Path tracing, part 1 of 2: Introduction

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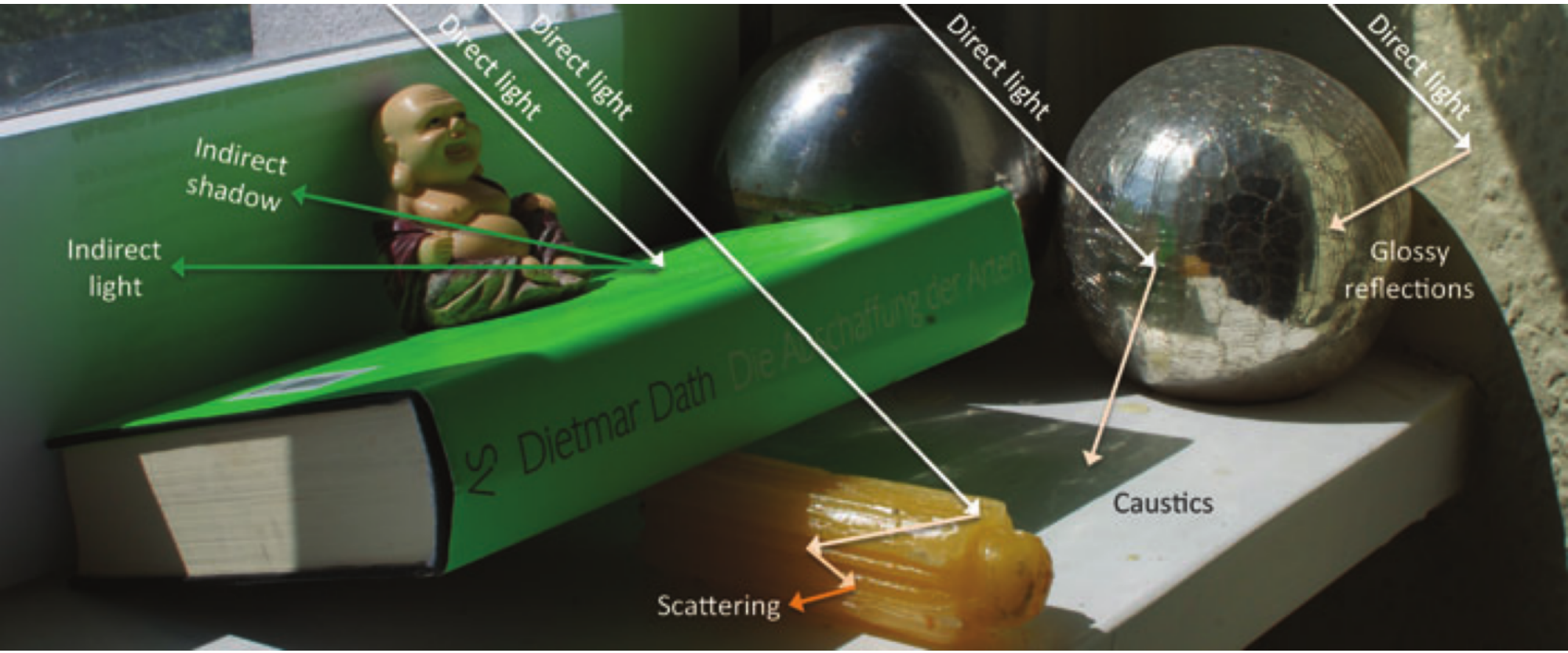
Goal: Full global illumination

Rasterization struggles with many light-transport phenomena.

Path tracing handles them all accurately.

But it takes effort to make it efficient.



doi.org/10.1111/j.1467-8659.2012.02093.x

Light transport

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Hardware-accelerated ray tracing

NVIDIA introduced GPUs with ray tracing cores in 2018.

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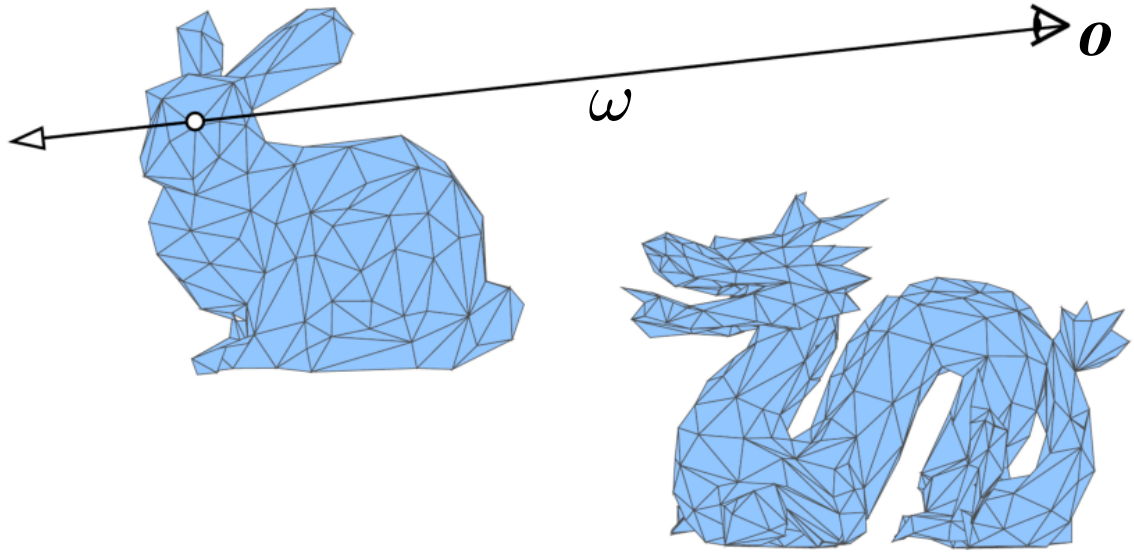
Available through Vulkan, Direct 3D 12, Metal,
NVIDIA OptiX, AMD Radeon Rays, Intel Embree.

Not through OpenGL, Direct3D 11, WebGL.

Ray tracing APIs

Goal: For a ray with origin $\boldsymbol{o} \in \mathbb{R}^3$ and direction $\omega \in \mathbb{R}^3$ find the closest scene triangle that it intersects (if any).



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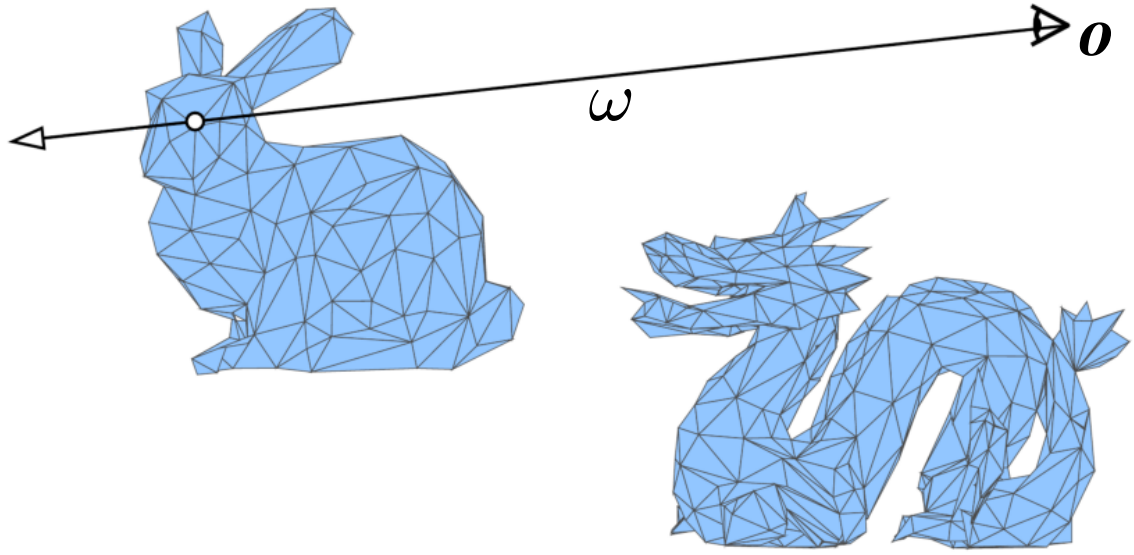


Use API to build acceleration structure for all scene triangles.

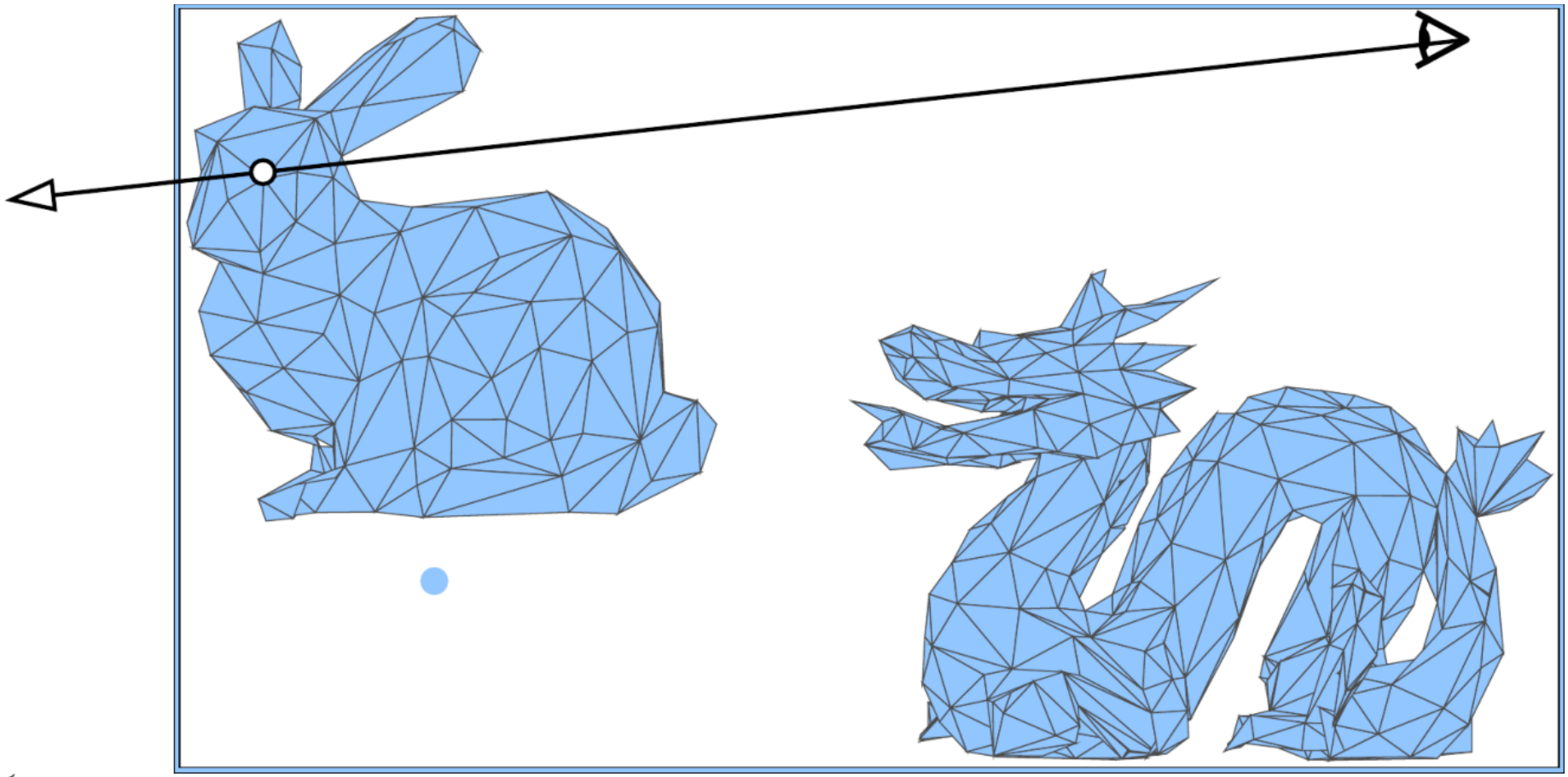
In a shader, pass $\boldsymbol{o}$, ω and acceleration structure to the API.

Then retrieve info about the hit triangle (if any).

Bounding volume hierarchy (BVH)

BVH = tree of bounding boxes with triangles in leafs.

If a ray does not hit a box, ray tracing ignores its subtree.



