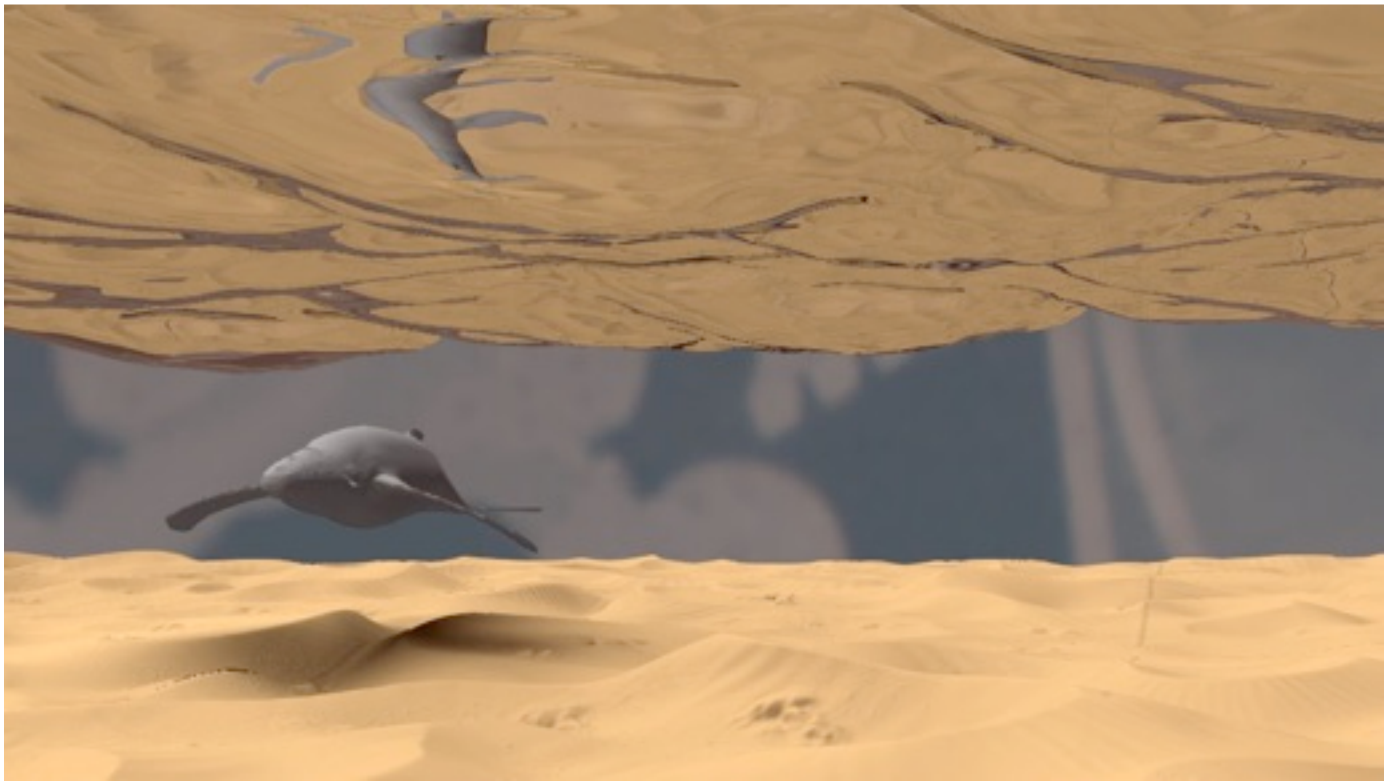
Practical Shading of Height Fields and Meshes using Spherical Harmonics Exponentiation

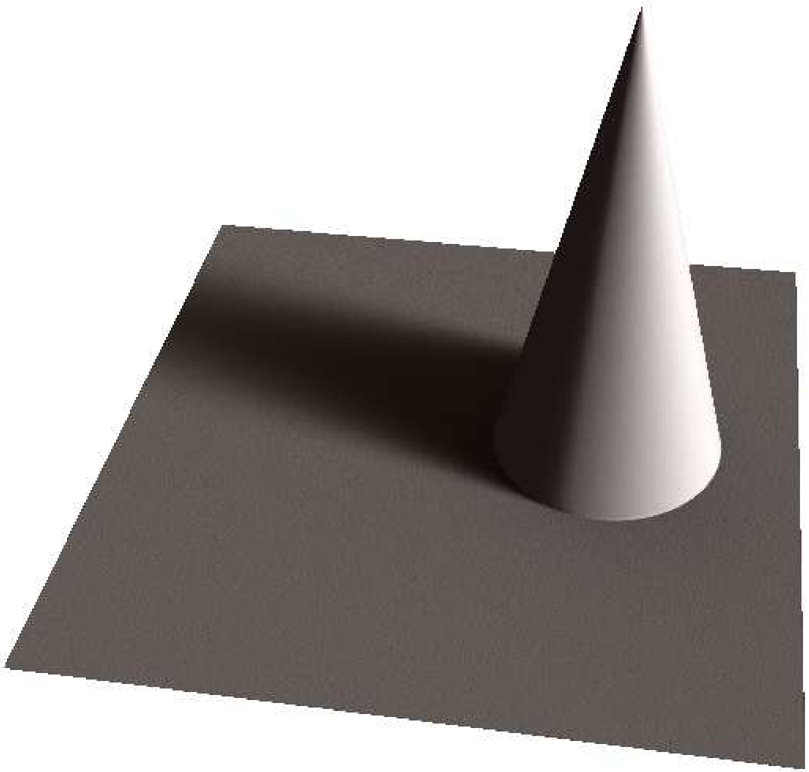


Aude Giraud

Derek Nowrouzezahrai

Université de Montréal

Goals & Motivation



[SN08]

[RWS*06;SGNS07]

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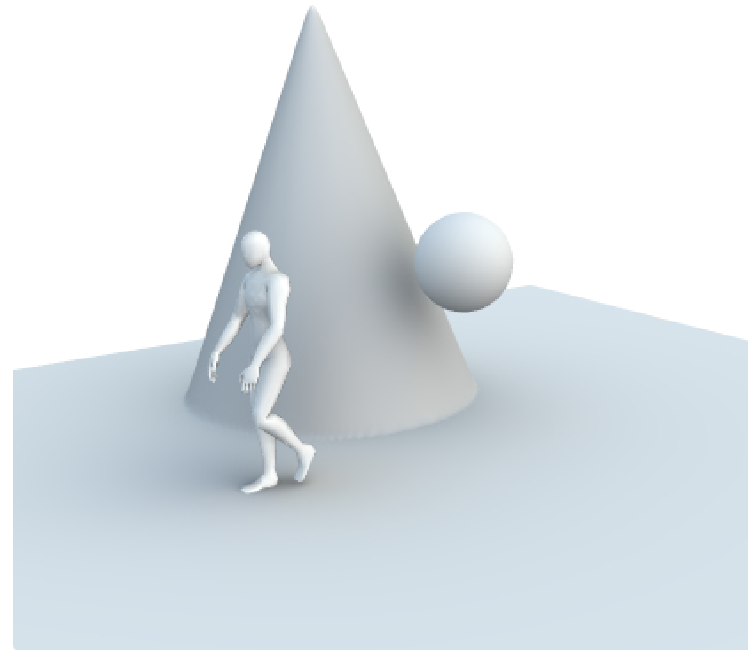

Our results

Contributions

- unifying SH exponentiation on HFs and meshes
  - dynamic geometry and HF visibility (no precomputation)
  - diffuse and glossy BRDFs in log SH

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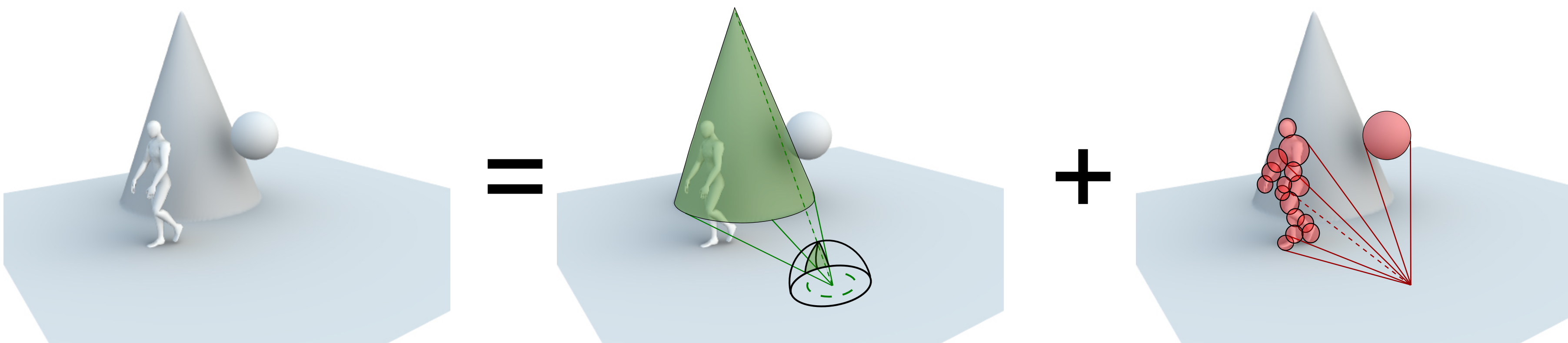

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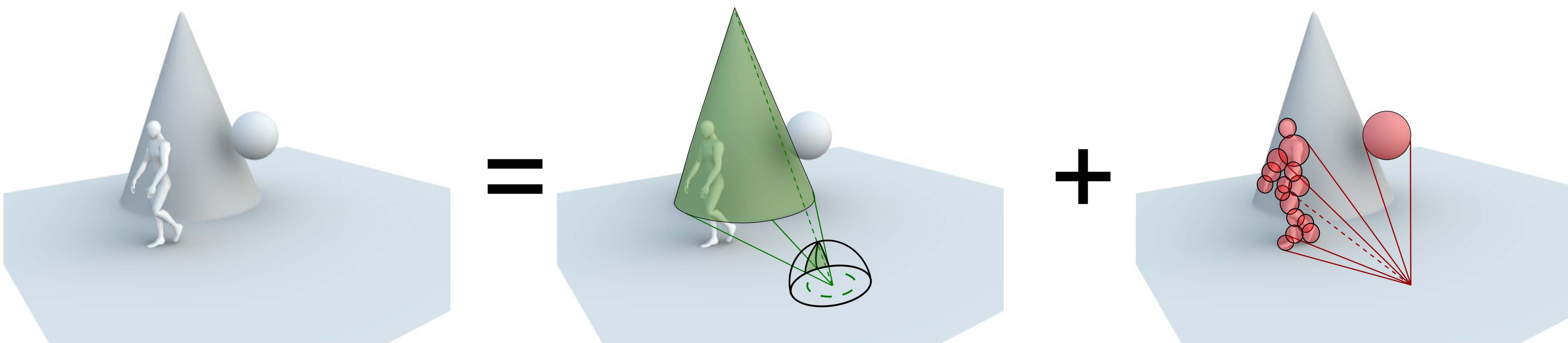

- real-time performance and simple implementation
- limitation: only ***soft direct illumination***
- applications:
  - landscape rendering (flight simulators, mapping/navigation)
  - interactive gaming

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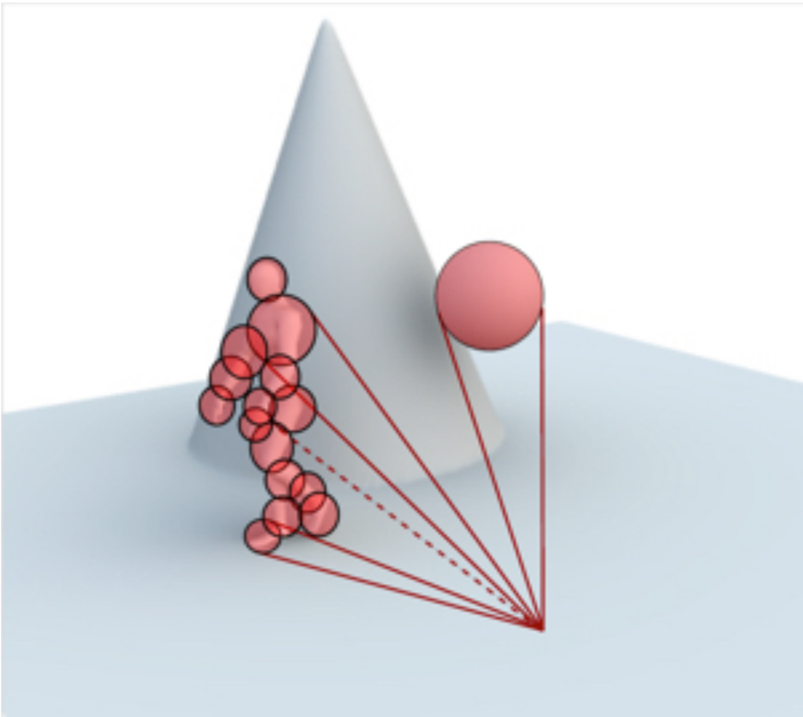

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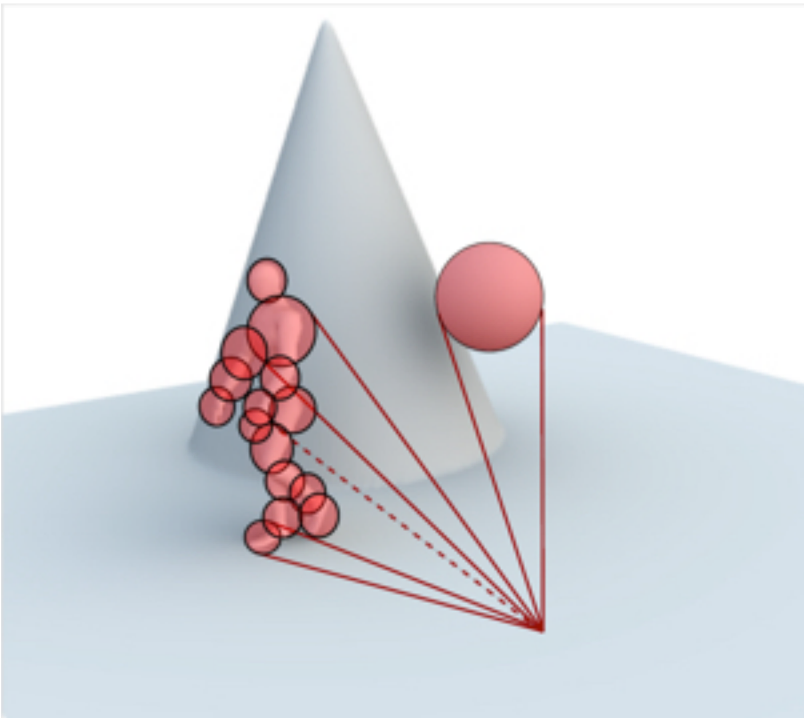

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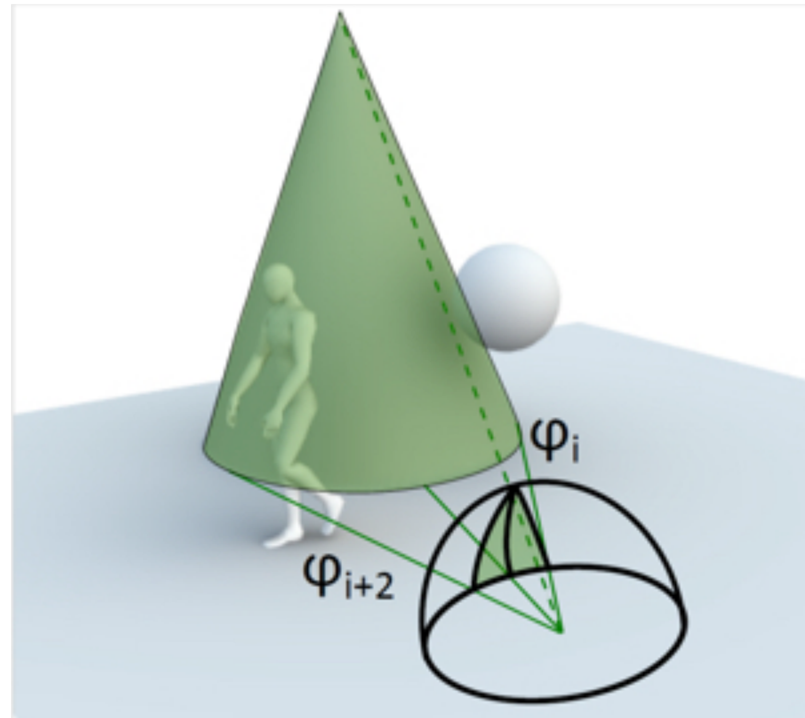

dynamic height field geometry

$$\mathbf{v}_{\log}^{\text{HF}}$$

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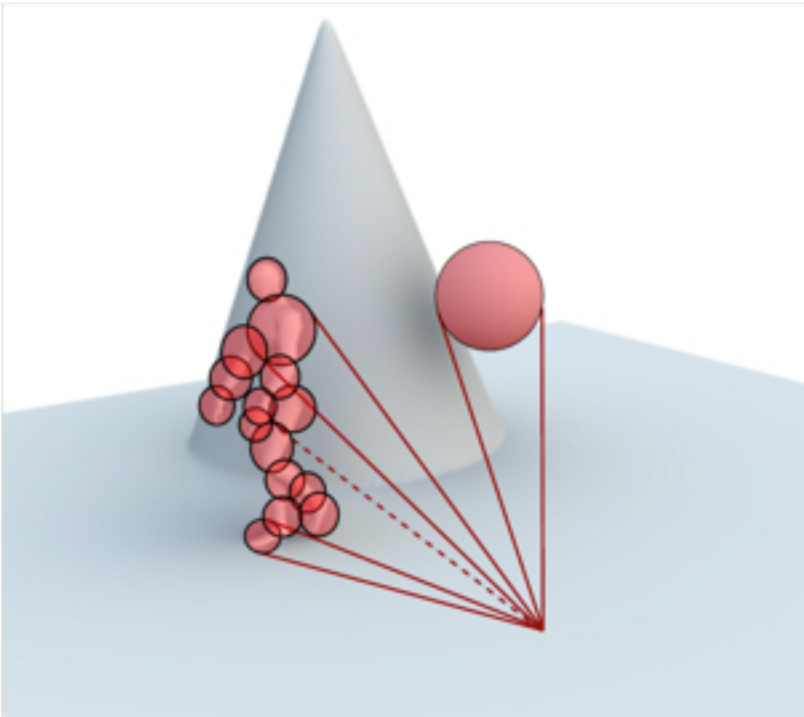
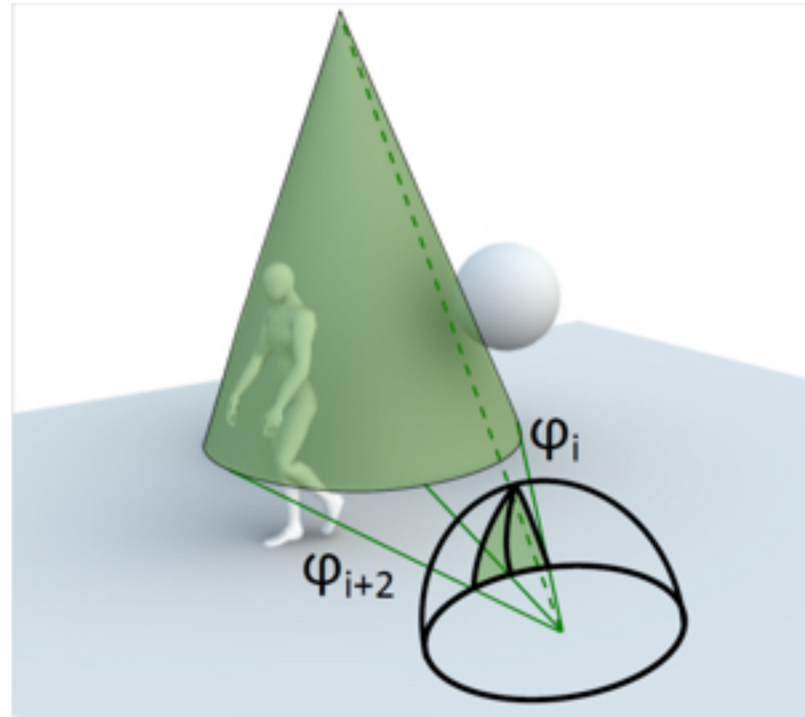


dynamic blocker "meshes"

$$\{\mathbf{v}^{0}_{\log}, \mathbf{v}^{1}_{\log}, \cdots, \mathbf{v}^{\mathrm{B\text{-}1}}_{\log}\}$$



dynamic height field geometry

$$\mathbf{v}^{\mathrm{HF}}_{\log}$$

- the **total** log-SH visibility vector is $\mathbf{V}_{\log} = \mathbf{v}^{\mathrm{HF}}_{\log} + \sum_{b=0}^{B-1} \mathbf{v}^{\mathrm{b}}_{\log}$

