Oskar Elek

Efficient Methods for Physically-based Rendering of Participating Media

Thesis committee:
Prof. Dr. Hans-Peter Seidel (advisor)
Dr. Tobias Ritschel (supervisor)
Prof. Dr.-Ing. Carsten Dachsbacher

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max planck institut informatik

Saarbrücken
2016-02-02

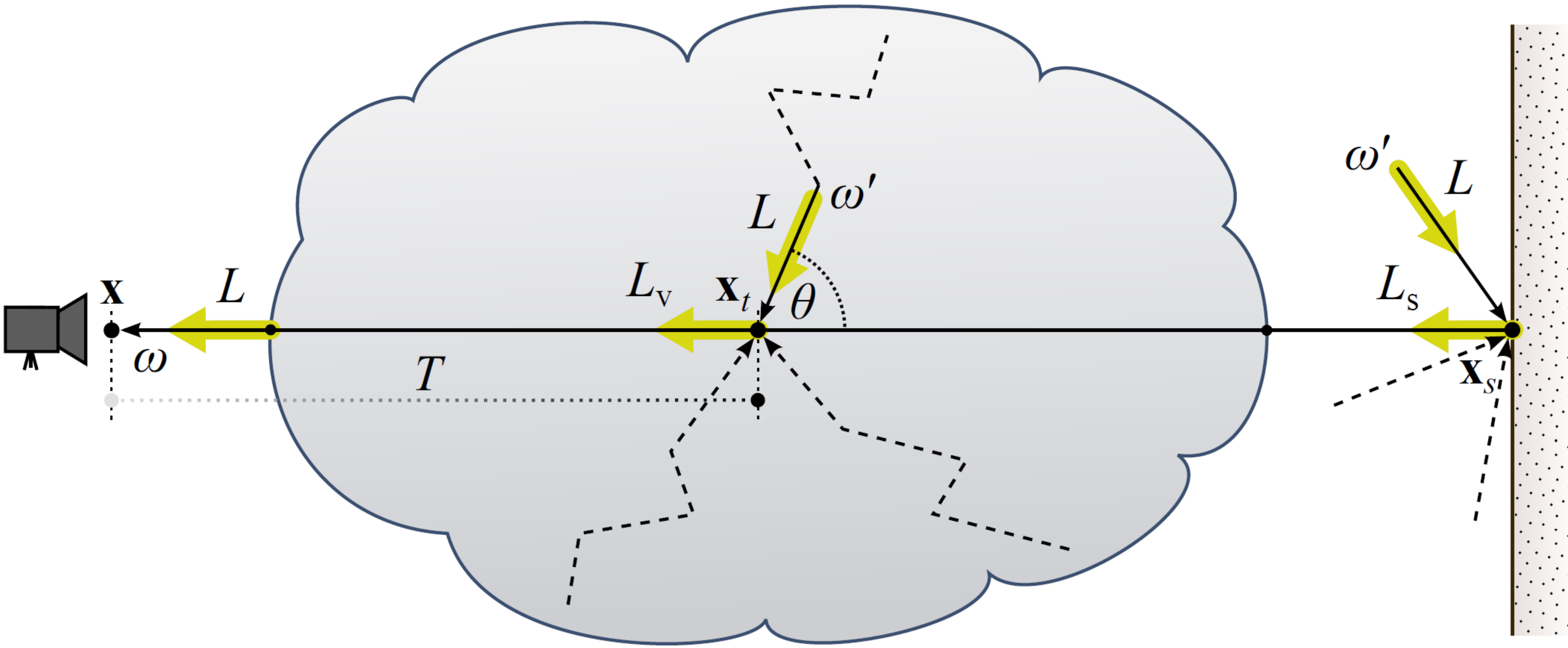
UNIVERSITÄT DES SAARLANDES

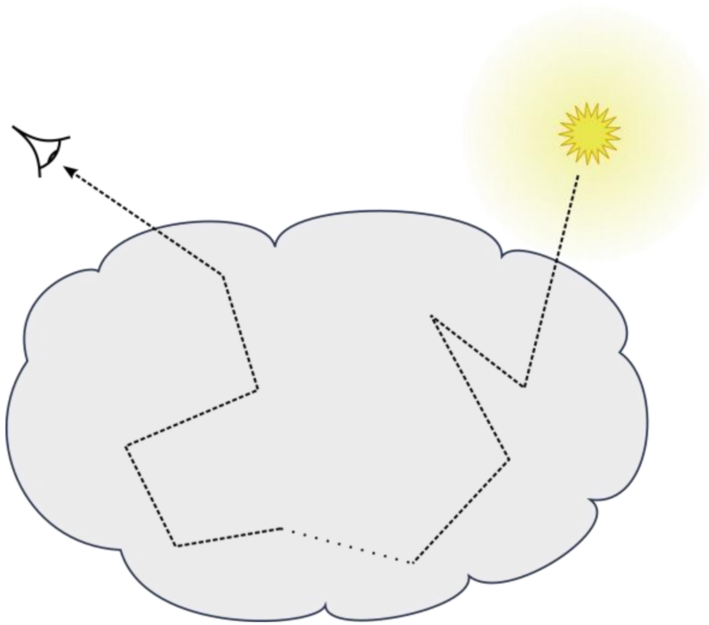
   

Participating Media: IRL

Radiative Transfer Equation (RTE):

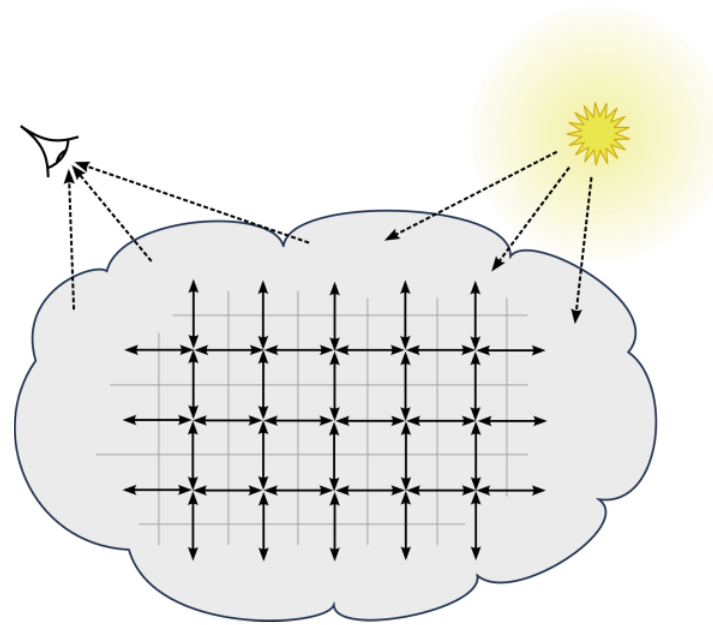


Participating Media: Simulation



Monte Carlo

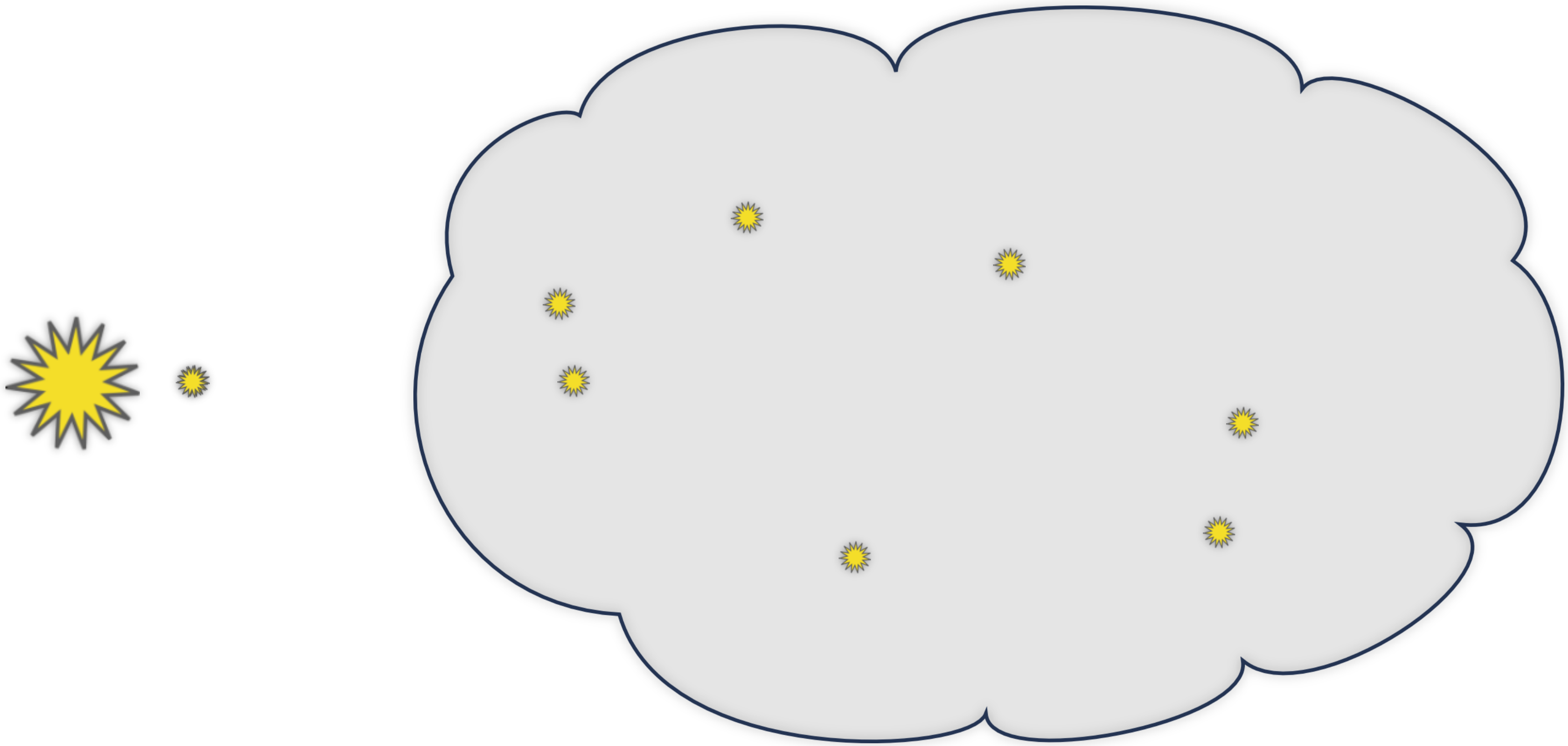
(Path Tracing, Photon Mapping, ...)



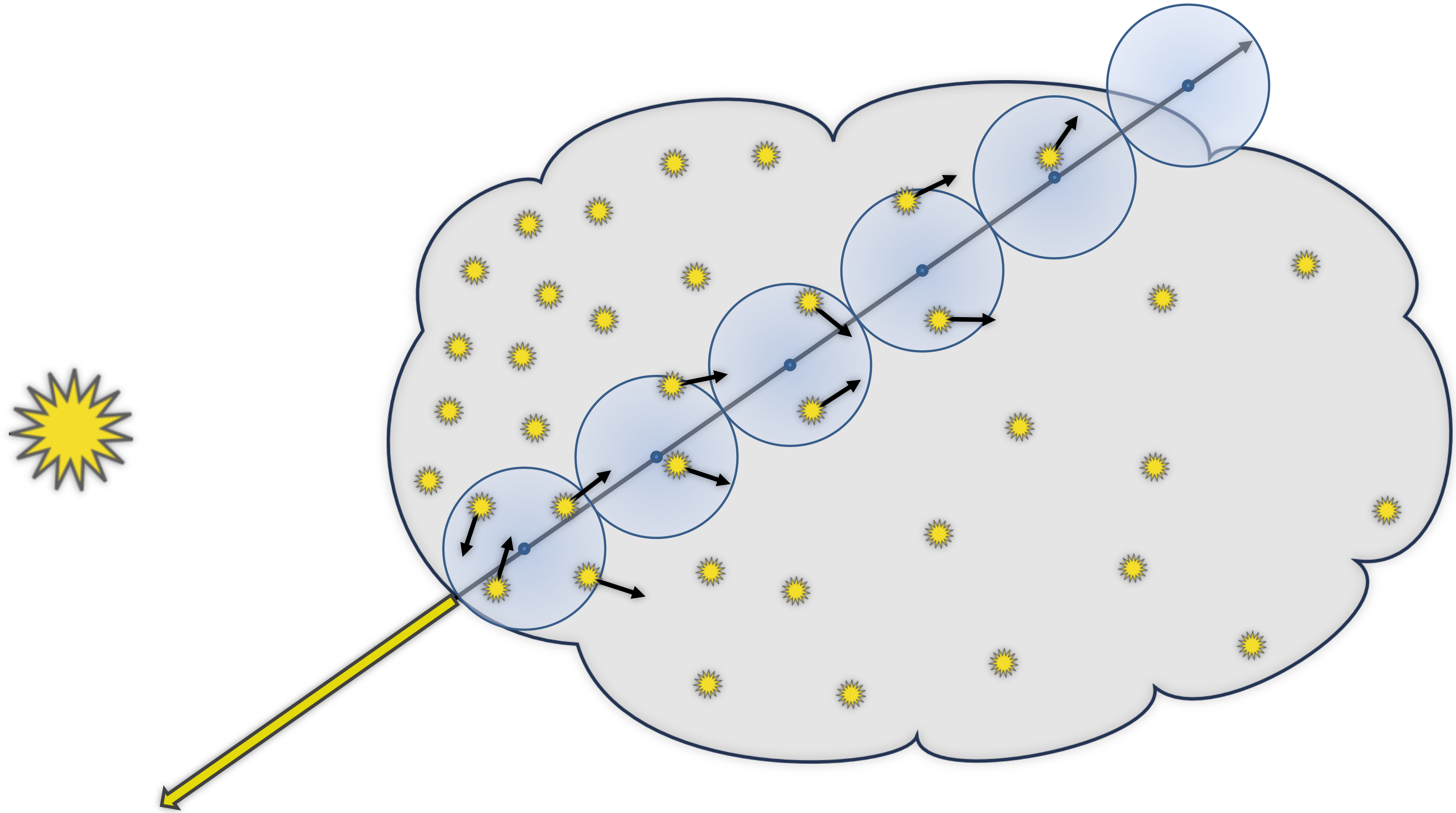
Finite Elements

(Diffusion, Discrete Ordinates, ...)

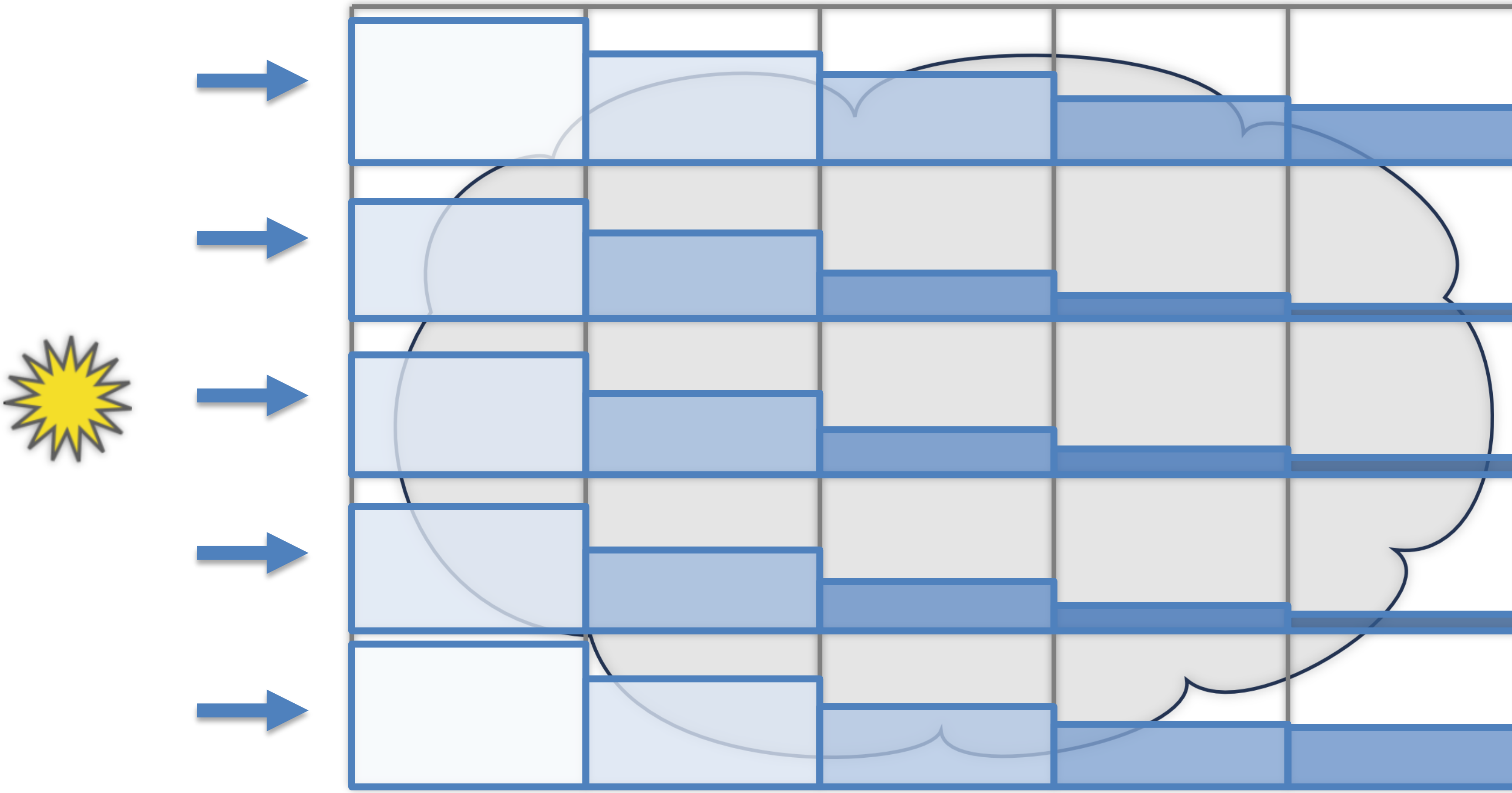
Participating Media: Simulation



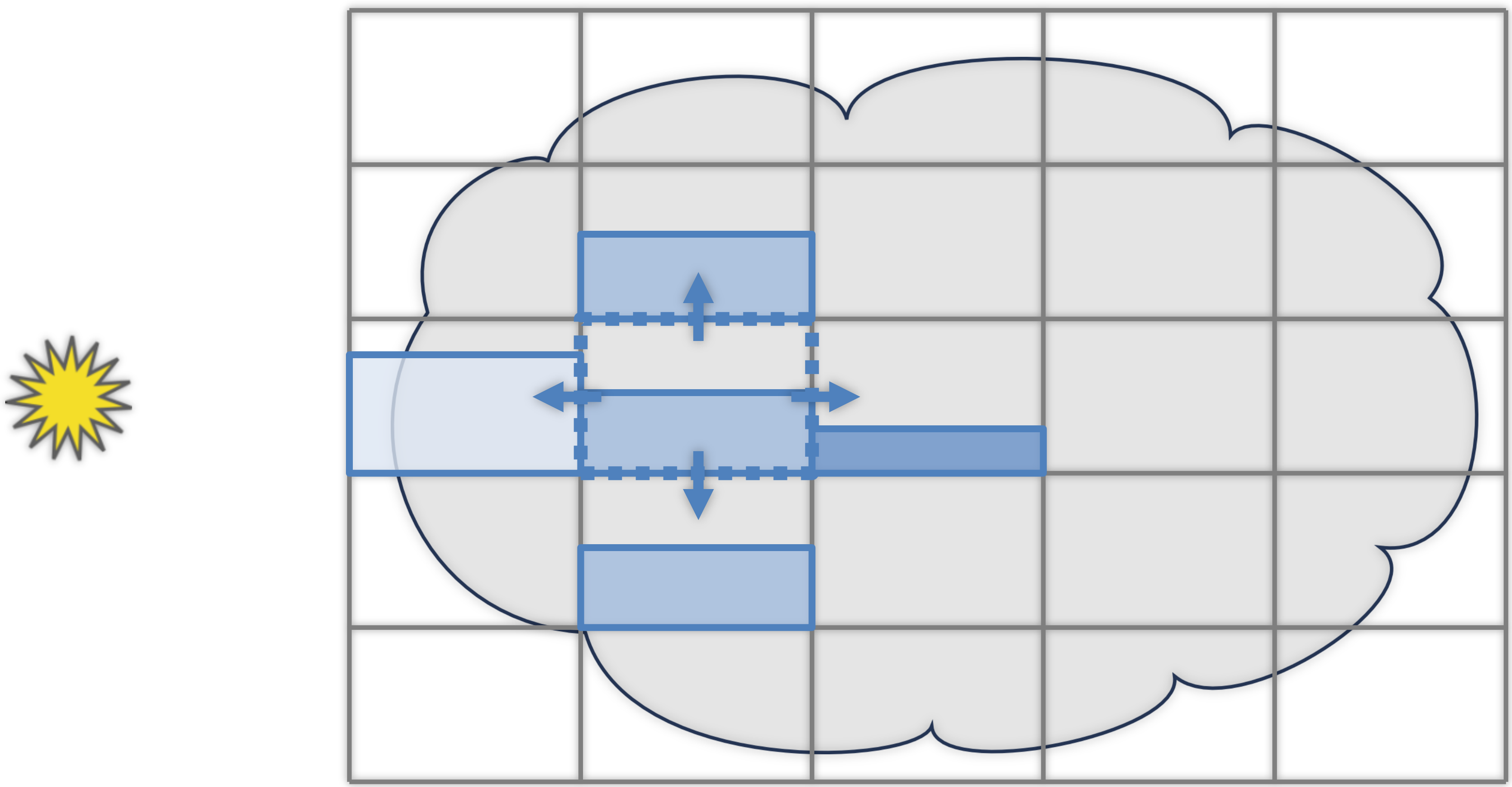
Example (MC): Photon Mapping



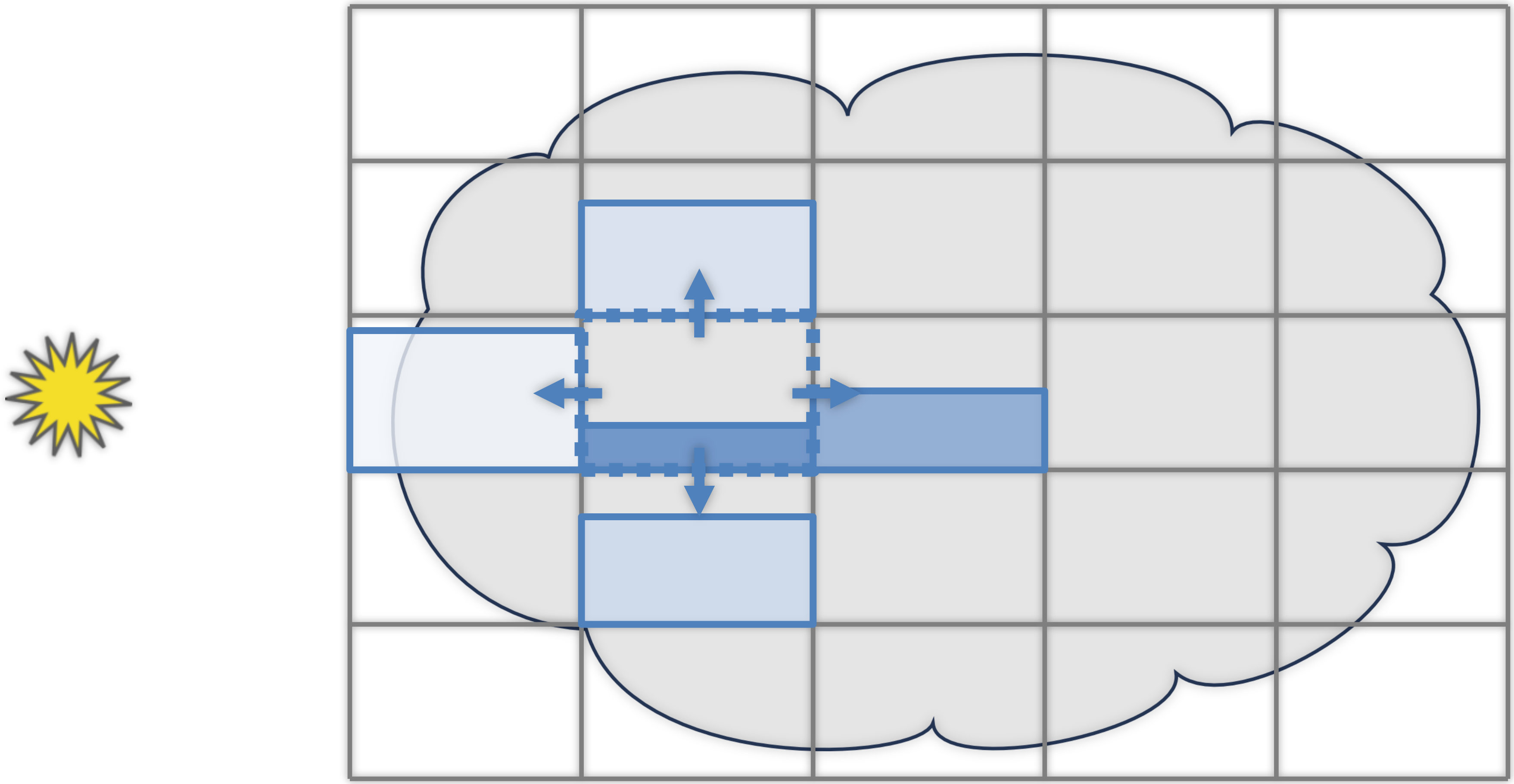
Example (MC): Photon Mapping



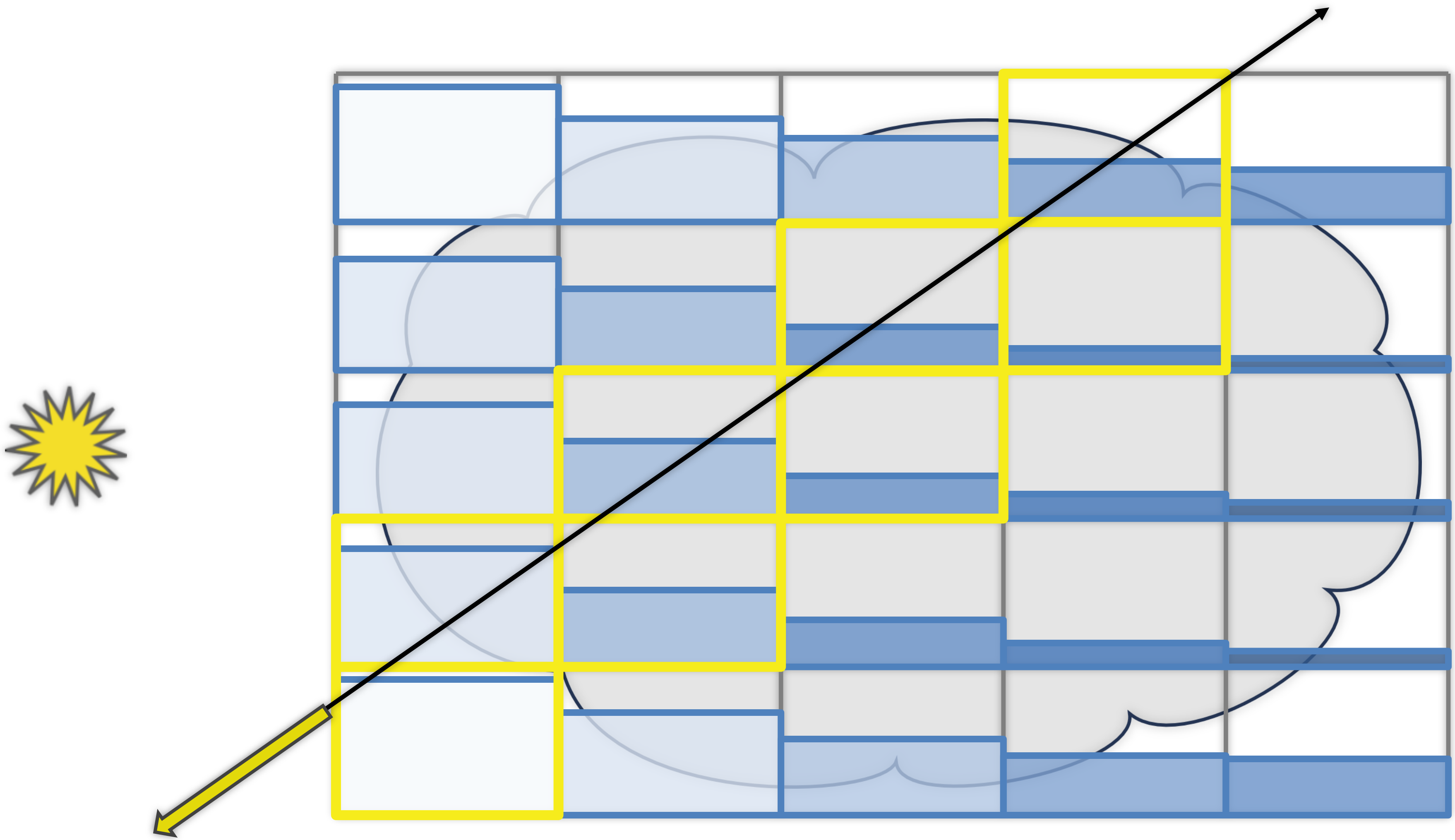
Example (FE): Diffusion



Example (FE): Diffusion

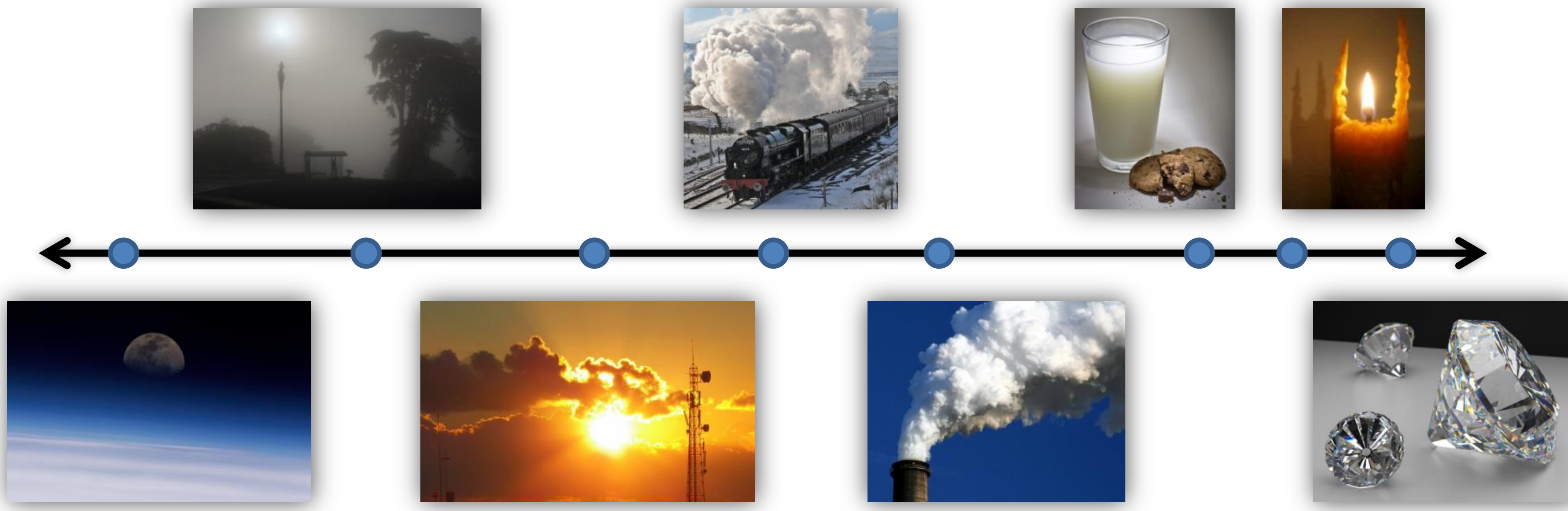


Example (FE): Diffusion



Example (FE): Diffusion

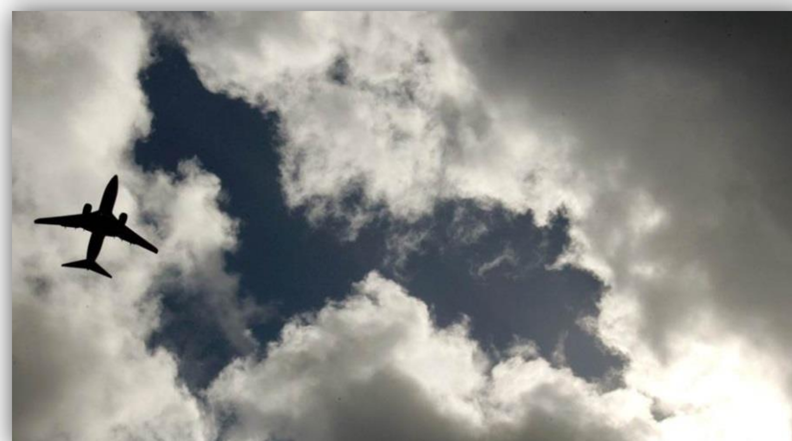
Optical thickness…



…heterogeneity,
scattering anisotropy…

Classification

INTERACTIVITY



Participating Media: Game Industry

Participating Media: Movie Industry

Real-Time Cloud Rendering

Screen-Space Scattering

Principal-Ordinates Propagation

Spectral Ray Differentials

Projects

Principal-Ordinates Propagation

[Best Student Paper @ Graphics Interface 2014]