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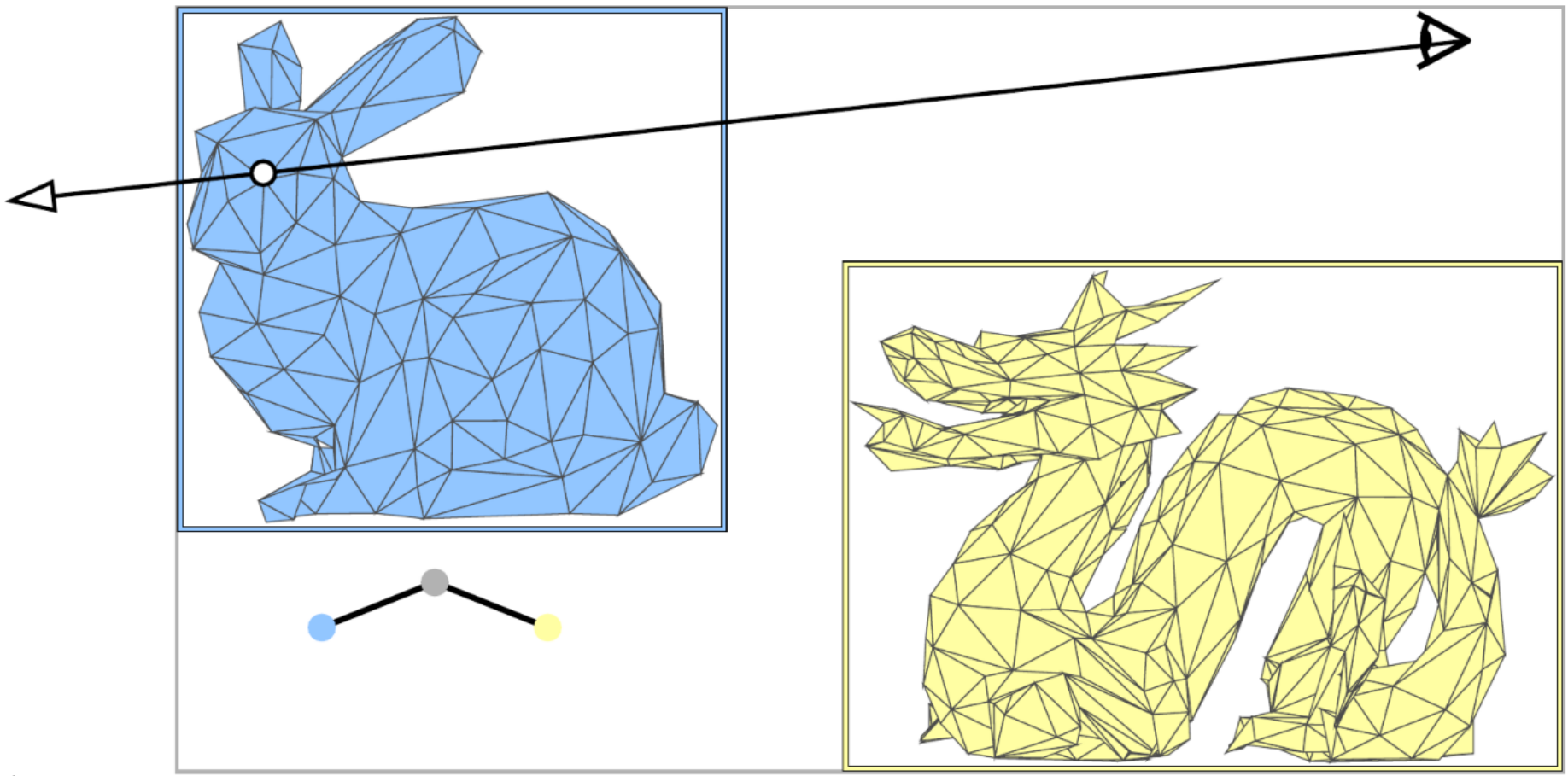

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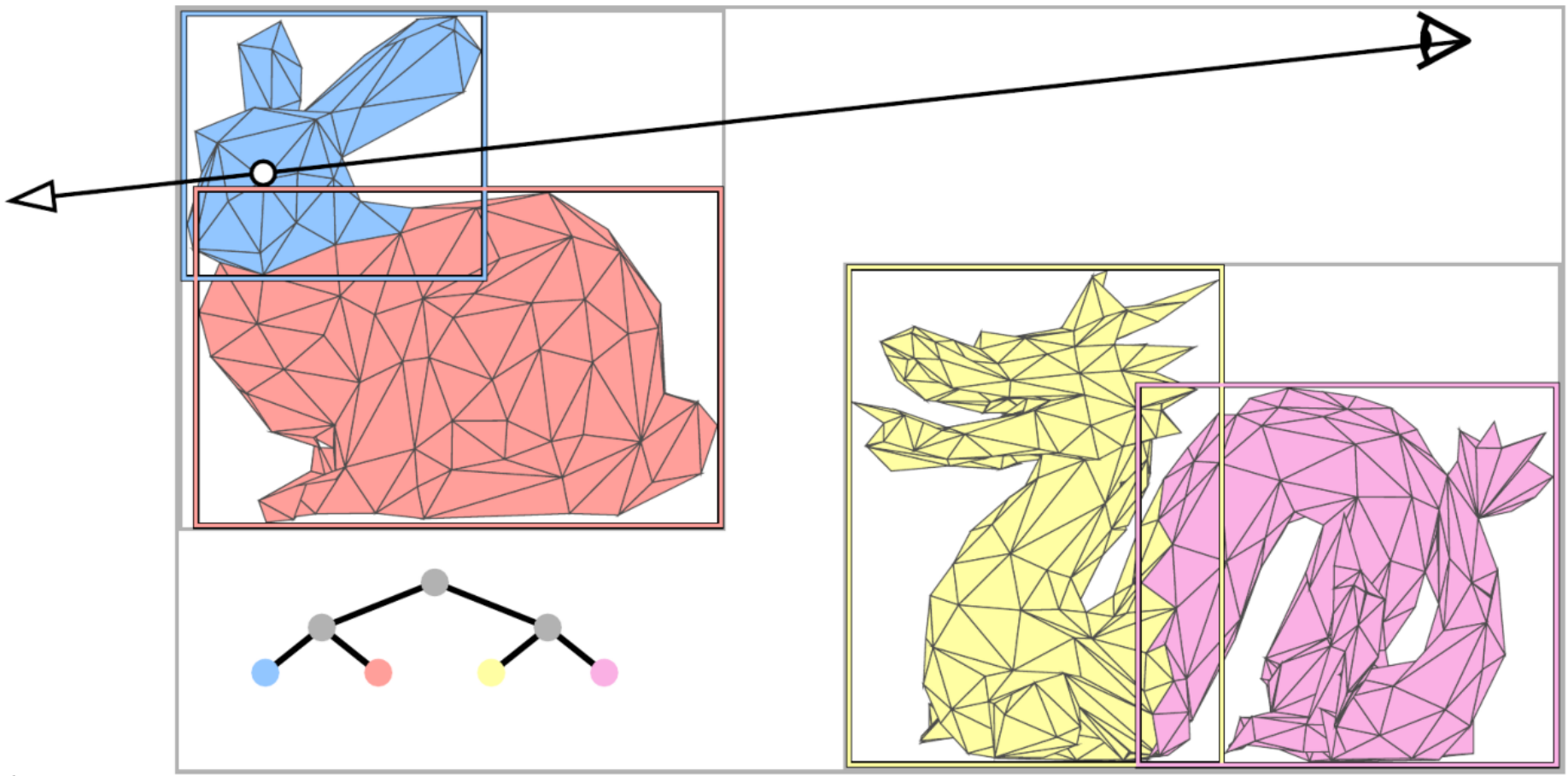

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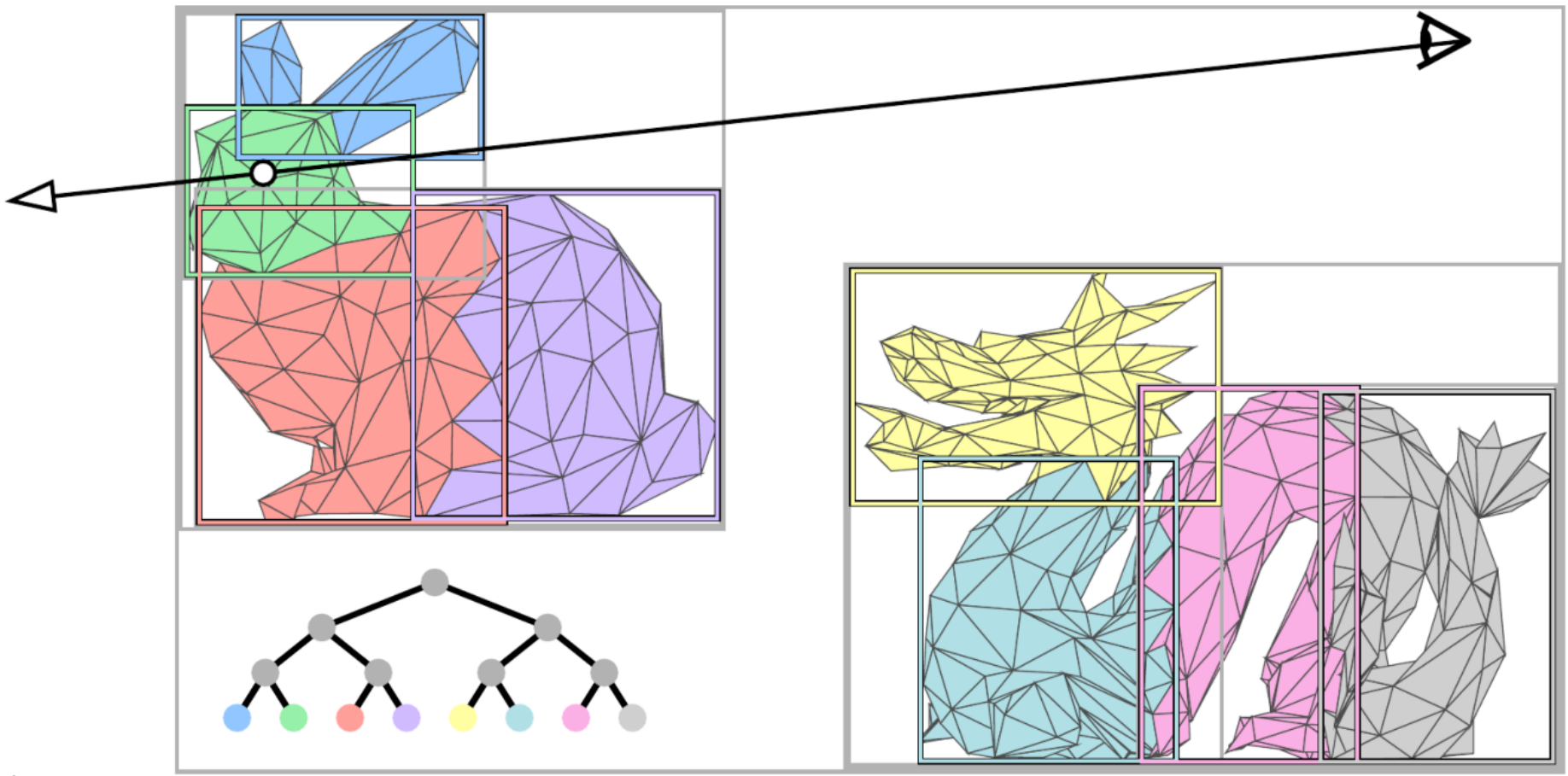


Shading data

For an intersection at $\boldsymbol{x}$, the API provides the triangle index and barycentric coordinates $w_0, w_1, w_2 \in [0, 1]$.

Load the triangle vertex positions $\boldsymbol{x}_0, \boldsymbol{x}_1, \boldsymbol{x}_2$.

