Hardware-Accelerated Global Illumination by **Image Space Photon Mapping**

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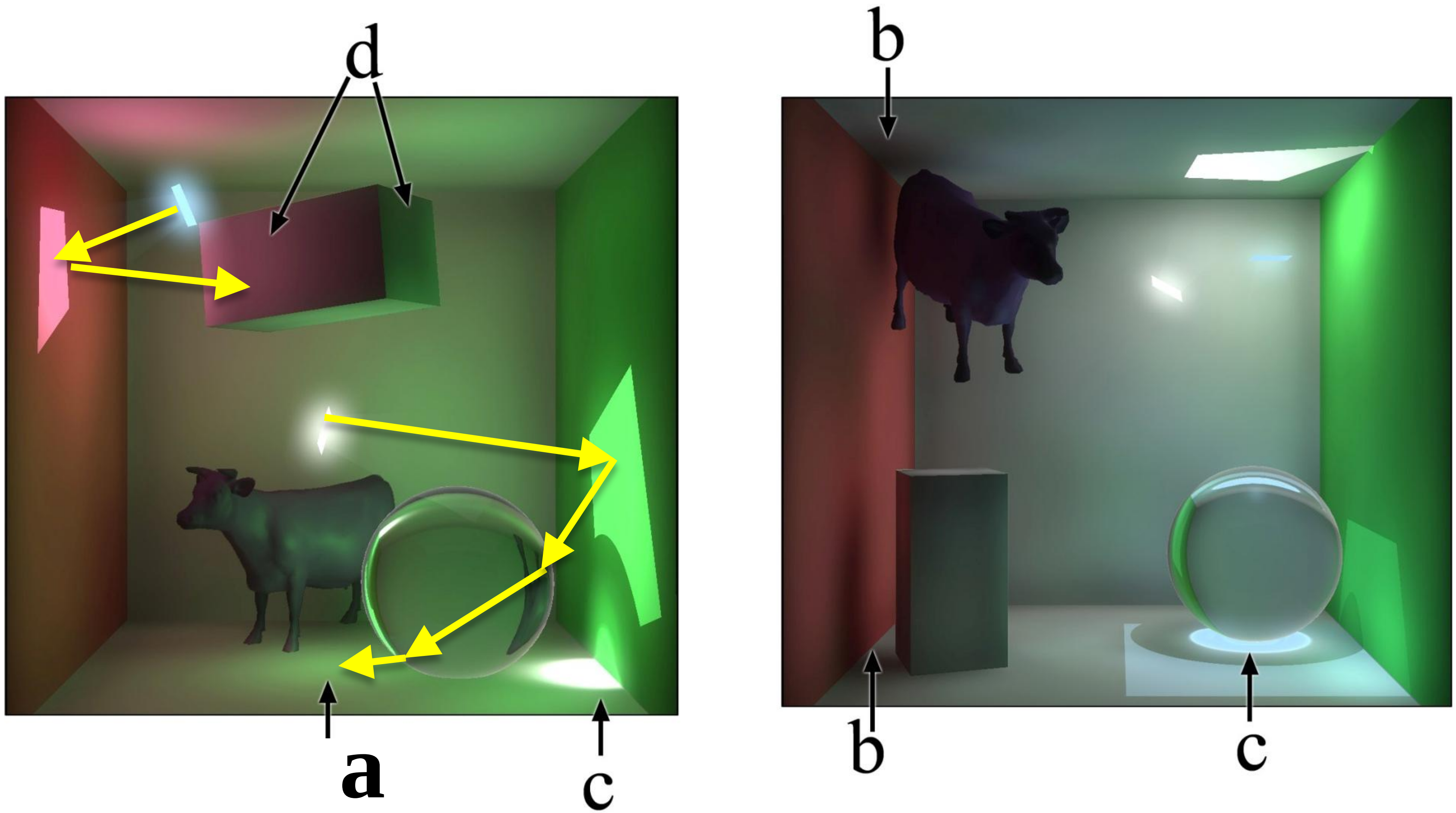
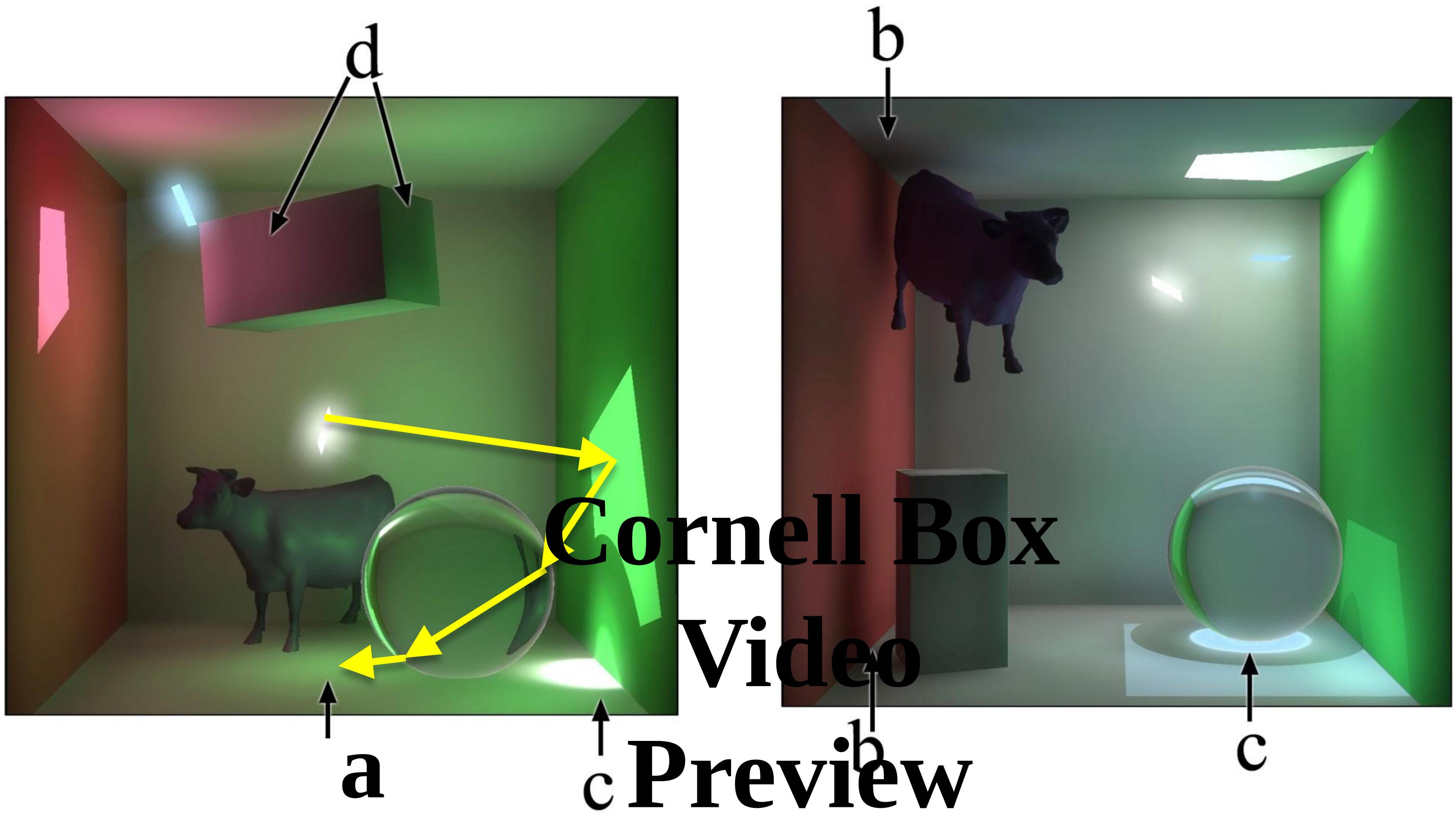
Goal: Global Illumination

