Fast, Flexible, Physically-Based Volumetric Light Scattering

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NVIDIA

Polygonal Volumetric Lighting

Fast, Flexible, and Physically-based

Fast: Scalable performance on all hardware

Flexible: Minimally invasive to integrate into existing engines

Physically-based: Easy mapping to real-world phenomenon

Source will be available on GitHub to registered developers

AGENDA

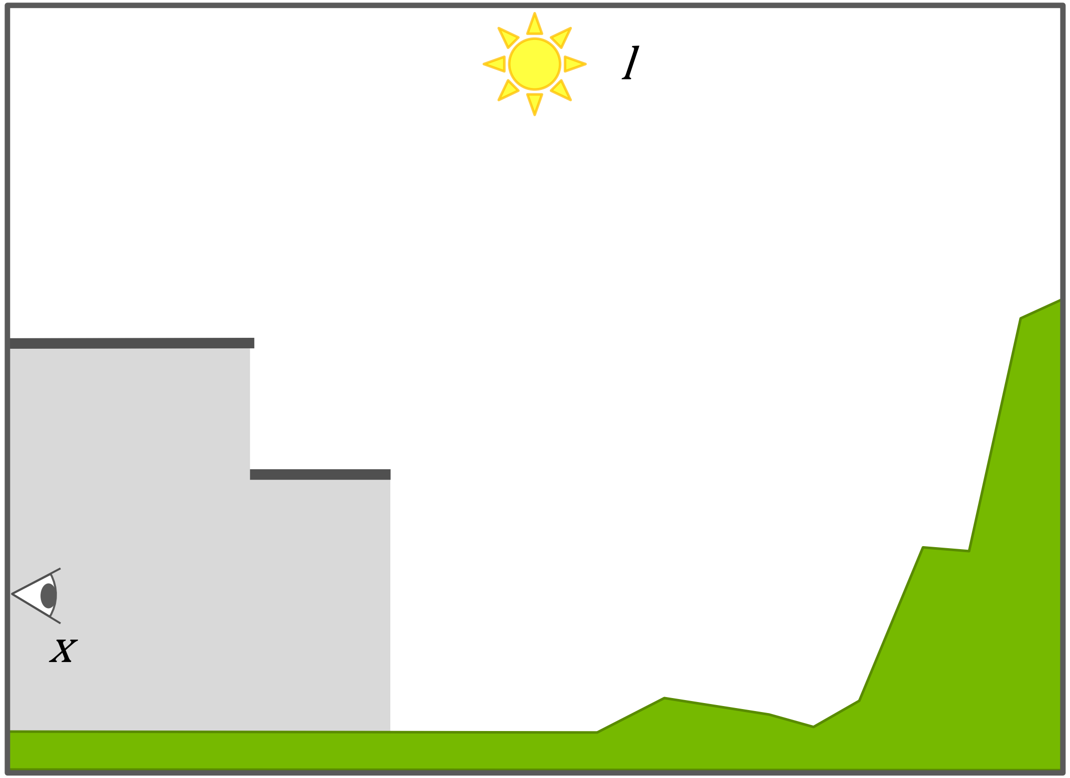
Background & Motivation

Algorithm Overview

Integration into *Fallout 4*

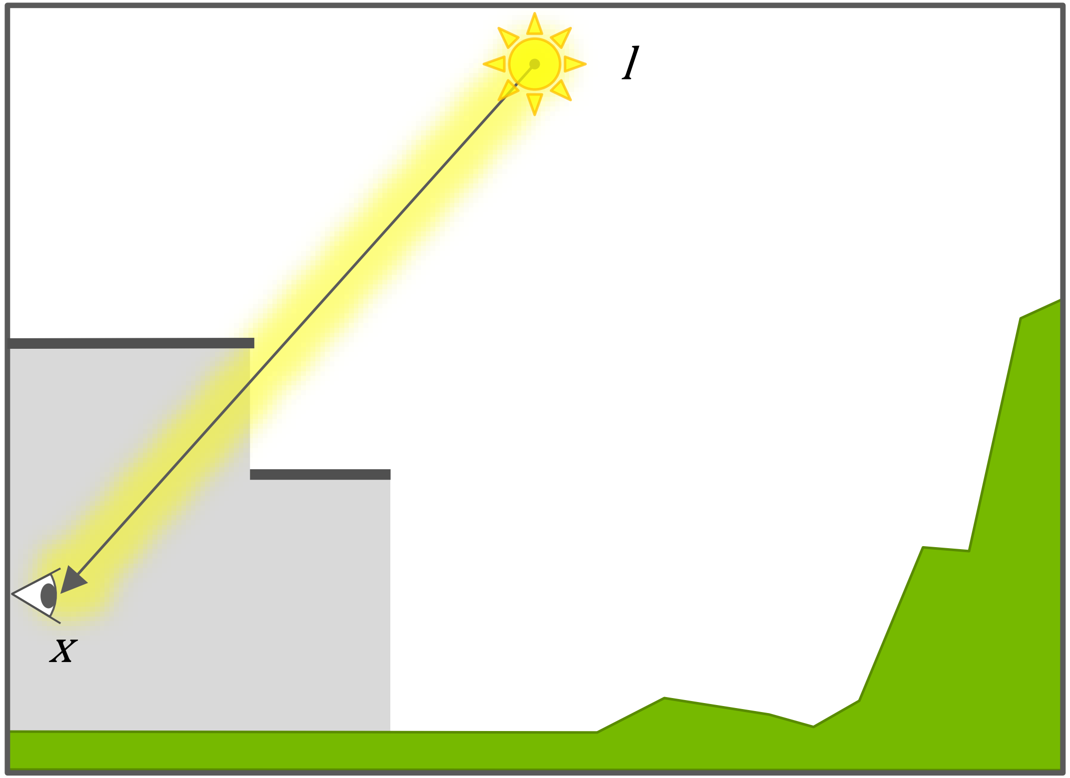
Background & Motivation

Light Propagation in a Vacuum



Light Propagation in a Vacuum

Directly Visible Light-Source

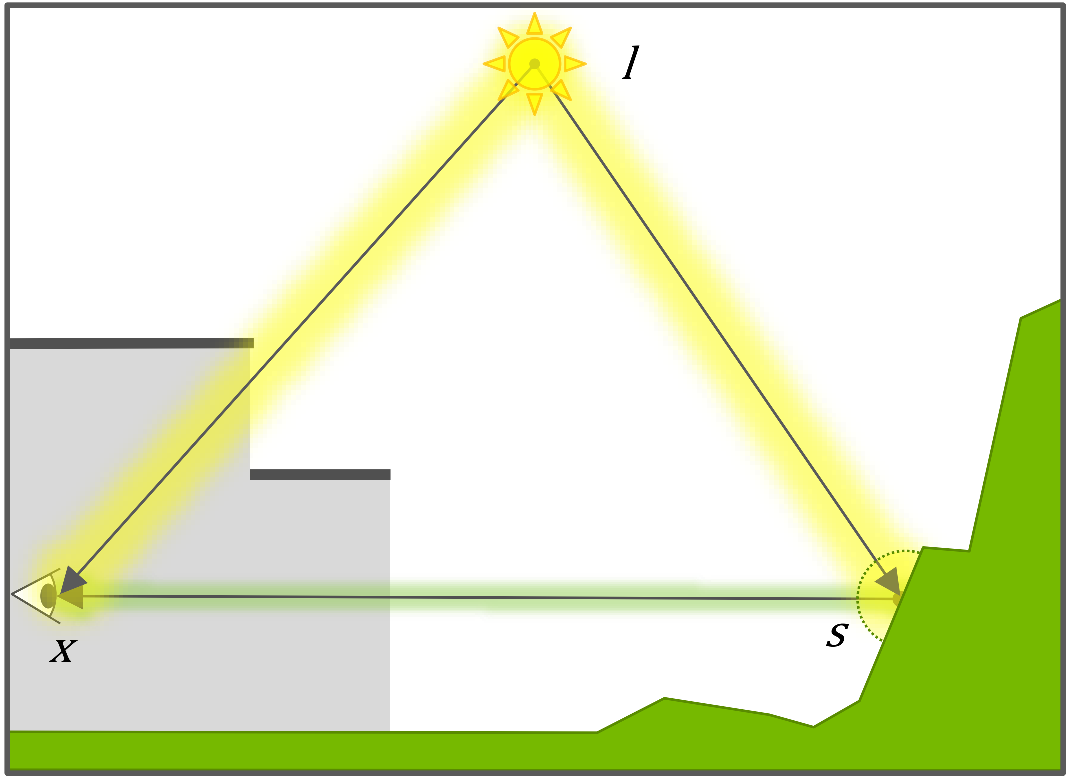


Direct Radiance:

$L_D = L(\omega_x)$

Light Propagation in a Vacuum

Direct Illumination

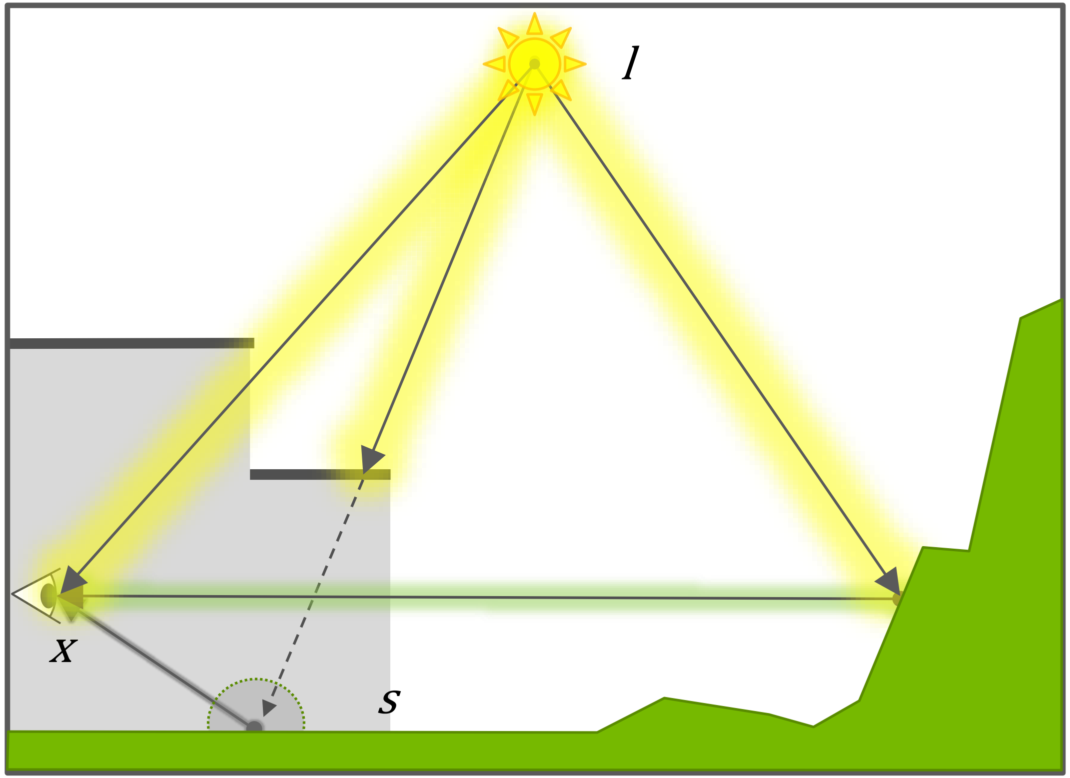


Direct Radiance:

$L_D = L(\omega_s)\rho_s(l, s, \omega_x)$

Light Propagation in a Vacuum

Shadows

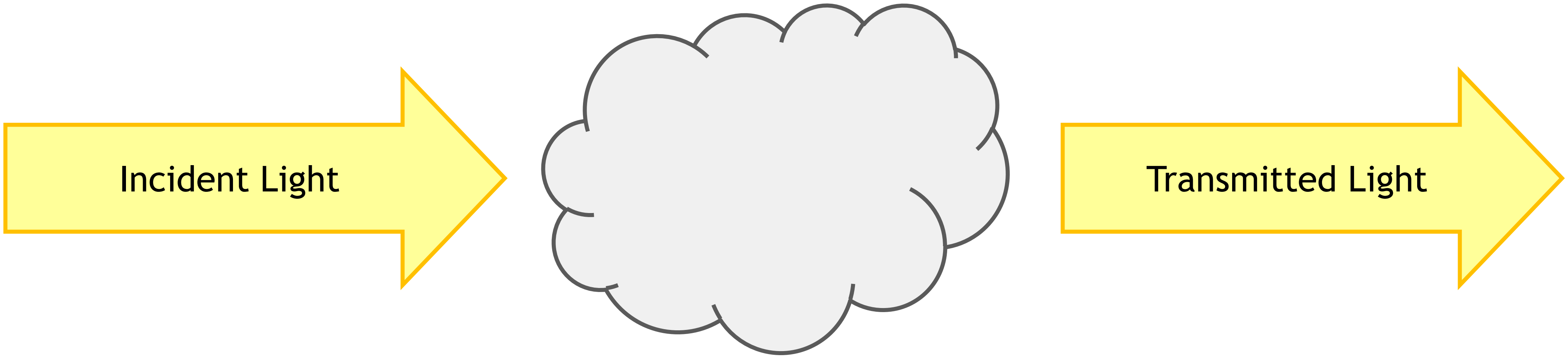


Direct Radiance:

$$L_D = L(\omega_s)\rho_s(l, s, \omega_x)V(s, l)$$

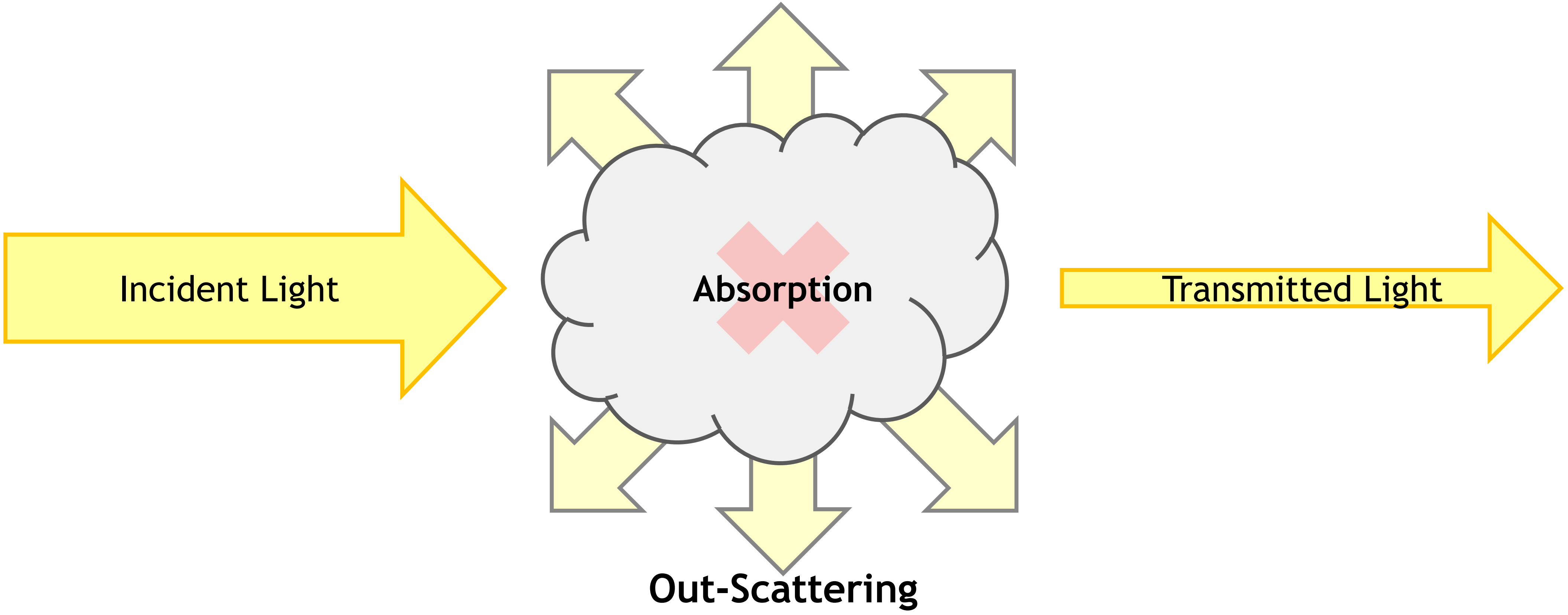
Participating Media

Transmittance & Extinction



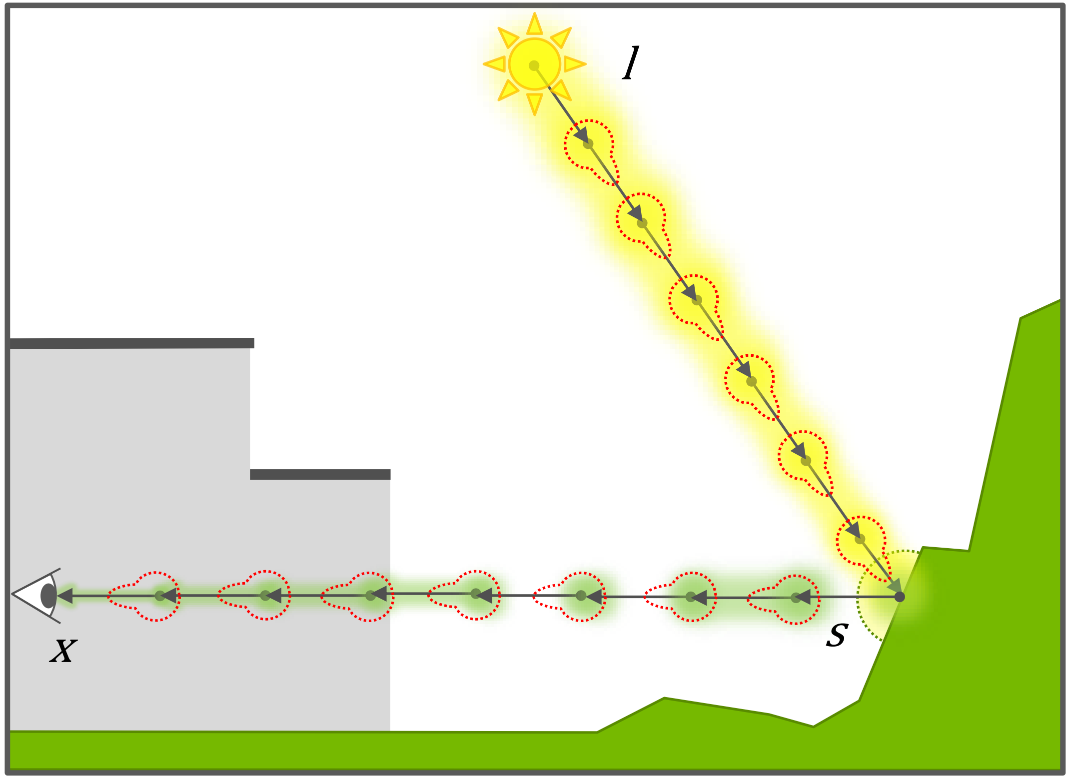
Participating Media

Transmittance & Extinction



Participating Media

Transmittance & Extinction



Direct Radiance:

$$L_D = L(\omega_s)\rho_s(l, s, \omega_x)V(s, l)$$

Transmitted Radiance:

$$L_T = L_D T(l, s) T(s, x)$$

Participating Media

Beer-Lambert Law

Transmittance:

$$T = 1 - \frac{\phi_s}{\phi_i} * \frac{\phi_a}{\phi_i} = 1 - \frac{\phi_{ex}}{\phi_i}$$

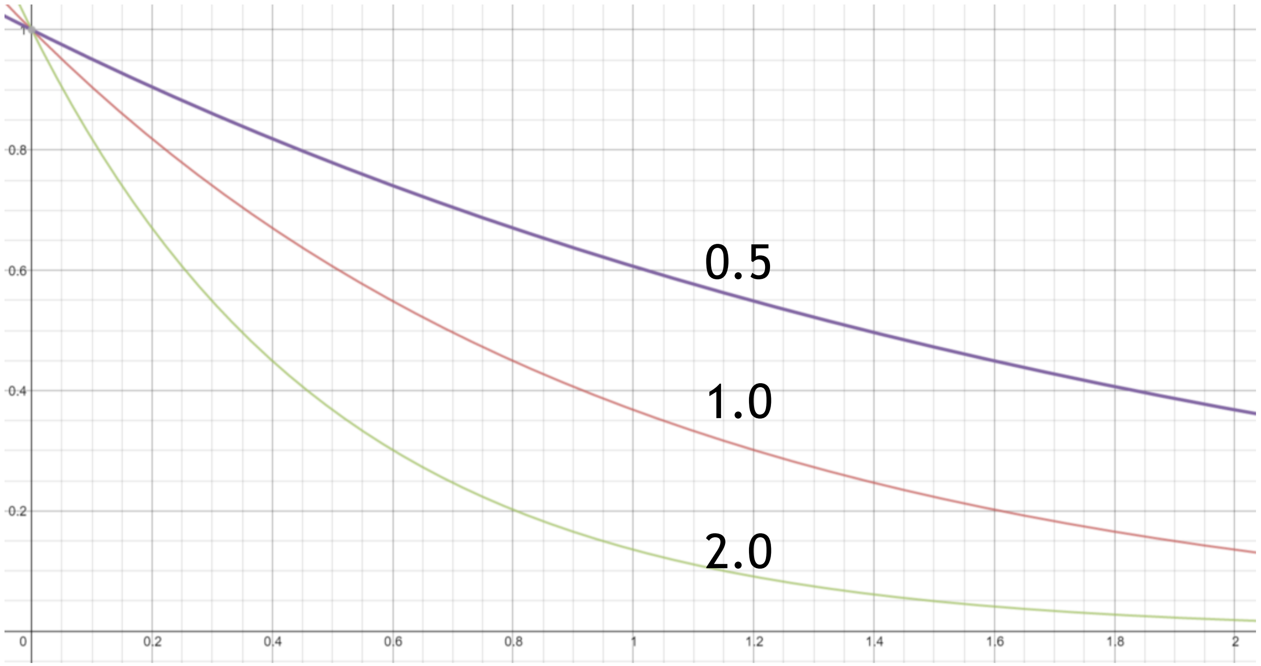
$$T(a,b) = e^{-\tau||b-a||}$$

Optical Thickness:

$$\tau_x = -\ln(1 - \frac{\phi_x}{\phi_i})$$

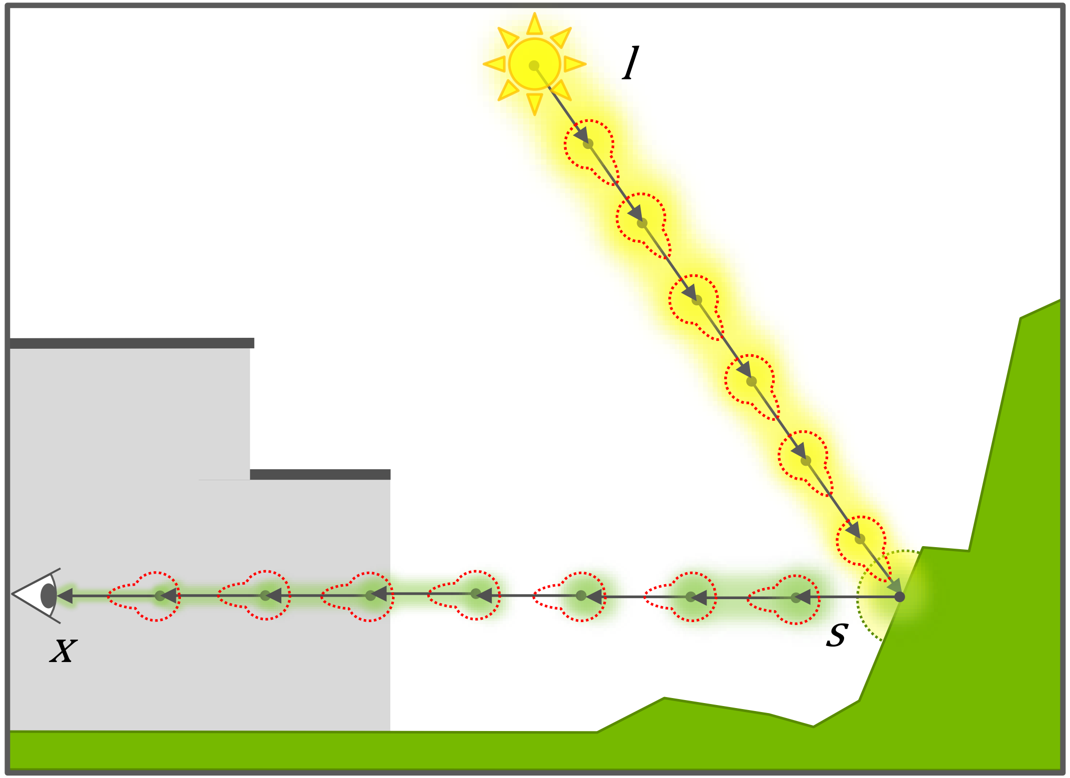
$$\tau_{ex} = \tau_s + \tau_a$$

Transmittance vs Distance



Participating Media

Transmittance & Extinction



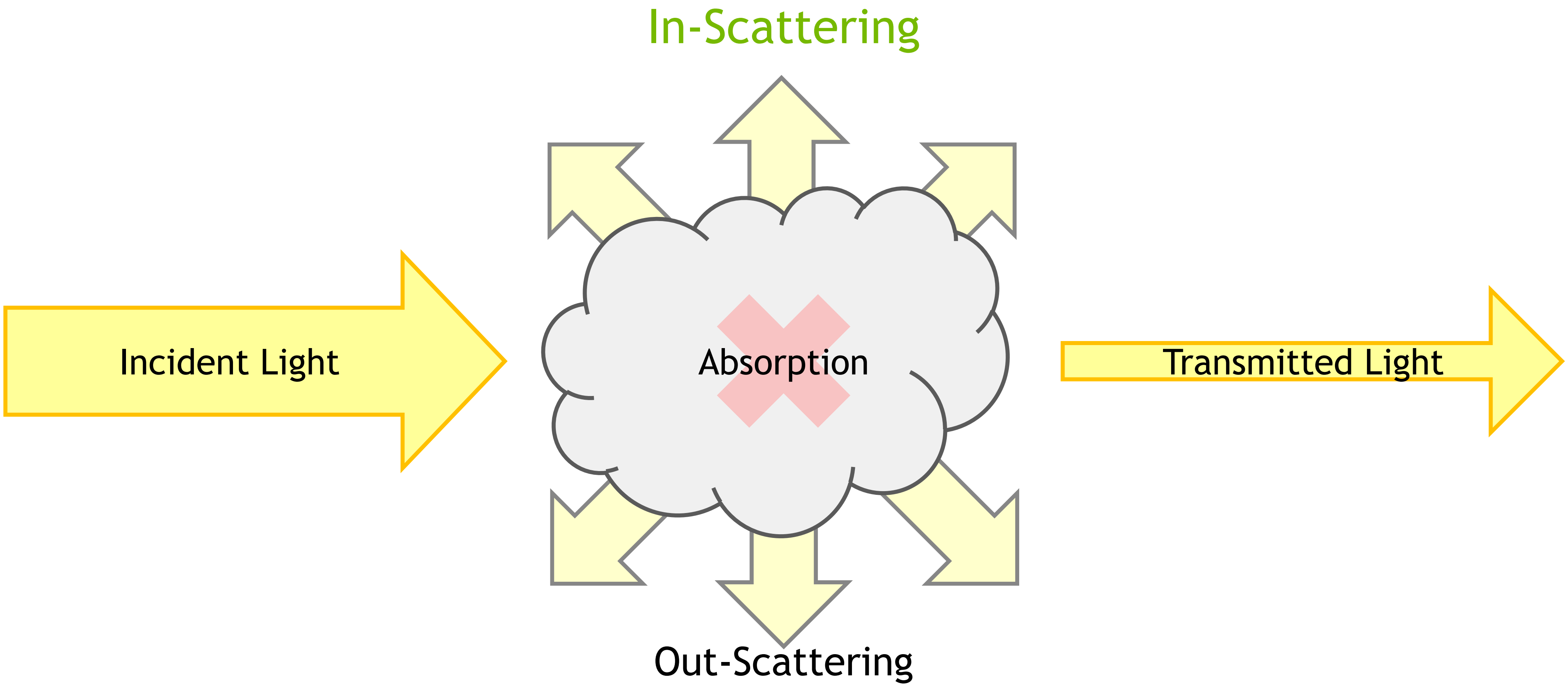
Direct Radiance:

$$L_D = L(\omega_s)\rho_s(l, s, \omega_x)V(s, l)$$

Transmitted Radiance:

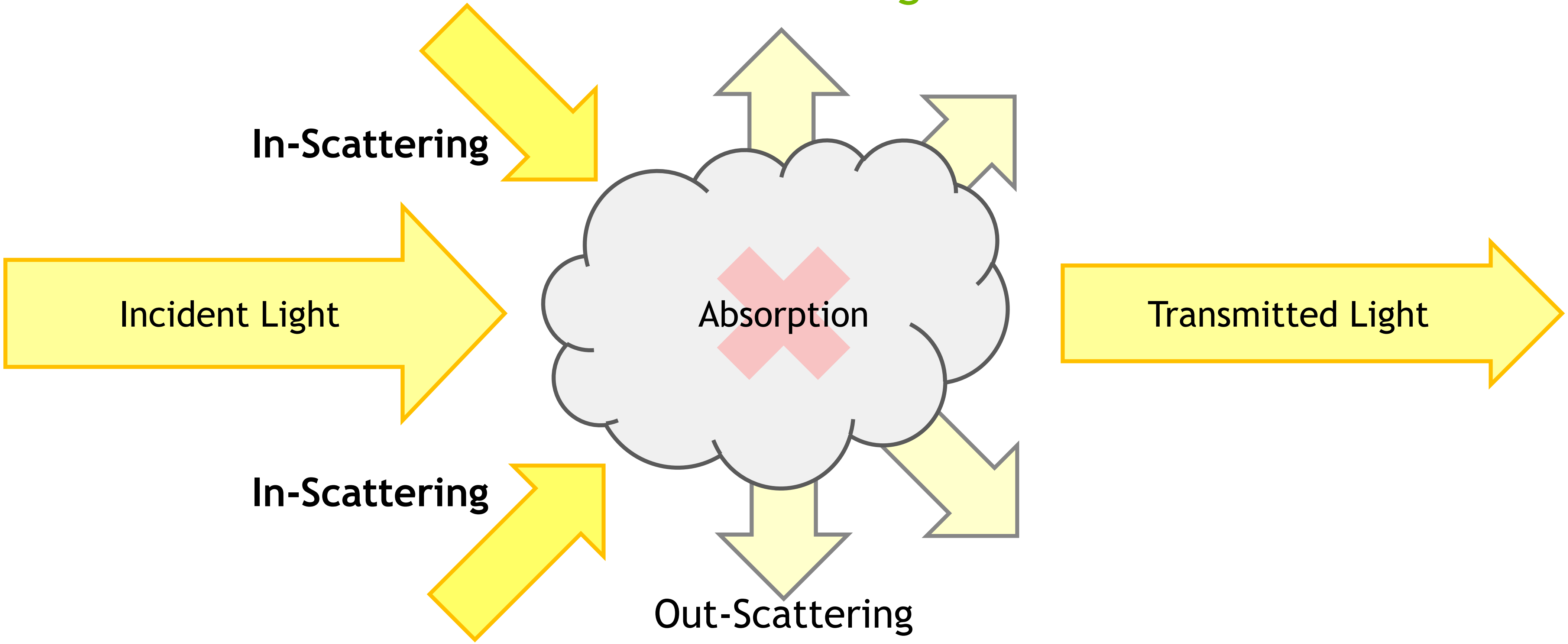
$$L_T = L_D e^{-\tau_{ex}(\overline{ls}+\overline{sx})}$$

