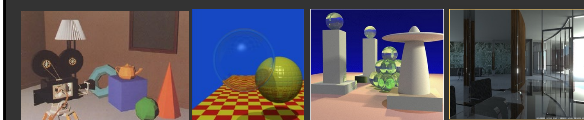
Computer Graphics II: Rendering

CSE 168[Spr 25],Lecture 15: Volumetric Rendering
Ravi Ramamoorthi

http://viscomp.ucsd.edu/classes/cse168/sp25



1

To Do

- Start working on final projects (initial results and proposal due in a week). Ask me if problems
- Volumetric rendering (this lecture) may be one component of the final project (but hard, be careful)
- Increasingly accurate appearance requires volumetric scattering (even for skin, hair, fur)
- Continues to be an active area of research

Many slides courtesy Pat Hanrahan/Matt Pharr (Stanford CS 348b) and Steve Rotenberg, Henrik Wann Jensen (UCSD CSE 168)

2

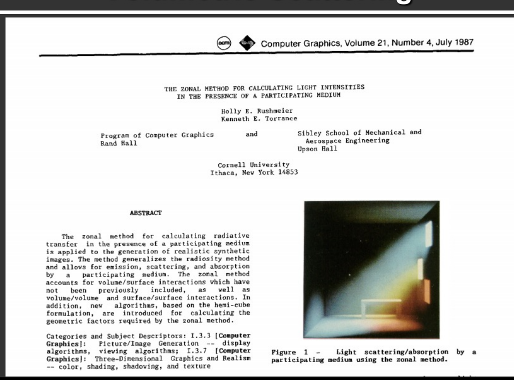
Volumetric Scattering

3

Volumetric Scattering

4

Volumetric Scattering



Computer Graphics, Volume 21, Number 4, July 1987

THE ZONAL METHOD FOR CALCULATING LIGHT INTENSITIES IN THE PRESENCE OF A PARTICIPATING MEDIUM

Holly E. Rushmeier
Kenneth E. Torrance

Program of Computer Graphics, Rand Hall and Sibley School of Mechanical and Aerospace Engineering, Upson Hall

Cornell University
Ithaca, New York 14853

ABSTRACT

The zonal method for calculating radiative transfer in the presence of a participating medium is applied to the generation of realistic synthetic images. The method generalizes the radiosity method and allows for emission, scattering, and absorption by a participating medium. The zonal method accounts for volume/surface interactions which have not been previously included, as well as volume/volume and surface/surface interactions. In addition, new algorithms, based on the hemi-cube formulation, are introduced for calculating the geometric factors required by the zonal method.

Categories and Subject Descriptors: I.3.3 [Computer Graphics]: Picture/Image Generation -- display algorithms, viewing algorithms; I.3.7 [Computer Graphics]: Three-Dimensional Graphics and Realism -- color, shading, shadowing, and texture

Figure 1 - Light scattering/absorption by a participating medium using the zonal method.

5

Volumetric Scattering

- Participating Media (light participates via scattering)
  - Volumetric phenomena like clouds, smoke, fire
  - Subsurface scattering, translucency (wax, human skin)
  - These are not surfaces with well-defined BRDFs
  - Rather volumes where light can scatter
  - Medium is often known as a participating medium
- Surface Rendering: Radiance Constant along Ray
  - Only true in absence of participating media
  - *No longer true for volumetric scattering*
  - *Often replace ray tracing with ray marching in medium*
- Volumetric Properties
  - BRDF replaced by phase function
  - Must consider absorption and scattering in medium

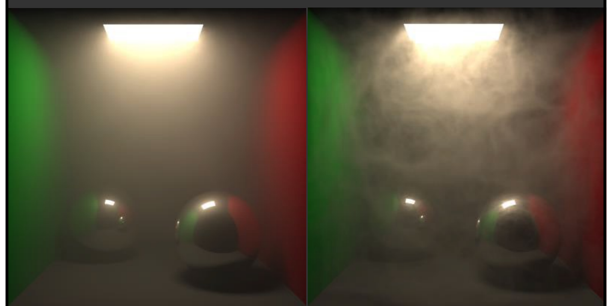
6

Homogeneous vs Heterogeneous

- Homogeneous: Properties constant everywhere
  - Example: Fog often represented as homogeneous
- Heterogeneous: Varies across space
  - Example: Smoke, fire etc.
  - Sometimes called inhomogeneous
- Homogeneous volumes often easier
  - Some computational shortcuts (transmittance etc.)
  - Some analytic formulae

