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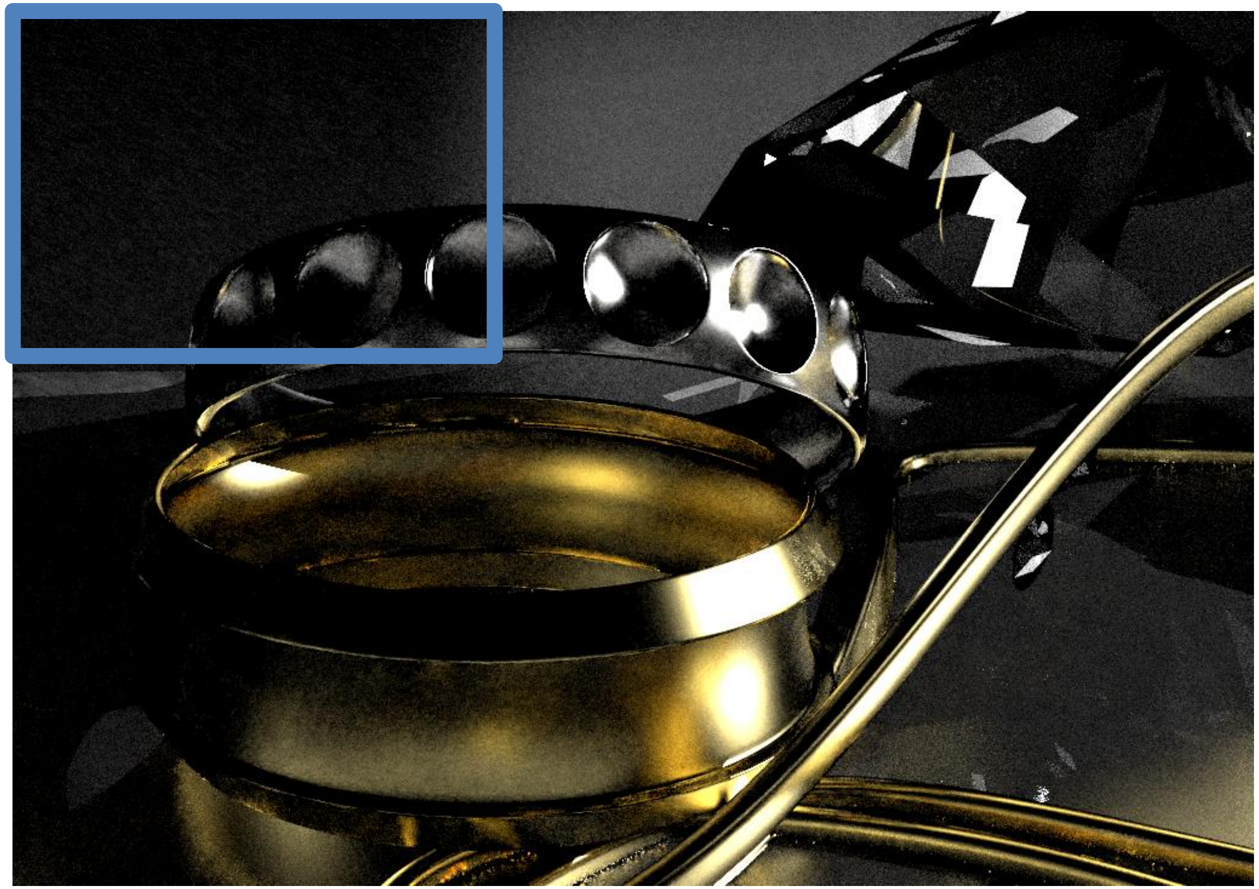
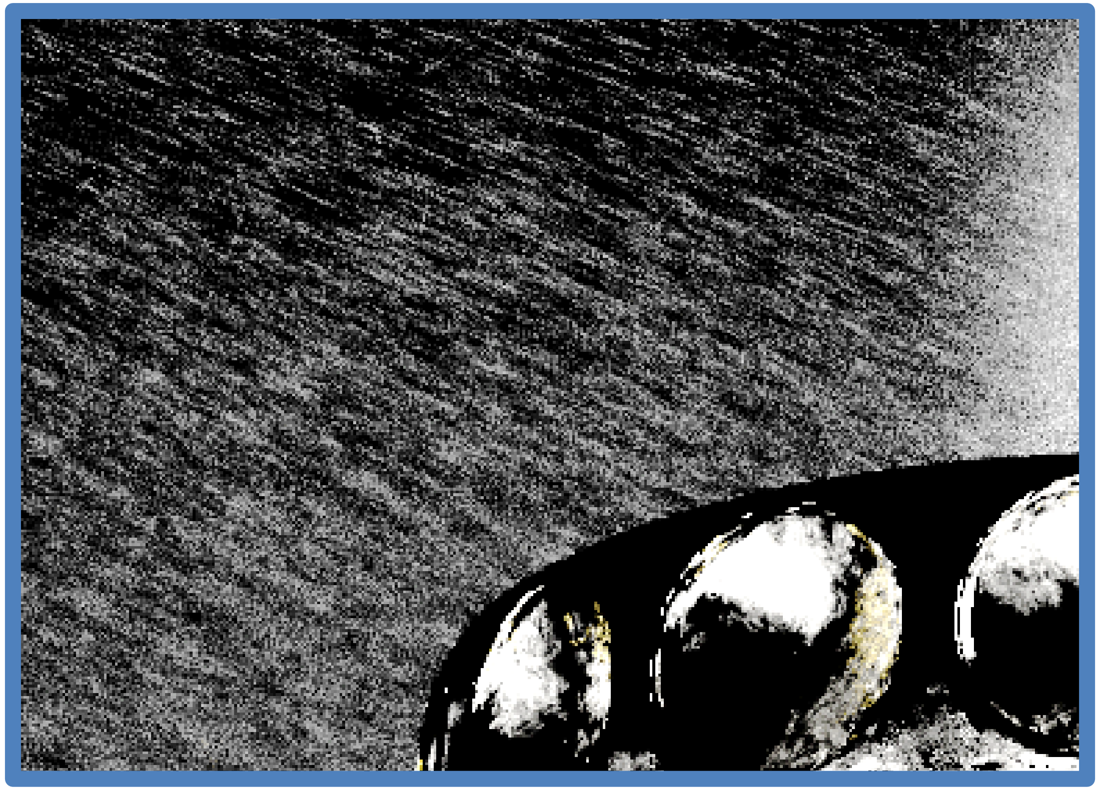
Improved half vector space light transport

Karlsruhe Institute of Technology

Motivation

- rendering images with half vector space light transport [KHD14]





- uneven exploration of certain flat areas *despite* explicit stratification!

