LIGHT TRANSPORT SIMULATION

in the ArchViz and Visual Effects industries

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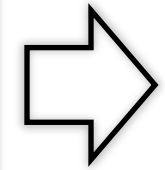
Industry collaboration

Image synthesis (Rendering)

Scene description

Image



Architecture

Film / SFX

Games

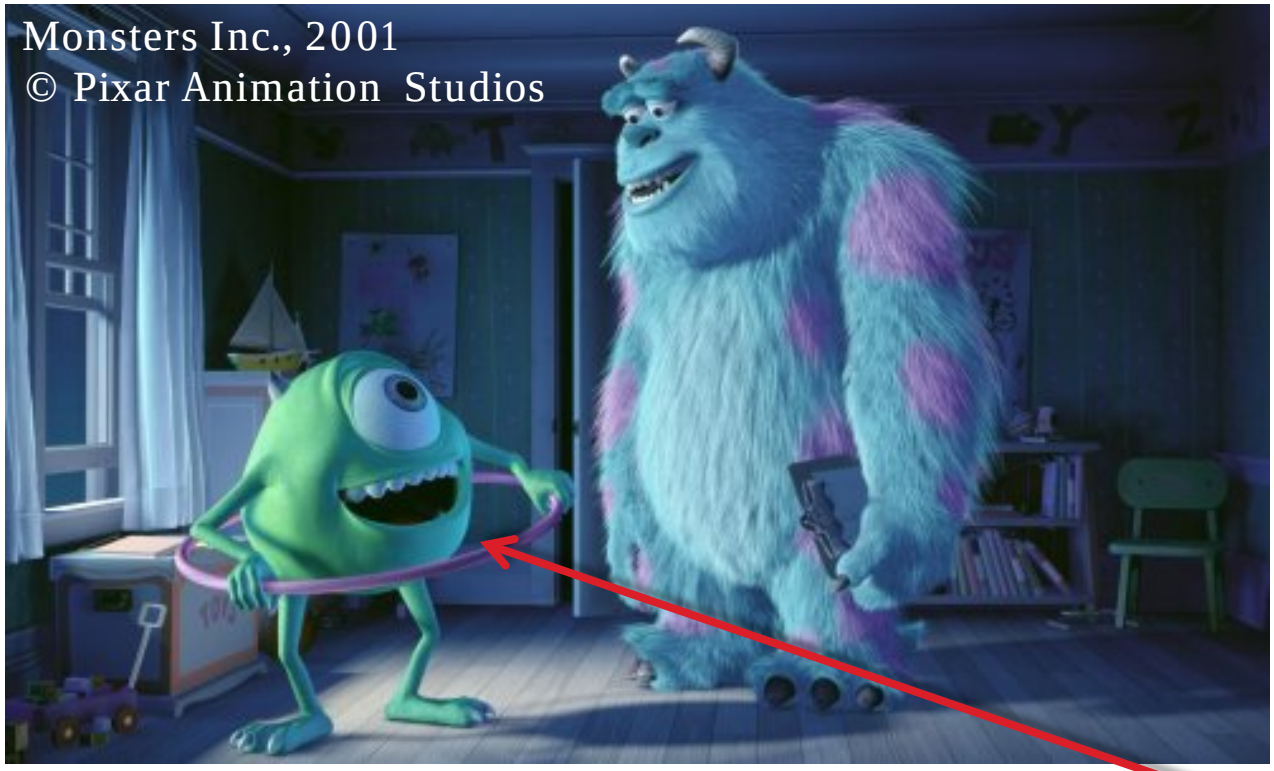
Light transport simulation

Ad-hoc solutions

Global illumination – Color bleeding

Image credit: Michael Bunnell

“Manual” global illumination



- Traditional approach in VFX
  - Manually placed lights to emulate GI effects

Global illumination – Caustics

Realistic rendering

=

Light transport simulation

(+ more)

Light transport – Global illumination

Archviz

Movies

Image courtesy of Columbia Pictures.
© 2006 Columbia Pictures Industries, Inc.

Light transport – Global illumination

Movies

- **2002, Shrek 2** (PDI/Dreamworks)
  - 1 bounce indirect

- **2006, Monster House** (Sony Imageworks)
  - **Full light transport** (path traced)
  - Arnold renderer

Image courtesy of Columbia Pictures.

Light transport – Global illumination

Movies

- **2006, Monster House** (Sony Imageworks)
  - **Full light transport** (path traced)
  - Arnold renderer

Image courtesy of Columbia Pictures.
© 2006 Columbia Pictures Industries, Inc.

- **Full light transport simulation**
  - Accuracy
  - Ease of use
  - **Visual consistency**

Light transport – Global illumination

- **More information**
  - "The State of Rendering"

- **Full light transport simulation**
  - Accuracy
  - Ease of use
  - **Visual consistency**


2SA 8801

A room with a view

Put a rocking chair in front of your favourite window and experience how relaxing it is to get away from it all by just coming home. Life is in full swing outside, but you feel totally calm.

IKEA®

Seat cushions filled with high resilience foam ide comfortable support for your body when pe when you rise. Cover: 53% linen, 47% viscose/rayon. W218×D88, H80cm. Risane natural.

02 New FABRIKÖR glass-door cabinet $399 The shelves in the cabinet are adjustable – makes it easy to adjust the height to suit what you want to store. May be completed with DIODER LED lighting strip. Powder coated steel and tempered glass. Designer: Nike Karlsson. W57×D47, H150cm. Light green 702.422.94

03 VÄRMDÖ rocking-chair $169 Wooden furniture that is suitable for both indoor and outdoor use. Solid pine. Designer: Nike Karlsson. W65×D74, H106cm. Black 002.059.59

04 BJÖRNLOKA rug, flatwoven $199 The durable, soil-resistant wool surface makes this rug perfect in your living room or under your dining table. The rug is machine-woven. User surface: 100% pure new wool. W170×L240cm. Beige/black 402.290.05

05 HEMNES coffee table $229 Stained, clear lacquered solid pine. Designer: Carina Bengs. L90×W90, H46cm. Grey-brown 402.579.51

Show products (3)

Fake or real?

Images courtesy
Dudek Digital Imaging

Fake or real?

Images courtesy
Maciek Ptaszynski

Image created by *Weta Digital*

vimeo >> “The Great Gatsby VFX”

vimeo >> “The Great Gatsby VFX”


corona
FERRERO ROCHER
Chakib Rabia©
2012

Research is going on

Light transport simulation
is **not** a solved problem

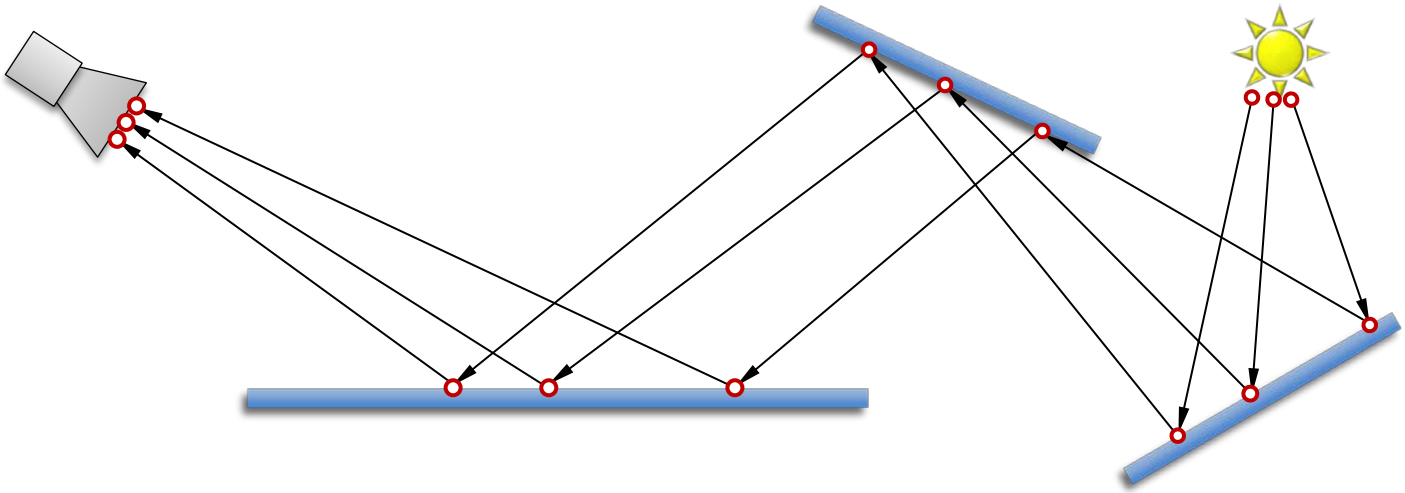
Limitations: Glossiness

Limitations: Participating media

Limitations: Complex visibility

Much recent progress

- Common denominator:
  Path integral formulation of light transport
  [Veach and Guibas 1995], [Veach 1997]



Outline

- Path integral formulation of light transport
- Bidirectional path tracing
- Photon mapping

preliminaries

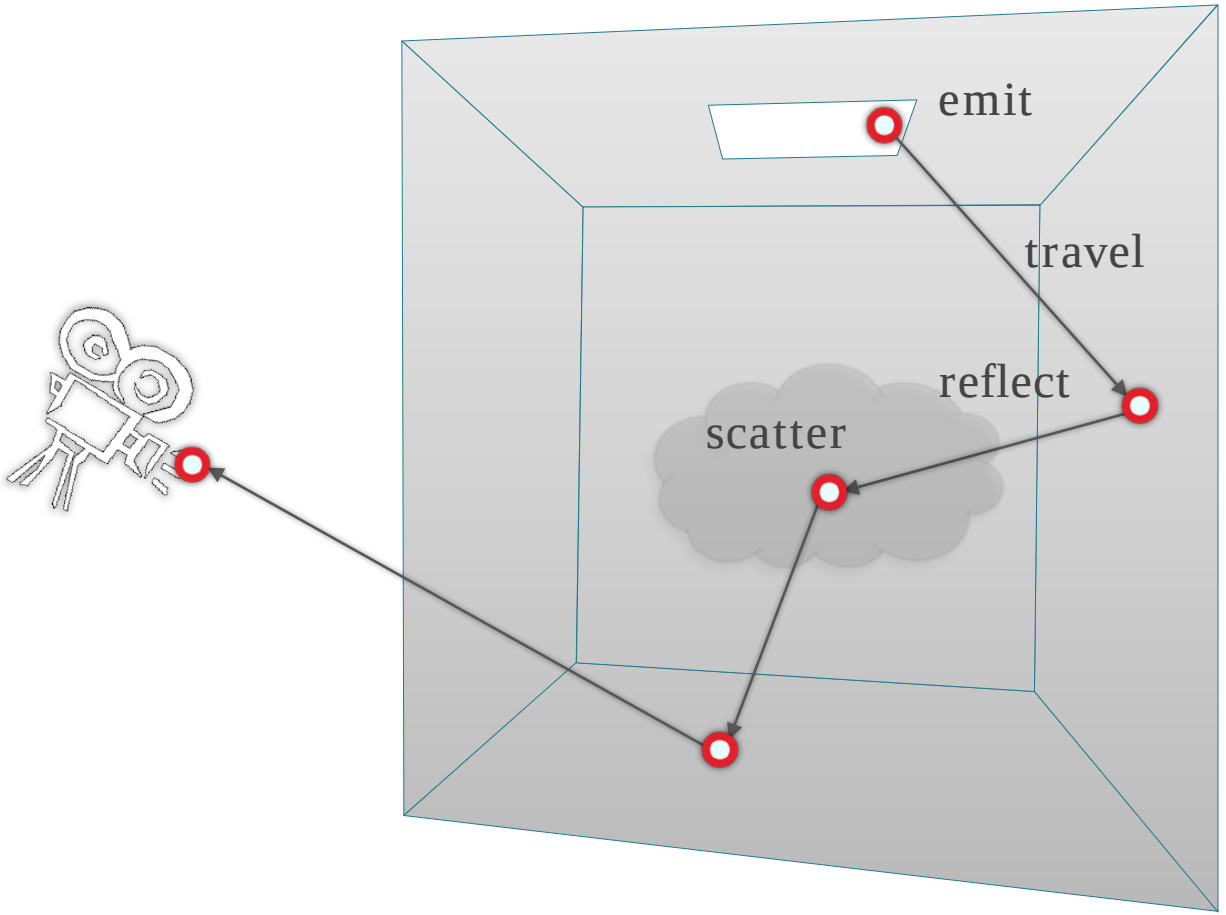
- Vertex Connection and Merging [SIGGRAPH Asia 2012]
- Unified Point Beams and Paths [SIGGRAPH 2014]
- Zero-variance Random Walks [SIGGRAPH 2014]
- On-line Learning of Parametric Mixture Models [SIGGRAPH 2014]

our contribution

PATH INTEGRAL FORMULATION OF LIGHT TRANSPORT

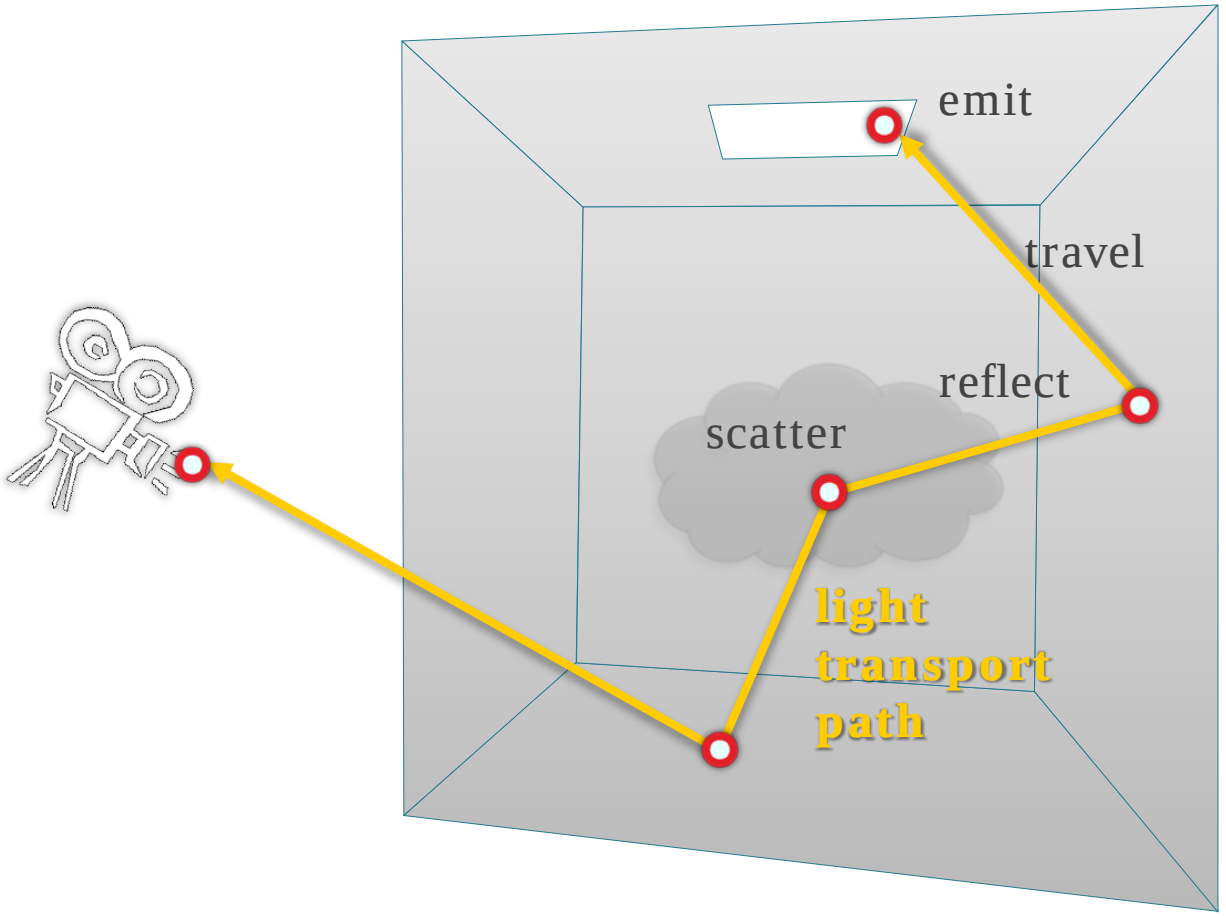
Light transport

- Geometric optics



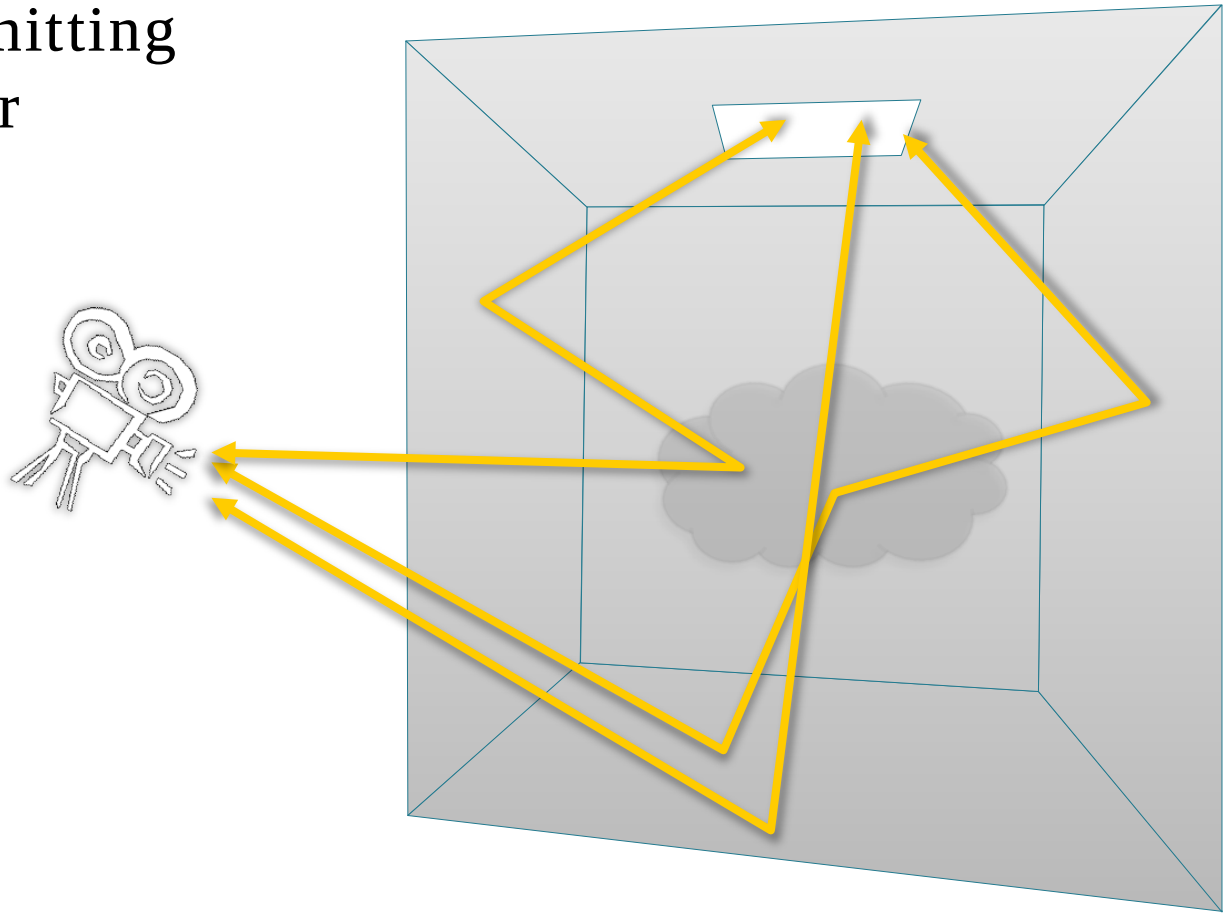
Light transport

- Geometric optics



Light transport

- **Camera response**
  - all paths hitting the sensor



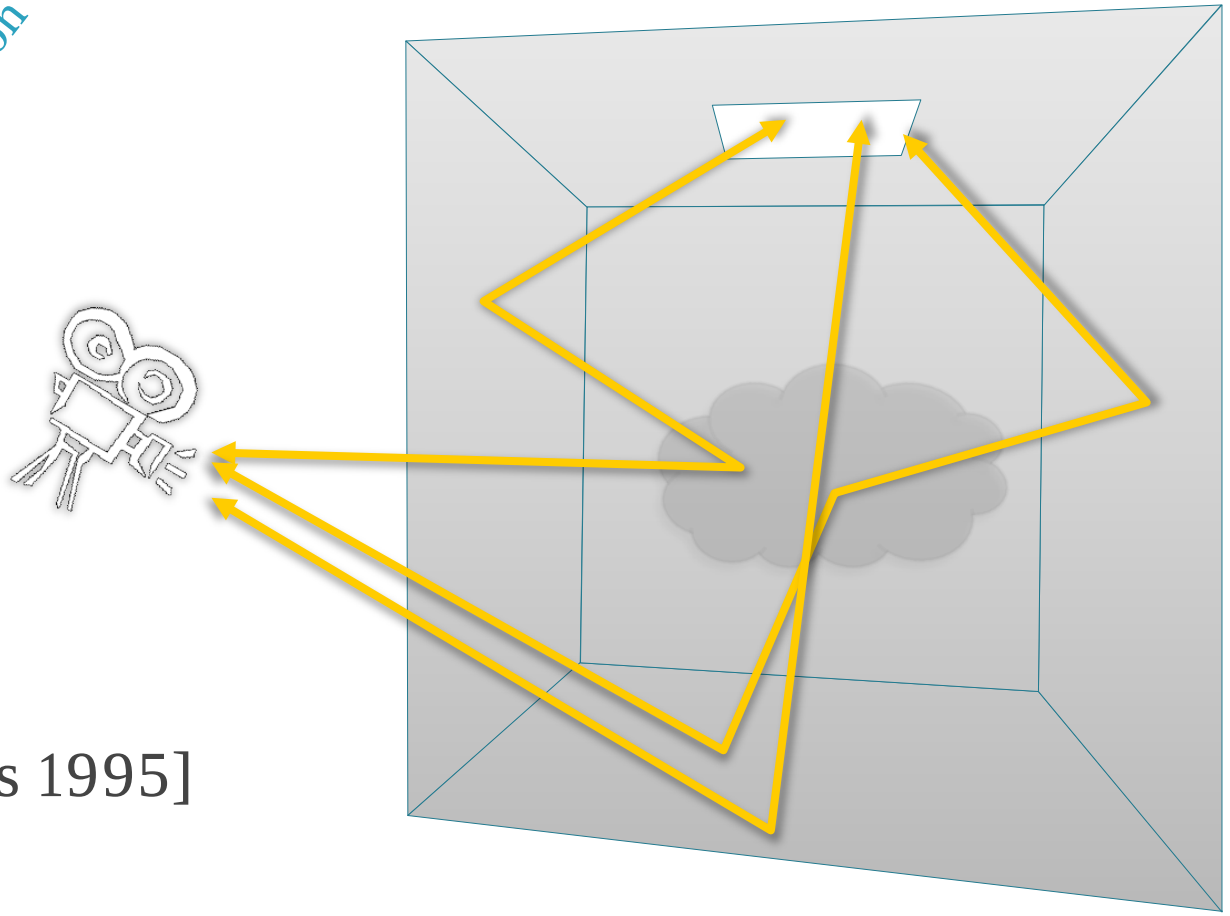
Path integral formulation

$$I_j = \int_\Omega f_j(\bar{x})\ \mathrm{d}\mu(\bar{x})$$

camera resp. (j-th pixel value)

all paths

measurement contribution function



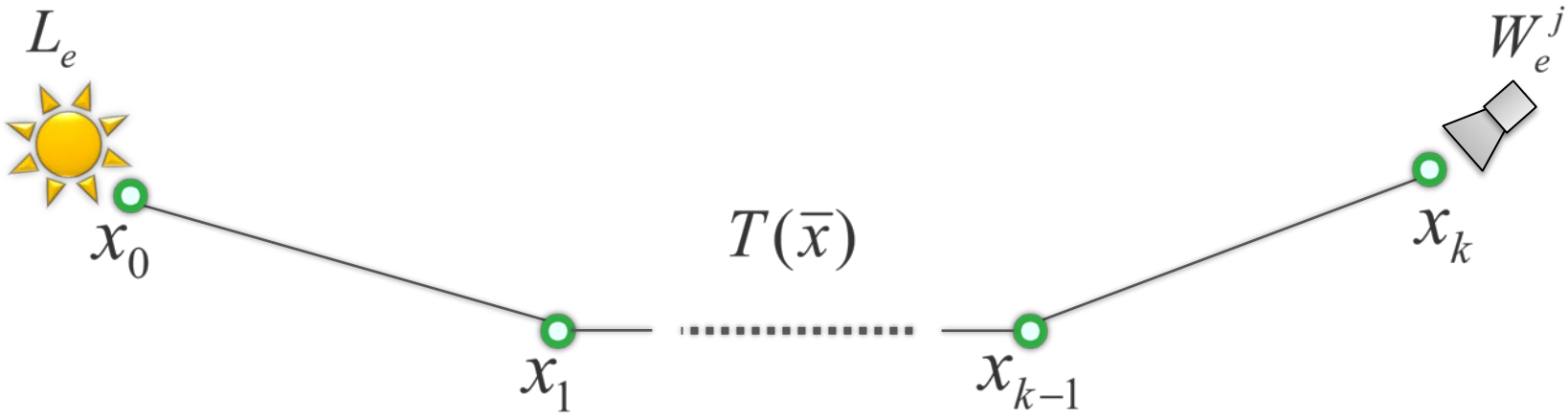
[Veach and Guibas 1995]
[Veach 1997]