7

Homogeneous vs Heterogeneous



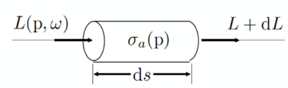
8

Volumetric Interactions

- 4 different processes affect radiance of a beam
  - Absorption
  - Out-Scattering
  - Emission
  - In-Scattering

9

Absorption



$$\mathrm{d}L(\mathrm{p},\omega) = -\sigma_a(\mathrm{p})\, L(\mathrm{p},\omega)\, \mathrm{d}s$$

Absorption cross section: $\sigma_a(\mathrm{p})$

- **Probability of being absorbed per unit length**
- **Units: 1/distance**

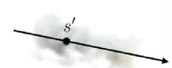
10

Absorption

11

Transmittance

$$\mathrm{d}L(\mathrm{p},\omega) = -\sigma_a(\mathrm{p})\, L(\mathrm{p},\omega)\, \mathrm{d}s$$



$$\frac{\mathrm{d}L(\mathrm{p},\omega)}{L(\mathrm{p},\omega)} = -\sigma_a(\mathrm{p})\, \mathrm{d}s$$

$$\log L(\mathrm{p} + s\omega, \omega) = -\int_0^s \sigma_a(\mathrm{p} + s'\omega, \omega)\, \mathrm{d}s' = -\tau(s)$$

Optical distance (depth): $\tau(s) = \int_0^s \sigma_a(\mathrm{p}')\, \mathrm{d}s'$

$$\mathrm{p}' = \mathrm{p} + s'\omega$$

Homogeneous medium–constant σ_a**:** $\tau(s) = \sigma_a s$

12

Transmittance and Opacity

$$\mathrm{d}L(\mathrm{p},\omega) = -\sigma_a(\mathrm{p})\, L(\mathrm{p},\omega)\,\mathrm{d}s$$

$$\frac{\mathrm{d}L(\mathrm{p},\omega)}{L(\mathrm{p},\omega)} = -\sigma_a(\mathrm{p})\,\mathrm{d}s$$

$$\log L(\mathrm{p}+s\omega,\omega) = -\int_0^s \sigma_a(\mathrm{p}+s'\omega,\omega)\,\mathrm{d}s' = -\tau(s)$$

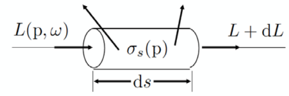
$$L(\mathrm{p}+s\omega,\omega) = \mathrm{e}^{-\tau(s)} L(\mathrm{p},\omega) = T(s)\,L(\mathrm{p},\omega)$$

Transmittance: $T(s) = \mathrm{e}^{-\tau(s)}$

Opacity: $\alpha(s) = 1 - T(s)$

13

Out-Scattering



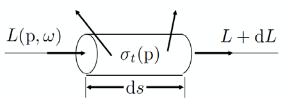
$$\mathrm{d}L(\mathrm{p},\omega) = -\sigma_s(\mathrm{p})\, L(\mathrm{p},\omega)\,\mathrm{d}s$$

Scattering cross-section: σ_s

- **Probability of being scattered per unit length**

14

Extinction



$$\mathrm{d}L(\mathrm{p},\omega) = -\sigma_t(\mathrm{p})\, L(\mathrm{p},\omega)\,\mathrm{d}s$$

Total cross section: $\sigma_t = \sigma_a + \sigma_s$

Albedo: $W = \frac{\sigma_s}{\sigma_t} = \frac{\sigma_s}{\sigma_a + \sigma_s}$

Optical distance from absorption and scattering:

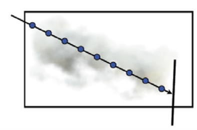
$$\tau(s) = \int_0^s \sigma_t(\mathrm{p}')\,\mathrm{d}s'$$

15

Ray Marching for Transmittance

$$\tau(s) = \int_0^s \sigma_t(x + s'\omega)\,\mathrm{d}s'$$

$$T(s) = \mathrm{e}^{-\tau(s)}$$



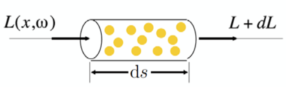
Monte Carlo not necessary for 1D—can use a Riemann sum:

$$\tau(s) \approx \frac{s}{N}\sum_i^N \sigma_t(x_i)$$

$$x_i = x + \frac{i + 0.5}{N}\omega$$

16

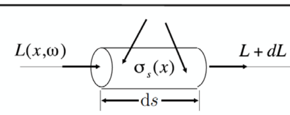
Emission



$$\mathrm{d}L(\mathrm{p},\omega) = \sigma_a(\mathrm{p}) L_\mathrm{e}(\mathrm{p},\omega)\,\mathrm{d}s$$