Participating Media



Participating Media

In-Scattering



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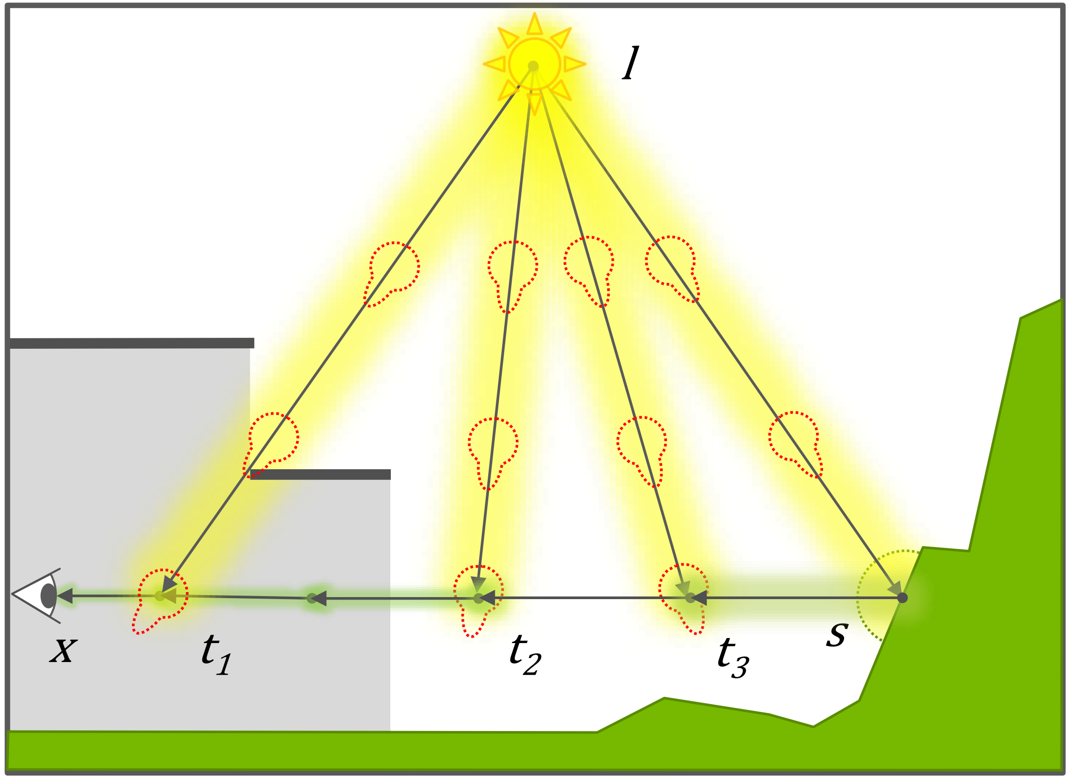

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In-Scattered Radiance:

$$L_S = \int_0^{\overline{sx}} L(t, l)V(t, l)\rho_m\left(\overrightarrow{tl}, \omega_x\right) e^{-\tau_{ex}(\overline{lt}+\overline{tx})} dt$$

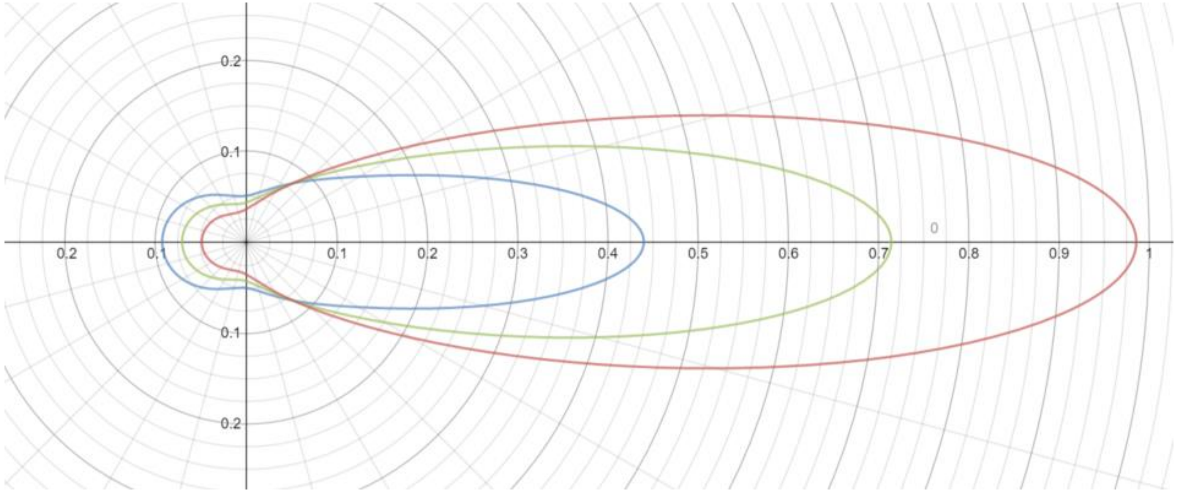
Phase Functions

Overview

Volume analog of BRDF

Directional distribution of energy relative to incident direction

Determined by the ratio of medium particles and their size relative to the light



Phase function for atmosphere on a clear day

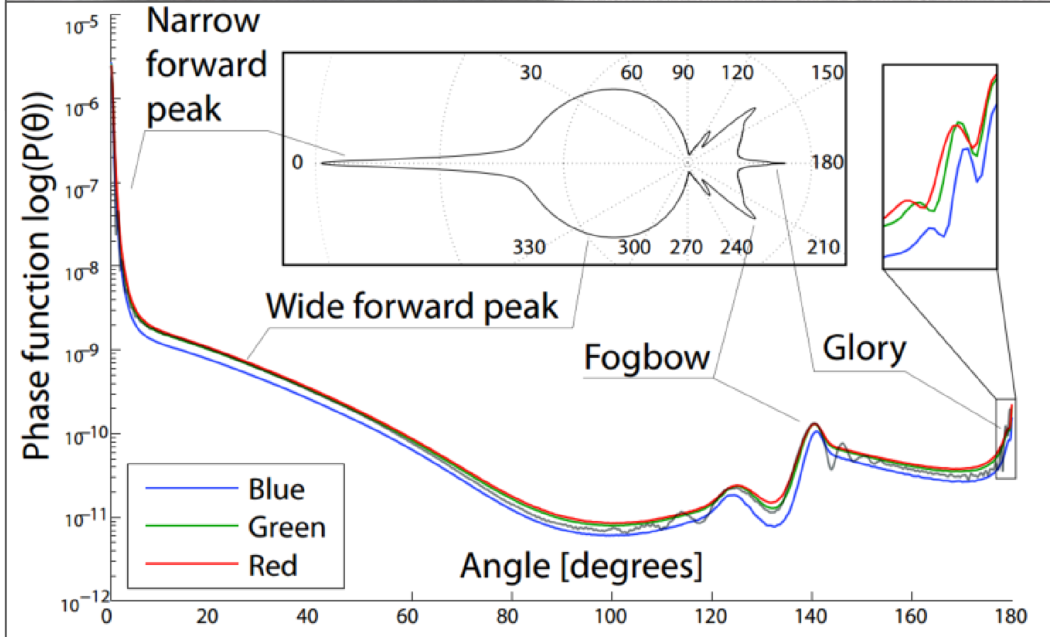
Phase Functions

Complex Phenomenon

Can be Wavelength-dependent

Can become arbitrarily complex depending on atmospheric conditions

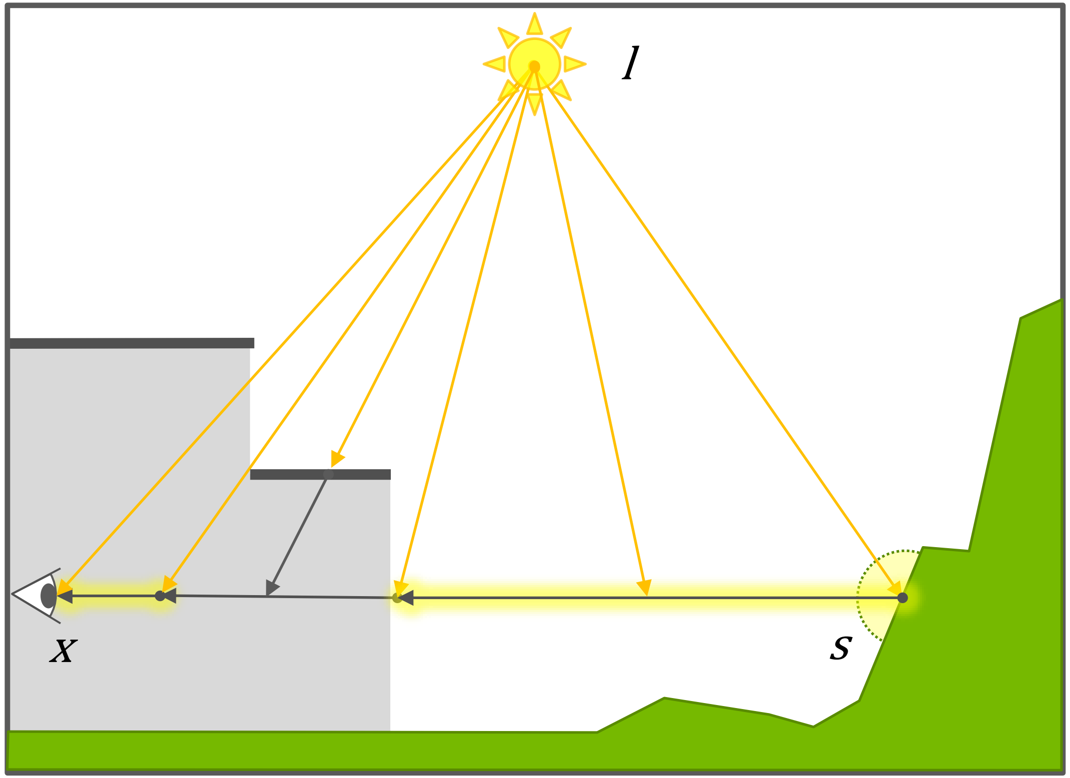
We can approximate common conditions with simple models



