REAL-TIME GLOBAL ILLUMINATION USING PRECOMPUTED LIGHT FIELD PROBES

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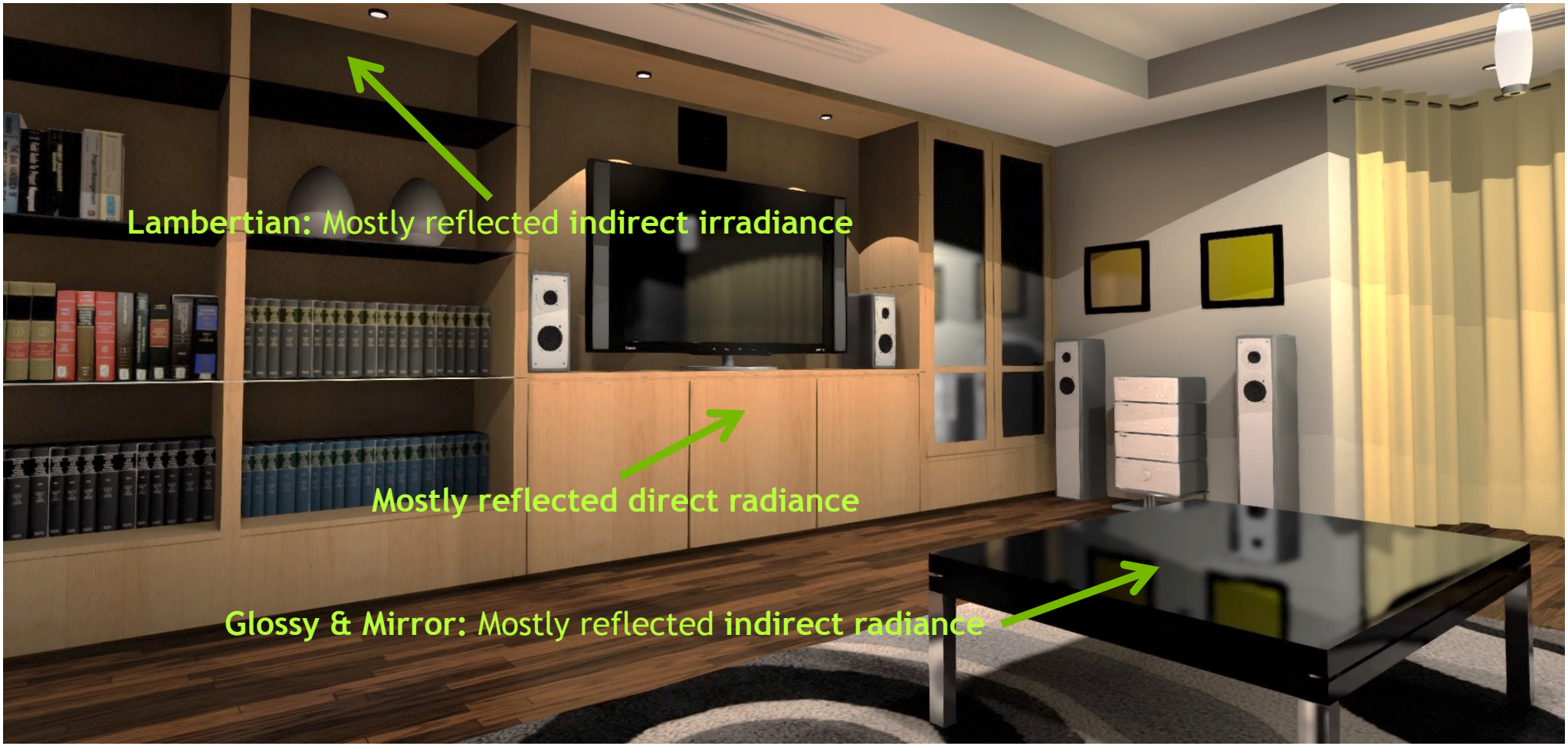
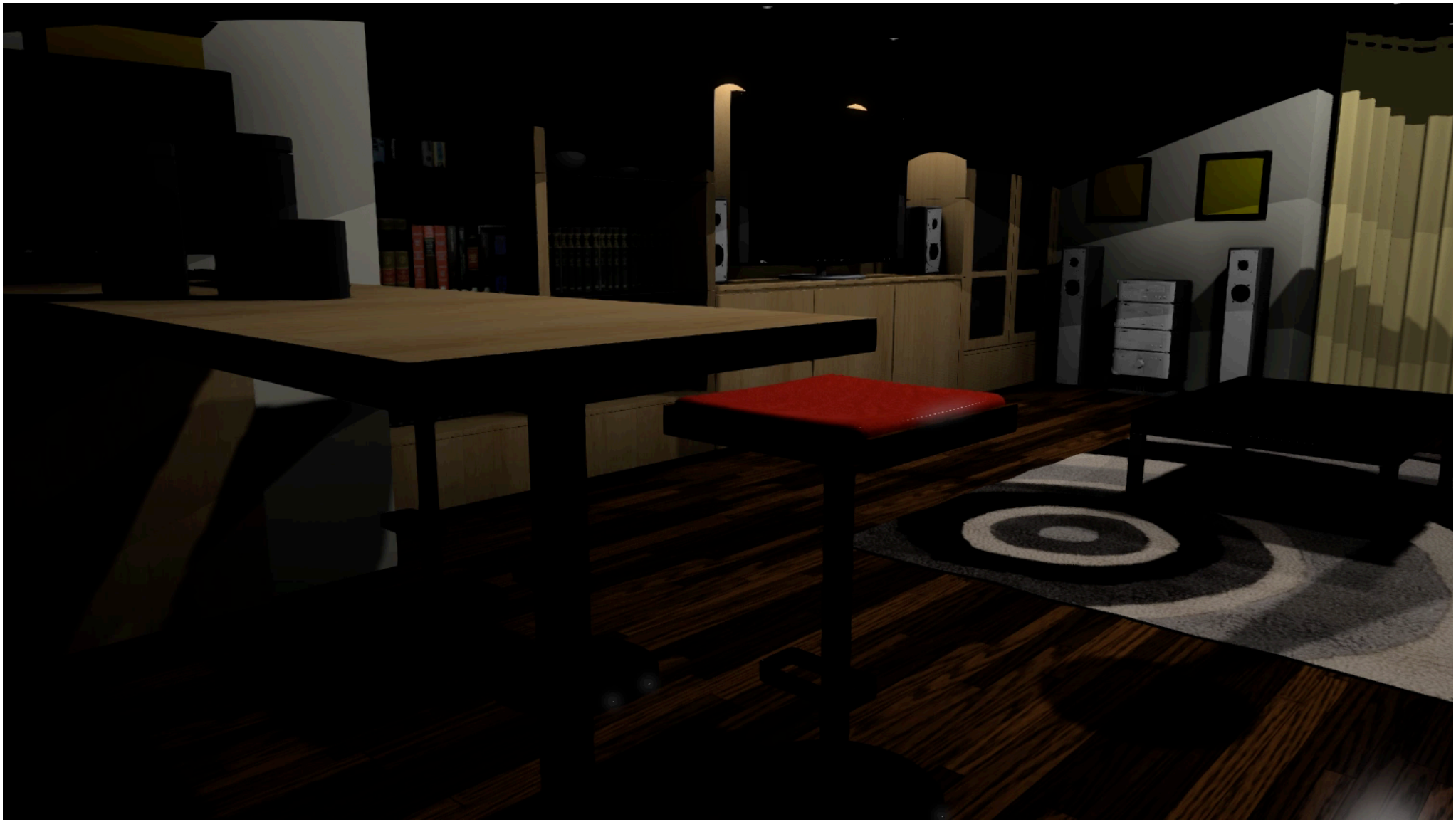
DIRECT ILLUMINATION ONLY

OUR GLOBAL ILLUMINATION RESULT



LIGHT FIELD PROBE GRID



State of the Art in Games

GLOBAL ILLUMINATION TODAY

Mirror reflections: screen-space ray cast + environment probes

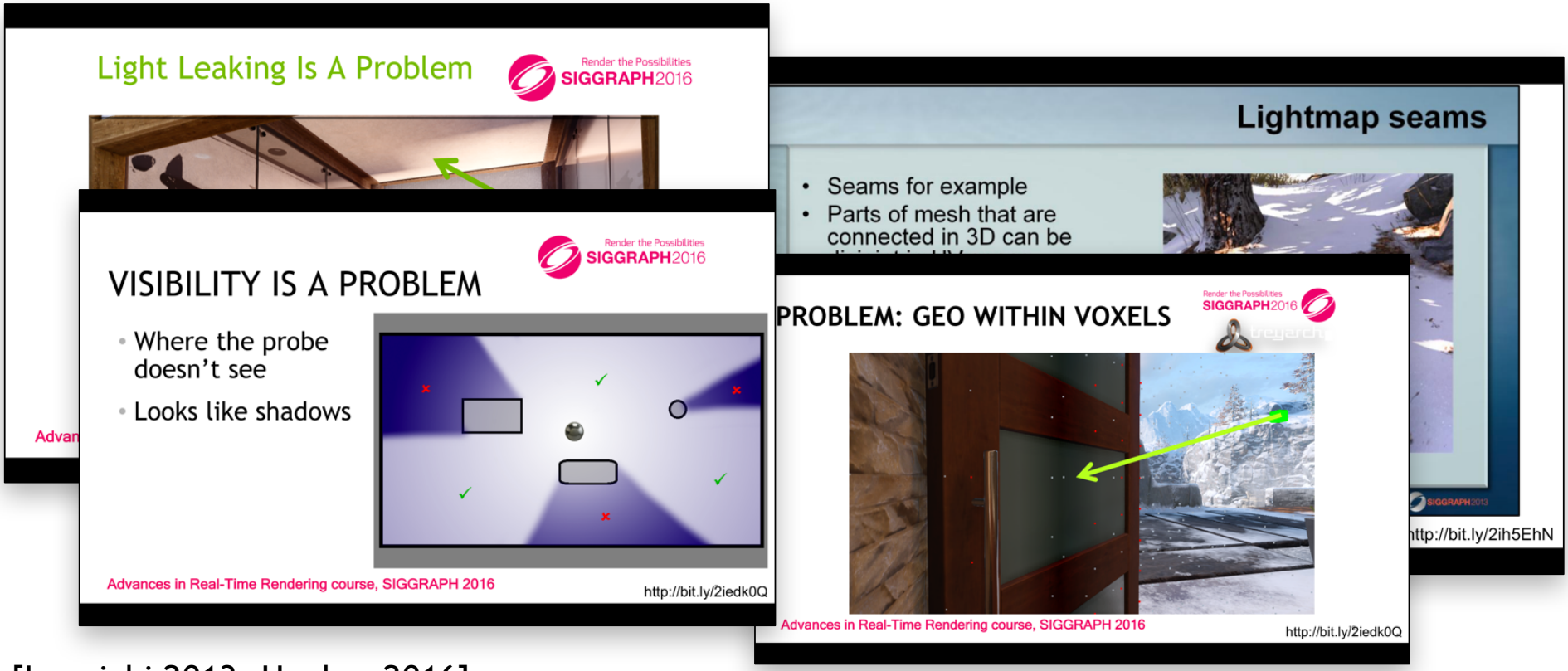
Glossy reflections: distorted preconvolved environment map probes

Matte reflections: light maps or irradiance/voxel probes

Transmission: blending or screen-space distortion

State of the Art in Games

GLOBAL ILLUMINATION TODAY



[Iwanicki 2013, Hooker 2016]

State of the Art in Games

CHALLENGES

Addressed by our work

- Missing reflections of off-screen objects
- Light leaks
- Shadow leaks
- Discontinuities and ghosting at probe boundaries
- Scene-dependent parameterization + proxies
- Inconsistency between static and dynamic receivers
- Duplicated shading code for baking & real-time renderers
- Lower-quality lighting on dynamic objects

Future work

- Dynamic objects not reflected
- Limited transparency & refraction

CONTRIBUTIONS

1. Robust **pixel-shader ray cast** by extending screen-space methods to light fields

2. Spatio-temporal **real-time denoising** strategy for 1 spp ray-traced samples

3. Optional: robust **visibility prefiltering for irradiance** probes

CONTRIBUTIONS

1. Robust **pixel-shader ray cast** by extending screen-space methods to light fields

   Octahedral radiance probes + depth + normals

   Amanatides-Woo-Musgrave hierarchical grid ray march

   Hand off between probes at ambiguous texels

2. Spatio-temporal **real-time denoising** strategy for 1 spp ray-traced samples

   Reprojection + bilateral filtering

   Separate lambertian and glossy reflection

3. Optional: robust **visibility prefiltering for irradiance** probes

   Variance shadow maps + irradiance probes

CONTRIBUTIONS

Focus of this talk

1. Robust **pixel-shader ray cast** by extending screen-space methods to light fields

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3. Optional: robust **visibility prefiltering for irradiance** probes

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Additional details in our GDC'17 talk and blog post

RELATED WORK

Selected Related Work

LIGHT FIELDS

Physics model of radiance in free space - Gershun 1936

Light field *slab*, image-based rendering with limited viewpoint

Levoy & Hanrahan, Gortler et al. 1996

MacMillan et al., Debevec et al.

