Participating Media

Part I: participating media in general

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Outline

- Motivation
- Introduction
- Properties of participating media
- Rendering equation
- Storage strategies
- Non-interactive rendering strategies
- Interactive rendering strategies
- Atmospheric rendering
- Cloud rendering

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Motivation – fluids

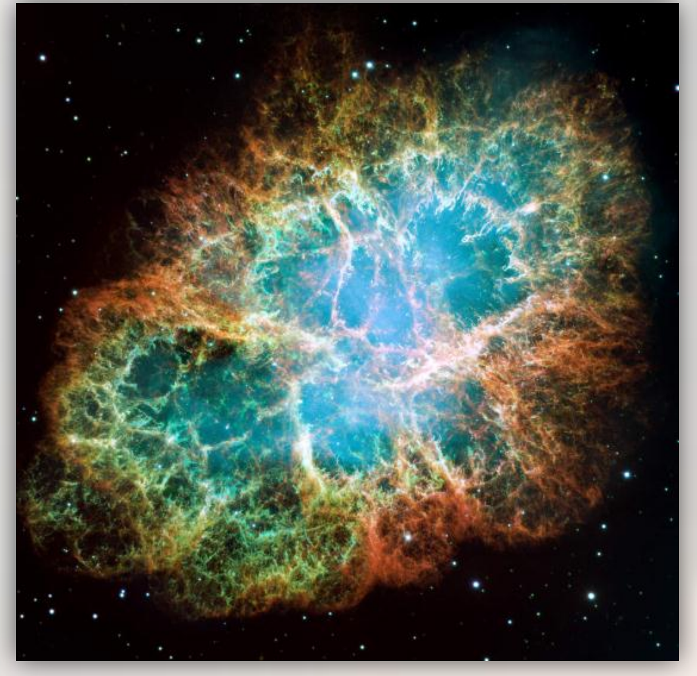


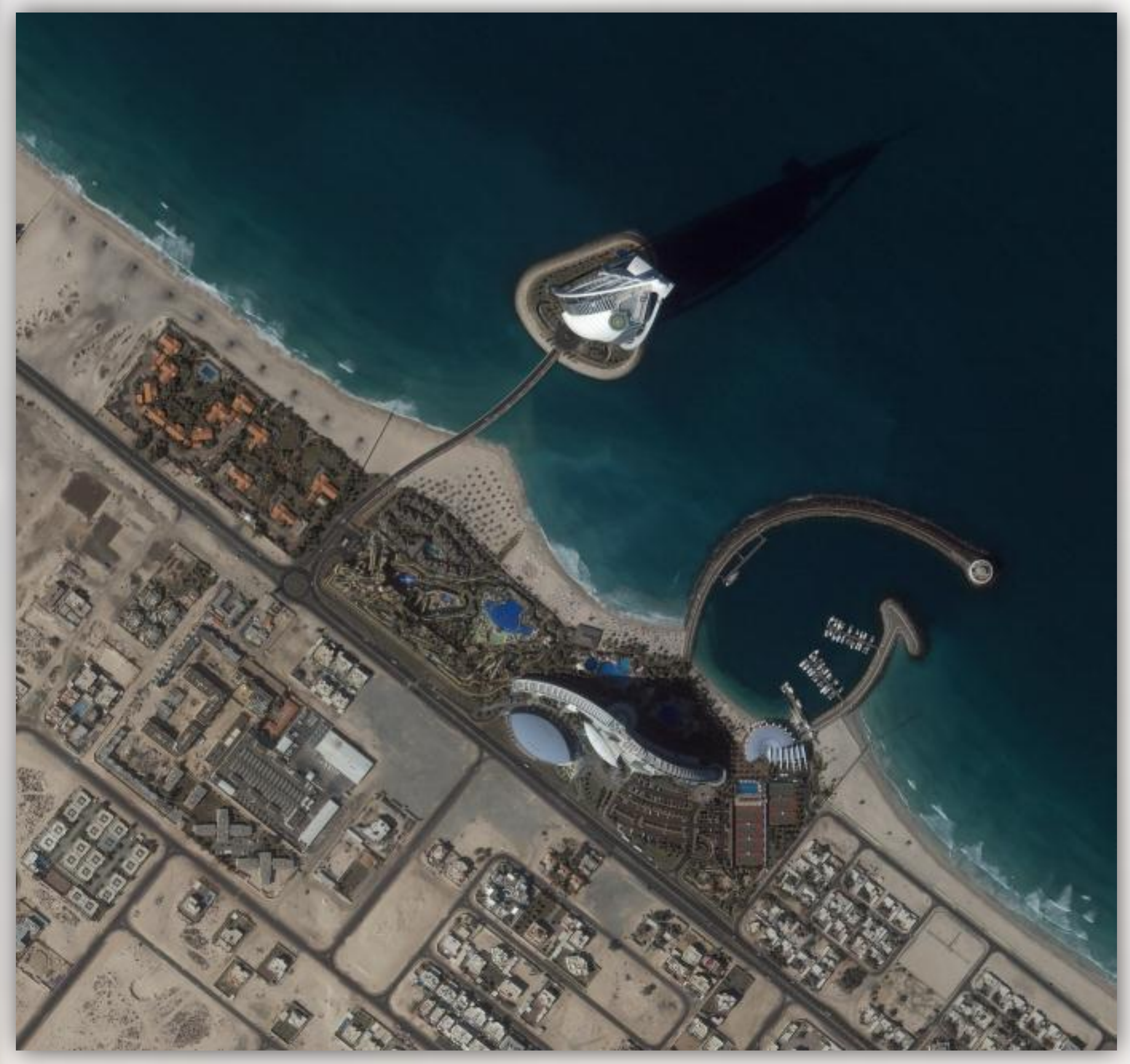

Motivation – solids






Motivation – beyond rendering





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  - CG connotation

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  - At lease 1 DoF more
  - Costly representation

Introduction

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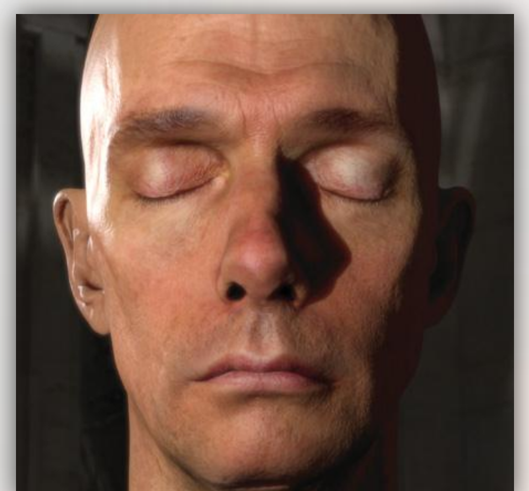
  - General meaning
  - CG connotation
- Why are PMa more challenging than B-rep rendering?
  - At lease 1 DoF more
  - Costly representation
- General scattering vs. sub-surface scattering (BSSRDF)



