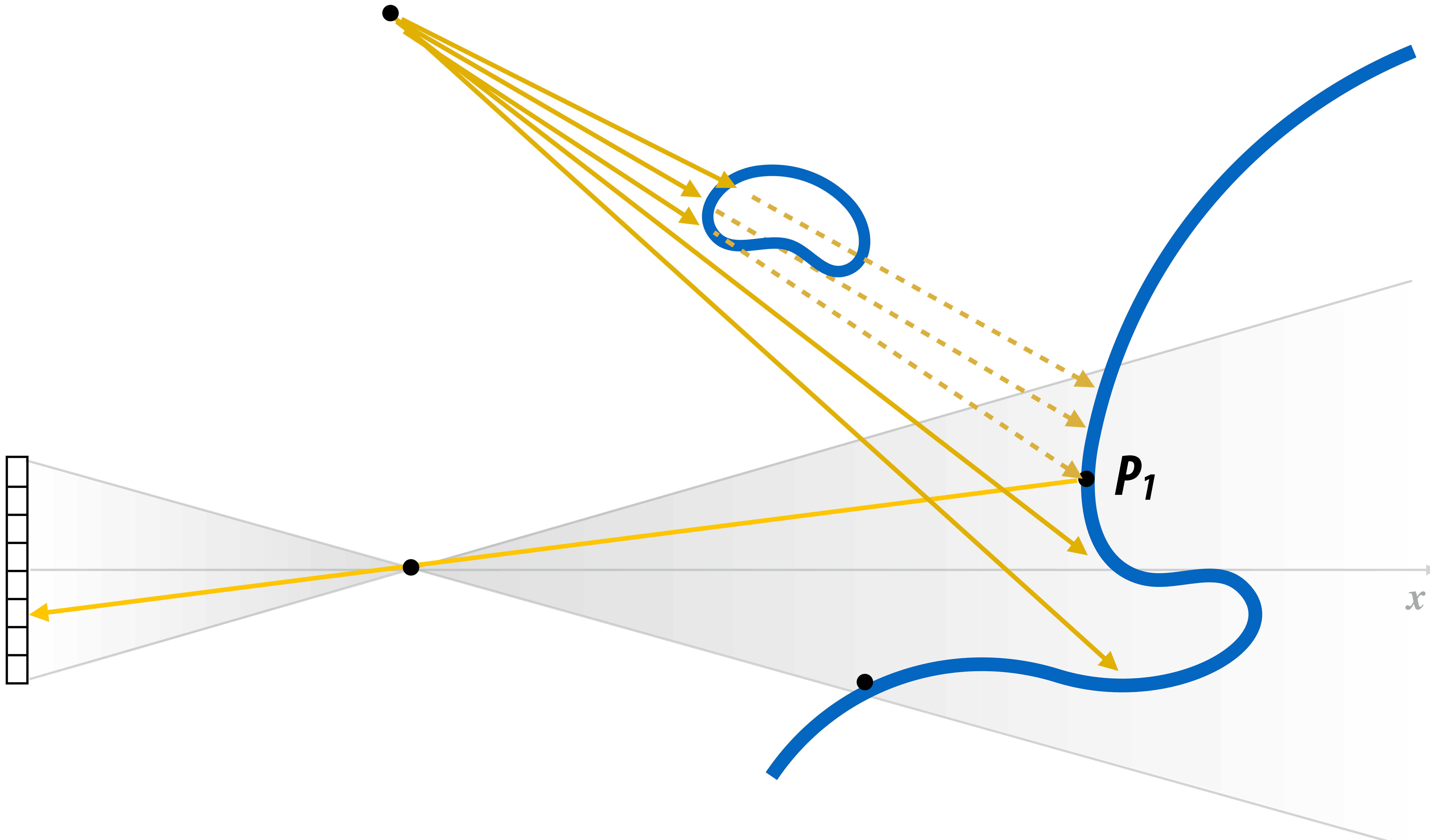
Shadow Map
(consider case where distance from light to surface is 0.5)

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 😰



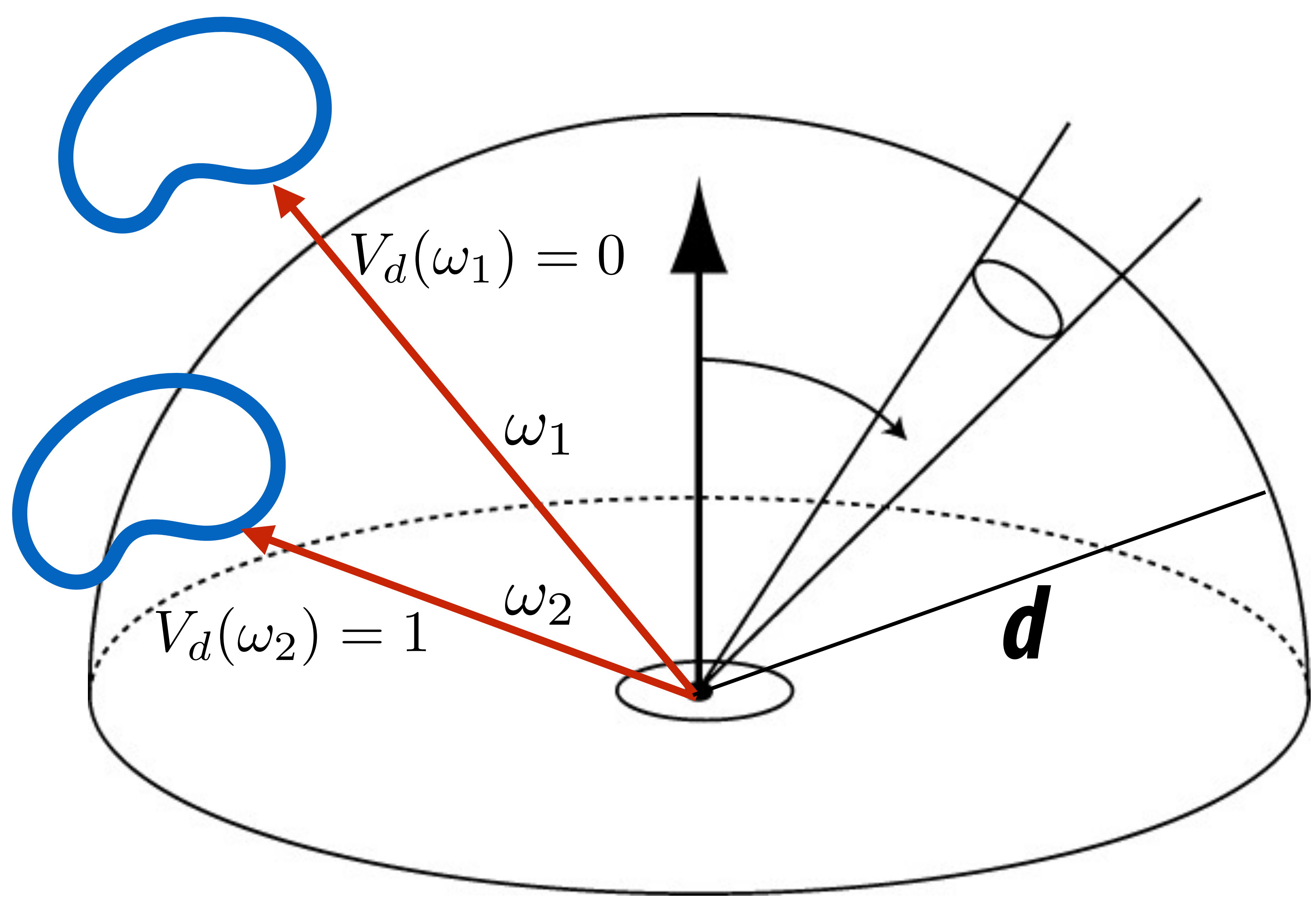
Ambient occlusion

Ambient occlusion

Idea:

Precompute "amount of hemisphere" that is occluded within distance *d* from a point.

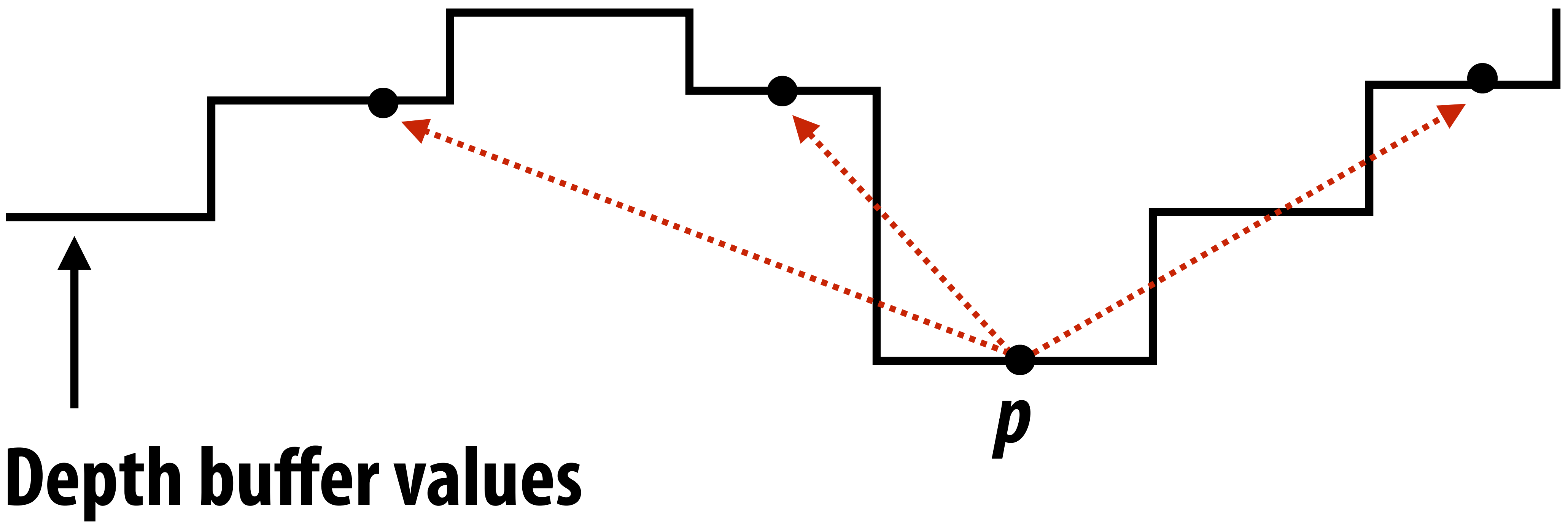
When shading, attenuate environment lighting by this amount.



"Screen-space" ambient occlusion in games

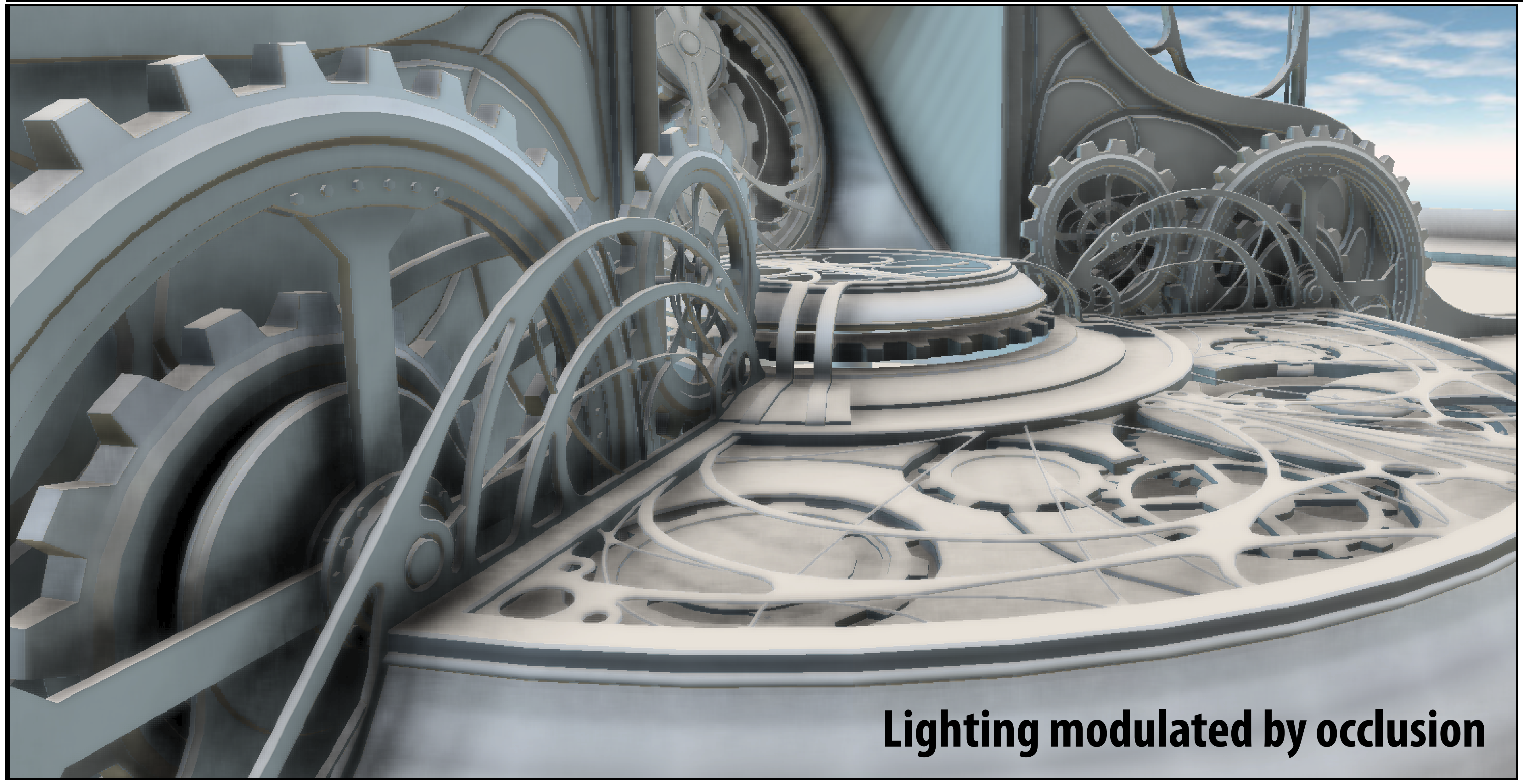
1. Render scene to depth buffer
2. For each pixel *p* ("ray trace" the depth buffer to estimate occlusion of hemisphere - use a few samples per pixel)
3. Blur the the occlusion map to reduce noise
4. Shade pixels, darken direct environment lighting by occlusion amount