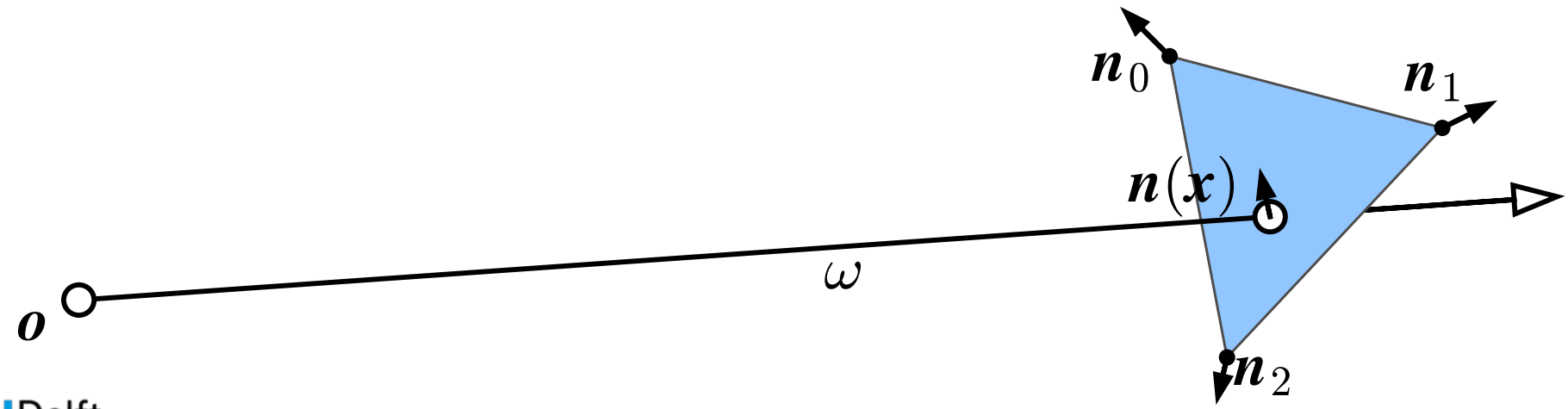
Interpolate: $\boldsymbol{x} = w_0 \boldsymbol{x}_0 + w_1 \boldsymbol{x}_1 + w_2 \boldsymbol{x}_2$

Shading data

For an intersection at $\boldsymbol{x}$, the API provides the triangle index and barycentric coordinates $w_0, w_1, w_2 \in [0, 1]$.

Load the triangle vertex normals $\boldsymbol{n}_0, \boldsymbol{n}_1, \boldsymbol{n}_2$.

Interpolate: $\boldsymbol{n}(\boldsymbol{x}) = \dfrac{w_0 \boldsymbol{n}_0 + w_1 \boldsymbol{n}_1 + w_2 \boldsymbol{n}_2}{\| w_0 \boldsymbol{n}_0 + w_1 \boldsymbol{n}_1 + w_2 \boldsymbol{n}_2 \|}$



Shading data

For an intersection at $\boldsymbol{x}$, the API provides the triangle index and barycentric coordinates $w_0, w_1, w_2 \in [0, 1]$.

Load the triangle vertex texture coordinates $\boldsymbol{t}_0, \boldsymbol{t}_1, \boldsymbol{t}_2$.

Interpolate: $\boldsymbol{t}(\boldsymbol{x}) = w_0\,\boldsymbol{t}_0 + w_1\,\boldsymbol{t}_1 + w_2\,\boldsymbol{t}_2$

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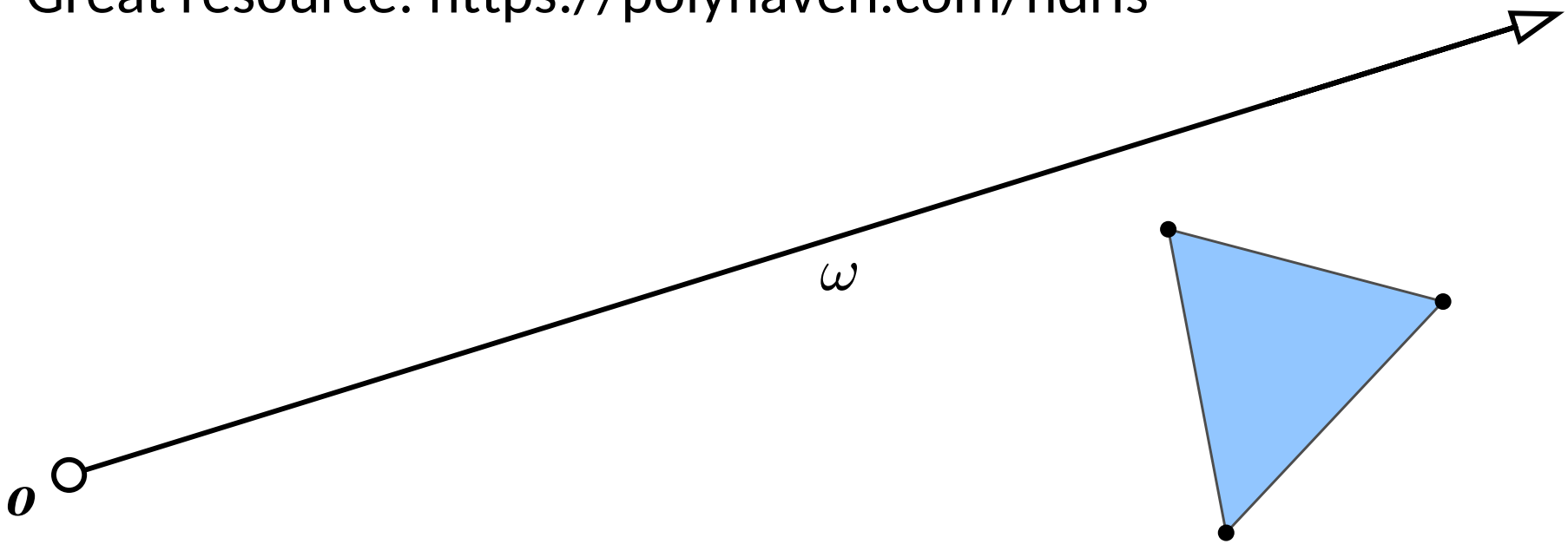
Sample textures at $\boldsymbol{t}(\boldsymbol{x})$, prepare BRDF parameters and determine the emitted radiance $L_e(\boldsymbol{x}, -\omega)$.

Shading data

If the ray misses all scene triangles,
we only compute an emitted radiance $L_e(-\omega)$.

E.g. a constant sky color,
or we sample a background texture (a.k.a. light probe/HDRI).

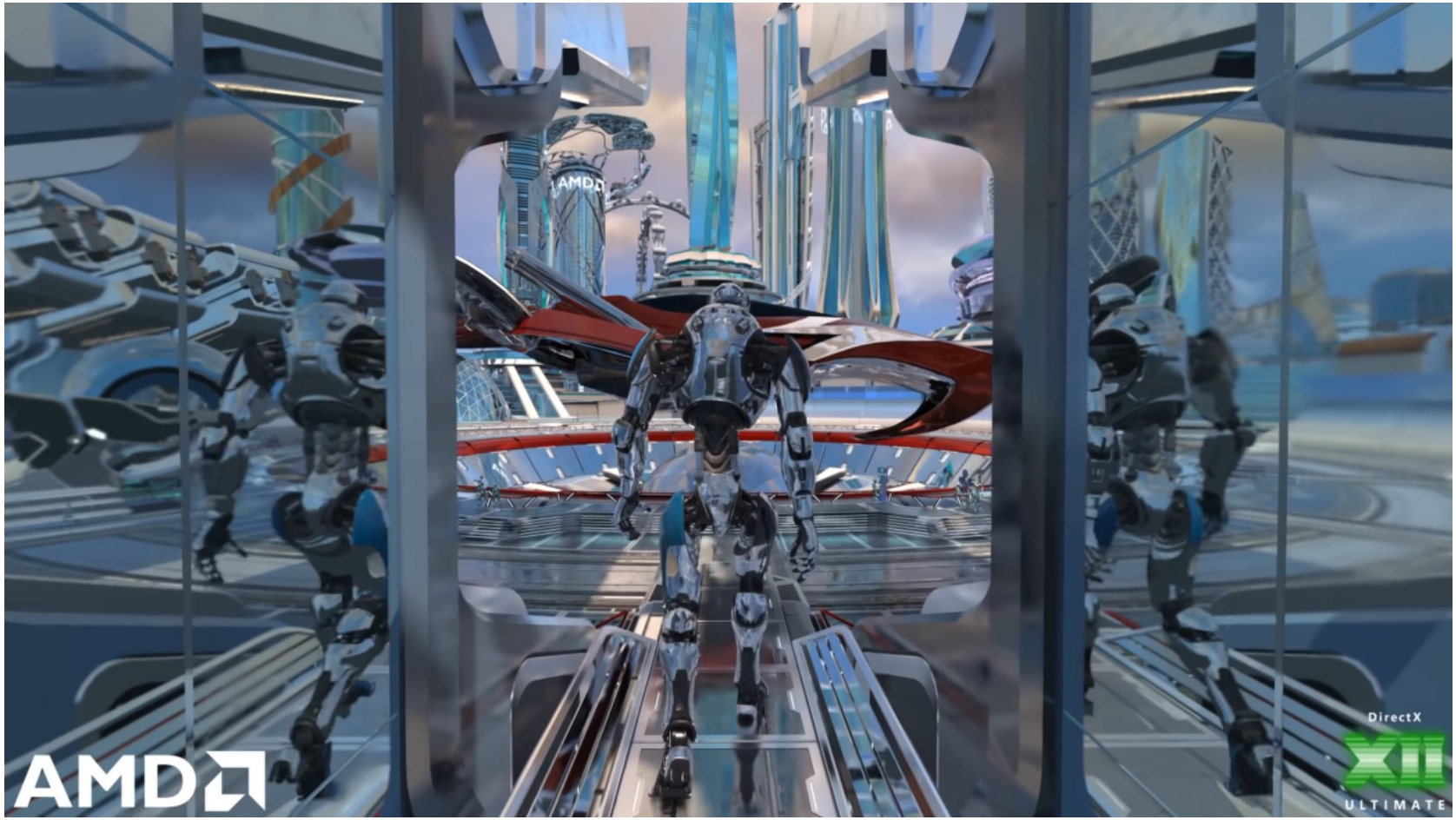
Great resource: https://polyhaven.com/hdris



Ray tracing effects

Gamedevs tend to embrace ray tracing for familiar effects:

Glossy reflections, soft shadows, ambient occlusion.



community.amd.com/t5/gaming/powering-next-generation-gaming-visuals-with-amd-rdna-2-and/ba-p/414239

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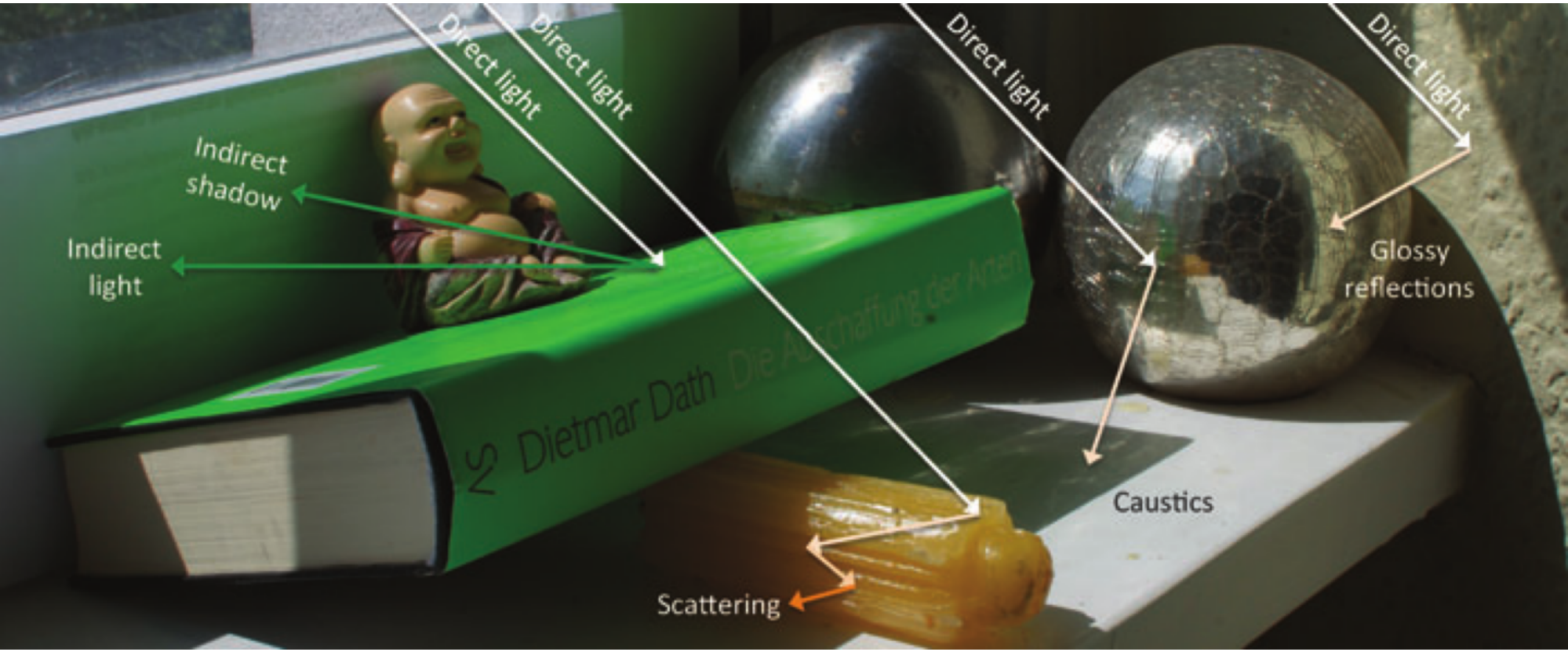
But we aim for full global illumination with path tracing.