Measurement contribution function

$$\bar{x} = x_0 x_1 \ldots x_k$$

$$f_j(\bar{x}) = L_e \; T(\bar{x}) \; W_e^j$$

L_e	$T(\bar{x})$	W_e^j
emitted radiance	path throughput	sensor sensitivity ("emitted importance")



Path integral formulation

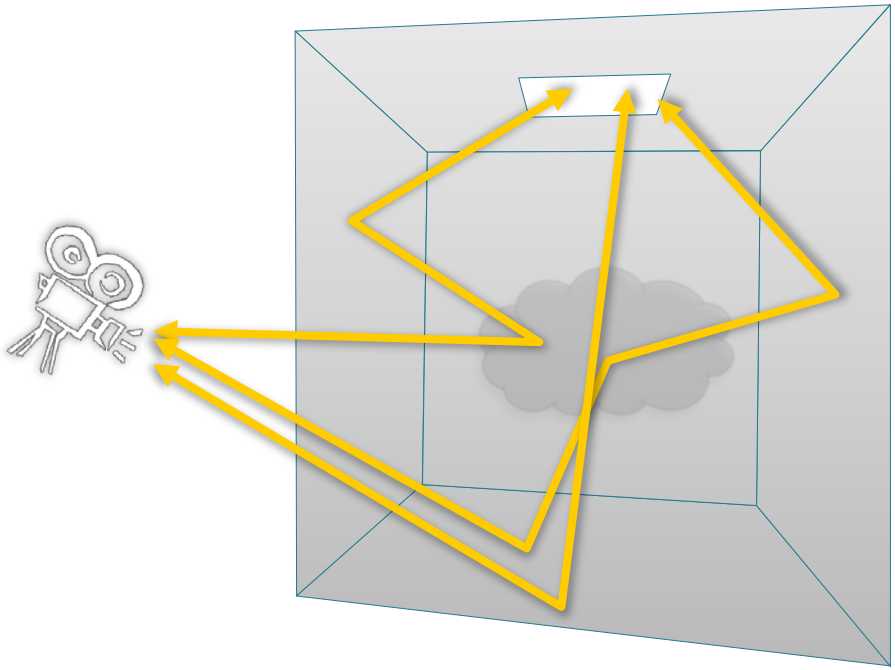
$$I_j = \int_\Omega f_j(\bar{x})\ \mathrm{d}\mu(\bar{x})$$

camera resp. (j-th pixel value)

all paths

measurement contribution function

?



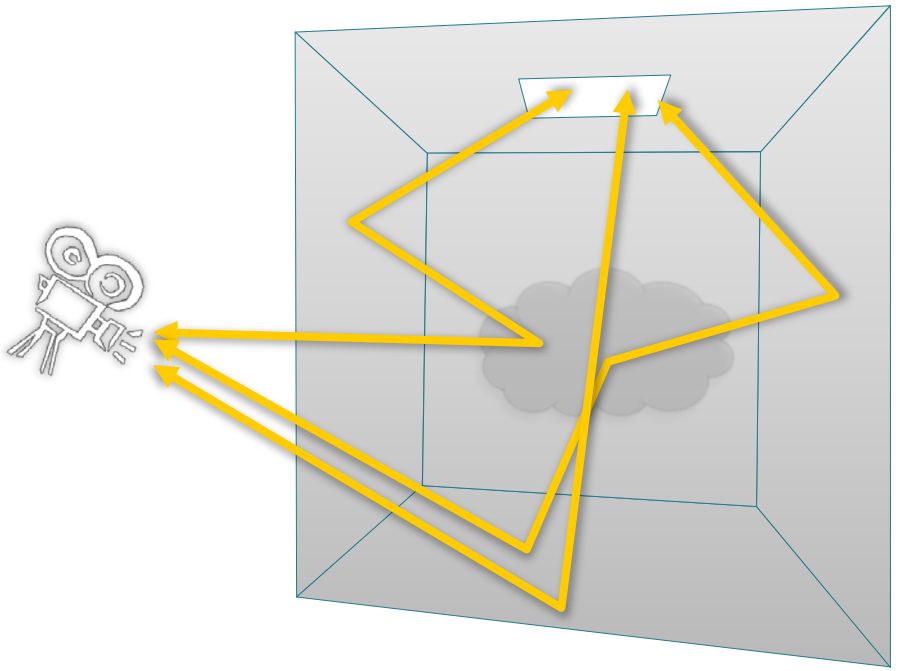
Path integral formulation

$$I_j = \int_\Omega f_j(\bar{x}) \; \mathrm{d}\mu(\bar{x})$$

$$= \sum_{k=1}^{\infty} \int_{M^{k+1}} f_j(x_0 \ldots x_k) \; \mathrm{d}A(x_0) \ldots \mathrm{d}A(x_k)$$

all path lengths

all possible vertex positions



Path integral

$$I_j = \int_\Omega f_j(\bar{x})\, \mathrm{d}\mu(\bar{x})$$

pixel value

all paths

contribution function

RENDERING :

EVALUATING THE PATH INTEGRAL

Path integral

$$I_j = \int_\Omega f_j(\bar{x})\, \mathrm{d}\mu(\bar{x})$$

pixel value

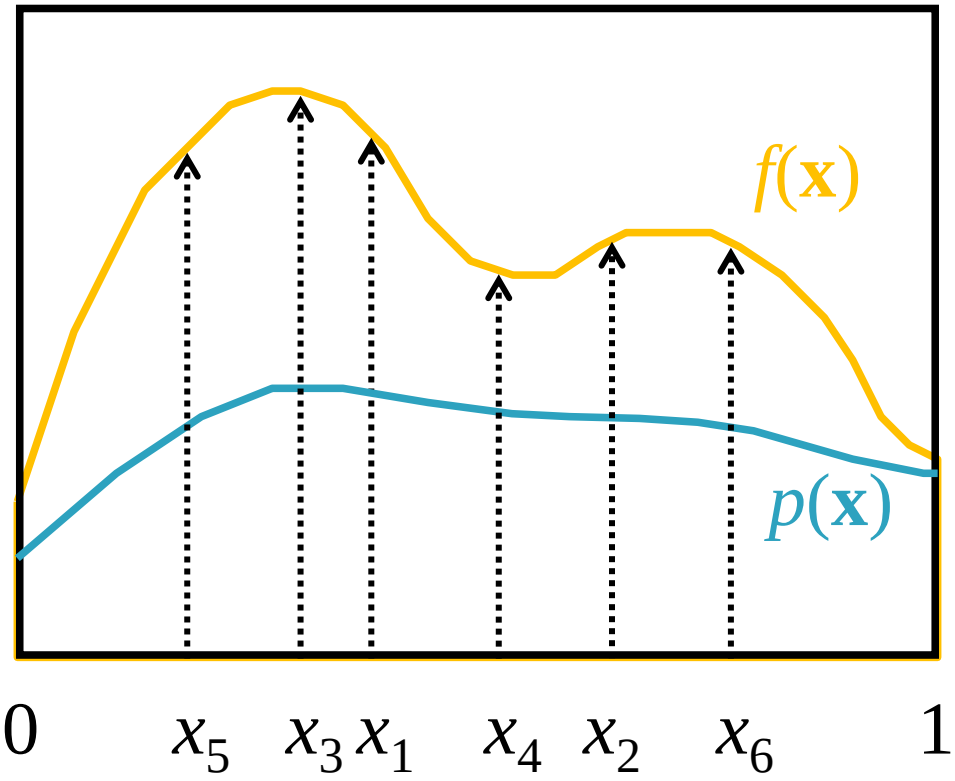
all paths

contribution function

- **Monte Carlo integration**

Monte Carlo integration

- General approach to numerical evaluation of integrals



Integral:

$$I = \int f(x)\mathrm{d}x$$

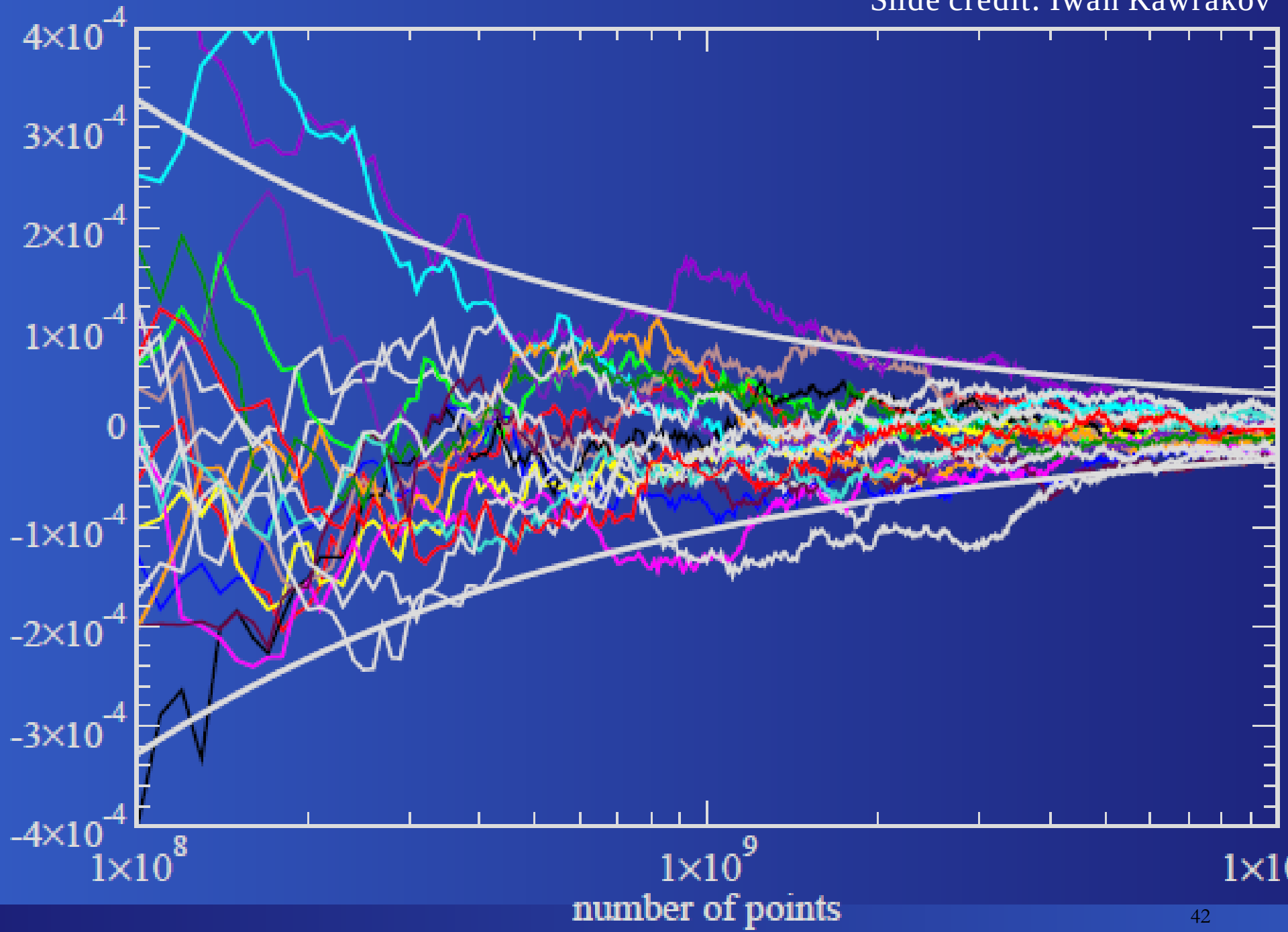
Monte Carlo estimate of I:

$$\langle I \rangle = \frac{1}{N}\sum_{i=1}^{N}\frac{f(x_i)}{p(x_i)}; \quad x_i \propto p(x)$$

Correct „on average“:

$$E[\langle I \rangle] = I$$

Slide credit: Iwan Kawrakov



MC evaluation of the path integral

Path integral

$$I_j = \int_\Omega f_j(\bar{x})\, \mathrm{d}\mu(\bar{x})$$

MC estimator

$$\left\langle I_j \right\rangle = \frac{f_j(\bar{x})}{p(\bar{x})}$$

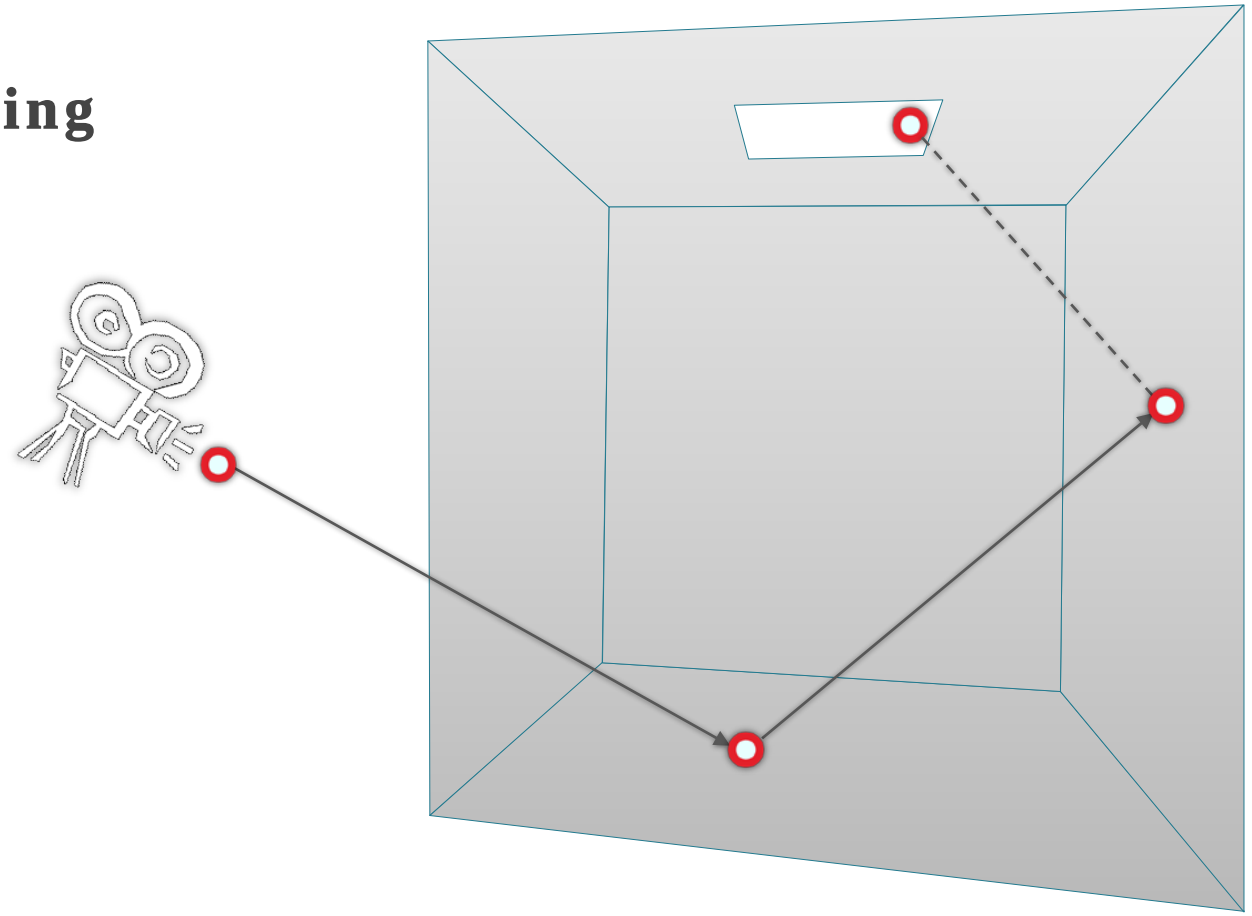
- Sample path $\bar{x}$ from some distribution with PDF $p(\bar{x})$?
- Evaluate the probability density $p(\bar{x})$?
- Evaluate the integrand $f_j(\bar{x})$ ✓

Path sampling

- Algorithms = different path sampling techniques

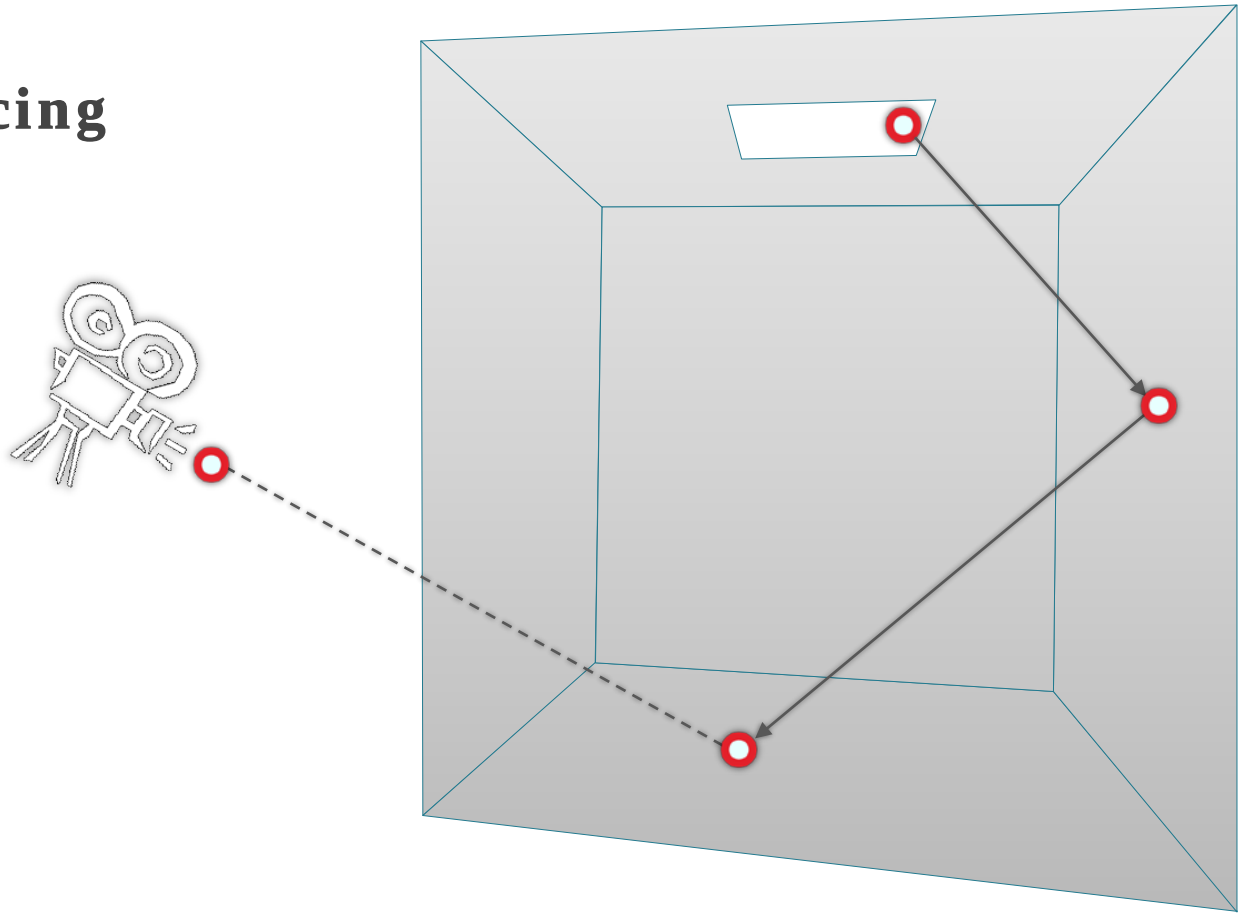
Path sampling

- Algorithms = different path sampling techniques
  - **Path tracing**



Path sampling

- Algorithms = different path sampling techniques
  - **Light tracing**



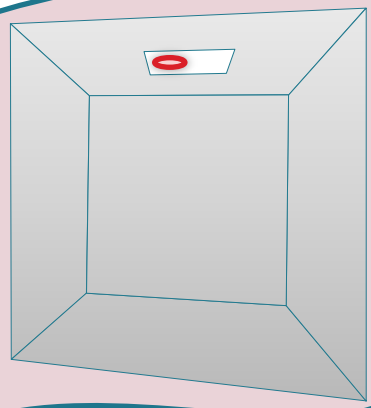
Path sampling

- Algorithms = different path sampling techniques
- **Same** general form of **estimator**