Dynamic Global Illumination

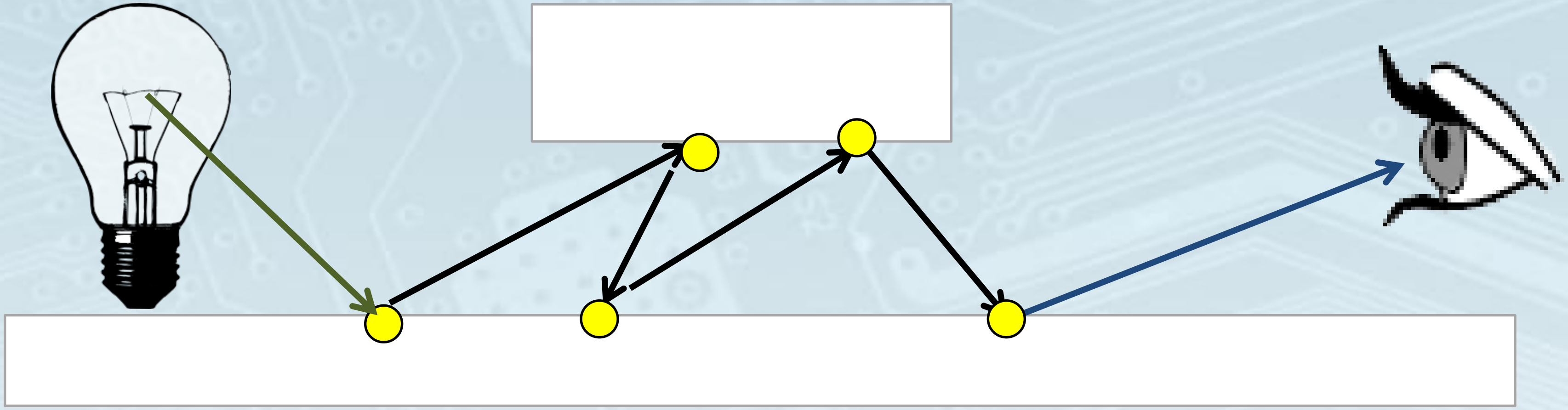


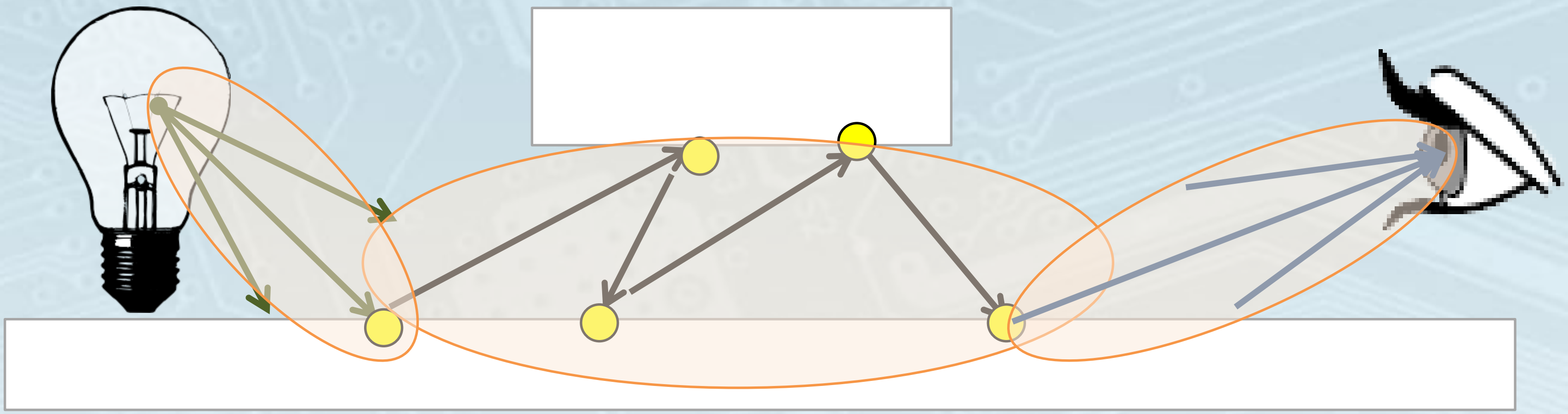
Goal: *Dynamic HD* Global Illumination



Cornell Box Video Preview

1920x1080, 20fps





Photon Mapping Time (seconds)

e.g., [Jensen 96, 01, Pharr and Humphreys 04]

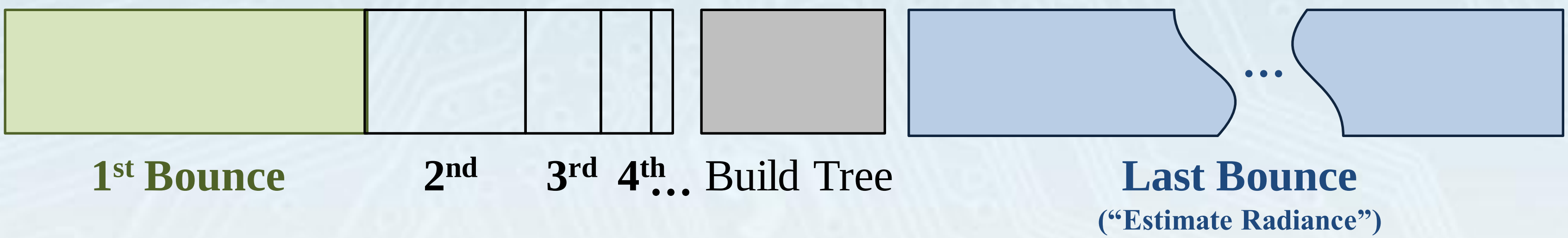
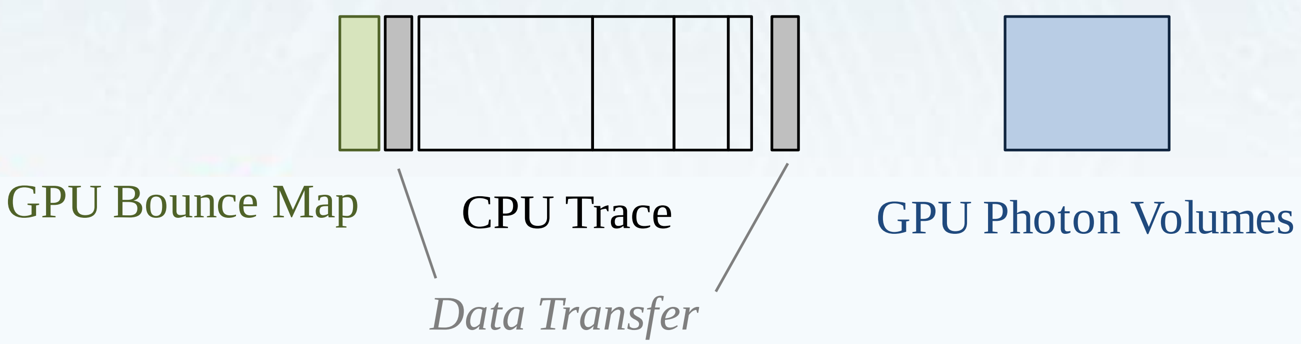


Image Space Photon Mapping (*milliseconds*)



Global Illumination Algorithms

Performance

Fast GPU methods

Diffuse caustics
[Kruger et al. 06, Shah and Konttinen 07, Wyman and Nichols 09]

Diffuse reflection
[Dachsbacher and Stamminger 05, 06, Dachsbacher et al. 07, Dong et al. 07]

Ambient occlusion
[Shanmugam & Arikan 07, Mittring 07]

Indirect shadowing
[Laine et al. 07, Ritschel et al. 08]

Best … or worst … of both

ISPM

[Parker et al. 99, Wald et al. 01, **Purcell et al. 03**, Lavignotte and Paulin 03, **Herzog et al. 07**, Horn et al. 07, Popov et al. 07, **Zhou et al. 08**, Robinson 09]

Path tracing [Kajiya 86]
MLT [Veach and Guibas 97]
Photon mapping [Jensen 96]
Stochastic ray tracing [Cook et al. 84]
Bidirectional path tracing [Veach and Guibas 94]

General CPU methods

Elegance

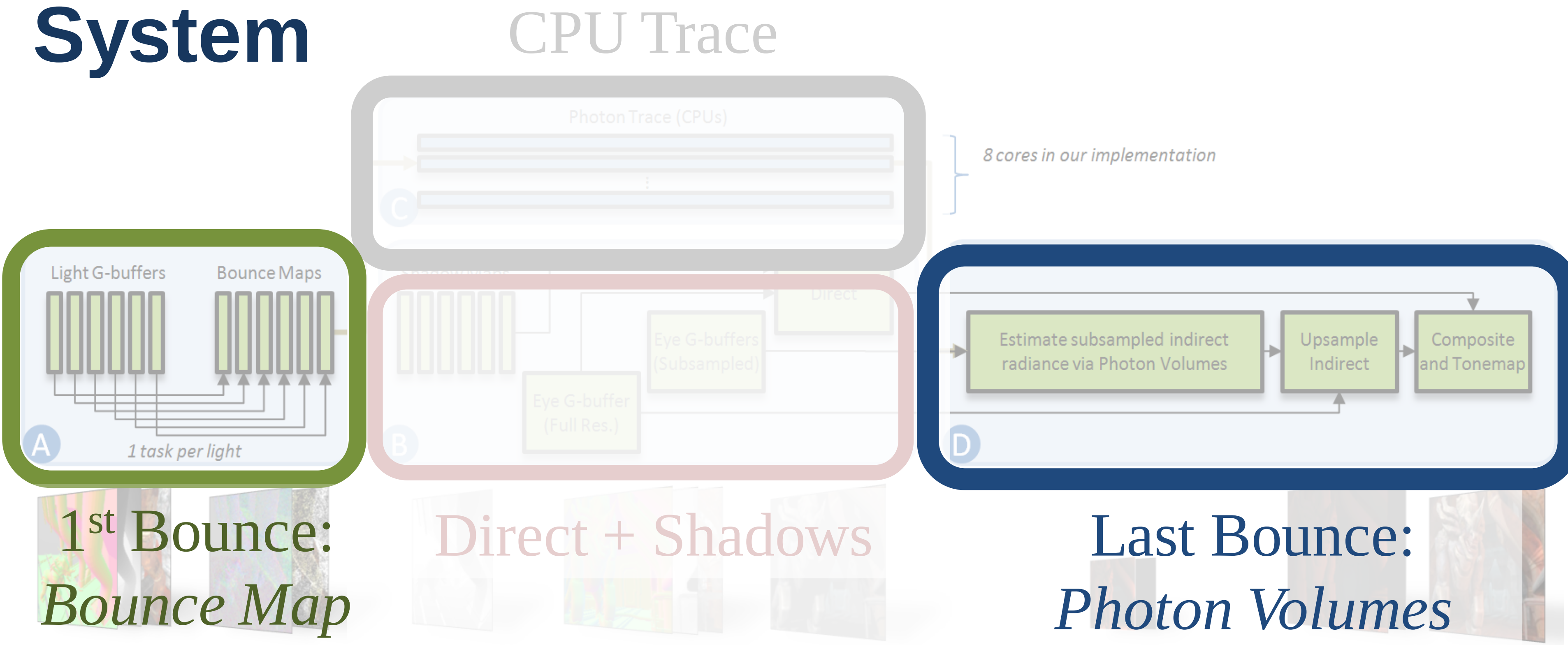
Assumptions

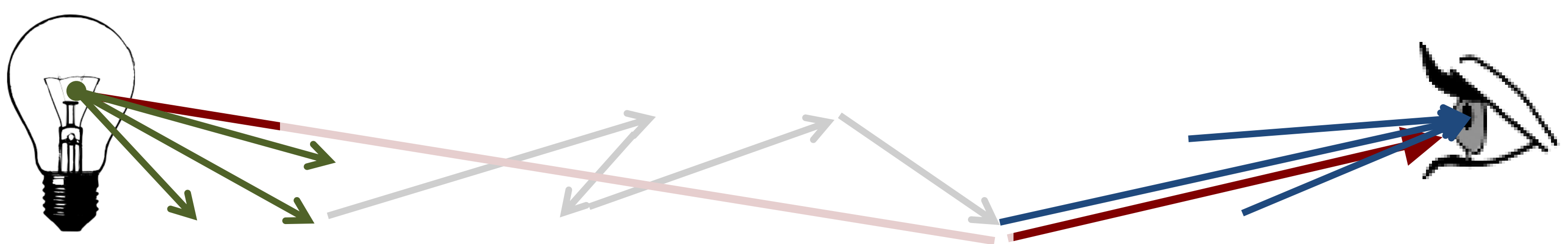
- Point light
- Pinhole camera

Limitations

- Clipping at near plane – annoying, but ignorable/avoidable
- **4x more expensive than direct illumination** (heavy fill consumption)
- Consistent, but biased (like photon mapping)