Wood et al. 2000

Arbitrary viewpoint, prefiltering, material editing, etc.

ATI Cubemapgen, Arikan 2005, Scherzer et al. 2012, Nguyen et al. 2014

New: true per-sample visibility, full ray trace from arbitrary viewpoint

Selected Related Work

SCREEN-SPACE SAMPLING

Rays (w/ accurate visibility)

Deterministic: Valient 2014, McGuire & Mara 2014, Widmer 2015

Stochastic: Stachowiak 2015, Jendersie et al. 2016

Volumes (w/ approximate visibility)

AO: Mittring 2007, Shanmugam & Arikan 2007, Filion 2008

Radiosity: Ritschel et al. 2009, Mara et al. 2016

New: application to light fields

Selected Related Work

PROBE RAY SAMPLING ("REFLECTIONS")

Environment maps - Blinn & Newell 1976

Cube maps – Greene 1986

Various **blended cube** map grid solutions, e.g., Source engine

Cube depth proxy – Bjorke 2004, Sebastien and Zanuttini 2012, Lagarde 2013, et al.

Polyhedral depth proxy - Szirmay-Kalos 2005

Heightfield depth - Evangelakos 2015, Donow 2016

New: multiple probes, per-sample geometry

Selected Related Work

PRECONVOLVED IRRADIANCE (“DIFFUSE”)

1970s Constant ambient

1990s Hemisphere ambient

1990s IBL

Circa 2000 Preconvolved irradiance cube & SH maps

(ATI cubemapgen/RTR2)