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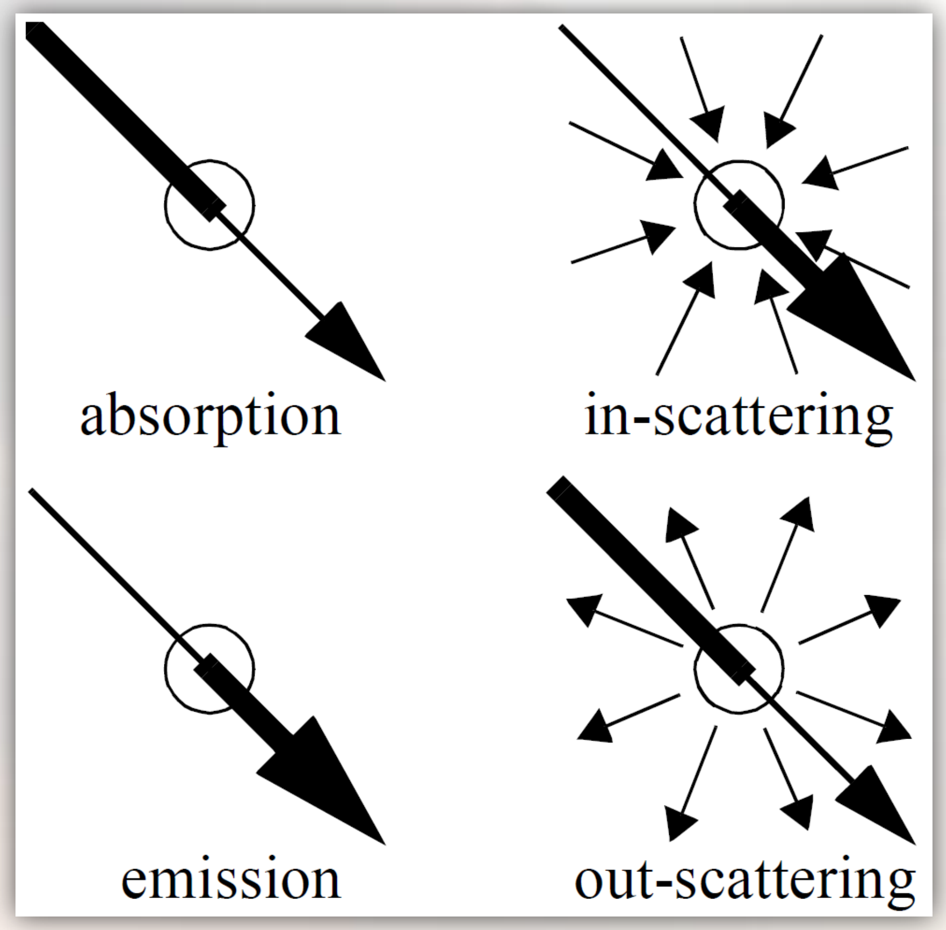
- 4 basic event types in PMa
  - Single vs. multiple scattering



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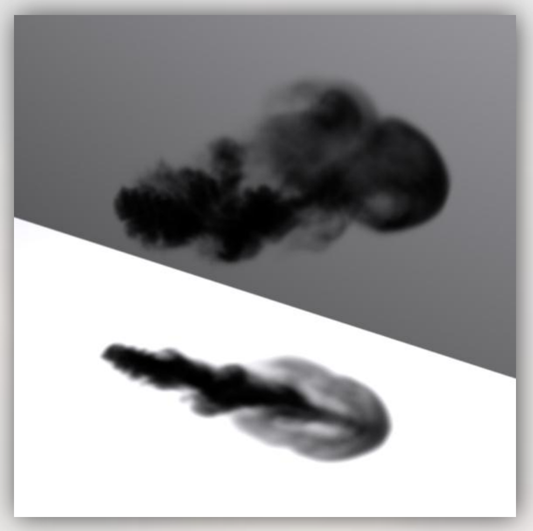

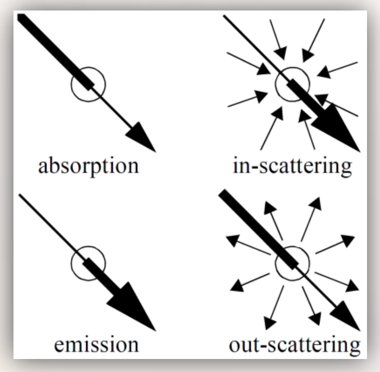

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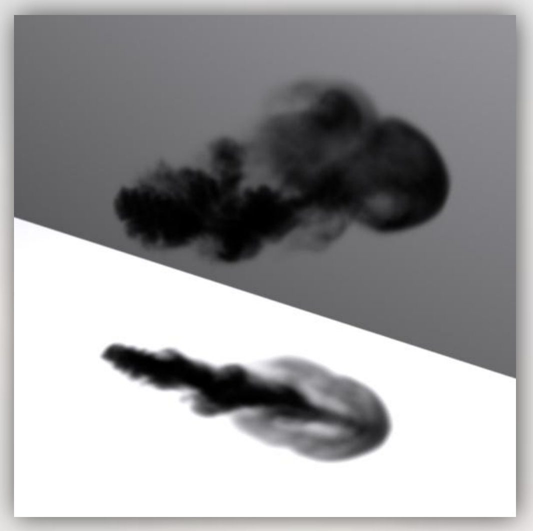

