Shiny Pixels and Beyond: Real-Time Raytracing at SEED

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Electronic Arts

SEED

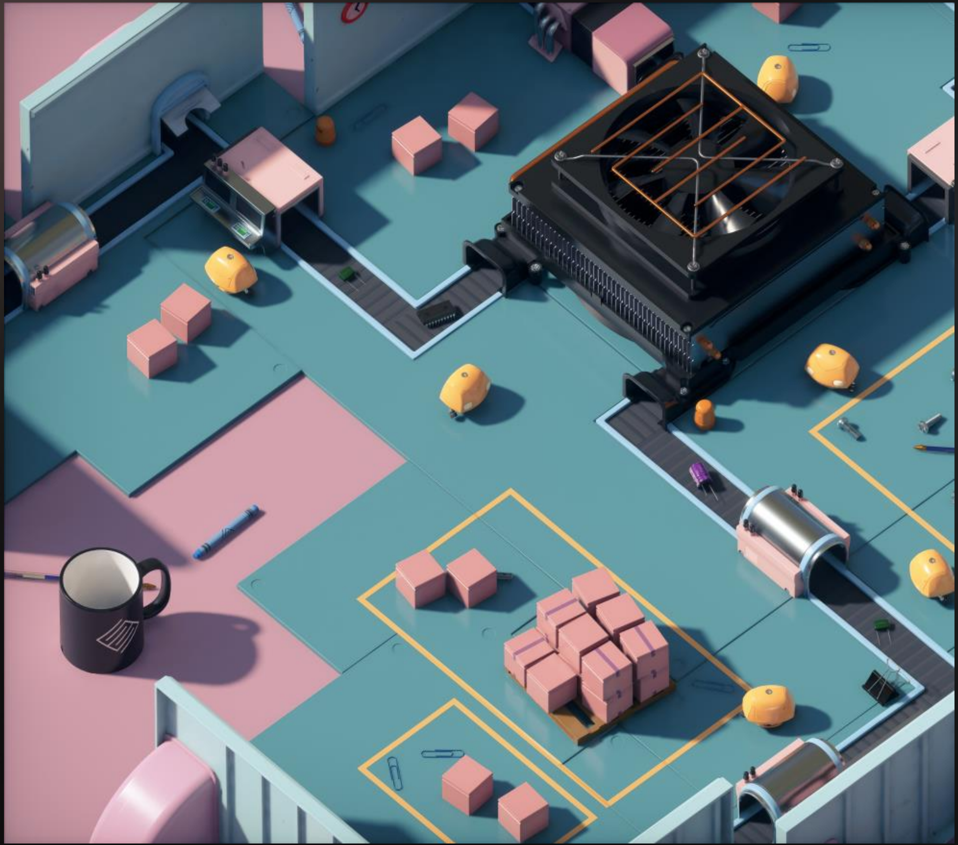
Watch the trailer here:

https://www.youtube.com/watch?v=LXo0WdIELJk

"PICA PICA"

Exploratory mini-game & world

- For our self-learning AI agents to play, not for humans ☺
- Uses SEED's ***Halcyon*** R&D engine
- Goals
  - Explore hybrid raytracing with DXR
  - Clean and consistent visuals
  - Procedurally-generated worlds
  - No precomputation



Why raytracing?

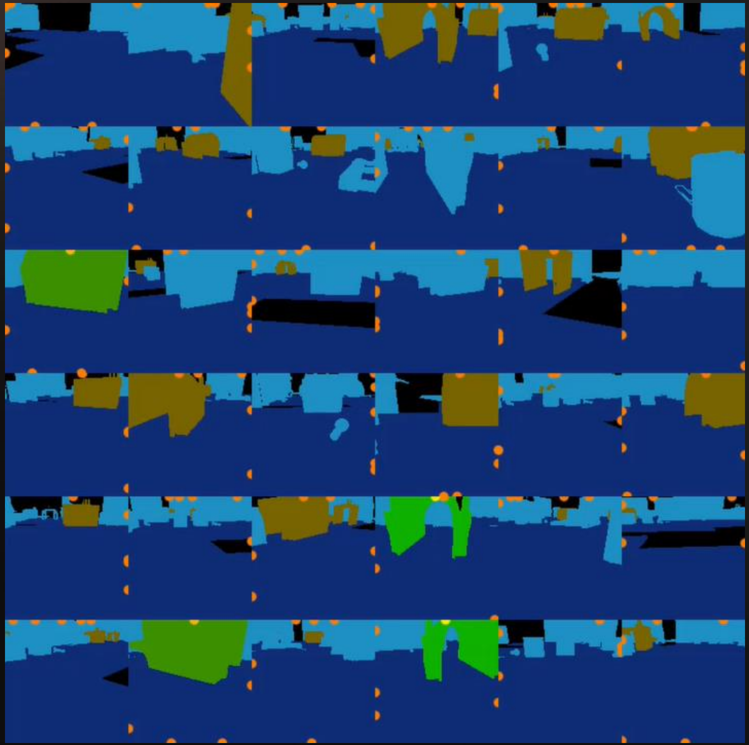
- Flexible new tool in the toolbox
- Solve sparse & incoherent problems
- Unified API + performance (DXR + RTX)
- Simple high quality - easy ground truth

Self-Learning AI

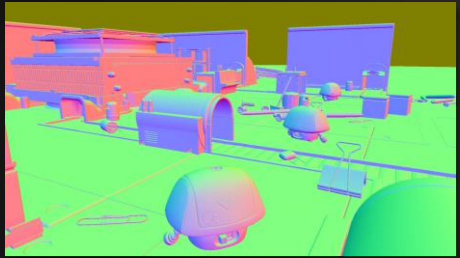
Using deep reinforcement learning

- *"Imitation Learning with Concurrent Actions in 3D Games" [Harmer 2018]*
- 36 semantic views - 1550 fps
- Training with TensorFlow
- Future: Inference with *WinML*

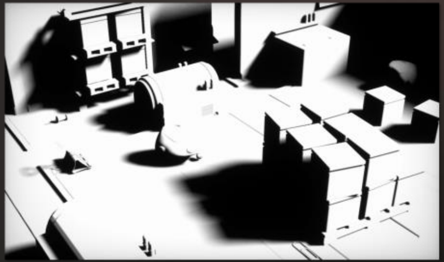
See *"Deep Learning - Beyond the Hype"* tomorrow



Hybrid Rendering Pipeline



Deferred shading (raster)



Direct shadows (raytrace or raster)

Direct lighting (compute)

Reflections (raytrace)

Global Illumination (raytrace)

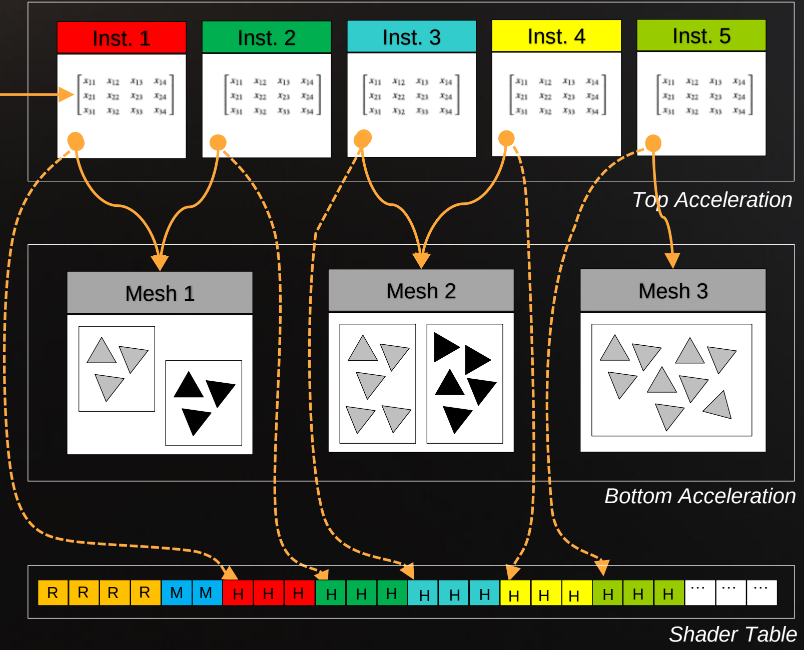
Ambient occlusion (raytrace or compute)

Transparency & Translucency (raytrace)

Post processing (compute)

XII ?

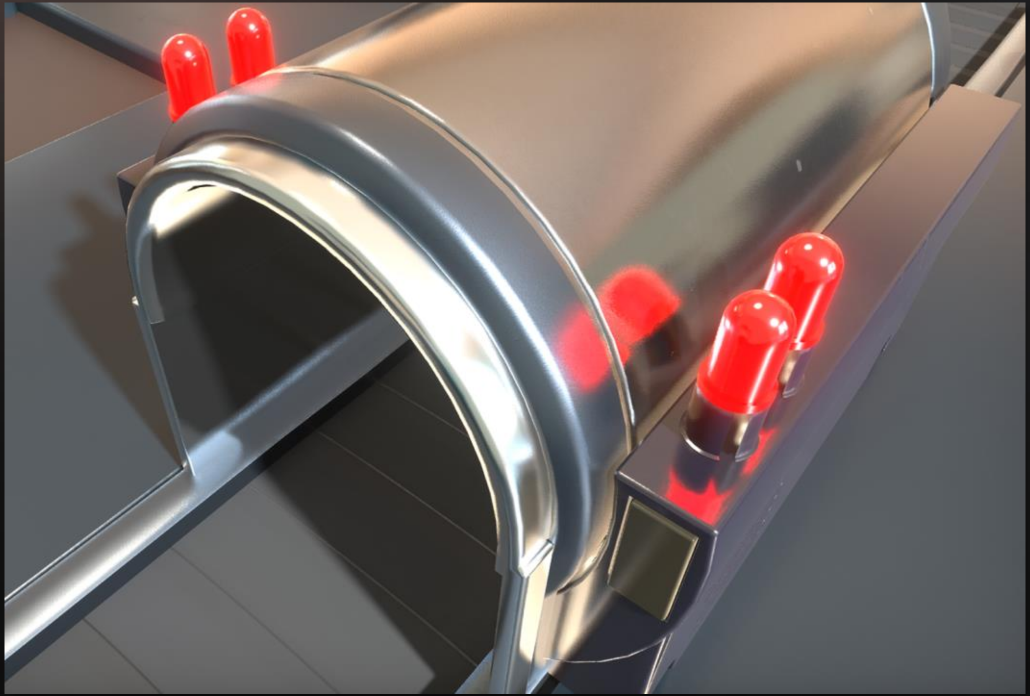
- **Spawn a Mesh?**
  - DXR: build its bottom acceleration structure
  - Multiple geometries for multiple materials
    - Triangles, AABBs, custom
  - Mesh instances specified in top acceleration
- **Move a Mesh?**
  - Update the instance's position/orientation in the top acceleration
- **Spawn [some] Rays?**
  - Multiple Hit and Miss shaders possible