Grid of irradiance maps

Depth proxy geometry

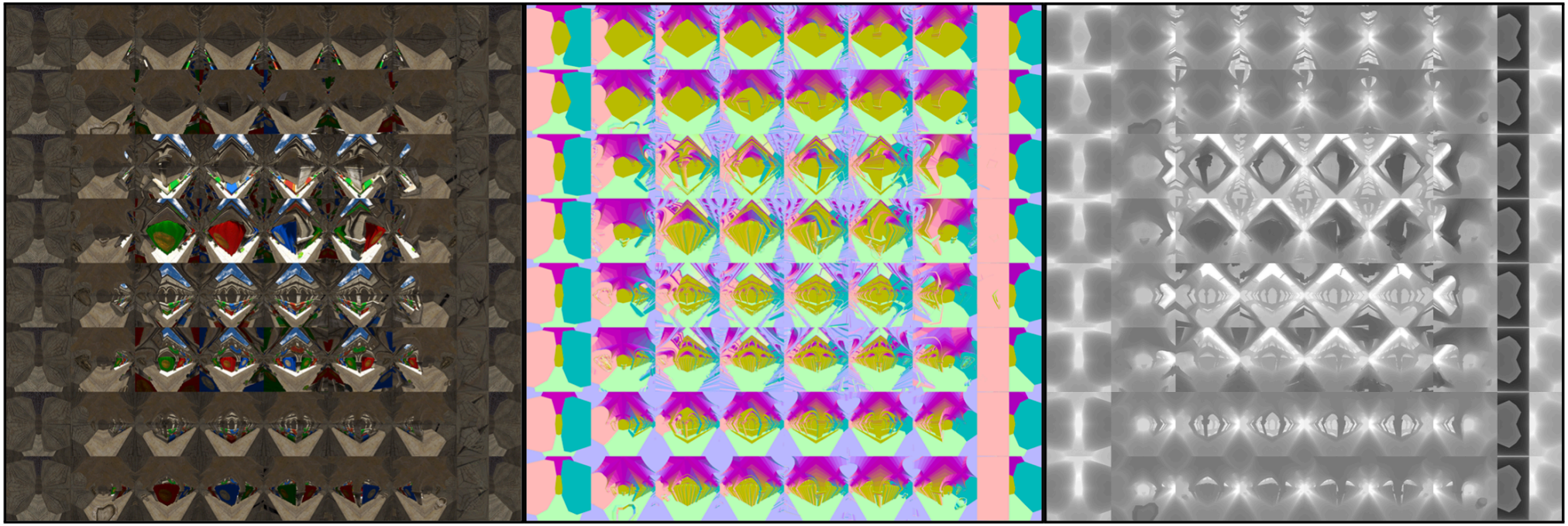
Far Cry 3

New: automatic leak prevention and smoothing

LIGHT FIELD PROBES

Light Field Probes

DATA STRUCTURE



HDR Radiance

R11G11B10F, BC6H

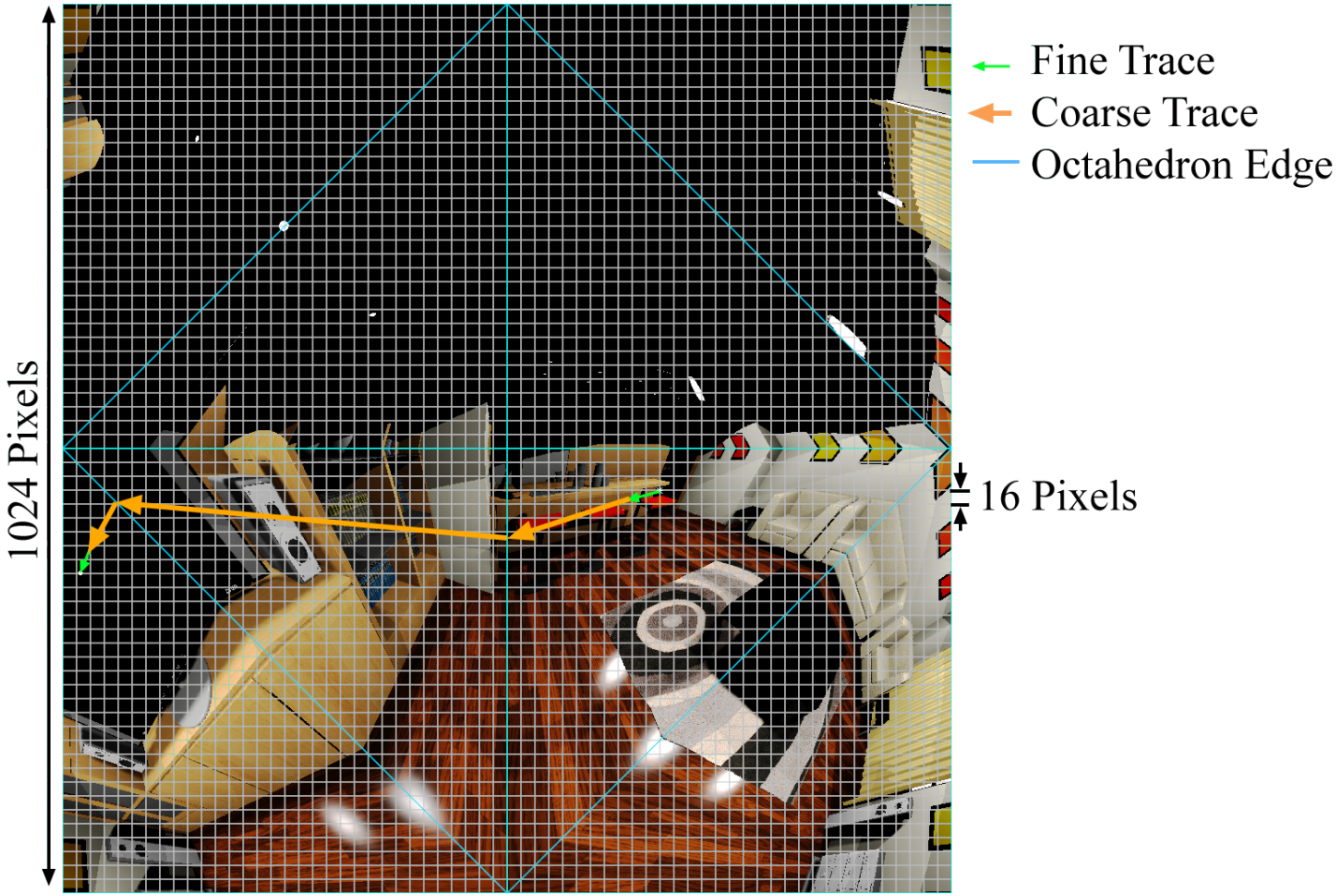
Compressed Surface Normals

RG8

Radial Distance

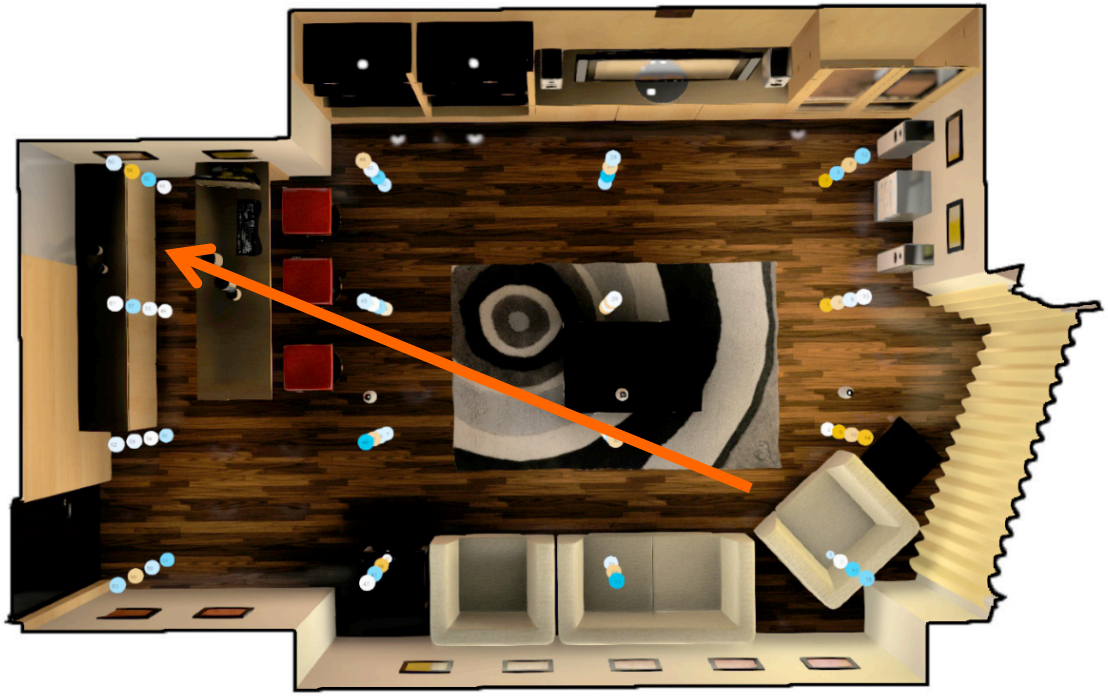
R16F

TRACING THROUGH ONE PROBE

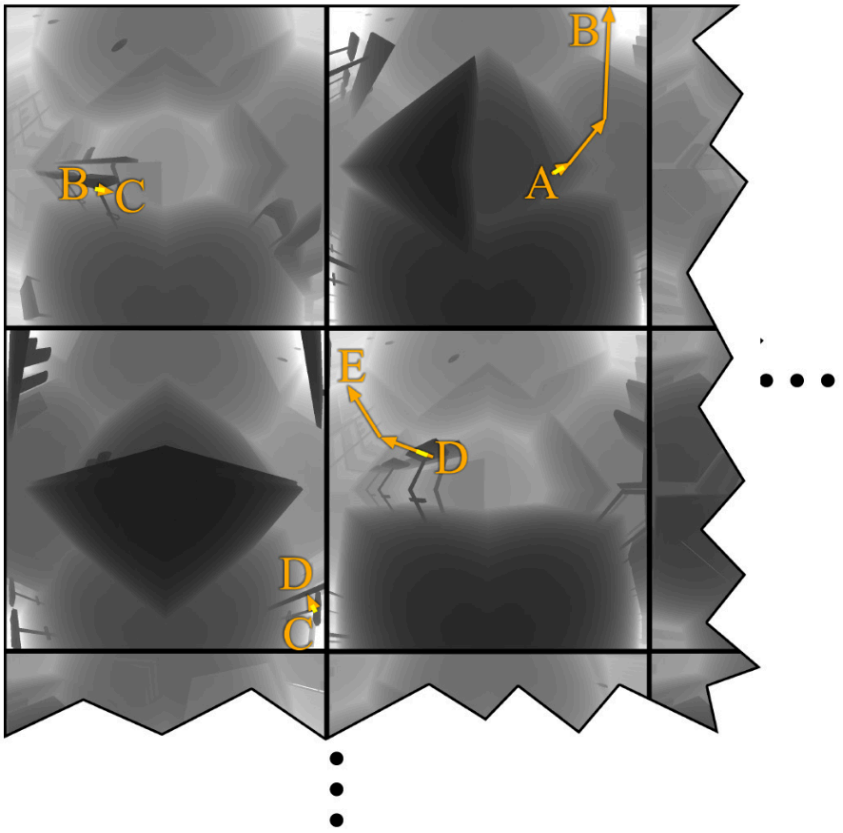


Light Field Probes

TRACING ACROSS MULTIPLE PROBES

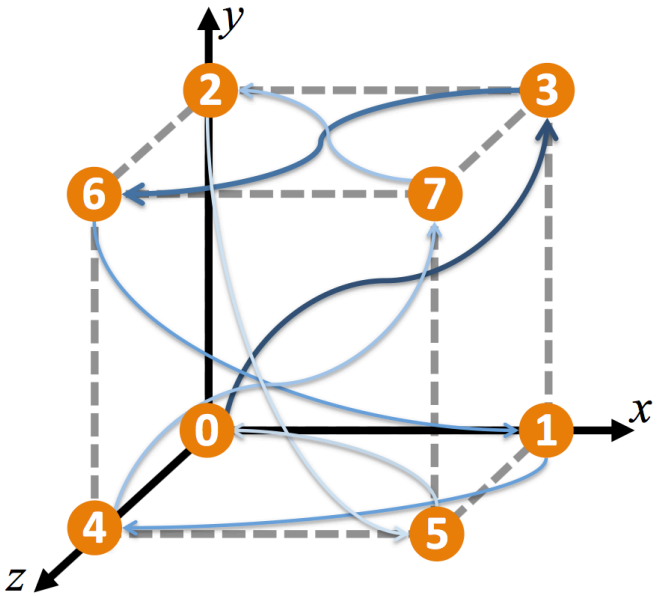


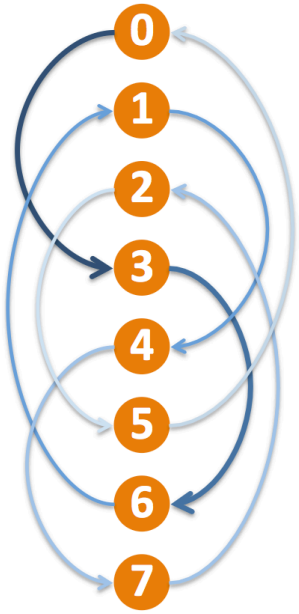
Light Probe Locations in Top View

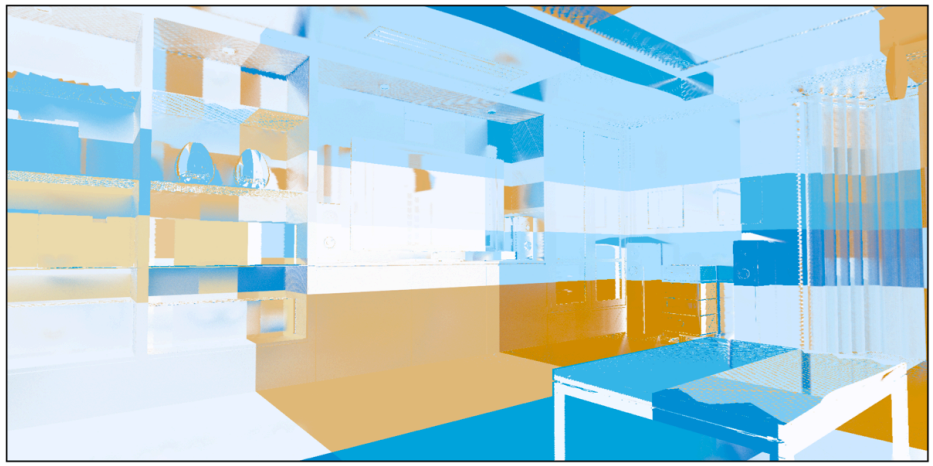


Path of one Ray Through Light Field

PROBE SELECTION HEURISTIC







```
def singleProbeTrace(ray, probe):
    compute the four 2D polyline segments
    for each polyline segment:
        for each 2D pixel and corresponding 3D point on the segment:
            compare the voxel in the radial distance texture to the ray:
                if hit: return (HIT, point)
                if hidden behind surface: return (UNKNOWN, point)
                # (otherwise, keep iterating)
    return (MISS, last polyline endpoint) # Reached the end of the line


def lightFieldTrace(ray):
    result = UNKNOWN
    while result == UNKNOWN:
        choose the next probe
        (result, endpoint) = singleProbeTrace(ray, probe)
        ray.origin = endpoint # Advance the ray to the last point checked
    return result
```

GLOBAL ILLUMINATION ALGORITHM

Key Idea: Given pixel-shader ray tracing, just sample *n* random indirect rays/pixel!

Optimization 1: Importance sample & reconstruct

Importance sample only 10 rays/pixel from the BRDF and spatio-temporally filter

Optimization 2: + factor the BRDF

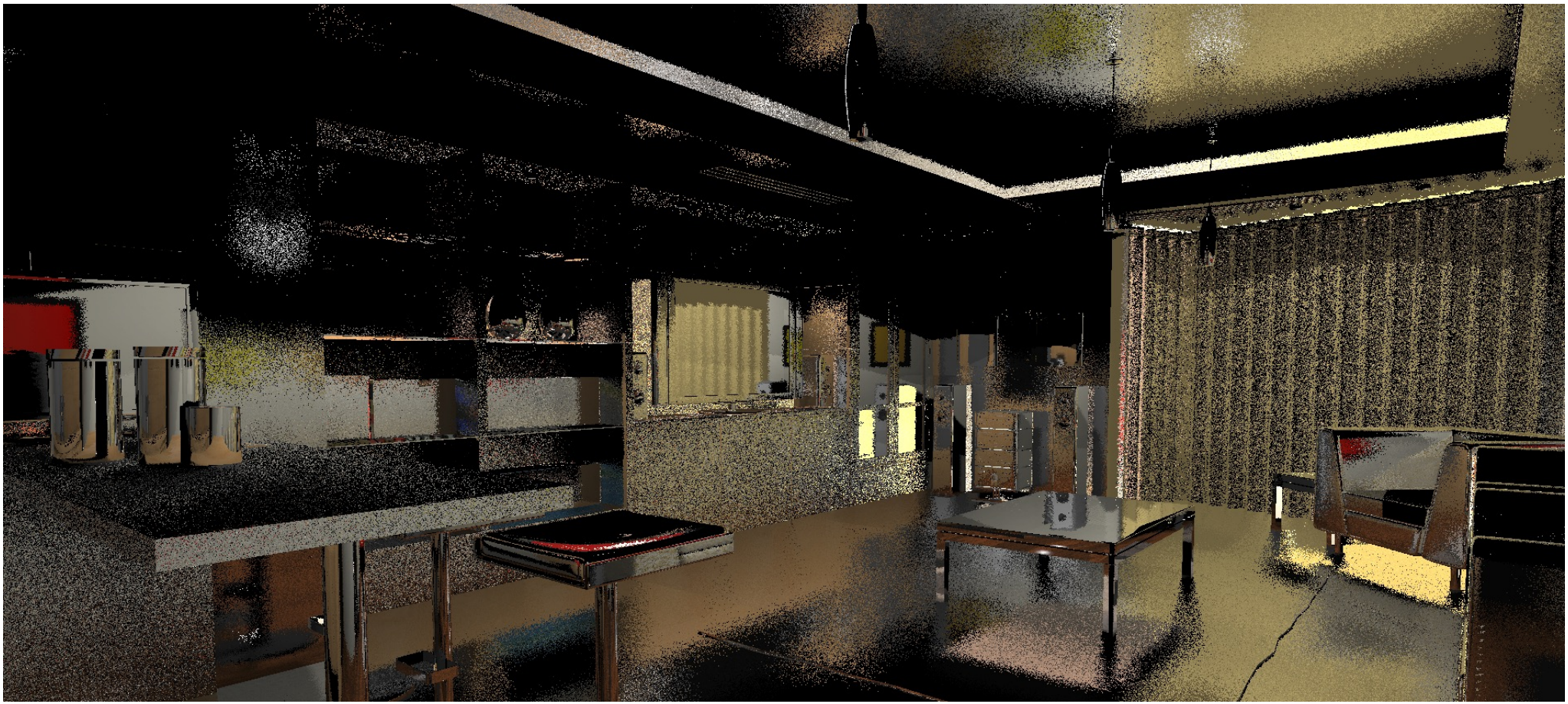
Importance sample 1 glossy & 1 lambertian ray/pixel and denoise separately

