Lecture 21:

Deferred Shading

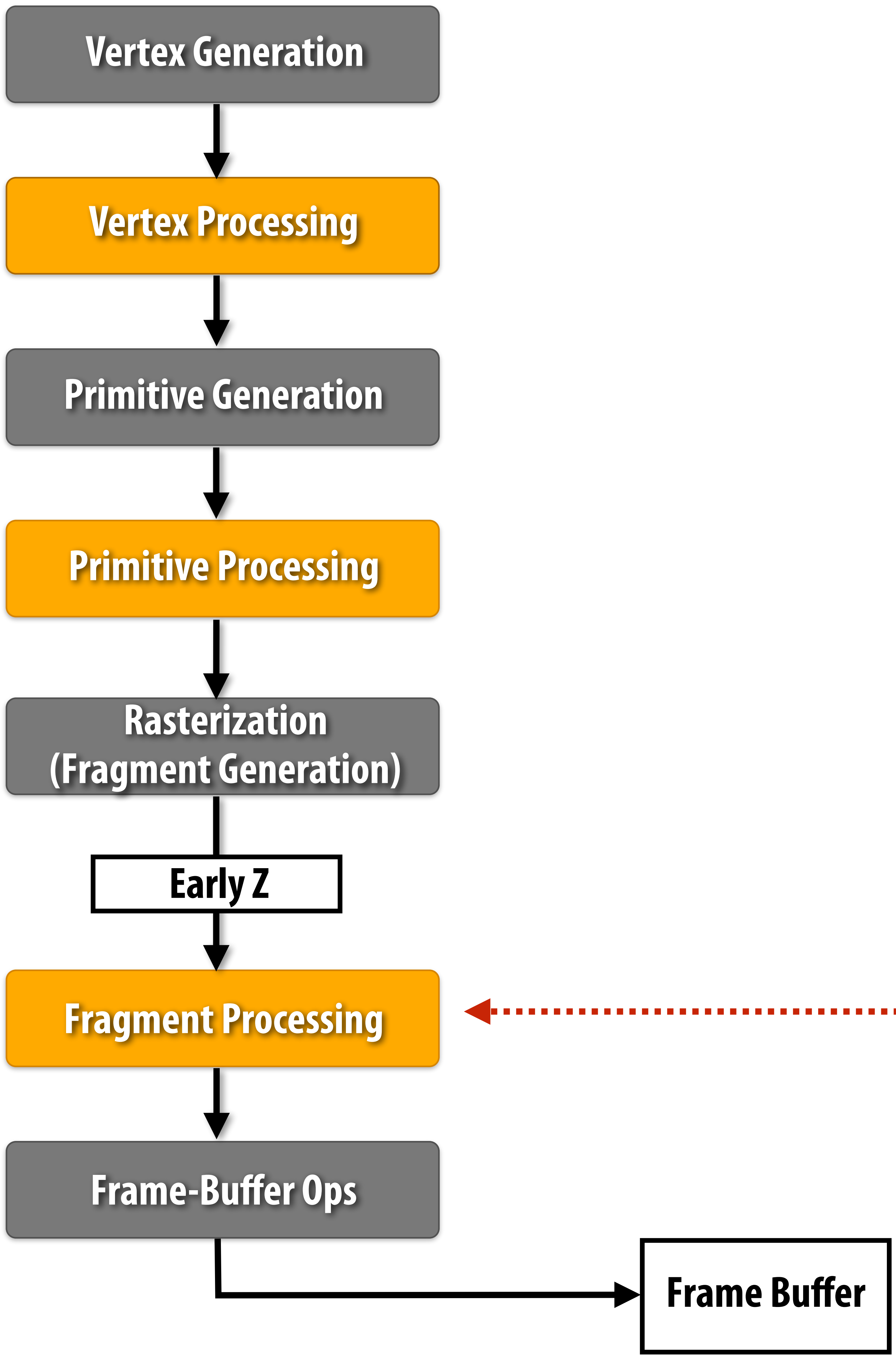
Visual Computing Systems

CMU 15-769, Fall 2016

Deferred shading

- **Popular algorithm used by many modern real-time renderers**
- **Idea: restructure the rendering pipeline to perform shading <u>after</u> all occlusions have been resolved**
- **Not a new idea: present in several classic graphics systems, but not directly implemented by modern GPU-accelerated graphics pipeline**
  - **However, modern graphics pipeline provides mechanisms to allow application to implement deferred shading efficiently**
  - **Natively implemented by PowerVR mobile GPUs**
  - **Classic hardware-supported implementations:**
    - **[Deering et al. 88]**
    - **UNC PixelFlow [Molnar et al. 92]**

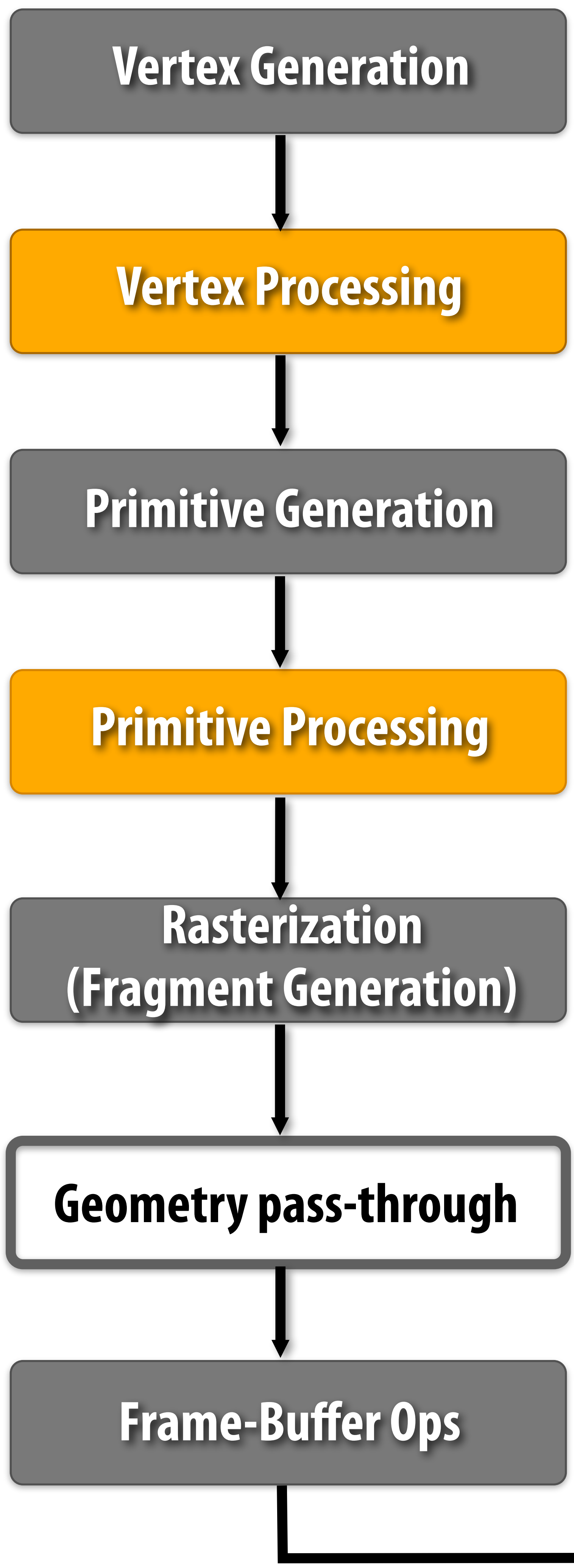
The graphics pipeline



“Feed-forward” rendering

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

Deferred shading pipeline

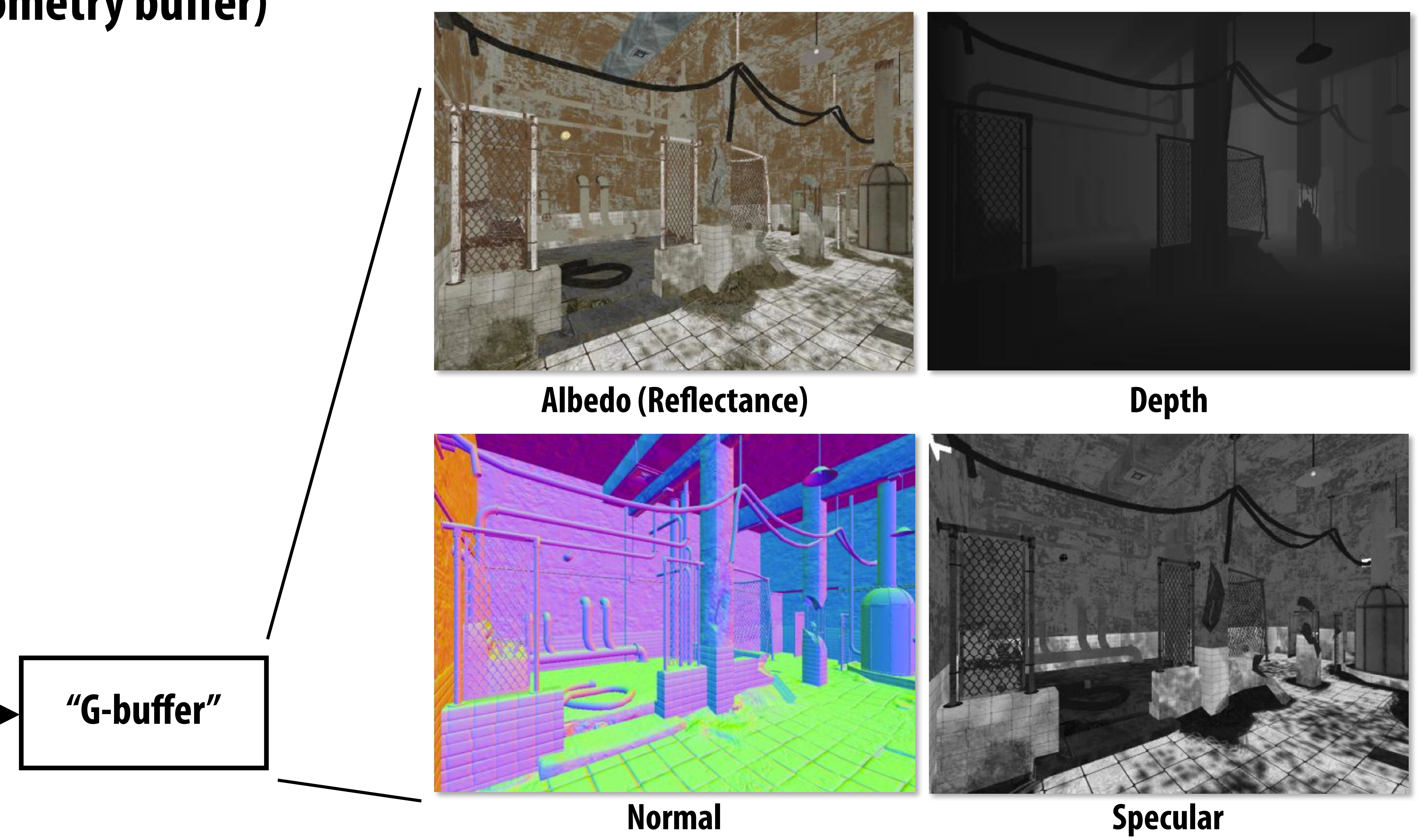


Two pass approach:

Do not use traditional pipeline to generate RGB image.