without ambient occlusion



with ambient occlusion

Ambient occlusion

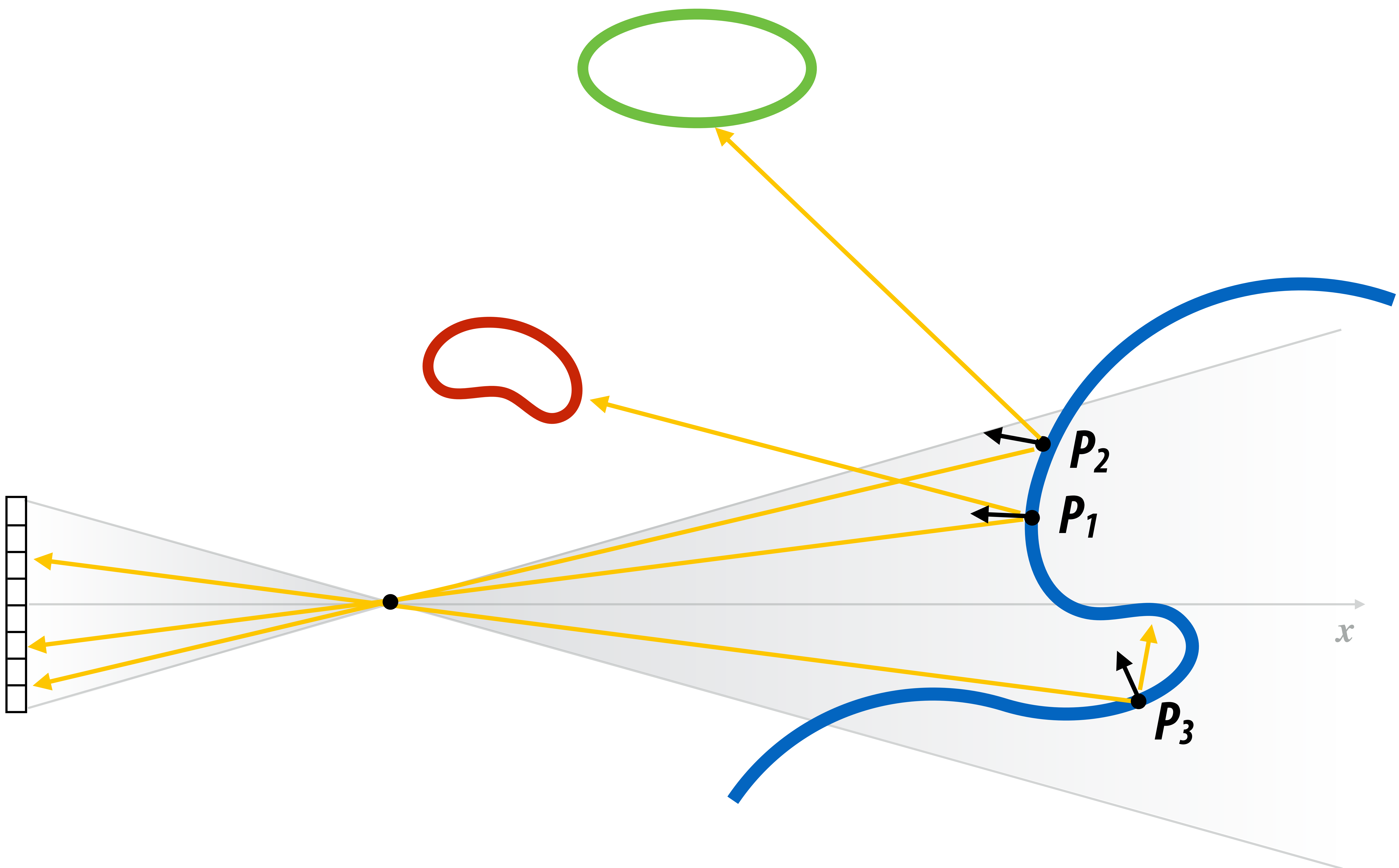


Reflections

Reflections

Image credit: NVIDIA

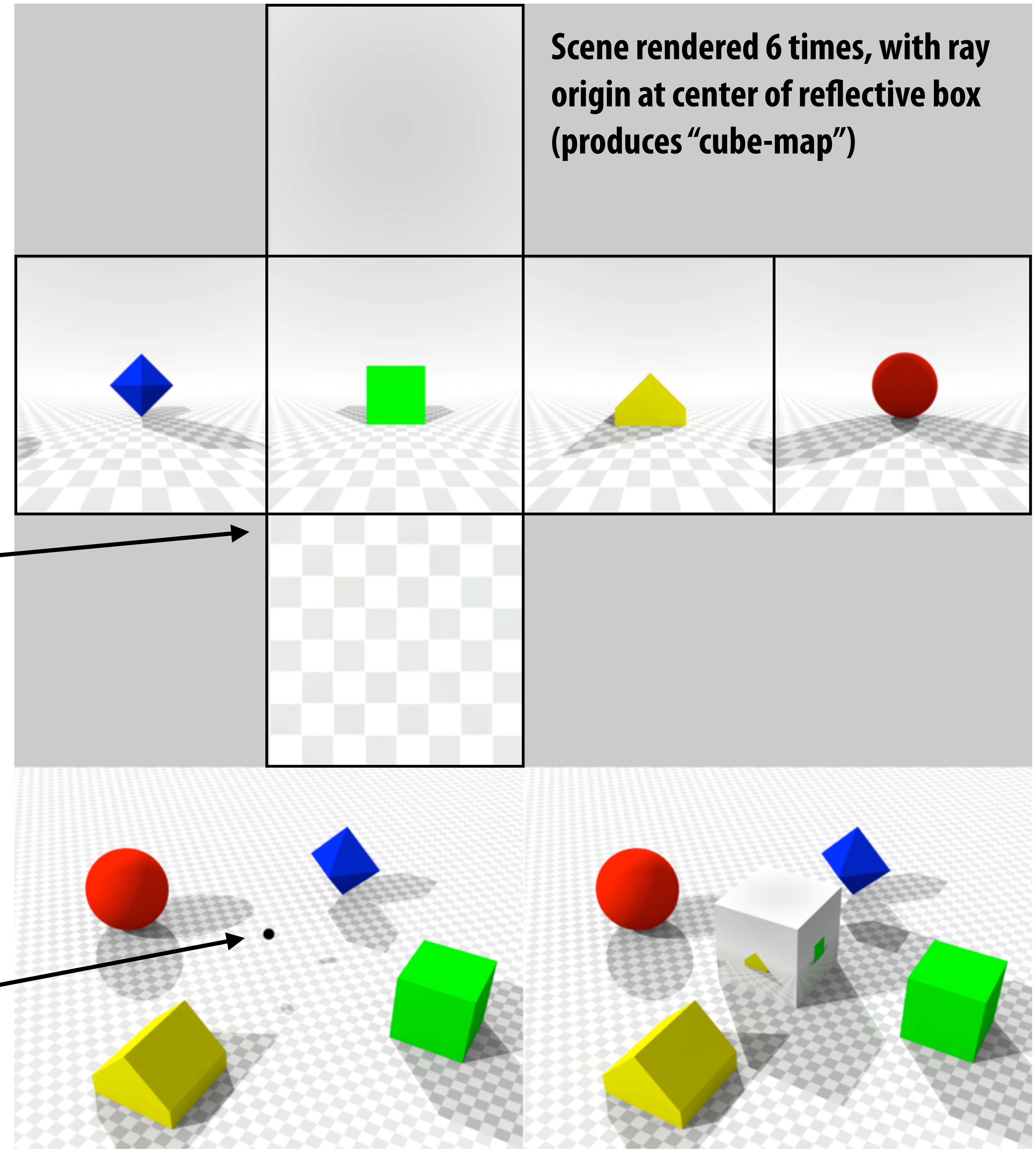
Recall: perfect mirror reflection



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

Interreflections

Diffuse interreflections

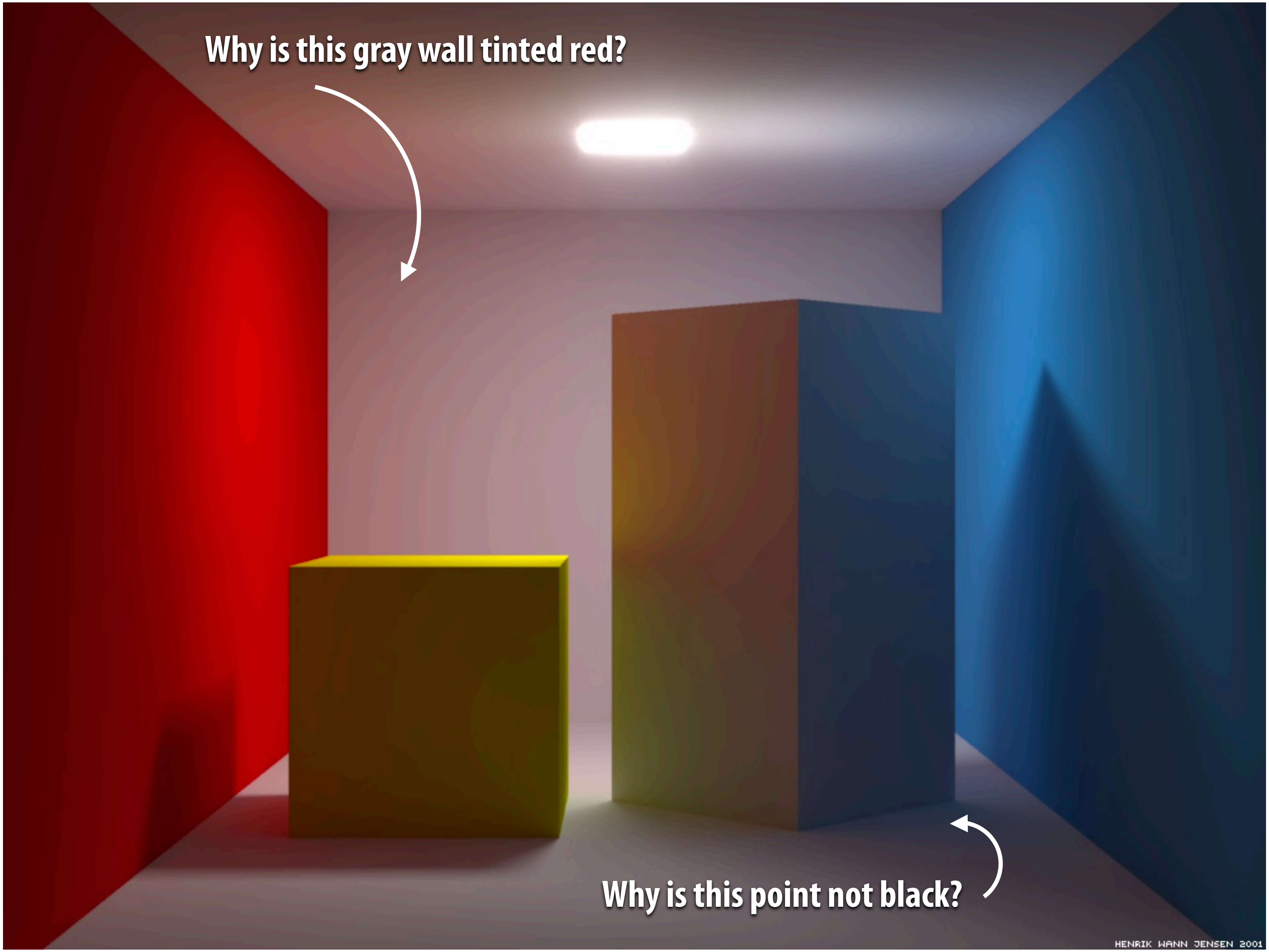
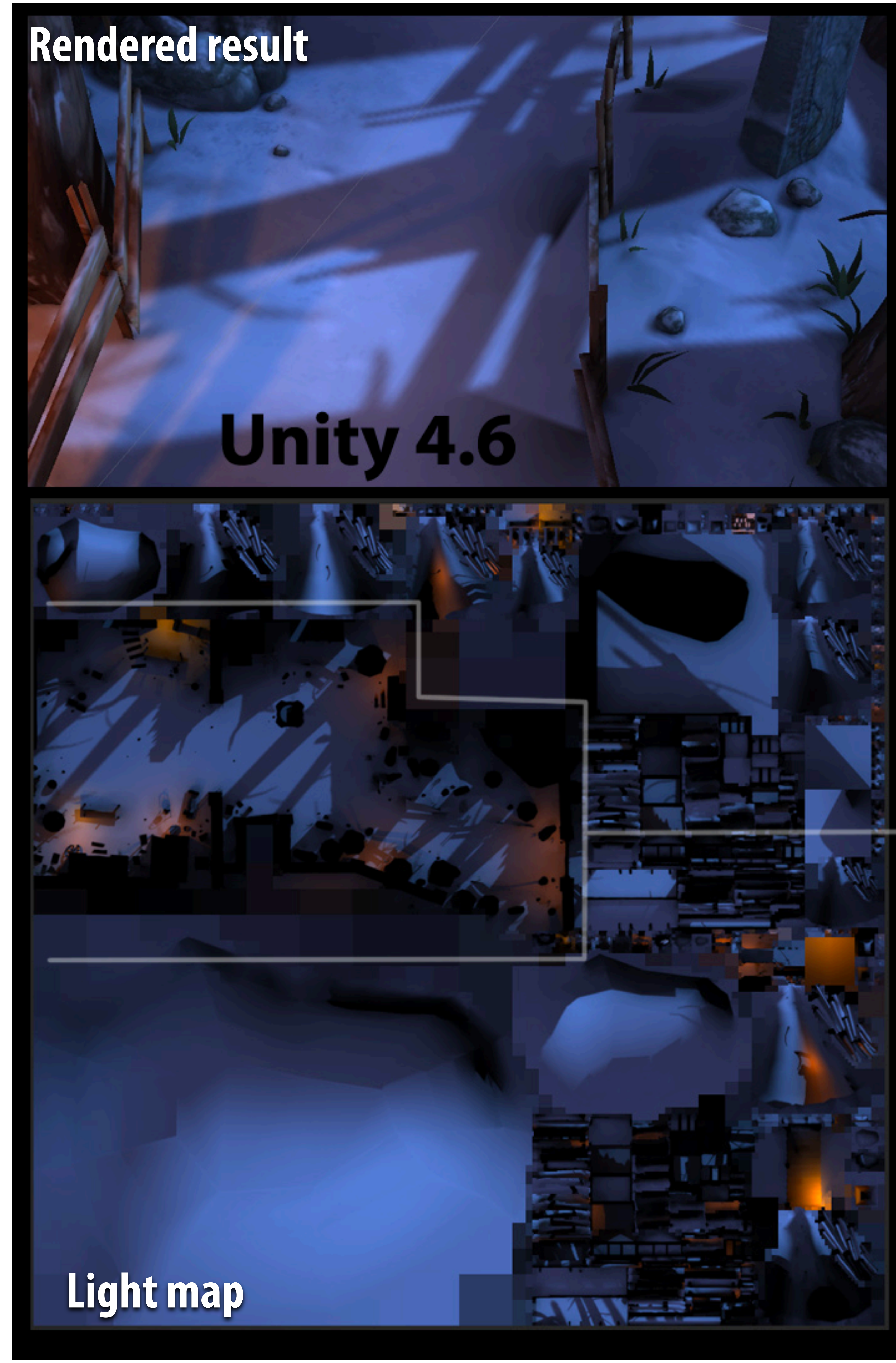