[Computers and Graphics 2014]



Motivation: Heterogeneous Media

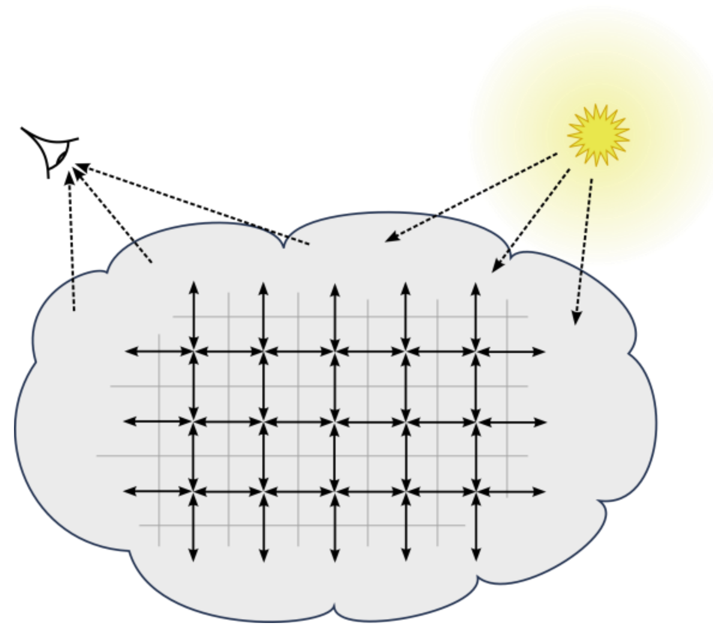
Simulation Paradigm

Wish-list:

- Physically plausible, general
- Interactive, dynamic (no preprocessing)

Monte Carlo

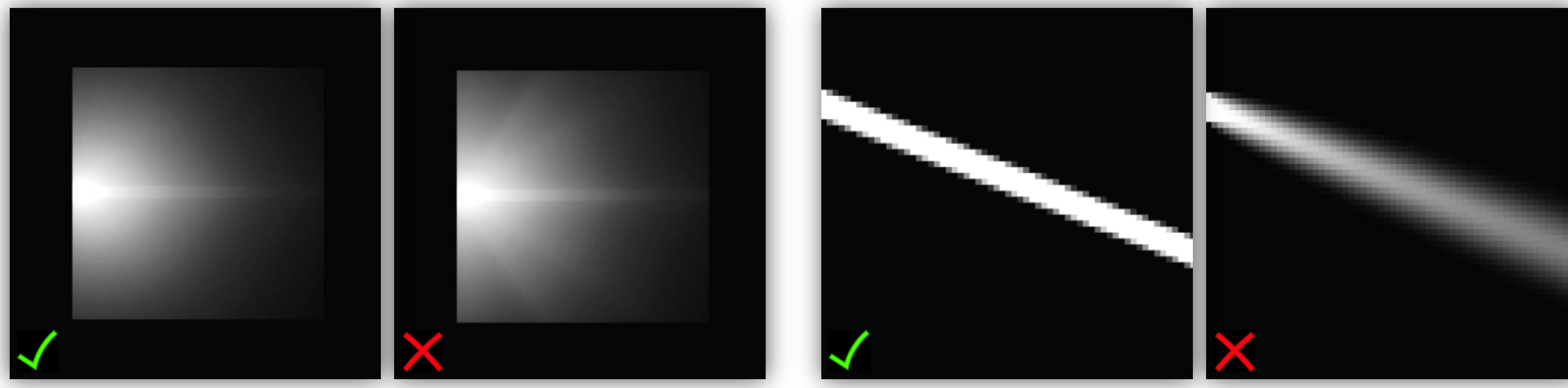
(Path Tracing, Photon Mapping, …)



Finite Elements

(Diffusion, Discrete Ordinates, …)

[Fattal @ ACM Trans. Graph. 2009]



Ray effect False scattering

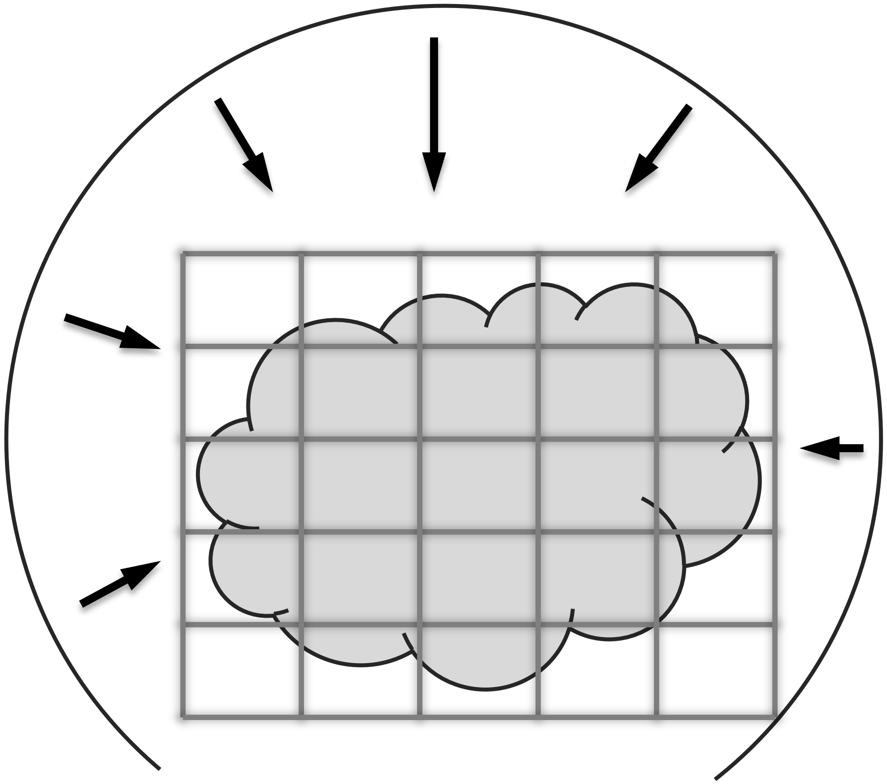
Finite Elements: Issues

Anisotropic scattering
(our method)

Isotropic scattering
(contemporary methods)

Finite Elements: Issues

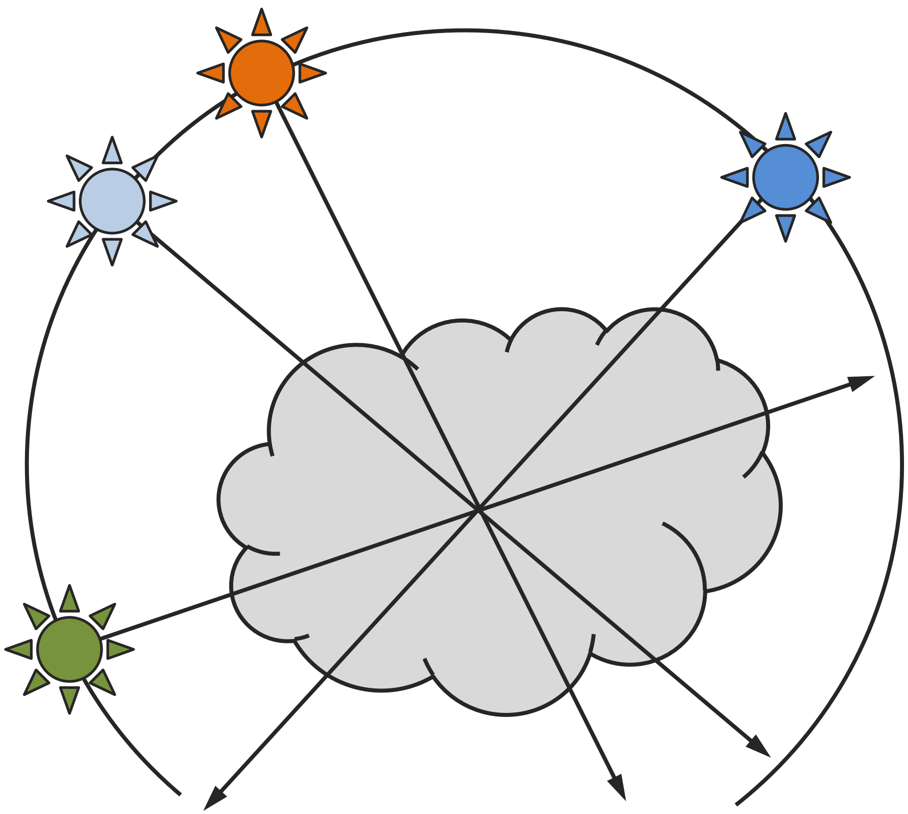
Idea: Instead of solving the transport globally…



Principal Ordinates

Idea: Instead of solving the transport globally…

…separate it, similar to Instant Radiosity



Principal Ordinates

Idea: Instead of solving the transport globally…

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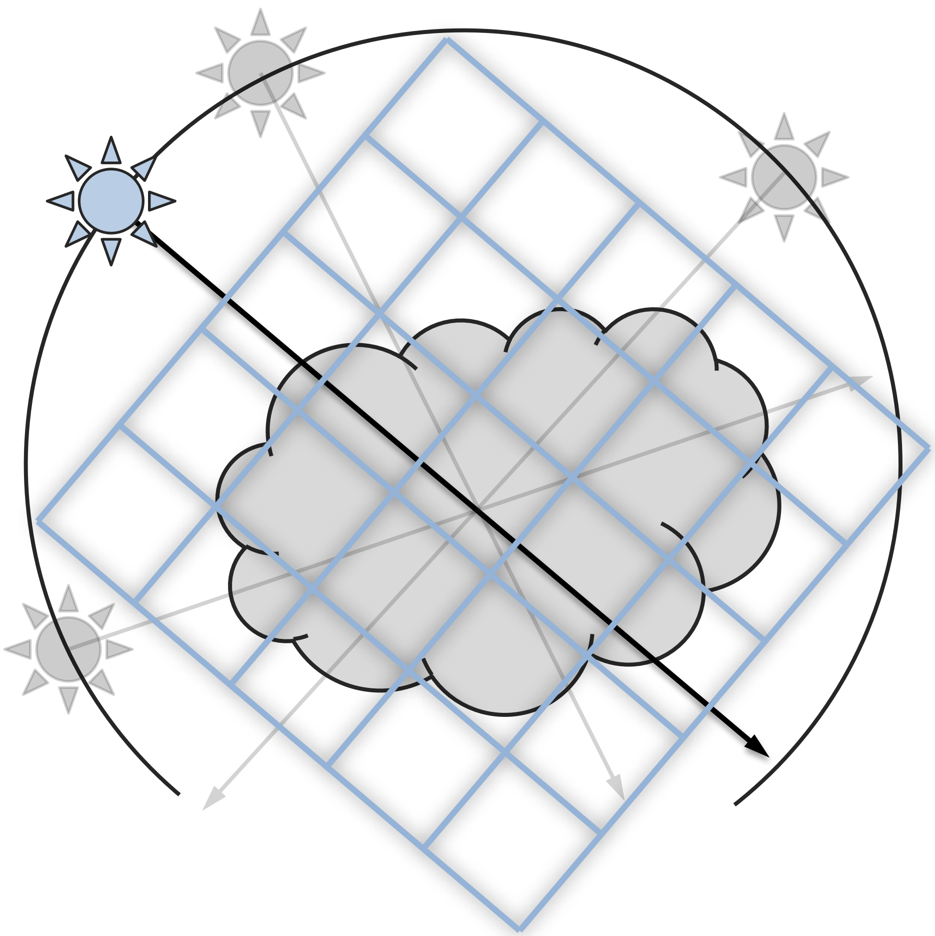
PRINCIPAL ORDINATES

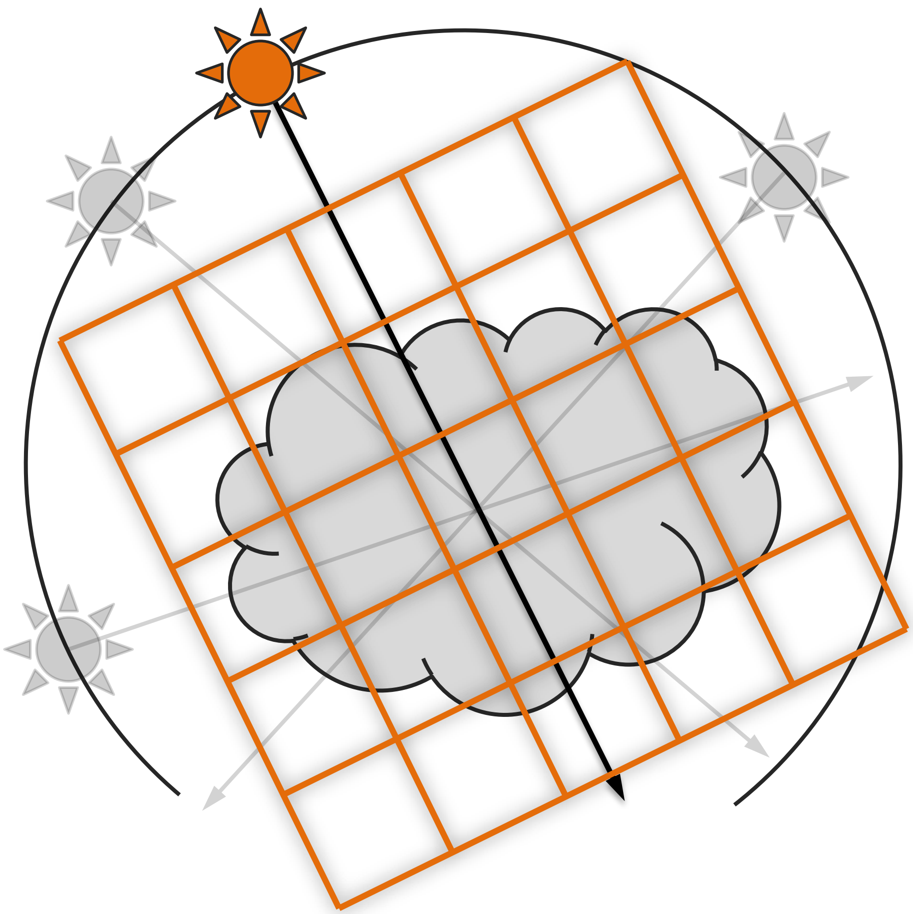
Idea: Instead of solving the transport globally…

…separate it, similar to Instant Radiosity

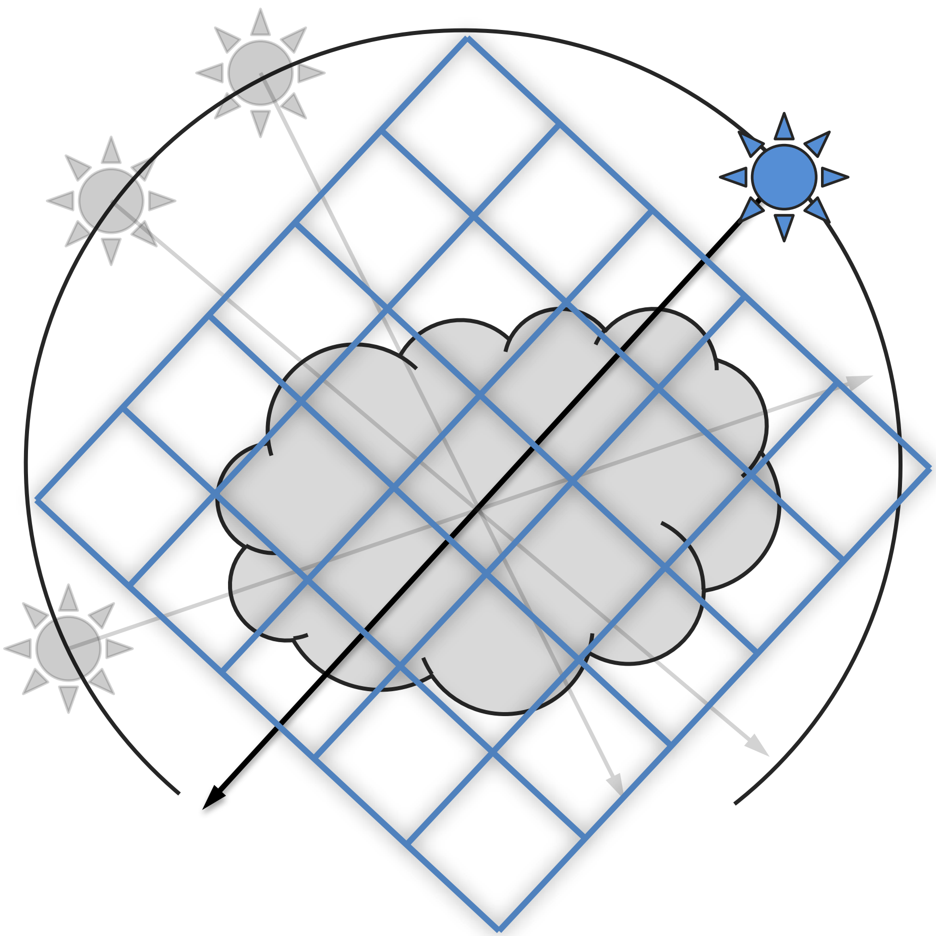
Principal Ordinates



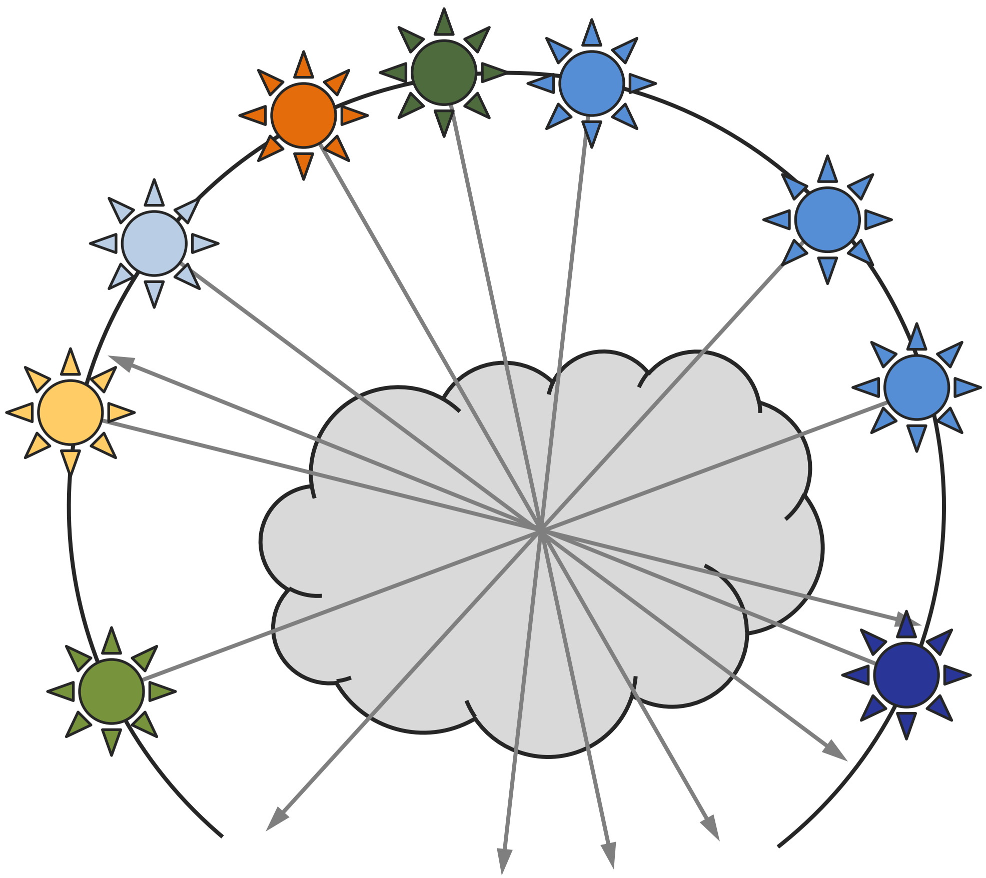
Principal Ordinates

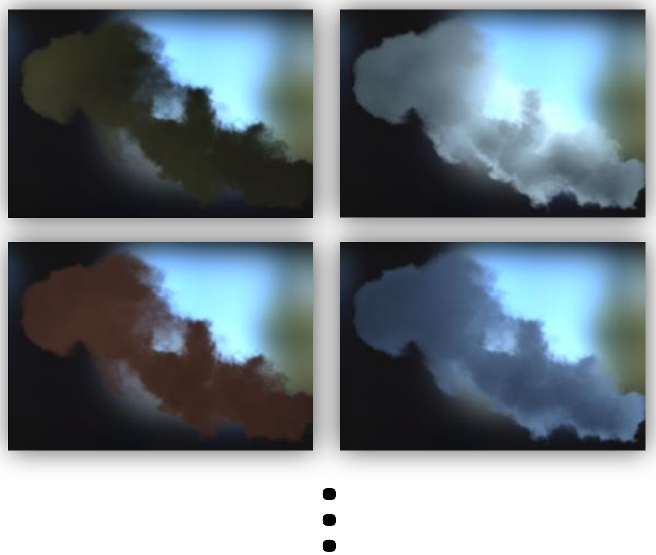


Principal Ordinates

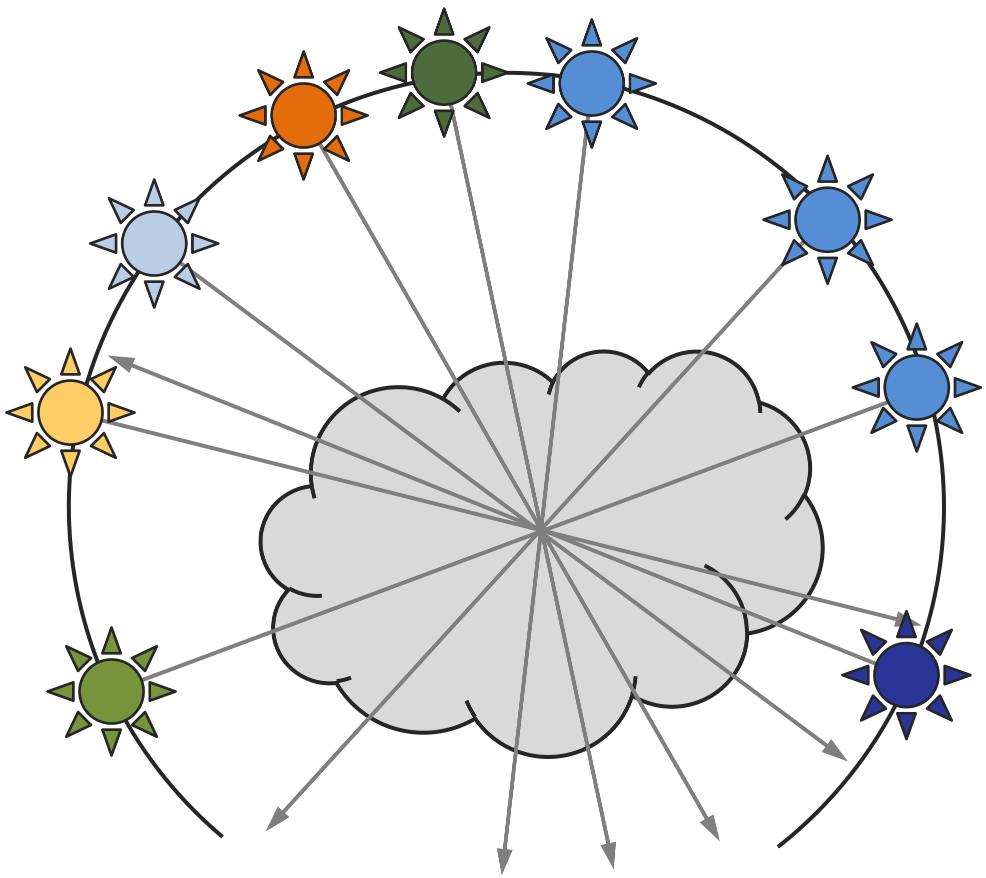


Principal Ordinates





Principal Ordinates



Principal Ordinates

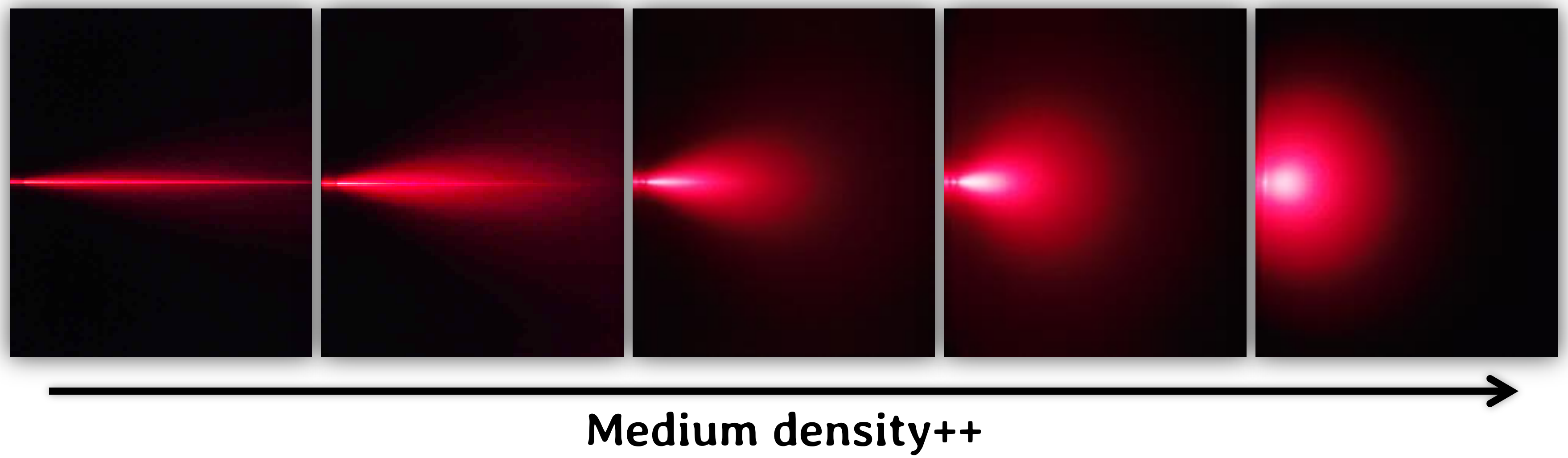
Scattering ≈ gradual loss of illumination coherence

[Premoze etal. @ EGSR 2004]

ABSTRACTION

Scattering ≈ gradual loss of illumination coherence

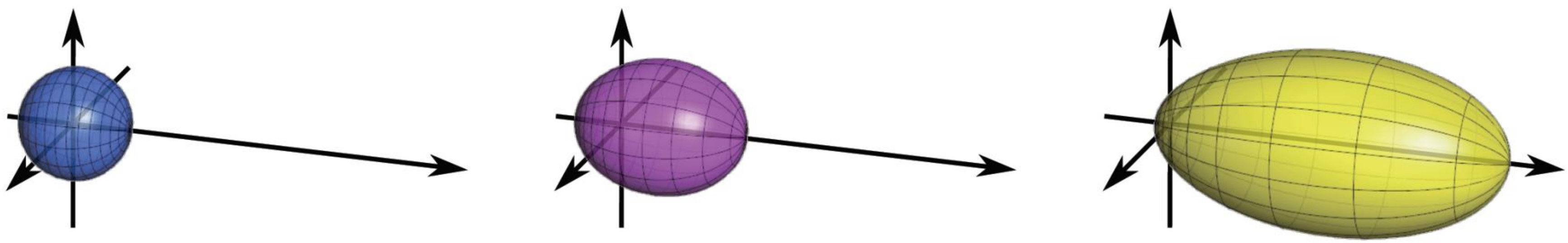
[Premoze etal. @ EGSR 2004]



ABSTRACTION

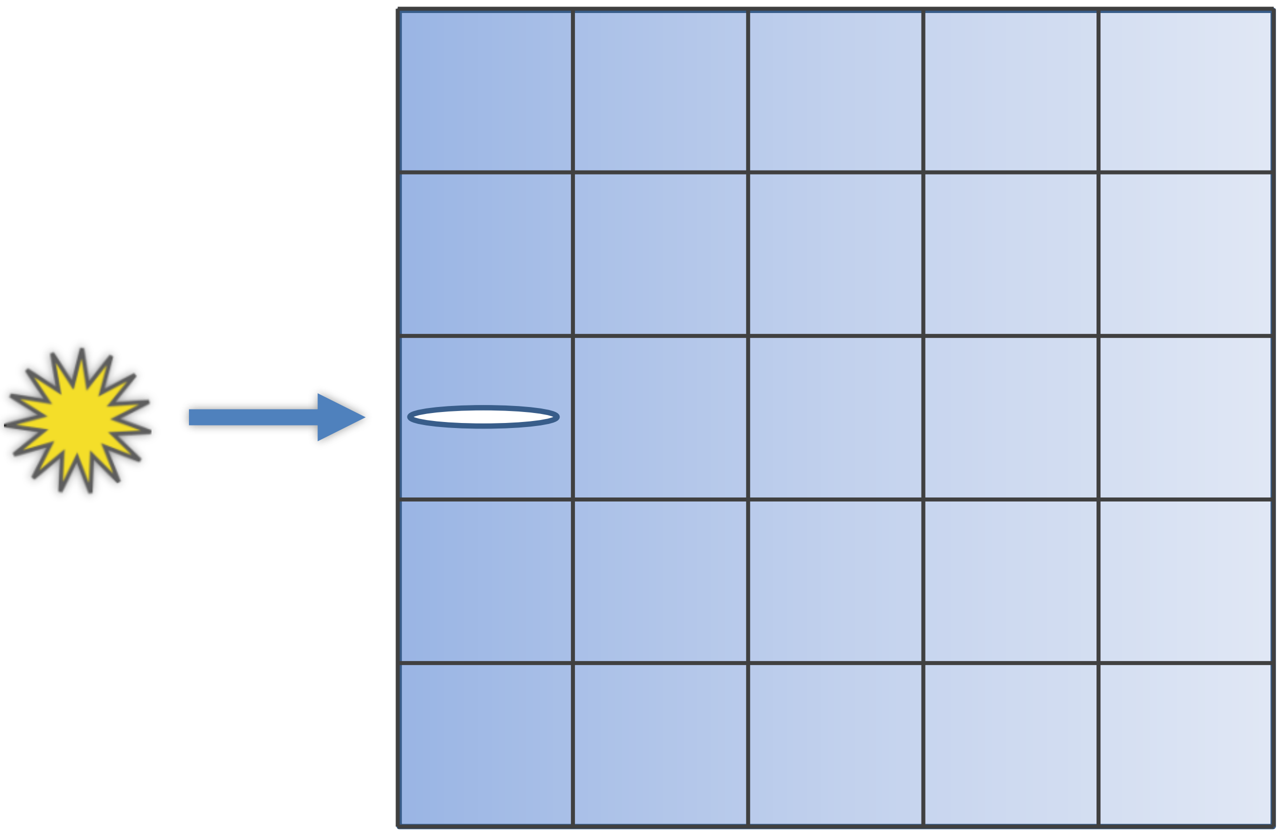
Henyey-Greenstein distribution

$$f_{\mathrm{HG}}(\theta, g) = \frac{1}{4\pi} \cdot \frac{1 - g^2}{(1 + g^2 - 2g\cos\theta)^{3/2}}$$

