CS 87/187, Spring 2016

Rendering Algorithms

Direct Illumination II

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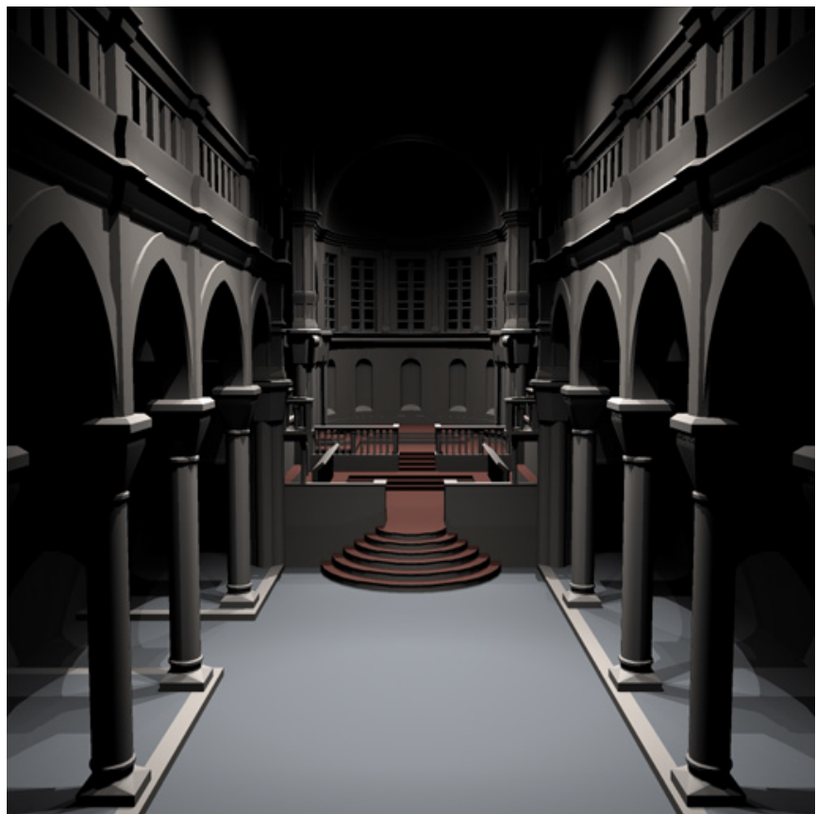
(with some slides adapted from Dr. Jan Novák and Dr. Paul Debevec)

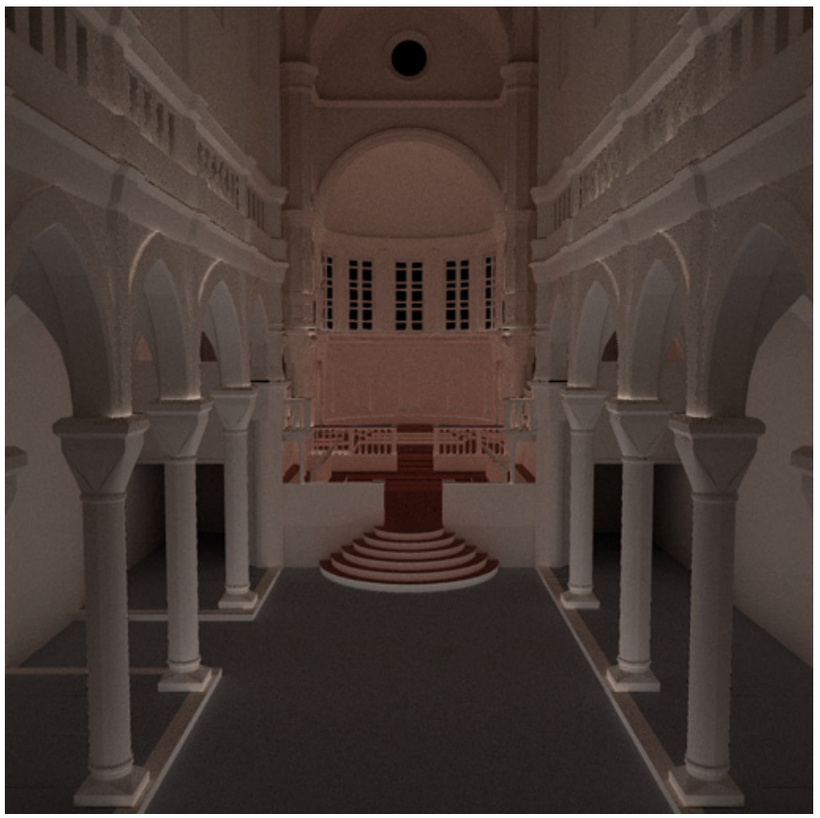
Dartmouth

Direct vs. Indirect Illumination

Direct illumination



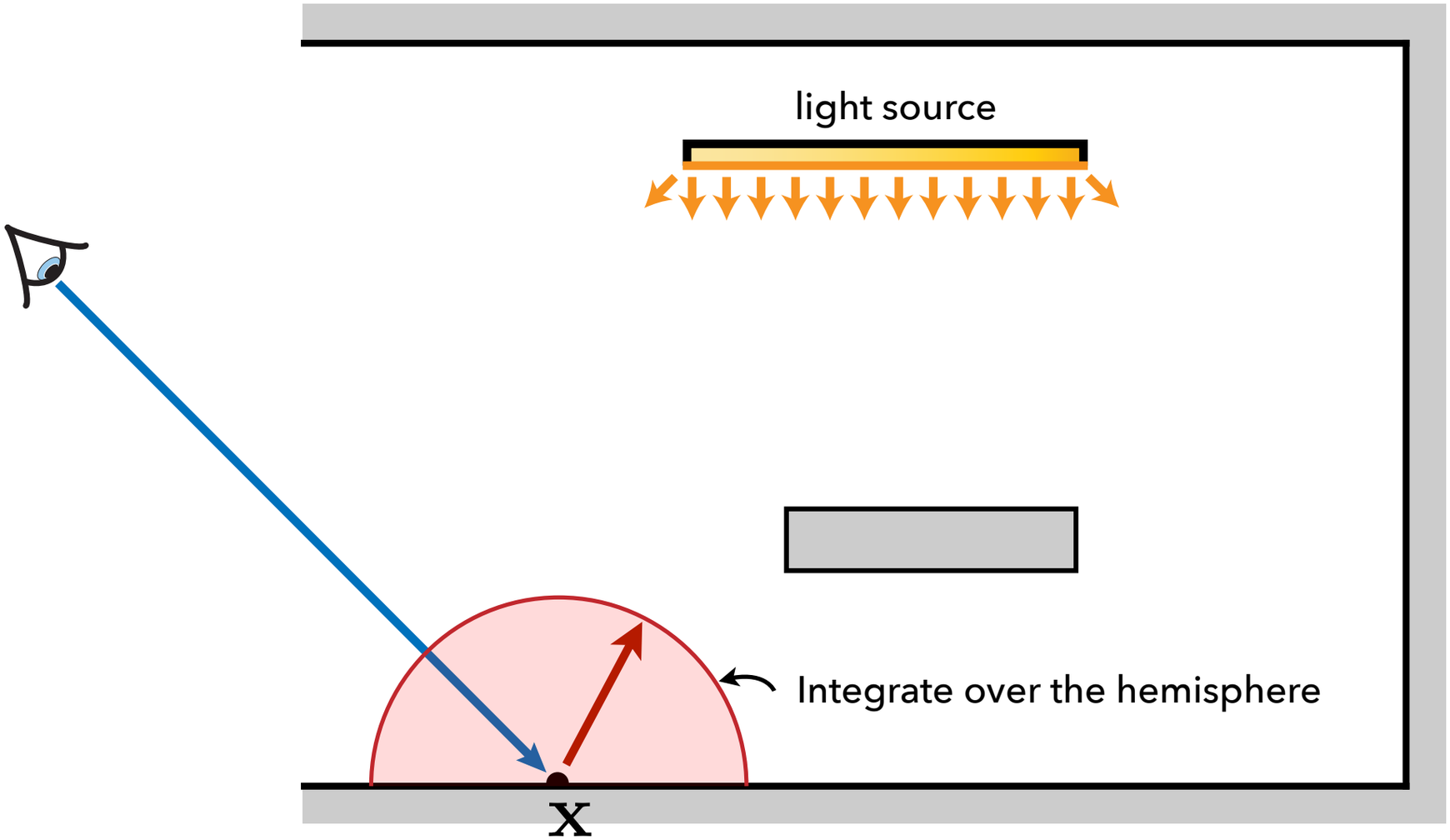
Indirect illumination



Direct + indirect illumination

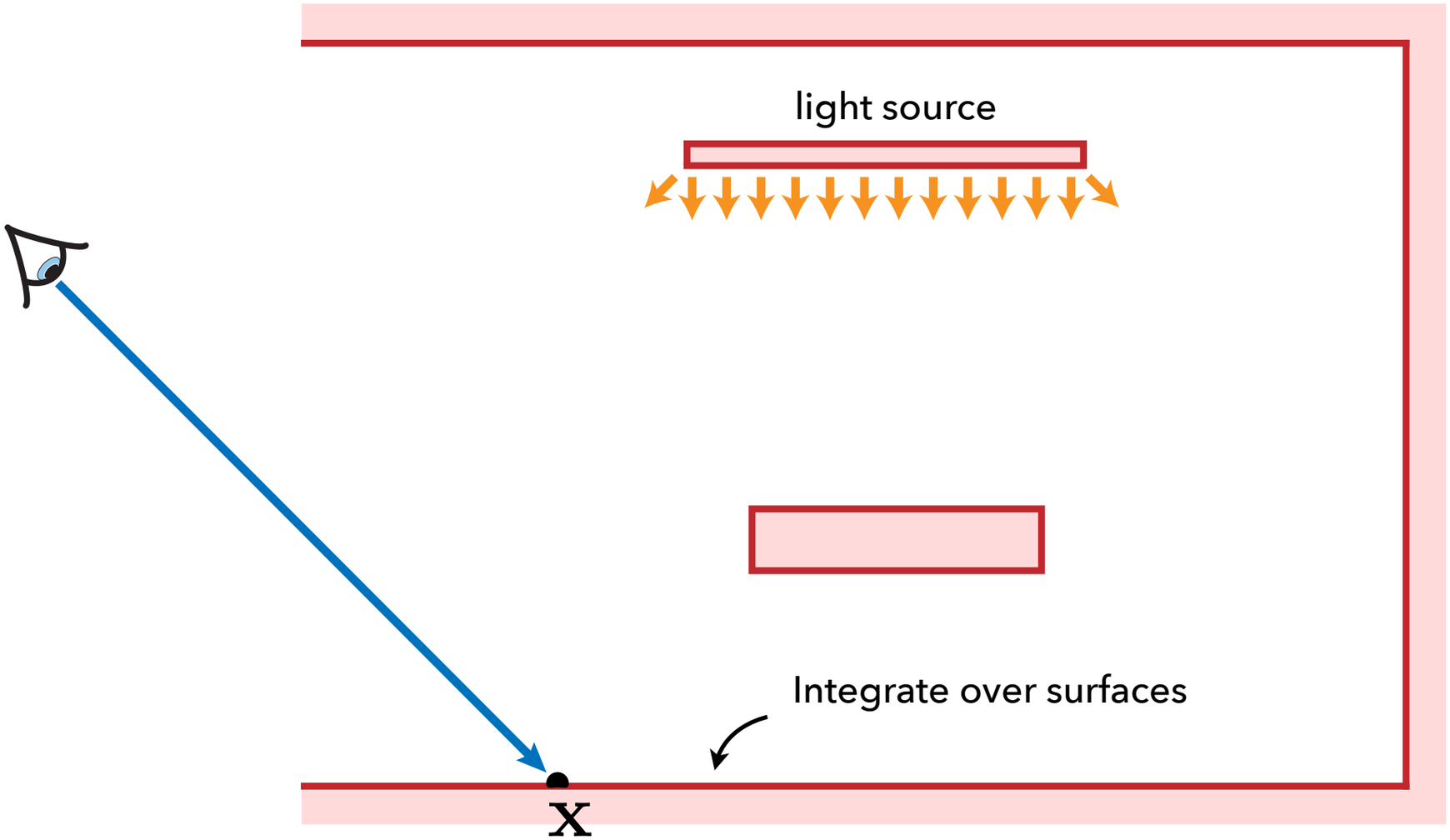
RE - Hemispherical Form

$$L_r(\mathbf{x}, \vec{\omega}_r) = \int_{H^2} f_r(\mathbf{x}, \vec{\omega}_i, \vec{\omega}_r) L_e(r(\mathbf{x}, \vec{\omega}_i), -\vec{\omega}_i) \cos\theta_i \, d\vec{\omega}_i$$



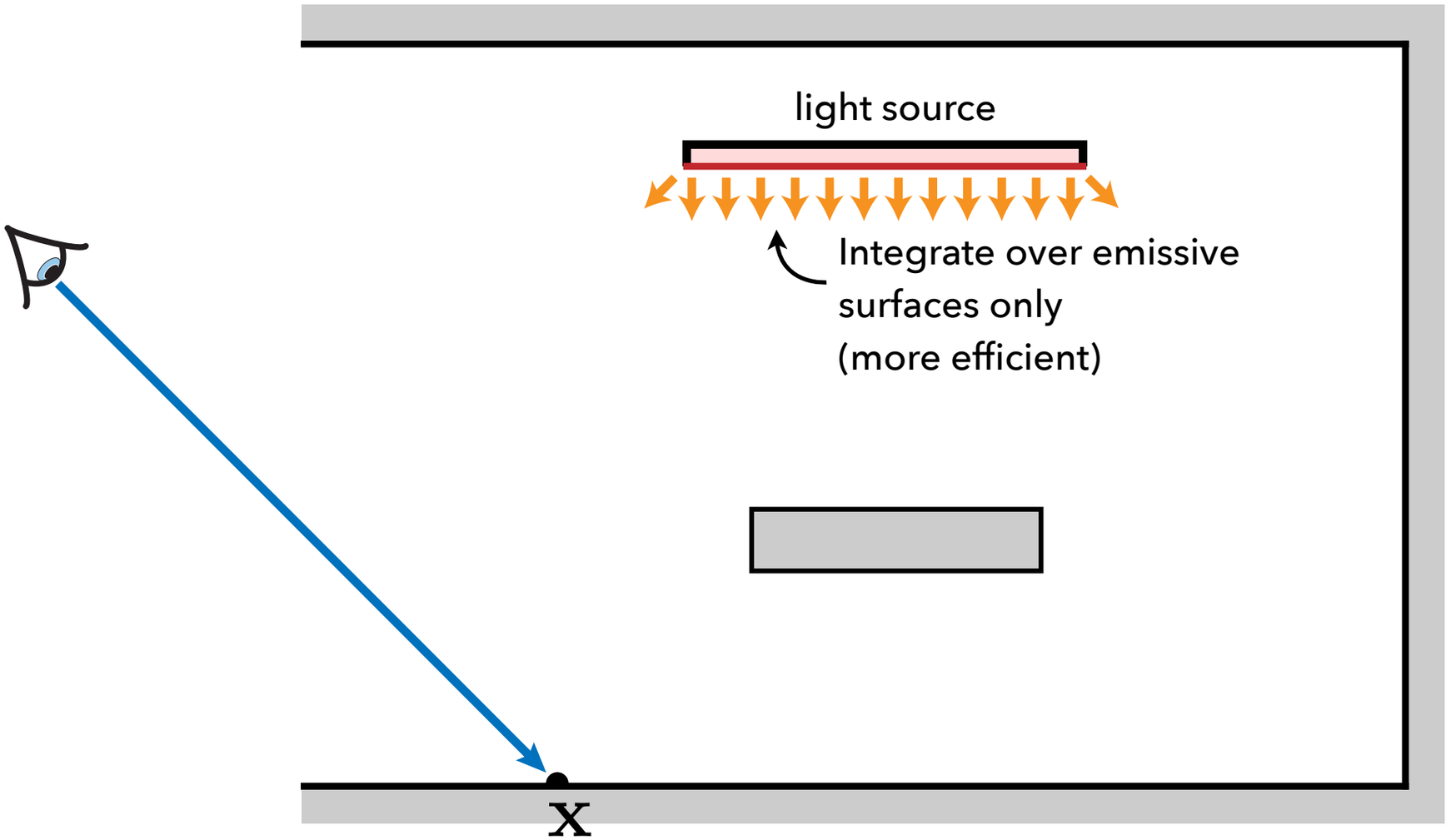
RE - Surface Area Form

$$L_r(\mathbf{x},\mathbf{z}) = \int_A f_r(\mathbf{x},\mathbf{y},\mathbf{z}) L_e(\mathbf{y},\mathbf{x}) V(\mathbf{x},\mathbf{y}) \frac{|\cos\theta_i|\,|\cos\theta_o|}{\|\mathbf{x}-\mathbf{y}\|^2} dA(\mathbf{y})$$



RE - Surface Area Form

$$L_r(\mathbf{x},\mathbf{z}) = \int_{A_e} f_r(\mathbf{x},\mathbf{y},\mathbf{z}) L_e(\mathbf{y},\mathbf{x}) V(\mathbf{x},\mathbf{y}) \frac{|\cos\theta_i|\,|\cos\theta_o|}{\|\mathbf{x}-\mathbf{y}\|^2} dA(\mathbf{y})$$



Light Sources

Point light | Spot light | Directional light | Quad light | Sphere light | Mesh light

Delta lights

(create hard shadows)

Area/Shape lights

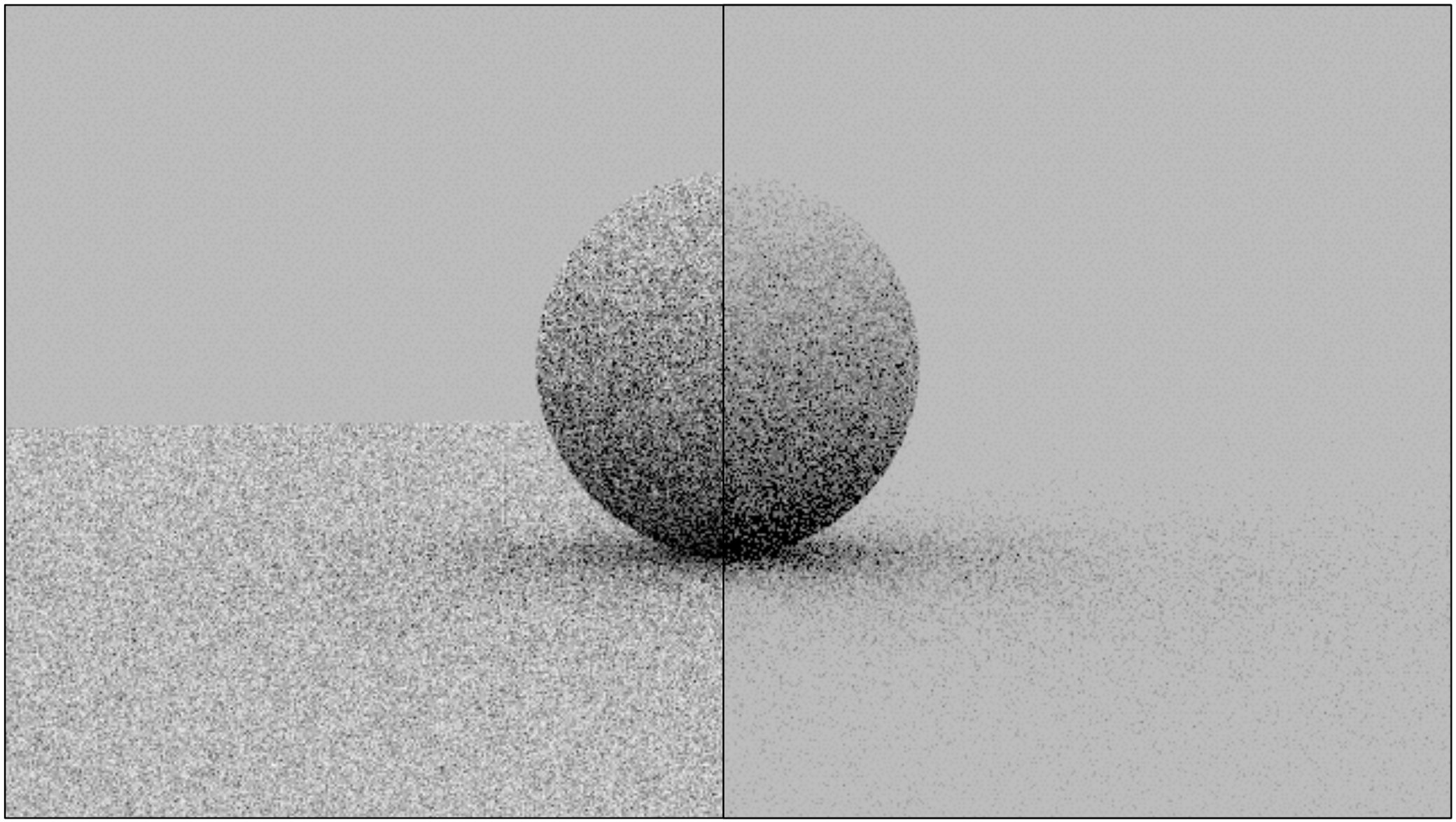
(create soft shadows)