$$\left\langle I_j \right\rangle = \frac{f_j(\bar{x})}{p(\bar{x})}$$

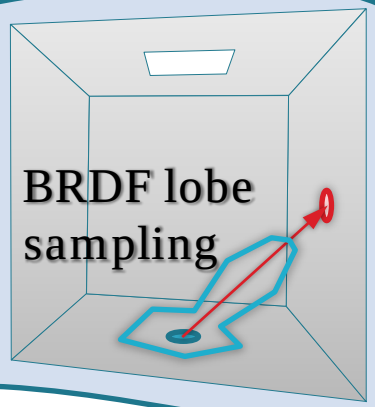
Local path sampling

- Sample one path vertex at a time

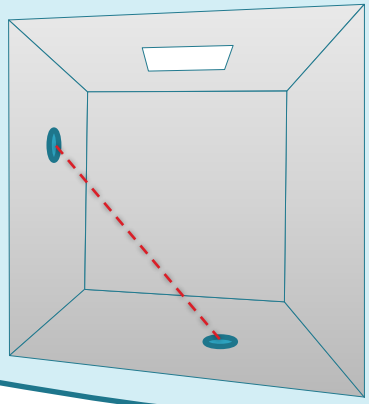


1. From an a priori distribution
   - lights, camera sensors

2. Sample direction from an existing vertex

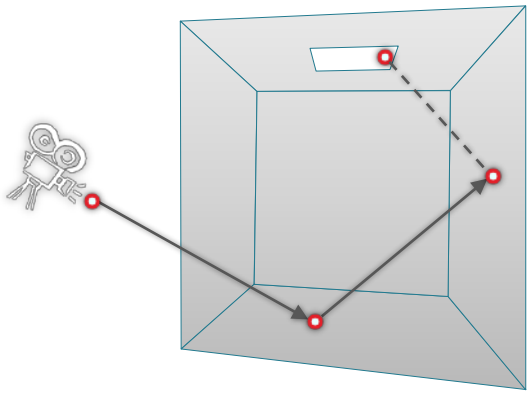


3. Connect sub-paths
   - test visibility between vertices

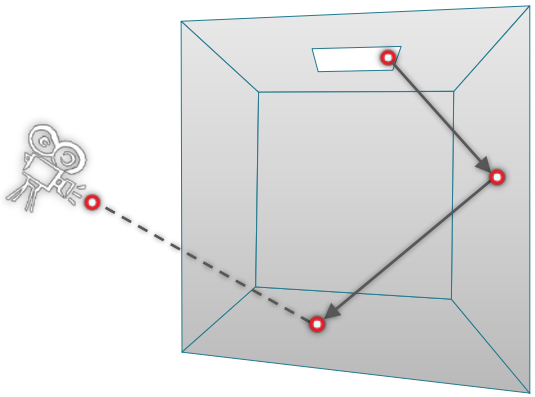


Use of local path sampling

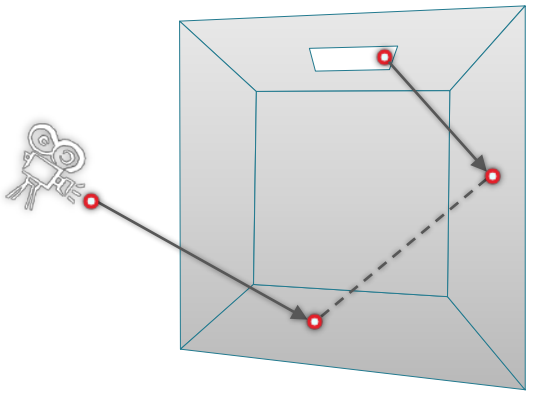
Path tracing



Light tracing



Bidirectional path tracing

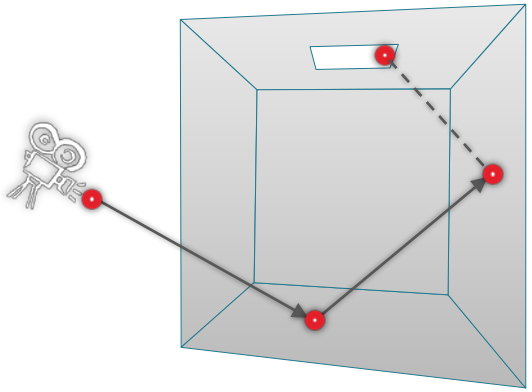


BIDIRECTIONAL PATH TRACING

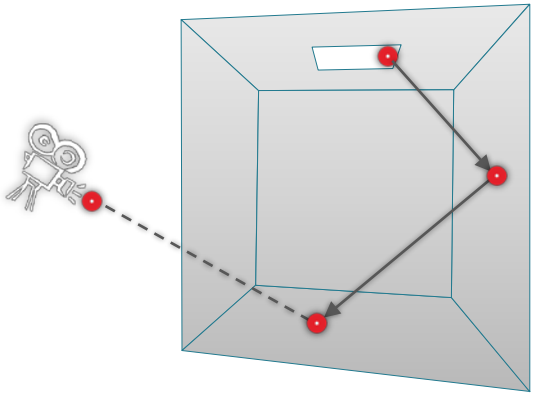
Bidirectional path tracing

Unidirectional path sampling

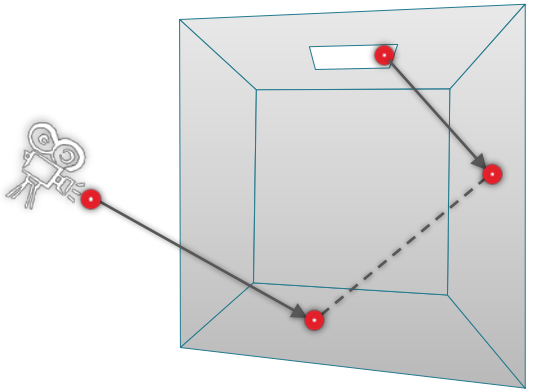
Path tracing



Light tracing

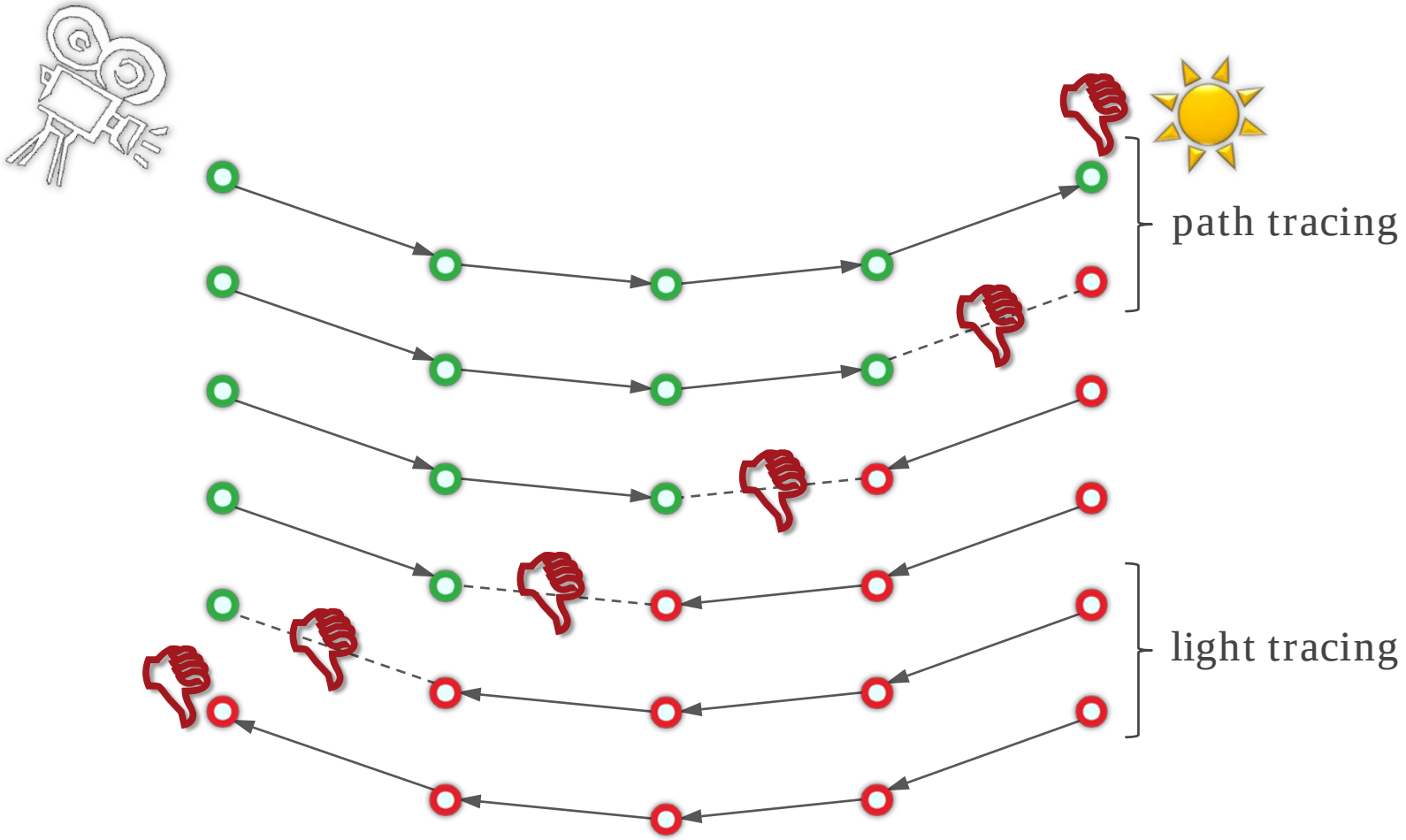


Bidirectional path sampling



All possible bidirectional techniques

- vertex on a **light sub-path**
- vertex on en **eye sub-path**



All possible bidirectional techniques

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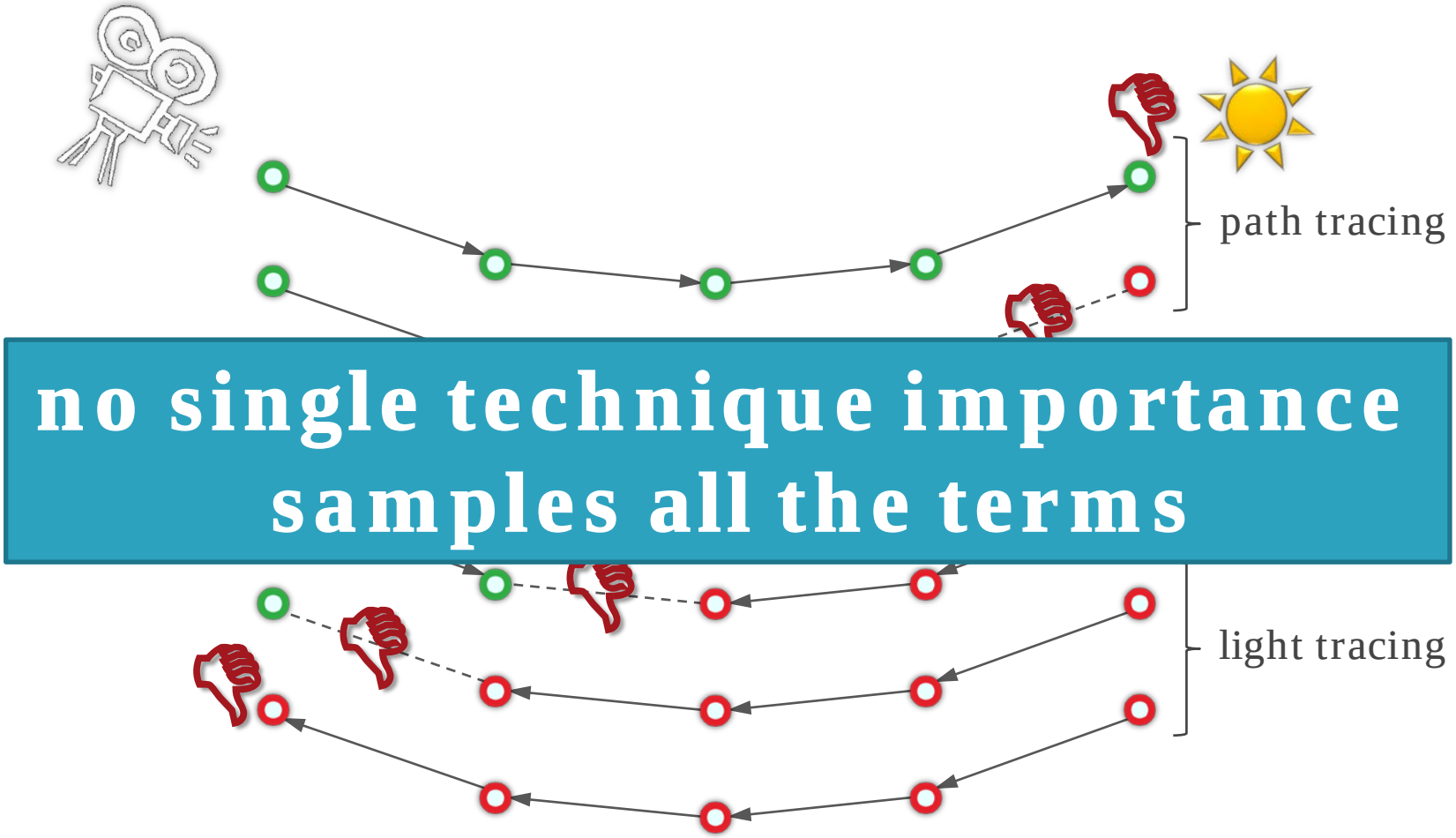
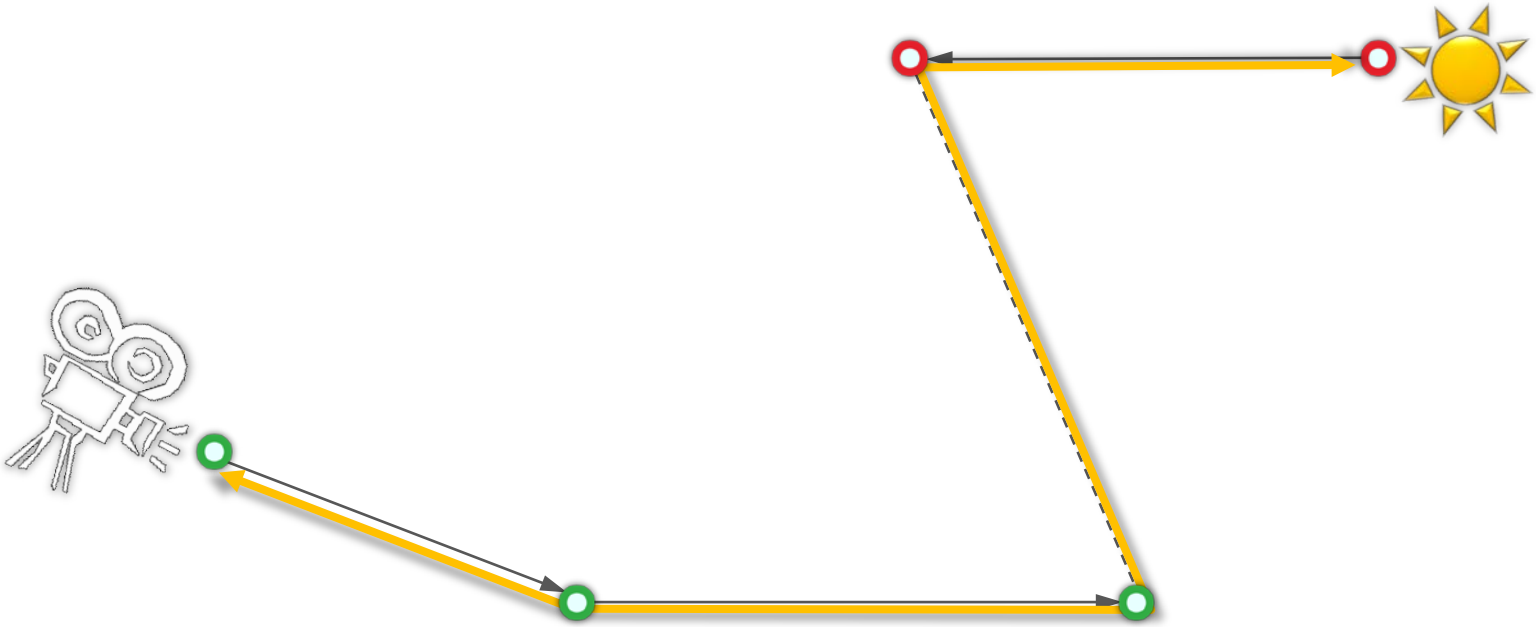


no single technique importance samples all the terms

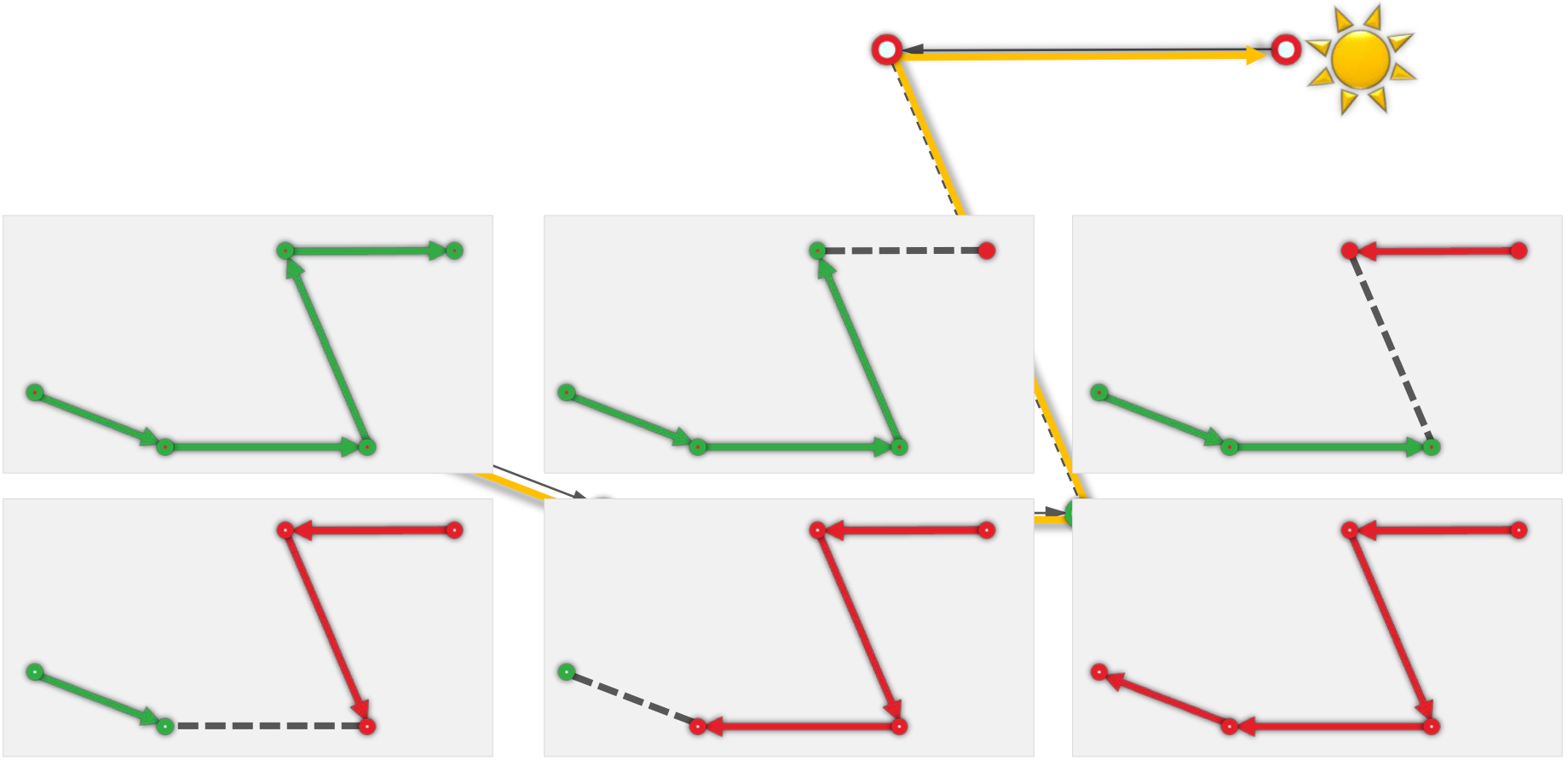
Bidirectional path tracing

- Use **all** of the above sampling techniques
- Weighted sum using
  Multiple Importance Sampling