Optimization 3: + preintegrate irradiance

Importance sample 1 glossy ray/pix and prefilter irradiance and visibility

Denoising Example #1

IMPORTANCE-SAMPLED RADIANCE @ 1SPP

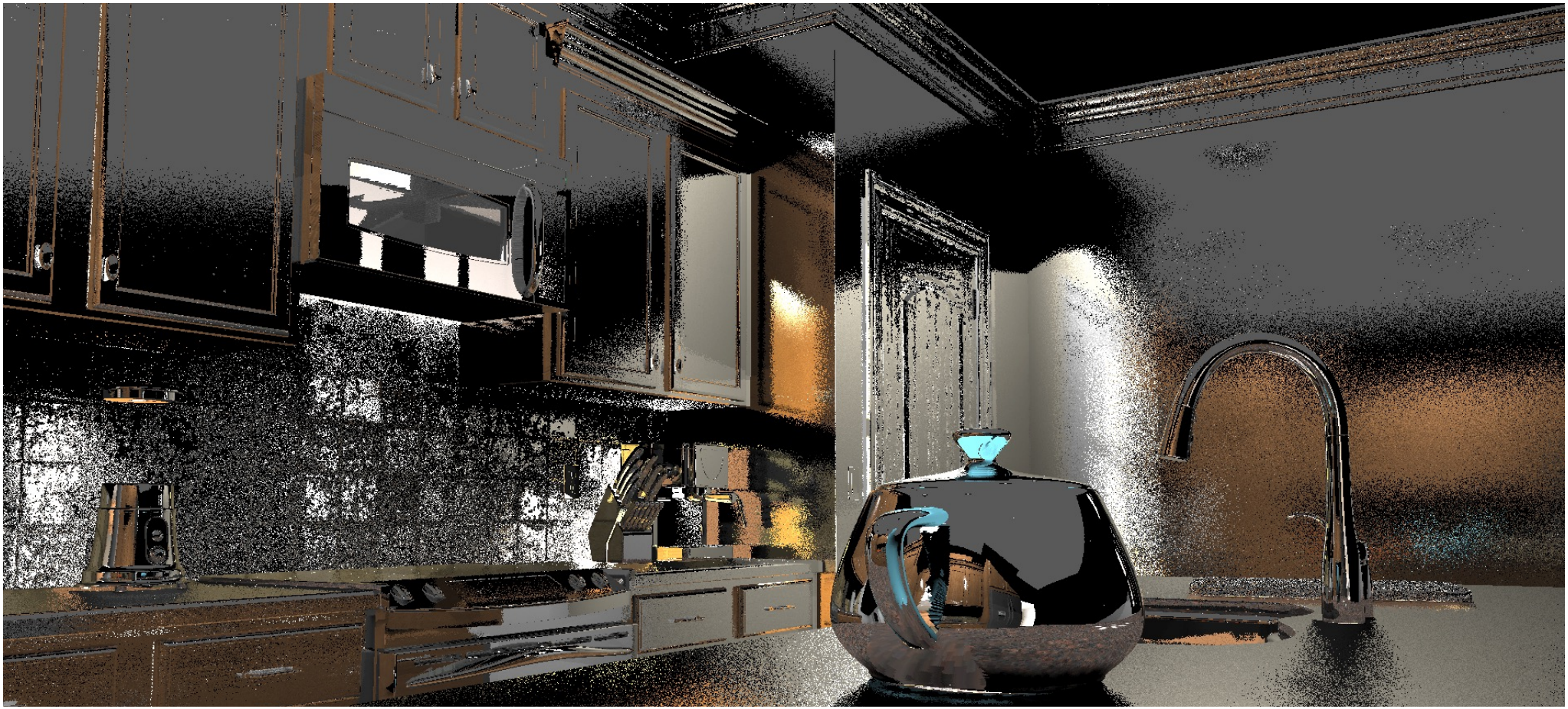


Denoising Example #1

FILTERED RADIANCE

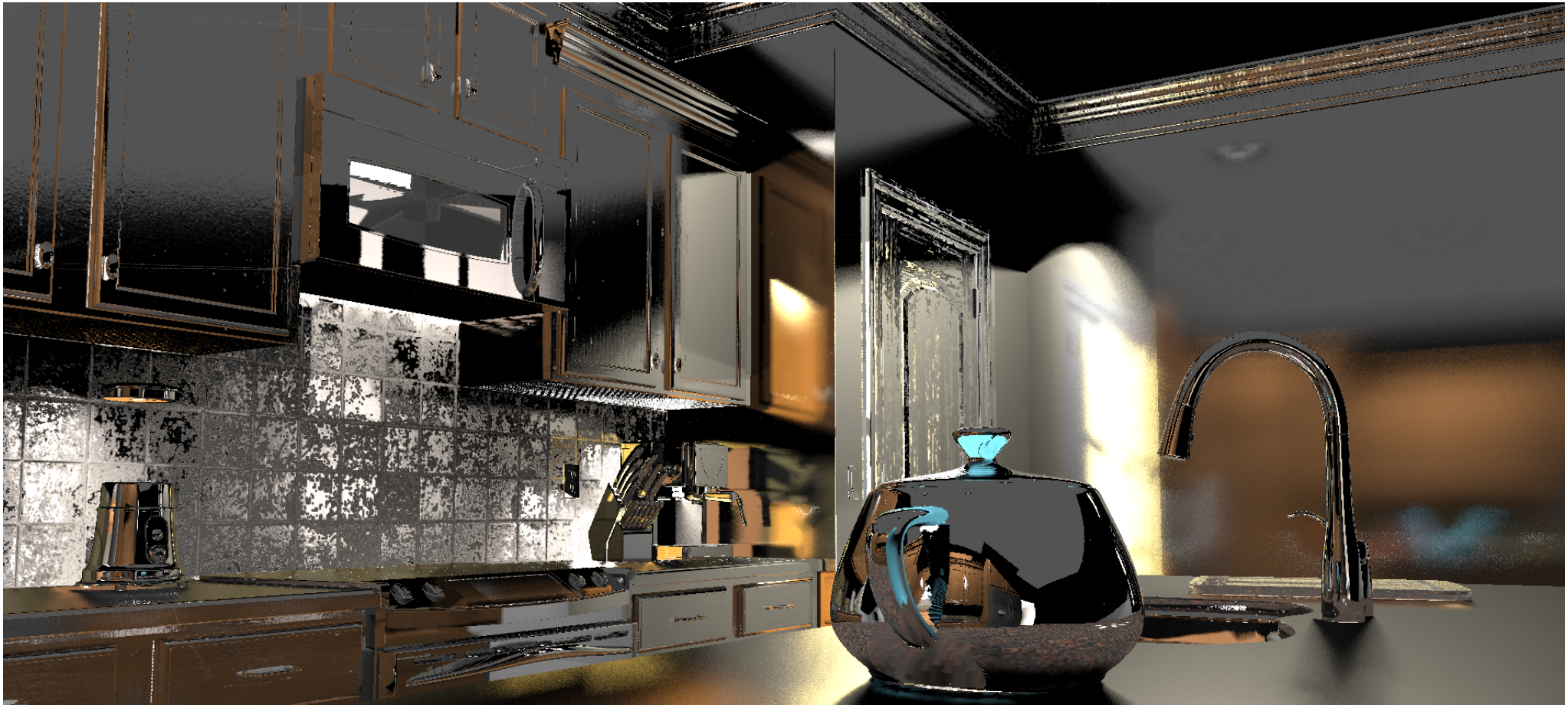
Denoising Example #2

IMPORTANCE-SAMPLED RADIANCE @ 1SPP



Denoising Example #2

FILTERED RADIANCE



Irradiance Optimization

PREFILTERED VISIBILITY

Irradiance ray samples have high variance even though the final result varies slowly…

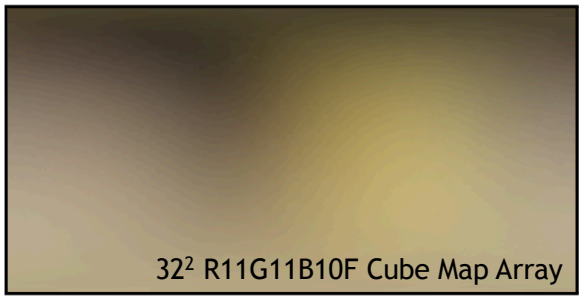
Prefiltered irradiance probes are a common trick…but leak light. Adding visibility tests creates hard shadow line errors.

Following variance shadow maps [Donnelly & Lauritzen], we store the first two moments of a depth distribution and perform a prefiltered Chebyshev depth test.

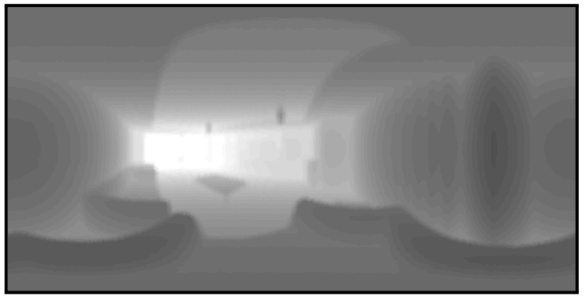
2x net speedup by prefiltering irradiance

Some overblurring of diffuse term

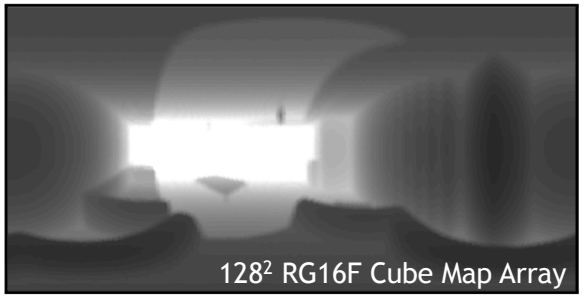
$E = \int_\Omega L\ \omega \cdot n$



$\int_G r$



$\int_G r^2$



IRRADIANCE PROBE WEIGHT

Smoothly fade out backfaces

$$w = \max(\text{trilinear}, \varepsilon) \cdot \max(\hat{n} \cdot v / \|\vec{v}\|, \varepsilon) \cdot \max(\sigma^2 / (\sigma^2 + (\|\vec{v}\| - m^2), \varepsilon)$$

Transition to nearest probe

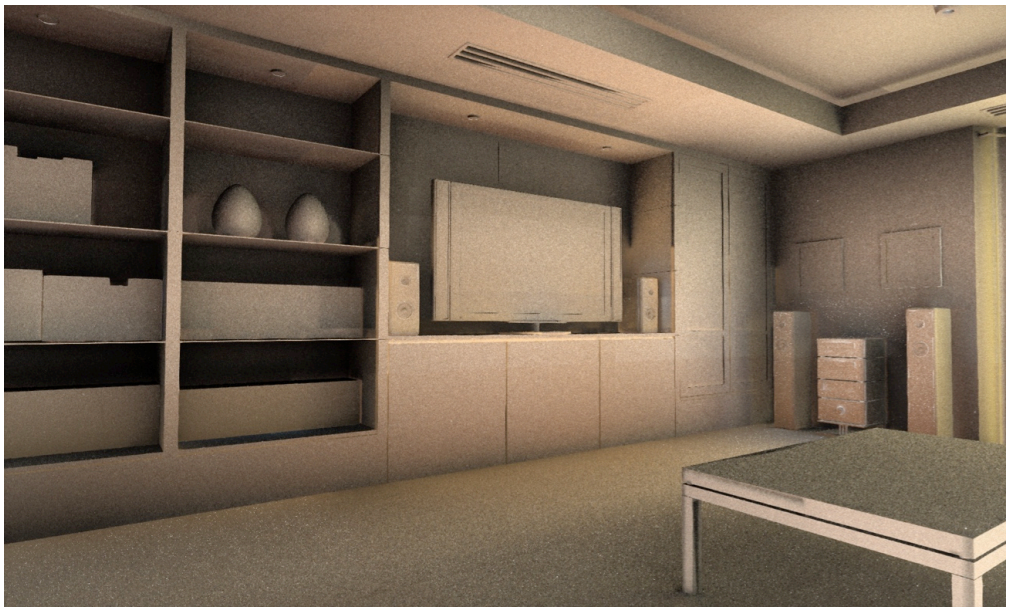
Chebyshev: Fraction of [weighted] sphere that is visible

where m = mean radius = interpolate(r), s = mean squared radius = interpolate(r^2),

$\hat{n}$ = surface normal, $\|\vec{v}\|$ = vector to probe, $\sigma^2 = |m^2 - s|$

IRRADIANCE APPROXIMATION QUALITY

Light field probe ray traced irradiance

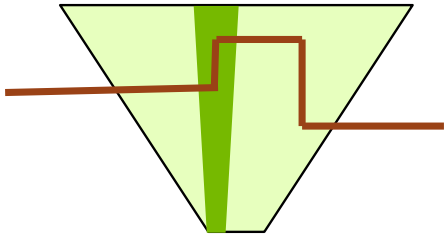


Probe w/ visibility approximation

WHAT ABOUT LEAKING FROM VSM?

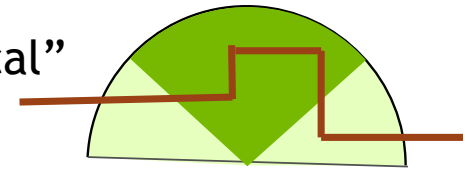
VSM leaks light & shadow with point sources:

- Point light shadow texels see bimodal depth distributions: 2 moments not enough
- Single shadow map for entire scene
- Chebyshev test is very conservative…leaks



VSM fits irradiance probes well:

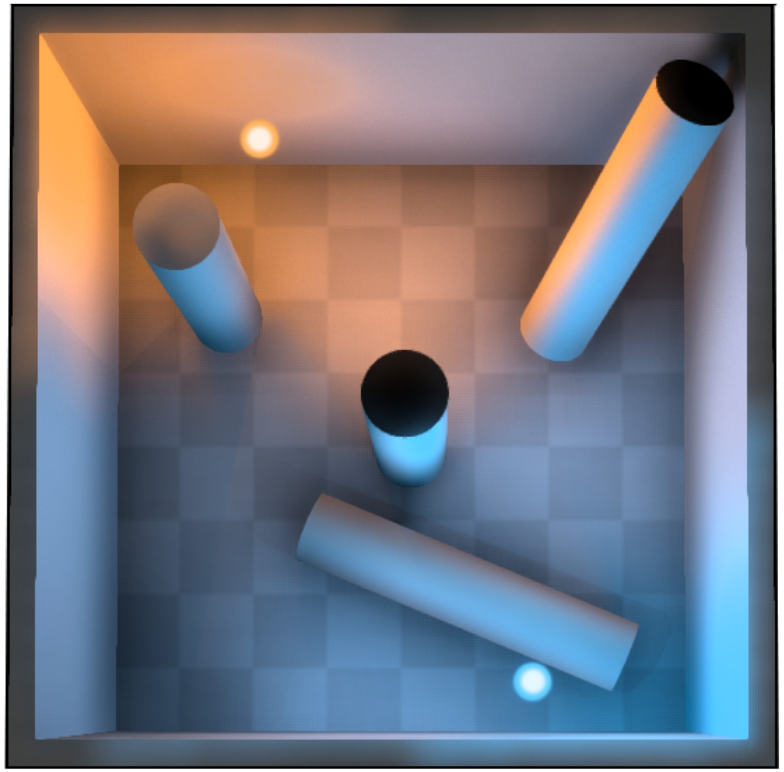
- Irradiance shadows integrate ¼ cosine-weighted sphere: smoother distribution
- Switch shadow maps every 2m and clamp depth, so always “local”
- Additional backface and trilinear terms for proximity