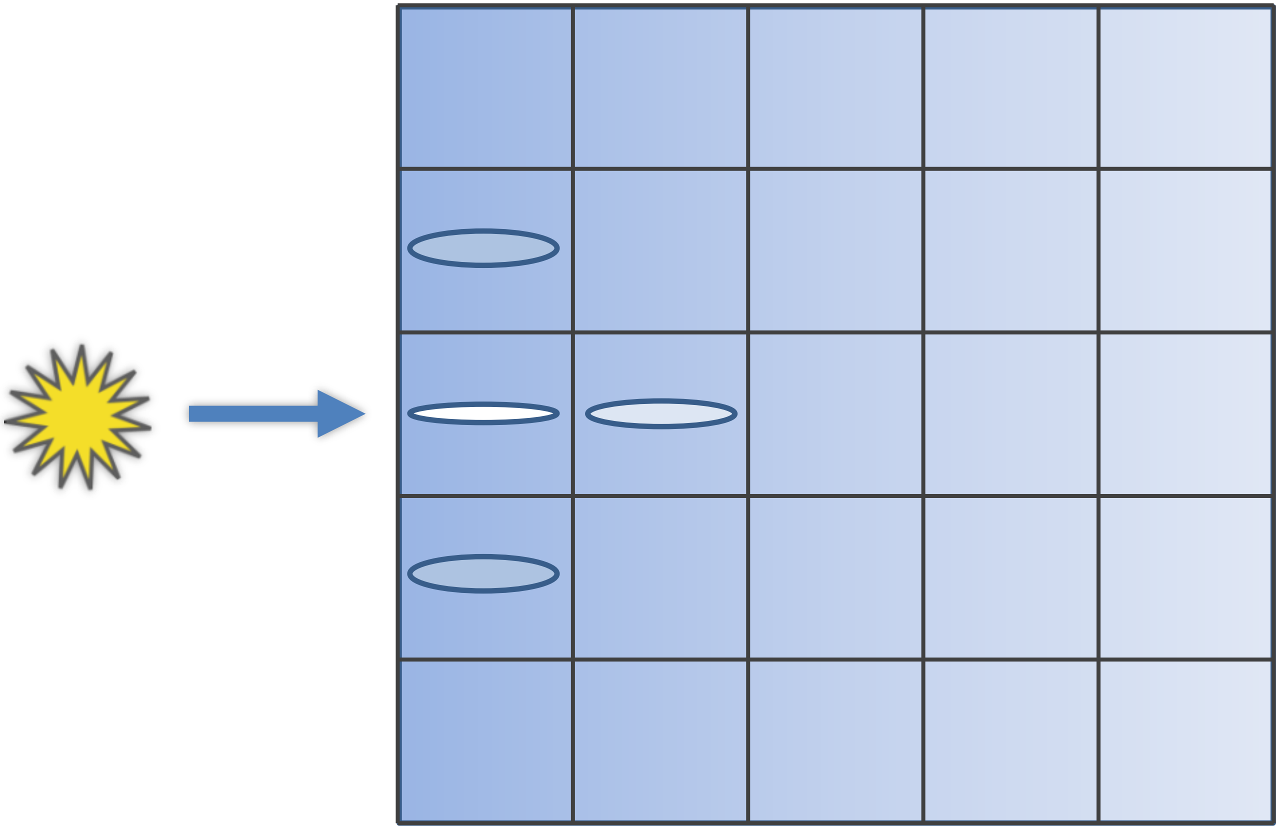


g=0 g=0.3 g=0.5

PROPAGATION BASIS



Light Propagation



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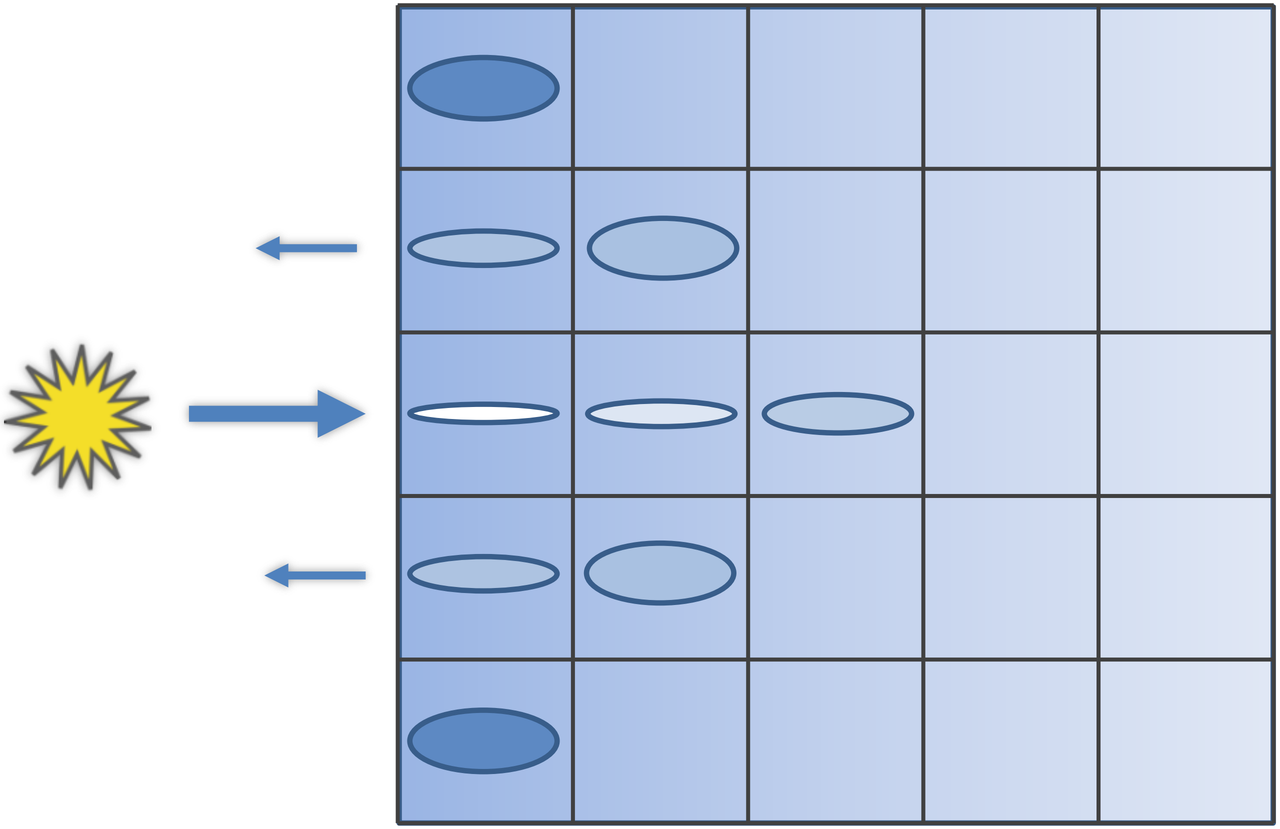
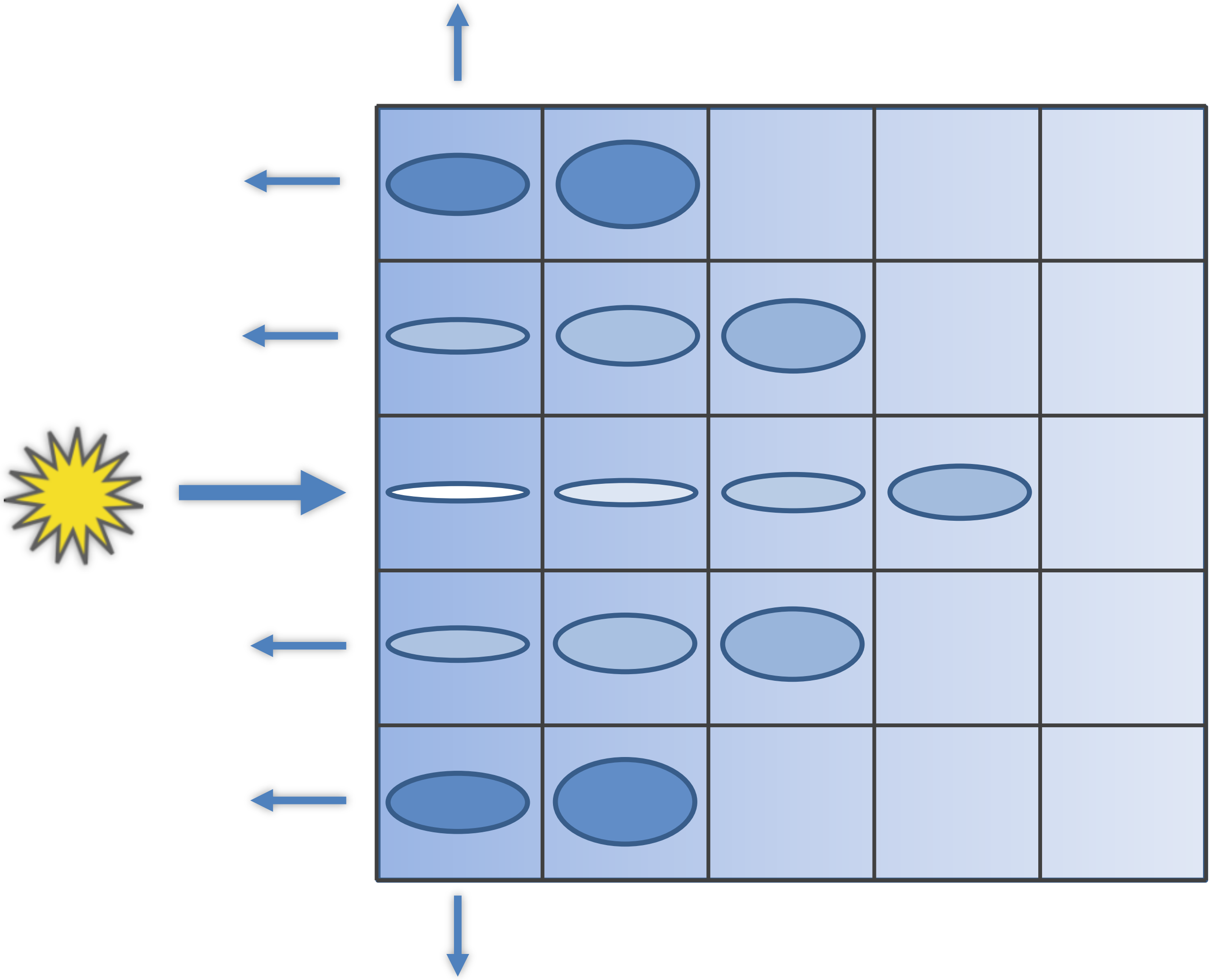
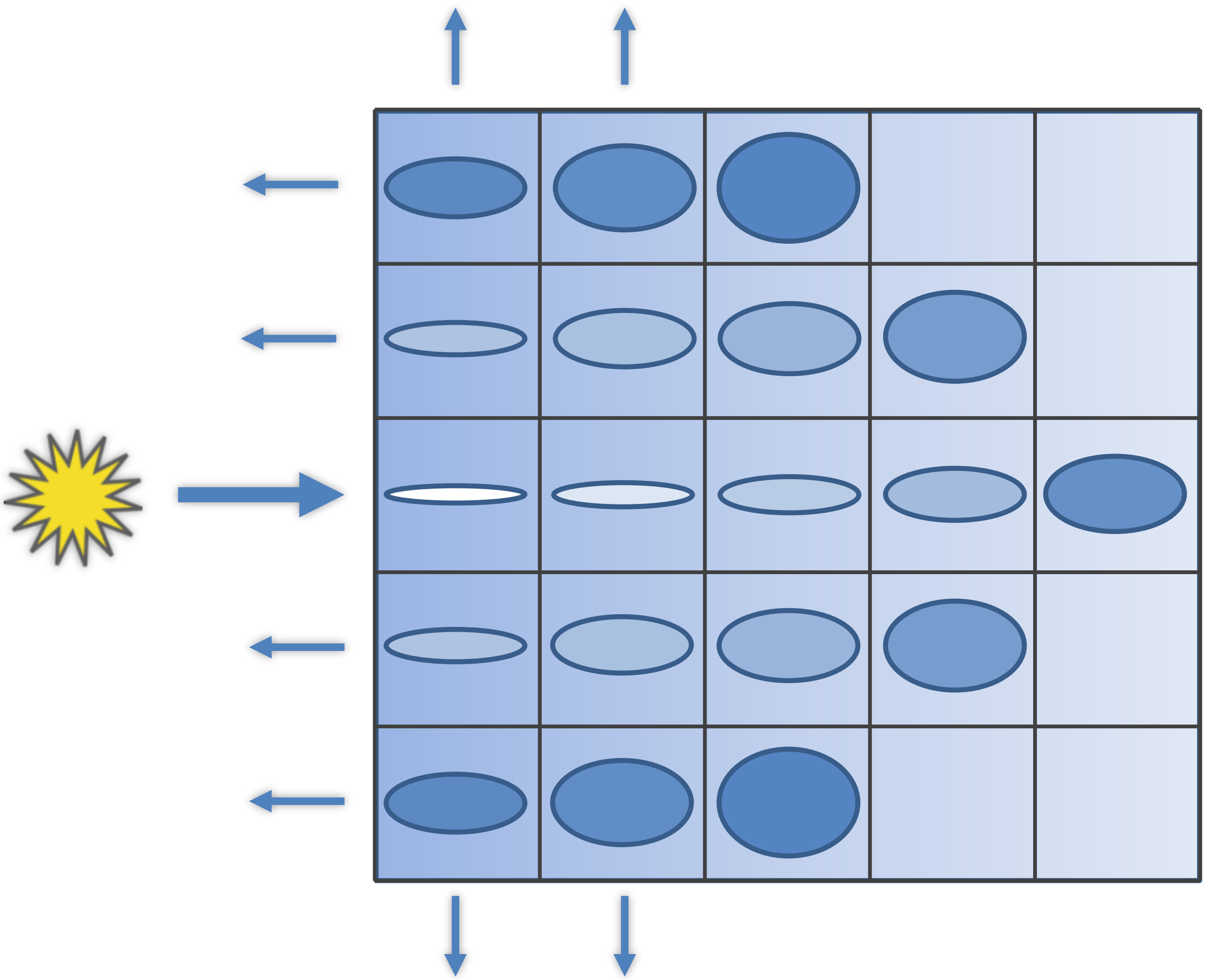


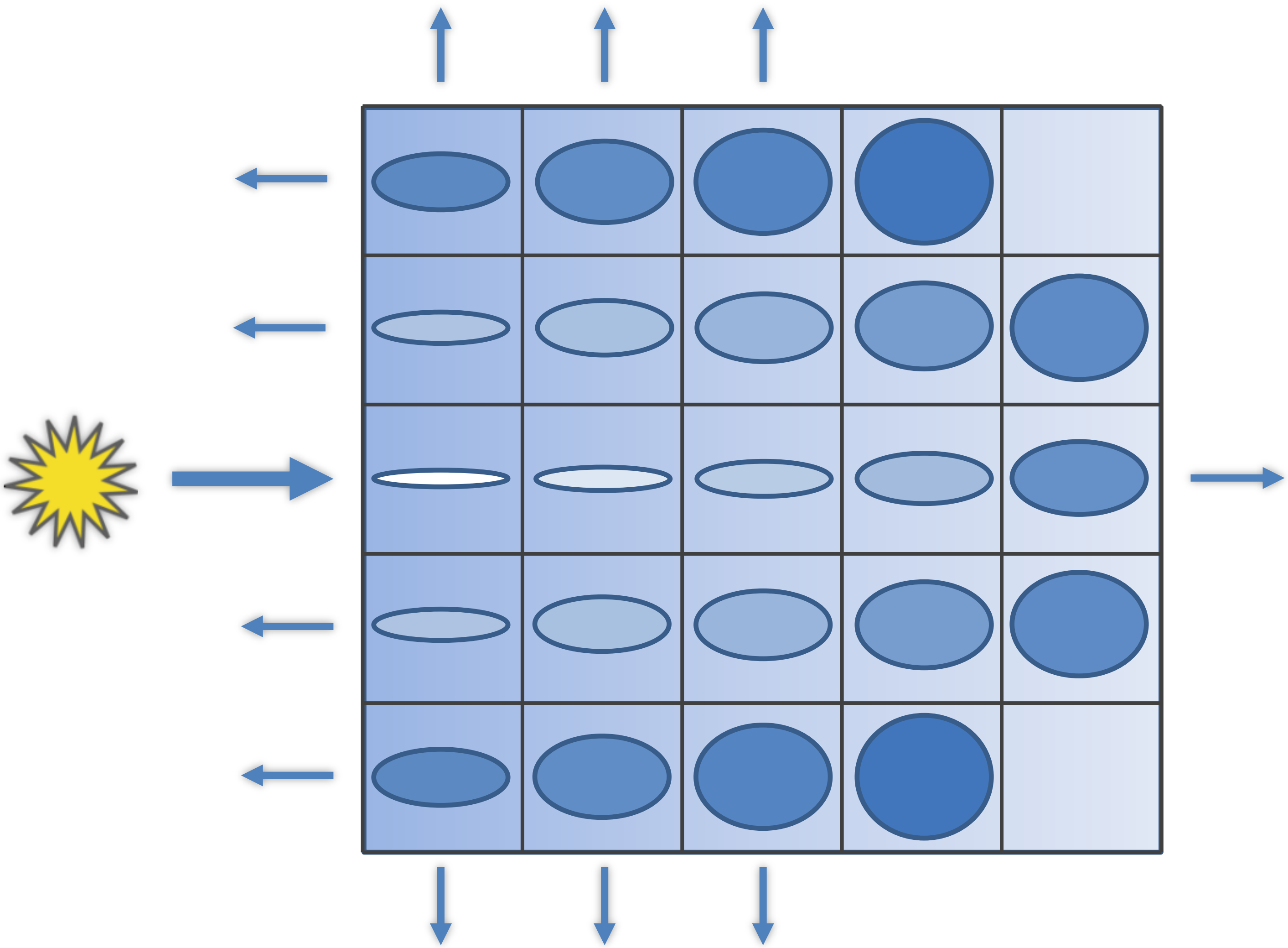
Light Propagation



Light Propagation



Light Propagation



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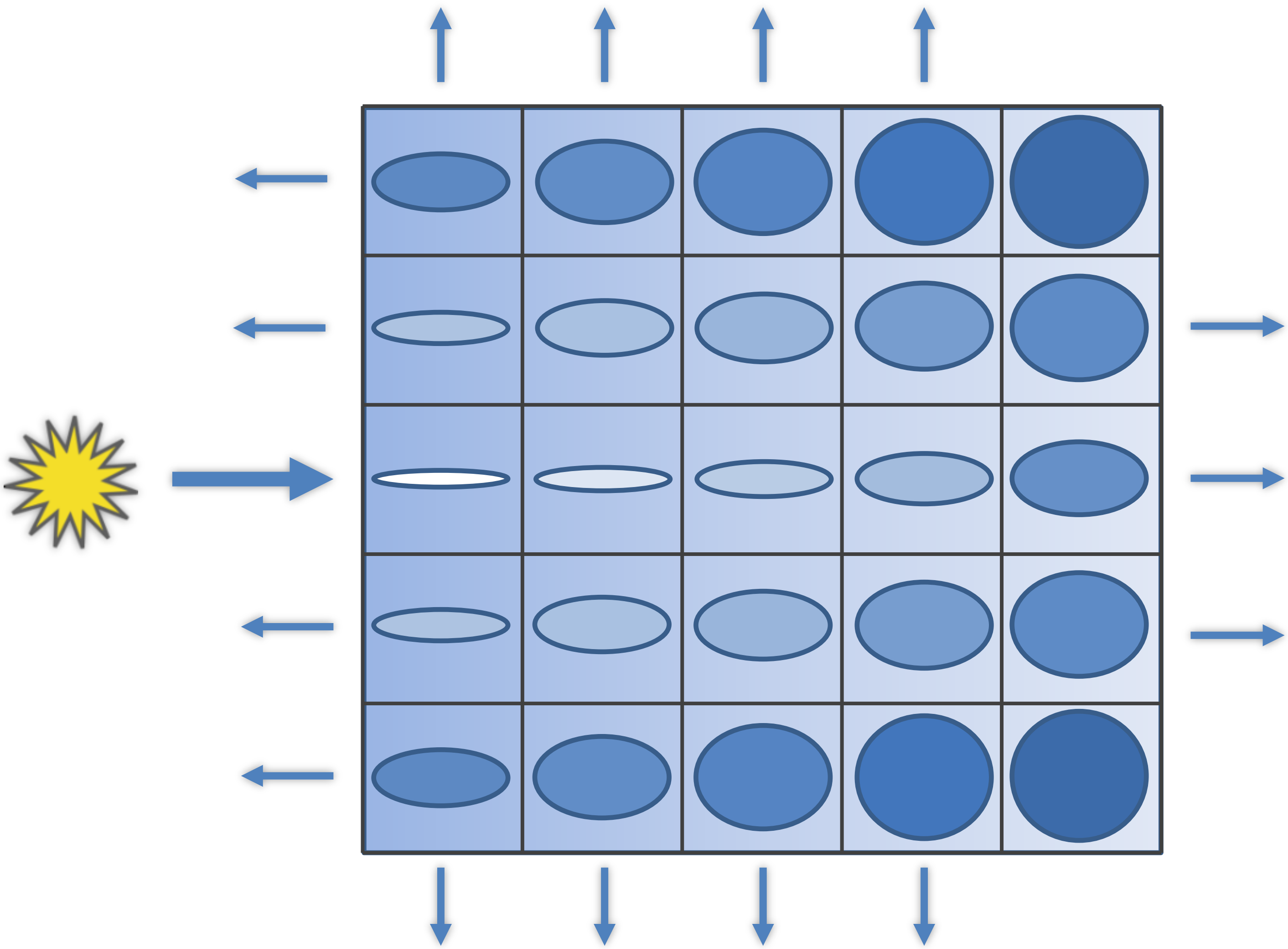
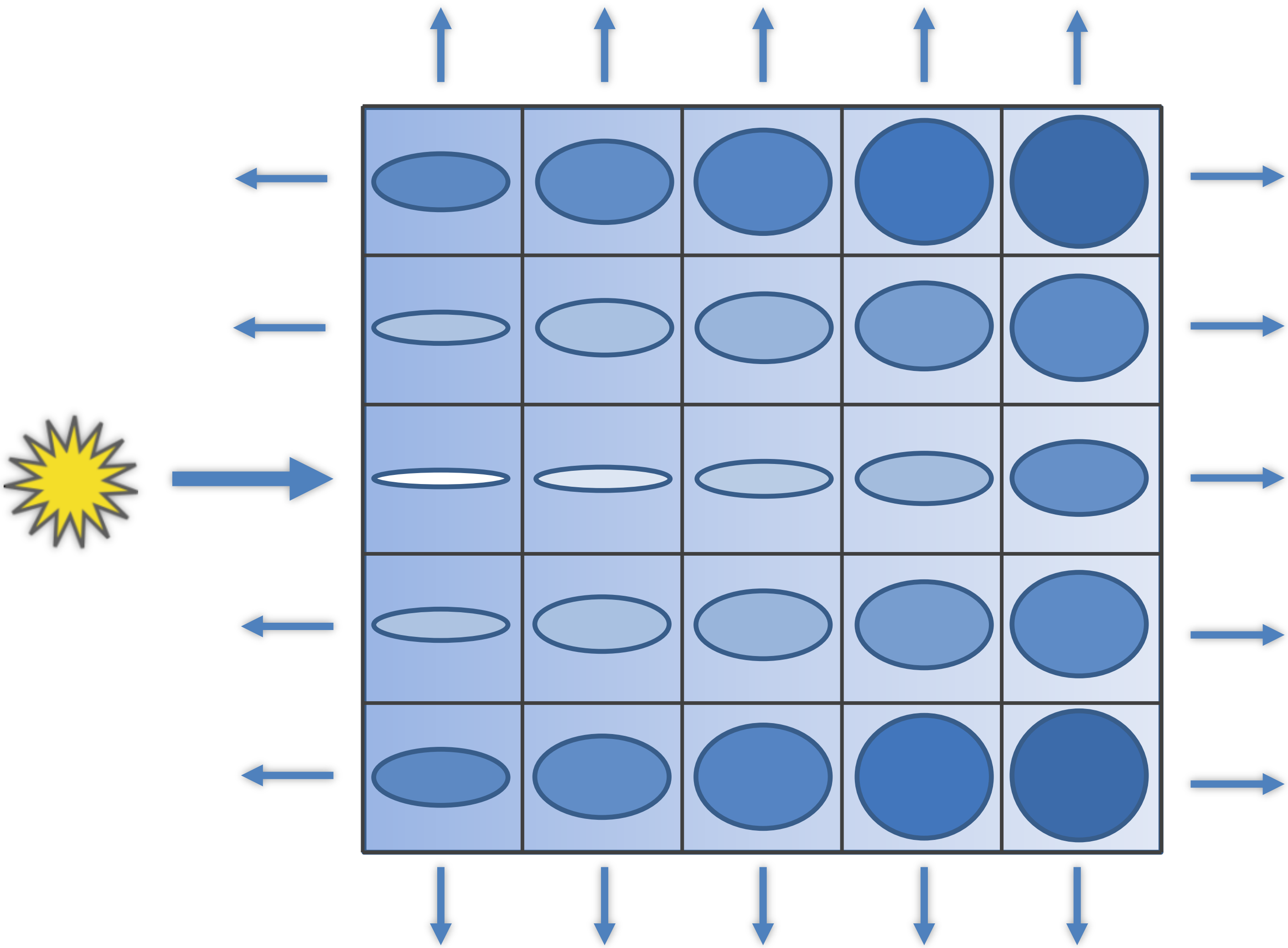
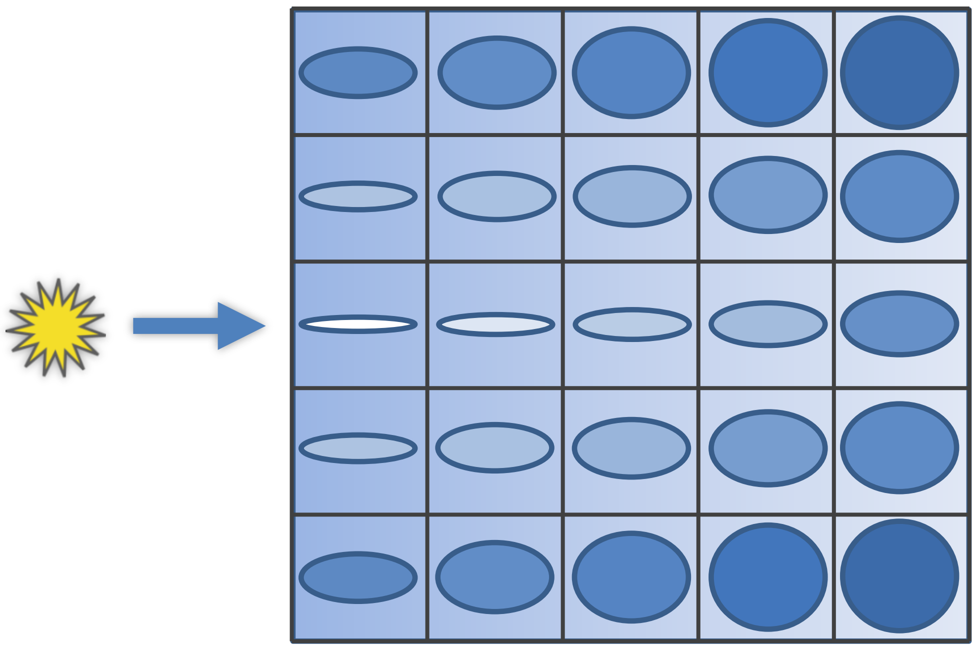


Light Propagation

Oskar Elek: Efficient Methods for Physically-based Rendering of Participating Media