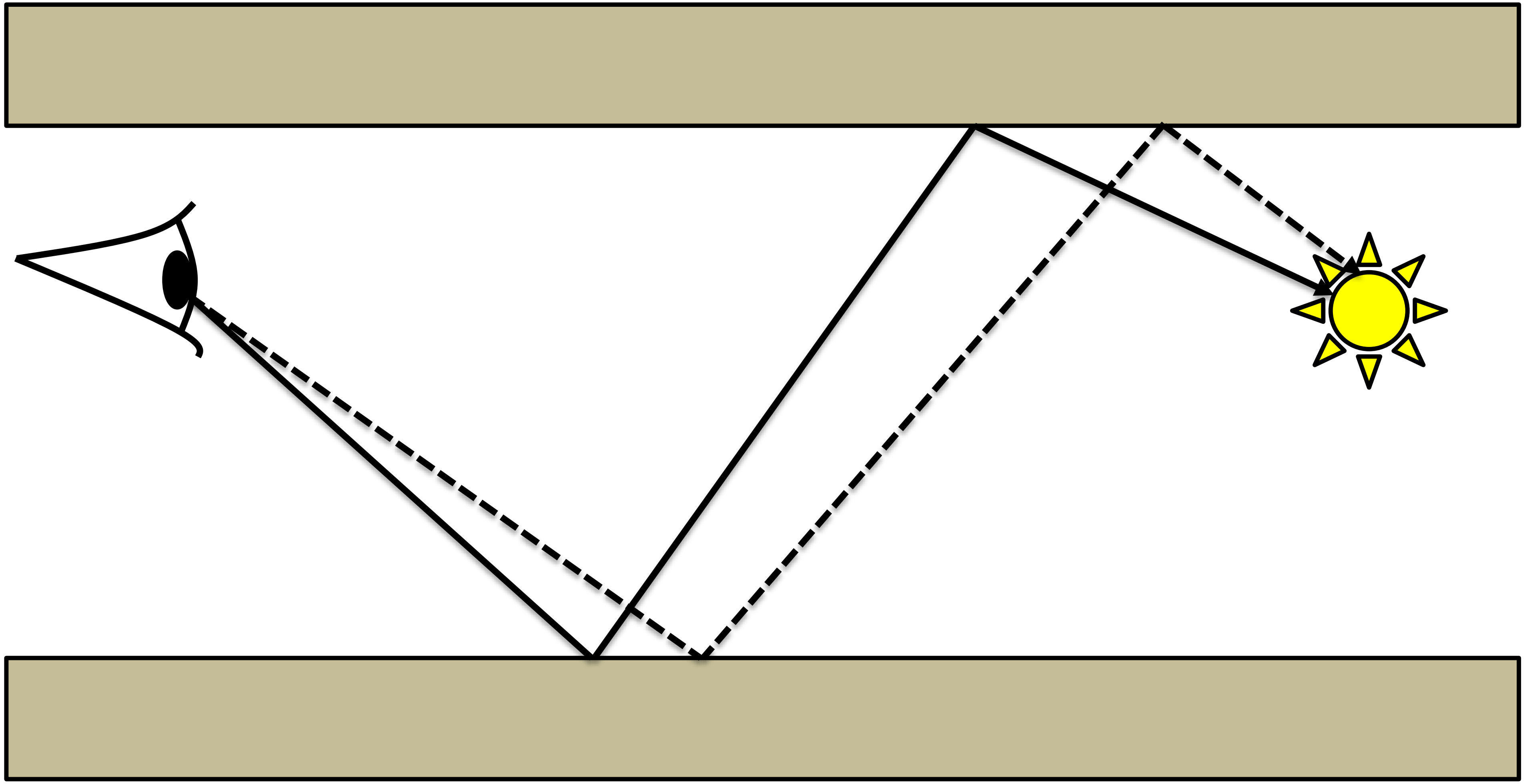
Motivation

- rendering images with half vector space light transport [KHD14]

- HSLT is confused about highly displaced meshes!

Quick summary on Metropolis light transport

- Markov chain: sample tentative new state (path)
  - perturb current path
  - accept with certain probability to maintain detailed balance