Raytraced Reflections

- Rasterize primary visibility
- Launch rays from the G-Buffer
- Raytrace at half resolution
- Reconstruct at full resolution
  - Spatiotemporal filtering

- Works on both flat and curved surfaces



Raytraced Reflections

Reflection Rays

Let’s launch some reflection rays:

1. Select one of the (2x2) pixels to trace
2. Reconstruct position and vectors
3. Initialize Halton & random number seq.
4. Initialize the payload
5. Prepare a new ray
6. Trace
7. Gather results from ray payload
    - Reflection Color, Direction, HitT, 1/pdf

```
RaytracingAccelerationStructure g_rtScene : register(t0, space0);
ConstantBuffer<RaytracingConstants> g_rt  : register(b0, space0);
RWTexture2D<float4> g_tex0                : register(u0, space0);
RWTexture2D<float4> g_tex1                : register(u1, space0);

[shader("raygeneration")]
void reflectionRaygen()
{
    uint2 px = DispatchRaysIndex();
    uint2 launchDim = DispatchRaysDimensions();

1   // Select one of the four full-res pixels to trace from
    const uint2 noiseCoord = (px / 2 + (g_rt.frameIndex / 2) * uint2(3, 7)) & 31;
    const uint subpixelIdx = g_blueNoise[noiseCoord.x + noiseCoord.y * 32] + g_rt.frameIndex;
    const uint2 gbufferPx = px * 2 + uint2(subpixelIdx & 1, (subpixelIdx >> 1) & 1);

2   // Reconstruct position and the various vectors
    const Gbuffer gbuffer = loadGbuffer(gbufferPx, g_gbuffer);
    const float depth = g_depth[gbufferPx];
    float2 uvPos = (gbufferPx + 0.5f) / g_rt.viewDimensions.xy;
    float4 csPos = float4(uvToCs(uvPos), depth, 1.0f);
    float4 wsPos = mul(g_rt.clipToWorld, csPos);
    const float3 P = wsPos.xyz / wsPos.w;
    const float3 E = g_rt.eyeWorldPosition;
    const float3 V = normalize(E - position);
    const float3 N = gbuffer.normal;

3   // Initialize the Halton sequence for each ray and random number generator to rotate the sequence
    Halton halton = haltonInit(px, g_rt.frameIndex, ...);
    uint seed = randomInit(px);

4   // Initialize a new payload
    Payload payload = payloadInit(seed, halton);

5   // Initialize a new ray
    RayDesc ray;
    ray.Origin = position + V * max(1, length(frame.position)) * 1e-4f;    // epsilon
    ray.Direction = sampleDirectionFromBrdf(gbuffer, V, N, halton, seed); // stochastic BRDF
    ray.TMin = 0;
    ray.TMax = 1000; // perf: ray stops at 1000 meters

6   // Launch the ray
    TraceRay(g_rtScene, RAY_FLAG_CULL_FRONT_FACING_TRIANGLES, RaytracingInstanceMaskAll,
             HitType_Primary, SbtRecordStride, MissType_Primary,
             ray, hitData);

7   g_tex0[px] = float4(hitData.lighting.rgb, depth);
    g_tex1[px] = float4(ray.Direction * hitData.hitT, 1.0f / brdfSample.pdf);
}
```

Reflections Raytracing HLSL Pseudo-Code

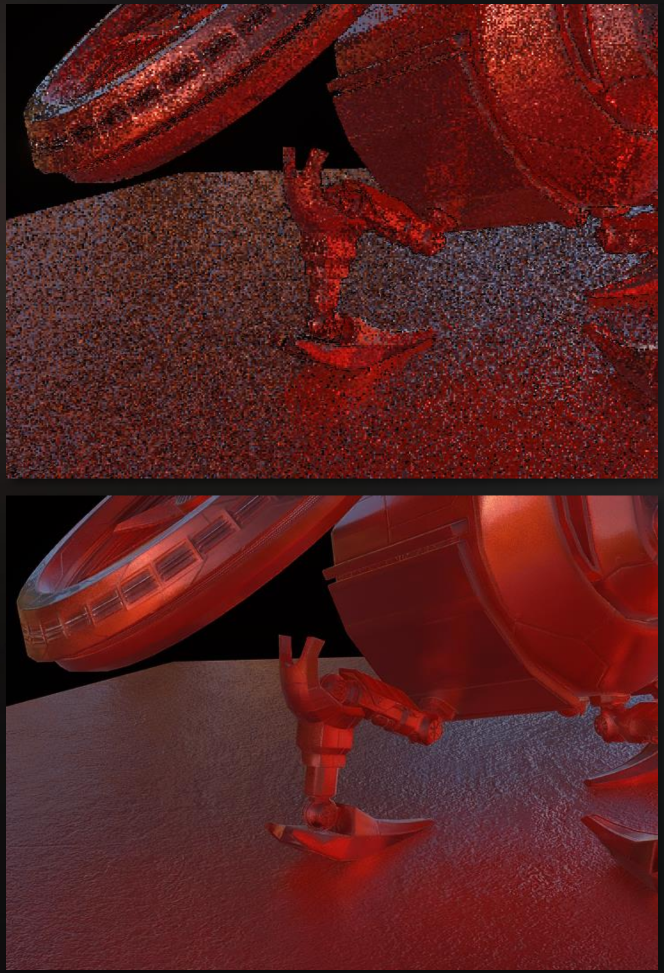
Reflection Filtering

Inspired by *Stochastic Screen-Space Reflections* [Stachowiak 2015]

- For every full-res pixel, sample 16 pixels in half-res ray results
  - Blue Noise offsets, decorrelated every 2x2 pixels

- Build color bounding box of ray-hit results
  - Clamp temporal history to bounding box

- Followed by a variance-driven bilateral filter
  - Helps with rough reflections



Unfiltered (Top) and Filtered (Bottom) Results

Screen-Space Reflections

G-Buffer Raytraced

Path Tracing Reference

Screen-Space Reflections

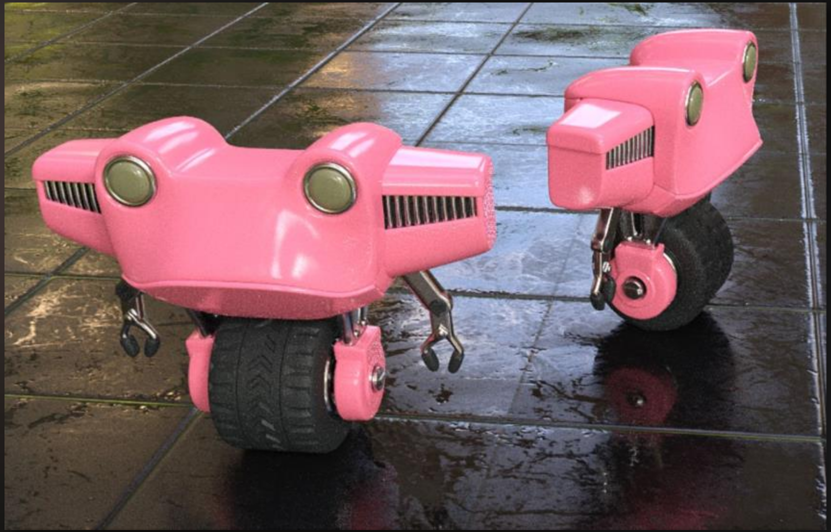
G-Buffer Raytraced

Path Tracing Reference

Materials

Combine multiple microfacet surface layers into a single, unified & expressive BRDF

- Inspired by *Arbitrarily Layered Micro-Facet Surfaces [Weidlich 2007]*
- Unified for all lighting & rendering modes
  - Raster, path-traced reference, and hybrid
- Energy conserving & Fresnel
- Rapidly experiment with different looks
  - Bake down number of layers for production



Objects with Multi-Layered Materials

Materials

Standard

- Aluminum
- Brushed Aluminum
- Coated Carbon
- Copper
- Silver Satin
- Shiny / Mat Plastic
- Dark Rubber

Exotics*

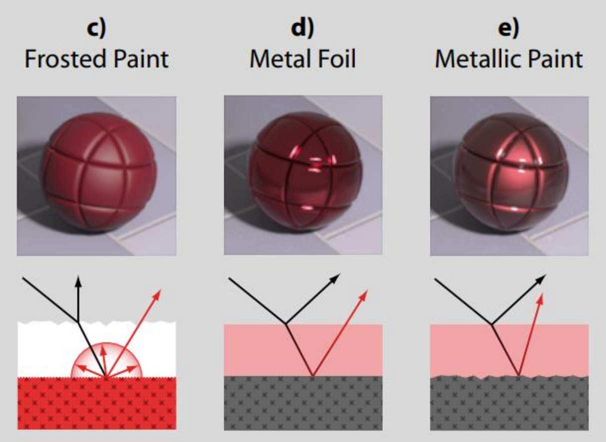
- Glass
- Rough Glass
- Jade / Marble

** Integrated in BRDF, but built separately*

Multi-Layered Materials

BRDF Sampling

- General idea: Launch one ray for the whole stack
  - Stochastically select a layer & sample
  - When evaluating material, estimate visibility vs other layers
    - Some energy is reflected, some is refracted:
      - Microfacet: Fresnel (refracted = 1-Fresnel)
      - Diffuse: reflected fraction equal to albedo, remaining light absorbed; no refraction
  - Sample BSDF of selected layer
    - Attenuated by layer(s) on top
- Result is temporally filtered
  - A single value for many layers requires clever filtering