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

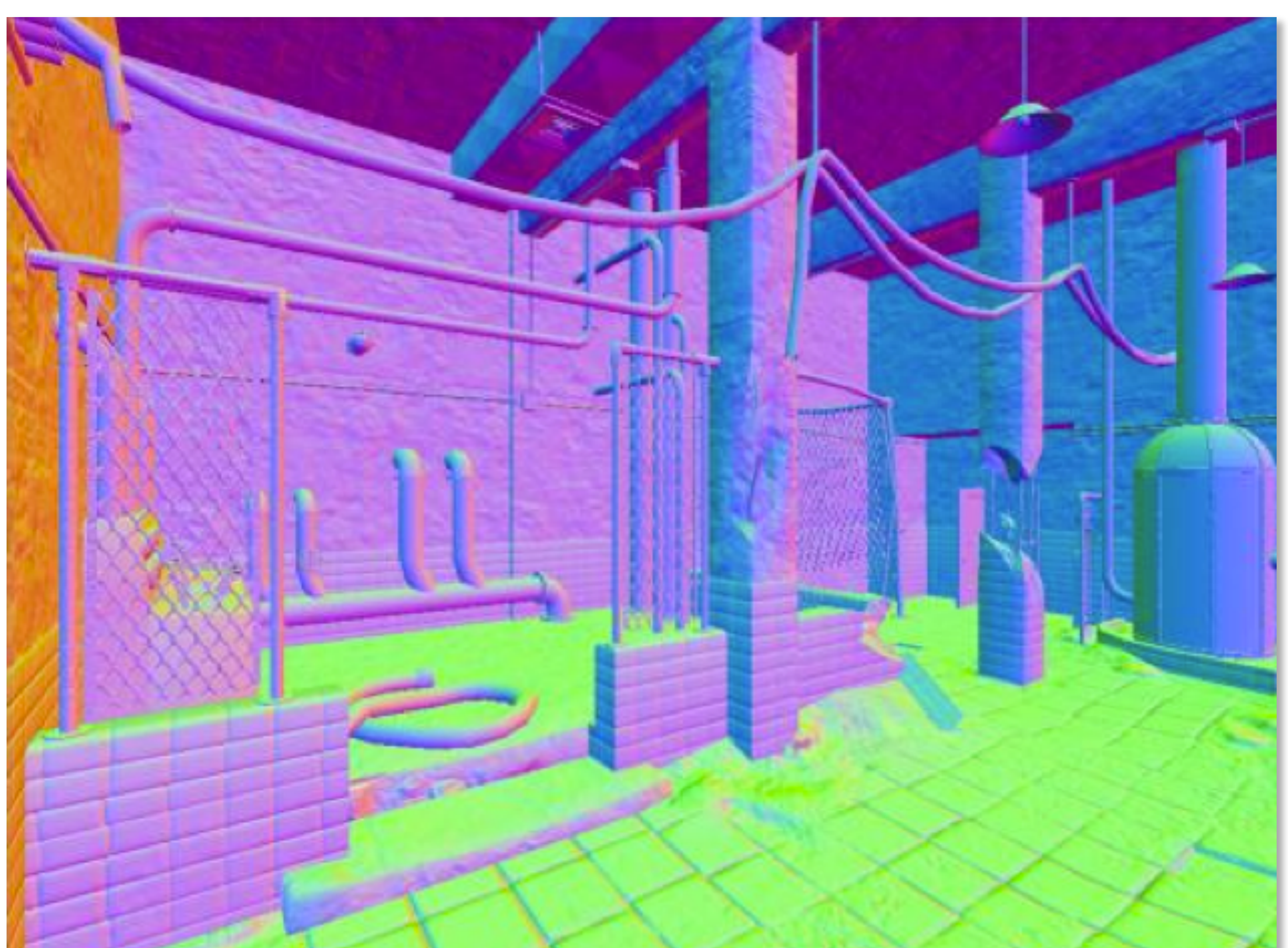
Rendering output is a screen-size 2D buffer representing information about the surface geometry visible at each pixel (called a "g-buffer", for geometry buffer)



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 (32-bits per pixel, per buffer)

<table>
<tr><th>R8</th><th>G8</th><th>B8</th><th>A8</th><th></th></tr>
<tr><td colspan="3">Depth 24bpp</td><td>Stencil</td><td>DS</td></tr>
<tr><td colspan="3">Lighting Accumulation RGB</td><td>Intensity</td><td>RT0</td></tr>
<tr><td colspan="2">Normal X (FP16)</td><td colspan="2">Normal Y (FP16)</td><td>RT1</td></tr>
<tr><td colspan="2">Motion Vectors XY</td><td>Spec-Power</td><td>Spec-Intensity</td><td>RT2</td></tr>
<tr><td colspan="3">Diffuse Albedo RGB</td><td>Sun-Occlusion</td><td>RT3</td></tr>
</table>

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

Implementation on modern GPUs:
- **Application binds "multiple render targets" (RT0, RT1, RT2, RT3 in figure) to pipeline**
- **Rendering geometry outputs to depth buffer + multiple color buffers**

More intuitive to consider G-buffer as one big buffer 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

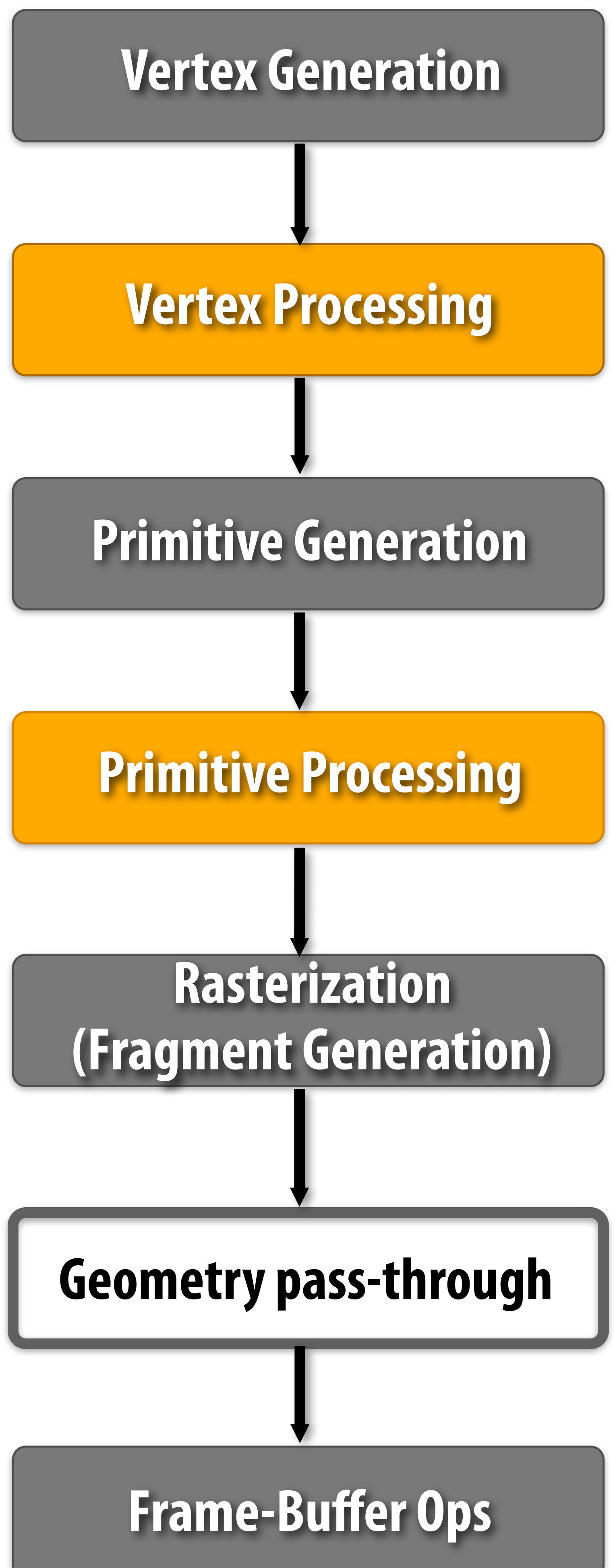
G-buffer layout in Bungie's Destiny (2014)

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

- **Material information 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

Source: N Tatarchuk: SIGGRAPH 2014 Courses

“Two pass” deferred shading



Two pass approach:

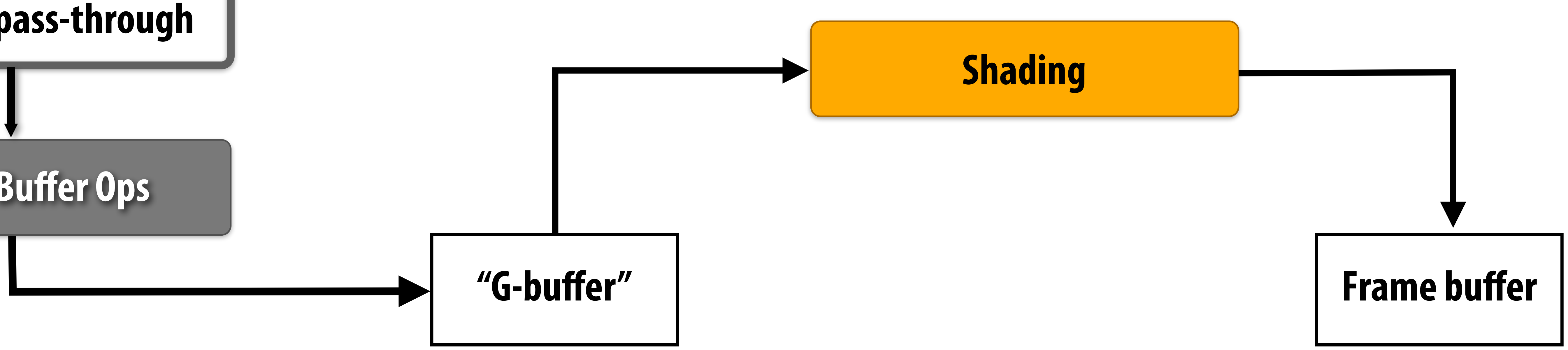
Do not use traditional pipeline to generate RGB image.

Fragment shader outputs surface properties (shader 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)

After all geometry has been rendered, execute shader for each sample in the G-buffer: shader reads geometry information for sample, computes RGB output

(shading is <u>deferred</u> until all geometry processing -- including all occlusion computations -- is complete)

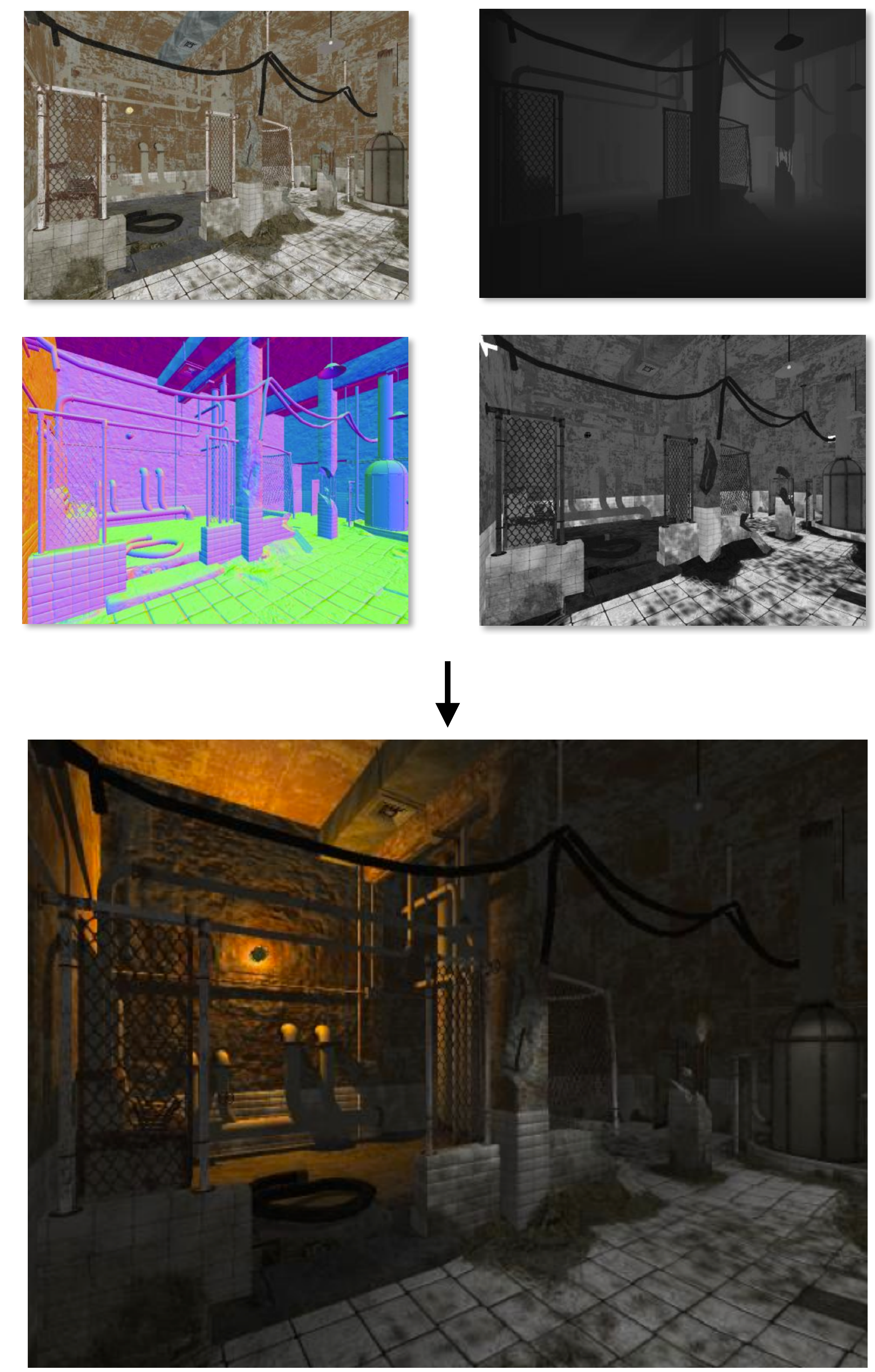


Two-pass deferred shading algorithm

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

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

  For each G-buffer sample, compute shading
  - Read G-buffer data for current sample
  - Accumulate contribution of all lights
  - Output final surface color for sample



