Lecture 12:

The Reyes Rendering Architecture

Visual Computing Systems
CMU 15-869, Fall 2013

A gallery of images rendered using Reyes

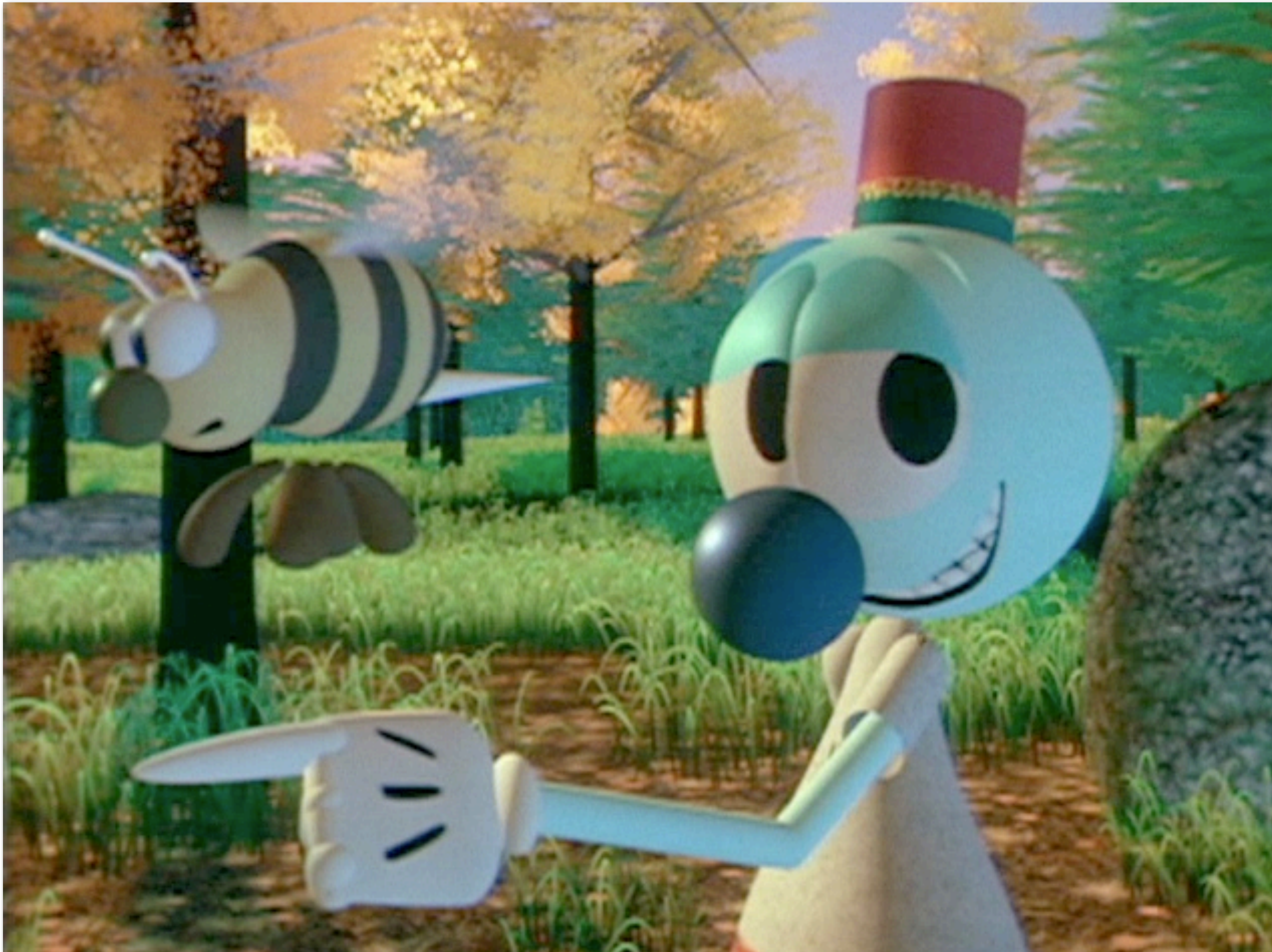


Image credit: Lucasfilm (Adventures of Andre and Walle B, 1984)

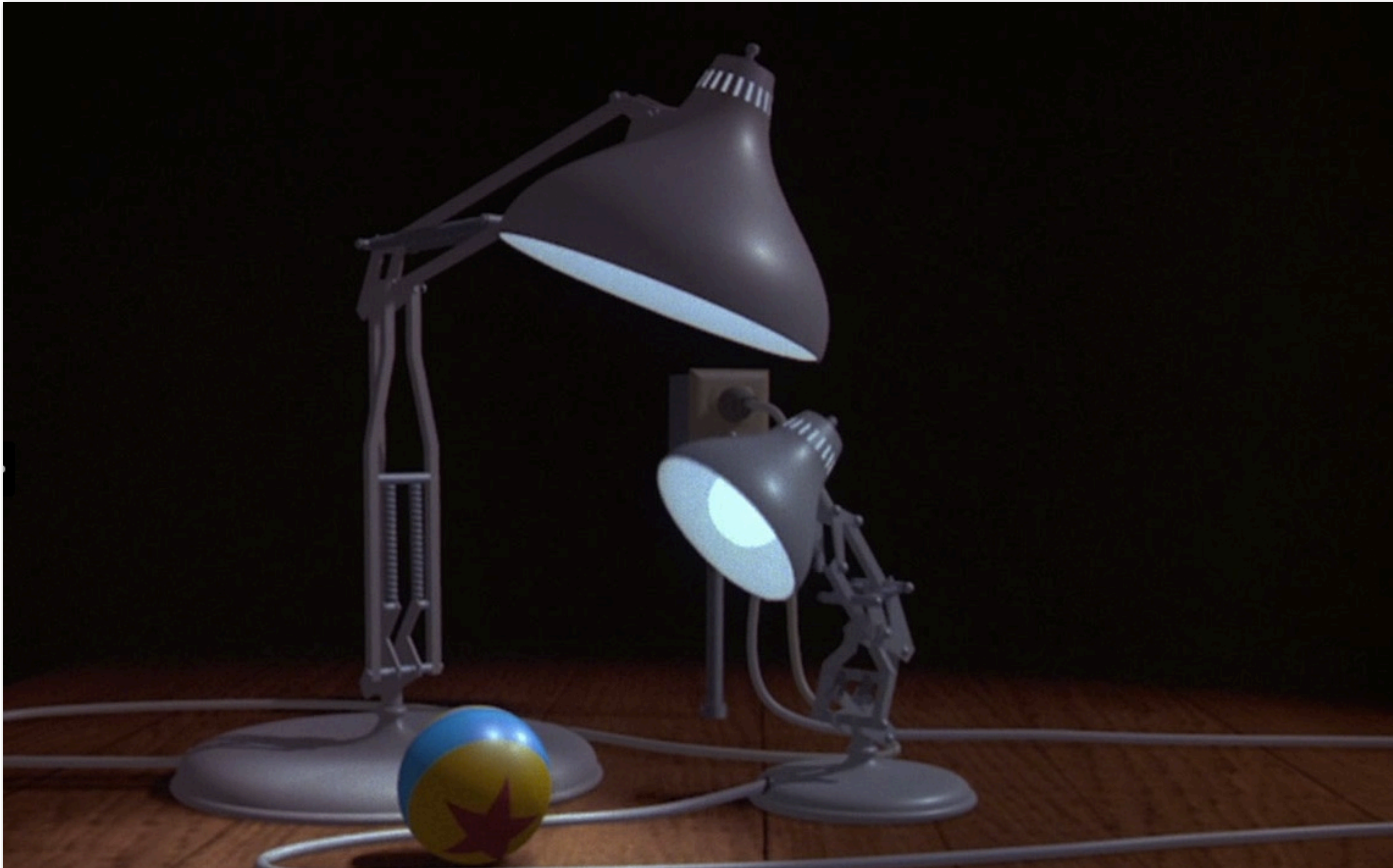


Image credit: Pixar (Luxo Jr., 1986)

Image credit: Pixar (Toy Story 2, 1999)

Image credit: Pixar (Wall-E, 2008)


Image credit: Pixar (Ratatouille, 2007)

Image credit: Pixar (UP, 2009)

Image credit: Pixar (UP, 2009)

Image credit: Pixar (UP, 2009)

Image credit: Pixar (UP, 2009)


Image credit: Pixar (UP, 2009)

Image credit: Pixar (Toy Story 3, 2010)

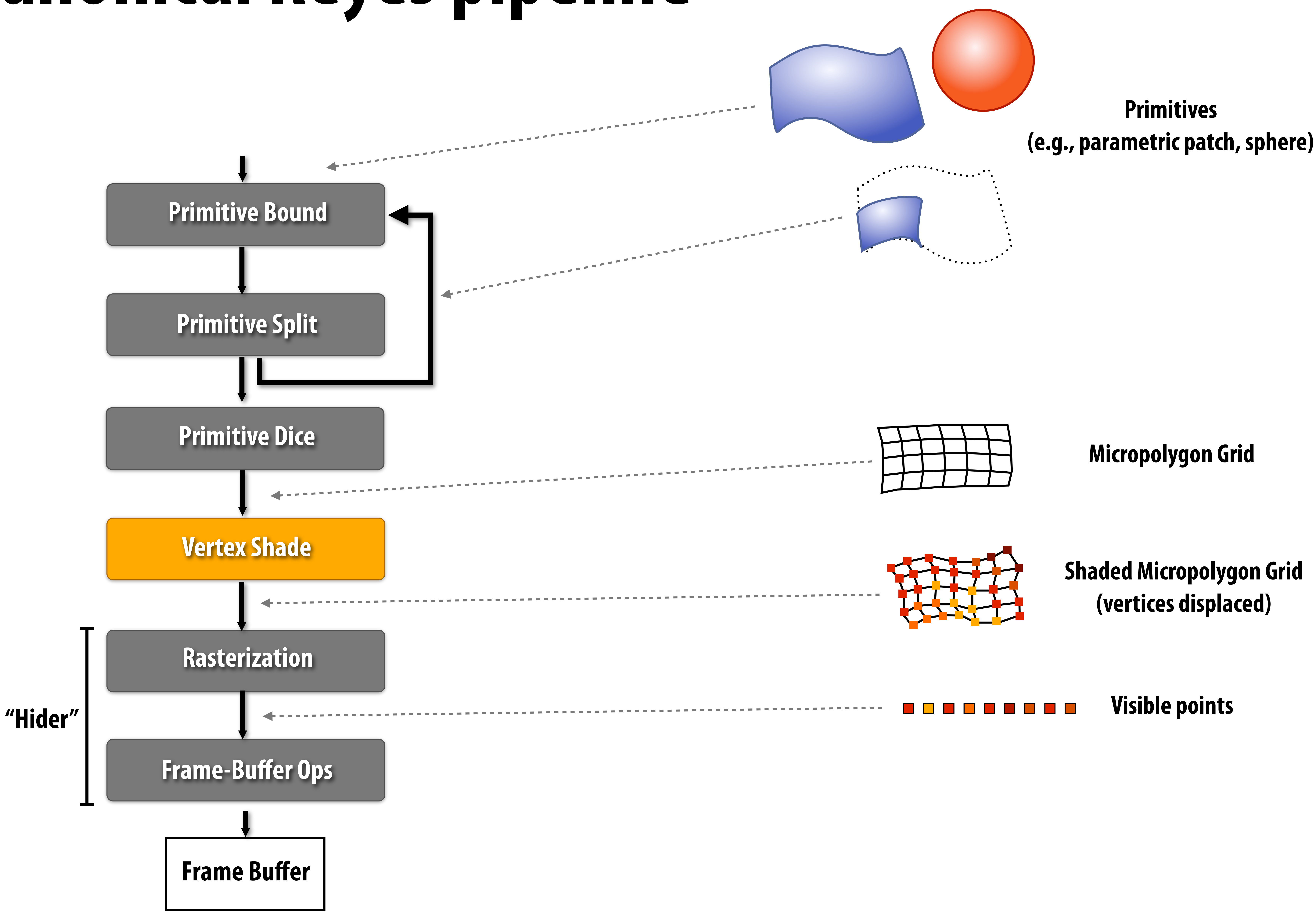
The Reyes image rendering architecture

- Reyes: acronym for Renders Everything You Ever Saw
  - Also a reference to Pt. Reyes, CA (just north of San Francisco)
  - Disagreement in graphics community about whether it is written Reyes or REYES. (Rob Cook says it's "Reyes")
- Developed at Lucasfilm (graphics group later became Pixar)
- Pixar's implementation is called Photorealistic Renderman (prman)
  - Renderman name was a take off on the Sony Walkman
- Rendering system for every Pixar film
  - And vast majority of other studio's special effects

Reyes goals

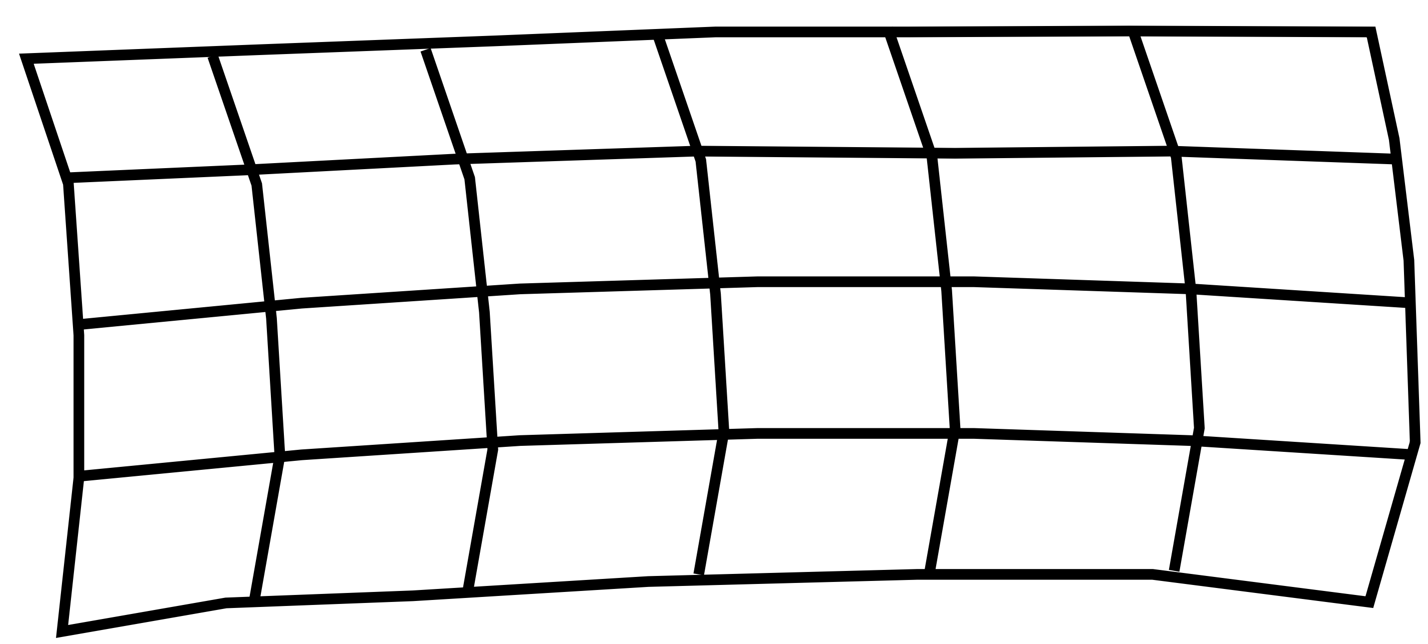
- High image quality: no visible faceting or aliasing
- Handle massive scene complexity
- Support large diversity in models, materials (shading)
- High performance: achieve all of the above in “reasonable” rendering time (minutes/hours frame)