Importance Sampling the Cosine

Uniform hemispherical sampling

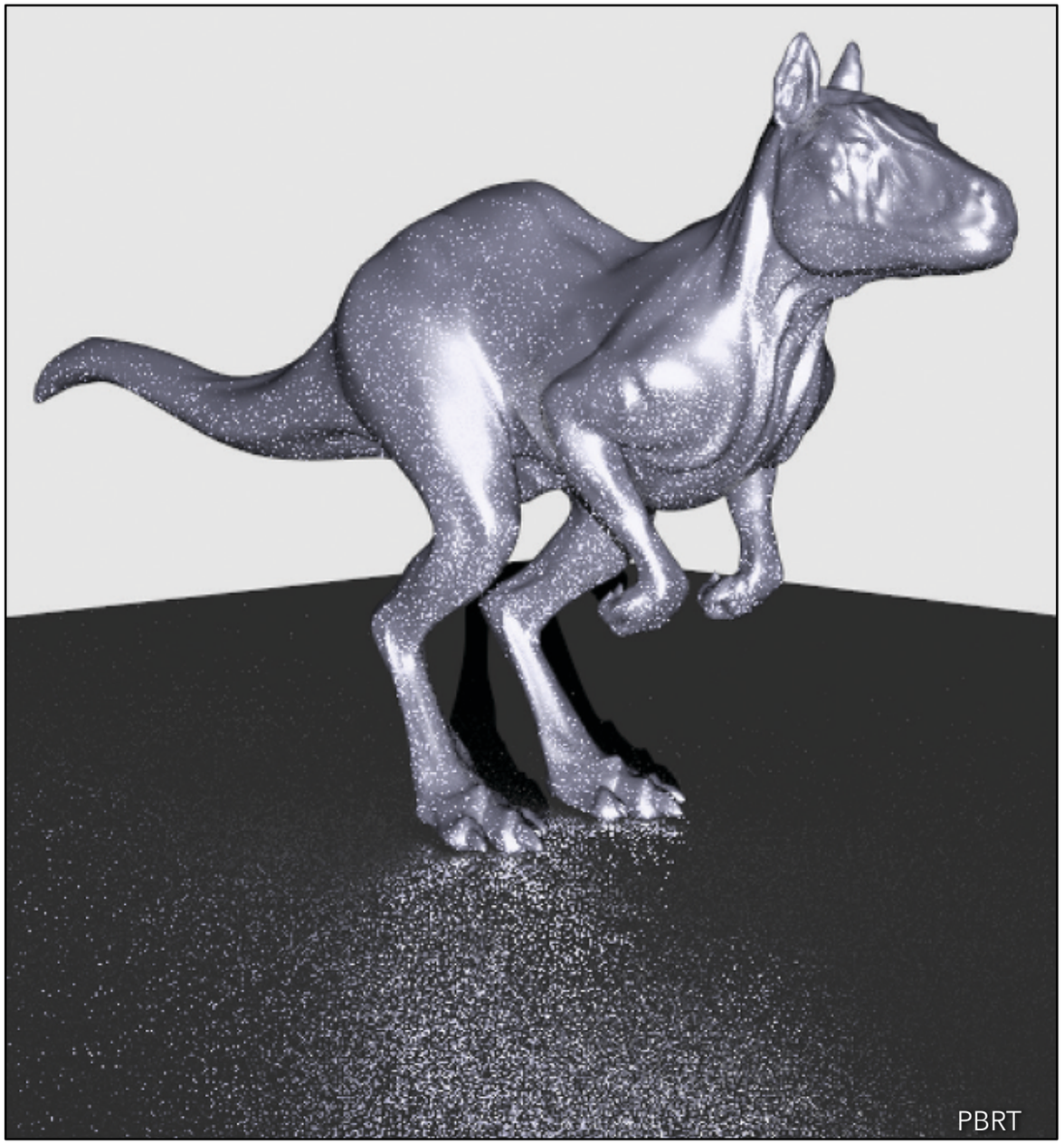
Cosine-weighted importance sampling

4 samples/pixel

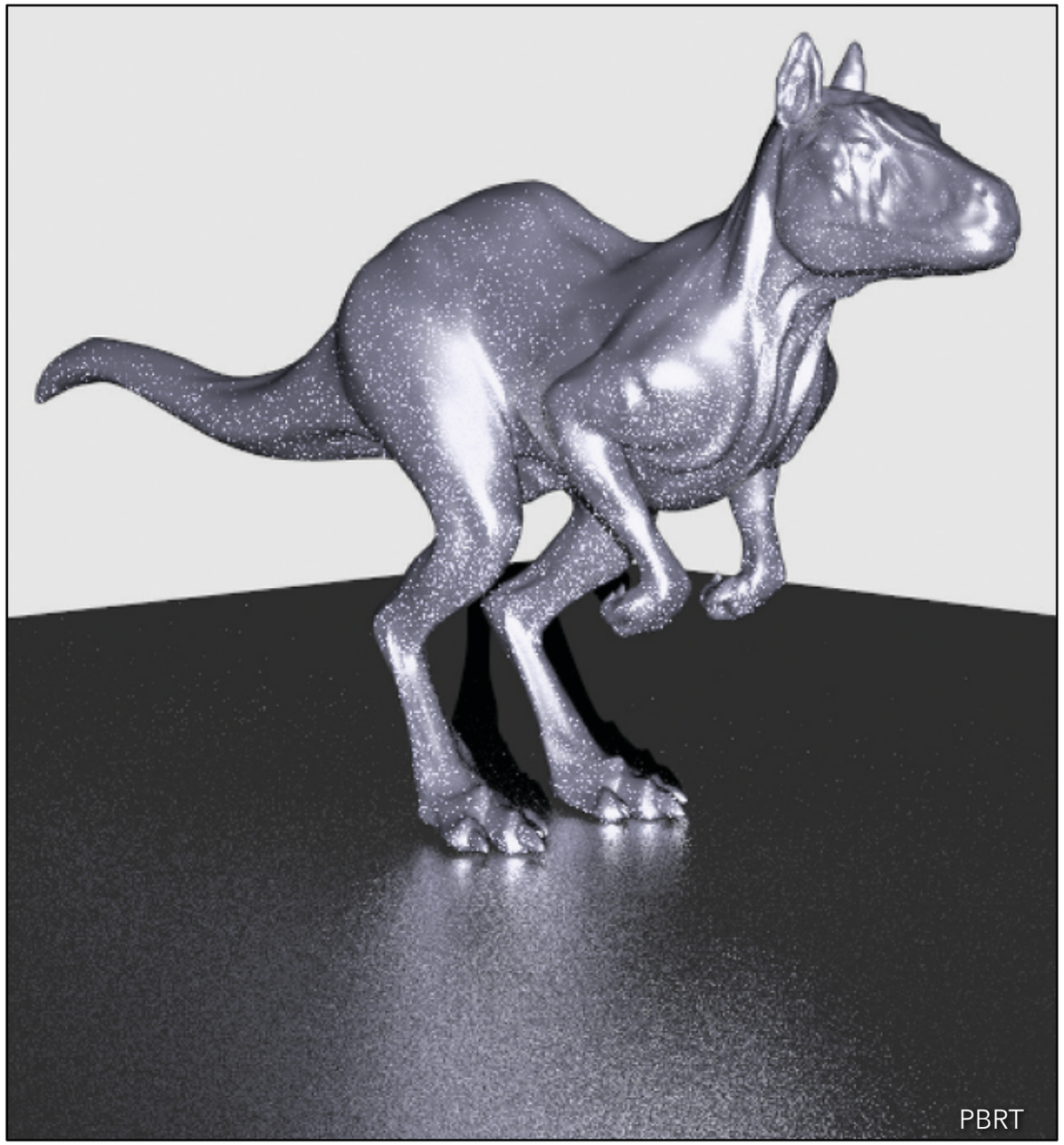


Importance Sampling the BRDF

Uniform hemispherical sampling



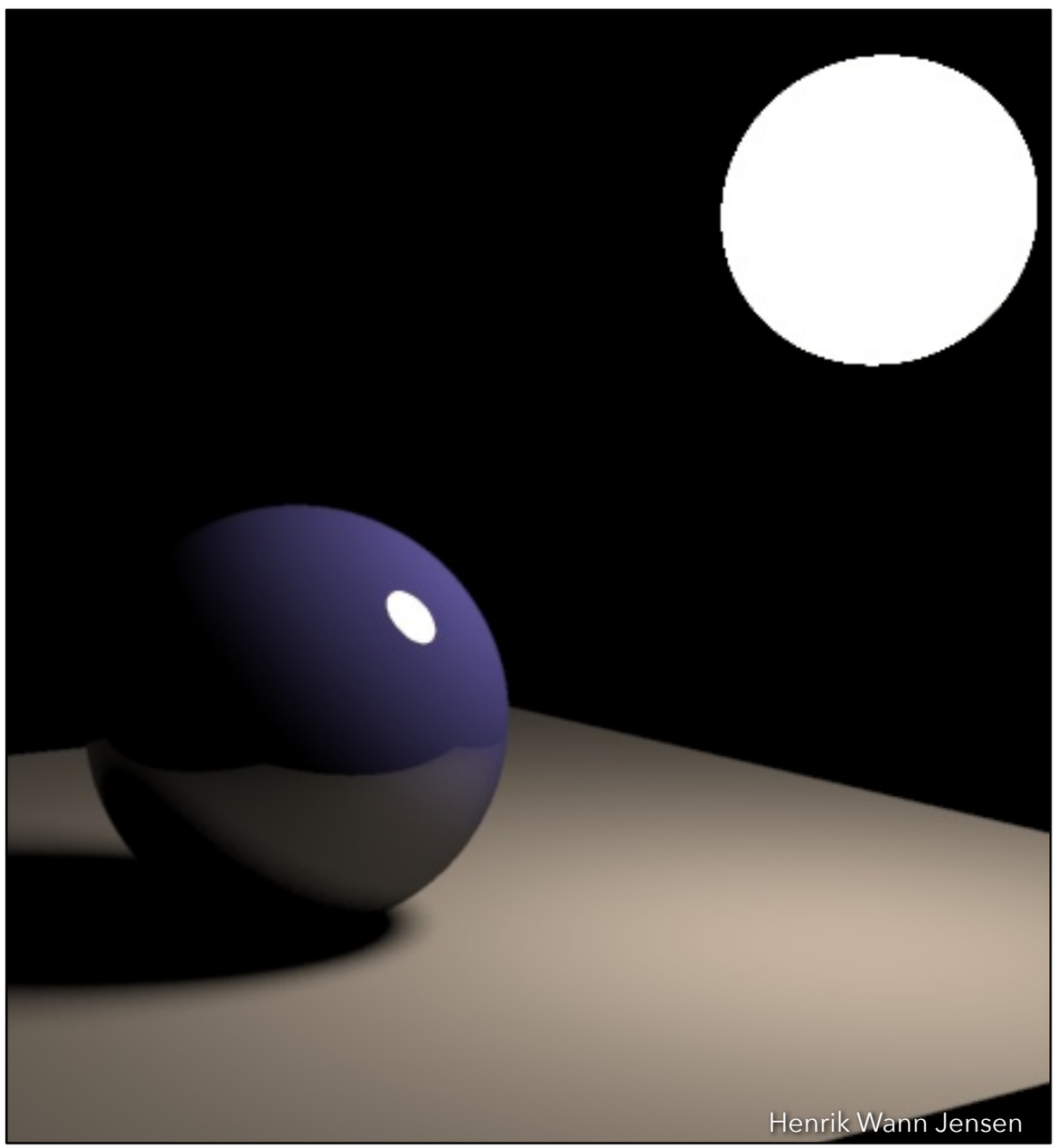
BRDF importance sampling



Importance Sampling the Light

Uniform hemispherical sampling

Uniform sampling of subtended solid angle



Multiple Importance Sampling

- *Multi-sample* model

$$\langle F^{\sum N_s} \rangle = \sum_{s=1}^{M} \frac{1}{N_s} \sum_{i=1}^{N_s} w_s(x_i) \frac{f(x_i)}{p_s(x_i)}$$

- *Balance* heuristic:

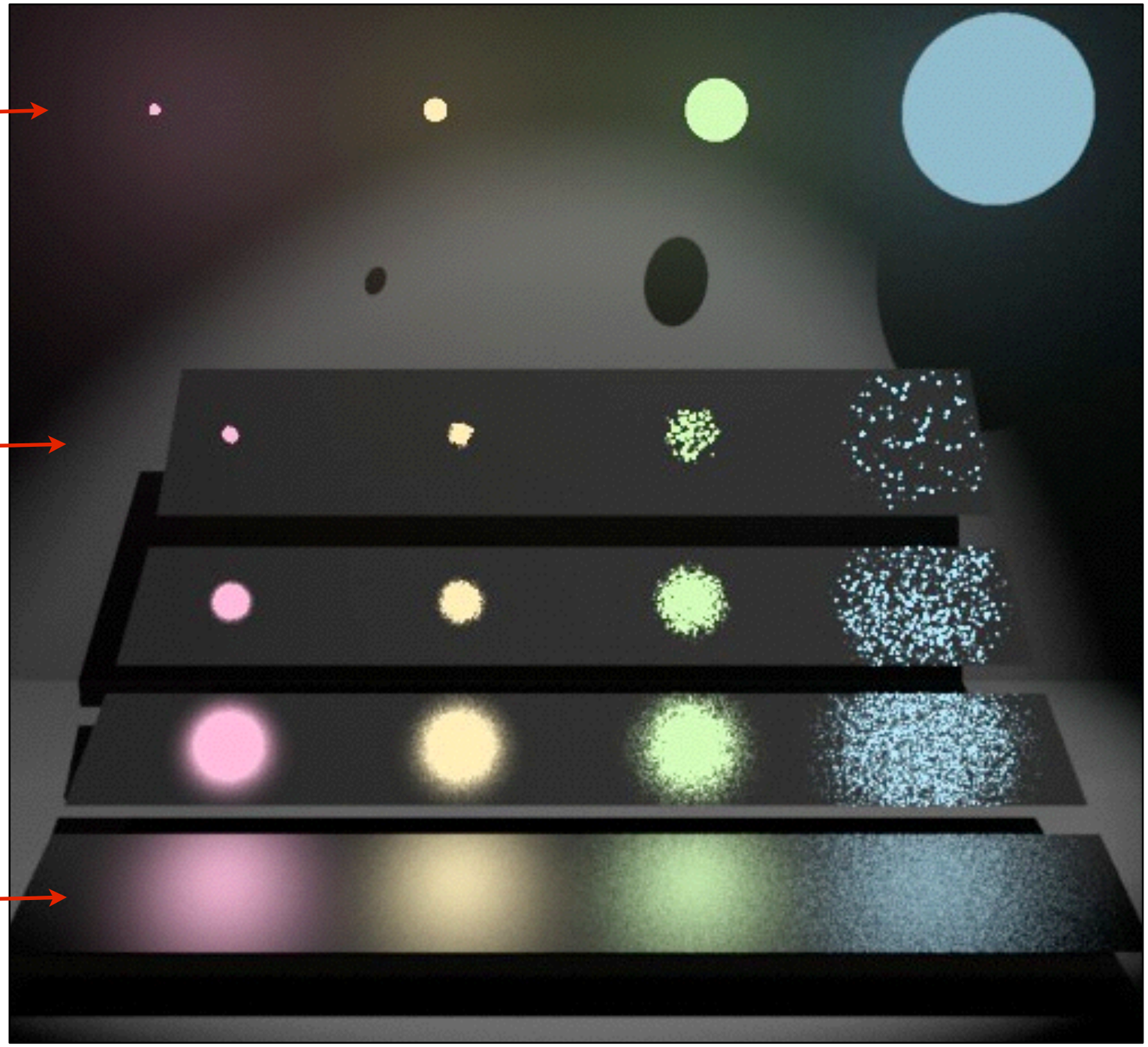
$$w_s(x) = \frac{N_s \, p_s(x)}{\sum_j N_j \, p_j(x)}$$

Sampling the Light

sphere lights

highly glossy surface

moderately glossy surface



Eric Veach and Leonidas J. Guibas 1995.

Sampling the BRDF

sphere lights

highly glossy surface

moderately glossy surface

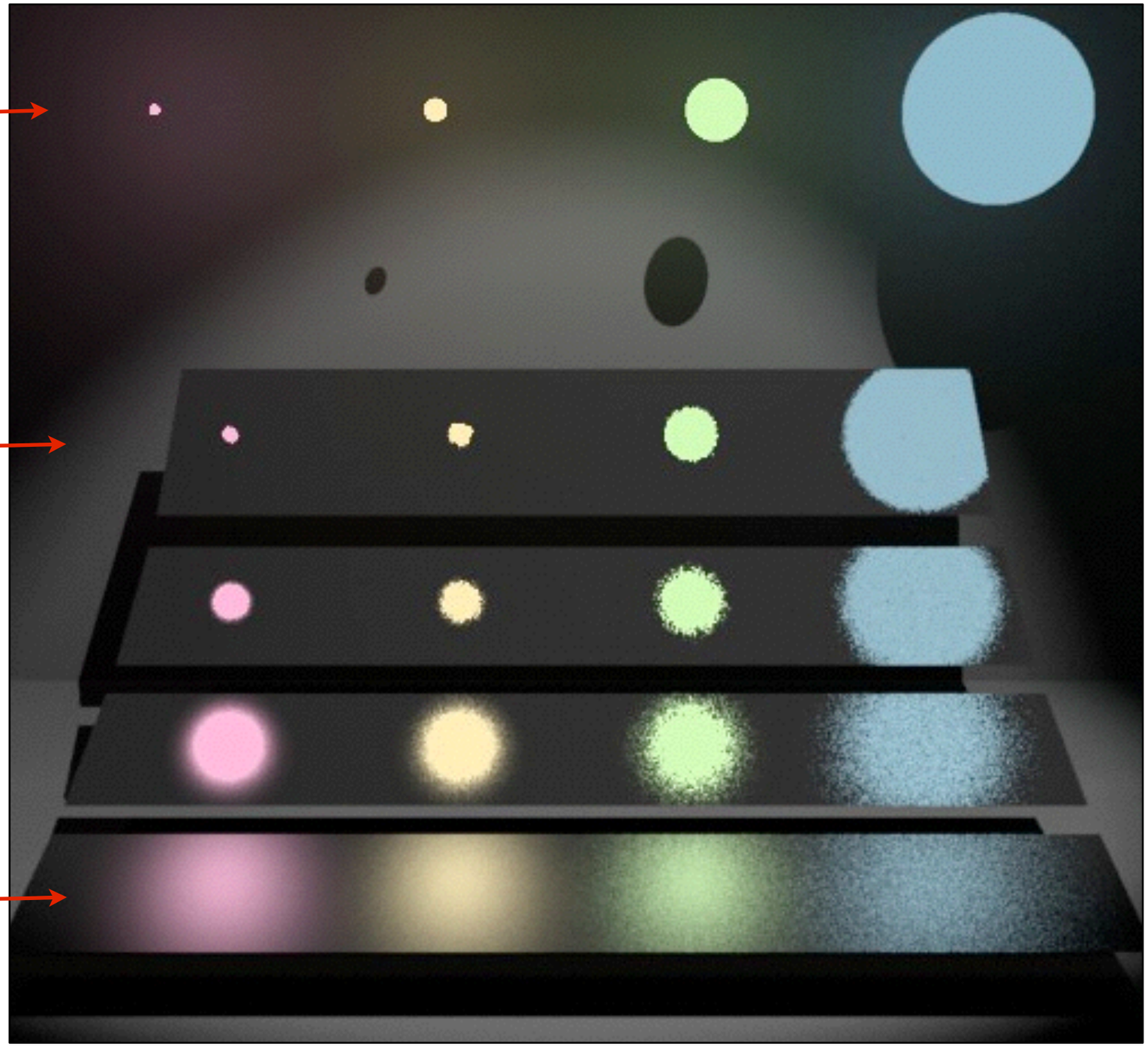
Eric Veach and Leonidas J. Guibas 1995.

Multiple Importance Sampling

sphere lights

highly glossy surface

moderately glossy surface



Eric Veach and Leonidas J. Guibas 1995.

Today's Menu

- Environment lighting (image-based lighting)
- Marginal/conditional inversion sampling
- Hierarchical sample warping
- Product sampling

Environment Lighting

Related techniques

- Reflection mapping
- Environment mapping/lighting
- Image-based lighting (IBL)

Environment Lighting

- Sidesteps tedious modeling of the environment by representing it using *one or more images*
- The image "wraps" around the virtual scene, serving as a *distant* source of illumination

source: 3delight

Reflection Mapping (1982)

Mike Chou and Lance Williams

Gene Miller and Ken Perlin

Flight of the Navigator (1986)

The Abyss (1989)

Terminator 2 (1991)

Fiat Lux

SIGGRAPH 99 Electronic Theater

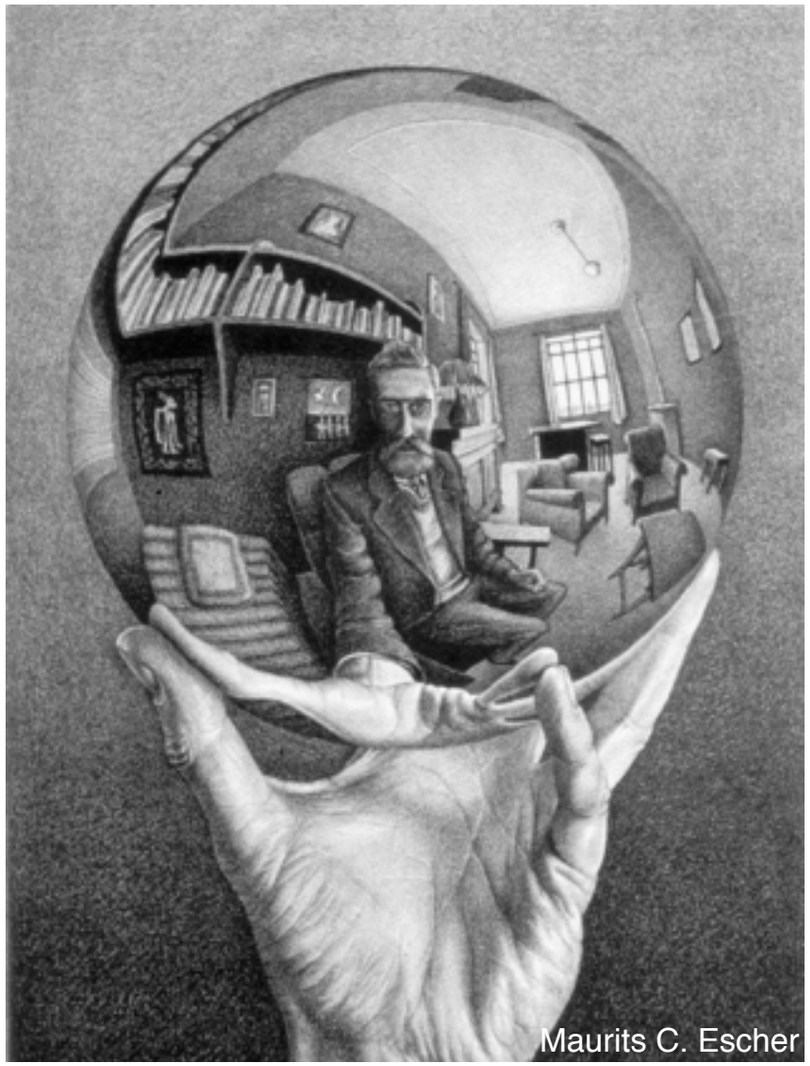
More details

- More details on Fiat Lux
  - http://www.pauldebevec.com/FiatLux/
- History of reflection mapping
  - http://www.pauldebevec.com/ReflectionMapping/

Acquiring Environment Lighting

- Mirrored ball + camera
- Fisheye lens images
- Stitching images together
- Panoramic camera

Acquisition - Low Tech.



Lightprobe

omnidirectional, 360° panoramic, **HDR** image

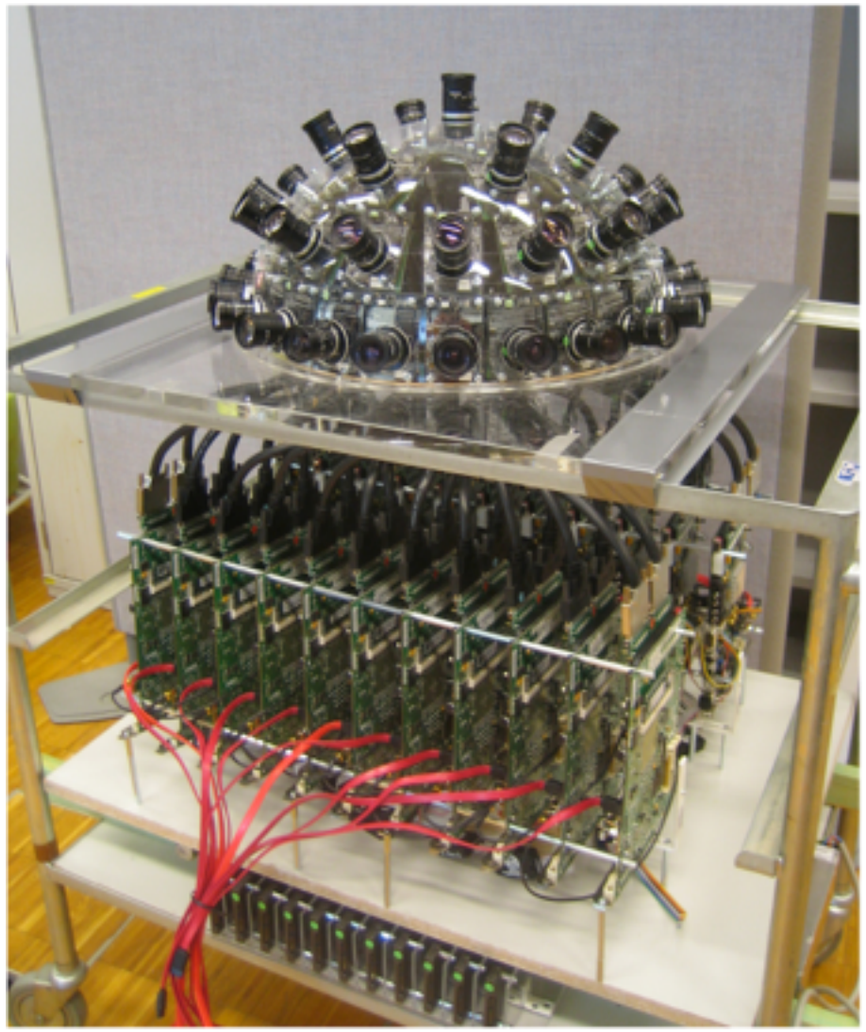
Acquisition - Even Lower Tech.