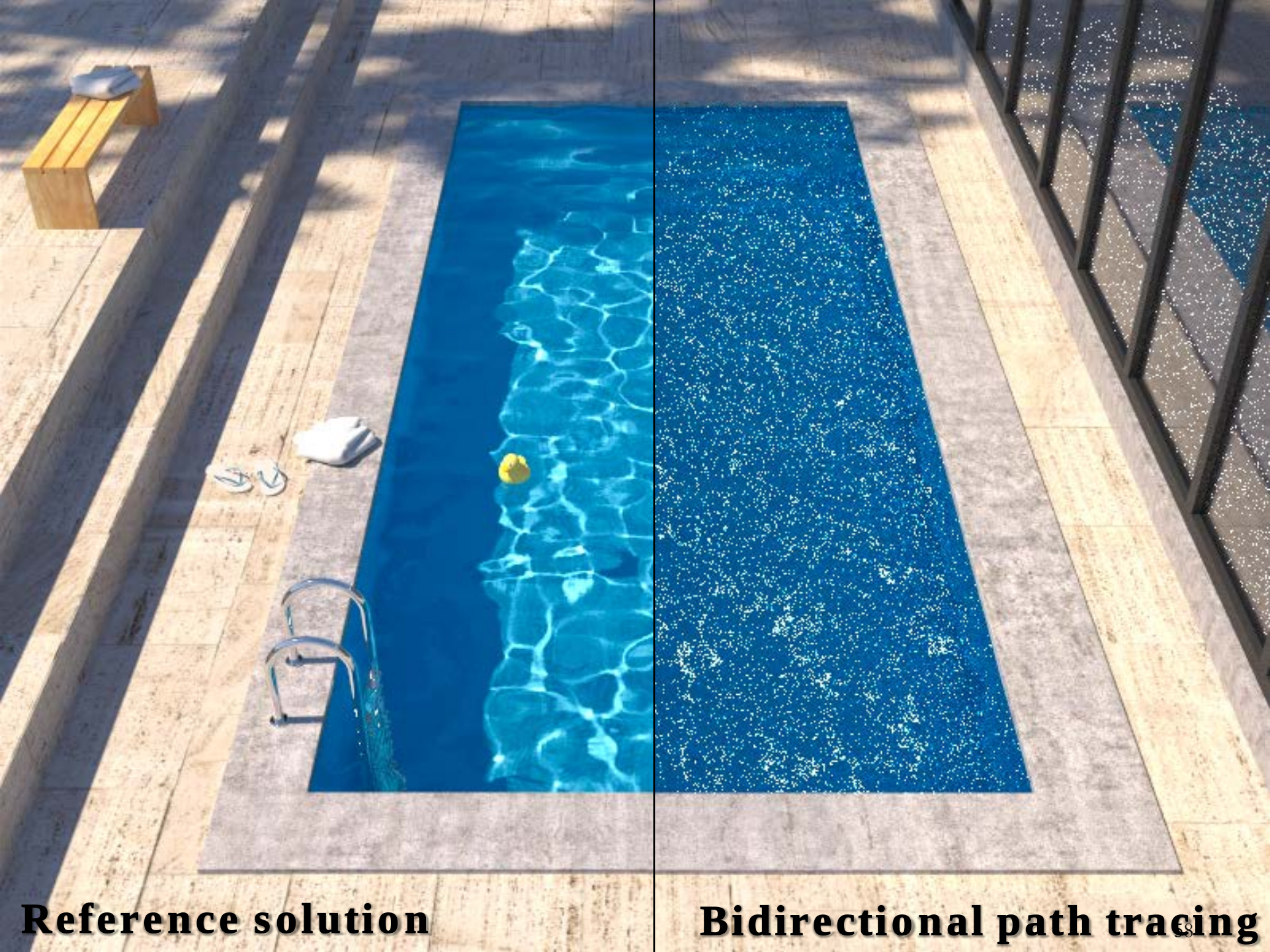
Naive BPT implementation



Other ways of generating the same path

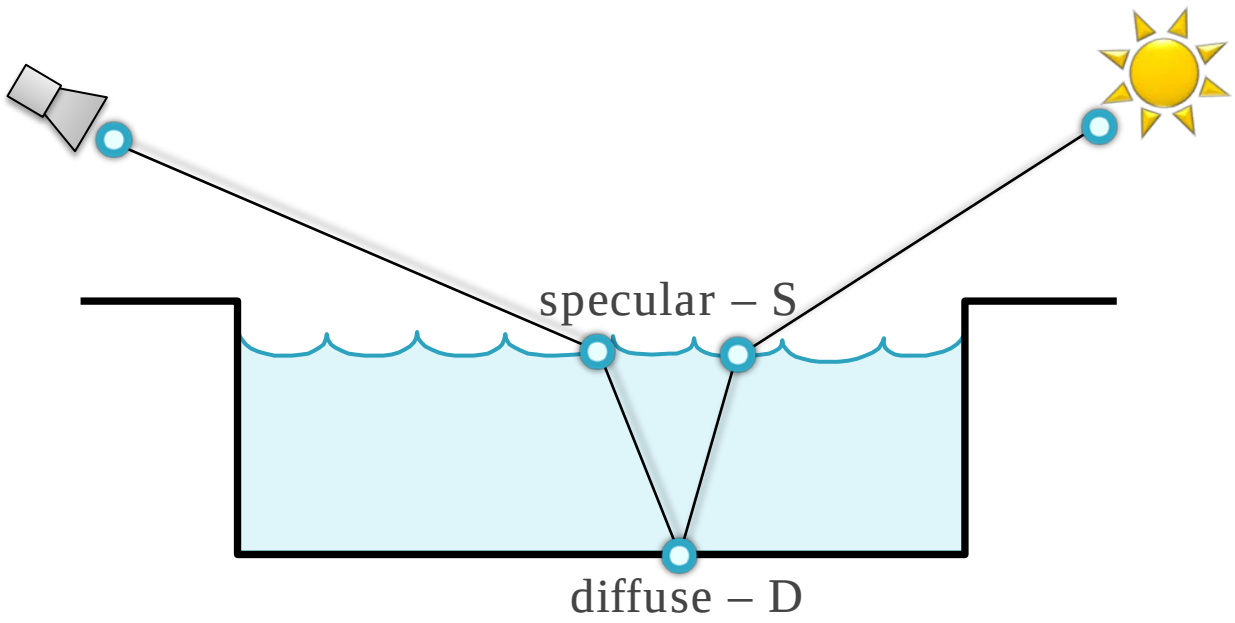


LIMITATIONS OF BIDIRECTIONAL PATH TRACING


Reference solution
Bidirectional path tracing

Insufficient path sampling techniques

- **SDS paths** sampled with zero (or very small) pdf

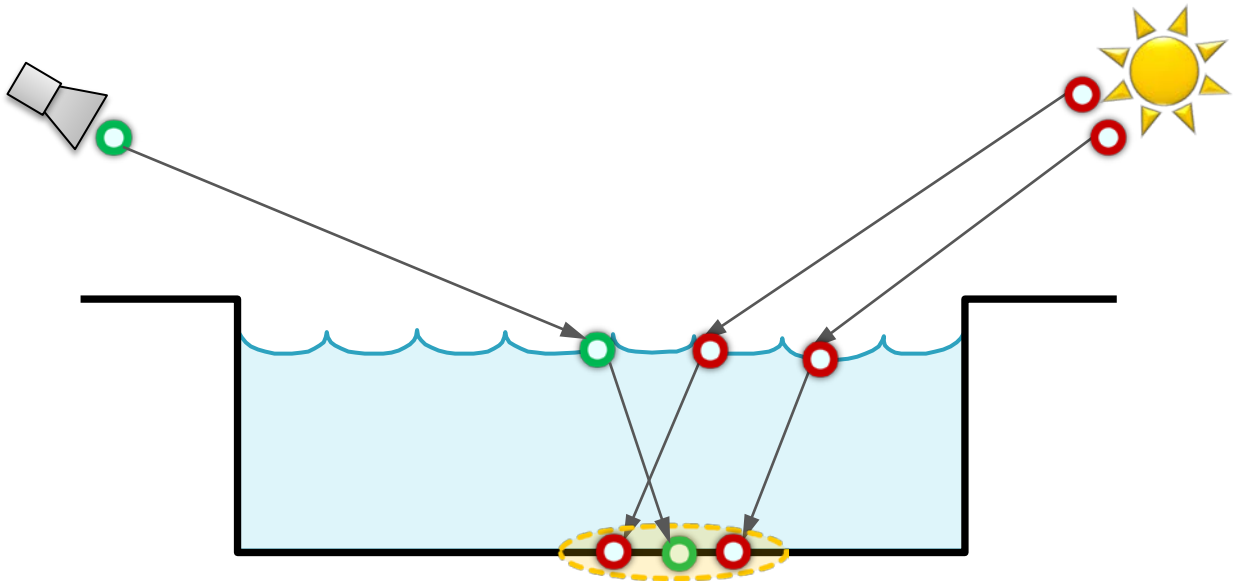


PHOTON MAPPING

(DENSITY ESTIMATION)

Photon mapping (Density estimation)

1. Many fwd walks + store particles (“photon map”)
2. Radiance estimate: (Kernel) **density estimation**



Summary so far

- Physically-plausible rendering = **light transport simulation**
- **Path-integral formulation**
  - Light transport = numerical evaluation of the path integral
- **Different algorithms** = different estimators of the path integral
- BPT, PM = among the **most robust** previous work

OUR WORK

Light Transport Simulation with Vertex Connection and Merging

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Saarland University

Jaroslav Křivánek
Charles University in Prague

Tomáš Davidovič
Saarland University

Philipp Slusallek
Saarland University

SIGGRAPH Asia 2012

Computer Graphics Charles University

SAARLAND UNIVERSITY

Bidirectional path tracing (30 min)

Photon mapping (Density estimation) (30 min)


Vertex connection and merging (30 min)

Overview

☹ **Problem**: different mathematical frameworks

- **BPT**: Monte Carlo estimator of a path integral
- **PM**: Density estimation

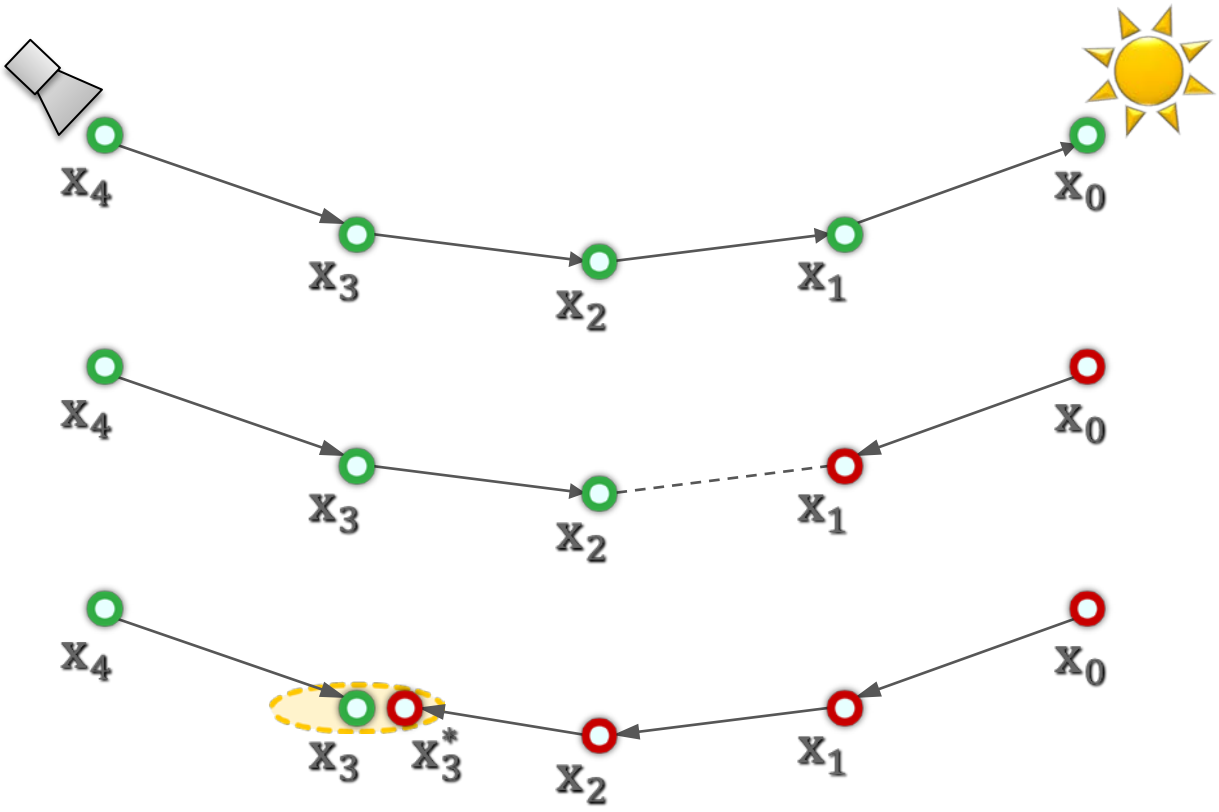
☝ **Key contribution:** Reformulate photon mapping in Veach's path integral framework

1) Formalize as path sampling technique
2) Derive path probability density

✓ Combination of BPT and PM into a **robust** algorithm

Sampling techniques

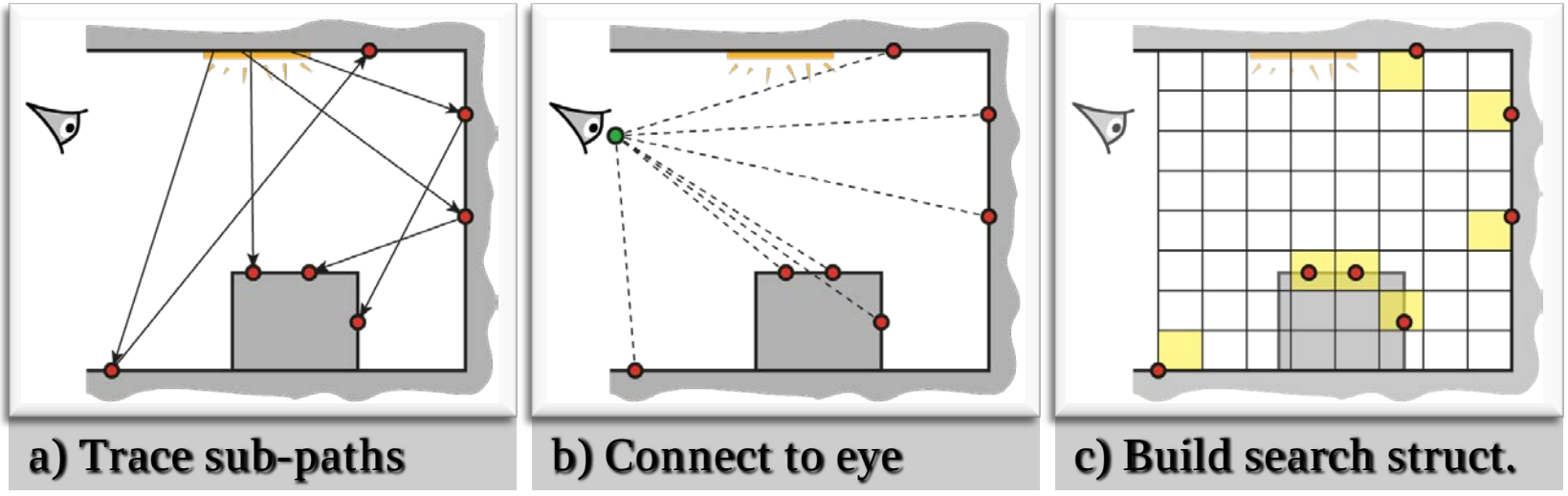
Light vertex
Camera vertex



Unidirectional	2 ways
Vertex connection	4 ways
Vertex merging	**5 ways**
Total	**11 ways**

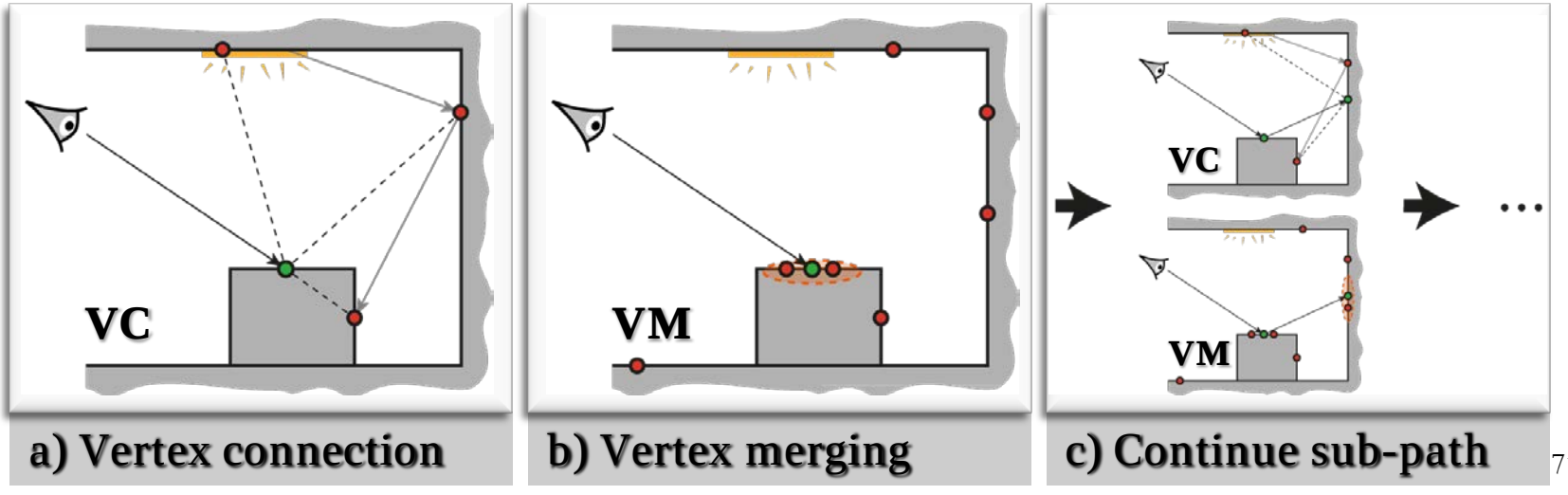
VCM – Algorithm overview

Stage 1: Light sub-path sampling



a) Trace sub-paths | b) Connect to eye | c) Build search struct.

Stage 2: Eye sub-path sampling



a) Vertex connection | b) Vertex merging | c) Continue sub-path

Bidirectional path tracing (30 min)

Stochastic progressive photon mapping (30 min)


Vertex connection and merging (30 min)

Relative technique contributions

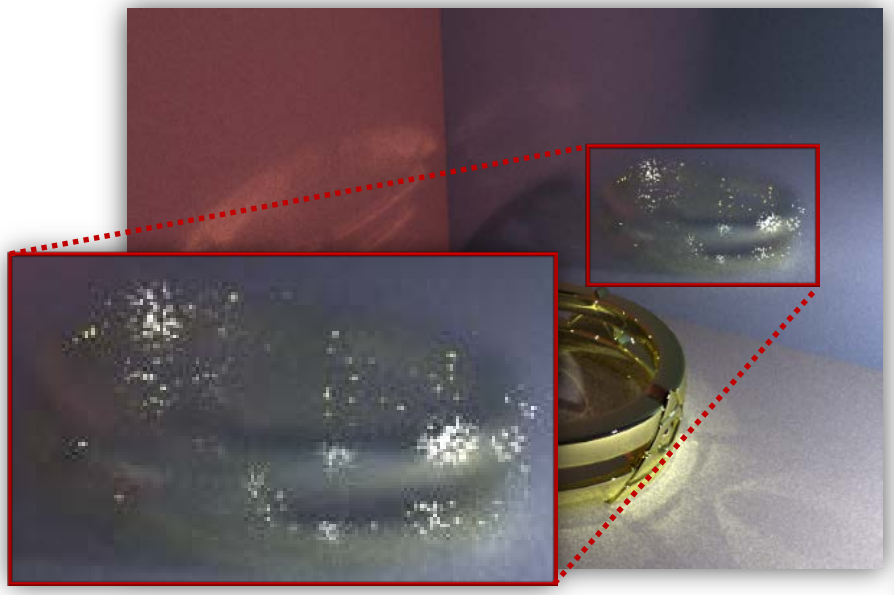
Bidirectional path tracing (30 min)

Stochastic progressive photon mapping (30 min)

Vertex connection and merging (30 min)

Relative technique contributions

Remaining challenges



Additional resources

- **Implementation technical report**
  Image comparisons
  [iliyan.com]

- **SmallVCM** – *open-source VCM implementation*
  [SmallVCM.com]

VCM in production

VCM: Summary

- Image synthesis requires **robust** estimators
- **Vertex Connection and Merging**
  - Bidirectional path tracing + Photon mapping (density est.)
  - Photon mapping (density est.) as a path sampling technique
- **Invaluable tools**
  - Multiple importance sampling
  - Path integral view of light transport

UNIFYING POINTS, BEAMS, AND PATHS IN VOLUMETRIC LIGHT TRANSPORT SIMULATION

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Toshiya Hachisuka
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Petr Vévoda
Charles University in Prague

Martin Šik
Charles University in Prague

Derek Nowrouzezahrai
Univesity of Montreal

Wojciech Jarosz
Disney Research Zurich

CHARLES UNIVERSITY

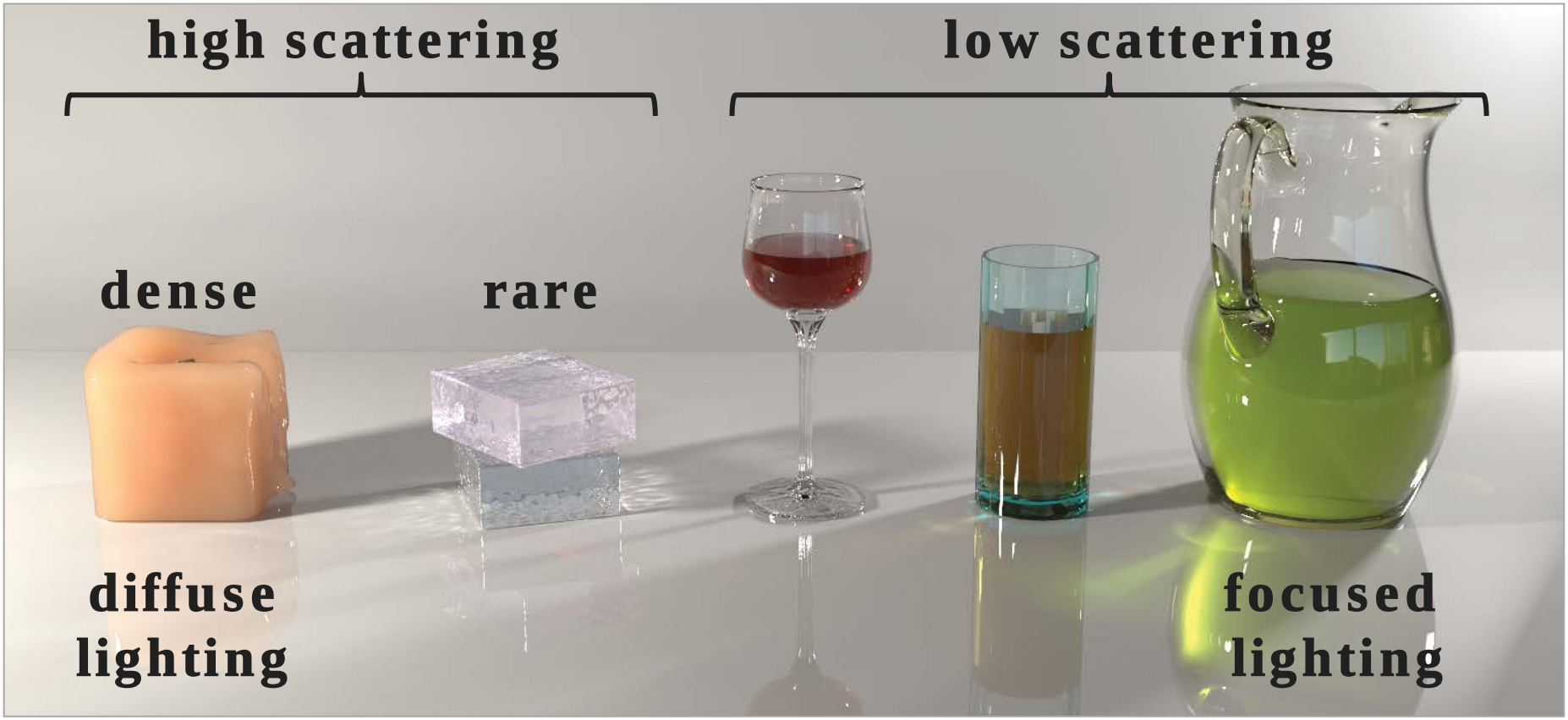
AARHUS UNIVERSITY

Université de Montréal

Disney Research, Zurich

Goal: Robust rendering of media

- Robust to: **media properties, lighting**



Existing volumetric rendering algorithms

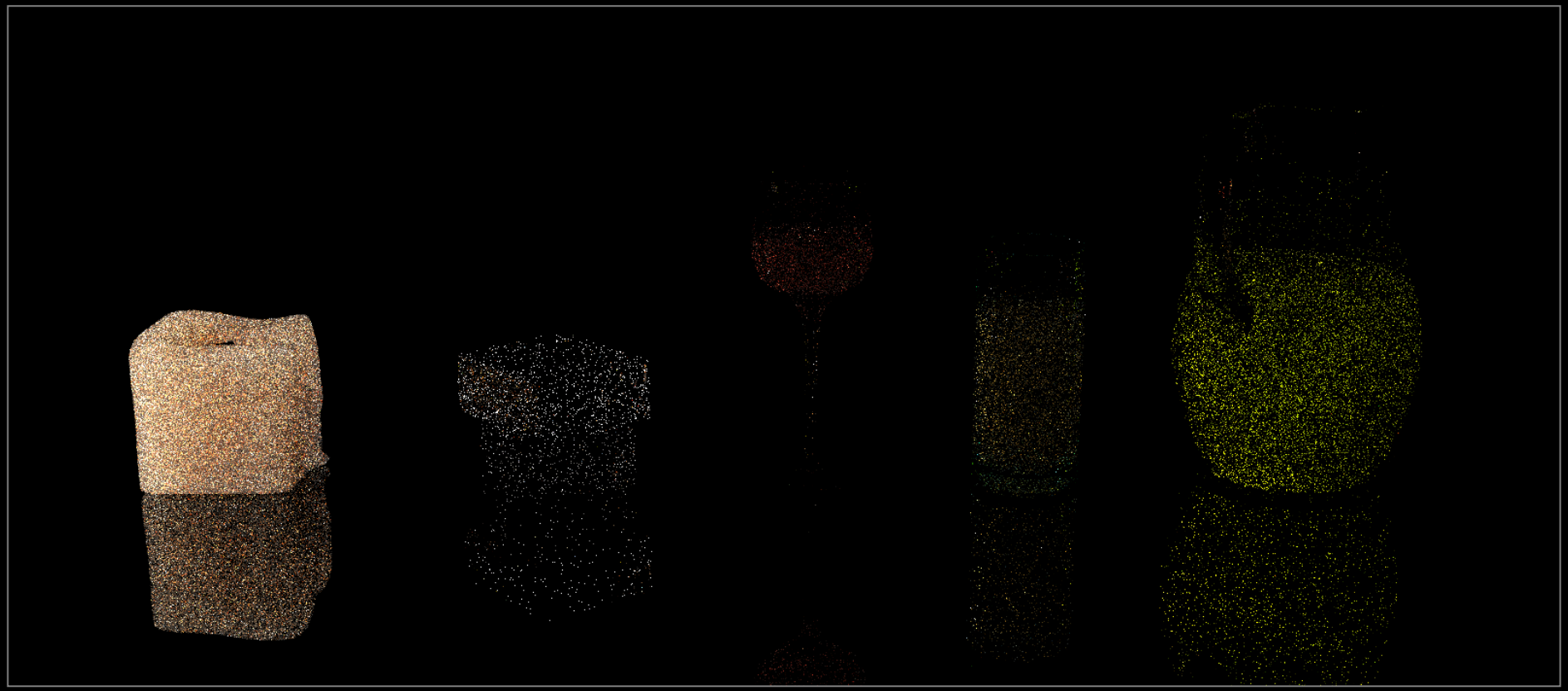
- **MC path integration**
  - Path tracing [Kajiya '86, Rushmeier and Torrance '88]
  - Bidirectional path tracing [Lafortune and Willems '96]