Algorithm Overview

Interval Integration

Overview

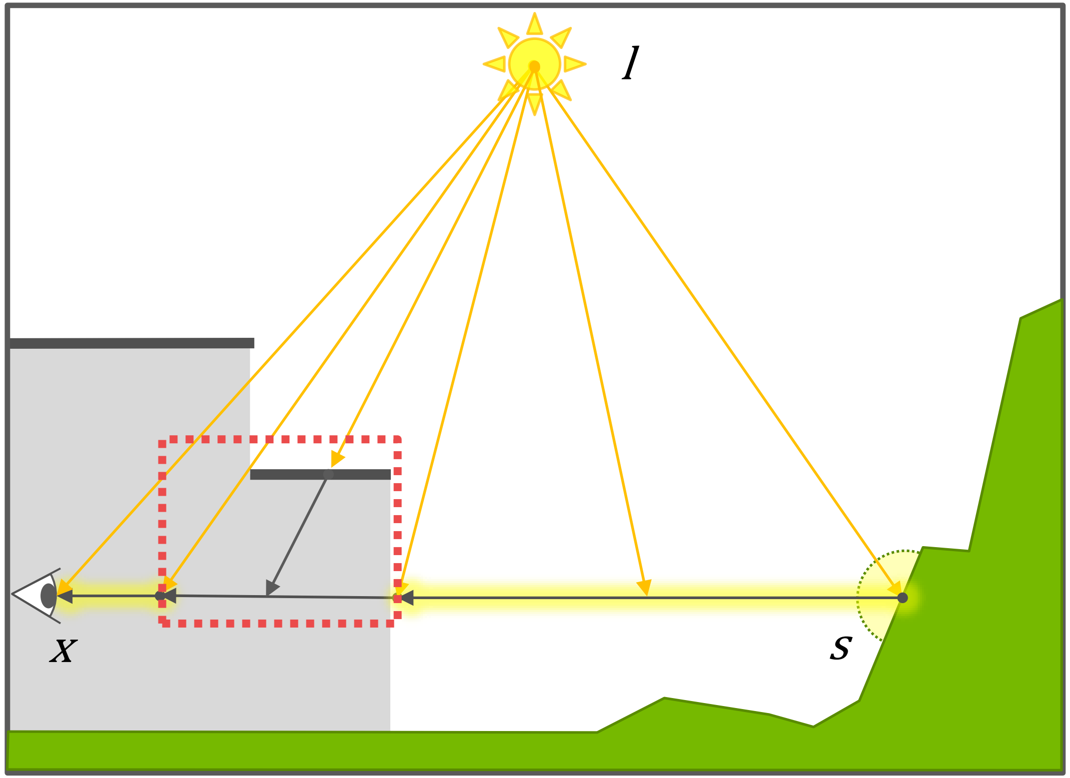


In-Scattered Radiance:

$$L_S = \int_0^{\overline{sx}} L(t,l)V(t,l)\rho_m\left(\overrightarrow{tl},\omega_x\right)e^{-\tau_{ex}(\overline{lt}+\overline{tx})}dt$$

Interval Integration

Non-Constant Visibility

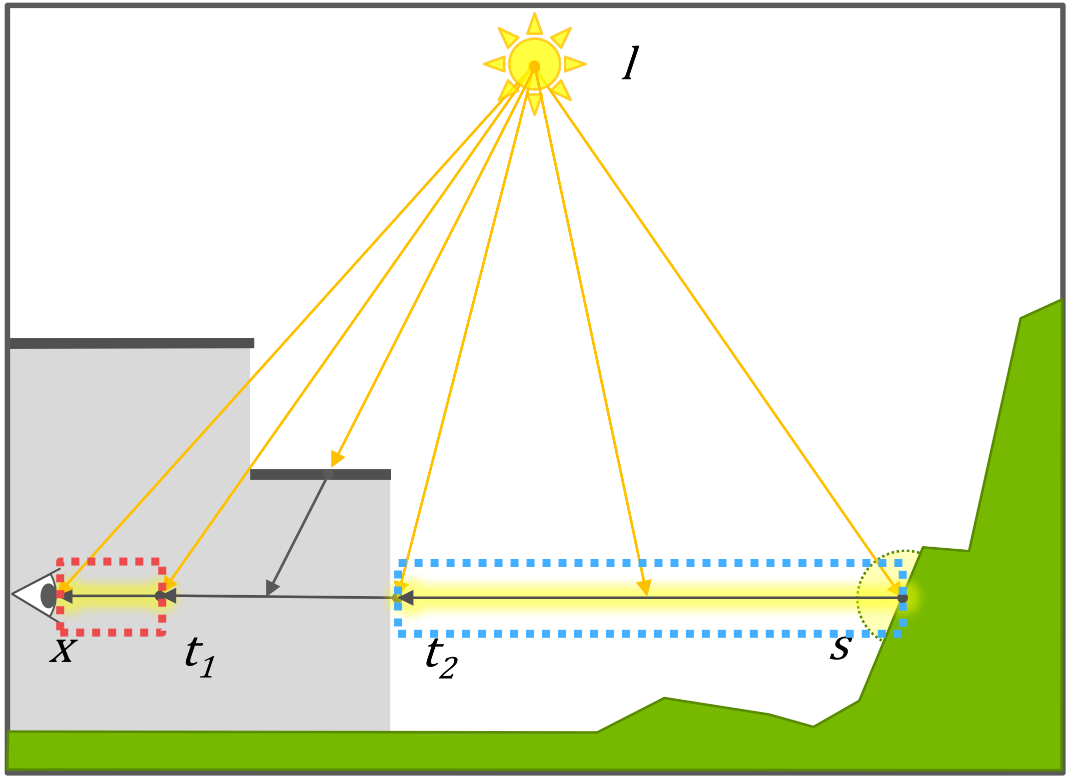


In-Scattered Radiance:

$$L_S = \int_0^{\overline{sx}} L(t,l)\boxed{V(t,l)}\rho_m\left(\overrightarrow{tl},\omega_x\right)e^{-\tau_{ex}(\overline{lt}+\overline{tx})}dt$$

Interval Integration

Sum of Intervals



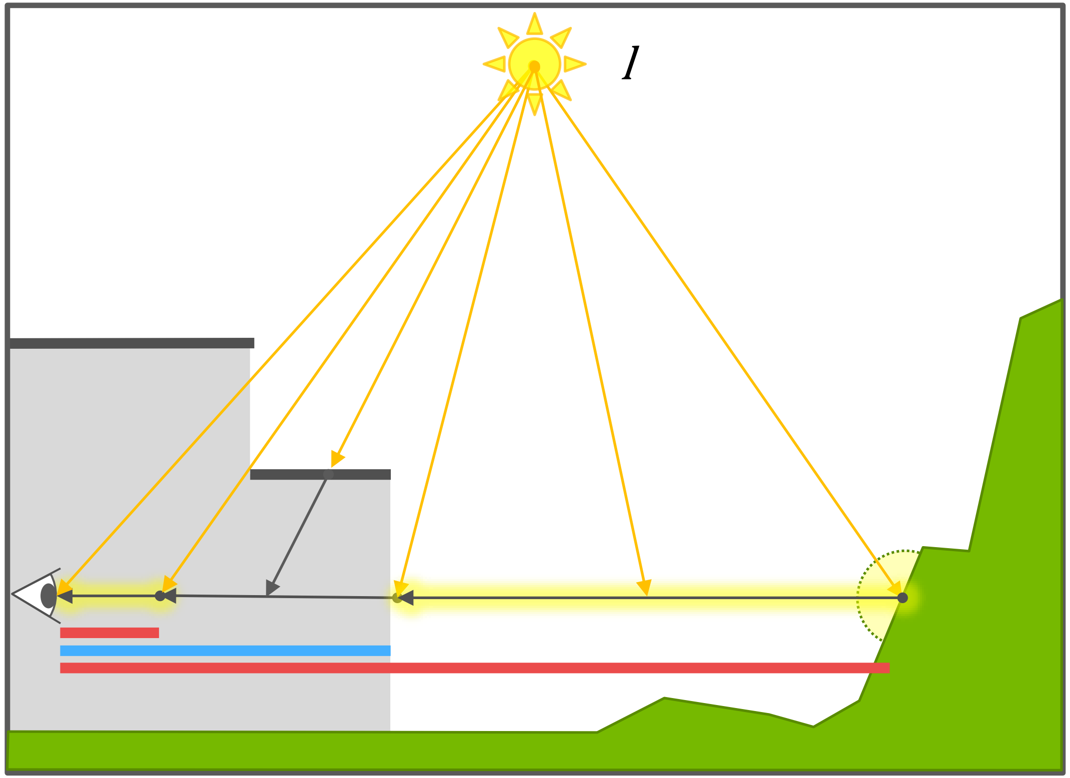
In-Scattered Radiance:

$$L_{S'}{}'(t) = L(t,l)\rho_m\left(\overrightarrow{tl},\omega_x\right)e^{-\tau_{ex}(\overline{lt}+\overline{tx})}$$

$$L_S = \boxed{\int_x^{t_1} L'_{S'}(t)dt} + \boxed{\int_{t_2}^{s} L'_{S'}(t)dt}$$

Interval Integration

Sum & Difference of Intervals



In-Scattered Radiance:

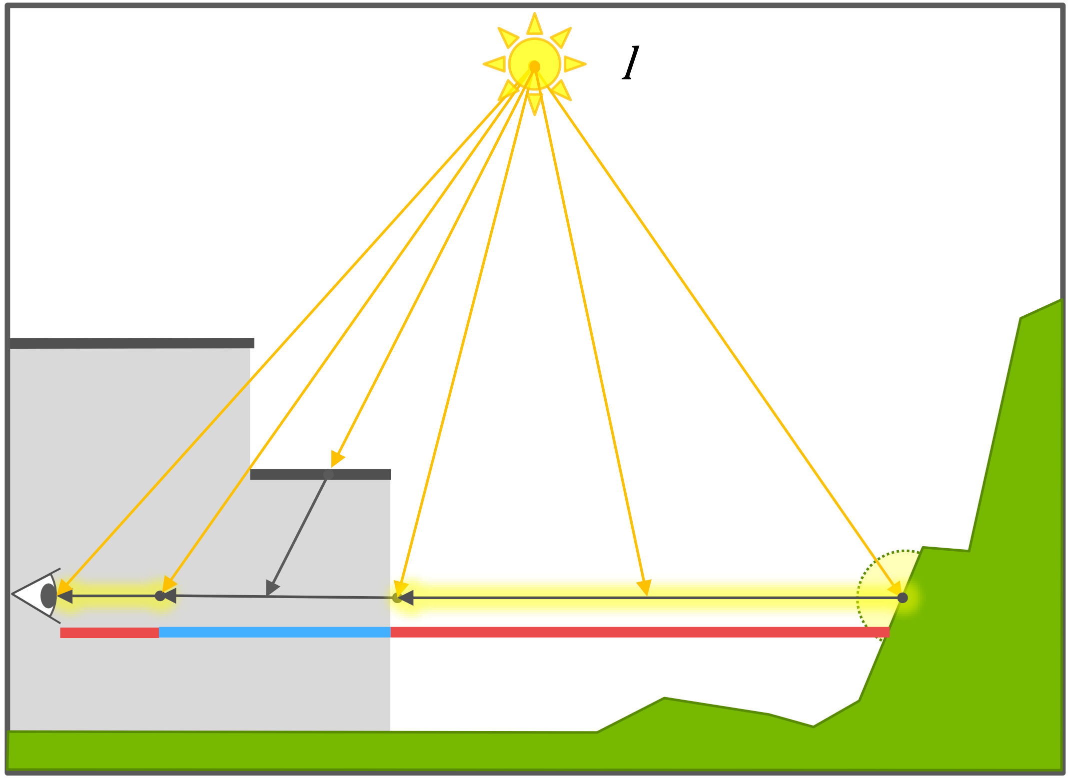
$$L_{S'}{}'(t) = L(t,l)\rho_m\left(\overrightarrow{tl},\omega_x\right)e^{-\tau_{ex}(\overline{lt}+\overline{tx})}$$