Gene Miller and Ken Perlin

Acquisition - Stitched Panorama

source: photoanswers.co.uk

Acquisition - High Tech.



lsm.epfl.ch

immersivemedia.com

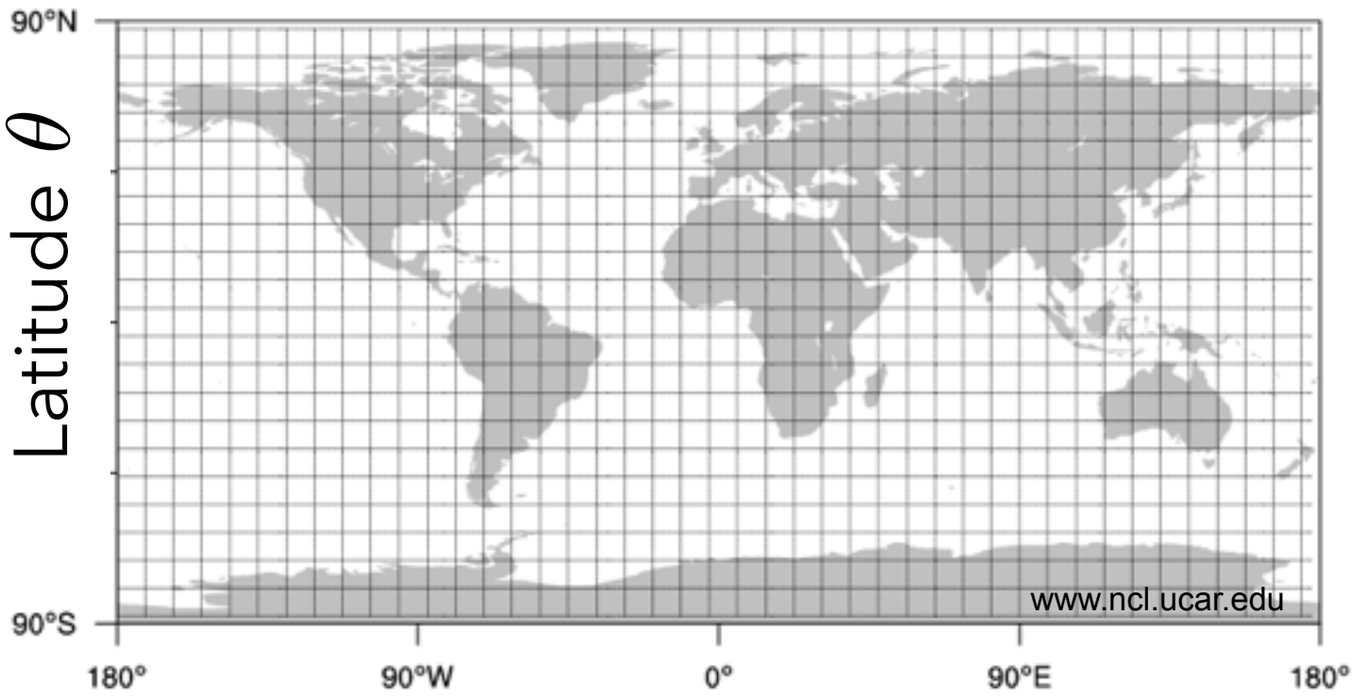
Storing Environment Maps

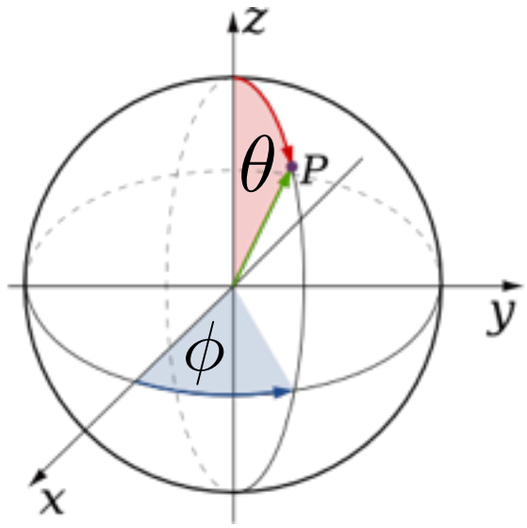
- Various ways to represent/parametrize environment maps
- Related to cartography
  - Projecting the earth (sphere) onto a plane

Mirror Ball

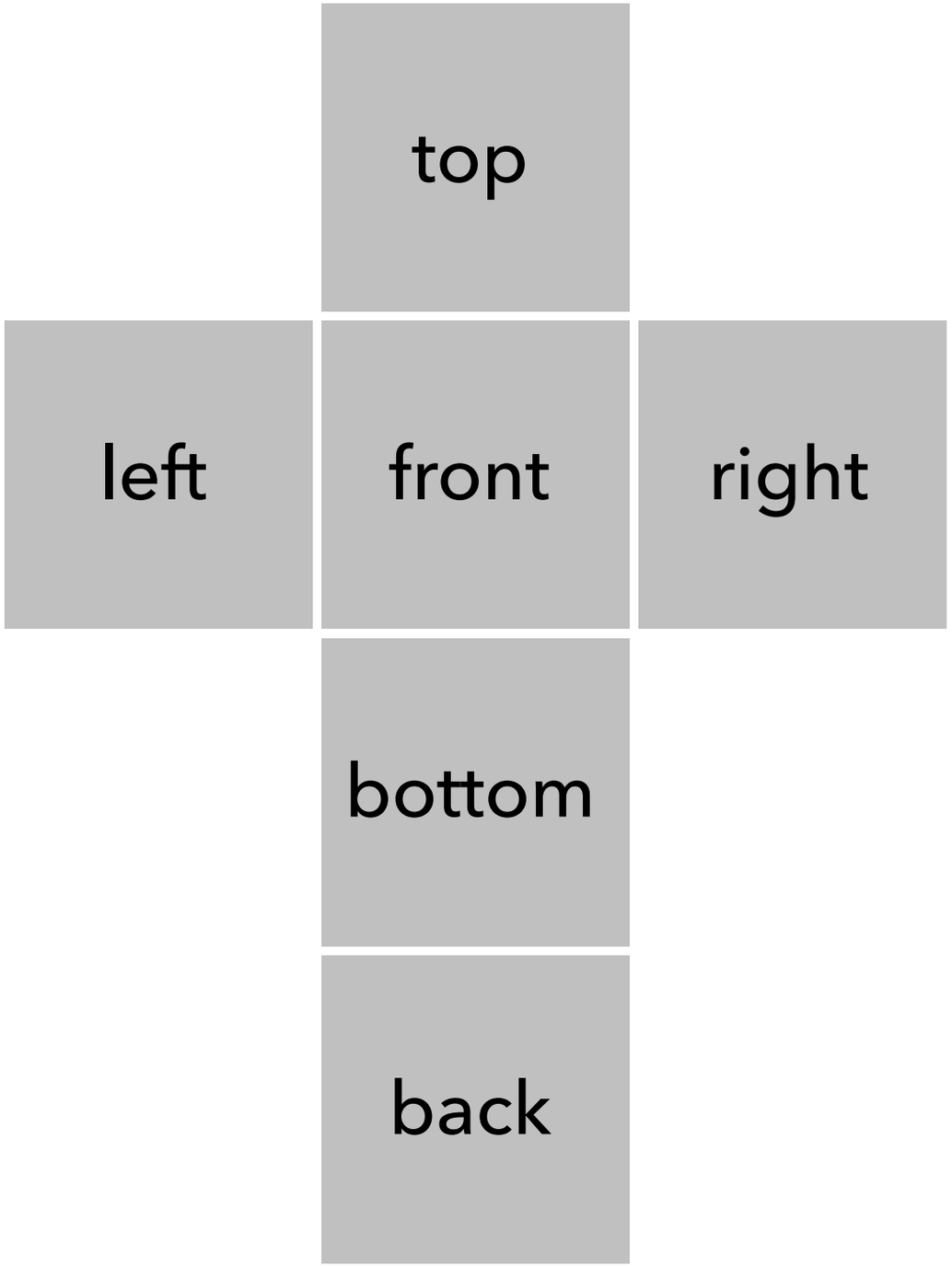
Angular Map

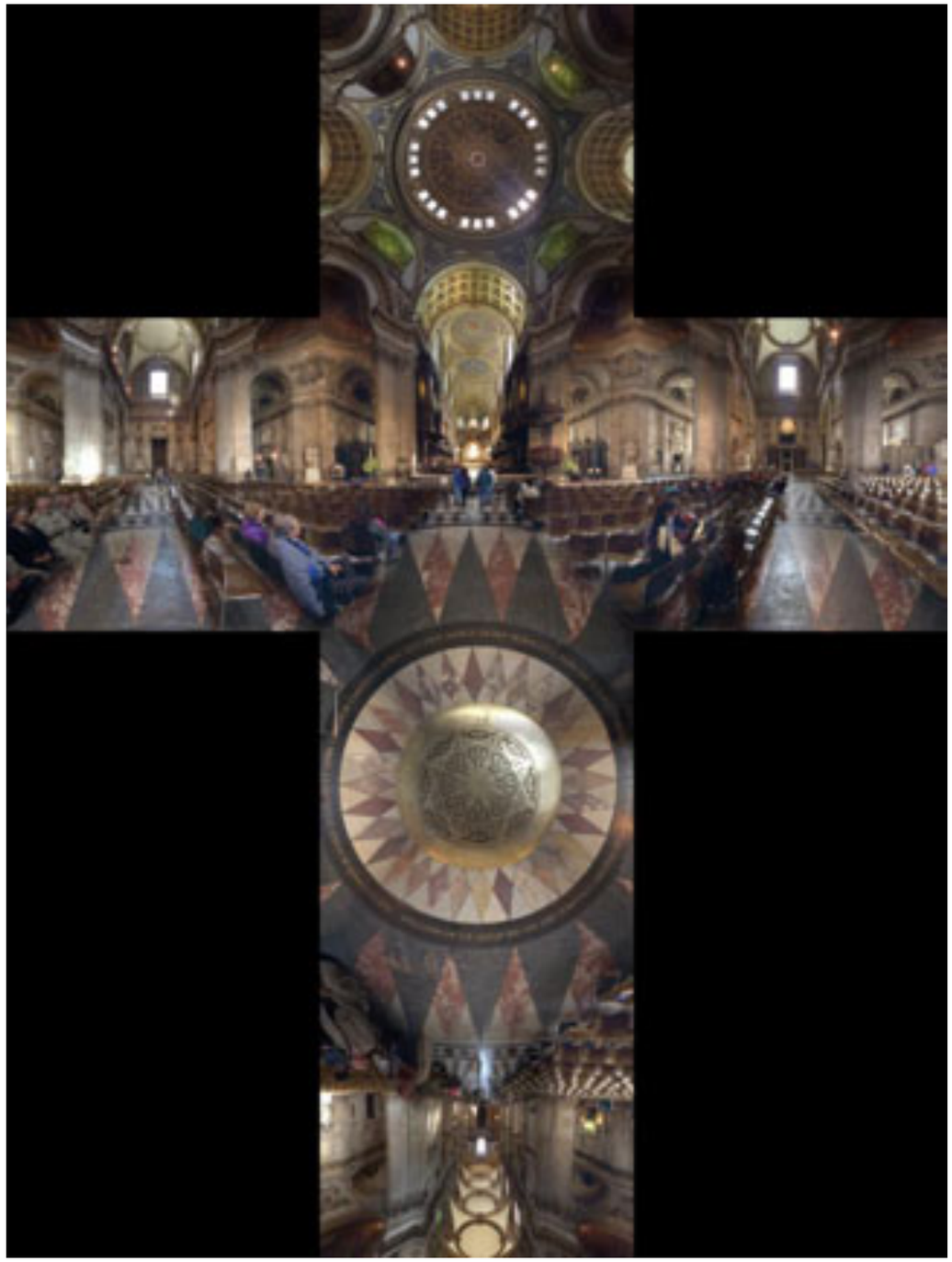
Latitude/Longitude Map





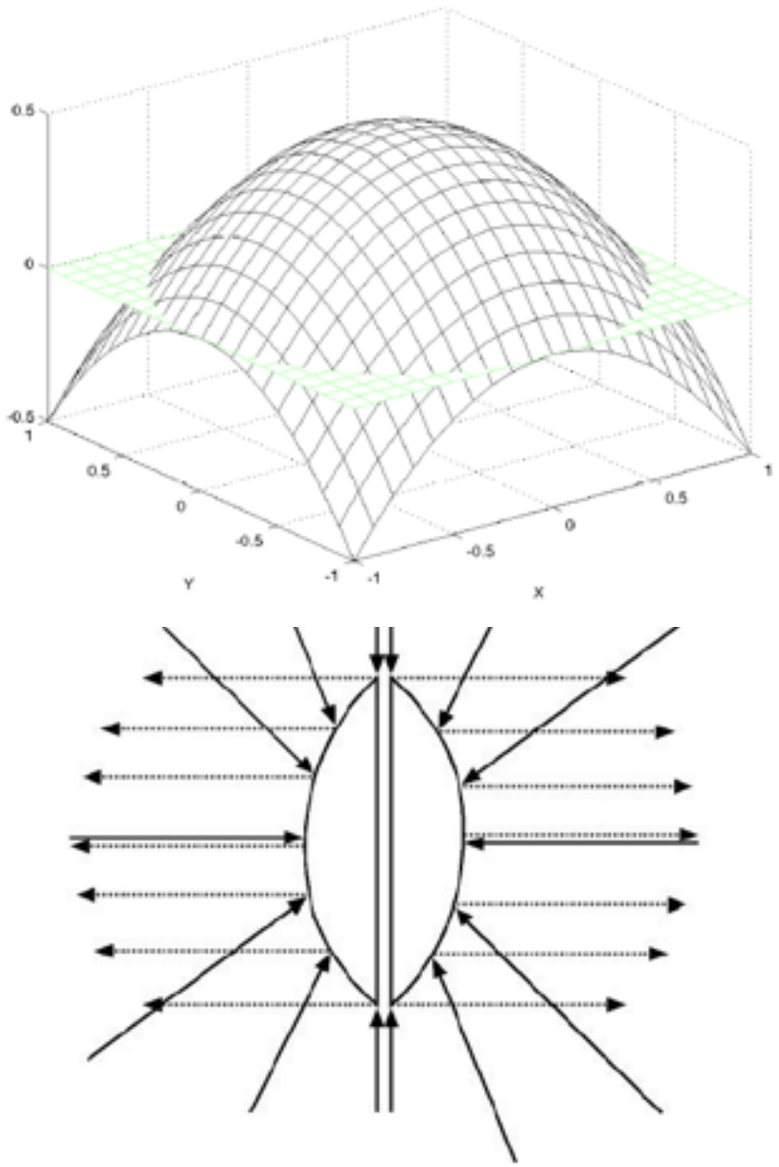
Cube Map (Skybox)





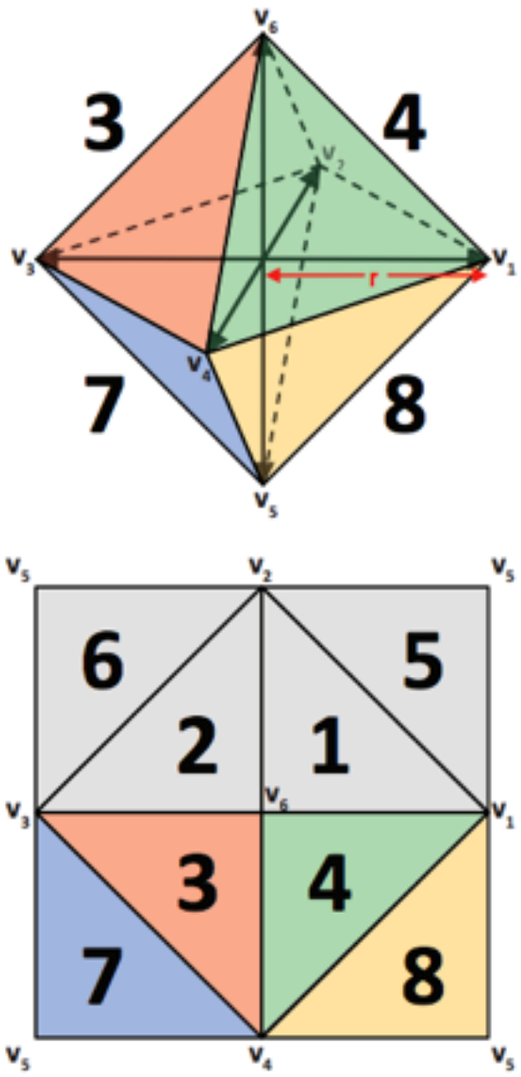
Other Parameterizations

Dual-paraboloid



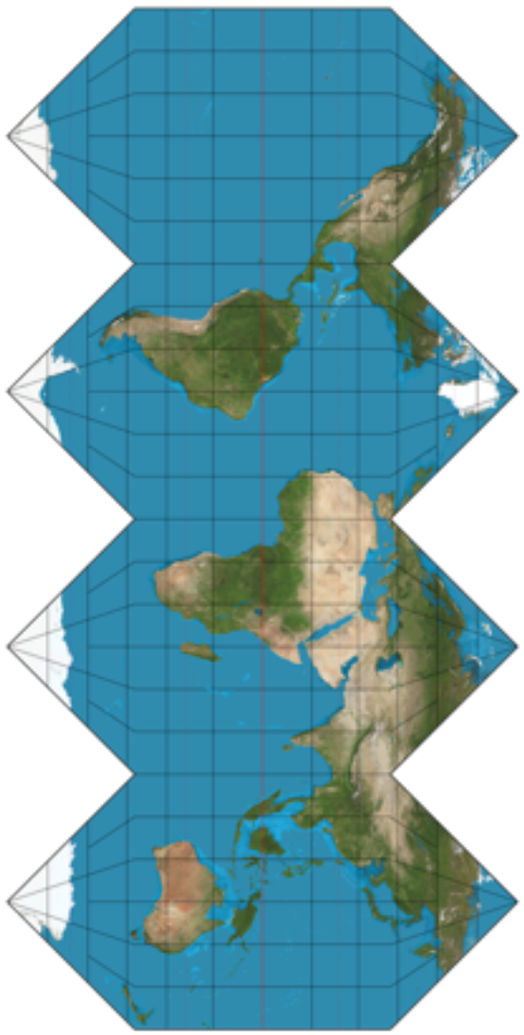
Courtesy of Brabec

Octahedron map



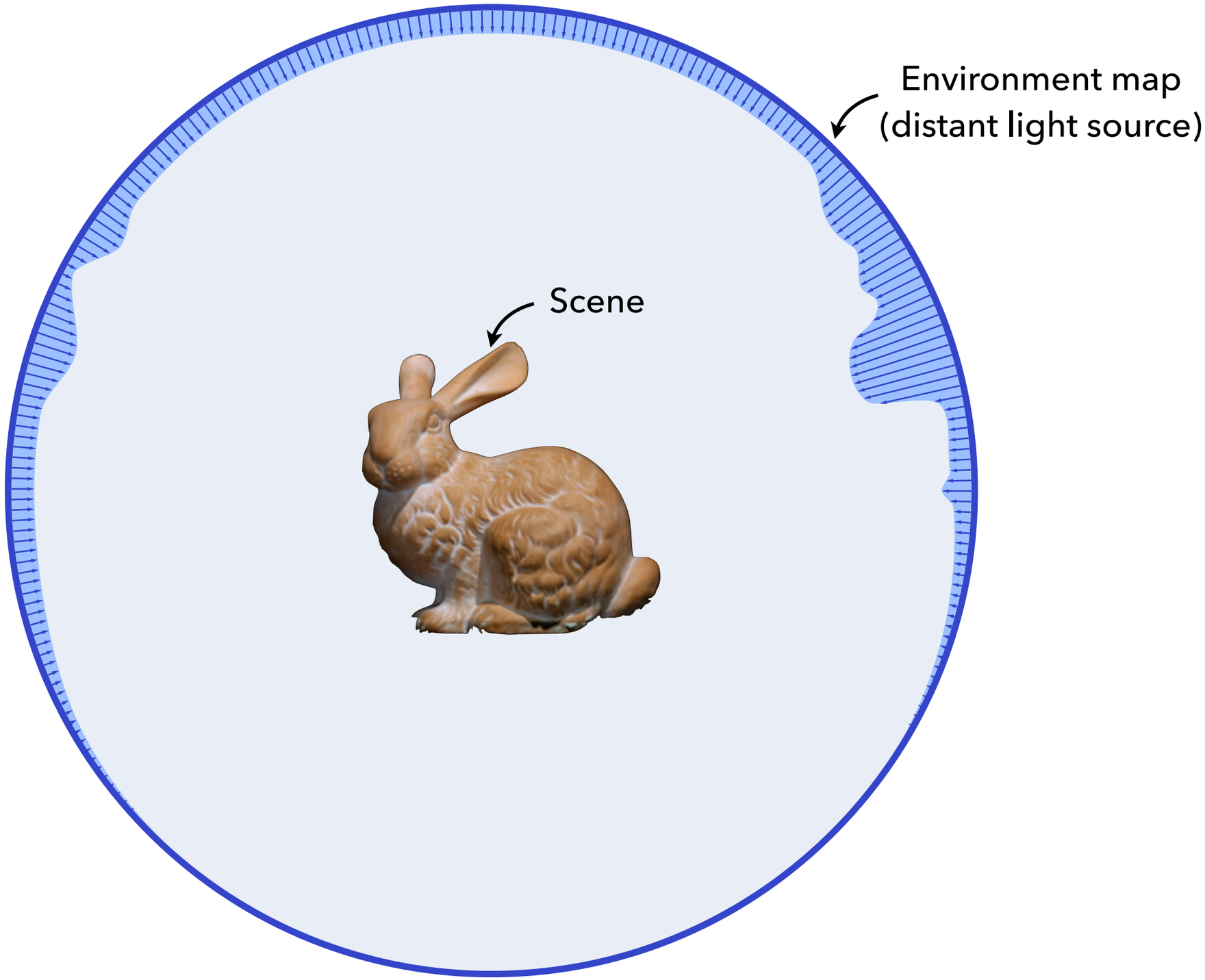
Courtesy of Engelhardt and Dachsbacher

HEALPix



Courtesy of Ryazanov

Environment Lighting



Environment Lighting

- The image "wraps" around the virtual scene, serving as a *distant* source of illumination

$$L_r(\mathbf{x}, \vec{\omega}_r) = \int_\Omega f_r(\vec{\omega}_i, \vec{\omega}_r) L_i(\mathbf{x}, \vec{\omega}_i) \cos\theta_i \, d\vec{\omega}_i$$