- **Photon density estimation**
  - Volumetric photon mapping [Jensen and Christensen '98]
  - Beam radiance estimate [Jarosz et al. '08]
  - Photon beams [Jarosz et al. '11]

- **Issue**
  - No existing algorithm is **robust** enough

Bidirectional path tracing
1 hour

Volumetric photon mapping
1 hour



Beam radiance estimate
1 hour

Photon beams
1 hour

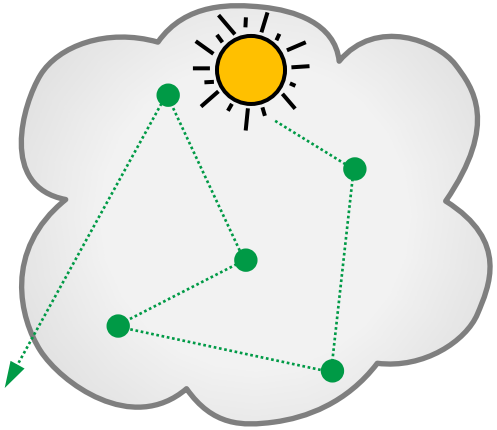
Our algorithm
1 hour

Our approach: Combine estimators

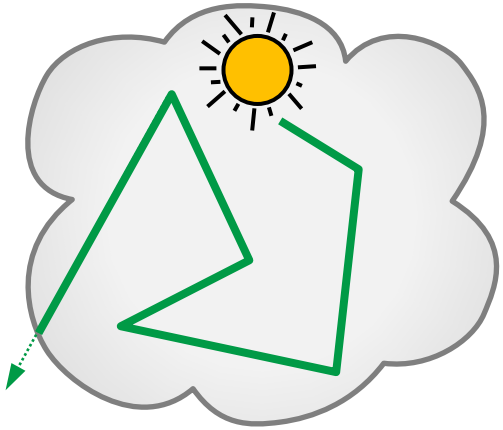
- **Multiple Importance Sampling** [Veach and Guibas '95]
- **Previous work**
  - Bidirectional path tracing (**BPT**) [Veach and Guibas '95]
  - Vertex connection and merging (**VCM**) [Georgiev et al. '12]
  - Unified path sampling (**UPS**) [Hachisuka et al. '12]
- **Our algorithm**
  - **"Unified points beams and paths" (UPBP)**

RADIANCE REP.:

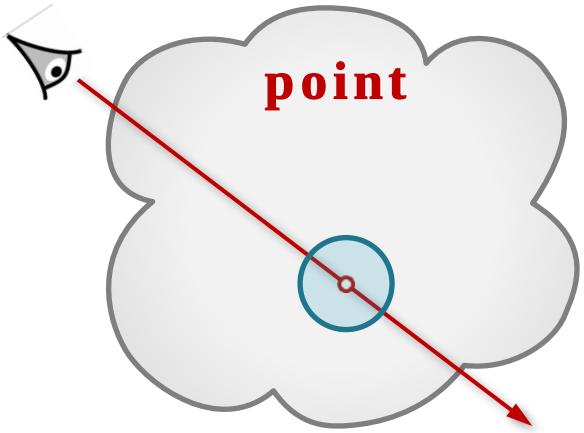
photon **points**



photon **beams**

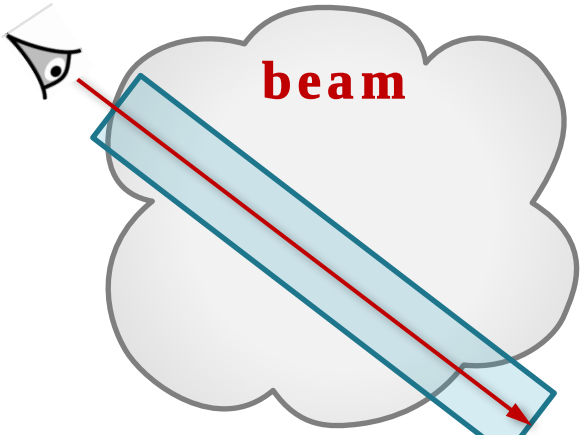


QUERY



Point - Point

Beam - Point



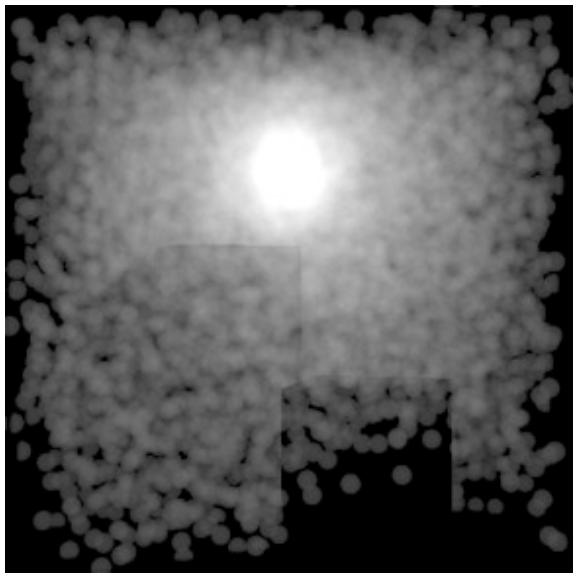
Point - Beam

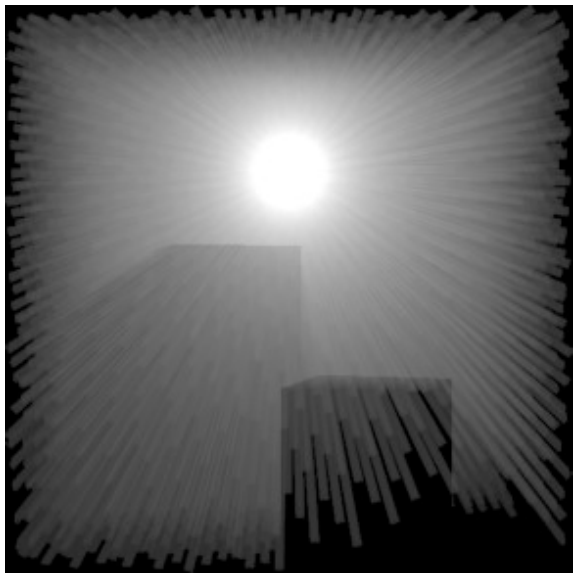
Beam - Point

Why combine points and beams?

- Won't photon beams always outperform photon points?

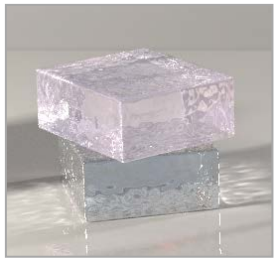
100k photon **points** | reference | 5k photon **beams**





from [Jarosz et al. '11a]

Our variance analysis



rare media

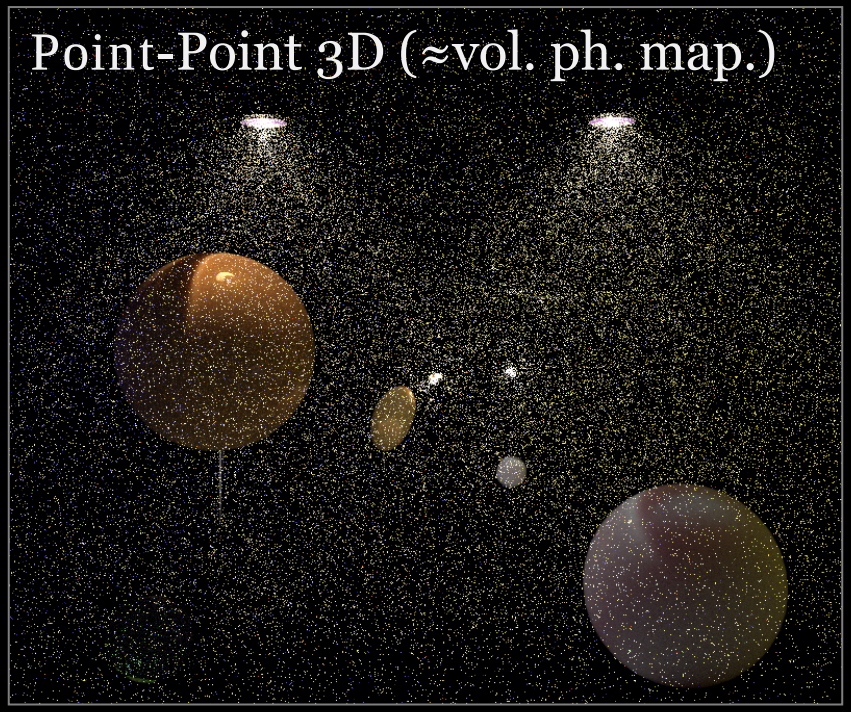
dense media

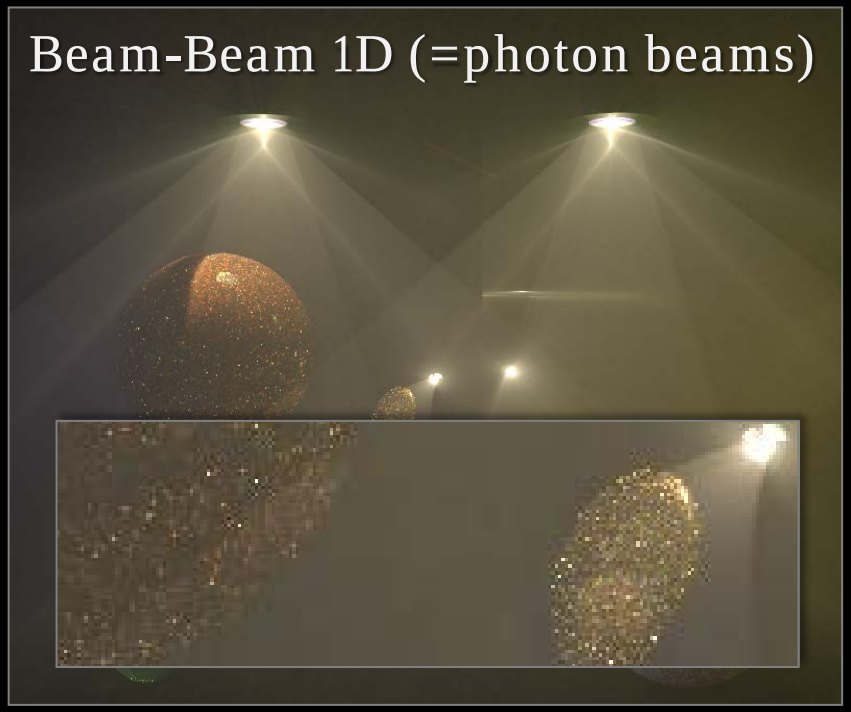
beams:		
points:		

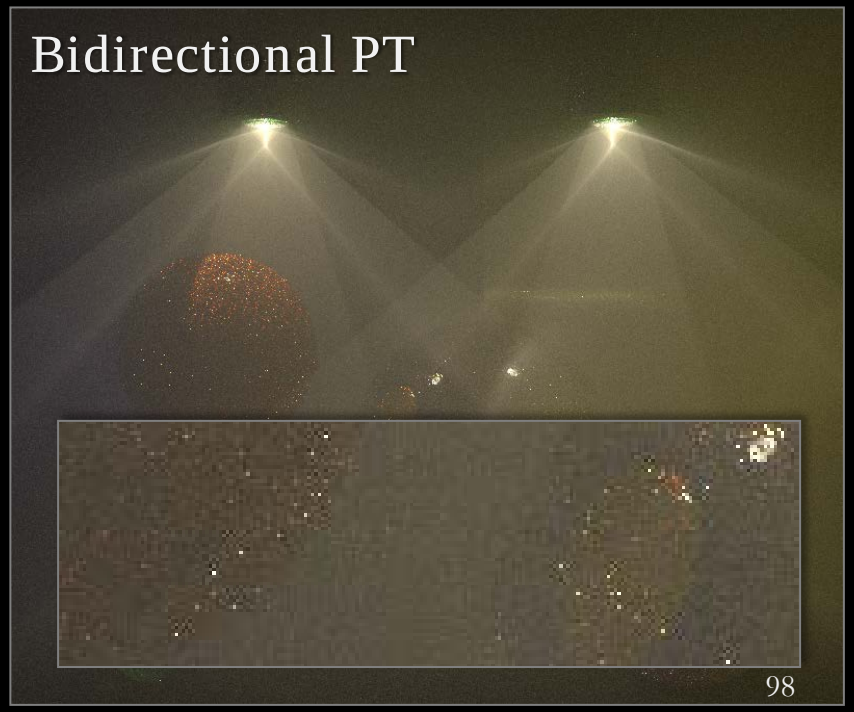

Full transport
rare, fwd-scattering fog
back-scattering
high albedo
back-scattering

Medium transport only

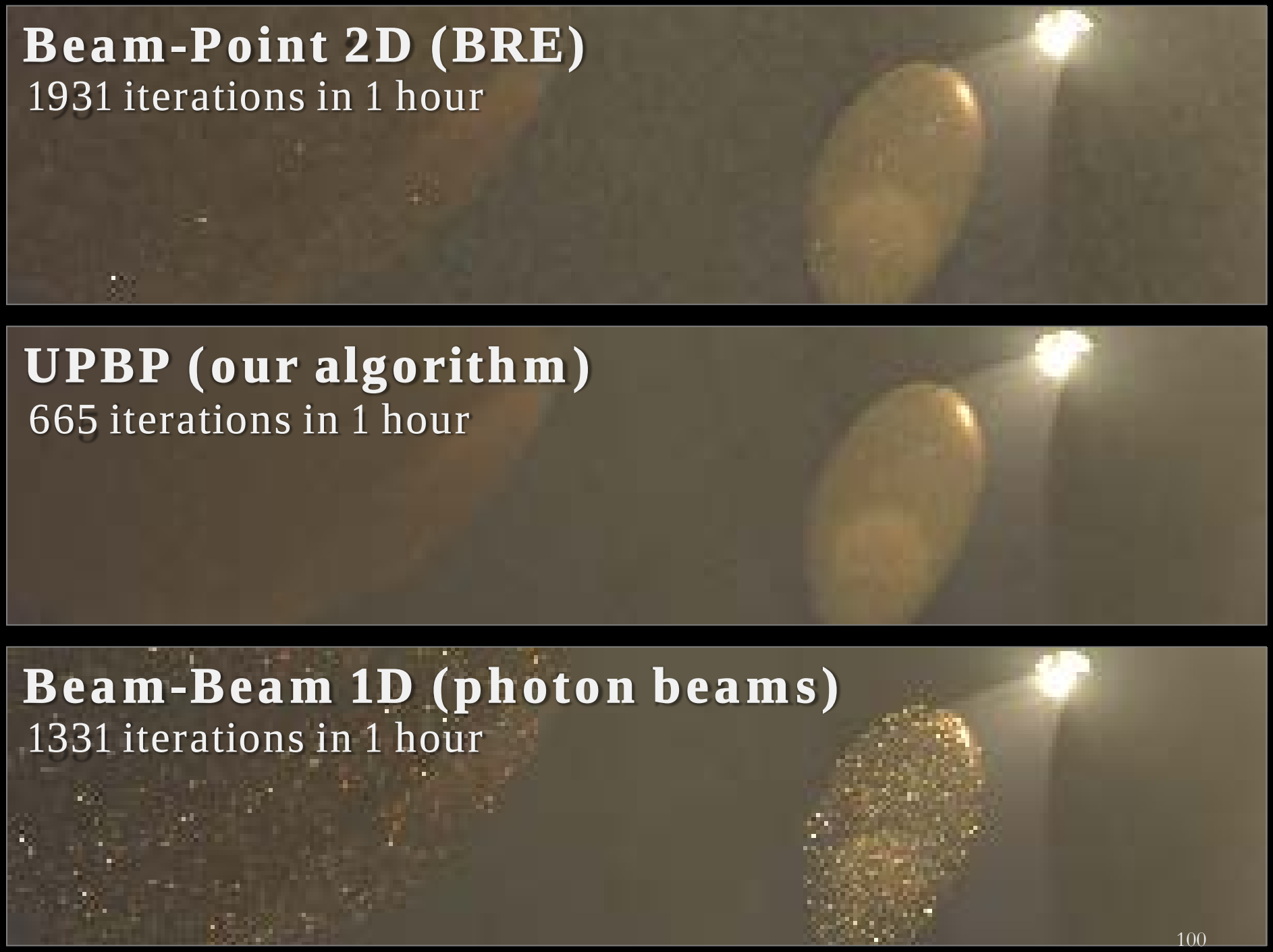
Previous work comparison, 1 hr



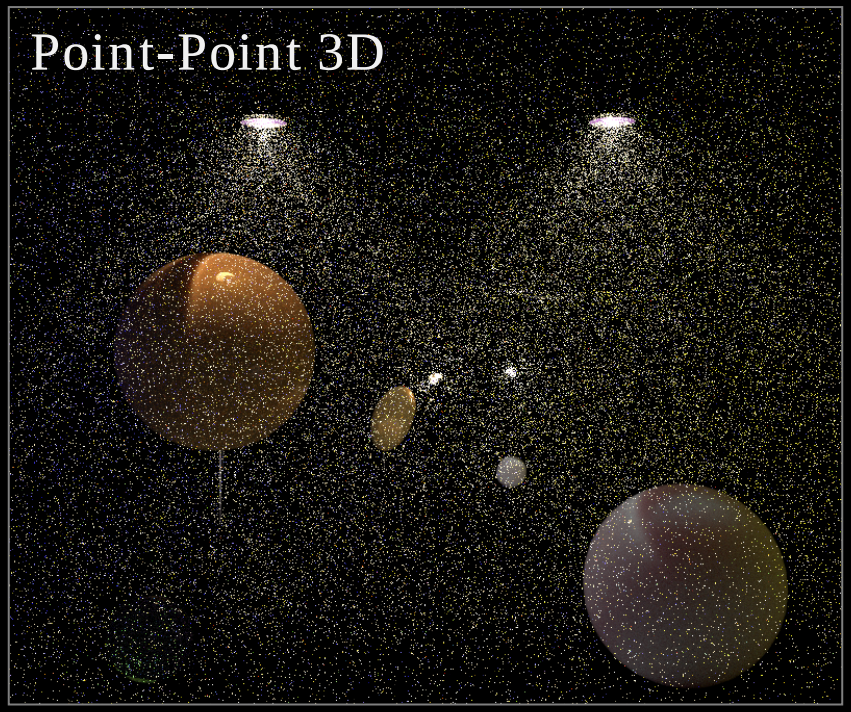


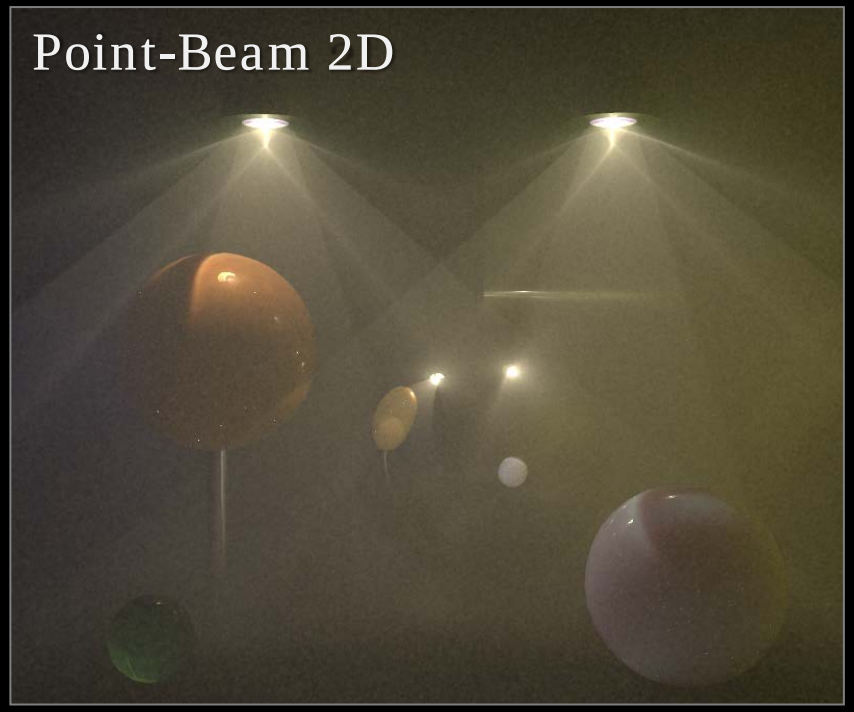


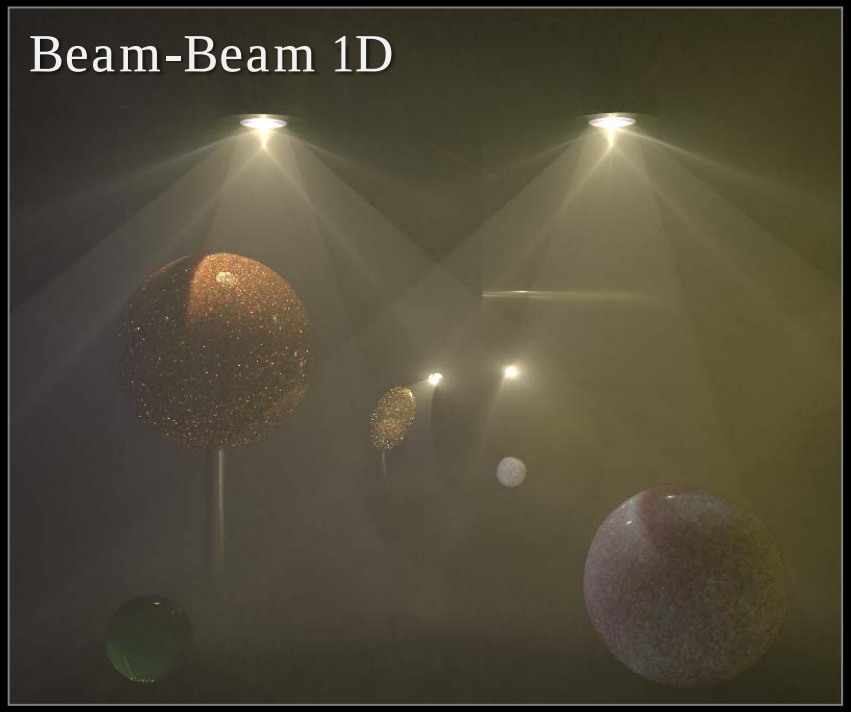
UPBP (our algorithm)
1 hour


Beam-Point 2D (BRE)
1931 iterations in 1 hour
UPBP (our algorithm)
665 iterations in 1 hour
Beam-Beam 1D (photon beams)
1331 iterations in 1 hour