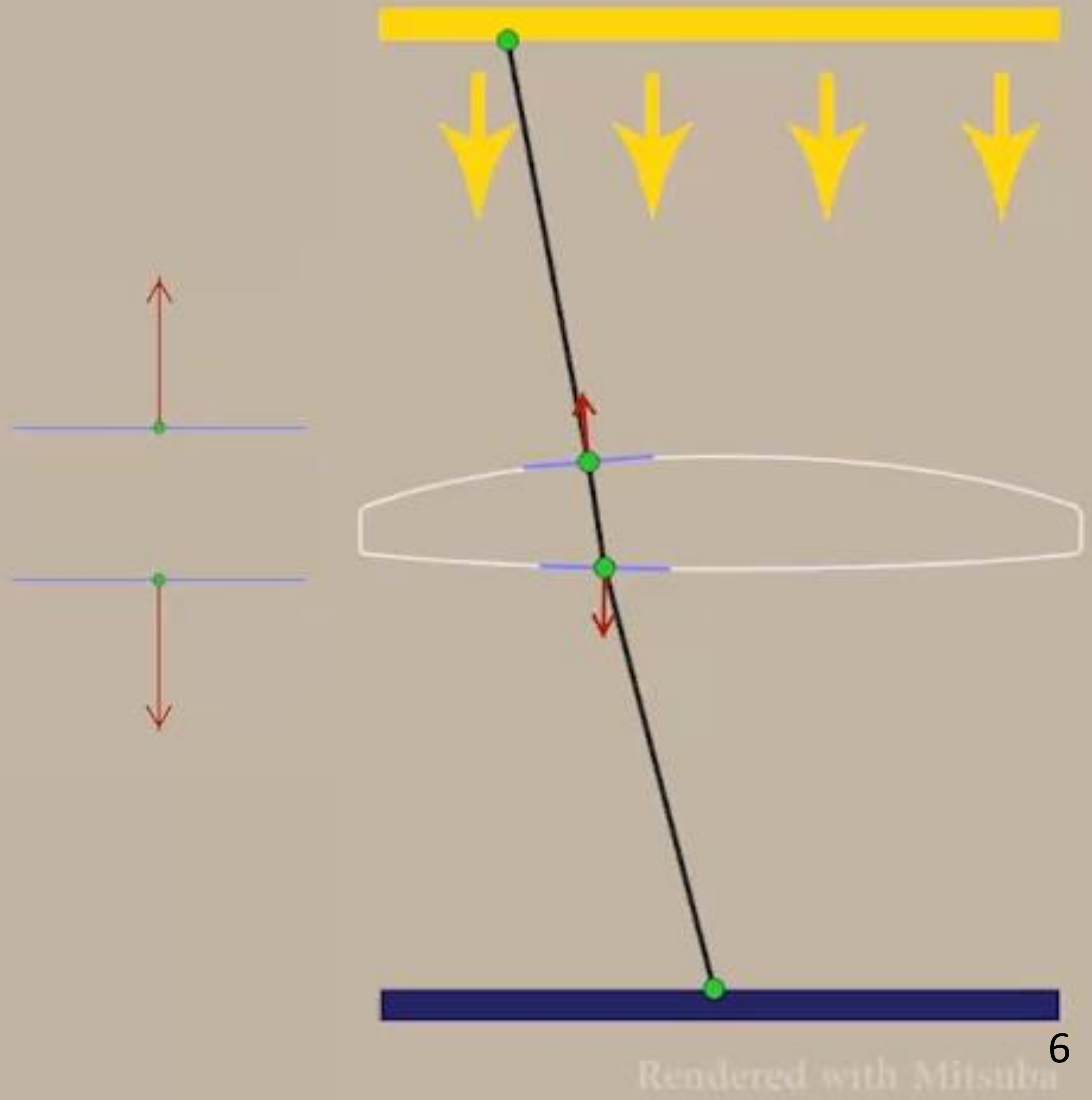
Veach's Metropolis light transport

- collection of mutation strategies
- all converted into common measure (product vertex area measure) for comparison
- rely on small mutation steps to meet
  - BSDF constraints (angular, half vectors)
  - geometry constraints (vertex location, e.g. point on light source or key holes)

- explicit control over these constraints?

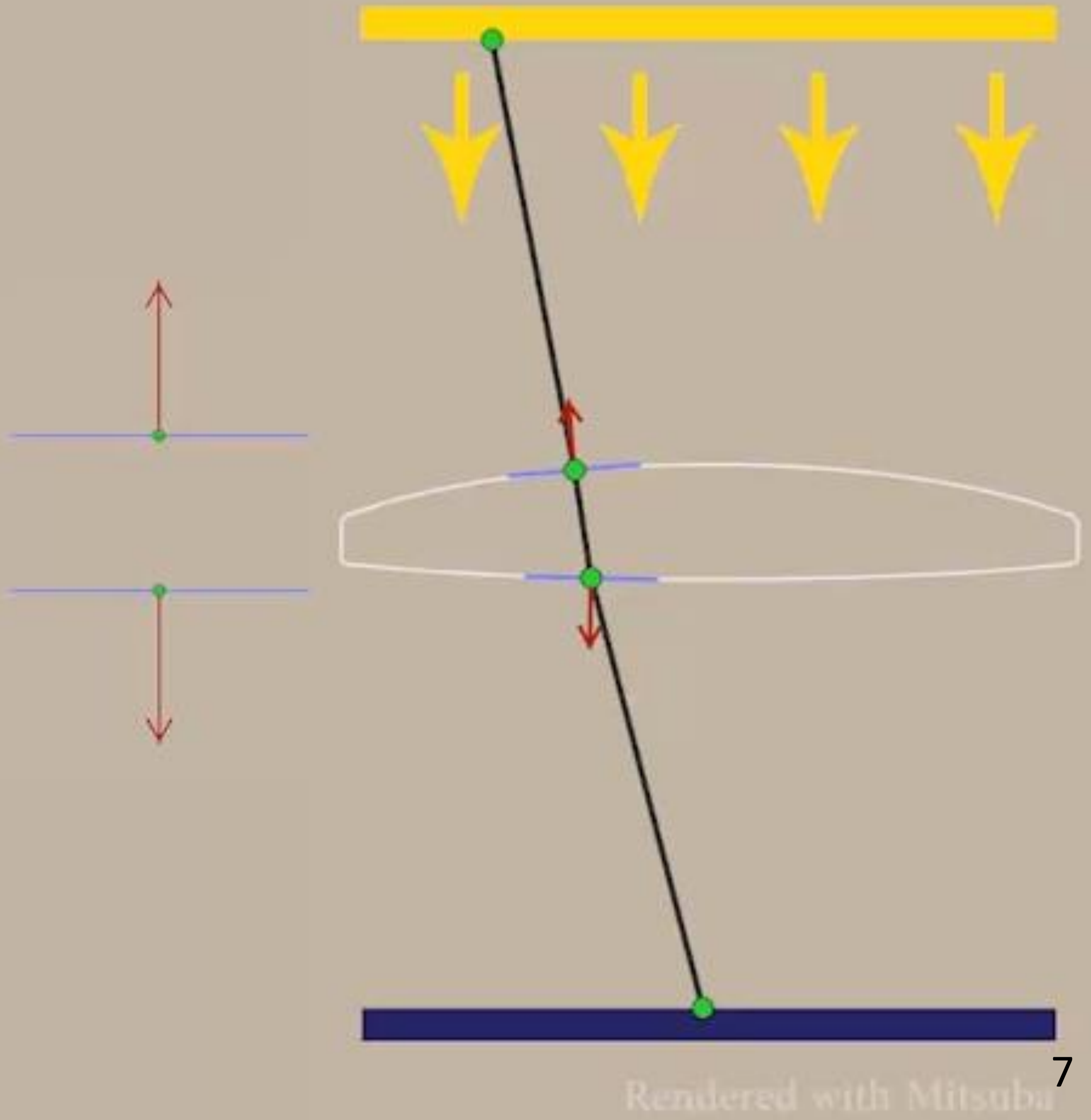
Manifold exploration [JM12] and specular constraints

- two endpoints with specular **hard constraints**
- move end point, keep constraints satisfied



Half vector space light transport [KHD14]

- rough scattering: use **soft constraints**
- keep end points fixed, change half vectors



