GPU TECHNOLOGY CONFERENCE

# Stochastic Rasterization

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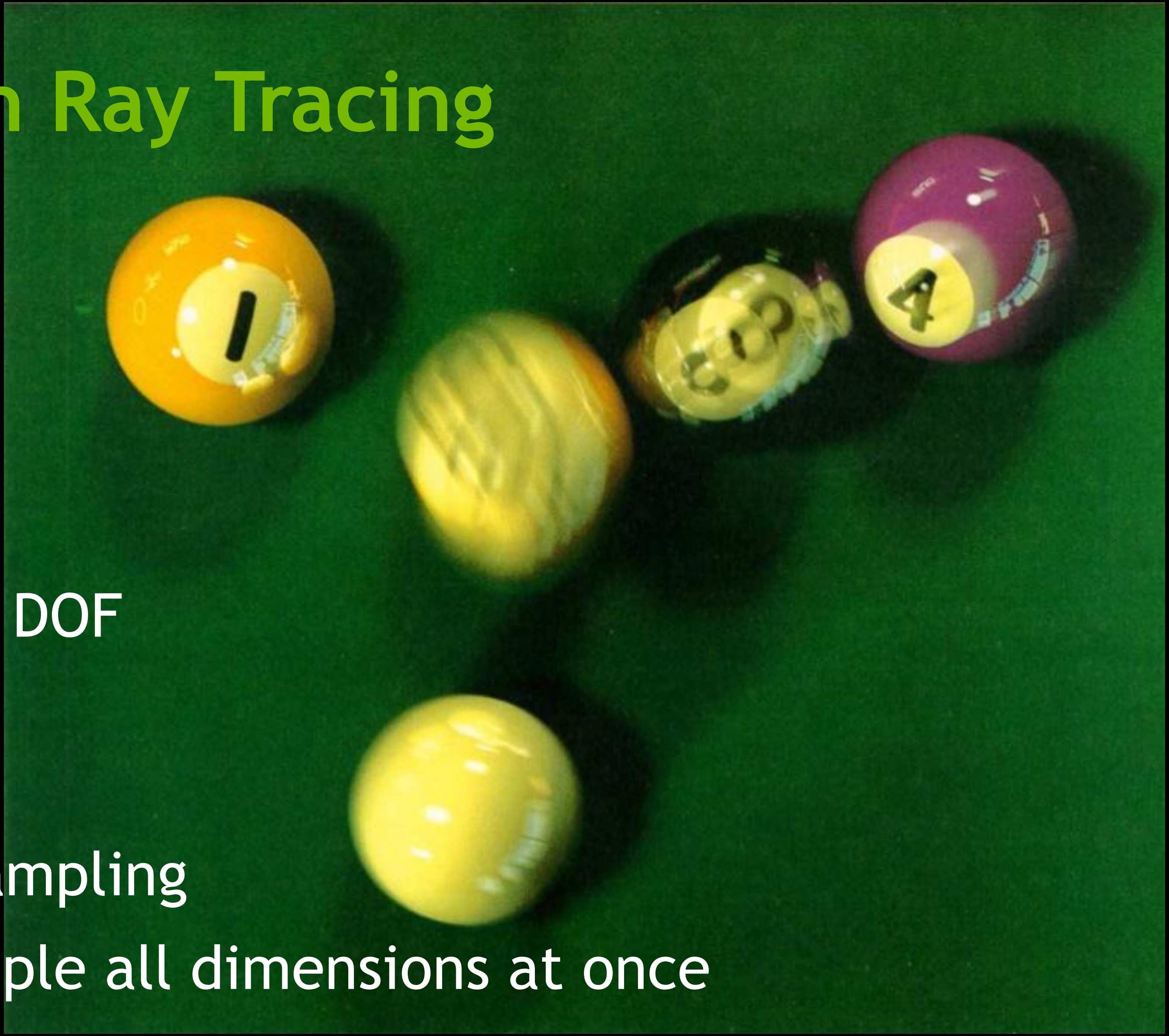
*NVIDIA Research*

9 fps on Geforce GT 280

>60 fps on Geforce GT 280

# Distribution Ray Tracing



- Spatial AA
  - pixel (x,y)
- Motion blur
  - time (t)
- Defocus blur / DOF
  - lens (u,v)

- Monte Carlo sampling
- Same rays sample all dimensions at once

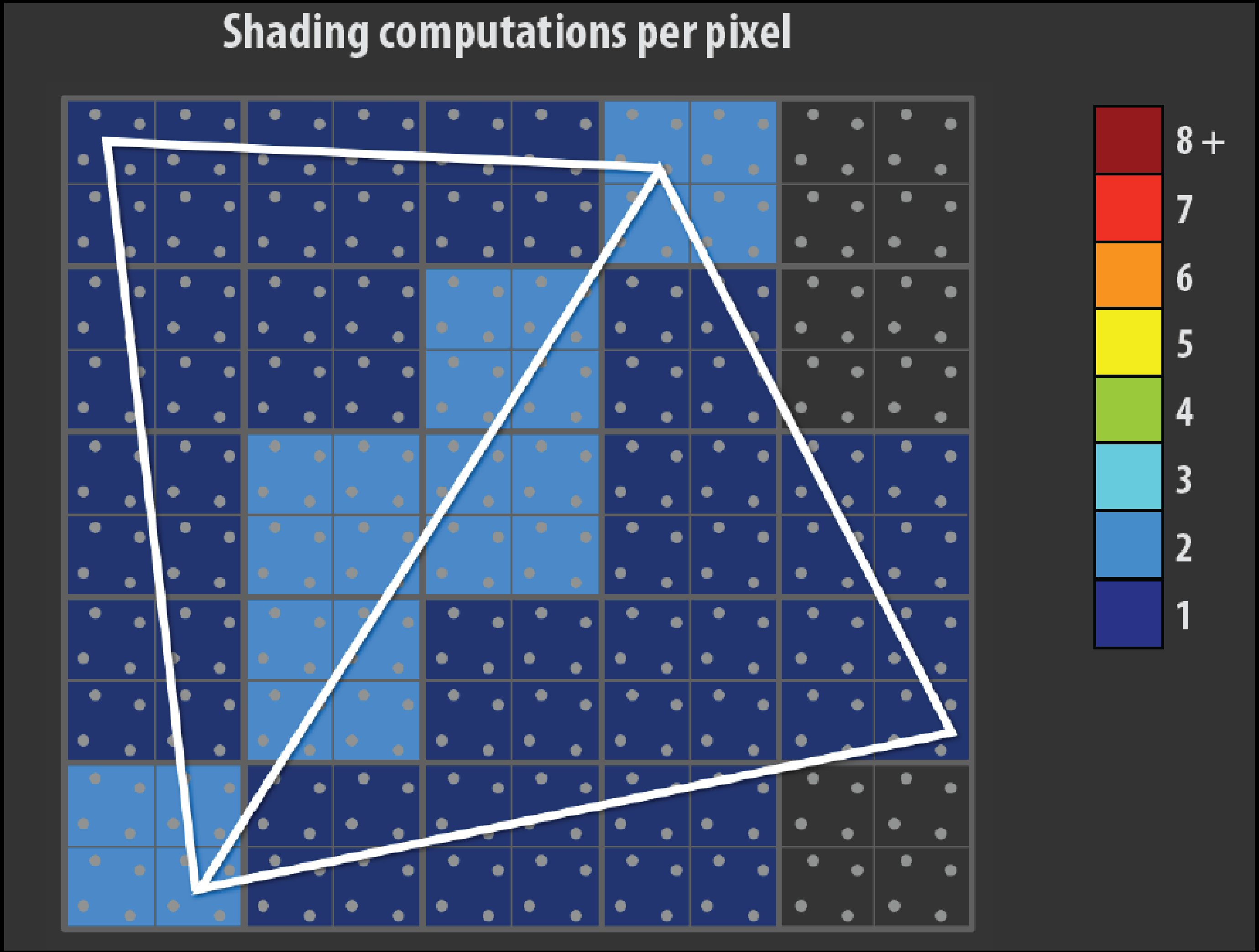
# Stochastic Rasterization

- The same thing, but leveraging hardware rasterization
- No rays
- Interactive speeds
- Transparency

# MSAA

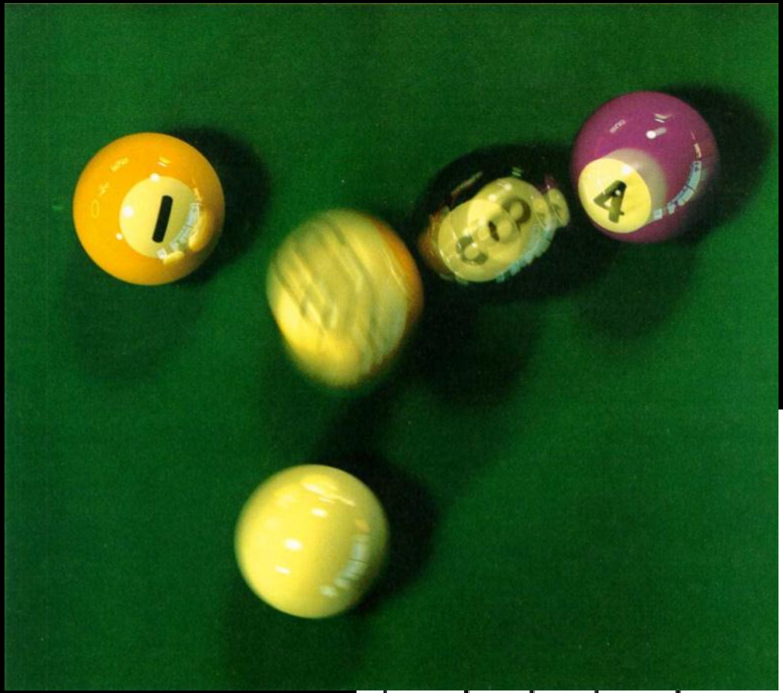
- Multi-Sample Anti-Aliasing
  - Hardware supports up to 8 samples per pixel
  - Spatial anti-aliasing only (triangle edges)
  - Not stochastic
- Shade once per pixel, not once per sample
  - Actually once / fragment
  - A major performance criterion for us

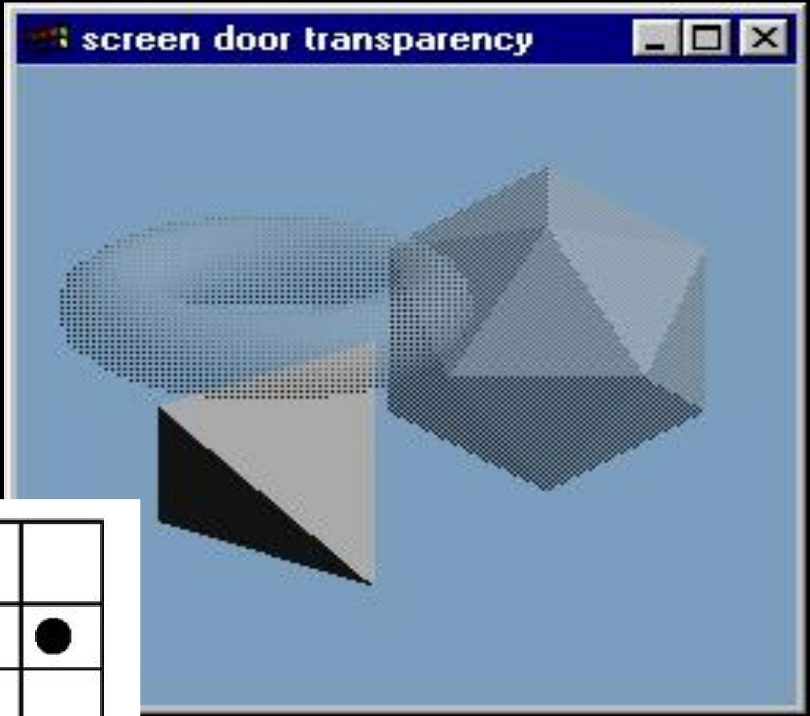
# MSAA

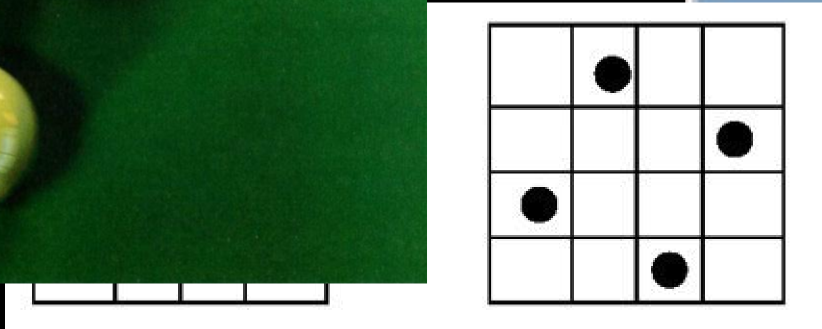



(Kayvon Fatahalian, "Beyond Programmable Shading" course, SIGGRAPH 2010)