System


CPU Trace
Photon Trace (CPUs)
8 cores in our implementation
C
Light G-buffers
Bounce Maps
1 task per light
A
Direct
Eye G-buffers (Subsampled)
Eye G-buffer (Full Res.)
B
Estimate subsampled indirect radiance via Photon Volumes
Upsample Indirect
Composite and Tonemap
D
1st Bounce:
Bounce Map
Direct + Shadows
Last Bounce:
Photon Volumes



Bounce Map

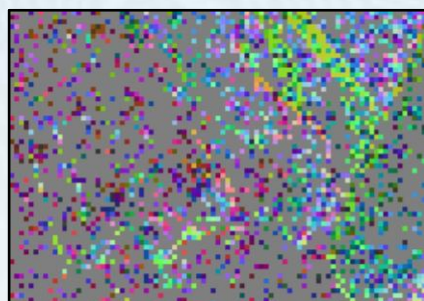
Position

Normal

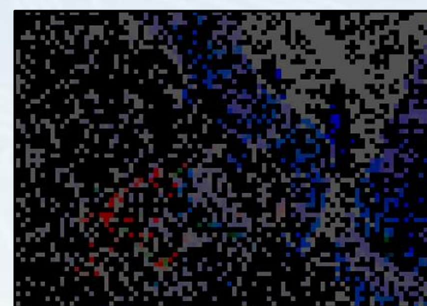
…

Material Parameters (BSDF)