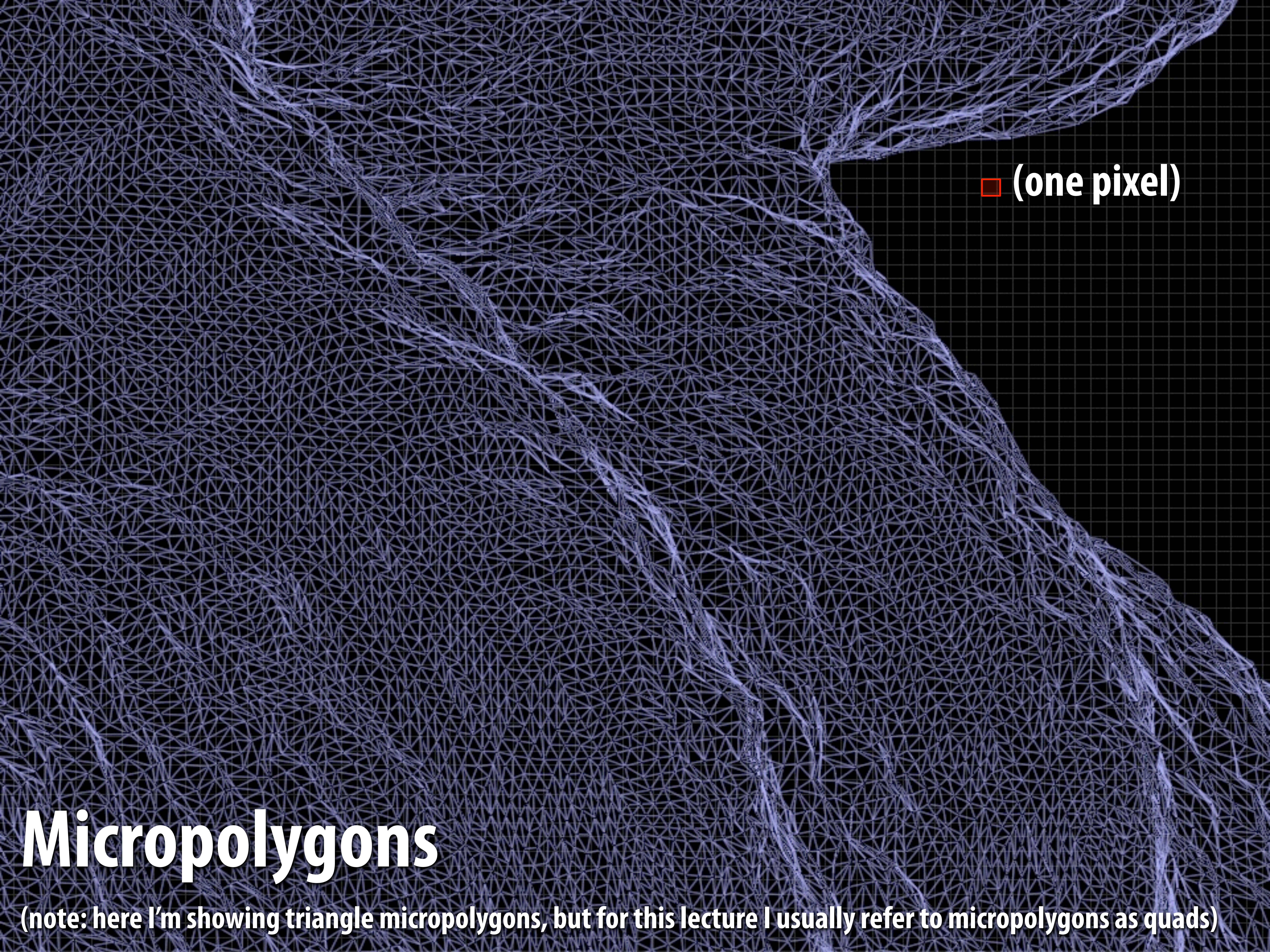
Canonical Reyes pipeline



Definitions

- **Micropolygon = canonical intermediate representation in the Reyes pipeline. Expectation is that projected polygon area <= 1 pixel**
- **Grid = micropolygon mesh corresponding to contiguous surface region**
- **Reyes pipeline state defines:**
  - Target micropolygon area (typically 1/4 to 1 pixels)
  - Maximum number of micropolygons in a grid (typically ~256)





Micropolygons

(note: here I'm showing triangle micropolygons, but for this lecture I usually refer to micropolygons as quads)

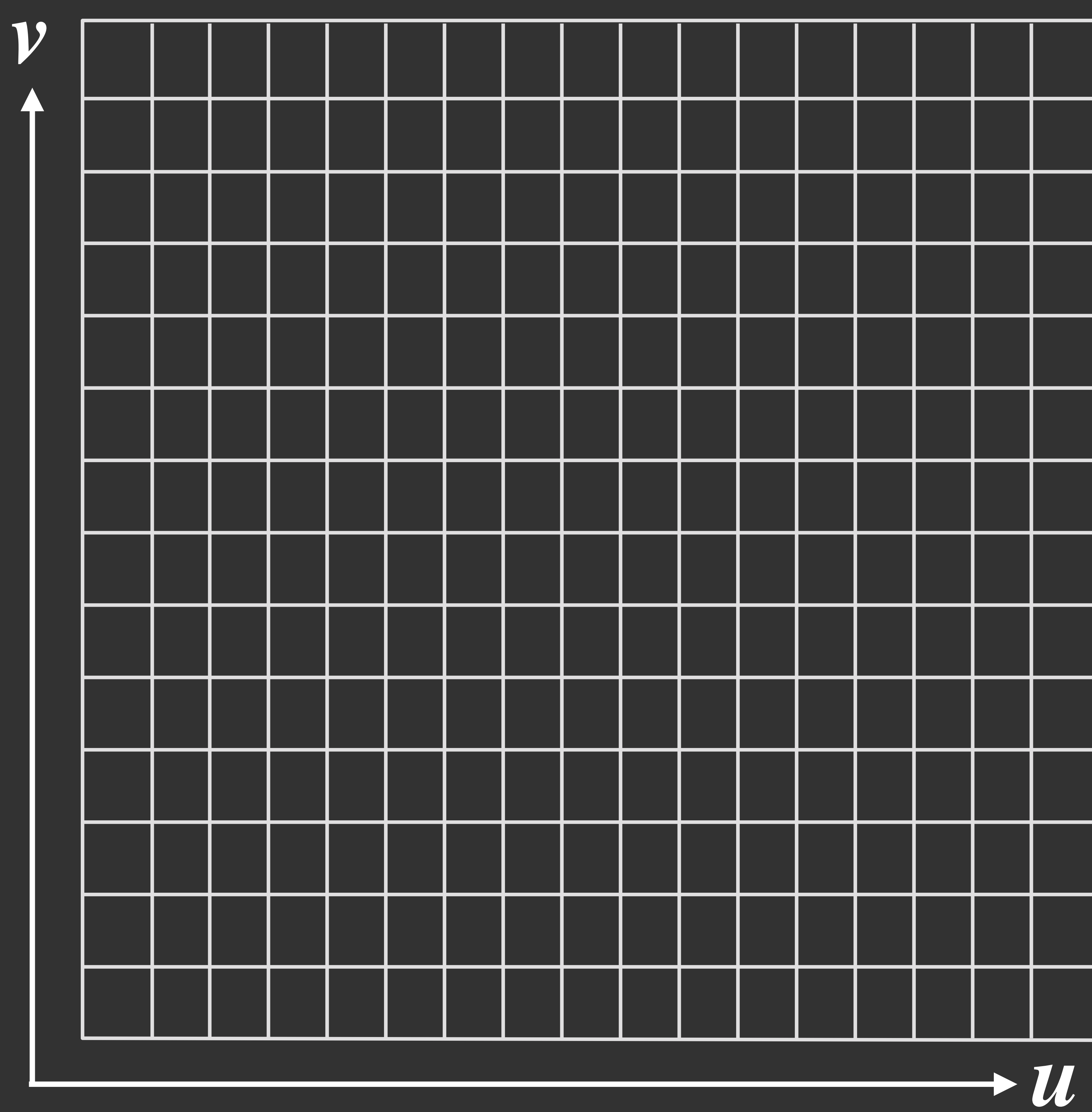
Tessellation

Tessellating primitives into micropolygon grids

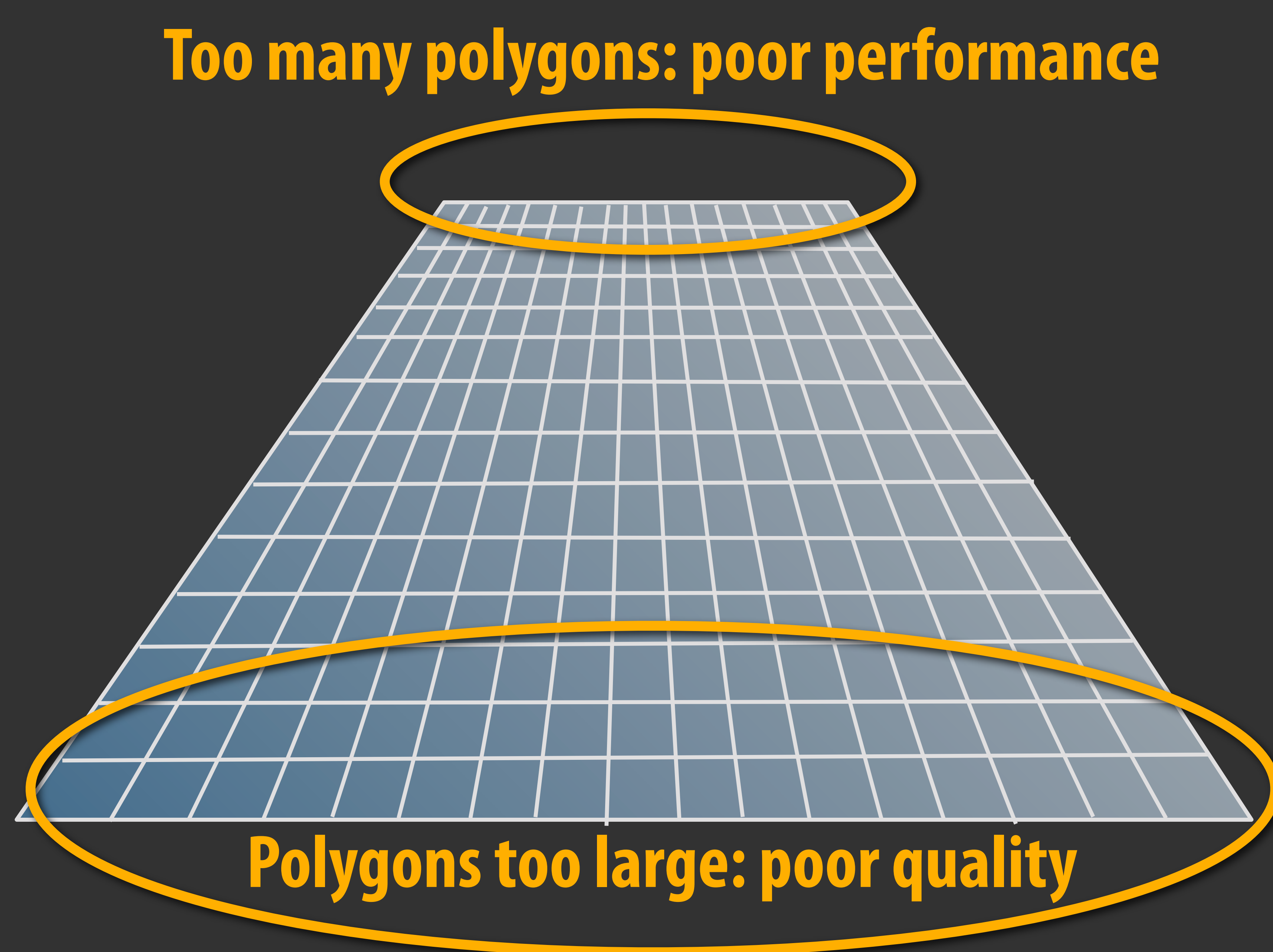
- **Goals**
  - Want micropolygons all about the same size
  - Want projected micropolygon areas to closely match target size
  - Ideally, grids should be reasonably large (close to max grid size)

- **Reyes tessellation**
  - Lane-Carpenter algorithm (often referred to as "split-dice")

Uniform patch tessellation is insufficient



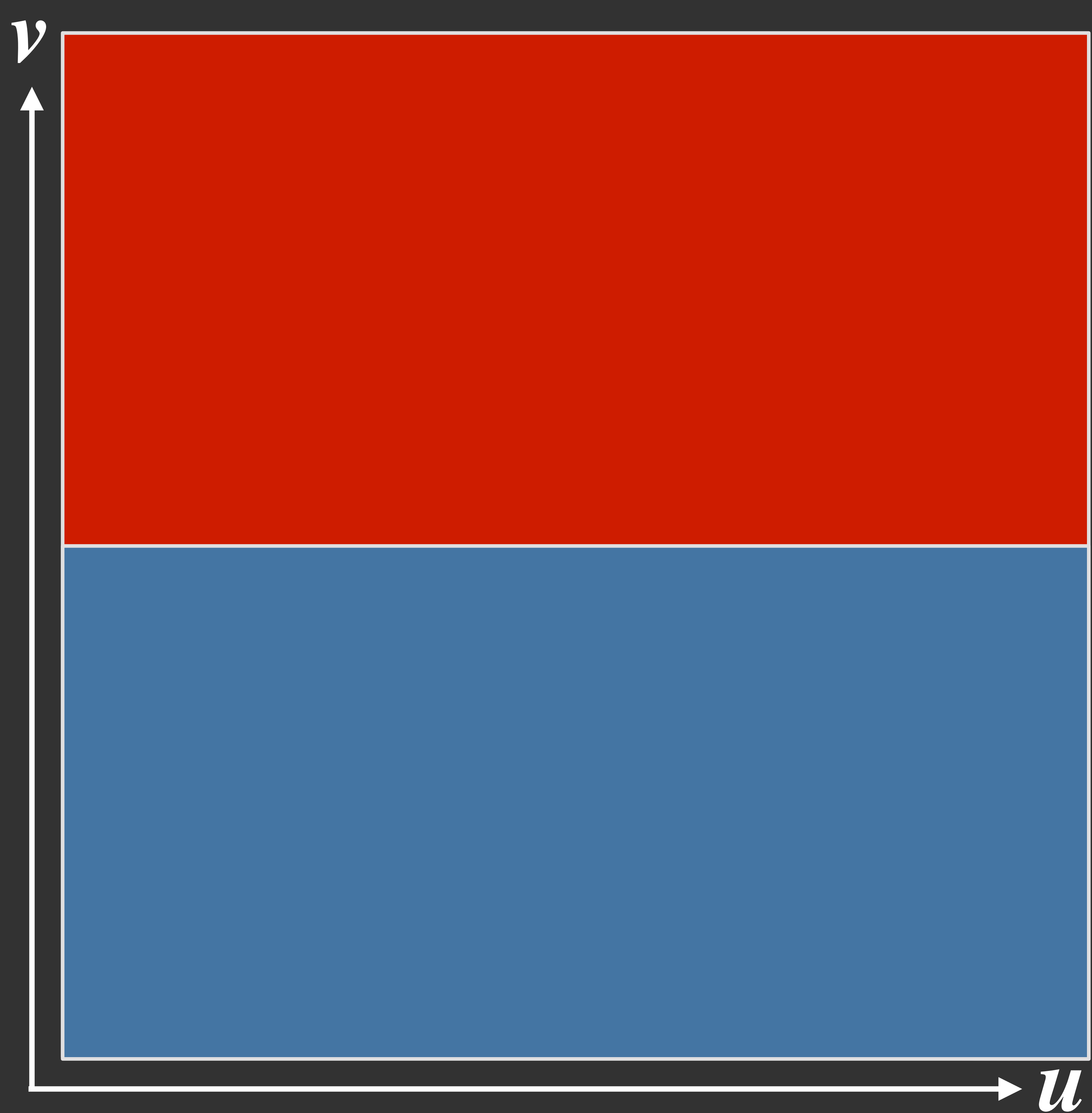
Uniform partitioning of patch
(parametric domain)