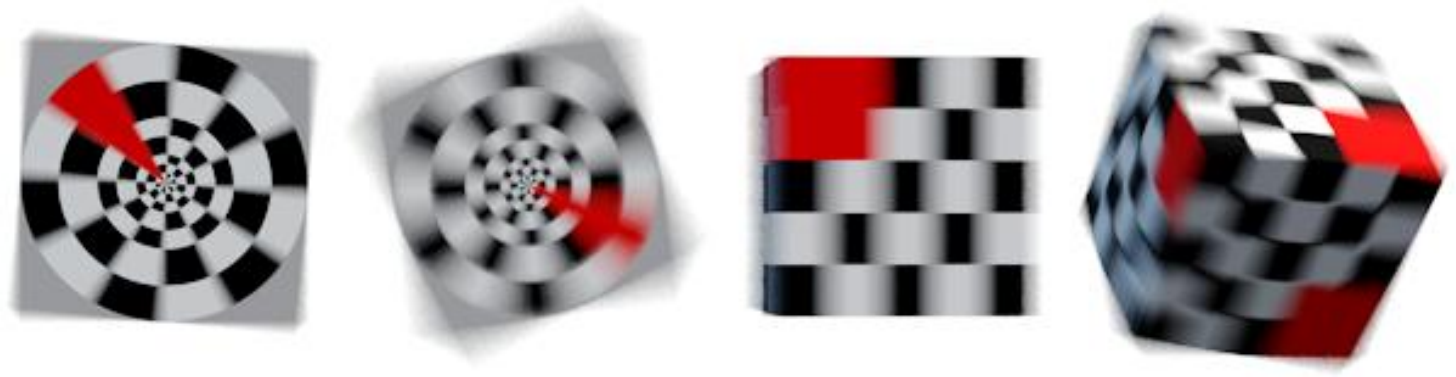
# Familiar stuff, sub-pixel





Pixel patterns for GeForce FX (left) and GeForce 6 Series (right) architectures showing horizontal and vertical values.

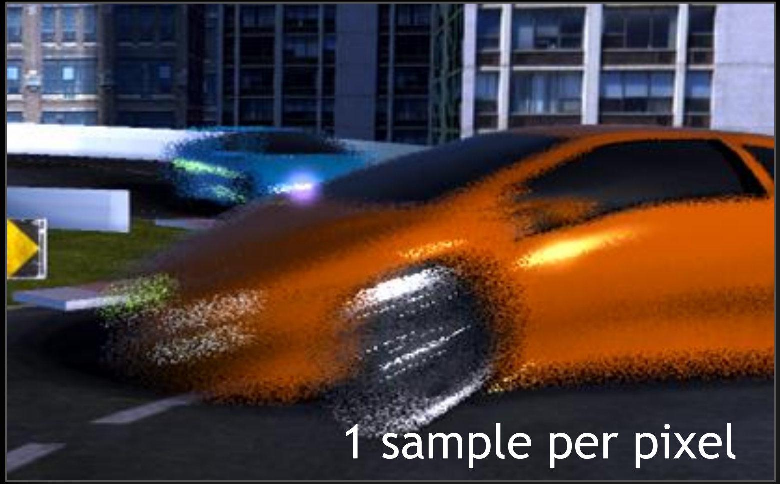


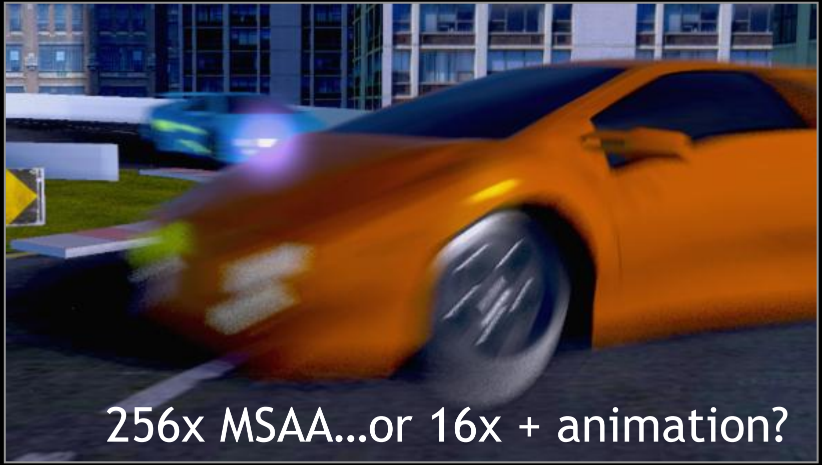
# Motion Blur

Conventional: no blur

Accumulation: ghosts

Stochastic: noisy

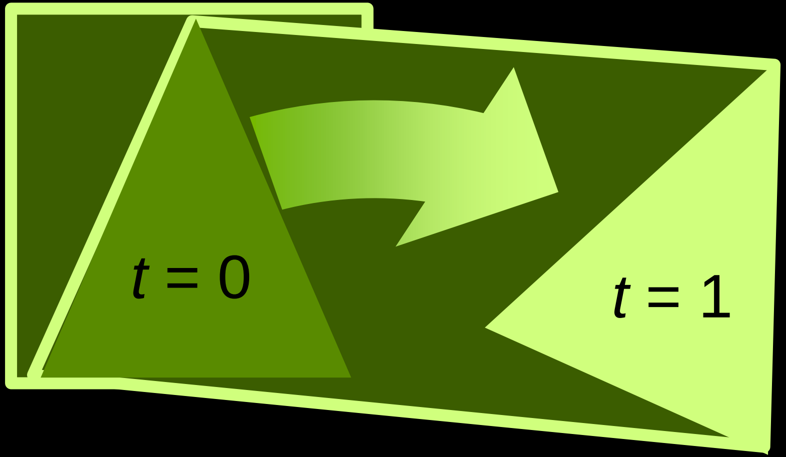


(2+1)D

# ~~2D~~ Rasterization

| | | |
|---|---|---|
| Geometry Shader | 1. | Bound the triangle's screen-space extent due to its shape ($xy$) and motion ($t$) |
| 2D Rasterizer | 2. | Iterate over the samples in that bound |
| Pixel Shader | 3. | Perform some $xyt$ inside-outside test per sample |
| | 4. | Shade the samples that pass |

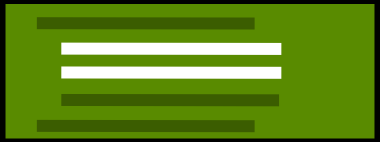


# Extending an Existing Renderer

C++ Host | Vertex Shader | Geometry Shader | Pixel Shader

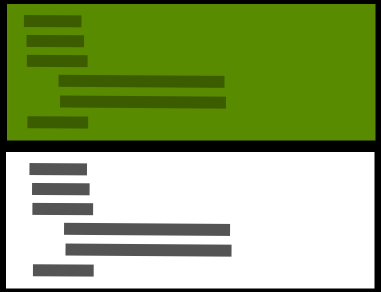
# Extending an Existing Renderer

## C++ Host



+ velocity attribute
+ camera velocity uniform

## Vertex Shader



+ duplicate transform code for prev. vtx

## Geometry Shader

+ convex hull of prev & current

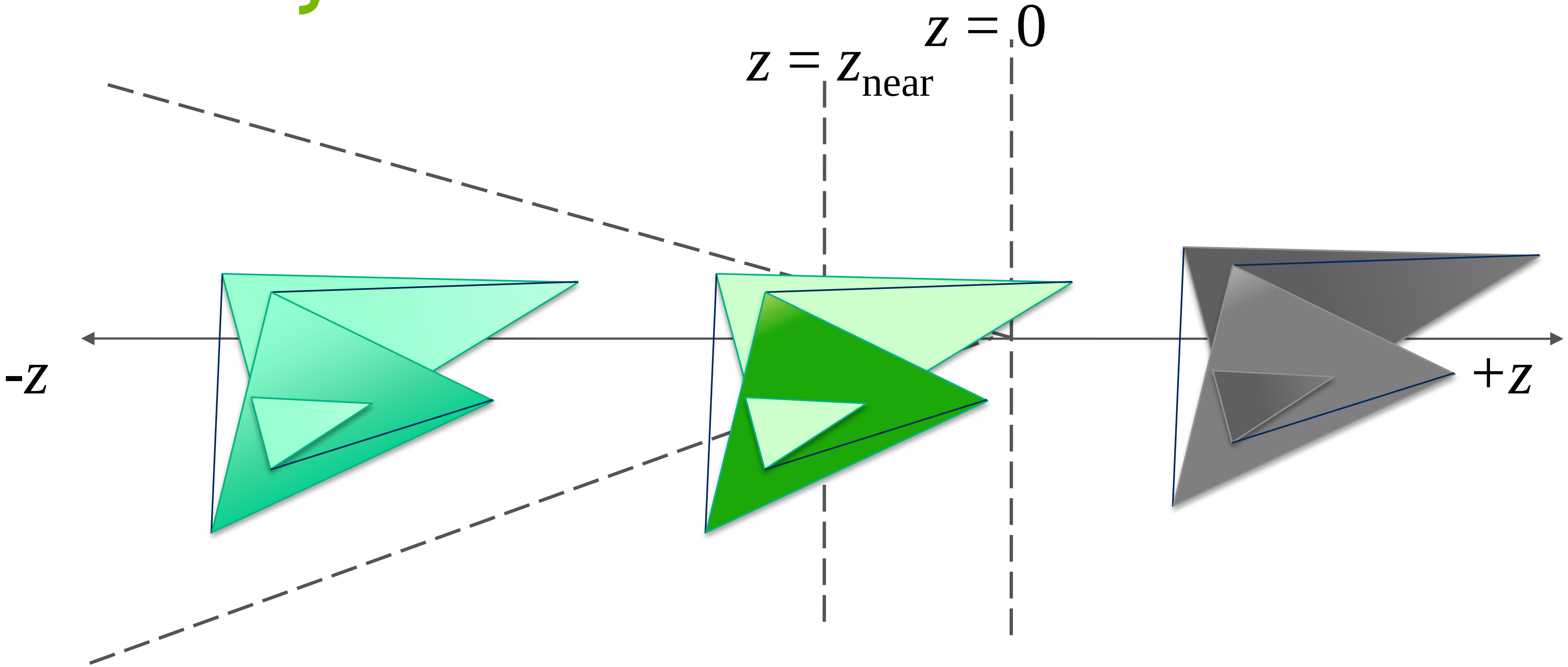
## Pixel Shader

+ set MSAA mask from ray-triangle tests

**Shading code is unmodified!**

(source code at nvidia.com/research)