Outgoing Power



Outgoing Direction

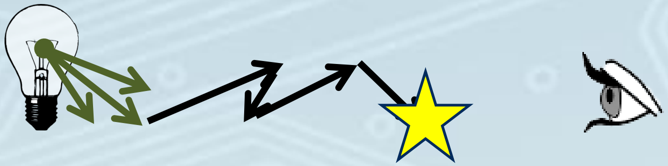


~~Refractive Index,~~
A Priori Differential Probability

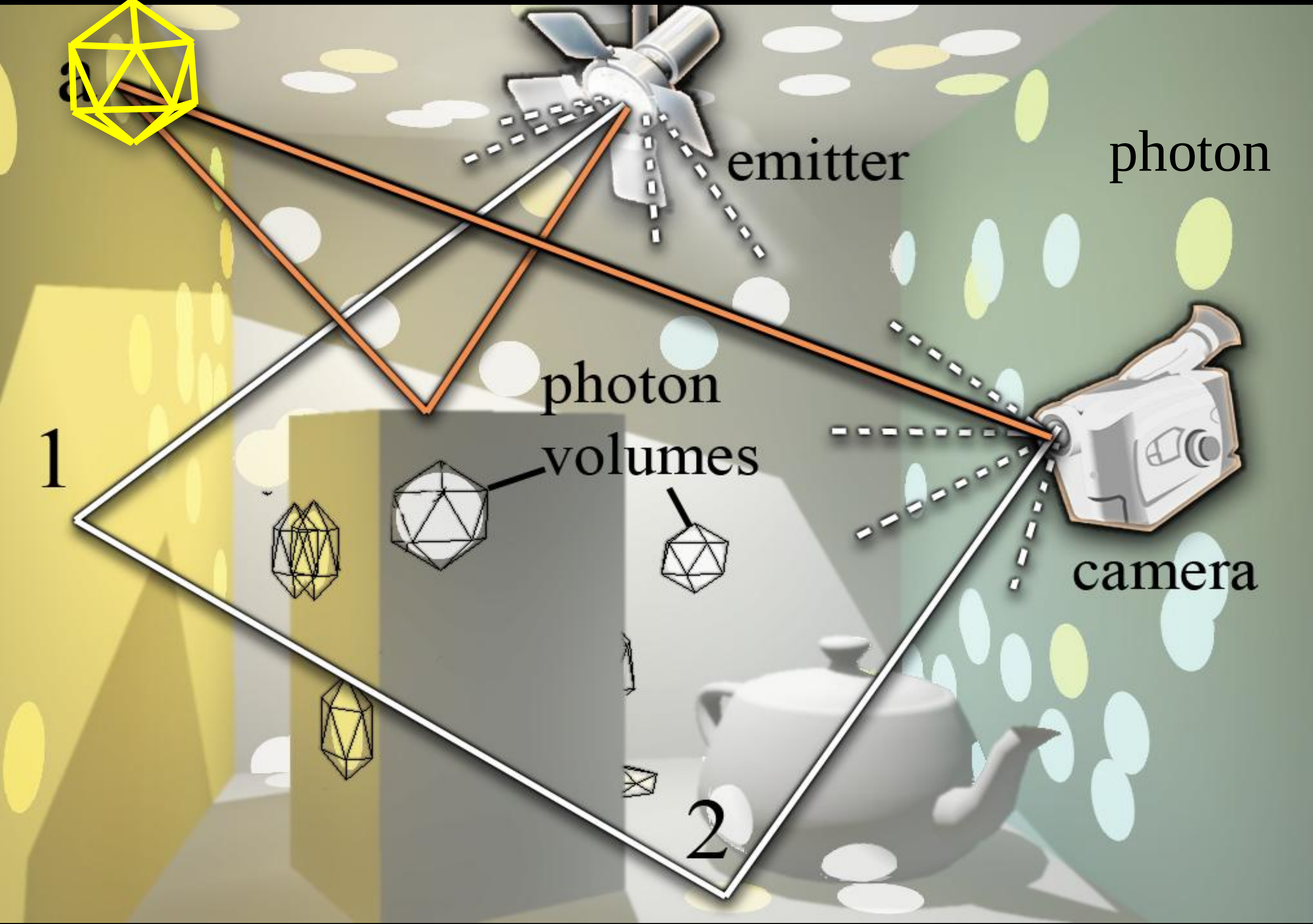
Run a CPU Trace

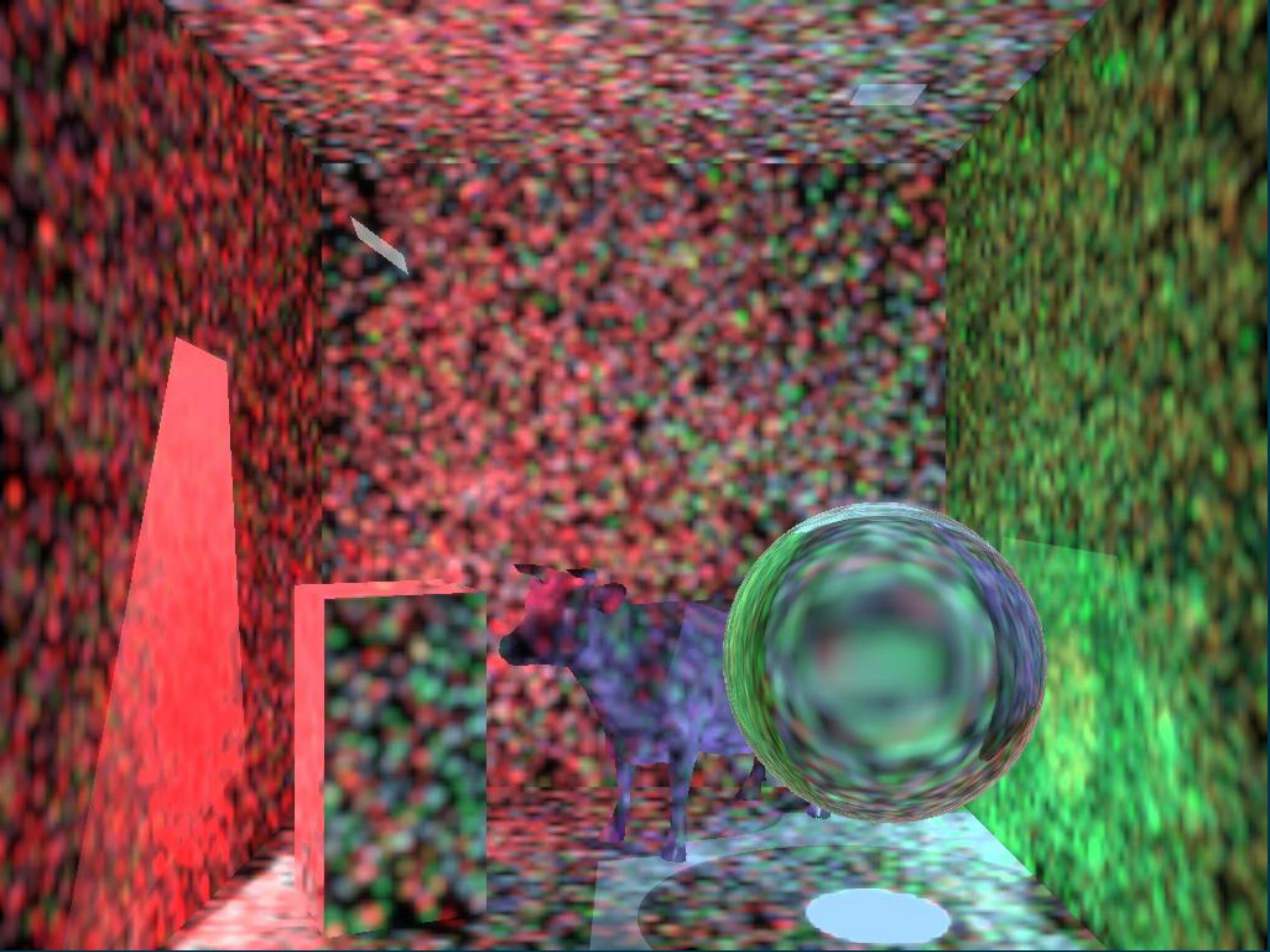
Compute Direct Illumination on the GPU

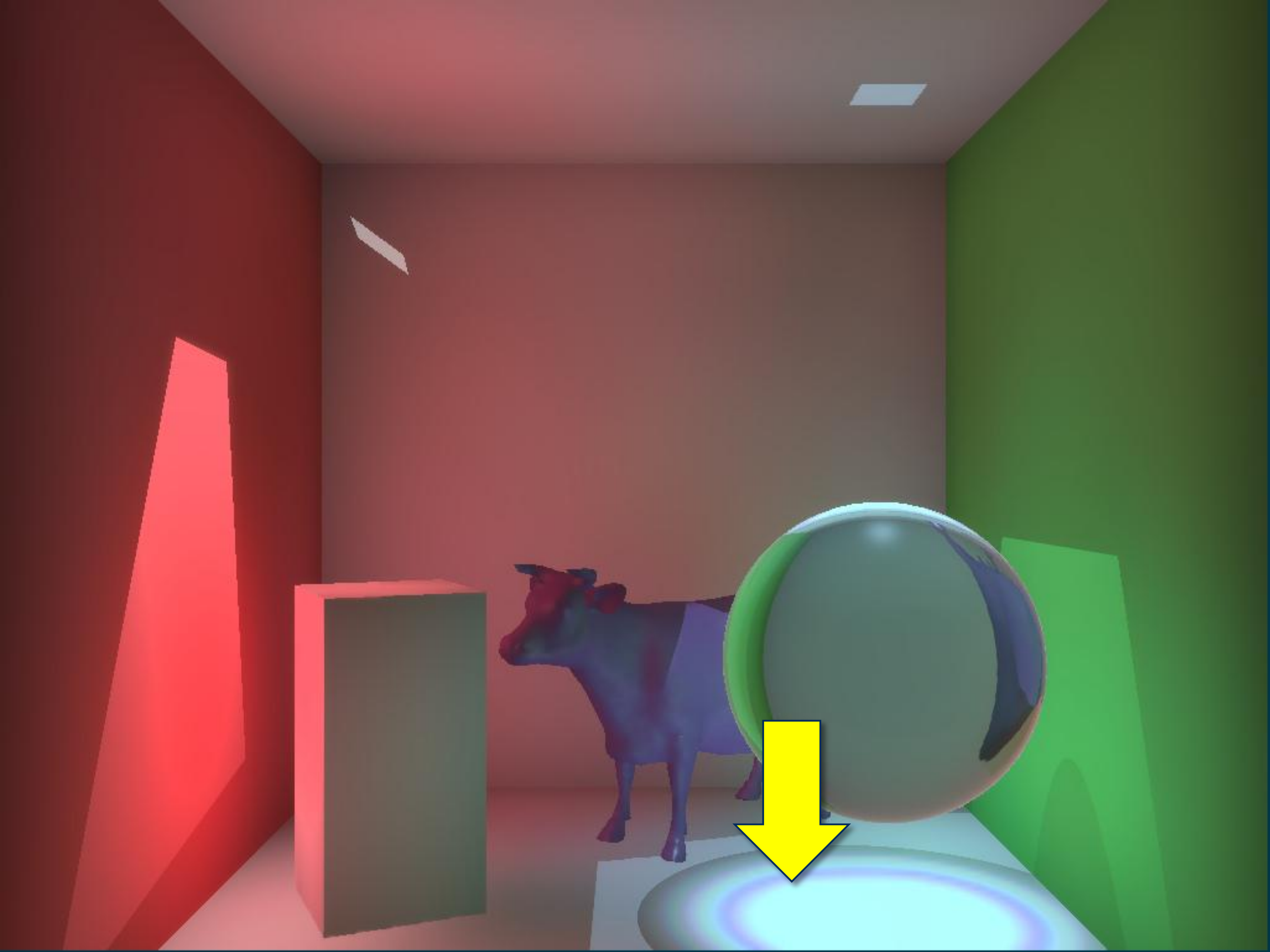
Radiance Estimate

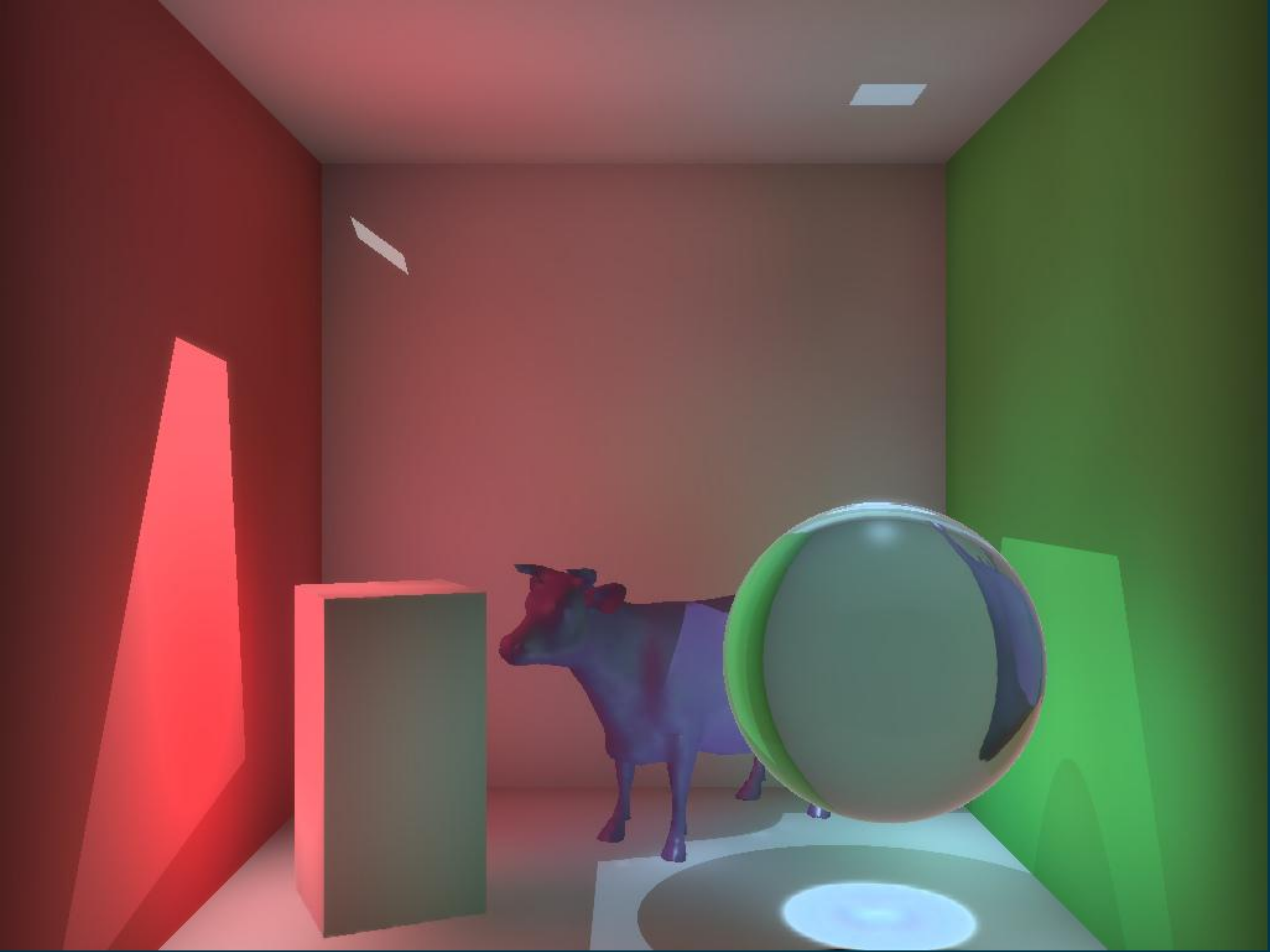


- Traditional photon mapping: *gather*
  - Per pixel
  - *k*-NN search in *k*-d tree
  - World-space (3D)
- Image-space photon mapping: *scatter*
  - Per photon
  - Hardware rasterization using photon volumes
  - Image space (2D)