Multi-Layered Materials [Weidlich 2007]

Transparency & Translucency

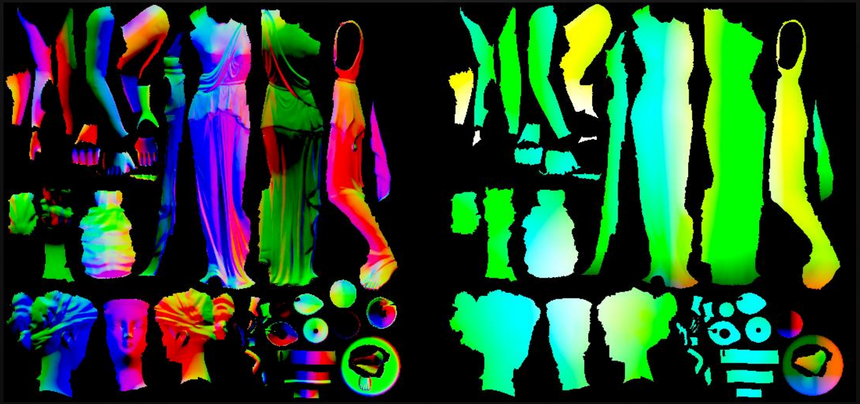
Raytracing allows to unify reflections and refractions

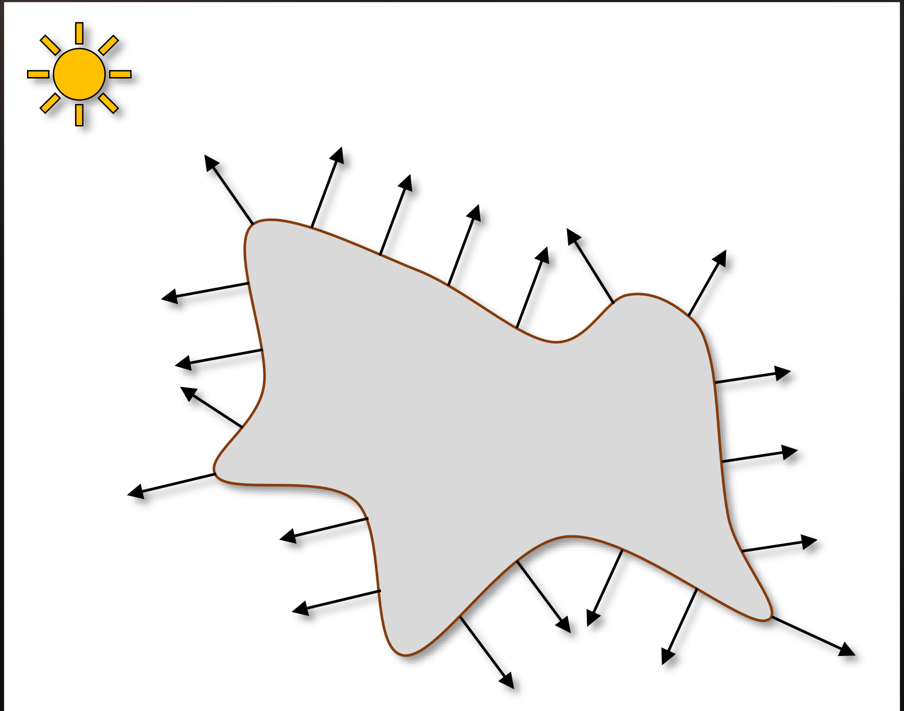
- **Glass**
  - Order-independent (OIT)
  - Handles multiple IOR transitions
- **Translucency**
  - Inspired from *Translucency in Frostbite* [Barré-Brisebois 2011]
  - Inner structure scattering based on lighting traveling inside the medium
- Performance: we do it in texture-space

Glass and Translucency

Translucency Breakdown

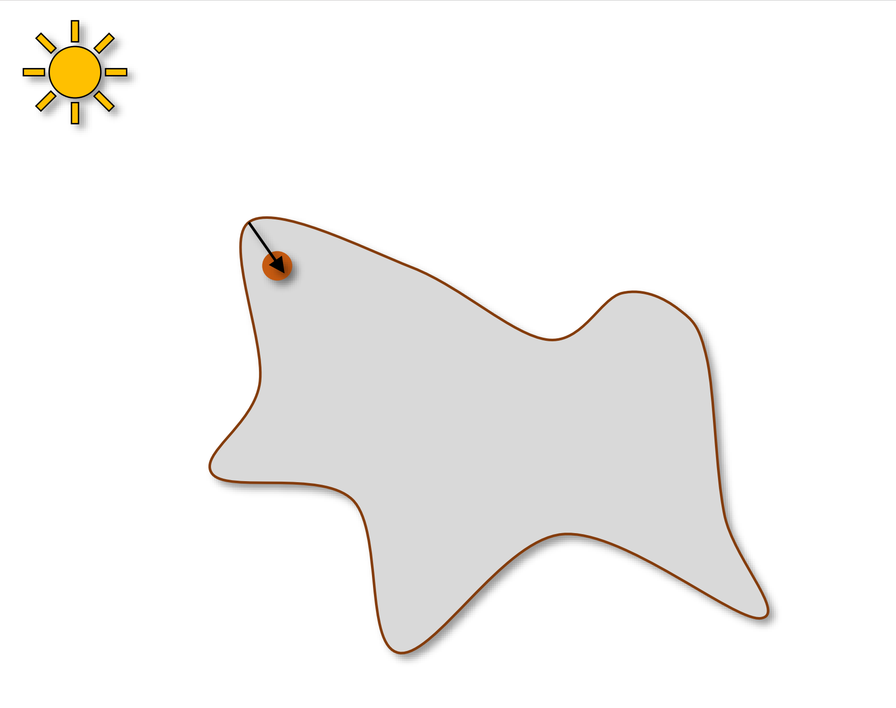
- For every valid position & normal





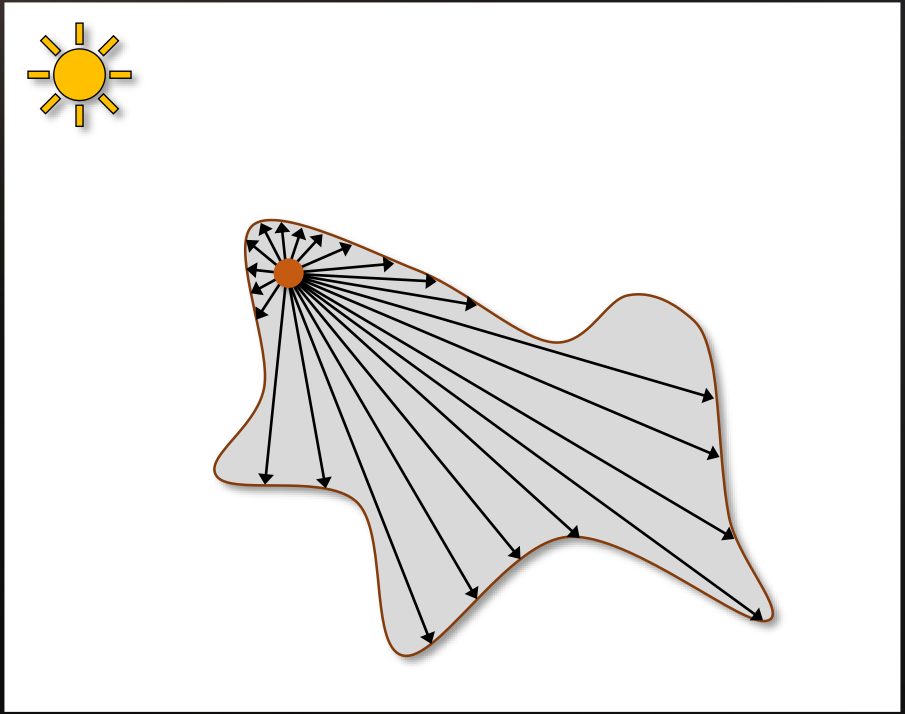
Translucency Breakdown

- For every valid position & normal
- Flip normal and push (ray) inside



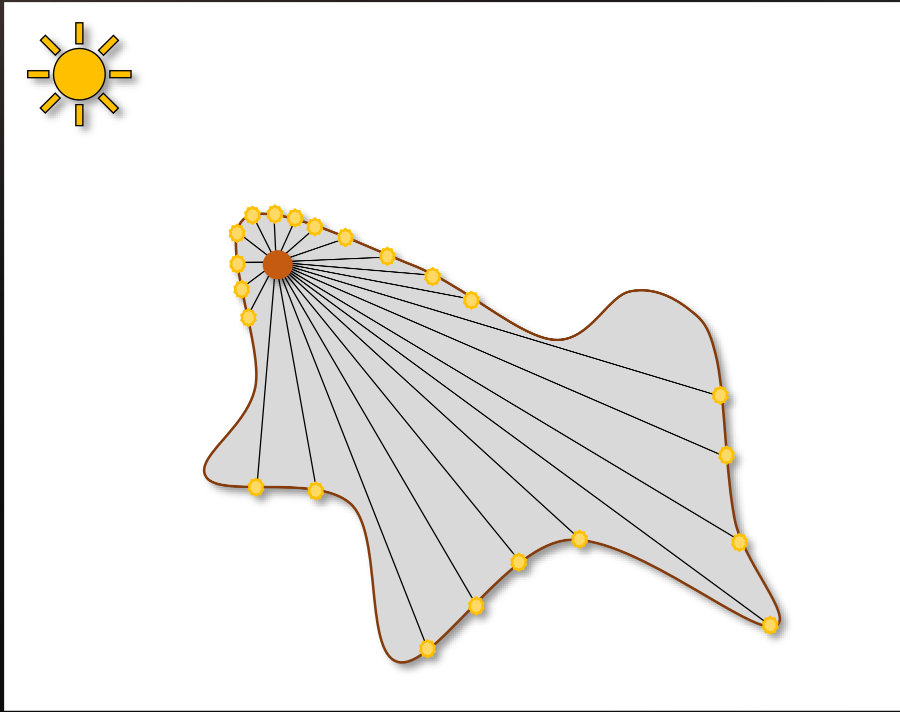
Translucency Breakdown

- For every valid position & normal
- Flip normal and push (ray) inside
- Launch rays in uniform sphere dist.
  - Alternatively, front + back cosine lobes
  - Perf: only do n-rays per frame