Final Image

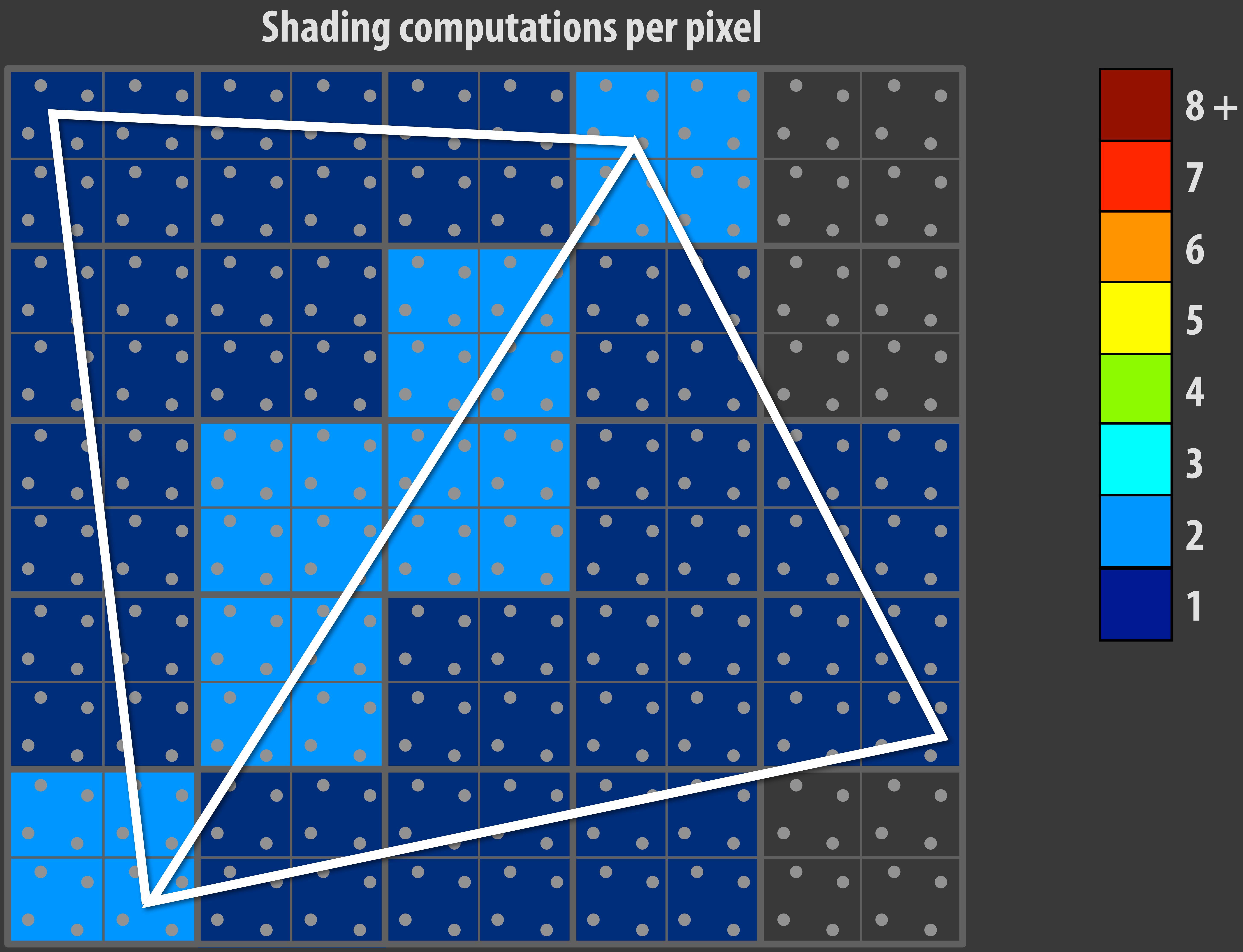
Image Credit: J. Klint, "Deferred Rendering in Leadworks Engine"

Motivation: why deferred shading?

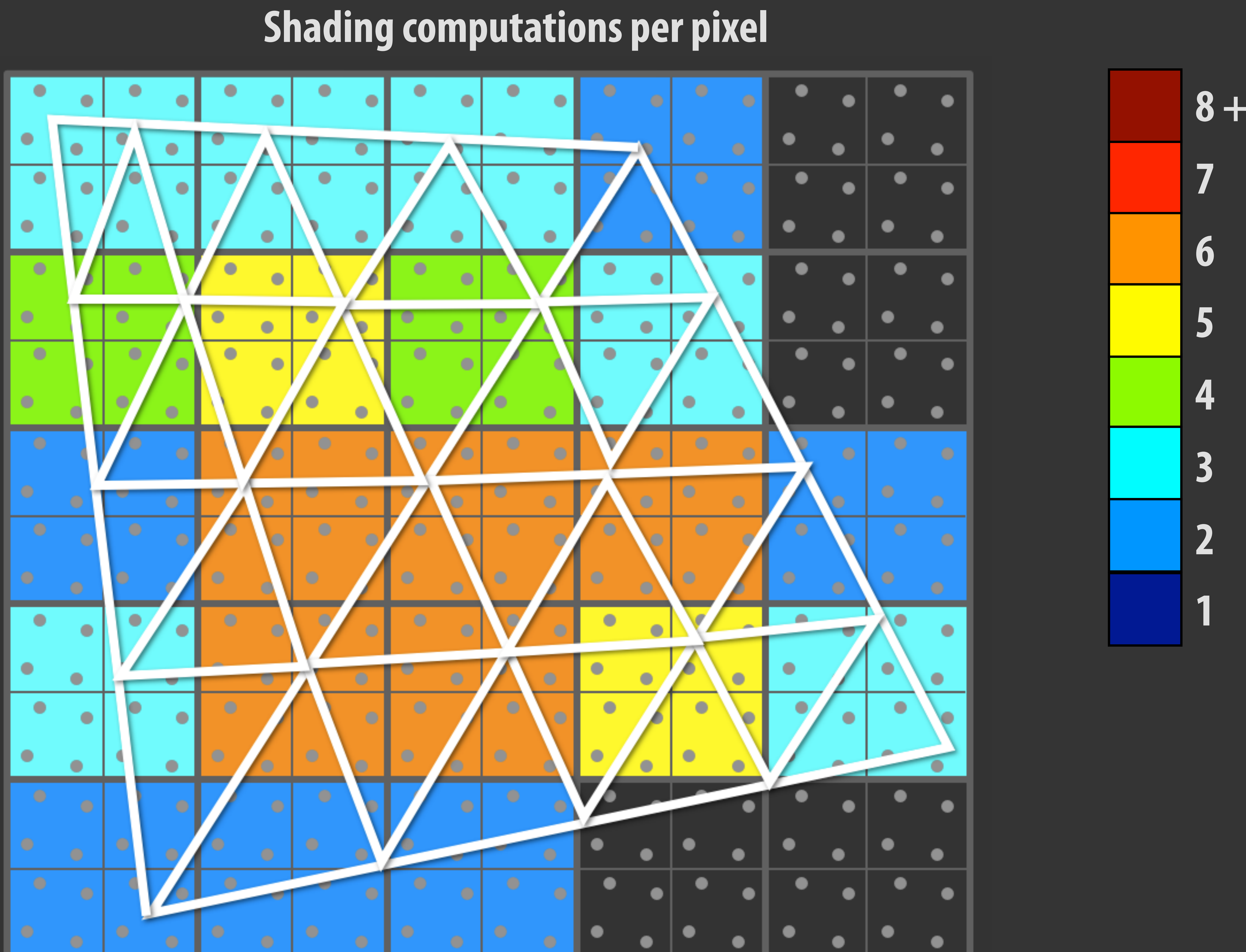
- **Shading is expensive: shade only visible fragments**
  - Deferred shading amounts to perfect early occlusion culling
  - Deferred shading is triangle order invariant (will only shade visible fragments, regardless of application's triangle submission order)
  - Also has nice property that the number of shaded fragments is independent of scene complexity (predictable shading performance)

- **Recall: forward rendering shades small triangles inefficiently**
  - Recall shading granularity is quad fragments: multiple fragments generated for pixels along triangle edges

Recall: forward shading shades multiple fragments at pixels containing triangle boundaries



Recall: forward shading shades multiple fragments at pixels containing triangle boundaries



Motivation: why deferred shading?

- Shade only visible surface fragments
- Forward rendering shades small triangles inefficiently (quad-fragment granularity)
- Increasing complexity of lighting computations
  - Growing interest in scaling scenes to many light sources