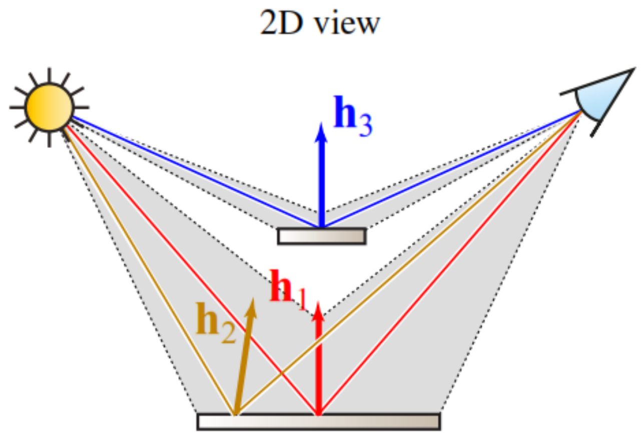
Half vector space light transport

- change of domains, perform integration in different space:
  - product vertex area measure

$$I_j = \int_{\mathcal{P}} f(\boldsymbol{X}) d\boldsymbol{X}$$

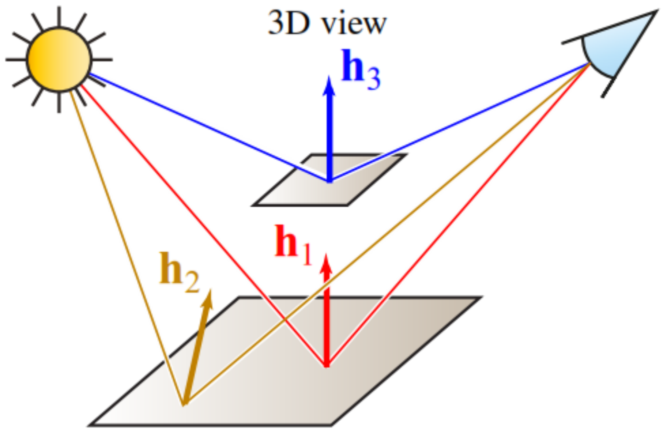
$$\boldsymbol{X} = (\boldsymbol{x}_0, \boldsymbol{x}_1, \dots, \boldsymbol{x}_{k-1}, \boldsymbol{x}_k)$$

  - half vector space (fixed end points $\boldsymbol{x}_0$and $\boldsymbol{x}_k$ and varying half vectors in between)



$$I_j = \int_{\Omega_h} f(\boldsymbol{X}(\boldsymbol{H})) \left|\frac{d\boldsymbol{X}}{d\boldsymbol{H}}\right| d\boldsymbol{H}$$

$$\boldsymbol{H} = (\boldsymbol{x}_0, \boldsymbol{h}_1, \dots, \boldsymbol{h}_{k-1}, \boldsymbol{x}_k)$$



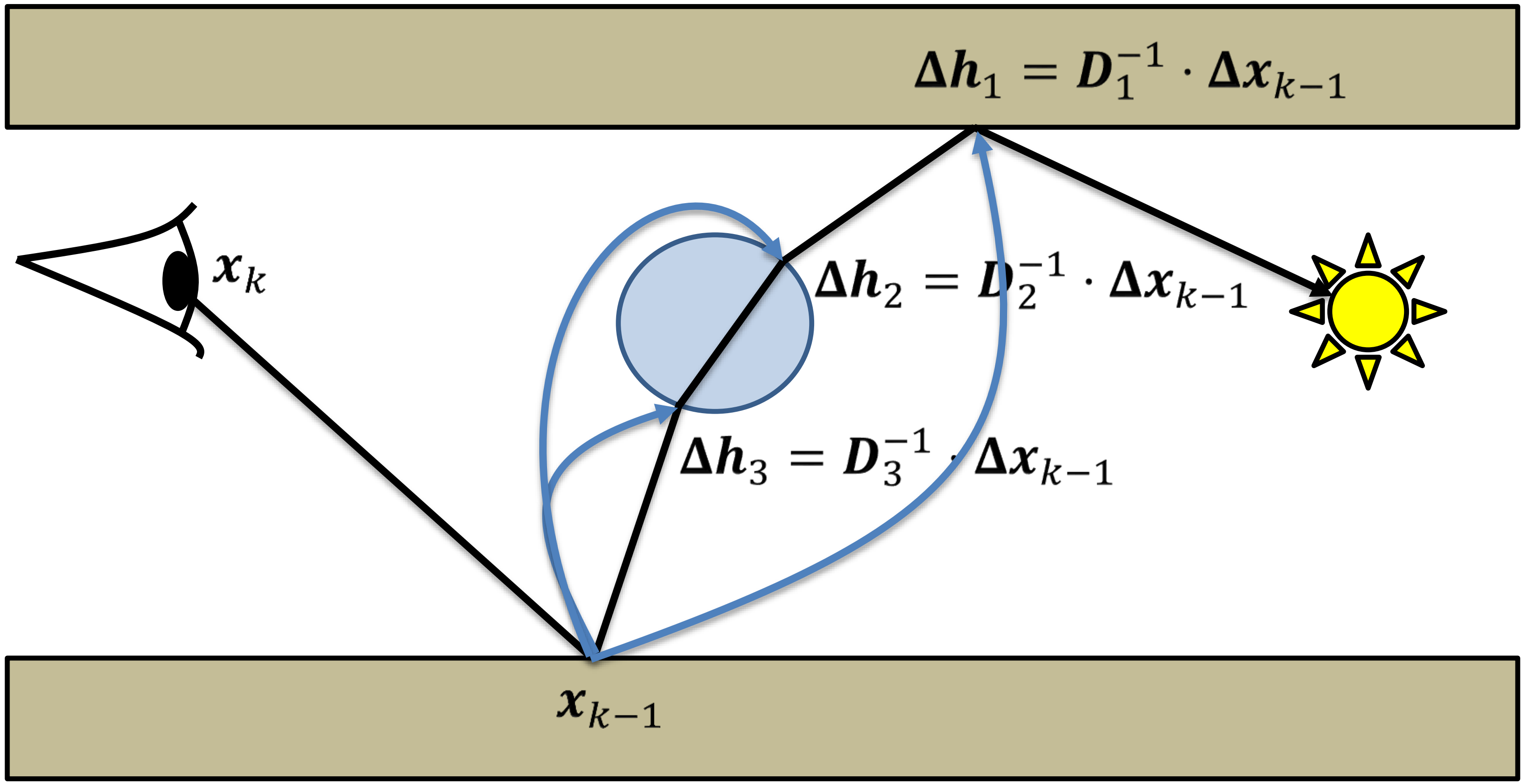
Outline: improved half vector space light transport

- more natural space of constraints for half vectors
  - leads to more **precise ray differentials**

- support highly **detailed displacement**
  - new **half vector multi chain perturbation** on sub-paths
  - improves performance **samples/second**

Pixel stratification: ray differentials

- control image space stratification from half vector space!
- ray differential matrices D_i^{-1} transport vertex offset $\Delta\boldsymbol{x}_{k-1}$ to half vectors $\boldsymbol{h}_i$
- convert pixel footprint to half vector domain or vertex area at every vertex!
- derive pixel footprint based on geometry and BSDF scattering separately!