a
emitter
photon
photon
volumes
1
camera
2







Photon Volumes

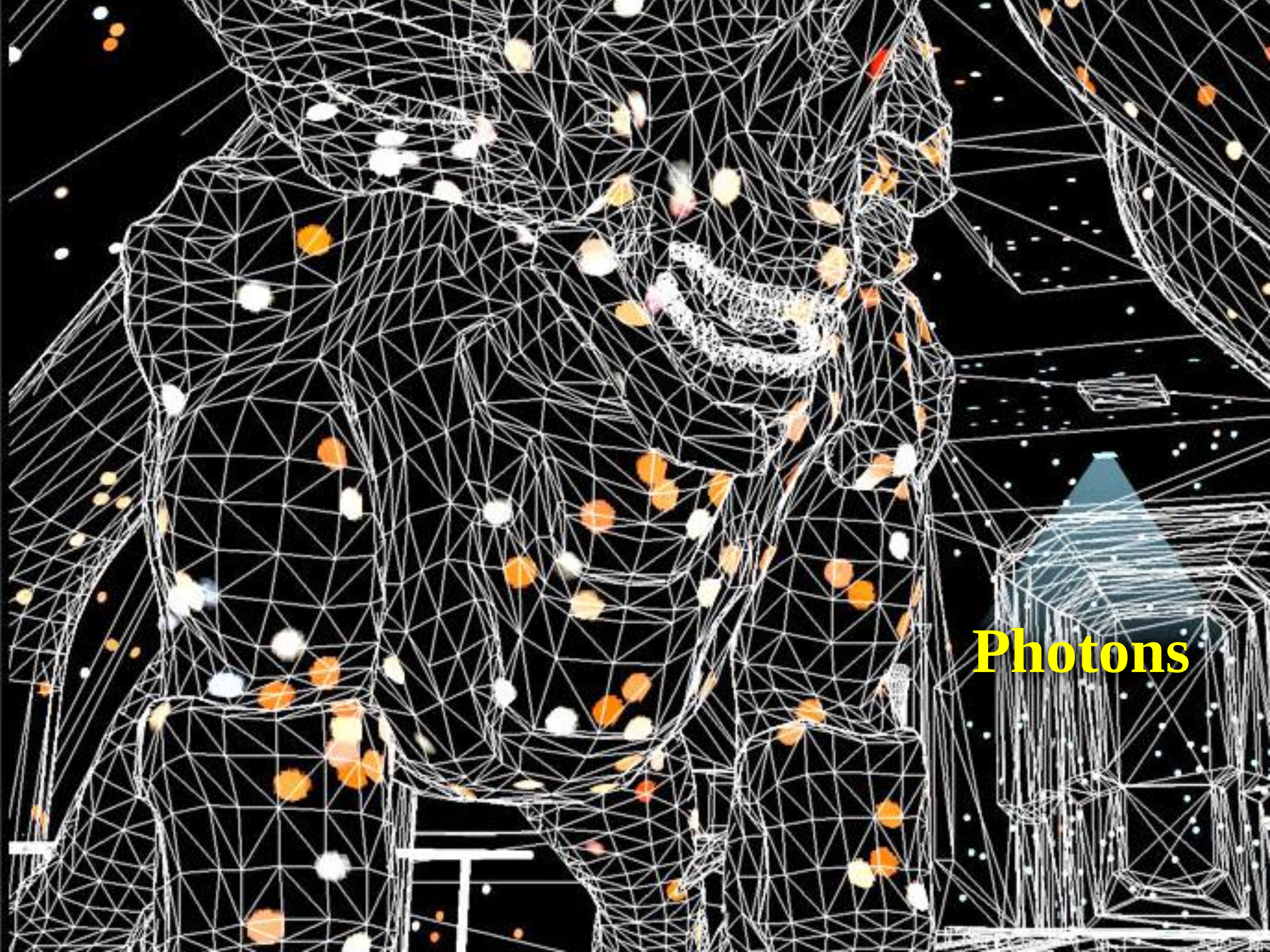
- Invoke an illumination contribution on all pixels for which a photon might be a valid estimate of incident radiance