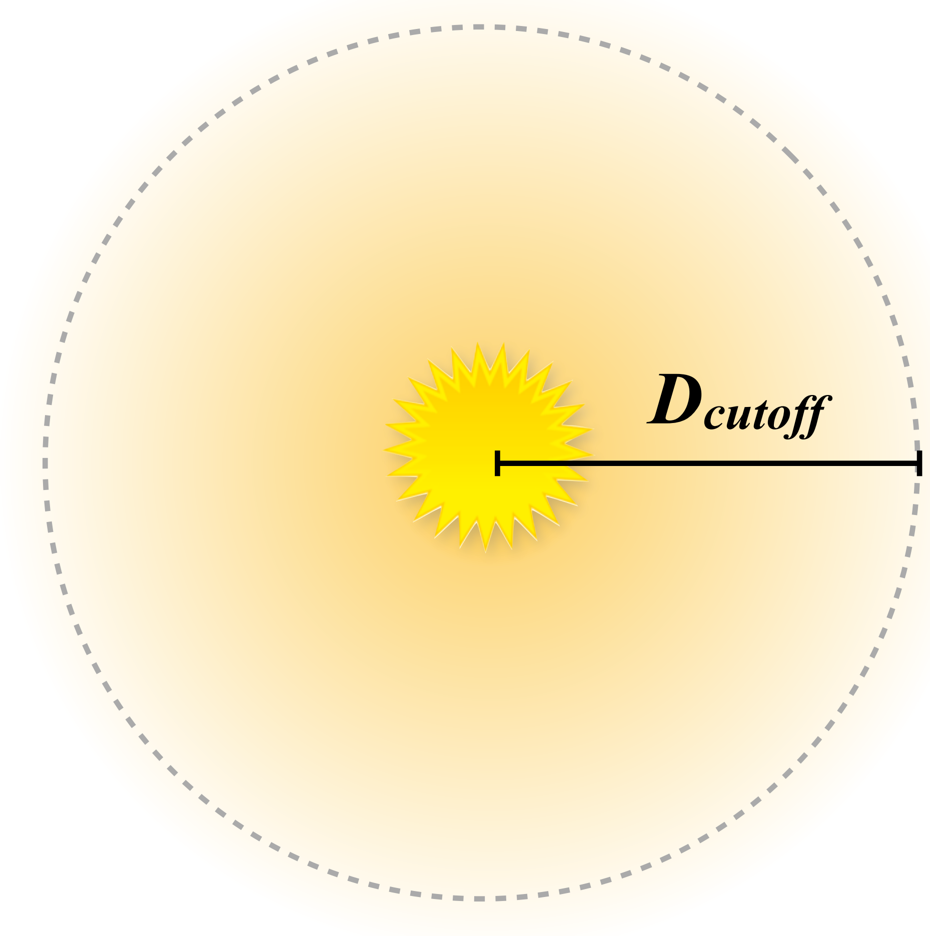
1000 lights

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

Lights

- Graphics applications employ many kinds of lights

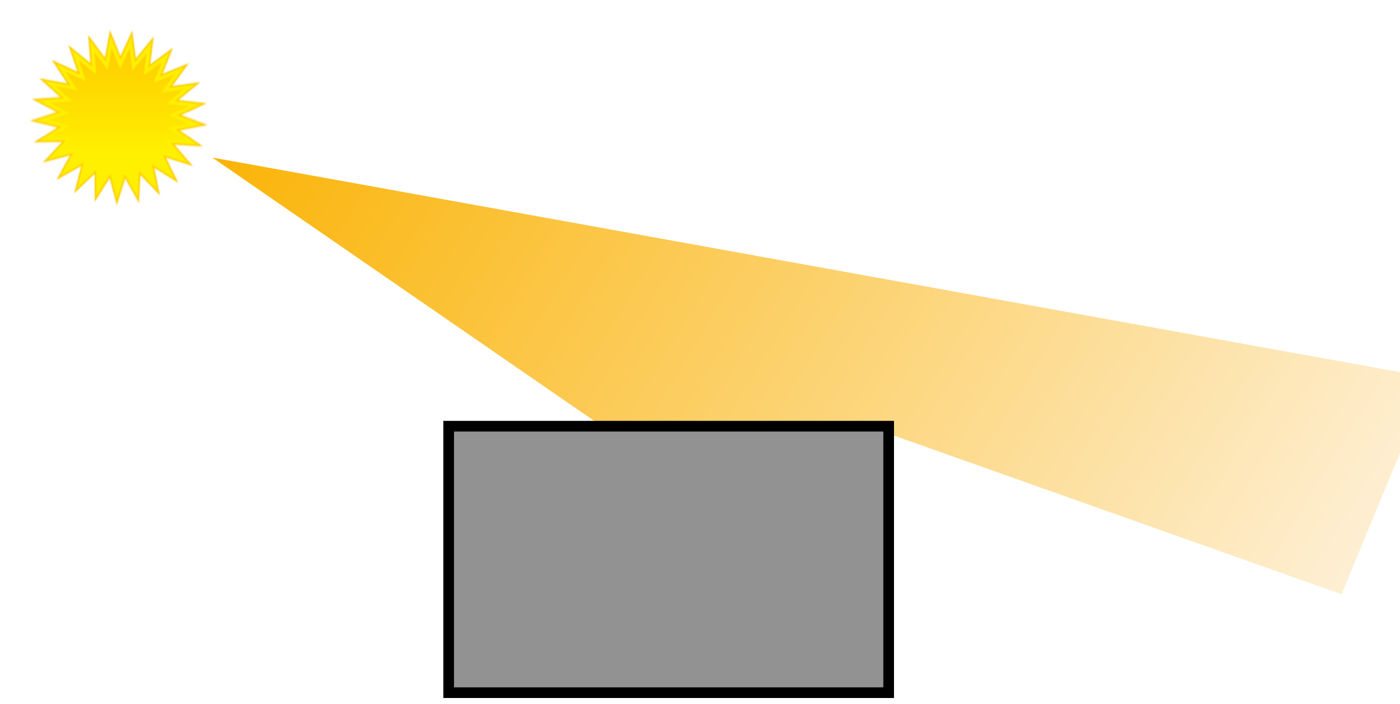
- For efficiency, lights often specify finite volume of influence



Omnidirectional point light (with distance cutoff)

Directional spotlight

Shadowed light



Environment light

Forward rendering: naive multiple-light shader

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

// uniform values (read-only inputs to all shader instancess)
sampler mySamp;
Texture2D<float3> myTex;
Texture2D<float> myEnvMaps[MAX_NUM_LIGHTS];
Texture2D<float> myShadowMaps[MAX_NUM_LIGHTS];
LightDefinition  lightList[MAX_NUM_LIGHTS];
int numLights;

// fragment shader receives surface normal and texture coords uv
float4 fragment_shader(float3 norm, float2 uv) {
  float3 kd = myTex.Sample(mySamp, uv);
  float4 result = float4(0, 0, 0, 0);
  for (int i=0; i<numLights; i++)
  {
     result += …   // eval contribution of light to surface reflectance here
  }
   return 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:

Triangle setup performed once, amortized across many samples

High coherence in shading computations (fragments are from the same triangle: same shader program, similar data access)

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;
  ...
}

sampler mySamp;
Texture2D<float3> myTex;
Texture2D<float> myEnvMaps[MAX_NUM_LIGHTS];
Texture2D<float> myShadowMaps[MAX_NUM_LIGHTS];
LightDefinition lightList[MAX_NUM_LIGHTS];
int numLights;

float4 shader(float3 norm, float2 uv)
{
  float3 kd = myTex.Sample(mySamp, uv);
  float4 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 ...
      }
  }
   return result;
}
```

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

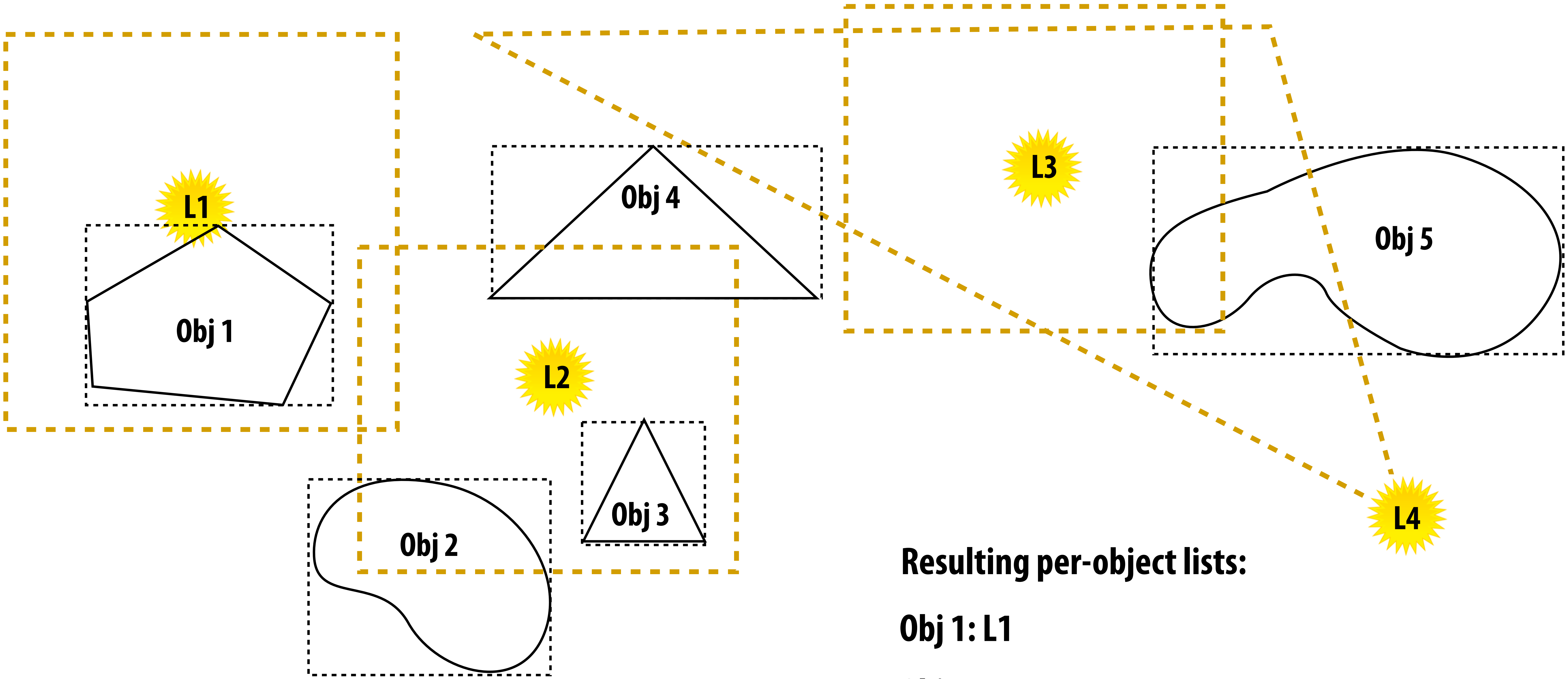
(spatial coherence in predicate should exist)

Forward rendering: techniques for scaling to many lights

- **Goal: avoid performing F x L "is-illuminated" checks**
- **Solution: application maintains per-object light lists**
  - Each object stores 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 bind data for relevant lights to pipeline
  - To avoid SIMD divergence: precompile shader variants that are specialized for different sets of bound lights (4-light version, 8-light version...)
    - Low execution divergence during fragment shading
    - Many graphics state changes, small draw command batch sizes (draw command = single object, or group of objects with the same number of lights)

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 specialized to a specific number of 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**
  - Computed conservatively per frame

- **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: low execution divergence during fragment shading
  - Bad: many graphics state changes (draw call = single object, or 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: Low execution divergence during fragment shading
  - 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]
```

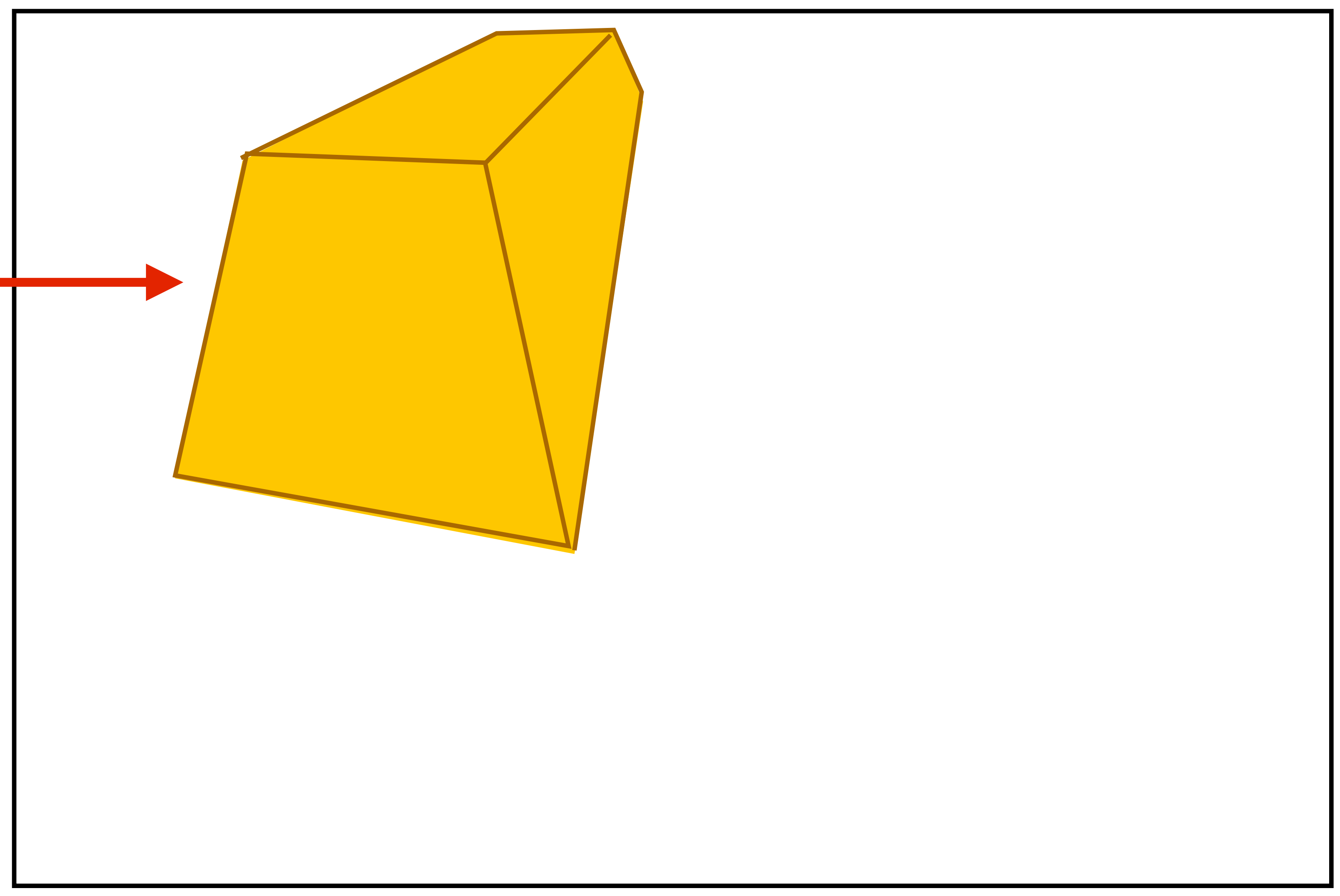
- **Bad:**
  - **High G-buffer footprint: G-buffer has large footprint (especially when G-buffer is supersampled!)**
  - **<u>High bandwidth costs</u> (read G-buffer each pass, output to frame buffer)**
  - **Exactly one shading computation per frame-buffer sample**
    - **Does not support transparency (need multiple fragments per pixel)**
    - **Challenging to implement MSAA efficiently (more on this to come)**