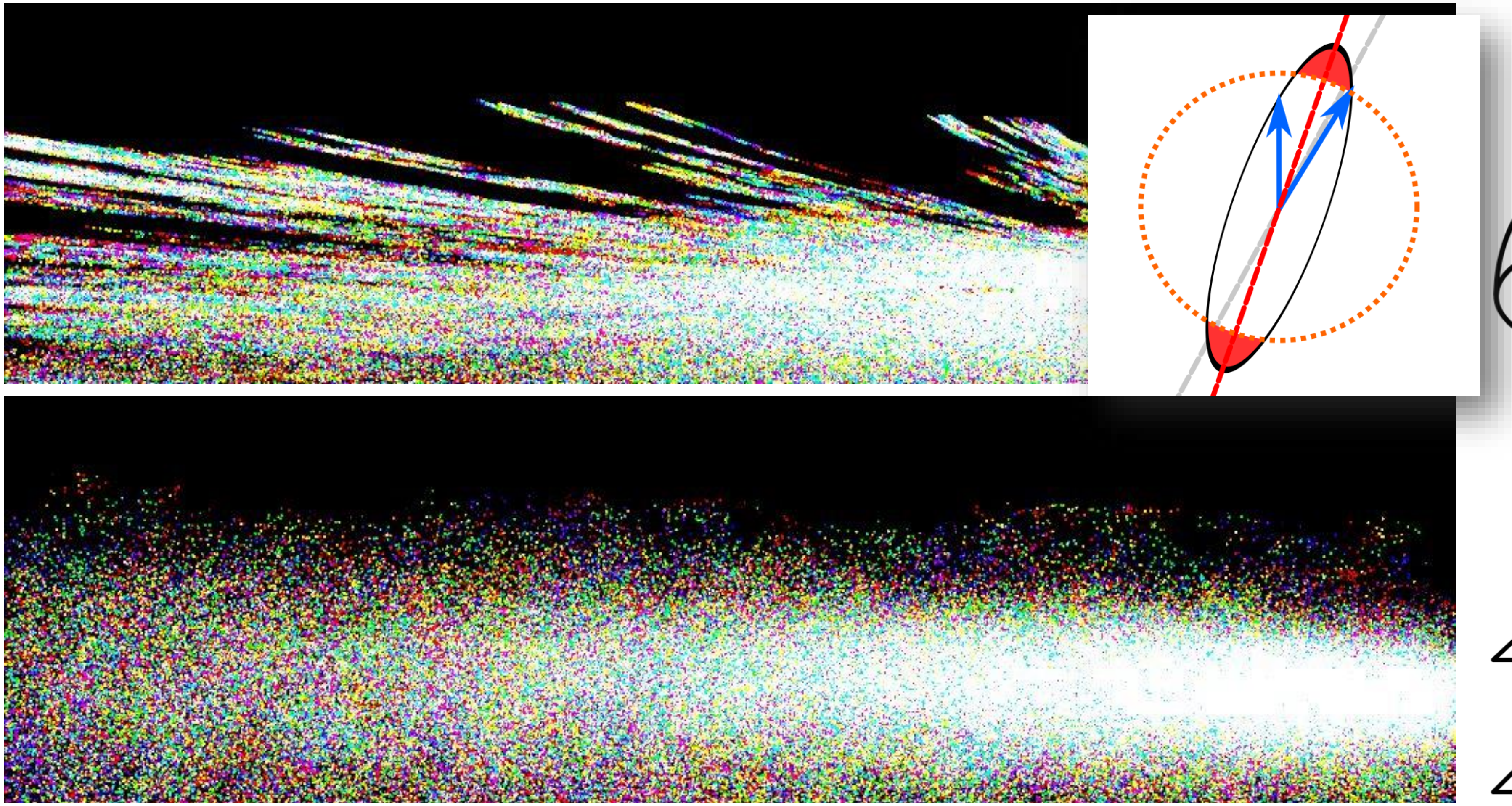


Ray differentials and measure spaces

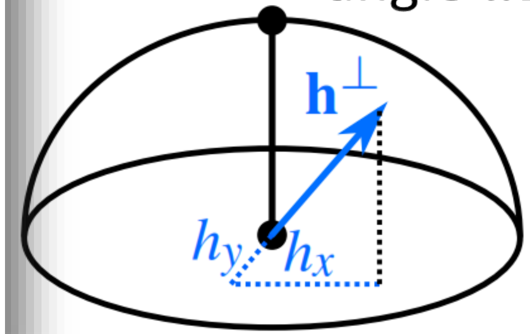
- projected solid angle has a bounded domain, plane/plane is unbounded
- need to cut off step size (first-order prediction!) at boundary, resulting in unwanted anisotropy
- plane/plane much more stable at grazing angle and for large step sizes