# Geometry Shader

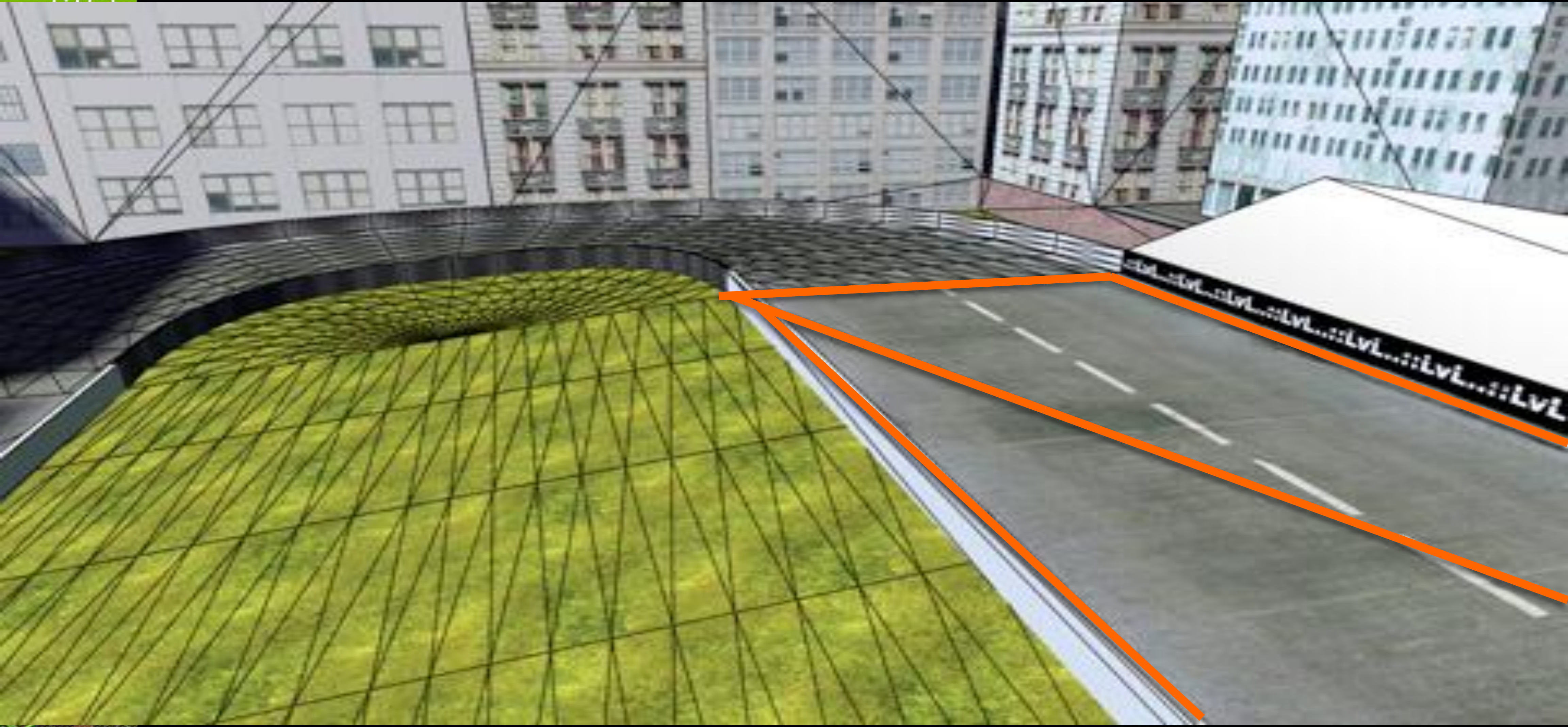



“Normal”: All $z < 0$: Projected Hull

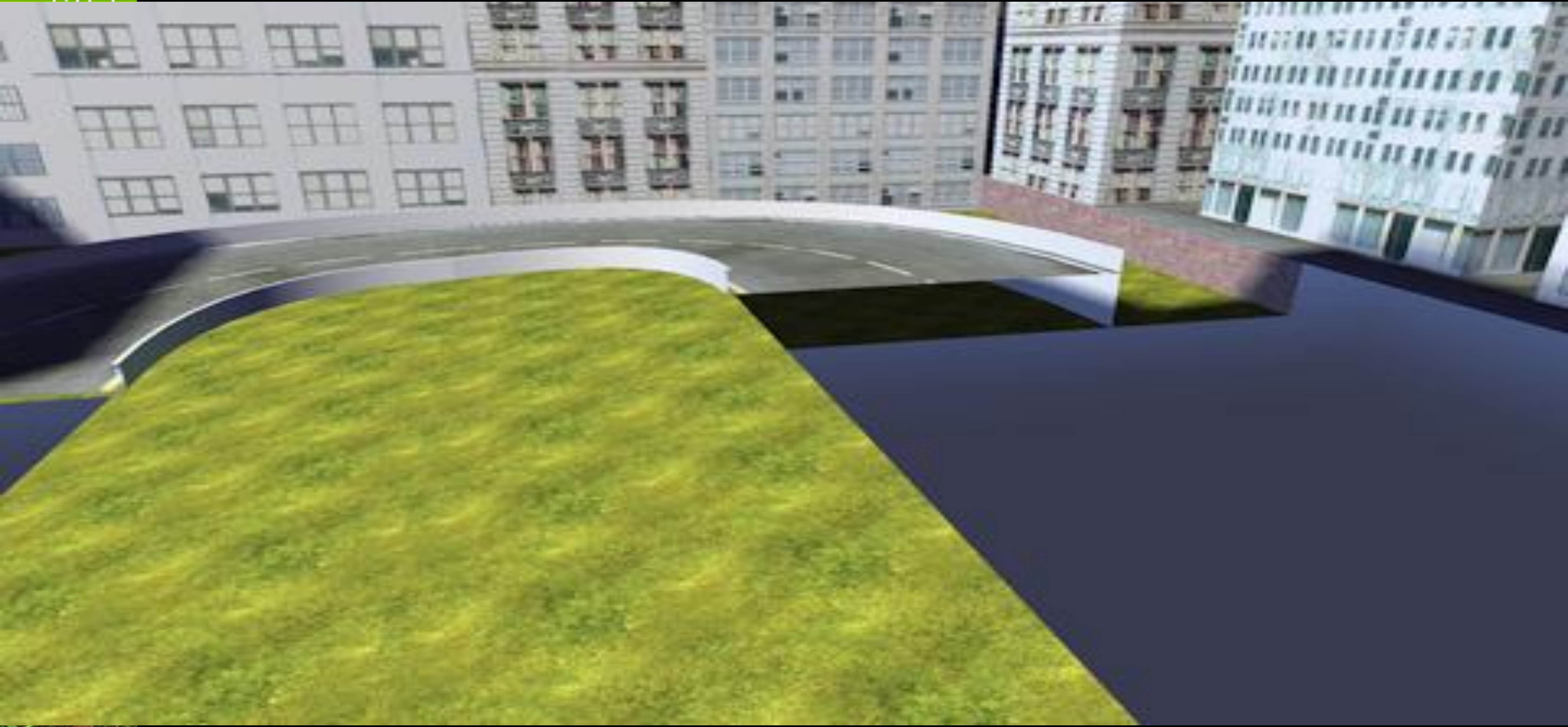
All $z > z_{near}$: Cull

“z=0 crossing”: $z_{min} < z_{near}$ and $z_{max} > 0$: Clip and Box

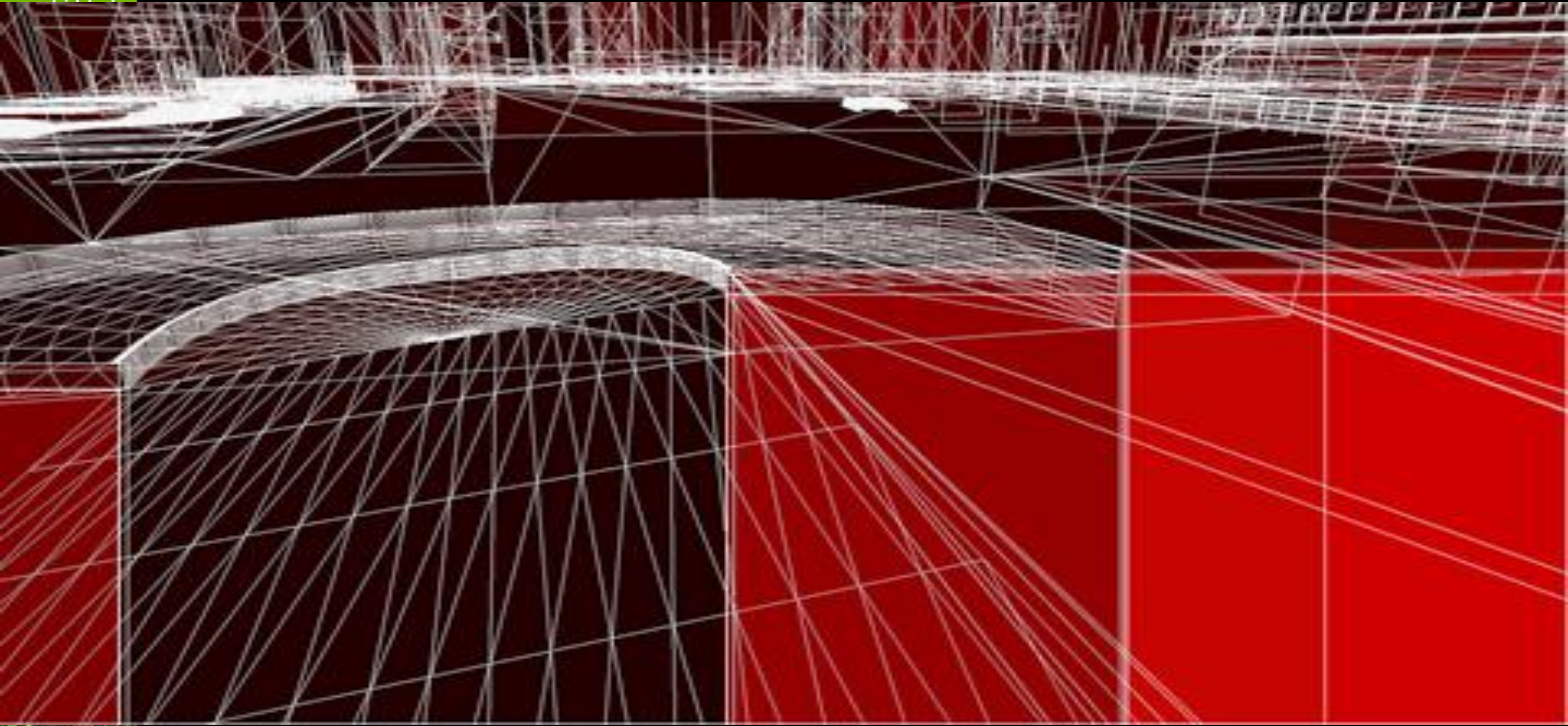
# Extreme Example of $z = 0$ Case



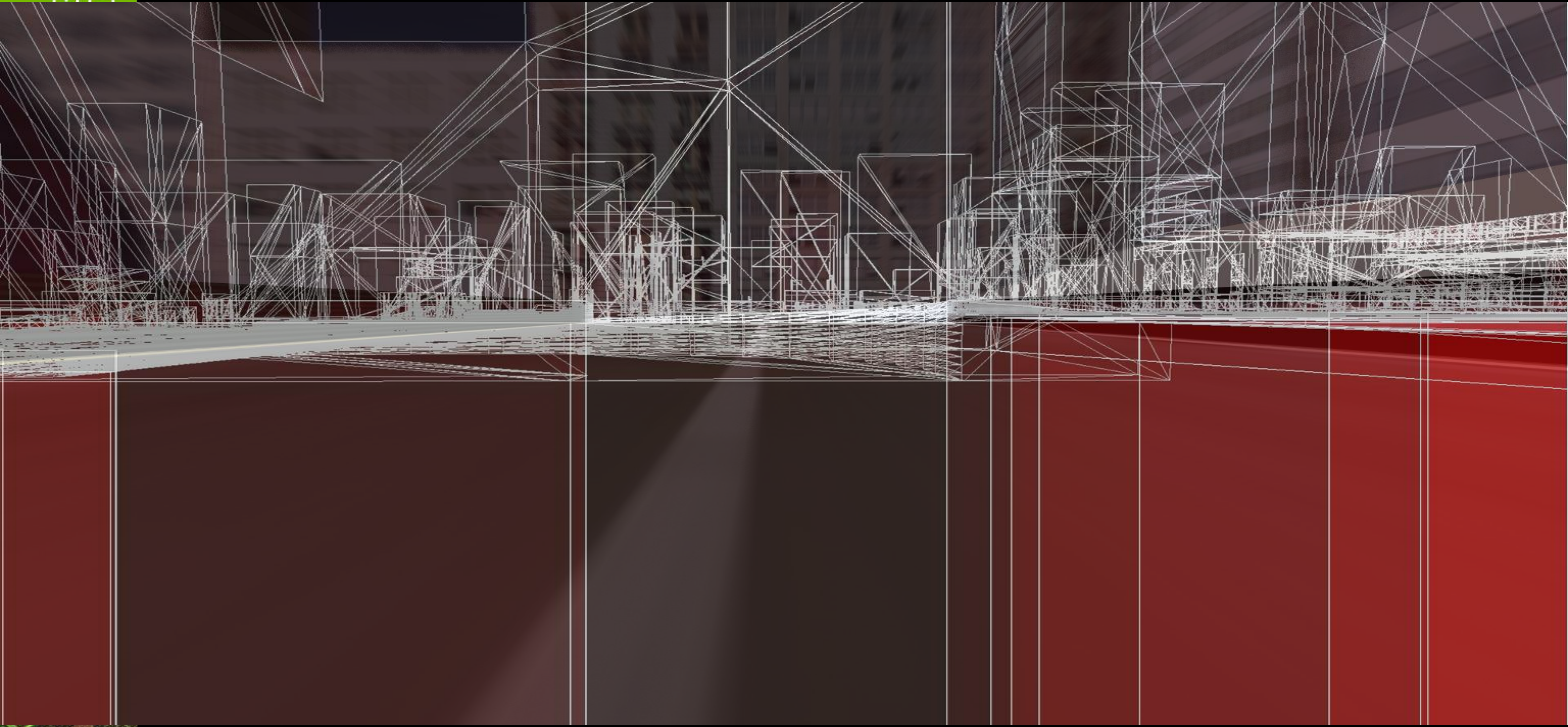
# Extreme Example of $z = 0$ Case



# Extreme Example of $z = 0$ Case

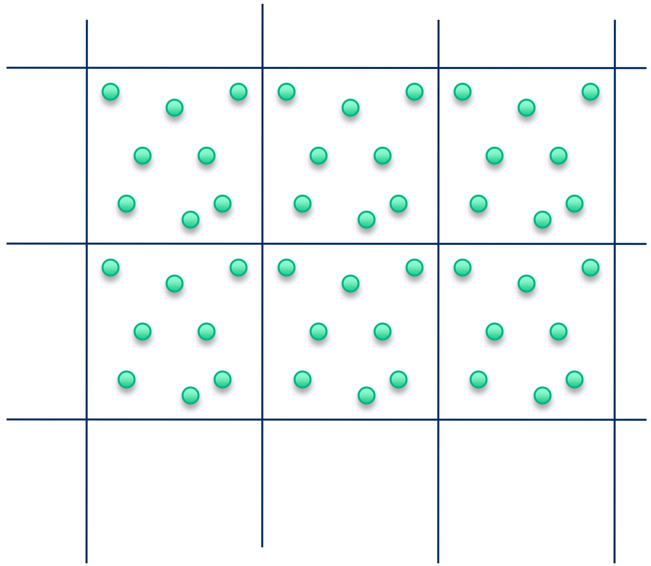


# Correct result for a moving camera



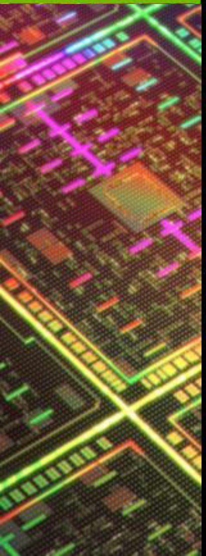
# Integration with MSAA

- Perform ray-triangle test per sample
- Override the pixel's coverage mask
- Shade at most once per pixel



- Use ray differentials (like screen-space derivatives) to set anisotropic MIP-map levels

# Pixel Shader



```
// Sample stochastic visibility
for (int i = 0; i < MSAA_SAMPLES; ++i) {
   getRay(origin, dir, i, gl_FragCoord.xy);
   if (intersectRay(origin, dir, time[i], u, v)) {
      gl_SampleMask[0] |= (1 << i);