Reducing deferred shading bandwidth costs

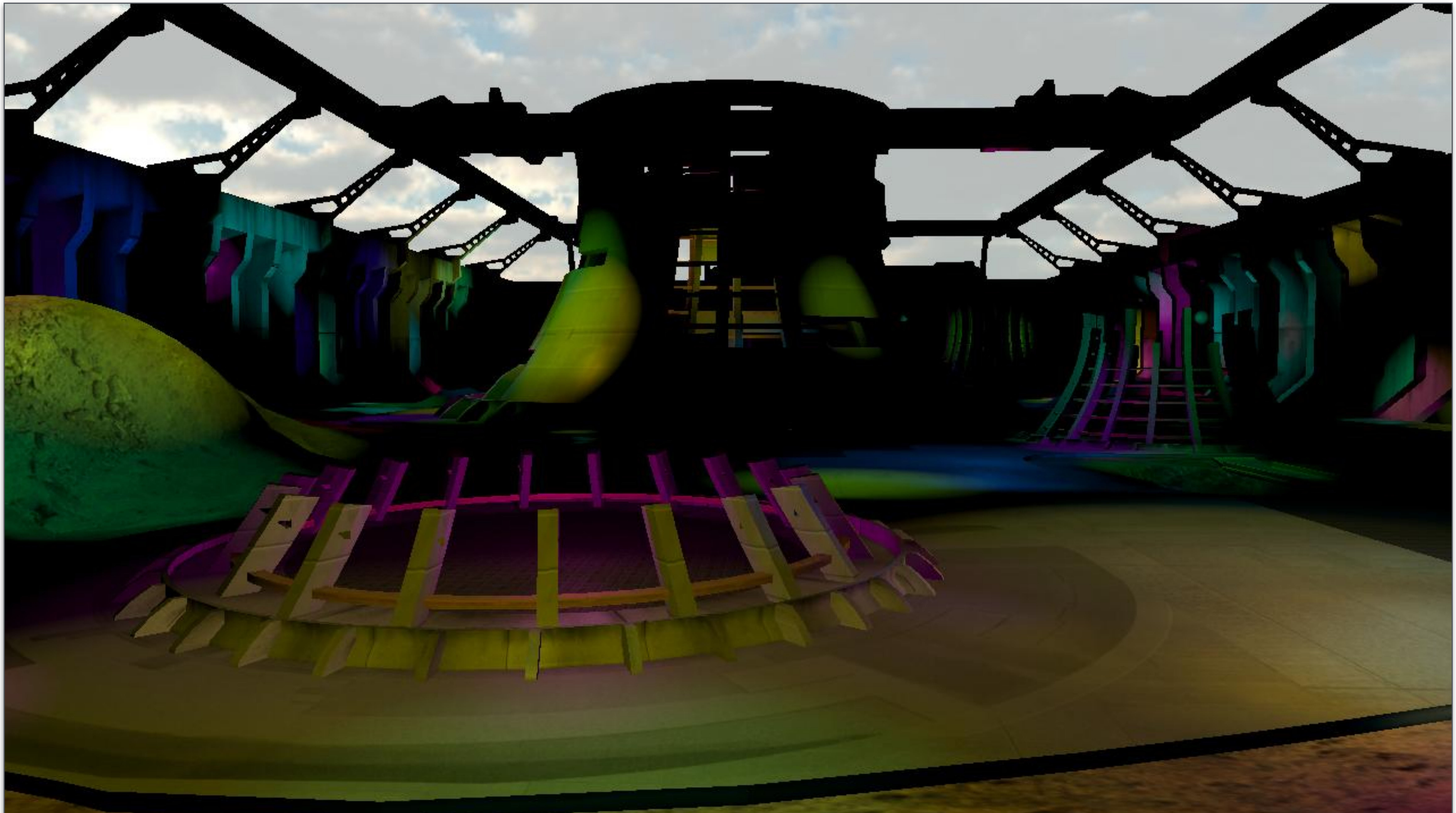
- **Batching: process multiple lights in each phase 2 accumulation pass**
  - Amortizes G-buffer load and frame buffer write across lighting computations for multiple lights
- **Only perform shading computations for G-buffer samples illuminated by light**
  - Technique 1: rasterize geometry of light 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

Tile-based deferred shading

[Andersson 09]

- Main idea: exploit coherence in light-sample interactions
  - Compute set of lights that influence a small tile of G-buffer samples, then compute contribution of lights to samples in the tile

- Efficient implementation enabled by "shared memory" available in CUDA/computer shader
  - Amortize G-buffer load, frame-buffer write across all lights
  - Amortize light data load across tile samples
  - Amortize light-sample culling across samples in a tile

Tile-based deferred shading

[Andersson 09]

Step 1: Perform G-buffer generation pass to create G-buffer and Z-buffer

Step 2: Shade G-buffer using compute mode GPU execution

Each compute kernel thread group is responsible for shading a 16x16 sample tile of the G-buffer (256 threads per group)

```
LightDescription perTileLightList[MAX_LIGHTS];    // stored in group shared memory

All threads cooperatively compute Z-min, Zmax for current tile from z-buffer

barrier;

for each light:                // parallel across threads in thread group (parallel over lights)
   if (light volume intersects tile frustum)
      append light to tileLightList // stored in shared memory

barrier;

for each sample:               // parallel across threads in group (parallel over samples)
   result = float4(0,0,0,0)
   load G-buffer data for sample
   for each light in perTileLightList:      // no divergence across samples
       result += evaluate contribution of light

   store result to appropriate position in frame buffer
```

Load depth buffer once

Cull lights at tile granularity

Read G-buffer once

Write final pixel color to frame buffer once

Tiled-based light culling

Yellow boxes: screen-aligned light volume bounding boxes
Blue boxes: screen tile boundaries

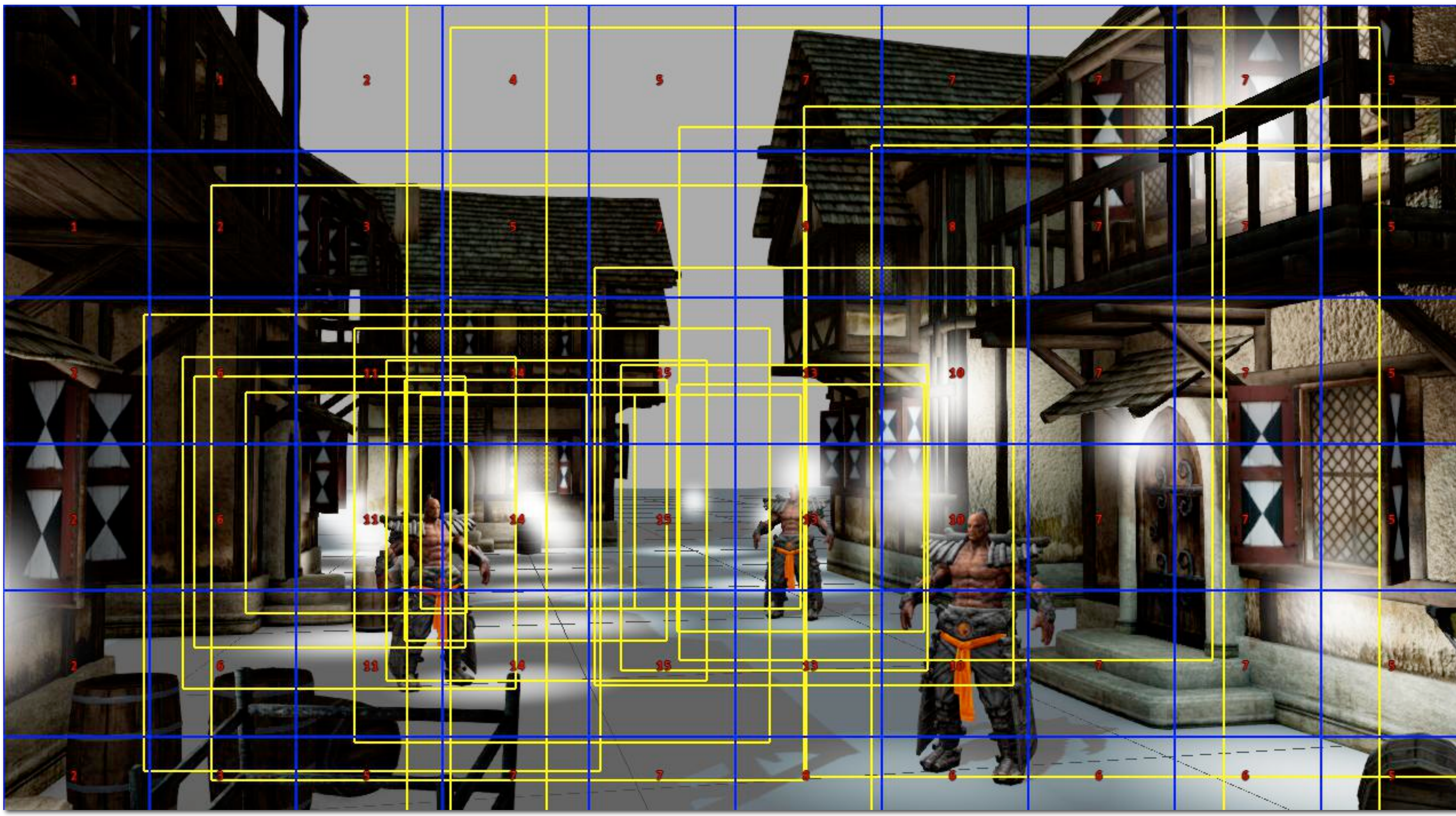
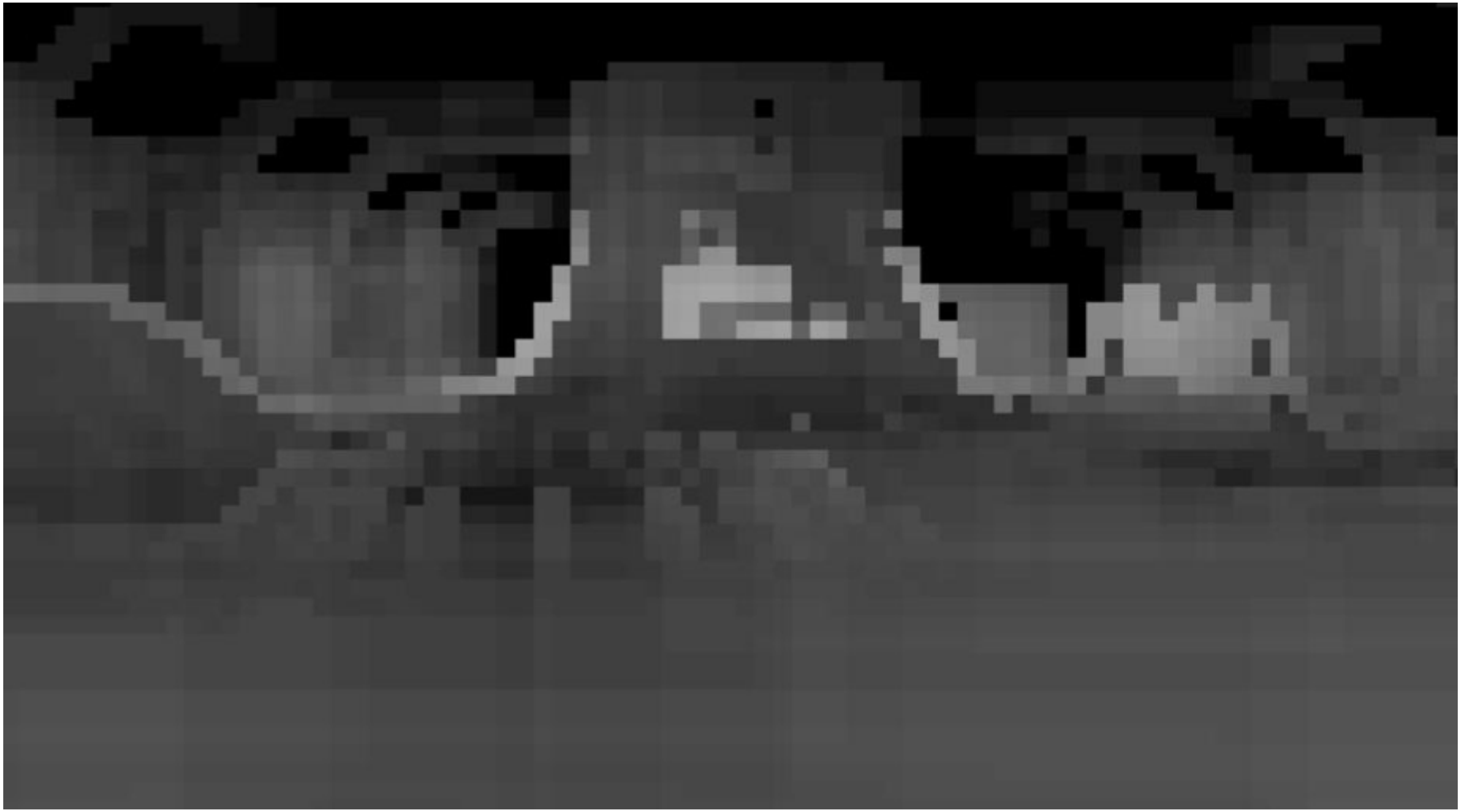