Image credit: Henrik Wann Jensen

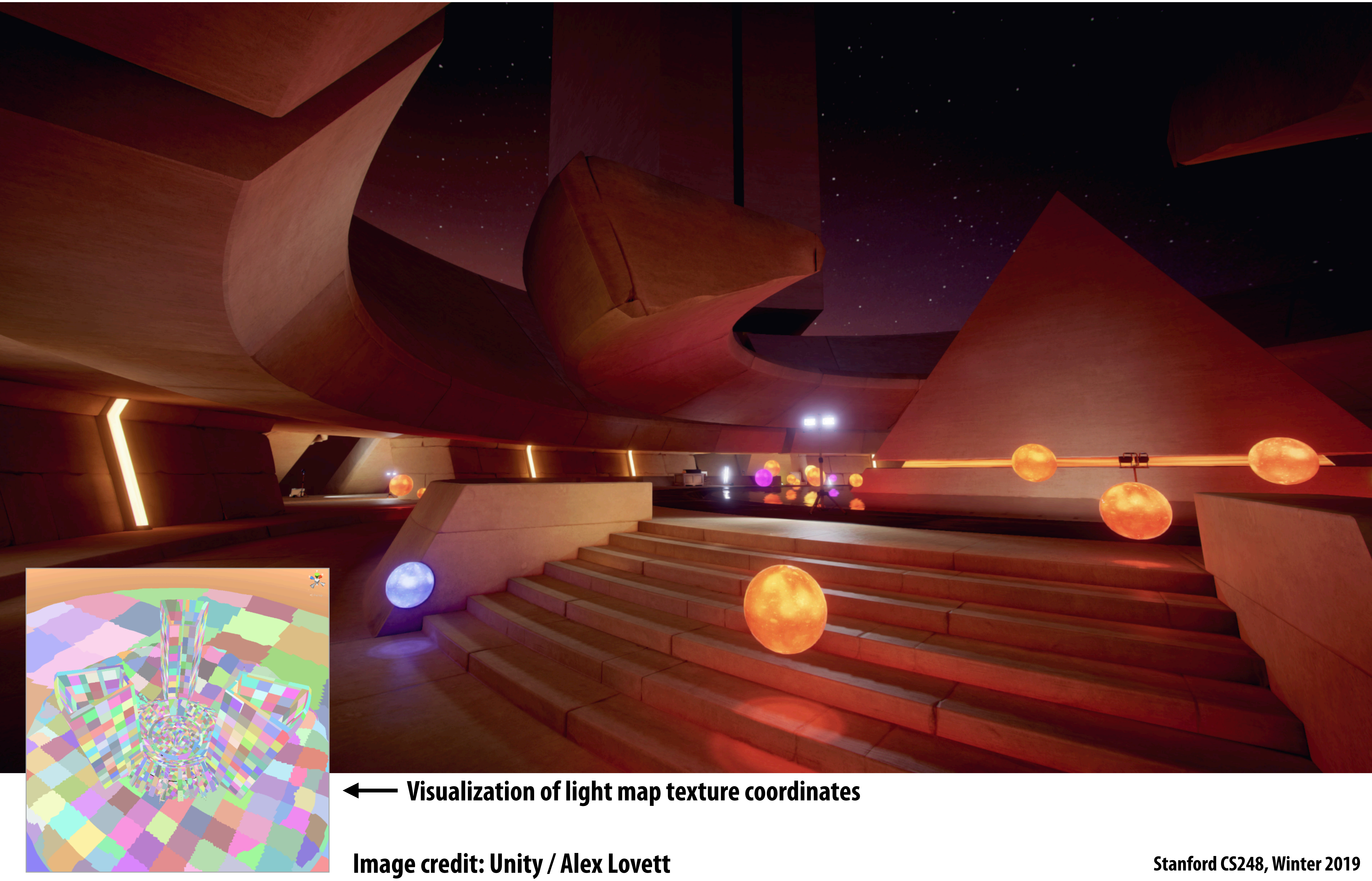
Precomputed lighting

- Precompute lighting for a scene offline (possible for static lights)
  - Offline computations can perform advanced shadowing, inter reflection computations

- "Bake" results of lighting into texture map



Precomputed lighting in Unity



← Visualization of light map texture coordinates

Image credit: Unity / Alex Lovett

Growing interest in real-time ray tracing

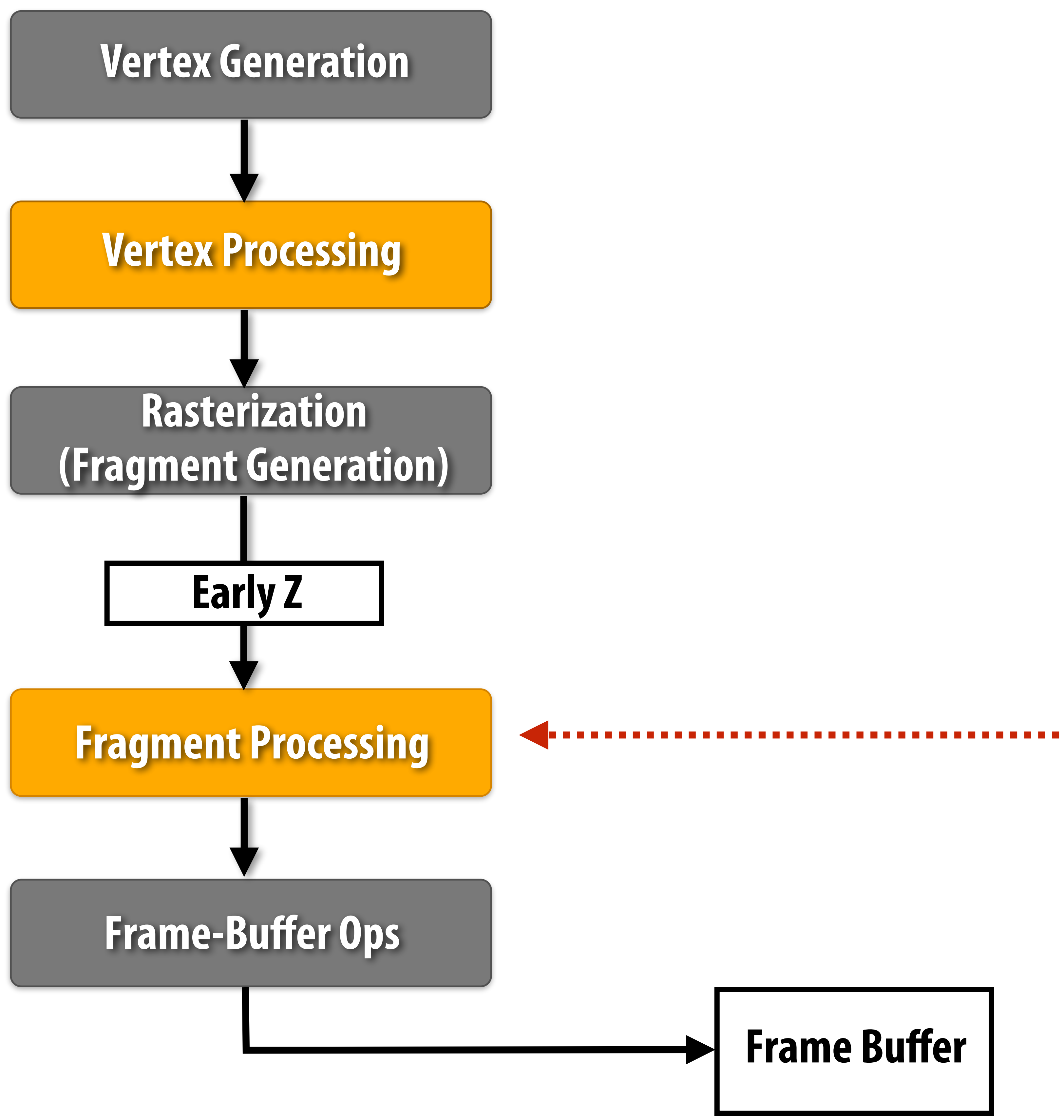
- I've just shown you an array of different techniques for approximating different advanced lighting phenomenon
- Challenges:
  - Different algorithm for each effect (code complexity)
  - Algorithms may not compose
  - They are approximations to the physically correct solution ("hacks!")
- Traditionally,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

This image was ray traced in real-time on a (very high end) GPU

Learn more in CS348B!

Deferred Shading

The graphics pipeline



"Forward" rendering

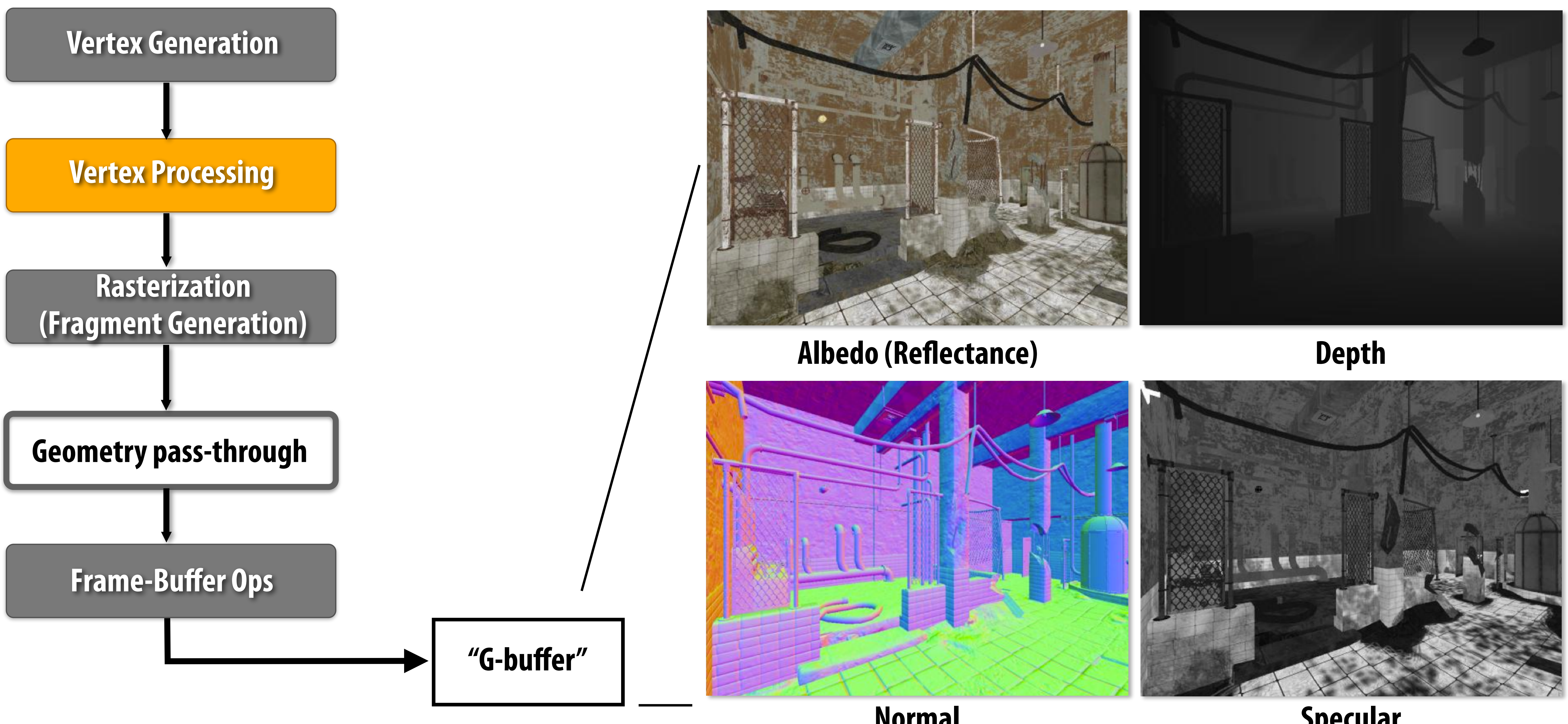
Typical use of fragment processing stage: evaluate application-defined function from surface inputs to surface color (reflectance)