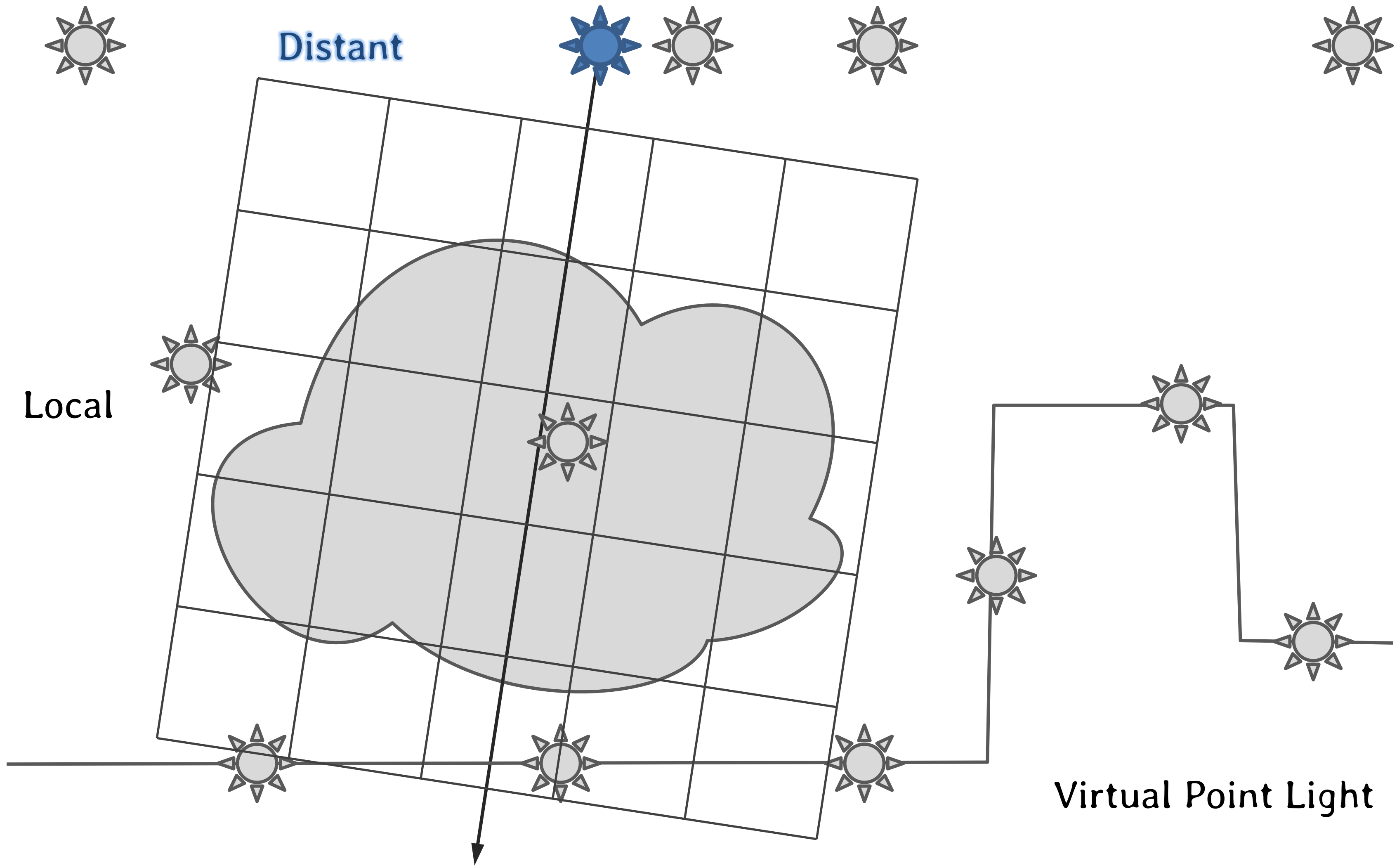
Light Propagation



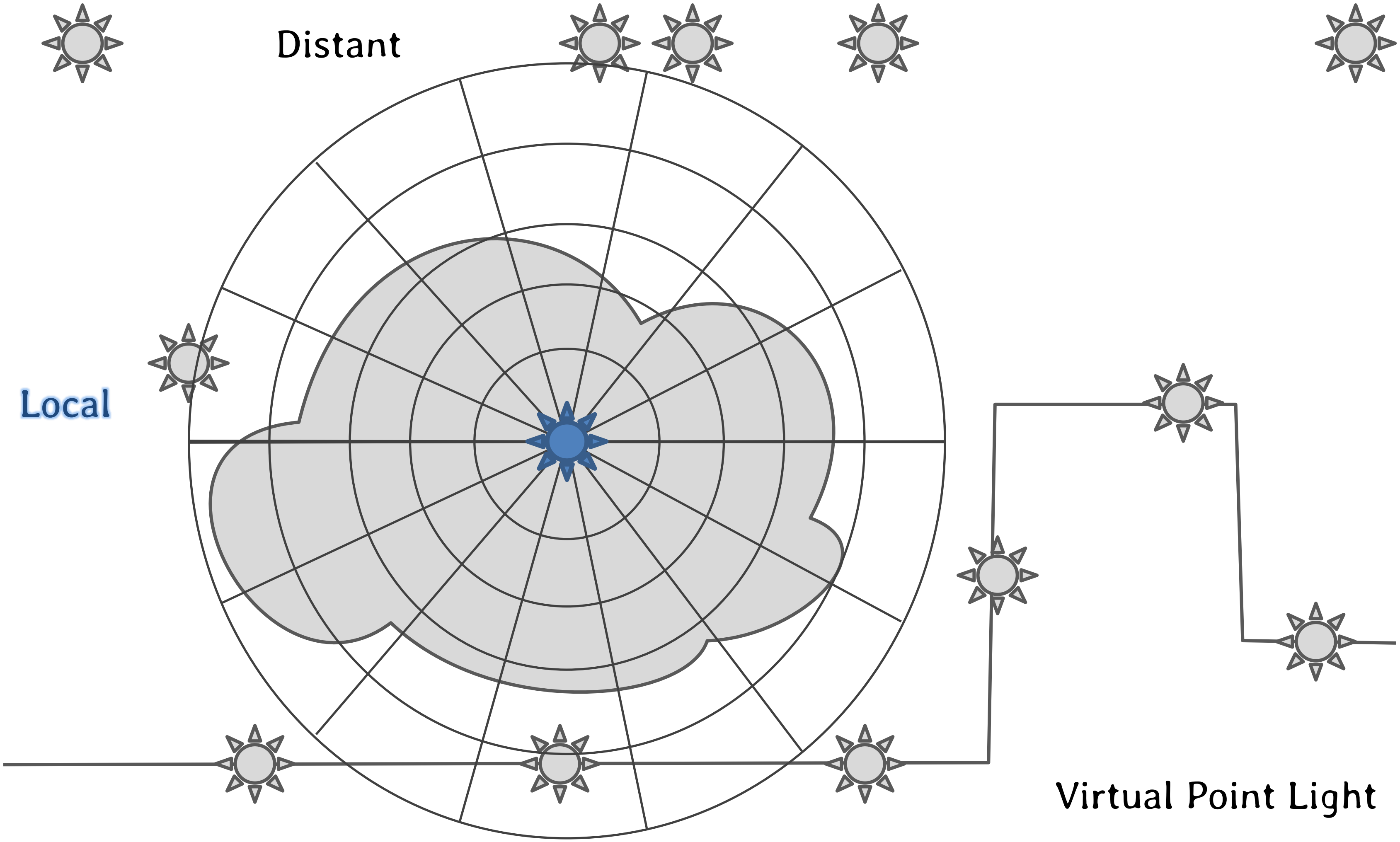
≈

[Premoze etal. @ EGSR 2004]

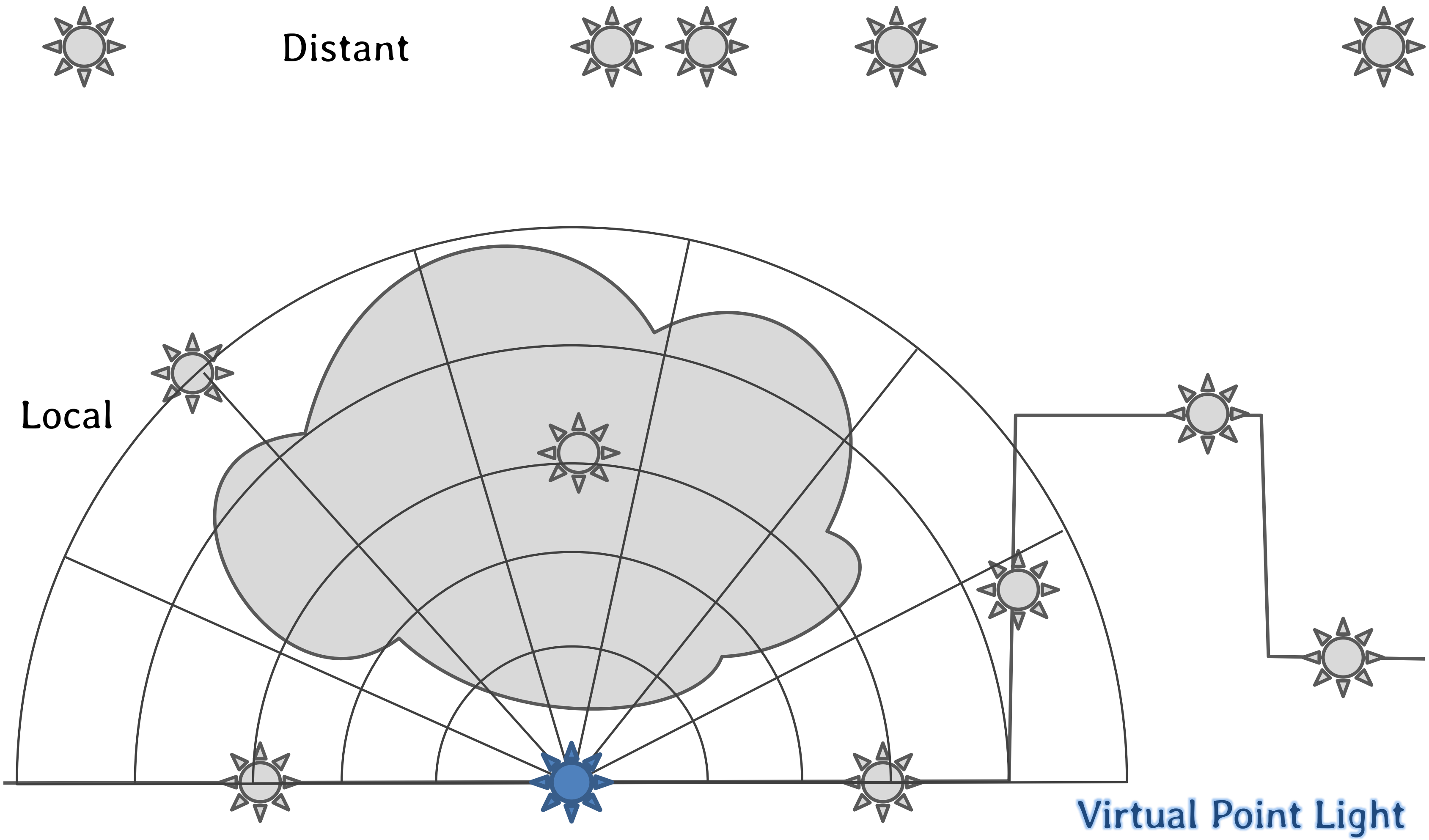
Light Propagation



Lattice ZOO



Lattice ZOO

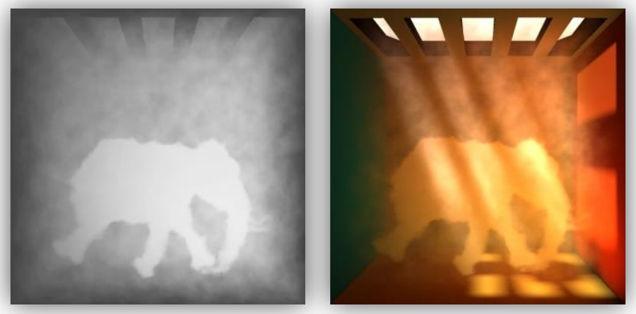


Lattice ZOO

Input:
- **Medium parametrization**
- **Scene definition**

Output:
- Final image

Pipeline



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PIPELINE

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- Scene definition

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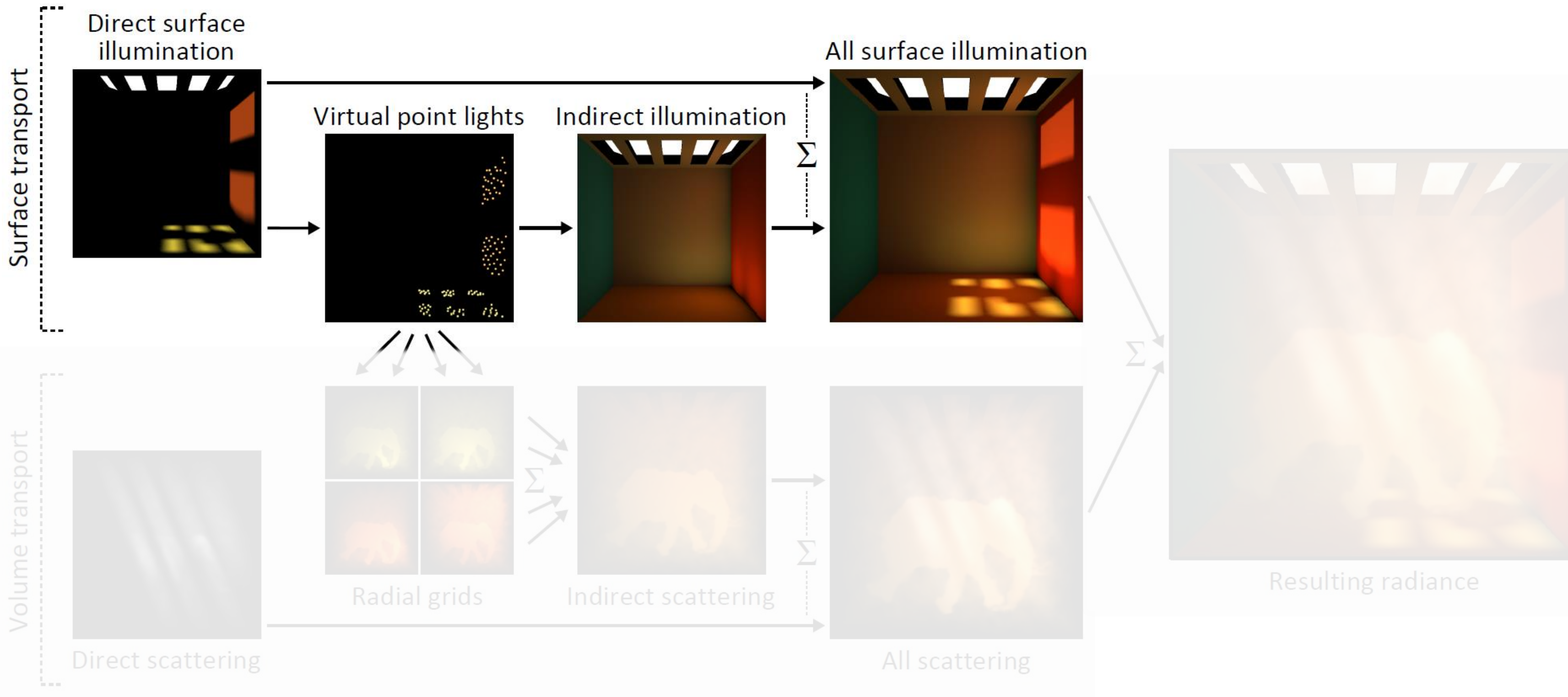
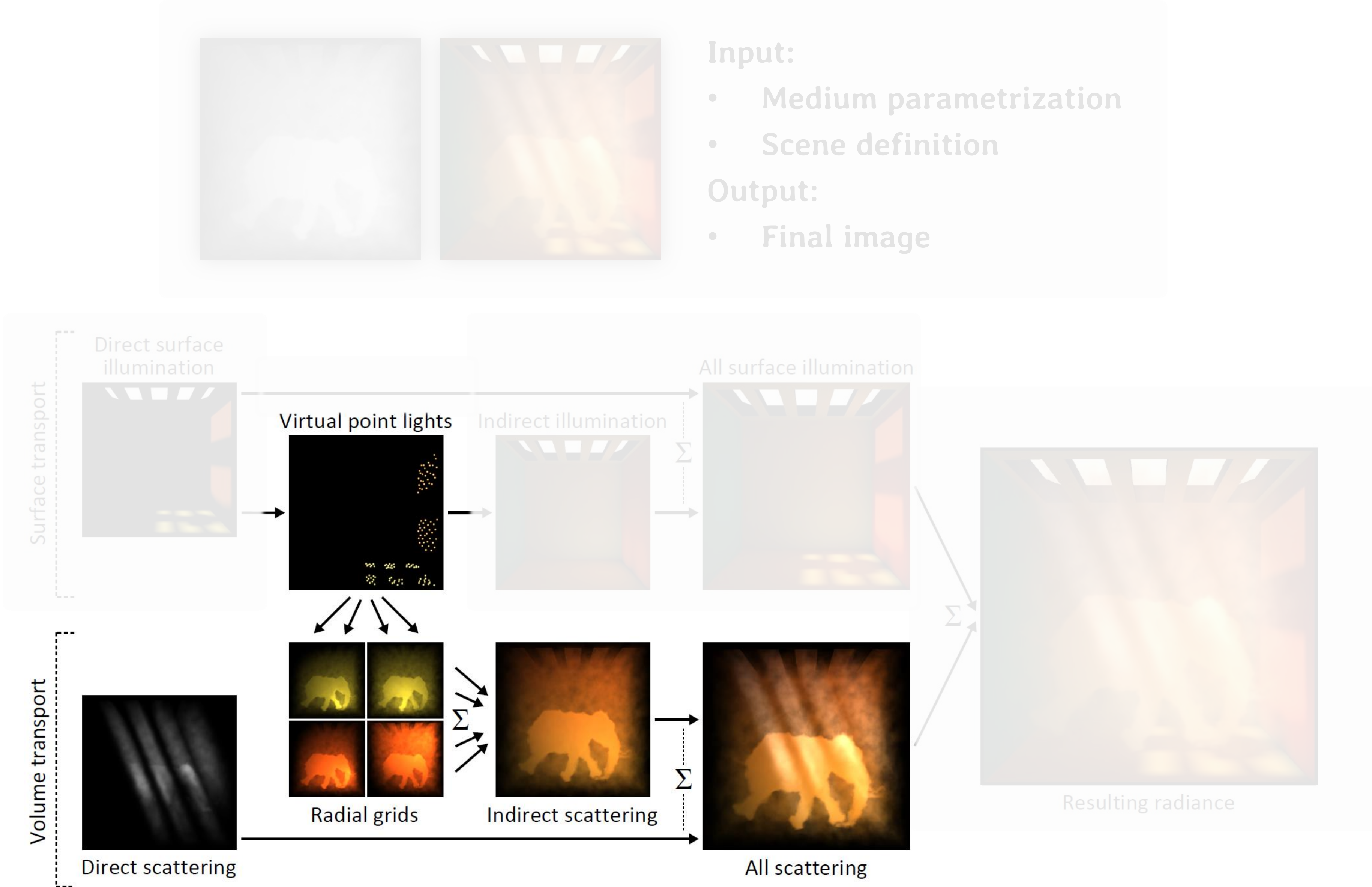


(For a single directional light)

Pipeline



(For a single directional light)

Pipeline

Input:

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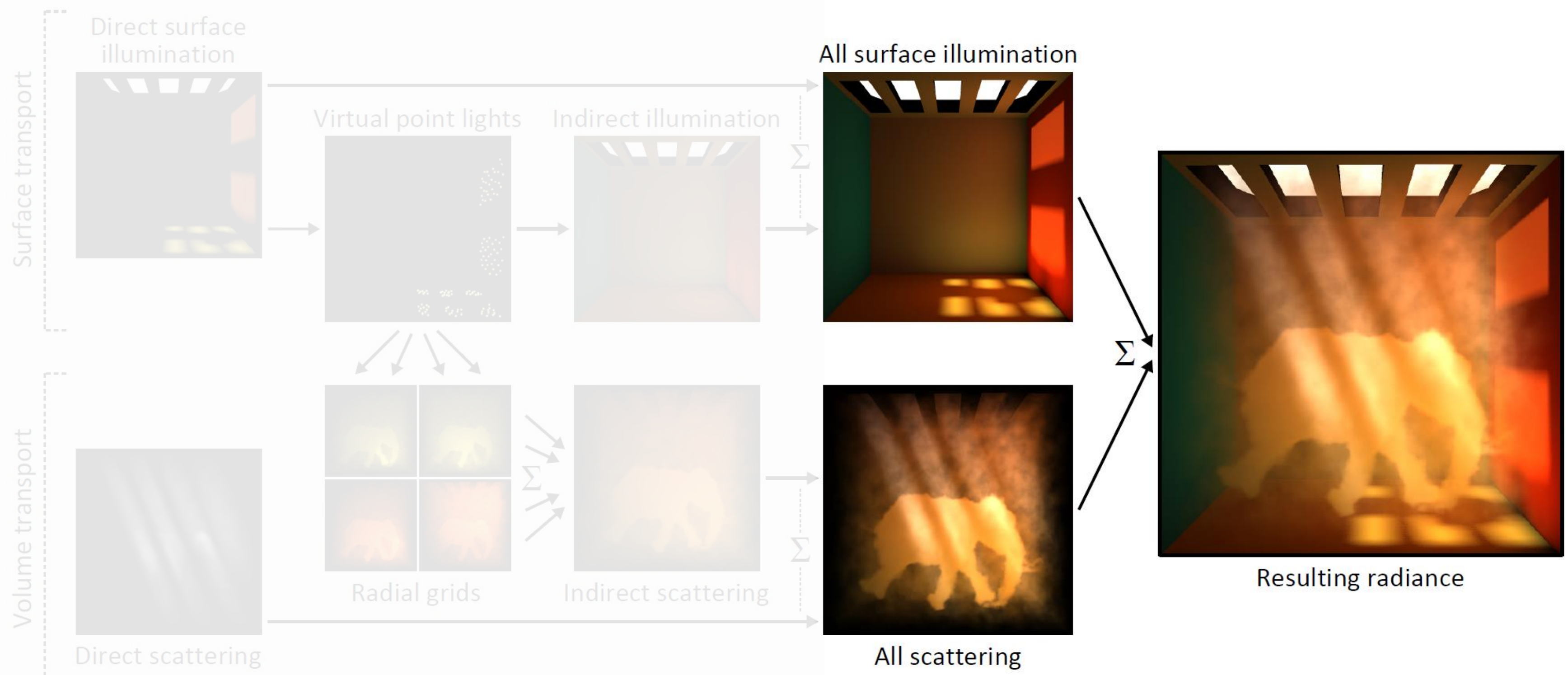

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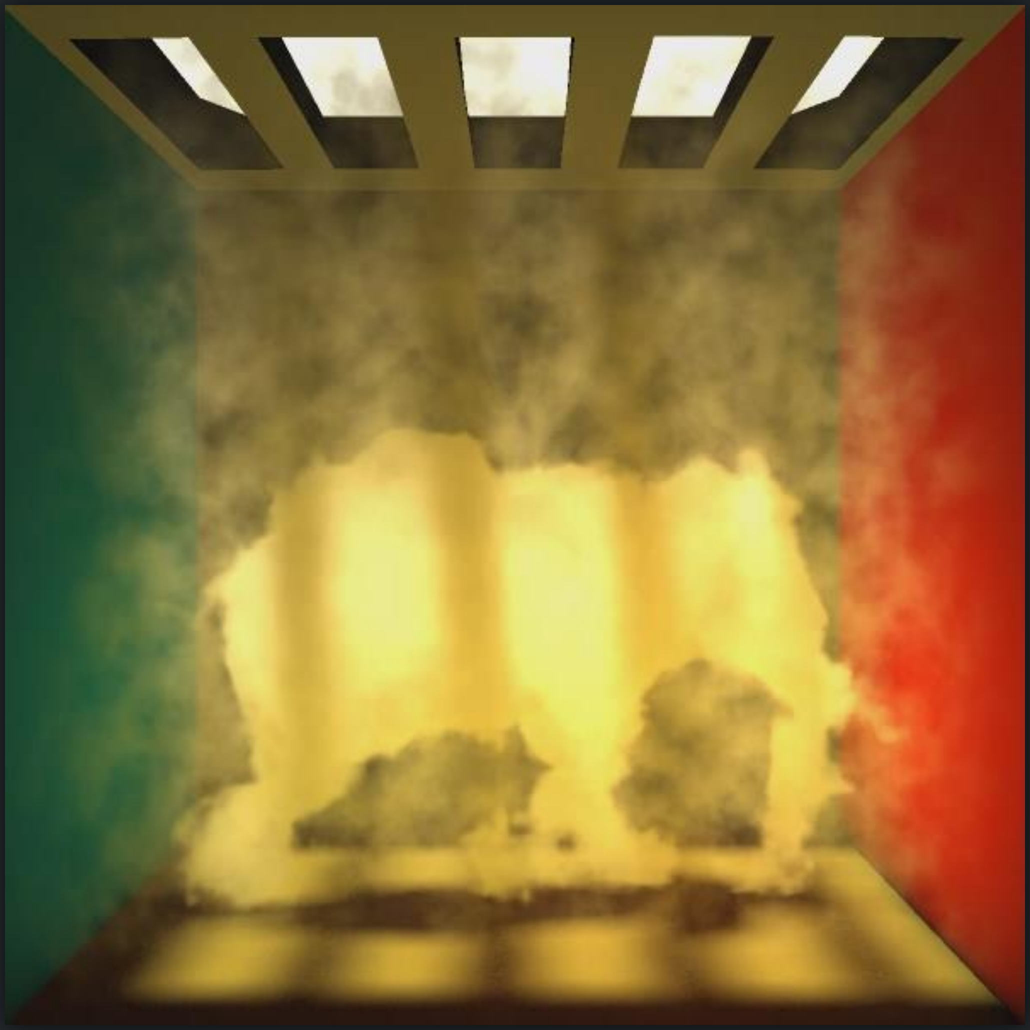


Rendered at 16Hz

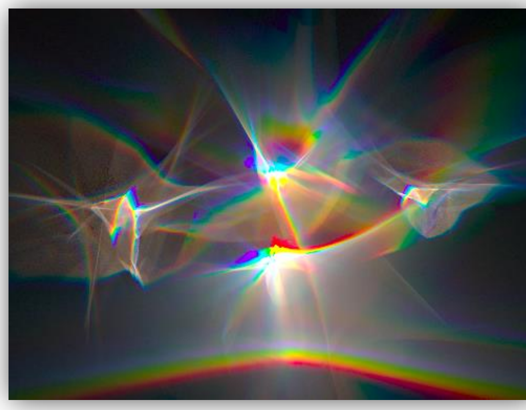
Results

Rendered at 25Hz

Results

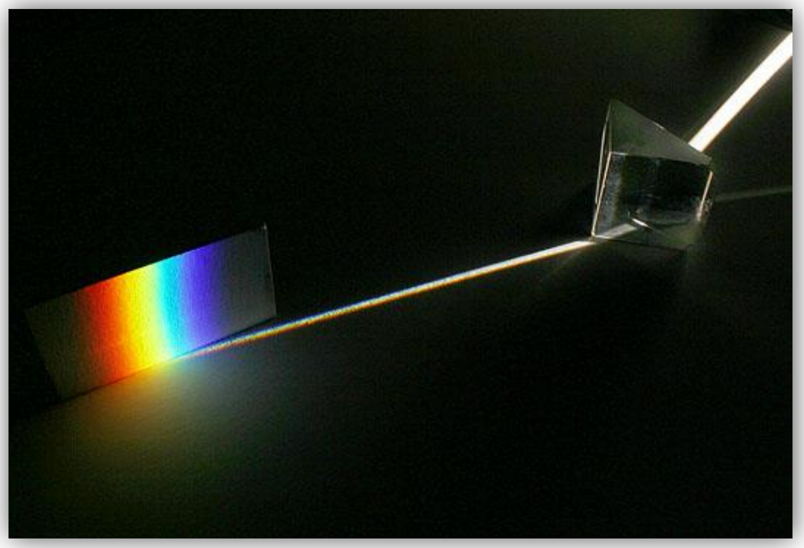
Principal-Ordinates Propagation

[Best Student Paper @ Graphics Interface 2014]
[Computers and Graphics 2014]

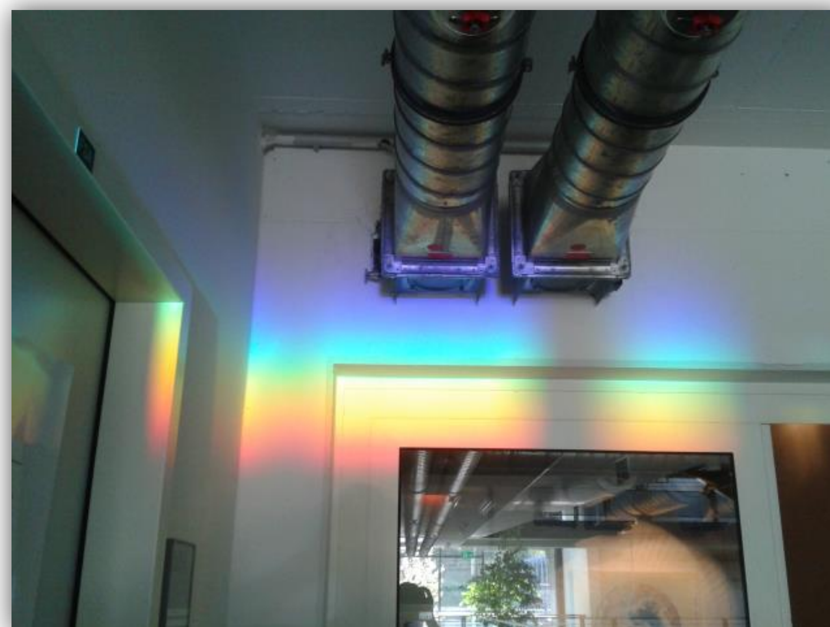


Spectral Ray Differentials

[Best Student Paper @ EG Rendering Symposium 2014]
[Vision, Modelling and Visualization 2014]

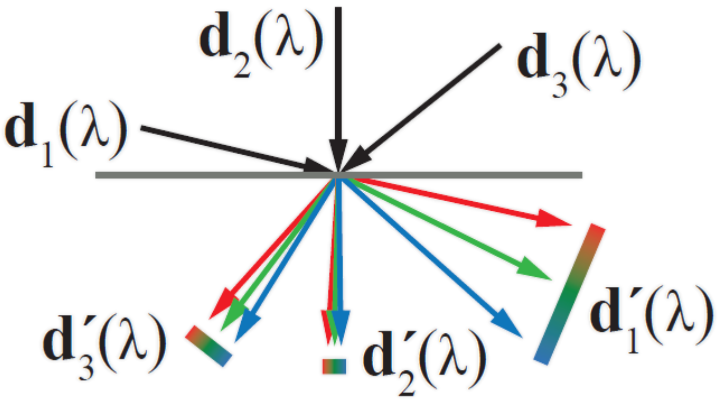


MOTIVATION: DISPERSION

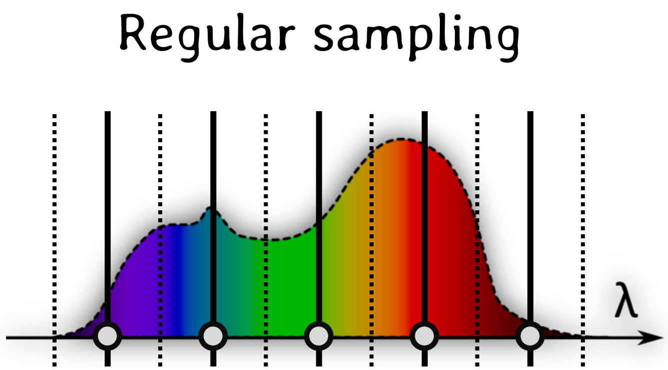


Motivation: Dispersion

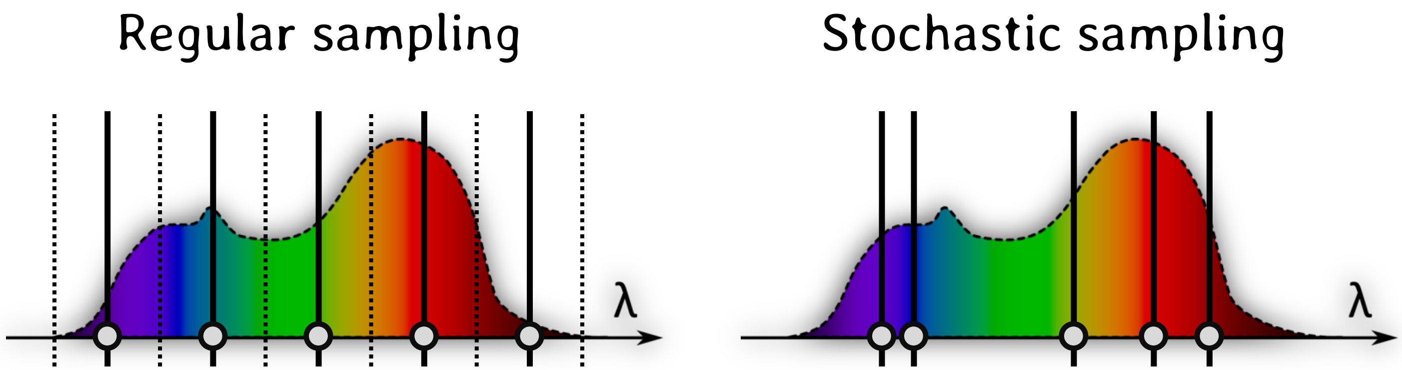
$$\frac{\sin\theta_1}{\sin\theta_2} = \frac{n_2}{n_1}$$