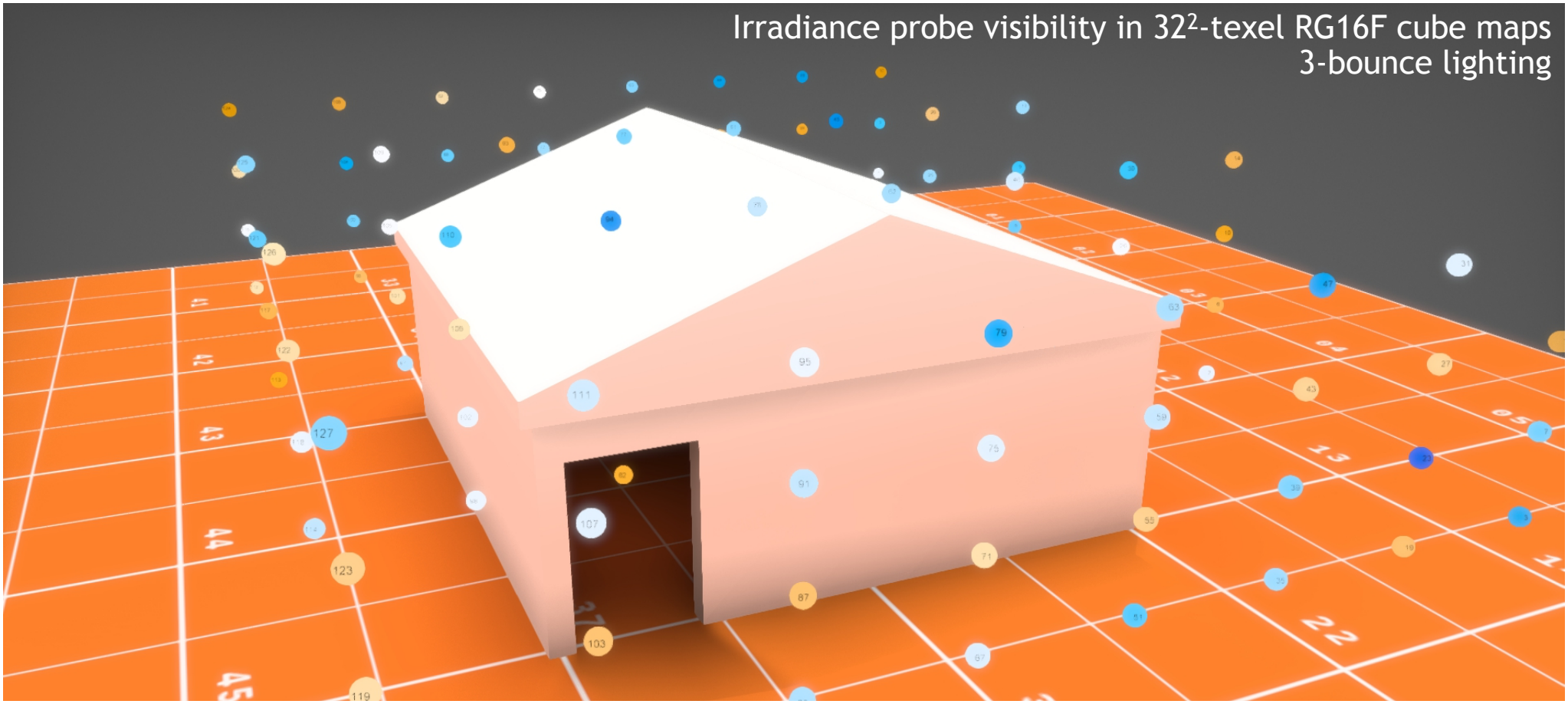
IRRADIANCE PROBES INSIDE GEOMETRY

Before: No visibility

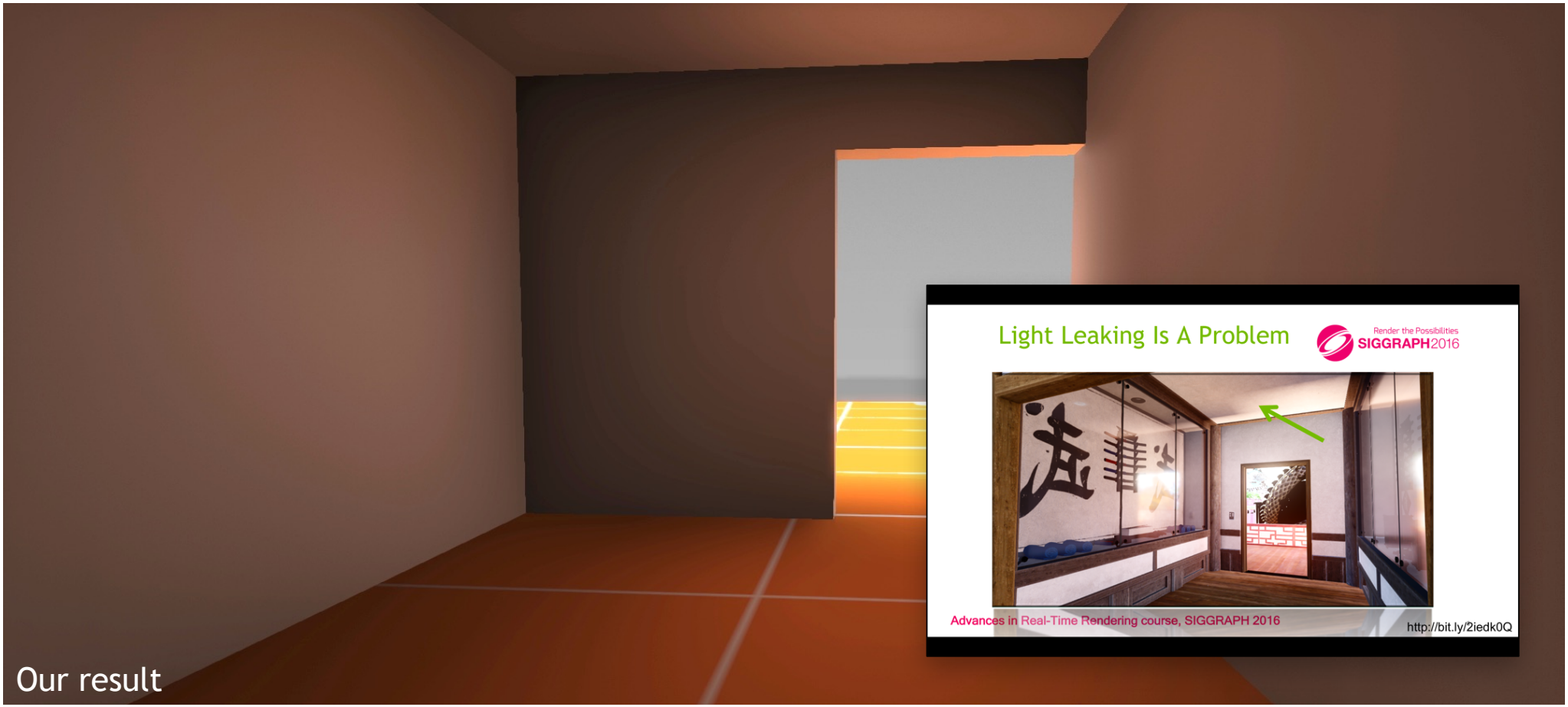
After: Our prefiltered visibility



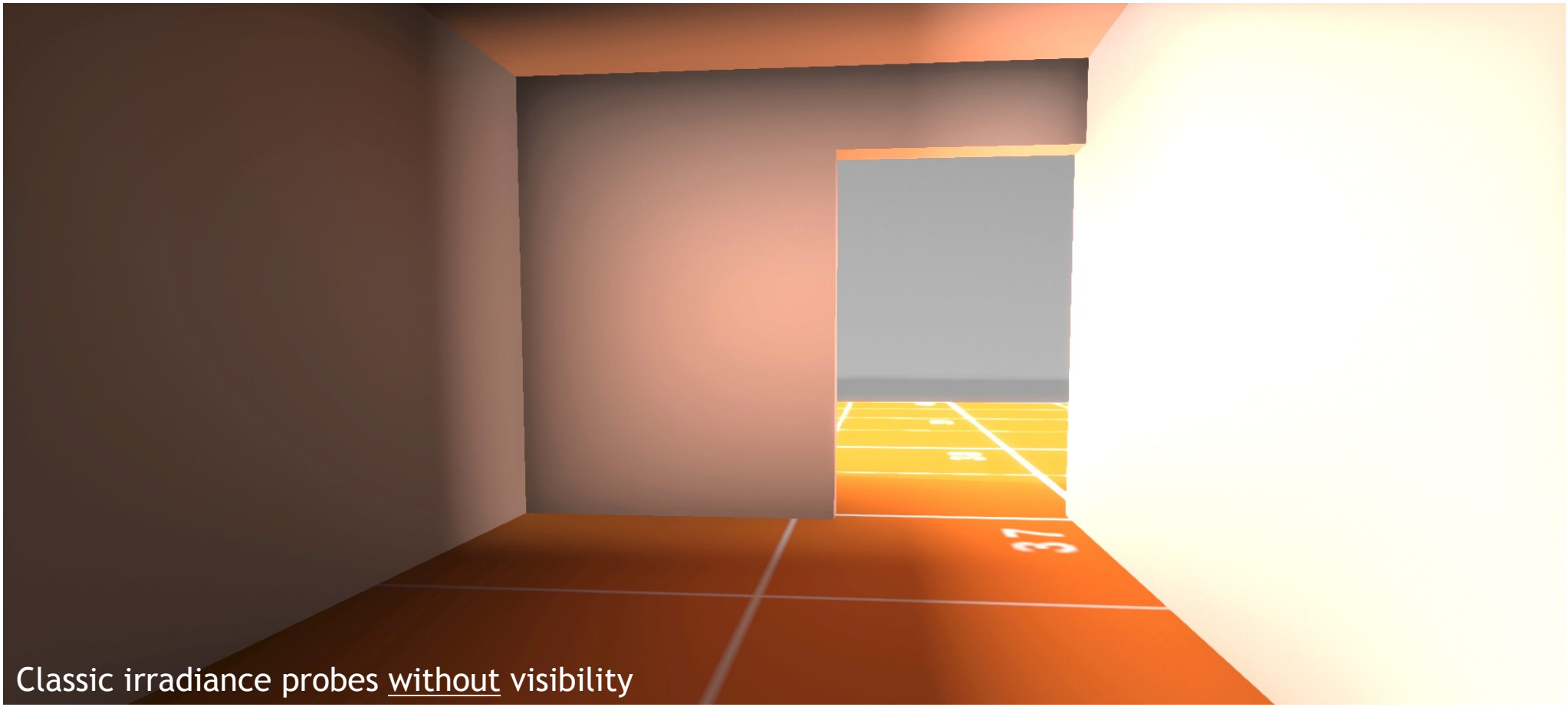
VISIBILITY TEST CASE



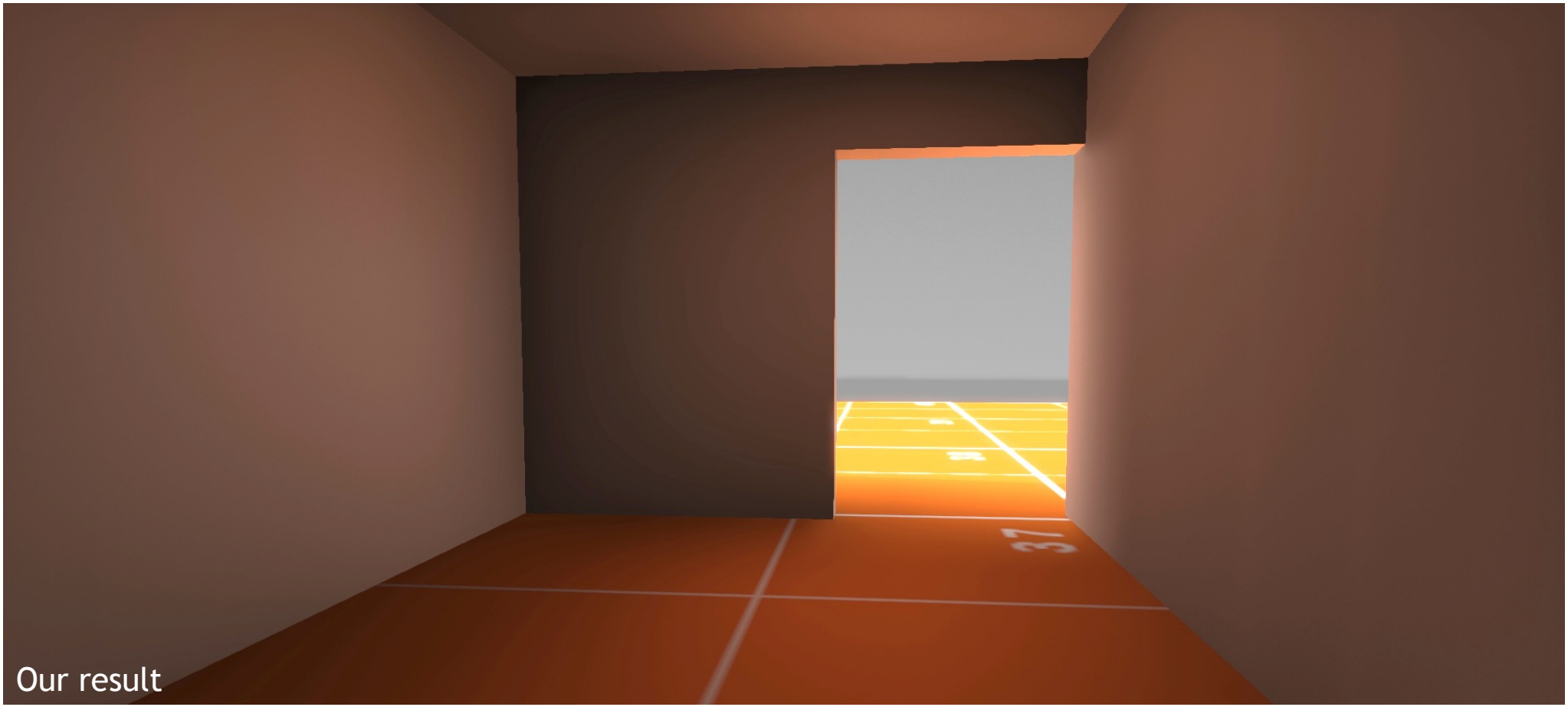
VIEW FROM INSIDE



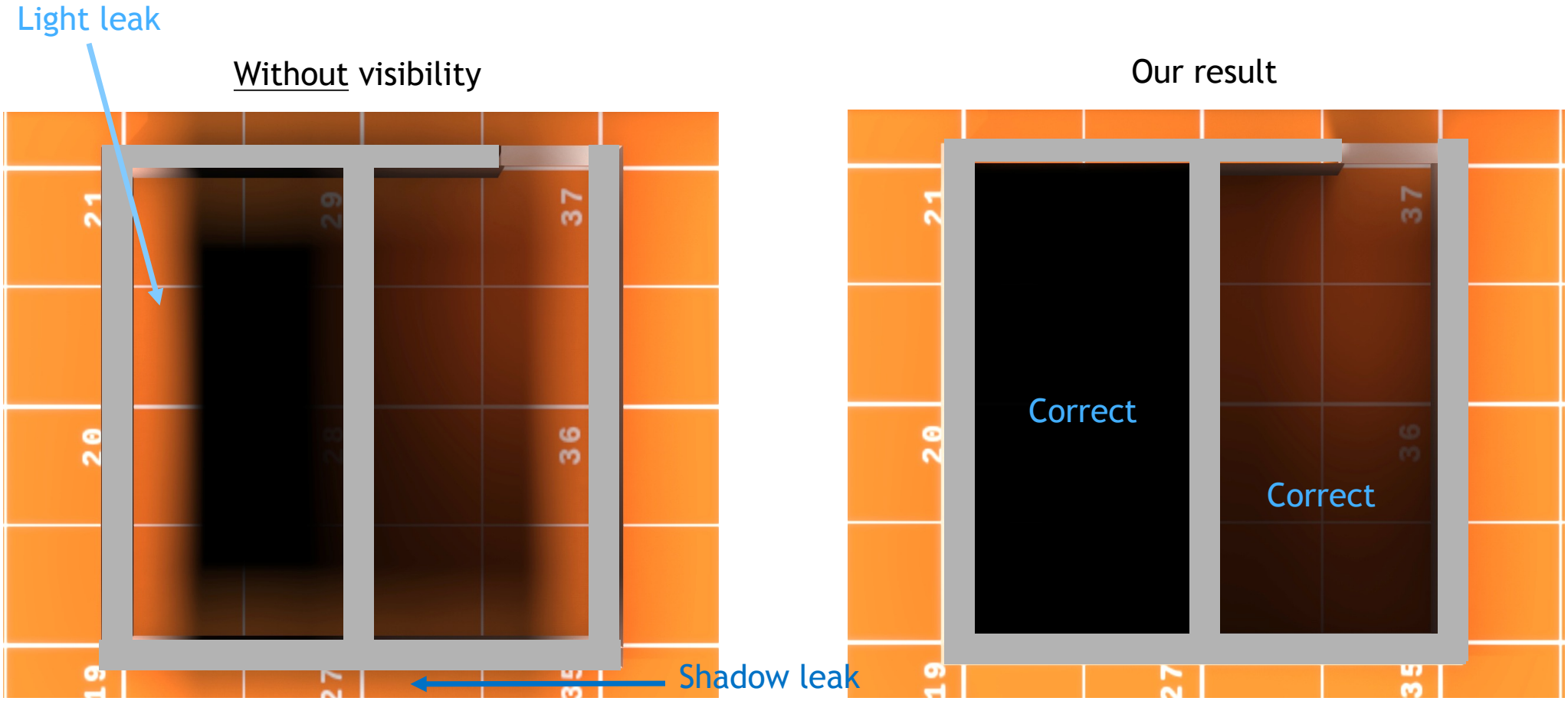
VIEW FROM INSIDE



VIEW FROM INSIDE