Deferred shading: two steps

Step 1: Do not use traditional pipeline to generate RGB image

Fragment shader now outputs surface properties (future shading inputs) (e.g., position, normal, material diffuse color, specular color)

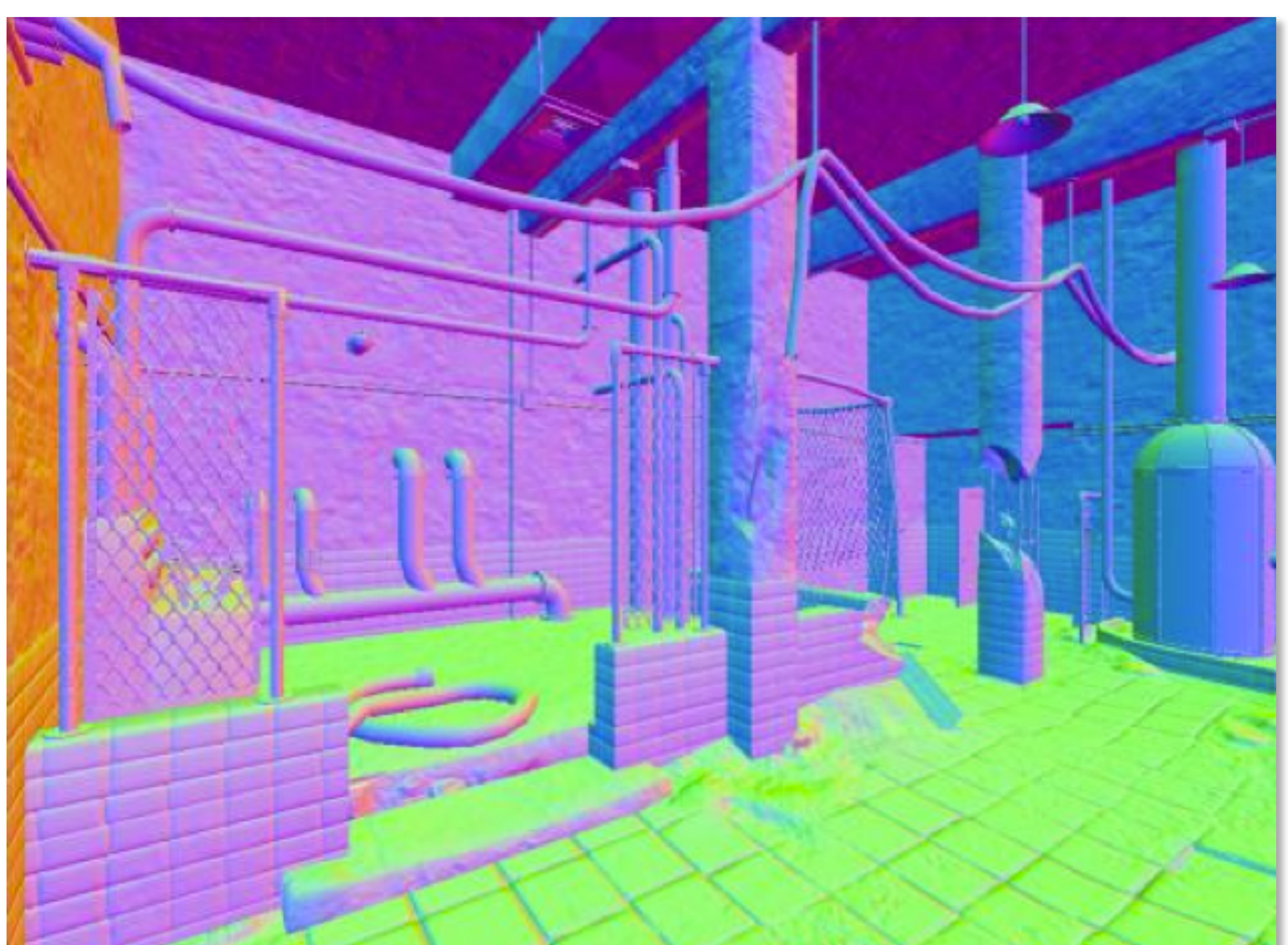
Rendering output is a screen-size 2D buffer representing information about the surface geometry visible at each pixel (called a "g-buffer", for geometry buffer)



G-buffer = “geometry” buffer

Albedo (Reflectance)

Depth



Normal

Specular

Image Credit: J. Klint, “Deferred Rendering in Leadworks Engine”

Example G-buffer layout

Graphics pipeline configured to render to four RGBA output buffers + depth (32-bits per pixel, per buffer)

R8	G8	B8	A8	
Depth 24bpp			Stencil	DS
Lighting Accumulation RGB			Intensity	RT0
Normal X (FP16)		Normal Y (FP16)		RT1
Motion Vectors XY		Spec-Power	Spec-Intensity	RT2
Diffuse Albedo RGB			Sun-Occlusion	RT3

Source: W. Engel, “Light-Prepass Renderer Mark III” SIGGRAPH 2009 Talks

Intuitive to consider G-buffer as one big render target with “fat” pixels

In the example above: 32 x 5 =160 bits = 20 bytes per pixel

96-160 bits per pixel is common in games

Compressed G-buffer layout

G-buffer layout in Bungie's Destiny (2014)

8	8	8	8	
Albedo Color RGB			Ambient Occlusion	RT0
Normal XYZ * (Biased Specular Smoothness)			Material ID	RT1
Depth			Stencil	DS

- Material information is compressed using indirection
  - Store material ID in G-buffer
  - Material parameters other than albedo (specular shape/roughness/color) stored in table indexed by material ID

Example material ID visualization

Source: N Tatarchuk: SIGGRAPH 2014 Courses, Matt Hoffman

Two-pass deferred shading algorithm

- **Pass 1: G-buffer generation pass**
  - Render complete scene geometry using traditional pipeline
  - Write visible geometry information to G-buffer

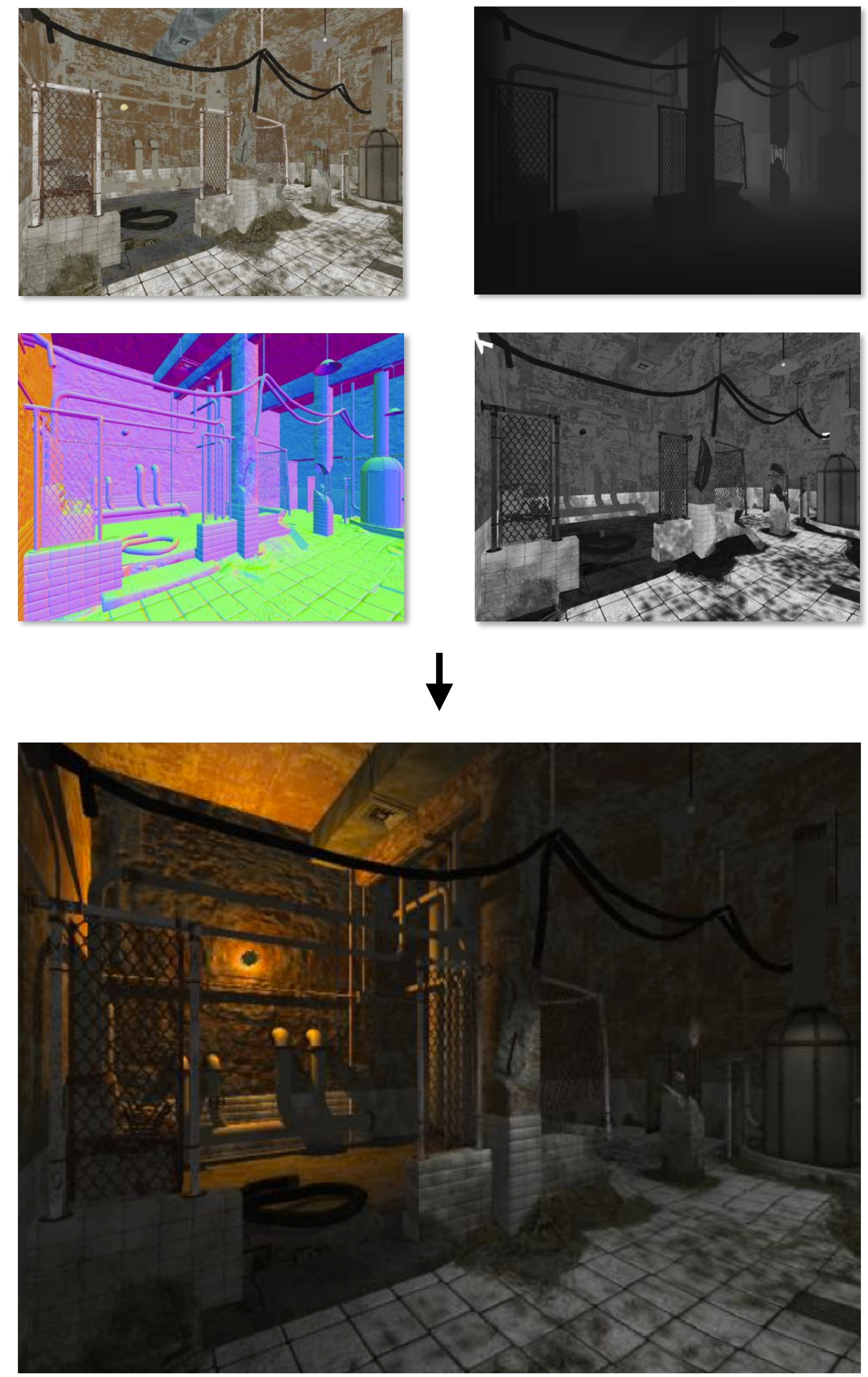
After all geometry processing is done…

- **Pass 2: shading/lighting pass**

  For each G-buffer sample (x,y):
  - Read G-buffer data for current sample (x,y)
  - Compute shading by accumulating contribution to reflectance of all lights
  - Output final surface color for sample (x,y)

Shading/lighting computations are "deferred" until all geometry processing is complete…

G-buffer Inputs



Final Image

Image Credit: J. Klint, "Deferred Rendering in Leadworks Engine"

Why is deferred shading so popular in modern games?

Motivation: why deferred shading?

- **Two performance reasons:**

- **Shading is expensive: deferred shading shades only visible fragments**
  - Exactly one shade per output screen sample, regardless of the number of triangles in the scene (minimal amount of work + predictable shading performance that is independent of scene size or triangle submission order)

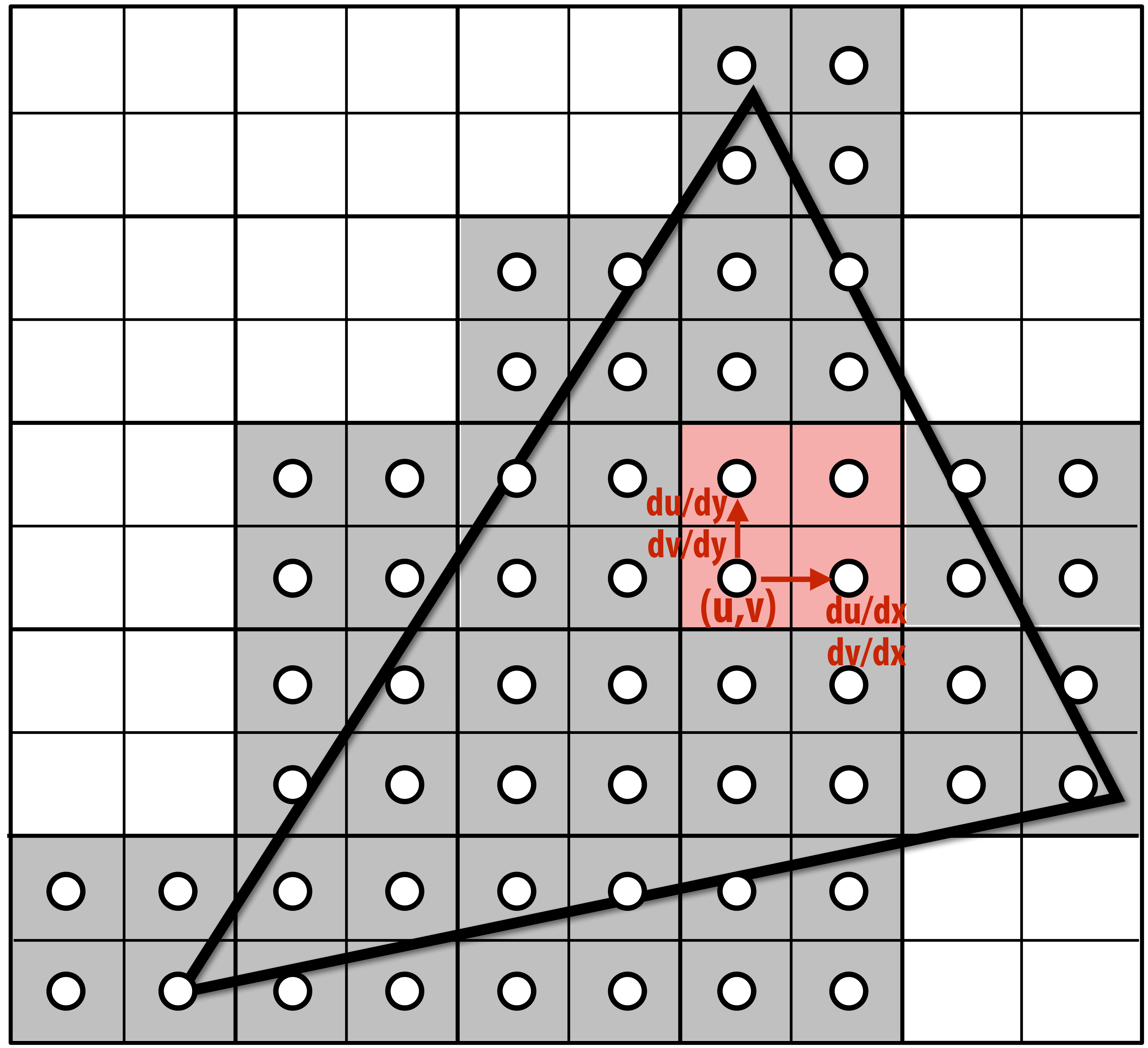
- **Forward rendering shades small triangles inefficiently**