- *Not virtual point lights (a.k.a. instant radiosity)*
- *Not 2D splatting*

Results

All at 1920 x 1080
No LOD
Lit from scratch every frame


Direct Only


Photons

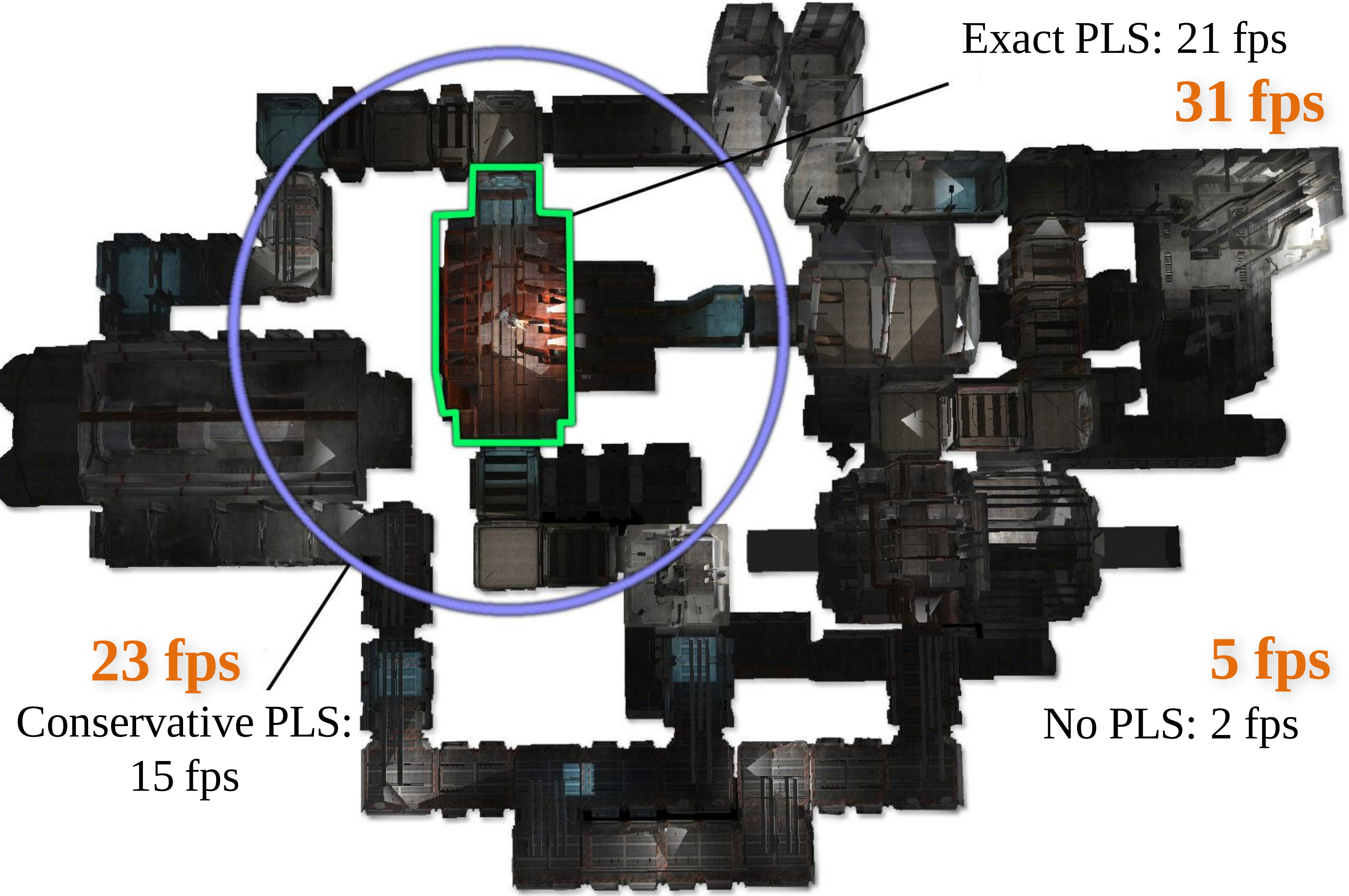

Indirect


Direct +
Indirect


Direct +
Ambient


Direct +
Indirect

Performance @ 1920 x 1080, 30 lights

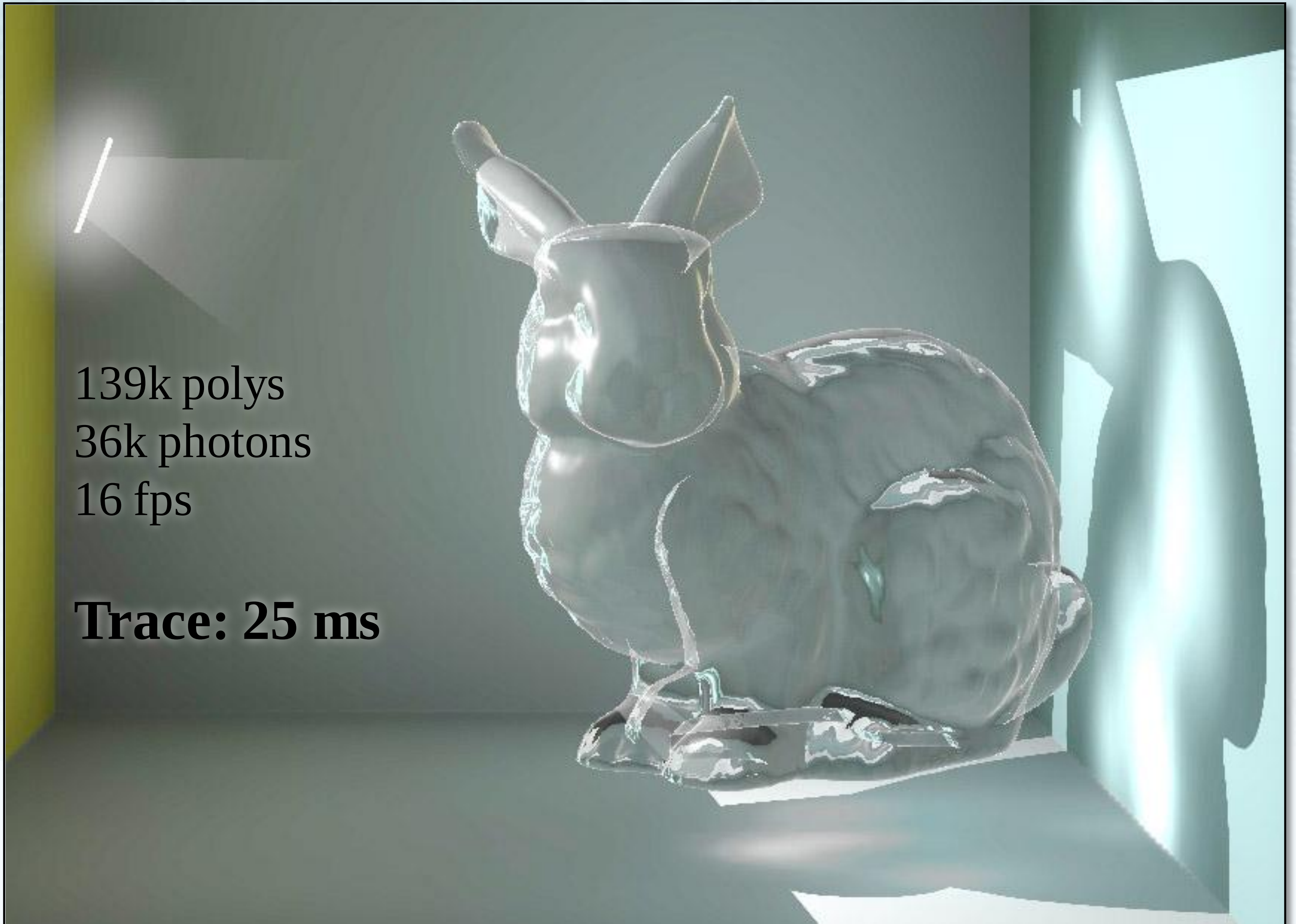


Performance Details

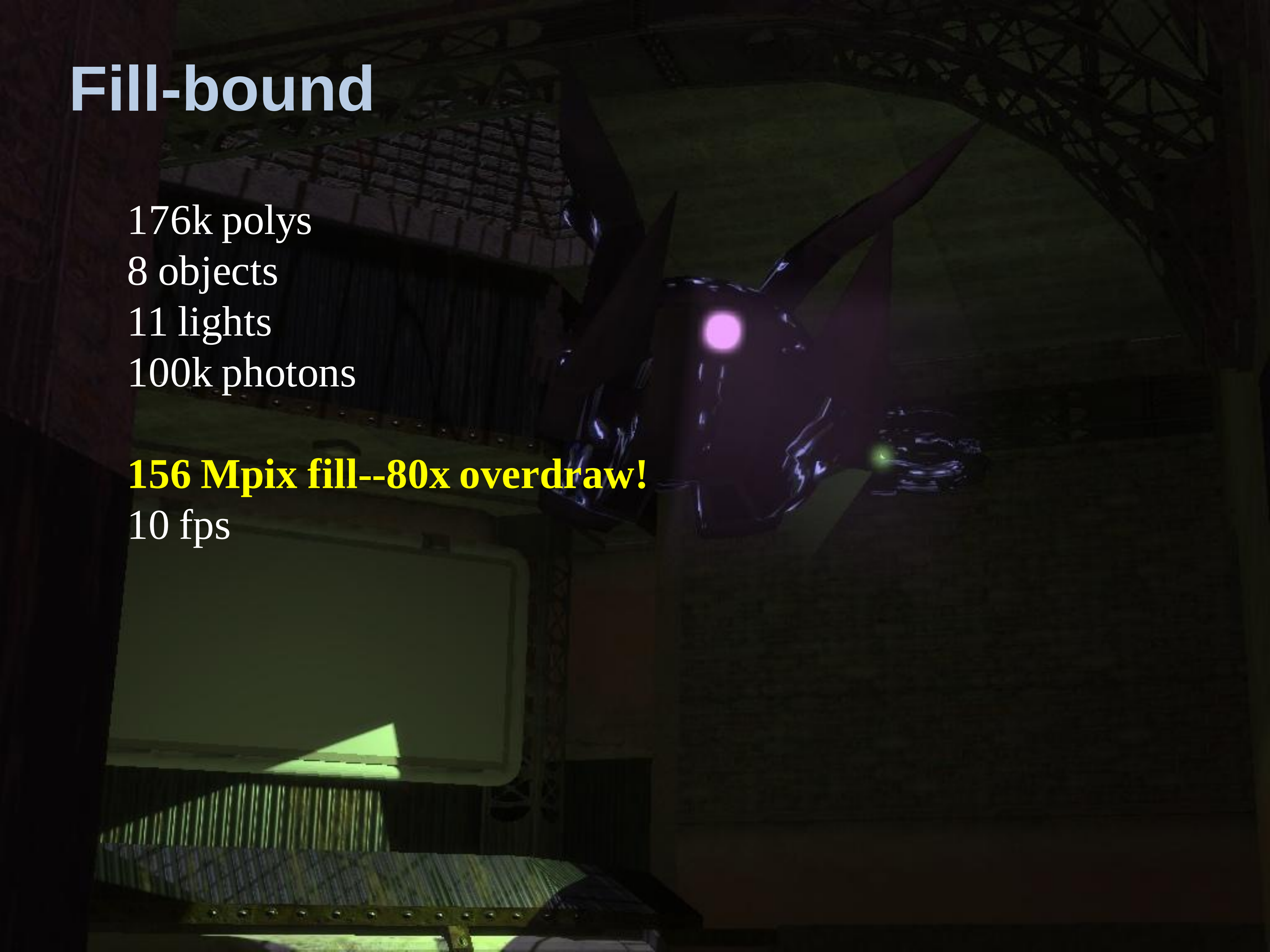
1: Scene	2: Figure	3: Polygons	4: Static Polys	5: Dynamic Polys	6: Dynamic Objects	7: Emitters	8: Emitted Photons	9: Indirect Bounces	10: Resolution	11: Subsampling	12: Total Photon Hits	13: Stored Photons	14: GPU Direct + Shadow Maps + Mirror + Transparency (ms)	15: GPU Bounce Maps (ms)	16: All CPU <-> GPU Copies (ms)	17: CPU Trace (ms)	18: GPU Radiance Estimate (ms)	19: Direct Only FPS	20: Full Global FPS
Ironworks (Car)	1	161,612	141,492	20,120	20	2	8,448	1	1920x1080	4x4	7,162	3,450	14.2	0.1	6.2	17.2	8.1	121.8	26.5
		161,612	141,492	20,120	20	2	8,448	3	1920x1080	4x4	8,846	5,134	14.2	0.1	6.3	24.8	10.2	121.8	20.6
Ironworks (Water)	8	121,962	66,734	55,228	1	1	26,896	1	1920x1080	4x4	37,806	18,852	8.9	0.1	13.5	49	8.2	159.9	13.4
		121,962	66,734	55,228	1	1	40,000	1	1920x1080	2x2	56,689	28,273	9	0.1	19.7	72.7	16.9	159.9	8.7
NS2 (Cargo Bay PVS)	13	73,081	58,319	14,762	1	4	20,356	3	1920x1080	6x6	12,228	7,143	12.5	0.1	8	21.6	9.6	138.9	21.4
(Cargo Bay PVS)		73,081	58,319	14,762	1	4	20356	1	1920x1080	6x6	10,004	4,919	12.6	0.1	7.6	16.1	8.8	138.9	26.7
(Circled PVS)		404,773	257,153	147,620	10	4	20,356	3	1920x1080	6x6	12,578	7,489	17.2	0.1	8.3	29.9	21.0	95.7	15.2
(Full Map)	9	1,190,405	880,403	310,002	21	30	95,948	3	1920x1080	6x6	97,982	61,000	150.2	0.7	67	284.4	14.5	6.5	2.0
Glass Sphere	11	8,034	4,022	4,012	2	5	26,640	2	512x512	6x6	19,343	10,941	2.2	0.6	9.8	8.9	3.8	199.0	38.8
		8,034	4,022	4,012	2	5	137,780	3	512x512	3x3	108,569	66,447	2.5	0.8	36.1	31.0	21.4	199.0	10.3
		8,034	4,022	4,012	2	5	18,000	2	1920x1080	6x6	12,935	7,319	9.0	0.3	7.6	4.0	11.3	163.0	34.1
Objects in Box	6	19,642	9,826	9,816	3	2	27,620	3	1920x1080	8x8	58,965	37,433	8.2	0.1	16.6	22.8	40.1	177.6	11.8
		19,642	9,826	9,816	3	2	27,620	2	1920x1080	10x10	52,047	30,515	8.3	0.1	16.1	17.2	23.2	177.6	15.8
Sponza Atrium	11	67,414	66,934	480	1	1	13,688	1	1920x1600	4x4	23,244	11,308	8.8	0.1	8.4	56.7	12.9	195.2	11.9
		67,414	66,934	480	1	1	6,240	1	1920x1080	4x4	10,573	5,136	8.8	0.1	5.4	28.2	7.2	195.2	22.4
Glass Bunny	7	277,814	138,912	138,902	1	1	29,928	2	1920x1080	6x6	55,139	32,767	9.8	0.1	15.1	45.4	35.3	137.0	9.6
		277,814	138,912	138,902	1	1	29,928	2	1920x1080	16x16	55,139	32,767	9.4	0.1	15.1	45.3	10.1		12.8
Caustic Ring	11	812	412	400	1	1	101,124	1	512x384	1x1	27,917	5,020	1.4	0.1	21.3	6.4	3.4	200	28
		812	412	400	1	1	324,900	1	512x384	1x1	89,919	16,030	1.4	0.3	63.5	20.1	9.6	200	10.9
	5	812	412	400	1	1	101,124	1	1920x1080	1x1	27917	5020	7.6	0.1	22.1	7.3	14.3	197.5	24.3

Key: **Bold: Corresponds to a figure** Highlight: Changed from first row Highlight: Bottleneck

Trace-bound



Fill-bound



176k polys
8 objects
11 lights
100k photons

156 Mpix fill--80x overdraw!
10 fps

Subsampling

- Joint-bilateral upsampling on normal and depth
- Subsample *incident* radiance, *not* pixel color (no diffuse surface assumption)