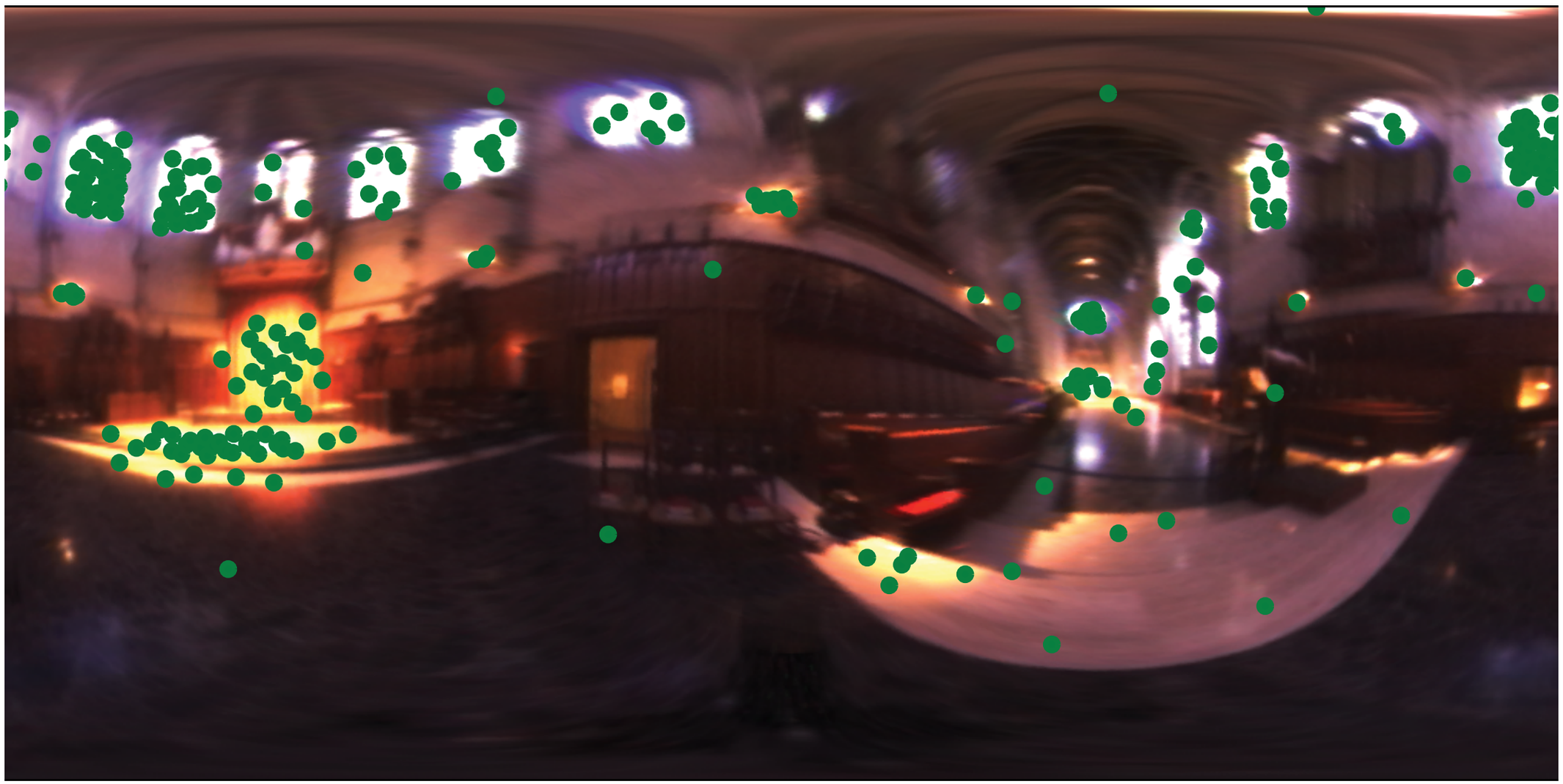
$$= \int_\Omega f_r(\vec{\omega}_i, \vec{\omega}_r) L_{\text{env}}(\vec{\omega}_i) V(\mathbf{x}, \vec{\omega}_i) \cos\theta_i \, d\vec{\omega}_i$$

Environment Lighting

Environment Lighting

$$L_r(\mathbf{x}, \vec{\omega}_r) = \int_\Omega f_r(\vec{\omega}_i, \vec{\omega}_r) L_{\text{env}}(\vec{\omega}_i) V(\mathbf{x}, \vec{\omega}_i) \cos\theta_i \, d\vec{\omega}_i$$

Importance Sampling L_{env}



$$p(\vec{\omega}_i) \propto L_{\text{env}}(\vec{\omega}_i)$$

Importance Sampling L_{env}

$$p(\vec{\omega}_i) \propto L_{\text{env}}(\vec{\omega}_i)$$

- Several strategies exist
- We'll discuss:
  - Marginal/Conditional CDF method
  - Hierarchical warping method

Visual Break

openfootage.net

Marginal/Conditional CDF

- Assume the lat/long parameterization
- Draw samples from joint $p(\theta, \phi) \propto L_{\text{env}}(\theta, \phi) \sin \theta$

Why the Sine?

- General case of integrating some $f(\vec{\omega})$ over S^2

$$d\vec{\omega} = \sin\theta d\theta d\phi$$

Comes from the Jacobian

$$\int_{S^2} f(\vec{\omega})\, d\vec{\omega} = \int_0^{2\pi}\int_0^{\pi} f(\theta,\phi)\sin\theta\, d\theta d\phi$$

$$\approx \frac{1}{N}\sum_{i=1}^{N}\frac{f(\theta_i,\phi_i)\sin\theta_i}{p(\theta_i,\phi_i)}$$

- If we set $p(\theta,\phi) \propto f(\theta,\phi)\sin\theta$ then the sines will effectively cancel out

Marginal/Conditional CDF

- Assume the lat/long parameterization
- Draw samples from joint $p(\theta, \phi) \propto L_{\text{env}}(\theta, \phi) \sin\theta$
  - Step 1: create scalar version $L'(\theta, \phi)$ of $L_{\text{env}}(\theta, \phi) \sin\theta$
  - Step 2: compute marginal PDF

$$p(\theta) = \int_0^{2\pi} L'(\theta, \phi)\, d\phi$$

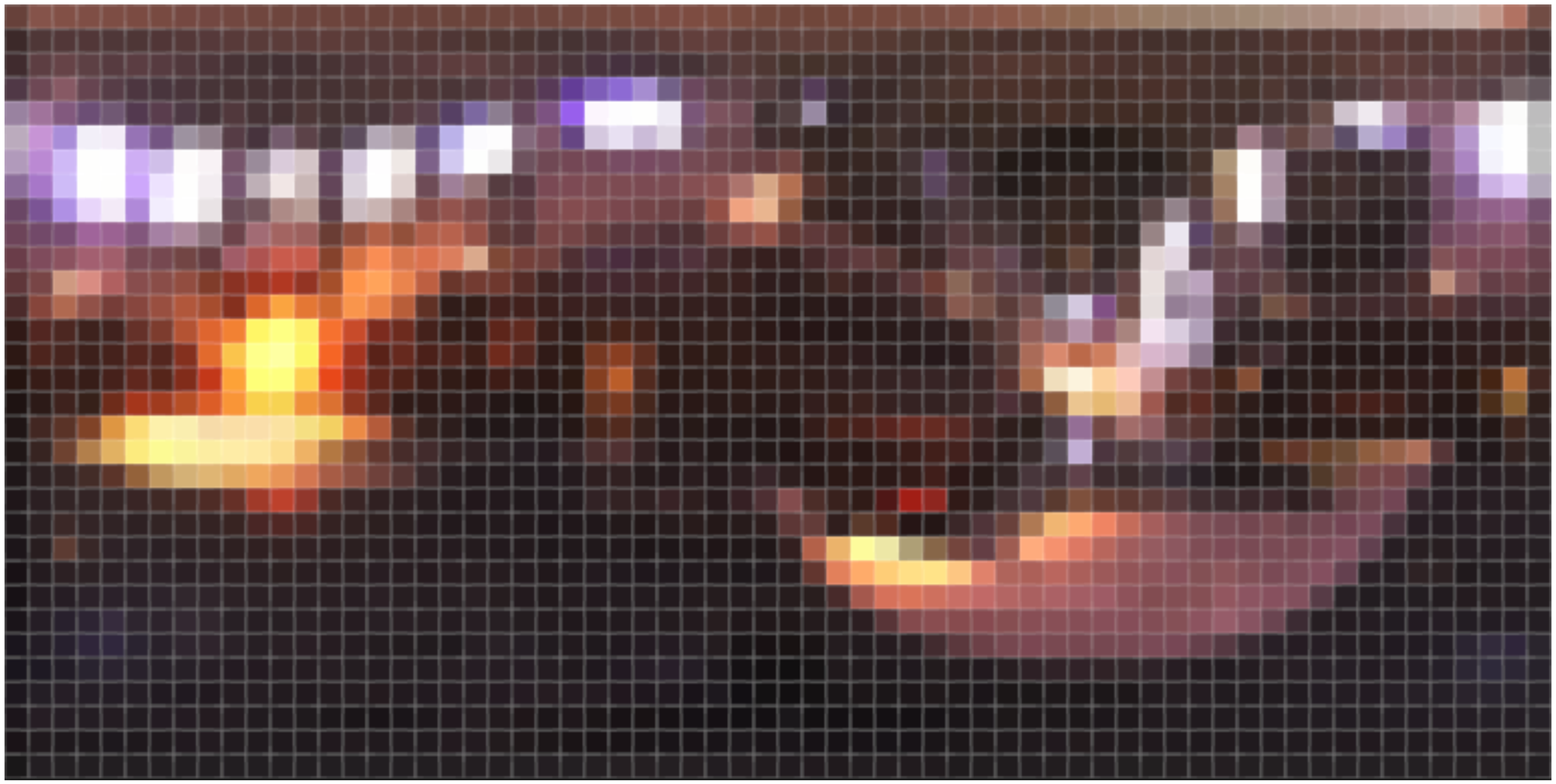
  - Step 3: compute conditional PDF

$$p(\phi|\theta) = \frac{p(\theta, \phi)}{p(\theta)}$$

  - Step 4: draw samples $\theta_i \sim p(\theta)$ and $\phi_i = p(\phi|\theta)$

Step 1: Scalar Importance Func.

Original environment map



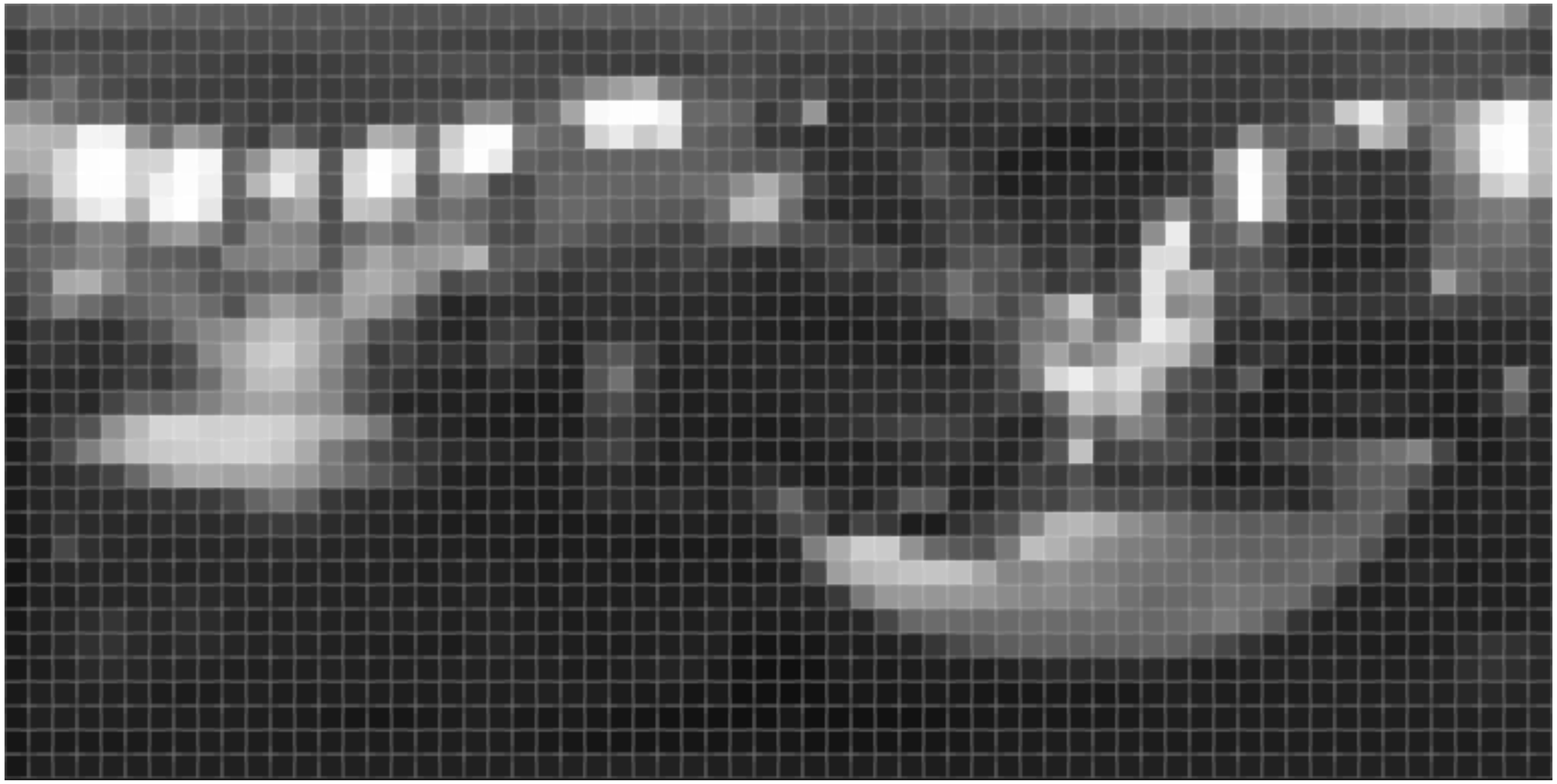
θ

ϕ

Step 1: Scalar Importance Func.

Scalar version

(average, max, or luminance of RGB channels)

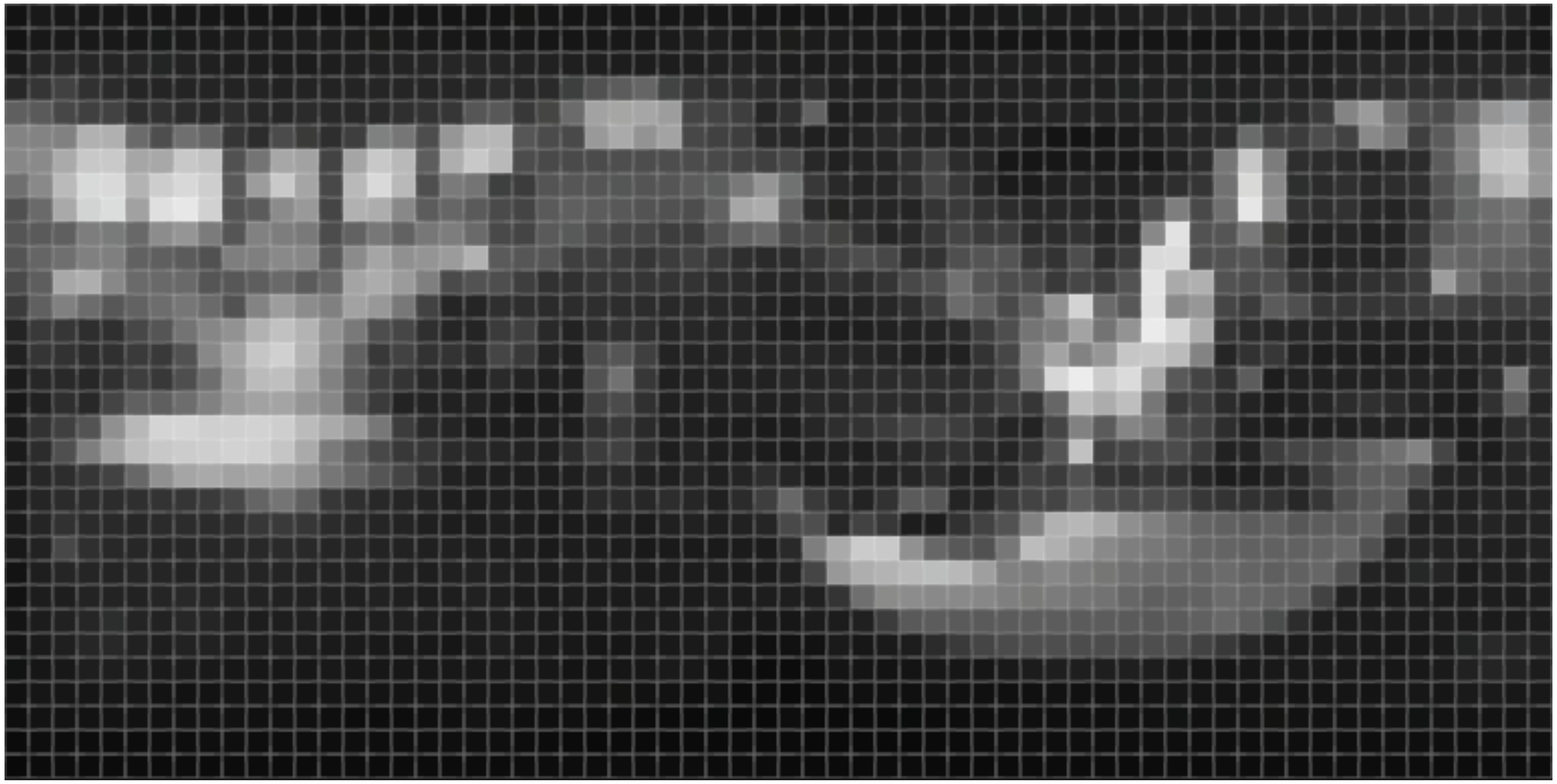


θ

ϕ

Step 1: Scalar Importance Func.