TOP VIEW CUTAWAY

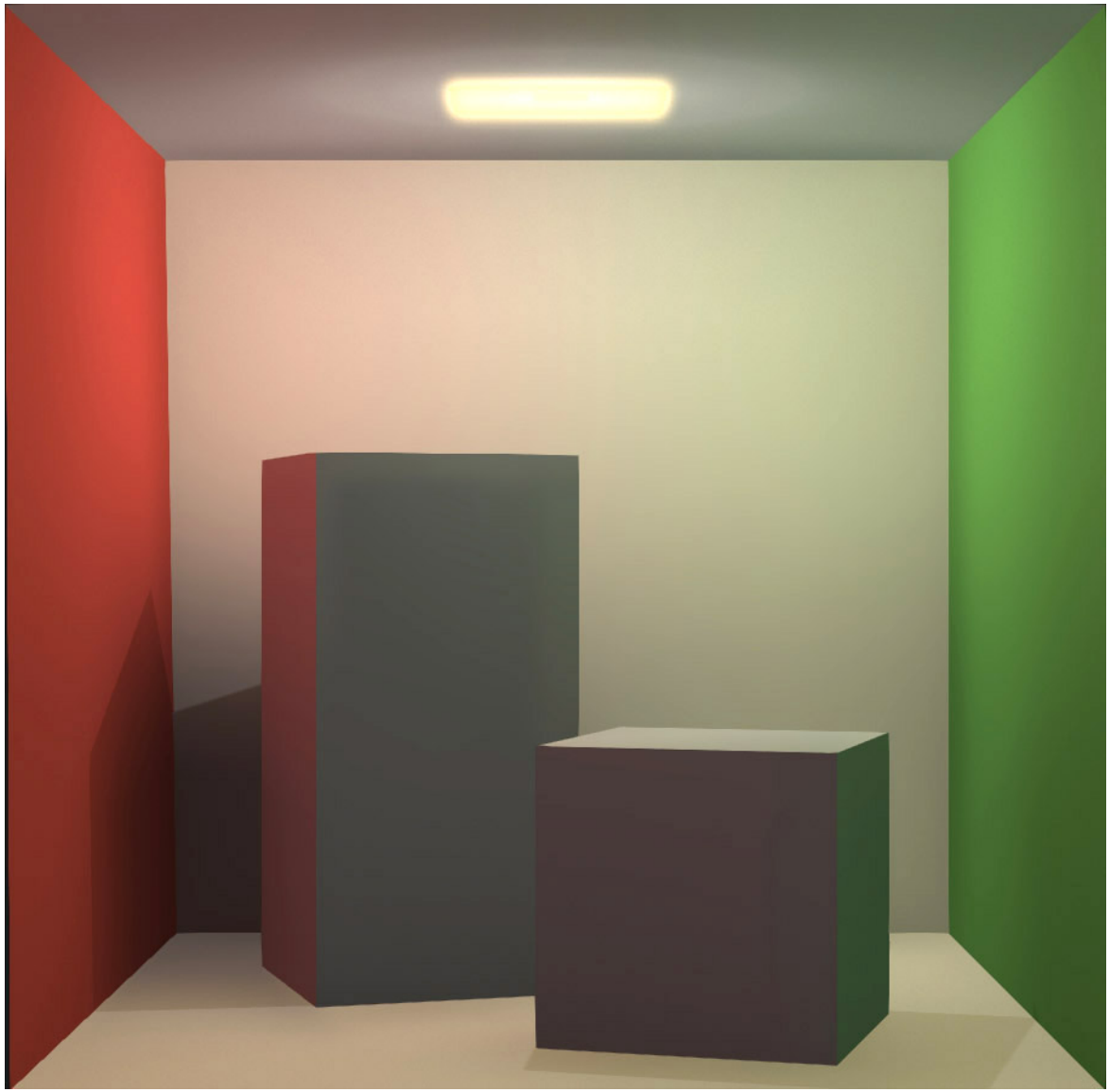


RESULTS

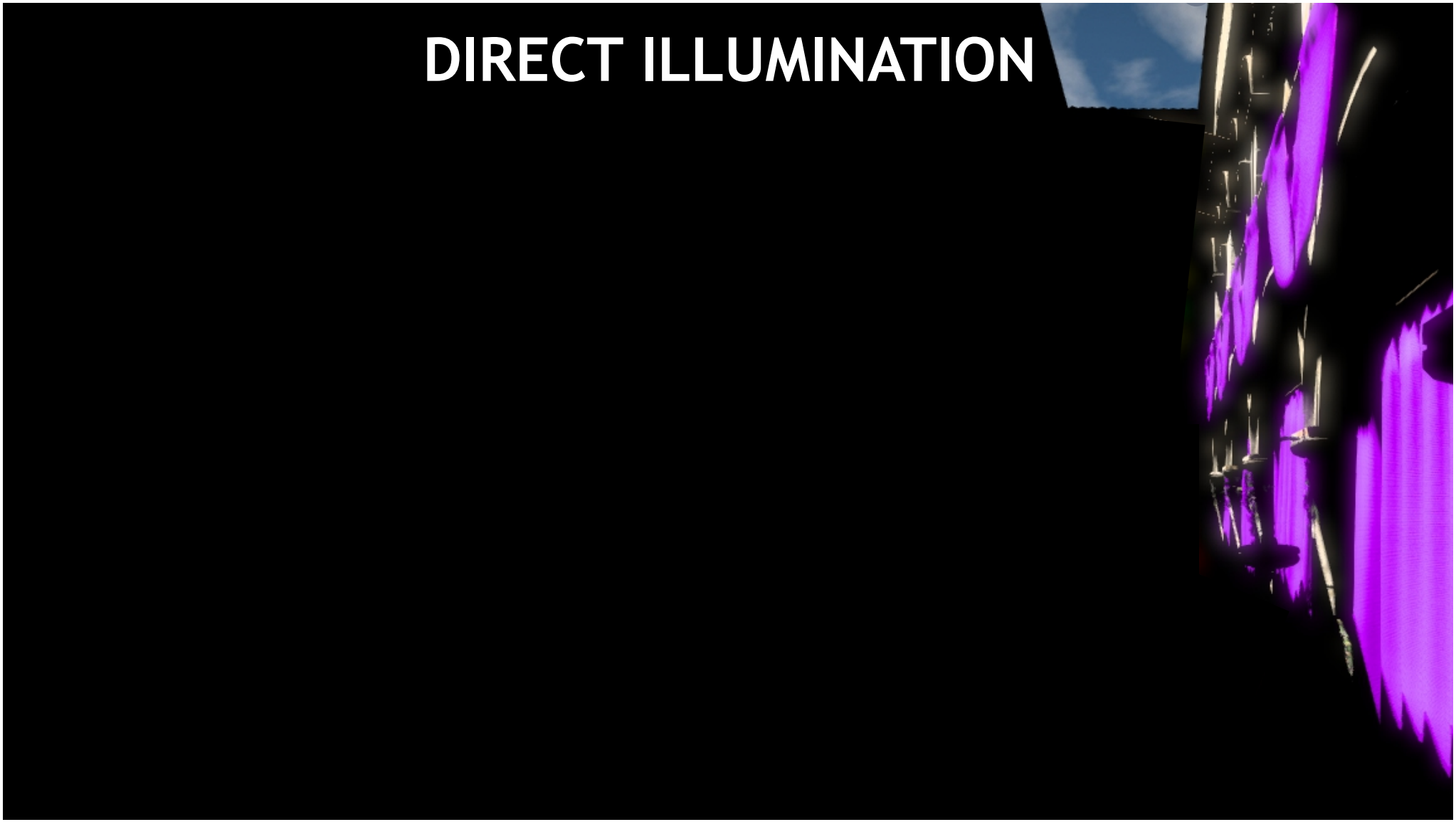
MEASURED PERFORMANCE

Scene	Probes	Resolution	Lambertian	Glossy
Cornell Box	2x2x2	2048^2	0.358	0.000
Cornell Box	2x2x2	256^2	0.302	0.000
Sponza (Statue)	8x2x4	512^2	0.332	0.151
Living Room	4x4x4	1024^2	0.293	4.401
Luxury Kitchen	4x4x4	1024^2	0.358	9.334
San Miguel	8x2x8	1024^2	0.520	47.170