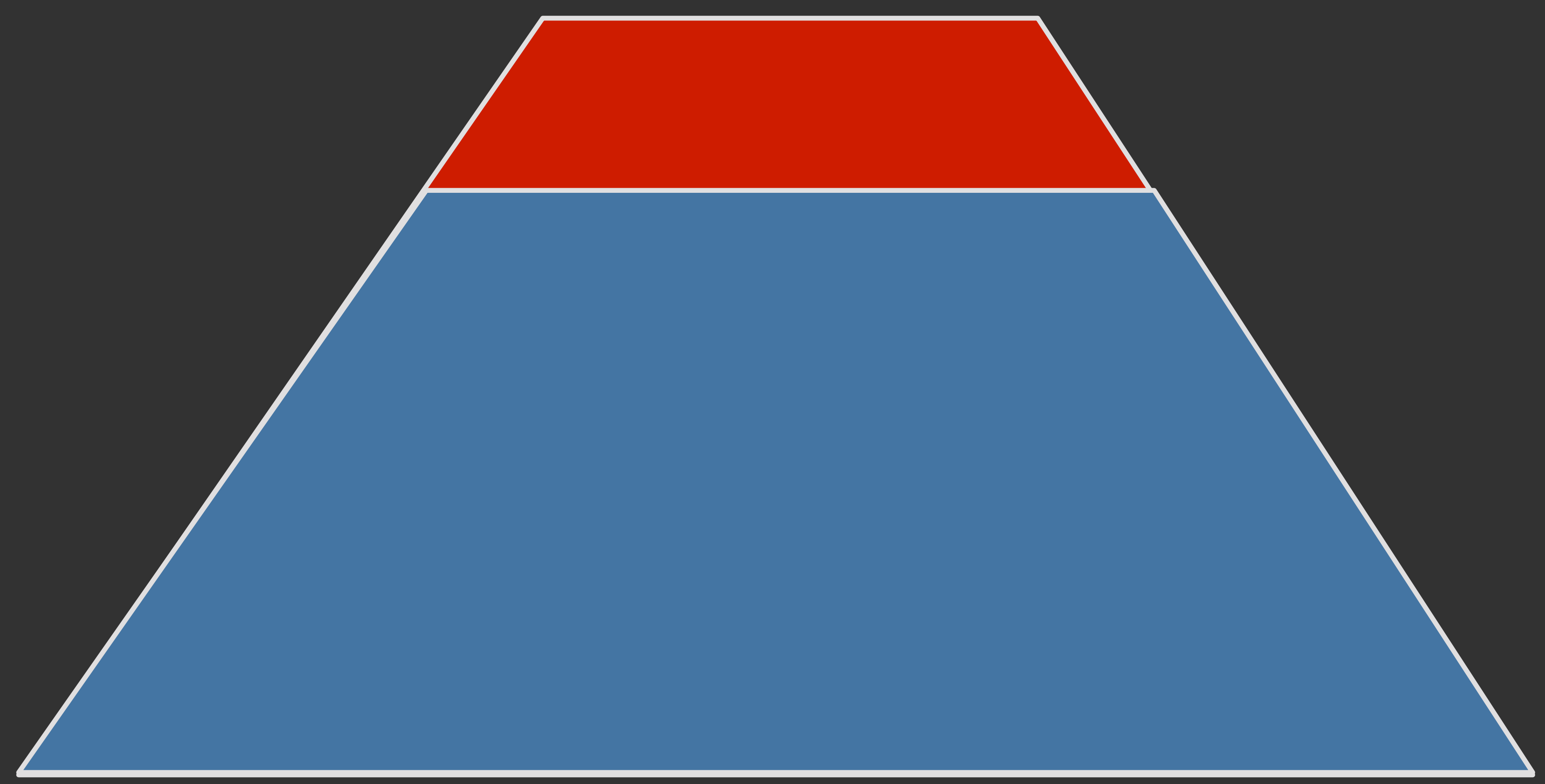
Patch viewed from camera

Split-dice adaptive tessellation

[Lane 80]



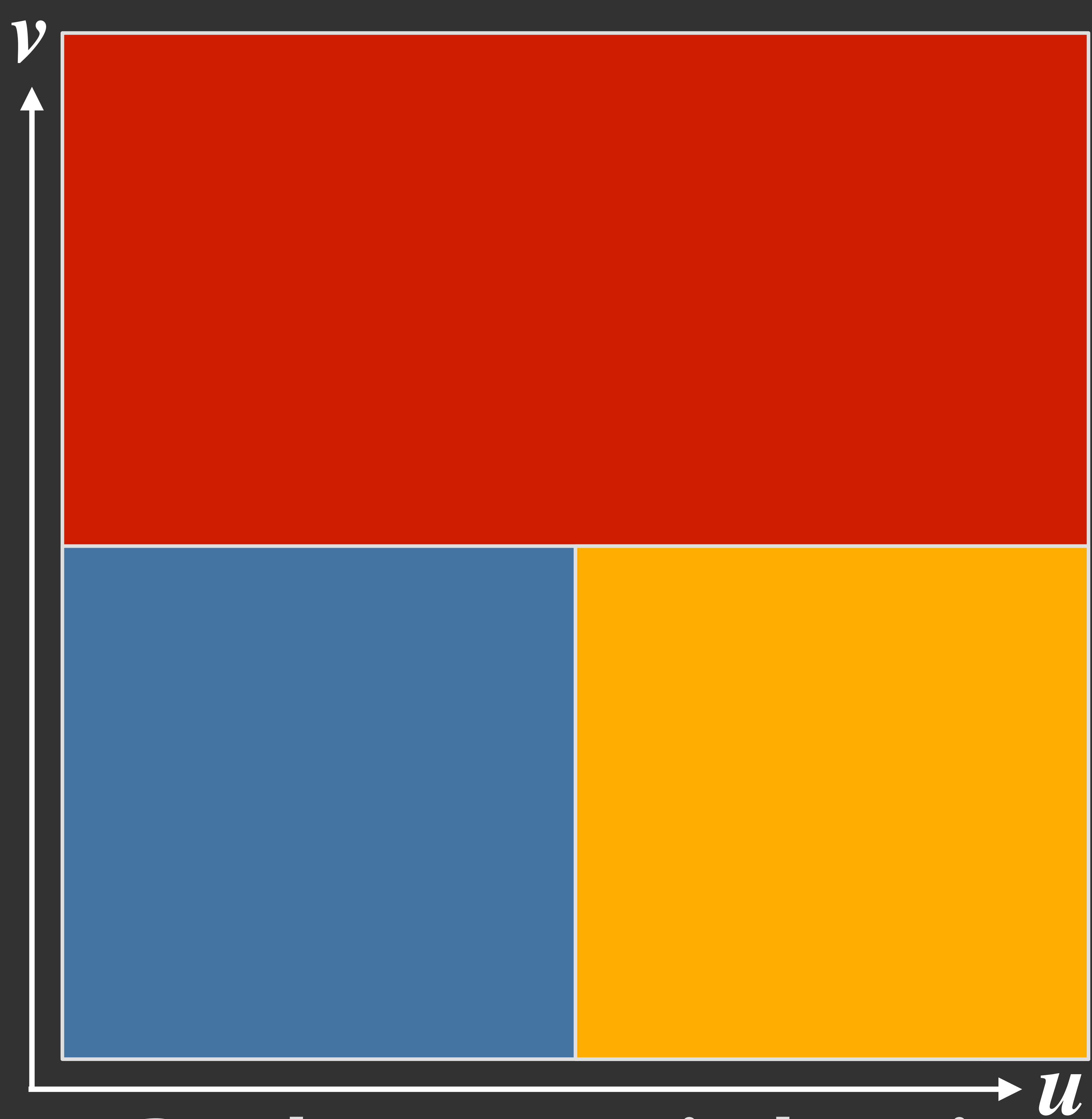
Patch parametric domain



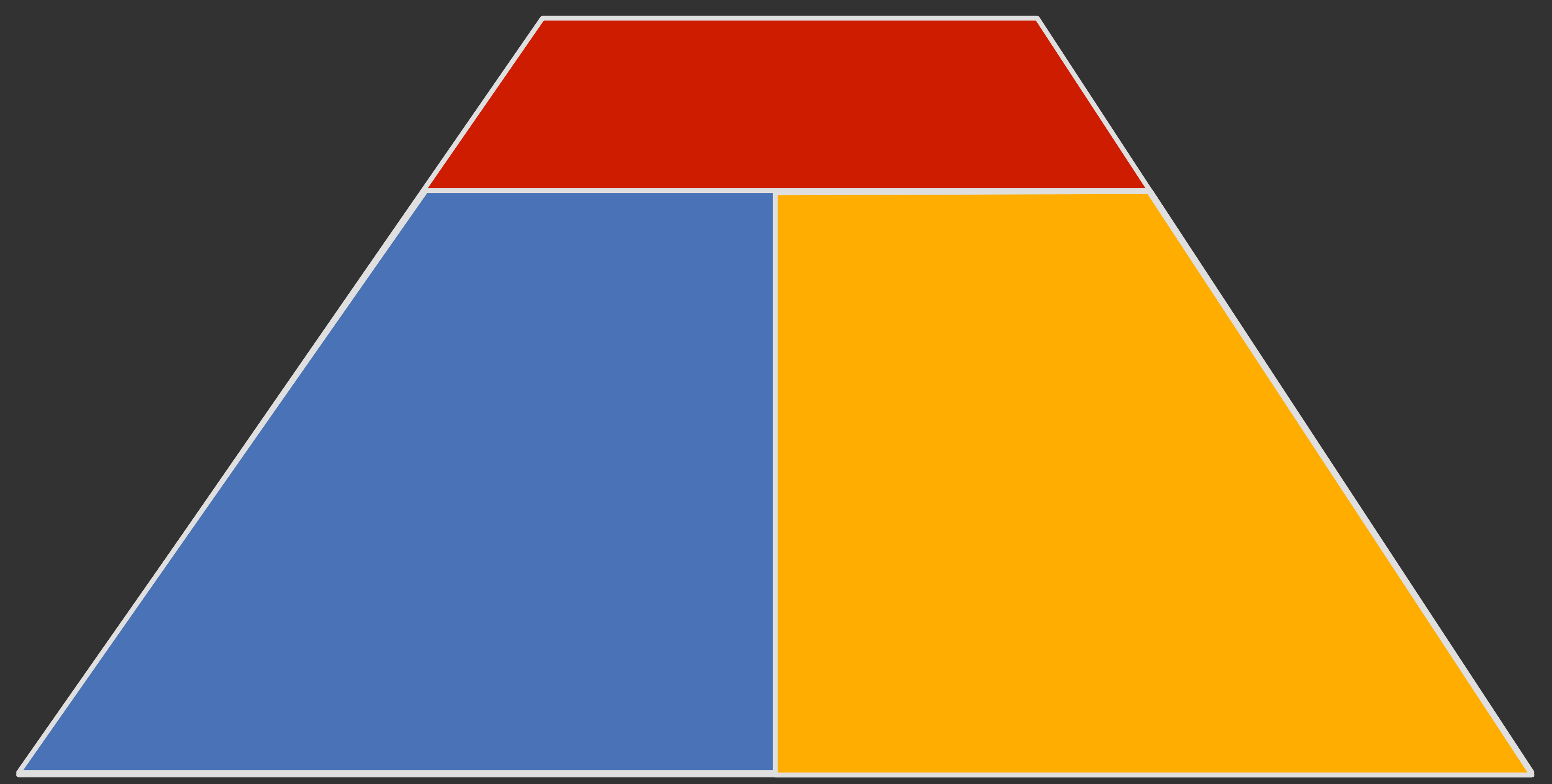
Patch viewed from camera

Split-dice adaptive tessellation

[Lane 80]