   }
}

if (gl_SampleMask[0] == 0) discard;

// Barycentric interpolation
vertex    = v0 * u + v1 * v + v2 * (1 – u – v);
normal    = n0 * u + n1 * v + n2 * (1 – u – v);
texCoord = t0 * u + t1 * v + t2 * (1 – u – v);

// Shade as usual…
```

# Multisample Rate: 1x

# Multisample Rate: 4x

# Multisample Rate: 8x

# Multisample Rate: 16x

# Multisample Rate: 64x

# Multisample Rate: 256x

# Bridge

Motion blur

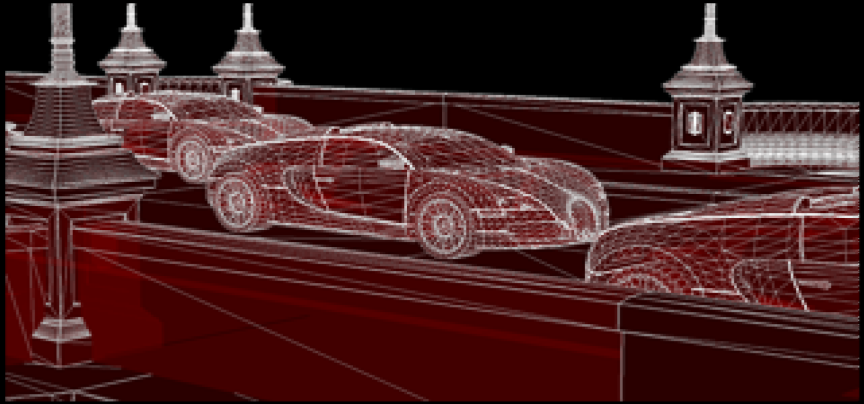
1.8M Triangles

8 vis, 4 tex, 1 shade / pix

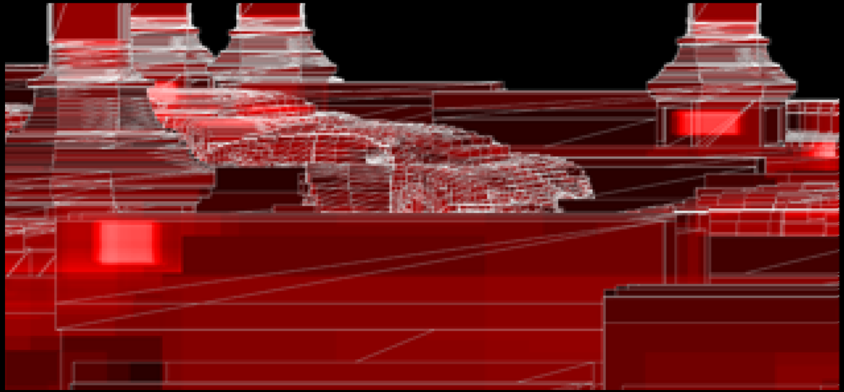
1280 × 720 @ 19 fps

GeForce GTX 480

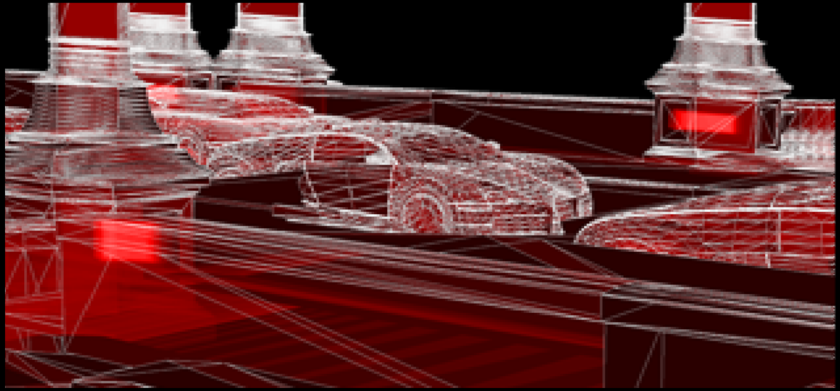
# Sample Test Efficiency



Scene



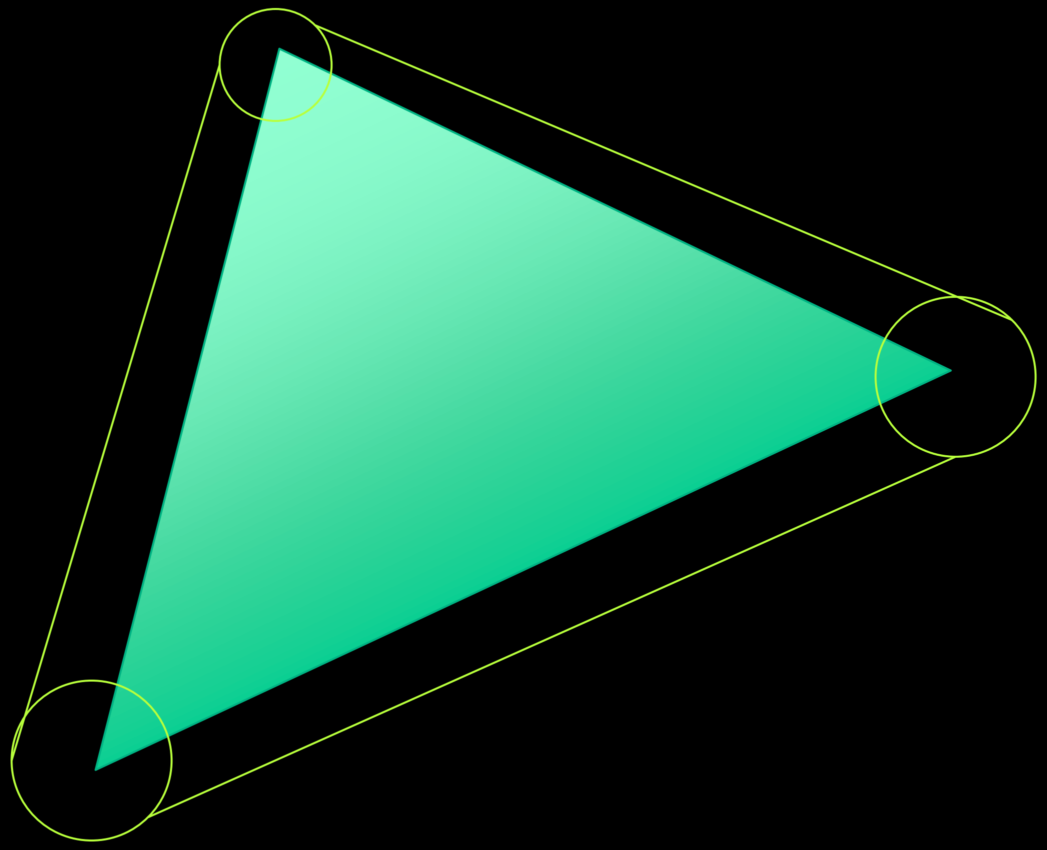
AABB



Convex Hull

# Depth of Field

# New Bounding Geometry



# Multisample Rate: 1x

# Multisample Rate: 4x

# Multisample Rate: 8x

# Multisample Rate: 16x

# Multisample Rate: 64x

# Fairy

Defocus blur
174k Triangles
8 vis, 4 tex, 1 shade / pix
1280 × 720 @ 10 fps
GeForce GTX 480