Snell's Law

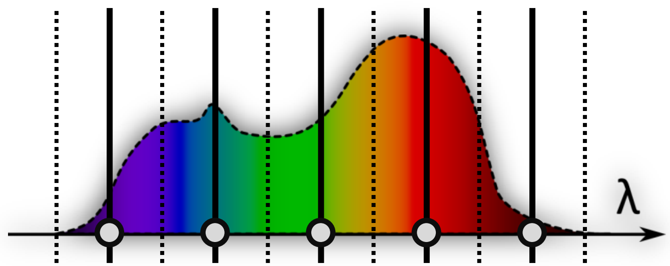


Spectral Rendering

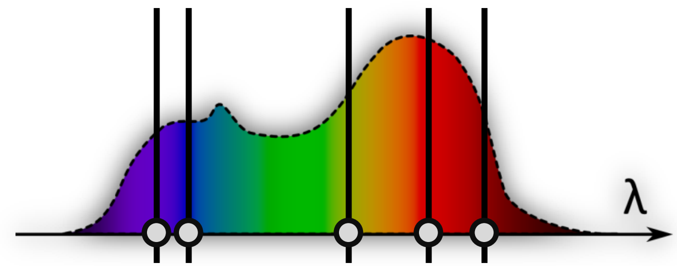


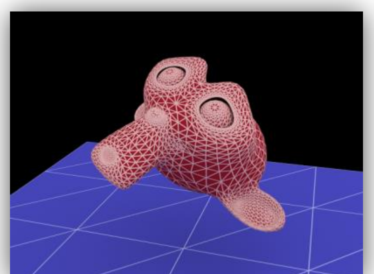
SPECTRAL RENDERING

Regular sampling

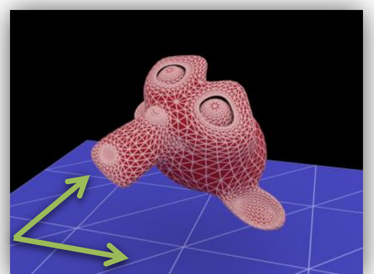


Stochastic sampling

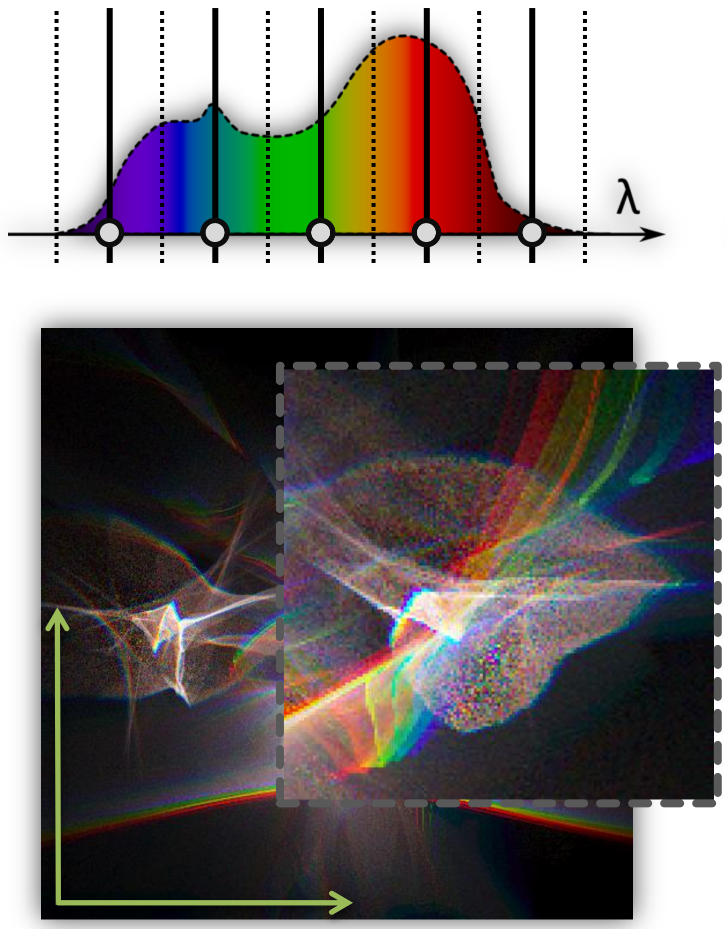




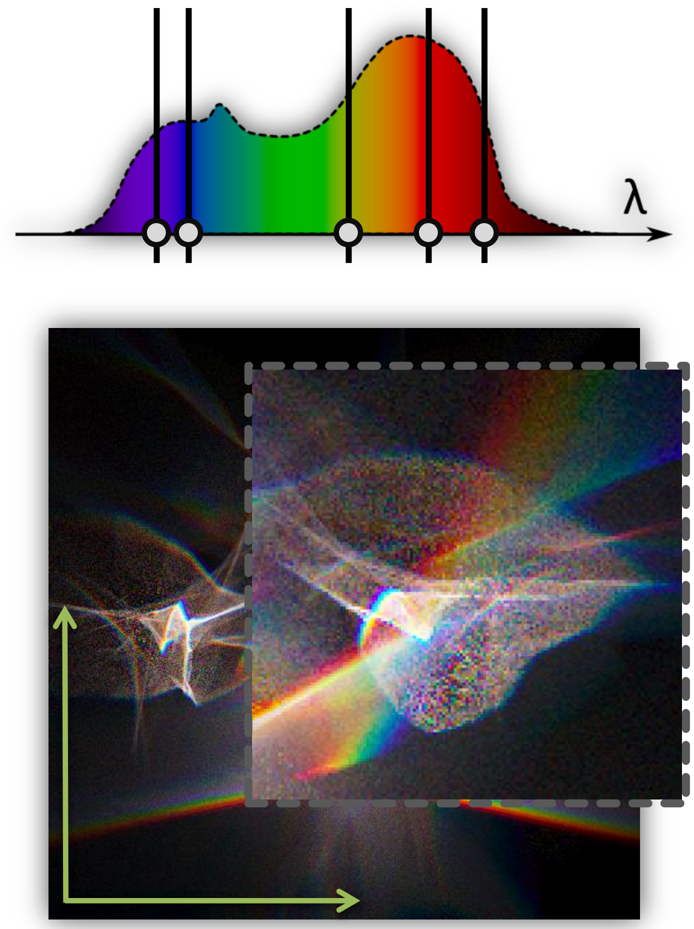
Spectral Rendering



Regular sampling



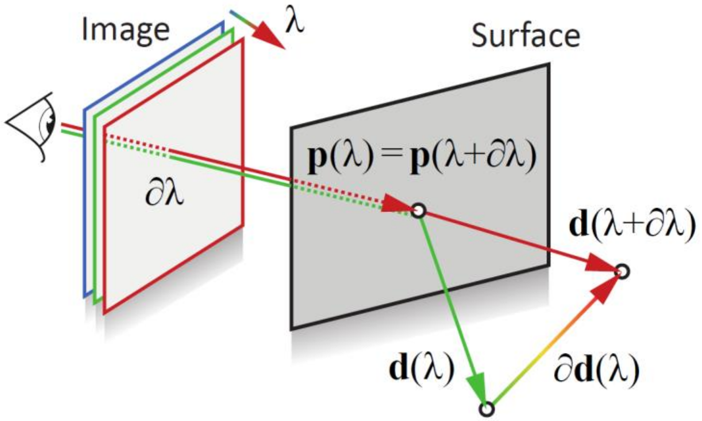
Stochastic sampling



Spectral Rendering

$$\mathbf{R}(\lambda) = (\mathbf{p}, \mathbf{d})$$

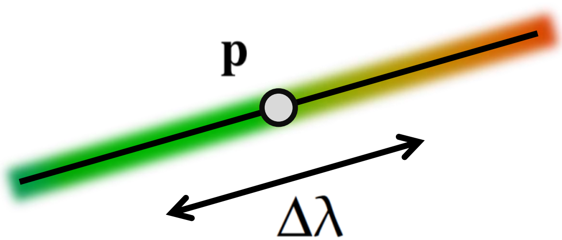
SRD: $\left(\frac{\partial \mathbf{p}}{\partial \lambda}, \frac{\partial \mathbf{d}}{\partial \lambda} \right)$

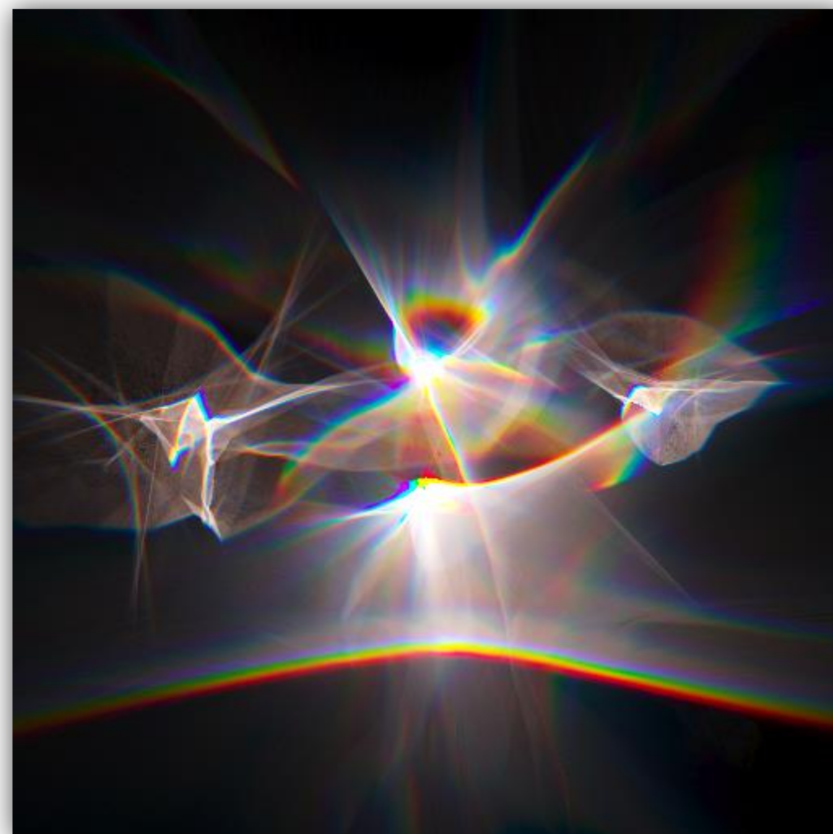


Spectral Ray Differential

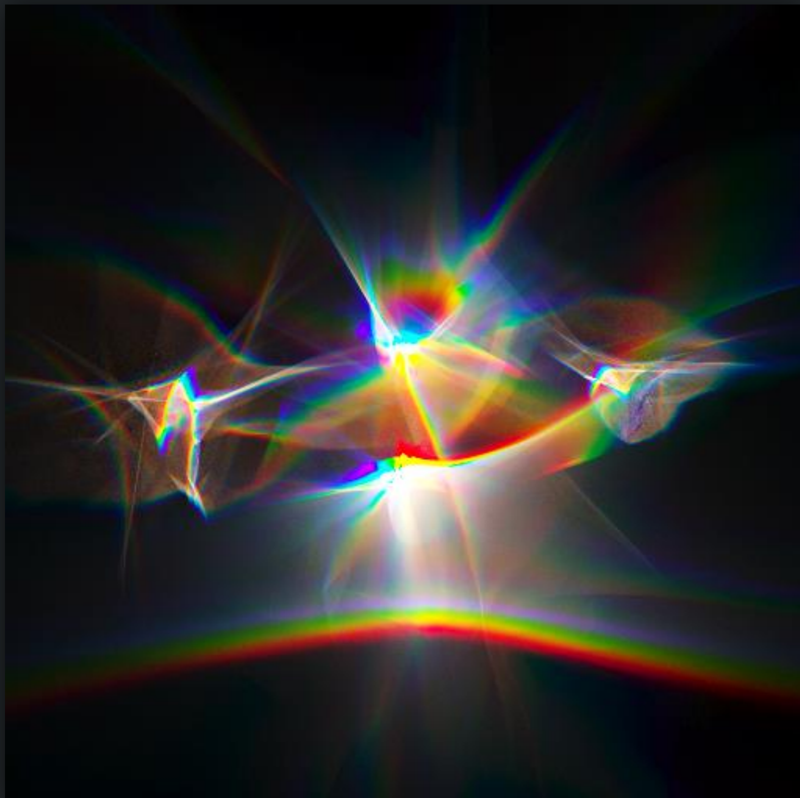
$$\mathbf{R}(\lambda) = (\mathbf{p}, \mathbf{d})$$

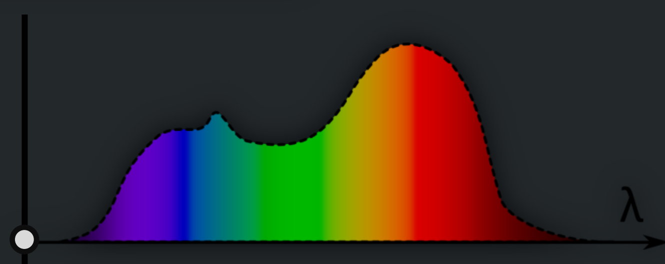
SRD: $$\left(\frac{\partial \mathbf{p}}{\partial \lambda}, \frac{\partial \mathbf{d}}{\partial \lambda} \right)$$





Spectral Ray Differential

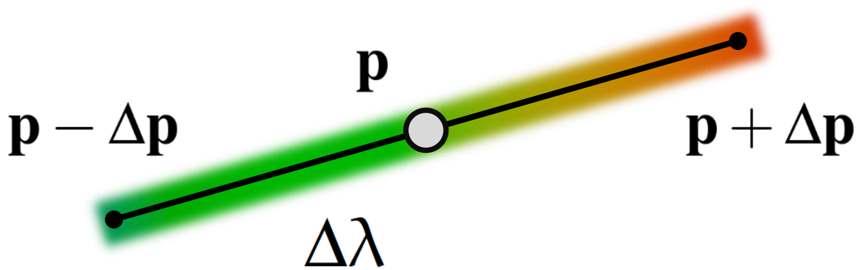




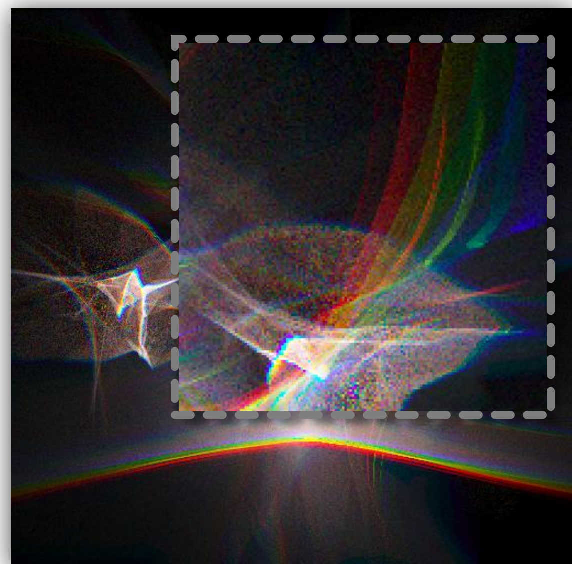
Spectral Ray Differential

First-order approximation:

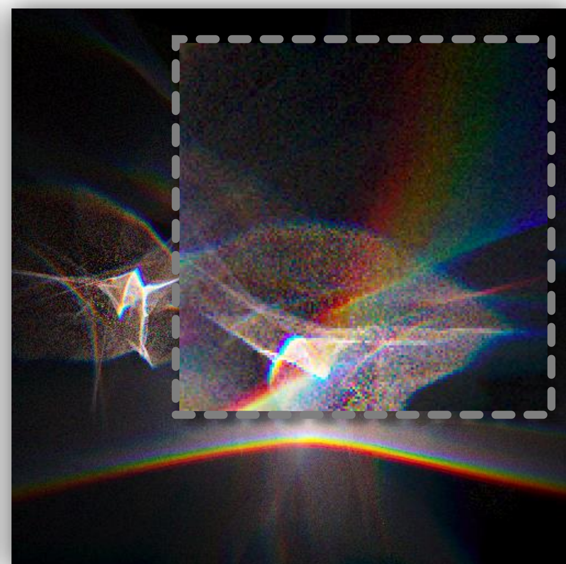
$$\mathbf{R}(\lambda + \Delta\lambda) - \mathbf{R}(\lambda) \approx \Delta\lambda \frac{\partial \mathbf{R}(\lambda)}{\partial \lambda}$$



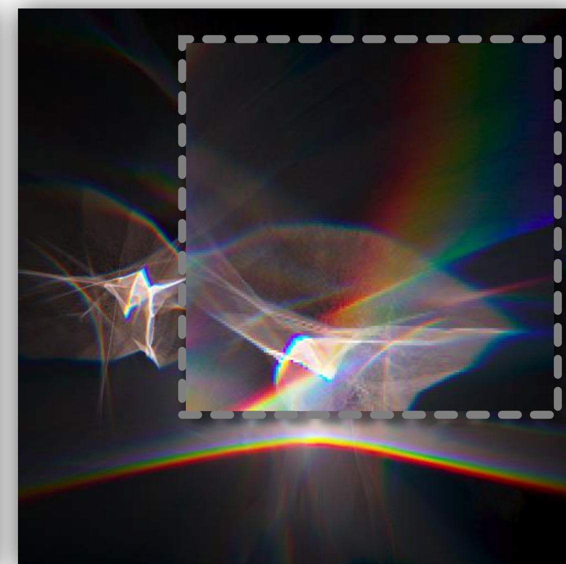
Reconstruction



Regular sampling

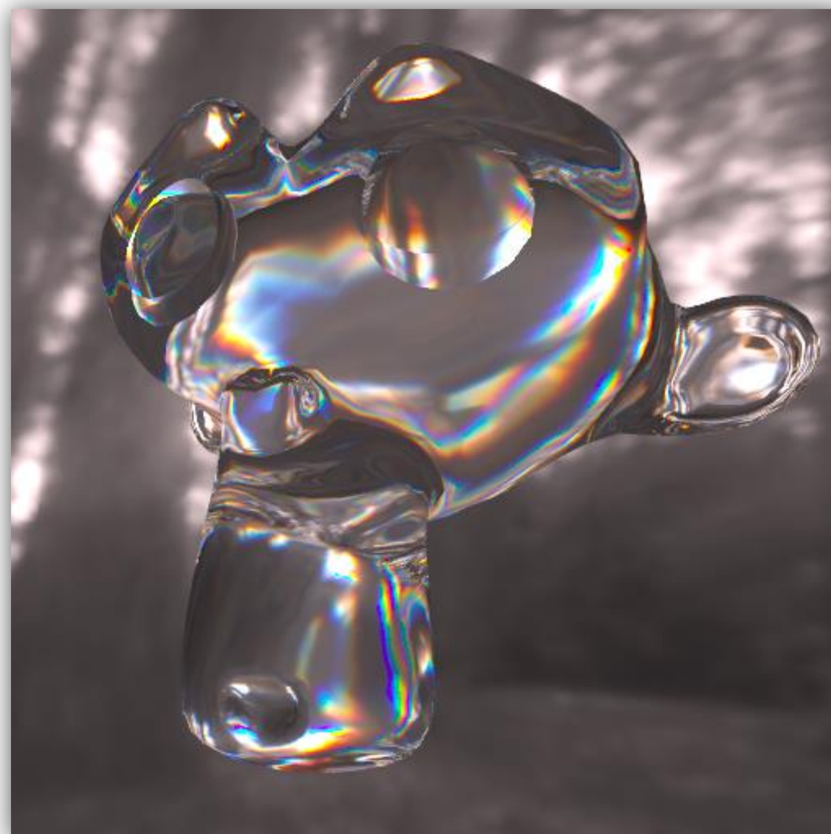


Stochastic sampling



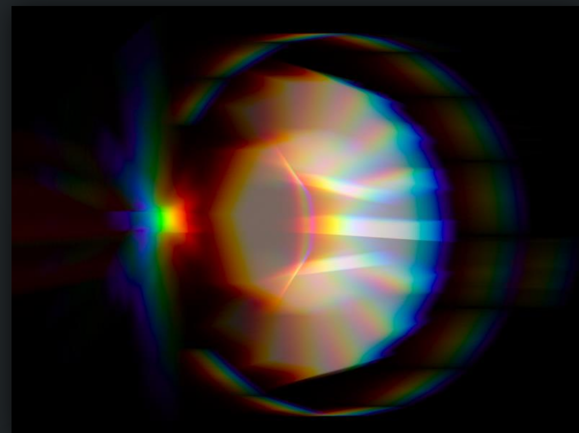
SRD

Results: Light Tracing

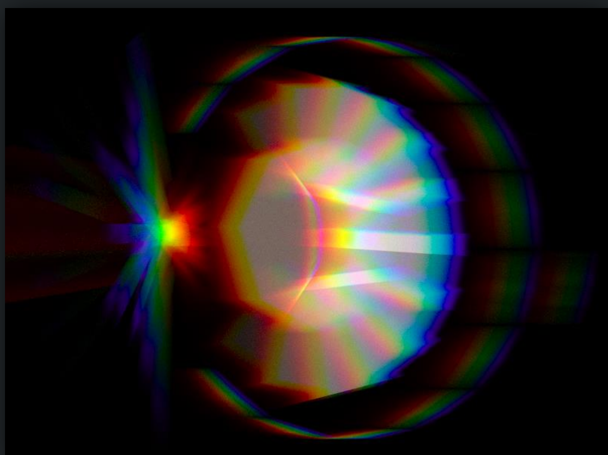


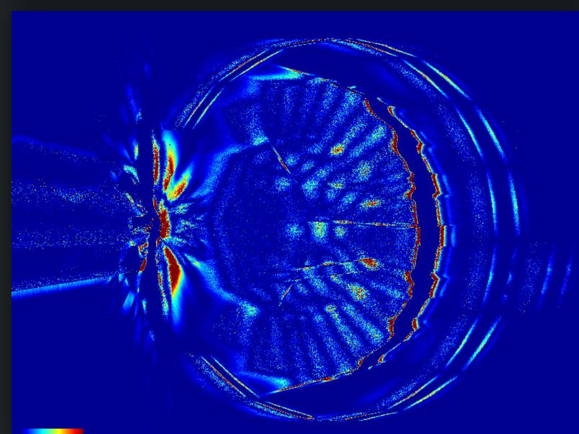
Results: Path Tracing

SRD (2k iterations)



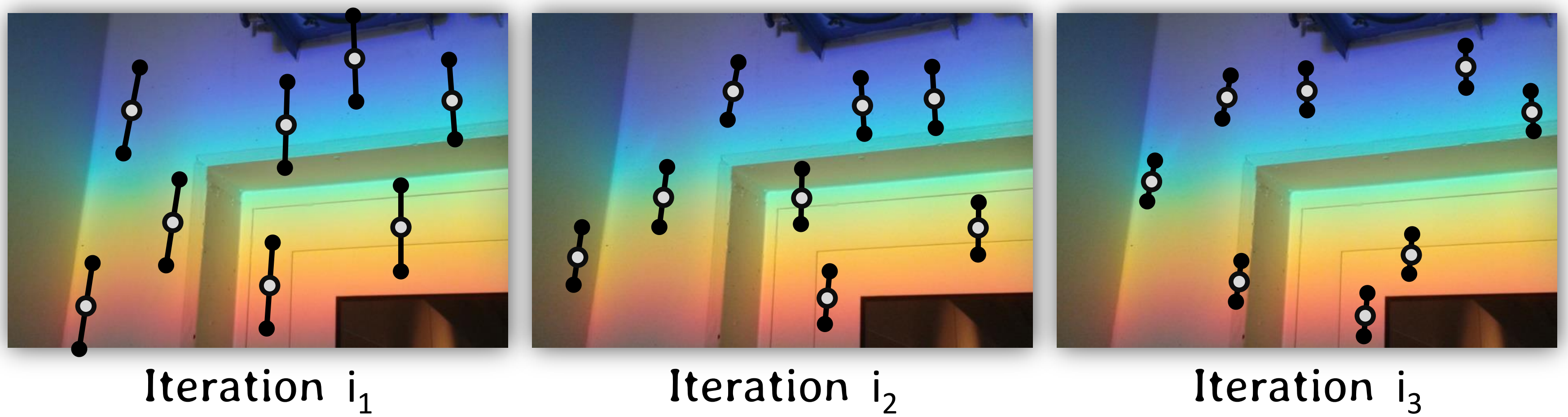
Reference (20k iterations)





Diff.

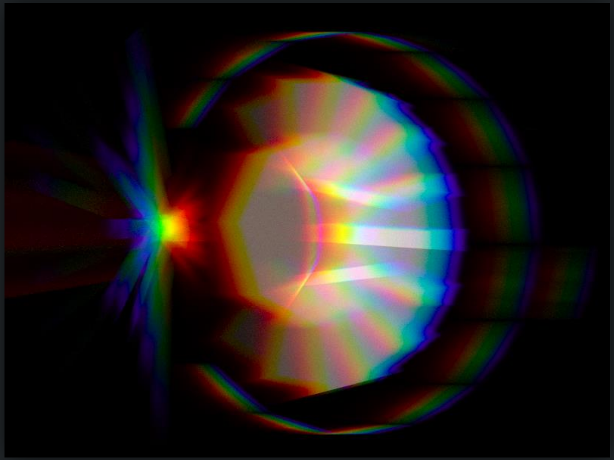
Bias of SRD



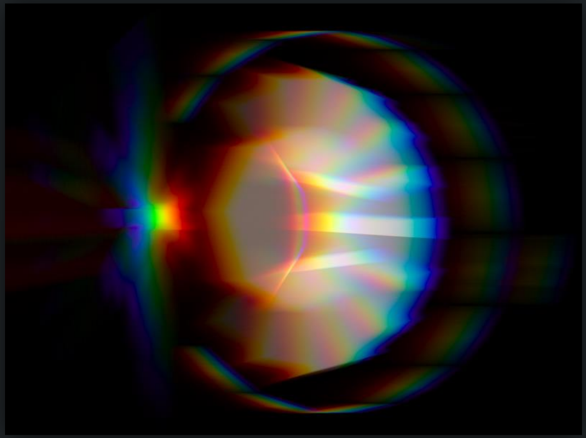
Progressive SRD

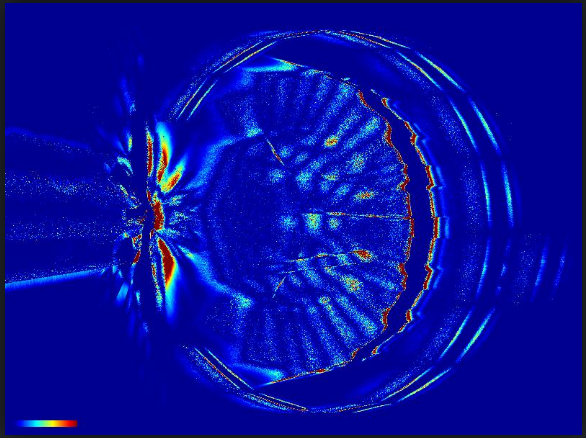
Progressive SRD

Reference (20k iterations)



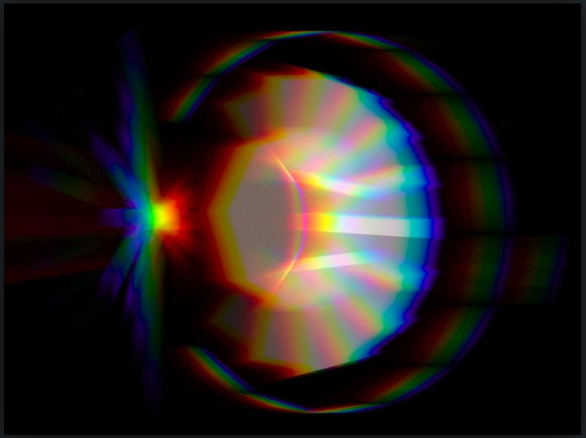
SRD (2k iterations)

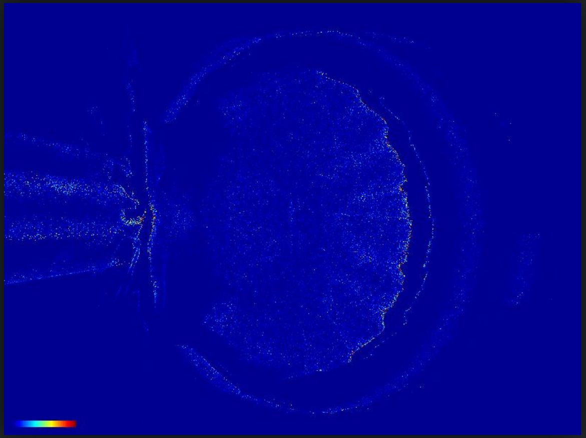




Diff.

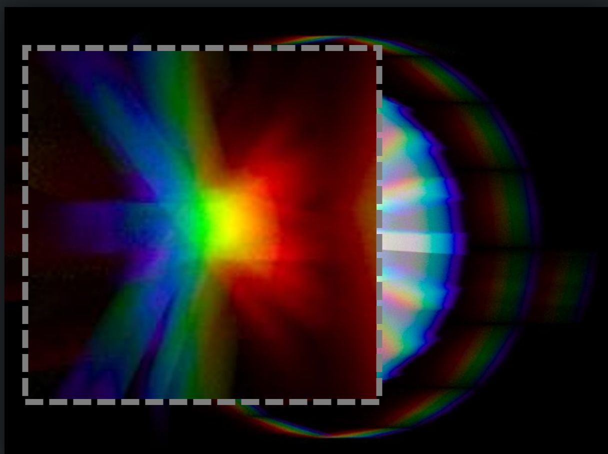
PSRD (2k iterations)



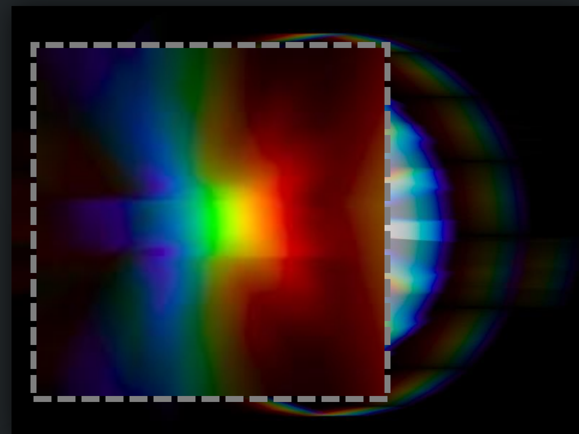


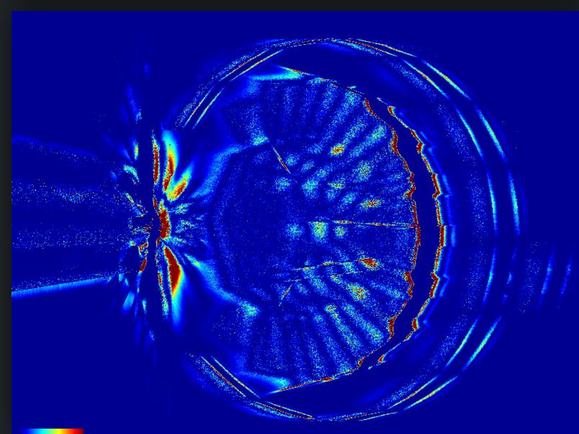
Diff.

