Hierarchical Russian Roulette for Vertex Connections

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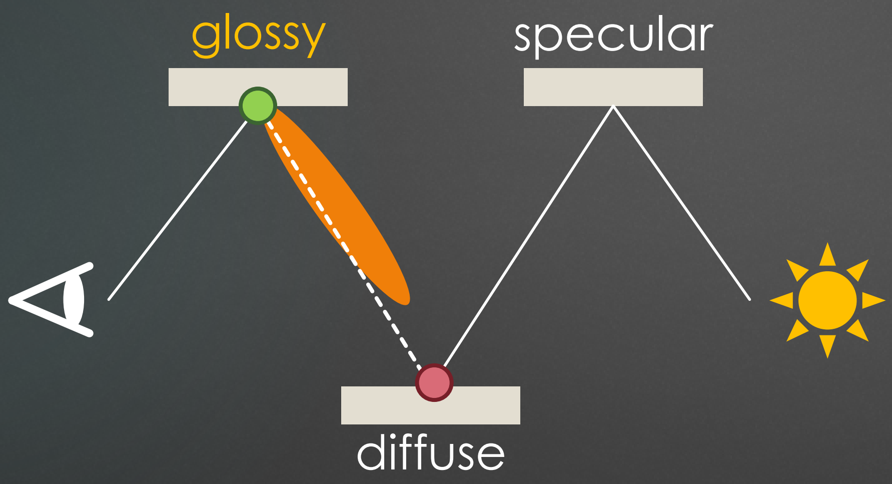
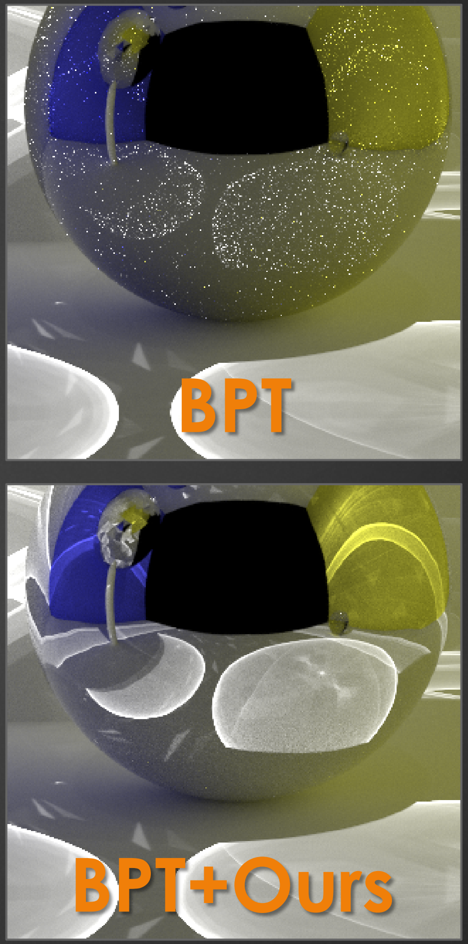
Specular-Diffuse-Glossy Paths in BPT

- Connectable
- Inefficient for extremely glossy surfaces ☹
- Need many samples ☹





GGX roughness: 0.0001

Previous Work

Stochastic light culling for VPLs
[Tokuyoshi16,17]

Our method for offline BPT

- ✗ SDG paths
- ✗ Uncorrelated variance
- ✗ Anisotropic BRDFs

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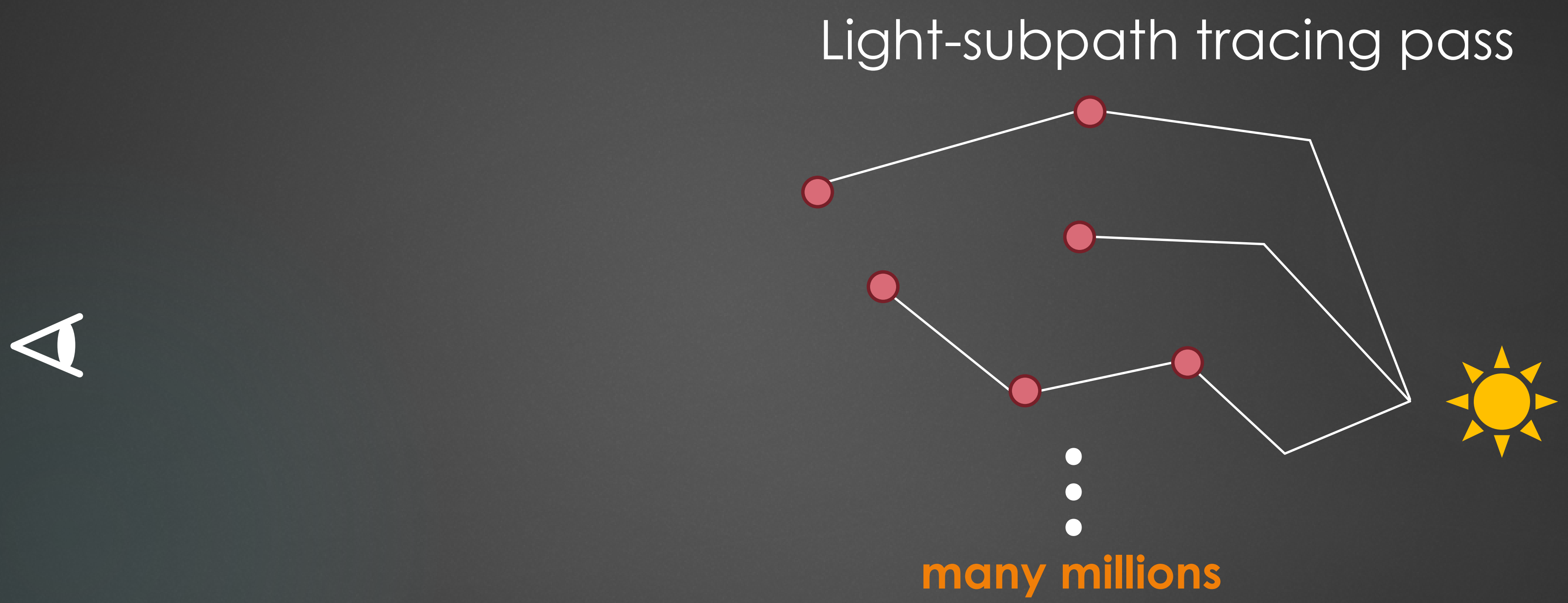
- ✓ Anisotropic BRDFs

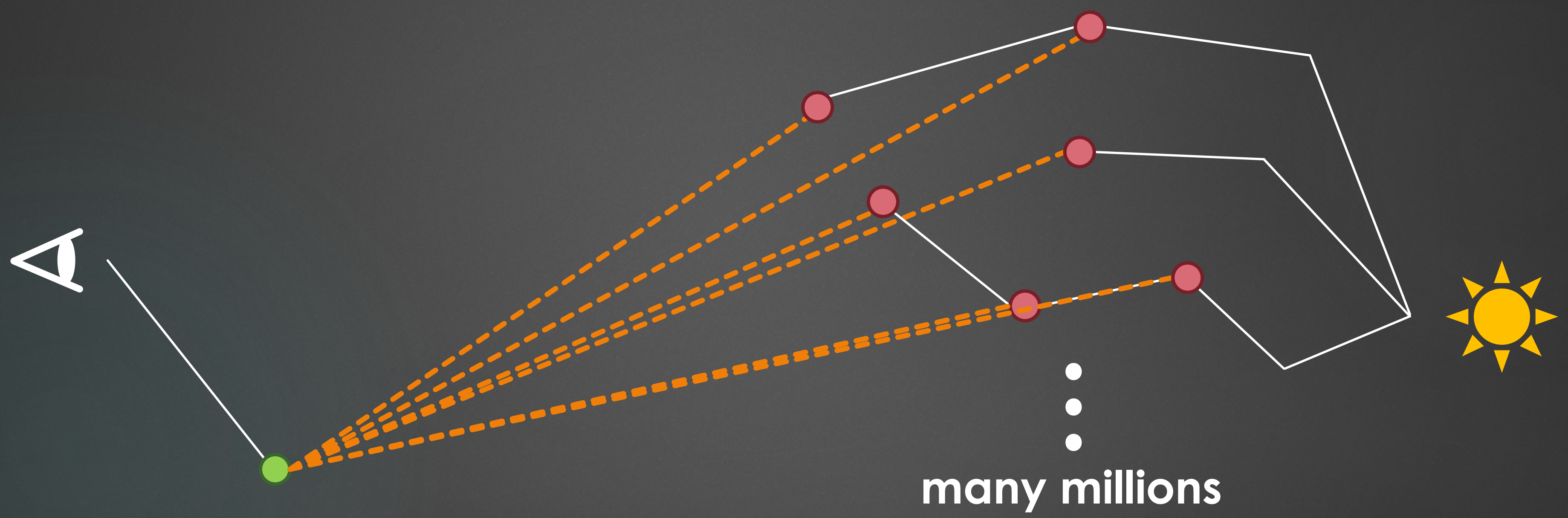
Overview of Our BPT



Store light vertices in a cache
similar to virtual point lights [Keller97]

Overview of Our BPT

Eye-subpath tracing pass



Russian roulette [Arvo90] for all the vertex connections
(Probability ∝ Scattering lobe / Distance^2)

Overview of Our BPT

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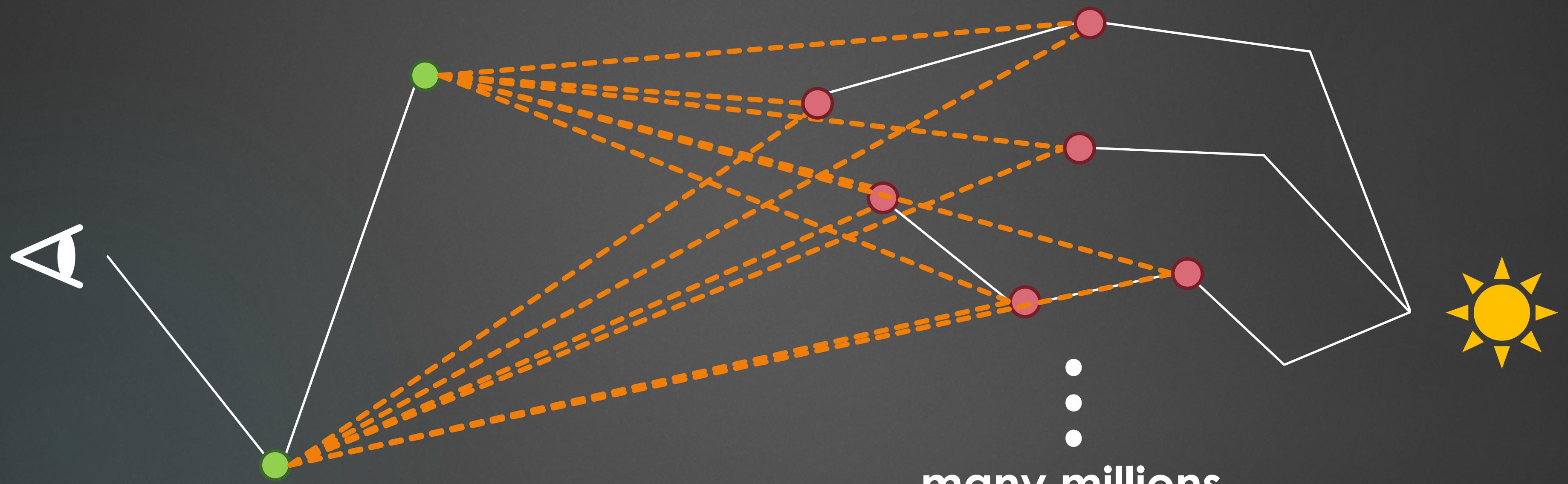