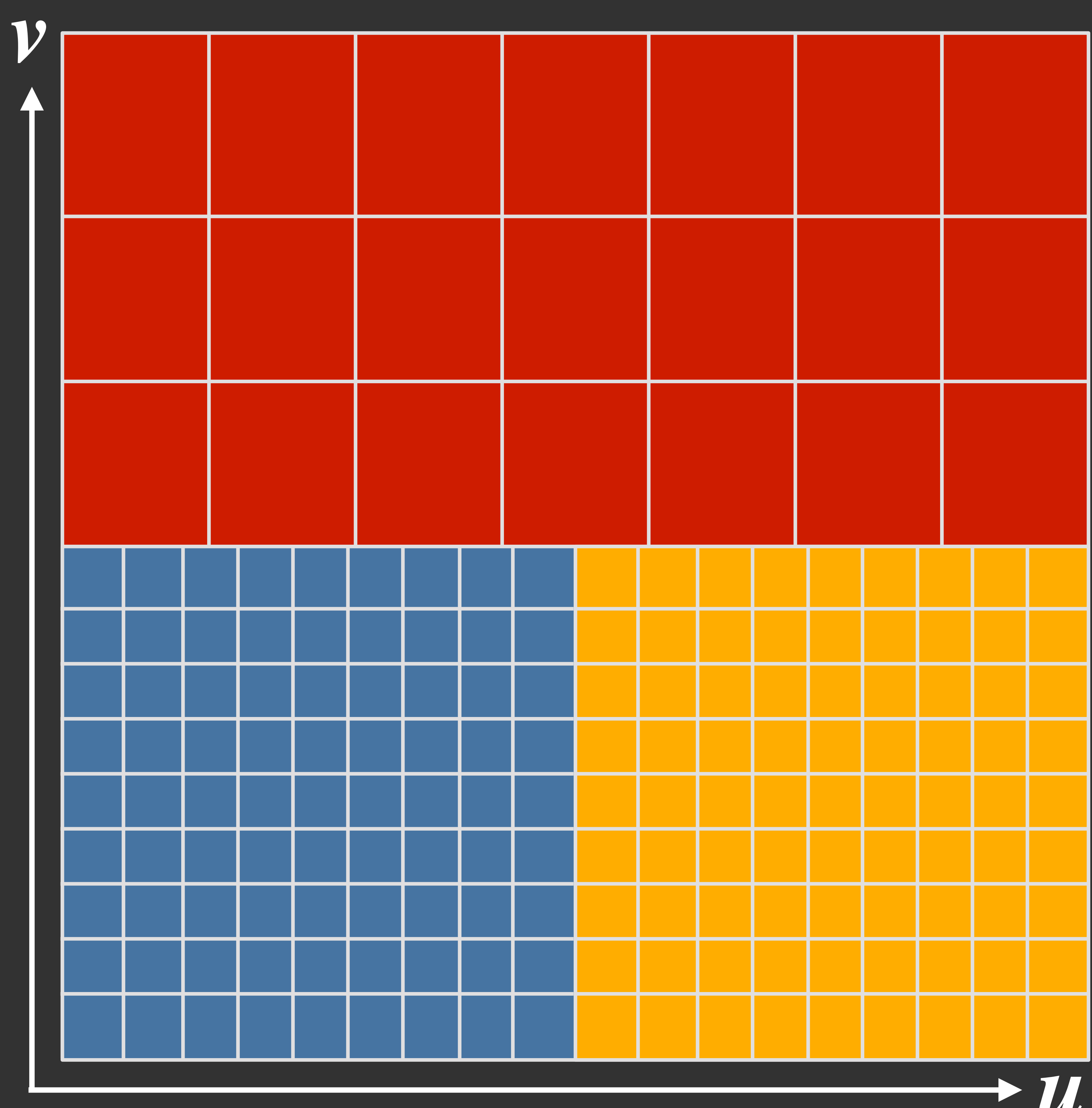
Patch parametric domain



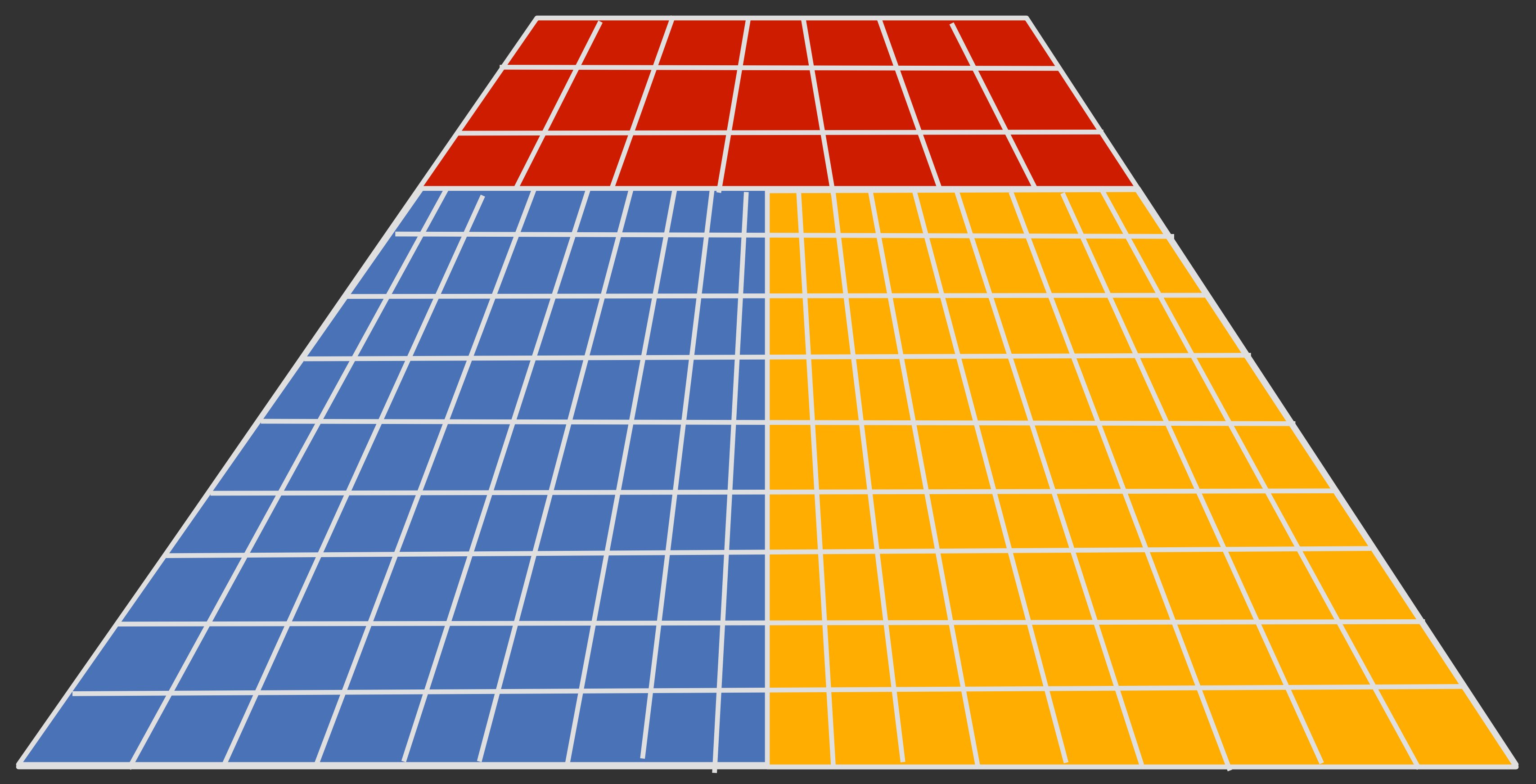
Patch viewed from camera

Split-dice adaptive tessellation

[Lane 80]



Patch parametric domain



Patch viewed from camera

Reyes primitive interface

```
class Primitive
{
   BBox3D          bbox();
   bool            canDice();
   List<Primitive> split();
   Grid            dice();
};
```

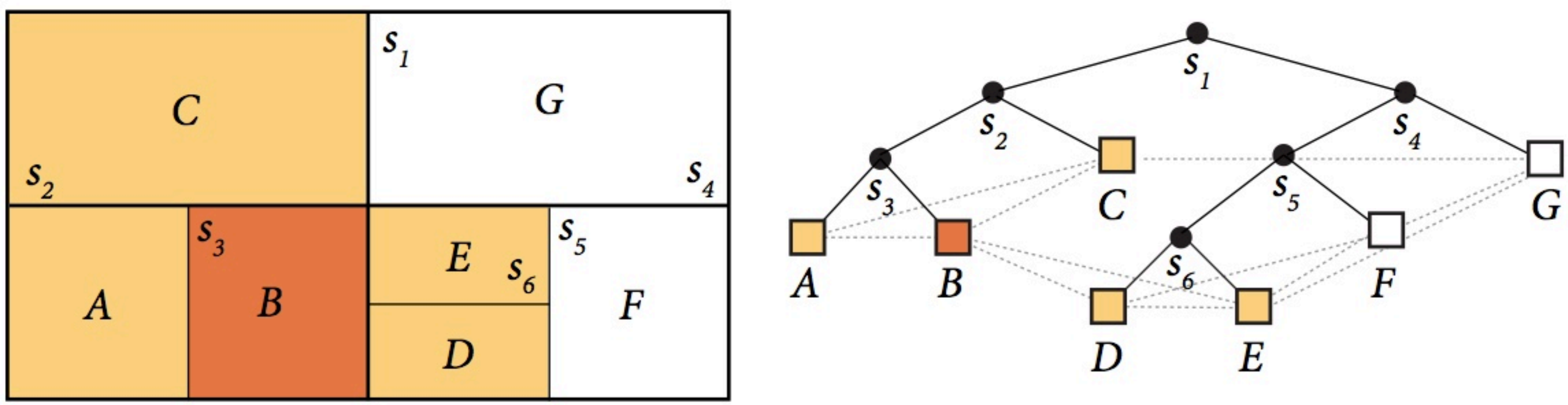
`Split` partitions primitive into one or more child primitives

`Split` may generate child primitives of a different type

Note: bbox is expanded by renderer to account for primitive motion over the frame (motion blur), surface displacement, etc.

Interesting implications of split

- Encapsulates adaptivity (keep dicing operation simple, regular, and fast)
- Divide and conquer algorithm:
  - Micropolygon generation order exhibits high spatial locality (recall hierarchical rasterization)
  - Provides temporal stability
- Splitting implicitly creates a hierarchy of grids
  - Very useful for frustum/depth culling at largest possible granularity
  - Use bbox to cull primitives prior to dicing (or prior to unnecessary splitt



- Splitting also enables clipless rasterization (see Reyes paper)

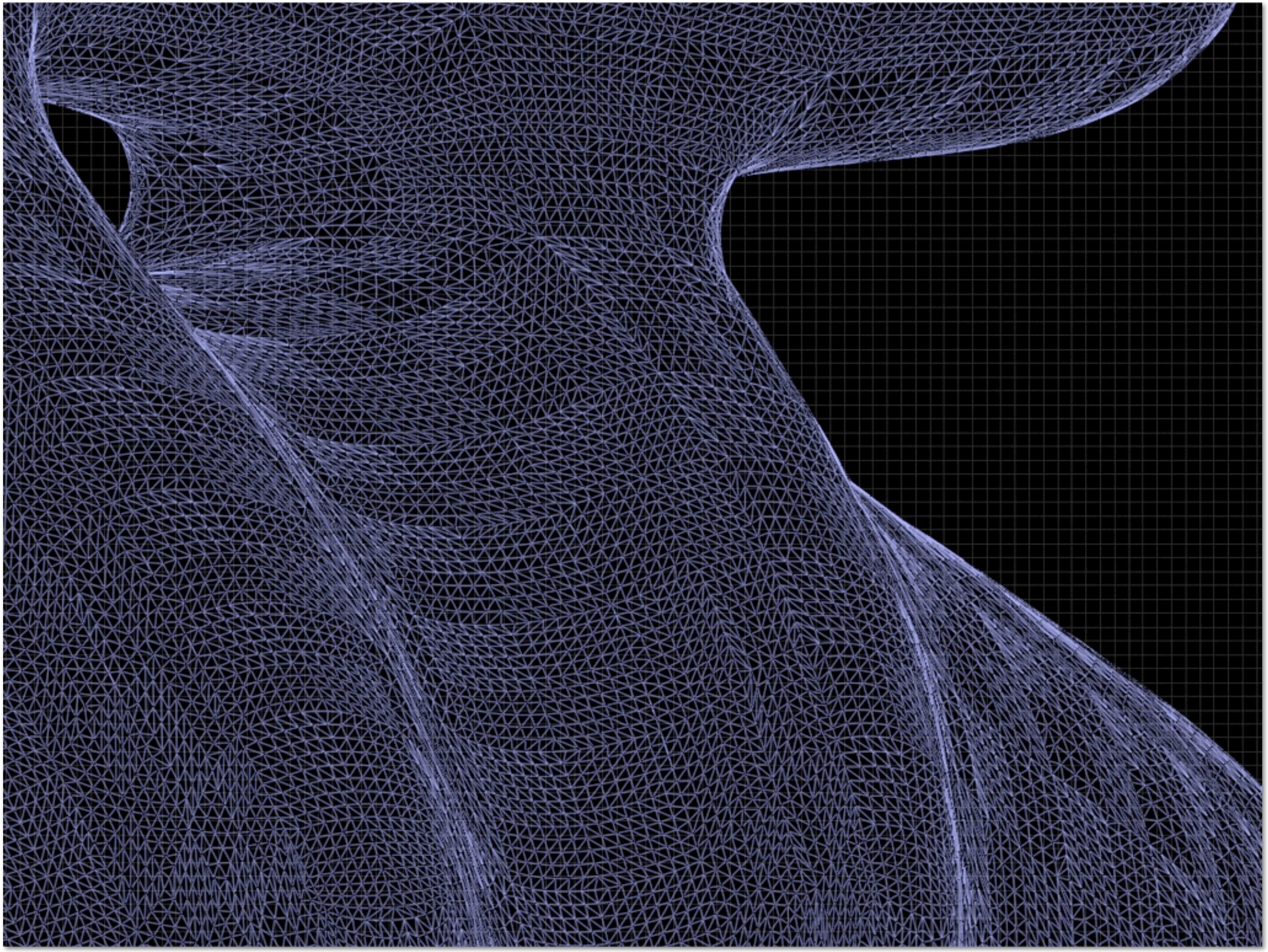
Shading

Reyes shades micropolygon grid vertices

- **Reyes invokes the shading function once for each grid vertex**
  - Shading function defined using Renderman Shading Language (RSL) ***
  - Shading function computes surface appearance at vertex
  - Shading function may also reposition vertex (displacement)

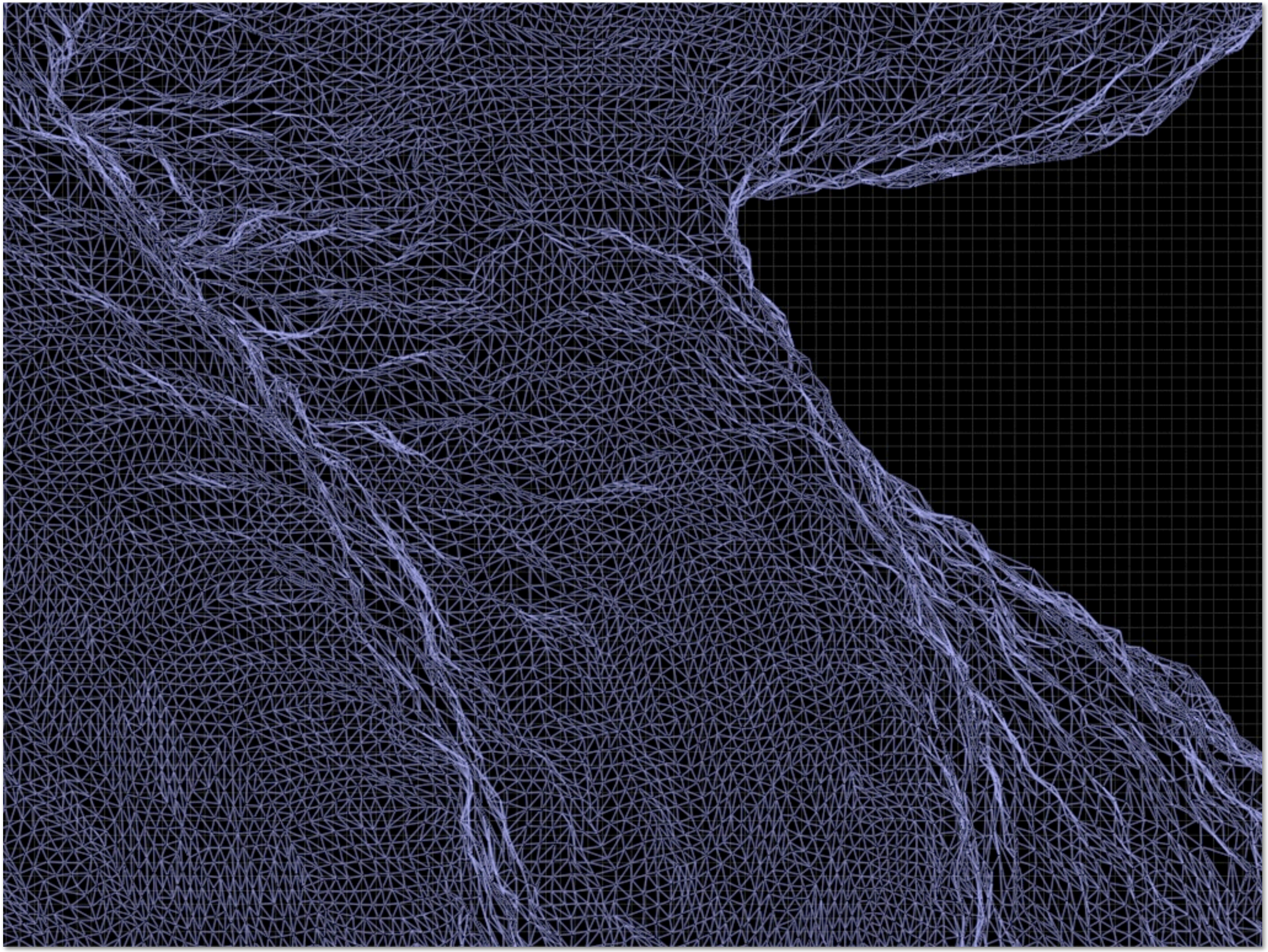
*** See shading languages lecture

Micropolygon mesh: before displacement



Micropolygon mesh: after displacement

(Noise function used to compute displacement amount.)