Image credit: HMREngine: http://www.hmrengine.com/blog/?p=399

Tile-based deferred shading: better light culling efficiency

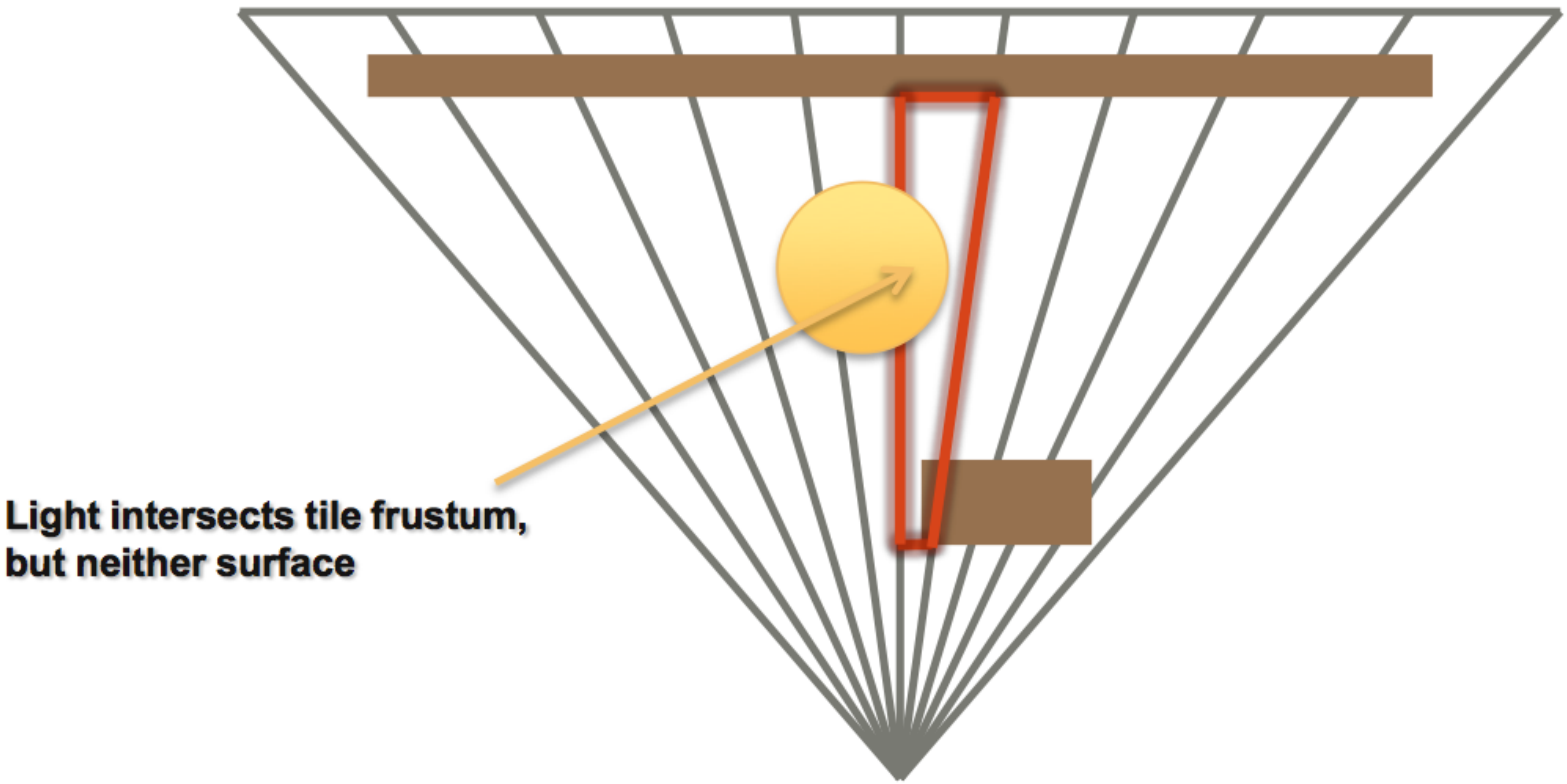
(16x16 granularity of light culling is apparent in figure)



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

Image Credit: A. Lauritzen

Culling inefficiency near silhouettes

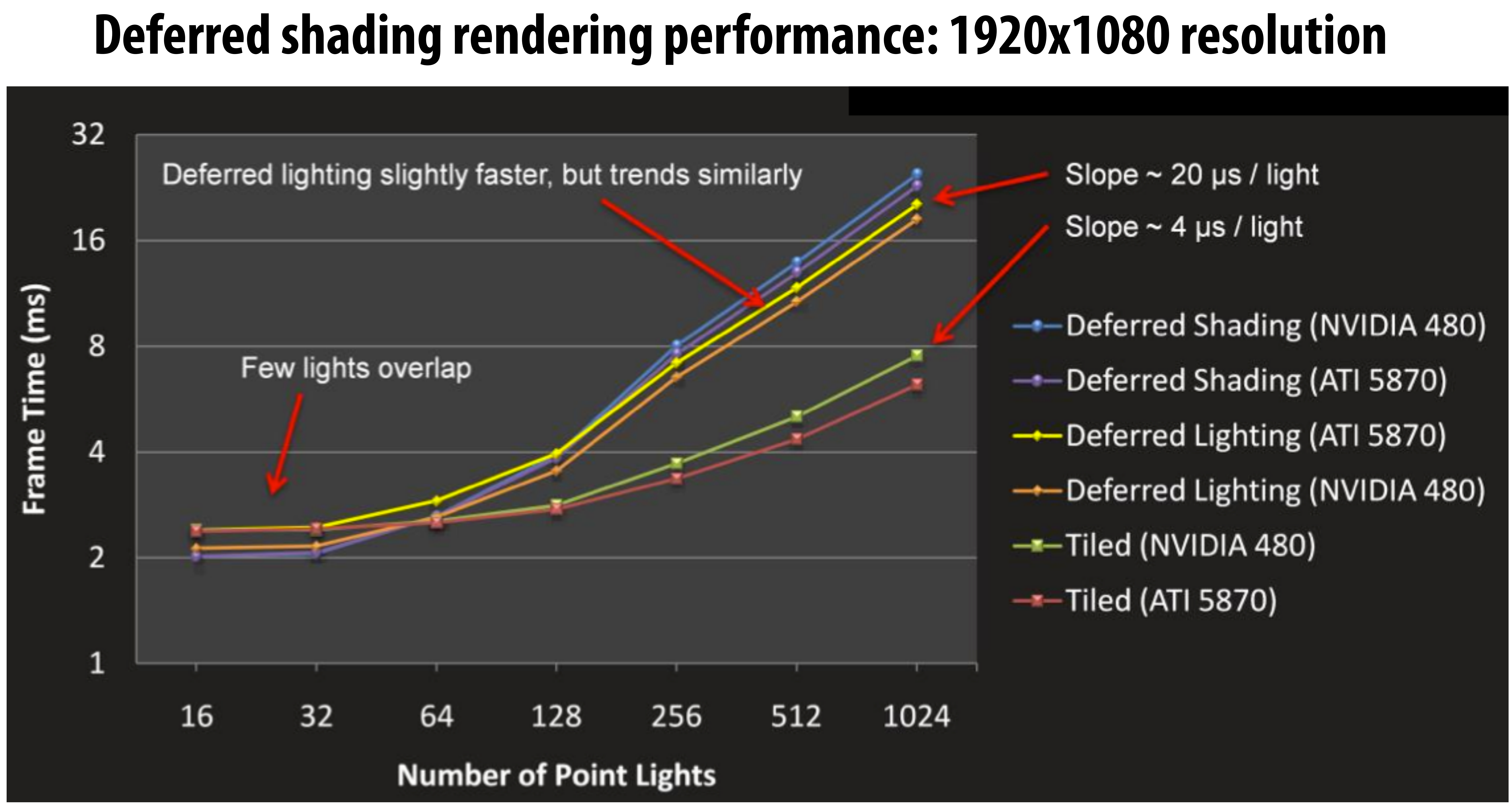


Tile screen boundaries + tile (zmin, zmax) define a frustum

Depth bounds are not tight when tile contains an object silhouette

Image Credit: A. Lauritzen

Tiled vs. conventional deferred shading



[Lauritzen 2009]

“Forward plus” rendering

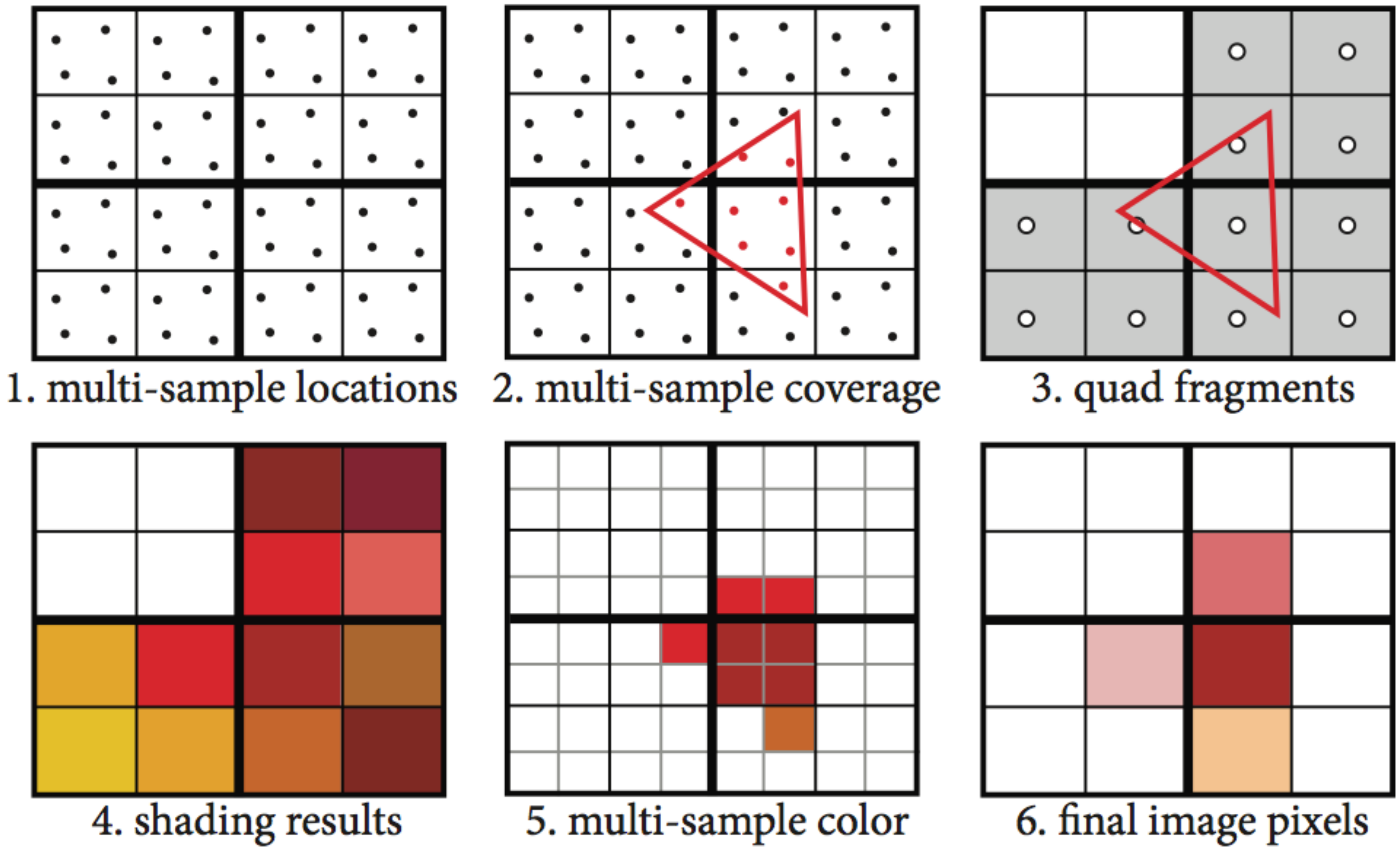
- **Tile-based (hierarchical) light culling is not unique to deferred shading**
- **“Forward+” rendering involves three phases**

```
Phase 1: Render “Z-prepass" to populate depth buffer (process all geometry)
Phase 2: In compute shader: compute zmin/zmax for all tiles, compute light lists for screen tiles
Phase 3: Render scene with shading enabled (process all geometry again)
              Fragment shader determines which tile it resides in
              Shader uses tile’s precomputed light list when computing surface illumination
```

- **Achieves light culling benefits of tiled-deferred approach in a forward renderer (it’s just another reordering of the loops!)**
  - **Primary difference is how shading is scheduled:**
    - **Forward+ recomputes shading inputs using a second geometry pass (“rematerialization” of shading inputs via extra computation) but stores light lists in memory between phase 2 and phase 3.**
    - **Tiled-deferred stores shading inputs in the G-buffer. It never stores light lists in off-chip memory (only compute shader shared memory) because the light list is consumed immediately after its construction in the shader.**

Challenge: anti-aliasing geometry in a deferred renderer

Recall: multi-sample anti-aliasing (MSAA)



Main idea: decouple shading sampling rate from visibility sampling rate

- Depth buffer: stores depth <u>per sample</u>
- Color buffer: stores color <u>per sample</u>
- Resample color buffer to get final image pixel values

MSAA in a deferred shading system

- Deferred shading performs exactly one shading computation per G-buffer sample *

- MSAA: shades once <u>per triangle</u> contributing coverage to samples in a pixel
  - So the effective shading rate is adaptive
  - For pixels in interior of projected triangle: this is one shading computation per pixel
  - For pixels on boundary of triangles, extra shading occurs
    - This is desirable: extra shading necessary to anti-alias object silhouettes
    - The undesirable consequence of MSAA is extra shading when two adjacent triangles from the same surface meet

* This is also why transparency is challenging in a deferred shading system

Two anti-aliasing solutions for deferred shading

- **Super-sample G-buffer**
  - Generate super-sampled G-buffer (e.g., 4 samples per pixel)
  - Shade all G-buffer samples
  - Resample shaded results to get final frame-buffer pixels
  - Problems:
    - Increased G-buffer footprint and G-buffer read/write bandwidth (remember: "fat samples" are stored per G-buffer sample)
      - 1900 x 1200 x 4 spp x 20 bytes per sample = 173 MB frame-buffer
    - Increases shading cost because deferred shading systems I described earlier shade at visibility rate, not once per pixel!