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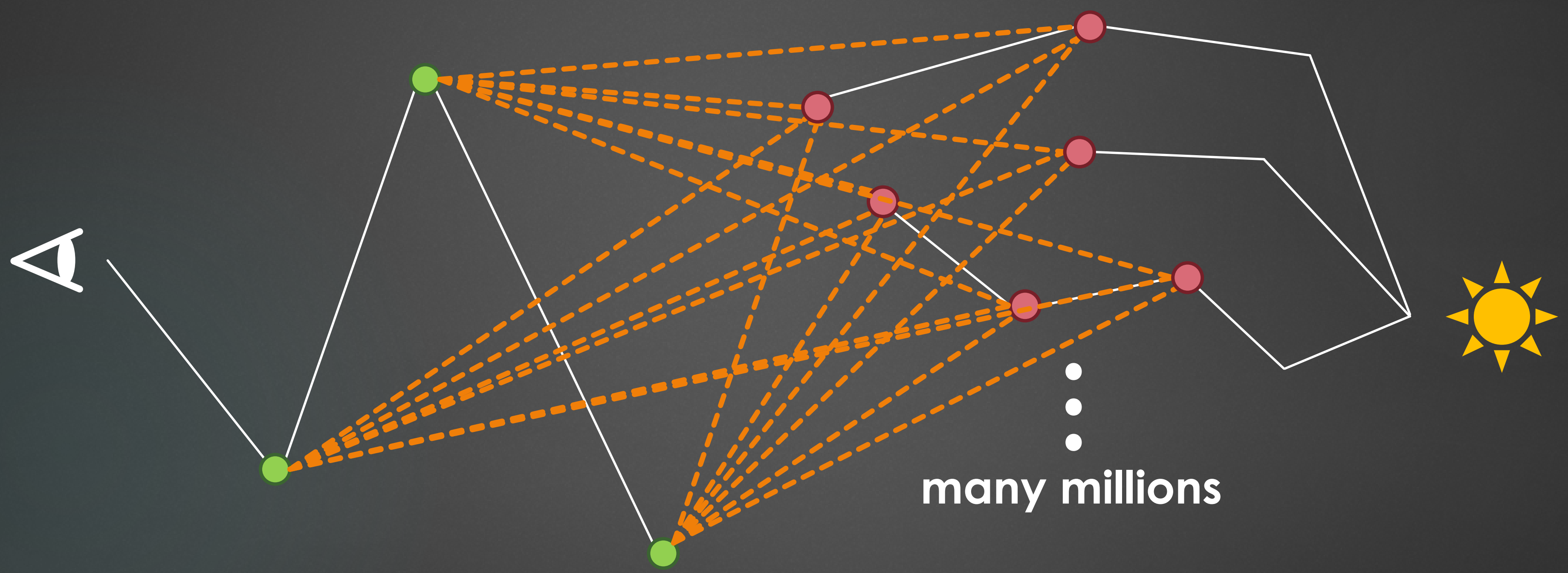

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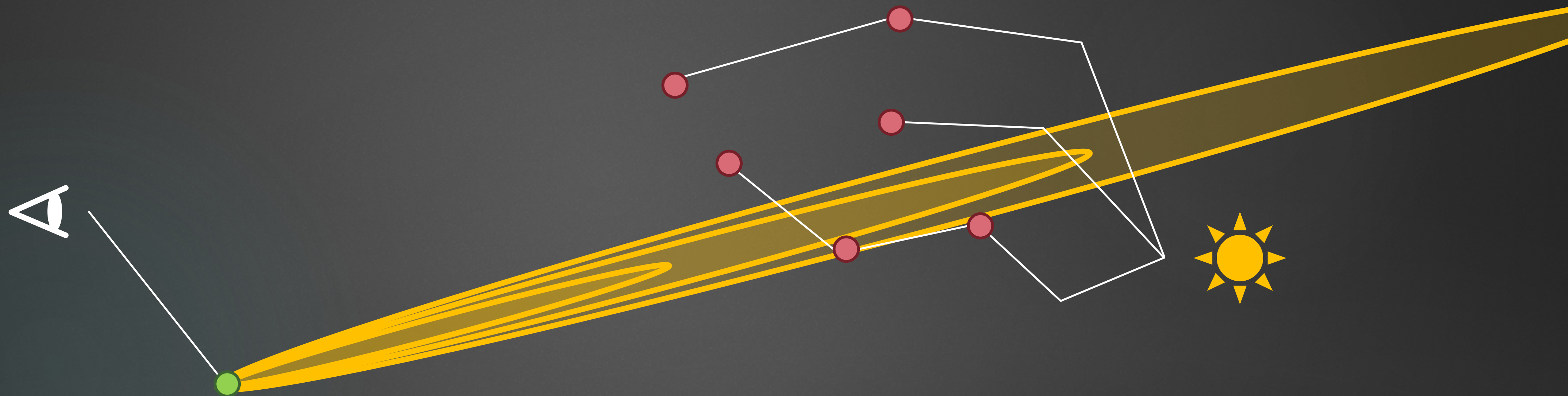
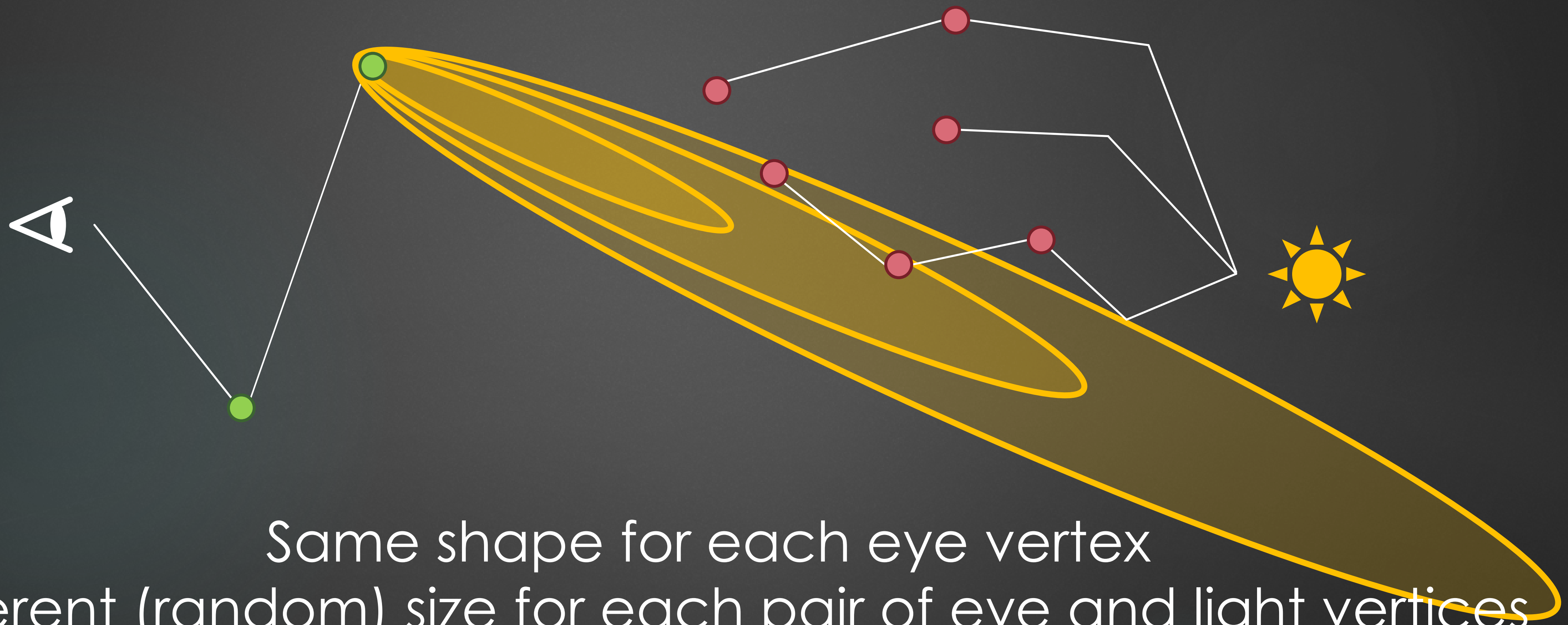
Acceptance Range in World Space



Same shape for each eye vertex
Different (random) size for each pair of eye and light vertices

Acceptance Range in World Space



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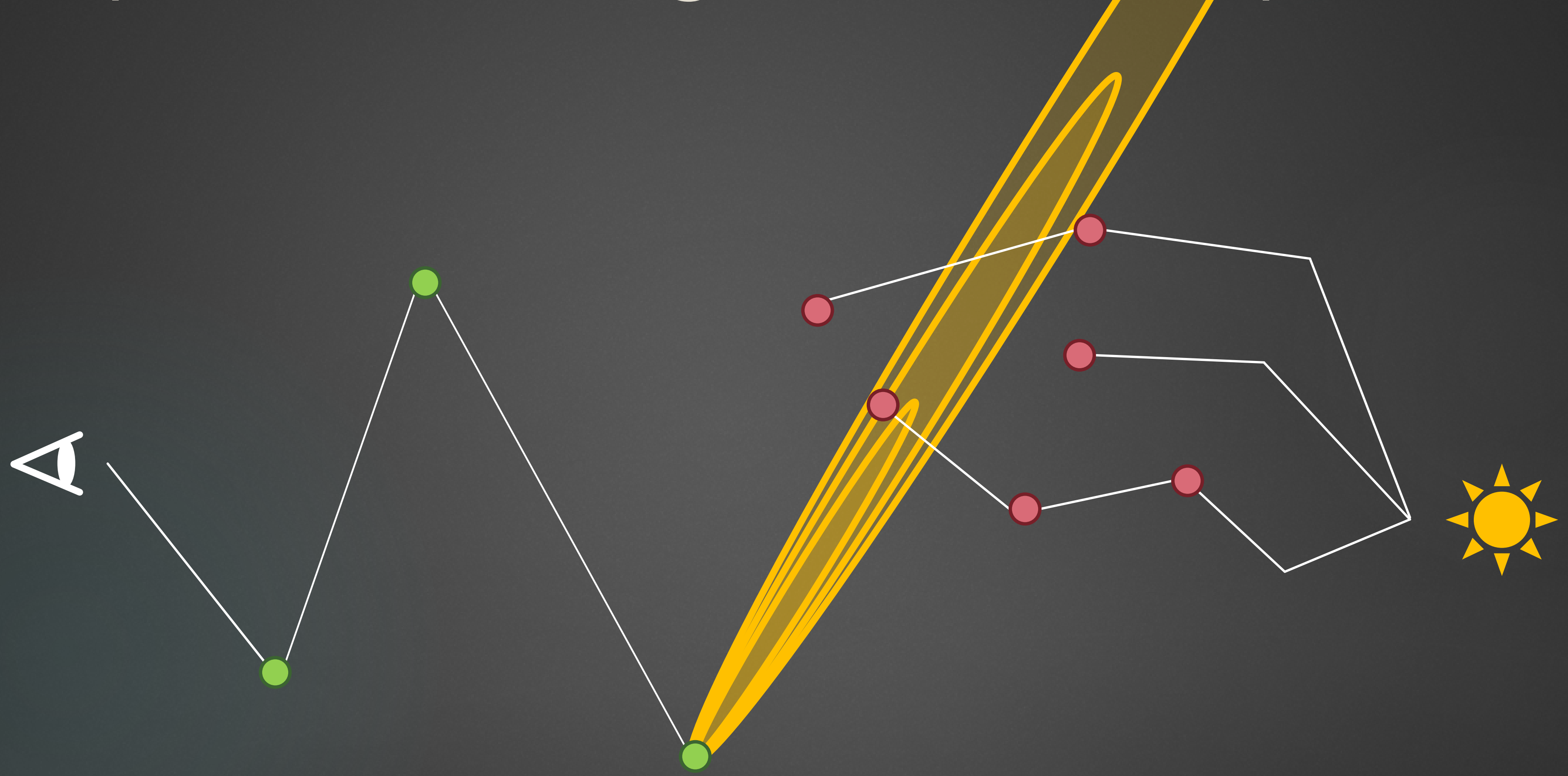
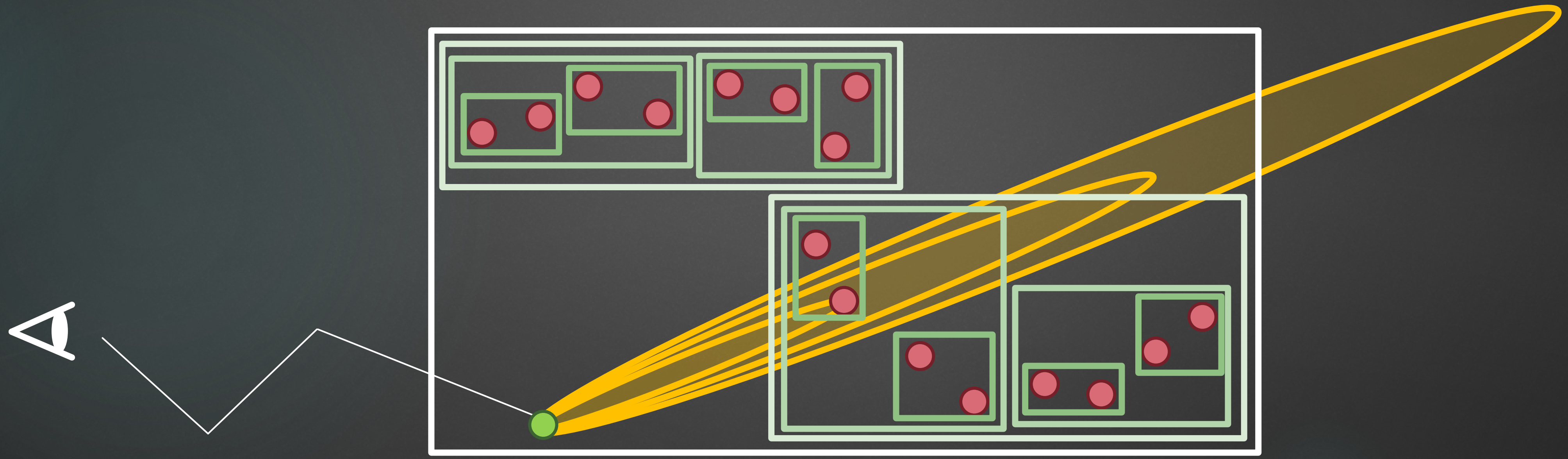