GPUs shade at the granularity of 2x2 fragments

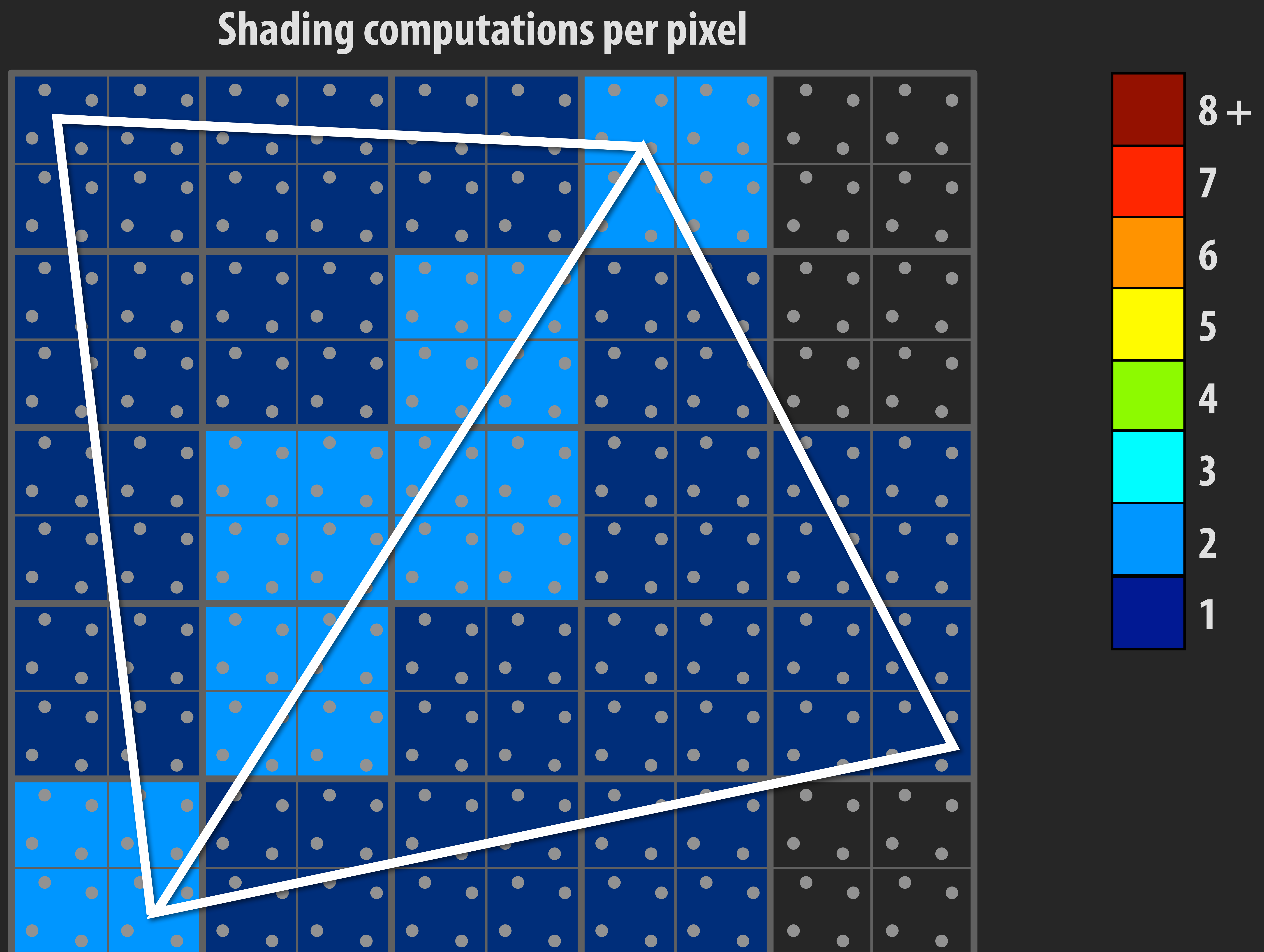
("quad fragment" is the minimum granularity of rasterization output and shading)

Enables cheap computation of texture coordinate differentials
(cheap: derivative computation leverages shading work that must be done by adjacent fragment anyway)

All quad fragments are shaded independently
(communication is between fragments in a quad fragment, no communication required between quad fragments)



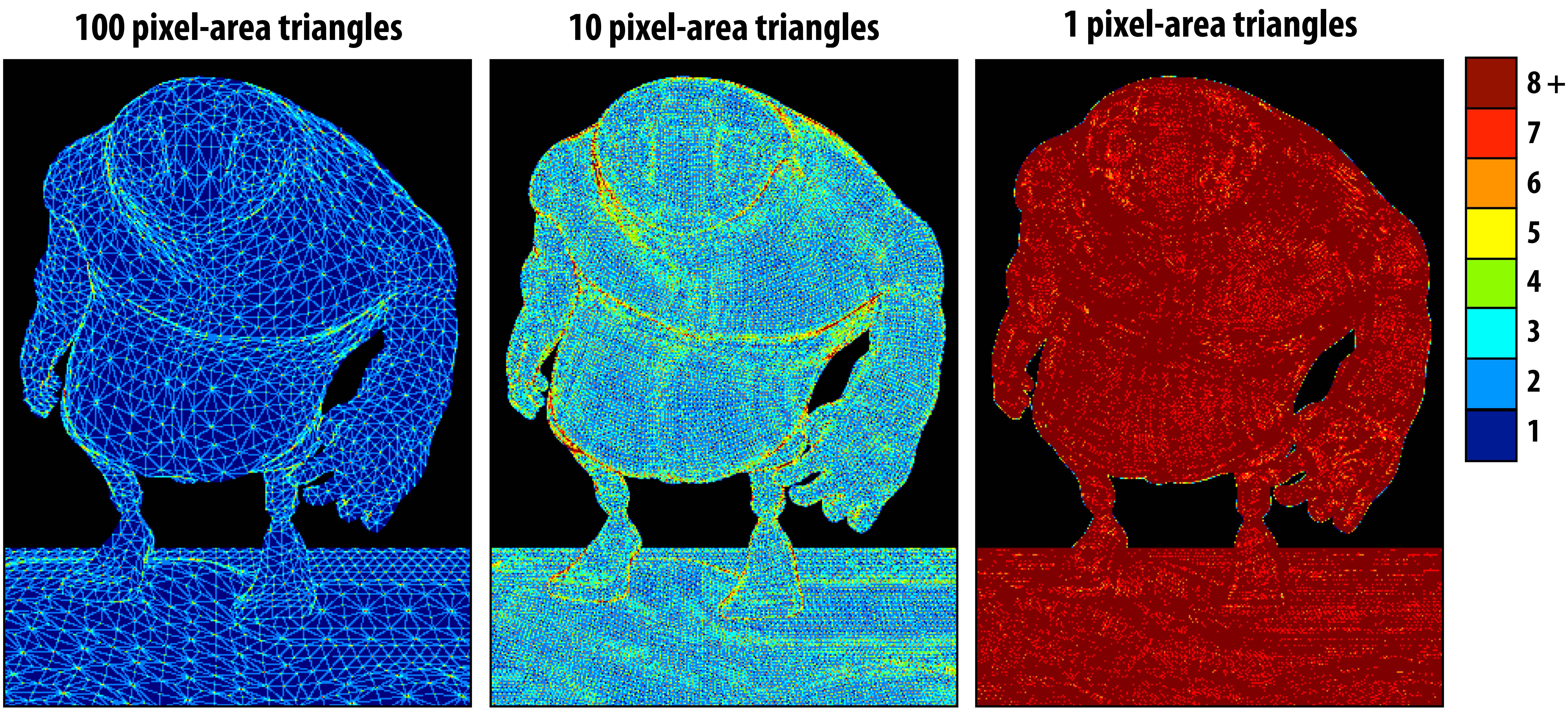
Implication: multiple fragments get shaded for pixels near triangle boundaries



Small triangles result in extra shading

Shaded quad fragments per pixel

(early-z is enabled + scene rendered in approximate front-to-back order to minimize extra shading due to overdraw)



Want to sample appearance approximately once per surface per pixel (assuming correct texture filtering)

But graphics pipeline generates at least one appearance sample <u>per triangle</u> per pixel (actually more, considering quad fragments)

Motivation: why deferred shading?

- Shade only visible surface fragments
- Forward rendering shades small triangles inefficiently (quad-fragment granularity)
- Scalability to increasingly complex lighting environments

1000 lights

[J. Andersson, SIGGRAPH 2009 Beyond Programmable shading course talk]

Forward rendering: naive multiple-light shader

```
struct LightDefinition {
  int type;
  ...
}

// uniform values (read-only inputs to all fragments)
uniform sampler2D myTex;
uniform sampler2D myEnvMaps[MAX_NUM_LIGHTS];
uniform sampler2D myShadowMaps[MAX_NUM_LIGHTS];
LightDefinition  lightList[MAX_NUM_LIGHTS];
int numLights;

// fragment shader receives surface normal and texture coords uv
varying vec3 norm;
varying vec3 uv;

void main() {
  vec3 kd = texture2d(myTex, uv);
  vec4 result = vec4(0, 0, 0, 0);
  for (int i=0; i<numLights; i++) {
     result += …   // eval contribution of light to surface reflectance here
  }

  gl_FragColor = result;  // output color of fragment shader
}
```

Rendering as a triple "for" loop

Naive forward rasterization-based renderer:

```
initialize z_closest[] to INFINITY                  // store closest-surface-so-far for all samples
initialize color[]                                  // store scene color for all samples
bind all relevant light data in buffers: light descriptors, shadow maps, etc.
for each triangle t in scene:                       // loop 1: triangles
    t_proj = project_triangle(t)
    for each sample s in frame buffer:              // loop 2: visibility samples
        if (t_proj covers s)
            for each light l in scene:              // loop 3: lights
                accumulate contribution of light l to surface appearance
            if (depth of t at s is closer than z_closest[s])
                update z_closest[s] and color[s]
```

Triangles are outermost loop:

Efficient rasterization techniques (tiled, hierarchical, bounding boxes) serve to reduce T x S complexity of finding covered samples.

Rendering as a triple "for" loop

Naive forward rasterization-based renderer:

```
initialize z_closest[] to INFINITY               // store closest surface-so-far for all samples
initialize color[]                               // store scene color for all samples
bind all relevant shadow maps, etc.
for each triangle t in scene:                    // loop 1: triangles
    t_proj = project_triangle(t)
    for each sample s in frame buffer:           // loop 2: visibility samples
        if (t_proj covers s)
            for each light l in scene:           // loop 3: lights
                accumulate contribution of light l to surface appearance
            if (depth of t at s is closer than z_closest[s])
                update z_closest[s] and color[s]
```

F x L loop: # fragments x # lights

In practice: not all lights illuminate all surfaces

Would like to be more efficient in computing these interactions (just like we were efficient computing triangle/visibility sample interactions)

Naive many-light shader with culling

```
struct LightDefinition {
  int type;
  ...
}

// uniform values (read-only inputs to all fragments)
uniform sampler2D myTex;
uniform sampler2D myEnvMaps[MAX_NUM_LIGHTS];
uniform sampler2D myShadowMaps[MAX_NUM_LIGHTS];
LightDefinition  lightList[MAX_NUM_LIGHTS];
int numLights;

// fragment shader receives surface normal and texture coords uv
varying vec3 norm;
varying vec3 uv;

void shader() {
  vec3 kd = texture2D(myTex, uv);
  vec4 result = float4(0, 0, 0, 0);
  for (int i=0; i<numLights; i++)
  {
      if (this fragment is illuminated by current light)
      {
         if (lightList[i].type == SPOTLIGHT)
            result += // eval contribution of light here
         else if (lightList[i].type == POINTLIGHT)
            result += // eval contribution of light here
         else if ...
      }
  }
  gl_FragColor = result;  // output color
}
```

Large footprint:

Assets for all lights (shadow maps, environment maps, etc.) must be allocated and bound to pipeline

SIMD execution divergence:

1. Different outcomes for "is illuminated" predicate
2. Different logic to perform test (based on light type)
3. Different logic in loop body (based on light type, shadowed/unshadowed, etc.)