$$L_{S'}(d) = \int_0^d L'_{S'}(t)dt$$

$$L_S = L_{S'}(t_1) - L_{S'}(t_2) + L_{S'}(s)$$

Interval Integration

Sum & Difference of Intervals



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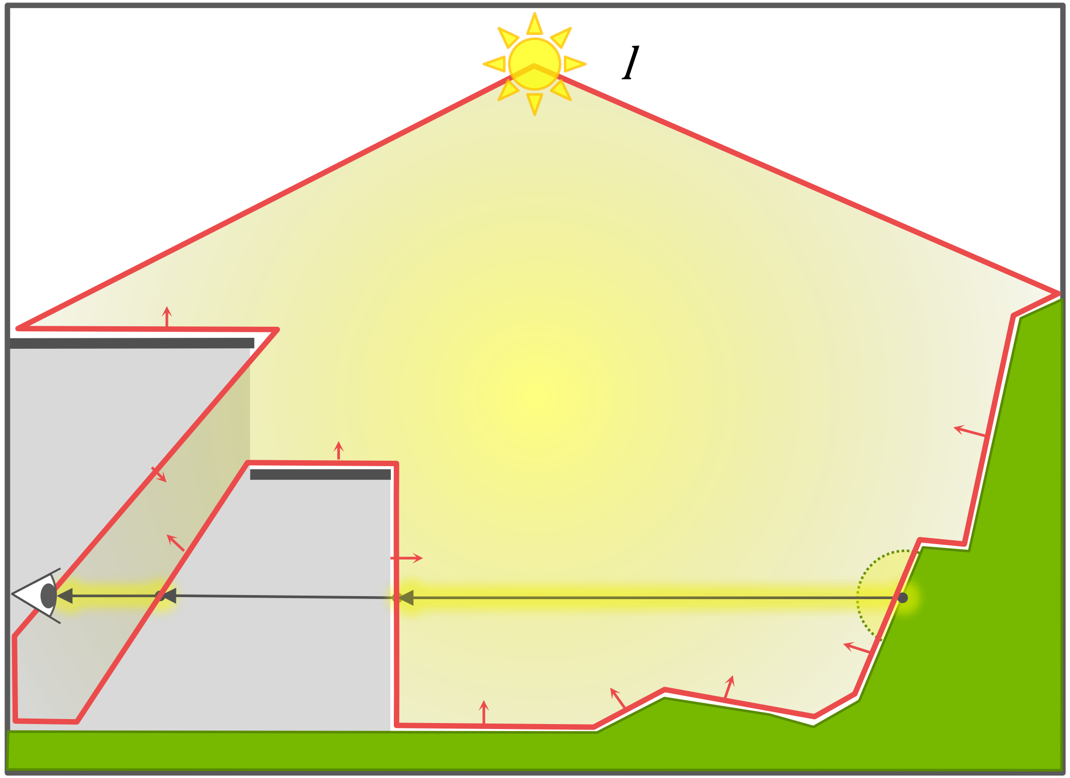
$$L_{S'}(d) = \int_0^d L'_{S'}(t)dt$$

$$L_S = L_{S'}(t_1) - L_{S'}(t_2) + L_{S'}(s)$$

$$L_S = \sum_{n\in G_f} L_{S'}(t_n) - \sum_{m\in G_b} L_{S'}(t_m)$$

Interval Integration

Intervals from Mesh



In-Scattered Radiance:

$$L_S = \sum_{n \in G_f} L_{S'}(t_n) - \sum_{m \in G_b} L_{S'}(t_m)$$

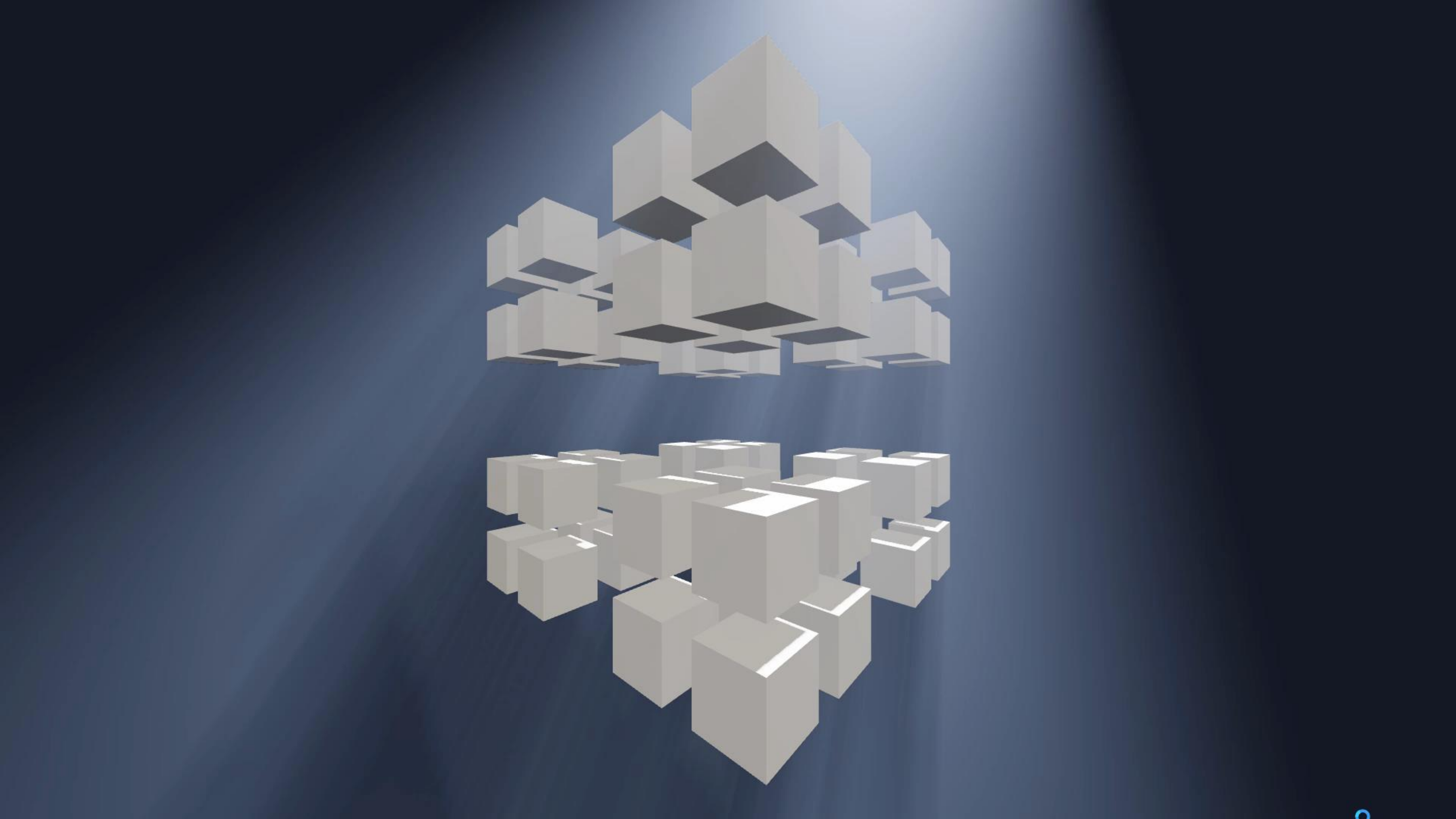
Use front and back faces of light volume as integration intervals

No Scattering

Light Volume


Gameworks Godrays Sample
Scattering Only

Composited Image



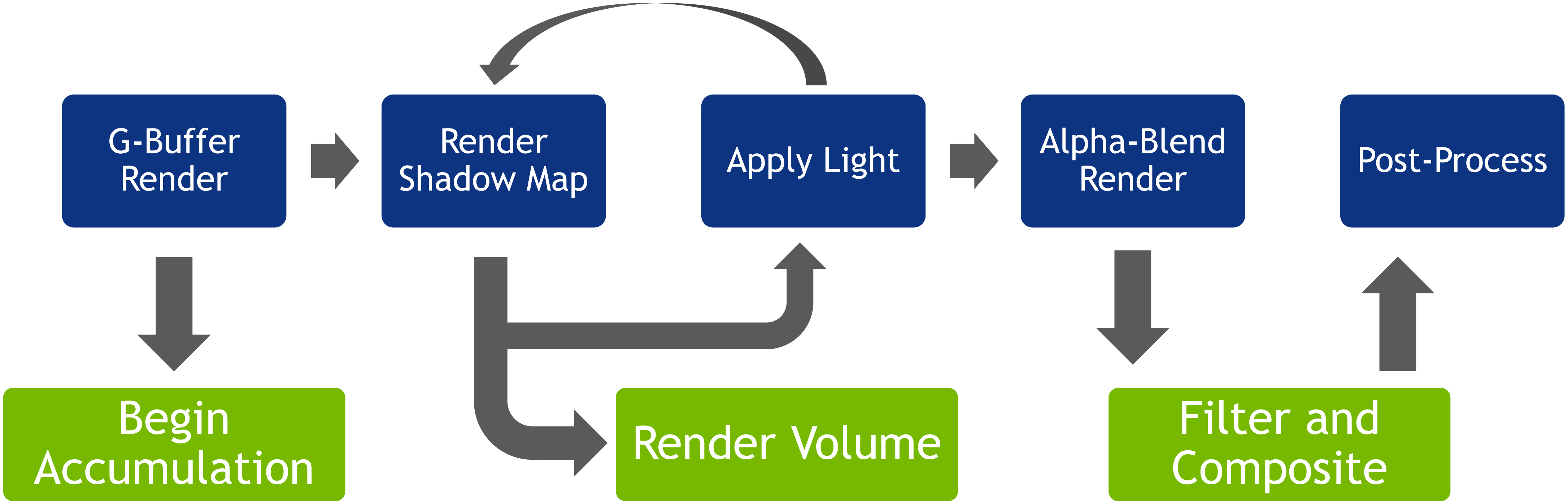
Workflow

High-Level API

- **Begin Accumulation**
  - Scene Depth
  - Medium Definition
- **Render Volume**
  - Light Shadow Map
- **Filter and Composite**
  - Scene Depth
  - Scene Render

Workflow

Generic Pipeline Example



Medium Specification

Multiple Phase Terms

- **Density** - Optical depth of that term in <RGB>
- **Phase Function** - Directional scattering distribution (applied per-channel)
- **Phase Parameters** - Eccentricity (for Henyey-Greenstein)