- **Intelligently filter aliased shading results**
  - Does not increase G-buffer footprint or shading cost
  - Current popular technique: morphological anti-aliasing (MLAA)

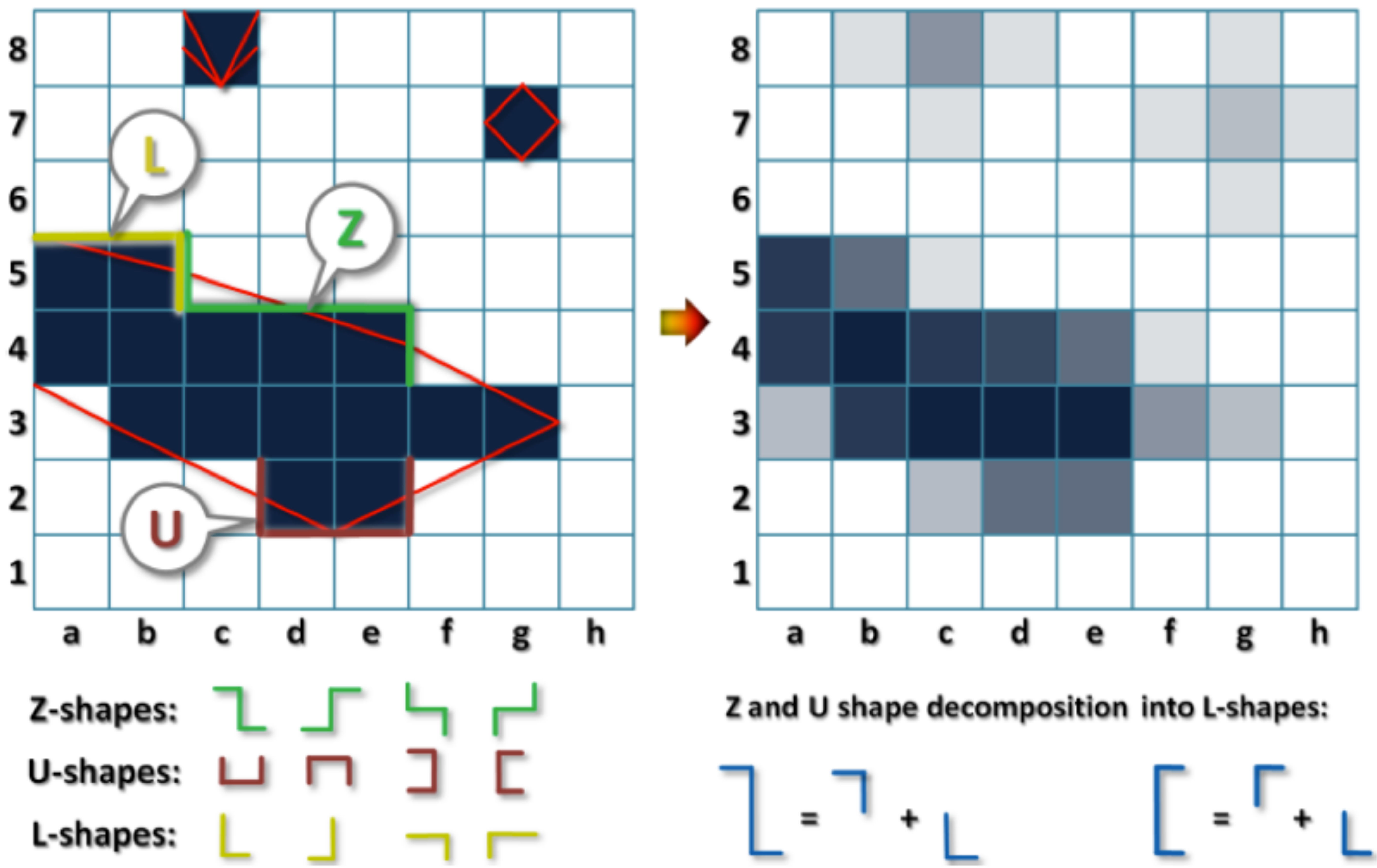
Morphological anti-aliasing (MLAA)

[Reshetov 09]

Detect careful designed patterns in rendered image

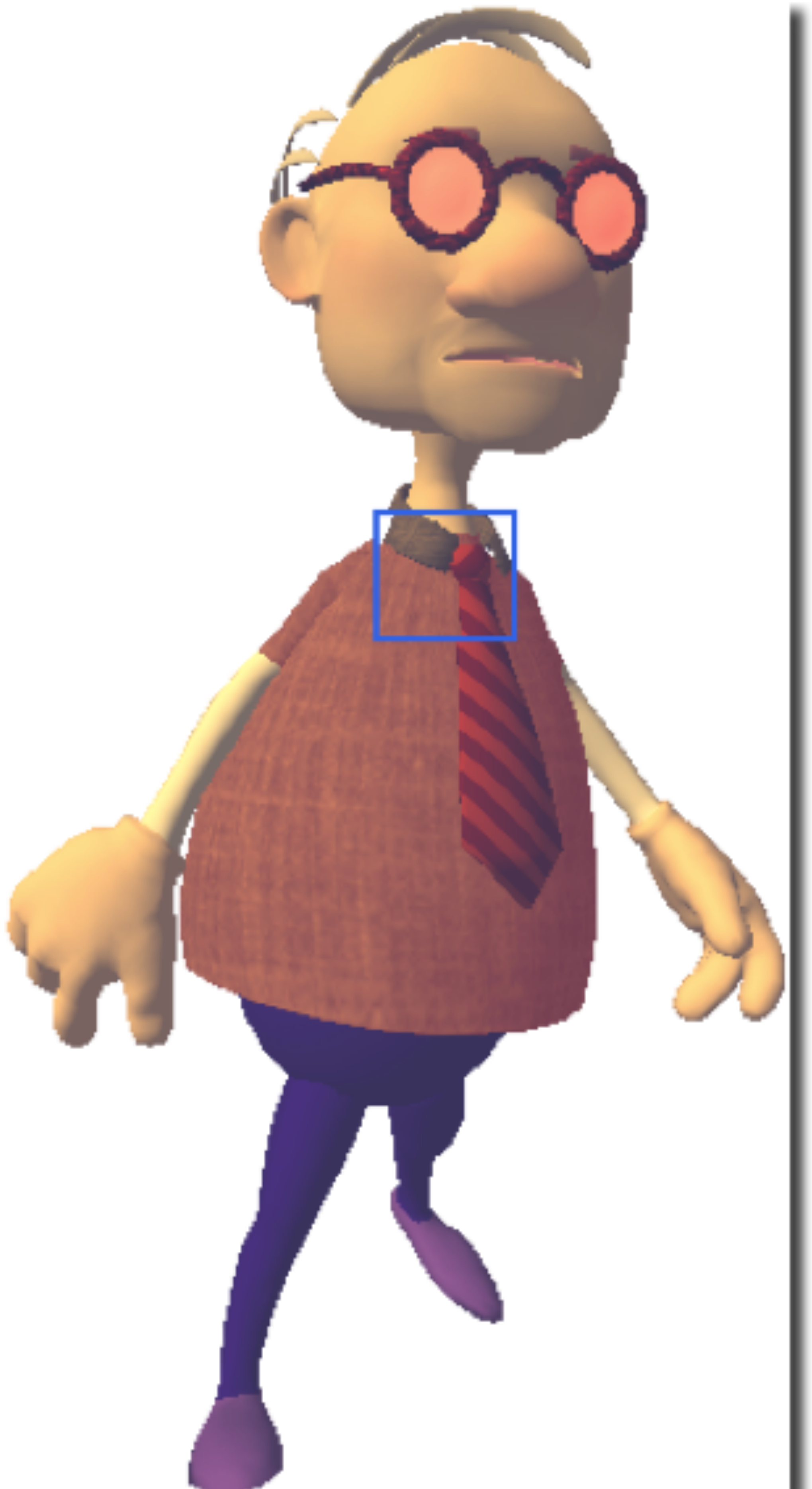
For detected patterns, blend neighboring pixels according to a few simple rules

(“hallucinate” a smooth edge)

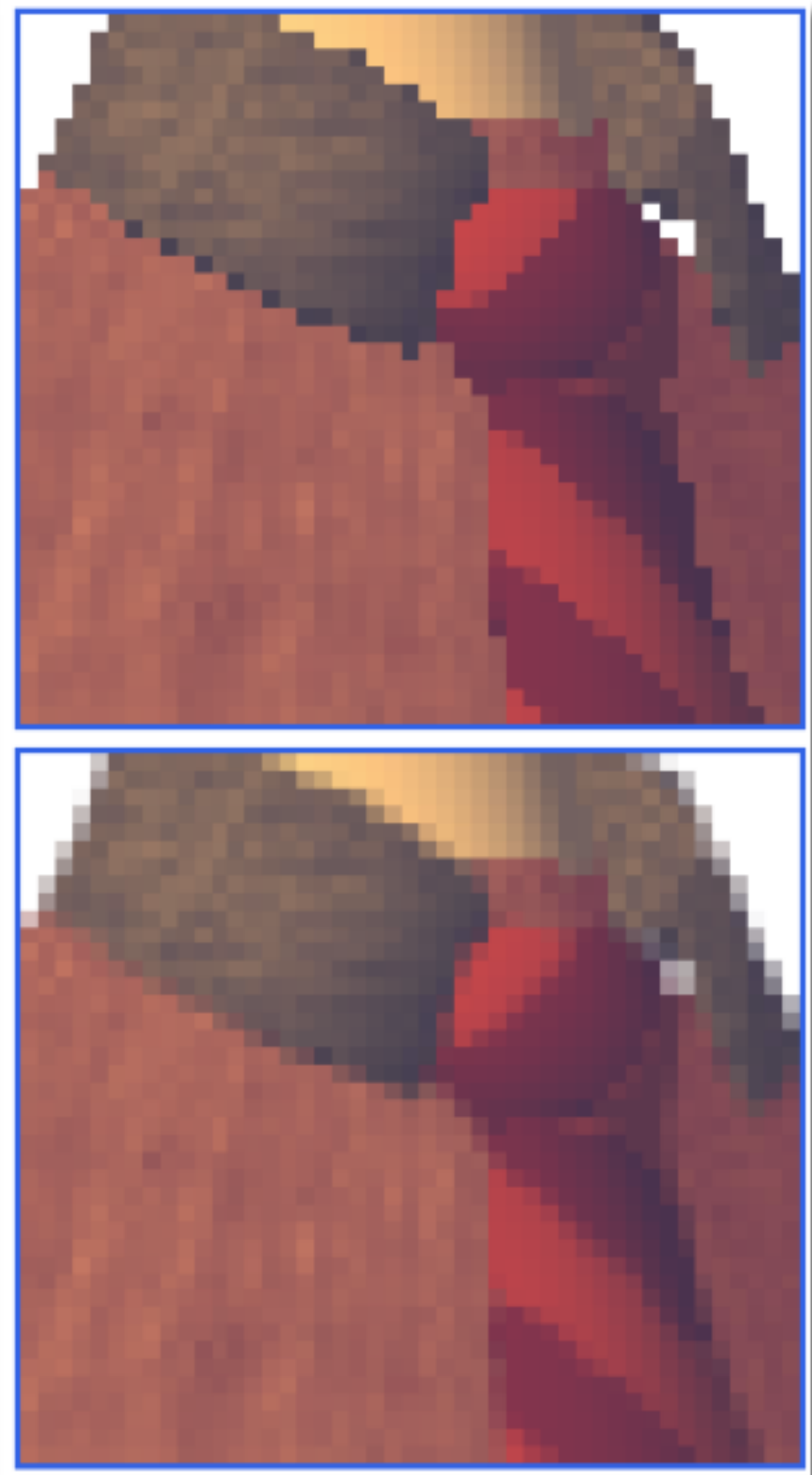


Morphological anti-aliasing (MLAA)