SH Exponentiation [RWS*06]

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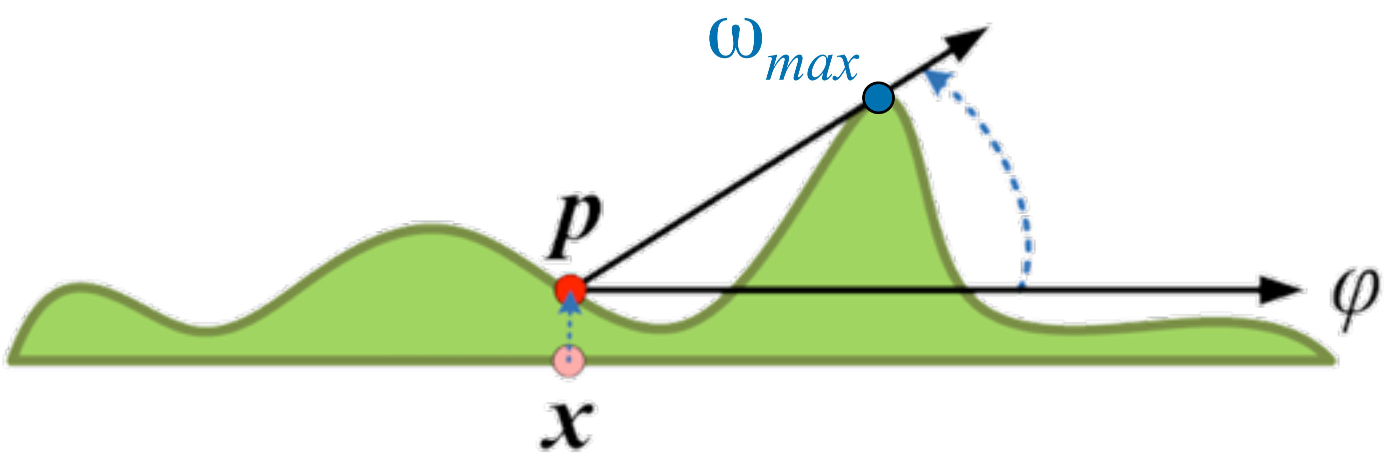
- Improved numerical stability with:
  - DC isolation
  - optimal linear-order approximation
  - SH scaling & squaring product accumulation

$$\mathbf{f} = \exp\left(\mathbf{f}_{\log}\right) \approx \mathbf{1} + \mathbf{f}_{\log} + \frac{\mathbf{f}_{\log}^2}{2} + \frac{\mathbf{f}_{\log}^3}{3!} + \cdots$$

Summary of Main Ideas

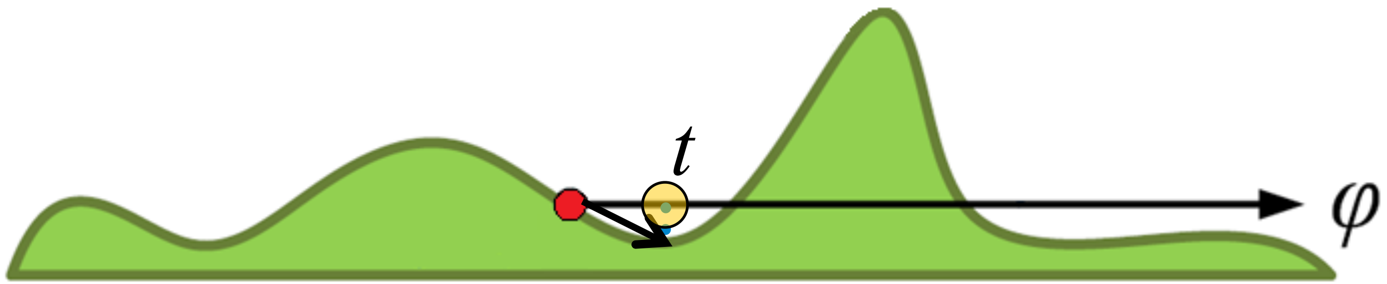
1. compute *HF self-visibility* (in *log-SH space*)
   - create multi-resolution height ***pyramids***
   - sample from pyramid levels
   - pre-filter data
   - compose visibility ***analytically*** in log-space
2. compute *HF cast-visibility* (onto meshes)
3. compute *mesh cast-visibility* (onto HF) **and** *self-visibility*
4. accumulate total spherical visibility
5. compute log-SH BRDF and perform final shading

HF Definitions and Notation [SN08]



Need to find maximum blocking angle ω_{max} along direction φ.

Calculating the Max Blocking Angle



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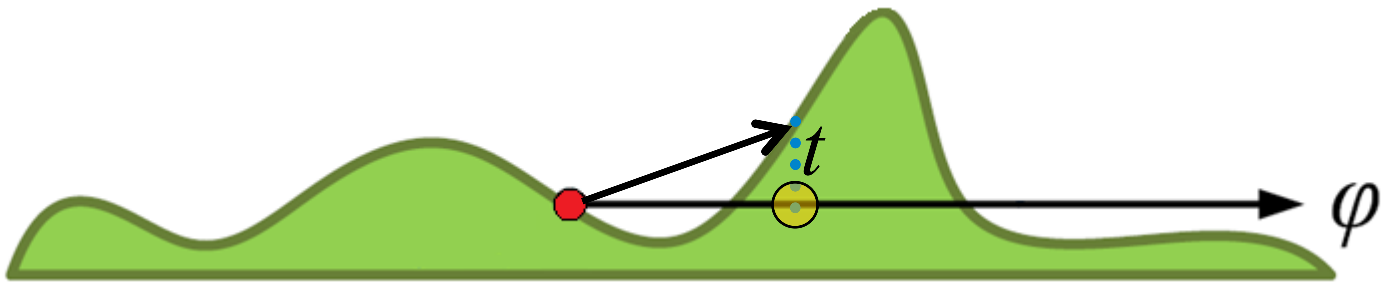

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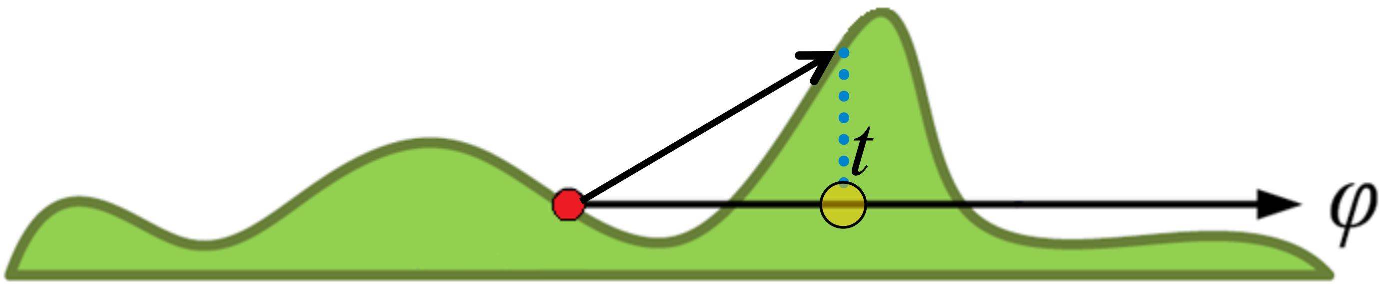

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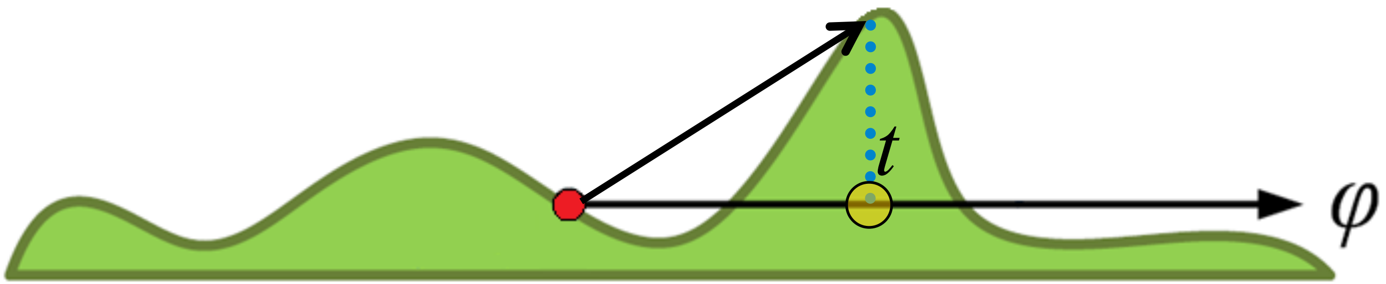

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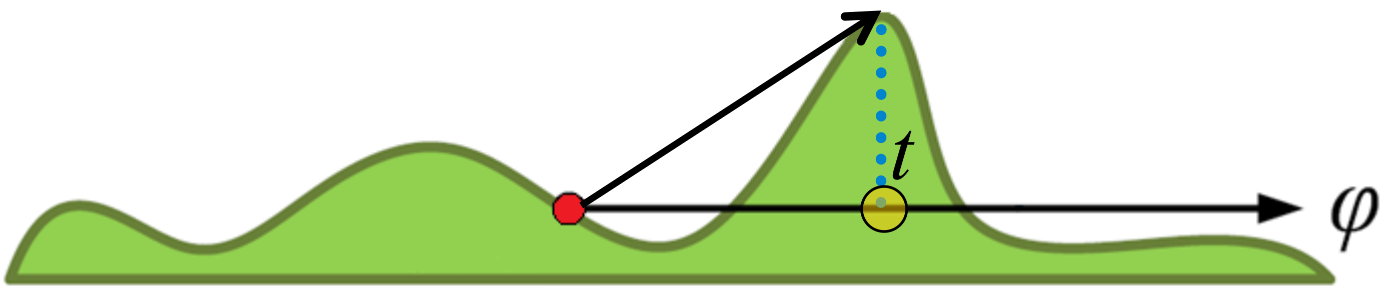

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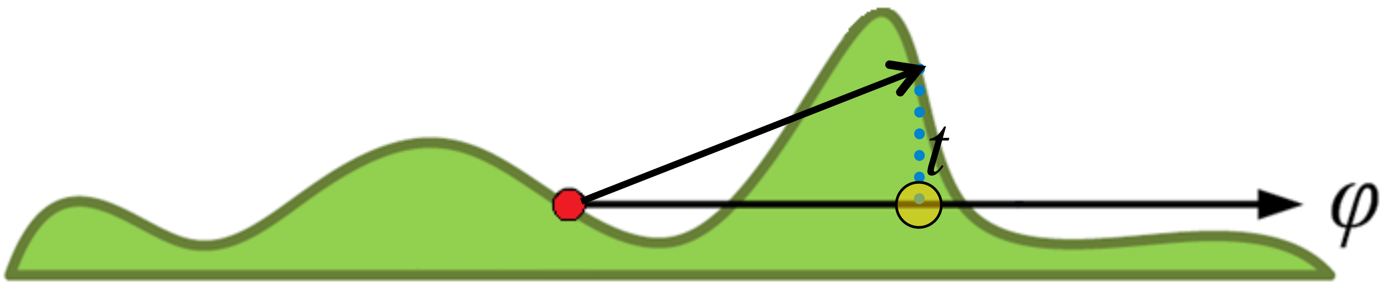

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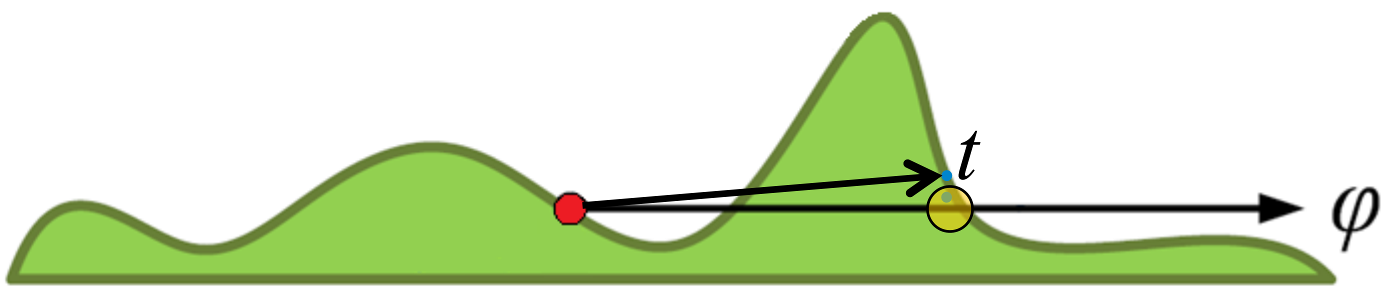

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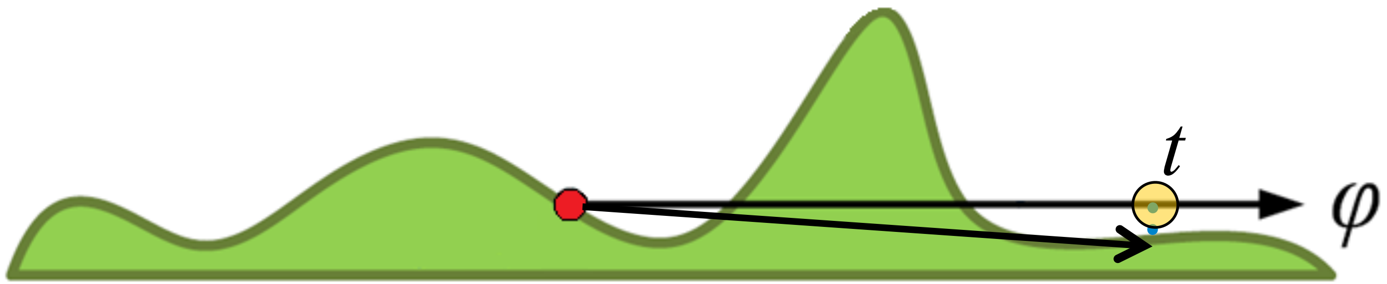

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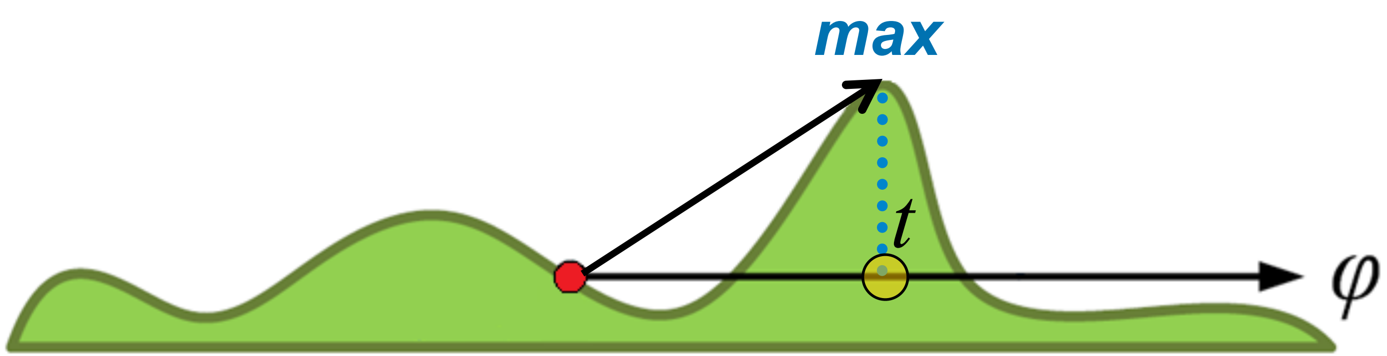

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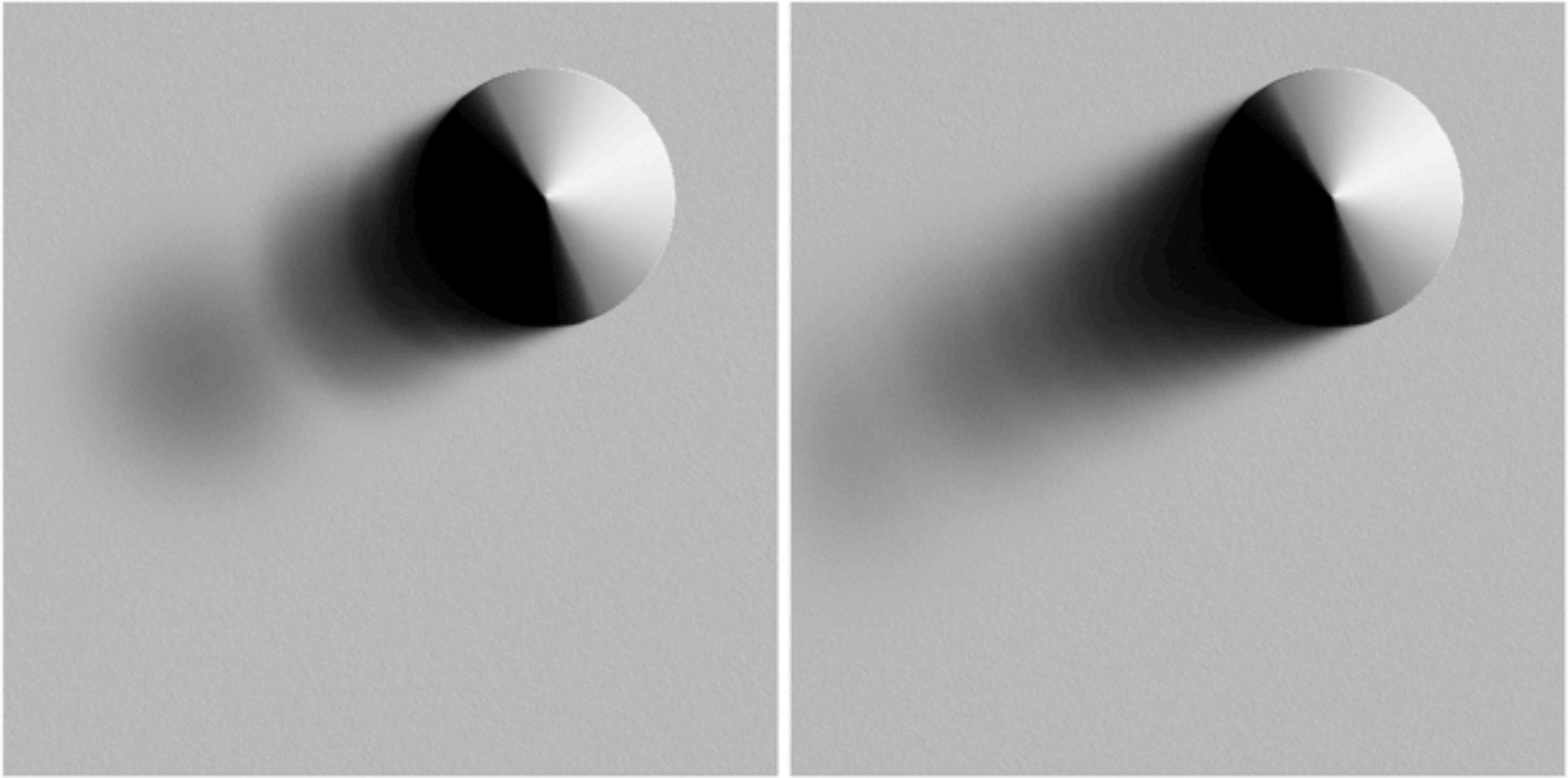
Brute Force Sampling [SN08]