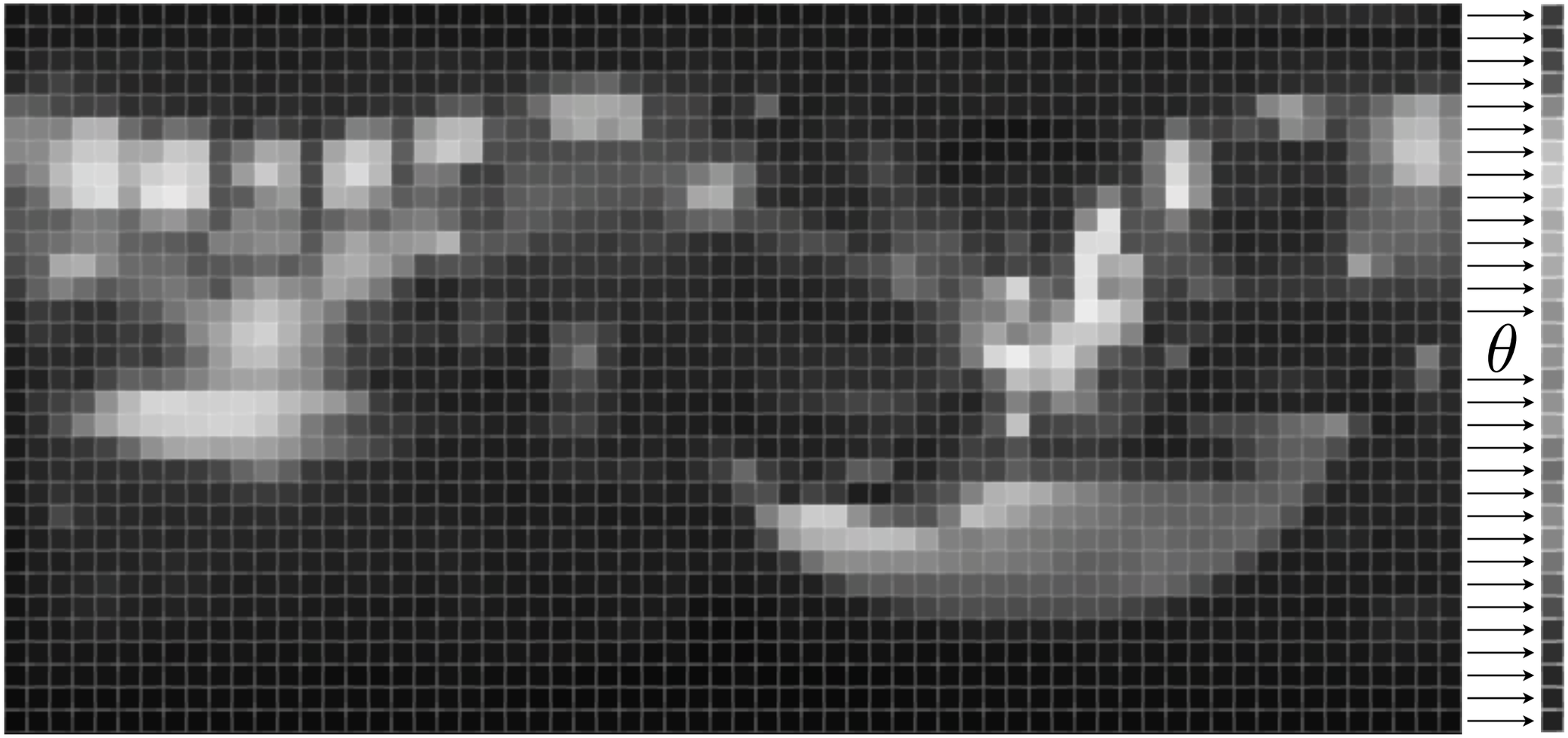
Multiplied by $\sin\theta$



θ

ϕ

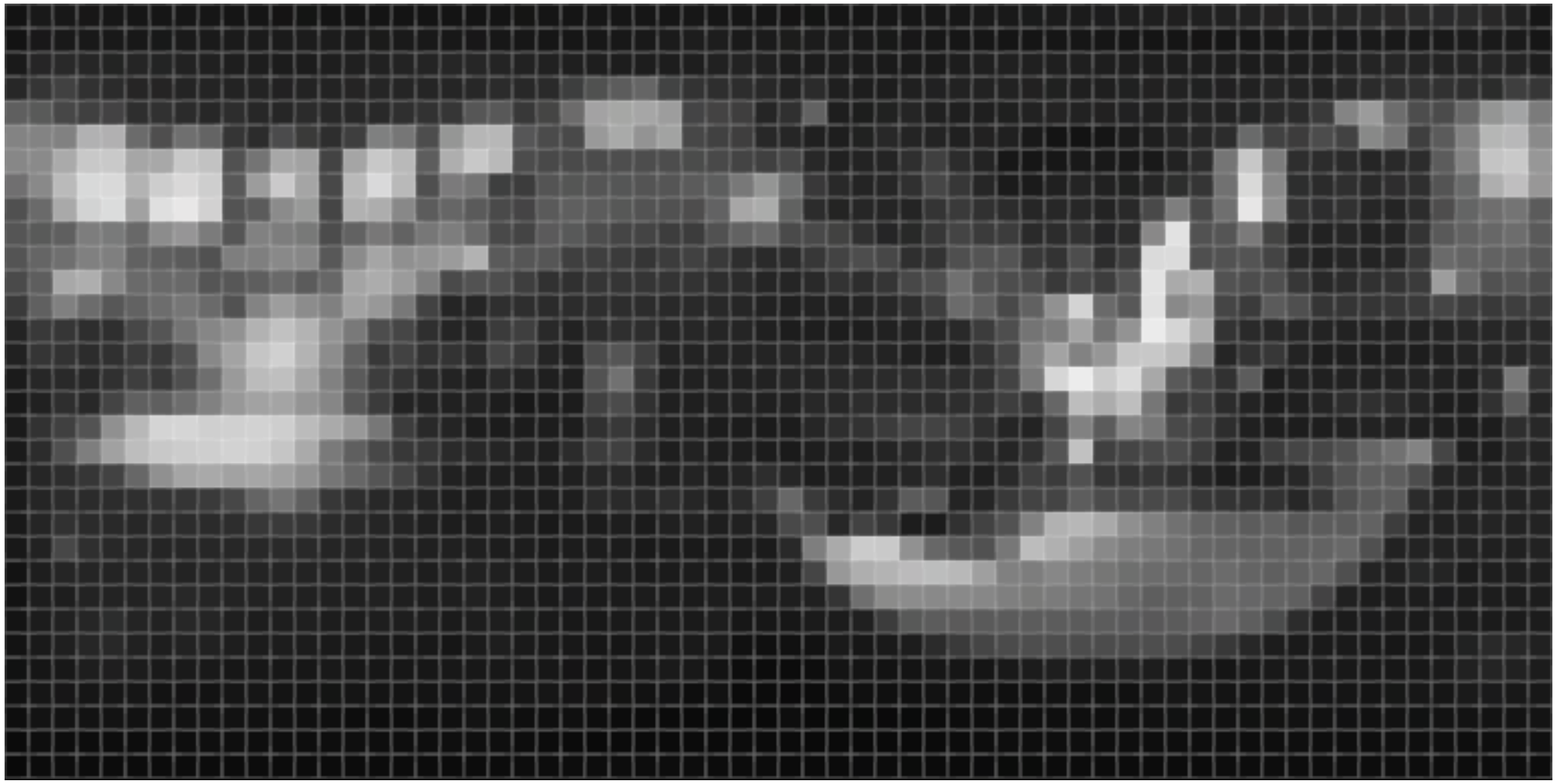
Step 2: Marginalization



ϕ Marginalize to get $p(\theta)$

Step 3: Conditional PDFs

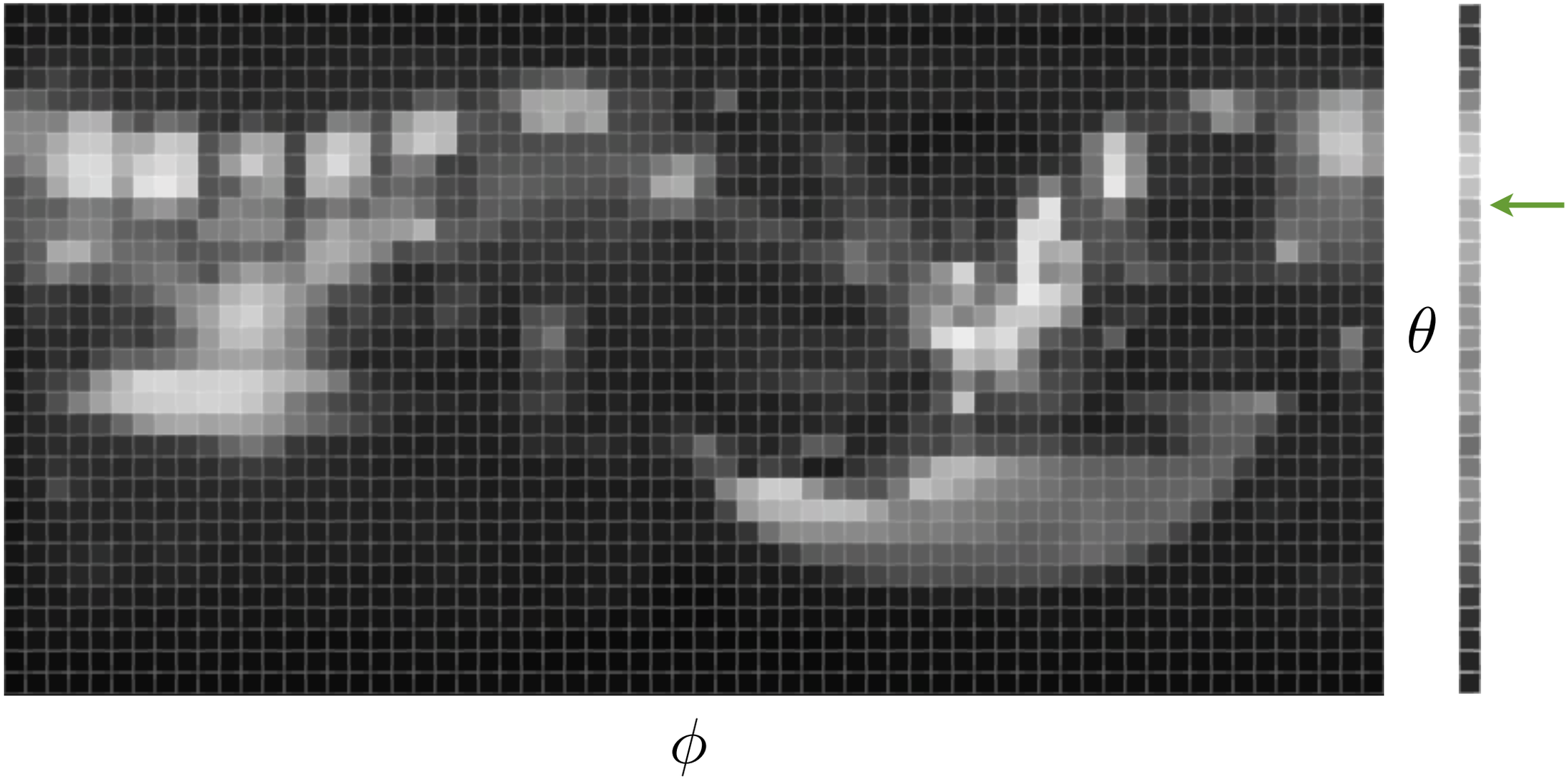
Once normalized, each row can serve as the conditional PDF



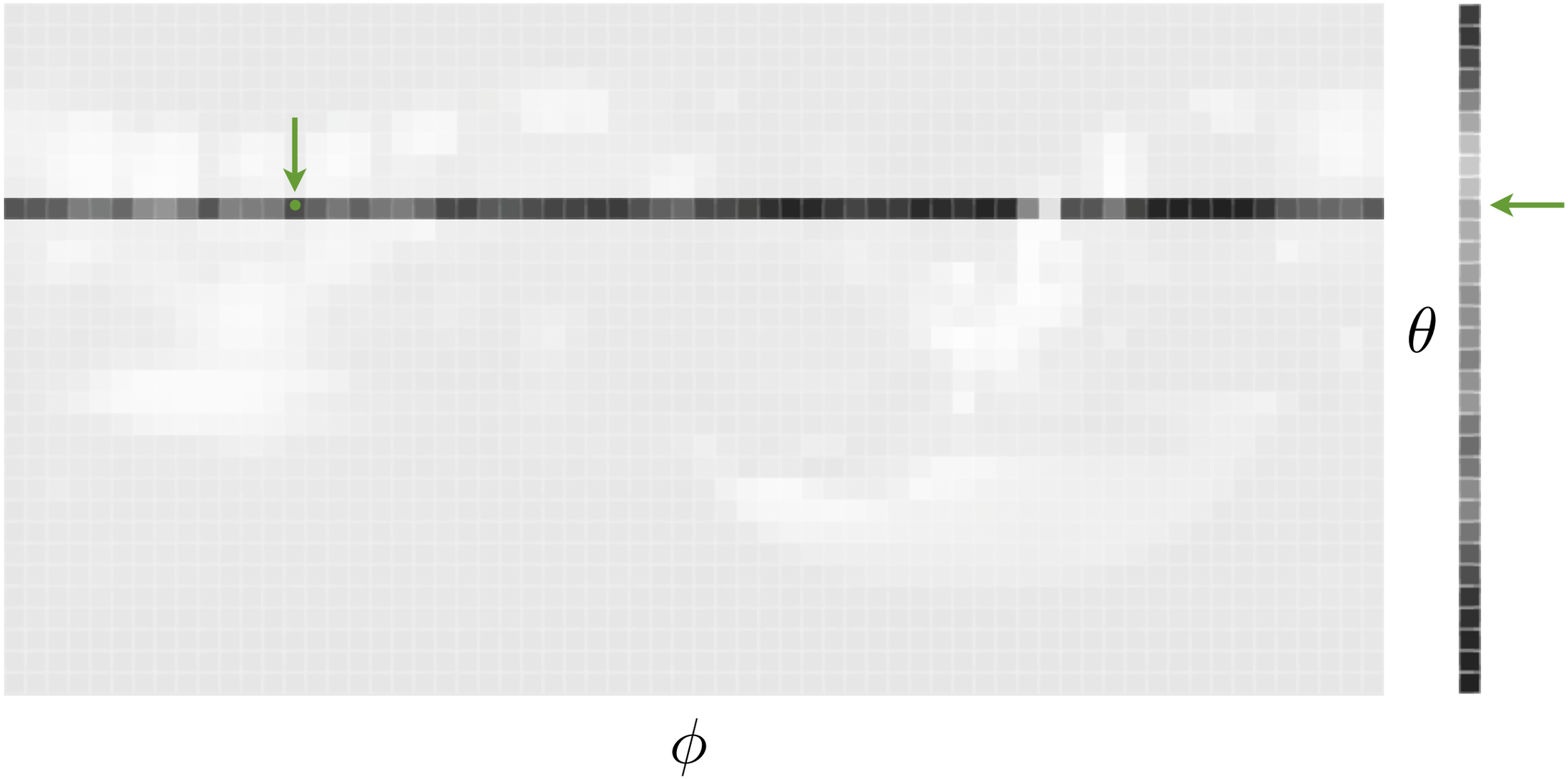
θ

ϕ

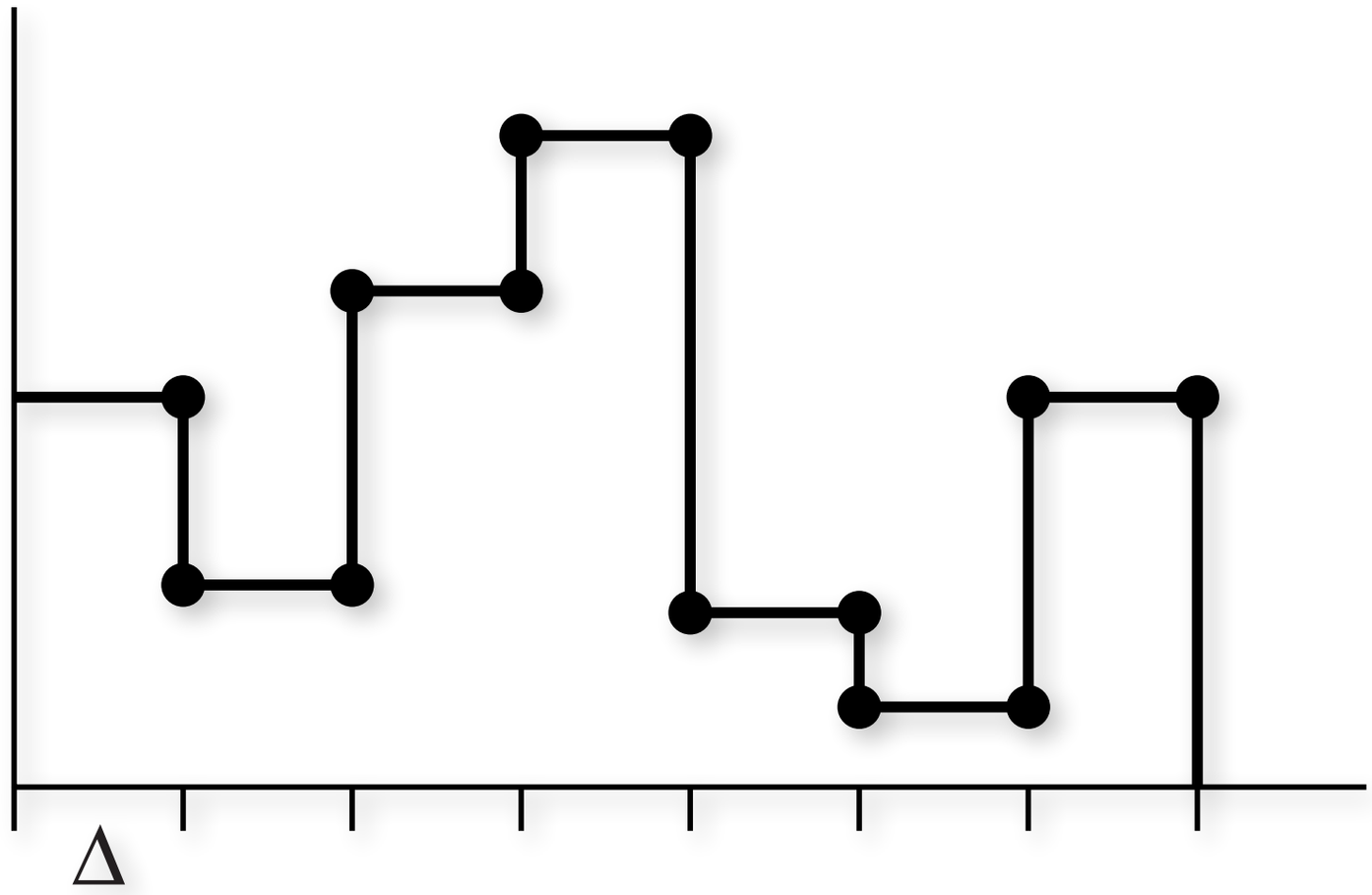
Step 4: Sampling



Step 4: Sampling

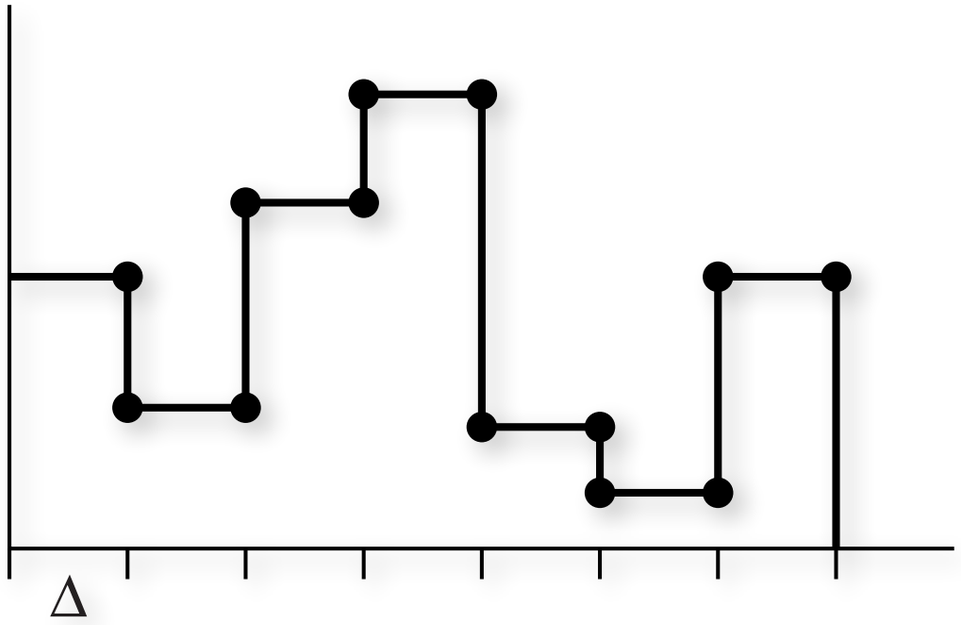


Sampling Discrete 1D PDFs

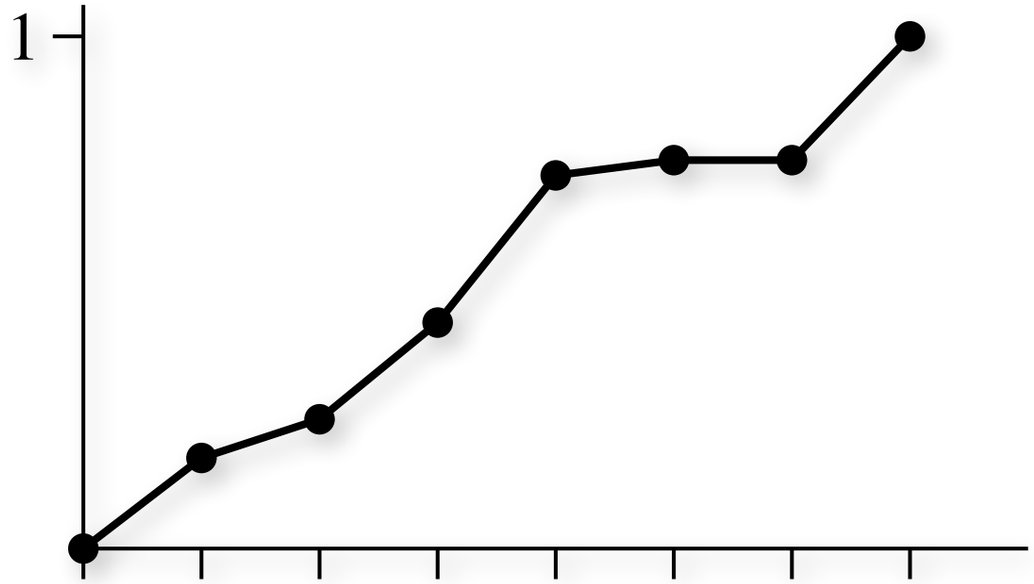


PDF

Sampling Discrete 1D PDFs



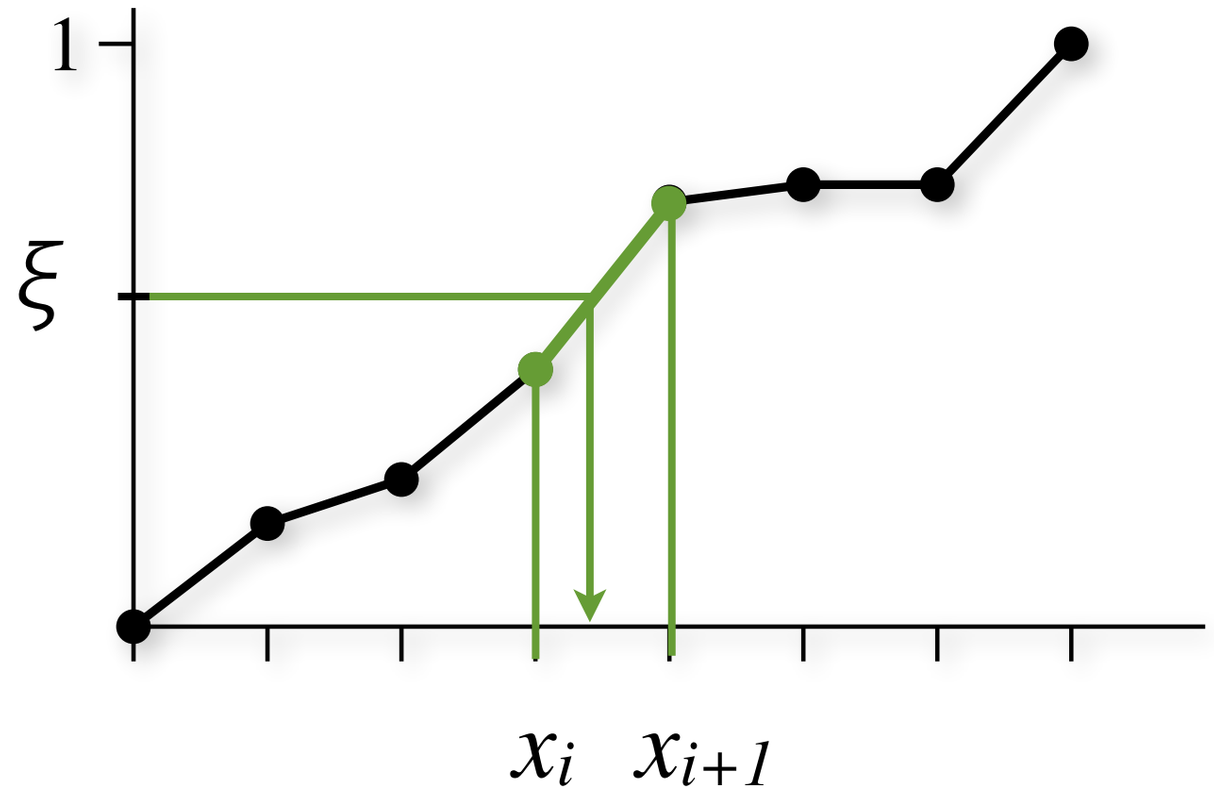
PDF



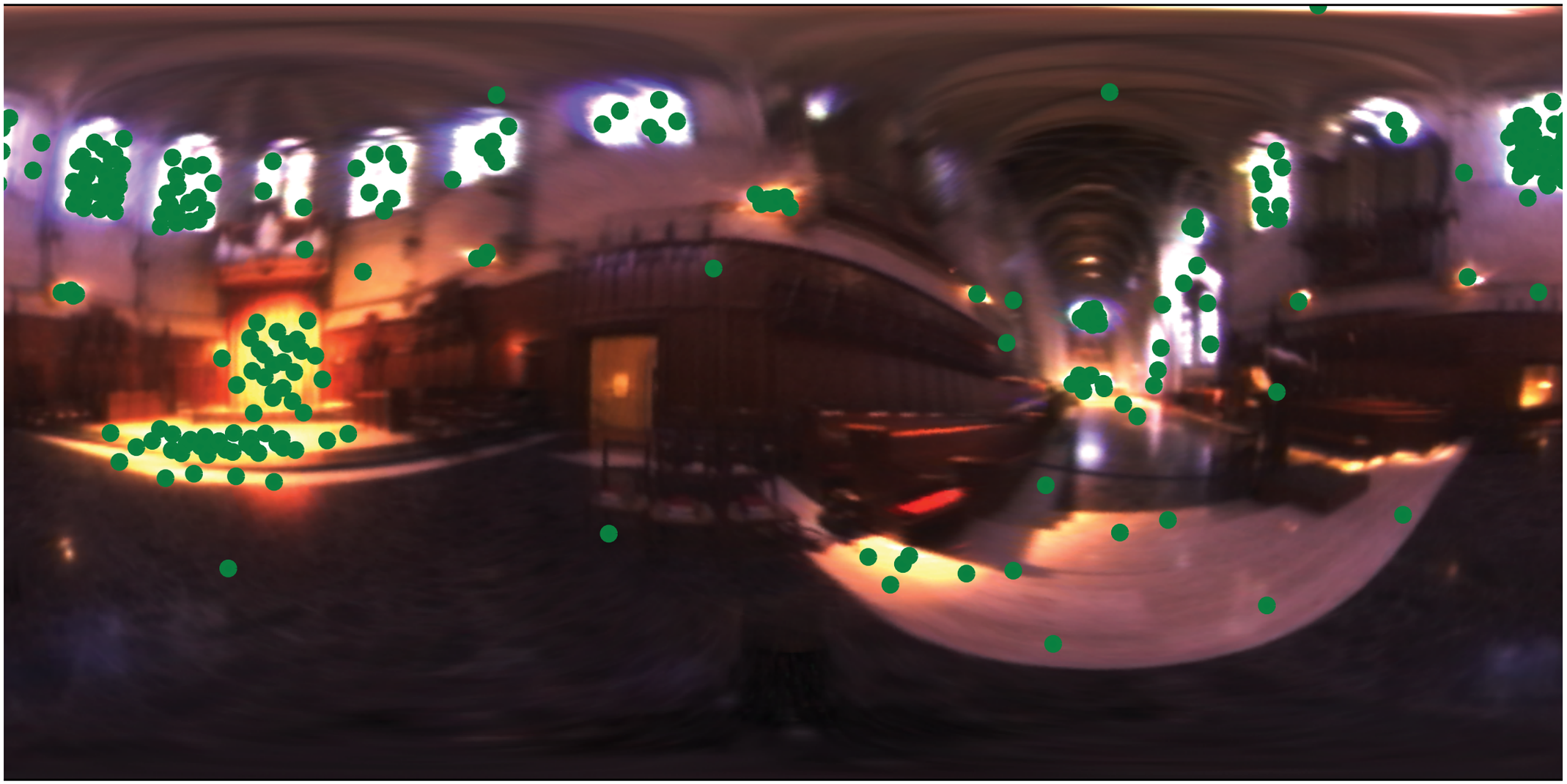
CDF

Sampling Discrete 1D PDFs

- Given a uniform random value ξ
- Using binary search find x_i and x_{i+1}
- Linearly interpolate to find x