Translucency Breakdown

- For every valid position & normal
- Flip normal and push (ray) inside
- Launch rays in uniform sphere dist.
    - Alternatively, front + back cosine lobes
    - Perf: only do n-rays per frame
- Compute lighting at intersection
    - Sample previous translucency result



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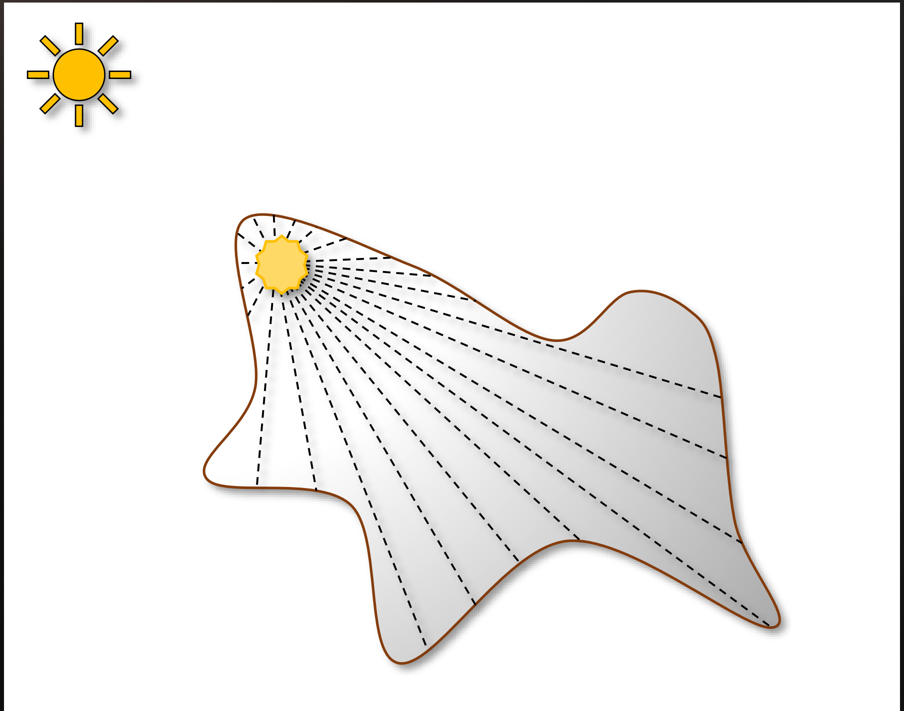
  - Sample previous translucency result
- Gather
  - Modulate with Beer-Lambert or Henyey-Greenstein phase function



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  - Alternatively, front + back cosine lobes
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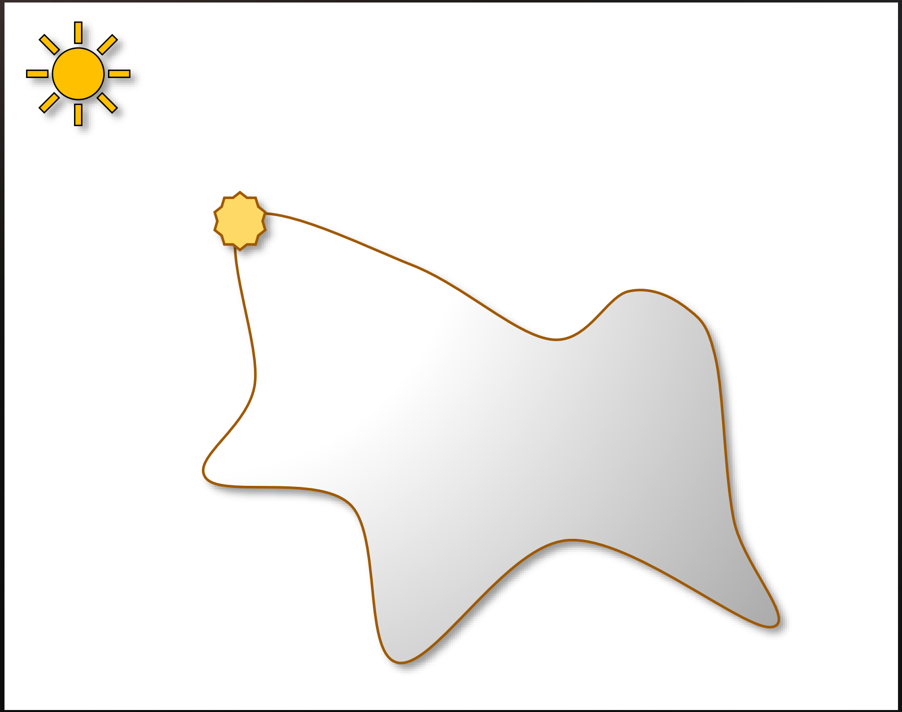
- Compute lighting at intersection
  - Sample previous translucency result
- Gather
  - Modulate with Beer-Lambert or Henyey-Greenstein phase function
- Store new BTDF value



Translucency Filtering

Result converges over a couple frames

- Denoised or temporally-accumulated
- Temporal: build an update heuristic
  - Exponential moving average can be OK
  - Game-specific threshold to update
  - Reactive enough for moving lights & objects
- Variance-adaptive mean estimation

Translucency Shadowing

Raytracing allows for globally shadowed translucency

- Global phenomena
  - Integration via feedback
  - Objects occlude each other
- Overall more grounded and visually-convincing translucency

Direct Lighting

Self-Shadowed Translucency

Transparency

Similar approach is used for glass

- Launch ray using view’s origin and direction
- Refract based on medium's index-of-refraction (IOR)
  - Snell’s law: *refract(ray, N, iorInput / iorOutput)*
  - DXR: HitKind() to handle IOR transitions (Air ⇔ Glass)
- Trace a ray in the scene & sample lighting
- Tint the result by glass color + chromatic aberration

Transparency

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- Tint the result by glass color + chromatic aberration

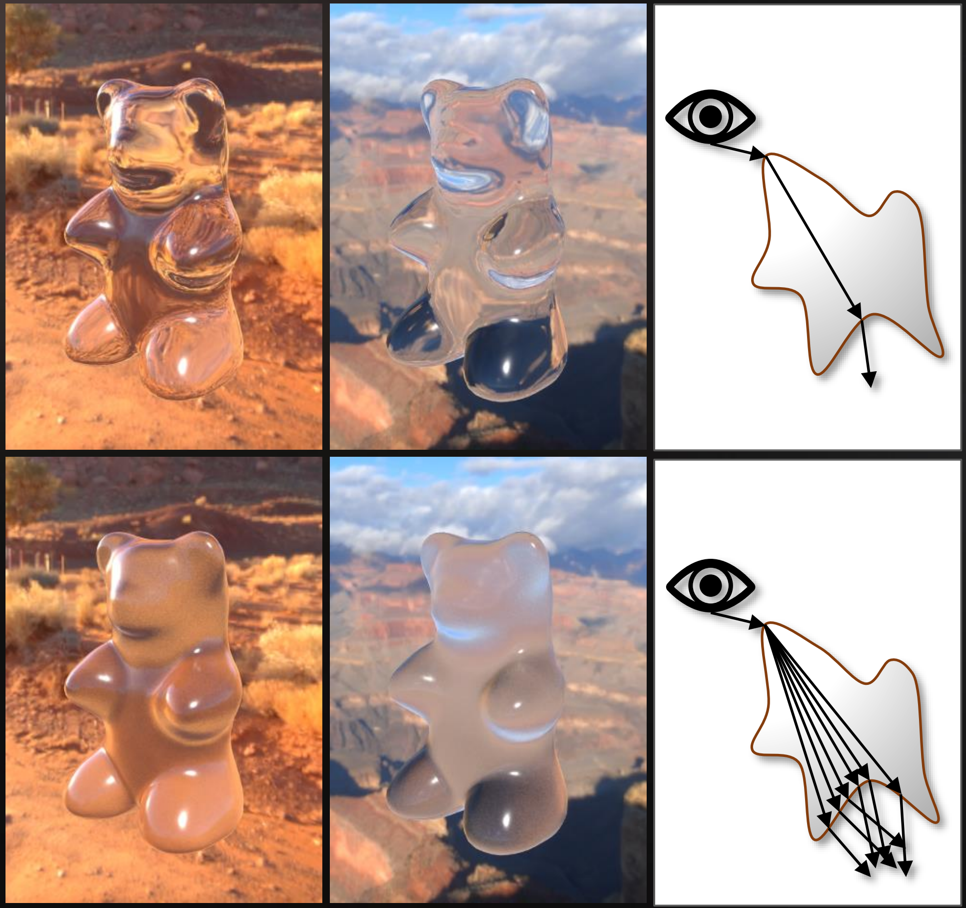
- Pen: we don’t handle transparent shadows yet

Transparency

Works for clear and rough glass

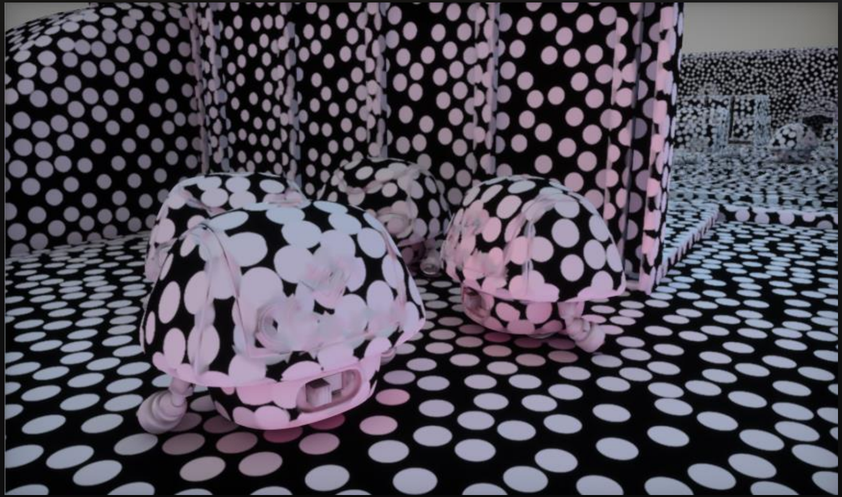
- Clear
  - No filtering required
- Rough / Blurry
  - Open cone angle with *Uniform Cone Sampling* [PBRT]
  - Wider cone → more samples
  - Or temporal filtering