TUDelft

The rendering equation

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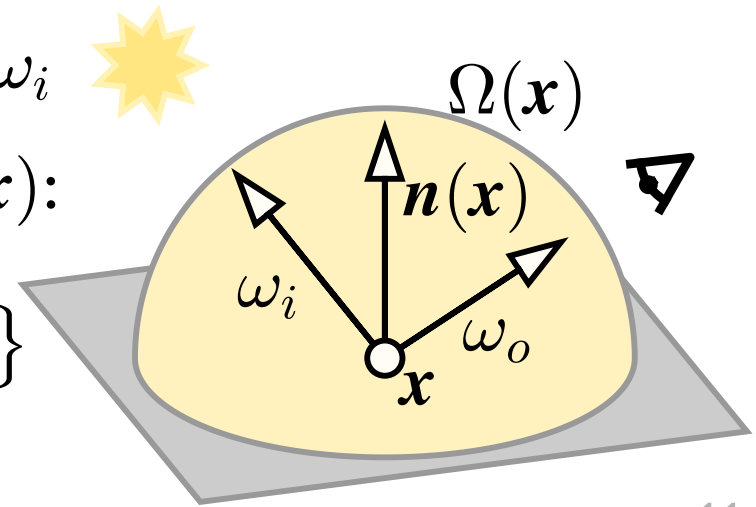
$$L_o(\boldsymbol{x}, \omega_o) = L_e(\boldsymbol{x}, \omega_o) + \int_{\Omega(\boldsymbol{x})} L(\boldsymbol{x}, \omega_i)\, \rho(\boldsymbol{x}, \omega_i, \omega_o)\, \boldsymbol{n}(\boldsymbol{x}) \cdot \omega_i \, \mathrm{d}\omega_i$$

Defines outgoing radiance $L_o(\boldsymbol{x}, \omega_o)$, i.e. color of surface point $\boldsymbol{x} \in \mathbb{R}^3$ seen from direction $\omega_o \in \Omega(\boldsymbol{x})$.

Emitted radiance $L_e(\boldsymbol{x}, \omega_o)$ is non-zero on lights.

Integral over incoming light directions ω_i in hemisphere $\Omega(\boldsymbol{x})$ around normal $\boldsymbol{n}(\boldsymbol{x})$:

$$\Omega(\boldsymbol{x}) := \left\{ \omega \in \mathbb{R}^3 \mid \|\omega\| = 1, \boldsymbol{n}(\boldsymbol{x}) \cdot \omega \geq 0 \right\}$$



The rendering equation: Integrand

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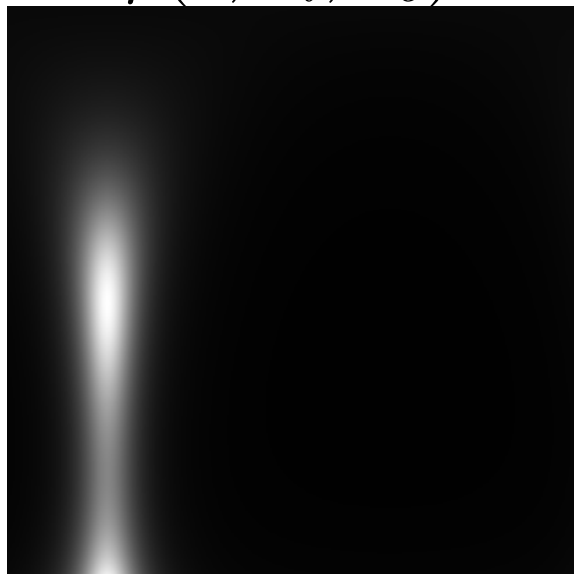
Incoming radiance
$L(\boldsymbol{x}, \omega_i)$

BRDF
$\rho(\boldsymbol{x}, \omega_i, \omega_o)$



Geometry term
$\boldsymbol{n}(\boldsymbol{x}) \cdot \omega_i$

The rendering equation: Challenges

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How do we compute incoming radiance?

Incoming radiance
$L(\boldsymbol{x}, \omega_i)$

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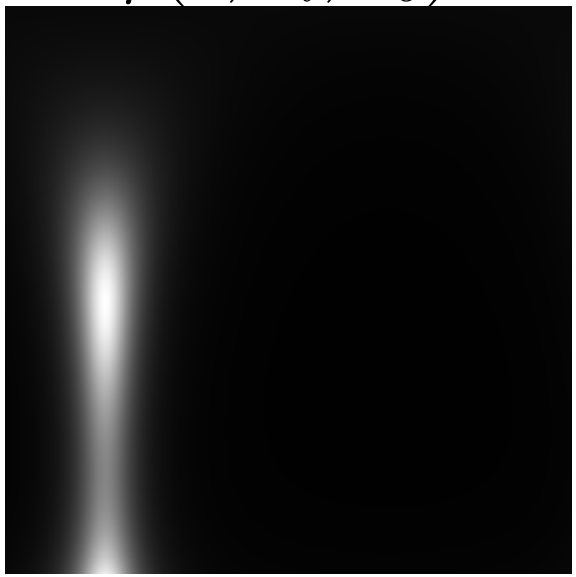

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How do we integrate over the hemisphere $\Omega(\boldsymbol{x})$?

Incoming radiance
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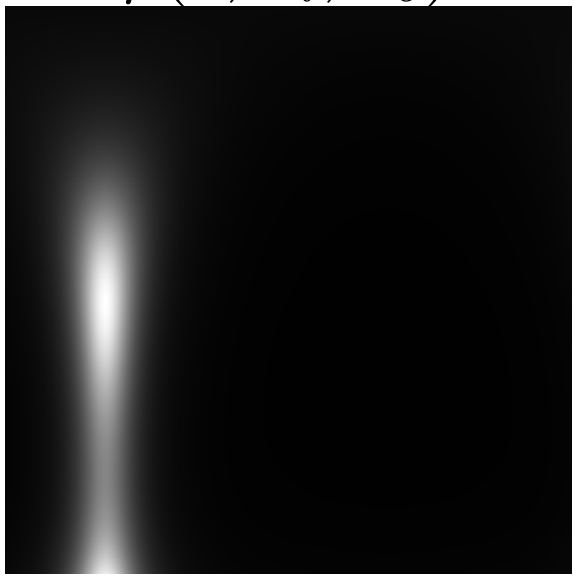


Geometry term
$\boldsymbol{n}(\boldsymbol{x}) \cdot \omega_i$

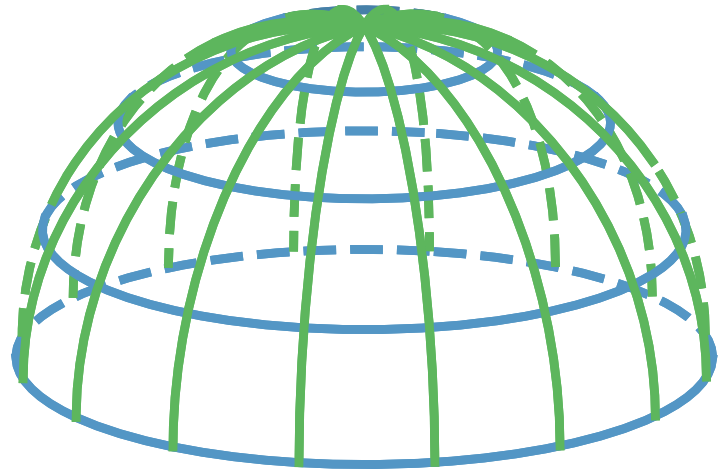
Spherical coordinates

Inclination $\theta \in [0, \pi]$, azimuth $\varphi \in [-\pi, \pi)$.

$$\omega_x(\theta, \varphi) := \cos(\varphi)\sin(\theta)$$

$$\omega_y(\theta, \varphi) := \sin(\varphi)\sin(\theta)$$

$$\omega_z(\theta, \varphi) := \cos(\theta)$$



Parametrization of the unit sphere:

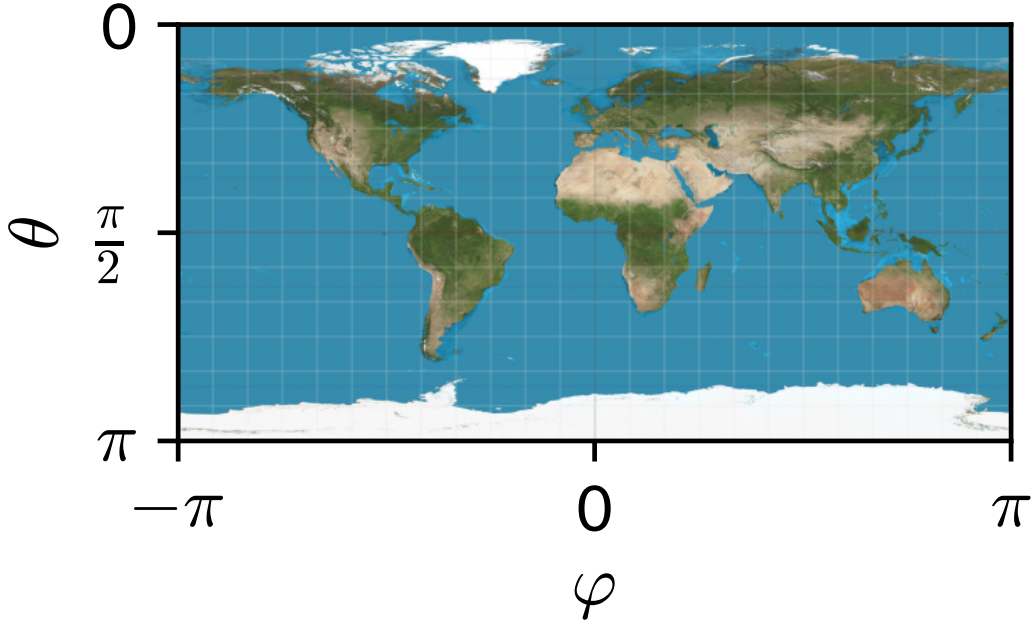
$$\omega_x^2 + \omega_y^2 + \omega_z^2 = (\cos^2\varphi + \sin^2\varphi)\sin^2\theta + \cos^2\theta = 1$$

For a fixed θ, we get a circle with constant z-coordinate.

$\theta \in [0, \frac{\pi}{2}]$ gives hemisphere Ω with $\omega_z(\theta, \varphi) \geq 0$.

Spherical integrals

Spherical coordinates are not area preserving.



To get correct integrals, we need the correction factor $\sin(\theta)$:

$$\int_{\Omega} f(\omega)\,\mathrm{d}\omega = \int_{-\pi}^{\pi}\int_{0}^{\frac{\pi}{2}} f(\omega(\theta,\varphi))\sin(\theta)\,\mathrm{d}\theta\,\mathrm{d}\varphi$$

Hemispherical integral $=$ two nested 1D integrals.

Interlude: Greek alphabet

Confused by those odd characters? Let me help.