Reference (20k iterations)



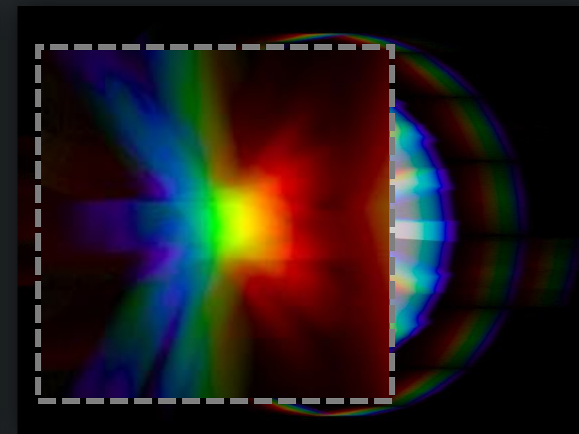
SRD (2k iterations)

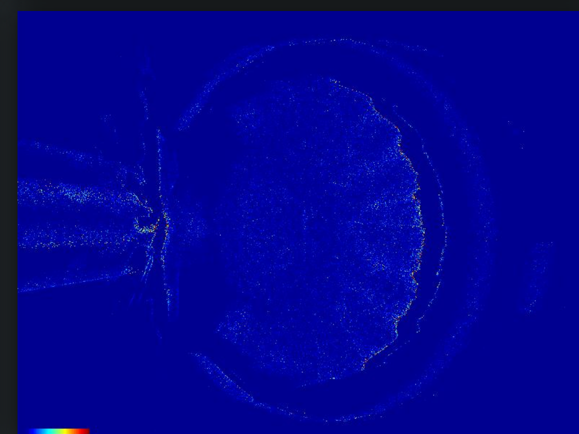




Diff.

PSRD (2k iterations)



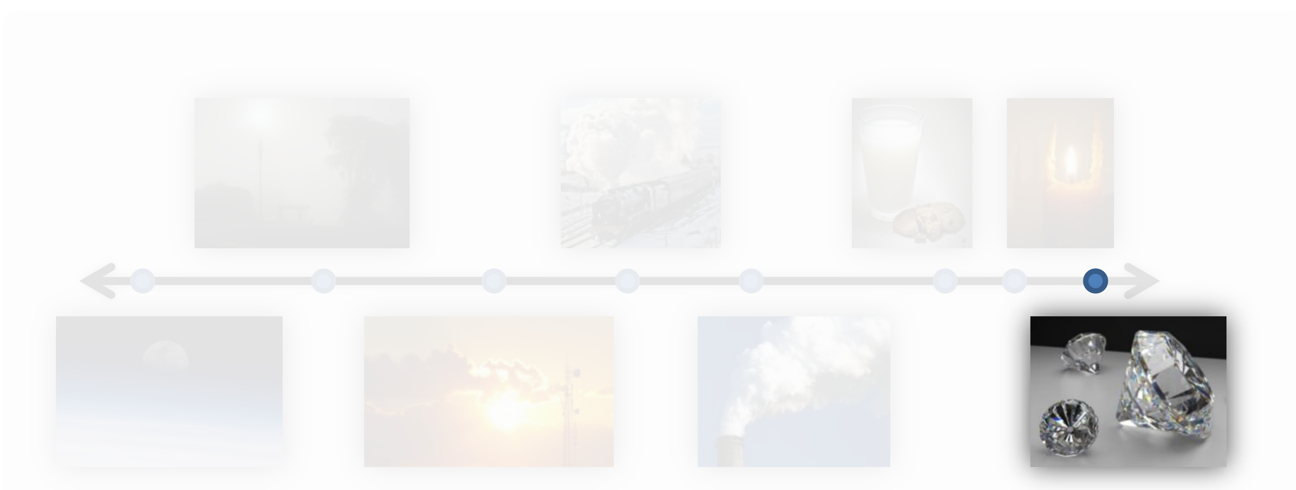


Diff.

Progressive SRD

Spectral Ray Differentials

[Best Student Paper @ EG Rendering Symposium 2014]
[Vision, Modelling and Visualization 2014]



Real-Time Cloud Rendering

Screen-Space Scattering

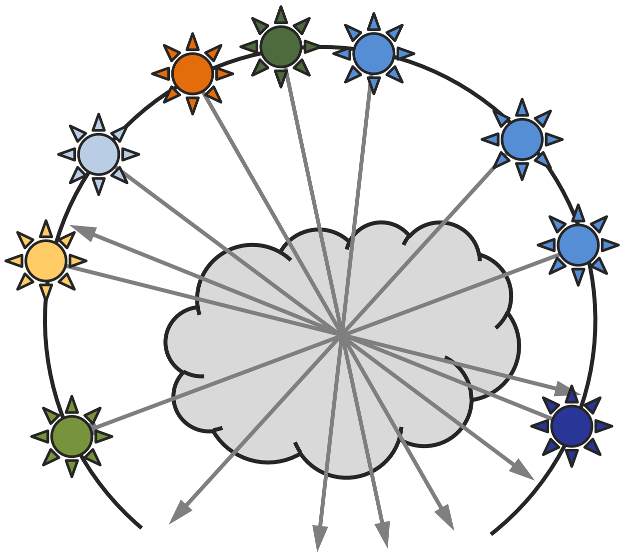
Principal-Ordinates Propagation

Spectral Ray Differentials

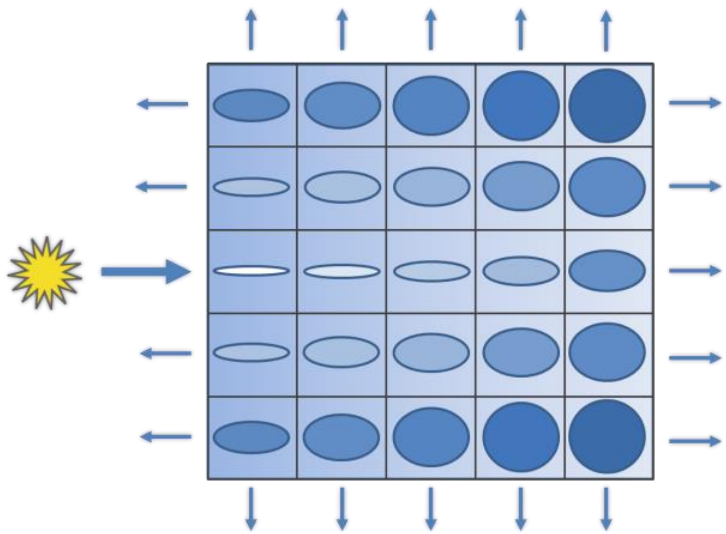
JUSTIFICATION

Principal-Ordinates Propagation

[Best Student Paper @ Graphics Interface 2014]
[Computers and Graphics 2014]

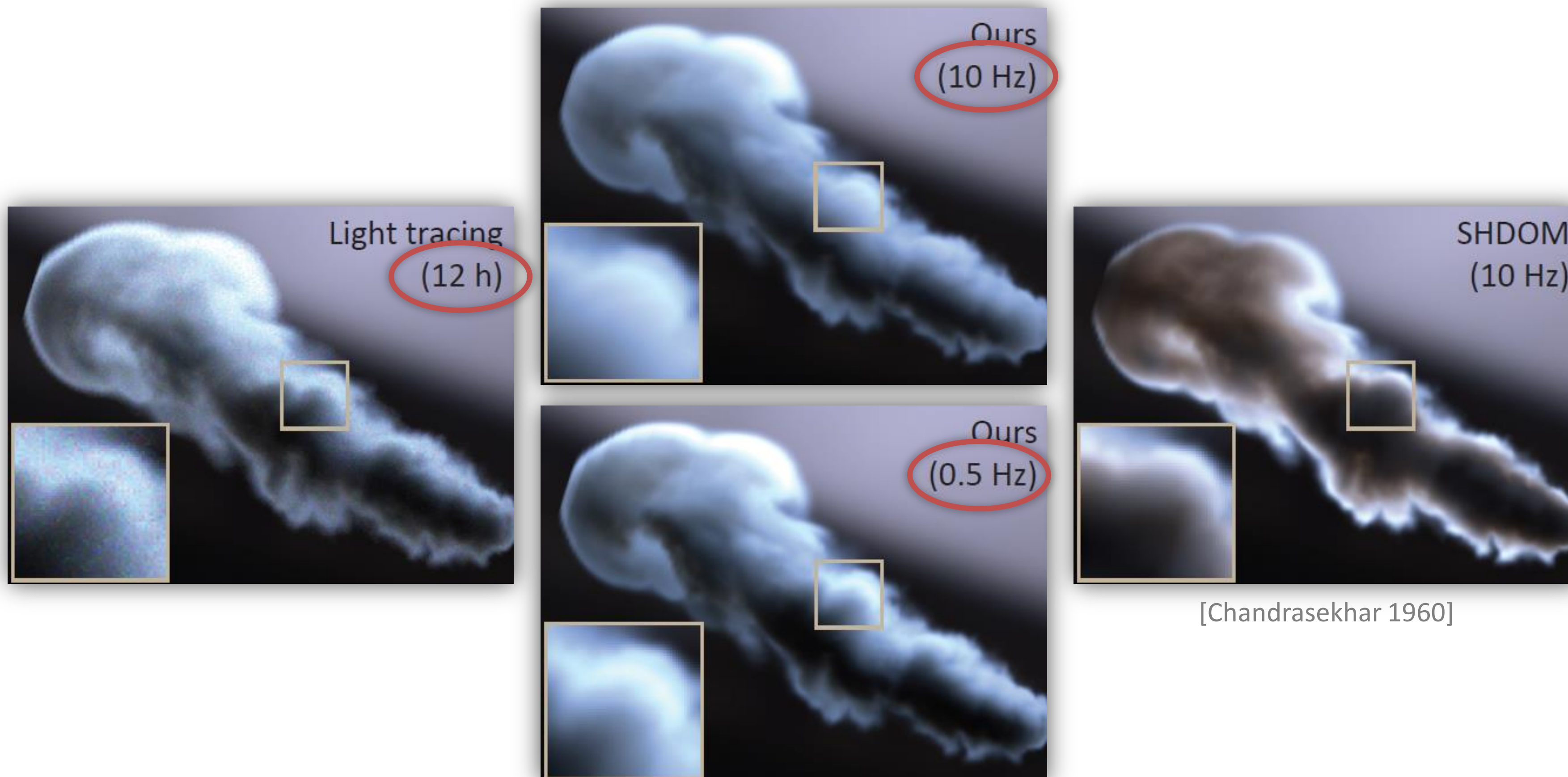


Separation of illumination into principal ordinates



Per-ordinate GPU-friendly anisotropic propagation scheme

CONTRIBUTIONS



[Chandrasekhar 1960]

EVALUATION

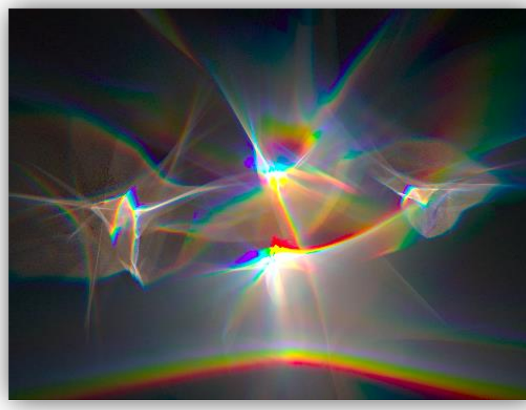
Light propagation volumes

[Billeter etal. @ I3D 2012]

Flux-limited diffusion

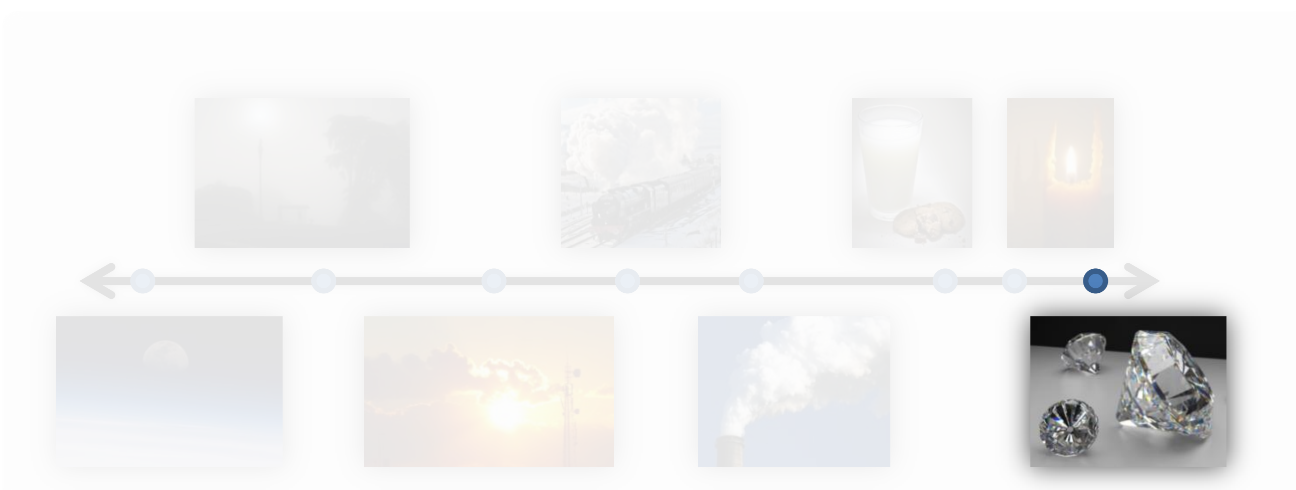
[Koerner etal. @ CGF 2014]

Relations



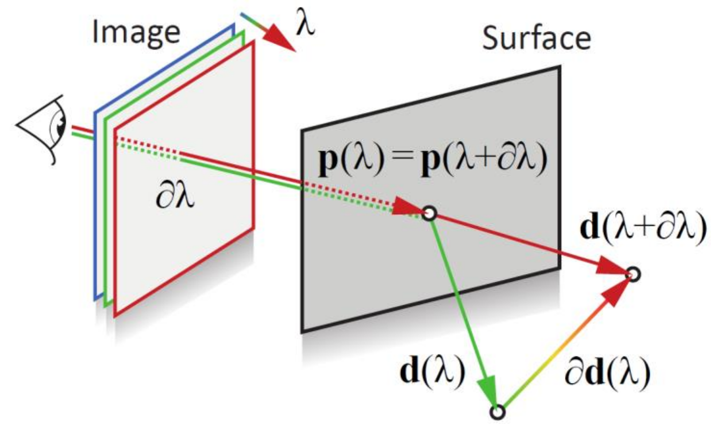
Spectral Ray Differentials

[Best Student Paper @ EG Rendering Symposium 2014]
[Vision, Modelling and Visualization 2014]



$$\frac{\partial \mathbf{R}}{\partial \lambda} = \left(\frac{\partial \mathbf{p}}{\partial \lambda}, \frac{\partial \mathbf{d}}{\partial \lambda} \right)$$

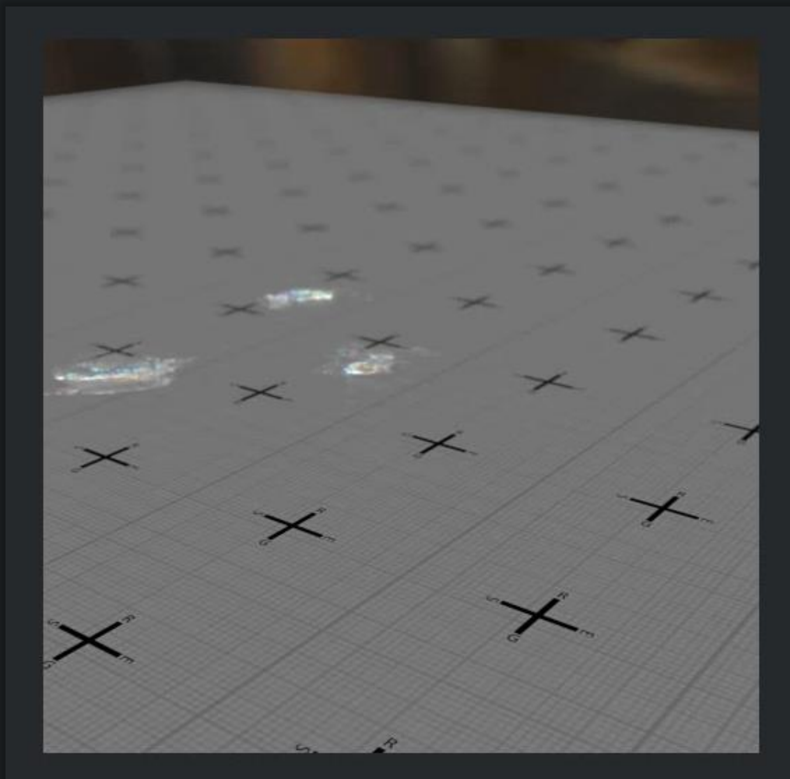
```
vec3 ∂n = normalDifferential(∂p);
float θ = dot(d,n);
float ω = sqrt(1 − sqr(η) + sqr(η)∗sqr(θ));
float μ = η∗θ + ω;
float ∂η = etaDifferential(η);
float ∂ι = dot(∂d,n) + dot(d,∂n);
float ∂O = (−η∗∂η + η∗∂η∗sqr(θ) + sqr(η)∗θ∗∂ι)/ω;
float ∂μ = ∂η∗θ + η∗∂ι + ∂O;
return ∂η∗d + η∗∂d − ∂μ∗n − μ∗∂n;
```



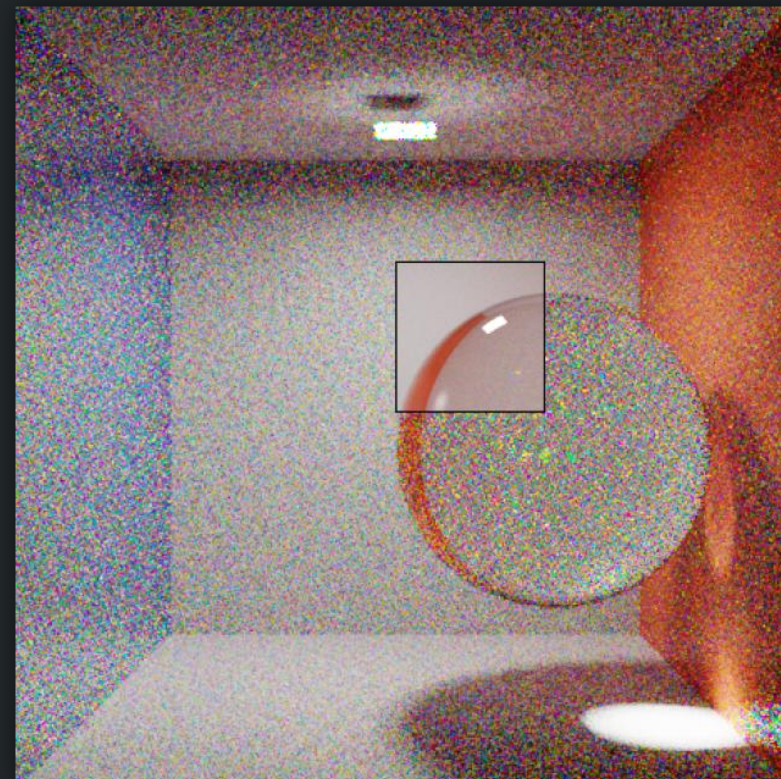
Derivation & reconstruction of ray differentiation after dispersion

Progressive formulation to achieve consistent solution

CONTRIBUTIONS



Interactive dispersion



Hero-wavelength sampling

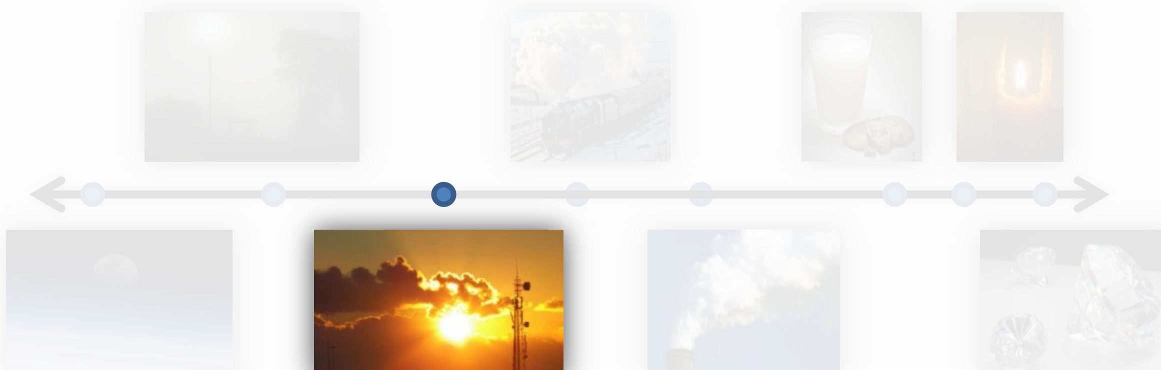
[Wilkie etal. @ EGSR 2014]

EVALUATION

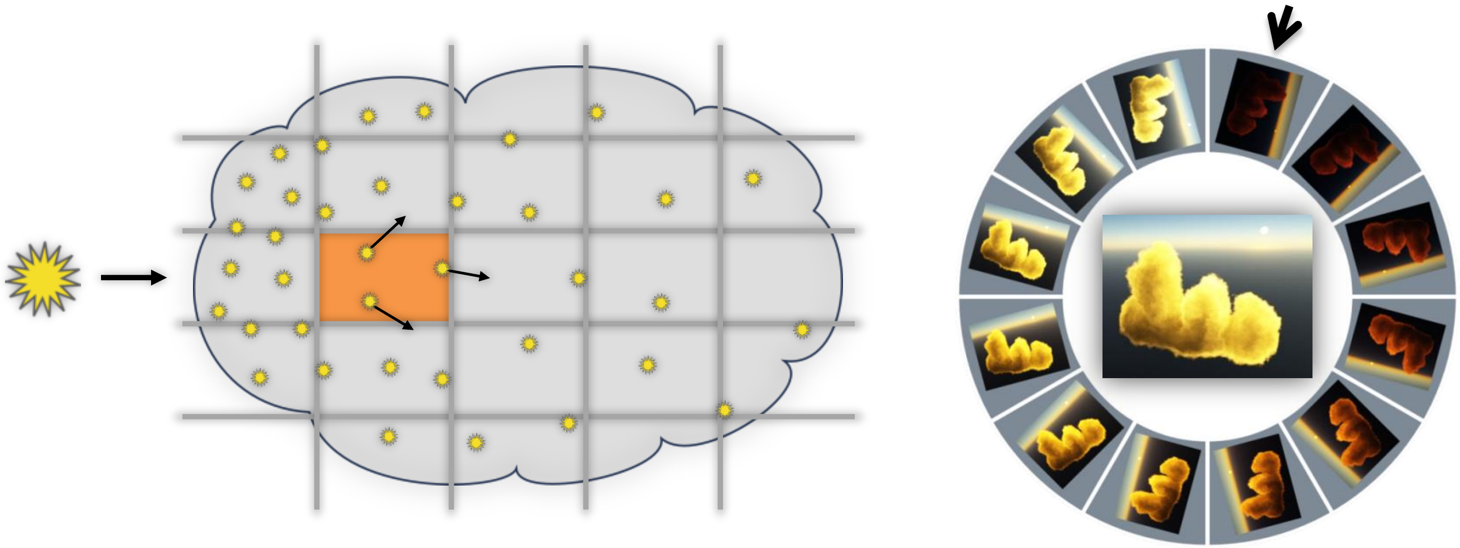
Real-Time Cloud Rendering

[Graphics Interface 2012]

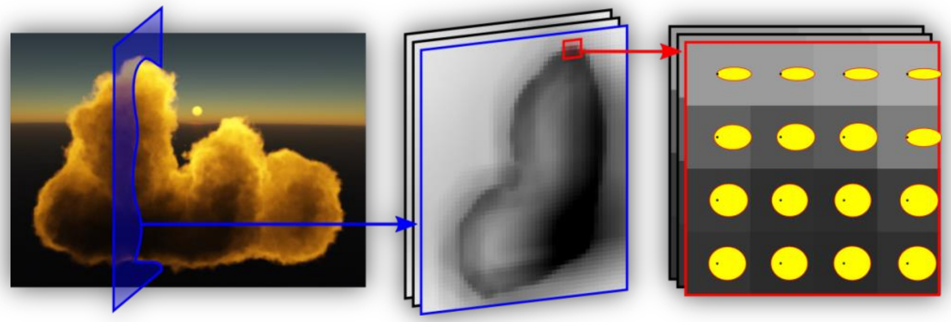
[Computers and Graphics 2012]



Motivation: Clouds

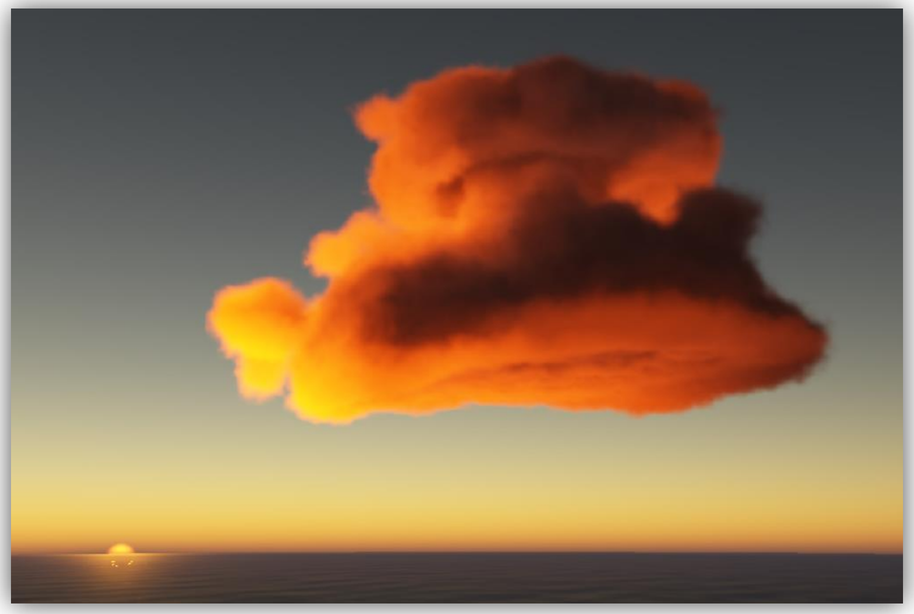


Amortized photon mapping with binning

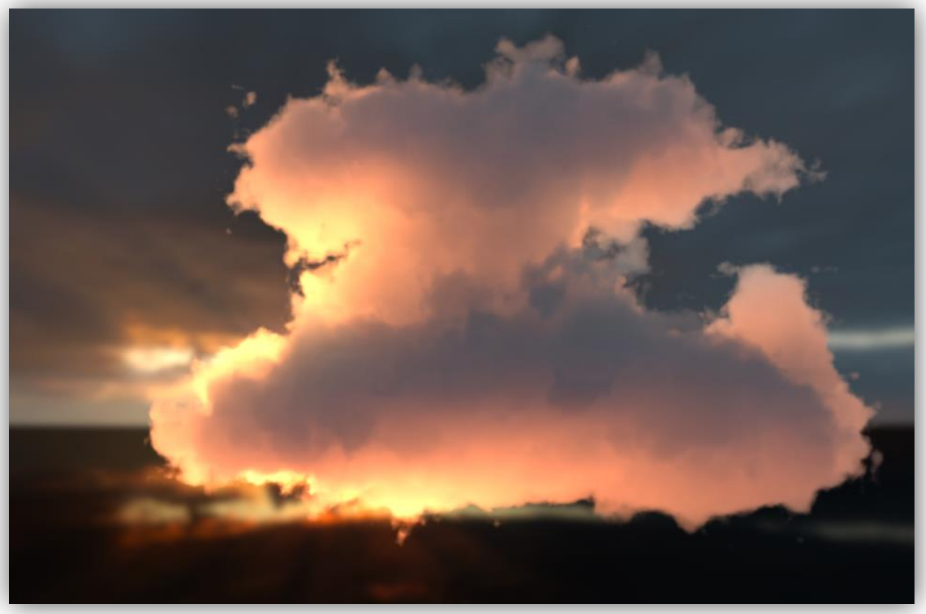


Fitted, analytic unimodal representation of cached light

CONTRIBUTIONS

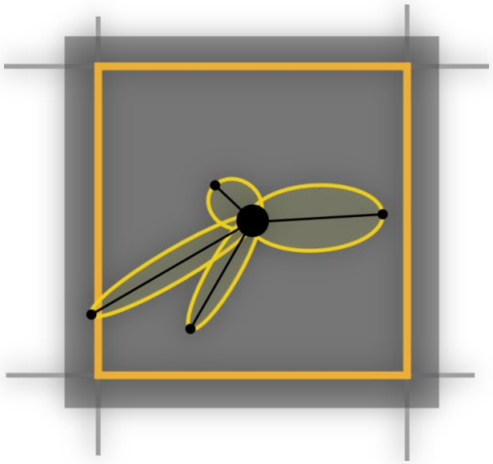


Ours (~100's Hz)

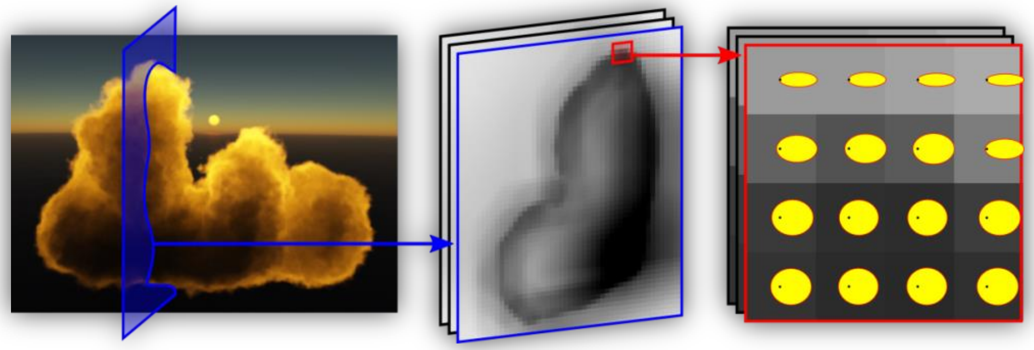


Principal-ordinates propagation (35 Hz)

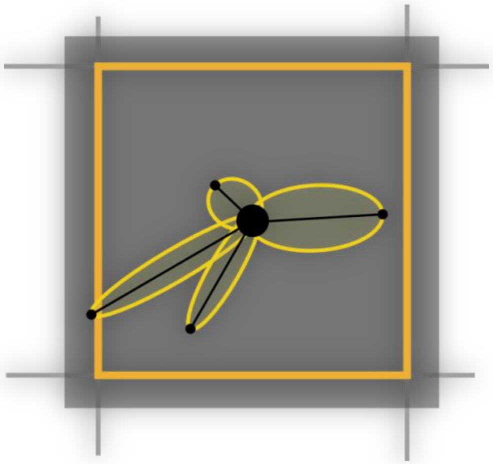
EVALUATION



Fitting of mixture models for volumetric path guiding



EVALUATION



Fitting of mixture models for volumetric path guiding

[Vorba etal. @ SIGGRAPH 2014]