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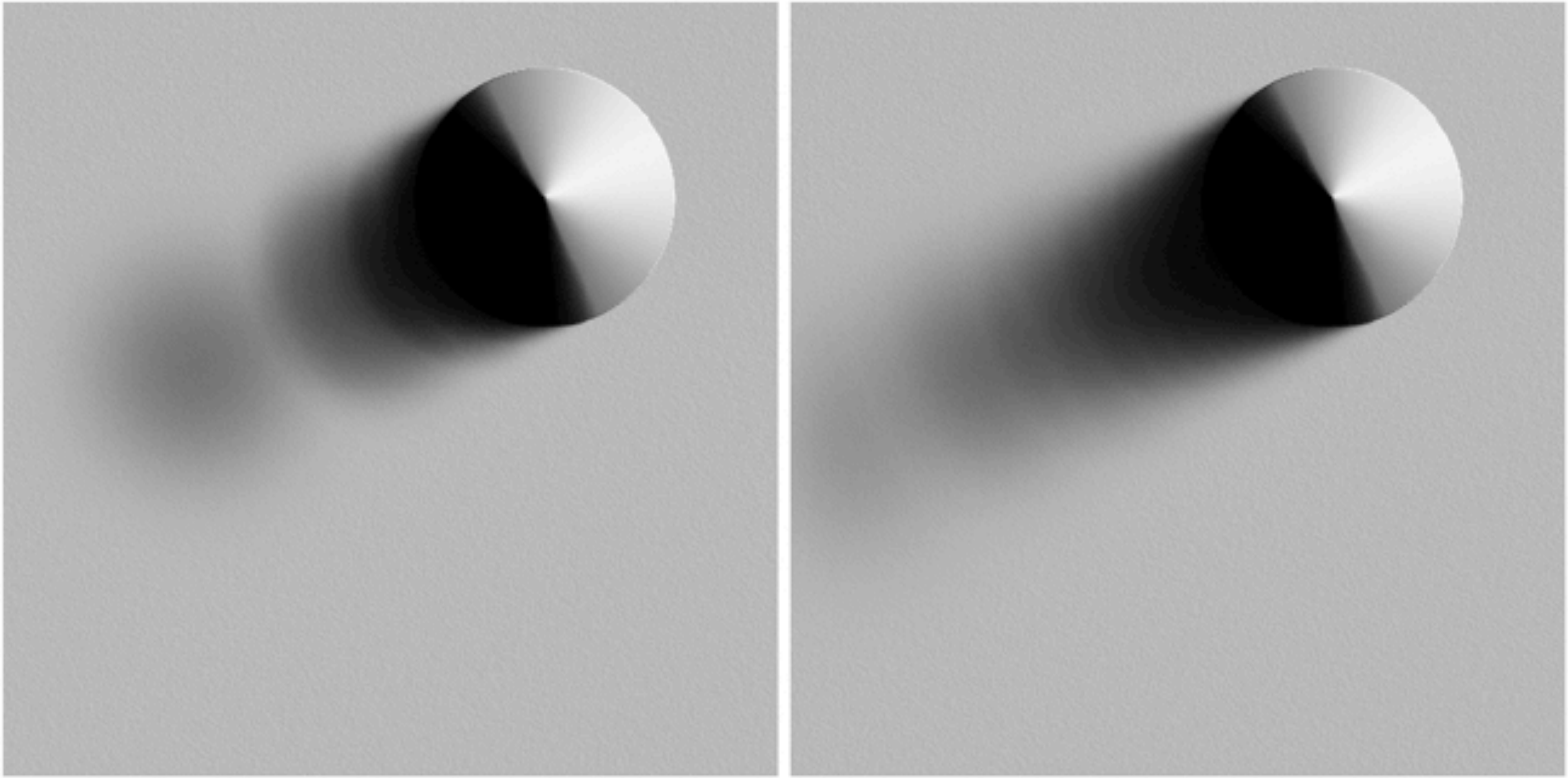

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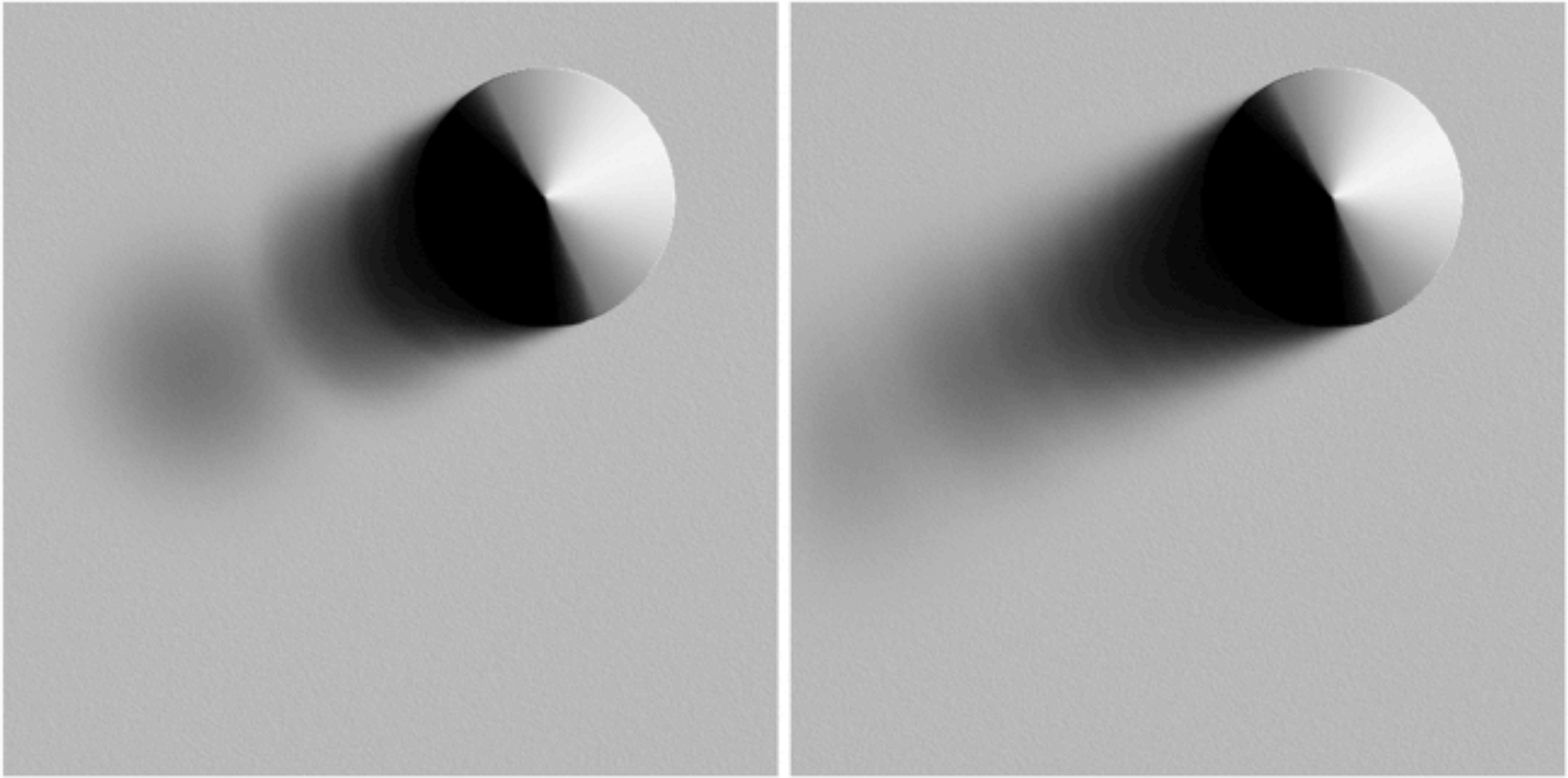

Problem: *aliasing* – need *many* samples in t.
Solution: *prefilter* data, apply *multi-scale sampling*.

Multi-Resolution Height Sampling [SN08]

f_i	height pyramid level i
$\tau_i = 2^{f(i)}$	sampling distance for level i

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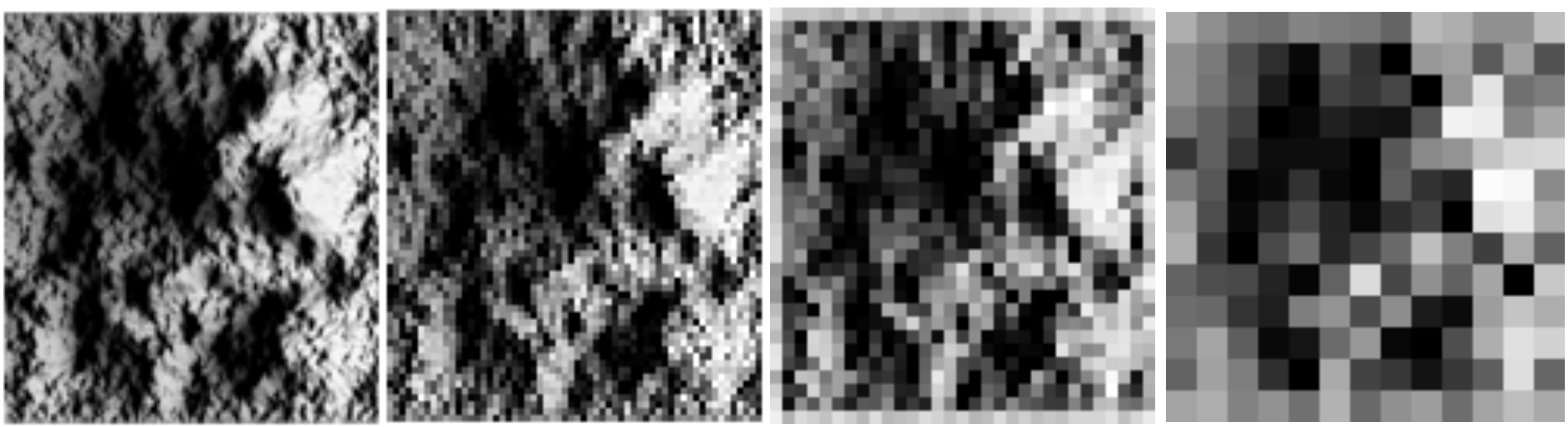

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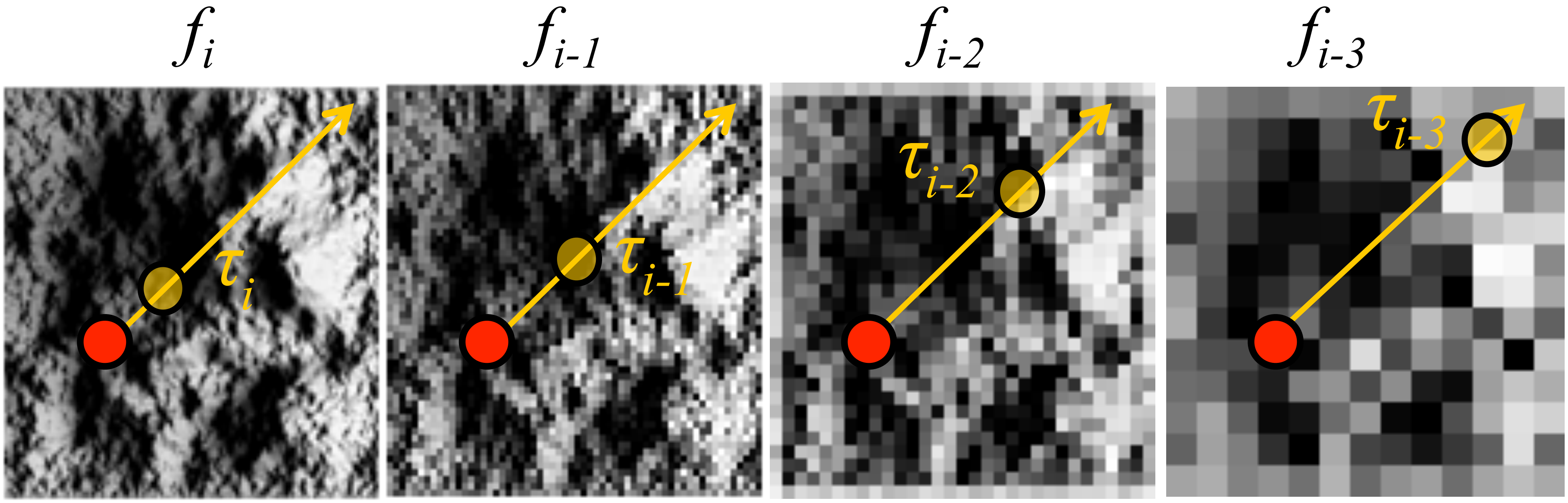
f_i height pyramid level i

$\tau_i = 2^{f(i)}$ sampling distance for level i

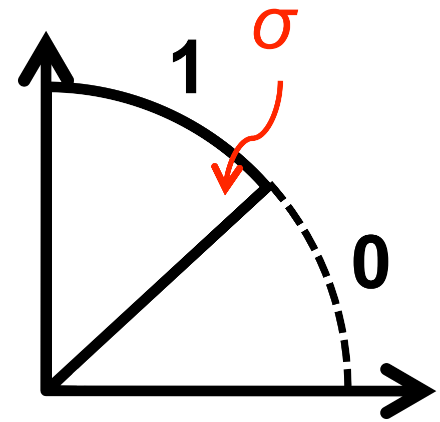
Sample coarser levels further from x.



Elevation Visibility

- starting with binary *visibility* for an elevation slice:

$$v(\omega;\sigma) = \begin{cases} 0, & \text{if } \omega \le \sigma \\ 1, & \text{otherwise.} \end{cases}$$



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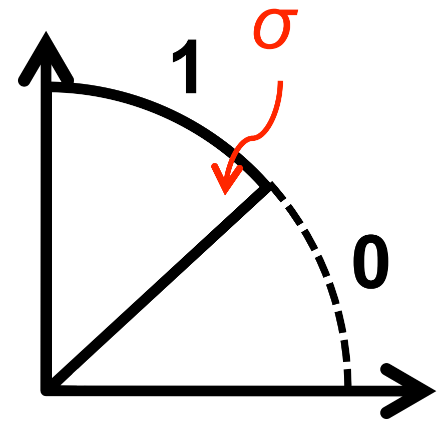
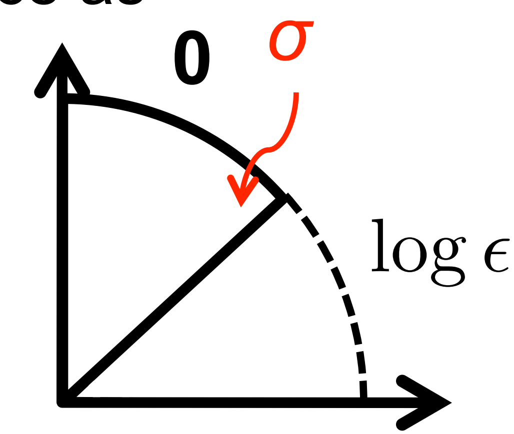


- we can express the *log-visibility* for the slice as

$$v_{\log}(\omega;\sigma) = \begin{cases} \log\epsilon, & \text{if } \omega \leq \sigma \\ 0, & \text{otherwise.} \end{cases}$$



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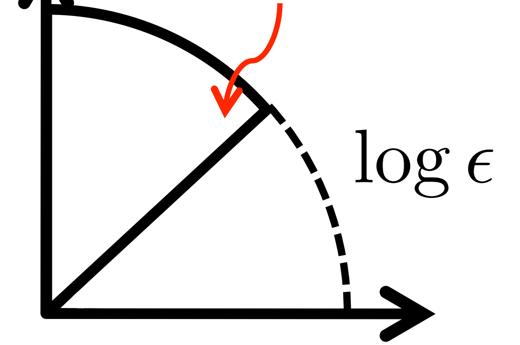

and represent it analytically in the **Normalized Legendre Polynomial** (**NLP**) basis:

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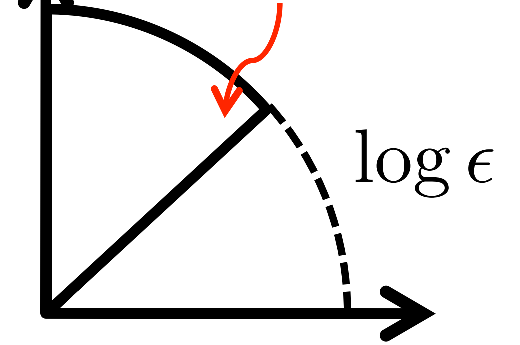

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$$= \log\epsilon \times \left[\frac{\sin\sigma+1}{\sqrt{2}}, \frac{-3\cos^2\sigma}{2\sqrt{6}}, \frac{-5\sin\sigma\cos^2\sigma}{2\sqrt{10}}, \frac{7\cos^2\sigma(-4+5\cos^2\sigma)}{8\sqrt{14}}\right]$$

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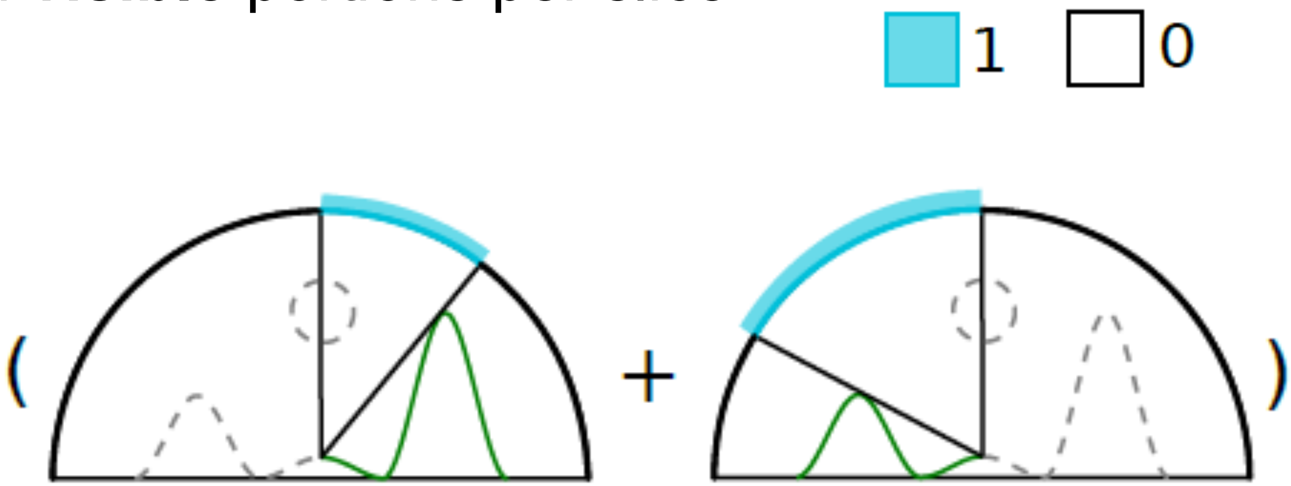