Name	Lowercase	Uppercase
alpha	α	A
theta	θ	Θ
pi	π	Π
rho	ρ	P
phi	φ	Φ
omega	ω	Ω

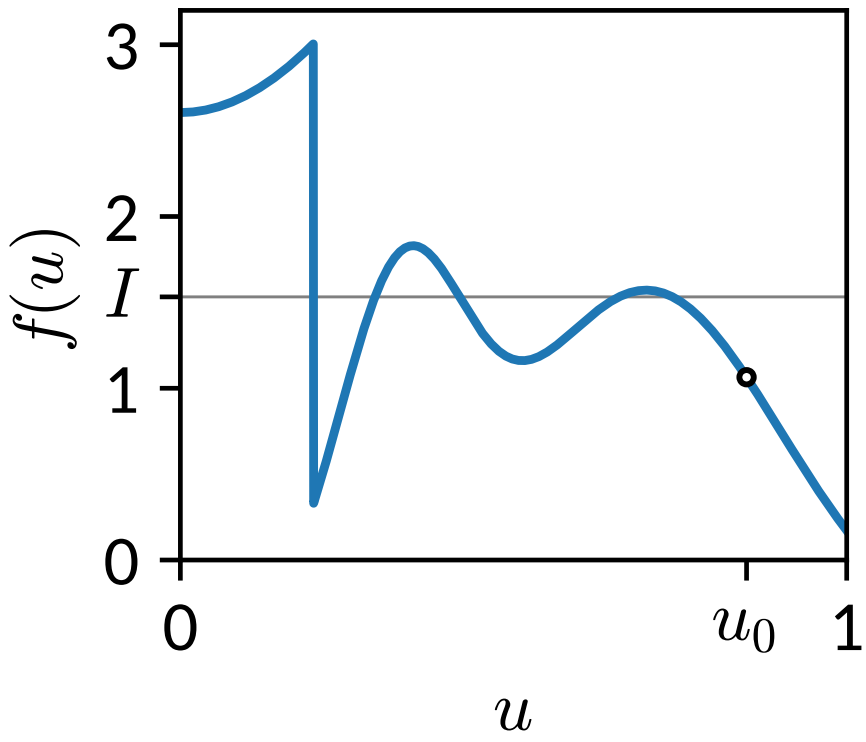
en.wikipedia.org/wiki/Greek_alphabet

Monte Carlo integration

1D Monte Carlo integration

Let u_0 be a random sample distributed uniformly in $[0, 1)$.

$$I := \int_0^1 f(u)\,\mathrm{d}u \approx f(u_0)$$



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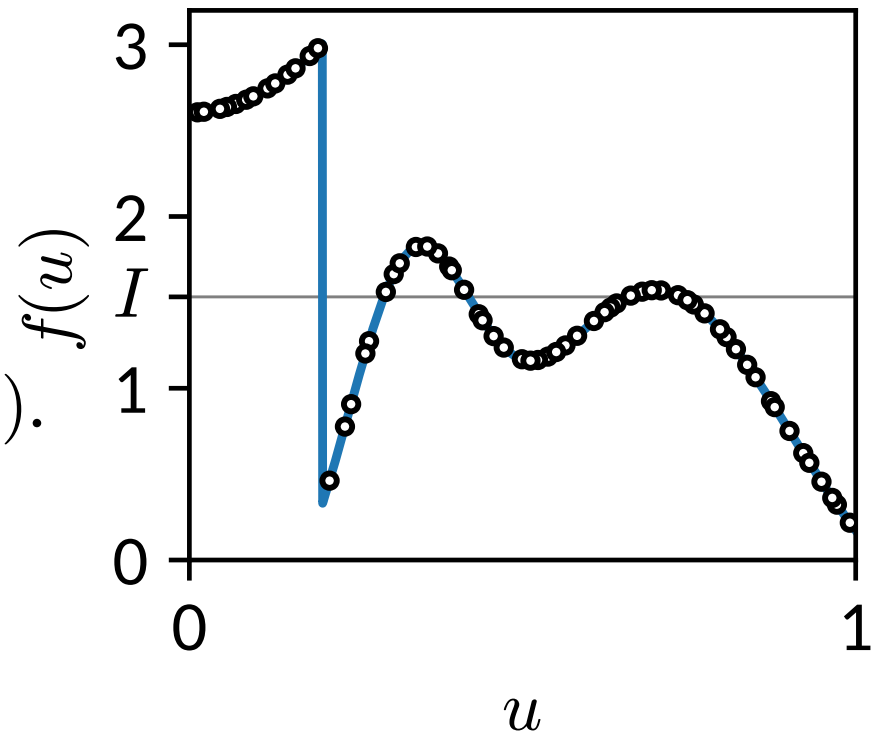

More generally: $u_0, \ldots, u_{N-1}$

independent and uniform in $[0, 1)$.

$$\int_0^1 f(u)\,\mathrm{d}u \approx \tfrac{1}{N} \sum_{j=0}^{N-1} f(u_j)$$

Law of large numbers:

$$I = \lim_{N\to\infty} \tfrac{1}{N} \sum_{j=0}^{N-1} f(u_j)$$ with 100% probability. Unbiased!

kD Monte Carlo integration

To integrate the kD-function $f\colon [0,1]^k \to \mathbb{R}$,

sample $\boldsymbol{u}_0, \ldots, \boldsymbol{u}_{N-1}$ uniformly in $[0,1)^k$.

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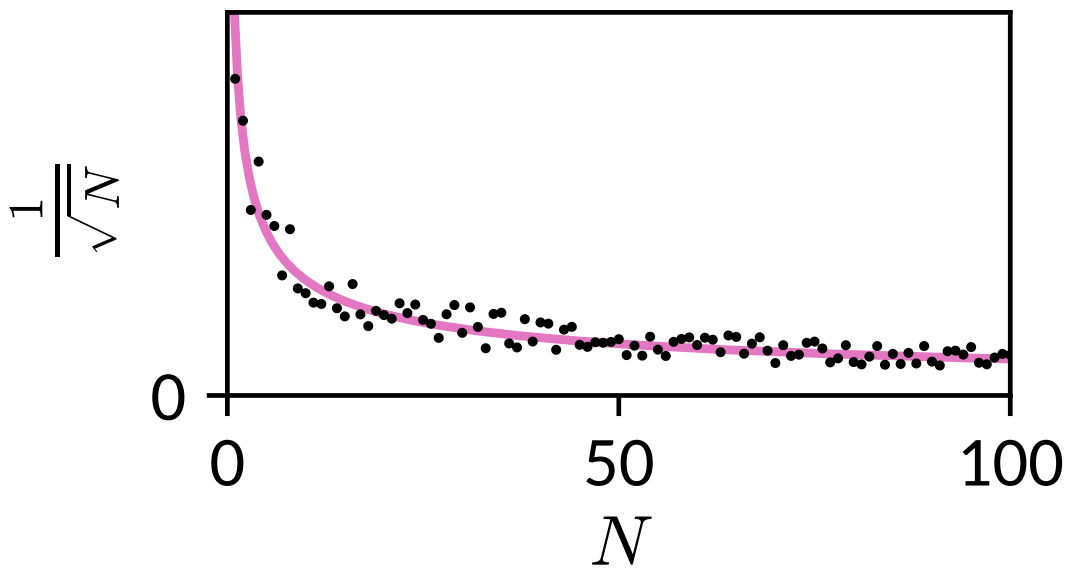
Central limit theorem: The error is proportional to $\frac{1}{\sqrt{N}}$.

Four times more samples, half the error.



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Four times more samples, half the error.

Sampling a kD grid gives an error proportional to $N^{-\frac{1}{k}}$.

Much worse for $k \geq 3$.

In path tracing, we essentially care about $k = \infty$.

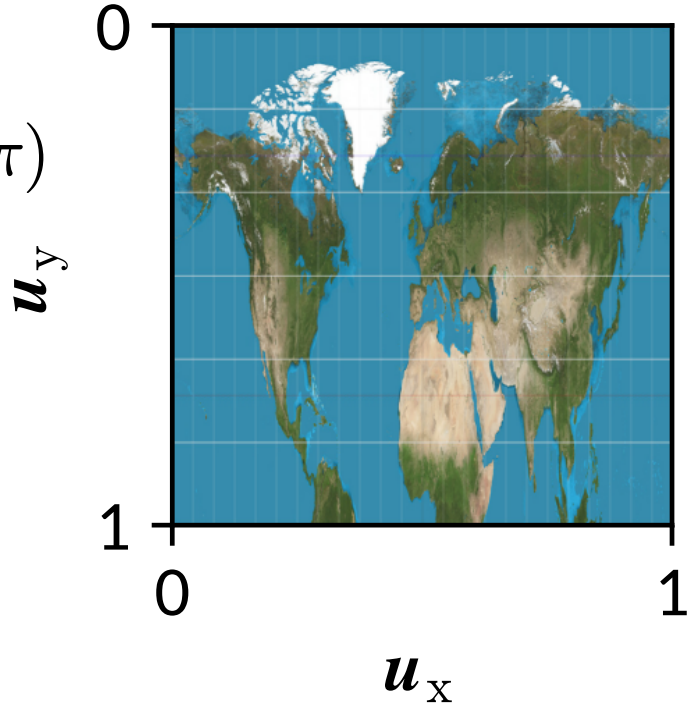
Hemispherical Monte Carlo integration

Sample $\boldsymbol{u}$ uniformly in $[0,1)^2$.

$\theta = \frac{\pi}{2}\,\boldsymbol{u}_{\mathrm{y}} \in [0, \frac{\pi}{2}), \quad \varphi = 2\pi\,\boldsymbol{u}_{\mathrm{x}} - \pi \in [-\pi, \pi)$

Parametrization of Ω:

$\omega(\boldsymbol{u}) := \omega(\theta, \varphi) = \omega(\frac{\pi}{2}\boldsymbol{u}_{\mathrm{y}}, 2\pi\,\boldsymbol{u}_{\mathrm{x}} - \pi)$



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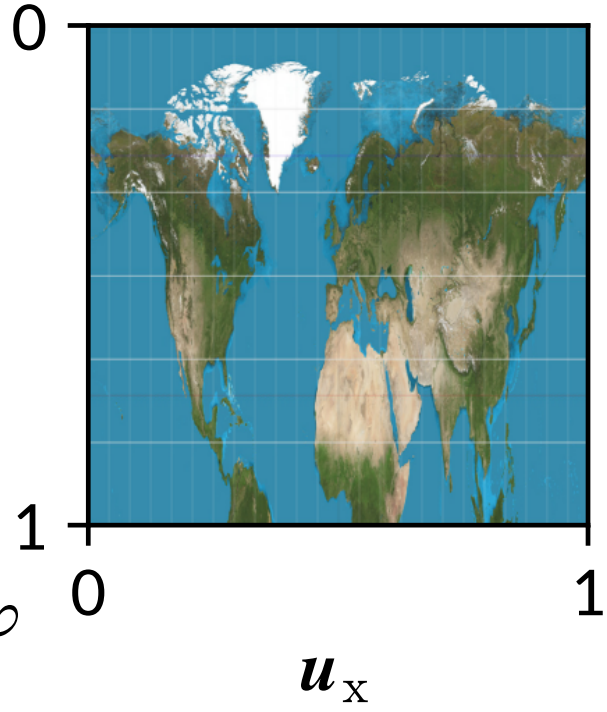

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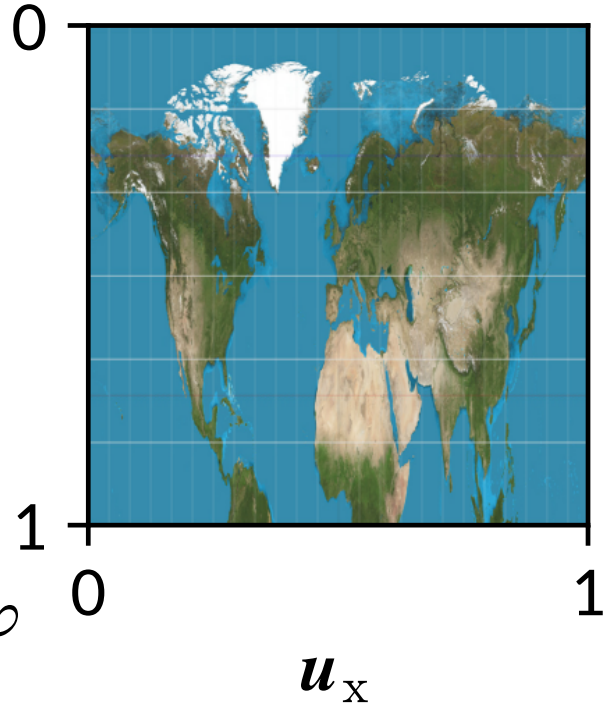