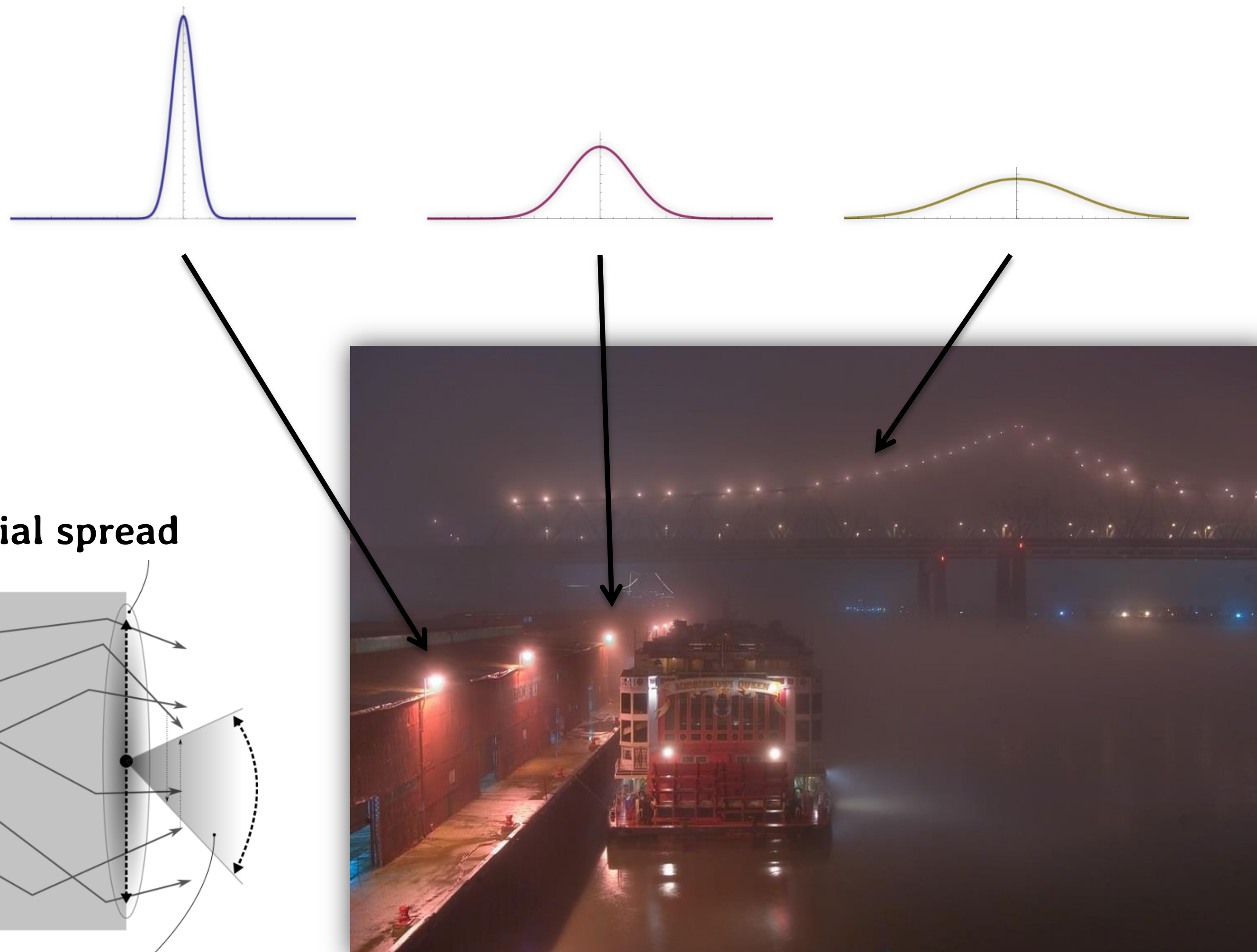
Evaluation

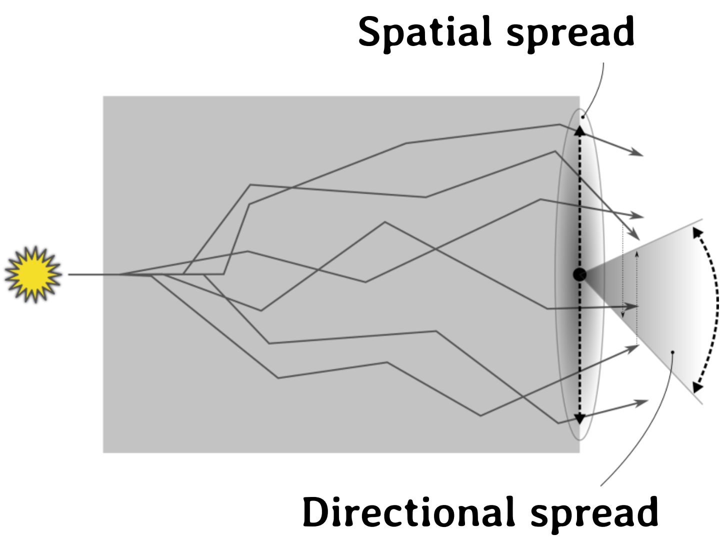
Screen-Space Scattering

[IEEE Computer Graphics & Applications 2012 – Special issue: Scattering]

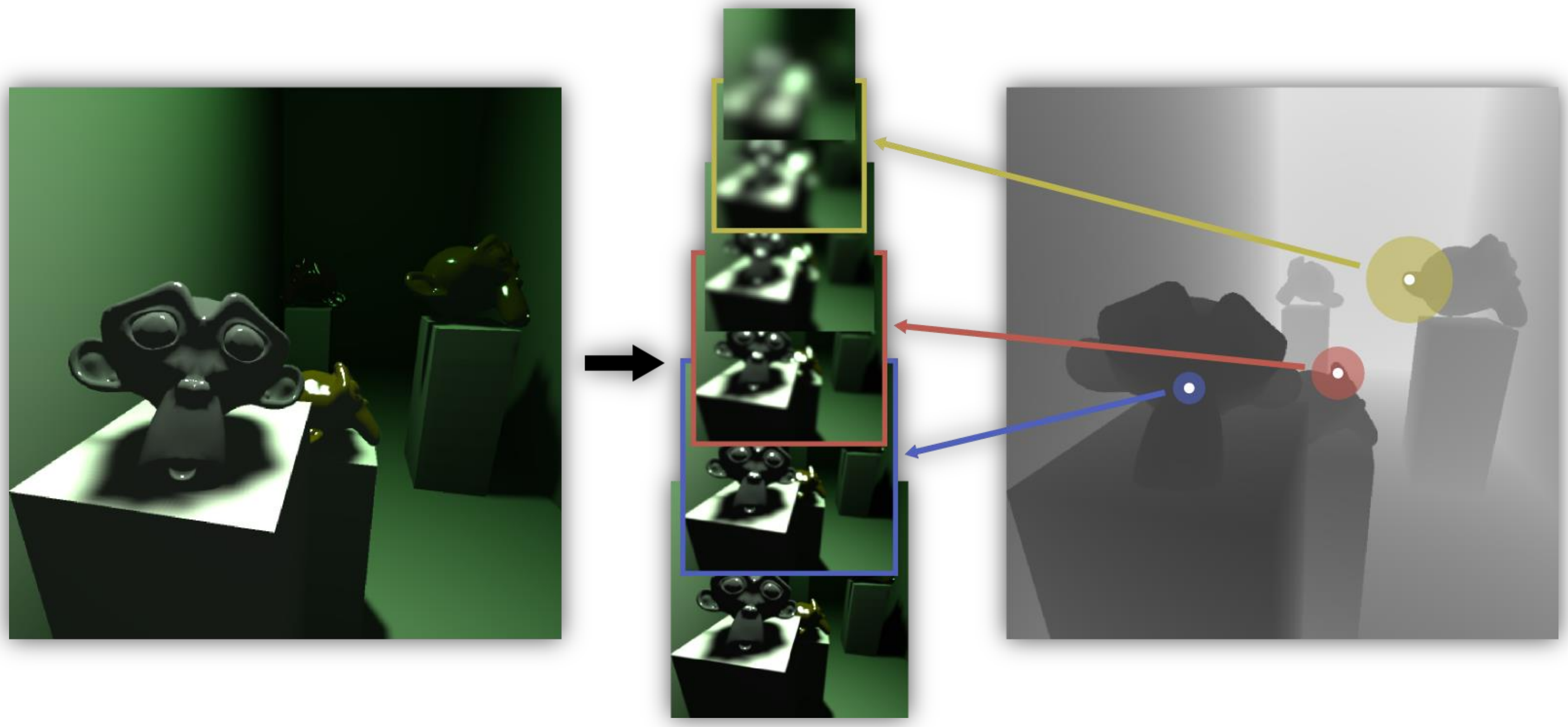
 

Motivation: Homogeneous Media





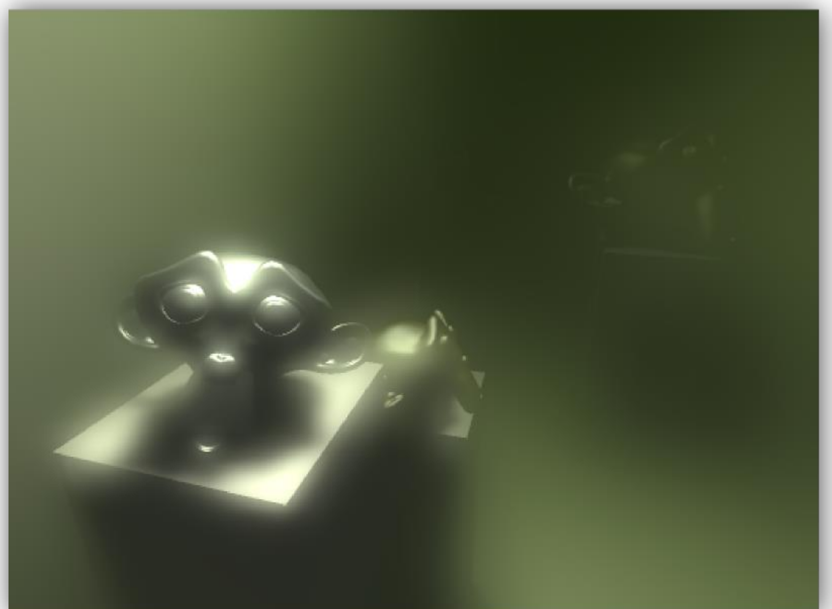
APPROACH



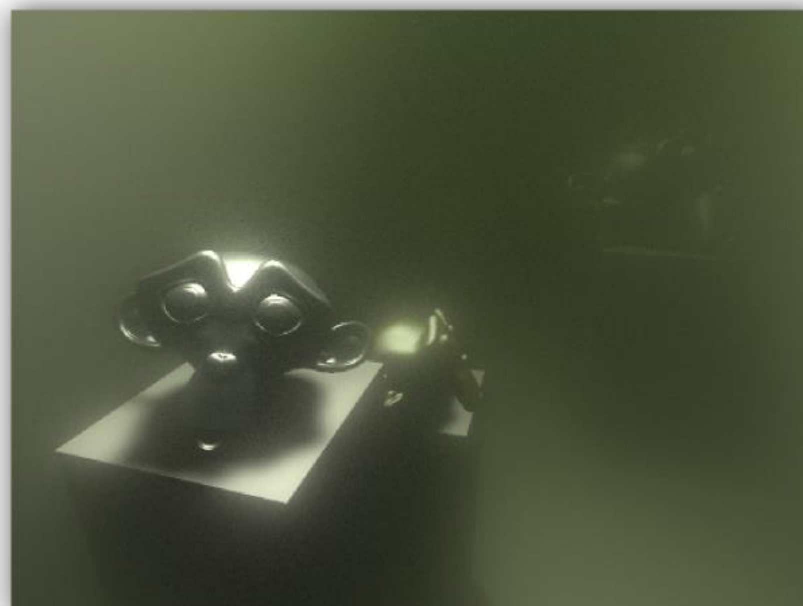
Fast GPU-friendly pyramidal filtering, based on image-space depth

CONTRIBUTIONS

Ours (2 ms)



Path Tracing (10 h)

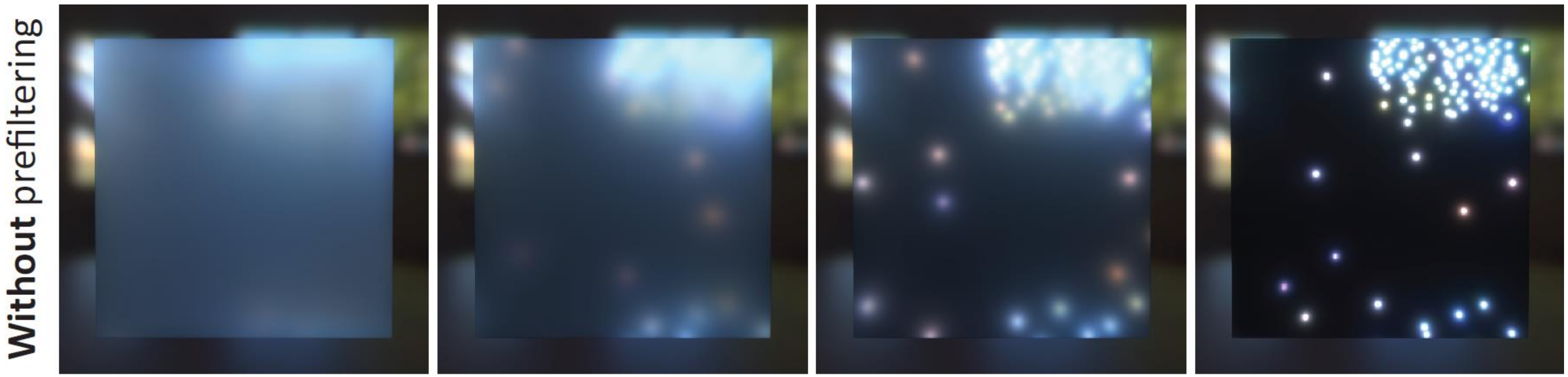


EVALUATION

physics + intuition = good

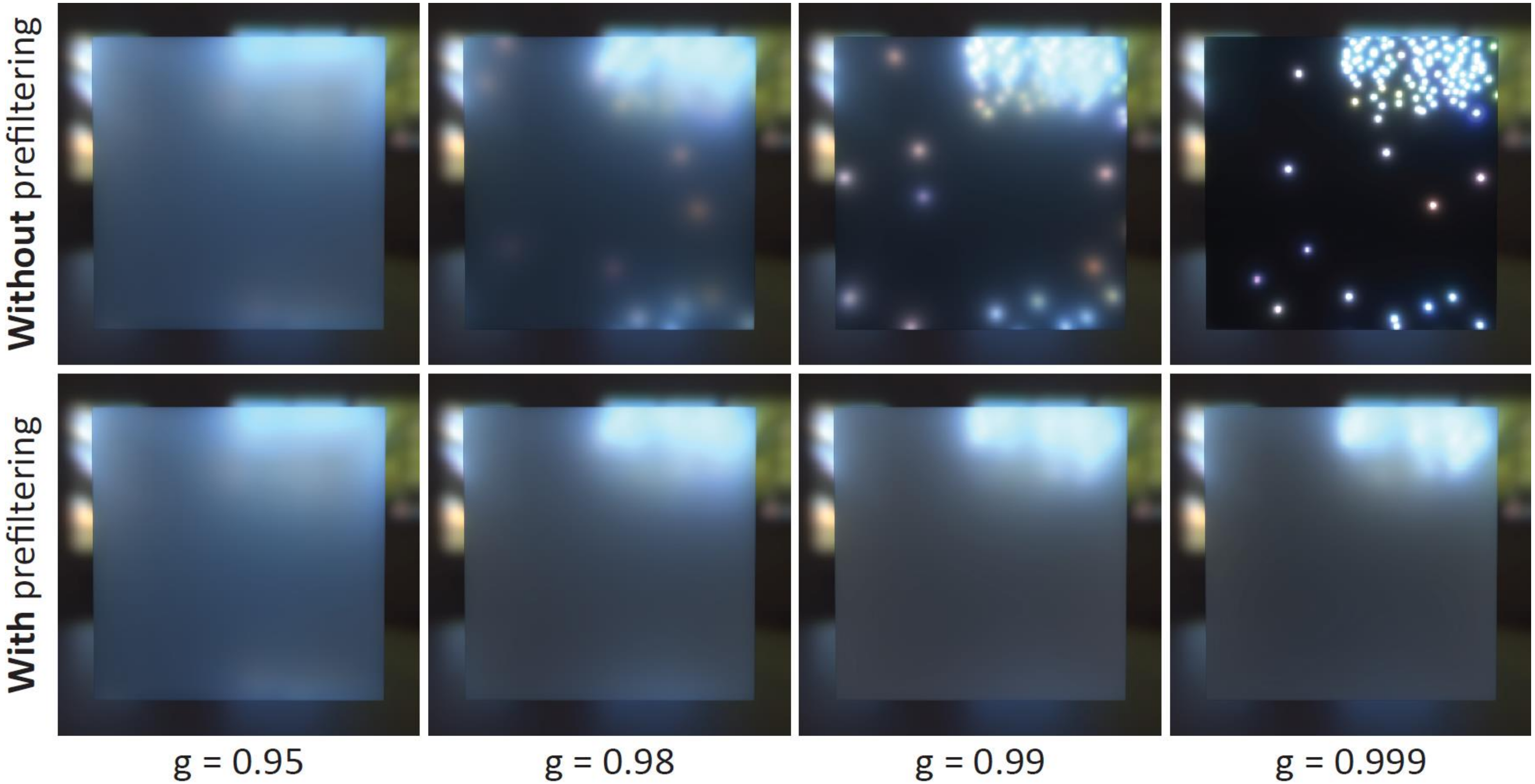
Conclusion

Additional Slides

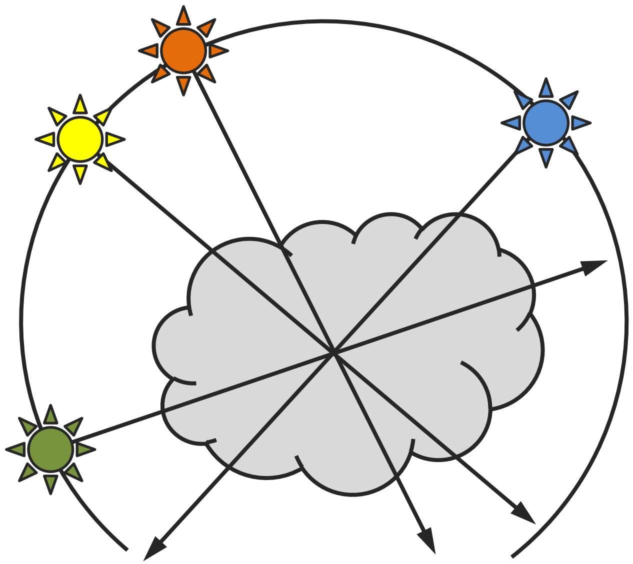


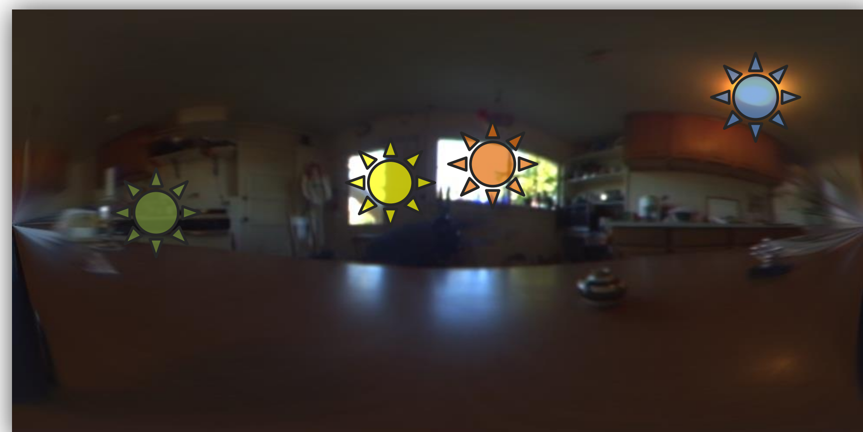
g = 0.95 g = 0.98 g = 0.99 g = 0.999

POP: Pre-filtering

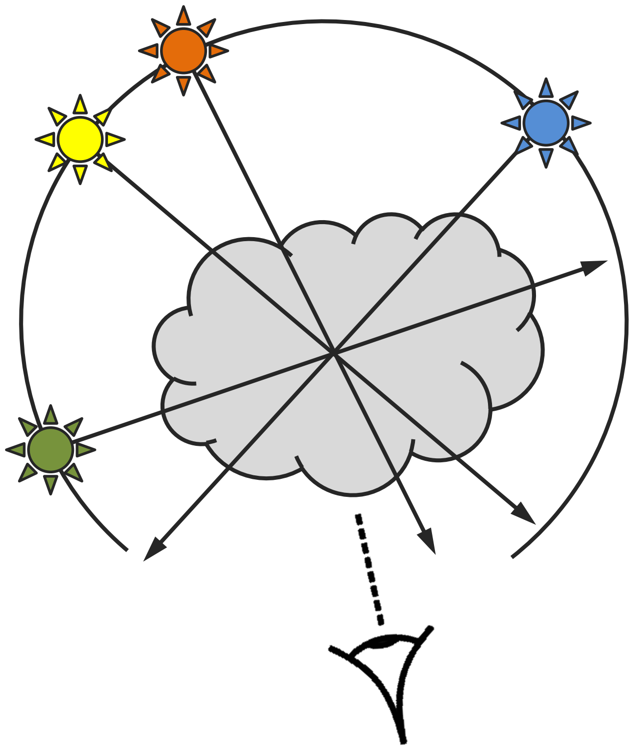


POP: Pre-filtering



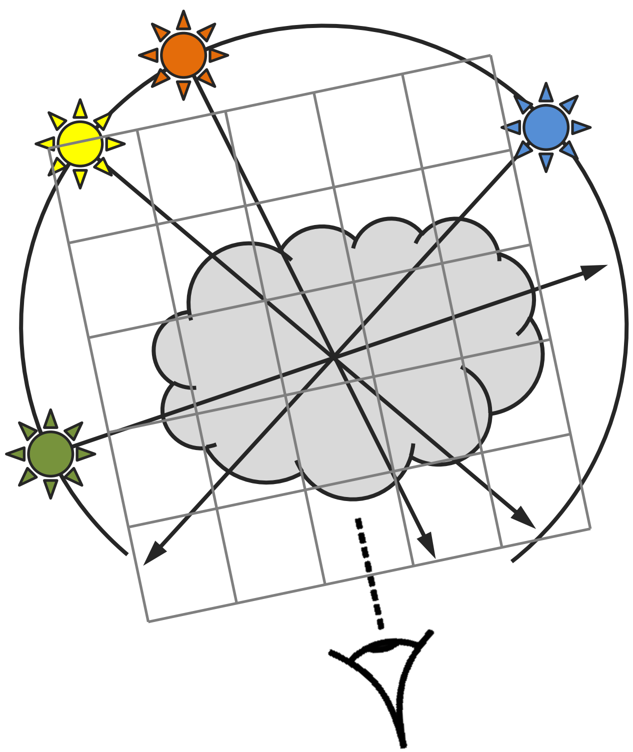


POP: Bi-directionality



Uni-directional

POP: Bi-directionality



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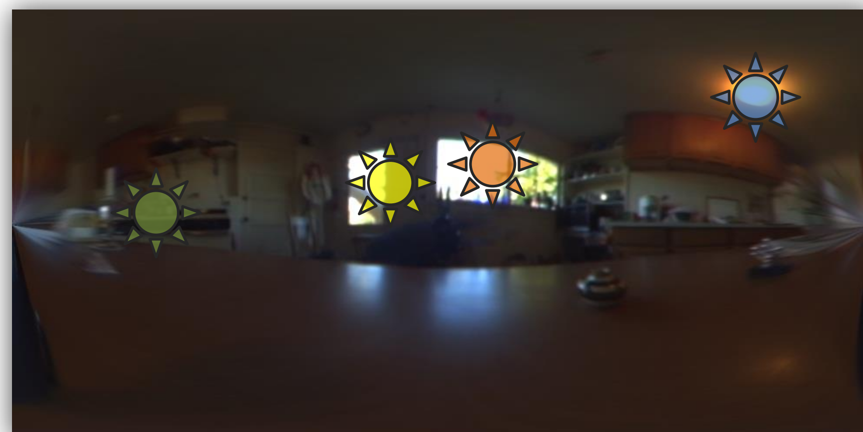
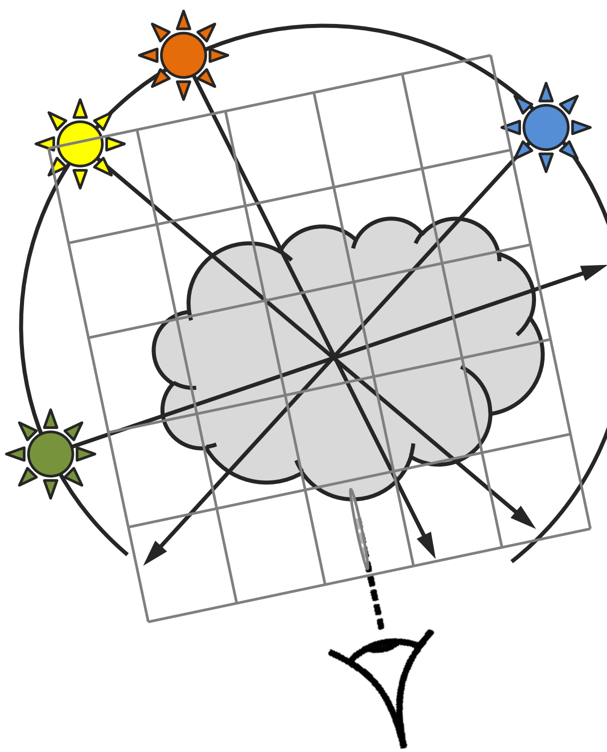


POP: Bi-directionality



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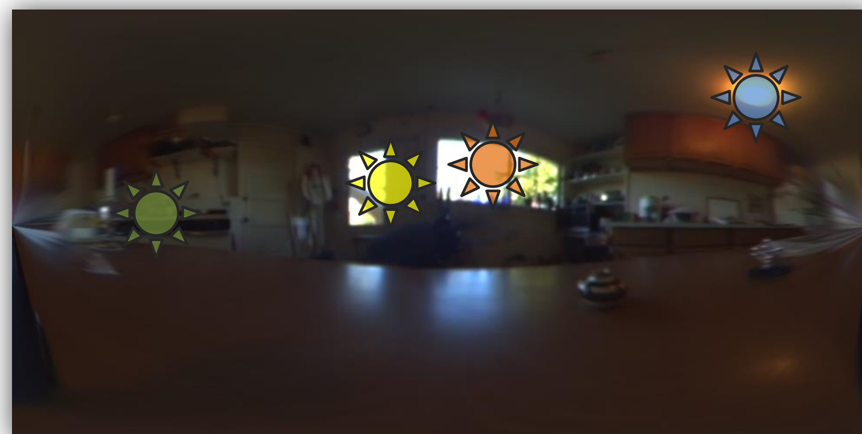
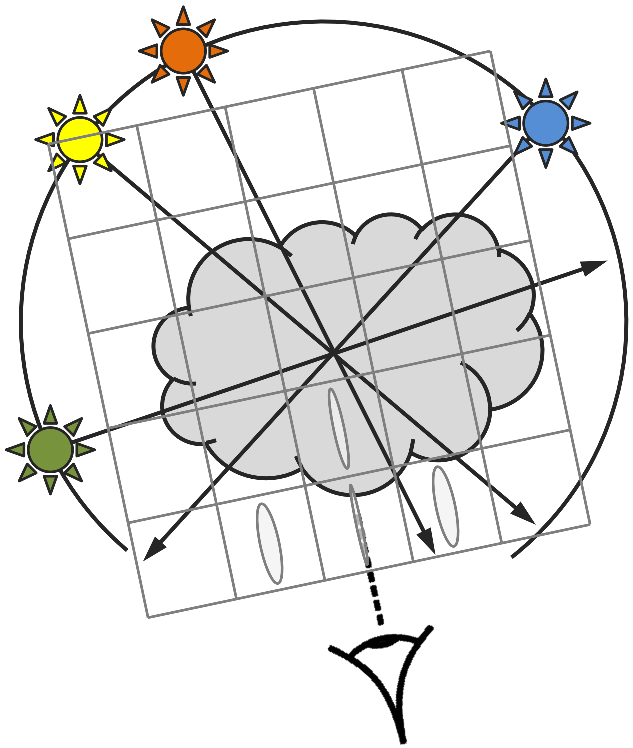
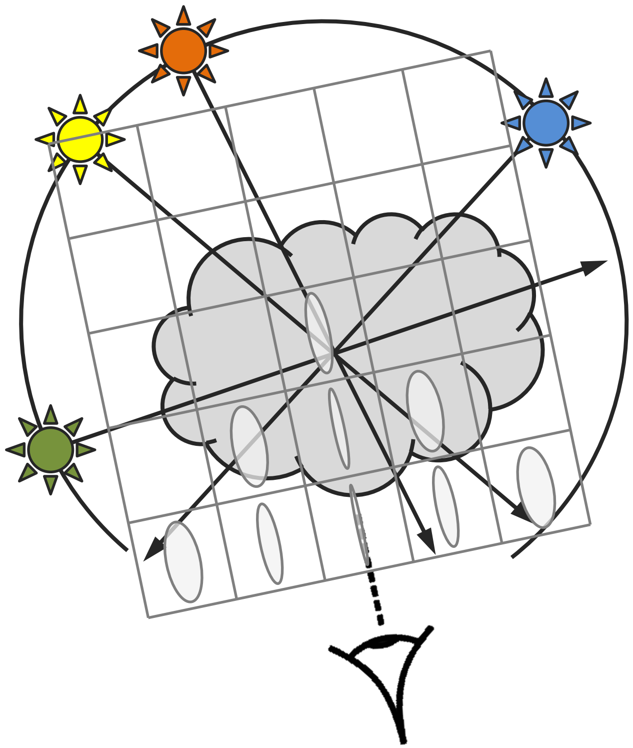