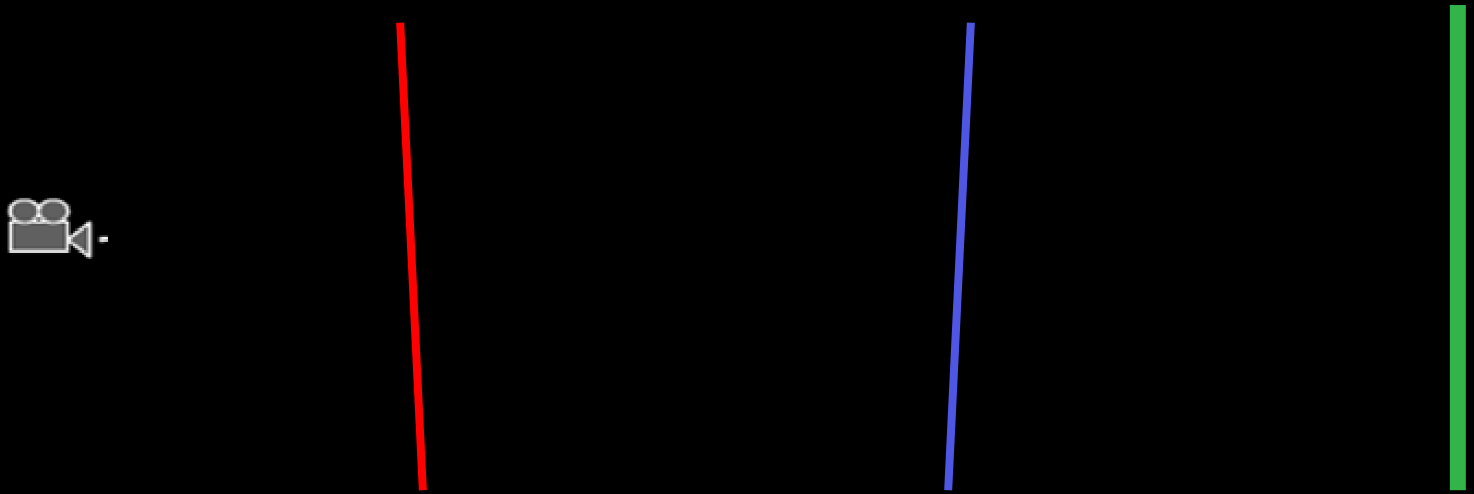
# Stochastic Transparency

# Transparency

- hair
- foliage
- particles
- windows

- shadows thereof

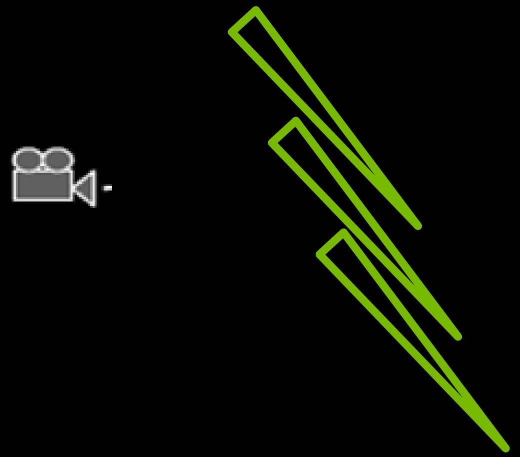
# Order dependent



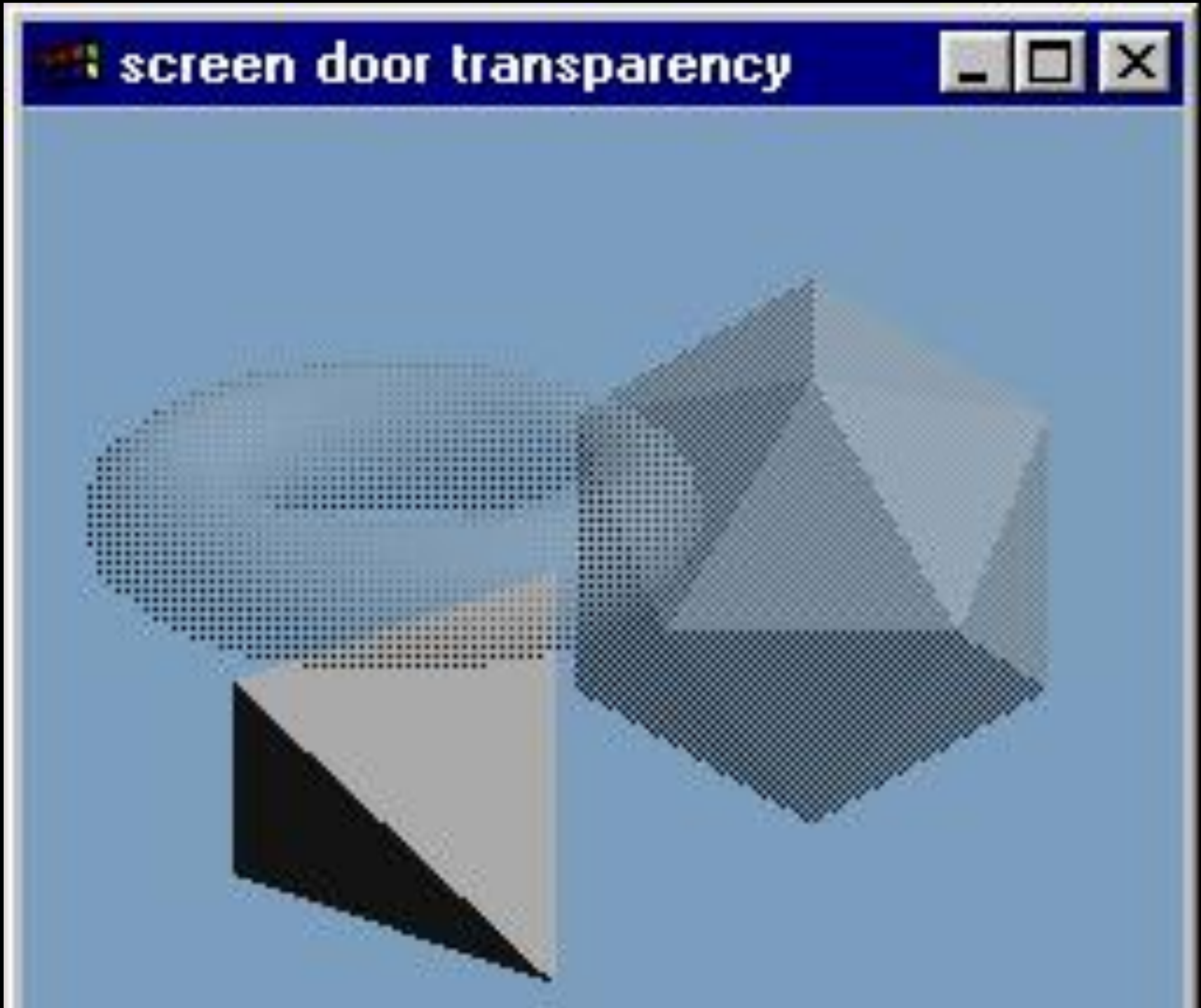
$$c = \alpha_1 c_1 + (1 - \alpha_1)(\alpha_2 c_2 + (1 - \alpha_2)\alpha_3 c_3)$$

# But sorting is painful

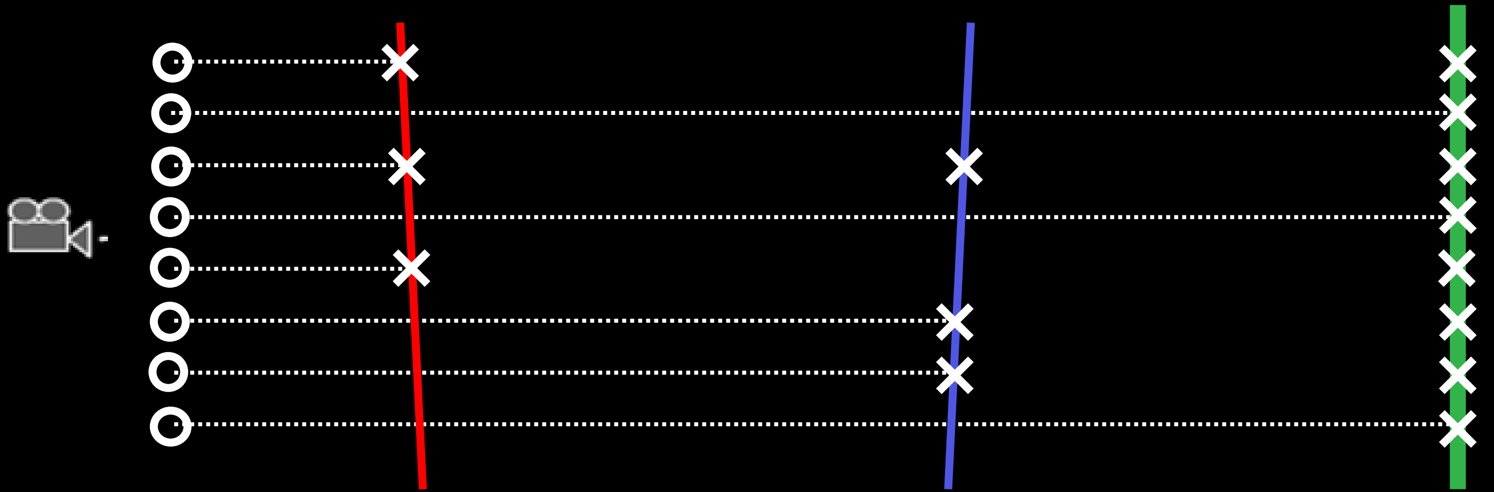
- Sort primitives
  - Fails for overlaps
  - Disrupts engine code
- Sort per pixel
  - A-Buffer
  - Unbounded memory



- Want:  Order Independent Transparency (OIT)


screen door transparency

# Correct on average



$$c = \alpha_1 c_1 + (1 - \alpha_1)(\alpha_2 c_2 + (1 - \alpha_2)\alpha_3 c_3)$$

- … *if* the masks are uncorrelated.
- Uses the z buffer to be order independent.