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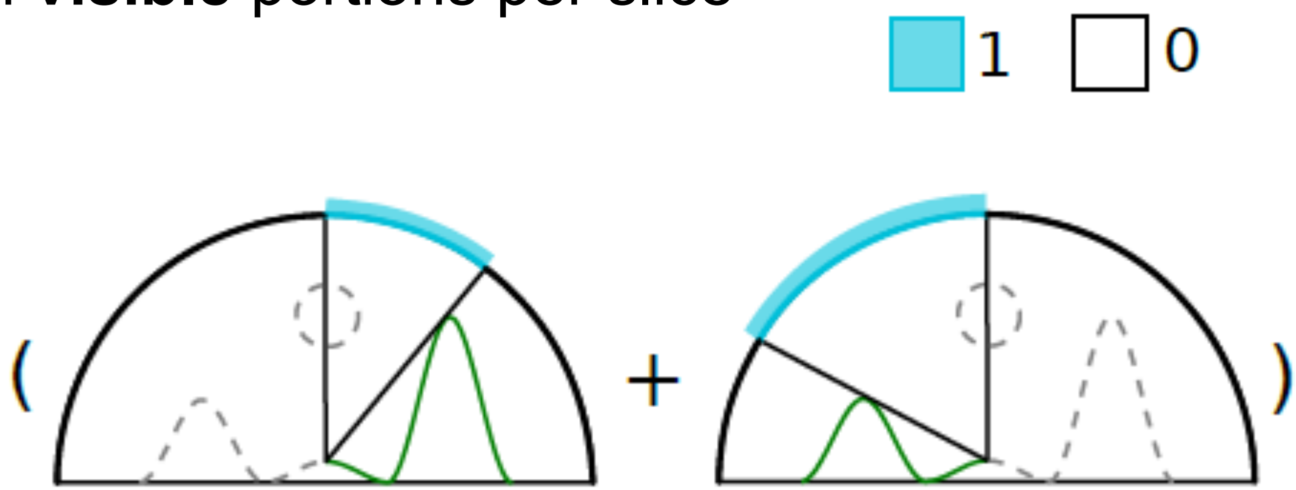

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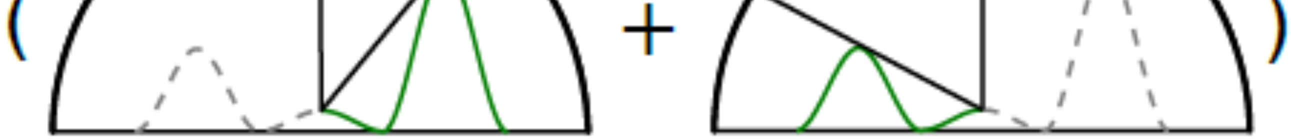

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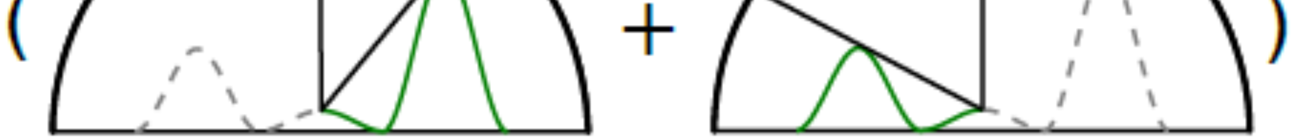

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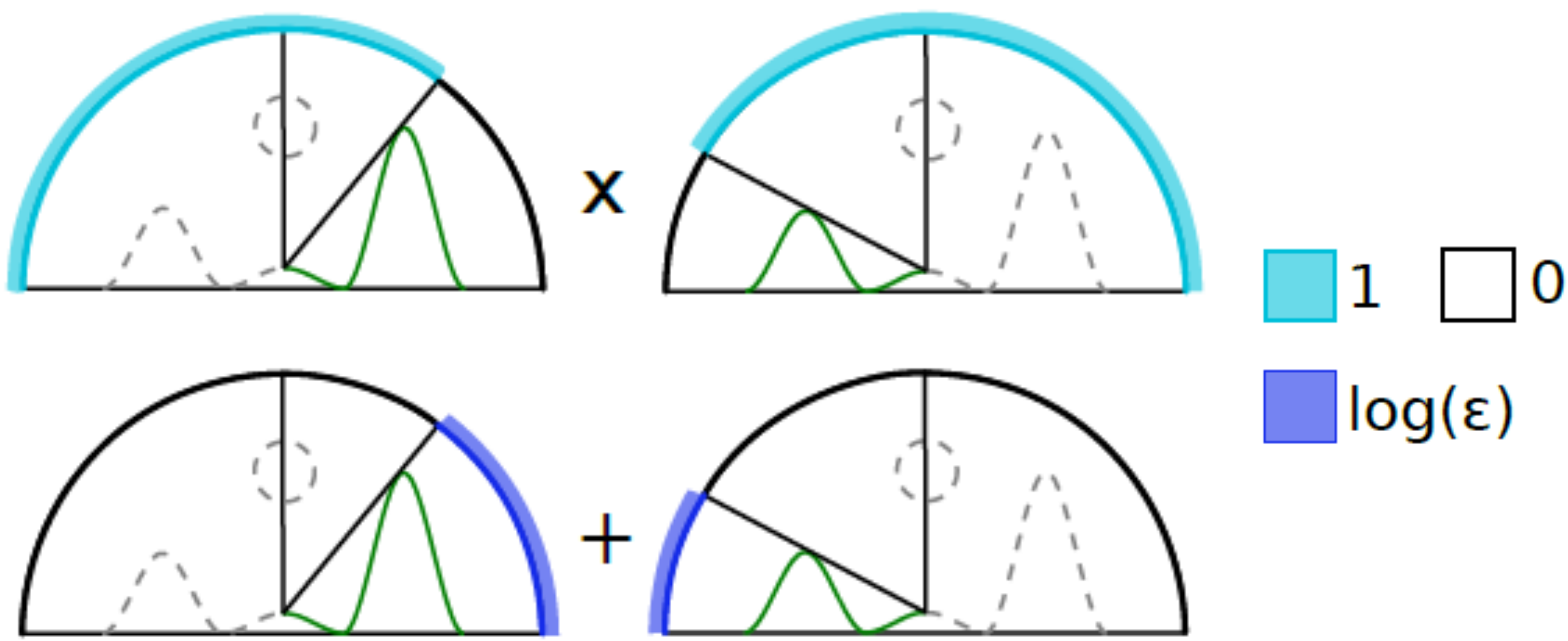

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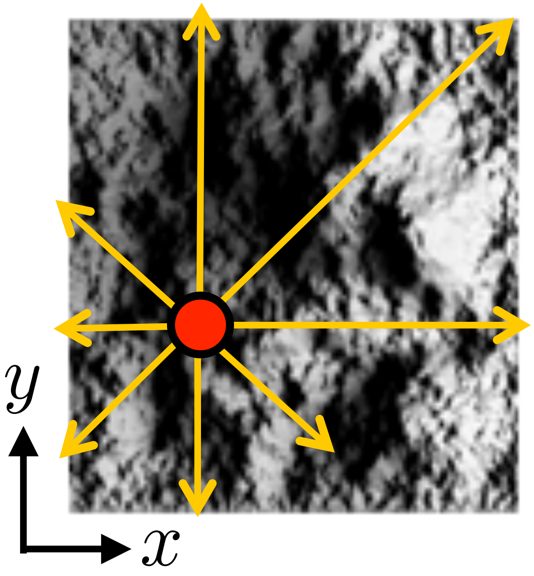

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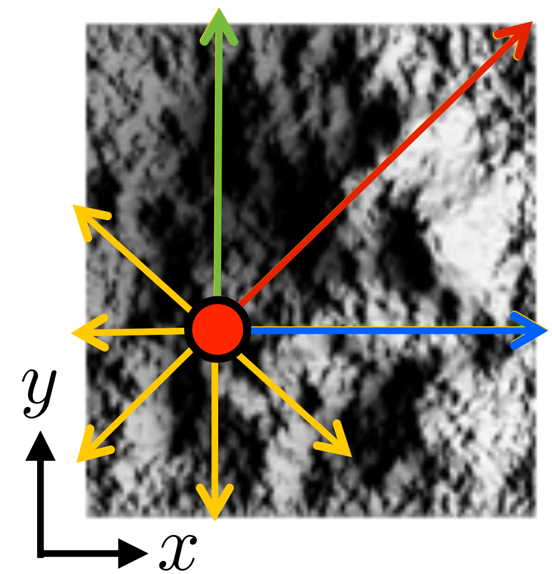

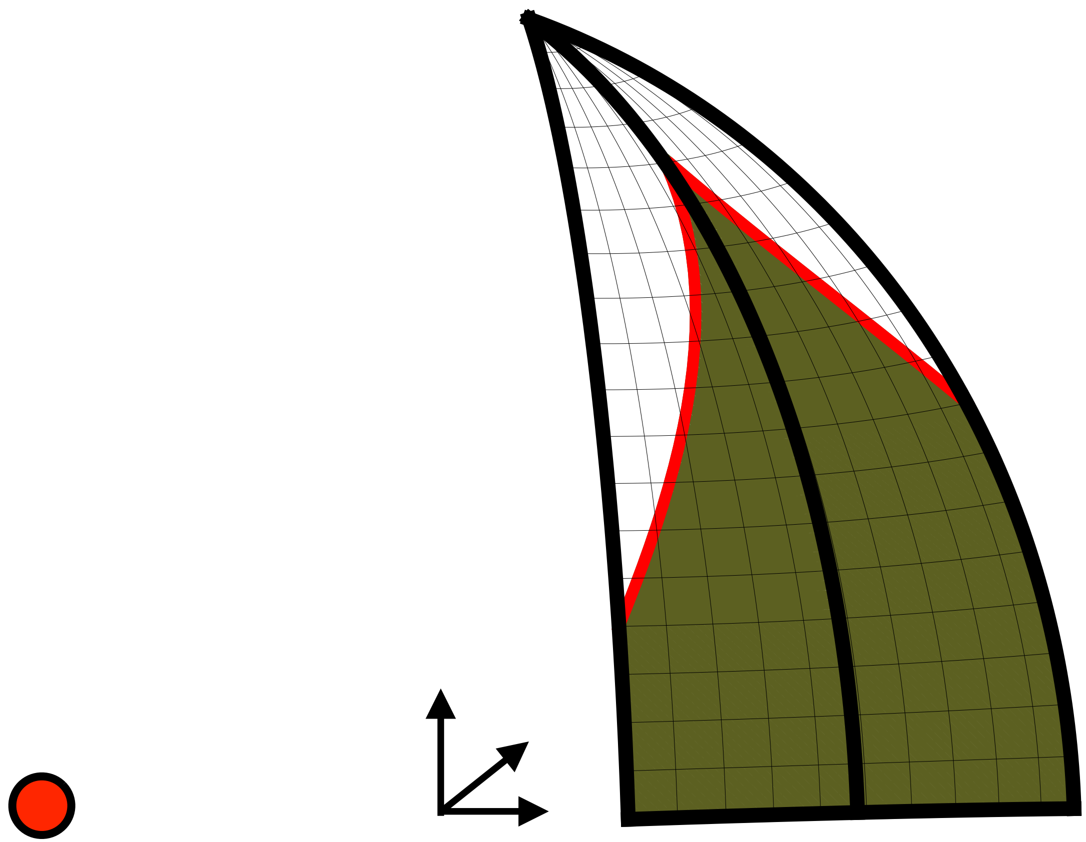

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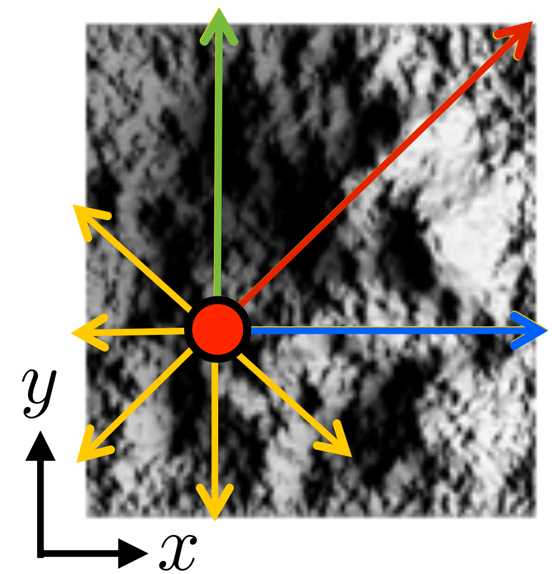
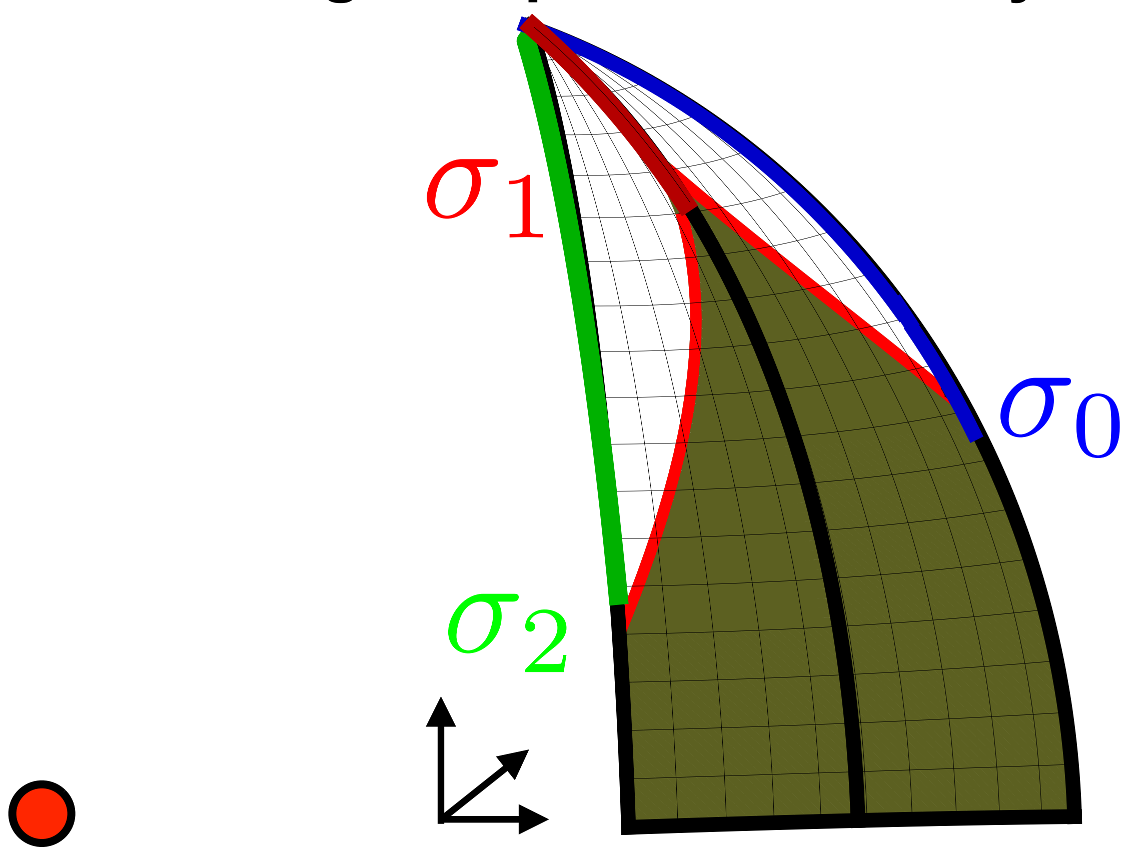
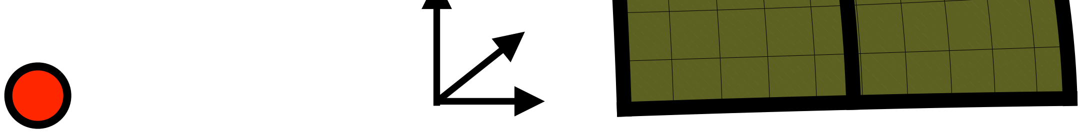






- requires 1 precomputed interpolation + projection matrix

$$\mathbf{v}_{\log}^{\text{wedge}} = \left[\quad \mathbb{M}_{lin} \quad \right] \begin{bmatrix} \mathbf{v}_{\log}(\sigma_0) \\ \mathbf{v}_{\log}(\sigma_1) \end{bmatrix}$$

- **rotate** and **sum** across each wedge's $\mathbf{v}_{\log}^{\text{wedge}}$ to form final log-SH vector $\mathbf{v}_{\log}^{\text{HF}}$

Summary of Main Ideas

1. compute *HF self-visibility* (in *log-SH space*)

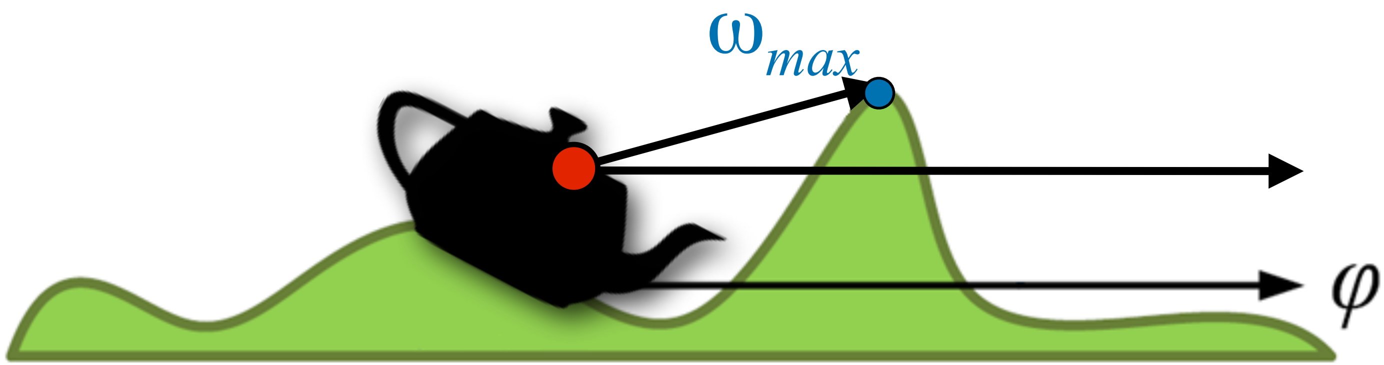
2. compute *HF cast-visibility* (onto meshes)
   - ***repeat*** multi-resolution marching
   - ***offset*** the height field queries

3. compute *mesh cast-visibility* (onto HF) **and** *self-visibility*

4. accumulate total spherical visibility

5. compute log-SH BRDF and perform final shading

Height Field Cast Visibility onto Meshes



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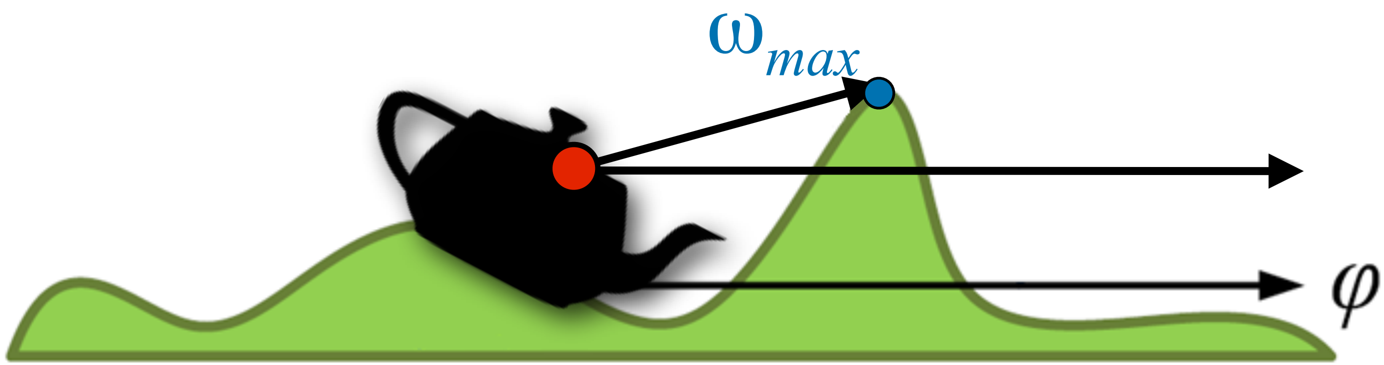