POP: Bi-directionality

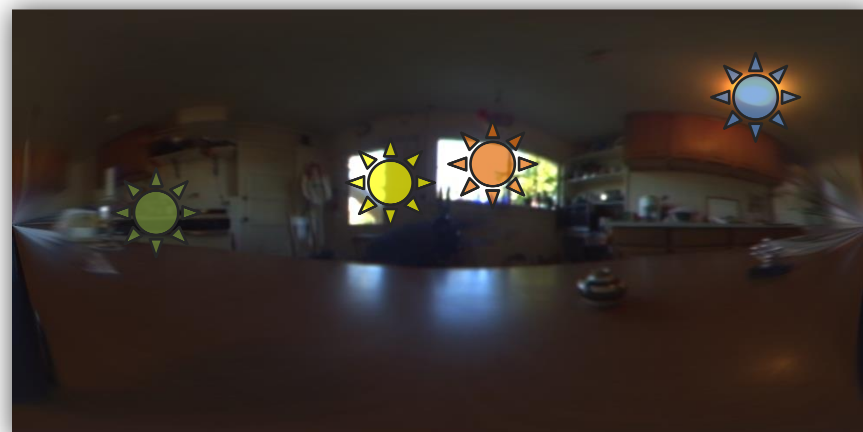
Uni-directional



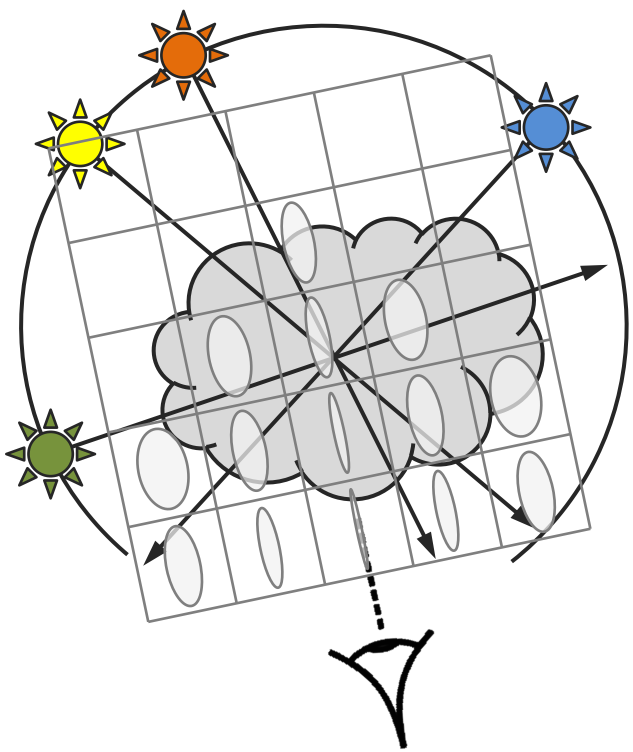
POP: Bi-directionality



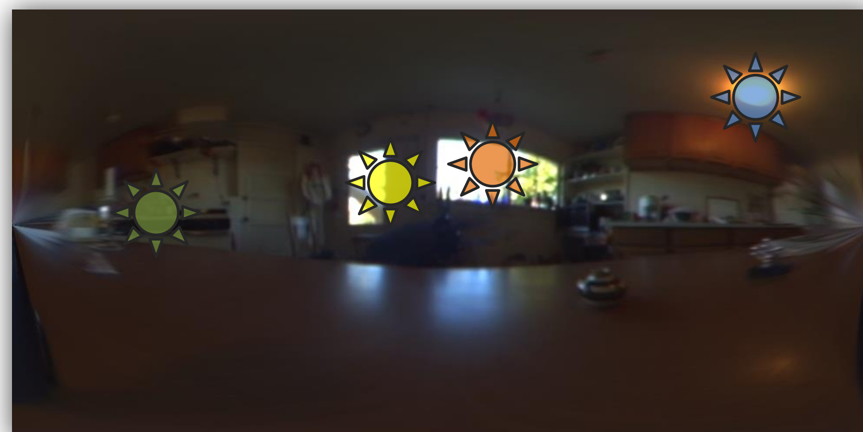
Uni-directional



POP: Bi-directionality

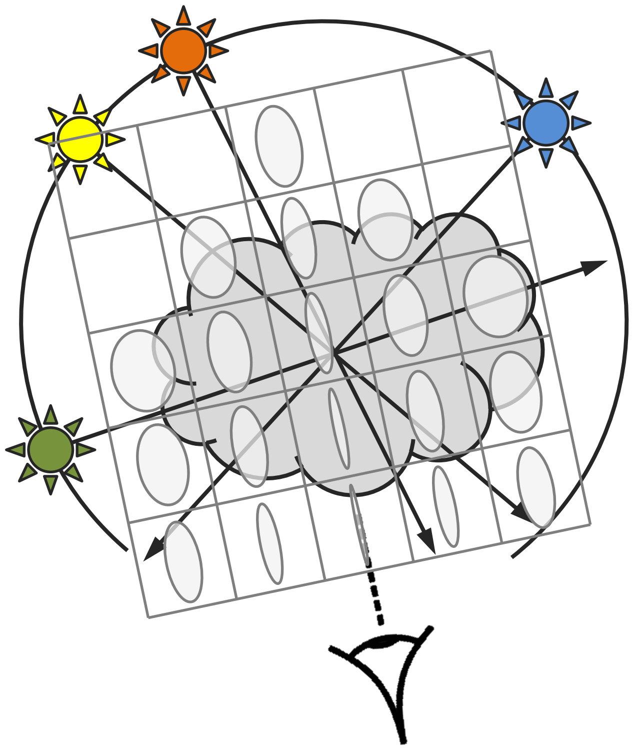


Uni-directional

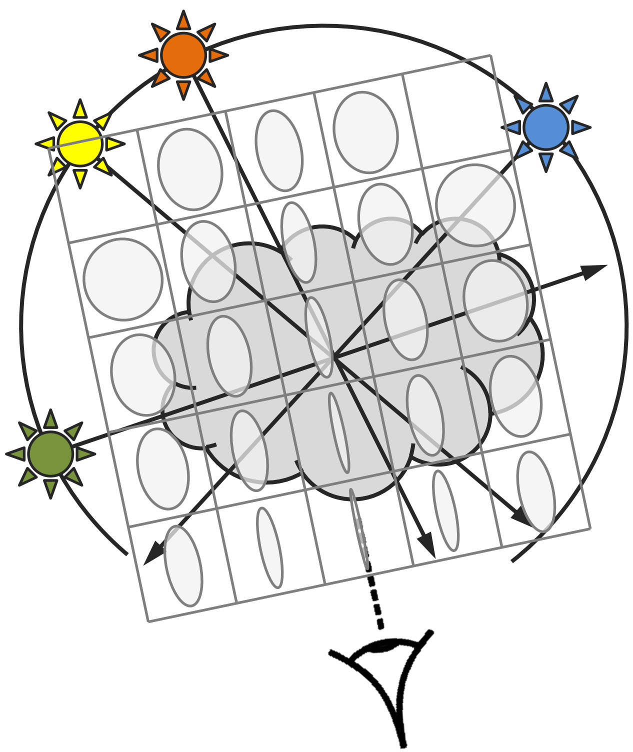


POP: Bi-directionality

Uni-directional



POP: Bi-directionality



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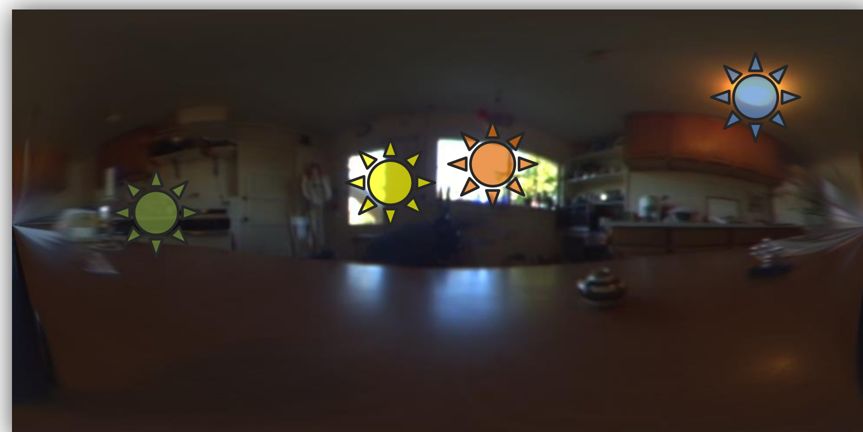
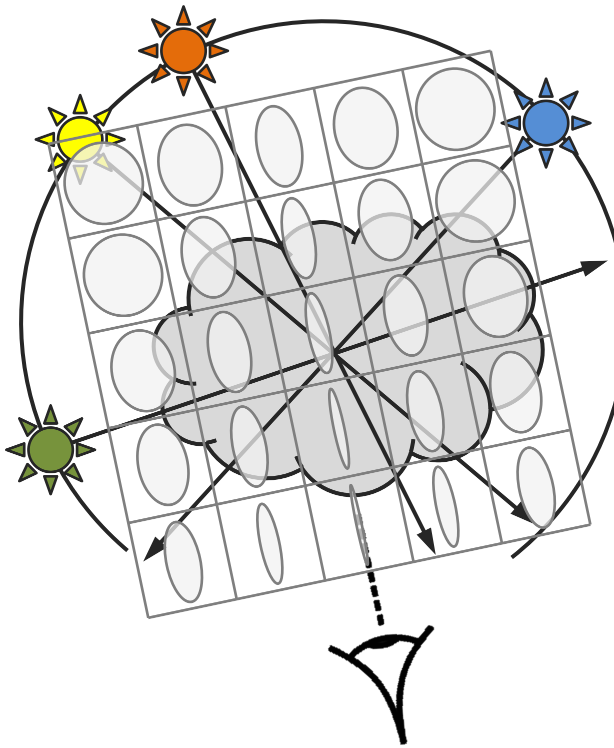
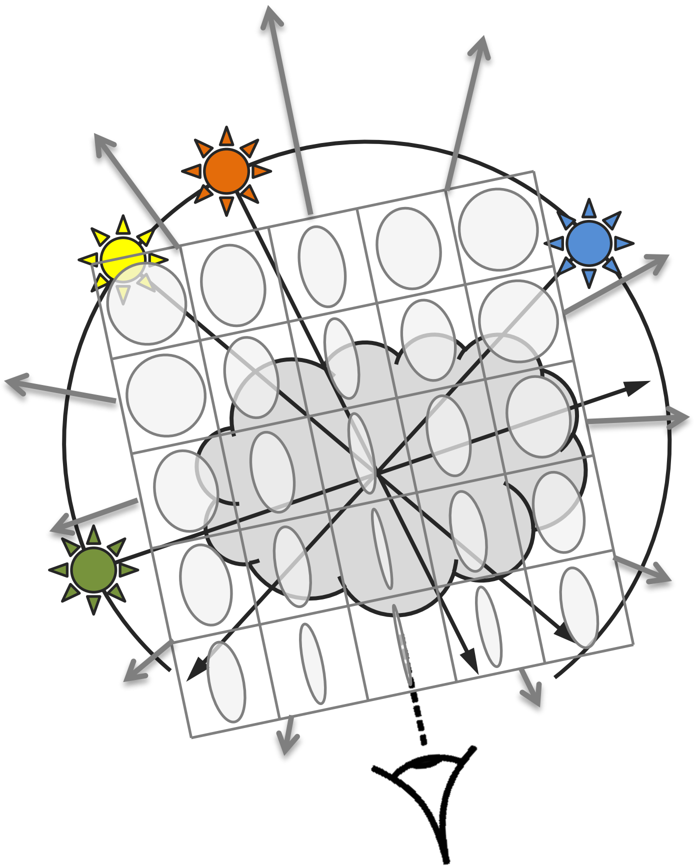


POP: Bi-directionality



Uni-directional

POP: Bi-directionality



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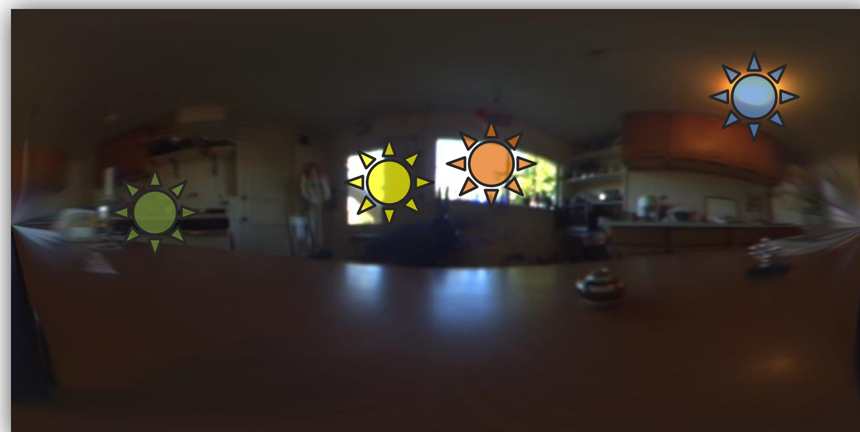
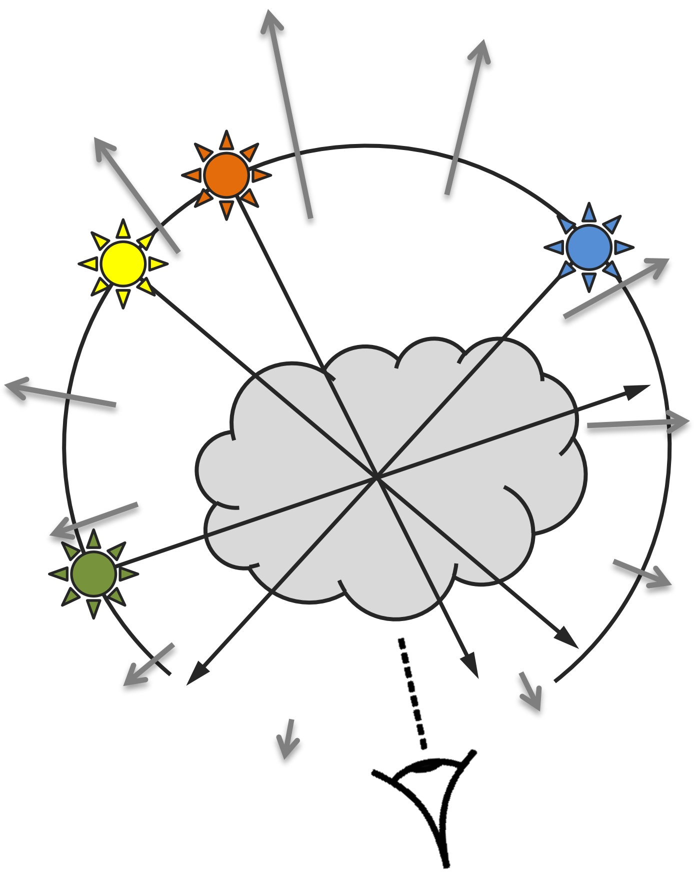


POP: Bi-directionality



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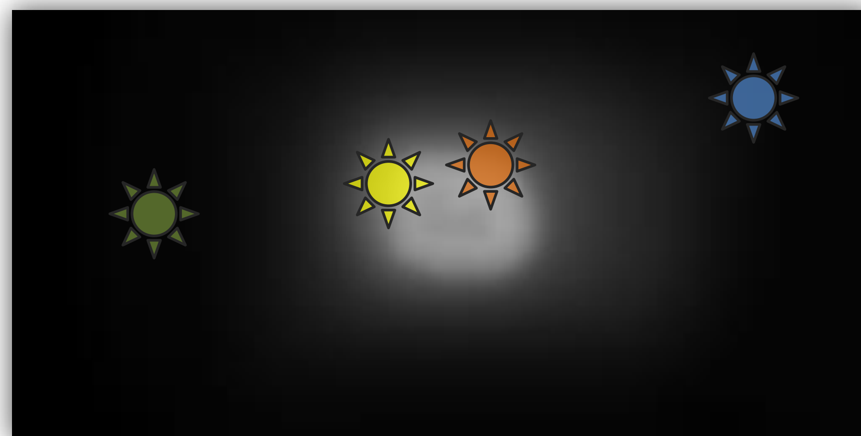
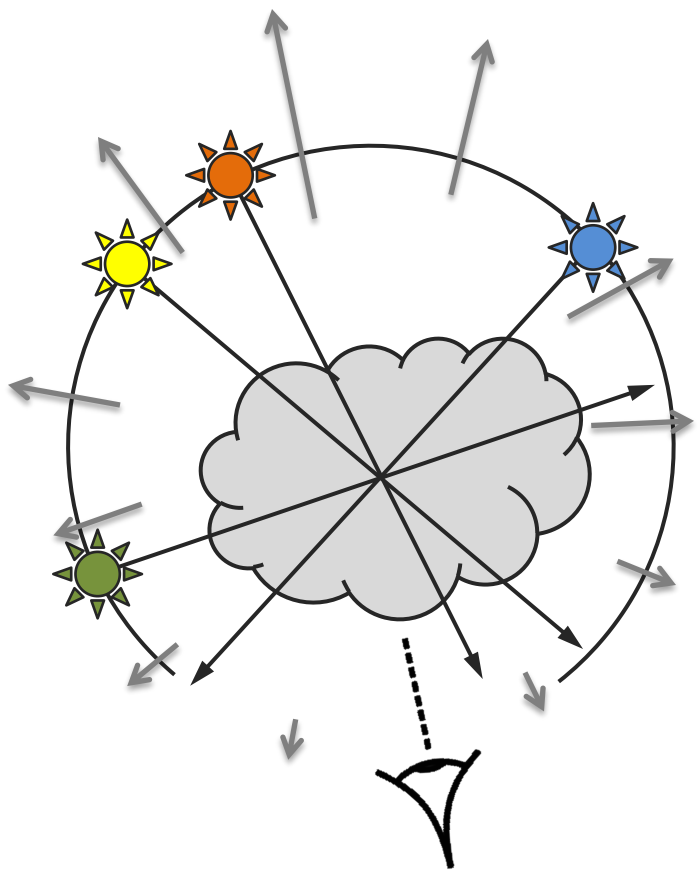
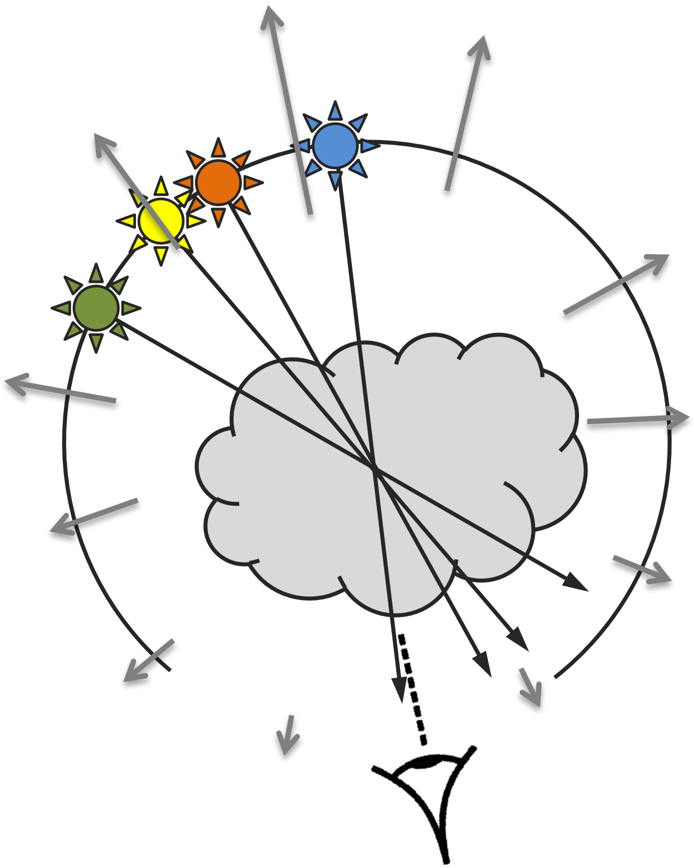


POP: Bi-directionality



Uni-directional

POP: Bi-directionality



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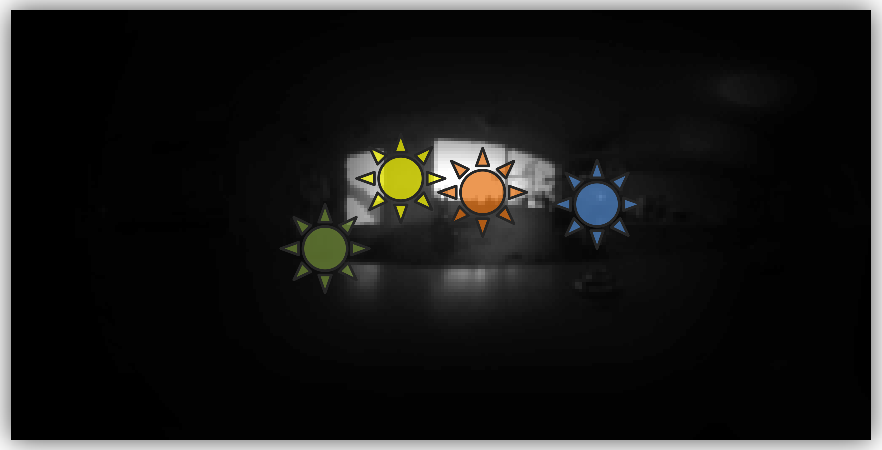
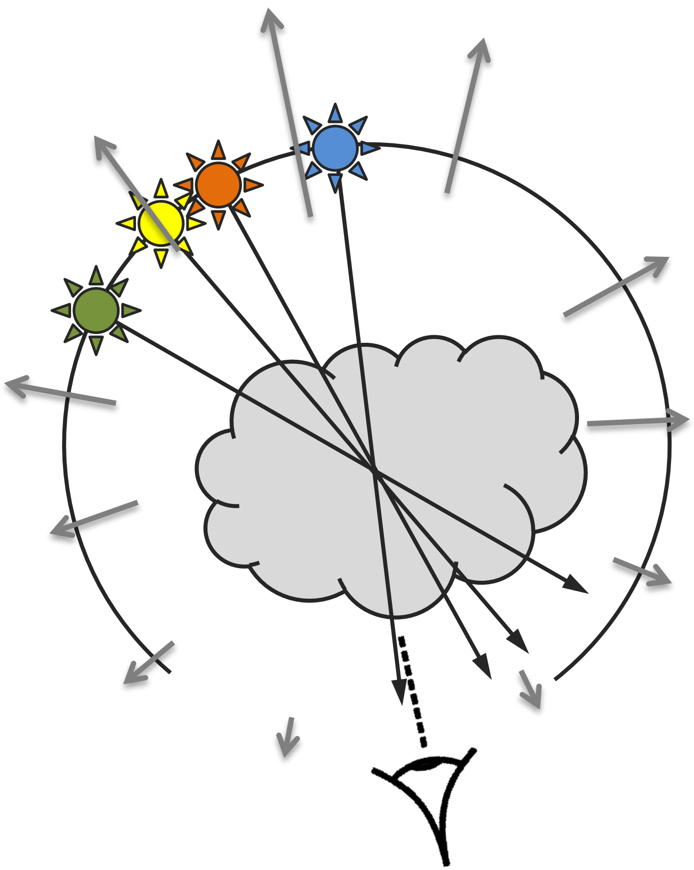
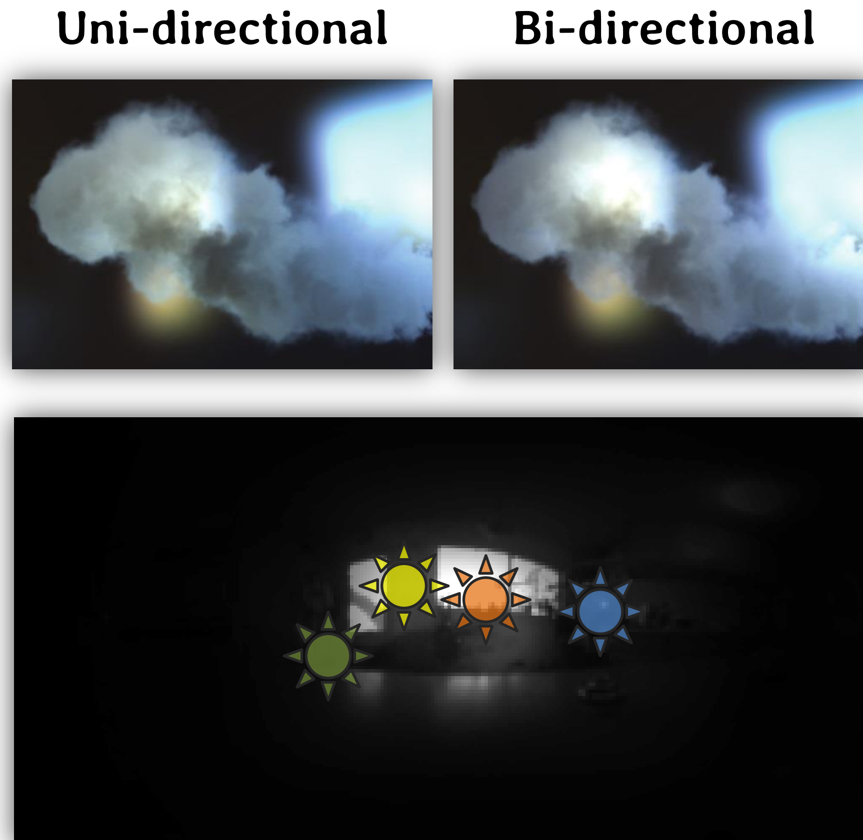
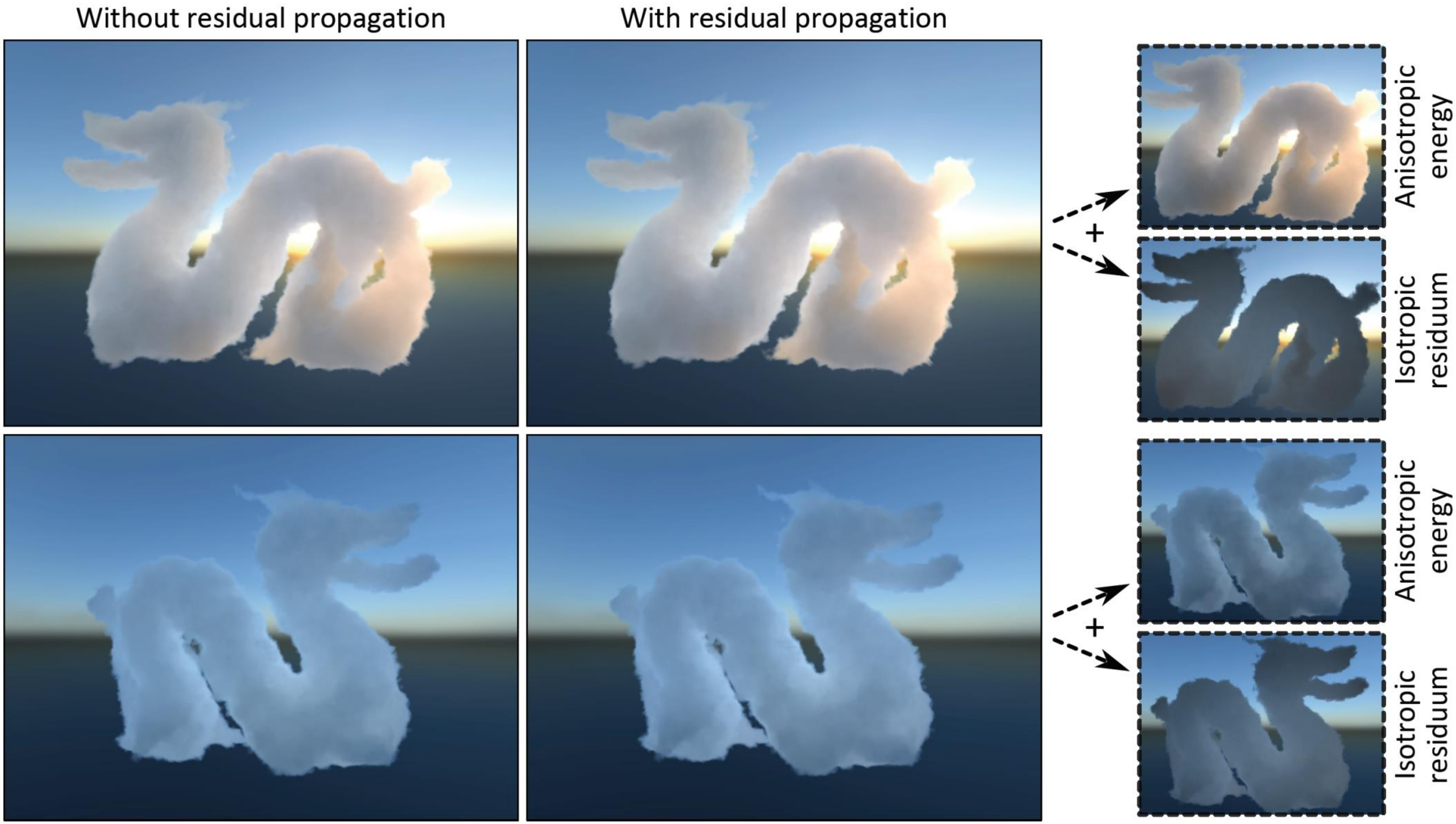


POP: Bi-directionality





POP: Bi-directionality



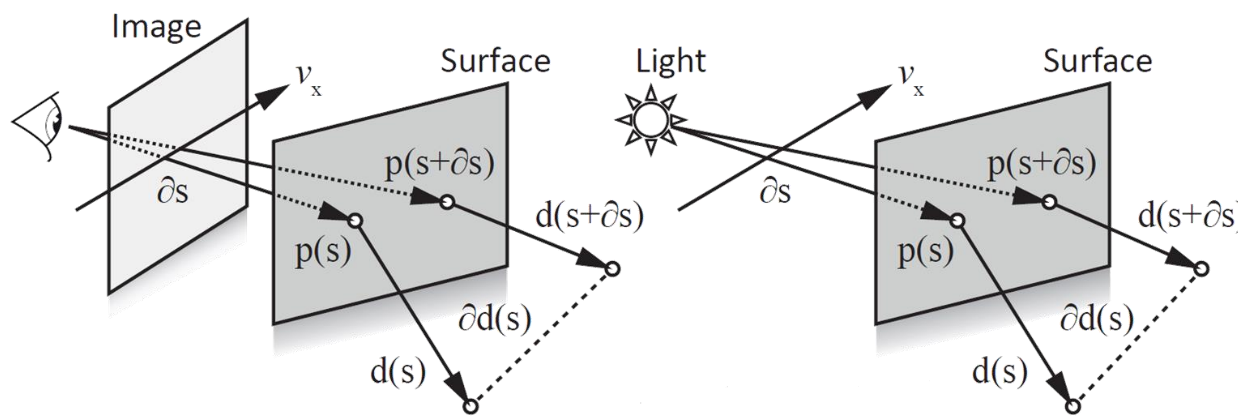
POP: Two-step Propagation

SRD: Ray Differentials

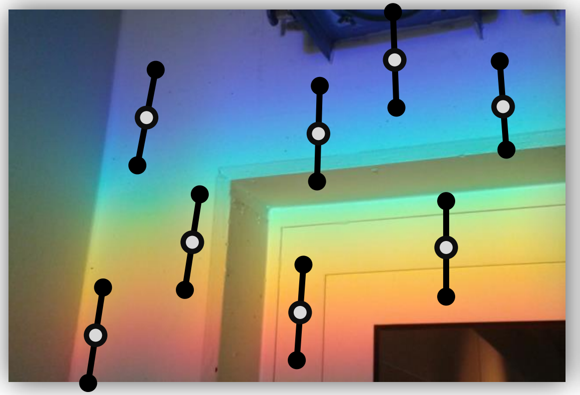
- **Introduced by Igehy in 1999**
- **Later extended to:**
  - **Paths** (Suykens, Willems @ EGWR 2001)
  - **Photons** (Schjoth, Frisvad, Erleben, Sporring @ Graphite 2007)
  - **Diffuse reflection** (Fabianowski, Dingliana @ EGSR 2009)

$$\frac{\partial \mathbf{R}}{\partial s} = \left(\frac{\partial \mathbf{p}}{\partial s}, \frac{\partial \mathbf{d}}{\partial s} \right)$$

$$\frac{\partial \mathbf{R}}{\partial t} = \left(\frac{\partial \mathbf{p}}{\partial t}, \frac{\partial \mathbf{d}}{\partial t} \right)$$



Progressive framework developed by
[Knaus & Zwicker 2011] and [Jarosz et al. 2011]


Iteration i_1


Iteration i_2


Iteration i_3

$$\frac{\Delta\lambda_{i+1}}{\Delta\lambda_i} = \frac{\mathrm{Var}[\epsilon_i]}{\mathrm{Var}[\epsilon_{i+1}]} = \frac{i+\alpha}{i+1} \qquad \alpha \in [0,1]$$

SRD: Progressiveness