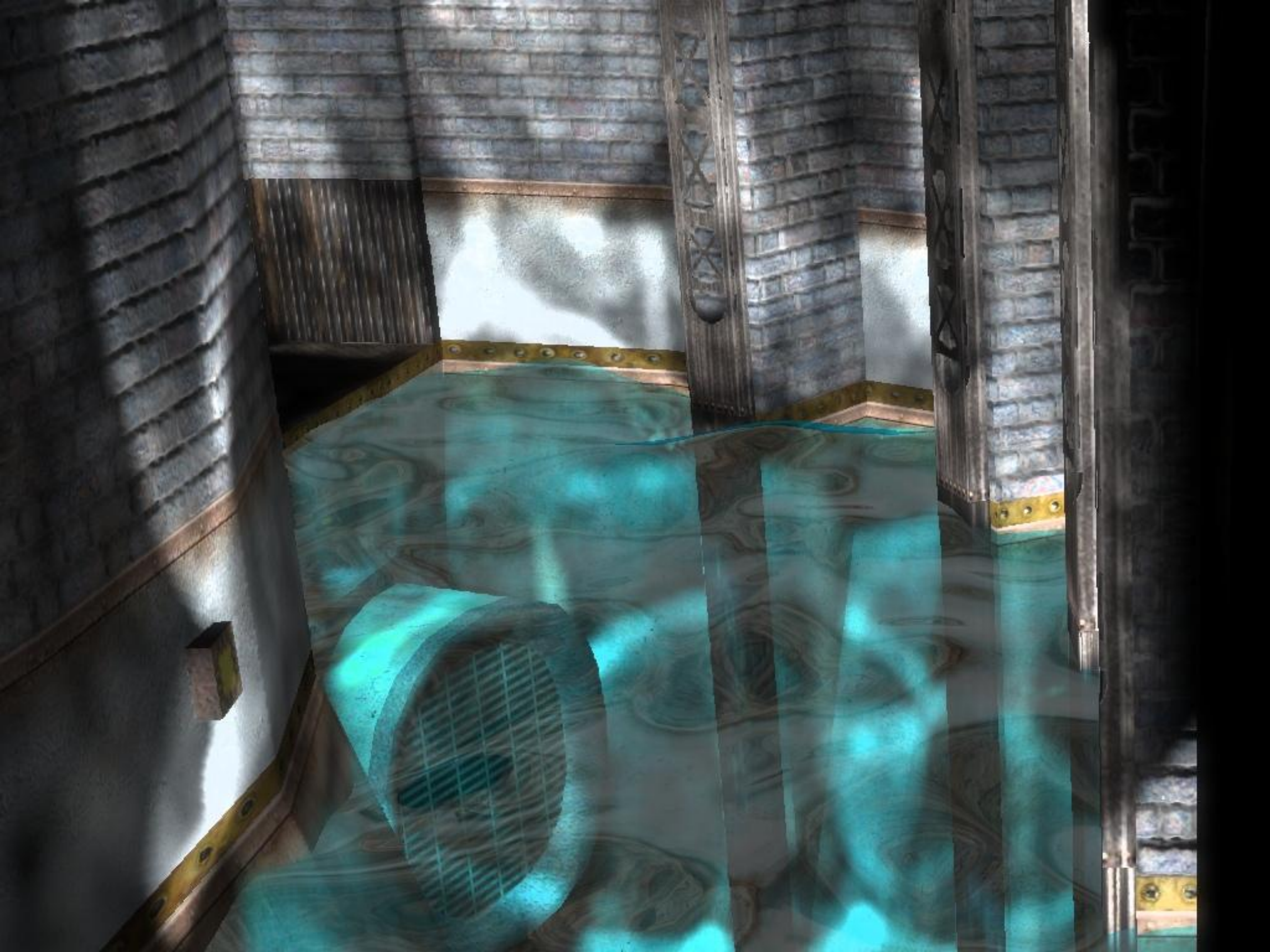
a) 16x16 Subsampling b) Bilinear weight c) × Normal weight d) × Depth weight e) 1x1 Sampling f) Error: 10 * |(d) - (e)|

Multi-bounce Video

Diffuse Interreflection Video

Caustics Video

Game Demo Video



ISPM Properties

- **General** physically-based method
  - Caustics, color bleeding, contact shadows, etc.
- As **fast** as *single*-phenomenon GPU algorithms
  - 1M poly scenes 1920x1080 @ 30 fps
  - …but lower quality for *that* phenomenon
- **Simple** implementation
  - ~600 statements in GLSL and C++

Thank You!