- Tint with phase function and more complex BTDF



Global Illumination

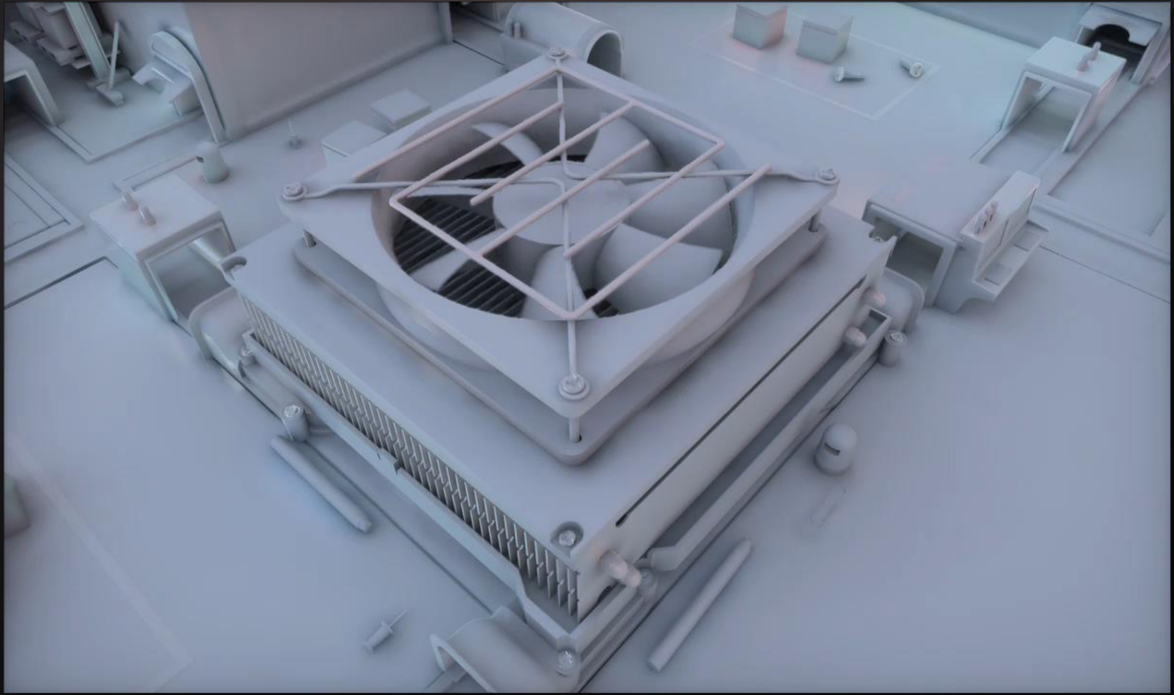
- We want a technique that:
  - Doesn’t require any precomputation
  - Doesn’t require parametrization (UVs, proxies)
  - Works for both static and dynamic scenes
  - Adaptive & refines itself on-the-fly
- Point-based / surfels for a dynamic world
  - Runtime Monte-Carlo integration



Surfel Placement

Surfel Spawning From Camera @ 1% speed

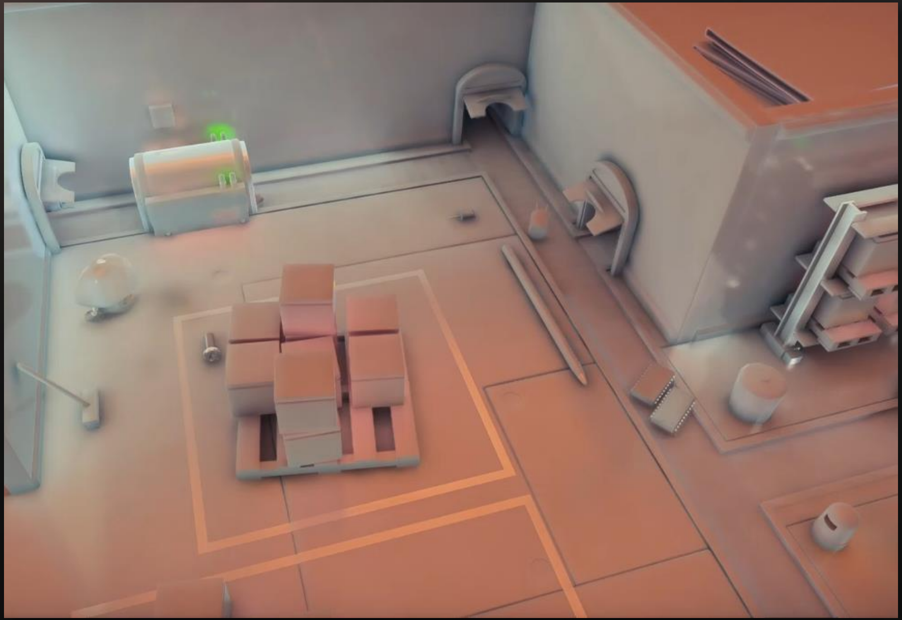
Surfel Placement



Skinned Surfels for Dynamic Objects

Sampling & Integration

- Compute surfel irradiance by PT
- When shooting rays/frame
  - Limit depth and number of paths
- Limiting depth != fewer bounces
  - Reuse results from previous frames
  - 1 = radiosity, ∞ = path tracing
- Variance-adaptive mean estimator
- Application (Binning, culling, half-res apply + upsample)



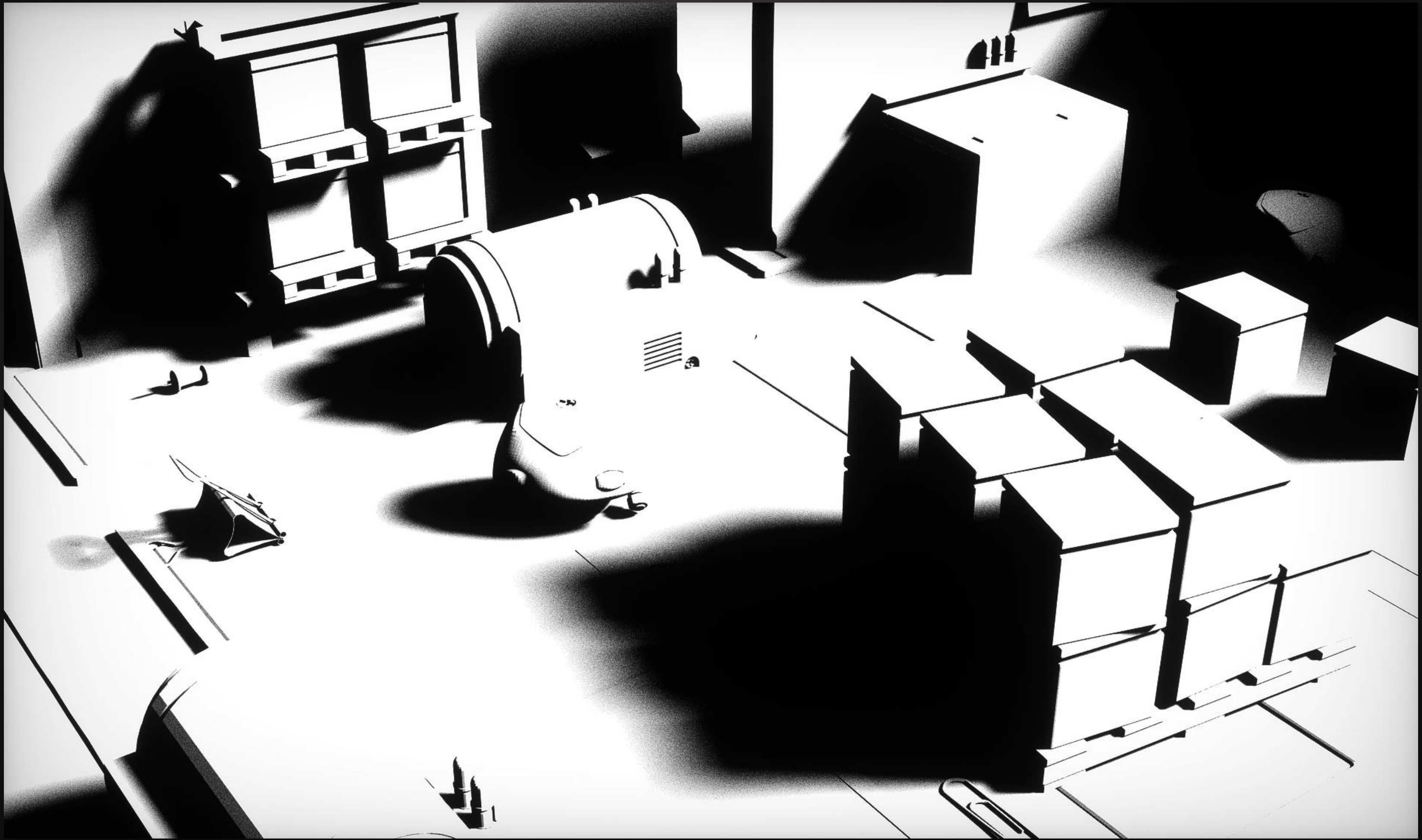
Progressive Integration (slowed down for clarity)