# Stochastic Transparency

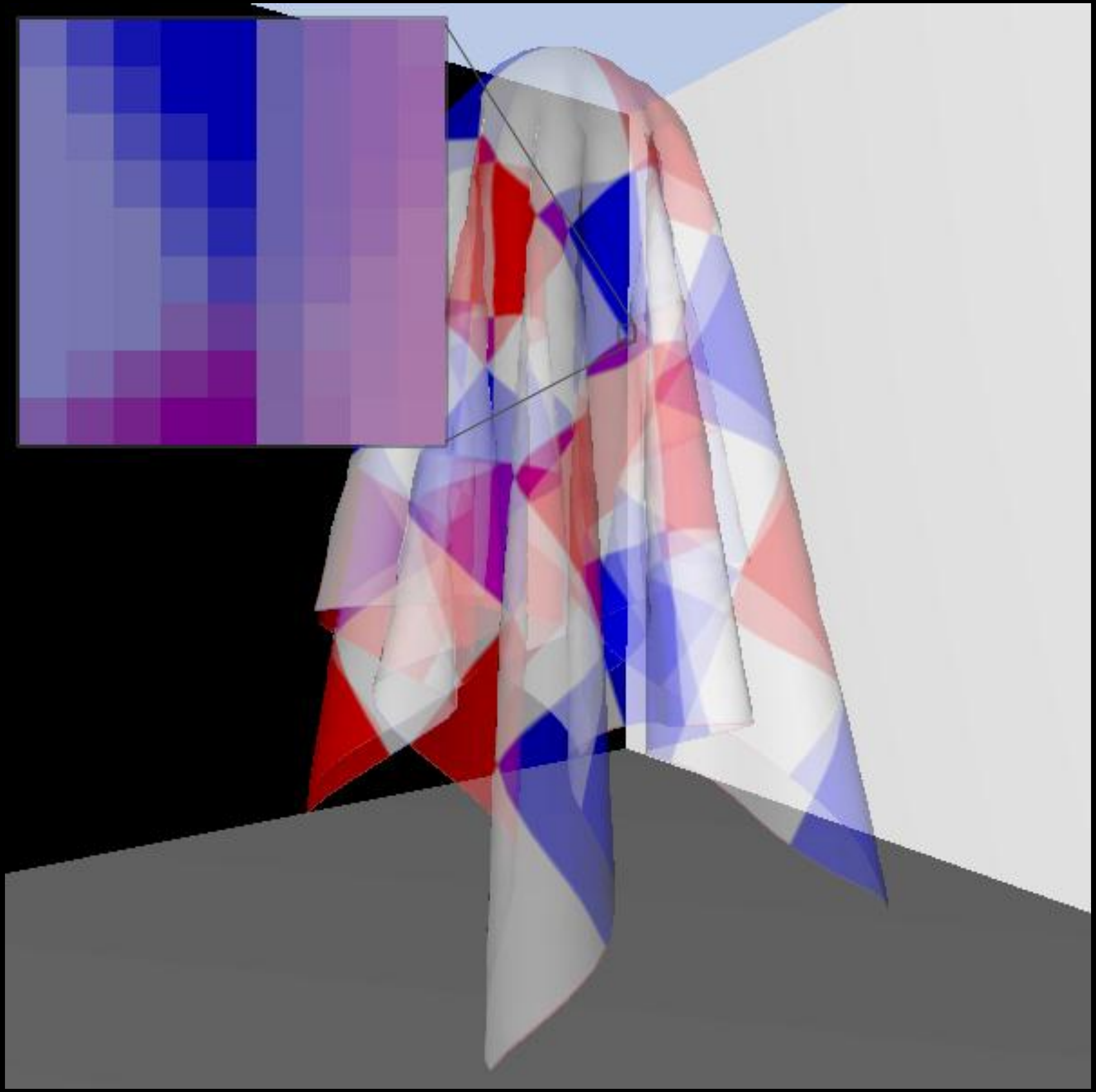
Screen-door + multi-sampling + random masks.

- Correct on average
- All cases unified in a single algorithm
  - Foliage, Smoke, Hair, Glass, mixtures
- One order-independent pass over the geometry
- Small fixed space (one MSAA frame buffer)
- But, noise

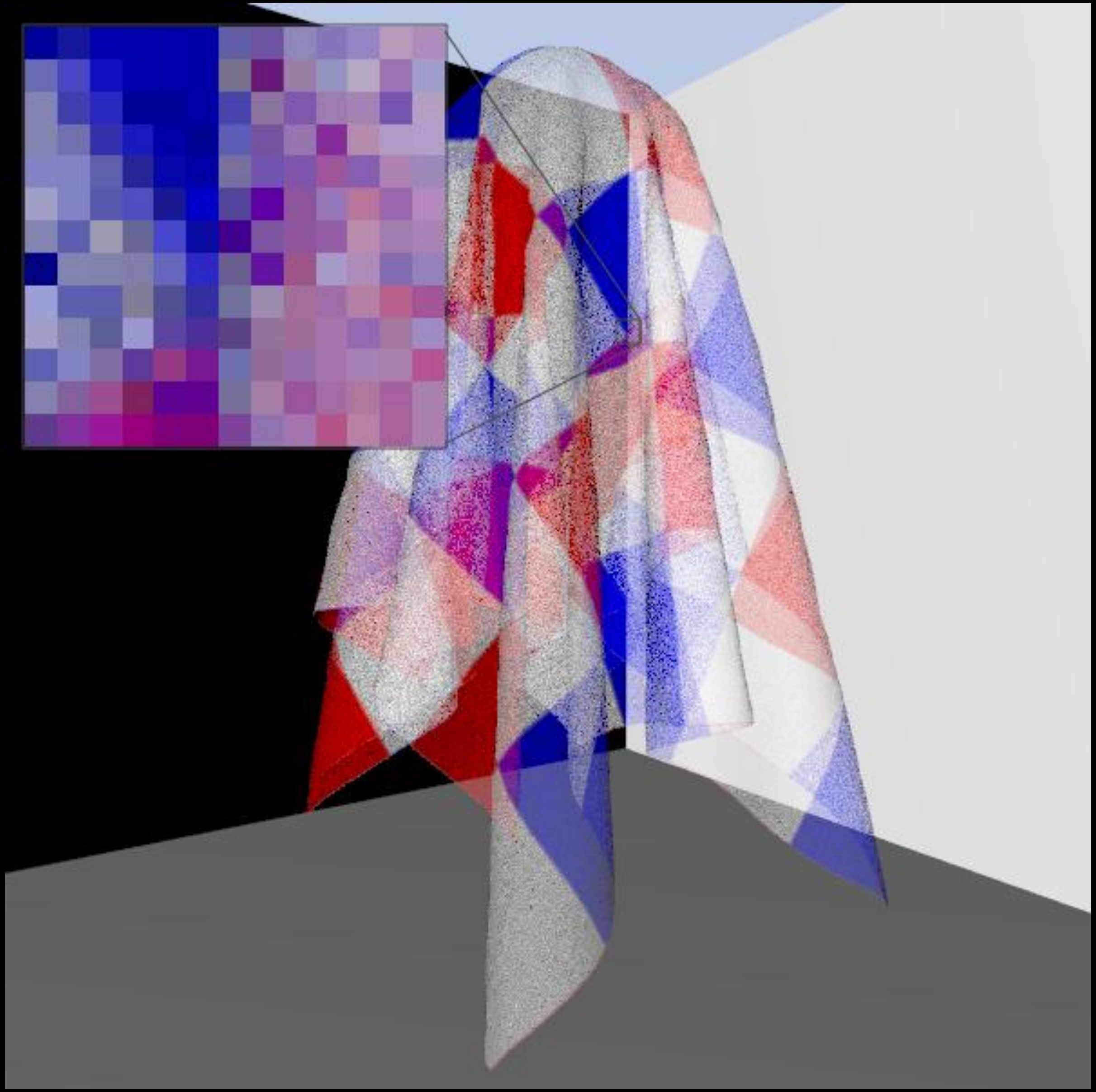
# MSAA helps

- Get S = 8*P samples per pixel, in P passes
- Pixel Shader sets 8-bit mask as pseudo-random function of alpha, x, y, prim ID.
- Spatial AA with the same samples
- Shading rate stays 1/fragment

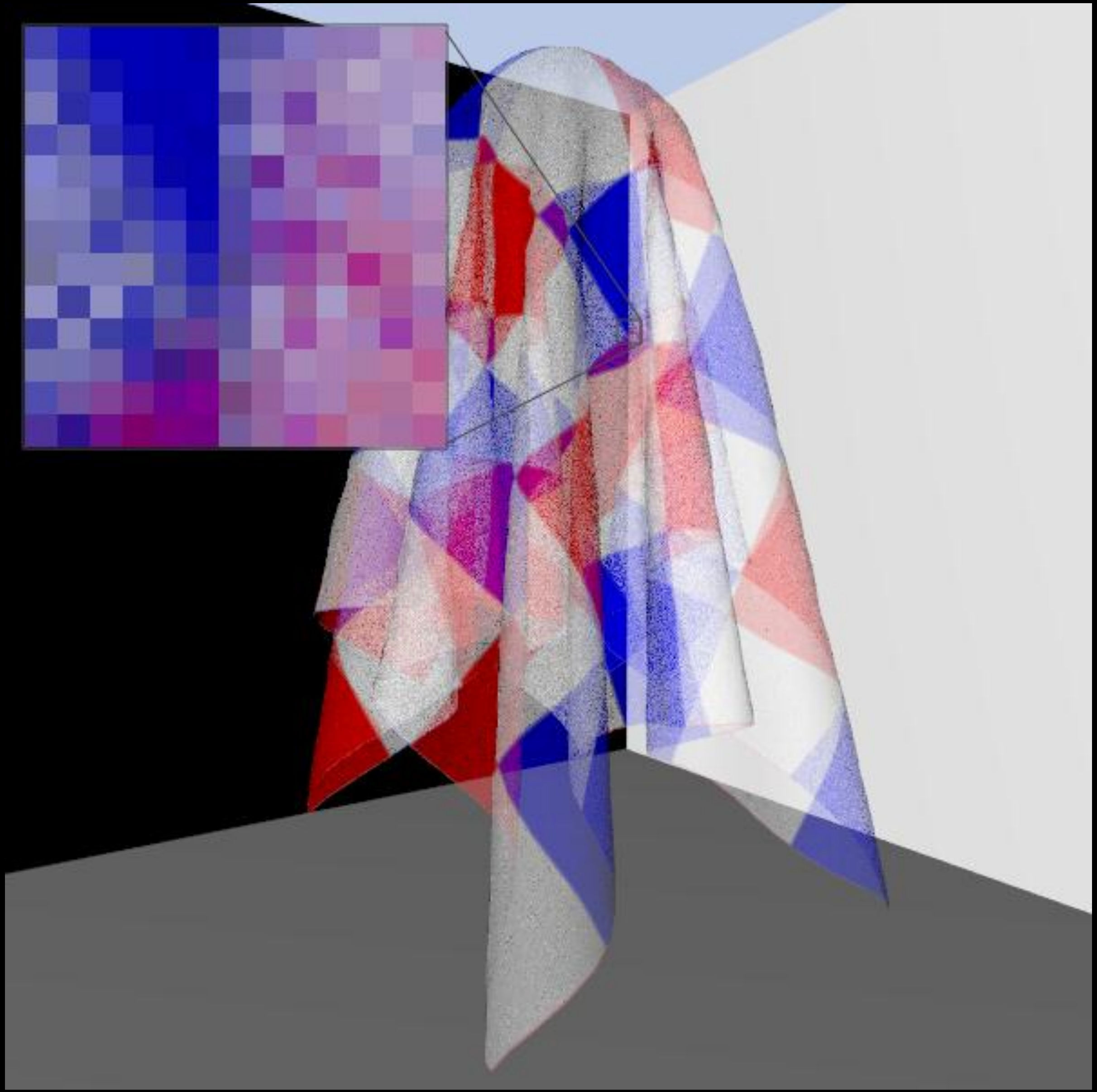
(Reference)