Work inefficient:

Predicate evaluated for each fragment/light pair: O(F x L) work

F = number of fragments

L = number of lights

Forward rendering: techniques for scaling to many lights

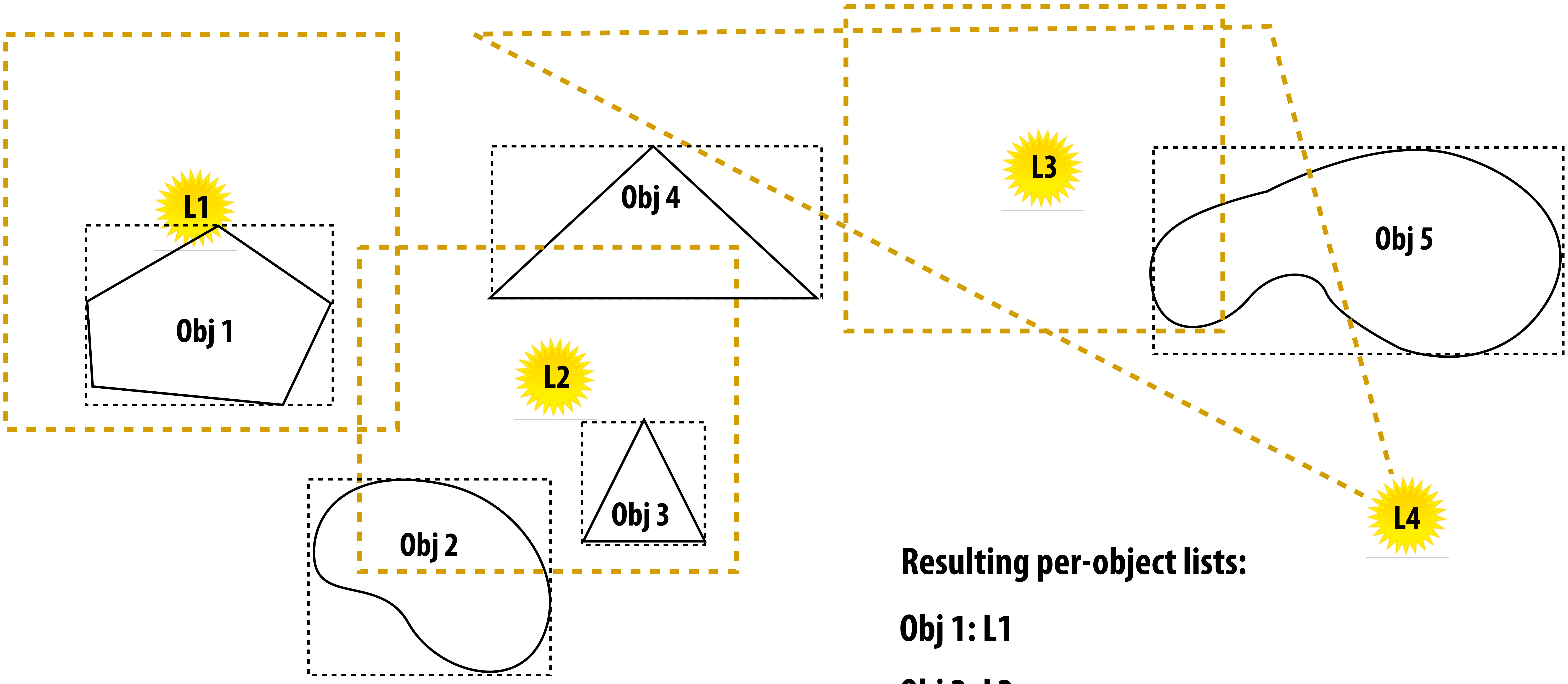
- Goal: avoid performing F x L "is-illuminated" checks

- One solution: application maintains per-object light lists
  - Each scene object maintains list of lights that illuminate it
  - CPU computes this list each frame by intersecting light volumes with scene geometry

    (light-geometry interactions computed per light-object pair, not light-fragment pair)

Light lists

Example: compute lists based on conservative bounding volumes for lights and scene objects



Resulting per-object lists:

Obj 1: L1

Obj 2: L2

Obj 3: L2

Obj 4: L2, L4

Obj 5: L3, L4

Forward rendering: techniques for scaling to many lights

- **Application maintains light lists**
  - Computed conservatively per frame
- **Option 1: draw scene in many small batches**
  - First generate data structures for all lights: e.g., shadow maps
  - Before drawing each object, only send data for relevant lights to graphics pipeline
  - Write different variants of shader that are specialized for different numbers of lights (4-light version, 8-light version...)
    - Implications:
      - Good: very efficient shaders with fewer conditionals
      - Bad: many "small" draw comments to sent to GPUs

Recall: rendering as a triple for-loop

Naive forward rasterization-based renderer:

```
initialize z_closest[] to INFINITY                // store closest surface-so-far for all samples
initialize color[]                                // store scene color for all samples
bind all relevant shadow maps, etc.
for each triangle t in scene:                     // loop 1: triangles
    t_proj = project_triangle(t)
    for each sample s in frame buffer:            // loop 2: visibility samples
        if (t_proj covers s)
            for each light l in scene:            // loop 3: lights
                accumulate contribution of light l to surface appearance
            if (depth of t at s is closer than z_closest[s])
                update z_closest[s] and color[s]
```

Reordering triangles for light coherence

Shader code is now specialized to exactly 4 lights:

```
initialize z_closest[] to INFINITY                  // store closest surface-so-far for all samples
initialize color[]                                  // store scene color for all samples
bind all relevant shadow maps, etc.
for each group of triangles with the same number of lights:    // loop 0: groups of triangles
   bind specific shader for number of lights
   for each triangle t in group:                       // loop 1: triangles
       t_proj = project_triangle(t)
       for each sample s in frame buffer:              // loop 2: visibility samples
          if (t_proj covers s)
             for lights 0 through 3:                   // loop 3: lights (specialized for 4 lights)
                accumulate contribution of light l to surface appearance
             if (depth of t at s is closer than z_closest[s])
                update z_closest[s] and color[s]
```

"Multi-pass" rendering for light coherence

```
initialize z_closest[] to INFINITY                   // store closest surface-so-far for all samples
initialize color[]                                   // store scene color for all samples
assume z buffer is initialized using a z prepass.
for each light l in scene:                                // loop 1: lights
   bind single light shader specific to current light type
   bind relevant shadow map, etc.
   for each triangle t lit by light:                      // loop 2: triangles
      t_proj = project_triangle(t)
      for each sample s in frame buffer:                  // loop 3: visibility samples
         if (t_proj covers s)
            accumulate contribution of light l to surface appearance   // specialized to 1 light
            if (depth of t == z_closest[s])
               update color[s]
```

Reorder loops: draw scene once per light

Each pass, only draw triangles illuminated by current light (per-light object lists)

Shader accumulates illumination of visible fragments from current light into frame buffer

Forward rendering: techniques for scaling to many lights

- Application maintains light lists
- Option 1: draw scene in many small batches
  - First generate data structures for all lights: e.g., shadow maps
  - Compute per-object light lists, before drawing each object, only bind data for relevant lights
  - Precompile specialized shaders for different sets of bound lights (4-light version, etc…)
  - For each object:
    - Render object with specialized shader for relevant lights
  - Good: can use specialized fragment shader for current type/number of lights
  - Bad: many draw comments to GPU (draw comment = single object, or small group of objects with the same number of lights)

Stream over scene geometry

- Option 2: multi-pass rendering
  - Compute per-light lists (for each light, compute illuminated objects)
  - For each light:
    - Compute necessary data structures (e.g., shadow maps)
    - Render scene with additive blending (only render geometry illuminated by light)
  - Good: Minimal footprint for light data
  - Good: can use specialized fragment shader for current type/number of lights
  - Bad: significant overheads: redundant geometry processing, many G-buffer accesses, redundant execution of common shading sub-expressions in fragment shader

Stream over lights

Basic many light deferred shading algorithm

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

Phase 1: Generate G-buffer

```
initialize color[]                            // store color for all samples
for each light in scene:                      // loop 1: lights
   bind single light shader specific to current light type
   bind relevant shadow map, etc.
   for each sample s in frame buffer:         // loop 2: visibility samples
          load gbuffer[s]
          accumulate contribution of current light to surface appearance into color[s]
```

Phase 2: Shade G-buffer

- **Good**
  - Only process scene geometry once (only in phase 1)
  - Outer loop of phase 2 is over lights:
    - Avoids light data footprint issues (stream over lights)
    - Continues to avoid divergent execution in fragment shader
  - Recall other deferred benefits: only shade visibility samples (and no more)
- **Bad?**