Same shape for each eye vertex

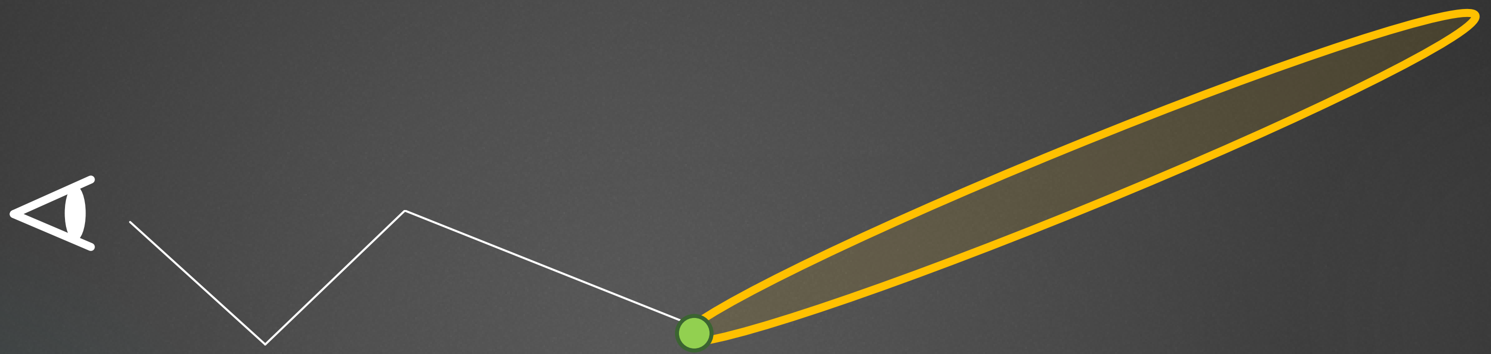
Different (random) size for each pair of eye and light vertices

Culling Using BVH

- Build a BVH for cached light vertices
- Hierarchical intersection tests between the range and each BVH node
- Ellipsoidal range is used for a simple intersection test



Stochastic Scattering Range



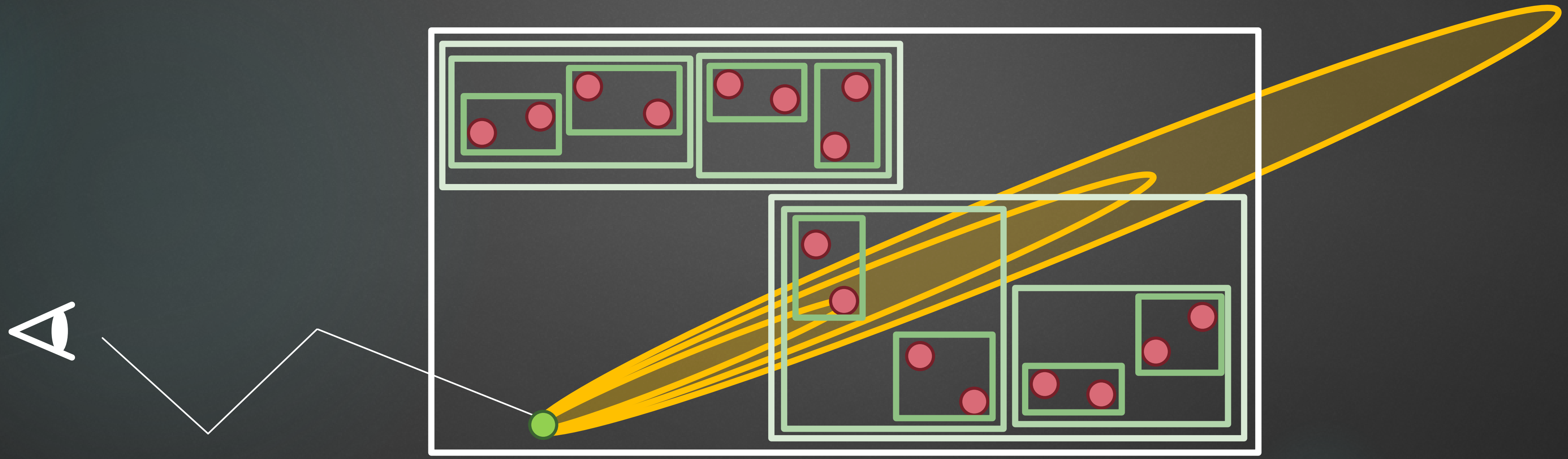
Approximated to make an ellipsoidal range

$$\text{Range} = \sqrt{\frac{\text{Constant} \times \text{Scattering lobe}}{\text{Uniform random number} \in [0,1)}}$$

Different for each pair of eye and light vertices

Range Size in BVH Traversal

- Random for each light vertex (i.e., leaf node)
- Use the largest size in each node for conservative intersection test



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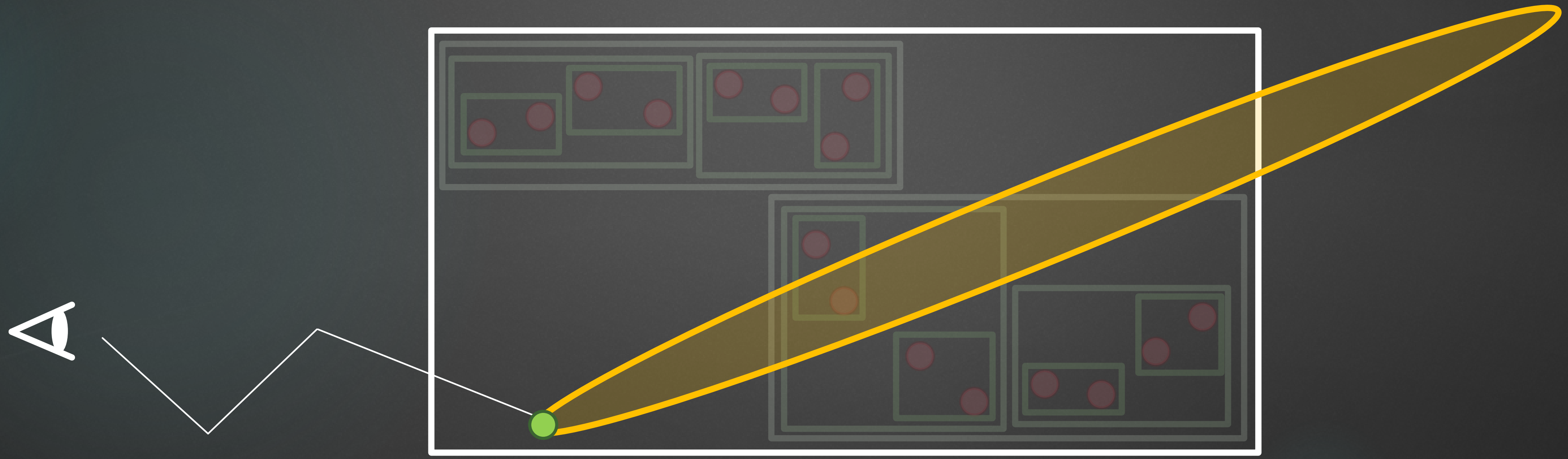

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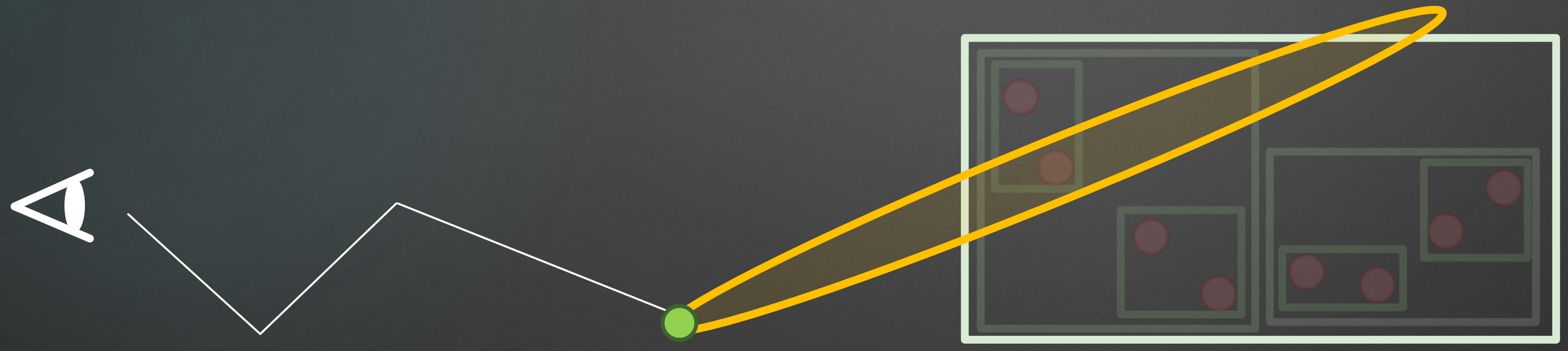

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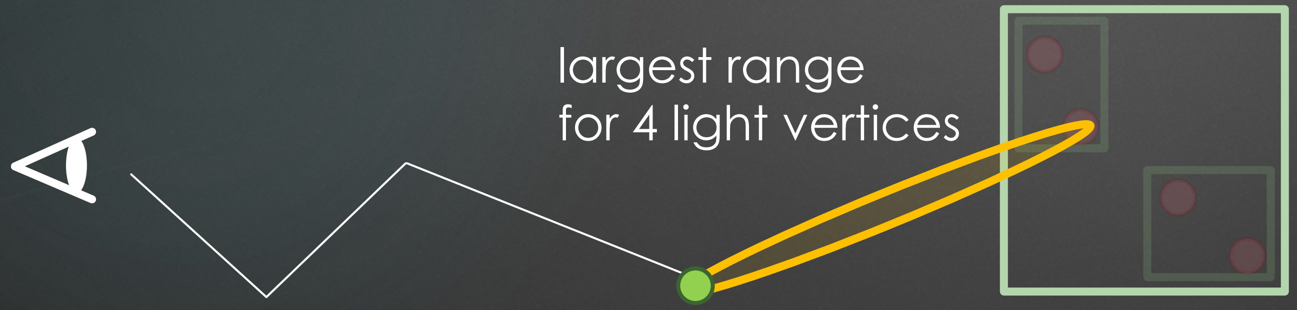

Range Size in BVH Traversal

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$$\text{Largest range} = \sqrt{\frac{\text{Constant} \times \text{Scattering lobe}}{\underline{\text{Minimum}} \text{ of uniform random numbers}}}$$

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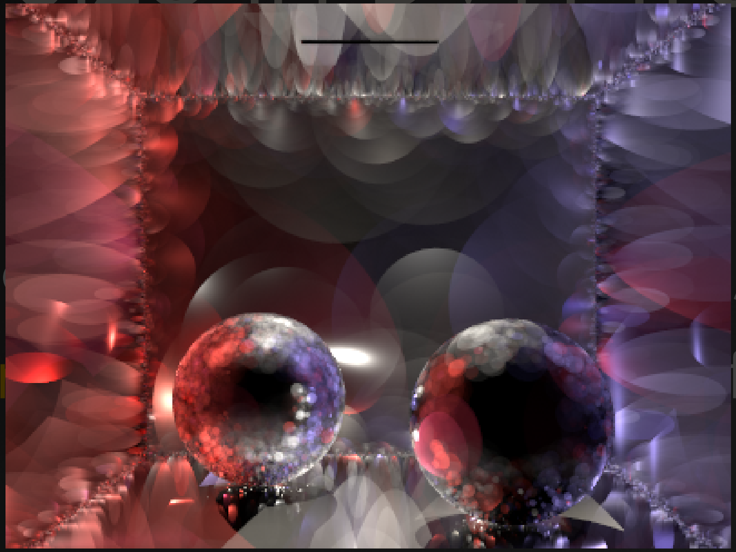
Pregenerate and store in each node?