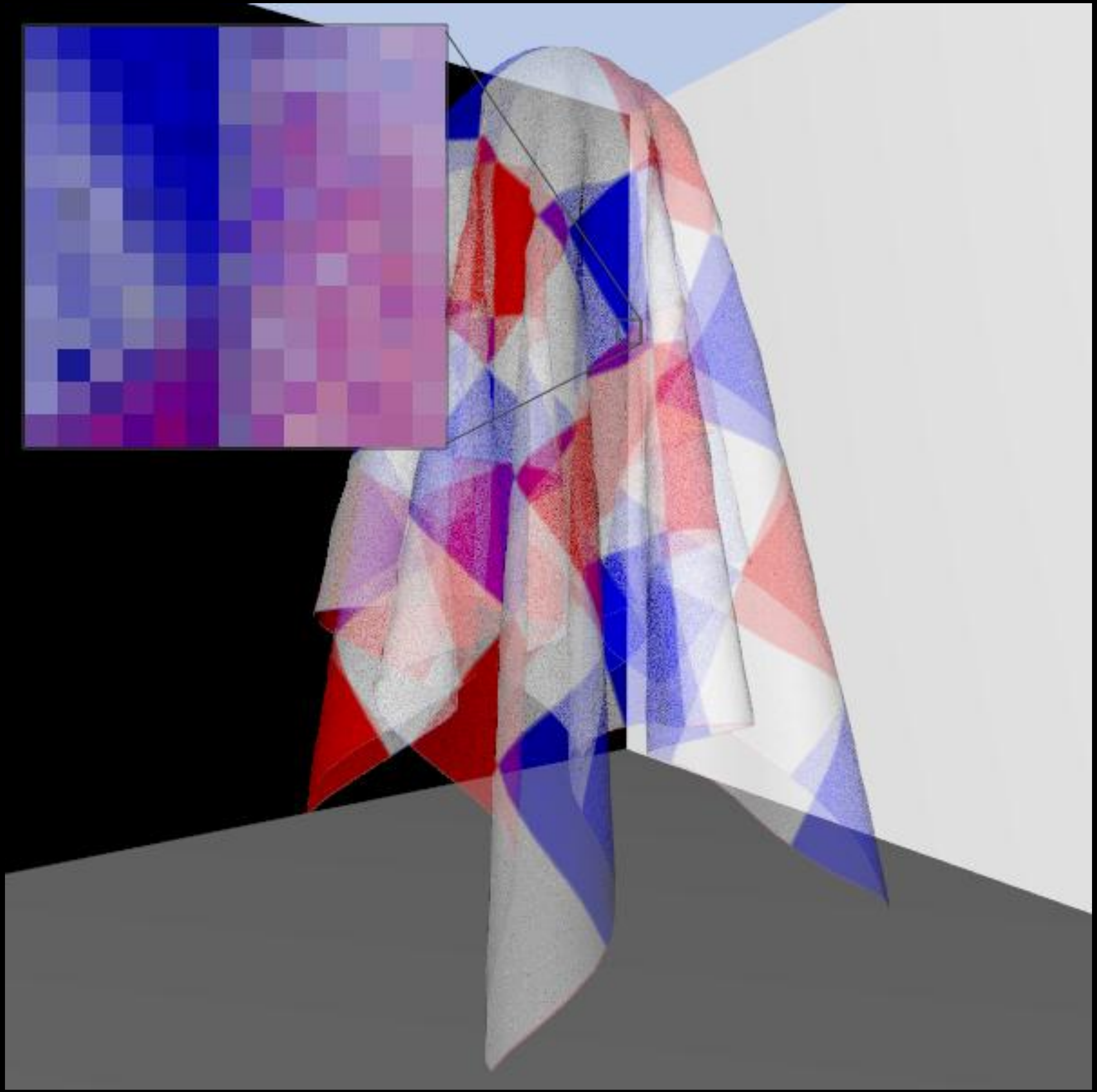
8 spp



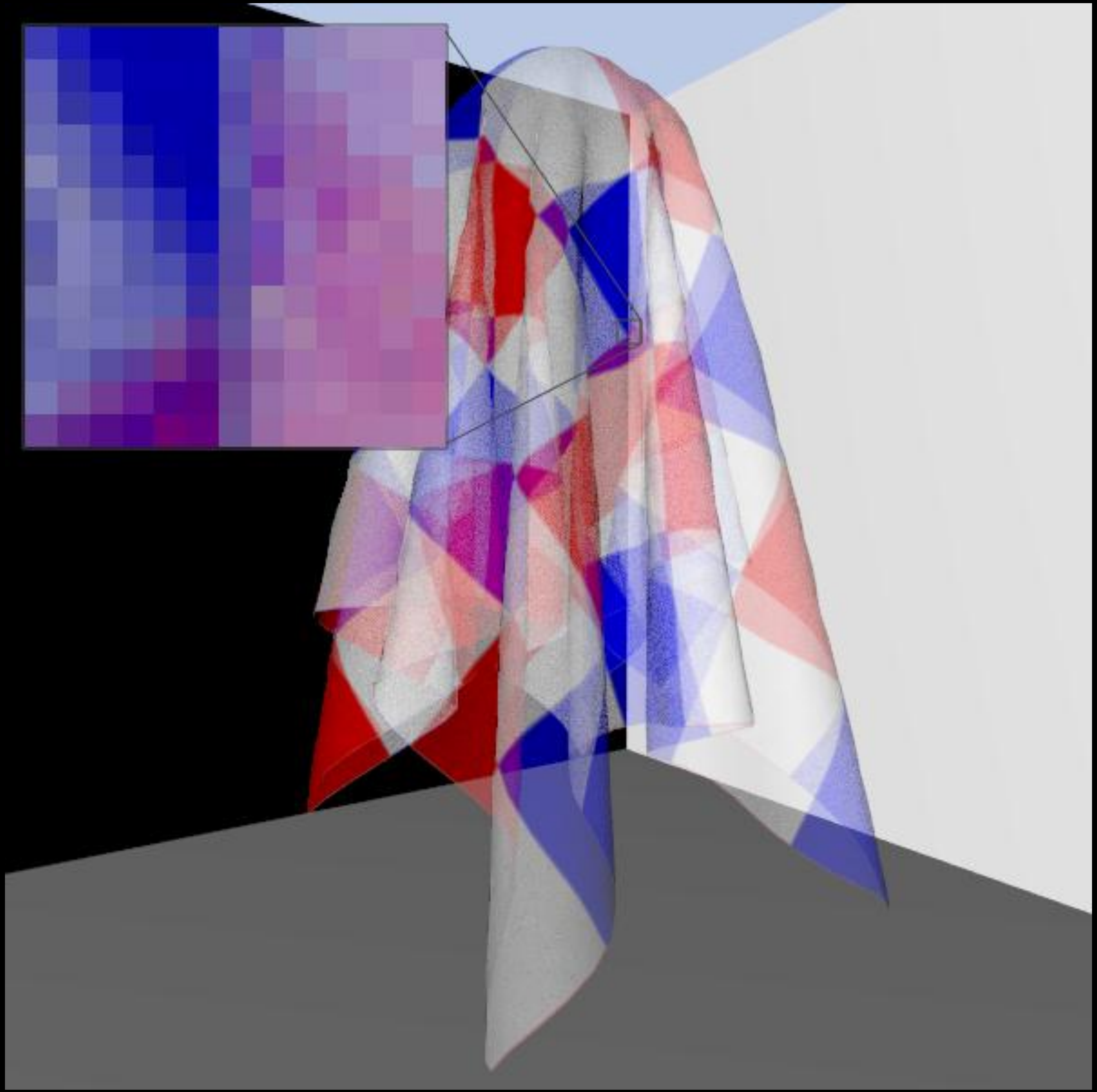
16 spp

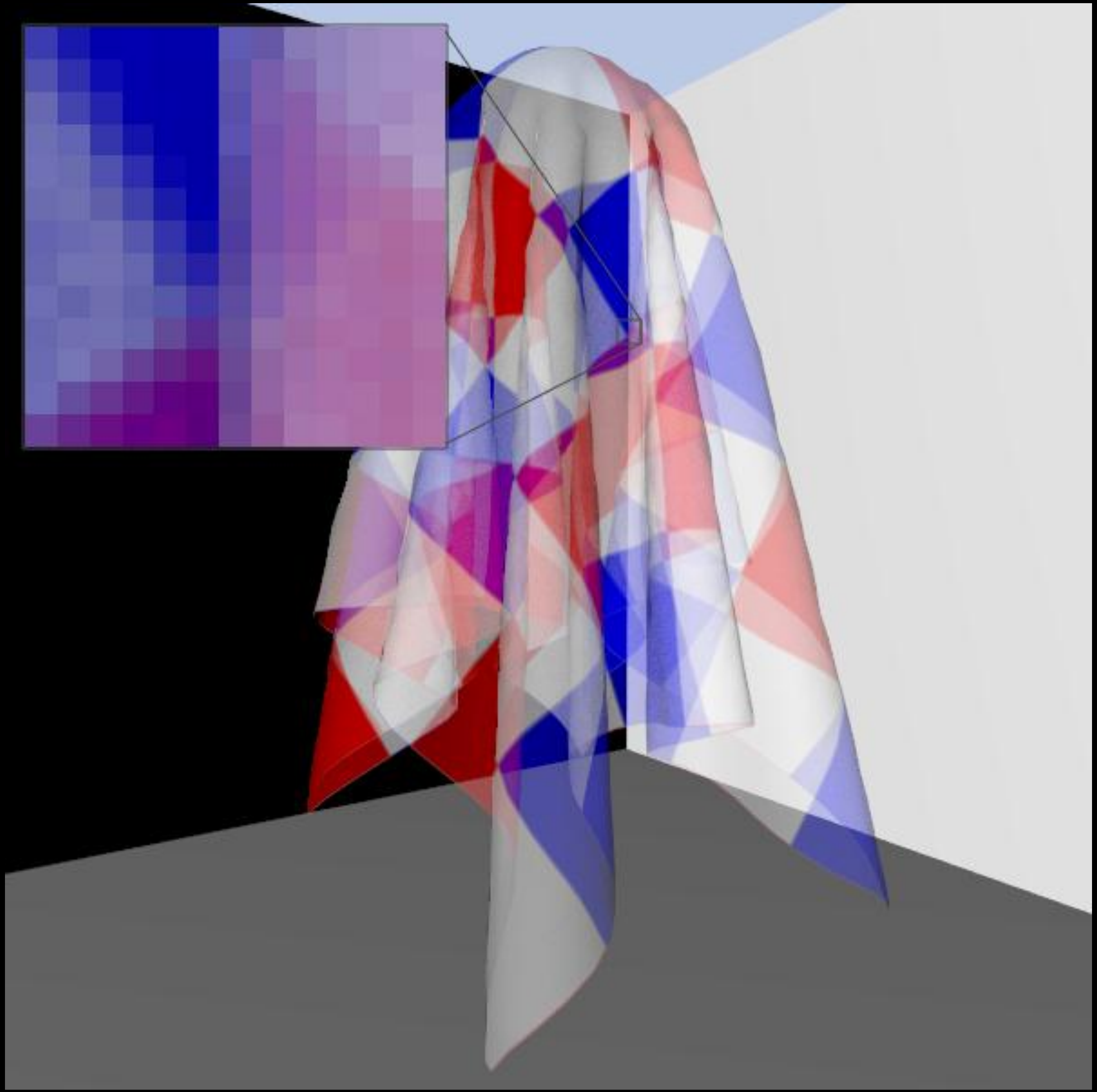


32 spp



64 spp





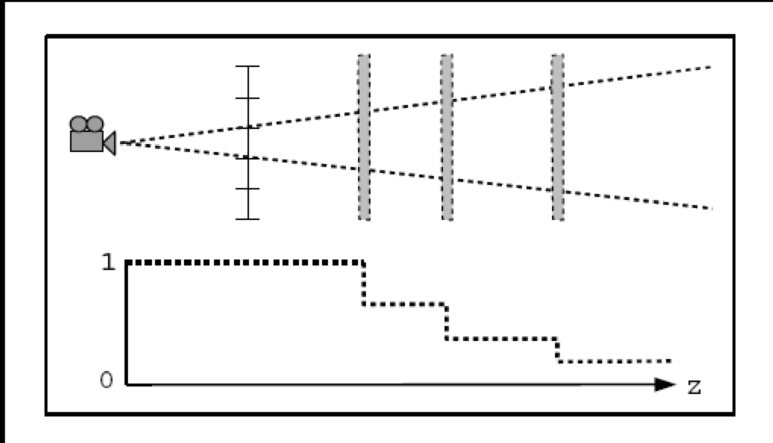
512 spp

# Stochastic Shadow Map

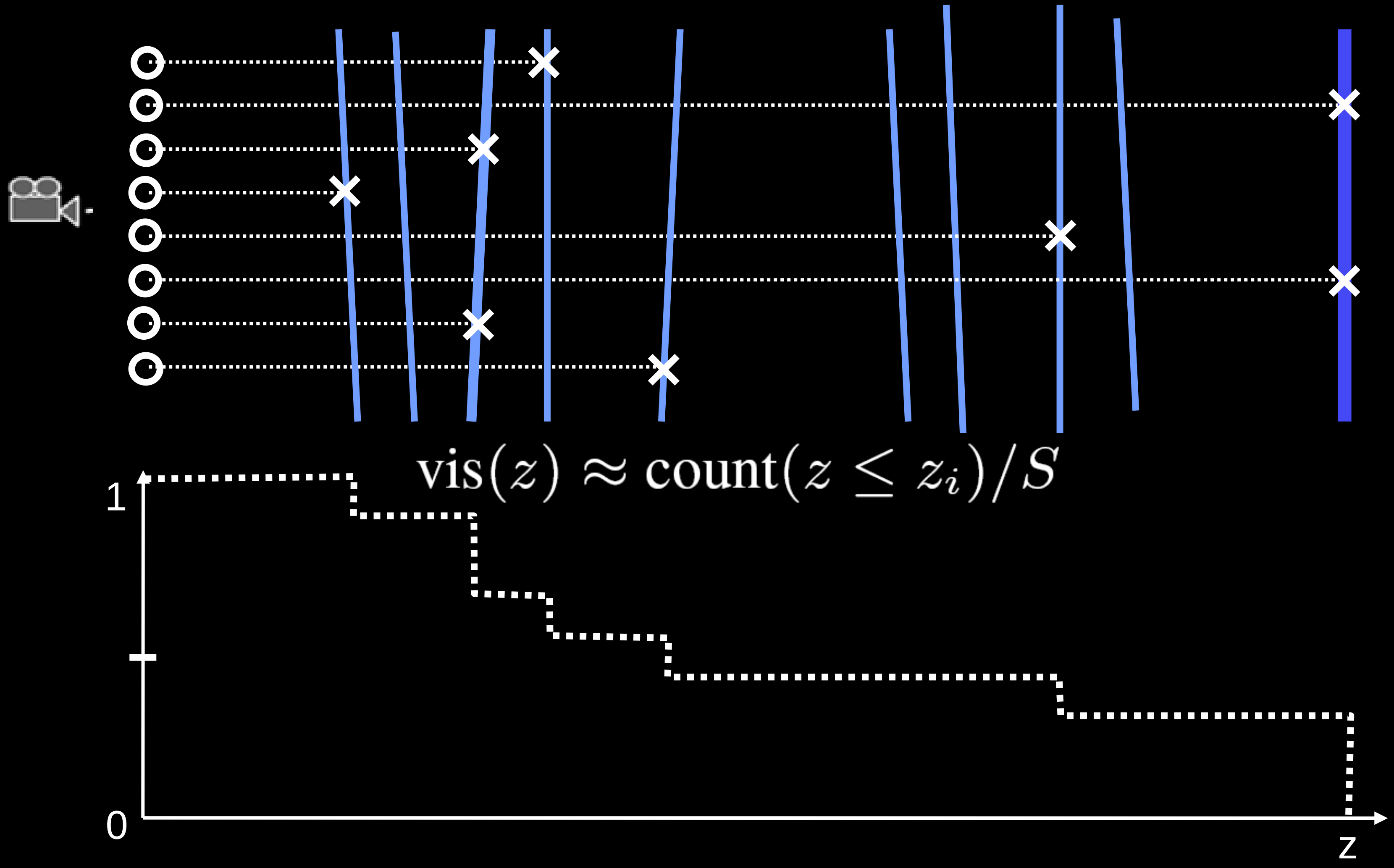
- Run Stochastic Transparency, rendering only z
- Optional:  Render with MSAA hardware

→ Each map pixel contains S depth values

- Models the deep shadow function vis(z) =
  How much light gets from camera to depth z



# Stochastic Shadow Map




$$\text{vis}(z) \approx \text{count}(z \leq z_i)/S$$

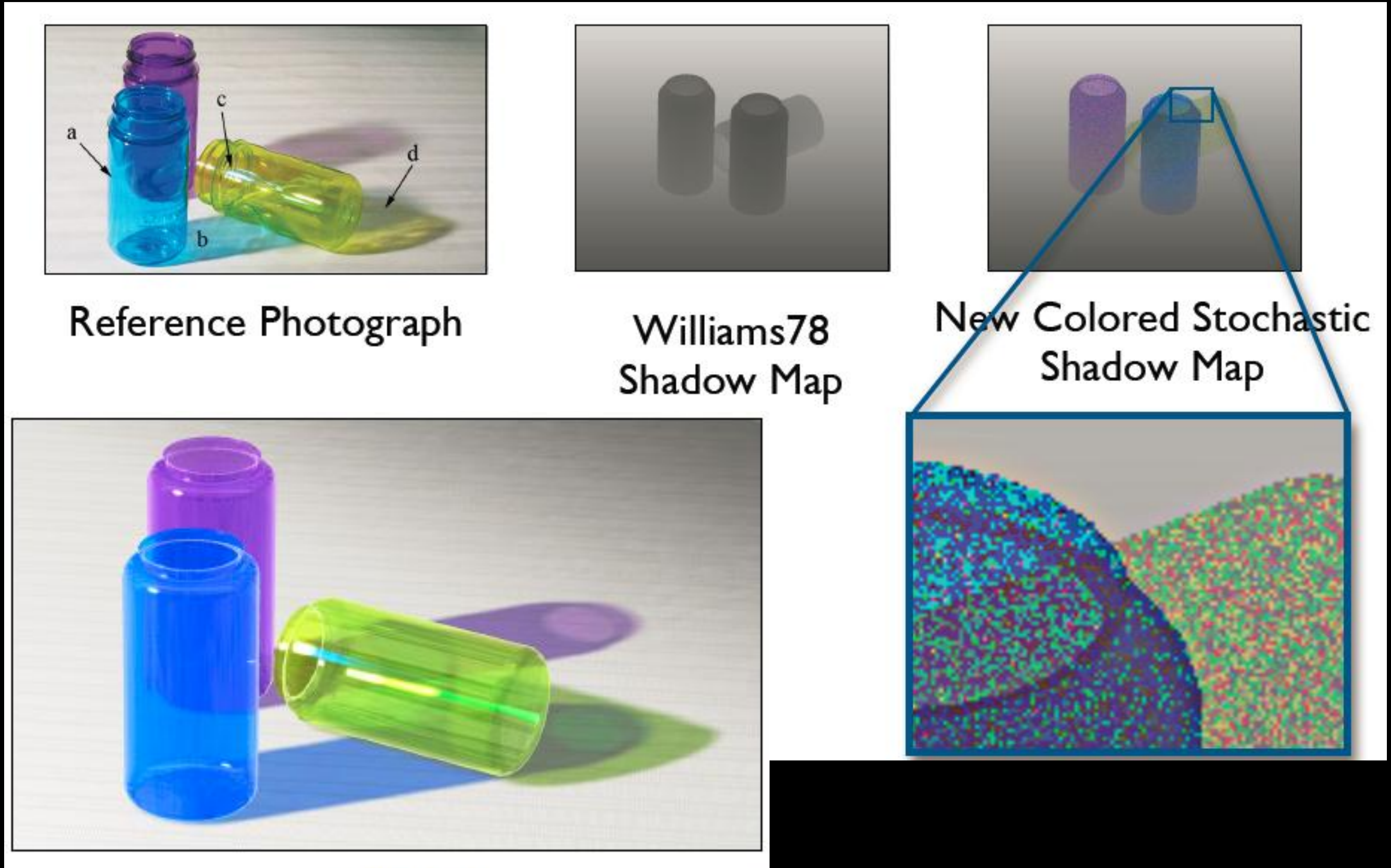
# Stochastic Shadow Map

- Every pixel looks the same
  - S z-values
  - z's not sorted

- Look-up is just PCF
  - S comparisons per shadow-map pixel

- Color, better reconstruction filter in [CSSM paper]

# Colored Stochastic Shadow Maps



# Depth-based Stochastic Transparency

- With an extra pass, you can do a lot better
- Shadow map from camera POV
- Final color is (parallel) sum:

$$c \quad = \quad \sum \mathrm{vis}(z_i)\alpha_i c_i$$

  – vis(z) estimated using shadow map
- Very convenient on GPU:
  – For sum, compare fragment z to shadow map z’s
  – MSAA z-buffer comparison can do S compares at once


FPS: 14.25 (70.20 ms/frame)

# Stochastic Transparency

- Randomized, sub-pixel screen-door transparency
- Distribute samples over an invisible dimension of Swiss cheese
- Correct on average but noisy
- Streaming, fixed space, parallel, MSAA
- Turns transparent stuff into opaque stuff
- … Which can then be handled by opaque-only algorithms (including stochastic MB + DOF)