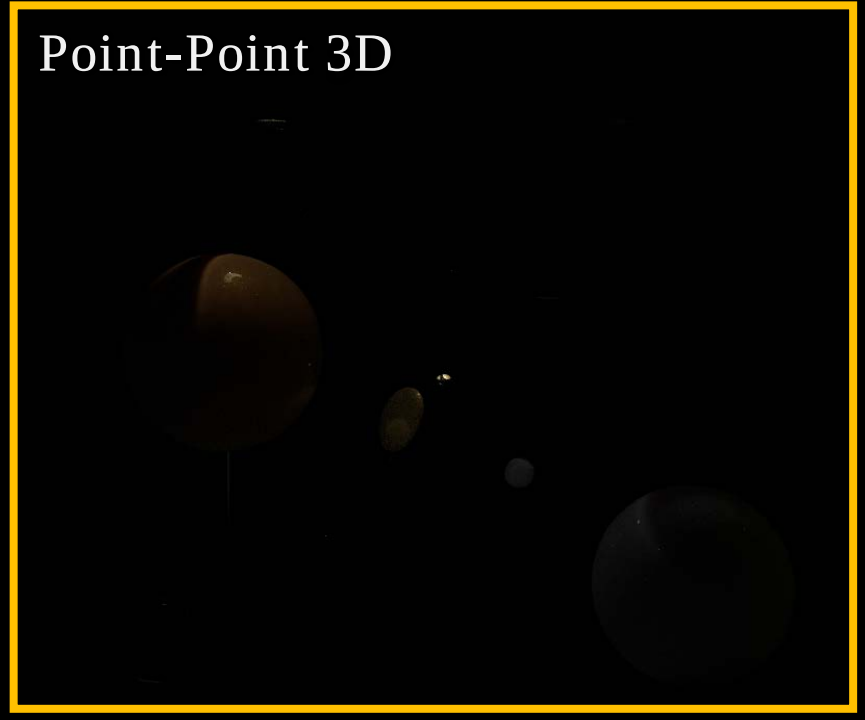
Previous work comparison, 1 hr

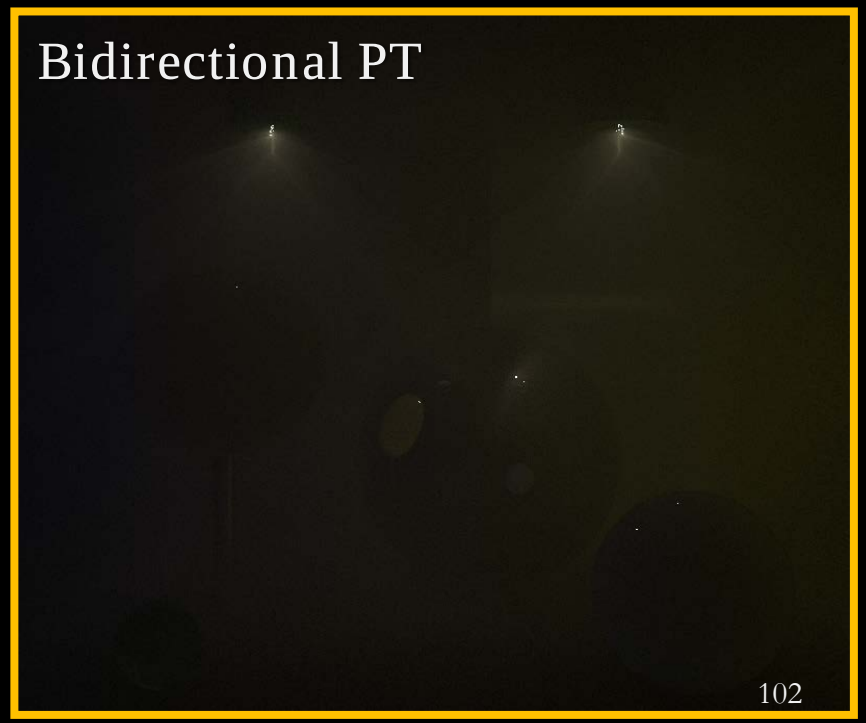


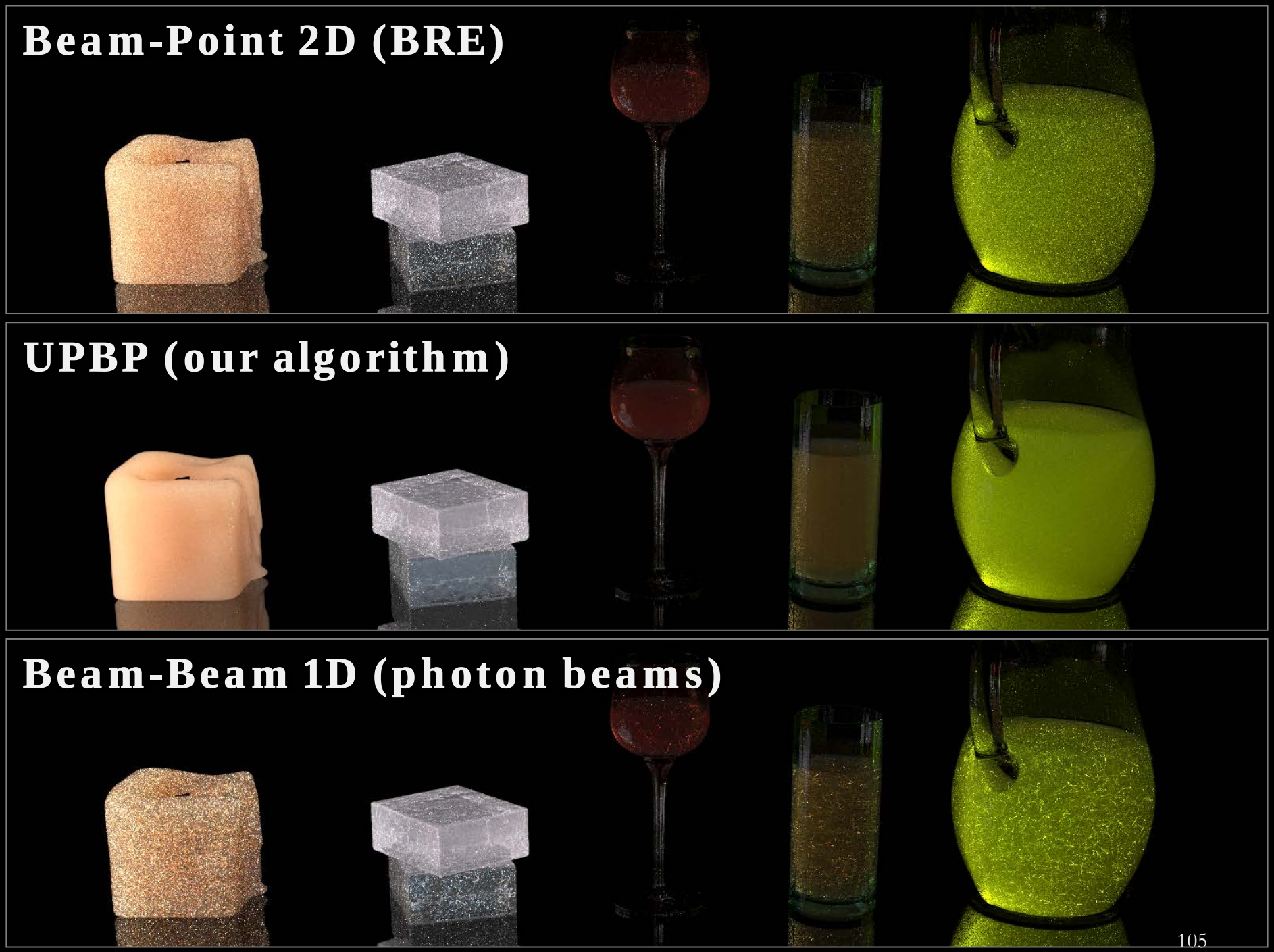




Weighted contributions



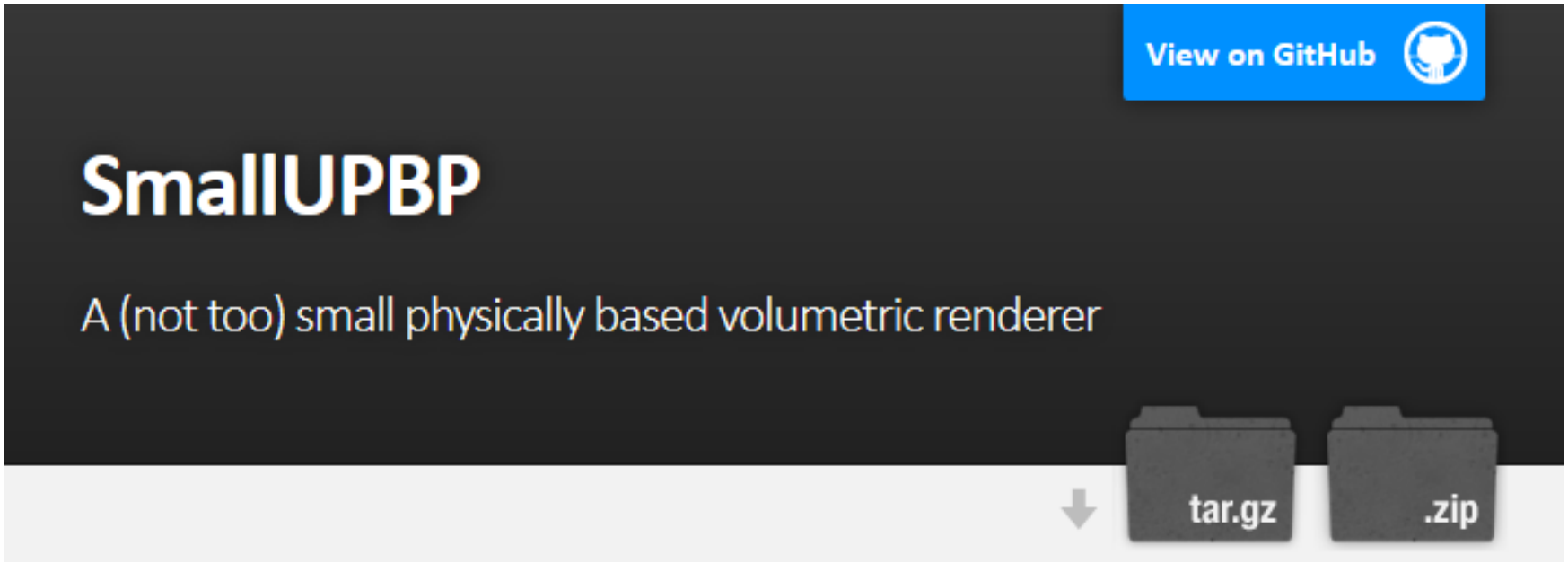



Beam-Point 2D (BRE)
UPBP (our algorithm)
Beam-Beam 1D (photon beams)

Conclusions

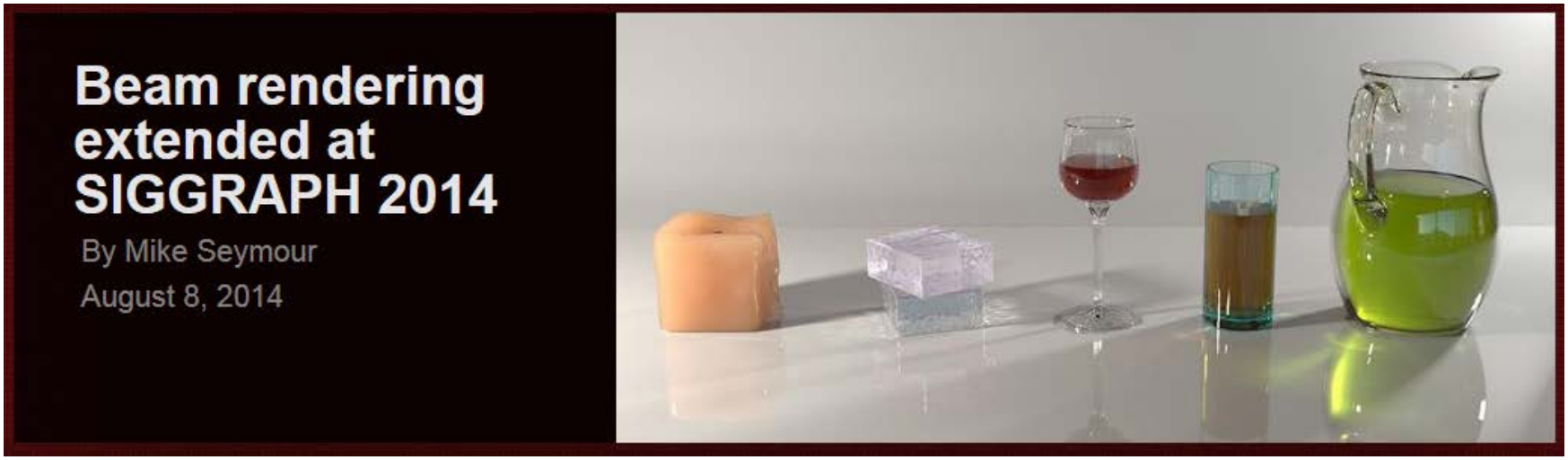
- **Photon beams are not always better than photon points**
  - Rare media: beams
  - Dense media: points
- **Practical combined algorithm**
  - Wide range of media properties