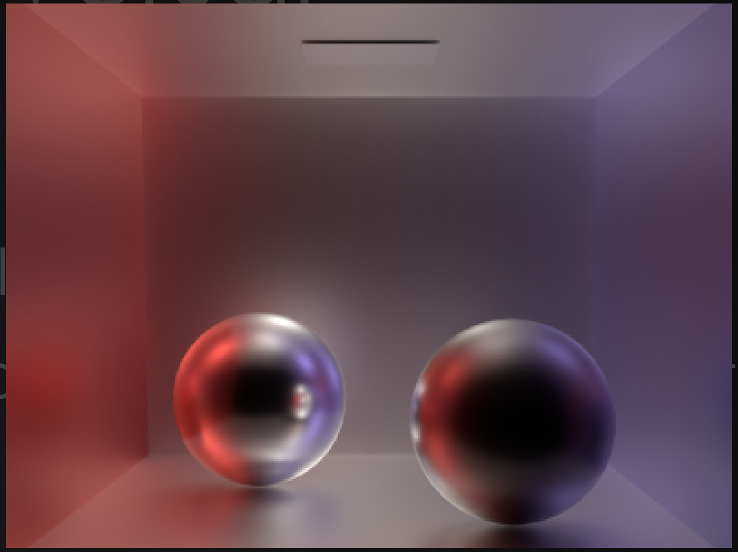
(Similar to lightcuts [Walter05] & stochastic light culling [Tokuyoshi16])

Range Size in BVH Traversal

- Random f… , I
- Use the la… fo… ion test



Pregeneration



Reference

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Correlation of variance ☹

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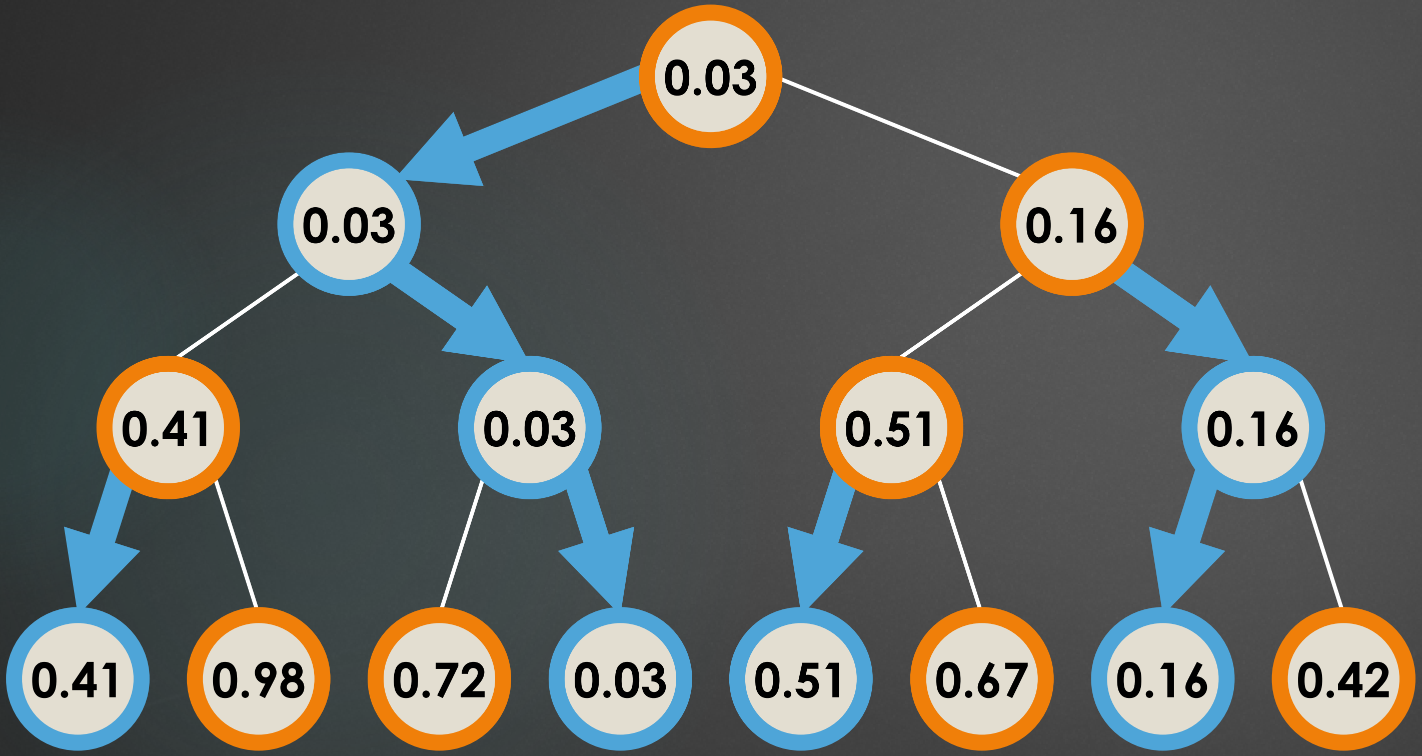
Different for each pair of eye vertex and BVH node

Top-down Minimum Random Number Generation

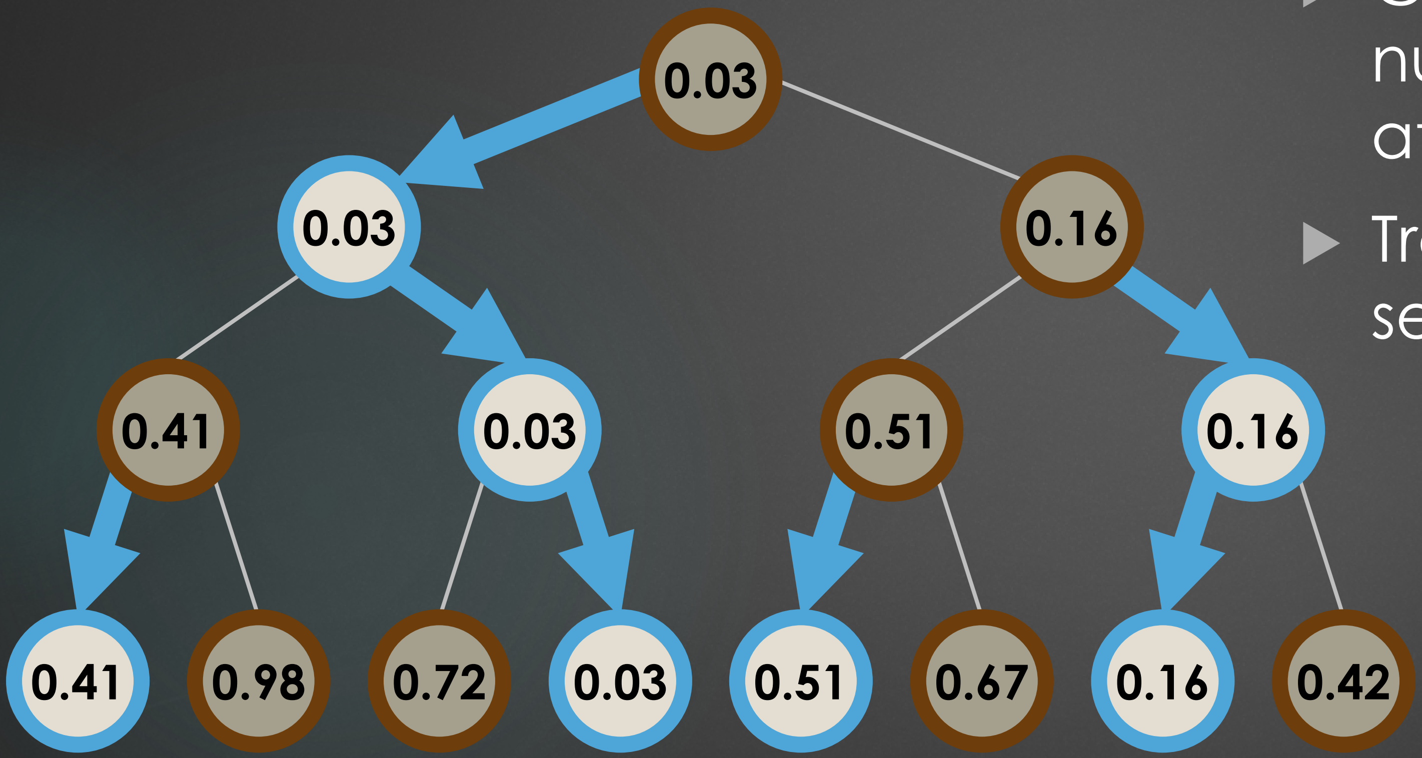


On-the-fly generation in BVH traversal

Top-down Minimum Random Number Generation

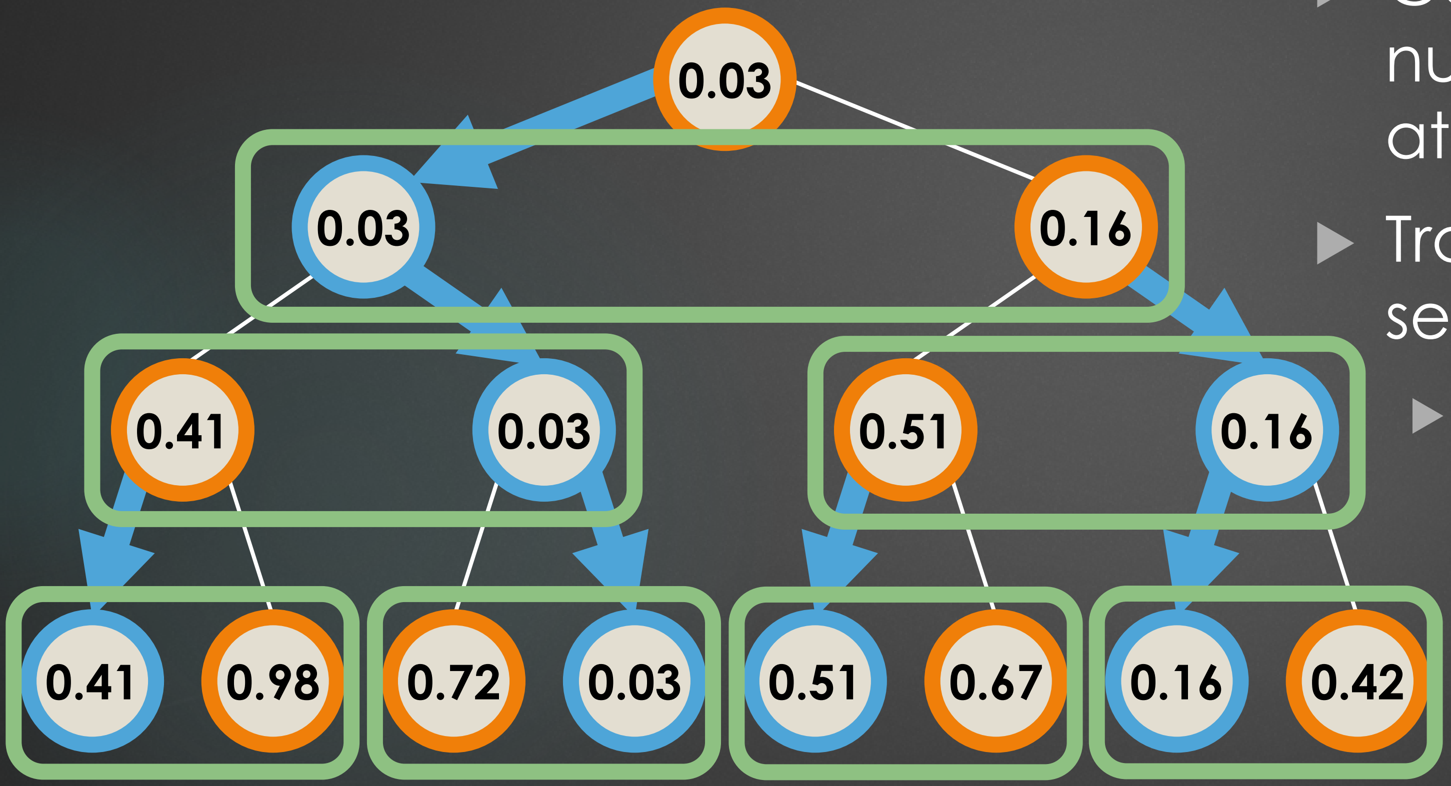
- Generate a minimum random number larger than the parent at each orange node