Basic many light deferred shading algorithm

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

initialize color[]                              // store color for all samples
for each light in scene:                        // loop 1: lights
   bind single light shader specific to current light type
   bind relevant shadow map, etc.
   for each sample s in frame buffer:           // loop 2: visibility samples
          load gbuffer[s]
          accumulate contribution of current light to surface appearance into color[s]
```

- **Bad:**
  - High G-buffer footprint: G-buffer has large footprint (especially when G-buffer is supersampled!)
  - High bandwidth costs (read G-buffer each pass, output to frame buffer)
  - Exactly one shading computation per frame-buffer sample
    - Does not support transparency (need multiple fragments per pixel)
    - Supersampling for anti-aliasing becomes expensive

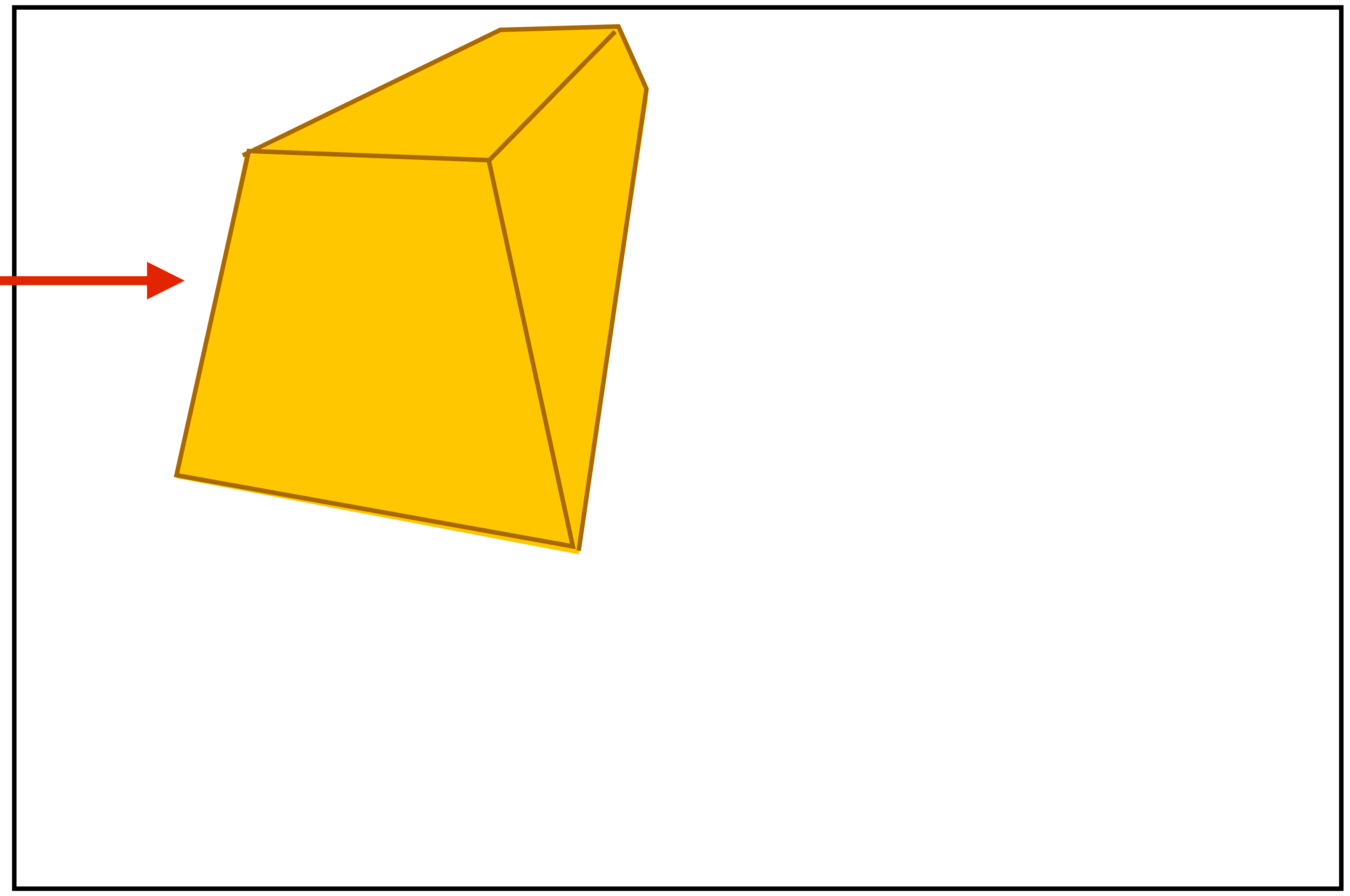
Reducing deferred shading bandwidth costs

- **Batching: process multiple lights in each phase 2 accumulation pass**
  - Amortizes G-buffer load and frame buffer write across lighting computations for multiple lights

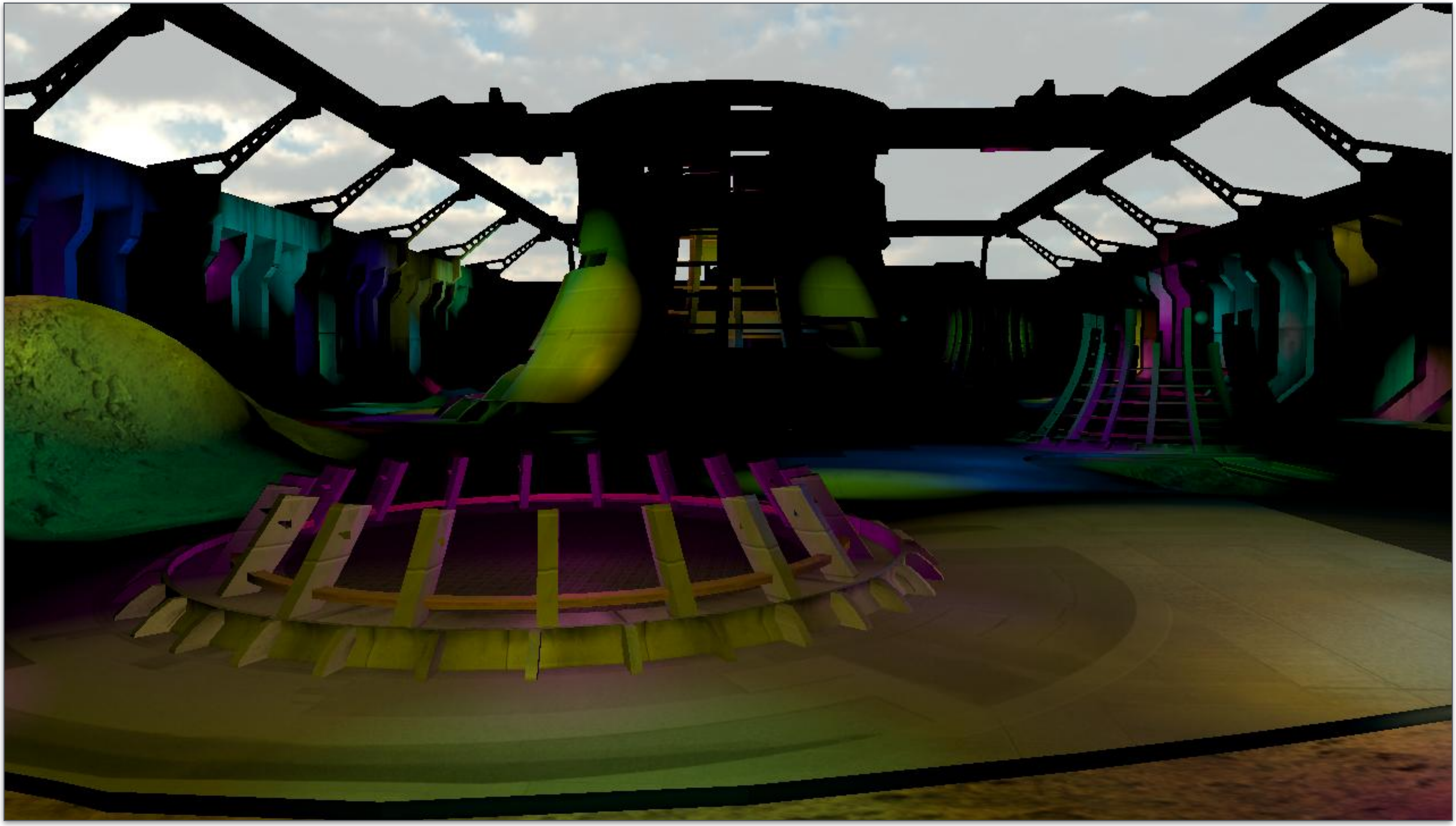
- **Only perform shading computations for G-buffer samples illuminated by light**
  - Technique 1: rasterize geometry of light volume (only generate fragments for covered G-buffer samples)
    - Light-fragment interaction predicate is evaluated by rasterizer, not in shader
  - Technique 2: CPU computes screen-aligned quad covered by light volume, renders quad
  - Many other techniques for culling light/G-buffer sample interactions

Light volume geometry

If volume is convex, rendering only the front-facing triangles of the light volume will generate fragments in the yellow shaded region
(these are the only g-buffer samples that can be effected by the light)



Scene with 256 lights



Visualization of light-sample interaction count

Per-light culling is performed using a screen-aligned quad per light
(depth of quad is nearest point in light volume: early Z will cull fragments behind scene geometry)