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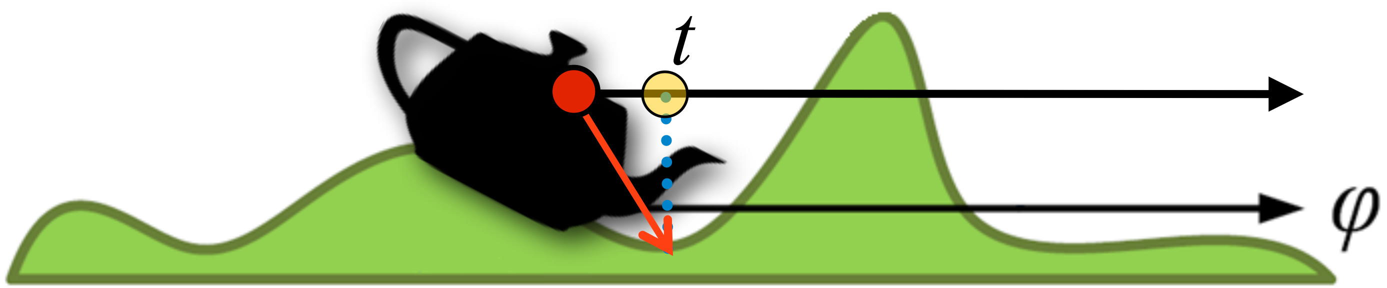
- Assume an infinite plane for the HF base elevation
  - minimum blocking angle can't go negative

Calculating the Max Blocking Angle



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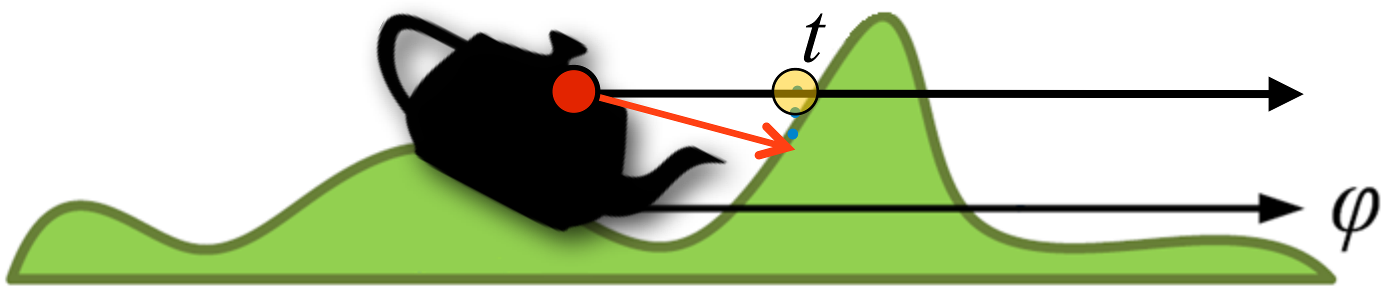

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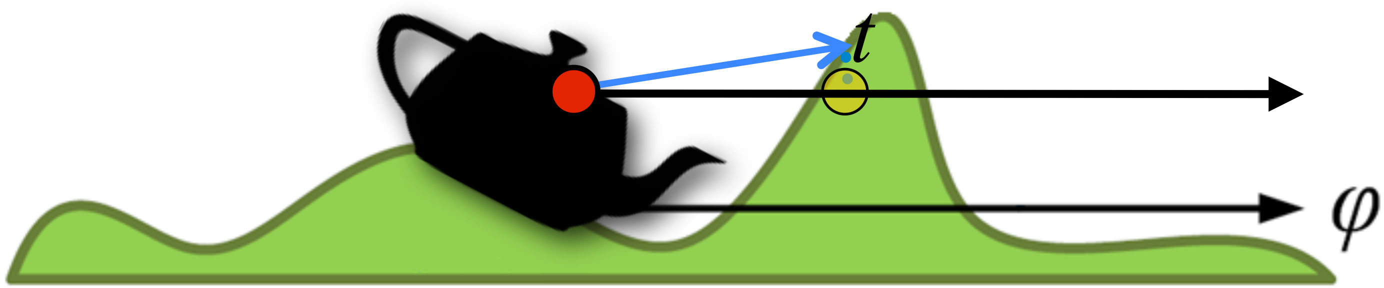

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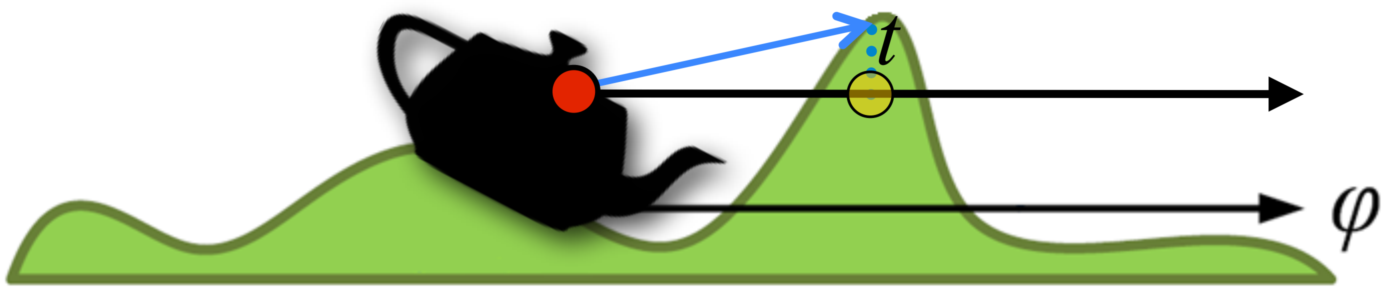

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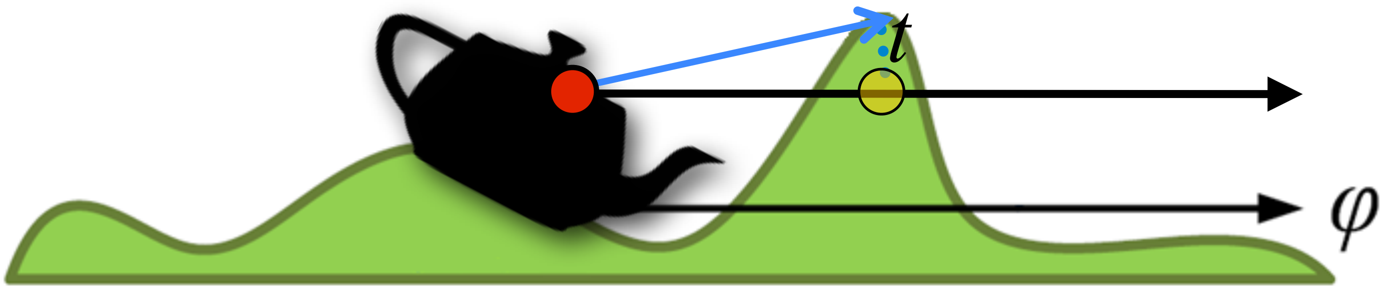

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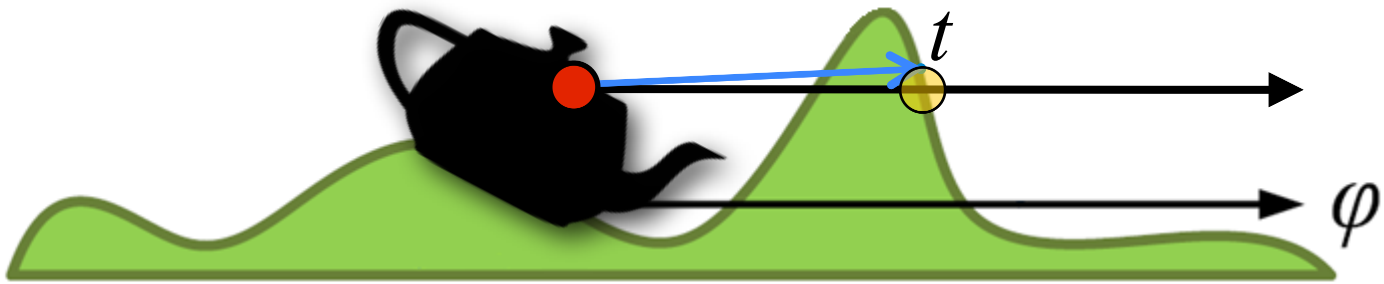

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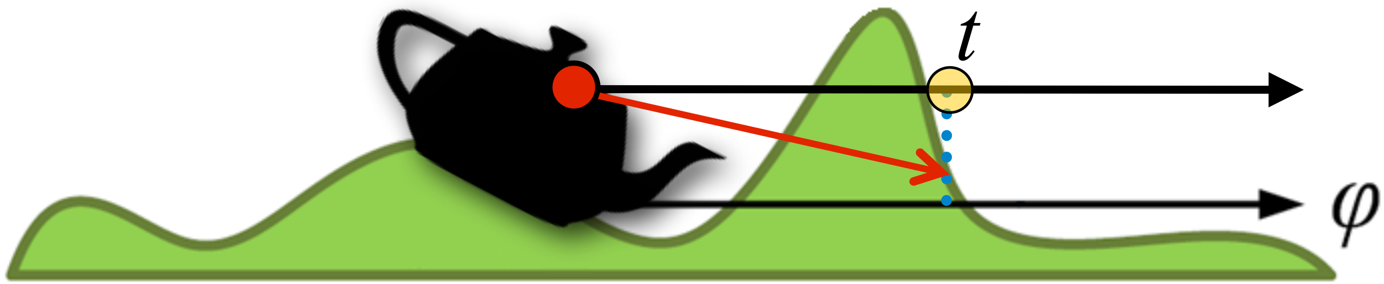

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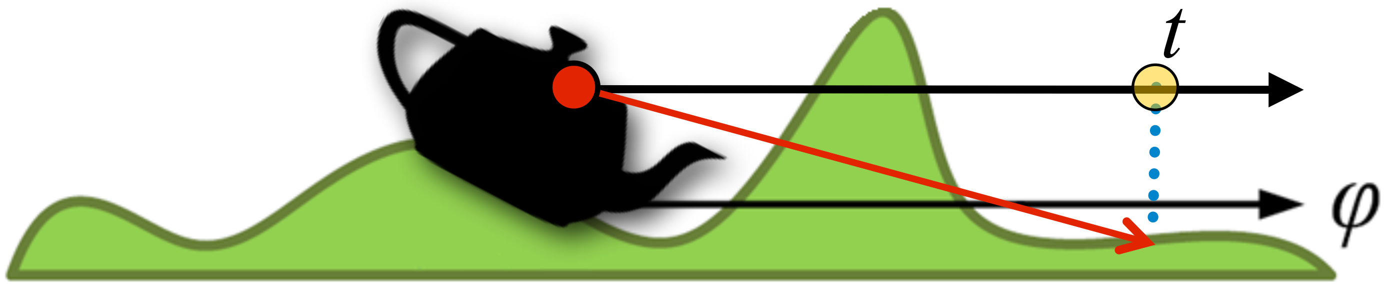

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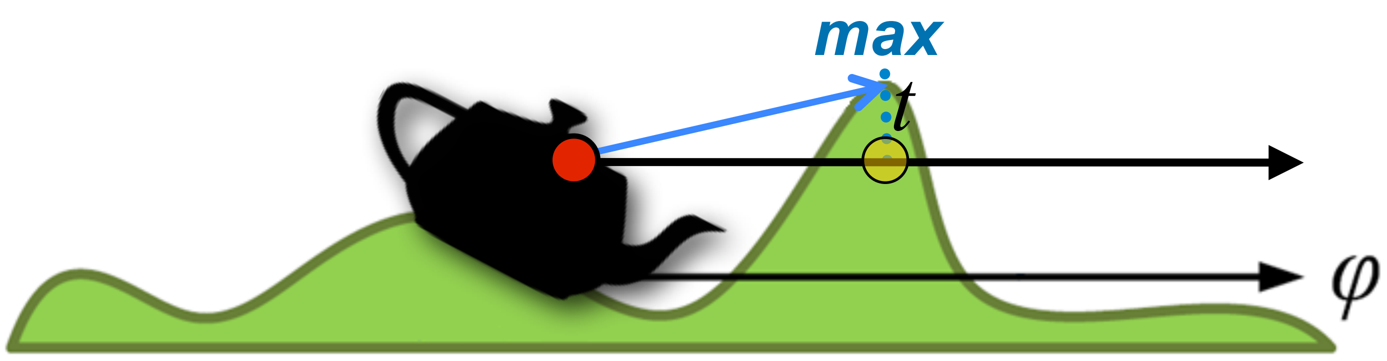


Summary of Main Ideas

1. compute *HF self-visibility* (in *log-SH space*)

2. compute *HF cast-visibility* (onto meshes)

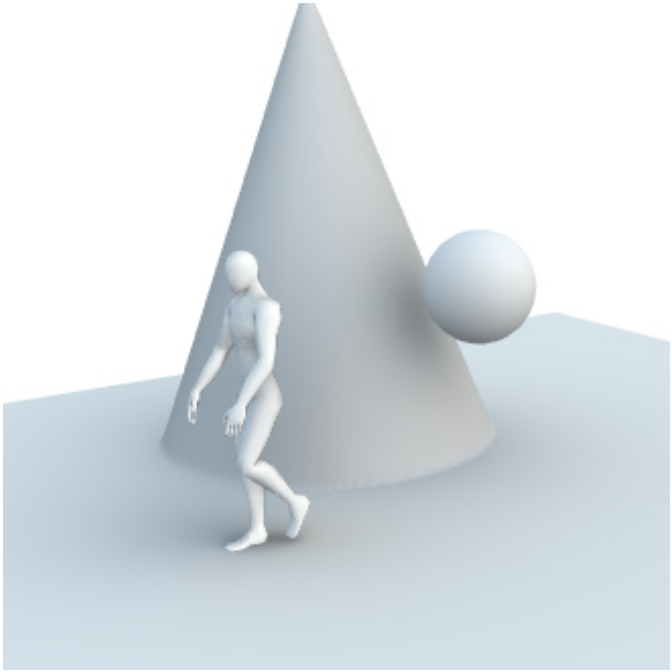
3. compute *mesh cast-visibility* (onto HF) **and** *self-visibility*
   - extend traditional SH exponentiation approach **[RWS*06;SGNS07]**
   - ***decompose*** dynamic mesh blockers into spheres
   - ***compute*** & ***accumulate log-SH visibility*** for spherical blockers
     - on the mesh shading points
     - ***repeat*** over the HF shading points
   - intelligently cull the sphere set during accumulation
     - reduces numerical accumulation error

4. accumulate total spherical visibility

5. compute log-SH BRDF and perform final shading

Spherical Blockers [RWS*06]

- approximate dynamic meshes with a set of spheres
  - precomputed once
  - skinned dynamically during animation/deformation



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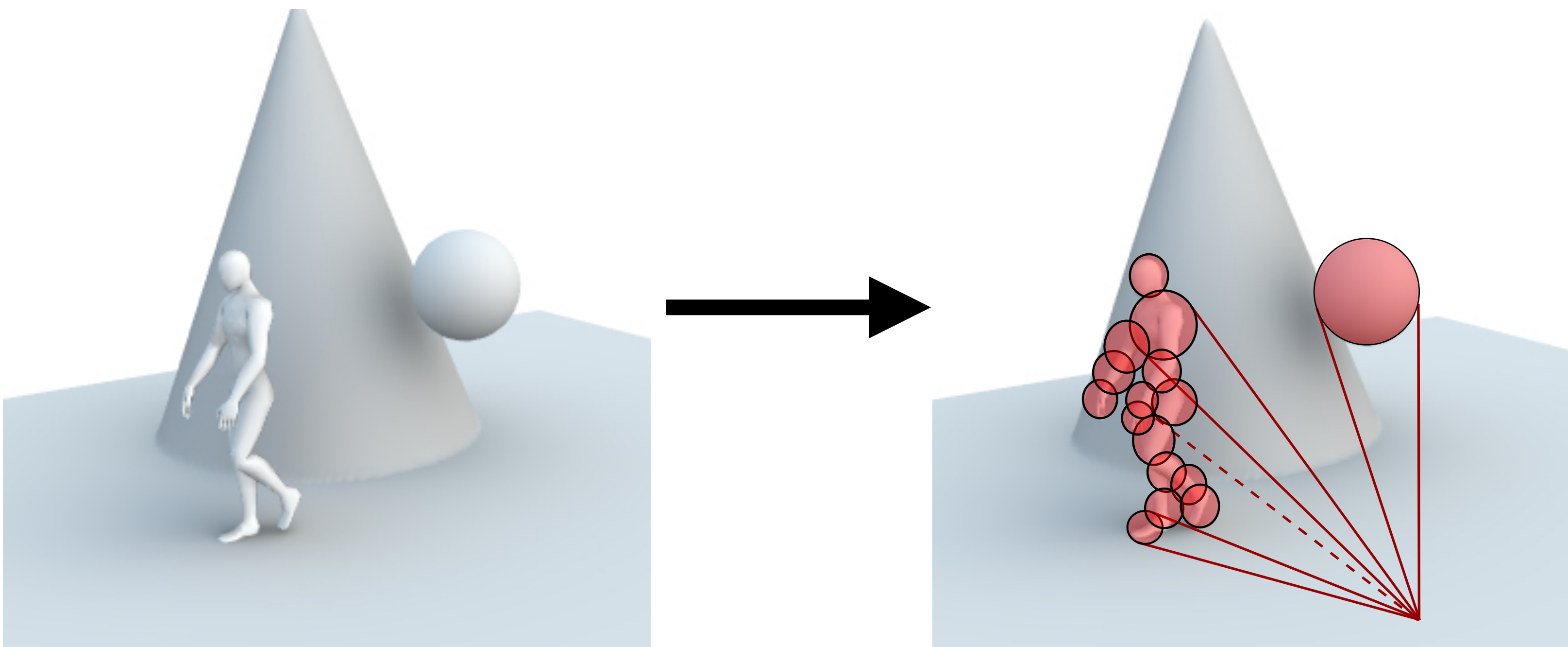
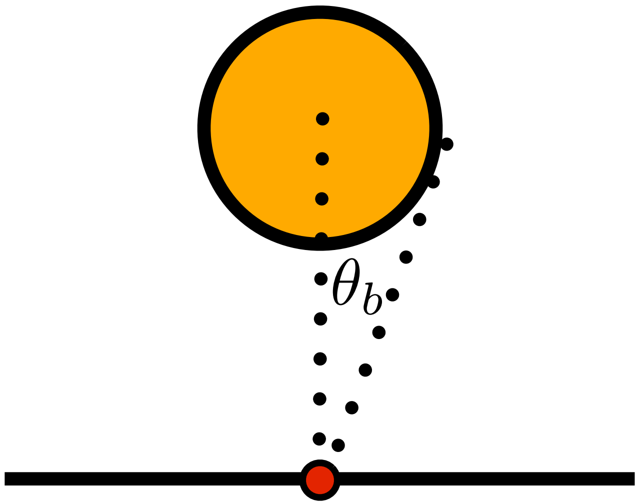