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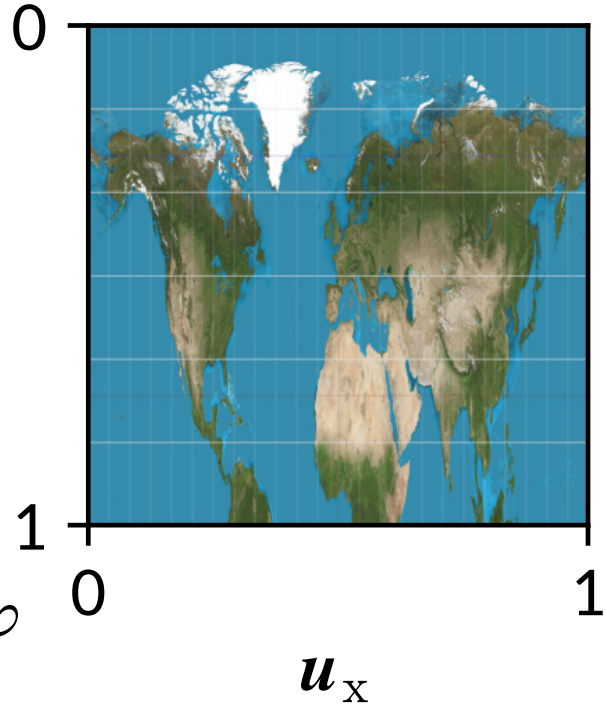

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$$\approx \pi^2 f(\omega(\boldsymbol{u}))\sin(\tfrac{\pi}{2}\boldsymbol{u}_{\mathrm{y}})$$

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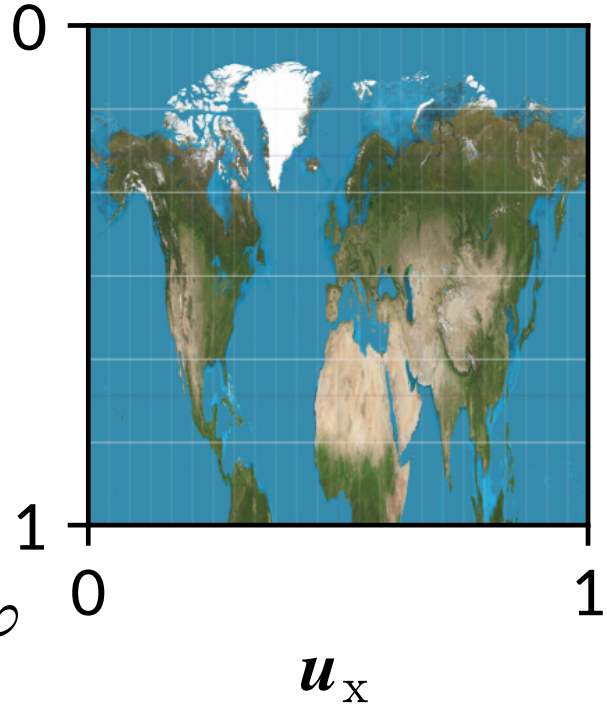

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$$\approx \pi^2 f(\omega(\boldsymbol{u}))\sin(\tfrac{\pi}{2}\boldsymbol{u}_{\mathrm{y}})$$

For hemisphere $\Omega(\boldsymbol{x})$, rotate coordinates to turn it into Ω.

Pseudorandom number generator

GLSL implementation of PCG 2D.

Returns $\boldsymbol{u}$ distributed uniformly in $[0, 1)^2$.

The seed can be e.g. pixel_index + 2^{16}frame_index.

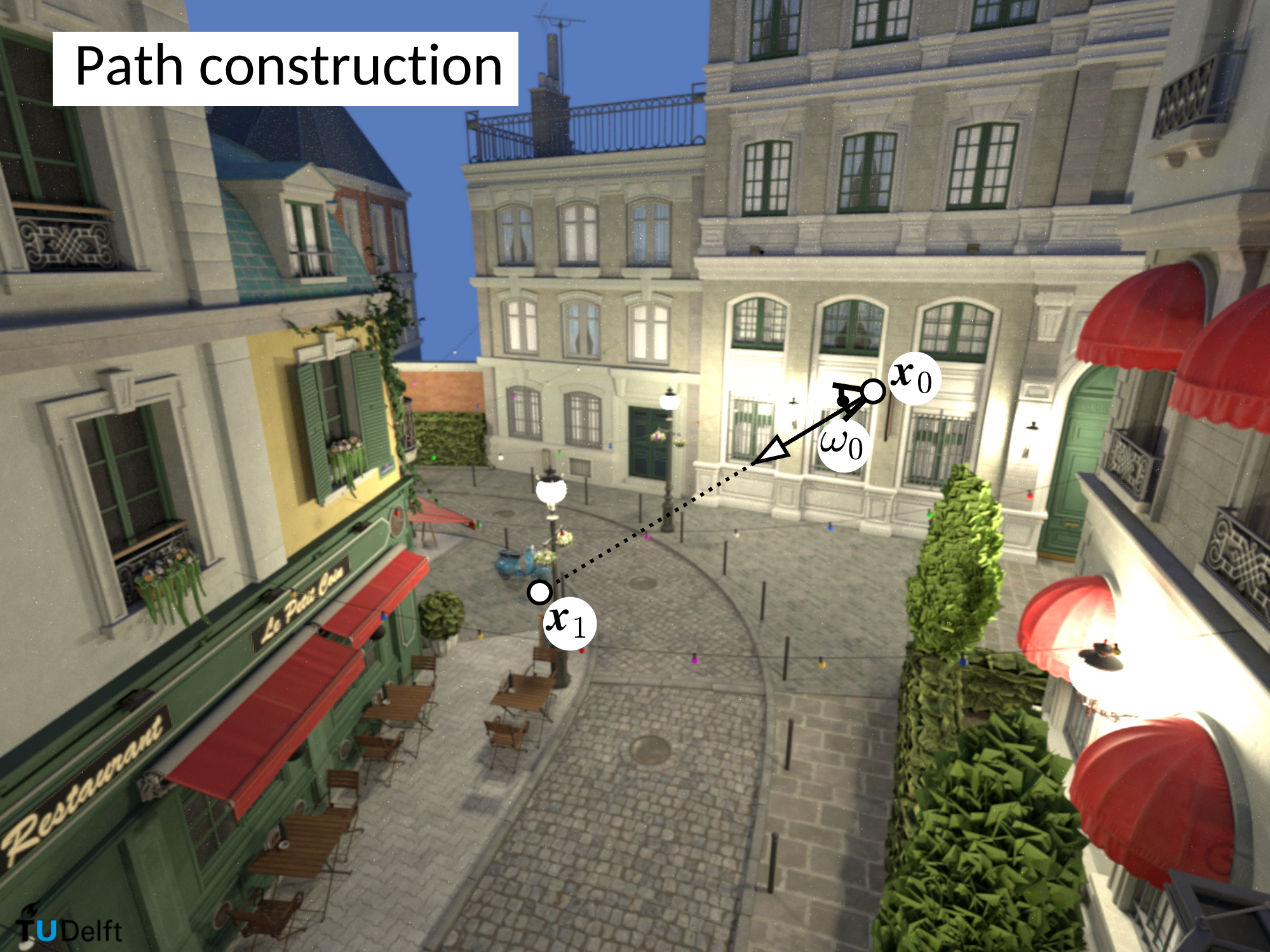
The seed gets updated and can be reused.

```
vec2 get_random_numbers(inout uvec2 seed) {
    seed = 1664525u * seed + 1013904223u;
    seed.x += 1664525u * seed.y;
    seed.y += 1664525u * seed.x;
    seed ^= (seed >> 16u);
    seed.x += 1664525u * seed.y;
    seed.y += 1664525u * seed.x;
    seed ^= (seed >> 16u);
    return vec2(seed) * pow(0.5, 32.0);
}
```