Top-down Minimum Random Number Generation



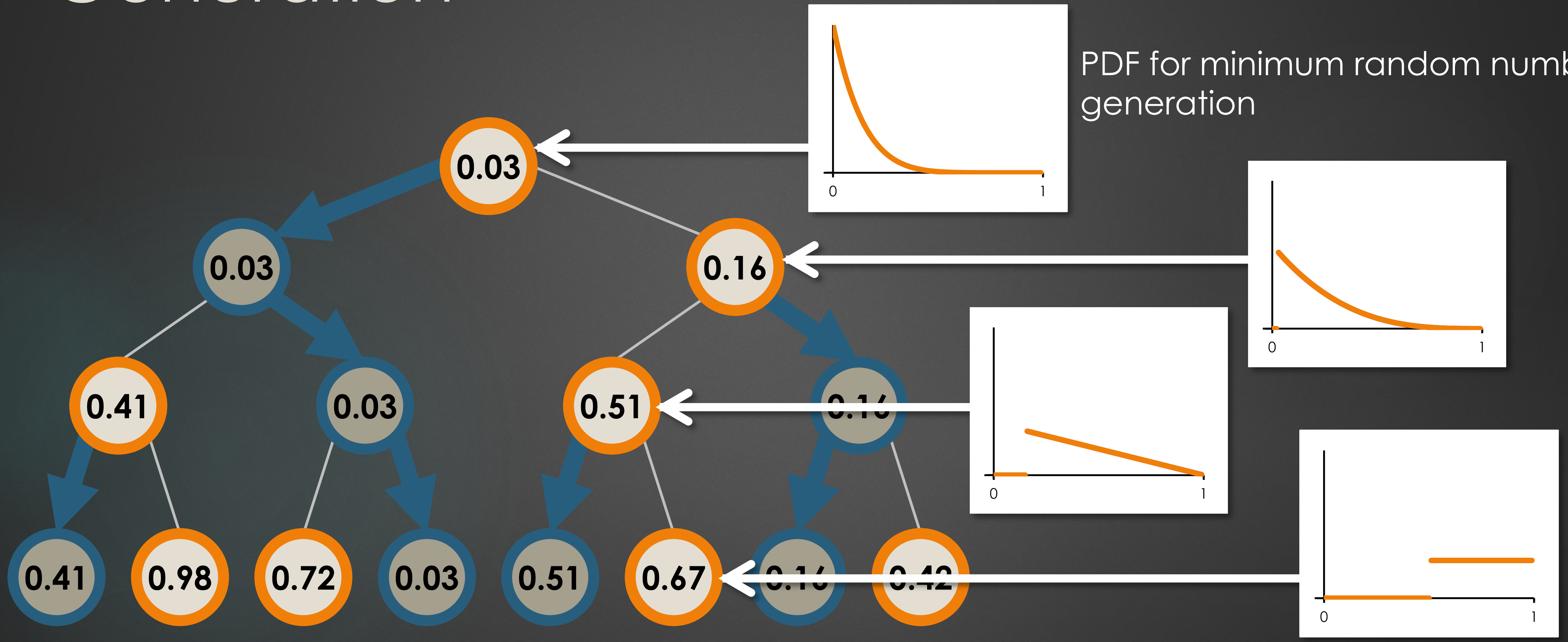
- Generate a minimum random number larger than the parent at each orange node
- Transmit to single randomly selected child node (blue)

Top-down Minimum Random Number Generation

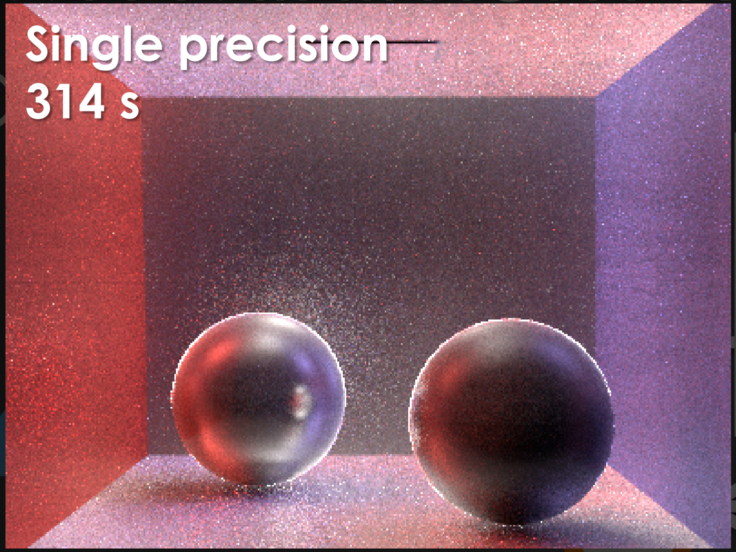


- Generate a minimum random number larger than the parent at each orange node
- Transmit to single randomly selected child node (blue)
  - Orange and blue nodes are siblings

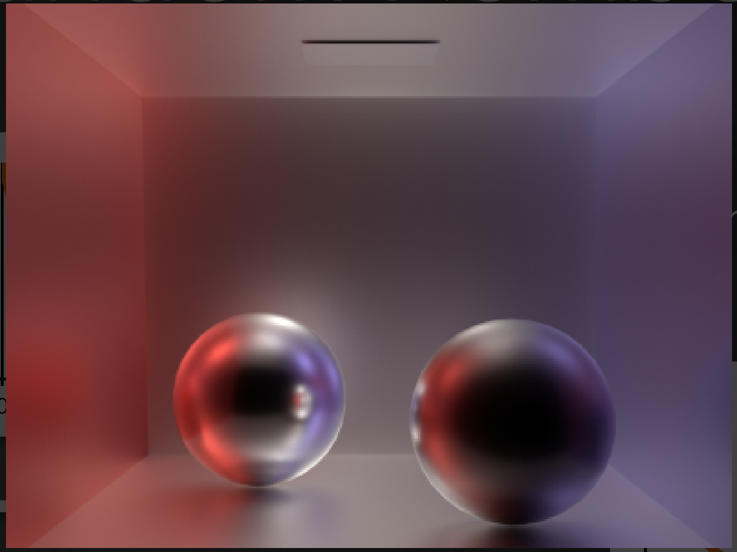
Top-down Minimum Random Number Generation



Top-down Minimum Random Number Genera



Ours

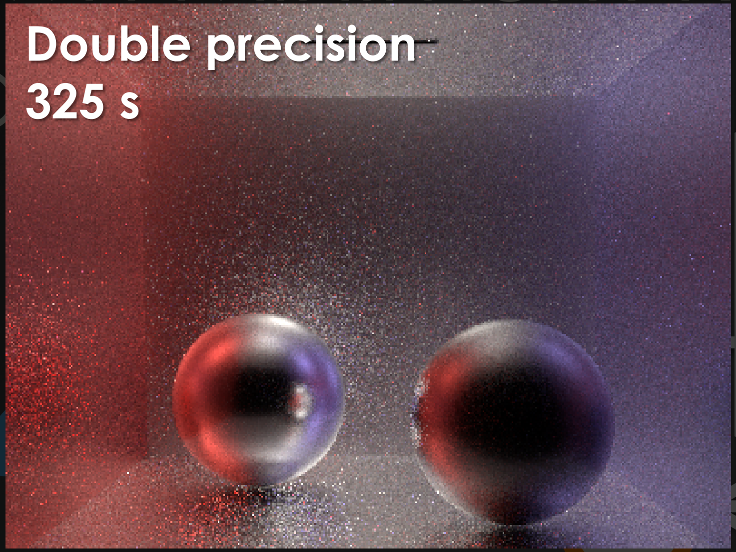


Reference

Numerical error ☹
for millions of leaf nodes

Top-down Minimum Random Number Genera

n random number



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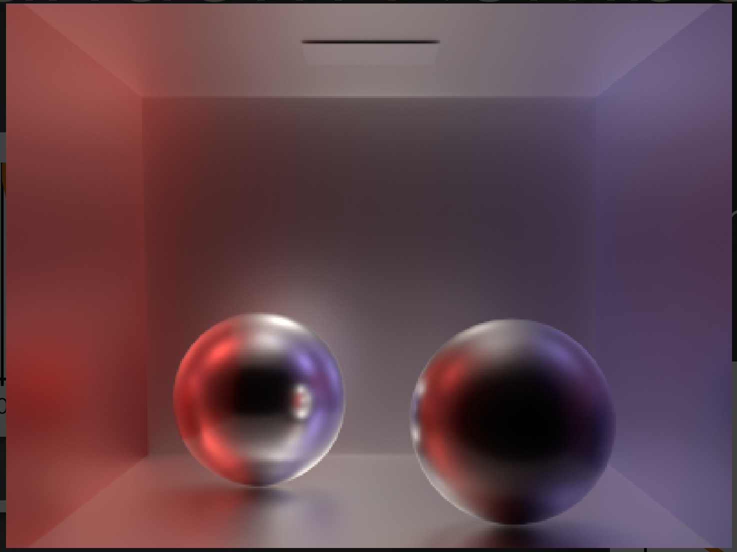

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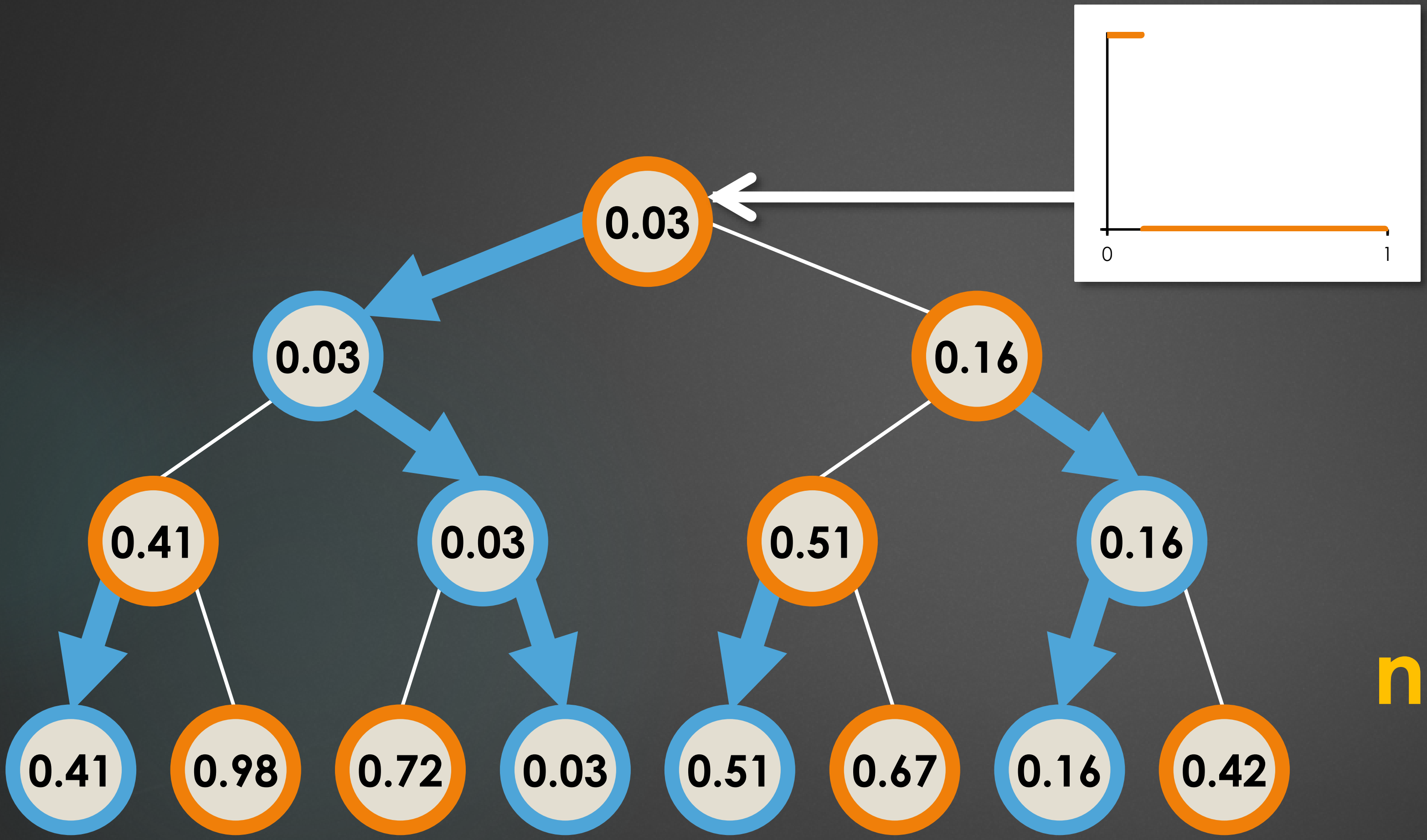
Semi-Stratified Sampling