Spherical Blocker Log SH Visibility

- can compute log-visibility SH coefficients ***analytically***
- begin with a canonical alignment:

$$\theta_b = \arcsin\left(r/d\right)$$



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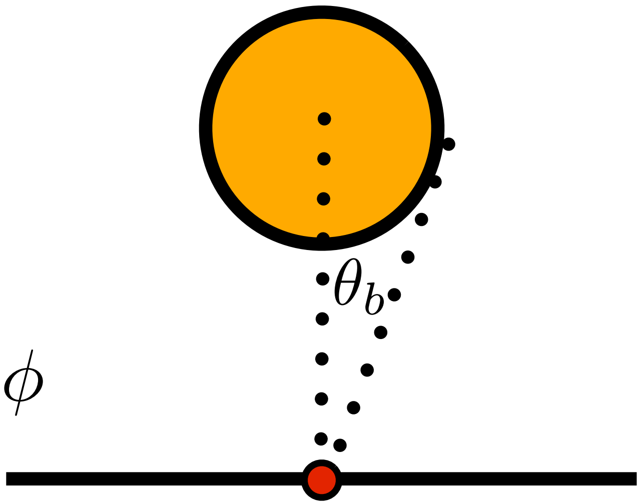

$$\int_{\theta=0}^{\theta_b} \int_{\phi=0}^{2\pi} (\log \epsilon)\ y_l^0(\theta,\phi)\ \sin\theta \, \mathrm{d}\theta \mathrm{d}\phi$$

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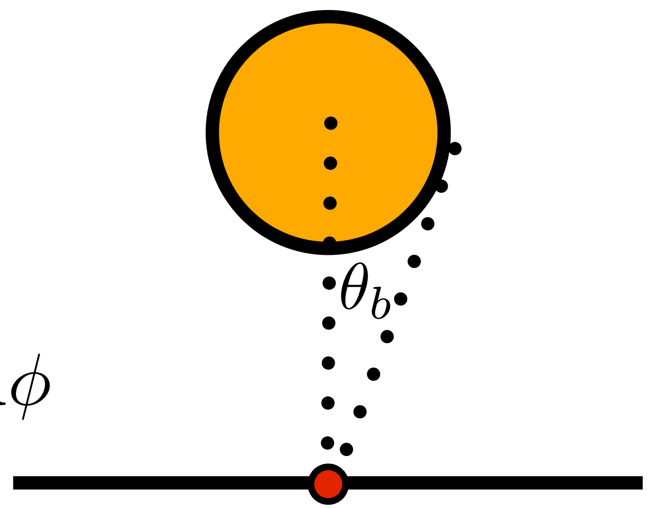

$$\int_{\theta=0}^{\theta_b}\int_{\phi=0}^{2\pi}(\log\epsilon)\ y_l^0(\theta,\phi)\ \sin\theta\,\mathrm{d}\theta\mathrm{d}\phi$$

- solve analytically (we use order-4 SH, so 4 ZH coefficients)

$$\mathbf{v}_l^{\log} = \log\epsilon\times\left[-\sqrt{\pi}(-1+\cos\theta_b),\ \frac{\sqrt{3\pi}}{2}\sin^2\theta_b,\right.$$
$$\left.\frac{\sqrt{5\pi}}{2}\cos\theta_b\sin^2\theta_b,\ \frac{\sqrt{7\pi}}{16}(3+5\cos(2\theta_b))\sin^2\theta_b\right]$$

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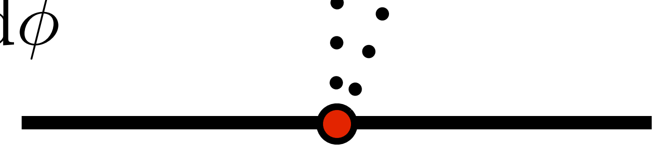

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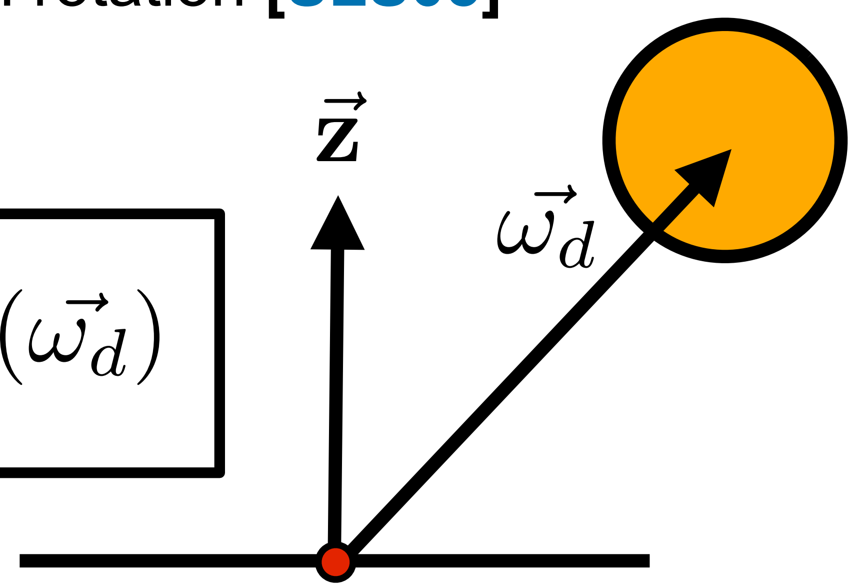
- align to shading frame with ZH rotation **[SLS05]**

$$\boxed{\mathbf{v}_{l,m}^{\log} = \sqrt{\frac{4\pi}{2l+1}}\, \mathbf{v}_l^{\log}\, y_l^m(\vec{\omega_d})}$$



Spherical Blocker Self- & Cast- Shadows

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- accumulate spherical blocker occlusion for both:

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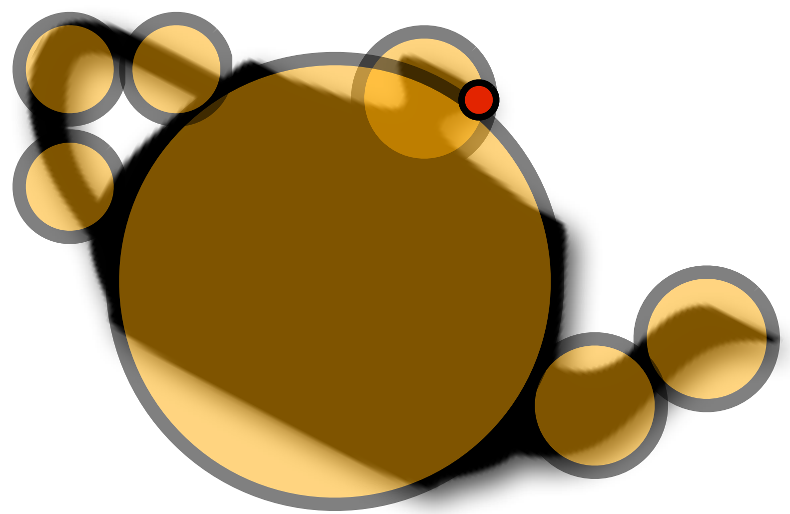

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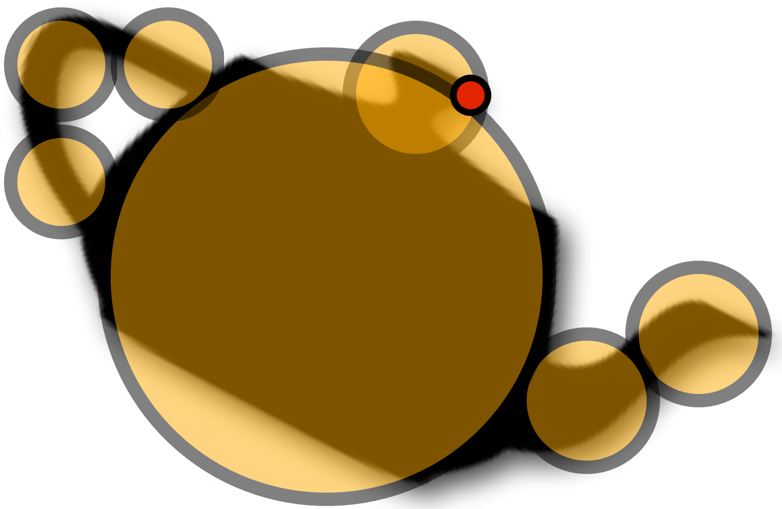
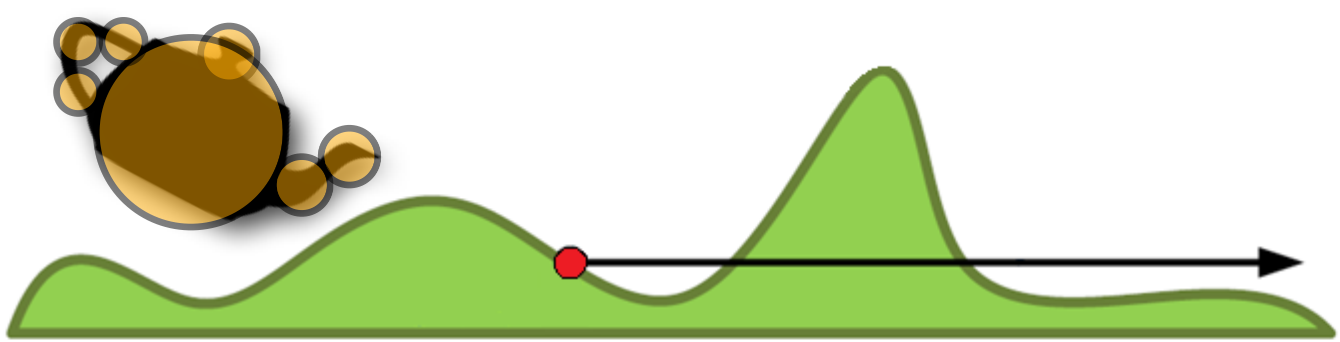


  - **and** dynamic object *cast-occlusion* onto the HF



Ratio Attenuation

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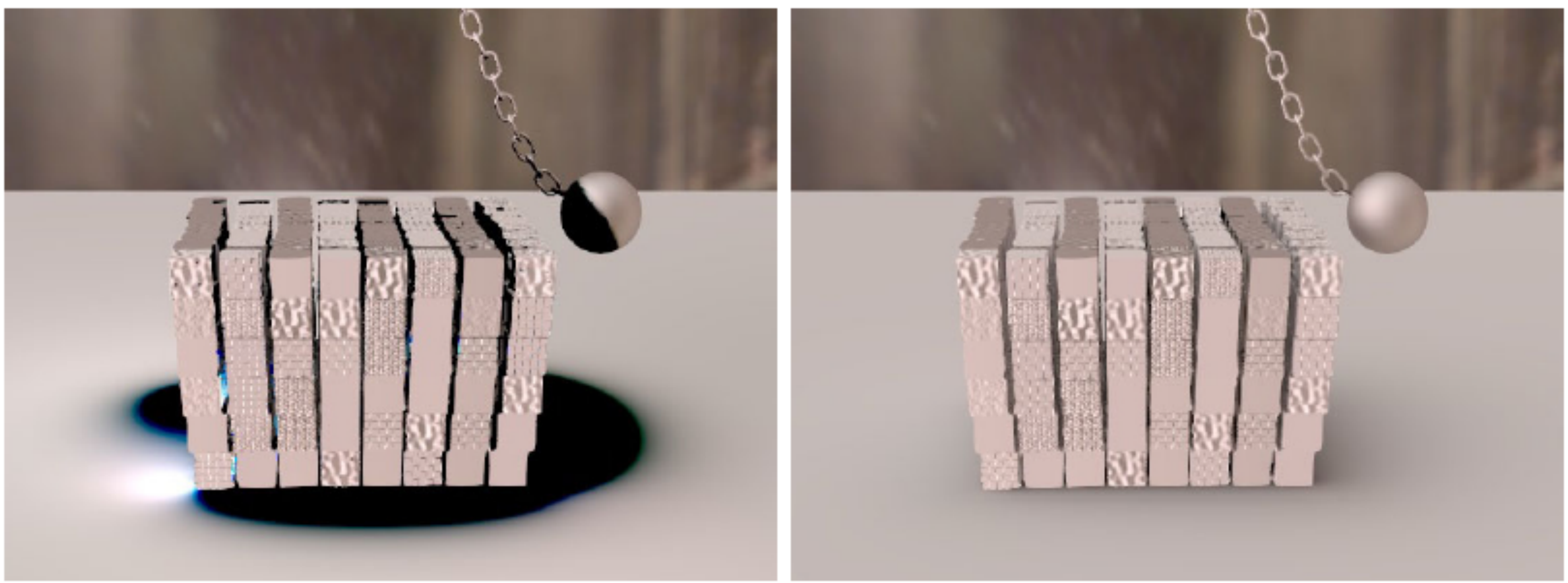
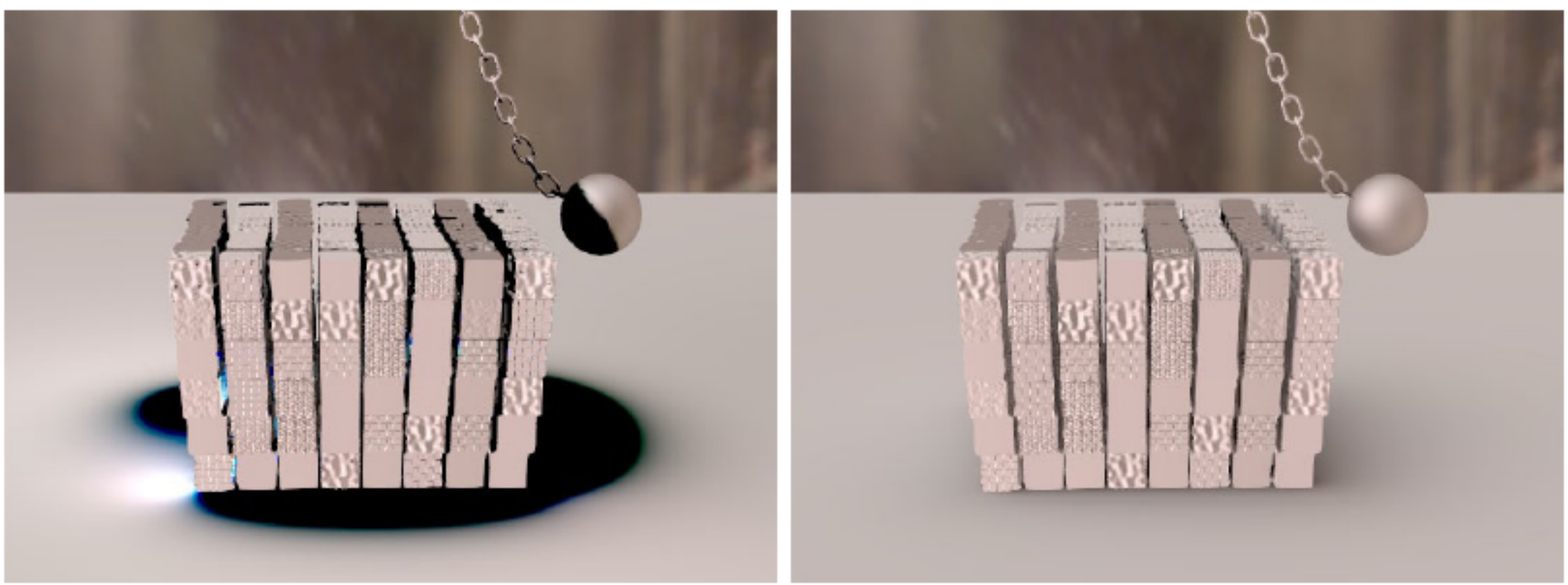
- SH exponentiation suffers from accumulation error when there are **many overlapping** blocker spheres



Ratio Attenuation

- SH exponentiation suffers from accumulation error when there are **many overlapping** blocker spheres
- we reduce accumulation error by:
  - weighting log-SH visibility by blocker solid angle, and
  - only accumulating blockers in upper shading hemisphere



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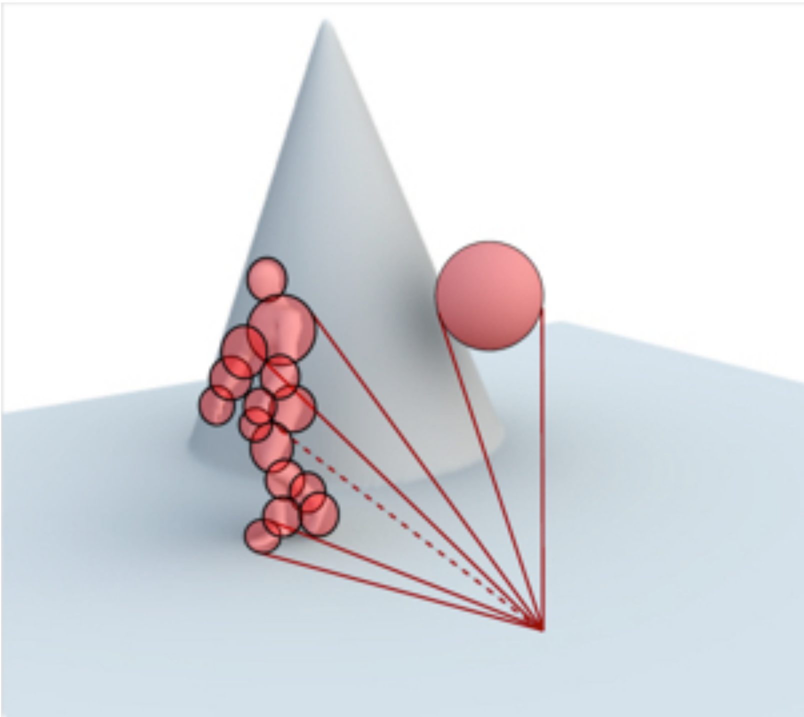
3. compute *mesh cast-visibility* (onto HF) **and** *self-visibility*

4. accumulate total spherical visibility
   - combine **per-slice** HF (log) visibility to form **full** spherical visibility **[NS09]**
   - ***accumulate*** dynamic mesh blocker log-visibility and HF log-visibility
   - perform **SH exponentiation**

5. compute log-SH BRDF and perform final shading

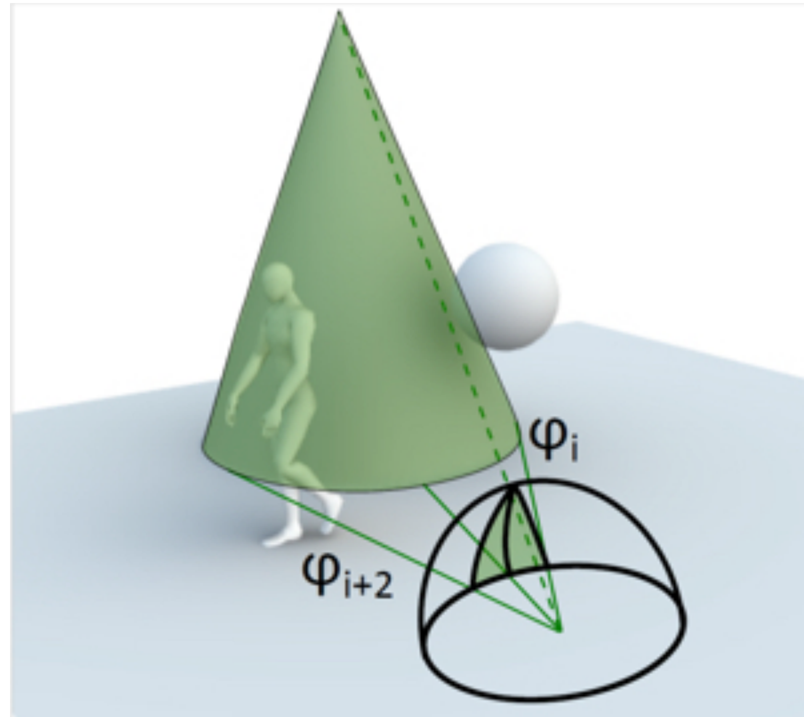
Accumulate Log-SH Visibility

Given spherical log-SH visibility for



dynamic blocker “meshes”

$$\left\{\mathbf{v}_{\log}^{0}, \mathbf{v}_{\log}^{1}, \cdots, \mathbf{v}_{\log}^{\mathrm{B-1}}\right\}$$



dynamic height field geometry

$$\mathbf{v}_{\log}^{\mathrm{HF}}$$

- the **total** log-SH visibility vector is $\mathbf{V}_{\log} = \mathbf{v}_{\log}^{\mathrm{HF}} + \sum_{b=0}^{B-1} \mathbf{v}_{\log}^{\mathrm{b}}$