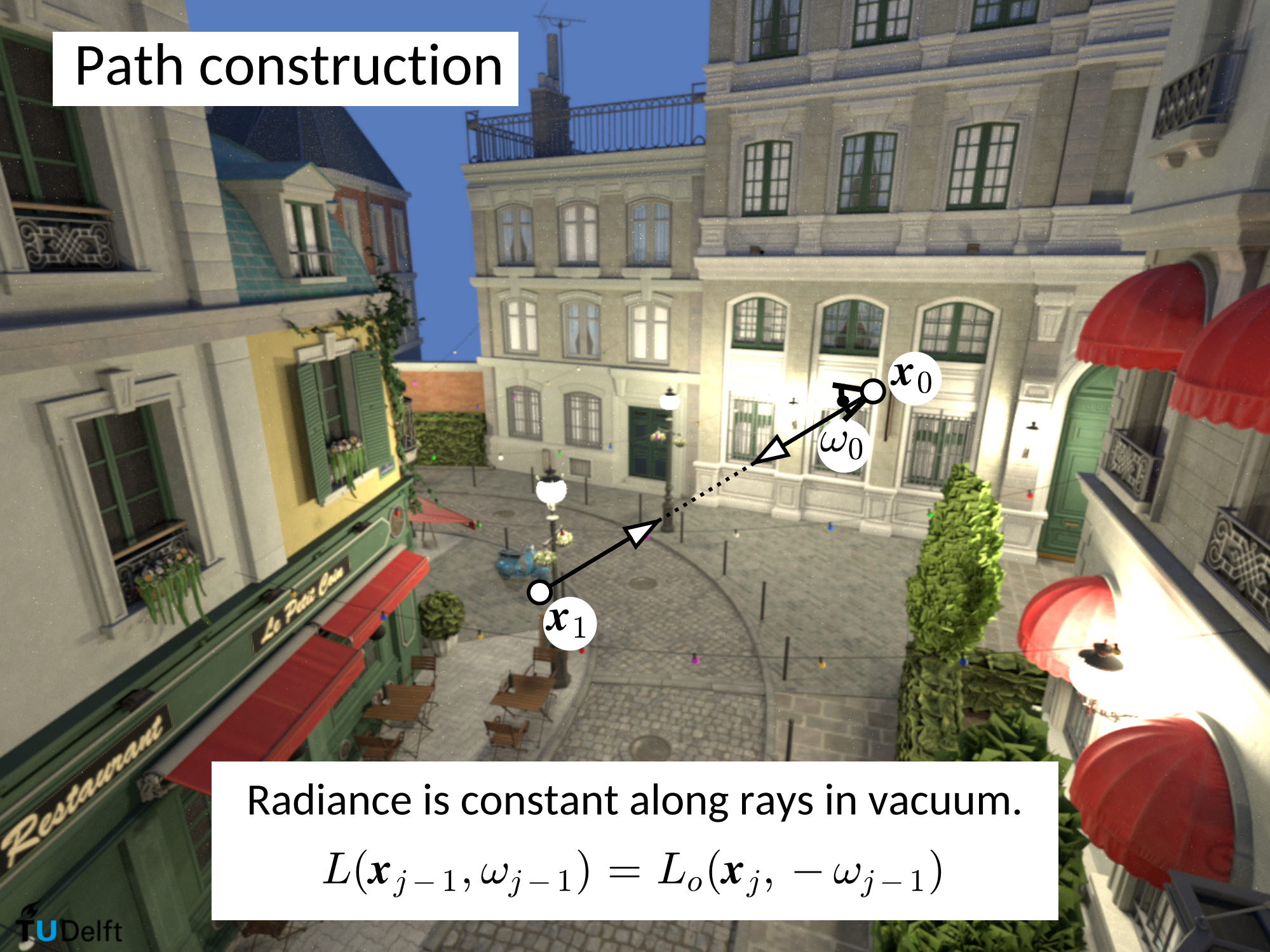
Path tracing

Path construction

Path construction



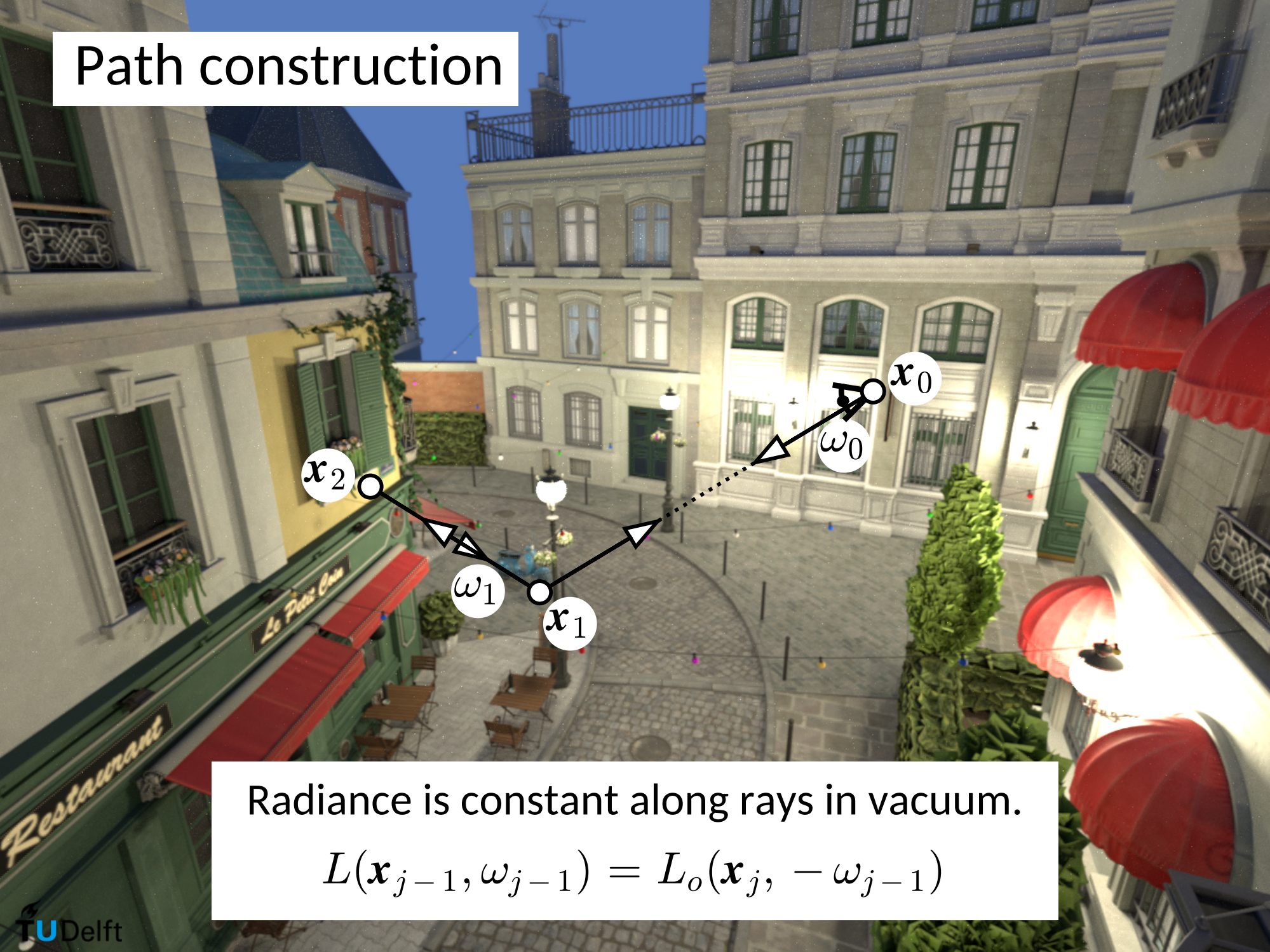
Path construction



Radiance is constant along rays in vacuum.

$$L(\boldsymbol{x}_{j-1}, \omega_{j-1}) = L_o(\boldsymbol{x}_j, -\omega_{j-1})$$

Path construction



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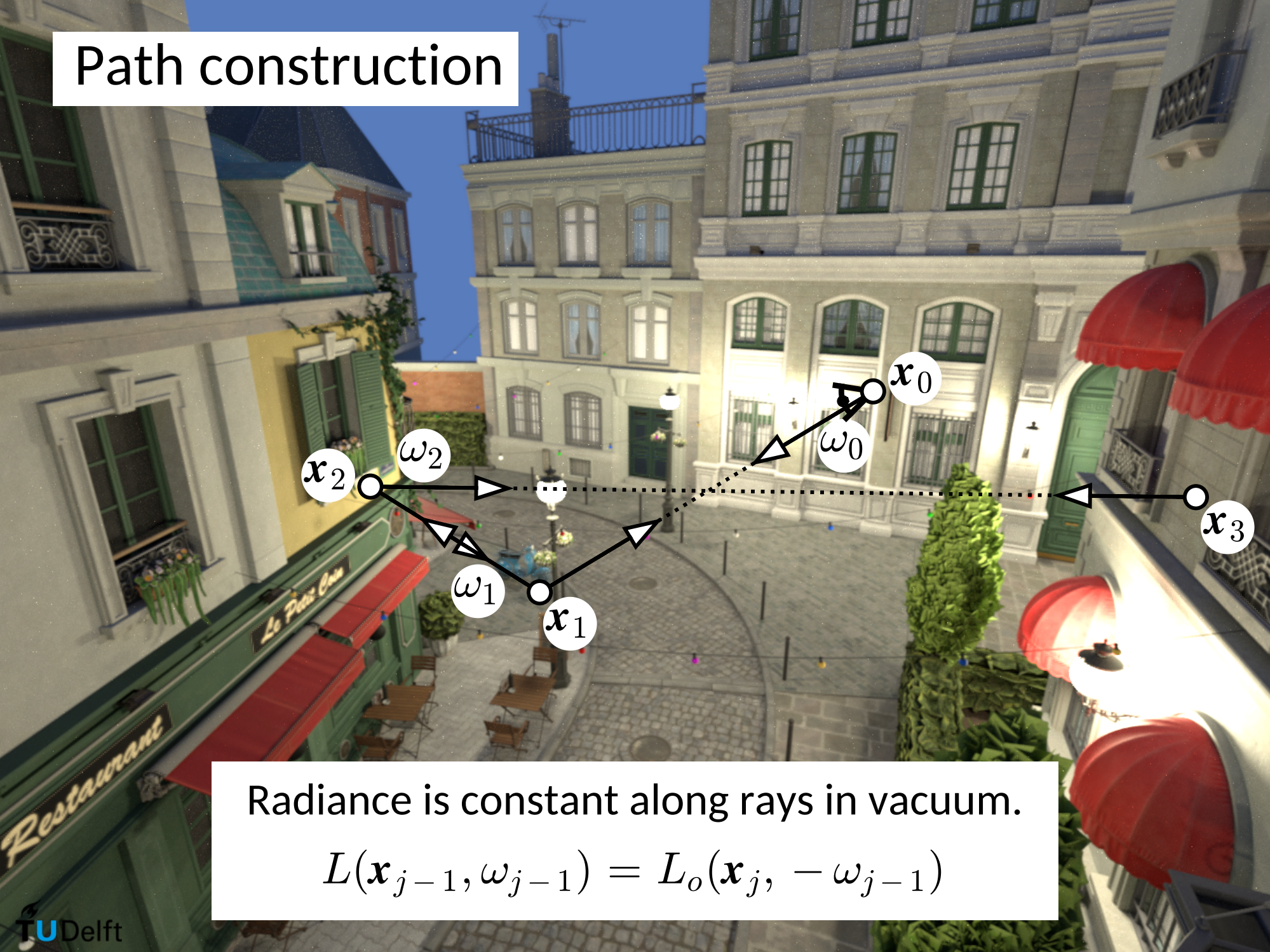

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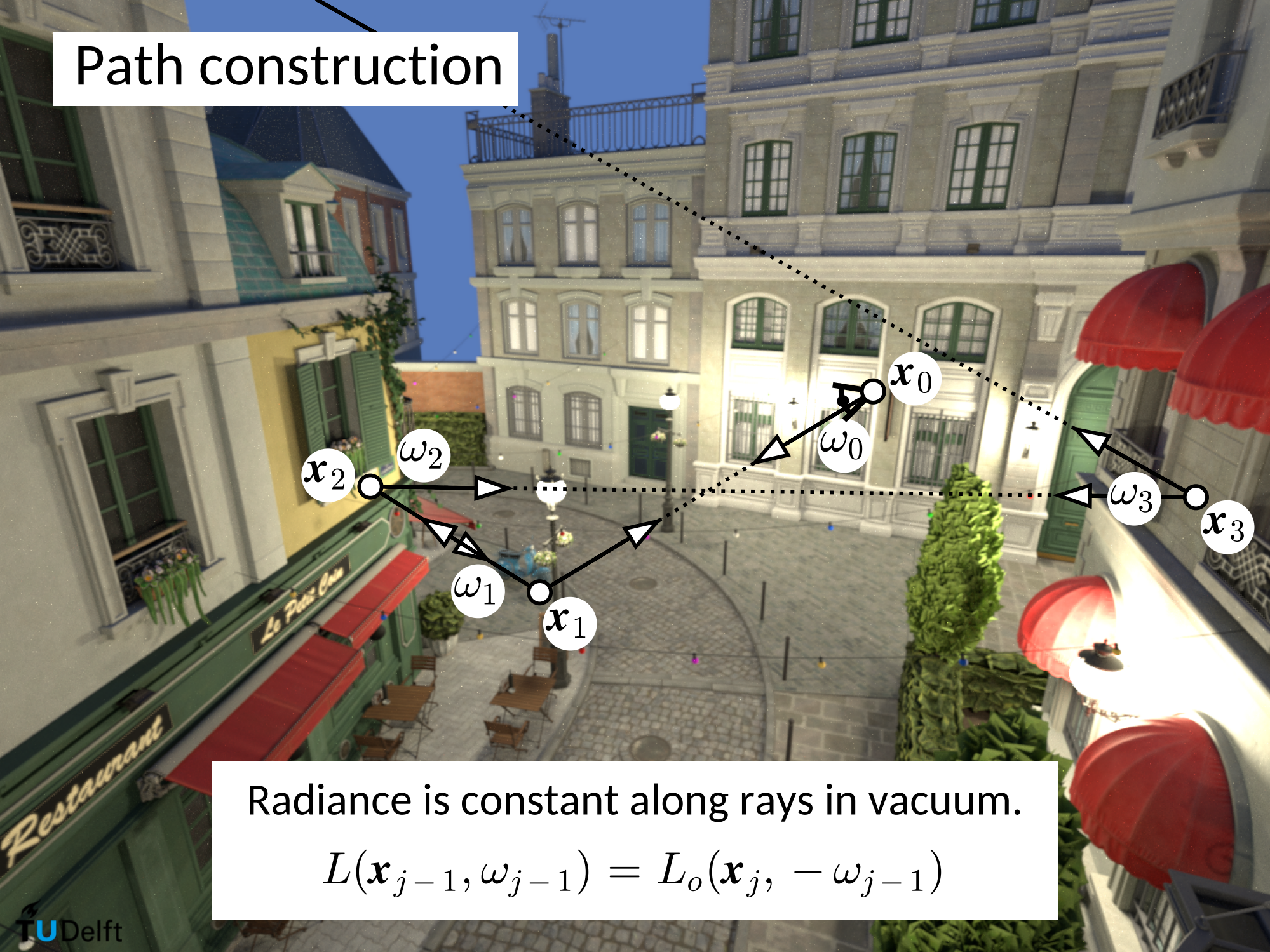

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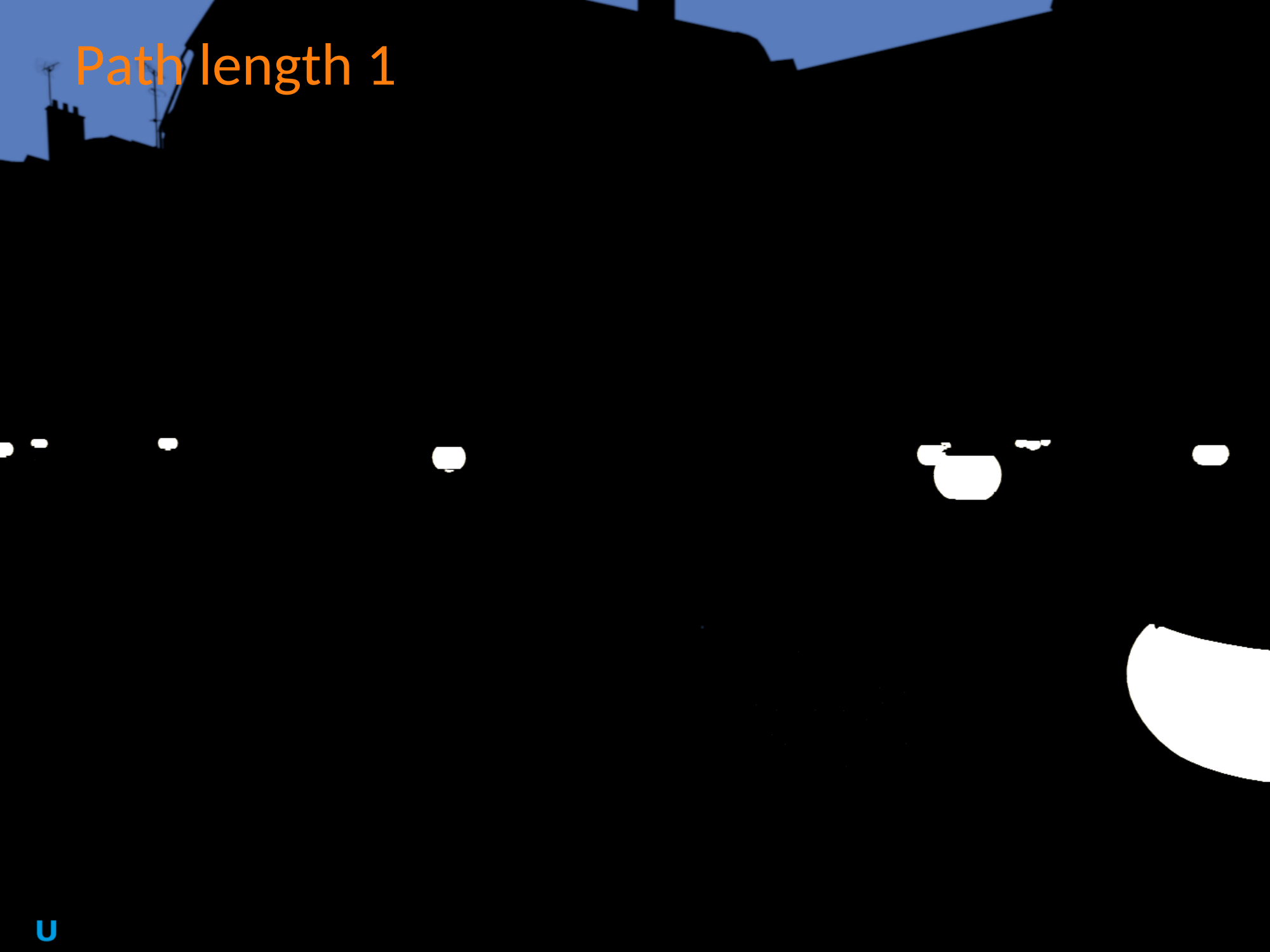
Path length 1