Why operate on grids?

- **Execution coherence**
  - All vertices on grid shaded with same shader
  - Permits SIMD implementation

- **Locality**
  - Grid is contiguous region of surface: shading points together increases texture locality

- **Compact representation**
  - For regular (tensor product) grid, topology is implicit (do not need to store polygon adjacency)
  - Quad micropolygon grid: each interior vertex shared by four micropolygons

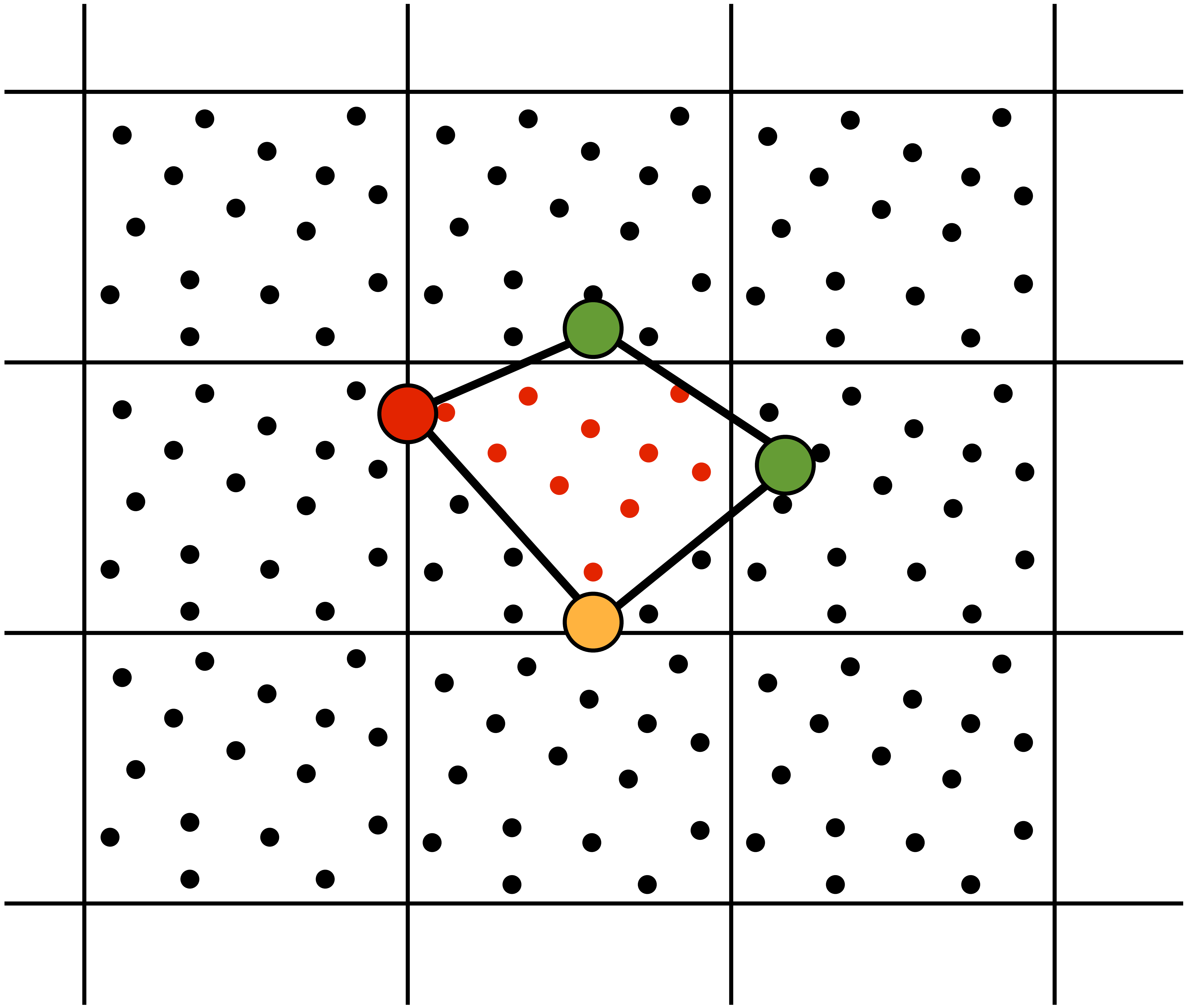
- **Connectivity leveraged to compute derivatives in shaders**
  - Can compute higher order derivatives

- **Preserve hierarchy**
  - Allows per-grid operations, in addition to per micropolygon or per-vertex
  - Useful for culling, etc.

Hiding
(visibility and occlusion)

Hiding micropolygons (rasterization + occlusion)

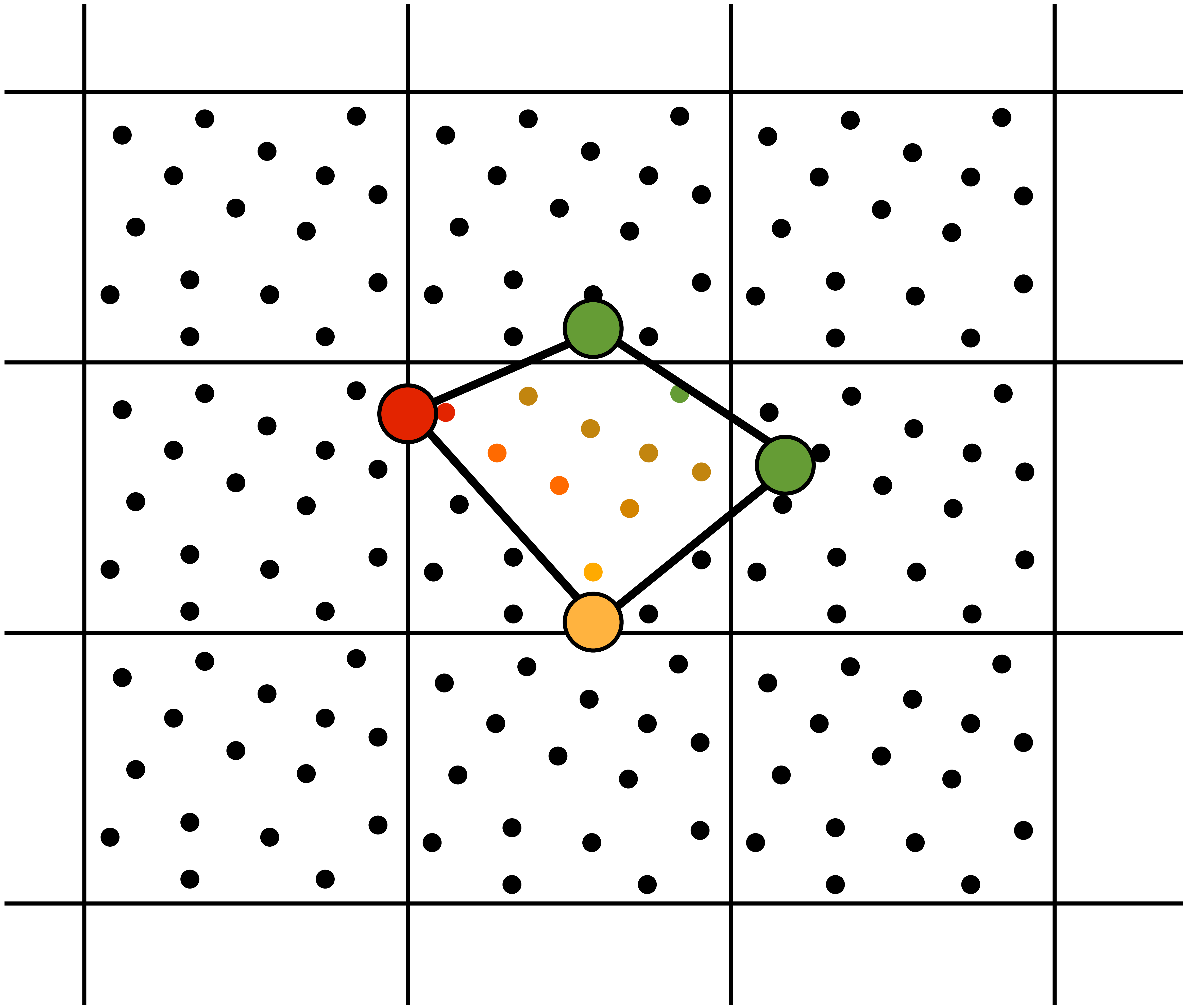
Option 1: micropolygon is flat shaded (apply color from one vertex to sample)



Note: many visibility samples per pixel to eliminate aliasing

Hiding micropolygons (rasterization + occlusion)

Option 2: interpolate per-vertex colors



Note: many visibility samples per pixel to eliminate aliasing

Aside: interesting sampling question

- Reyes samples surface appearance uniformly in surface parametric space (within in grid)
  - Uniform in parametric space $\simeq$ uniform in object space, but not uniform in screen space due to projection
  - Textures filtered using object-space surface derivatives

- Surface is projected, and then appearance is <u>resampled</u> uniformly in screen space at visibility sample points

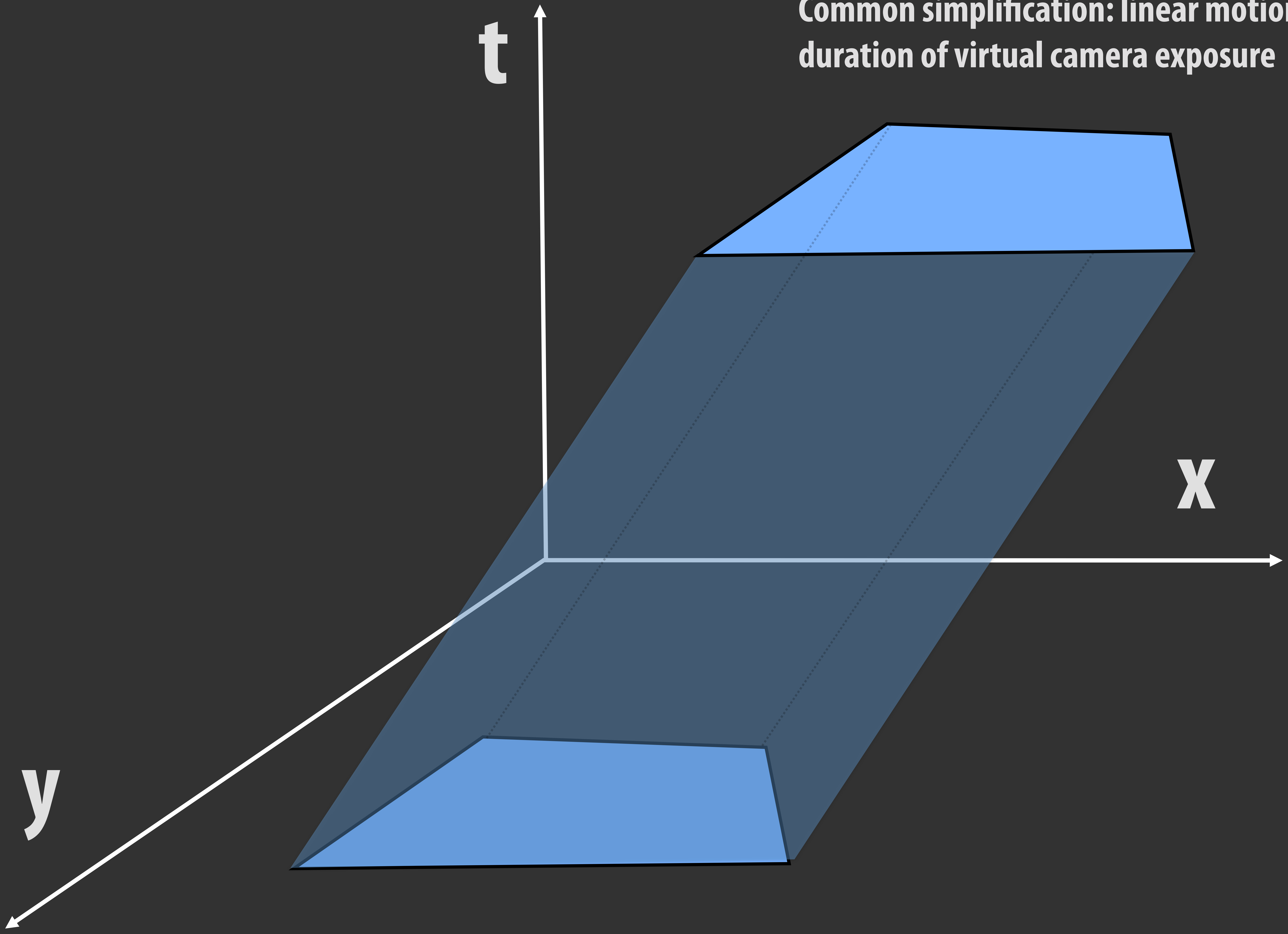
- OpenGL/Direct3D pipeline samples surface appearance uniformly in screen space
  - Textures filtered using screen-space surface derivatives

Is there a preferred solution? (not well understood)

Consider:
High frequency surface appearance: due to bumpy geometry, due to high frequency texture
Surfaces at grazing angles to camera (near silhouettes)
What is lost in resampling step?