Resulting Sample Distribution



Visual Break

openfootage.net

Visual Break

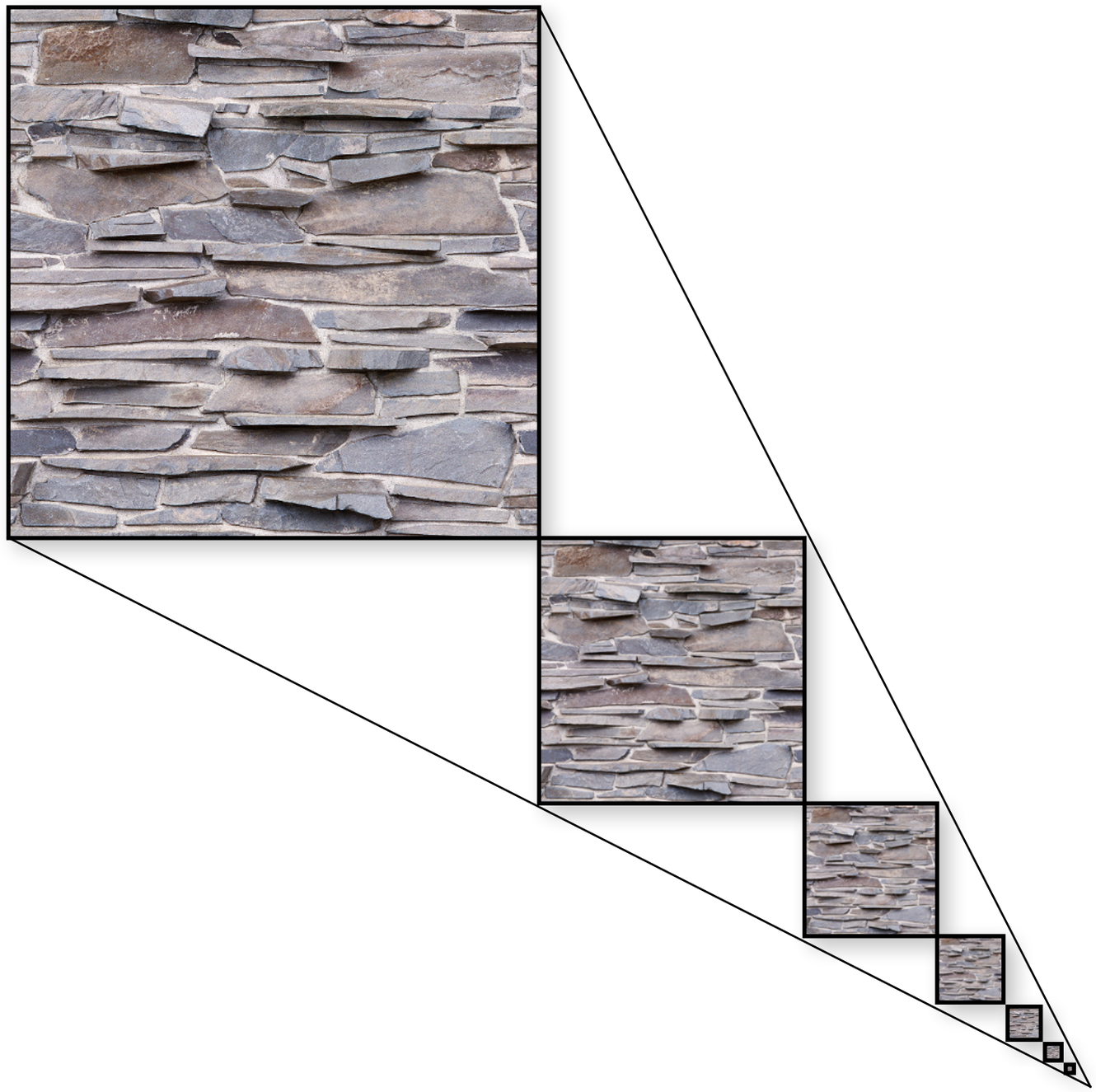
openfootage.net

Hierarchical Sample Warping

Clarberg, Jarosz, Akenine-Möller, Jensen. "Wavelet Importance Sampling," 2005.

- Given:
  - input point set, and
  - hierarchical representation of density function (mip-map)

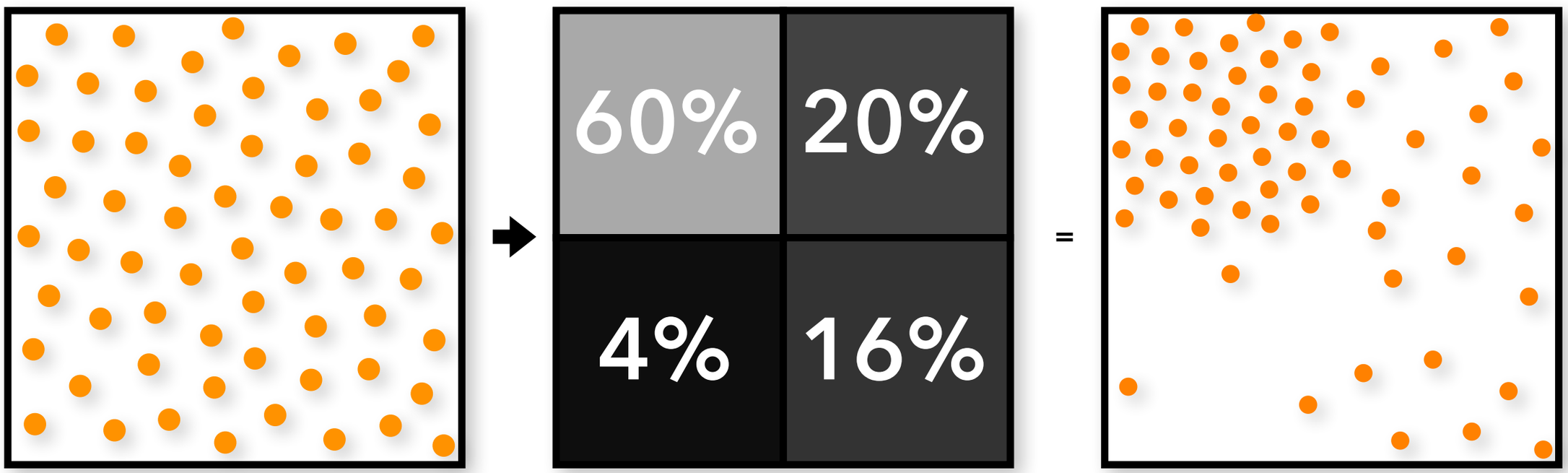
Mip-Map

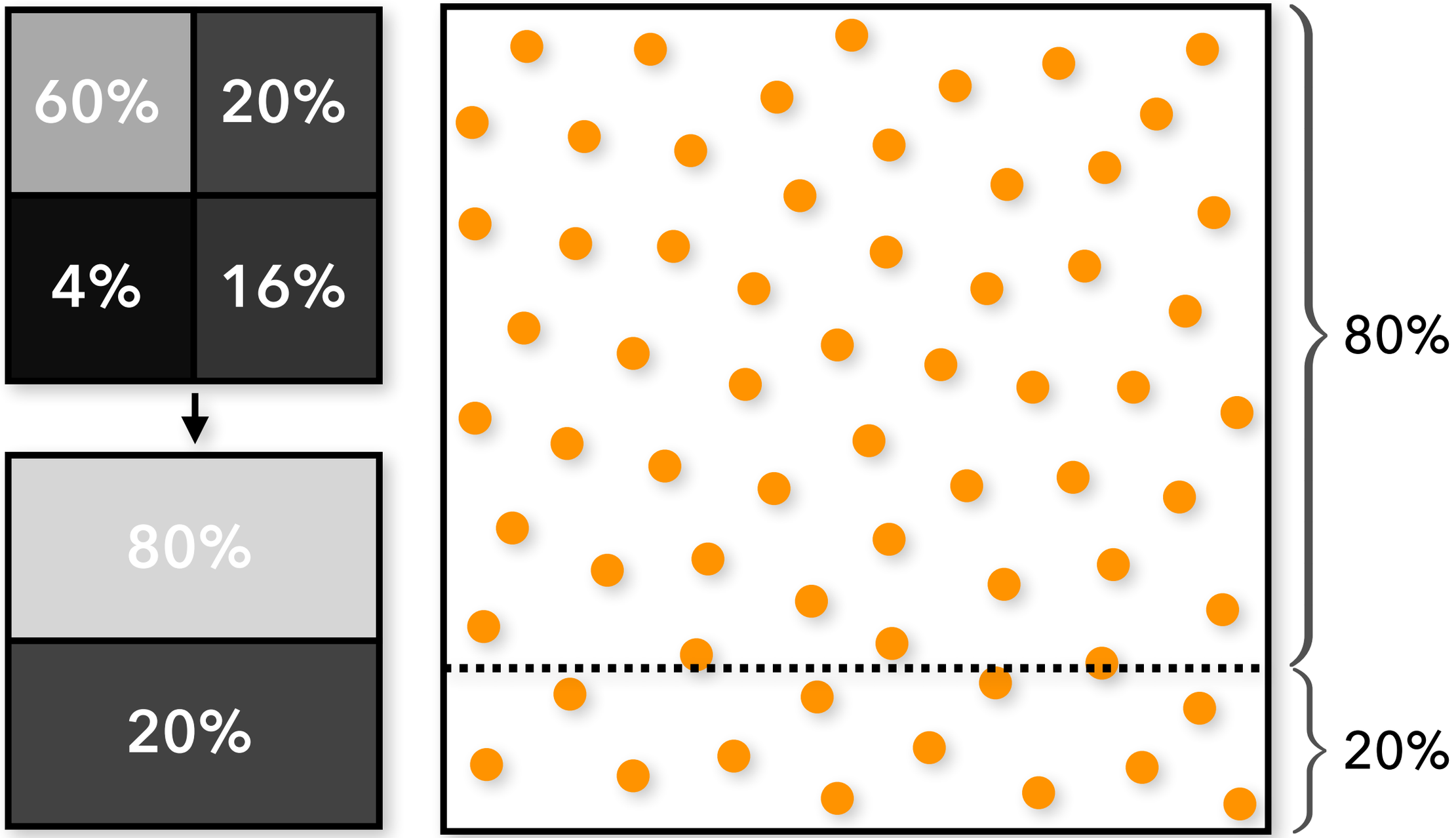


Hierarchical Sample Warping

Clarberg, Jarosz, Akenine-Möller, Jensen. "Wavelet Importance Sampling," 2005.

- Given:
  - input point set, and
  - hierarchical representation of density function (mip-map)
- Recursively warp point set to match the importance function

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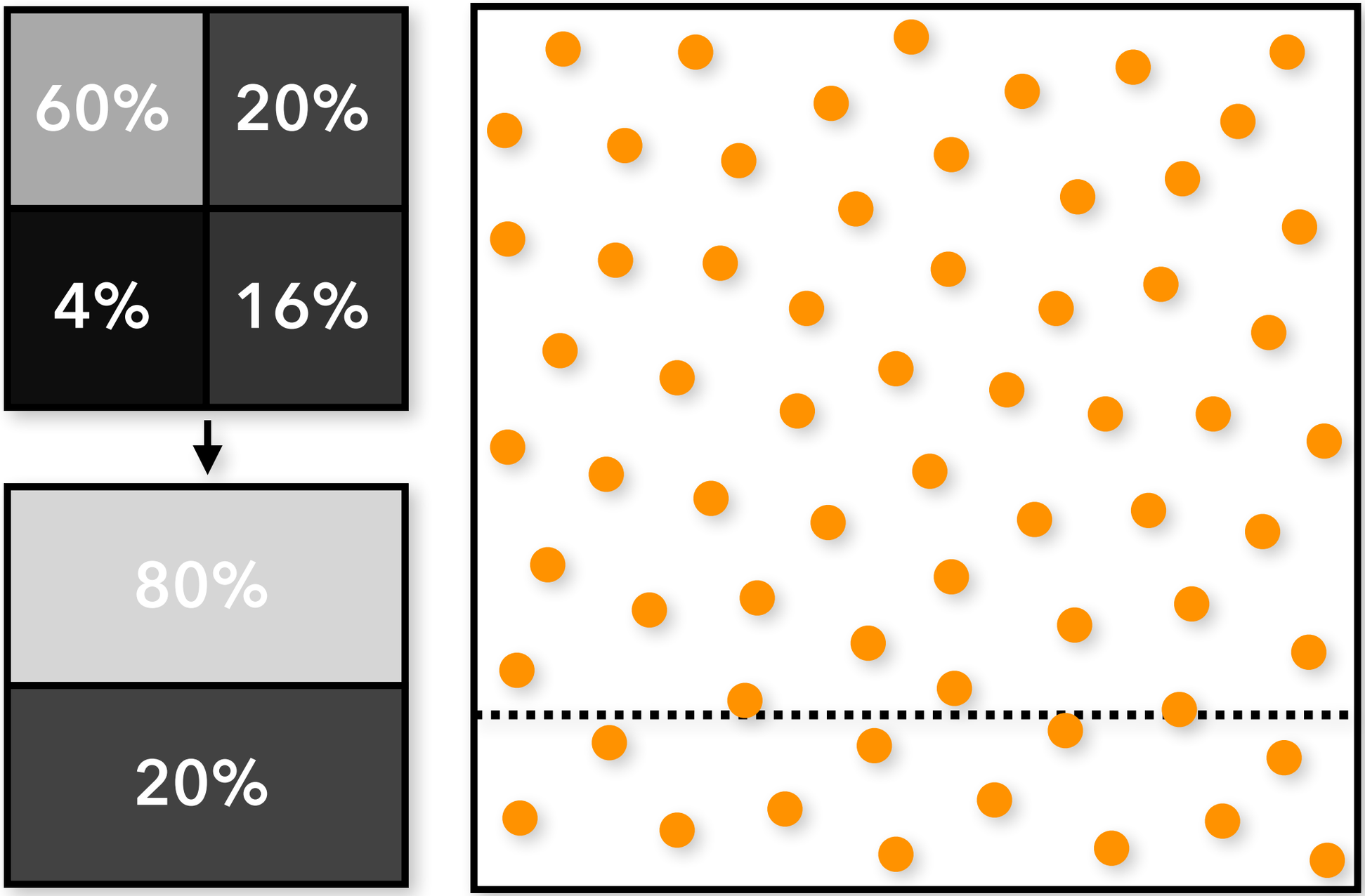
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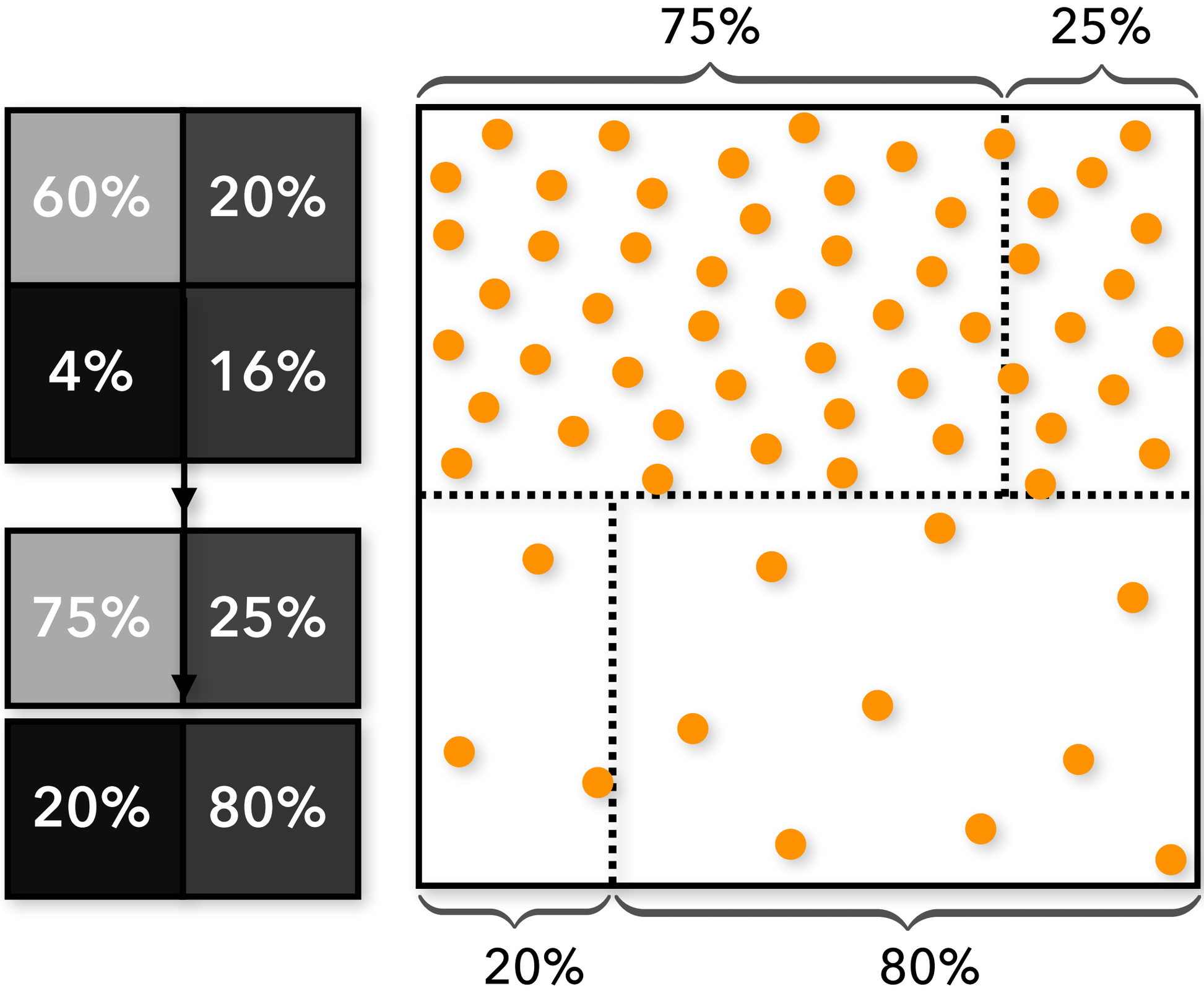
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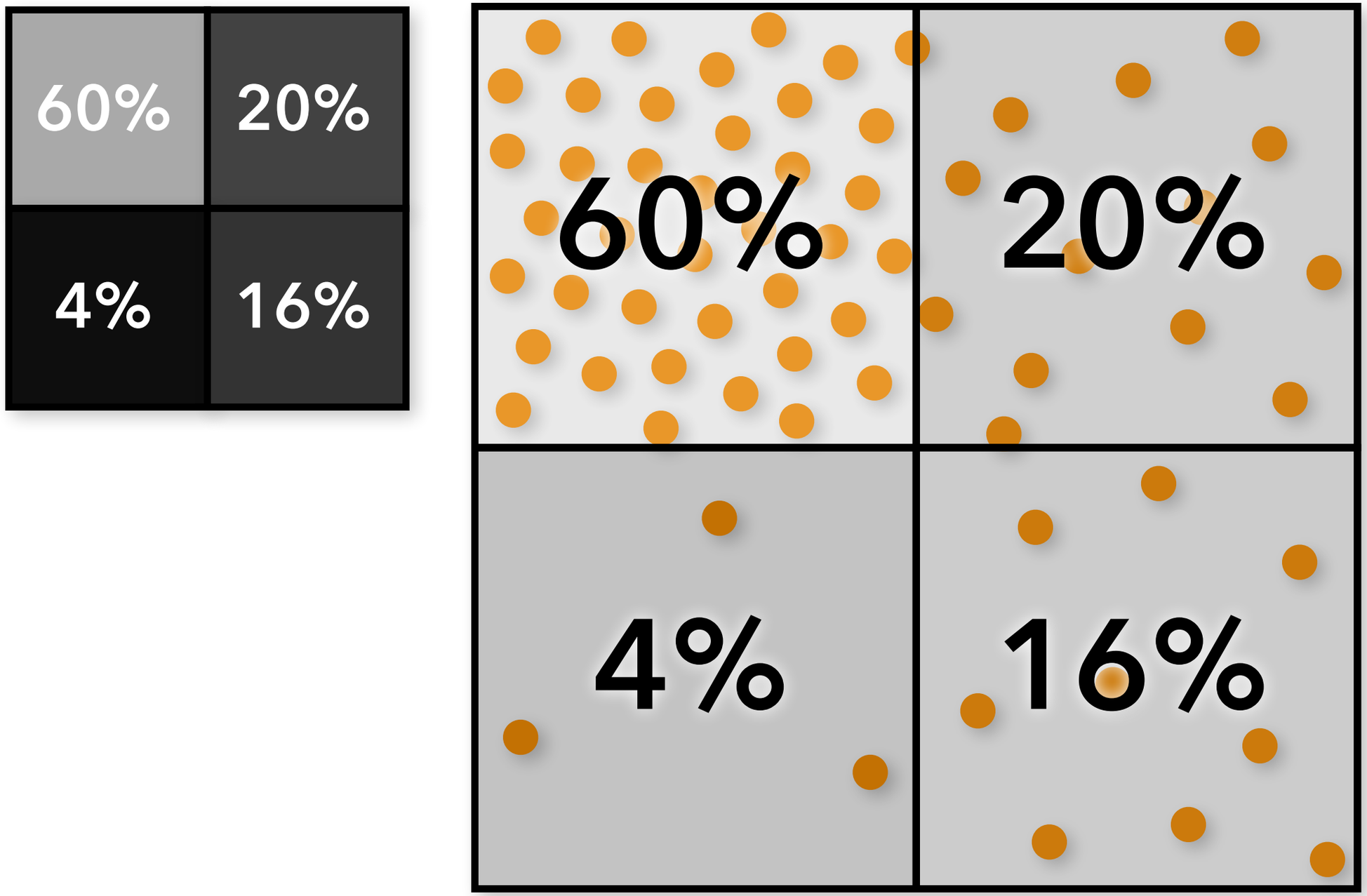