Source code



http://www.smallupbp.com/

Media coverage



fxguide

http://www.fxguide.com/featured/beam-rendering-extended-at-siggraph-2014/

UPBP in production

A ZERO-VARIANCE-BASED SAMPLING SCHEME FOR MONTE CARLO SUBSURFACE SCATTERING

Jaroslav Křivánek
Charles University in Prague

Eugene d'Eon
Weta Digital

The work was done while both authors were with **Weta Digital**

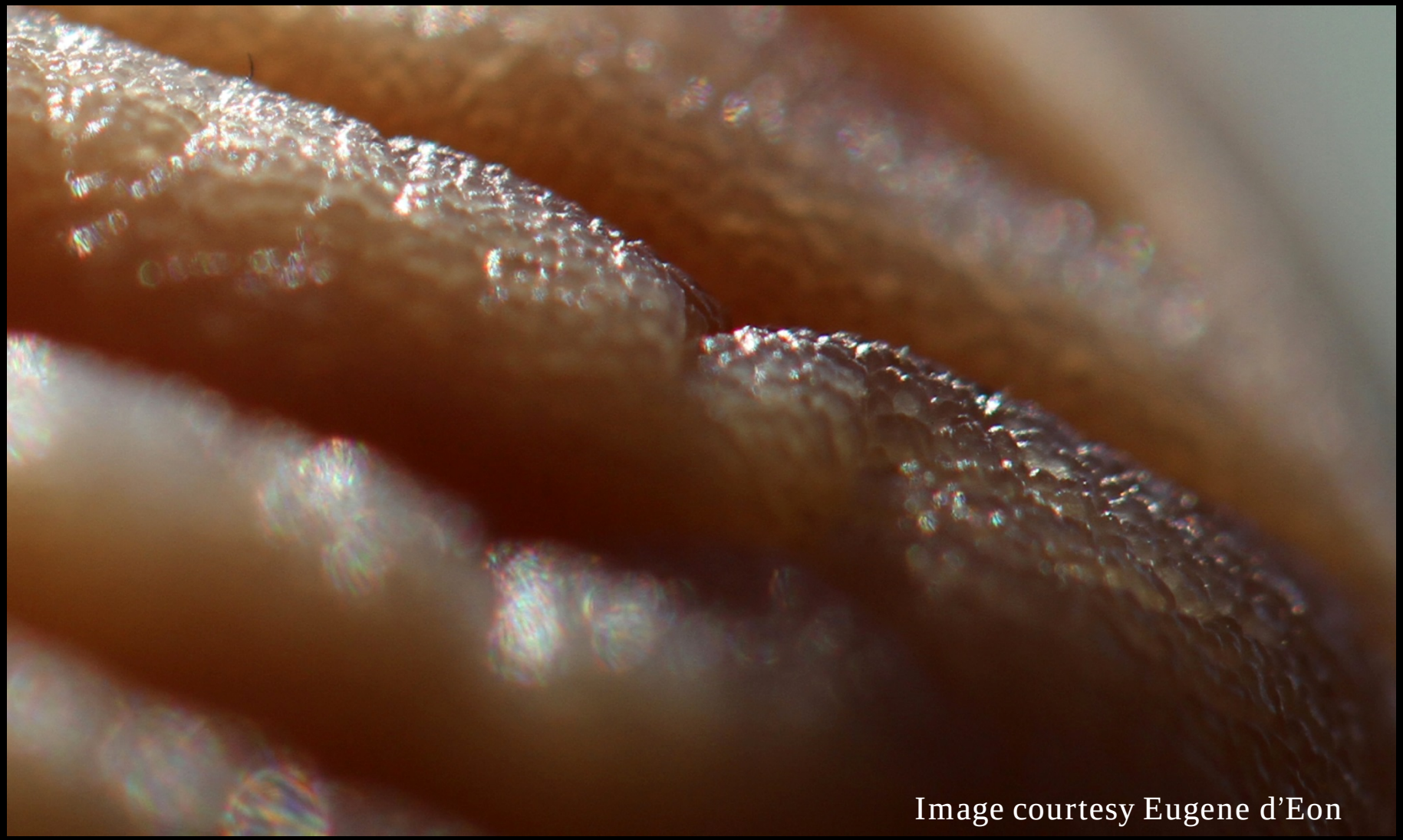
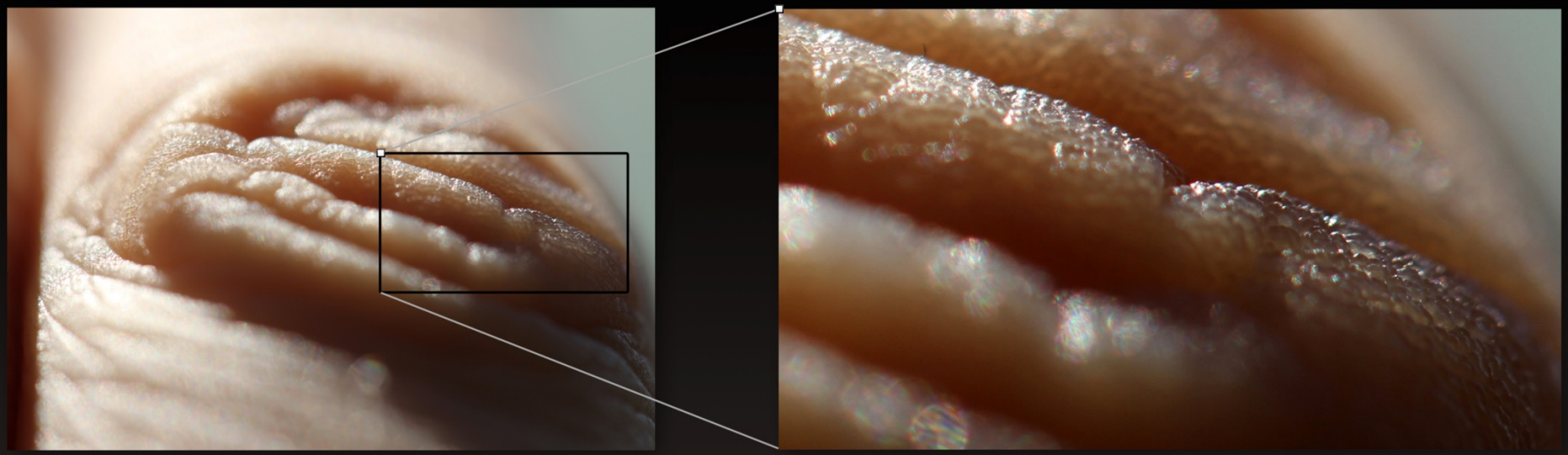
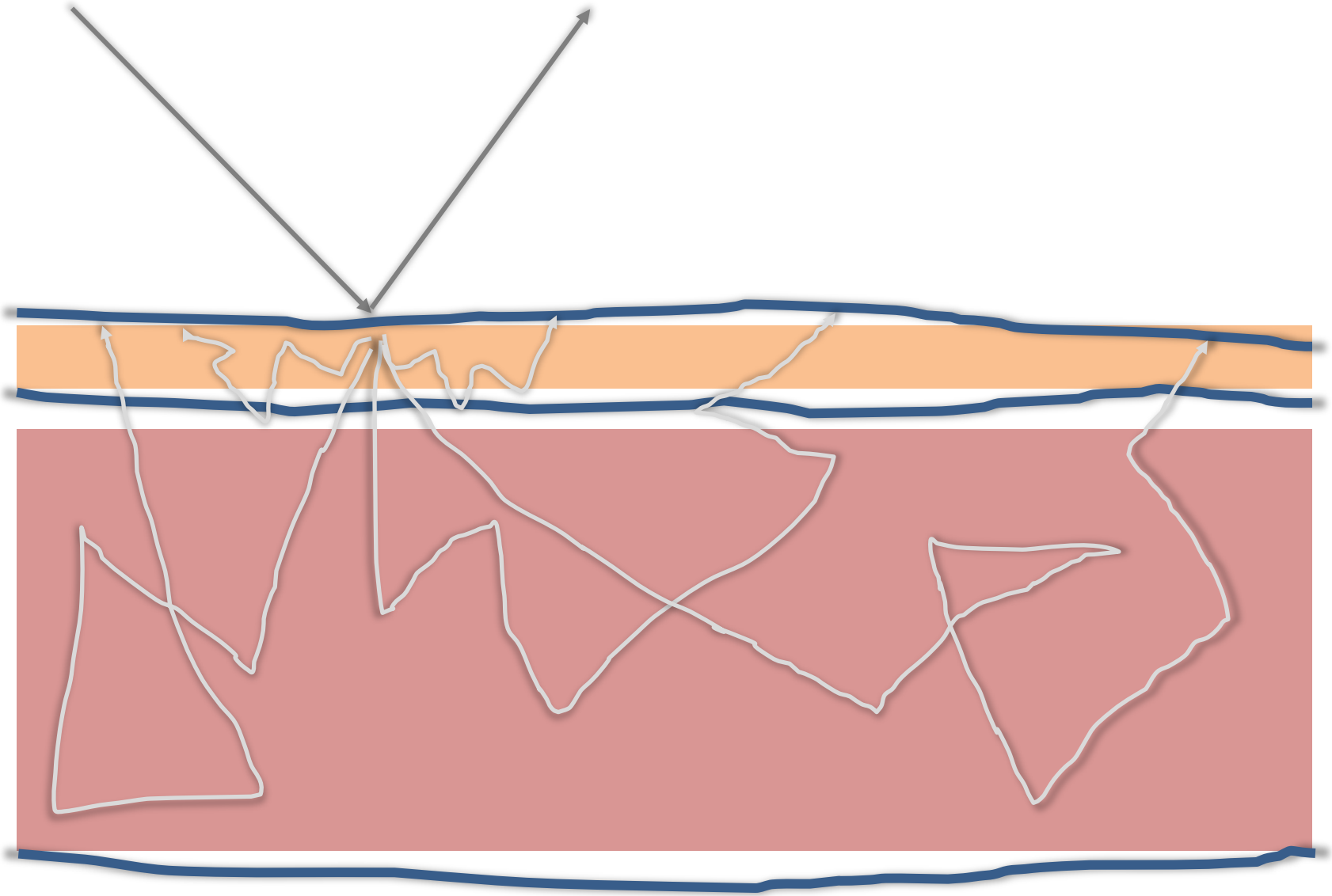
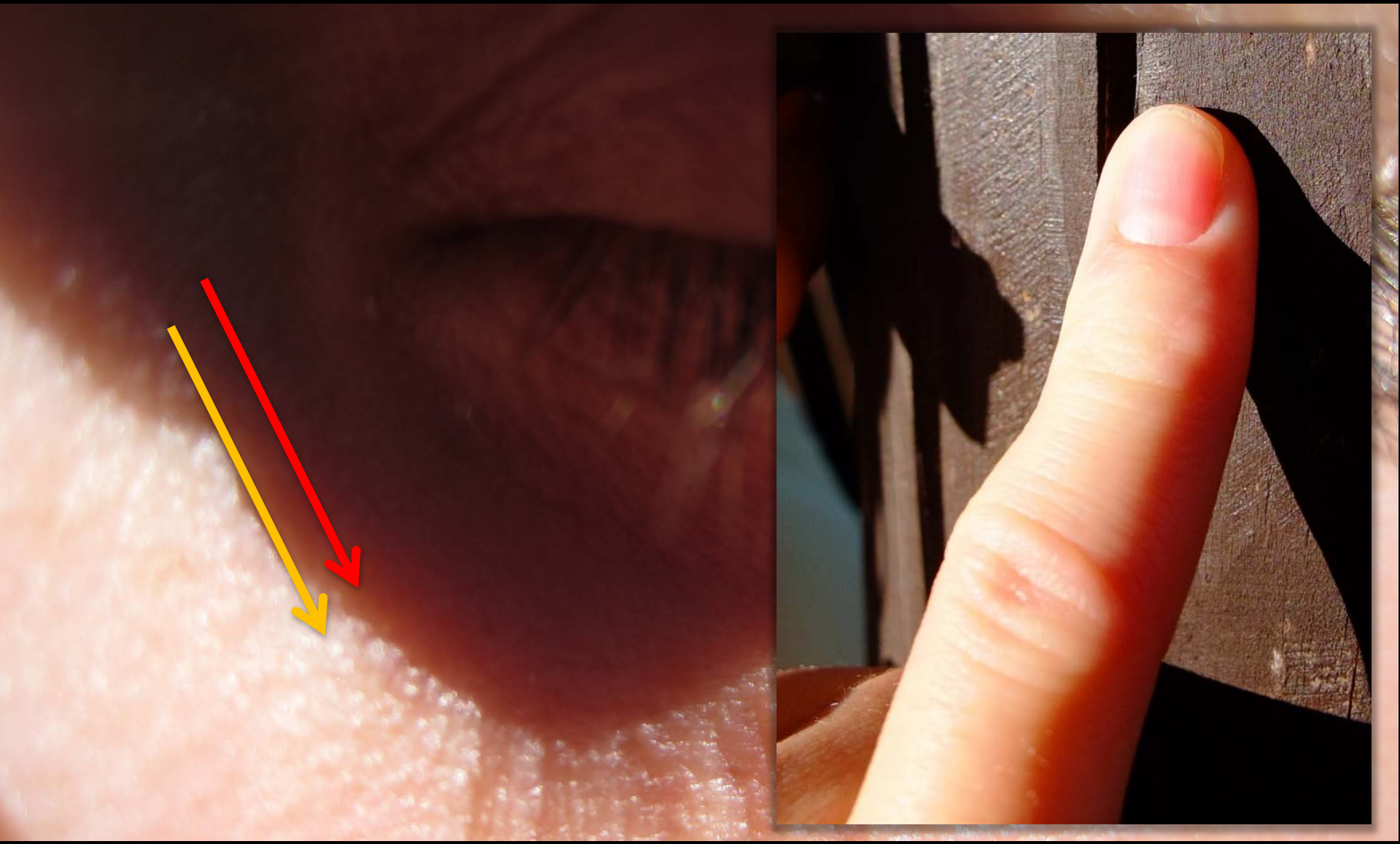


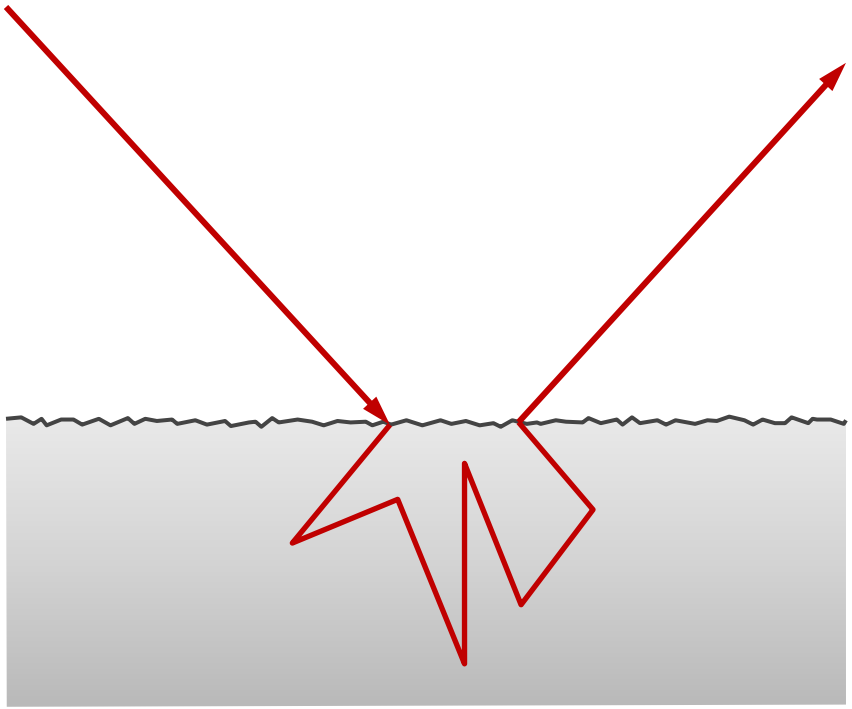
Image courtesy Eugene d’Eon





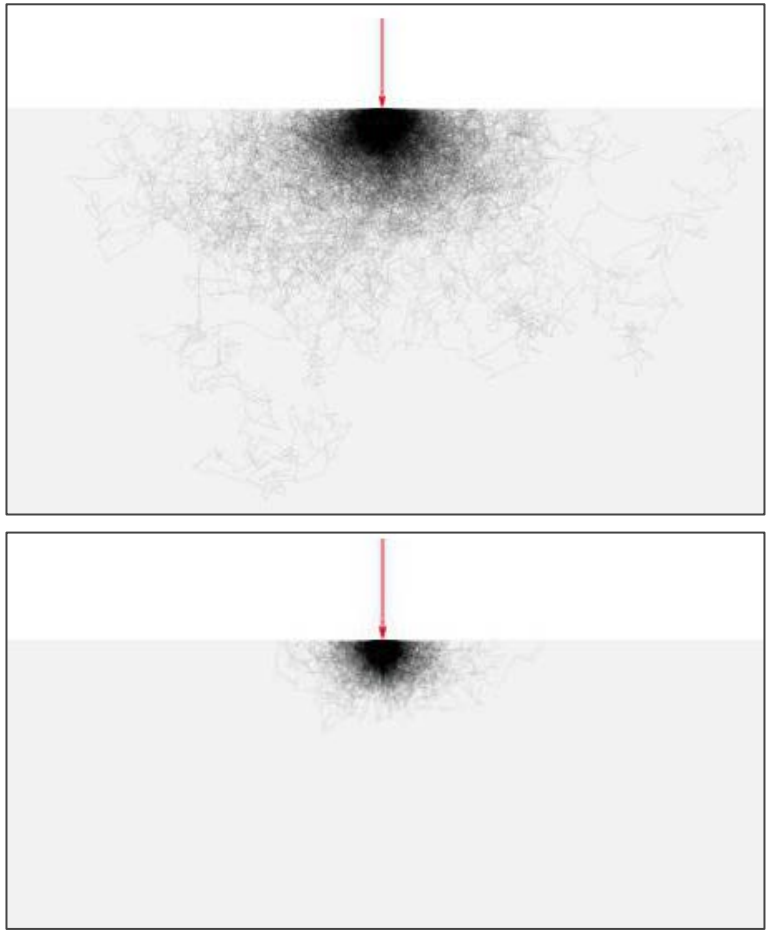


Monte Carlo subsurface scattering



Motivation

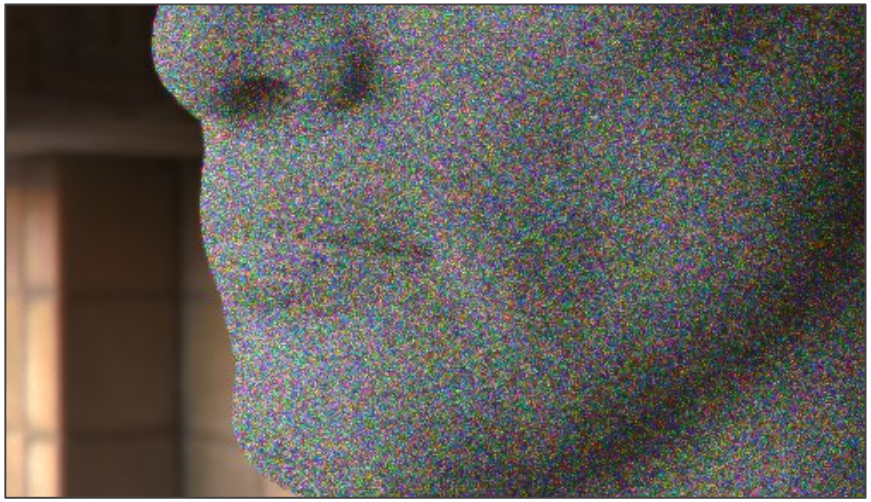
- **Classical random walk**
  - Oblivious to the boundary
- **Goal**
  - Guide paths toward the boundary



Teaser

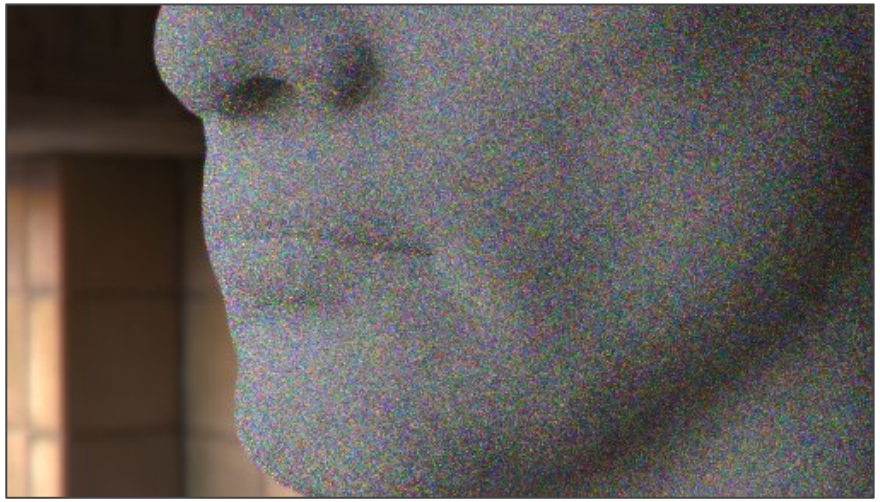
Classical random walk

Oblivious to the boundary



New method

Guides paths toward the boundary



- Variance reduction
- Efficiency improvement (shorter paths on average)

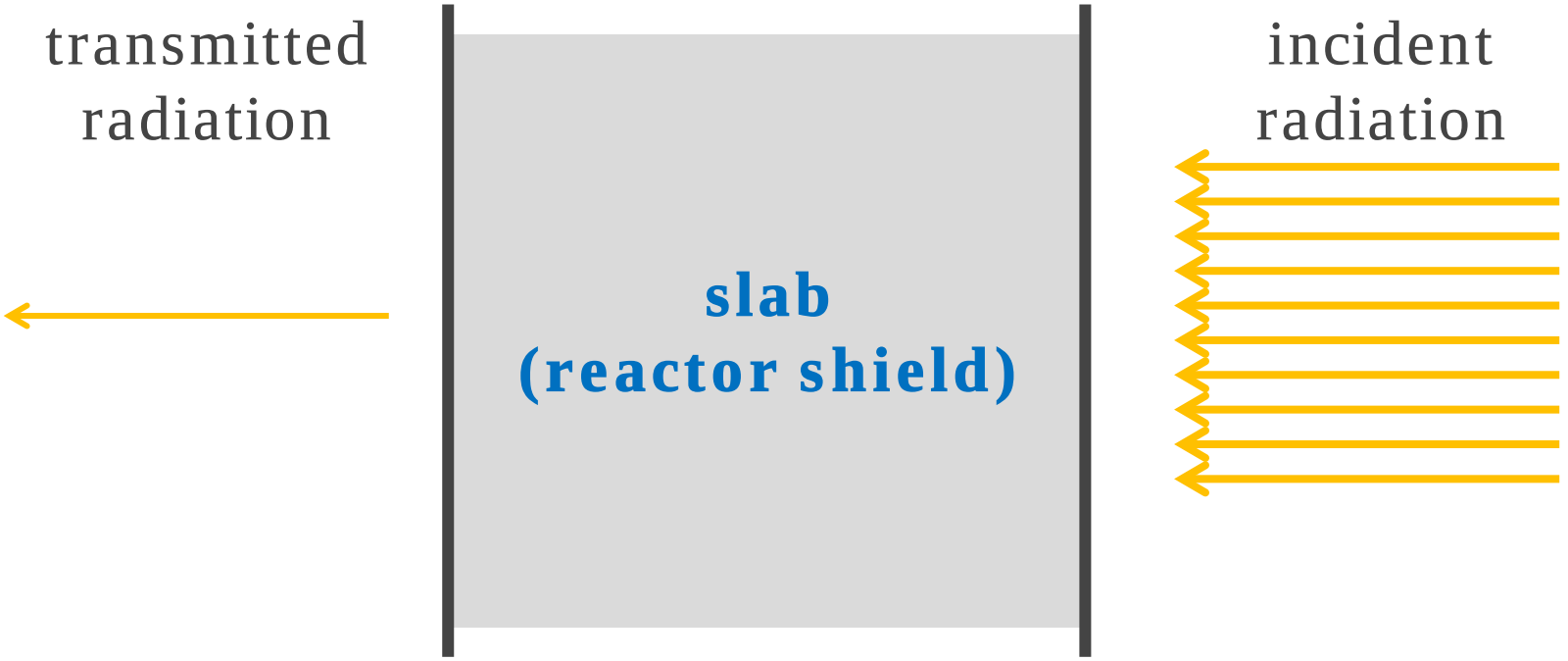
Monte Carlo Subsurface Scattering

- Accurate, no assumptions about the geometry
- Fits smoothly into a physically-based path tracer

- **BUT** slow
  - Hundreds of scattering events to get an accurate answer

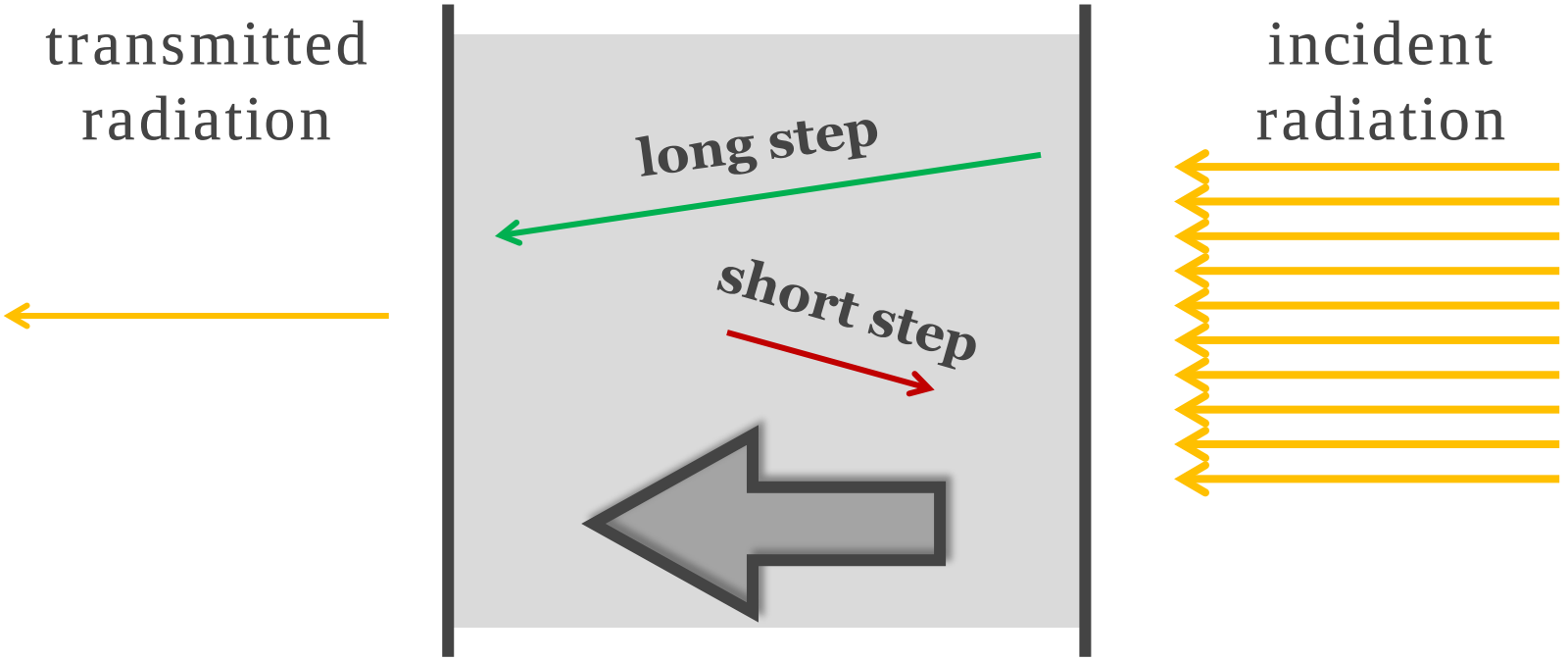
Previous work in neutron transport

- "**Deep penetration problems**" (reactor shield design)
  - Blind MC: **One in a billion** particles makes it through



Previous work in neutron transport

- **Path stretching**
  [Clark '66, Ponti '71, Spanier '71]
  - heuristic, manual "stretching parameter" setting