17

In-Scattering



$$S(\mathrm{p},\omega) = \sigma_s(\mathrm{p}) \int_{S^2} p(\omega' \to \omega)\, L(\mathrm{p},\omega')\,\mathrm{d}\omega'$$

Phase function: $p(\omega' \to \omega)$

Reciprocity: $p(\omega' \to \omega) = p(\omega \to \omega')$

Energy conservation: $\int_{S^2} p(\omega' \to \omega)\,\mathrm{d}\omega' = 1$

18

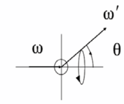
Scattering Phase Functions

- Light interacts with volume, scatters in some spherical distribution
- Similar to light scattering off a surface
- Phase function analogous to a surface BRDF
- Depends only on cosine of incident-outgoing
- Like BRDFs, volumetric phase functions must be reciprocal and conserve energy
- Similar to BRDFs, we will want to do importance sampling and evaluation of phase functions

19

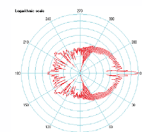
Phase Functions

Phase angle $\cos\theta = \omega \cdot \omega'$



Phase functions

- **Isotropic:** $p(\cos\theta) = \frac{1}{4\pi}$
- **Rayleigh:** $p(\cos\theta) = \frac{3}{4}(1+\cos^2\theta)$ **with** $\sigma_s \propto \frac{1}{\lambda^4}$
- **Mie:**



[Philip Laven]

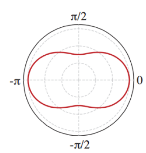
20

Rayleigh Scattering

- Rayleigh scattering describes the scattering of light by particles much smaller than the wavelength

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

$$\sigma_s = \frac{2\pi^5}{3}\frac{d^6}{\lambda^4}\left(\frac{n^2-1}{n^2+2}\right)^2$$



- Where λ is the wavelength of light, d is the diameter of the particle, and n is the index of refraction of the particle
- The strong dependence on wavelength (λ^{-4}) causes greater scattering towards the blue end of the spectrum
- The blue color of the sky is caused by Rayleigh scattering of sunlight by air molecules

21

Rayleigh Scattering: Blue Sky, Red Sunset

From Greenler: Rainbows, Halos, and Glories

CS348b Lecture 17 Pat Hanrahan / Matt Pharr, Spring 2019

22

Mie Scattering

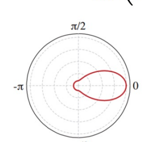
- Scatter electromagnetic waves by spherical particles
- Size of particles same scale as wavelength of light
- Water droplets in atmosphere, fat droplets in milk
- After Gustave Mie, Ludvig Lorenz

23

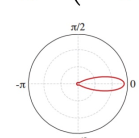
Empirical Mie Approximation

- The following empirical function is often used to approximate the shape of Mie scattering

$$p(\cos\theta) = \frac{1}{4\pi}\left(\frac{1}{2} + \frac{(z+1)}{2}\left(\frac{1+\cos\theta}{2}\right)^z\right)$$



z=8



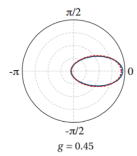
z=32

24

Henyey-Greenstein Function

- The Henyey-Greenstein phase function is an empirical function originally designed to model the scattering in galactic dust clouds

$$p(\cos\theta) = \frac{1-g^2}{4\pi(1+g^2-2g\cos\theta)^{1.5}}$$



- It uses an anisotropy parameter *g* that ranges between -1 (full backscatter) and 1 (full forward scatter), and is isotropic for *g*=0

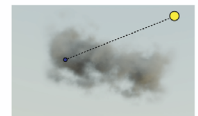
25

Direct Illumination in a Volume

$$S_d(p',\omega) = \sigma_s(p') \int_{S^2} p(\omega' \to \omega)\, L_d(p',\omega')\, d\omega'$$

Can treat like direct illumination at a surface

- **Sample from phase function's distribution**
- **Sample from light source distributions**
- **Weight using multiple importance sampling**



26

Direct Illumination in a Volume

$$S_d(p',\omega) = \sigma_s(p') \int_{S^2} p(\omega' \to \omega)\, L_d(p',\omega')\, d\omega'$$

Estimator: $\sigma_s(p') \frac{1}{N} \sum_i^N \frac{p(\omega_i \to \omega)\, L_d(p',\omega_i)}{p(\omega_i)}$

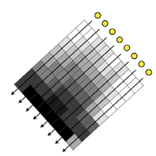
Computing direct lighting, L_d **can be expensive**