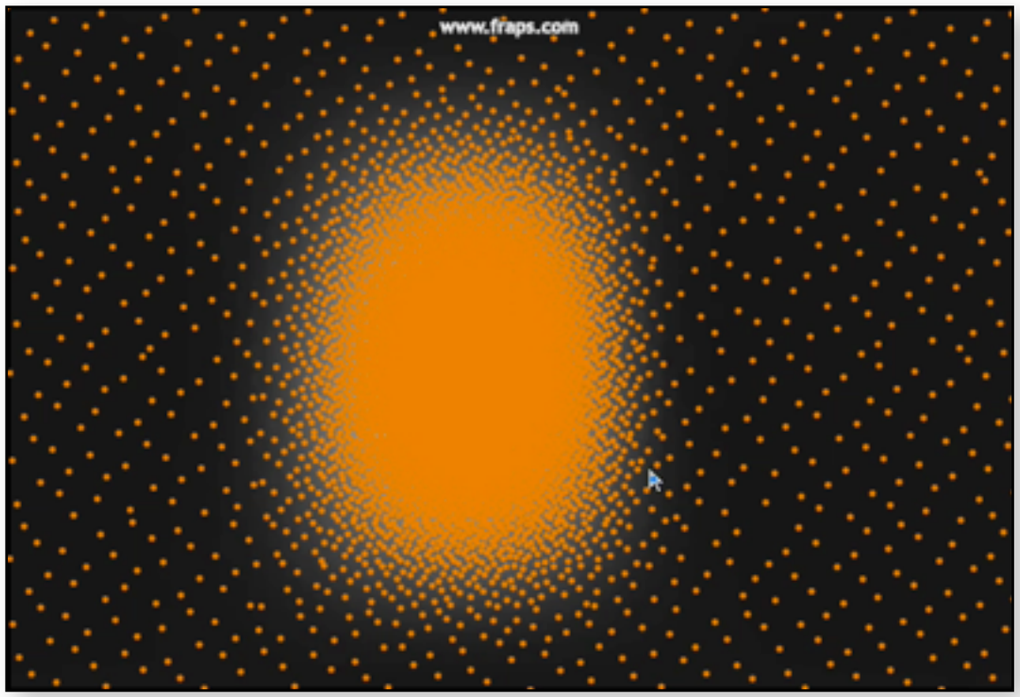
repeat on each quadrant recursively

Environment Lighting

$$
\begin{aligned}
L_r(\mathbf{x}, \vec{\omega}_r) &= \int_\Omega f_r(\vec{\omega}_i, \vec{\omega}_r) L_i(\mathbf{x}, \vec{\omega}_i) \cos\theta_i \, d\vec{\omega}_i \\
&= \int_\Omega f_r(\vec{\omega}_i, \vec{\omega}_r) L_{\text{env}}(\vec{\omega}_i) V(\mathbf{x}, \vec{\omega}_i) \cos\theta_i \, d\vec{\omega}_i \\
&\approx \frac{1}{N} \sum_{i=1}^{N} \frac{f_r(\vec{\omega}_i, \vec{\omega}_r) L_{\text{env}}(\vec{\omega}_i) V(\mathbf{x}, \vec{\omega}_i) \cos\theta_i}{\text{pdf}(\vec{\omega}_i)}
\end{aligned}
$$

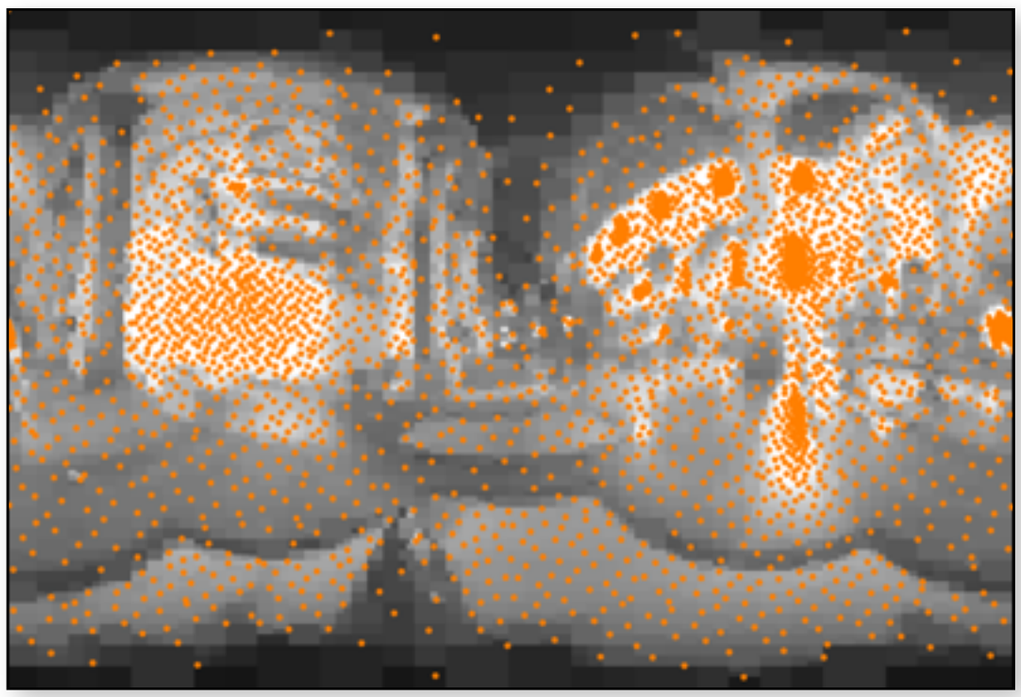
- What pdf should/can we use?
  - prop. to f_r
  - prop. to L_{env}

Sample Distributions



BRDF

or



Lighting

BRDF

Lighting

1 3 10 30 60 100

Samples / Pixel

BRDF

Lighting

1 3 10 30 60 100

Samples / Pixel

Product Sampling

Environment Lighting

- Could use MIS
  - pdf is a linear combination of f_r and L_{env}
- Can we sample the *product* $(f_r \cdot L_{env} \cdot \cos\theta_i)$ directly?

Clarberg, Jarosz, Akenine-Möller, Jensen. "Wavelet Importance Sampling," 2005.

Subr and Arvo. "Steerable Importance Sampling," 2007.

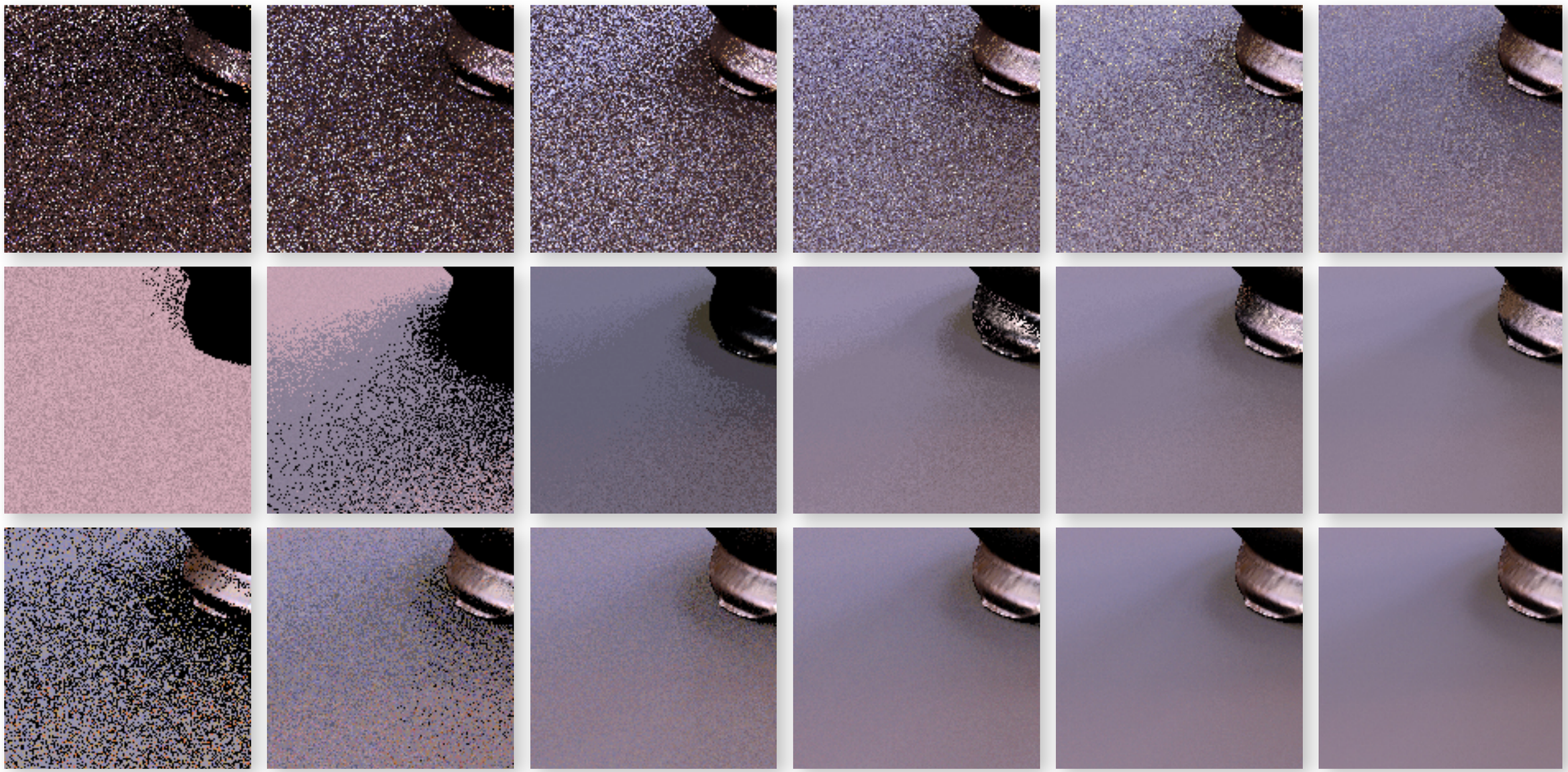
Jarosz, Carr, Jensen. "Importance Sampling Spherical Harmonics," 2009.

many more...

BRDF

Lighting

Product



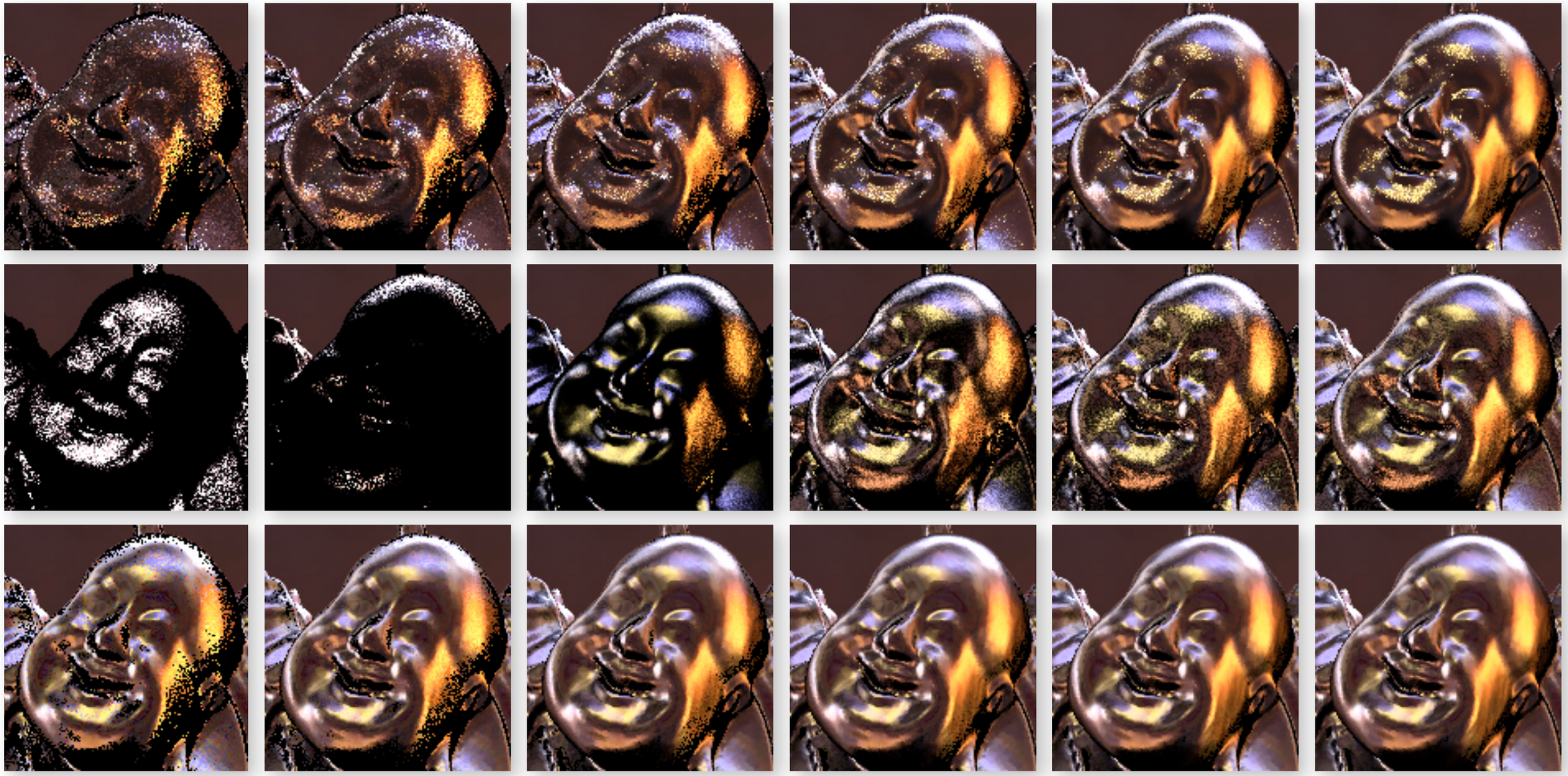
1 3 10 30 60 100

Samples / Pixel

BRDF

Lighting

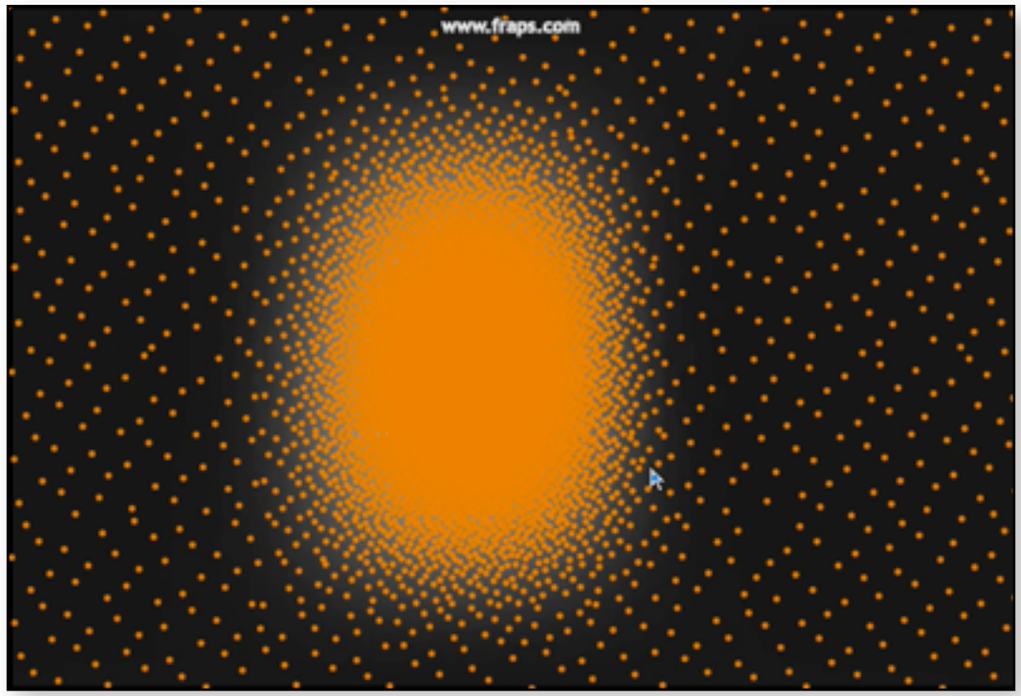
Product



1 3 10 30 60 100

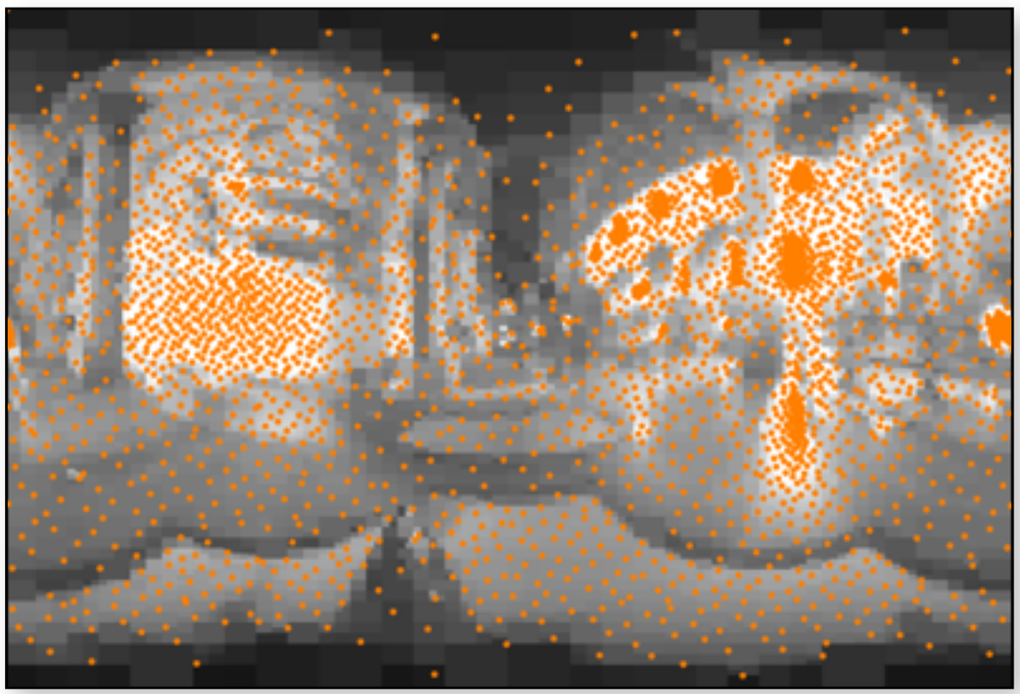
Samples / Pixel

Sample Distributions



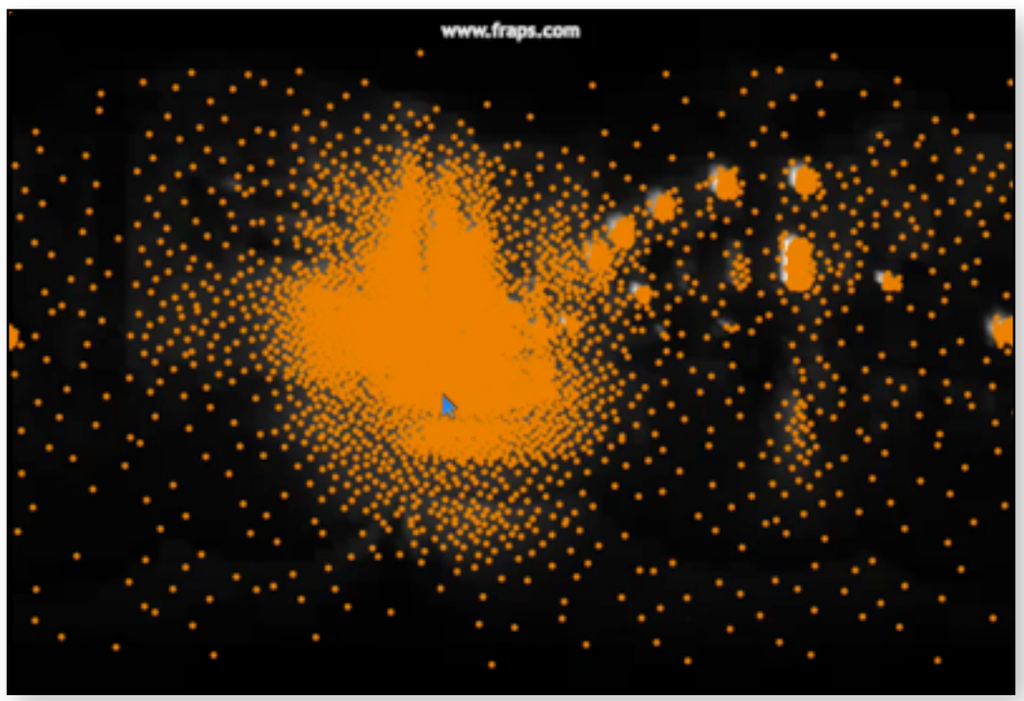
BRDF

x



Lighting

=



BRDF x Lighting

Clarberg, Jarosz, Akenine-Möller, Jensen. “Wavelet Importance Sampling,” 2005.

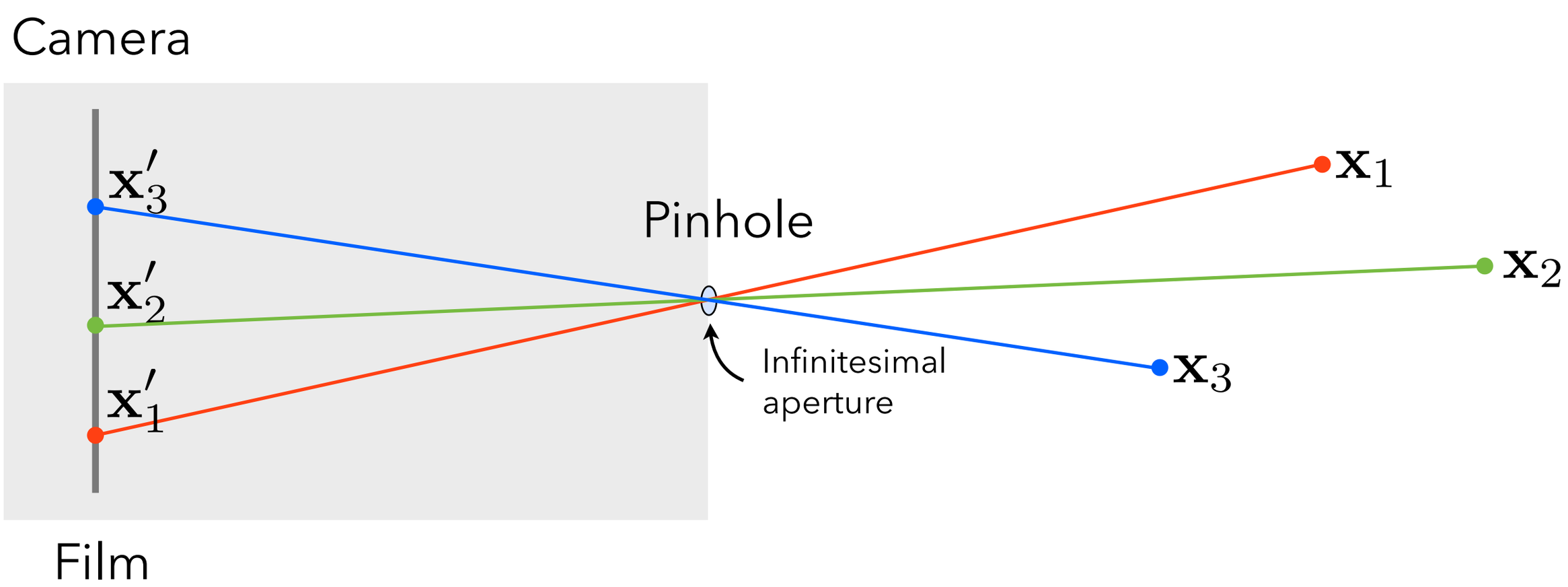
Questions?