Zero-variance random walk theory

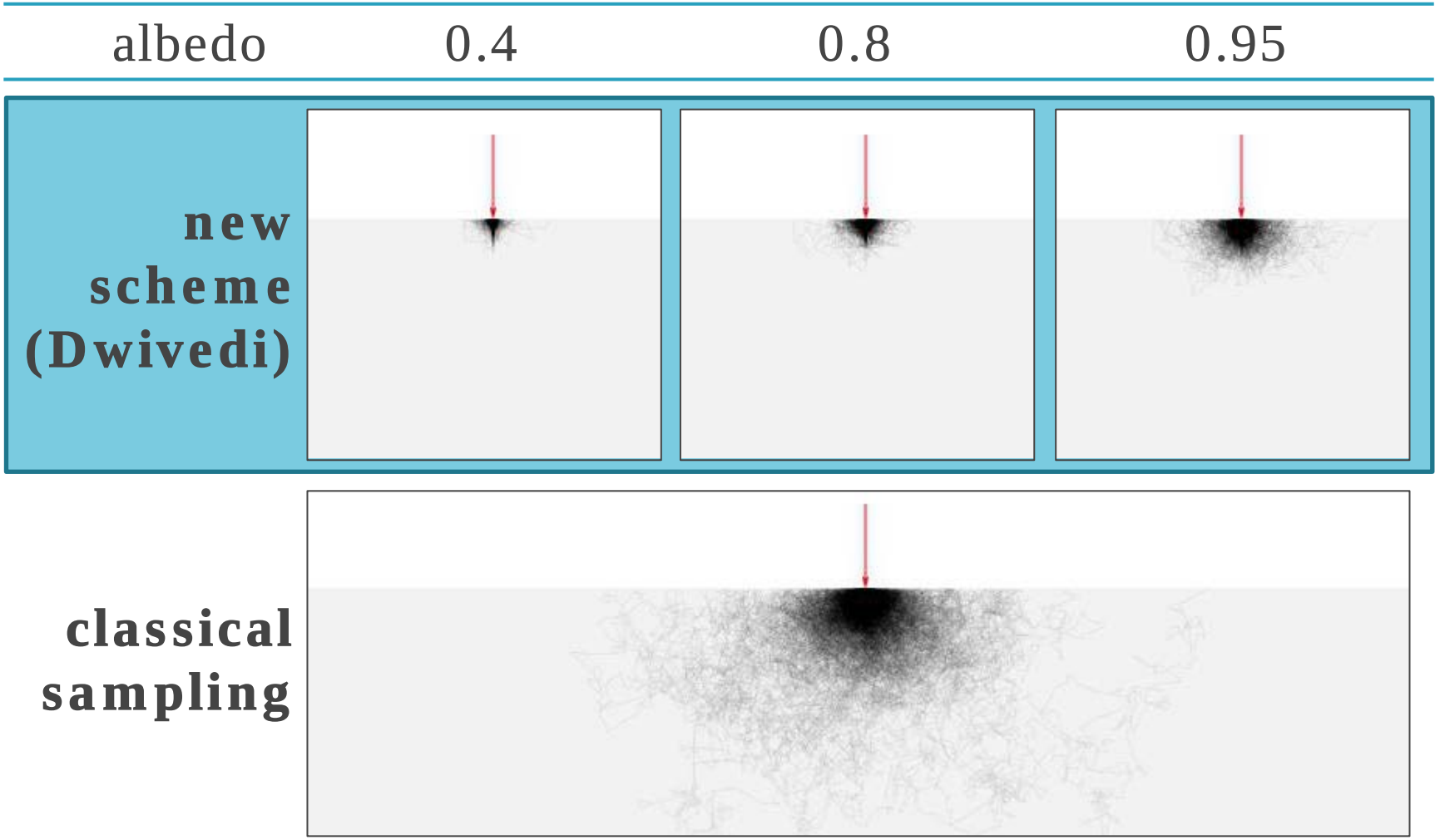
- Zero variance random walk theory
  [Kahn '54, Kalos and Whitlock '08, **Hoogenboom '08, Booth '11**]

- **[Dwivedi '81]**
  - Synergistic **path stretching** and **angular sampling**
  - Solid theory, no heuristics

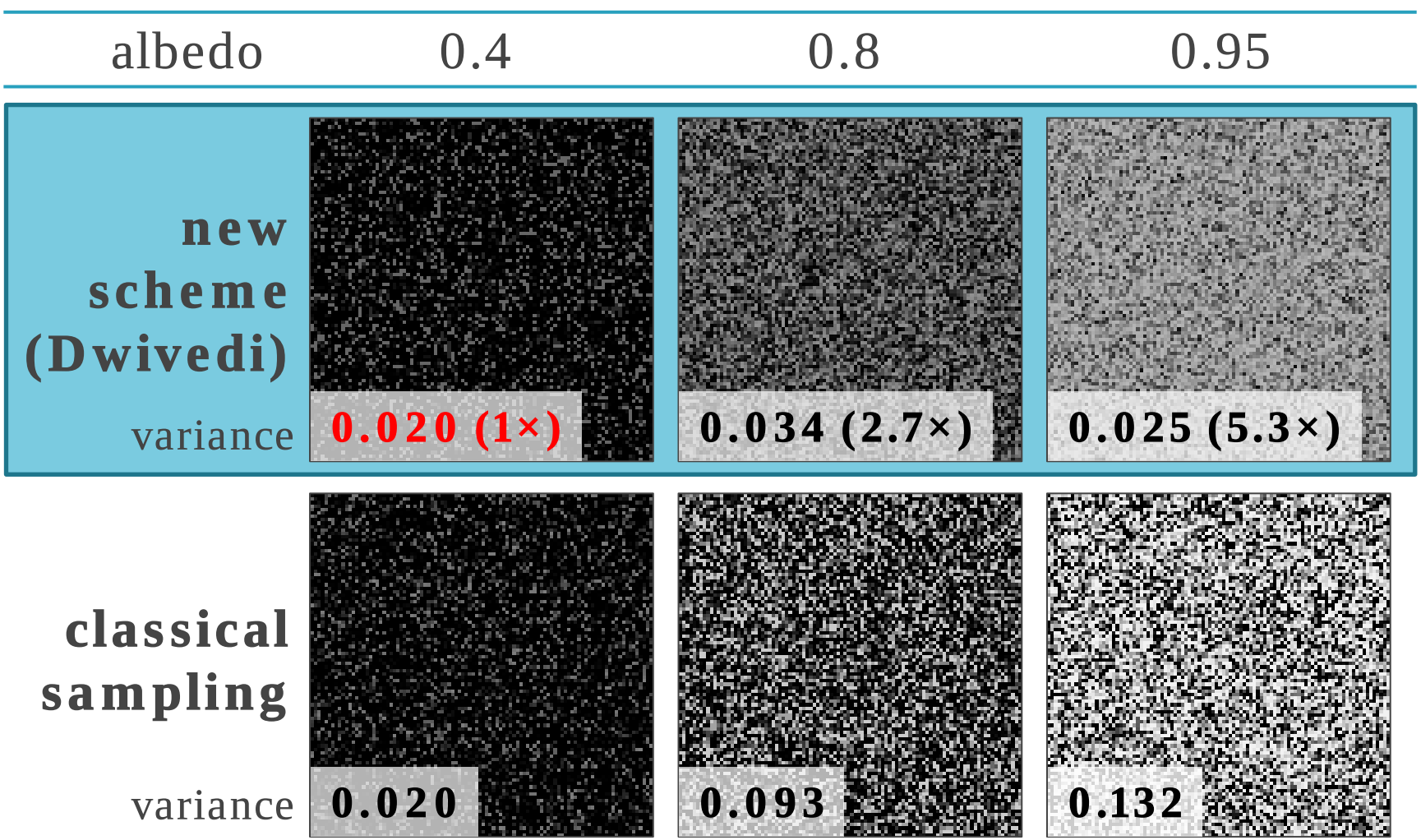
- We apply and extend these ideas in SSS in computer graphics

RESULTS

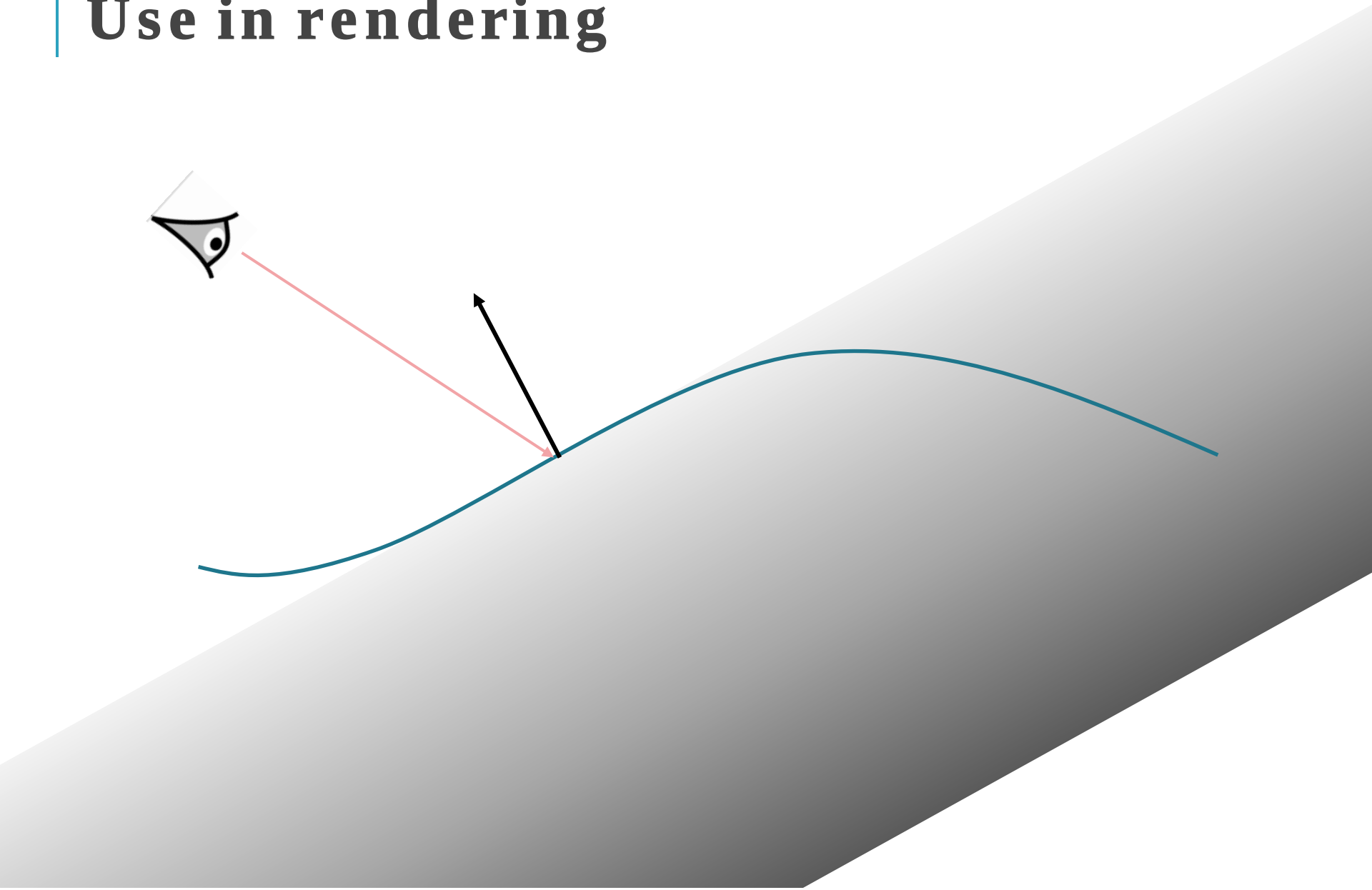
Semi-infinite half-space test



Semi-infinite half-space test

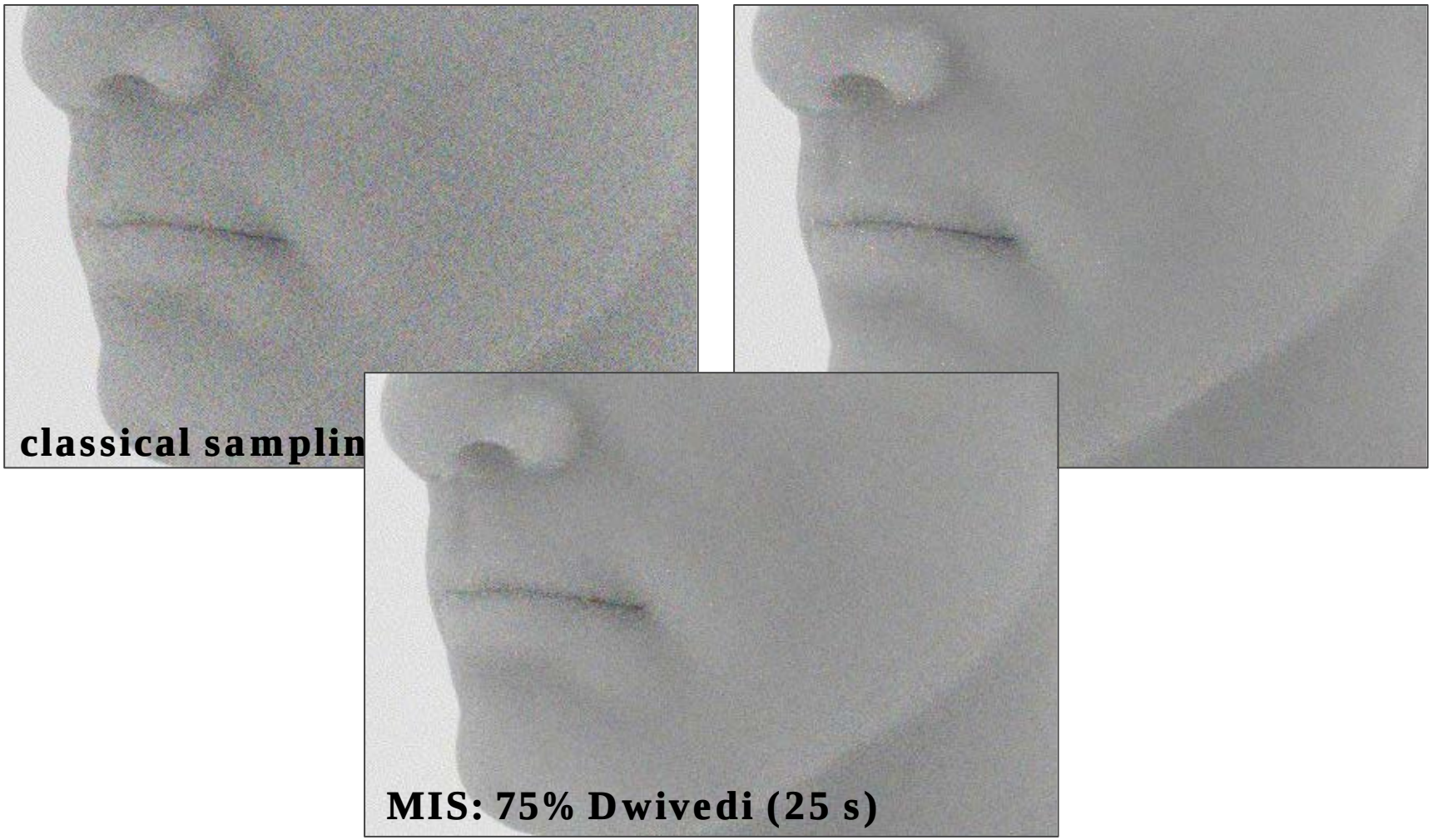


Use in rendering



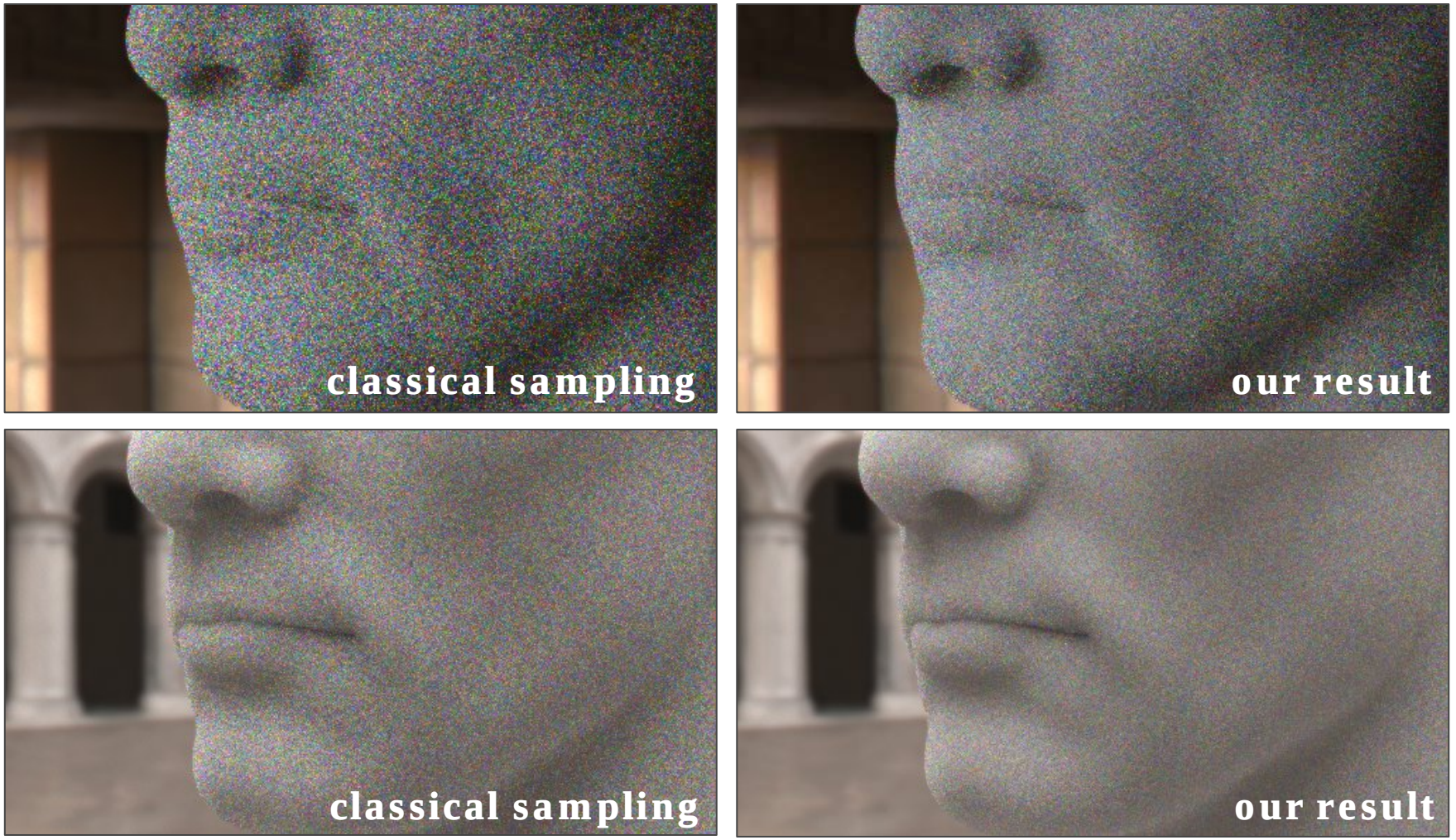
Use in rendering – White sky illum.

25 samples per pixel



Use in rendering – IBL

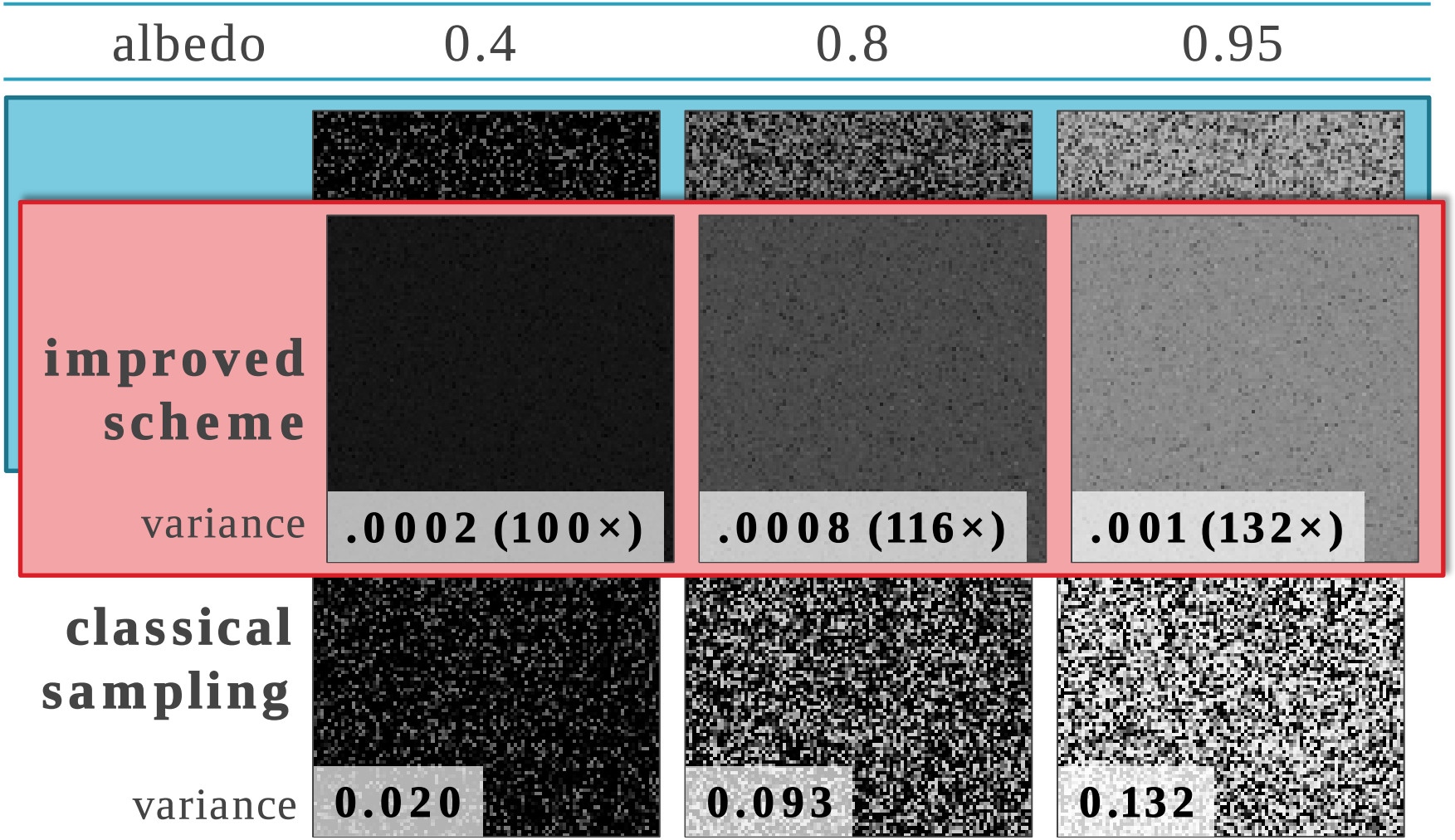
equal-time comparison, 100 samples per pixel, 75% Dwivedi,



Work in progress

- Improved sampling
  - Take boundary into account
  - Better radiance approximation
    - Matching 1^{st} and 2^{nd} moments of the true solution

Semi-infinite half-space test



Future work

- Boundary conditions (Fresnel, rough)
- Anisotropic scattering
- More rendering tests
- Other applications of zero-variance schemes

Summary

- Monte Carlo solution for subsurface scattering
- Zero-variance MC schemes
- “Caseology” – analytic solutions for half-space problems

Computer Graphics Charles University

WRAP-UP

Summary

- Light transport for image synthesis
  - Advanced research
  - **Boundary of CG and other fields**
- **Our contribution**
  - Generic, robust and efficient algorithms
  - Wide adoption in practice
- **Our plans**
  - **Enable new application domains**

We're hiring!

- **Corona renderer**
  - skilled programmers needed

Collaboration

- **Let us know!**


2015
HiVisComp


2016
HiVisComp

THANK YOU!

Questions?

Jaroslav Křivánek
Light Transport Simulation with
Vertex Connection and Merging

Computer
Graphics
Charles
University

[cgg.mff.cuni.cz/~jaroslav]