Table 1: *Rendering times for indirect light in milliseconds*

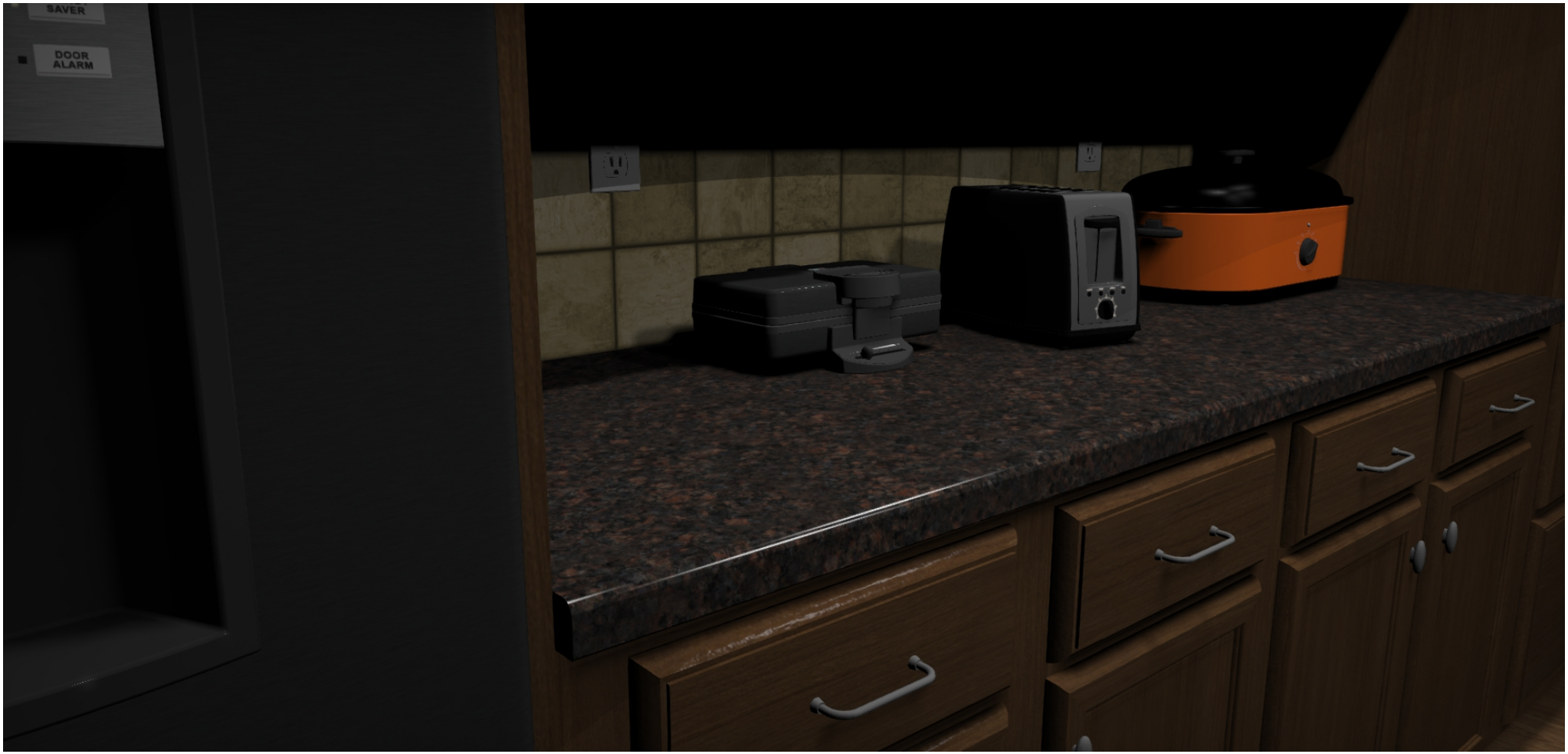


DIRECT ILLUMINATION




GLOBAL ILLUMINATION

DIRECT ILLUMINATION



GLOBAL ILLUMINATION

DIRECT ILLUMINATION

GLOBAL ILLUMINATION

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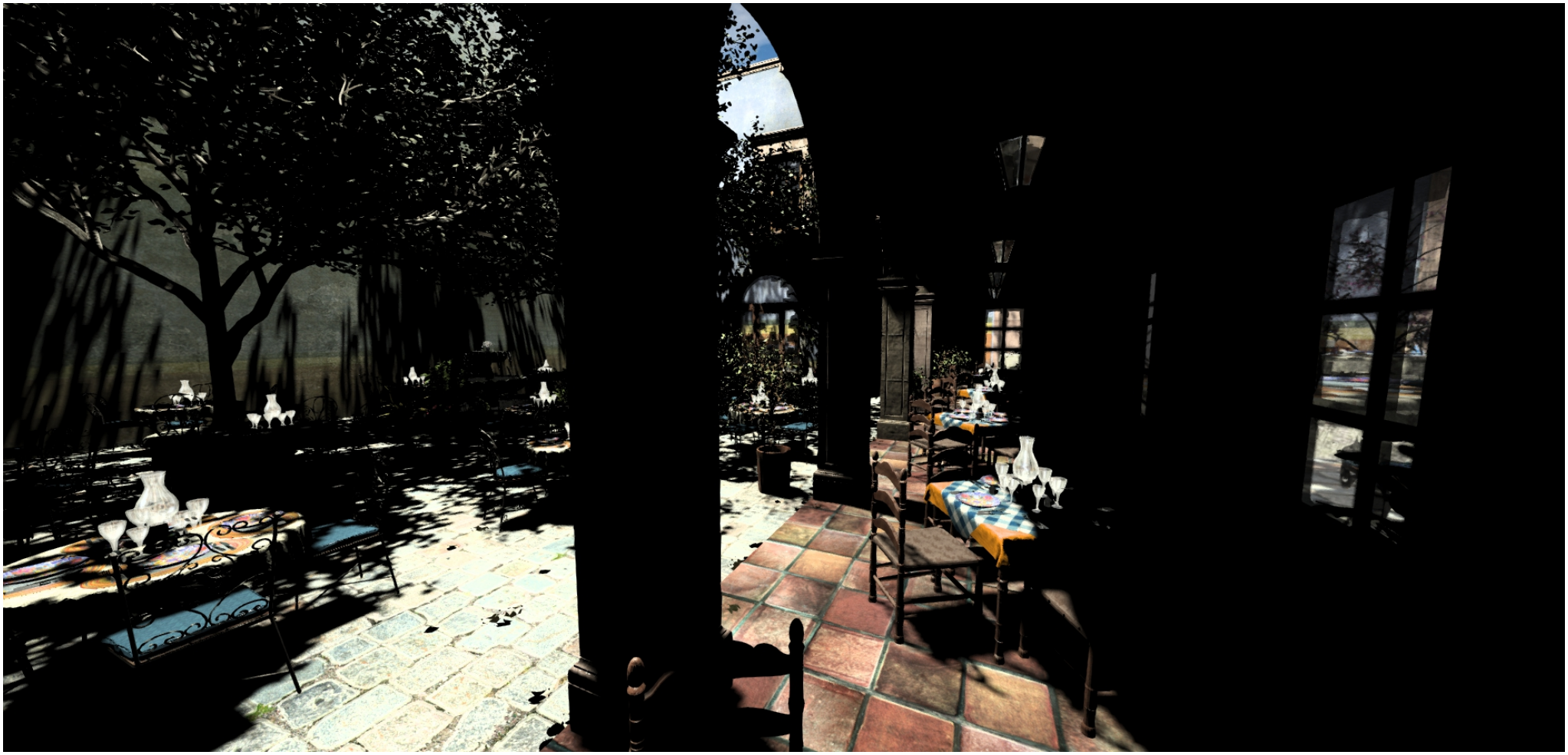
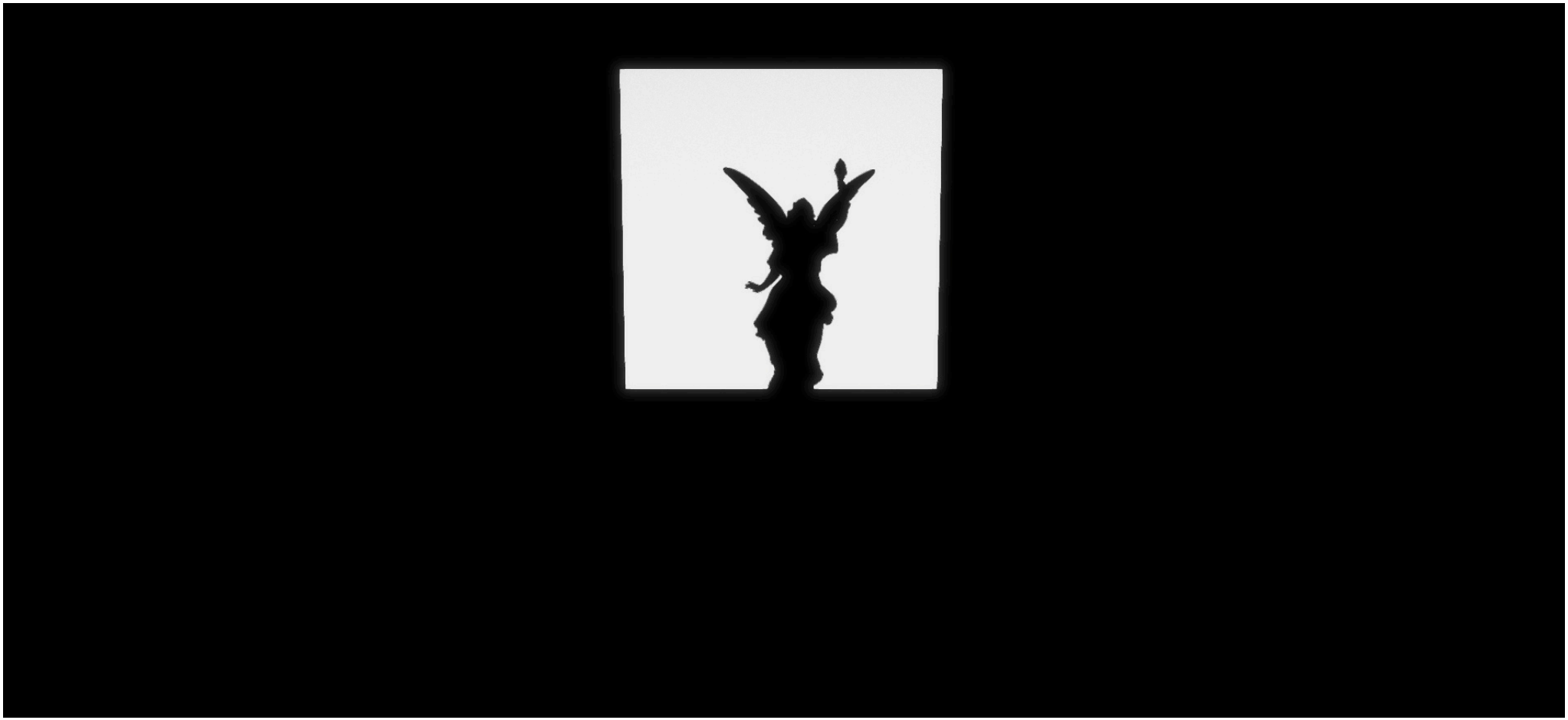