- **Not just a shadow ray– need to compute transmittance**

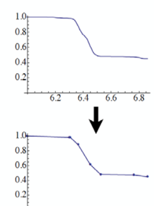
27

Transmittance for Shadow Rays

Besides Monte Carlo, precomputed transmittance can be faster for point, distant lights



3D grid [Kajiya and von Herzen 1984]



Deep Shadow Maps [Lokovic & Veach 2000], Adaptive Volumetric Shadow Maps [Salvi et al. 2010]

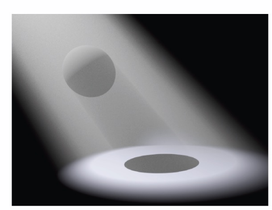
28

Single-Scattering

29

Single-Scattering

Minneart: Color and Light In The Open Air



pbrt: Spot-Lit Ball In The Fog

CS348b Lecture 17 — Pat Hanrahan / Matt Pharr, Spring 2019

30

The Volume Rendering Equation

Integro-differential equation:

$$\frac{\partial L(\mathrm{p},\omega)}{\partial s} = -\sigma_t L(\mathrm{p},\omega) + S(\mathrm{p},\omega)$$

Integro-integral equation:

$$L(\mathrm{p},\omega) = \int_0^\infty T(\mathrm{p}')\, S(\mathrm{p}',\omega)\,\mathrm{d}s'$$

Attenuation: absorption and scattering

$$\mathrm{e}^{-\int_0^{s'} \sigma_t(\mathrm{p}'')\,\mathrm{d}s''}$$

Source: in-scattering (and emission)

$$\sigma_s(\mathrm{p}') \int_{S^2} p(\omega' \to \omega)\, L(\mathrm{p}',\omega')\,\mathrm{d}\omega'$$

CS348b Lecture 17 Pat Hanrahan / Matt Pharr, Spring 2019

31

Volumetric Path Tracing

Integro-integral equation:

$$L(\mathrm{p},\omega) = \int_0^\infty T(\mathrm{p}')\, S(\mathrm{p}',\omega)\,\mathrm{d}s'$$

Monte Carlo integration: sample $s' \sim p(s)$

Estimator: $\dfrac{T(\mathrm{p}')S(\mathrm{p}',\omega)}{p(s')}$

CS348b Lecture 17 Pat Hanrahan / Matt Pharr, Spring 2019

32

Evaluating the Estimator: S

Include indirect illumination in the source term:

$$S(x,\omega) = \sigma_s(x) \int_{S^2} p(\omega' \to \omega)\, L(x,\omega')\,\mathrm{d}\omega'$$

$$L(x,\omega') = L_d(x,\omega') + L_i(x,\omega')$$

- **Compute direct lighting as before**
- **Sample incident direction from the phase function's distribution, trace a ray recursively...**

$$L_i(x,\omega') \approx \frac{p(\omega'' \to \omega')\, L(x,\omega'')}{p(\omega'')}$$

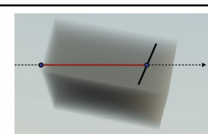
Uniform spherical directions: $p(\omega'') = \dfrac{1}{4\pi}$

CS348b Lecture 17 Pat Hanrahan / Matt Pharr, Spring 2019

33

Linear Sampling of T

We want samples along a finite ray [0,t_{max}].



- **Uniform probability along the ray:**

$$p(t) = \frac{1}{t_{\max}}$$

- **Sampling recipe:**

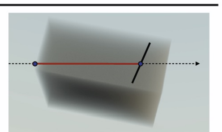
$$\xi = \int_0^t p(t)\,\mathrm{d}t \qquad t = \xi t_{\max}$$

CS348b Lecture 17 Pat Hanrahan / Matt Pharr, Spring 2019

34

Exact Sampling of Uniform T

We want samples along a finite ray [0,t_{max}], $p(t) \propto \mathrm{e}^{-\sigma t}$



- **Normalize to find PDF:**

$$\int_0^{t_{\max}} \mathrm{e}^{-\sigma t}\,\mathrm{d}t = -\frac{1}{\sigma}(\mathrm{e}^{-\sigma t_{\max}} - 1) = c \qquad p(t) = c\mathrm{e}^{-\sigma t}$$