Shadows

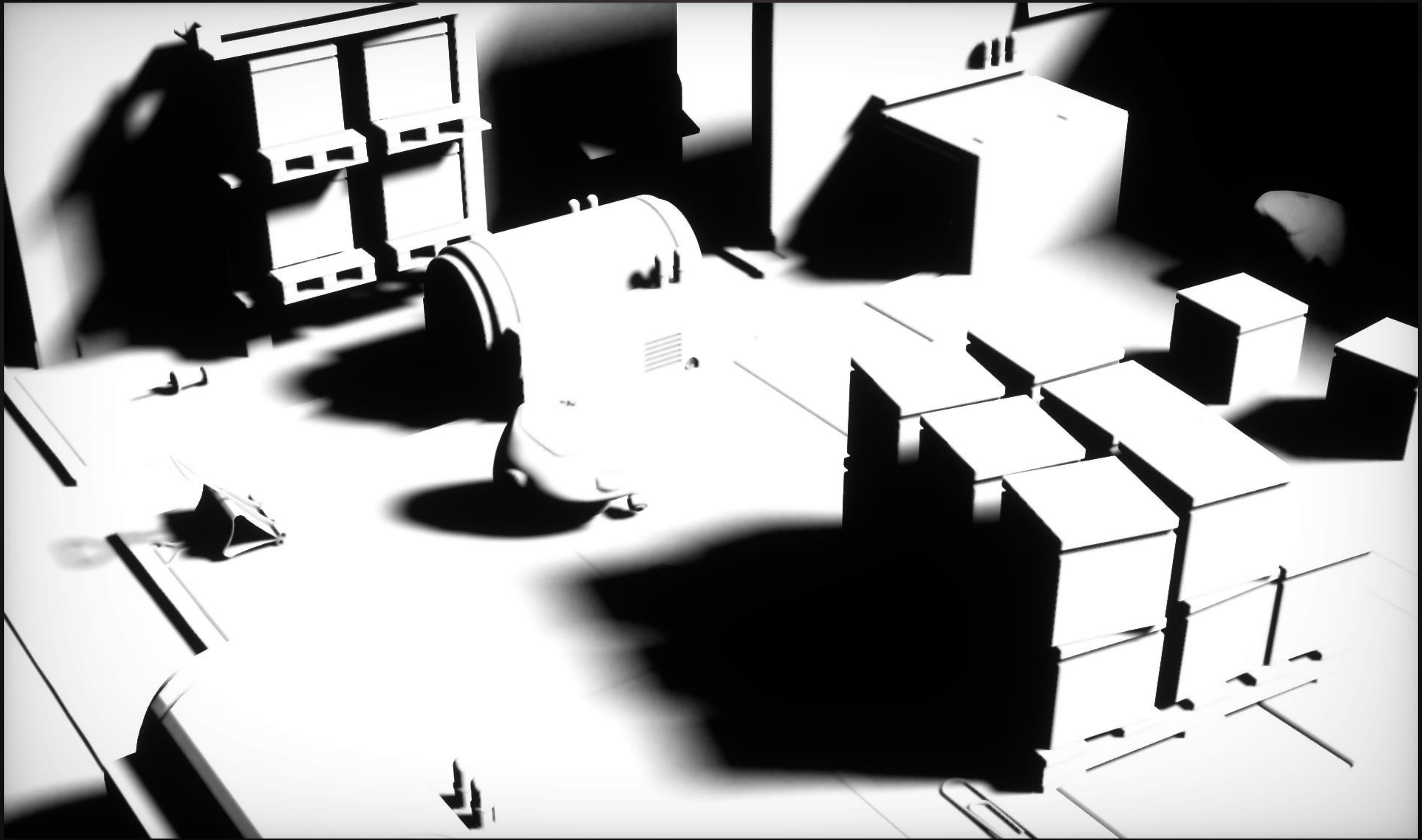
Accumulated and filtered in screen-space

- *Raygen*: Launch a ray towards light
  - Payload's ***miss*** flag set to true *(from Miss Shader)* if it doesn't hit geometry
  - Penumbra driven by *uniform cone sampling* [PBRT]
- Temporal Reprojection
  - Accumulates shadow and variance + TAA-style bounding box clamping
- Filter (SVGF-like) [Schied and NVIDIA 2017]
  - Multipass weighted spatial blur, driven by variance from temporal accumulation

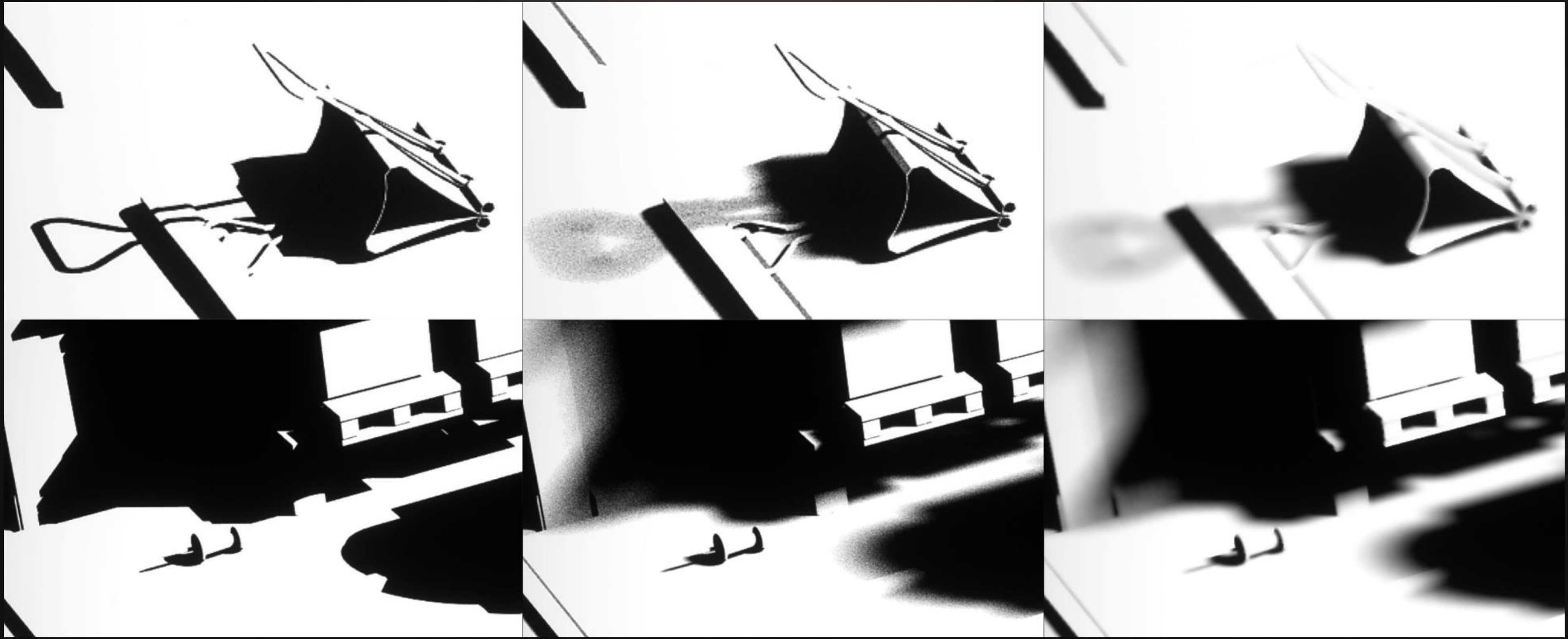
Hard Raytraced Shadows



Soft Raytraced Shadows (Unfiltered)



Soft Raytraced Shadows (Filtered)



Hard Raytraced Shadows | Soft Raytraced Shadows (Unfiltered) | Soft Raytraced Shadows (Filtered)

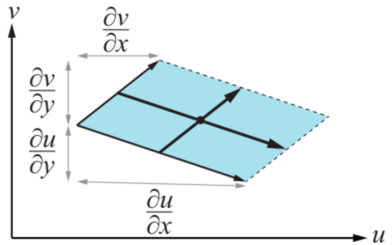
Texture Level-of-Detail

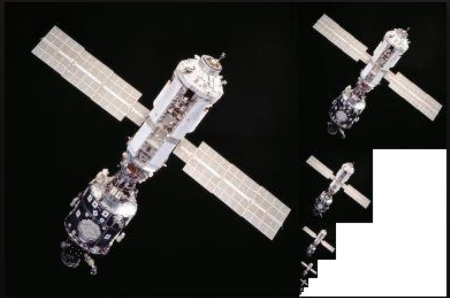
What about texture level of detail?

- Mipmapping [Williams 1983] is the standard method to avoid texture aliasing:

$$\lambda(x, y) = \log_2 \lceil \rho(x, y) \rceil$$

$$\rho(x, y) = \max\left\{ \sqrt{\left(\frac{\partial u}{\partial x}\right)^2 + \left(\frac{\partial v}{\partial x}\right)^2}, \sqrt{\left(\frac{\partial u}{\partial y}\right)^2 + \left(\frac{\partial v}{\partial y}\right)^2} \right\}$$





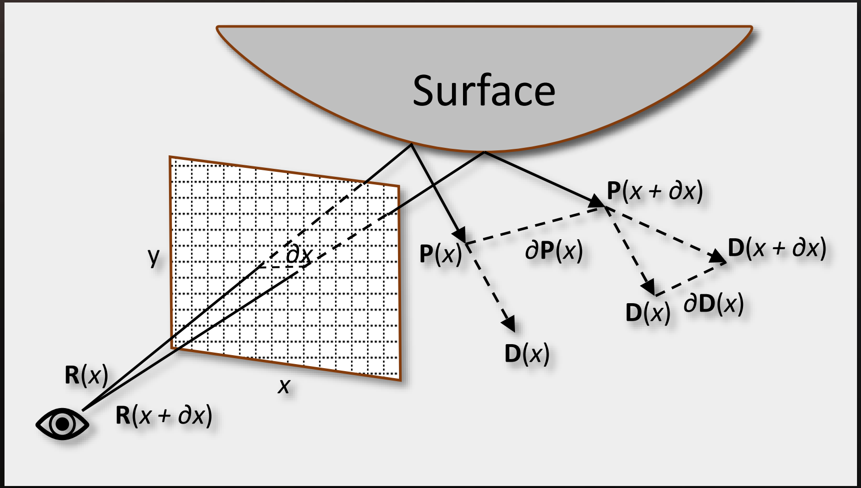
Left: level-of-detail (λ), partial derivatives and the parallelogram-approximated texture-space footprint of a pixel. Right: mipmap chain

- Screen-space pixel maps to approximately one texel in the mipmap hierarchy
- Supported by all GPUs for rasterization via shading quad and derivatives

Texture Level-of-Detail

No shading quads for ray tracing!

- Traditionaly: *Ray Differentials*
  - Estimates the footprint of a pixel by computing world-space derivatives of the ray with respect to the image plane
  - Have to differentiate (virtual offset) rays
  - Heavier payload (12 floats) for subsequent rays (can) affect performance. Optimize!