PDF for minimum random number generation

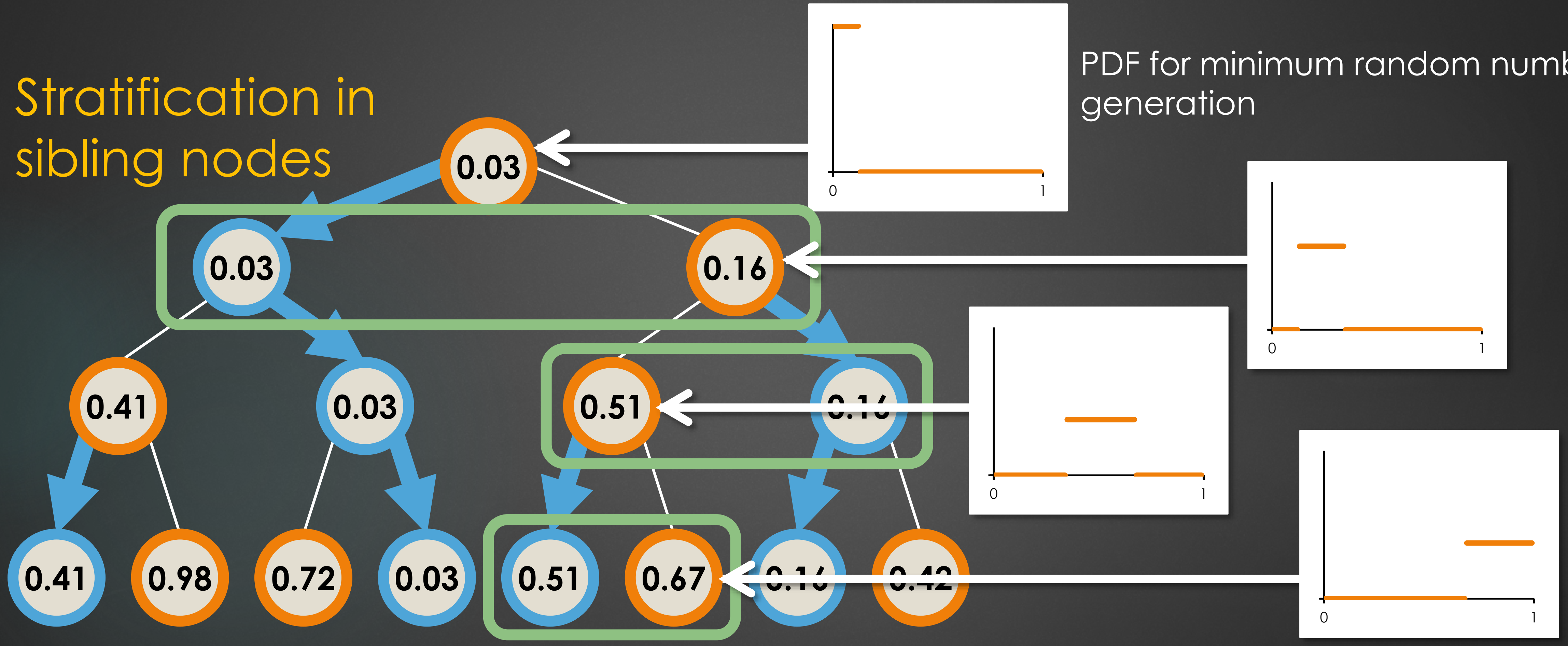
Uniform in the stratum

Simple & numerically stable

☺

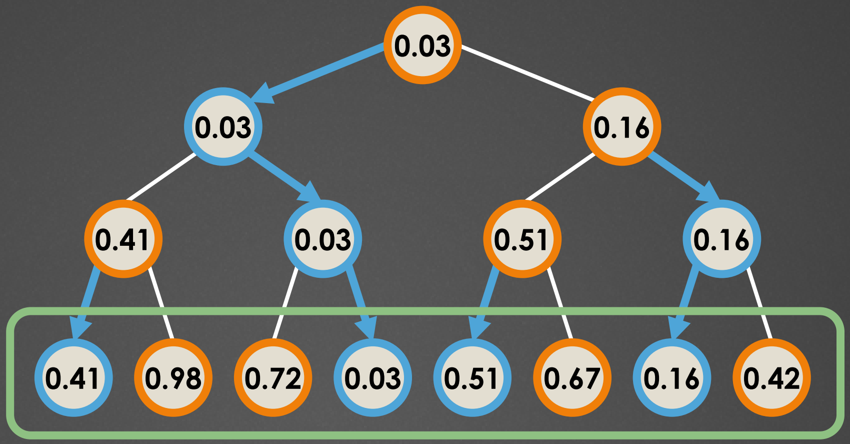
Semi-Stratified Sampling

Stratification in sibling nodes

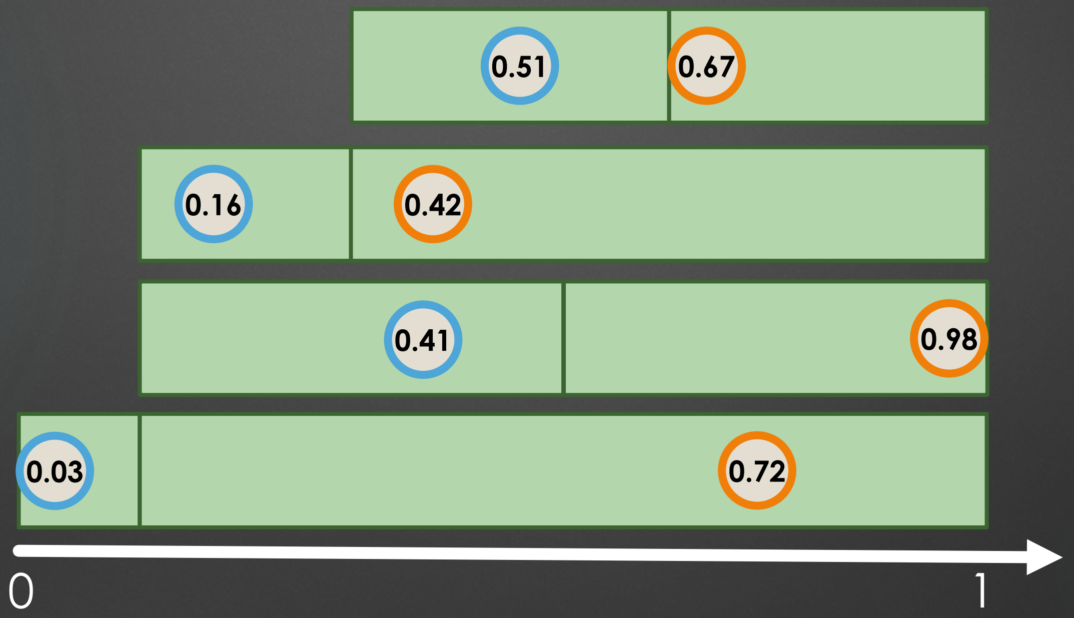


PDF for minimum random number generation

Overlaps of Strata at the Leaf Level



Stratified only in two sibling nodes



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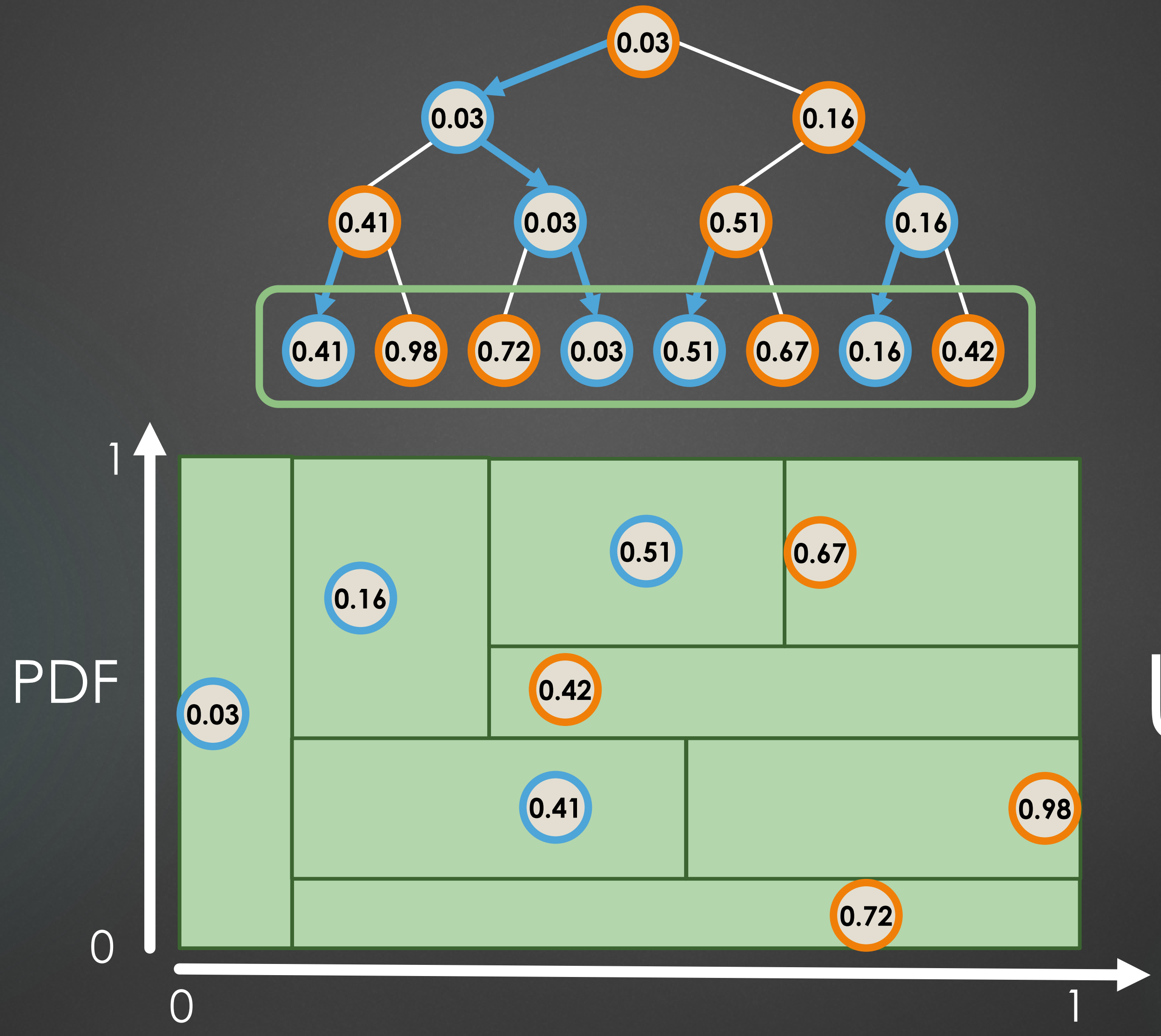
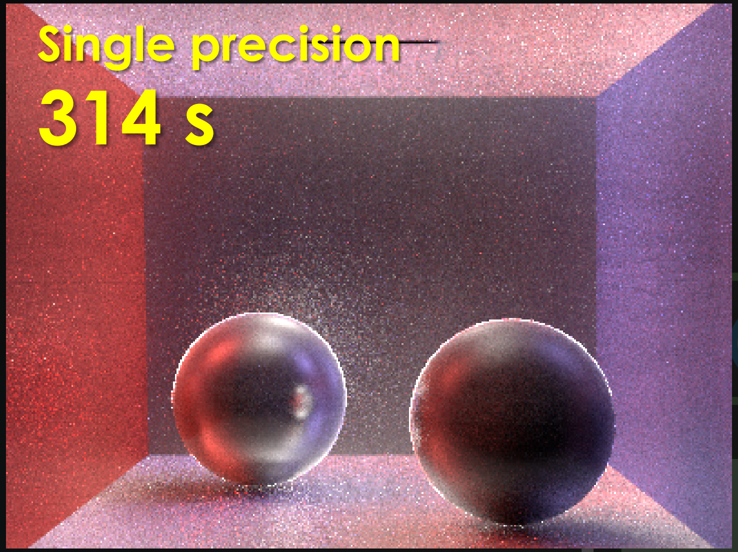
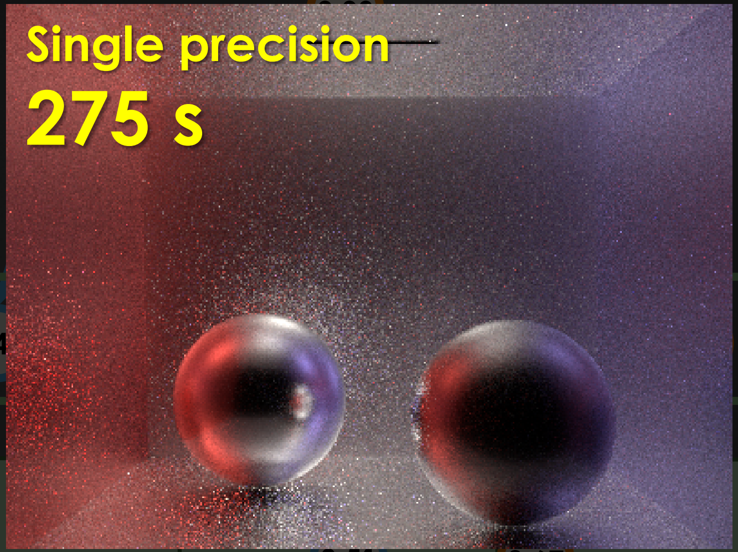