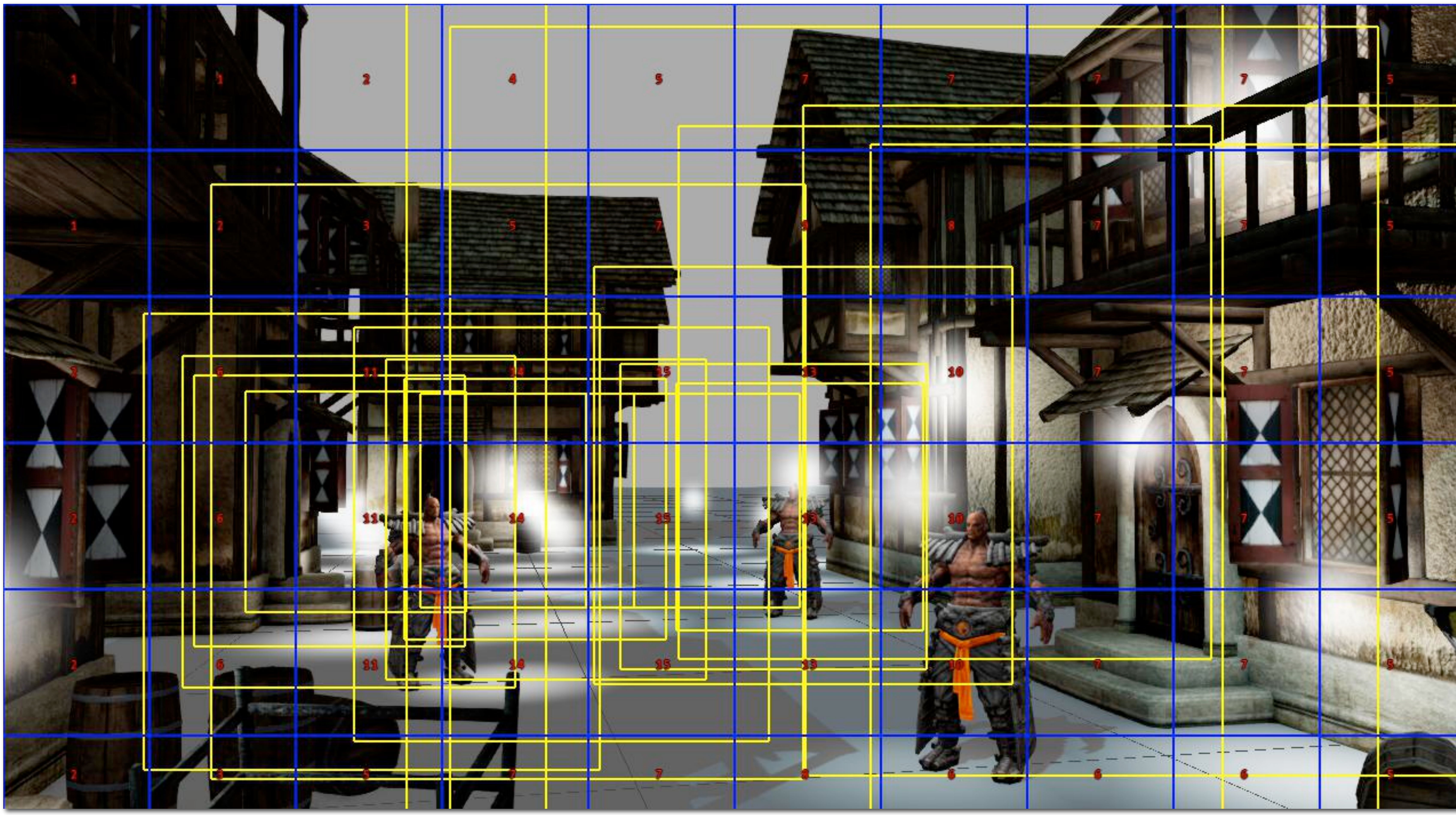
Number of lights evaluated per G-buffer sample
(scene contains 1024 point lights)

Image Credit: A. Lauritzen

Screen tiled-based light culling

Main idea: build list of lights that effect each screen tile (not each object)

Project light volume, then intersect in 2D with tiles



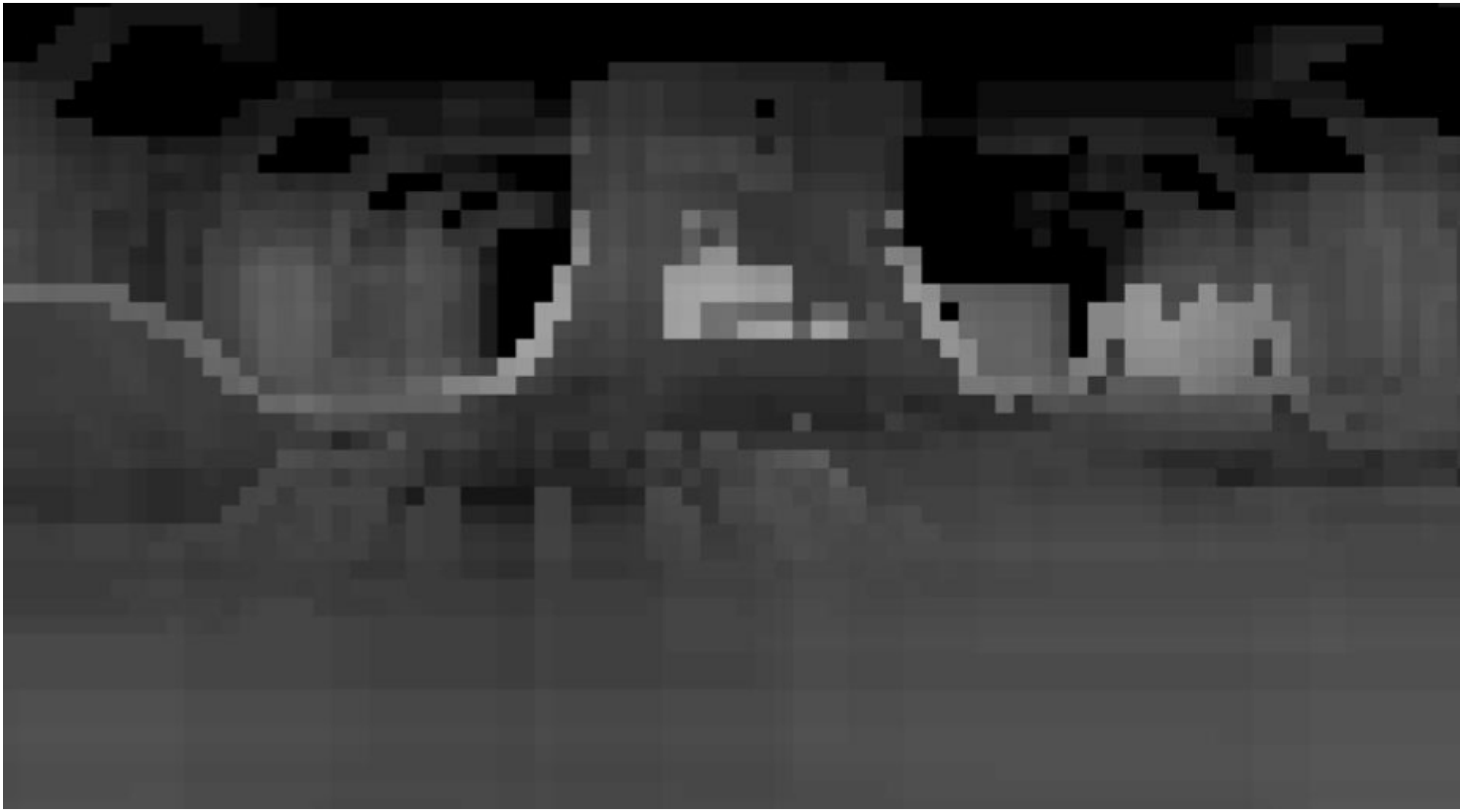
Yellow boxes: screen-aligned light volume bounding boxes

Blue boxes: screen tile boundaries

Image credit: HMREngine: http://www.hmrengine.com/blog/?p=399

Tile-based deferred shading: better light culling efficiency

(16x16 granularity of light culling is apparent in figure)



Number of lights evaluated per G-buffer sample
(scene contains 1024 point lights)

Image Credit: A. Lauritzen

Challenge: anti-aliasing geometry in a deferred renderer

Supersampling in a deferred shading system

- In assignment 1, you anti-aliased rendering via supersampling
  - Stored N color samples and N depth samples per pixel

- Deferred shading makes supersampling challenging due to large amount of information that must be stored per pixel
  - 2800 x 1800 (my Mac laptop I'm presenting on today)
  - 4 samples per pixel
  - 20 bytes per G-buffer sample

  = 403 MB G-buffer

  (24 GB/sec of memory bandwidth just to read and write the G-buffer at 30 fps)

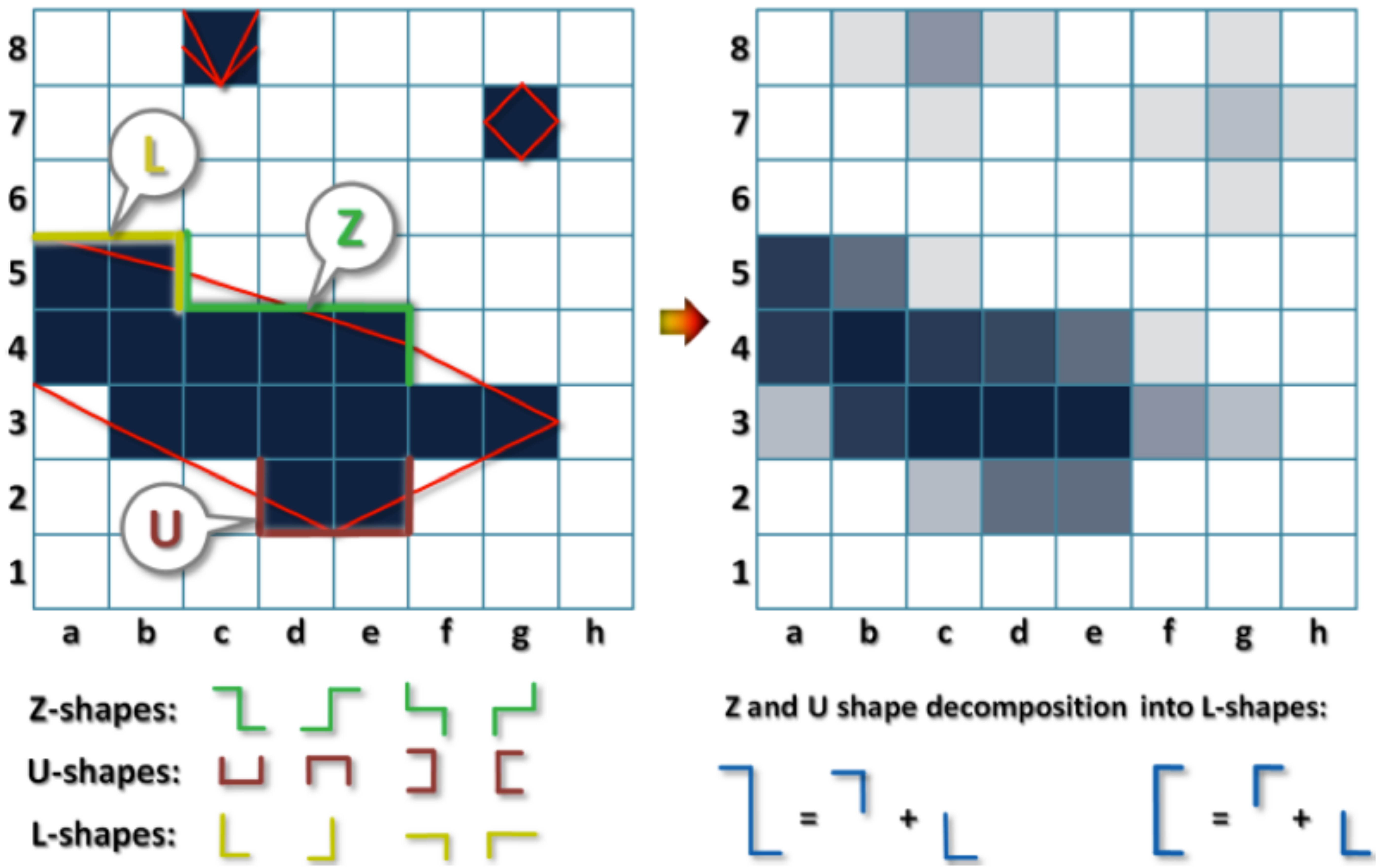
Morphological anti-aliasing (MLAA)

[Reshetov 09]

Detect careful designed patterns in rendered image

For detected patterns, blend neighboring pixels according to a few simple rules

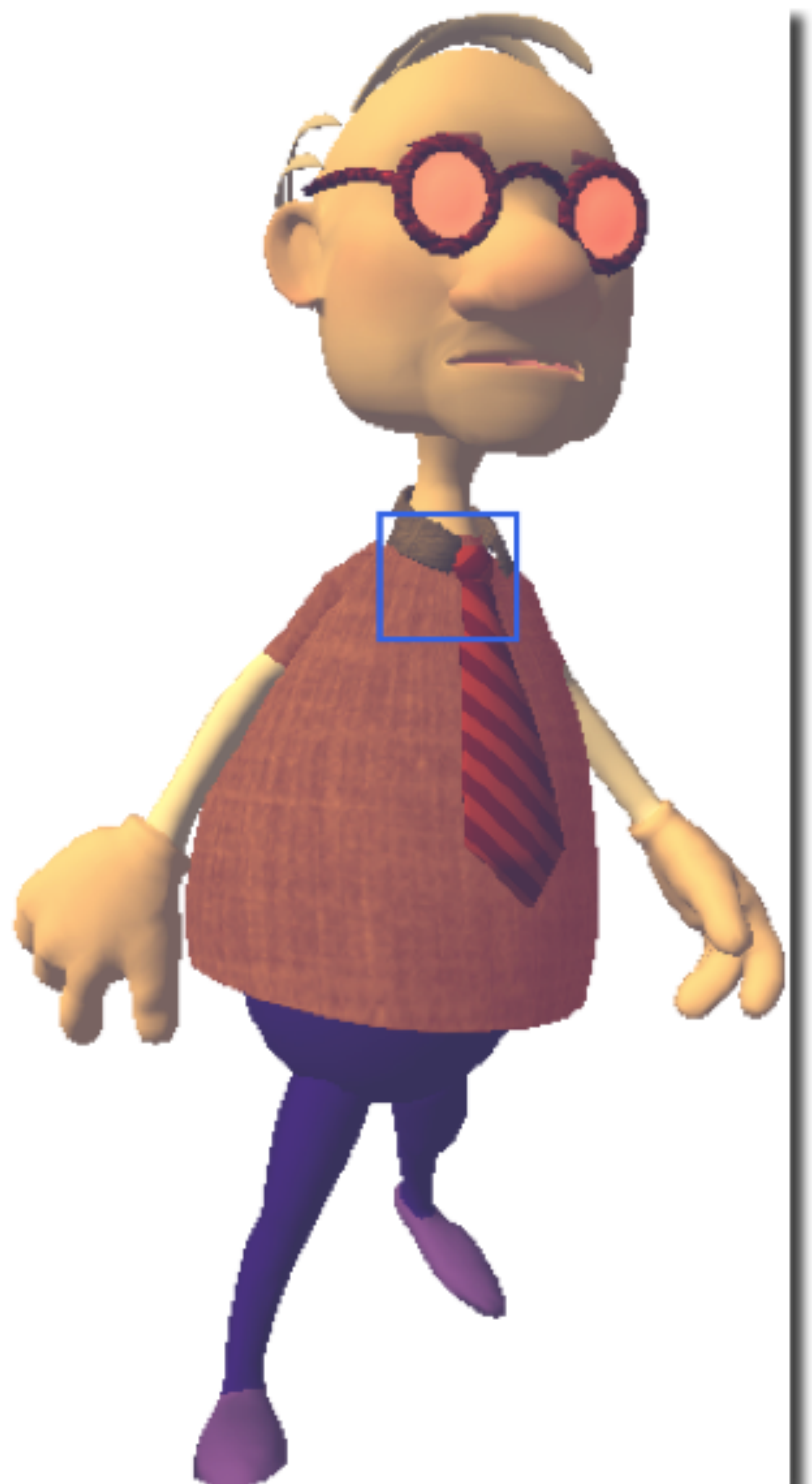
("hallucinate" a smooth edge.. it's a hack!)



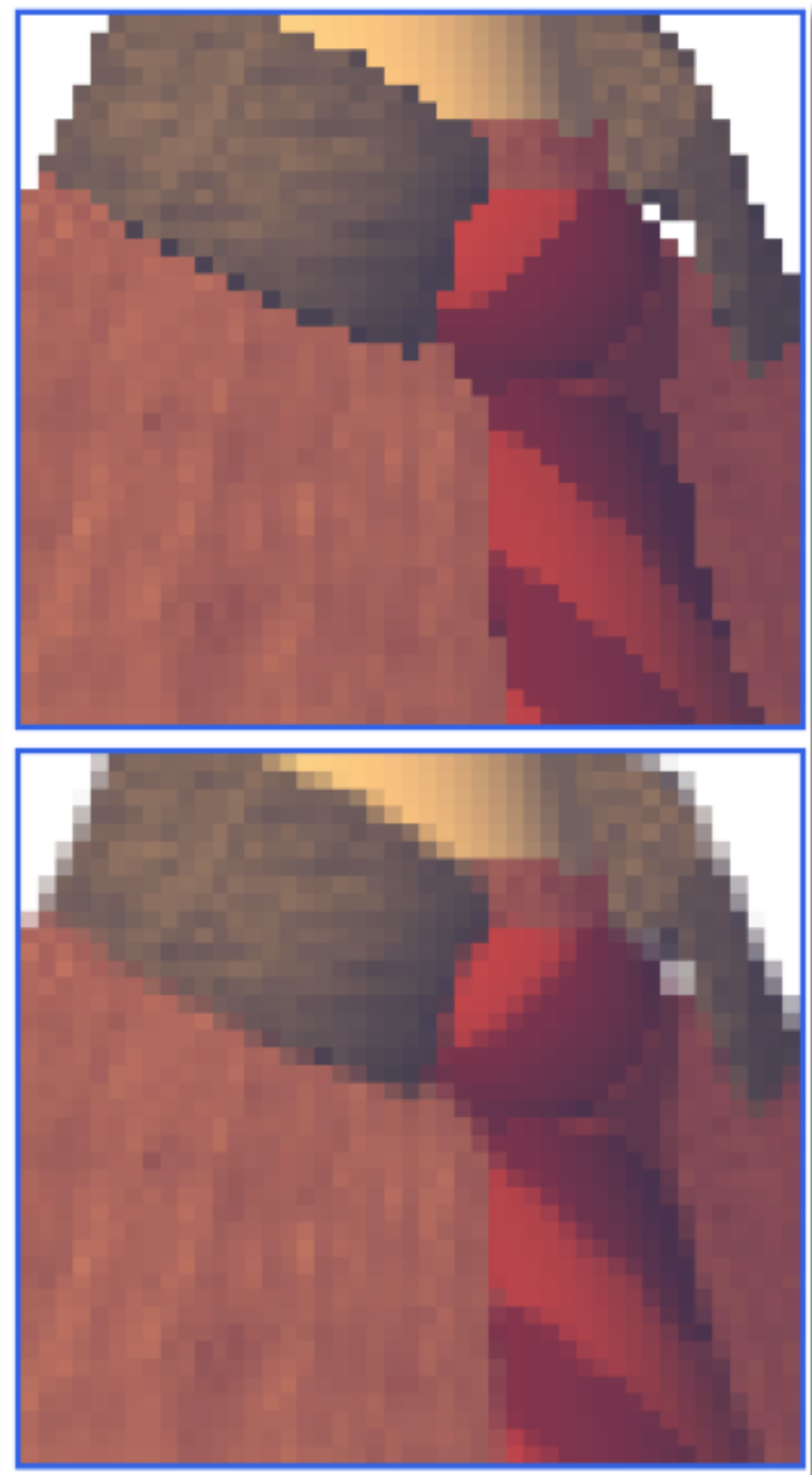
Note: modern interest in replacing MLAA patterns with DNN-based anti-aliasing.

Morphological anti-aliasing (MLAA)

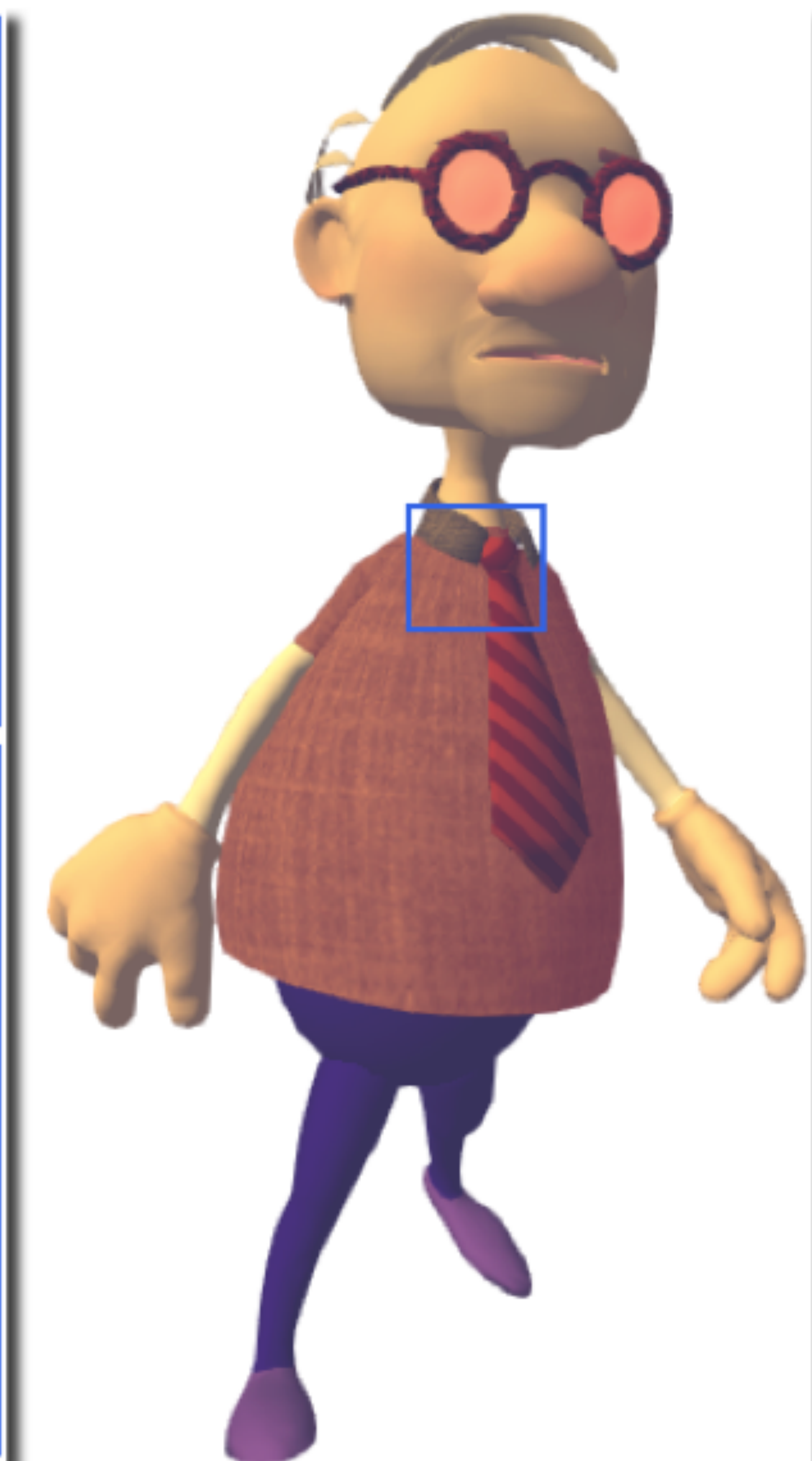
[Reshetov 09]



Aliased image
(one shading sample per pixel)



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



After filtering using MLAA

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