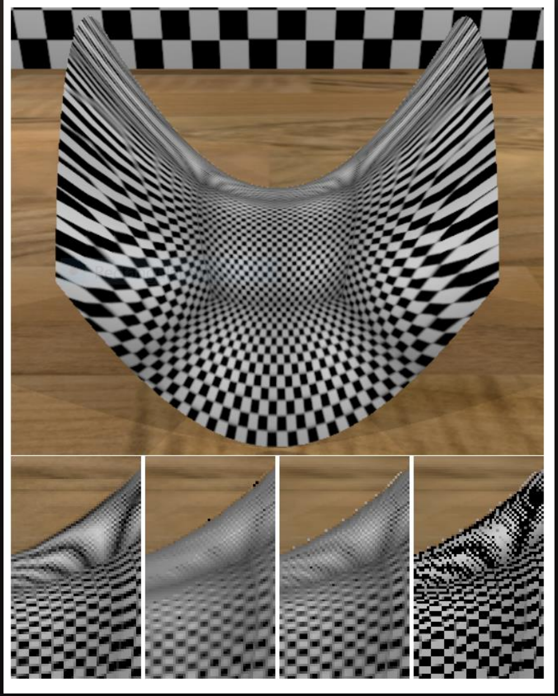
Ray Differentials [Igehy99]

- Alternative: always sample mip 0 with bilinear filtering (with extra samples)
  - Leads to aliasing and additional performance cost

Texture Level-of-Detail

Together with NVIDIA Research, we developed a texture LOD technique for raytracing:

- Heuristic based on ***triangle properties***, a ***curvature estimate***, ***distance***, and ***incident angle***
  - Similar quality to *ray differentials* with single trilinear lookup
  - Single value stored in the payload for subsequent rays
- Upcoming publication by:
  - *Tomas Akenine-Möller (NV), Magnus Andersson (NV), Colin Barré-Brisebois (EA), Jim Nilsson (NV), Robert Toth (NV)*



Ground Truth, Ray Differentials, Ours, Mip0

Summary

- Just the beginning – important new tool going forward
- Unified API – easy to experiment and integrate
- Flexible but complex tradeoffs - noise vs ghosting vs perf
- Can enable very high quality cinematic visuals
- Lots more to explore – perf, raster vs trace, sparse render, denoising, new techniques

SEED @ GDC 2018

- **DirectX: Evolving Microsoft's Graphics Platform (presented by Microsoft)**
  - Johan Andersson and Colin Barré-Brisebois
  - Content will be available online soon at www.ea.com/seed
- **Deep Learning - Beyond the Hype**
  - Magnus Nordin
  - Room 2016, West Hall, Thursday, March 22nd, 11:30am - 12:30pm
- **Creativity of Rules and Patterns: Designing Procedural Systems**
  - Anastasia Opara
  - GDC Show Floor, Thursday, March 22nd, 12:30PM-1:00PM and Friday, March 23rd @ 11:00AM-11:30AM

Thanks

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  - Joakim Bergdahl
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  - Henrik Halen
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  - Andrew Lauritzen
  - Magnus Nordin
  - Niklas Nummelin
  - Anastasia Opara
  - Kristoffer Sjöö
  - Tomasz Stachowiak
  - Ida Winterhaven
  - Graham Wihlidal
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  - Ivan Nevraev
  - Amar Patel
  - Matt Sandy
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  - Jiho Choi
  - Peter Harrison
  - Alex Hyder
  - Jon Jansen
  - Aaron Lefohn
  - Ignacio Llamas
  - Henry Moreton
  - Martin Stich

References

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Stockholm – Los Angeles – Montréal – Remote

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We‘re Hiring!

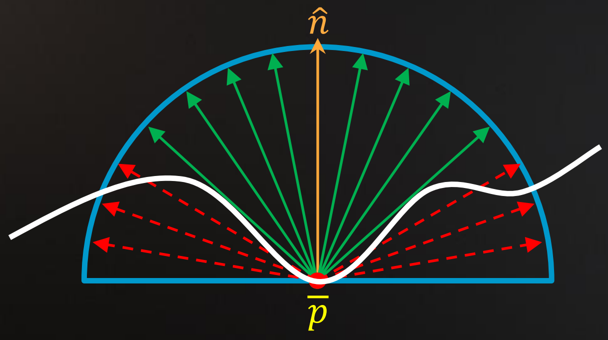
Questions?

Bonus

Ambient Occlusion

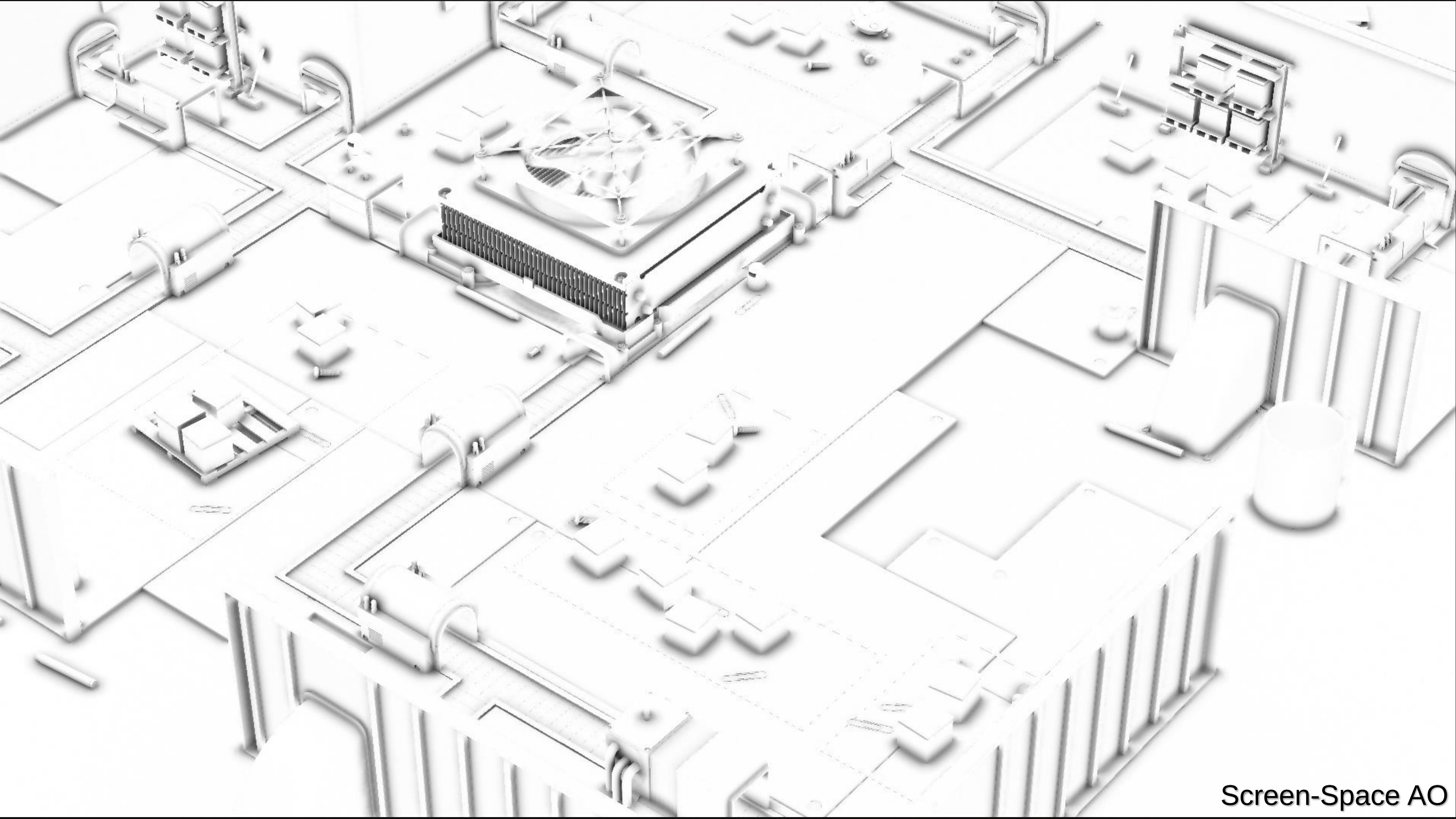
Ambient Occlusion (AO) [Langer 1994] [Miller 1994] maps and scales directly with real-time ray tracing:

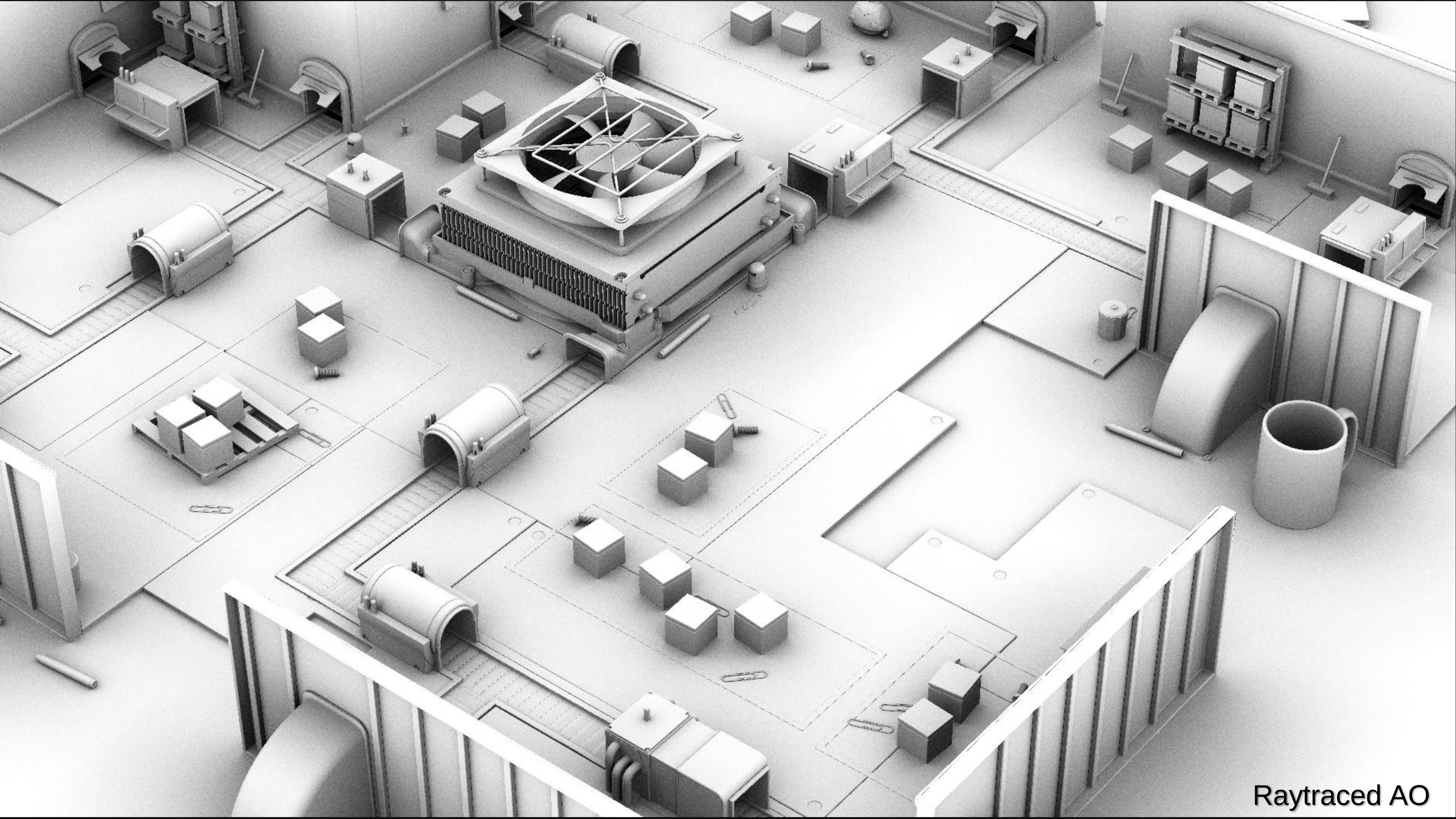
- Integral of the visibility function over the hemisphere Ω for the point $\overline{p}$ on a **surface** with normal $\hat{n}$ with respect to the projected solid angle



$$A_{\overline{p}} = \frac{1}{\pi}\int_{\Omega} V_{\overline{p},\widehat{w}}(\hat{n} \cdot \widehat{w})d\omega$$

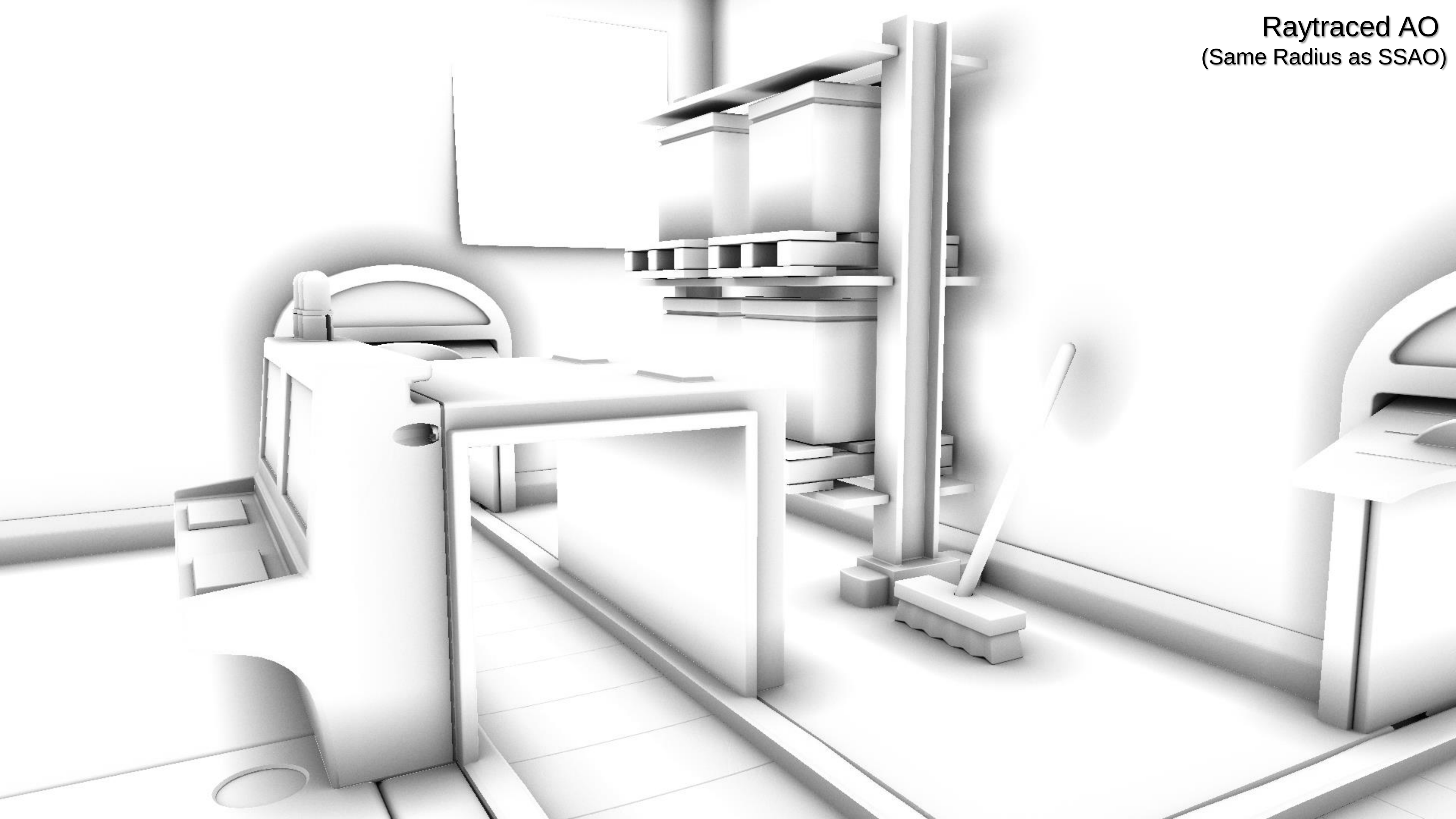
- Games often approximate this in screen-space
- With RT, more grounded & improves visual fidelity!
  - Random directions $\widehat{w}$
  - Can be temporally accumulated or denoised


Screen-Space AO



Raytraced AO


Screen-Space AO

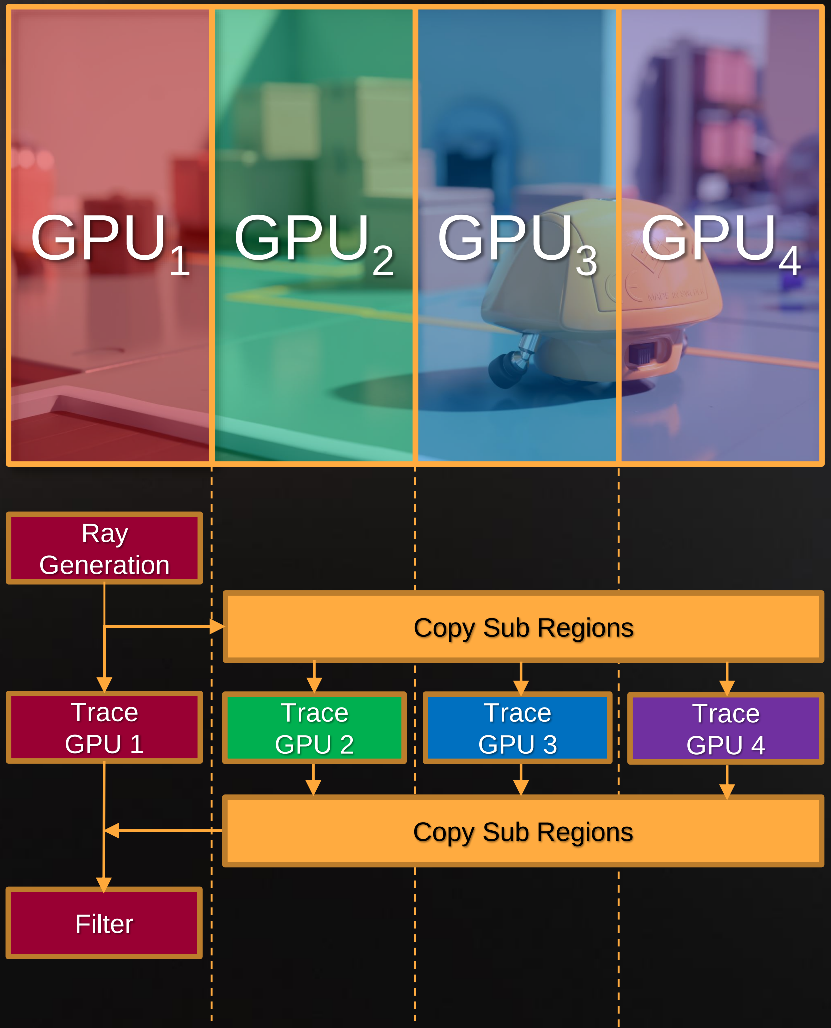

Raytraced AO
(Same Radius as SSAO)


Raytraced AO
(Far-field)

mGPU

Explicit Heterogenous Multi-GPU

- Parallel Fork-Join Style
- Resources copied through system memory using copy queue
- Minimize PCI-E transfers
- Approach
  - Run ray generation on primary GPU
  - Copy results in sub-regions to other GPUs
  - Run tracing phases on separate GPUs
  - Copy tracing results back to primary GPU
  - Run filtering on primary GPU



Ray Tracing Gems

Call for Papers

- A new book series with focus on real-time and interactive ray tracing for game development using the DXR API.
- We invite articles on the following topics:
  Basic ray tracing algorithms, effects (shadows, reflections, tec), non-graphics applications, reconstruction, denoising, & filtering, efficiency and best practices, baking & preprocessing, ray tracing API & design, rasterization and ray tracing, global Illumination, BRDFs, VR, deep learning, etc.
- Important dates
  - 15th of October 2018: submission deadline for full papers
  - GDC 2019: publication of Ray Tracing Gems (paper version + e-book)
- Tomas Akenine-Möller will lead the editorial team
  http://developer.nvidia.com/raytracinggems/