Unbiased

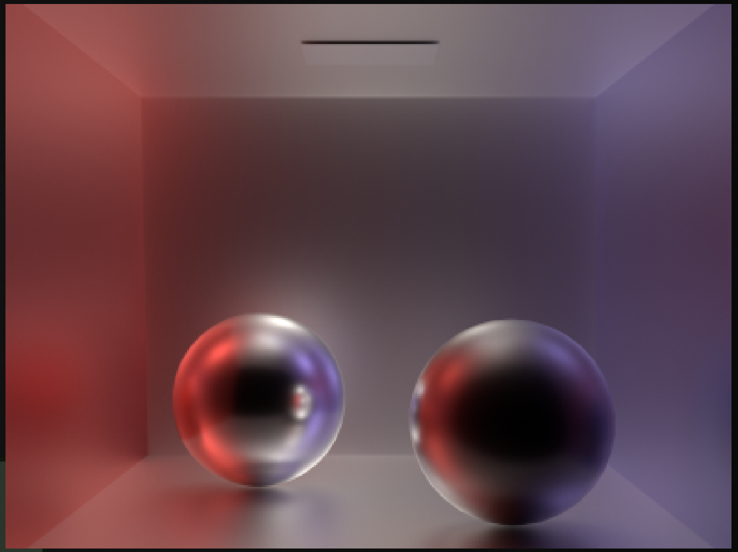
Overlaps of Strata at the Leaf Level



Non-stratified



Semi-stratified



Reference

Unbiased

Range for Anisotropic Microfacet BRDFs

Anisotropic Scattering Lobes

- Scattering lobe is anisotropic for microfacet BRDFs
  - Even if the NDF is isotropic
- Make a tight ellipsoidal range
- Approximate the scattering lobe using a *Squared Ellipsoidal Lobe*

$$\text{Probability} = \min\left(\frac{\text{Constant} \times \text{Scattering lobe}}{\text{Distance}^2}, 1\right)$$

$$\text{Range} = \sqrt{\frac{\text{Constant} \times \text{Scattering lobe}}{\text{Uniform random number}}}$$

GGX-based Squared Ellipsoidal Lobe

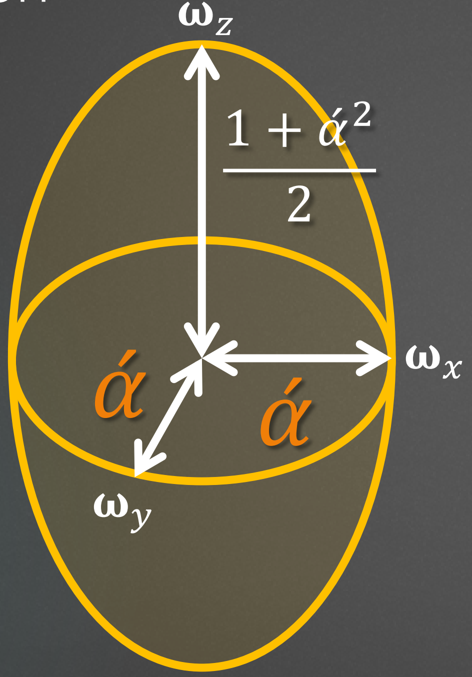
Isotropic GGX distribution

$D(\cos\theta, \acute{\alpha})$

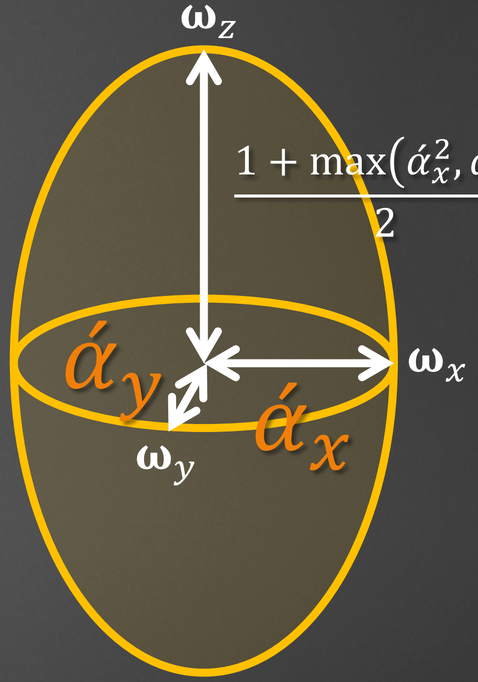
$$\sqrt{\pi\acute{\alpha}^2 D\left(\cos\frac{\theta}{2}, \acute{\alpha}\right)}$$

Spheroid

[Tokuyoshi17]



$(\cos\theta = \boldsymbol{\omega} \cdot \boldsymbol{\omega}_z)$



$$\sqrt{K\left(\boldsymbol{\omega}; \begin{bmatrix}\boldsymbol{\omega}_x \\ \boldsymbol{\omega}_y \\ \boldsymbol{\omega}_z\end{bmatrix}, \acute{\alpha}_x, \acute{\alpha}_y\right)}$$

Ellipsoid

GGX-based Squared Ellipsoidal Lobe

$$K\left(\boldsymbol{\omega}; \begin{bmatrix}\boldsymbol{\omega}_x \\ \boldsymbol{\omega}_y \\ \boldsymbol{\omega}_z\end{bmatrix}, \acute{\alpha}_x, \acute{\alpha}_y\right) = \frac{4\acute{\alpha}_{\max}^4}{\left(U - v_z + \acute{\alpha}_{\max}^2 (U + v_z)\right)^2}$$

$$\acute{\alpha}_{\max} = \max(\acute{\alpha}_x, \acute{\alpha}_y)$$

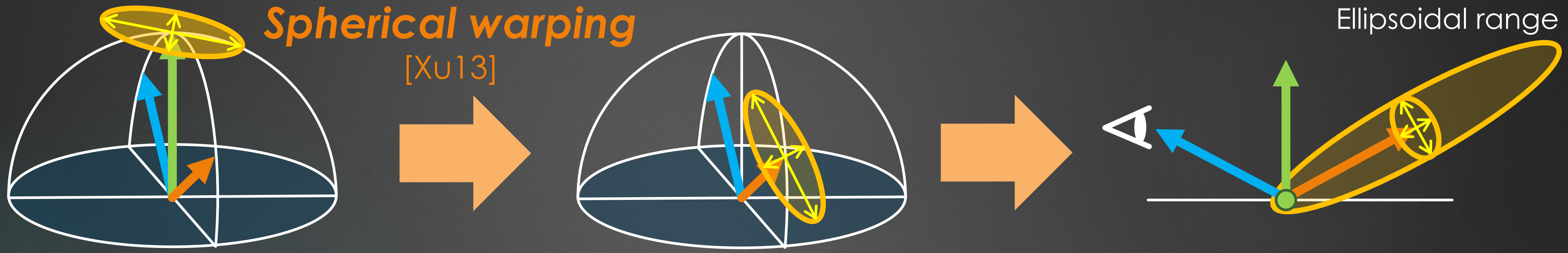
$$[v_x, v_y, v_z] = [\boldsymbol{\omega} \cdot \boldsymbol{\omega}_x, \boldsymbol{\omega} \cdot \boldsymbol{\omega}_y, \boldsymbol{\omega} \cdot \boldsymbol{\omega}_z]$$

$$U = \sqrt{\frac{\acute{\alpha}_{\max}^2}{\acute{\alpha}_x^2} v_x^2 + \frac{\acute{\alpha}_{\max}^2}{\acute{\alpha}_y^2} v_y^2 + v_z^2}$$

Approximately equal to an anisotropic GGX lobe for small roughness

$$\approx 4\pi \acute{\alpha}_x \acute{\alpha}_y D\left(\boldsymbol{\omega}; \begin{bmatrix}\boldsymbol{\omega}_x \\ \boldsymbol{\omega}_y \\ \boldsymbol{\omega}_z\end{bmatrix}, 2\acute{\alpha}_x, 2\acute{\alpha}_y\right)$$

Analytical Lobe Approximation



$$\pi\alpha_x\alpha_y D\left(\boldsymbol{\omega}_\mathrm{h}(\boldsymbol{\omega}); \begin{bmatrix}\mathbf{t}_x\\ \mathbf{t}_y\\ \mathbf{n}\end{bmatrix}, \alpha_x, \alpha_y\right) \approx \pi\alpha'_x\alpha'_y D\left(\boldsymbol{\omega}; \begin{bmatrix}\boldsymbol{\omega}_x\\ \boldsymbol{\omega}_y\\ \boldsymbol{\omega}_z\end{bmatrix}, \alpha'_x, \alpha'_y\right) \approx K\left(\boldsymbol{\omega}; \begin{bmatrix}\boldsymbol{\omega}_x\\ \boldsymbol{\omega}_y\\ \boldsymbol{\omega}_z\end{bmatrix}, \frac{\alpha'_x}{2}, \frac{\alpha'_y}{2}\right)$$

GGX NDF | GGX scattering lobe | Squared ellipsoidal lobe

Results

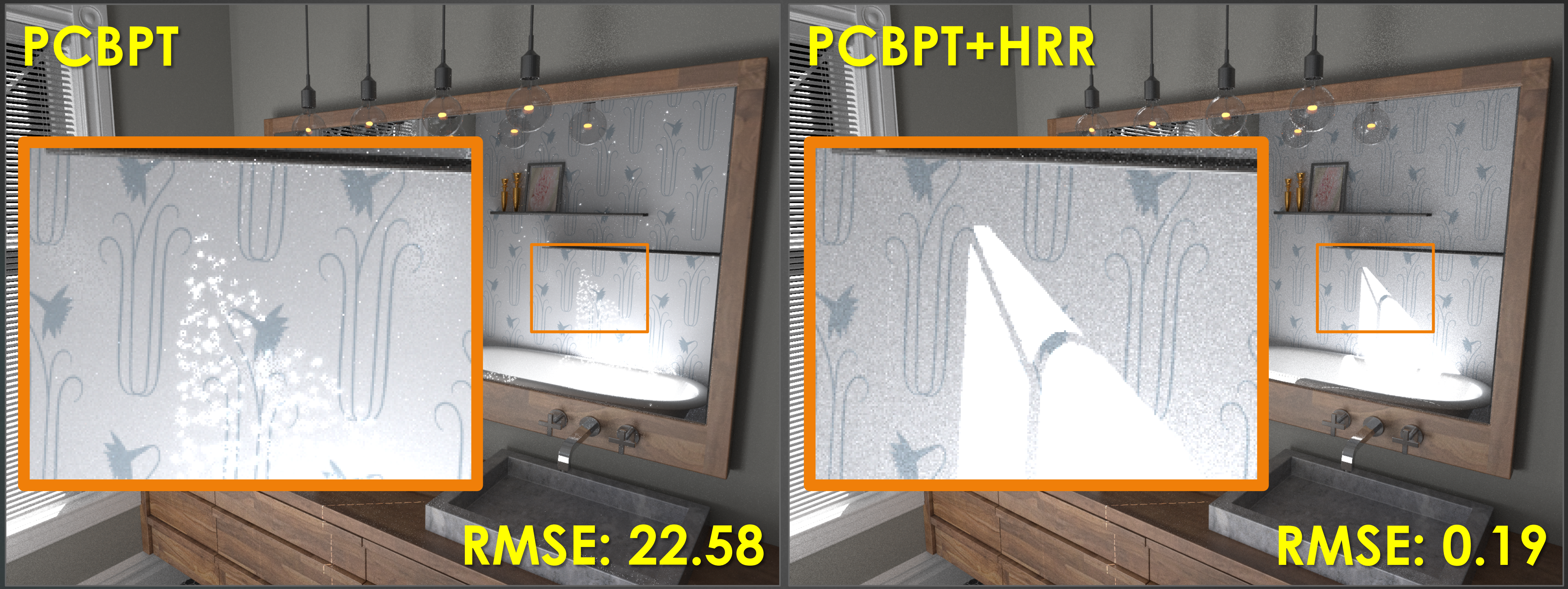
1600×1200 SCREEN RESOLUTION

AMD RYZEN™ THREADRIPPER™ 2990WX PROCESSOR

Combination with PCBPT [Popov15] (15 min)

Caustics reflected on the mirror (GGX roughness: 0.0001)