Absorption - Optical depth of light absorption <RGB>

Terms are summed together per-channel to produce composite medium

Medium Specification

Rayleigh Scattering

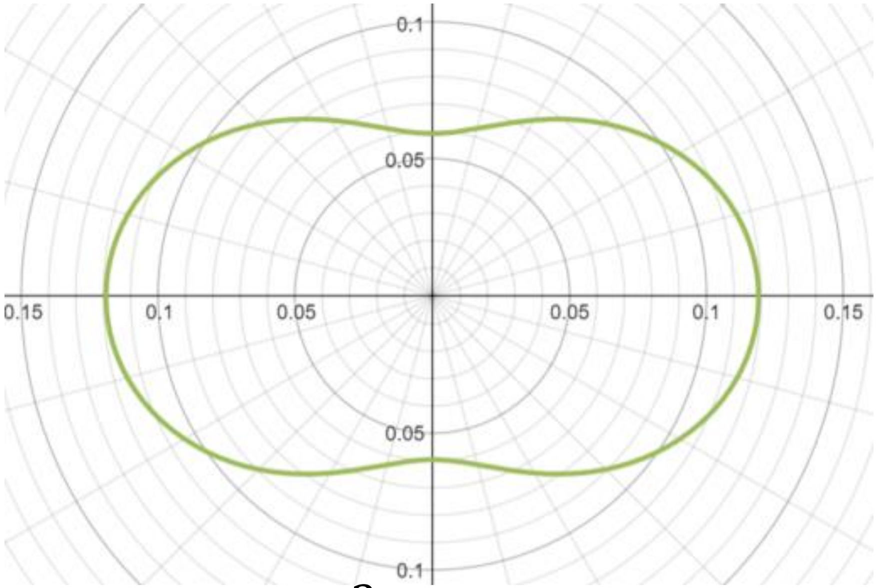
Particles much smaller than wavelength of light (O2, N2, etc.)

Generally constant at a given altitude

Wavelength dependent

Relative optical depth for CIE-RGB:

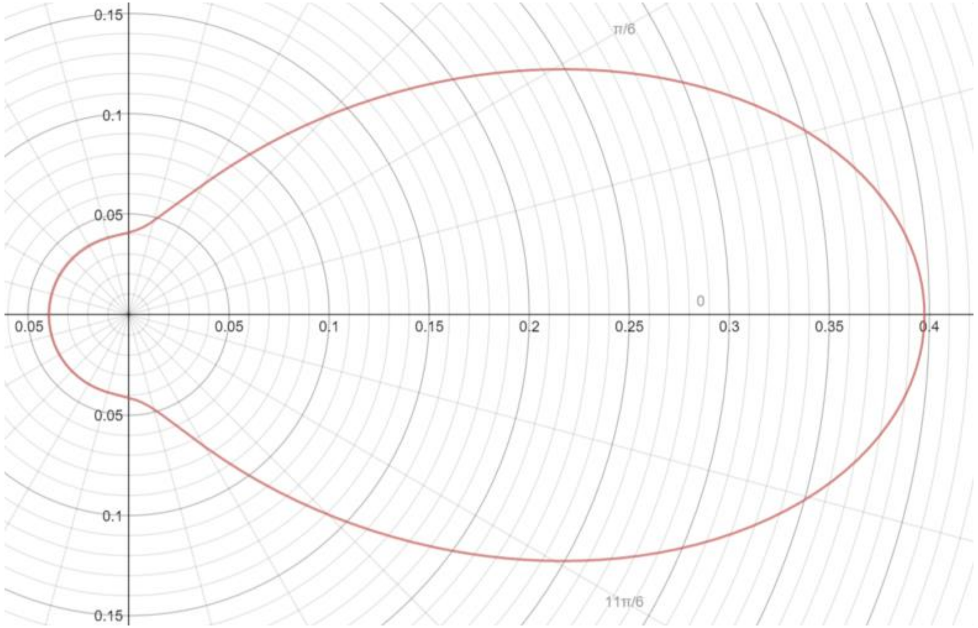
- R: 0.596×10^{-5}
- G: 1.324×10^{-5}
- B: 3.310×10^{-5}



$$\rho(\theta) = \frac{3}{16\pi}(1 + cos^2(\theta))$$

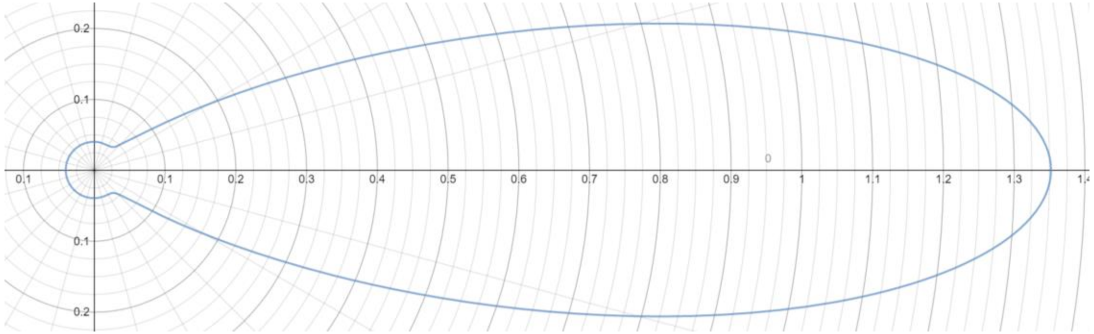
Medium Specification

Mie-Lorenz Approximation



Mie-Hazy: Light fog

$$\rho(\theta) = \frac{1}{4\pi}\left(\frac{1}{2} + \frac{9}{2}\left(\frac{1+\cos\theta}{2}\right)^{8}\right)$$



Mie-Murky: Dense fog

$$\rho(\theta) = \frac{1}{4\pi}\left(\frac{1}{2} + \frac{33}{2}\left(\frac{1+\cos\theta}{2}\right)^{32}\right)$$

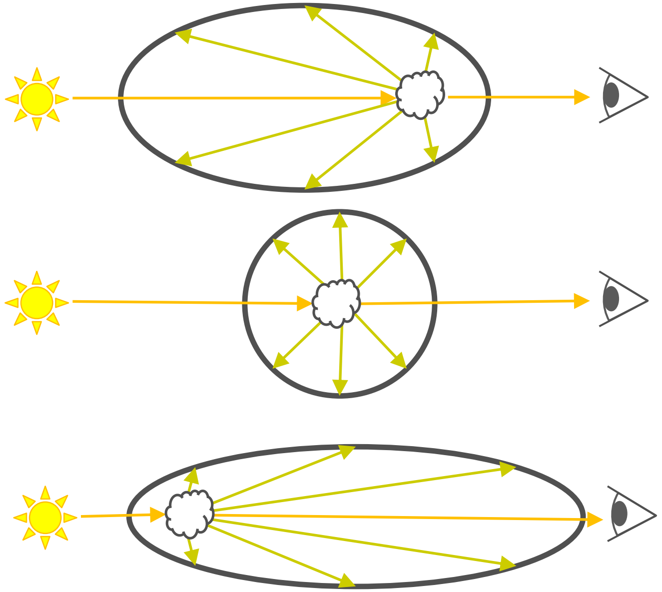
Medium Specification

Henyey-Greenstein Function

Tunable phase function with a specified eccentricity g=(-1, 1)

- g < 0: back-scattering
- g = 0: isotropic scattering
- g > 0: forward scattering

Multiple terms can be combined to approximate complex functions



Volume Rendering

Overview

Convert light description + shadow map into geometry

Solve Integral at each intersection and add or subtract based on facing

Different solvers based on light type

- **Directional Light** - Analytical Solution
- **Omnidirectional Light** - Look-up Texture
- **Spot Light** – Look-up Texture or Numerical Integration

Volume Rendering

Directional Light

$$L_{S'}(d) = L(d,l)\rho_m(\overrightarrow{xl},\omega_x)\frac{1-e^{-\tau_{ex}d}}{\tau_{ex}}$$

With some assumptions we can simplify the integral for directional light

- **Constant Direction** (parallel light-source)
- **Constant Power** (Light distance >> medium depth)

Reduces to analytic function evaluated in pixel-shader

Volume Rendering

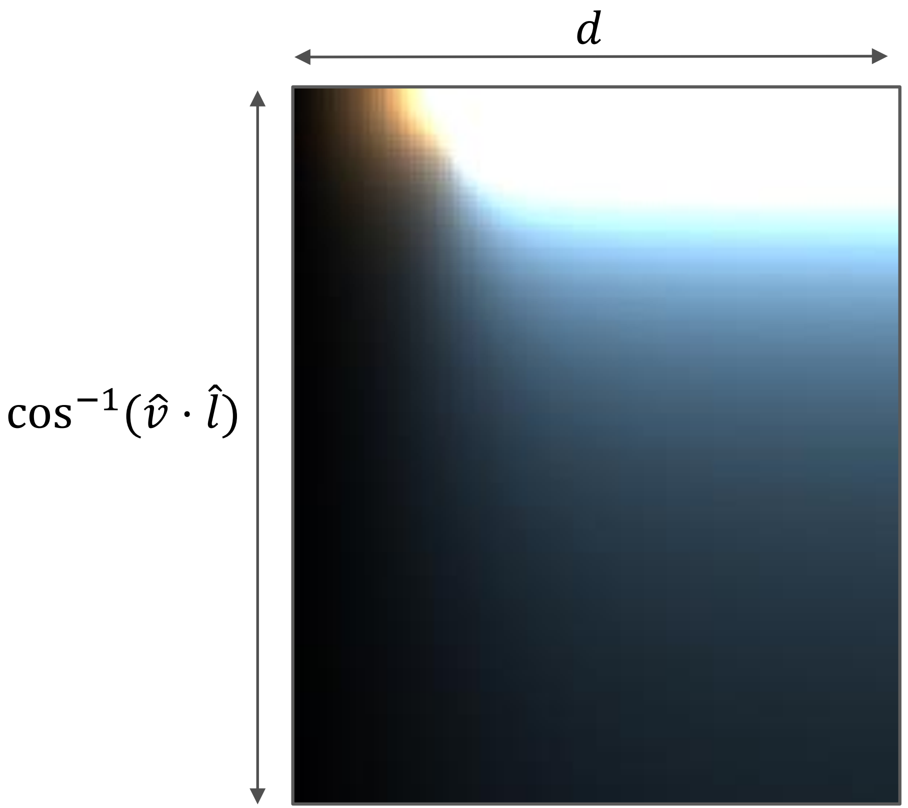
Omnidirectional Light

Local lights too complex for analytical solutions

All terms can be expressed in with respect to direction and distance

Create a Look-up texture:

- Map to 2D space
- evaluate differential
- Numerically integrate with CS



Volume Rendering

Spot Lights

Spotlights are worse case than omnidirectional lights

Angular falloff complicates integral

Interval needs to be clamped to cone intersection

Can be simplified

- No Falloff
- Fixed Falloff
- Variable Falloff

Volume Rendering

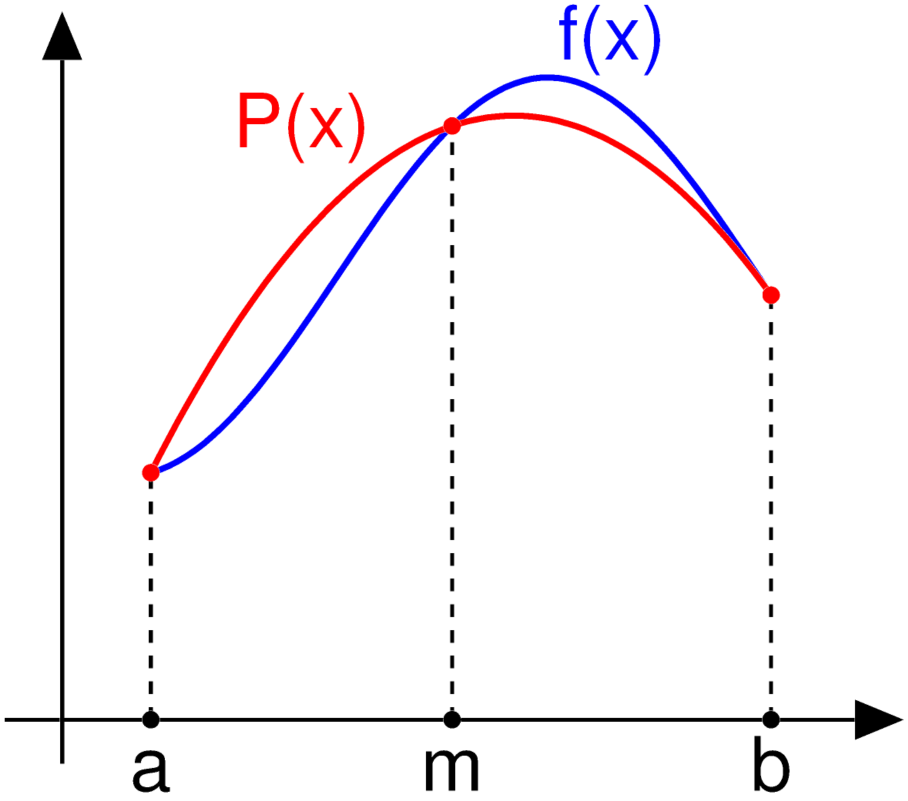
Numerical Integration

No Falloff: Treat as point light

Fixed Falloff: Use modified point LUT

For other cases, integrate in the PS

1) Do cone intersection as before
2) Numerically integrate (Newton-Cotes)
3) Use the result as the integral



Apply Lighting

MSAA/Temporal Resolve

Use MSAA when down-sampling

- Preserves shading rate savings
- Improves edge quality

Resolve MSAA accumulation buffer before compositing

If temporal sampling, feed resolved accumulation through TAA system

Apply Lighting

Composite Results

Bilateral upsampling: helpful at ¼-resolution, situational at ½-resolution

Additively blend resolved/filtered output with scene

Use dual-source blending to attenuate based on medium+depth

Integration into *Fallout 4*

Fallout 4 Integration

Feb: Development/Integration Begins

March: Artists authoring environments

April-June: Console Ports

July-August: Optimization (PC+Console)

Dedicated NVIDIA QA resources

Indoor, Dusty
(Final Image)

Indoor, Dusty
(In-Scattering Only)

Outdoors, Clear
(No Scattering)

Outdoors, Clear
(In-Scattering Only)

Outdoors, Clear
(Final Image)

Outdoors, Foggy
(No Scattering)

Outdoors, Foggy
(In-Scattering Only)

Outdoors, Foggy
(Final Image)

Outdoors, Dusty
(No Scattering)

Outdoors, Dusty
(In-Scattering Only)

Outdoors, Dusty
(Final Image)

Gpu Performance

Concord, High Quality @ 1080p

	BEGIN	RENDER VOLUME	FILTER & COMPOSITE	TOTAL
GTX 980 Ti	0.037 ms	0.908 ms	0.264 ms	**1.209 ms**
GTX 970	0.049 ms	1.364 ms	0.389 ms	**1.802 ms**
Radeon Fury X	0.038 ms	2.581 ms	0.305 ms	**2.924 ms**

Gpu Performance

Concord, Medium Quality @ 1080p

	BEGIN	RENDER VOLUME	FILTER & COMPOSITE	TOTAL
GTX 980 Ti	0.035 ms	0.415 ms	0.394 ms	**0.844 ms**
GTX 970	0.049 ms	0.610 ms	0.565 ms	**1.224 ms**
Radeon Fury X	0.041 ms	1.074 ms	0.636 ms	**1.751 ms**

INTEGRATION TIPS

- Maximize Dynamic Range
- Make sure shadow maps are consistent
- Temporal filter low-res effects separately
- Be aware of worst-case scenes

Implementation Issues

Reduced Dynamic Range Limits Contrast

Problem: Hard to get intense effects without washing out scene

Intensity proportional to light source power

Real-world effects involve 10,000:1 contrast between source and scene!

Baked-in ambient normalizes intensity between bright and dark areas

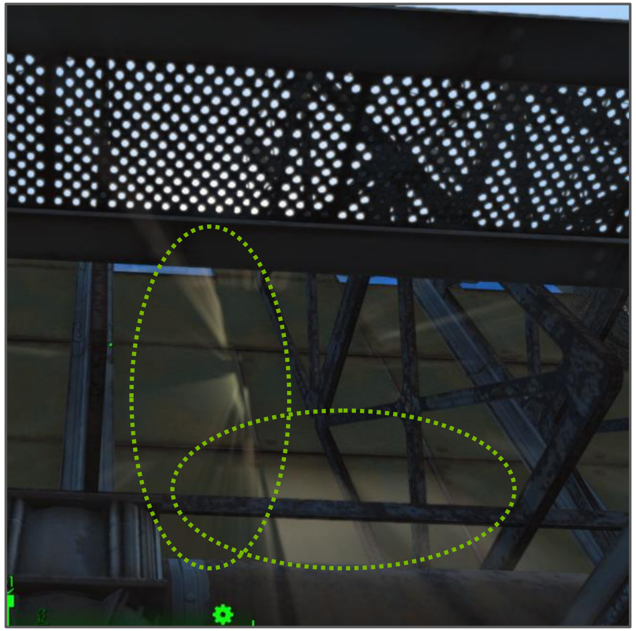
Simply increasing medium density causes wash-out

Solution: Need HDR with real adaptation between dark and bright

Implementation Issues

Shadow Map/Scene Inconsistencies

Problem: Shadow Map inconsistencies become much more noticeable



Implementation Issues

Shadow Map/Scene Inconsistencies

Problem: Shadow Map inconsistencies become much more noticeable

"Bug" in art, but not noticeable because surface and shadows not usually visible

May only render front-faces to shadow map, but there may not have consistent geometry/alpha masks on both sides

May not render "distant" occluders to the shadow map

May use a separate, high-detail map for certain occluders

Solution: be consistent with your shadow map contents!

Implementation Issues

Temporal Jittering Causes Flicker

Problem: Temporal AA jitter causes flickering

Temporal AA jitters to increase effective resolution, then filters to smooth

Library runs at ½ - ¼ resolution to improve performance

A 1 px flicker at full-res could become 4x4 px in the down-sampled buffer!

Full-res temporal filter not designed to smooth artifacts that large

Solution: Added separate TAA resolve to down-sampled buffers

Implementation Issues

Perf Drop with High Frequency Occluders

Problem: Poor perf in specific views

Cost proportional to total pixel coverage

Dense occluders are no problem but create overhead at low angles

Ex: Sunset through the woods

Solution: Adjust tessellation factor based on view angle

Solution: Pre-filter shadow map

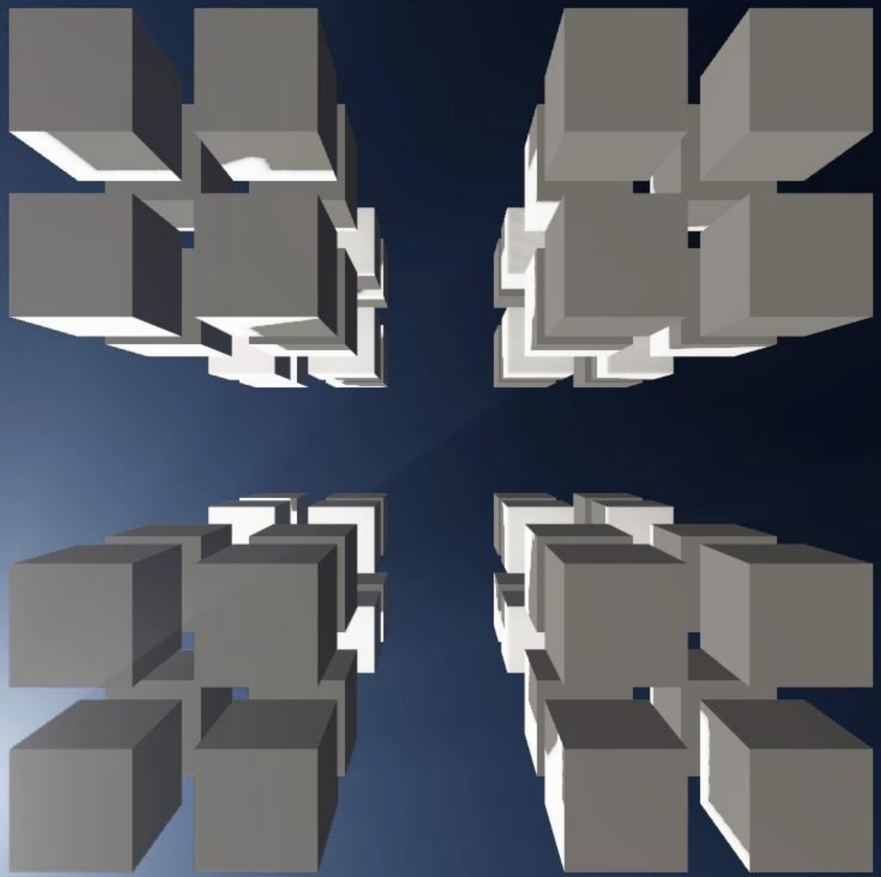
SUMMARY

Gameworks Volumetric Lighting is…

- Fast enough for entire spec range
- Flexible enough for almost any engine
- Compatible with physically-based engines
- Currently available in DirectX 11 (with ports being added according to demand)

http://developer.nvidia.com

Questions?



RELATED READING

Hoffman, N., and A. J. Preetham. 2002. Rendering Outdoor Scattering in Real Time. http://amd-dev.wpengine.netdna-cdn.com/wordpress/media/2012/10/ATI-LightScattering.pdf

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