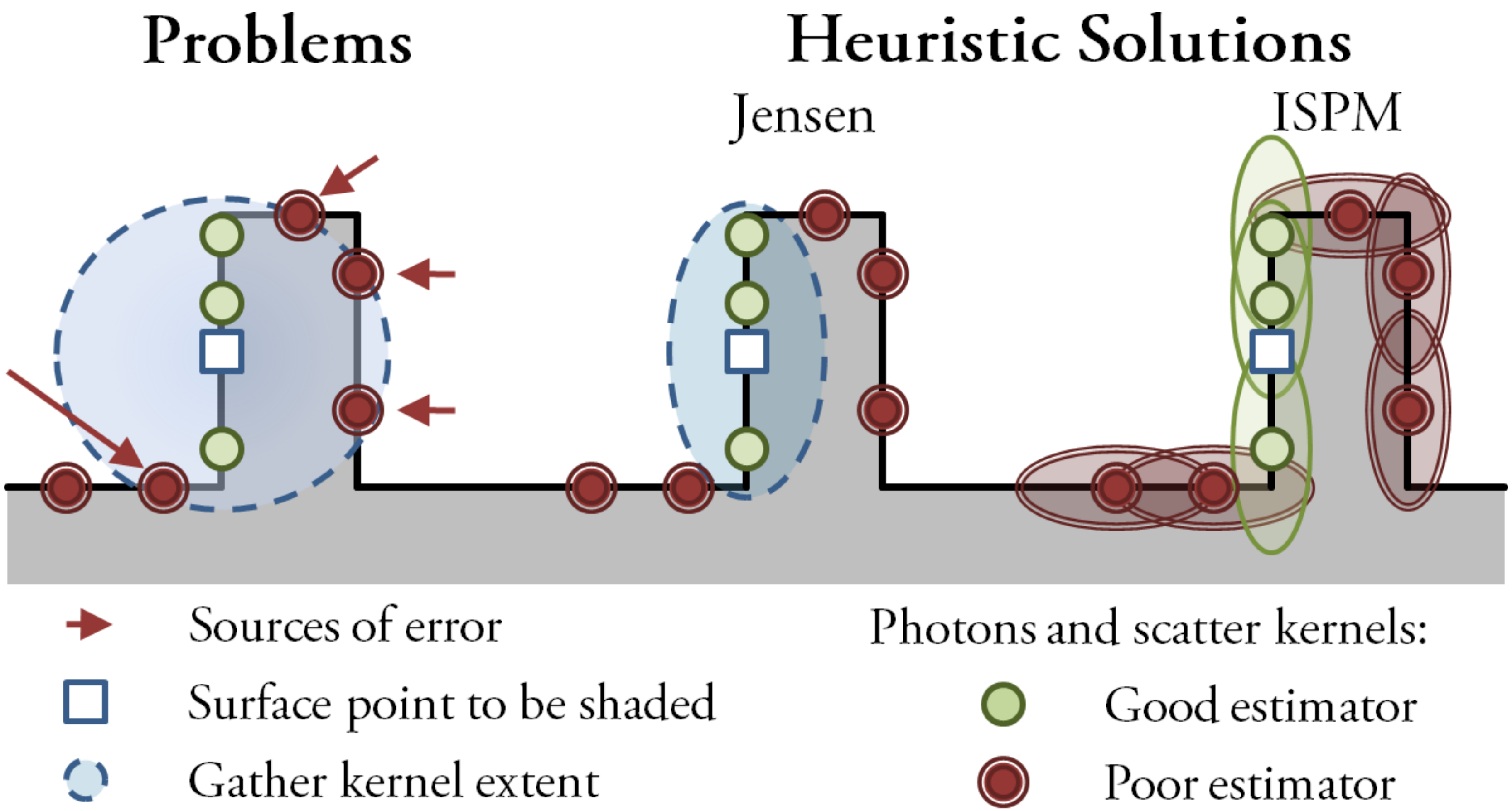
Download our source code

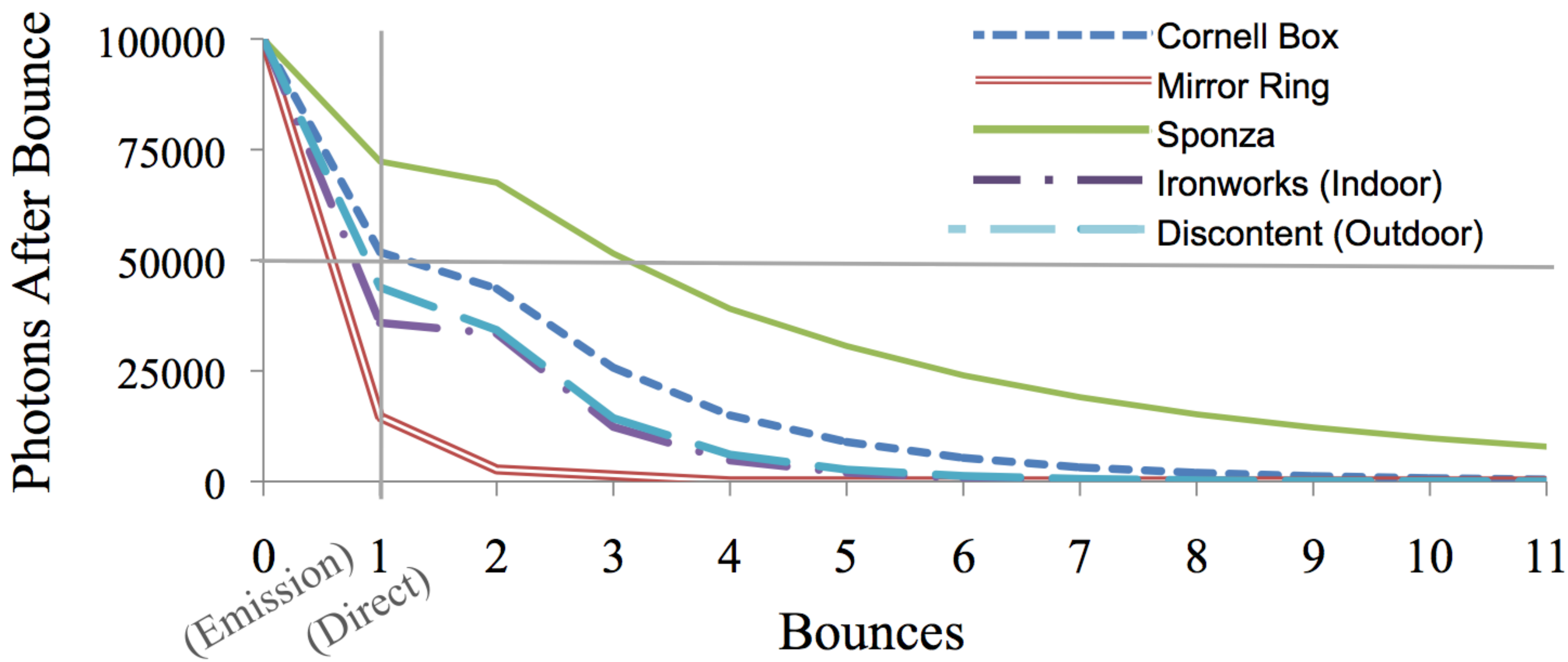
- ISPM: http://graphics.cs.williams.edu

- G3D: http://g3d-cpp.sf.net

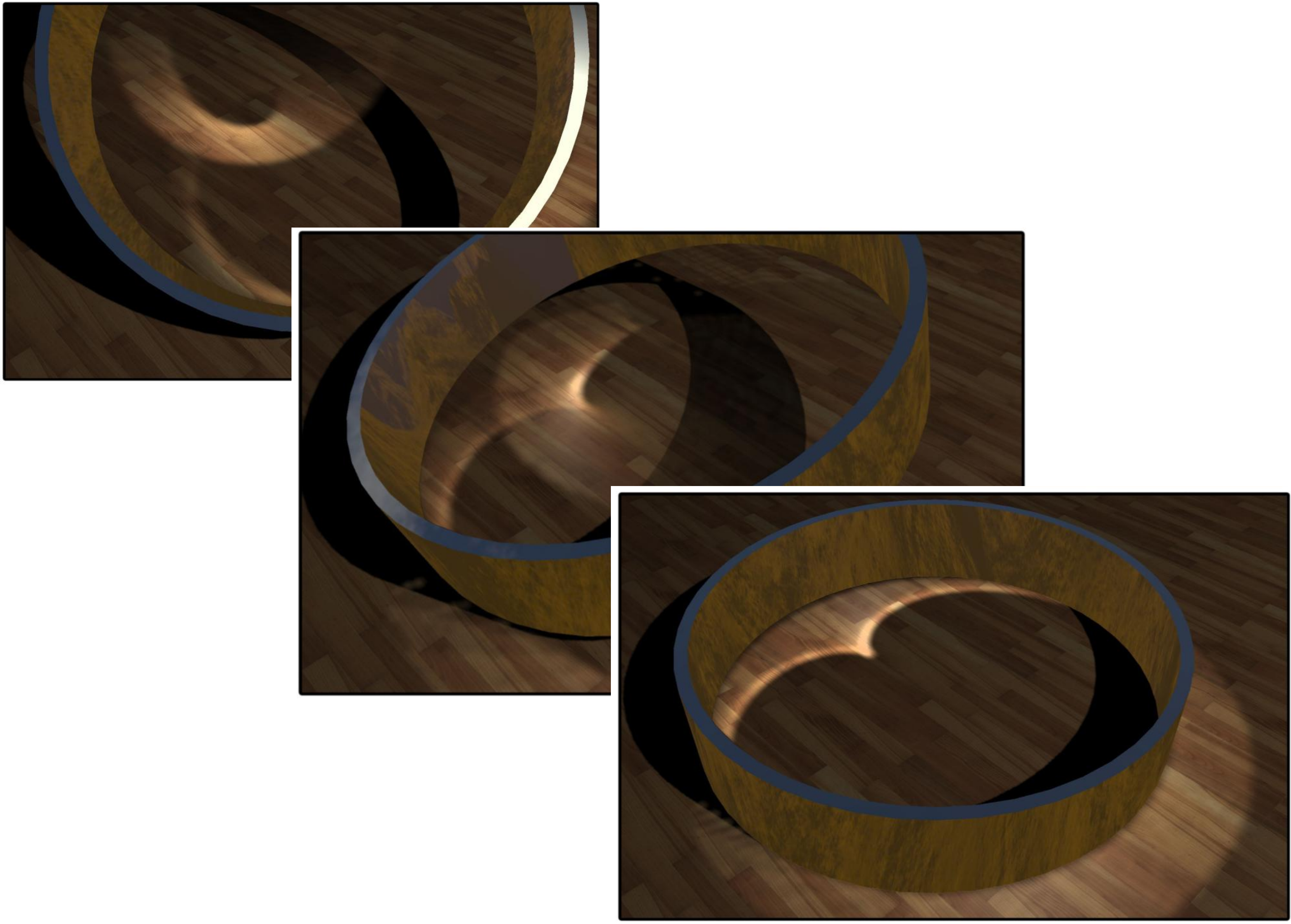
- Onos and NS Theme from *Natural Selection 2* by Unknown Worlds Entertainment
- Nexus 6 from *Tremulous*
- Bunny from The Stanford 3D Scanning Repository
- Ironworks from *Quake Live* by id Software
- Sponza Atrium by Marko Dabrovic

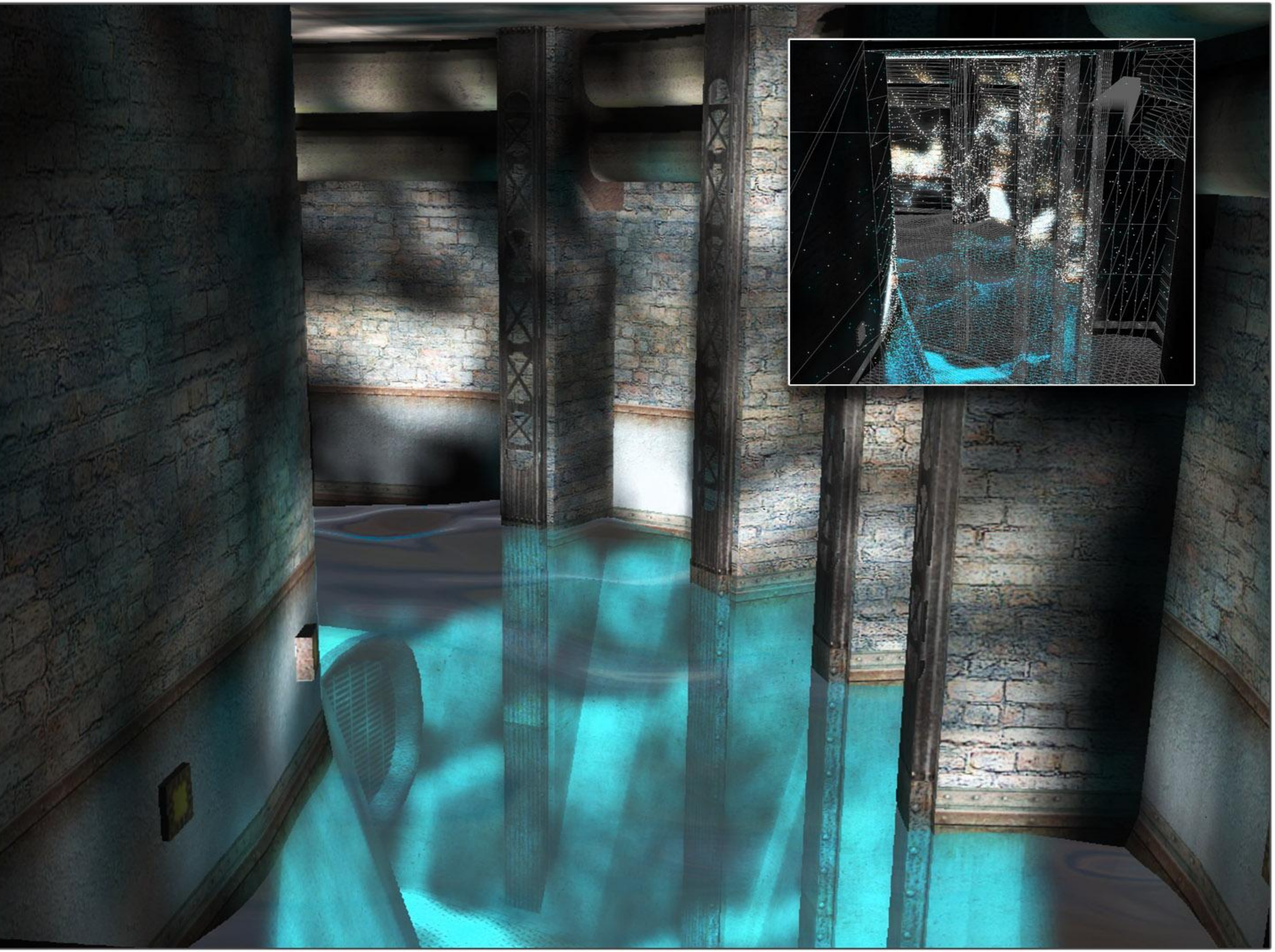
- Special thanks to Evan Hart, Qi Mo, Kefei Lei, Daniel Fast, Eric Enderton, and anonymous HPG09 reviewers


Problems
Heuristic Solutions
Jensen
ISPM
Sources of error
Surface point to be shaded
Gather kernel extent
Photons and scatter kernels:
Good estimator
Poor estimator



Photons After Bounce
100000
75000
50000
25000
0
0
(Emission)
1
(Direct)
2
3
4
5
6
7
8
9
10
11
Bounces
Cornell Box
Mirror Ring
Sponza
Ironworks (Indoor)
Discontent (Outdoor)





Radiance Estimate

$$L_o(\vec{s},\vec{\omega}_o) = \int f(\vec{x},\vec{\omega}_i,\vec{\omega}_o) * L_i(\vec{s},\vec{\omega}_i) * \max(0,\vec{\omega}_i,\vec{n})d\vec{\omega}_i$$

$$\Delta L_o(\vec{s},\vec{\omega}_o) = f(\vec{s},\vec{\omega}_i,\vec{\omega}_o) * \Phi_i * \max(0,\vec{\omega}_i \cdot \vec{n}) * \kappa(\vec{x}-\vec{s},\vec{n}_p)$$

ERT r =

$$\kappa(\vec{x}-\vec{s},\vec{n}_p) = \mathrm{texture1D}(\mathrm{gaussian}, t)$$

rho)

$$t = \frac{|\vec{x}-\vec{s}|}{r_{xy}}\left(1-\left|\frac{(\vec{x}-\vec{s})}{|\vec{x}-\vec{s}|}\cdot\vec{n}_p\right|\frac{r_{xy}-r_z}{r_z}\right)$$

Future Work

- Tracing on GPU
- Fill rate
- Shaping photon volume
- Game-specific optimizations and analysis
  - *The Cornell box is harder to render than Natural Selection 2!*