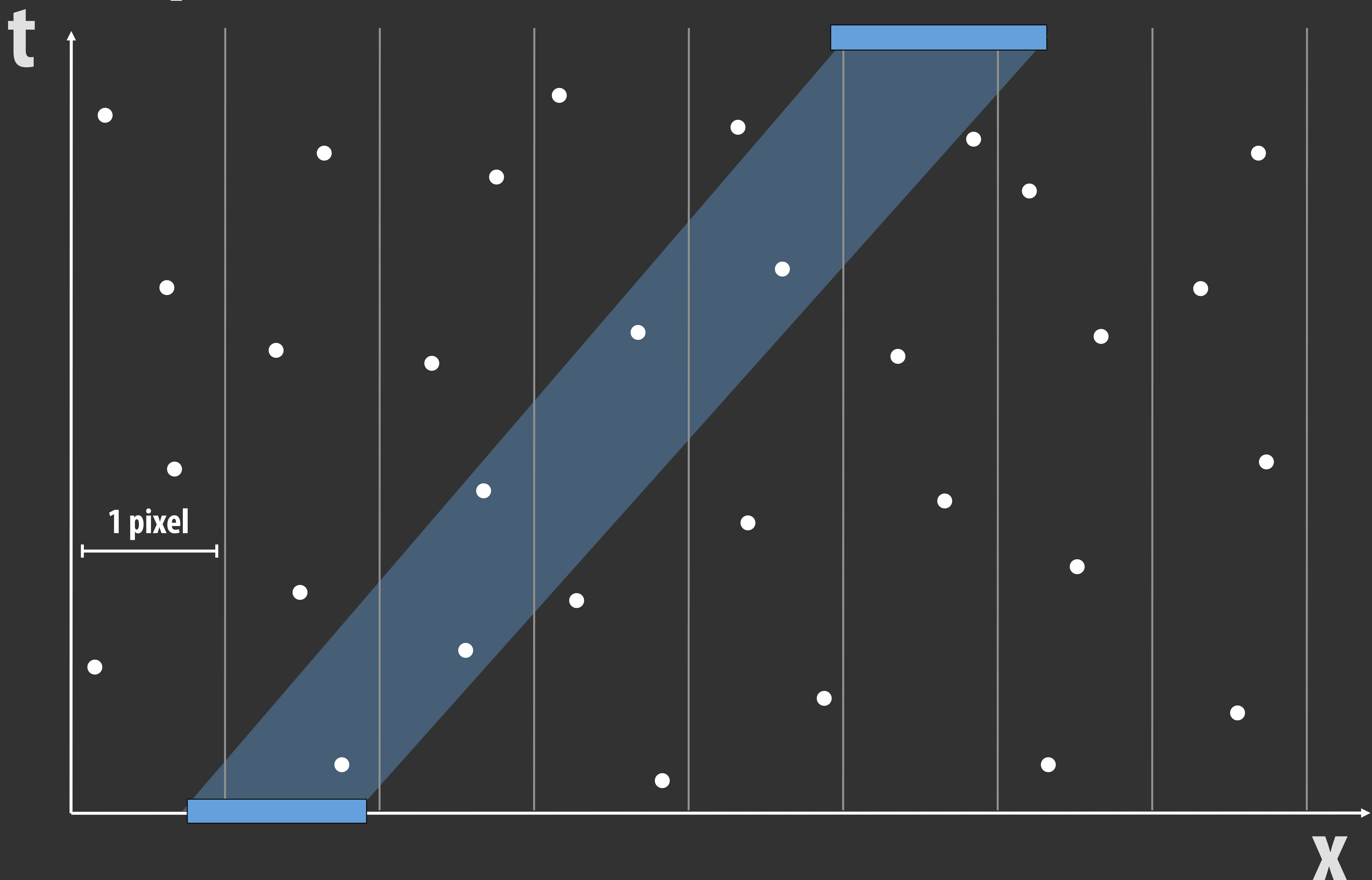
Motion blur

Moving micropolygon

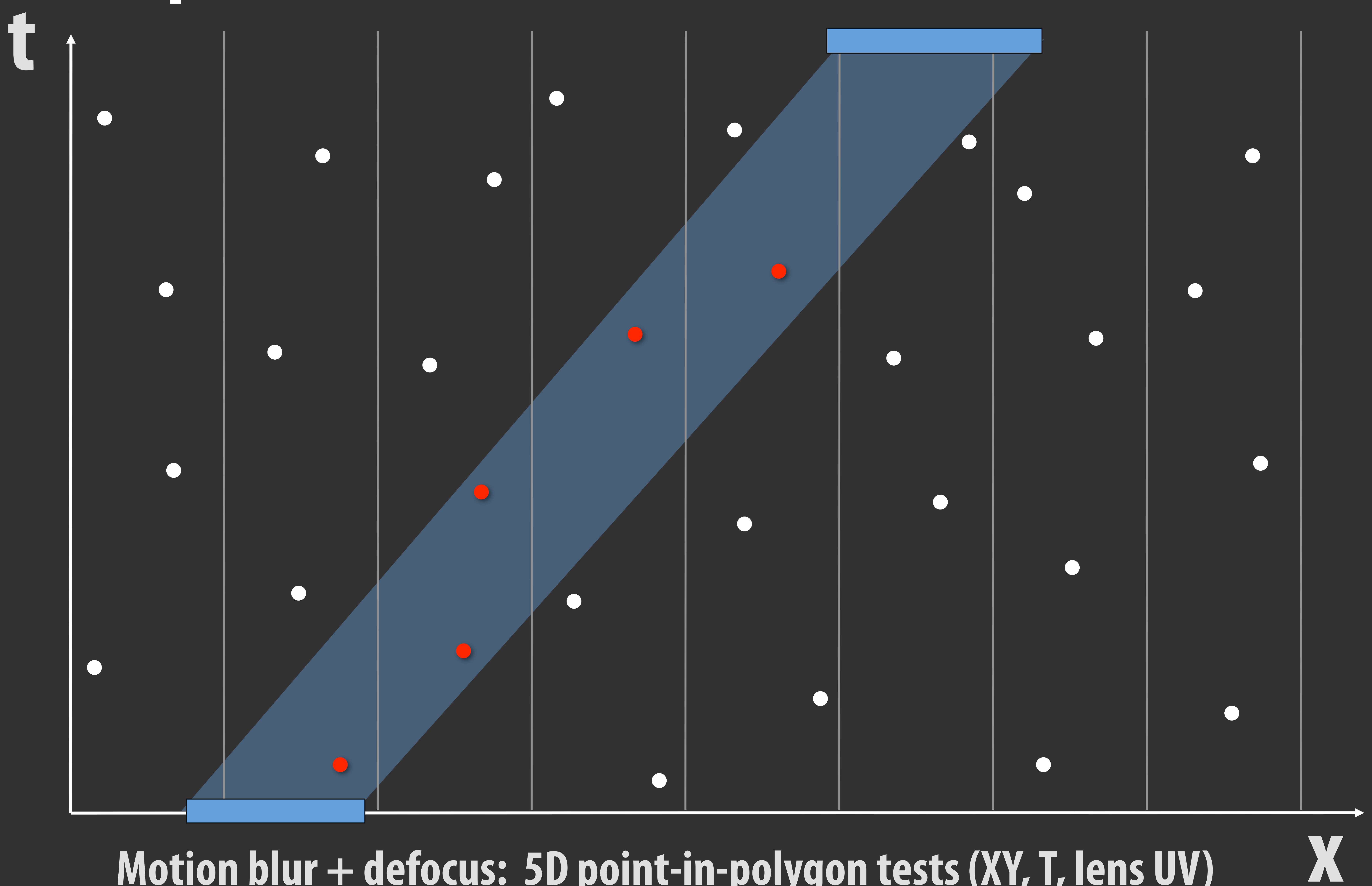


Common simplification: linear motion for duration of virtual camera exposure

X,T plane (visibility samples distributes in space and time)

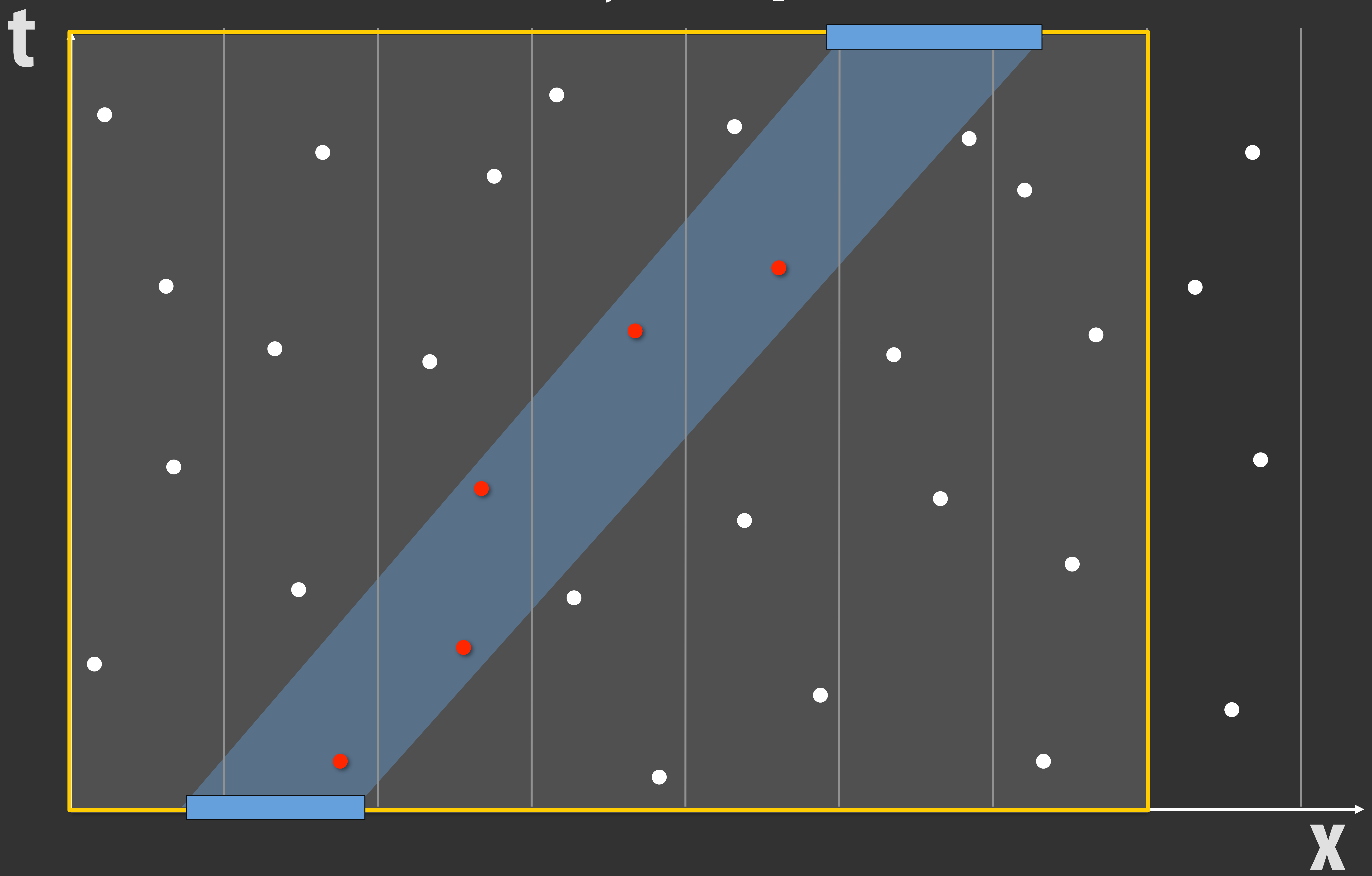


X,T plane

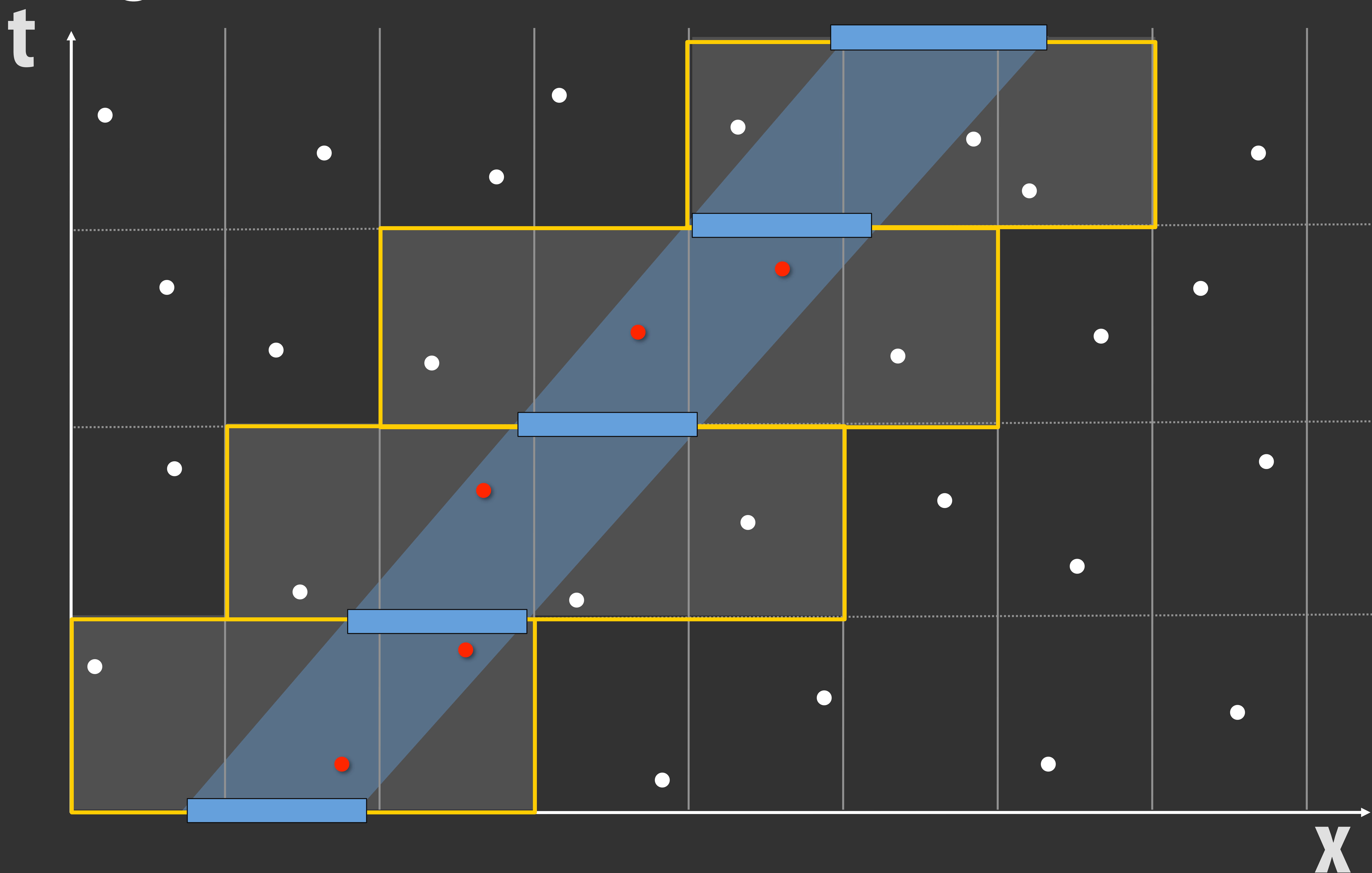


Motion blur + defocus: 5D point-in-polygon tests (XY, T, lens UV)