Path length 2
TU Delft


Path length 3
TU Delft


Path length 4
TU Delft


Path length 5
TU Delft

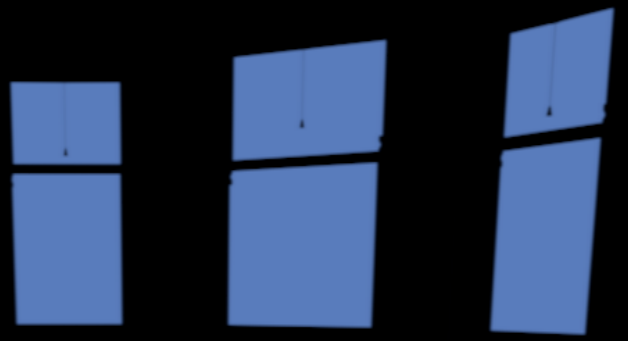

Path length 6
TU Delft


Path length 7
TU Delft

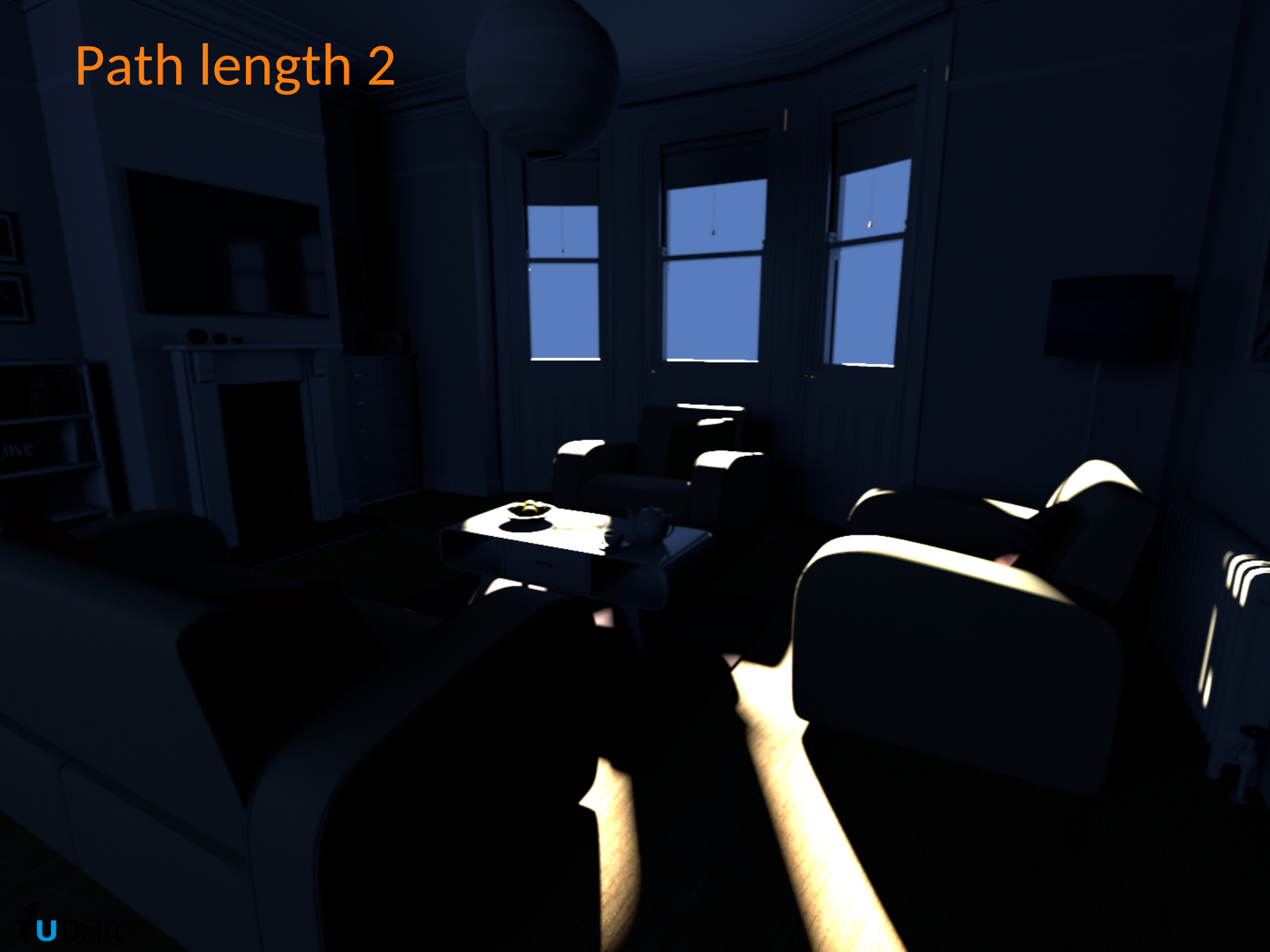

Path length 8
TU Delft

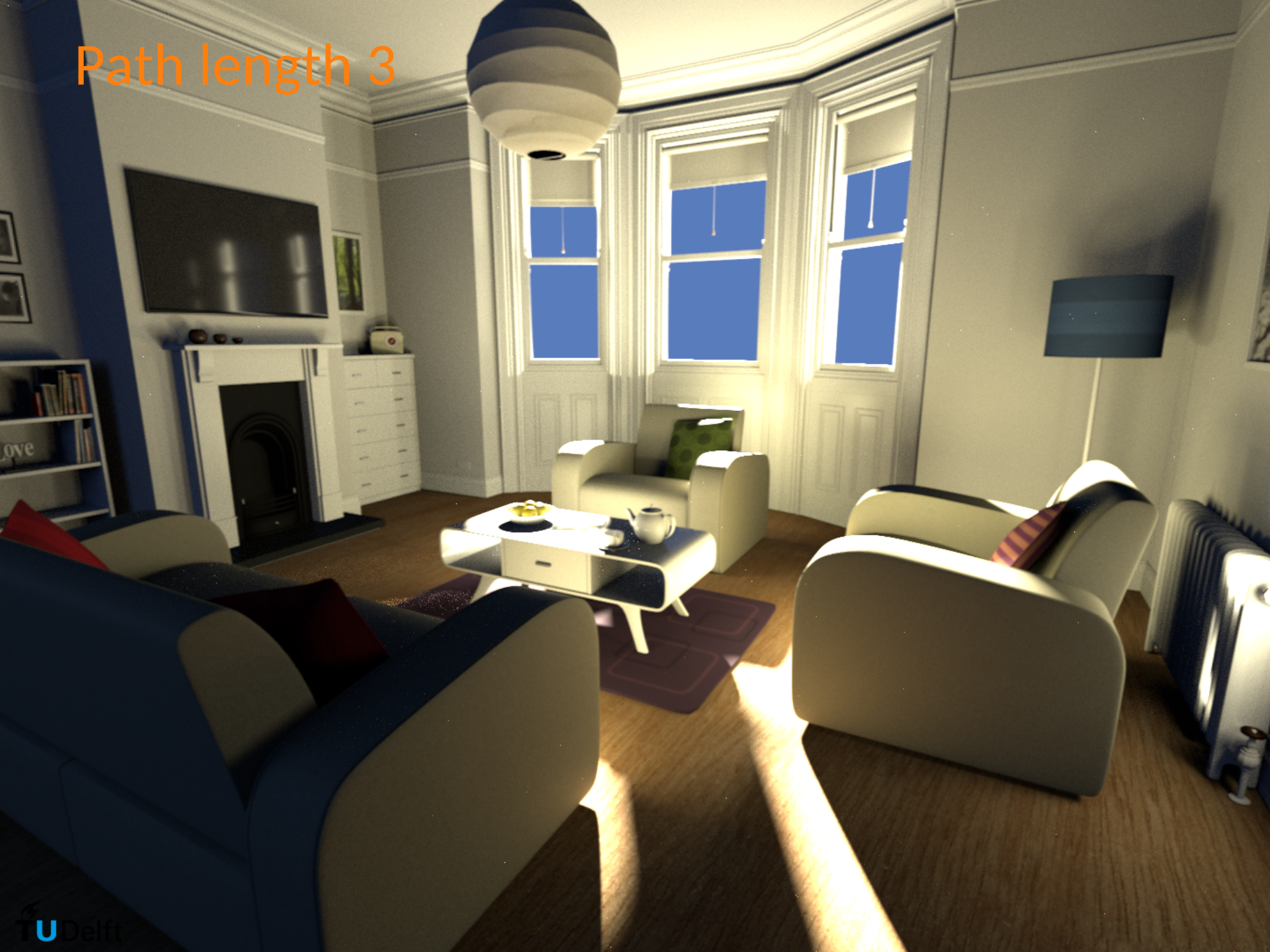

Path length 9
TU Delft

Path length 1



Path length 2




Path length 3
TU Delft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TUDelft


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Path length 7
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Path length 8
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Path length 9
TUDelft

path_trace$(\boldsymbol{x}_{k-1}, \omega_{k-1}, k-1)$

Input: Ray $\boldsymbol{x}_{k-1}, \omega_{k-1}$ and current path length $k-1$.

Output: Estimate of incoming radiance $L(\boldsymbol{x}_{k-1}, \omega_{k-1})$.

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Output: Estimate of incoming radiance $L(\boldsymbol{x}_{k-1}, \omega_{k-1})$.

Trace ray $\boldsymbol{x}_{k-1}, \omega_{k-1}$.

If it missed all scene triangles: Return background emission.

For hit point $\boldsymbol{x}_k$: Get shading data and $L_{e,k} := L_e(\boldsymbol{x}_k, -\omega_{k-1})$.

If $k-1 =$ max. path length: Return $L_{e,k}$.

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$\omega_k := Q\omega(\boldsymbol{u}) \in \Omega(\boldsymbol{x}_k)$ ($\boldsymbol{u}$ uniform in $[0,1)^2$, $Q \in \mathbb{R}^{3\times 3}$ rotation).

Recurse: $L_k :=$ path_trace$(\boldsymbol{x}_k, \omega_k, k)$

Return $L_{e,k} + \pi^2 L_k \, \rho(\boldsymbol{x}_k, \omega_k, -\omega_{k-1}) \, \boldsymbol{n}(\boldsymbol{x}_k) \cdot \omega_k \sin(\frac{\pi}{2}\boldsymbol{u}_y)$.

Path tracing

Compute camera ray $\boldsymbol{x}_0, \omega_0$.

$$L := \frac{1}{N} \sum_{j=0}^{N-1} \text{path\_trace}(\boldsymbol{x}_0, \omega_0, 0)$$

L is the pixel color.

Path tracing

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Useful to show intermediate results while summing over j.

That is called progressive rendering.

Start over when the scene or the camera changes.

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Now rendering is solved.

Or is it?


TUDelft


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