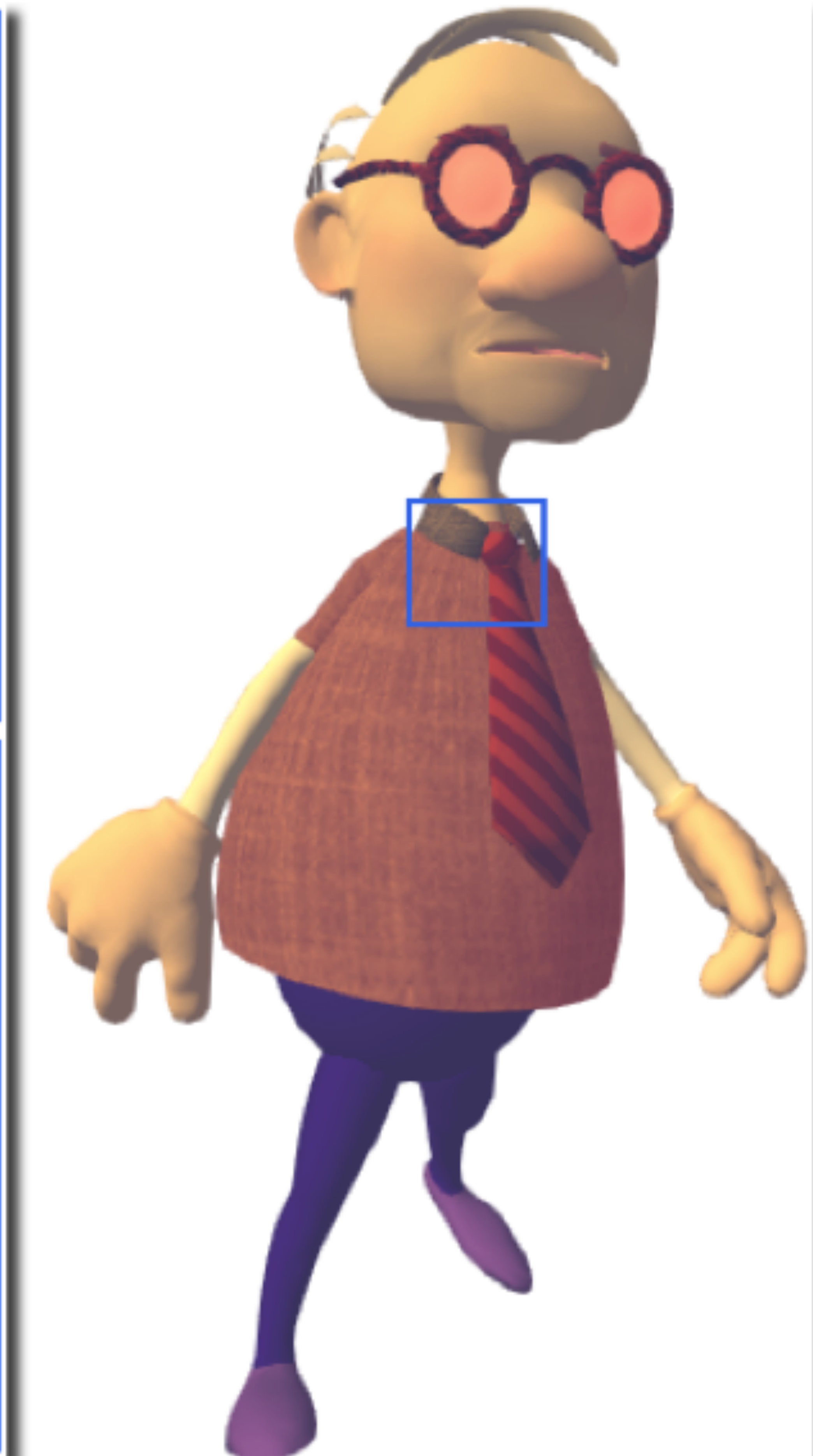
[Reshetov 09]



Aliased image
(one shading sample per pixel)



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



After filtering using MLAA

Anti-aliasing solutions for deferred shading

- **Super-sample G-buffer, super-sample shading**
  - Increases G-buffer footprint and shading cost

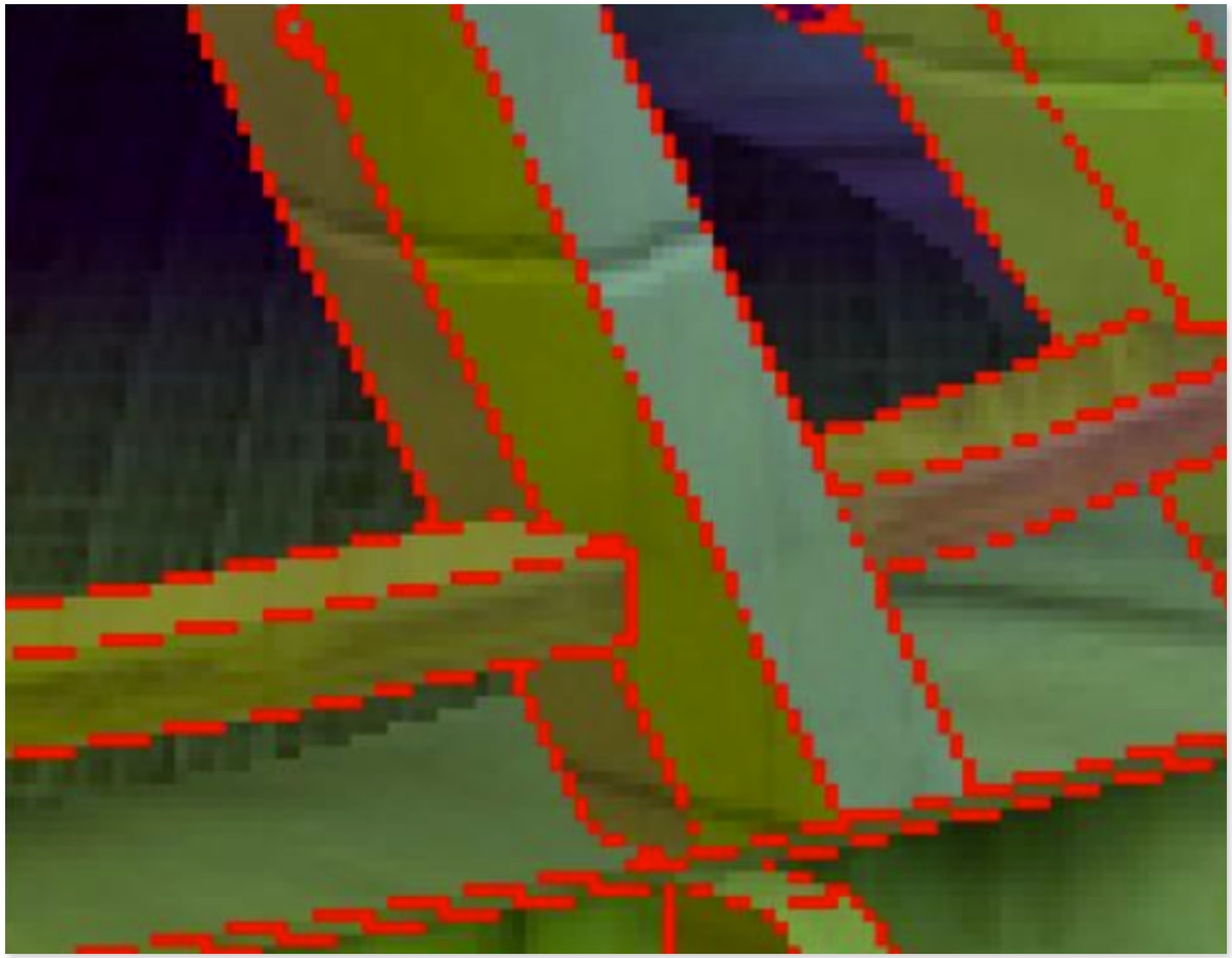
- **Intelligently filter aliased shading results (MLAA popular choice)**
  - Does not increase G-buffer footprint or shading costs, but may produce artifacts (hallucinates edges/detail)

- **Application implements MSAA on its own (without HW support)**
  - Render super-sampled G-buffer
  - Launch one shader instance for each output image sample, not each G-buffer sample
  - New shader implementation:

```
Detect if pixel contains an edge  // how might this be done without geometry information?
If pixel contains an edge:
     Shade all G-buffer samples for pixel (sequentially in shader)
     Resample results into single per pixel color output (e.g., using box filter)
else:
     Shade only one G-buffer sample for this pixel, store result
```

  - Increases G-buffer footprint, but approximately same shading cost as MSAA
  - Additional BW cost (to detect edges) + potential execution divergence in shader

Handling divergence when implementing MSAA in a shader



Red pixels = These pixels contain edges (require additional shading)

Adaptive shading rate increases divergence in shader execution (recall eliminating shading divergence was one of the motivations of deferred shading)

Can apply standard gamut of data-parallel programming solutions:
e.g., multi-pass solution:
- **Phase 1: categorize pixels, set stencil buffer**
- **Phase 2: shade pixels requiring one shading computation**
- **Phase 3: flip stencil value, shade pixels requiring N shading computations**

This solution is a common bandwidth vs. execution coherence trade-off!
(recall earlier in lecture: same principle applied when sorting geometry draw calls by active lights)

Tile-based deferred shading (TBDR) in modern mobile GPUs

- Motivation: energy-efficient rendering
  - Philosophy: aggressive cull unnecessary fragment work to conserve energy

- Implementation of OpenGL ES graphics pipeline by imagination PowerVR GPUs is sort-middle tiled with deferred shading
  - Note: deferred shading is implemented as an optimization by the OpenGL system, not on top of the graphics pipeline by the application as discussed so far in this lecture

Phase 2 implementation of tiled renderer: (bin processing)

```
For each bin:
   For each triangle in bin's triangle list:
      Rasterize triangle (store only triangle id per G-buffer sample)

   // Determine quad fragments that contribute to frame buffer
   For each sample in tile:
      Given triangle id, compute fragment that corresponds to sample
      Add fragment to list of fragments to shade (if not in list already)

   // Shade only fragments that contribute coverage
   For each fragment that must be shared:
      Shade fragment and contribute results into frame buffer
```

T0	T0	T0	T0	T7
T4	T0	T0	T0	T7
T4	T4	T2	T0	T7
T4	T4	T2	T4	T4

G-buffer stored what triangle covers each sample, not the full set of surface properties (these can be computed as needed based on the triangle ID)

Deferred shading summary

- **Main idea: perform shading calculations for opaque surfaces after all geometry processing operations (rasterization, occlusions) are complete**

- **Modern motivations**
  - Scaling scenes to complex lighting conditions (many lights, diverse lights)
  - High geometric complexity (due to tessellation) increases overhead of Z-prepass, so it's useful to store and reload results of geometry processing (rather than repeat it)
  - Tiny triangles increase overhead of quad-fragment-based forward shading

- **Computes (more-or-less) the same result as forward rendering; reorder key rendering loops to change schedule of computation**
  - Key loops: for all lights, for all samples, for all drawing primitives
  - Different <u>footprint</u> characteristics
    - Trade footprint of scene light data structures for G-buffer footprint
  - Different <u>bandwidth</u> characteristics
  - Different <u>execution coherence</u> characteristics
    - Traditionally deferred shading has traded bandwidth for increased batch sizes and coherence
    - Tile-based methods improve bandwidth requirements considerably
    - MSAA changes bandwidth, execution coherence equation yet again

- **Keep in mind: not a technique used for transparent surfaces**

Final comments

- Which is better, forward or deferred shading?
  - Depends on context
  - Is geometric complexity high? (prepass might be costly)
  - Are triangles small? (forward shading has overhead)
  - Is multi-sample anti-aliasing desired? (G-buffer footprint might be too large)
  - Is there significant divergence impacting lighting computations?

- Common tradeoff: memory bandwidth vs. execution coherence
  - Another example of relying on high bandwidth to achieve high ALU utilization
  - In real-time graphics: typically manifests as multi-pass algorithms

- One lesson from today: when considering new techniques or a new system design, be cognizant of interoperability with existing features and optimizations
  - Deferred shading is not compatible with hardware-accelerated MSAA implementations (application must role its own version of MSAA... and still takes a large G-buffer footprint hit)
  - Deferred shading does not support transparent surfaces