old

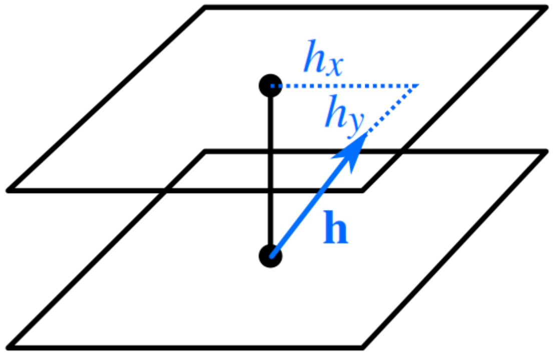
new



projected solid angle $d\boldsymbol{h}^{\perp}$



plane/plane $d\boldsymbol{h}^{||}$



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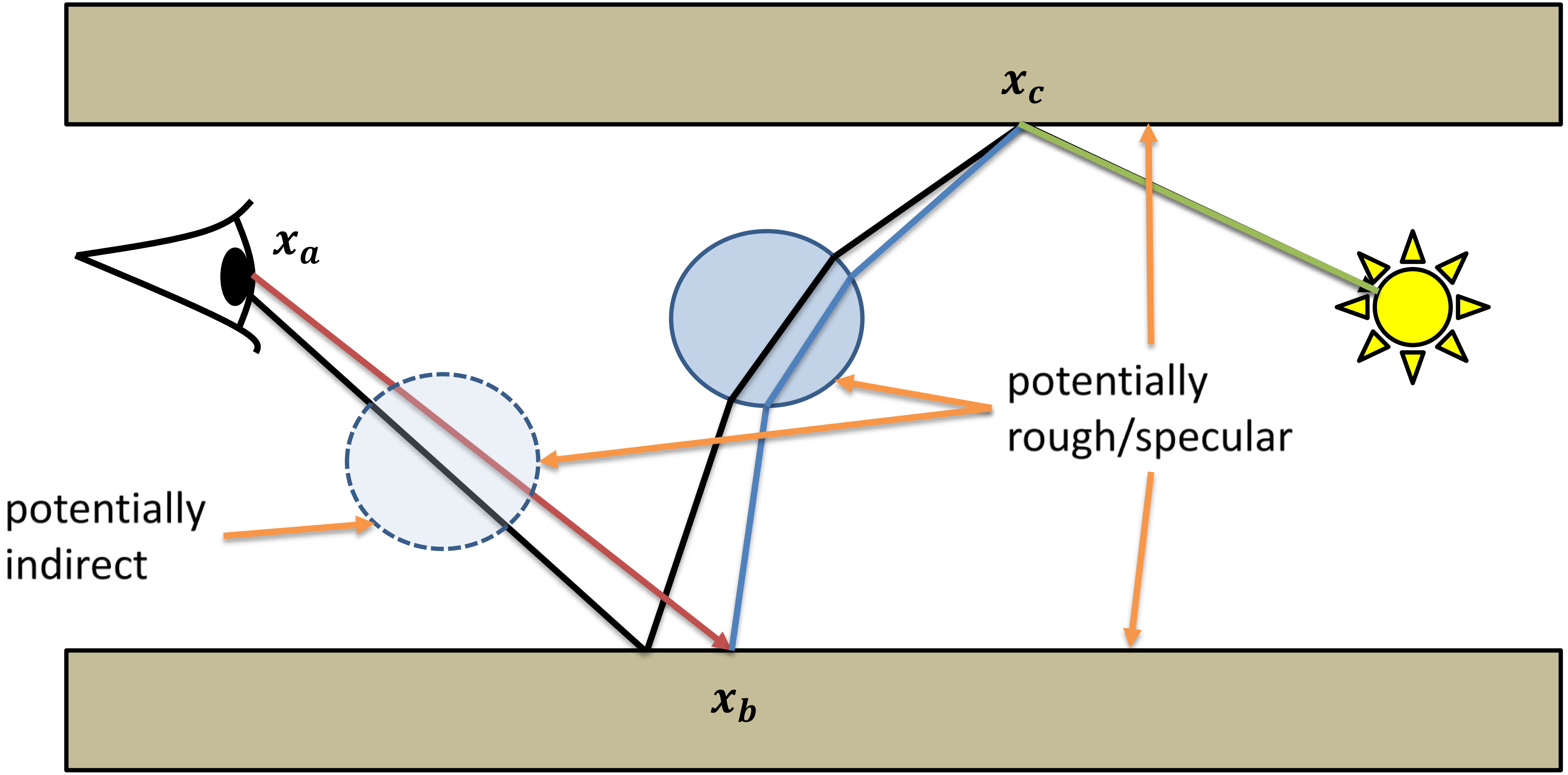
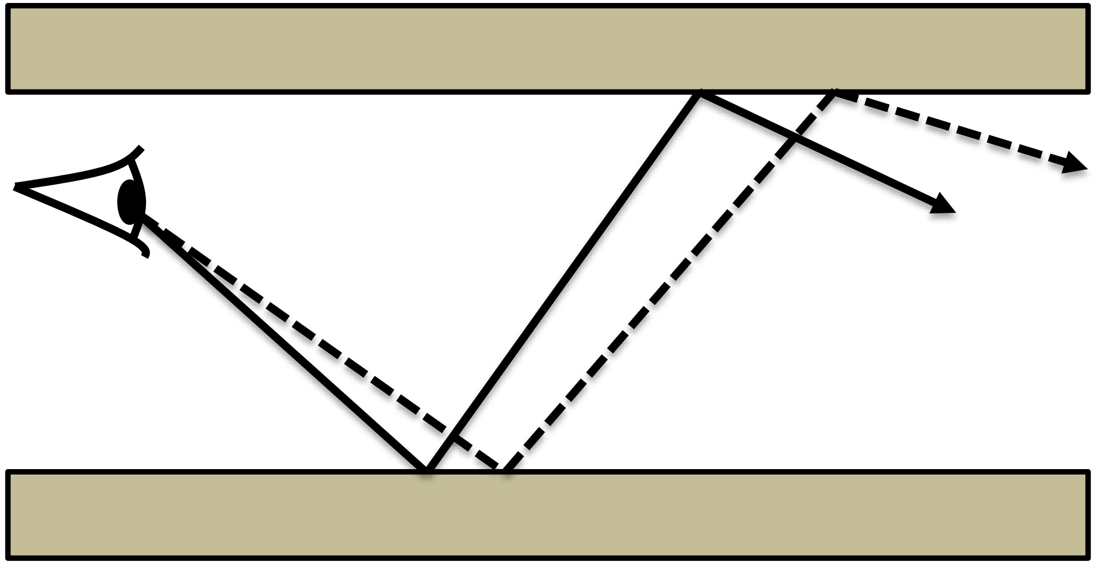
Breaking up paths into segments (much the same as manifold exploration)

- $(x_a, \dots, x_b)$: half vector multi chain perturbation (not half vector space, since end point moves!)
- $(x_b, \dots, x_c)$: connect through ``specular chain" only that nothing is strictly diffuse or specular
- $(x_c, \dots, x_0)$: stays untouched



Half vector multi chain perturbation

- do a pixel step, cast ray, perturb half vector, cast ray to resulting outgoing direction, iterate.
  - essentially a perturbation of outgoing solid angles
  - similar to Kelemen but in the Veach framework
    (half vector sampling is close to BSDF importance sampling)
  - similar to Veach‘s multi chain but using half vectors
    (respecting BSDFs angular bandwidth precisely)



Choice of breakup points a, b, c

- $a = k$ at the camera since we want to mutate the pixel coordinate
- b at a vertex with high roughness, so BSDF evaluation will give a good contribution

$$P(x_i = x_b) \sim \alpha_i$$

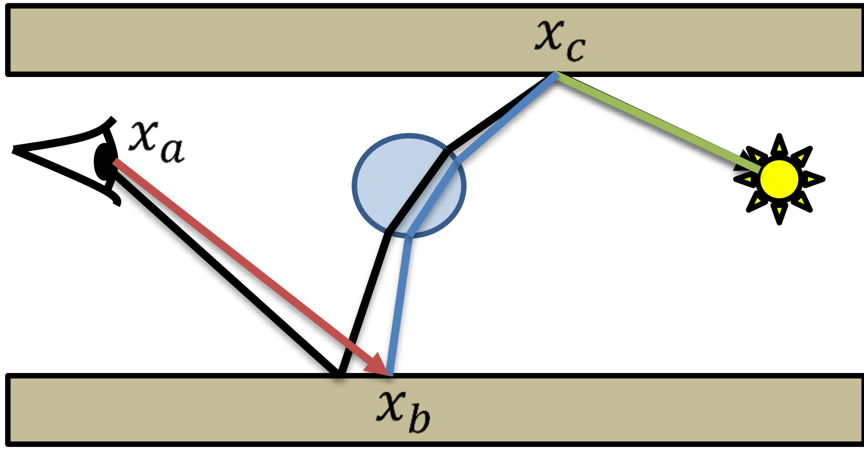
- mix in full multi chain and full half vector space (and normalise):

$$P(x_0 = x_b) = P(x_k = x_b) \sim 0.1$$

- c at the light source for minimum correlation, but closer to a and b is faster and did not lead to artefacts in our experiments:

$$P(x_i = x_c) \sim \alpha_i \cdot \|x_i - x_{i+1}\|^2$$

- squared distance to penalise degenerate geometry terms



Results: displaced geometry (skin, iris)