GLOBAL ILLUMINATION

MIXED STATIC AND DYNAMIC RECEIVERS

DIRECT [POINT SOURCE] ILLUMINATION



GLOBAL ILLUMINATION

FUTURE WORK

Dynamic probe scheduling

Inspired by Martin and Einarsson 2012

For low-res irradiance probes, just EWMA-filter + real-time ray trace

Light field compression

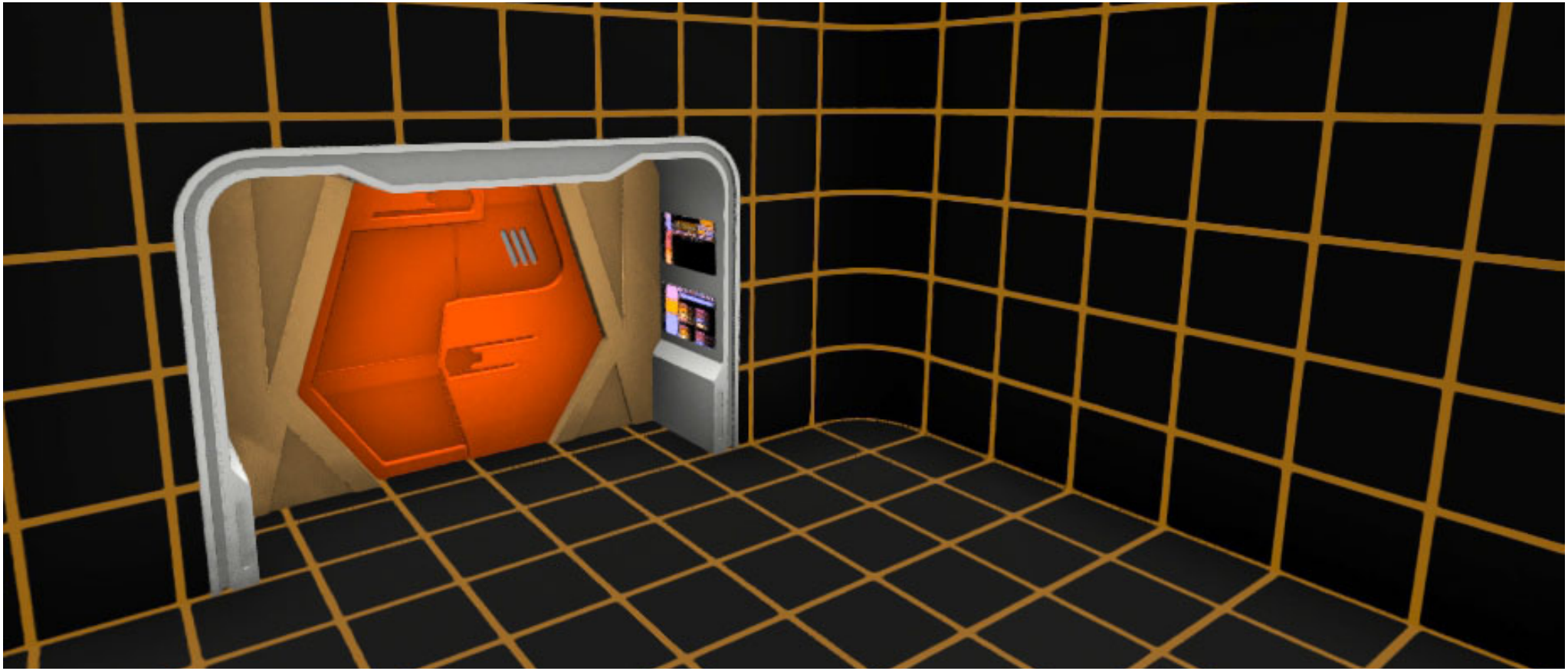
Inspired by Chang et al. 2006, Hurlburt & Geldreich 2017

Primary rays

Inspired by Flynn 2016

Some early results on our data structure…

PRIMARY RAYS FROM LIGHT FIELD PROBES



PRIMARY RAYS FROM LIGHT FIELD PROBES

PRIMARY RAYS FROM LIGHT FIELD PROBES

Light Field Probes

CONCLUSIONS

Addressed real-world problems identified by game developers:

- Light & shadow leaks
- Discontinuities & occlusions
- Authoring time/cost

First real-time ray tracing of full light field with occlusion ← longer-term significance

Prefiltered visibility irradiance probes ← shorter-term significance

Spatio-temporal denoising ← ad hoc, but always relevant

See the paper and website

MORE DETAILS & RESULTS ONLINE

Hierarchical grid optimization

Octahedral probe encoding and packing

Normal and depth compression

Irradiance backface weighting

Biasing to avoid self-shadowing

Parameter comparisons

Pre- vs. post-filtered irradiance visibility

Varying probe density

Varying probe resolution

Irregular probe grids

Tracing primary rays

https://casual-effects.com#research

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JT Hooker, Volumetric global illumination at Treyarch, SIGGRAPH 2016 Courses


Without visibility, 3-bounce lighting


128² visibility, 3-bounce lighting


32² visibility, 3-bounce lighting


$\underline{2}^2$ visibility, constant variance, 3-bounce lighting

IRRADIANCE

20 years ago, games added “ambient light” and “environment map reflections” to keep areas in shadow from being completely black.

Today, most game engines instead use indirect light equations similar to*

Complicated math, environment probes, and screen-space ray tracing

Material Lambertian color fetched from texture

Fresnel coefficient varies with view angle

$$\text{shadeIndirect}(...) = \text{lerp}(\text{microfacetStuff}, E(X,\hat{n}) \cdot \rho_L, F) / \pi$$

Irradiance: weighted average of incoming indirect light from all directions. Changes (very slowly) with position *X* and surface normal *n*.

* They are actually factored into lookup textures of precomputed integrals in most engines, but that’s not important for today

ENVIRONMENT MAP

LIGHT FIELD PROBE RAY TRACE

IRRADIANCE RESOLUTION REGIMES

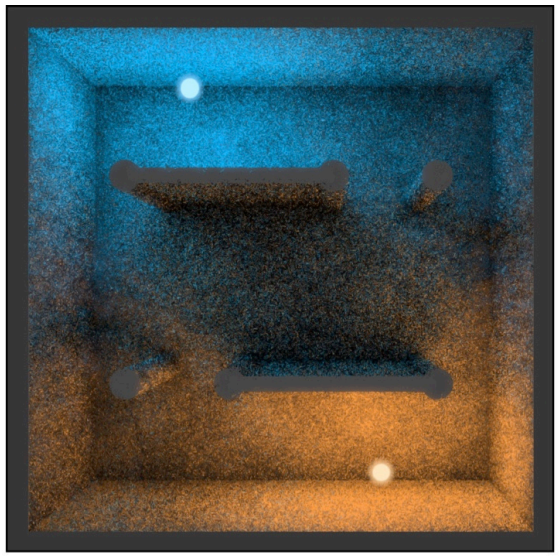
128^2 x 6 x 4 B: r & r^2 @ 16F. Robust to leaks and probe positions

32^2 x 6 x 4 B: r & r^2 @ 16F. Robust to leaks, shadowing biased by probes

4^2 x 6 x 2 B: r, hardcode r^2. Some leaking, but better than state of the art at low cost

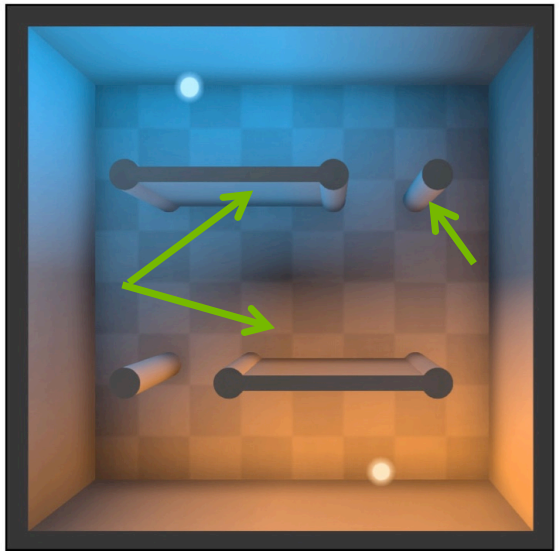
IRRADIANCE PROBE INDIRECT SHADOWING

Ray traced (13ms)

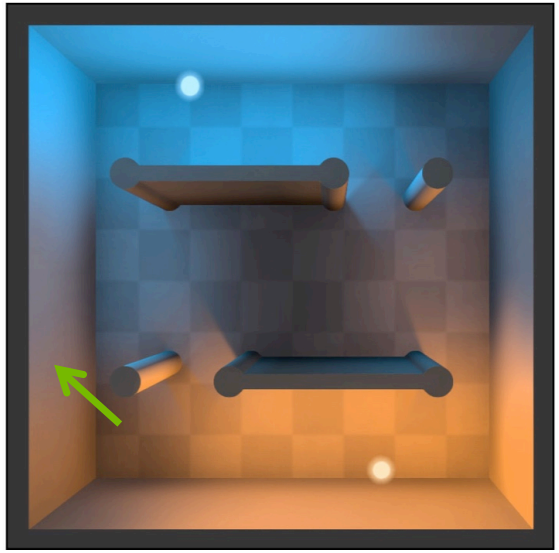


4 Probes

Before

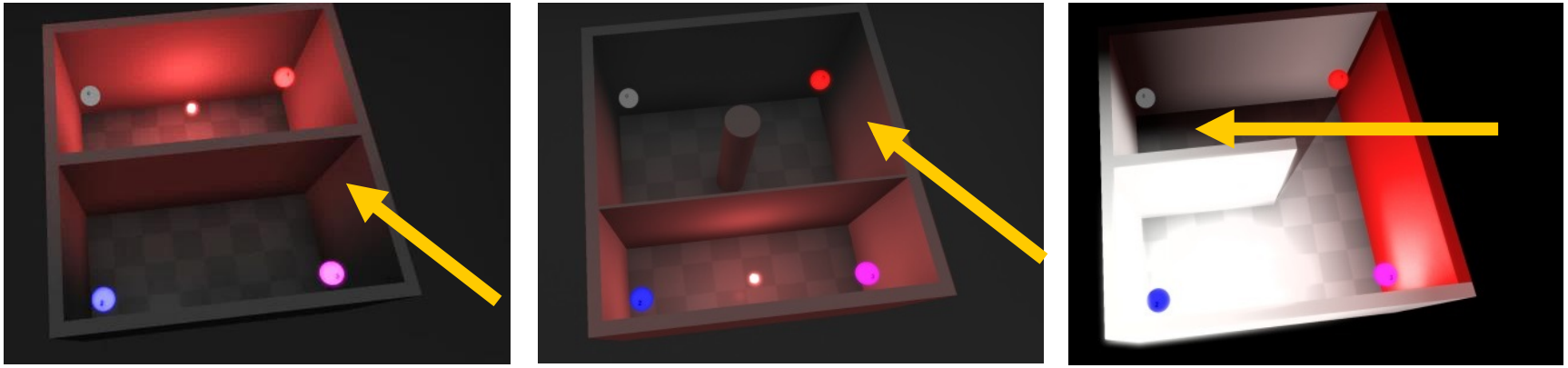


After: Prefiltered vis. (0.2ms)



PREFILTERED VISIBILITY MINIMIZES LEAKS

Before: No visibility



After: Our prefiltered visibility