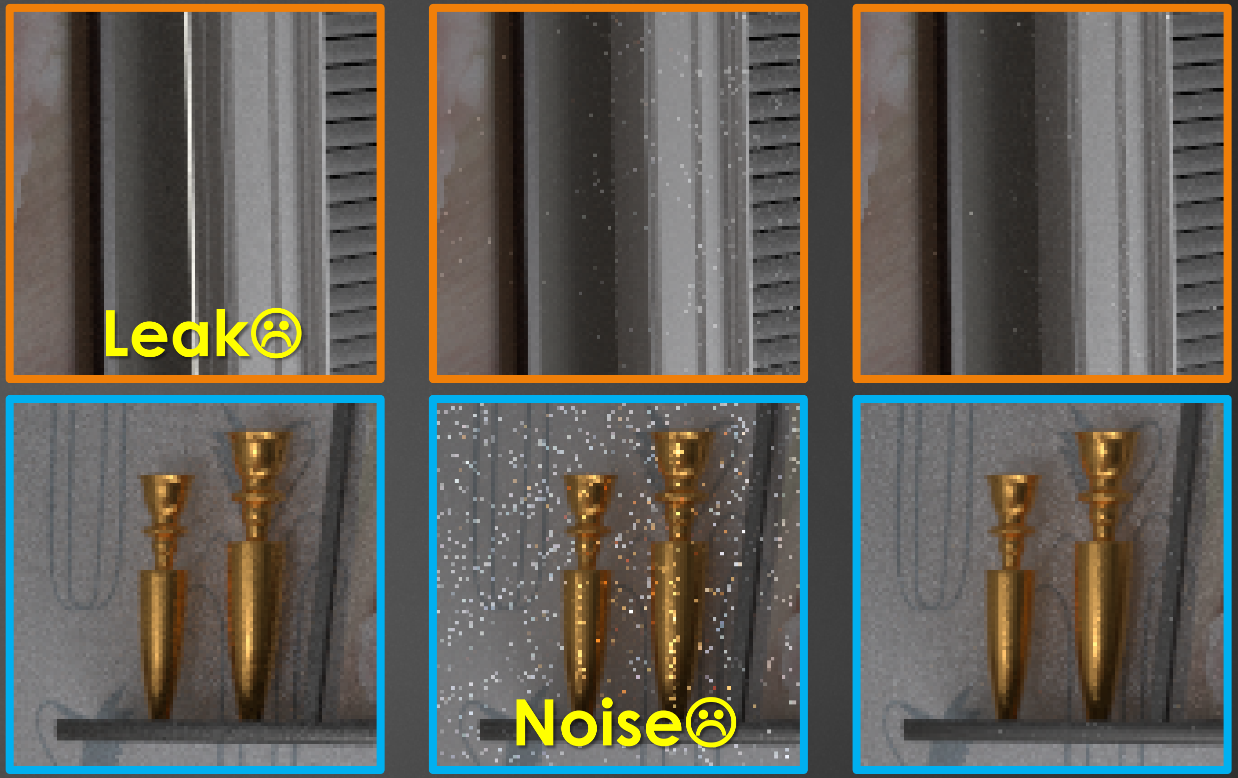
Combination with PCBPT [Popov15] (15 min)



Caustics reflected on the mirror (GGX roughness: 0.0001)

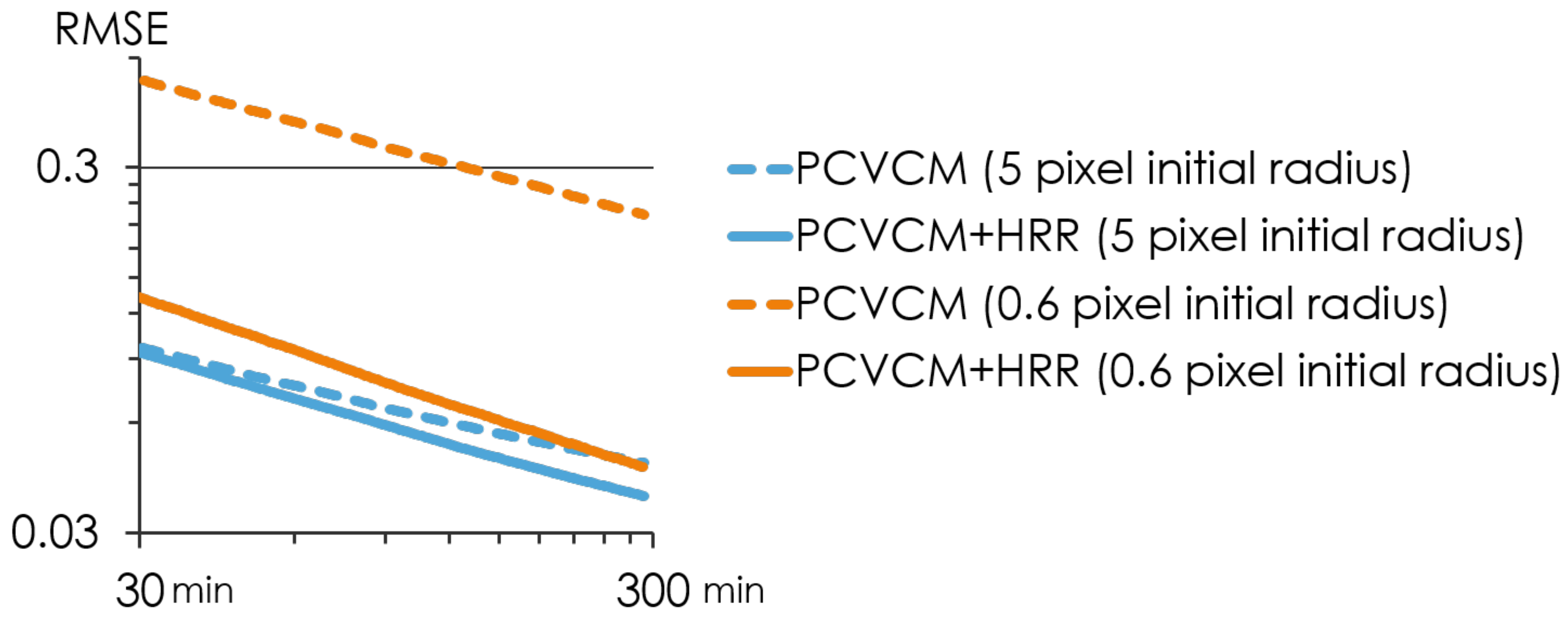
Combination with VCM [Georgiev12, Hachisuka12] (60 min)

PCVCM: PCBPT + vertex merging



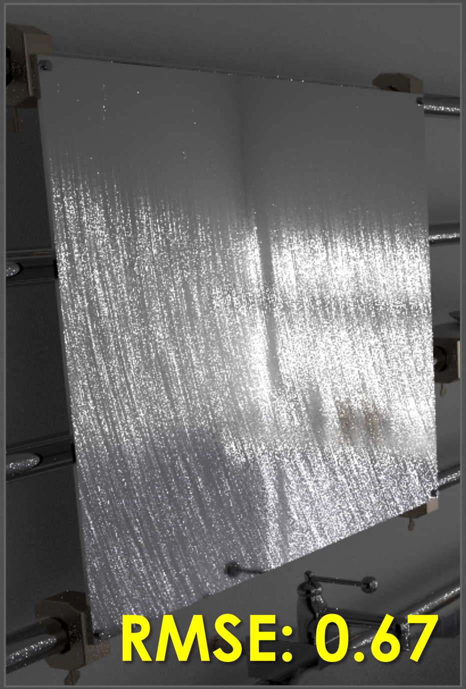
	PCVCM	PCVCM	PCVCM+HRR
Initial merging radius:	5 pixels	0.6 pixel	0.6 pixel
	(9311 iterations)	(9475 iterations)	(7090 iterations)

Convergence Speed



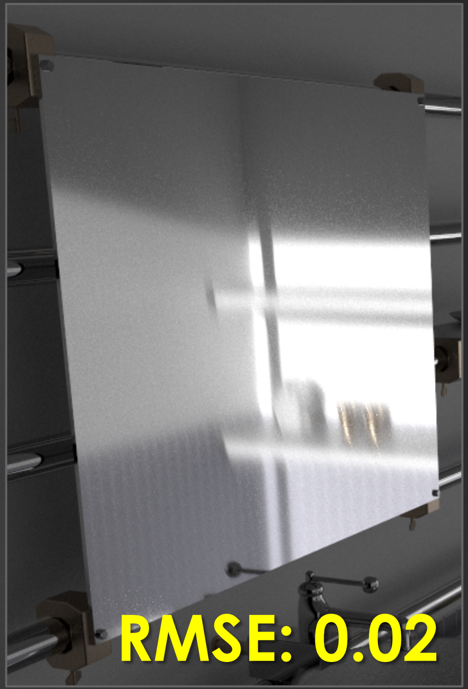
Anisotropic BRDF (15 min)

Roughness: (0.0001, 0.01)



PCBPT

PCBPT+HRR
(spheroidal range)



PCBPT+HRR
(ellipsoidal range)

Related Work: Many-Light Methods

Pregenerated random numbers (require storage)

- Correlation can be reduced by sacrificing the memory usage [Walter06], but cannot be avoided completely

	MIS for SDG paths	Uncorrelated variance	Anisotropic BRDFs
Lightcuts [Walter05]	✗	✗	✗
Stochastic light culling [Tokuyoshi16,17]	✗	✗	✗
Many-light importance sampling [Estevez18]	✗	✓	✗
Ours	✓	✓	✓

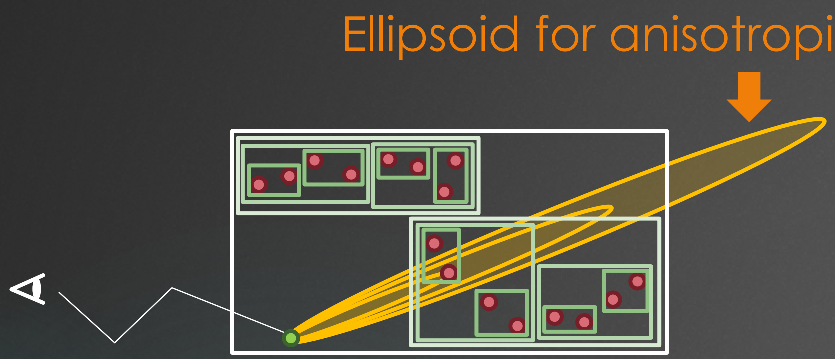
On-the-fly random number generation (no storage)

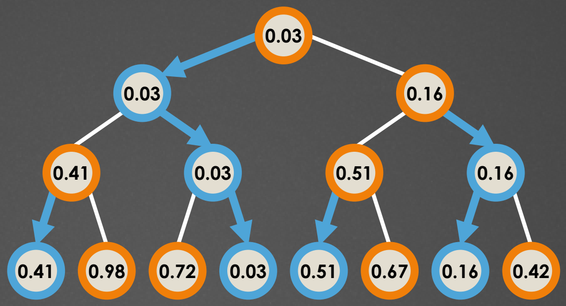
Limitations

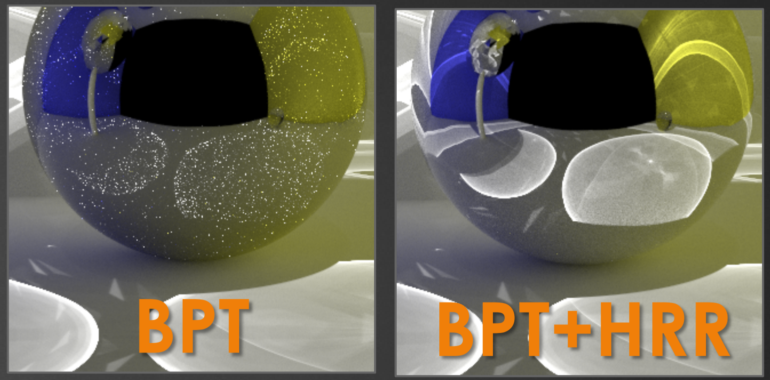
PCBPT+HRR | Reference | PCBPT+HRR | PCBPT+HRR (+outlier rejection) | PCVCM+HRR

- Perfectly specular surfaces
- Fireflies can still occur on near singularities
  - Can be removed easily by VCM or using outlier rejection [Zirr18]
- Glossy-to-glossy interreflections
- Correlation of paths due to path reuse (similar to VCM)
  - Future work: correlation-aware MIS heuristics [Jendersie19]

Conclusions







- BVH-based acceleration for many Russian roulettes
- On-the-fly minimum random number generation in BVH traversal
- Efficient ellipsoidal range for anisotropic BRDFs
- Limited to glossy reflections, but efficient for extremely glossy reflections
  - E.g., GGX roughness: 0.0001 (hard to distinguish from perfectly specular surfaces)

Thank you for your attention

References

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