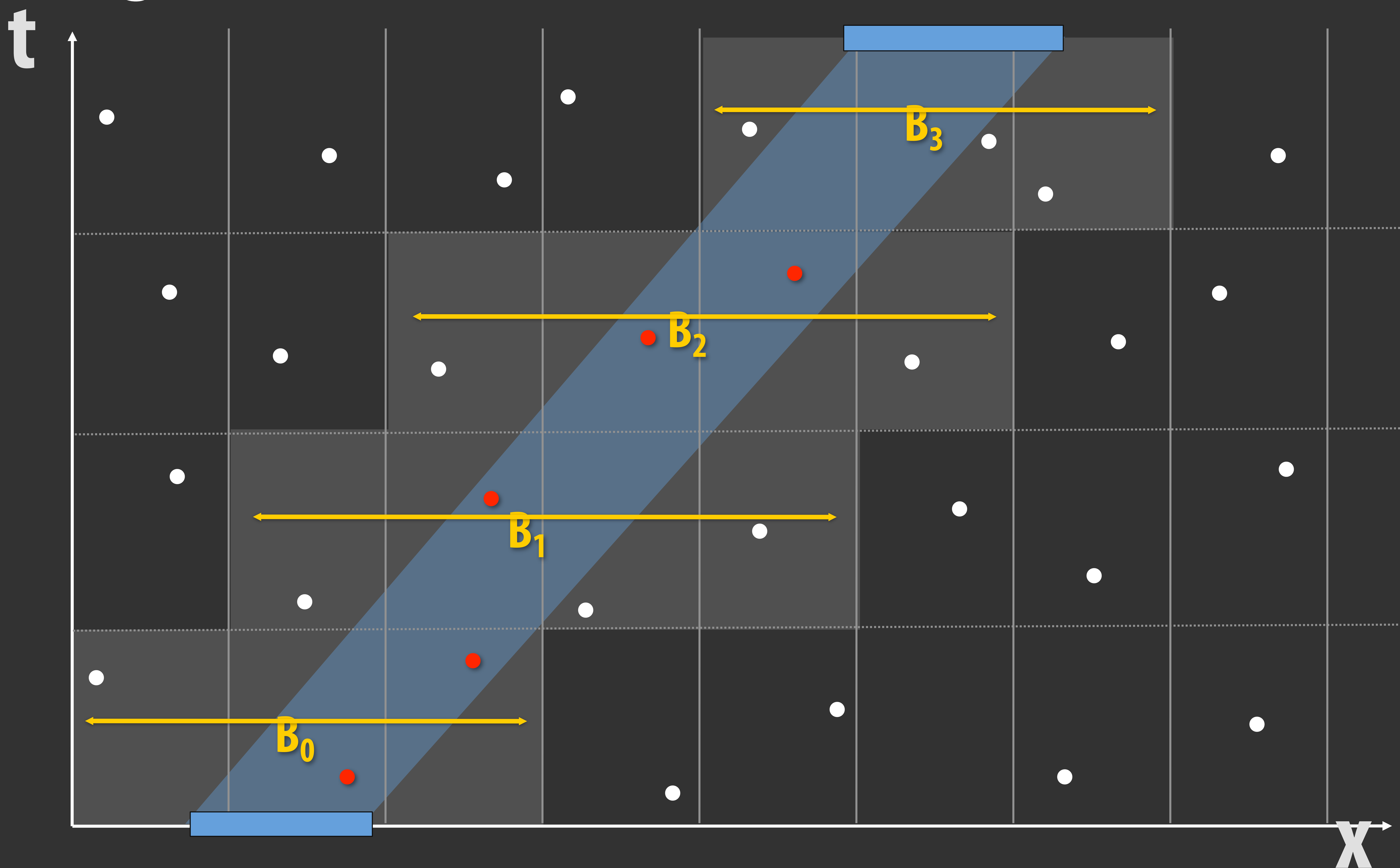
Candidate visibility samples



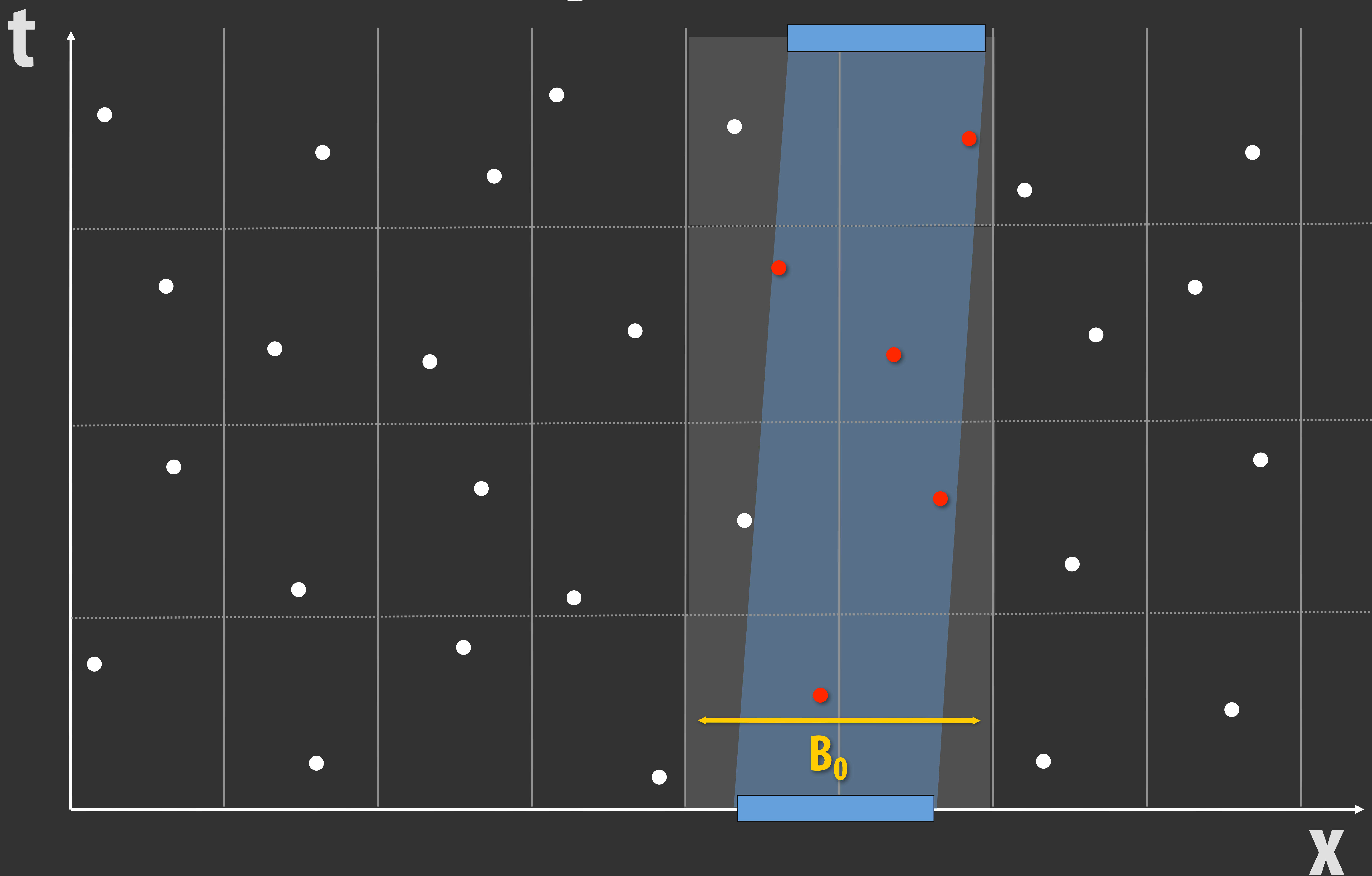
Tighter bounds (4 time intervals)



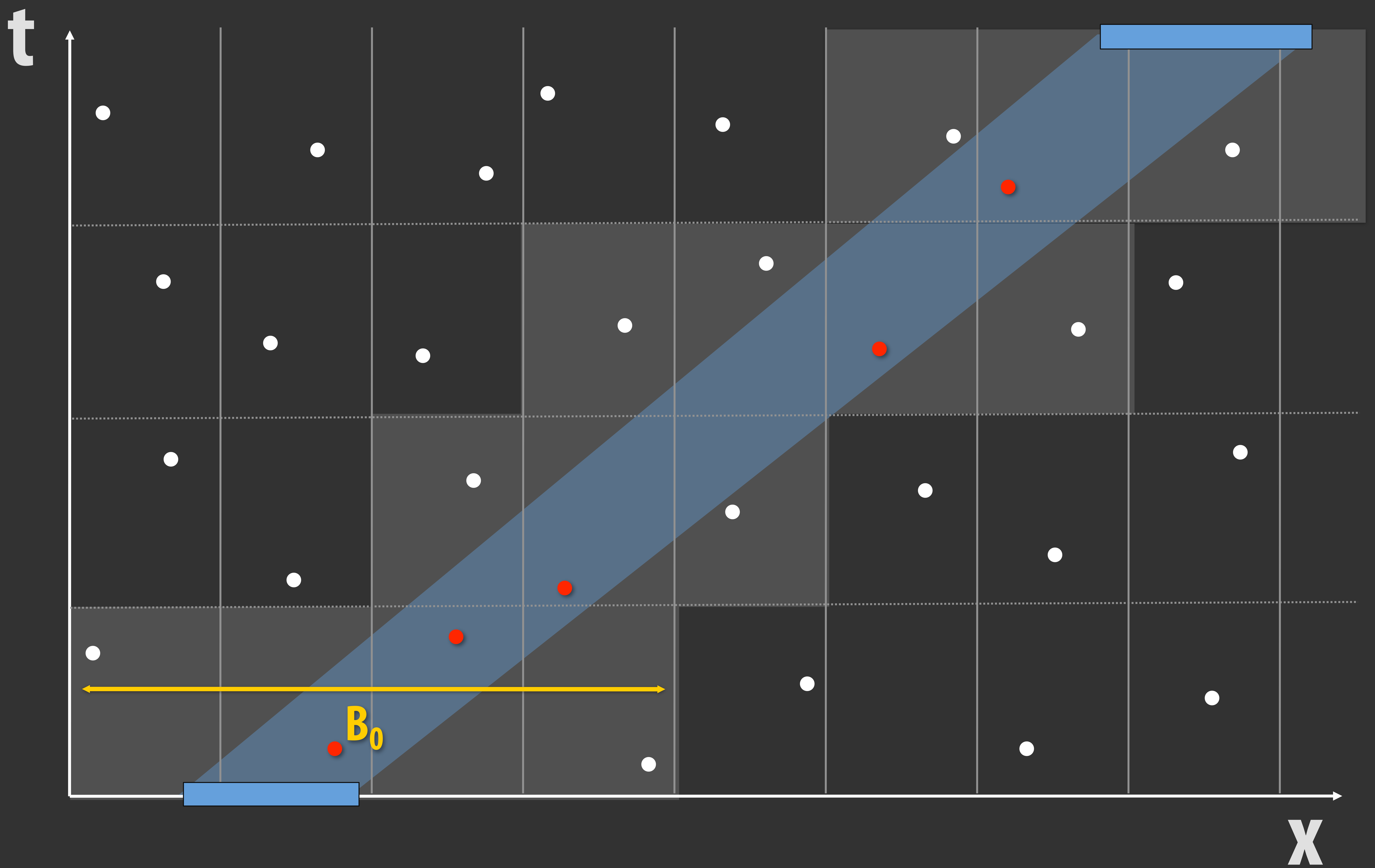
Tighter bounds (4 time intervals)



Slow motion = tight bounds

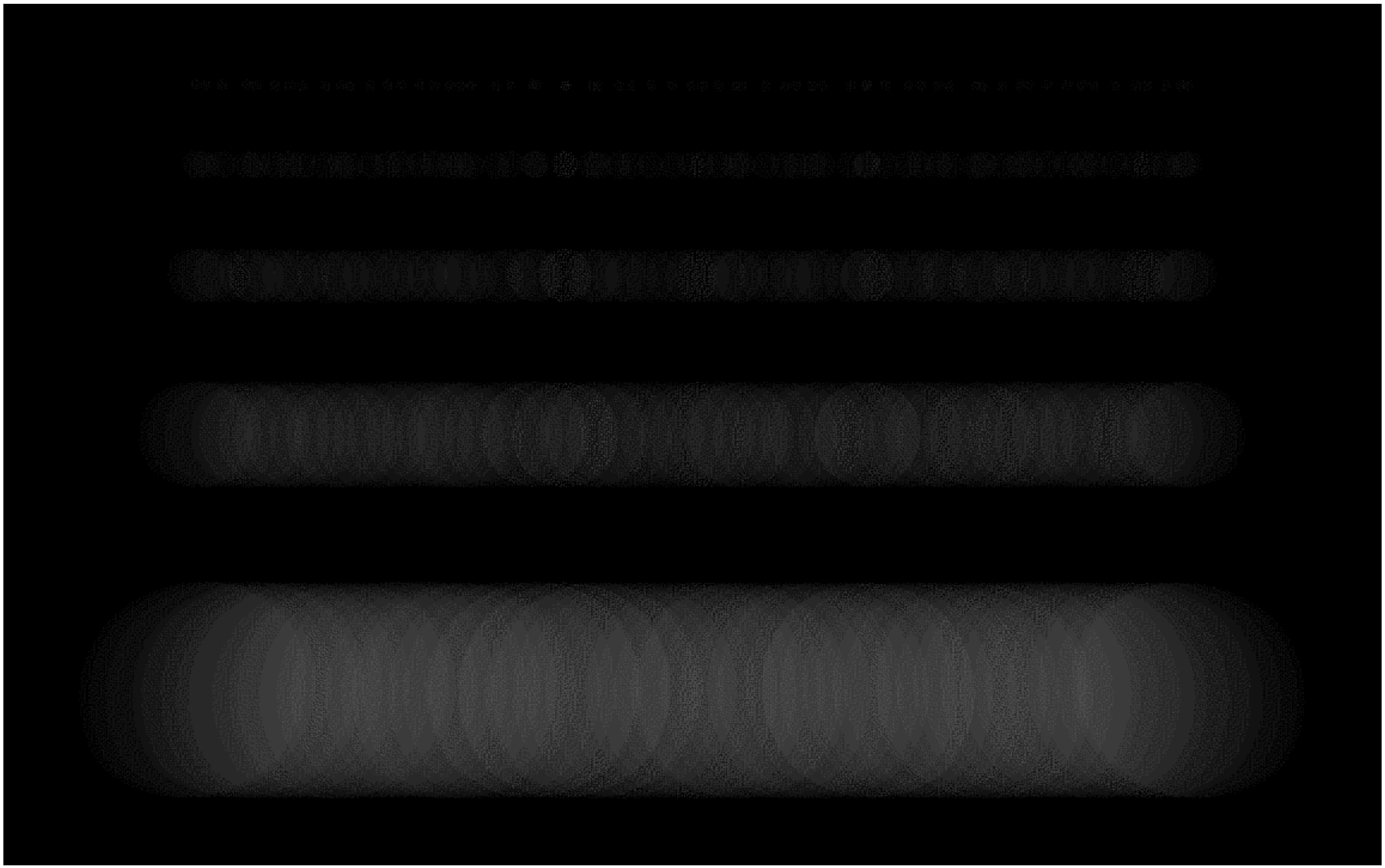


Fast motion = loose bounds



Stochastic rasterization results

White ball moving rapidly across screen
(movies shown in class)