# Advanced Topics

- Stratified sampling
- Sample test efficiency
- Reconstruction

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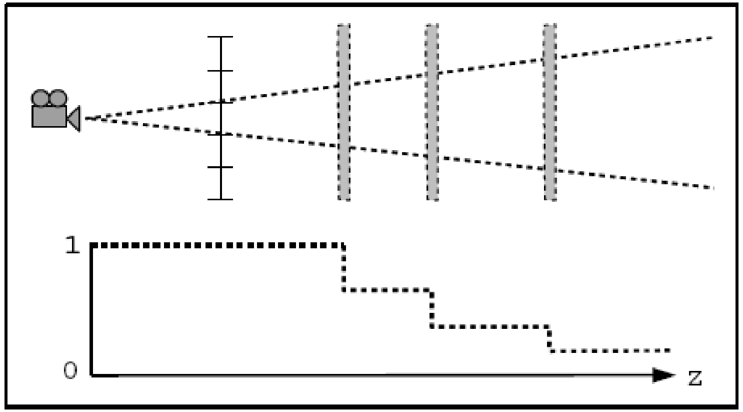
# Bibliography


- "Hardware-Accelerated Stochastic Rasterization on Conventional GPU Architectures," McGuire, Enderton, Shirley & Luebke, HPG 2010
- "Stochastic Transparency," Enderton, Sintorn, Shirley & Luebke, TVCG 2011
- "Colored Stochastic Shadow Maps," McGuire & Enderton, I3D 2011
- "Stratified Sampling for Stochastic Transparency," Laine & Karras, EGSR 2011
- "Clipless Dual-Space Bounds for Faster Stochastic Rasterization," Laine, Aila, Karras & Lehtinen, Siggraph 2011
- "A Local Image Reconstruction Algorithm for Stochastic Rendering," Shirley, Aila, Cohen, Enderton, Laine, Luebke & McGuire, I3D 2011
- "Temporal Light Field Reconstruction for Rendering Distribution Effects," Lehtinen, Aila, Chen, Laine & Durand, SIGGRAPH 2011

# Backup

# Deep Shadow Maps



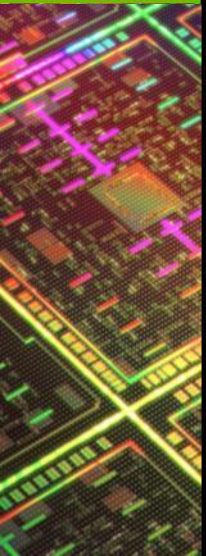
*(a) A stack of semitransparent objects*

"Deep Shadow Maps", Lokovic and Leach (Siggraph 2000)

- How much light gets from camera to depth z =

$$\mathrm{vis}(z) = \prod_{z_i < z} (1 - \alpha_i)$$

= How much light gets from depth z to camera



# Transparency without sorting

Porter-Duff:

$$c = \alpha_1 c_1 + (1 - \alpha_1)(\alpha_2 c_2 + (1 - \alpha_2)\alpha_3 c_3)$$

Rearrange to find the contribution of each fragment:

$$c = \sum \mathrm{vis}(z_i)\alpha_i c_i$$

using our friend

$$\mathrm{vis}(z) = \prod_{z_i < z} (1 - \alpha_i)$$

The sum is order independent, given vis(z).

Approximate vis(z) → approximate sum.