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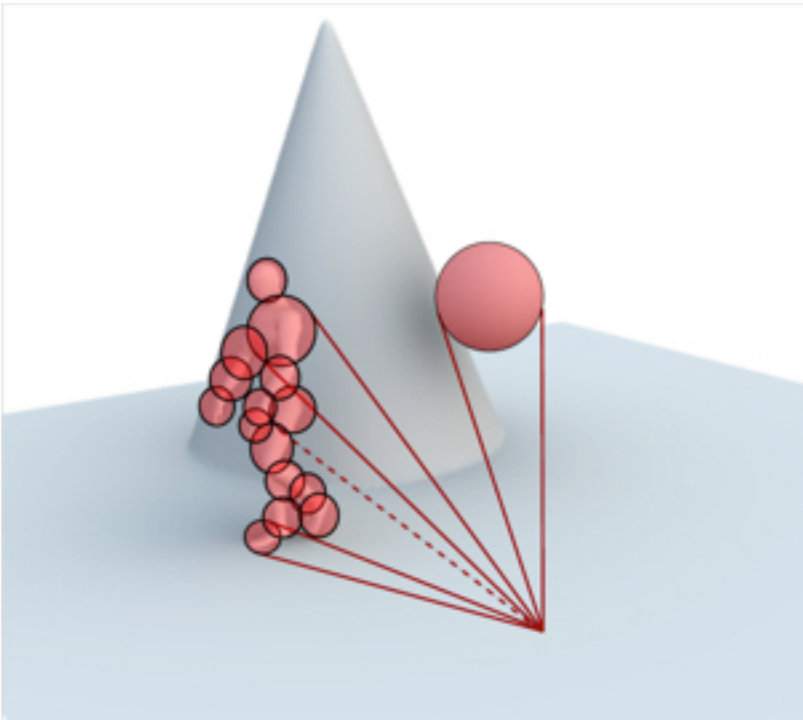

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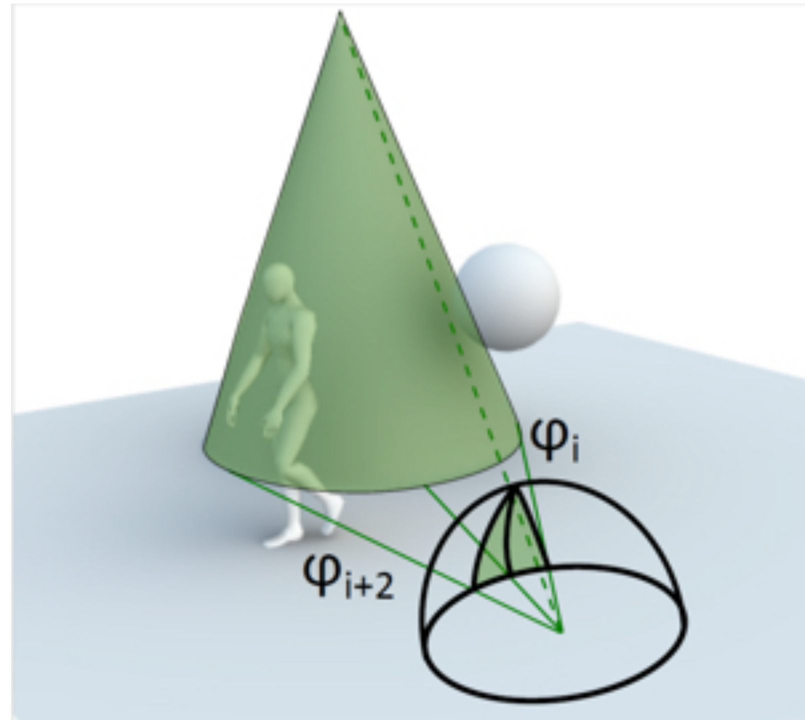

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- the **total** log-SH visibility vector is $\mathbf{V}_{\log} = \mathbf{v}_{\log}^{\mathrm{HF}} + \sum_{b=0}^{B-1} \mathbf{v}_{\log}^{\mathrm{b}}$

$$\mathbf{V} = \exp\left(\mathbf{V}_{\log}\right) \approx \mathbf{1} + \mathbf{V}_{\log} + \frac{{\mathbf{V}_{\log}}^{2}}{2} + \frac{{\mathbf{V}_{\log}}^{3}}{3!} + \cdots$$

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1. compute *HF self-visibility* (in *log-SH space*)
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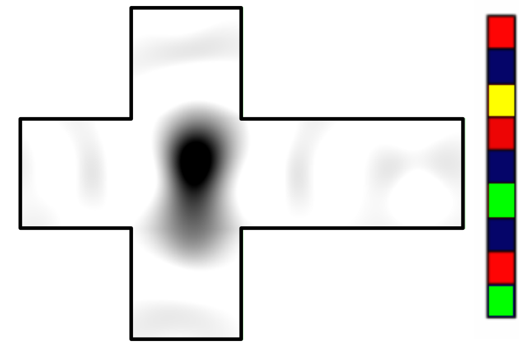
3. compute *mesh cast-visibility* (onto HF) **and** *self-visibility*
4. accumulate total spherical visibility
5. compute log-SH BRDF and perform final shading
   - simplify triple-product shading to double-product shading
   - ***formulate*** view-evaluated BRDF in log-SH space
   - ***accumulate*** BRDF with multi-product visibility

Traditional Triple Product SH Shading

$$\mathbf{V} = \exp\left(\mathbf{V}_{\log}\right)$$ spherical SH visibility



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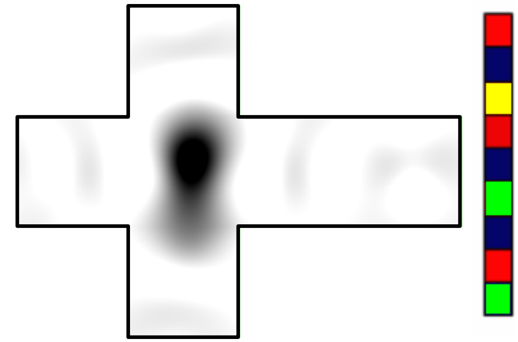
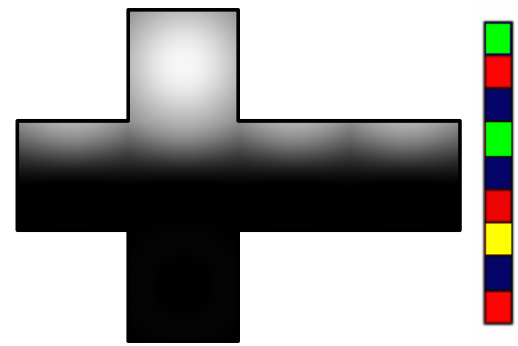


$$\mathbf{f}_r(\omega_o)$$

view-evaluated BRDF



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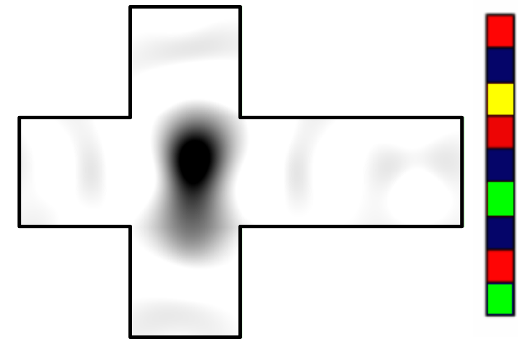

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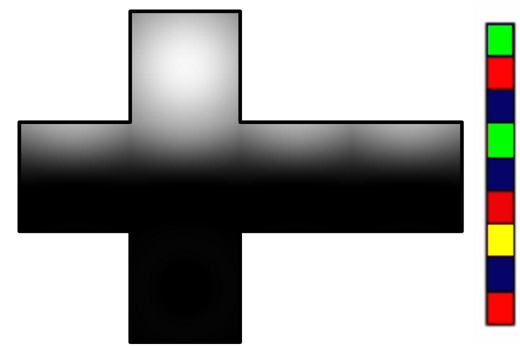
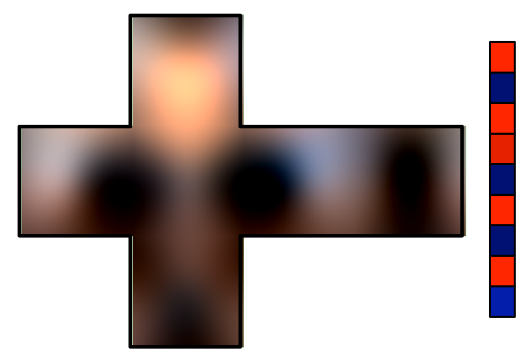
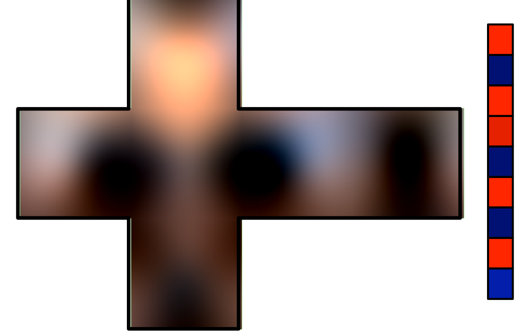


$$\mathbf{L}_e$$

lighting environment



$\mathbf{L}_e$ lighting environment



- final shading traditionally ([**RWS*06;SGNS07**]) computed with triple-product SH integration:

$$L_o(\omega_o) = \sum_{ijk} [\mathbf{L}_e]_i \, [\mathbf{V}]_j \, [\mathbf{f}_r(\omega_o)]_k \, \Gamma_{ijk}$$

where

$$\Gamma_{ijk} = \int_{S^2} y_i(\omega) \, y_j(\omega) \, y_k(\omega) \, \mathrm{d}\omega$$

are the SH *tripling coefficients*, a sparse order-3 tensor.

- Triple product shading computation is still costly!

Log-BRDF Shading

- We already use log-space to perform a multi-product

$$\mathbf{V} = \exp\left(\mathbf{V}_{\log}\right) \approx \prod_{b=0}^{B-1} \mathbf{V}_b$$

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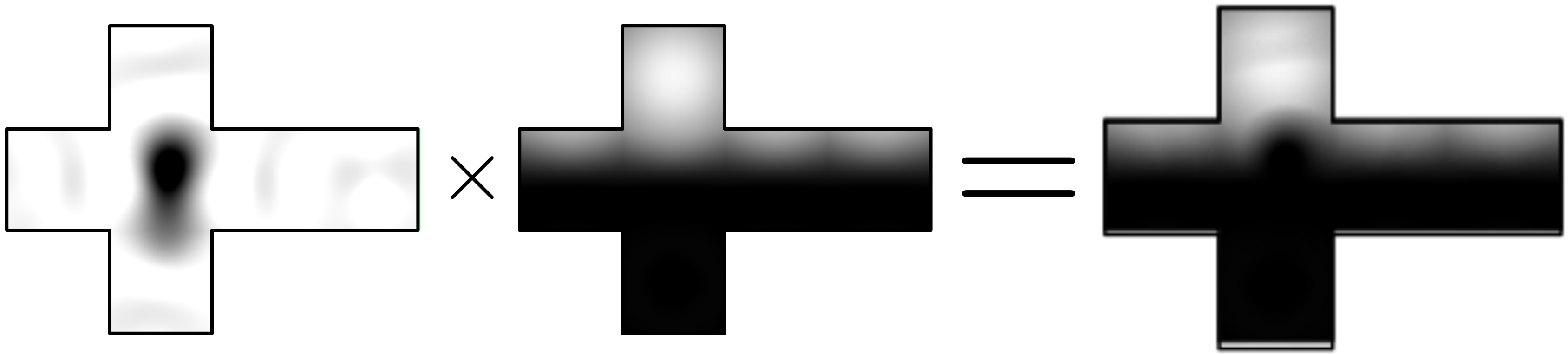

SH transfer

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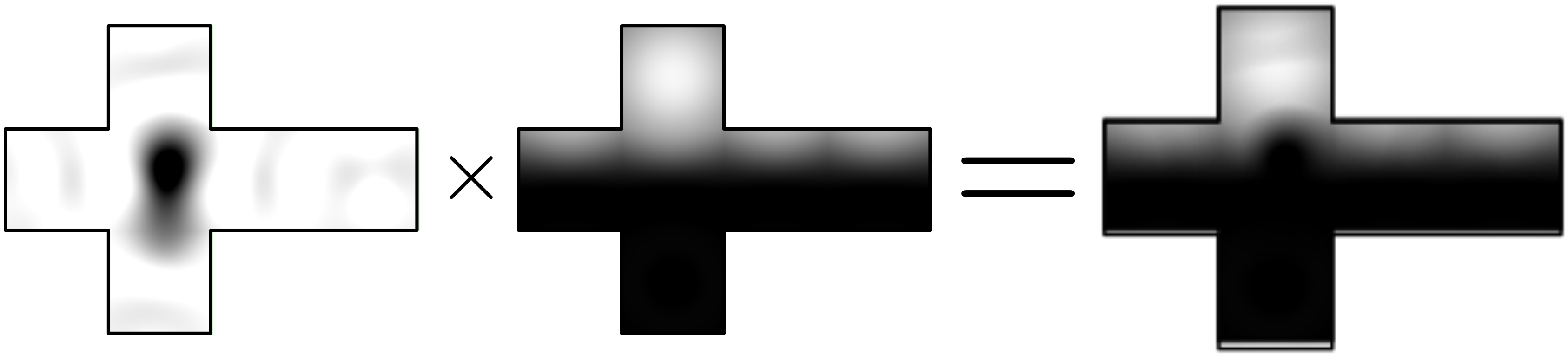
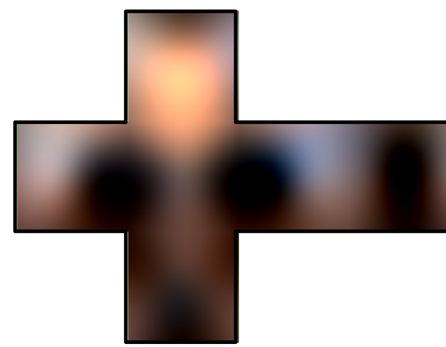
$\mathbf{T}$



SH transfer

$\mathbf{L}_e$

lighting environment



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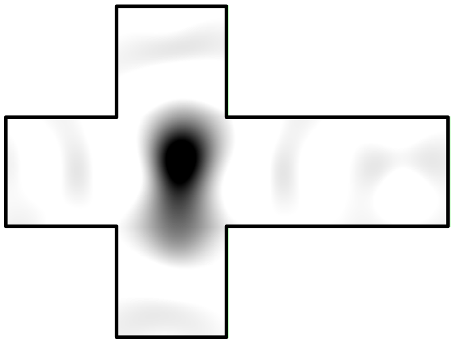
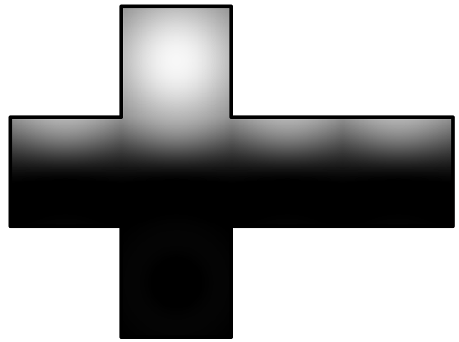


$\times$



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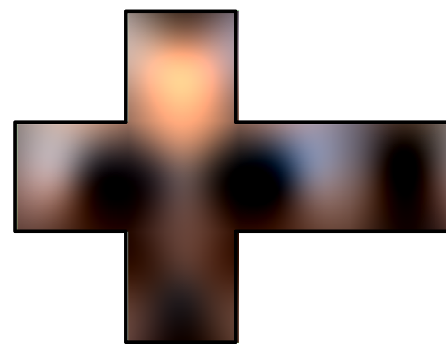
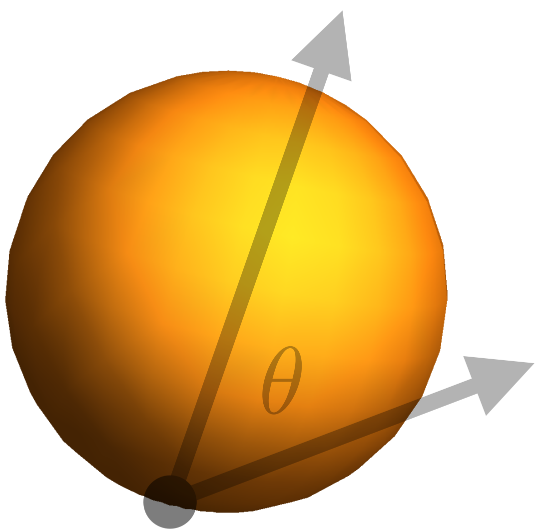


- Now shading requires a cheap *double-product* SH integral!
  - but how do we compute the ***log-BRDF*** *SH coefficients*?