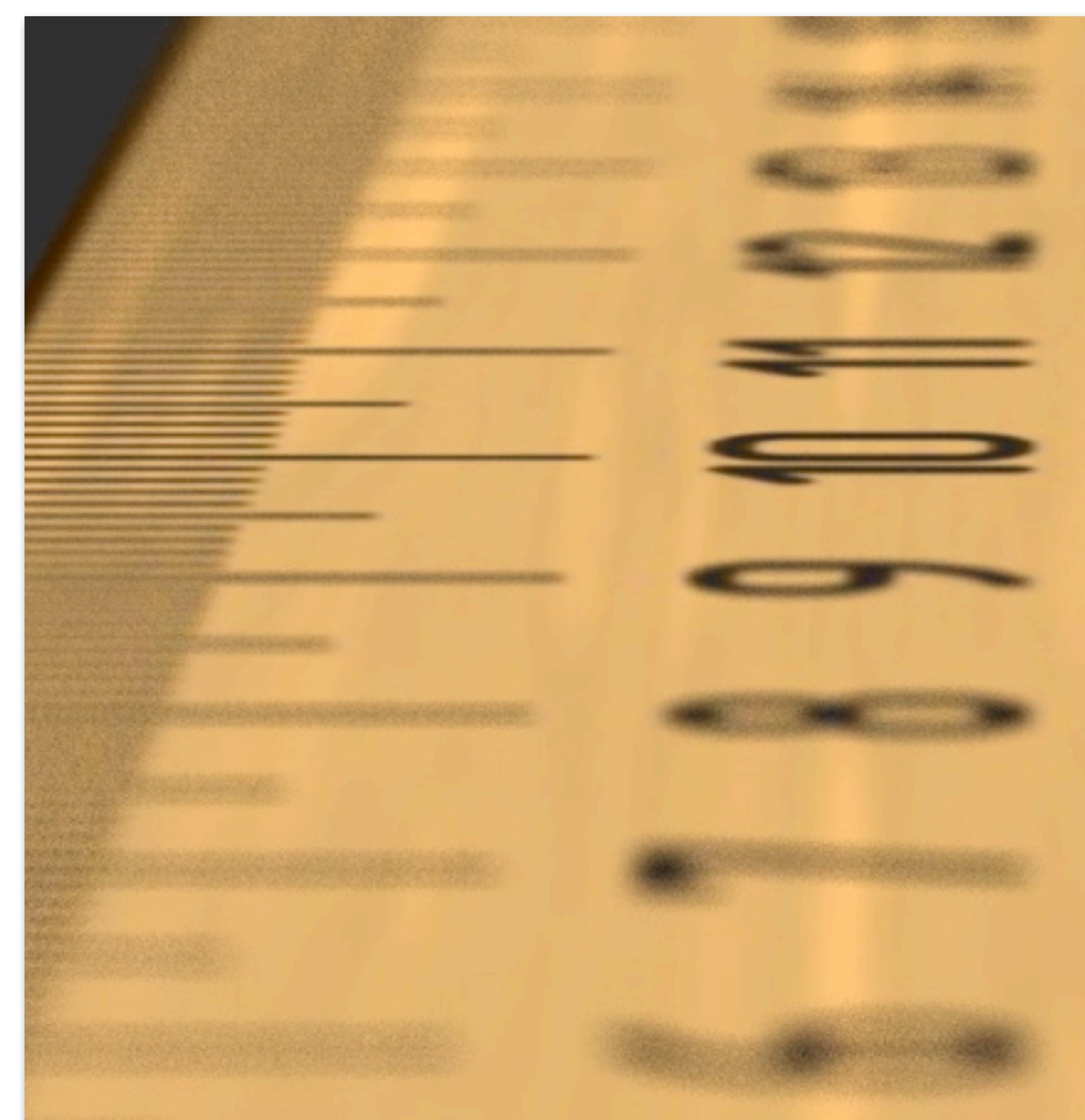


Stochastic rasterization results

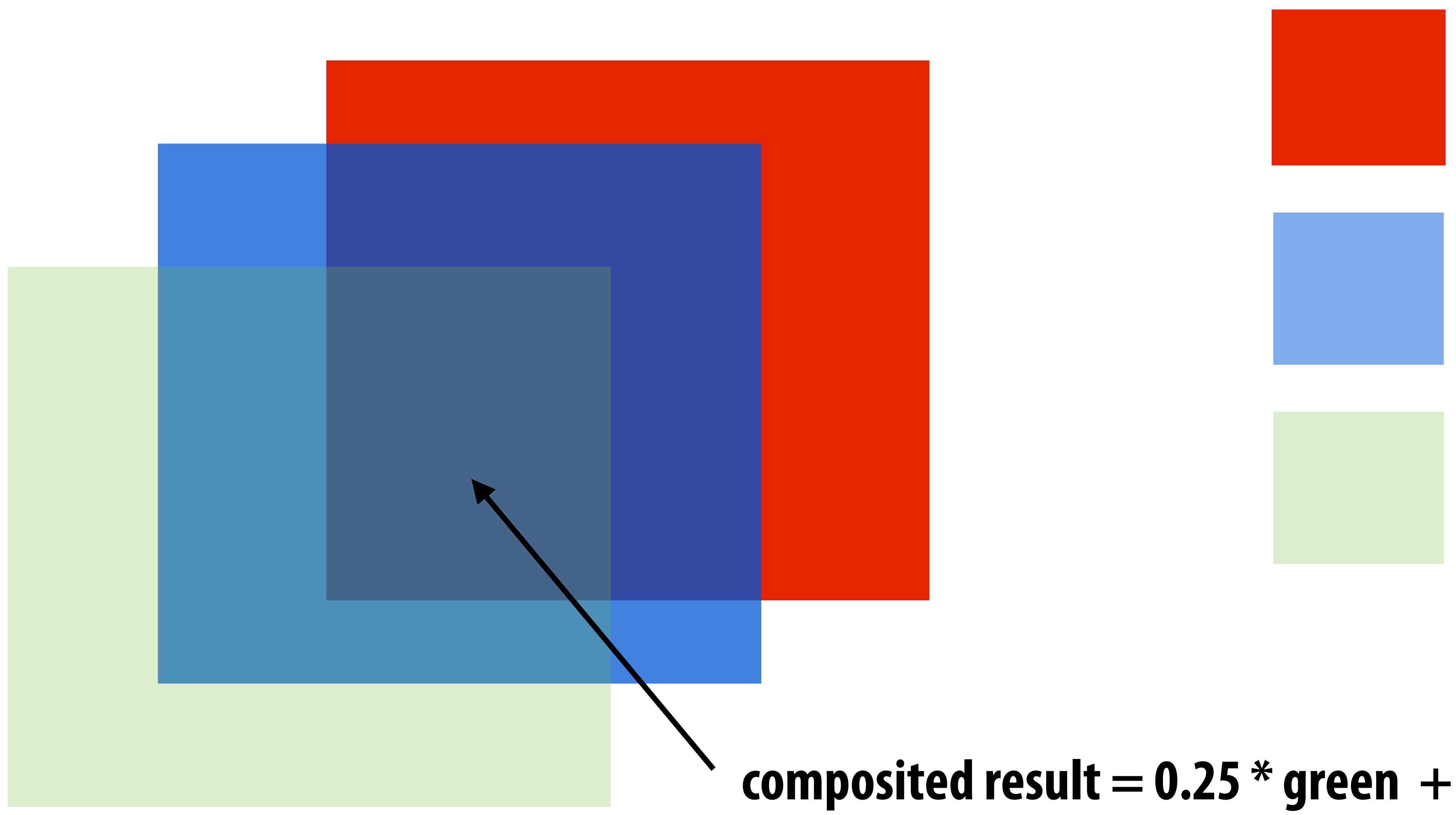
White ball moving rapidly across screen
(movies shown in class: see web site)

Stochastic sampling for motion blur (and defocus blur)

- Need high visibility sampling rates to remove noise in renderings with large motion blur, or camera defocus
- 64 - 128 visibility samples per pixel common in film rendering
  - Large frame buffer!



Transparent surfaces



OpenGL/Direct3D solution relies on pipeline ordering semantics:
Application sorts surfaces, renders surfaces back-to-front ***
Set frame-buffer blend mode:

```
frag.alpha * frag.color + (1-frag.alpha) * fb_color
```

*** front-to-back rendering solution exists as well

Transparency when using Z-buffer for occlusion

- **Application sorting is a pain**

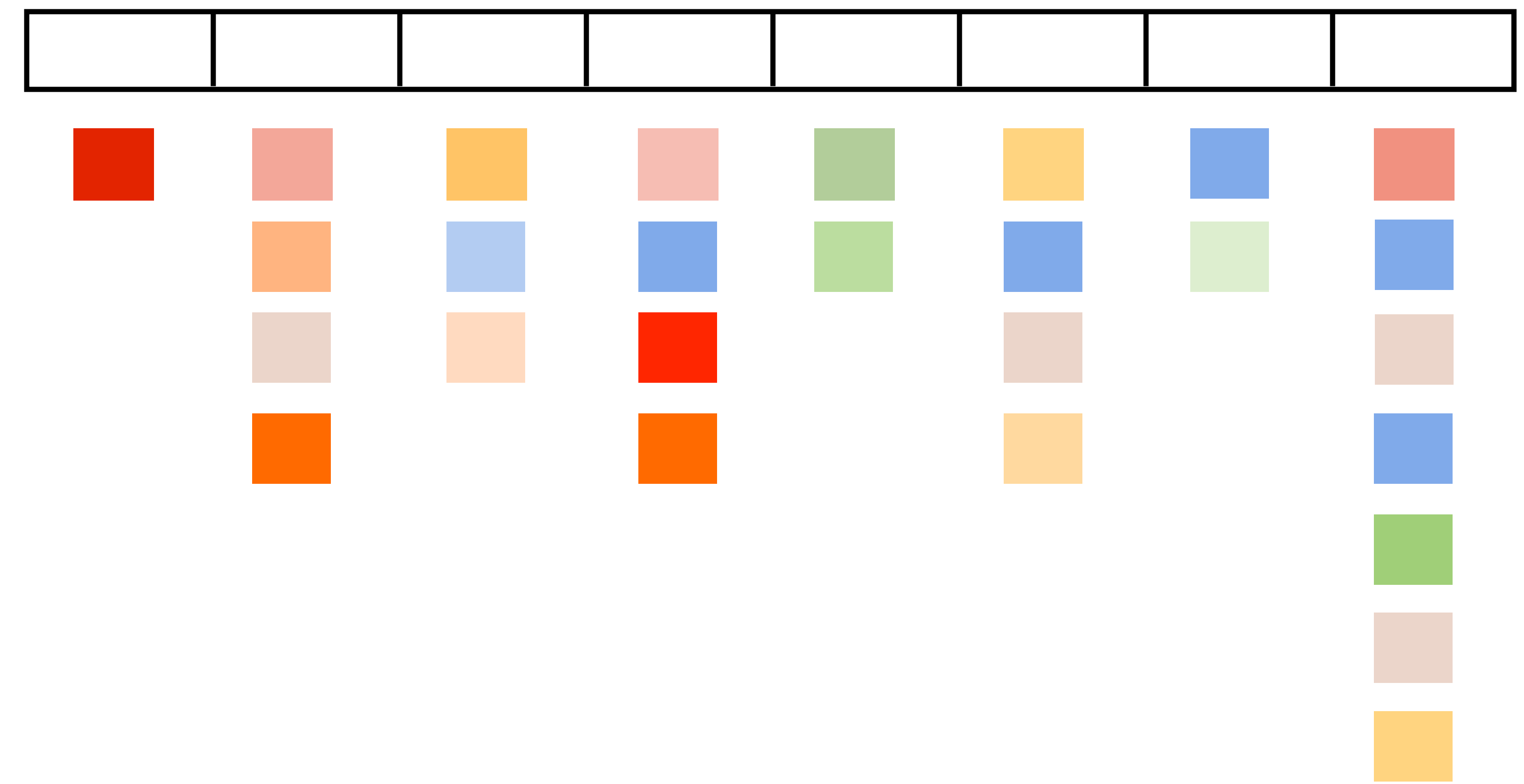
- **Depth sort order not well defined with triangles (interpenetration), let alone complex Reyes primitives**

- **Further complicated by motion blur**

A-buffer

[Carpenter 84]

- Store list of "visible points" at each visibility sample
  - visible point = {rgb, alpha, z}



- When frame rendering is complete:

```
For each sample:
   Sort visible points in list by Z
   Blend front-to-back (or back-to-front)
```

- Provides primitive order-independent solution for rendering transparency
- Cost: variable storage per visibility sample
- Many optimizations to prune list as rendering proceeds
  - e.g., don't need to add visible points behind an opaque point in the list

Reyes A-buffer

- Many visibility samples per pixel (recall: 64-128)
- Many visible points per sample (under conditions of significant transparency)

1920x1080 rendering (1080p)

64 visibility samples per pixel

4 visible points per sample (rgb,a,z)

~10 GB A-buffer !!!

Reyes implementations use bucketing

- Recall "sort middle tiled chunked" (assignment 1)
- Motivation here is to keep the A-buffer for a bucket in memory

  (previously we discussed how some implementations of OpenGL use a similar sorting scheme to: gain parallelism, keep a tile of frame-buffer on chip)

```
for each primitive, place in screen bucket
for each bucket
    allocate G-buffer for bucket
    for each primitive
       split-dice to create grids // each split, cull primitives falling outside of bucket
       shade + hide grids
    for each bucket g-buffer sample
       composite visible points
```

Reyes summary

- **Key algorithms**
  - High quality, split-dice tessellation
  - Shades per-vertex, prior to rasterization
  - Visibility via stochastic point sampling to simulate motion blur, camera defocus
  - Correct rendering of transparent surfaces via the A-buffer

- **Key system concepts**
  - Micropolygons: common intermediate representation for all primitive types
  - Micropolygon grids for locality and SIMD shading
  - Bucketed rendering to fit tiles of A-buffer in memory (high depth complexity due to transparency and high visibility sampling rates)

    (not discussed today: lots of smarts in a performant Reyes implementation to keep working set in memory)

Readings

- *The Reyes Image Rendering Architecture*. R. Cook et al. SIGGRAPH 1987