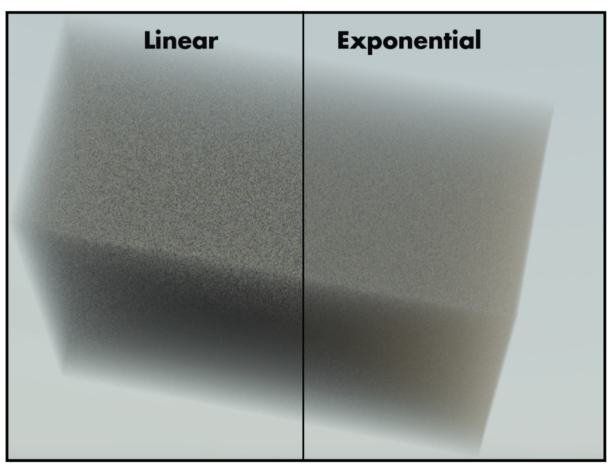
- **Invert to find t for a random sample:**

$$\xi = \int_0^t p(t)\,\mathrm{d}t$$

$$t = -\frac{1}{\sigma}\log(1 - \xi(1 - \mathrm{e}^{-\sigma t_{\max}}))$$

CS348b Lecture 17 Pat Hanrahan / Matt Pharr, Spring 2019

35



36

Volumetric Path Tracing

Integro-integral equation:

$$L(\mathrm{p},\omega) = \int_0^\infty T(\mathrm{p}')\, S(\mathrm{p}',\omega)\, \mathrm{d}s'$$

Monte Carlo integration: sample $s' \sim p(s)$

Estimator: $\dfrac{T(\mathrm{p}')S(\mathrm{p}',\omega)}{p(s')}$

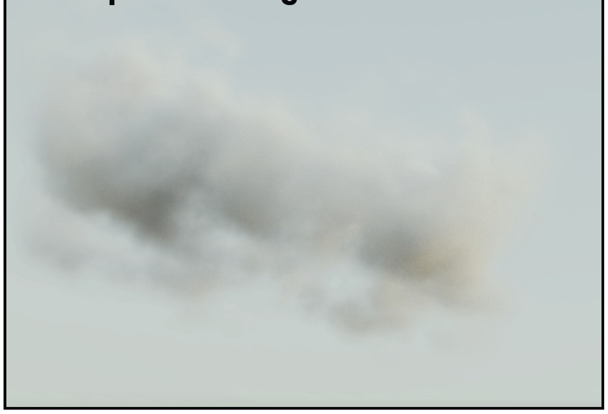
CS348b Lecture 17 Pat Hanrahan / Matt Pharr, Spring 2019

37

Single-Scattering

38

Multiple Scattering



39

Clouds

40

Translucency

- Translucency is a volumetric lighting effect with additional effects at the surface (usually rough dielectric type interaction)
- These can be modeled through standard volumetric lighting techniques, or can be optimized through some further methods designed specifically for sub-surface scattering

41

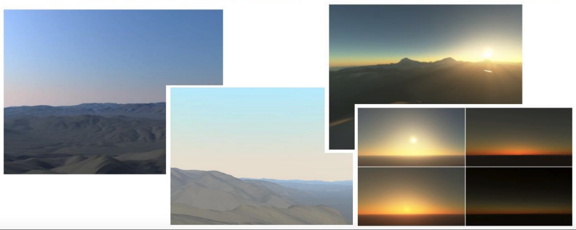
Fire

- "Physically Based Modeling and Animation of Fire", Nguyen, Fedkiw, Jensen, 2003

42

Sky Rendering

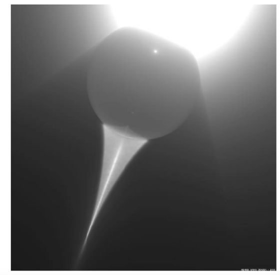
- "A Practical Analytical Model for Daylight", Preetham, Shirley, Smits, 1999
- "A Physically Based Night Sky Model", Jensen, Durand, Stark, Premoze, Dorsey, Shirley, 2001
- "Precomputed Atmospheric Scattering", Bruneton, Neyret, 2008
- "An Analytic Model for Full Spectral Sky-Dome Radiance", Hosek, Wilkie, 2012



43

Volumetric Caustics

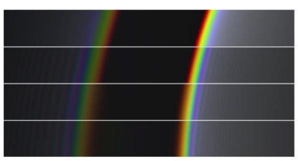
- "Efficient Simulation of Light Transport in Scenes with Participating Media using Photon Maps", Jensen, Christensen, 1998

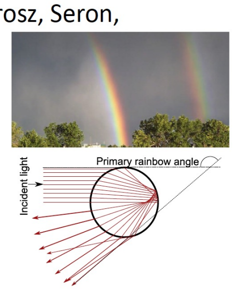


44

Rainbows

- "Physically Based Simulation of Rainbows", Sadeghi, Munoz, Laven, Jarosz, Seron, Gutierrez, Jensen, 2012





45

Atmospheric Phenomena

Corona

Ice Crystal Halo

Glory

46