- 64spp, relatively lightweight 5M polygons but strongly varying geometric derivatives

reference
20h

HSLT
113s

HSLT 157s
no displacement

improved
HSLT 54s

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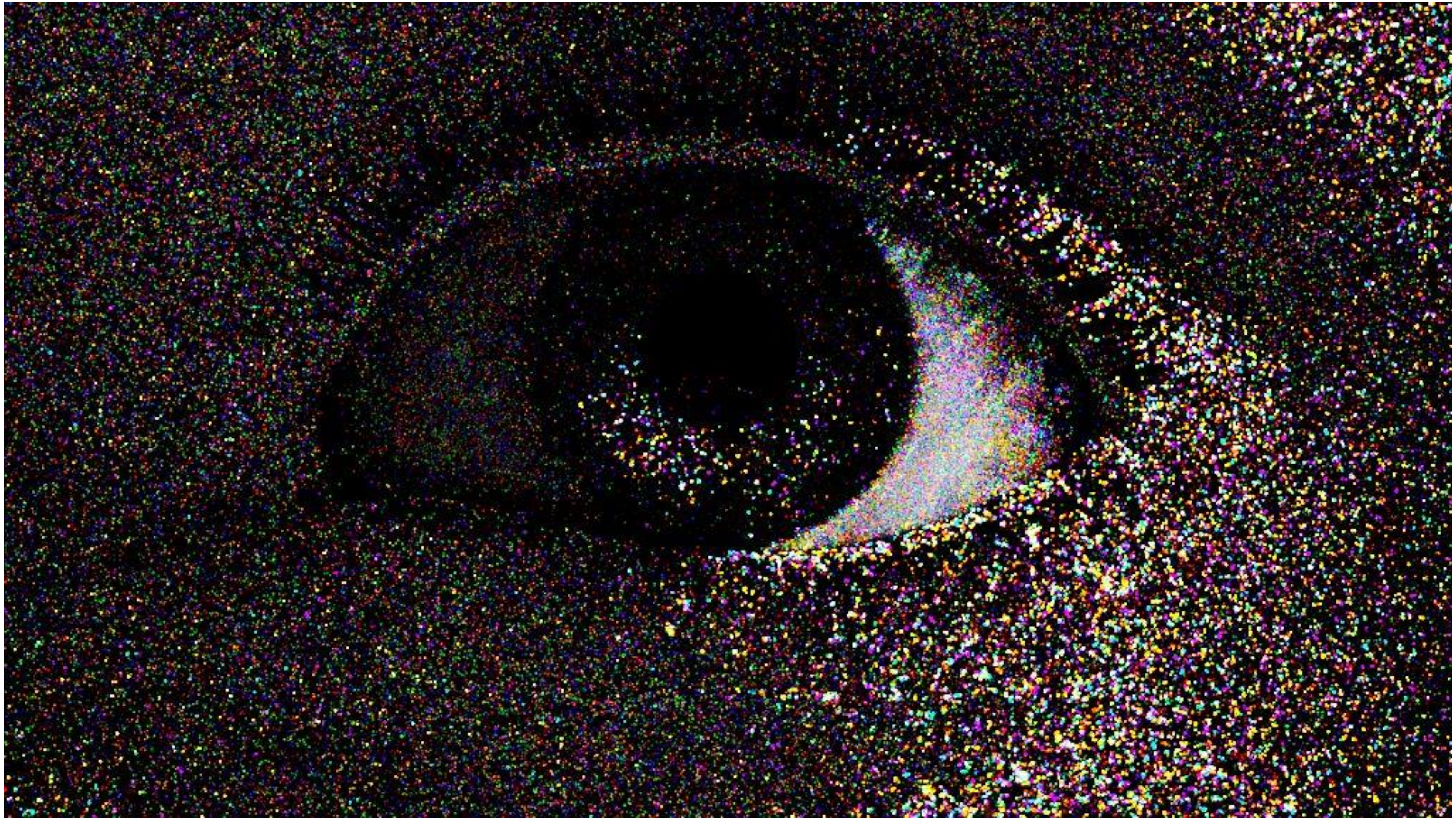