Log-BRDF SH Coefficients

- We compute the log-**ZH** BRDF coefficients *numerically* for:
  - diffuse BRDFs,
  - and Phong BRDFs



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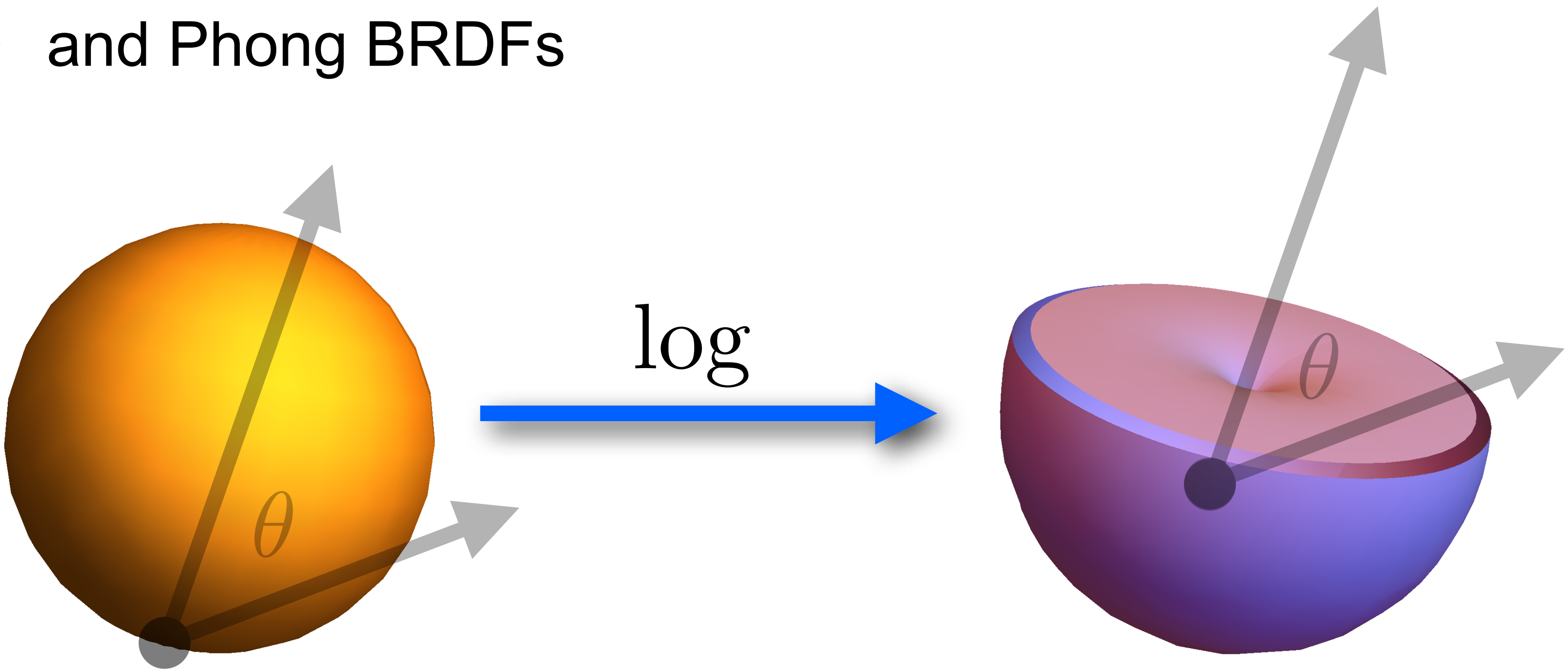

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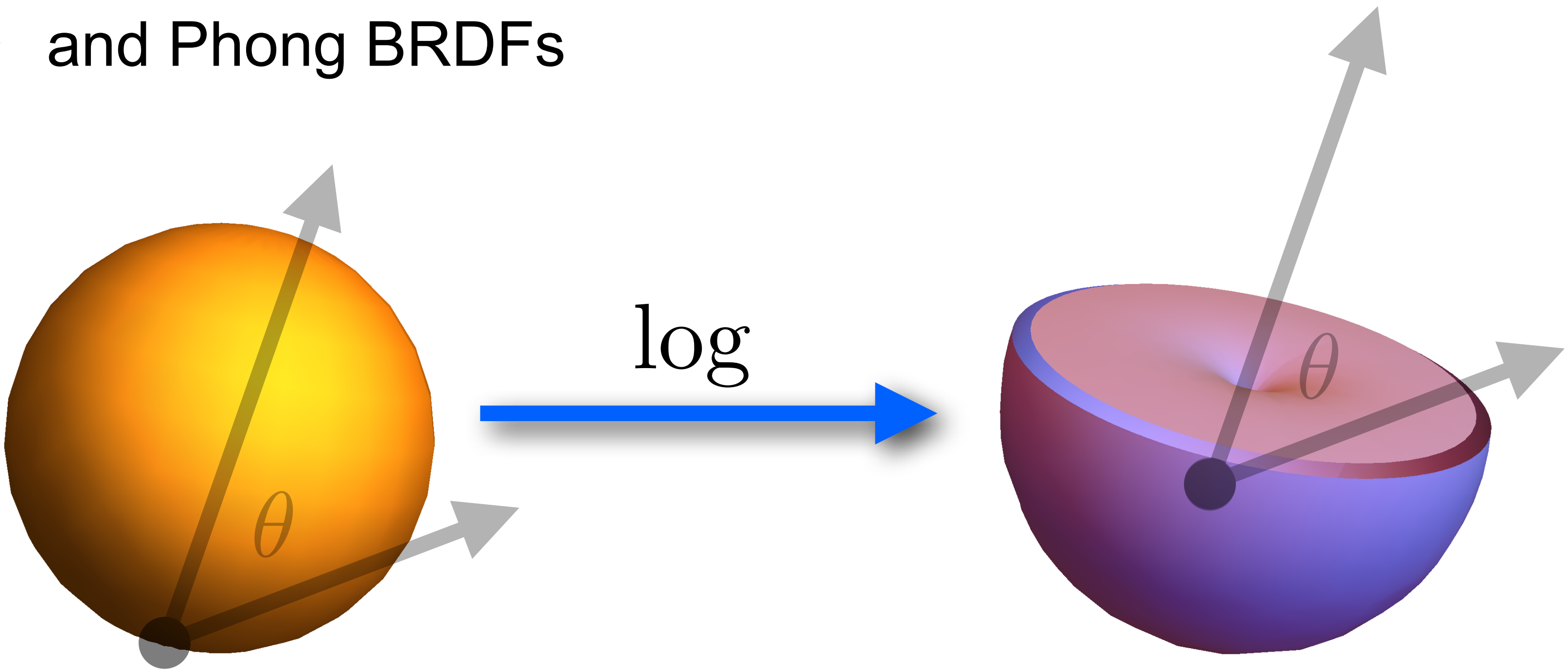

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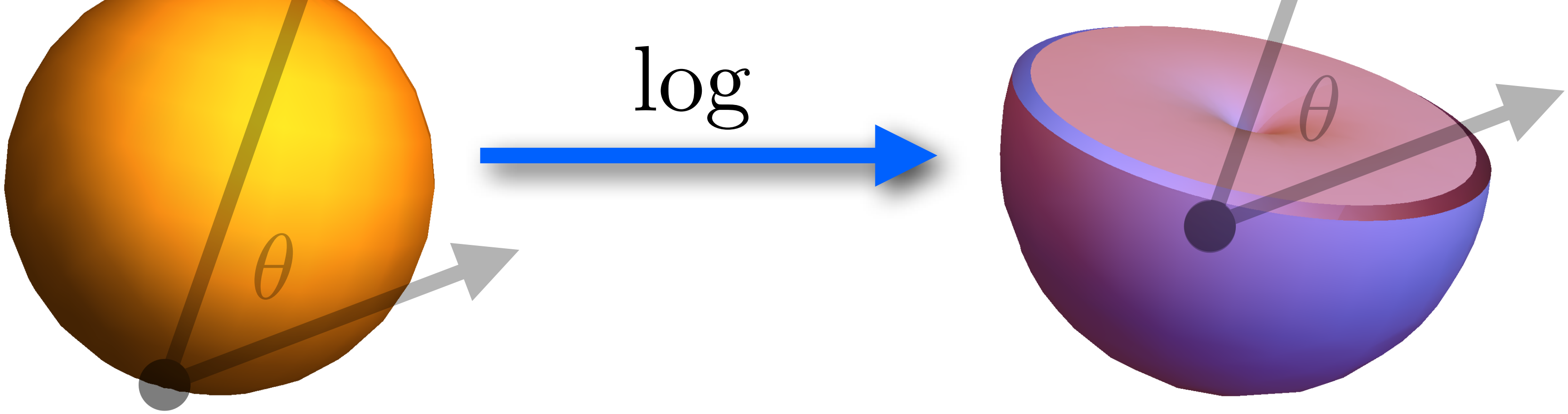
- Need to treat hemispherical clamping carefully!



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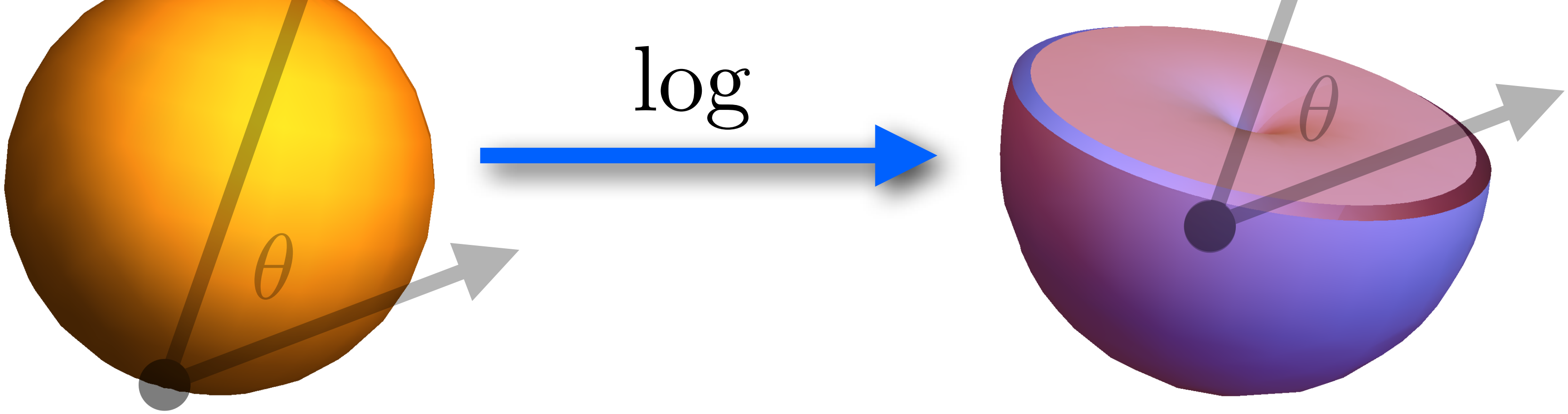
$$f_{l,0}^{\log} = \int_{H^{2+}} \log\left(\tfrac{\alpha+1}{2\pi}\max(\cos^\alpha\omega_\theta, \epsilon)\right)\; y_l^0(\omega)\,\mathrm{d}\omega +$$

$$\int_{H^{2-}} (\log\epsilon)\; y_l^0(\omega)\,\mathrm{d}\omega$$



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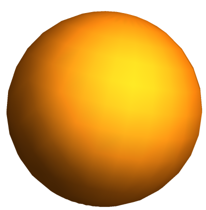
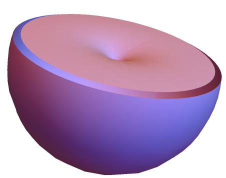
- We compute & tabulate order-4 ZH coefficients numerically

Log-BRDF Error

- In a ***worse case*** lighting scenario, log-SH BRDF shading still maintains a cosine-like fall-off profile



SH



log-**SH**

α

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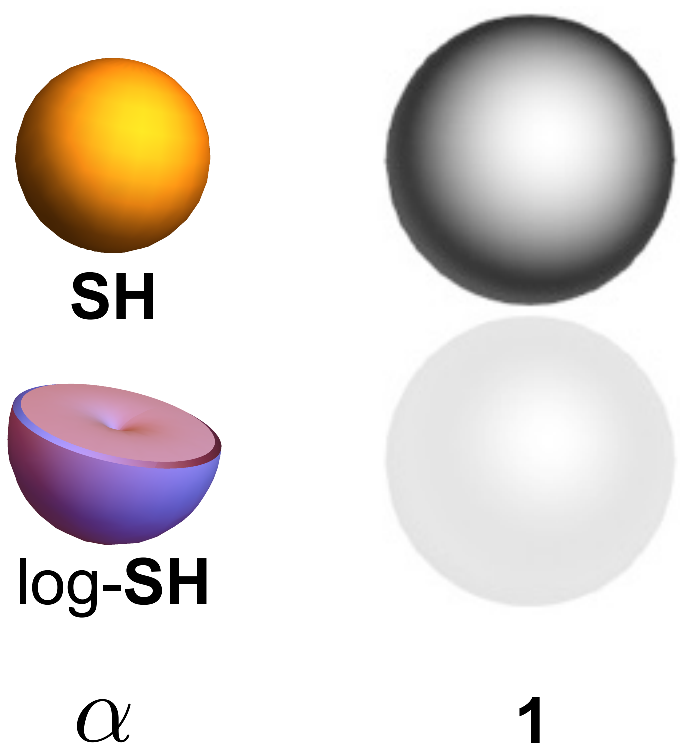

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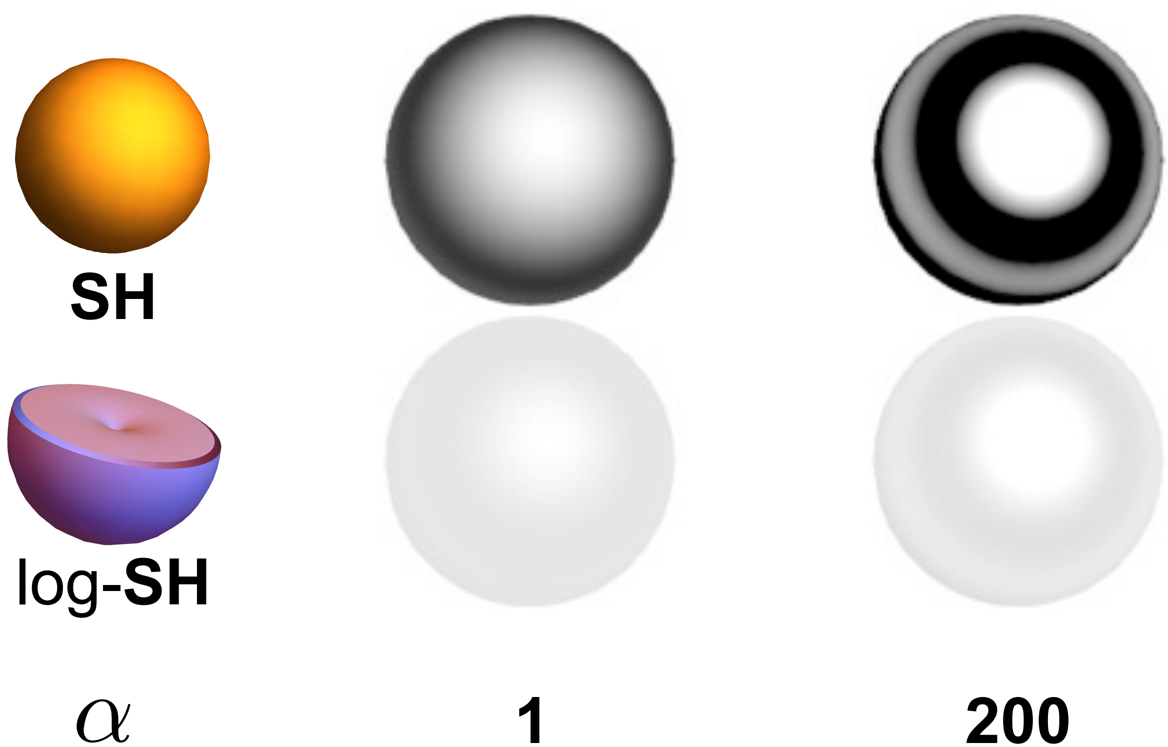

Results

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- Hybrid image/object-space renderer
  - spherical blockers splatted onto screen **[SGNS07]**
  - multi-resolution HF ray-marching in HF object-space
  - rendered at 960 x 540 with (avg.) pixel coverage of 83%.

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Wrecking Ball	Whale in Ocean	Cone Man
402 blockers + HF	50 blockers + HF	25 blockers + HF
15Hz (GTX 480)	10 Hz (GTX 480)	68 Hz (GTX 480)

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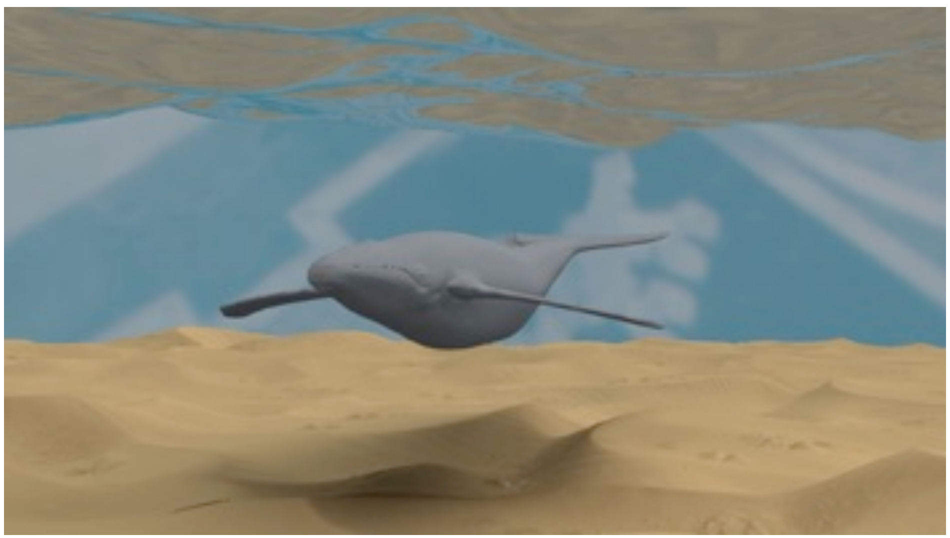
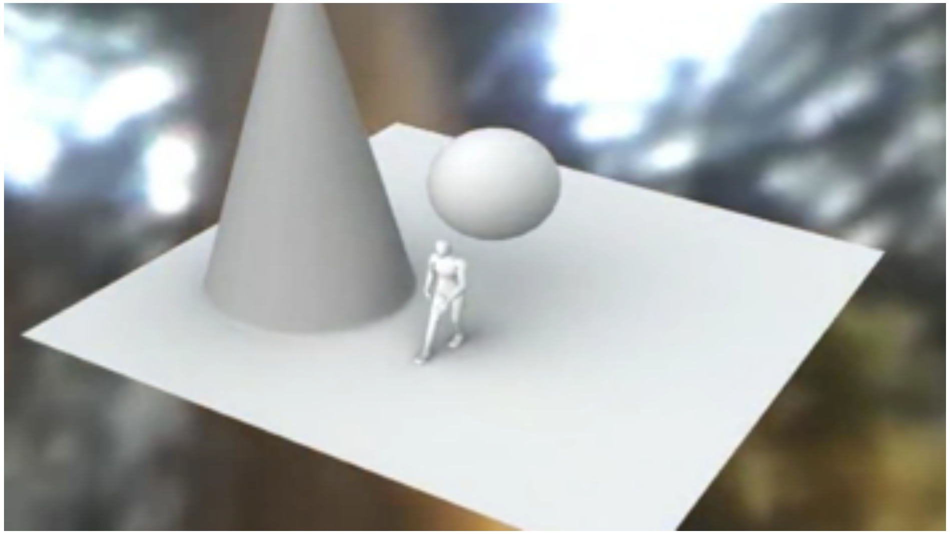
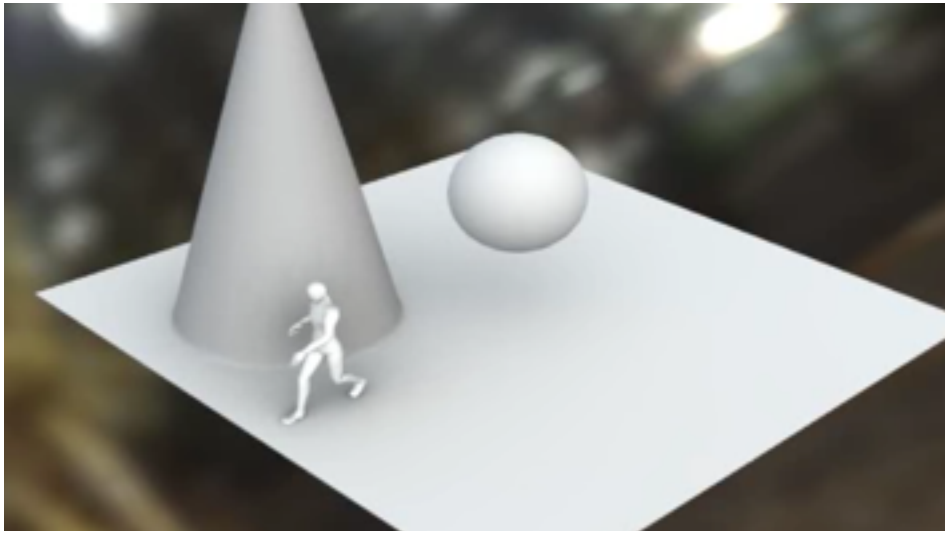


Wrecking Ball	Whale in Ocean	Cone Man
402 blockers + HF	50 blockers + HF	25 blockers + HF
15Hz (GTX 480)	10 Hz (GTX 480)	68 Hz (GTX 480)

Results

- Hybrid image/object-space renderer
  - spherical blockers splatted onto screen [SGNS07]
  - multi-resolution HF ray-marching in HF object-space
  - rendered at 960 x 540 with (avg.) pixel coverage of 83%.





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- Propose Log-SH BRDF formulation to reduce triple-product shading to double-product shading

Future Work

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  - leverage negative blocking angle formulation of **[NS09]**

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- generalize geometry
  - local height field displacements
  - tiled height field representations
  - non-spherical blockers

We acknowledge the helpful suggestions of the anonymous reviewers.

Thanks! Any questions?