The Avengers (2012)

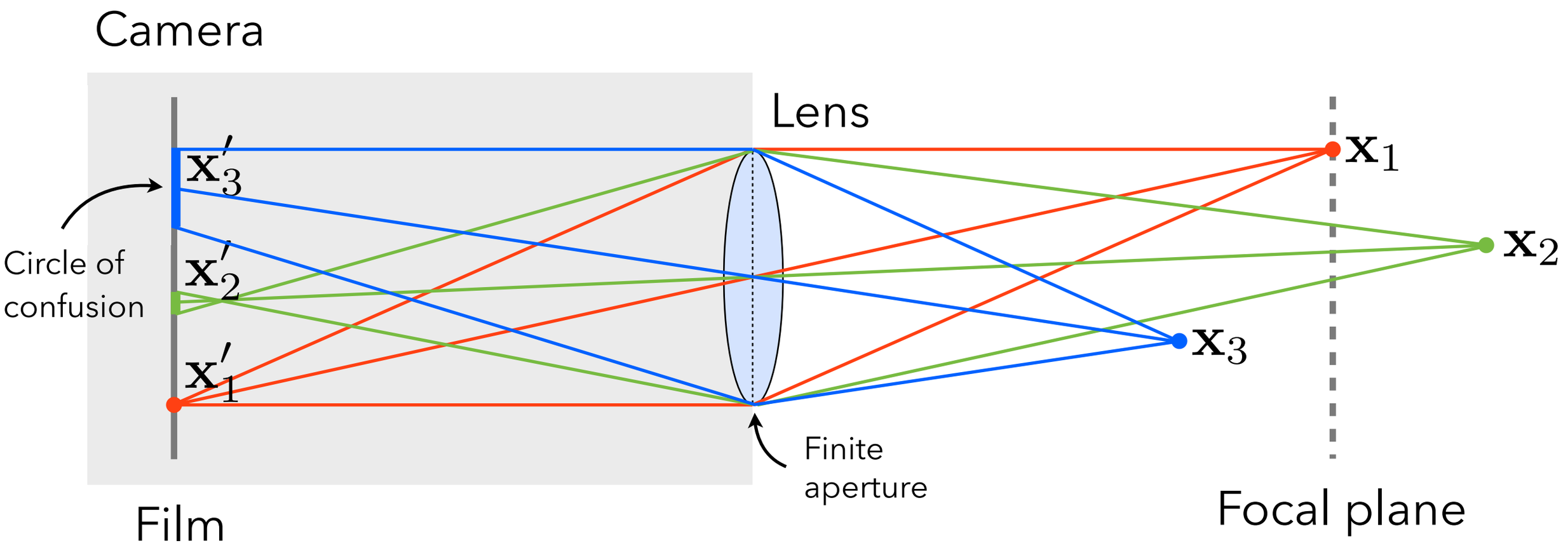
Advanced Camera Models

Pinhole Camera (Camera Obscura)

Pinhole Camera

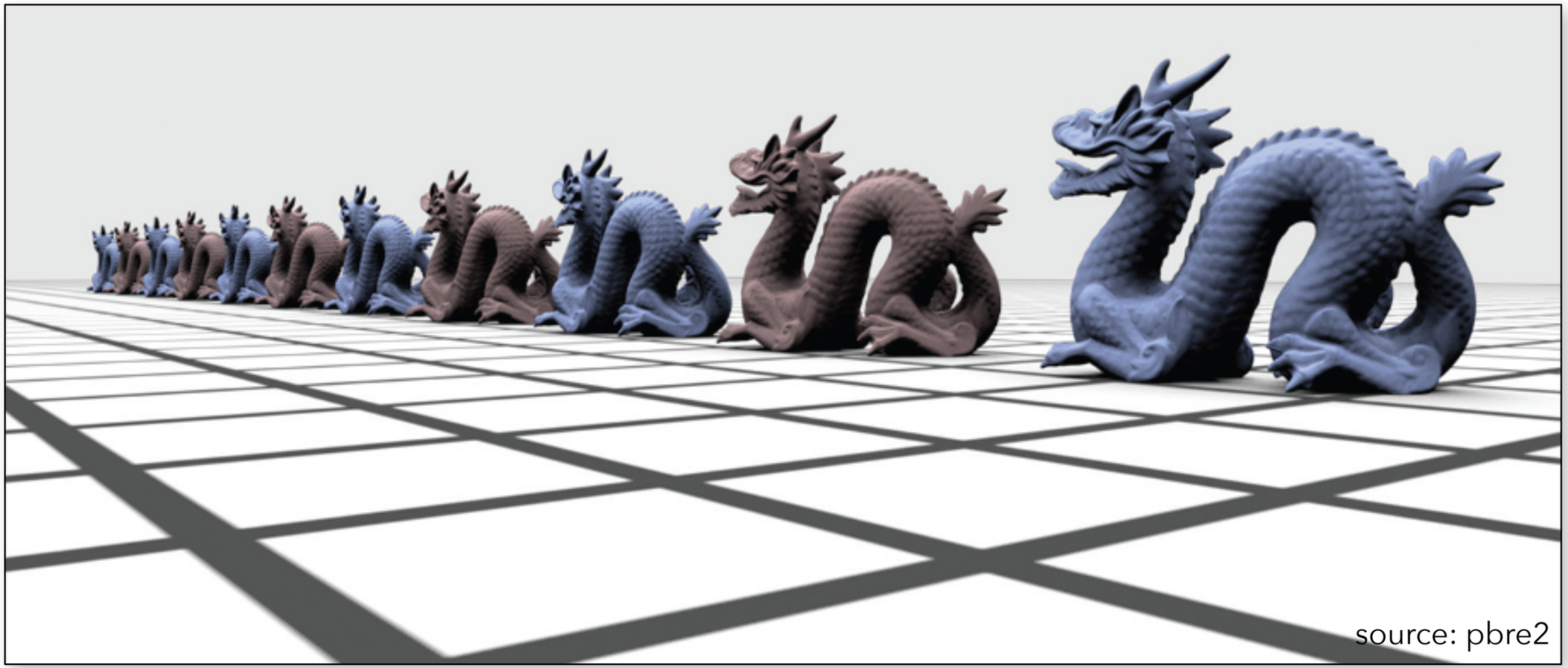


Thin Lens Camera

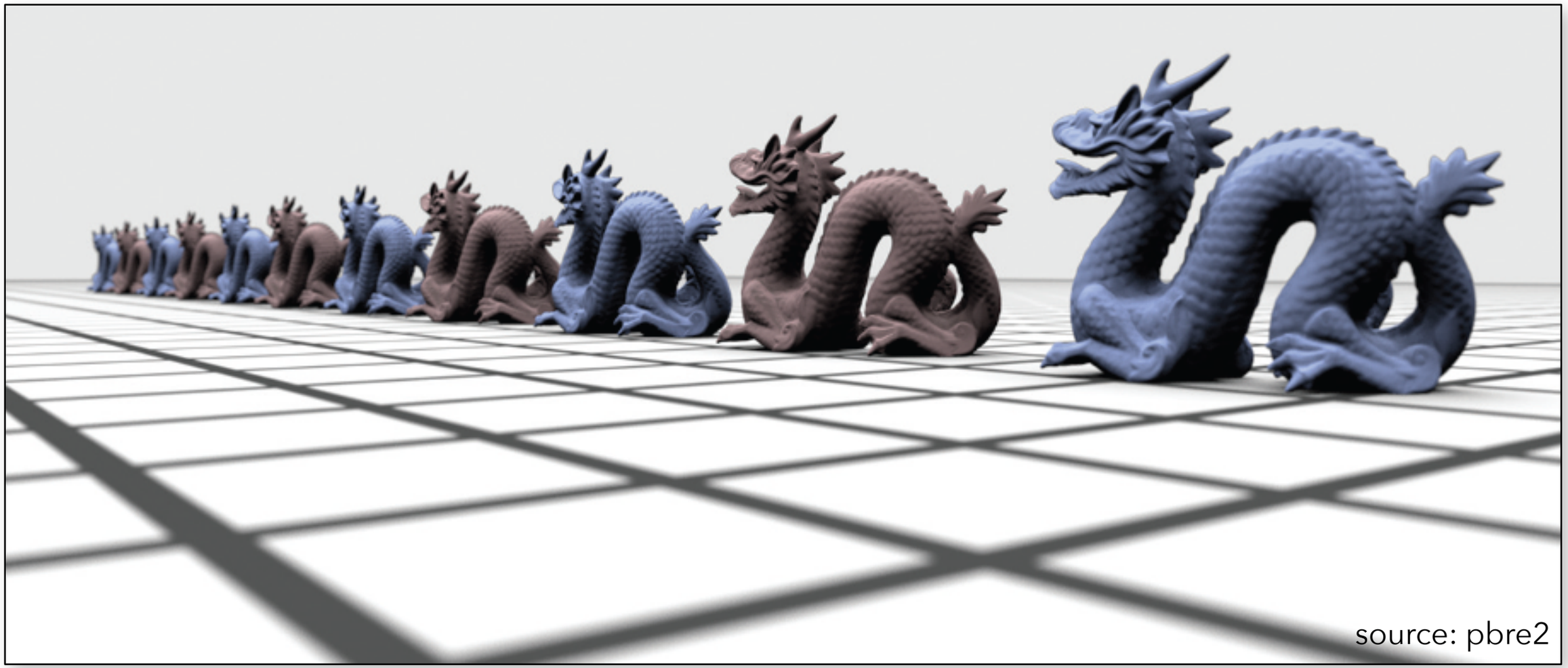


Depth of Field

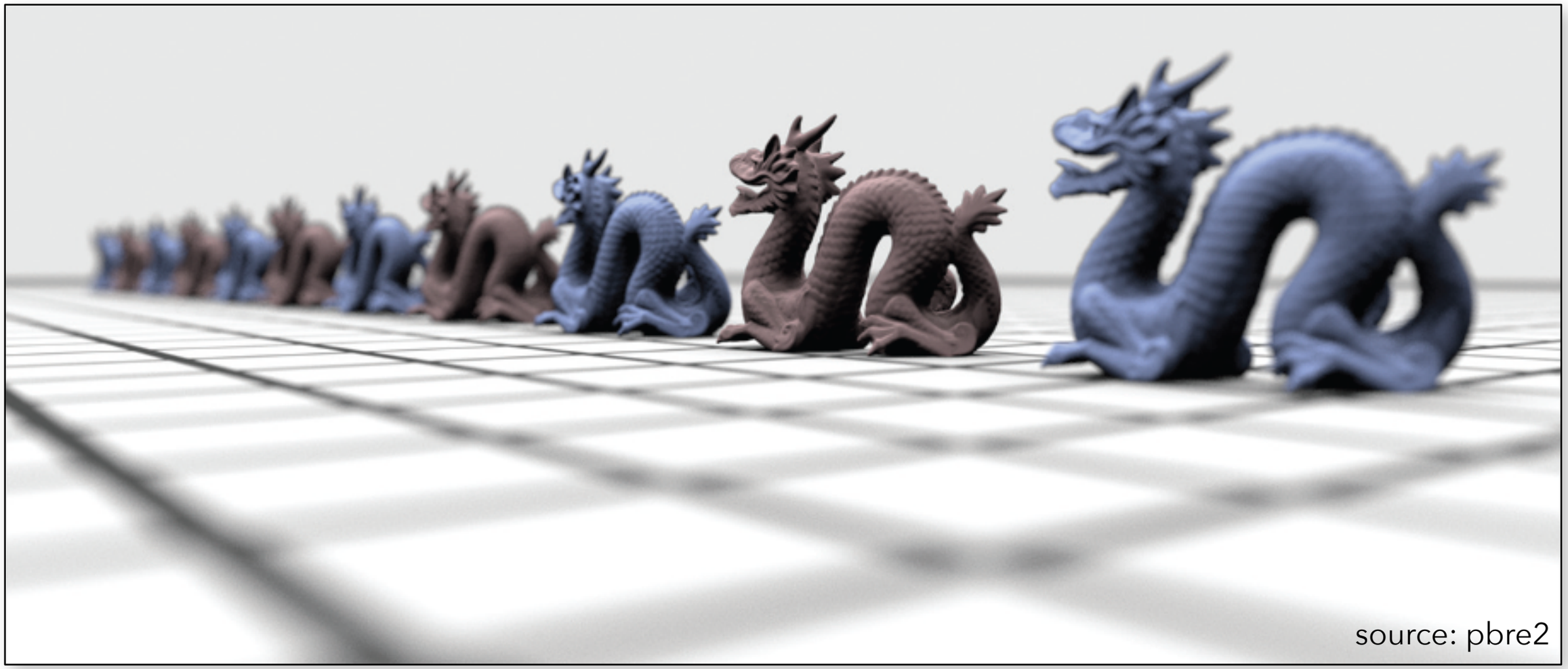
Pinhole Camera



Thin-Lens Camera (small aperture)



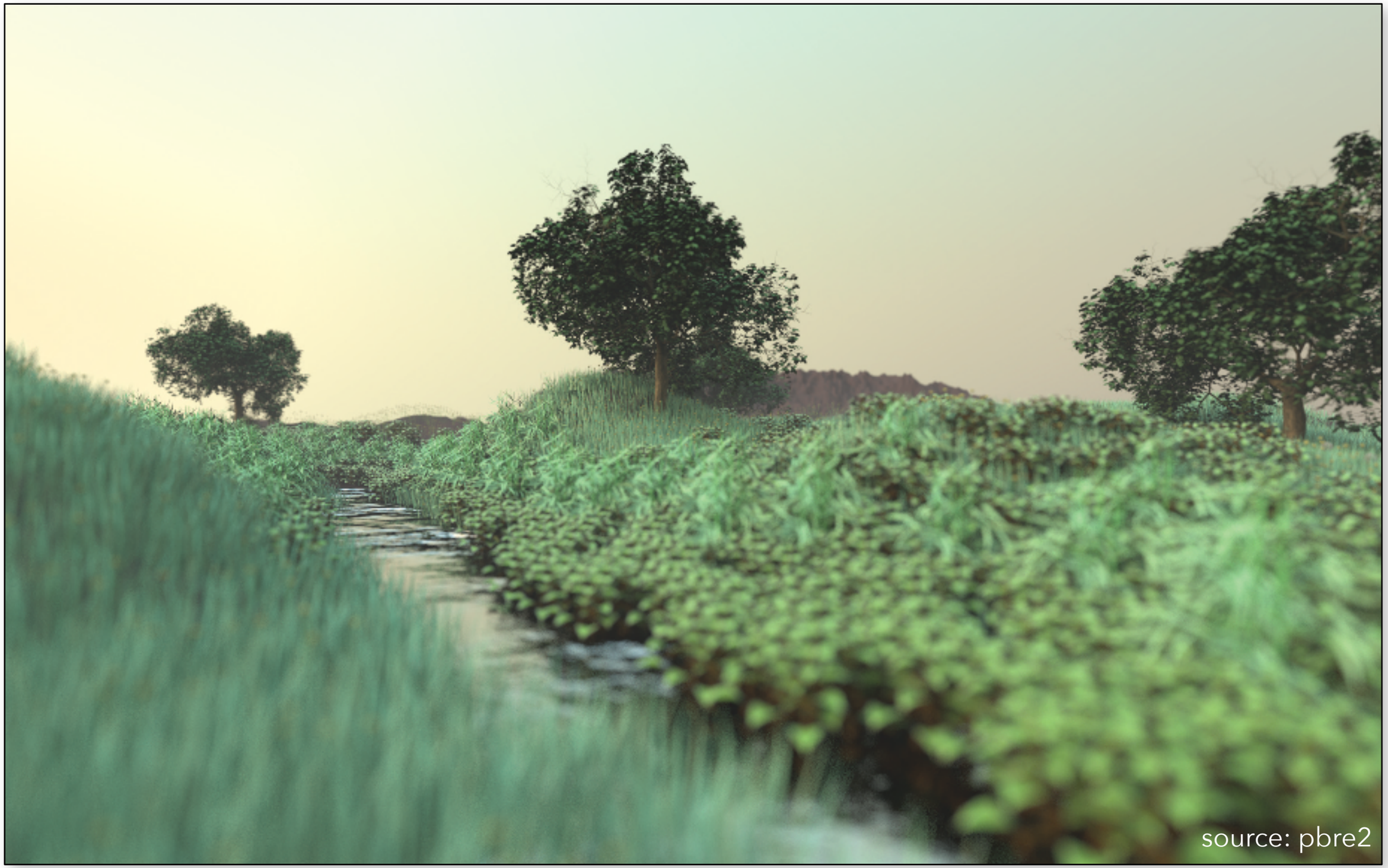
Thin-Lens Camera (larger aperture)



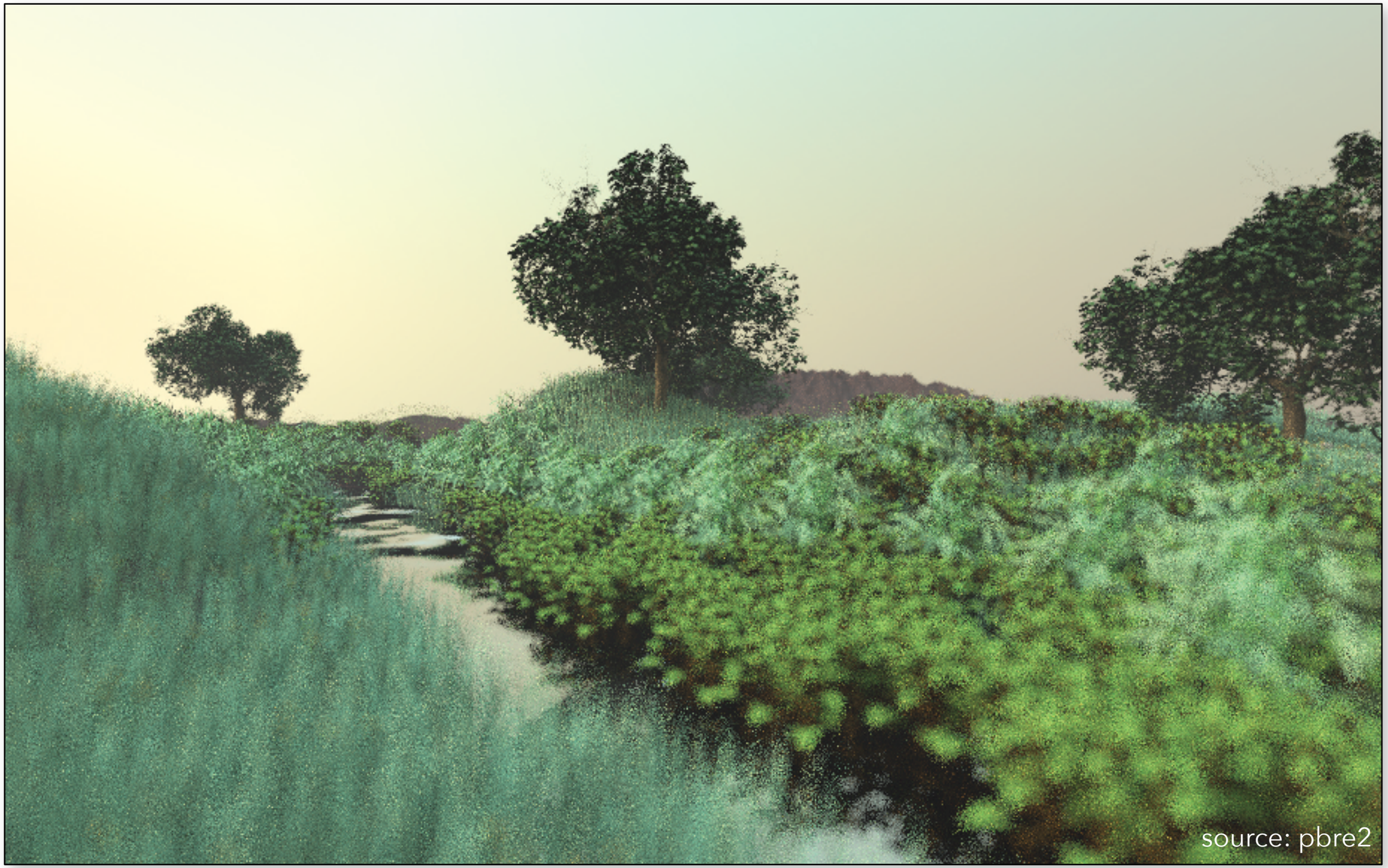
Thin-Lens Camera (huge aperture)

source: pbre2

Depth of Field



Depth of Field



Depth of Field

- *Depth of field* = the range of distances within which objects appear in focus
- Integration over pixel area and *aperture area*
- Typically, the lens geometry is defined by the *radius* and the *distance* to the focal plane
- Sample the aperture, figure out the outgoing direction so that the points on the focal plane are in focus

Depth of Field (Miniaturization)

Depth of Field (Bokeh)

DoF (Cheap lens/Bad Bokeh)

Depth of Field (Bokeh)

Bokeh (Cat's Eyes)

Bokeh (Cat's Eyes)

Cat's Eyes

source: toothwalker.org

Implementing a Thin-lens

- Blackboard & Book

Motion Blur

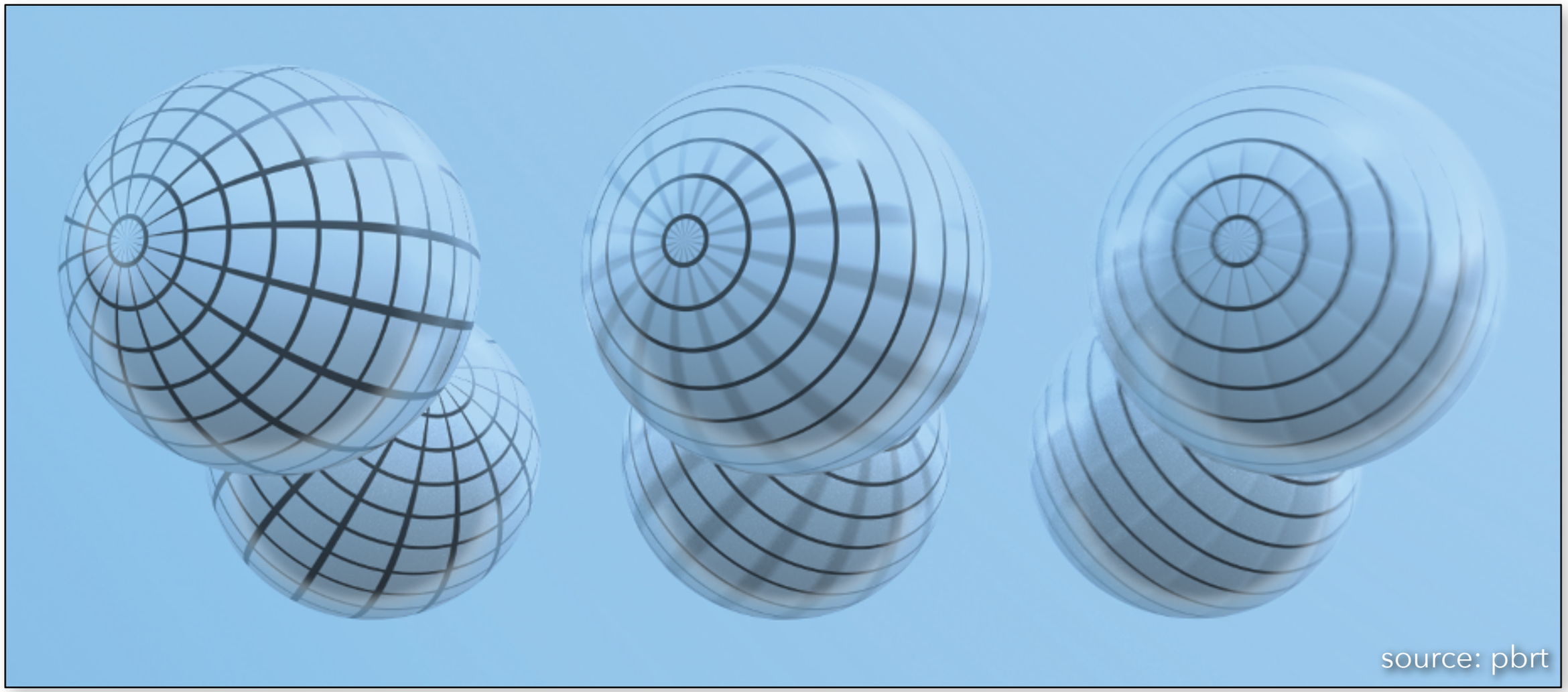
- Real cameras have a finite exposure time (shutter speed)
- Integration over time

Motion Blur

Motion Blur

Motion Blur

Motion Blur



Motion Blur

- Moving camera (easy):
  - trace many rays/pixel, each ray gets a random time
  - origin/direction of camera ray based on time value
- Object motion blur?
  - each ray gets a random time
  - intersect with transformed objects based on time
    - acceleration structures?

Motion Blur

- We typically specify object positions/ orientations using matrix transformations
- How can we interpolate two transformations?
- Naïve/bad: interpolate matrix entries

Next time

- More improvements to Monte Carlo