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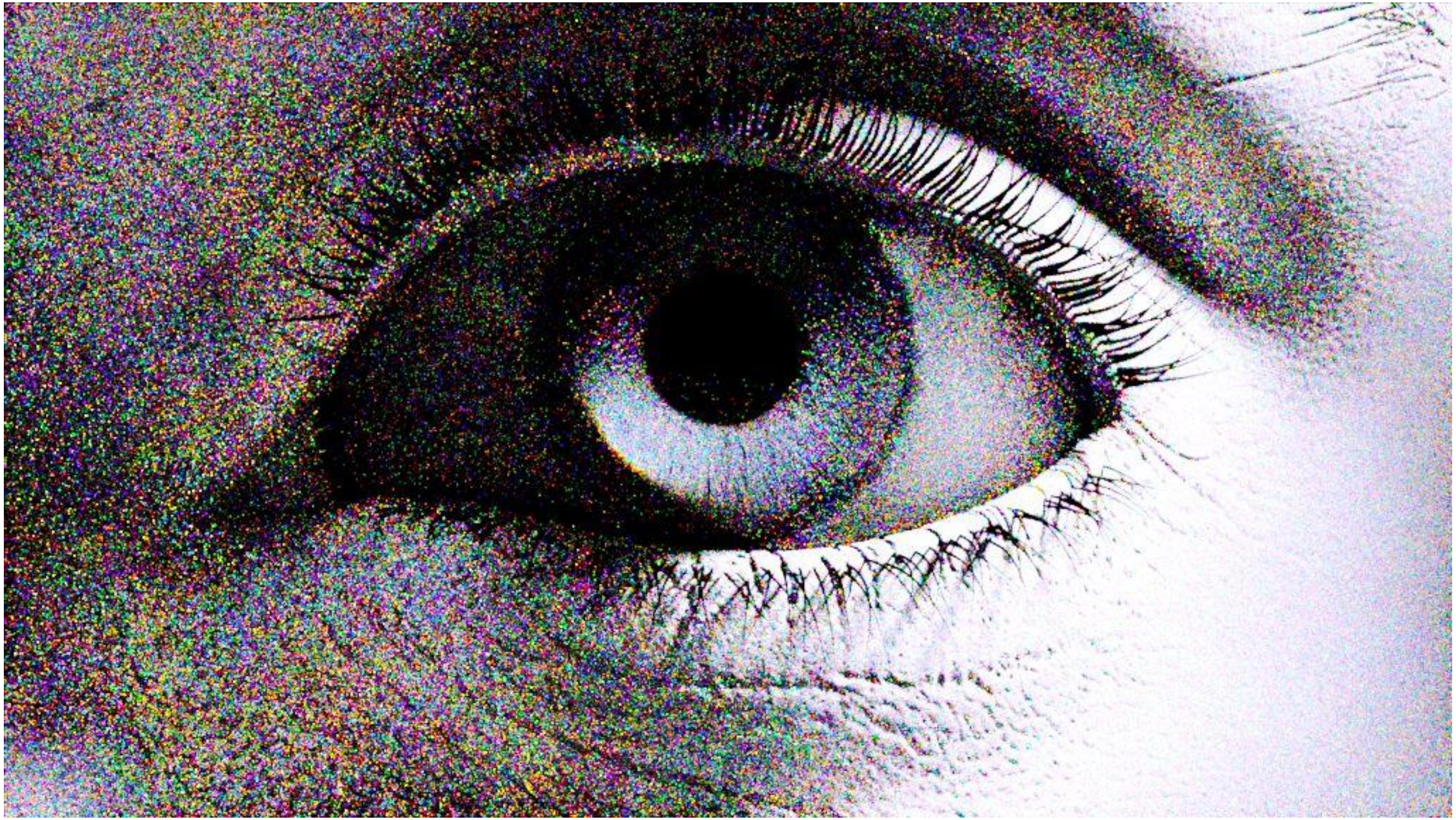

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Results: long glossy chains

- jewellery: difficult since no clear breakup point (all surfaces are glossy or specular)
- we detect this robustly
- only moderately faster, since we choose full half vector space mutation most of the time

improved HSLT 40min 2067spp

HSLT 40min 1558spp

Limitations and Future Work

- still need smooth surfaces for effective exploration using geometrical constraint derivatives
- no simple extension to participating media

- our choice of breakup points is simplistic
  - not using any differential geometry information to find breakup points yet
  - sub-optimal but good enough and fast to evaluate? (proof us wrong!)

Conclusion

- made half vector space light transport more robust
  - more natural space of half vectors, Beckmann is a real Gaussian
  - leads to better step sizes and more precise ray differentials
  - better handling of displaced geometry
  - depth of field (see paper)
  - spectral/wavelength dependent (see paper)

- source code online: https://www.mitsuba-renderer.org/repos/mitsuba.git
  - still working on improving it though

thank you for listening!

backup slides

Half vector space measurement

- simplified mesaurement with half vectors in projected solid angle [JM12, KHD14]

$$f(\boldsymbol{X})\left|\frac{d\boldsymbol{X}}{d\boldsymbol{H}^{\perp}}\right| = \left|\frac{d\boldsymbol{o}_0^{\perp}}{d\boldsymbol{x}_k}\right| \prod_{i=1}^{k-1} f_r(\boldsymbol{i}_i,\boldsymbol{o}_i)\left|\frac{d\boldsymbol{o}_i}{d\boldsymbol{h}_i}\right| \left|\frac{\langle \boldsymbol{o}_i,\boldsymbol{n}_i\rangle}{\langle \boldsymbol{h}_i,\boldsymbol{n}_i\rangle}\right|$$

transfer matrix **[WMLT07]**

- in plane/plane:

$$\left|\frac{d\boldsymbol{o}_0^{\perp}}{d\boldsymbol{x}_1}\right|\left|\frac{d\boldsymbol{x}_1}{d\boldsymbol{x}_k}\right| = G_1 \cdot |T_1|$$

$$f(\boldsymbol{X})\left|\frac{}{d\boldsymbol{H}}\right| = \left|\frac{}{d\boldsymbol{x}_k}\right| \prod_{i=1} f_r(\boldsymbol{i}_i,\boldsymbol{o}_i)\left|\frac{d\boldsymbol{o}_i}{d\boldsymbol{h}_i}\right| \left|\langle \boldsymbol{o}_i,\boldsymbol{n}_i\rangle\langle \boldsymbol{h}_i,\boldsymbol{n}_i\rangle^3\right|$$

- don‘t divide the cosine, more numerically stable!

Measurement for half vector multi chain perturbation

- simplified mesaurement in half vector space

$$f(\boldsymbol{X})\left|\frac{d\boldsymbol{X}}{d\boldsymbol{H}}\right| = \left|\frac{d\boldsymbol{o}_0^\perp}{d\boldsymbol{x}_k}\right| \prod_{i=1}^{k-1} f_r(\boldsymbol{i}_i, \boldsymbol{o}_i)\left|\frac{d\boldsymbol{o}_i}{d\boldsymbol{h}_i}\right| \left|\langle \boldsymbol{o}_i, \boldsymbol{n}_i\rangle\langle \boldsymbol{h}_i, \boldsymbol{n}_i\rangle^3\right|$$

- half vector multi chain:

convert projected solid angle to plane/plane half vectors

$$f(\boldsymbol{X})\left|\frac{d\boldsymbol{X}}{d\mathbf{H}^{\boldsymbol{o}}}\right| = \prod_{i=1}^{k-1} f_r(\boldsymbol{i}_i, \boldsymbol{o}_i)\left|\frac{d\boldsymbol{o}_i}{d\boldsymbol{h}_i}\right| \left|\langle \boldsymbol{o}_i, \boldsymbol{n}_i\rangle\langle \boldsymbol{h}_i, \boldsymbol{n}_i\rangle^3\right|$$

- difference: last vertex free to move, do not require generalised geometric term

$$\left|\frac{d\boldsymbol{o}_0^\perp}{d\boldsymbol{x}_k}\right| = \left|\frac{d\boldsymbol{o}_0^\perp}{d\boldsymbol{x}_1}\right| \left|\frac{d\boldsymbol{x}_1}{d\boldsymbol{x}_k}\right| = G_1 \cdot |T_1|$$

- both only evaluated for the respective sub-path
- transition probability in half vector domain