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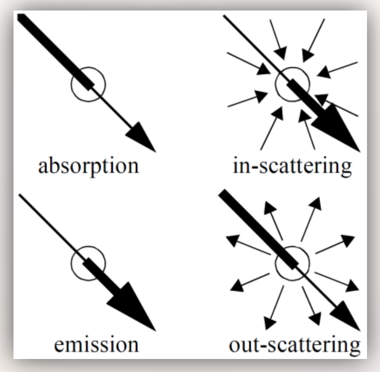

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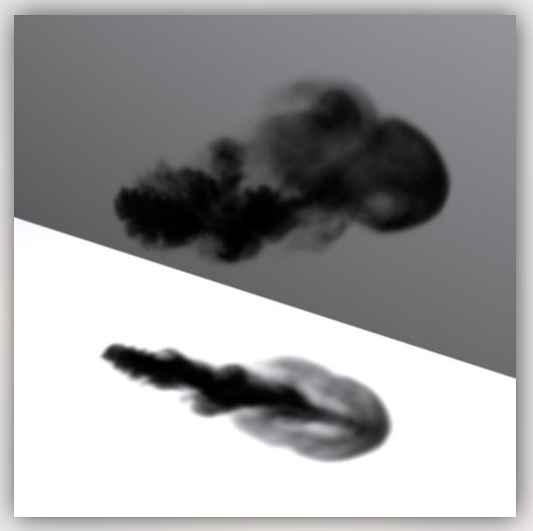

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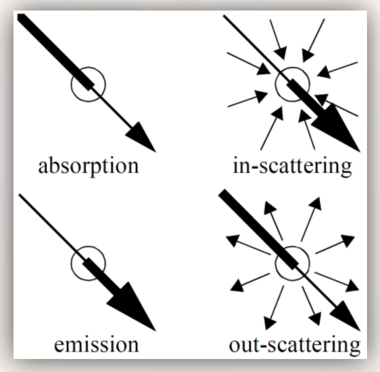

Properties – event types

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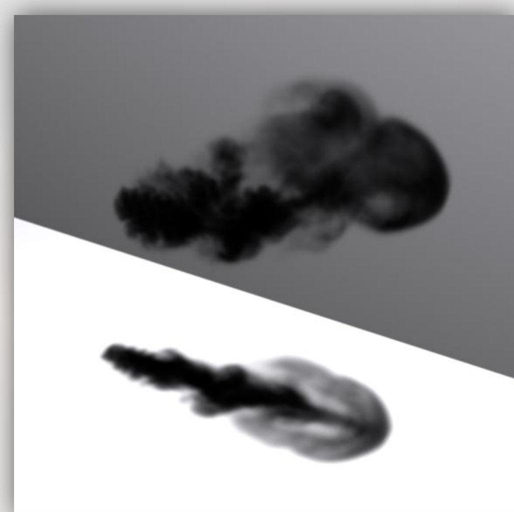

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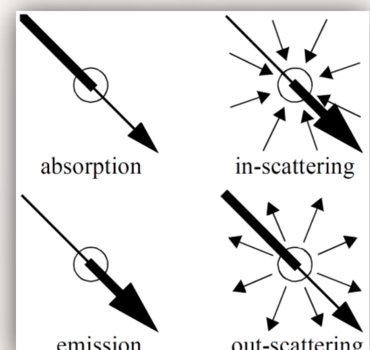

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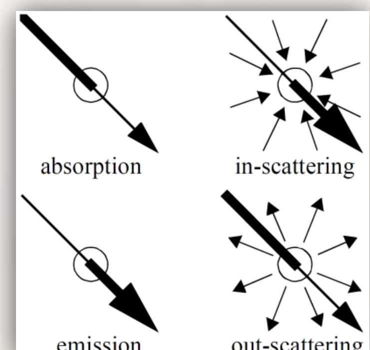
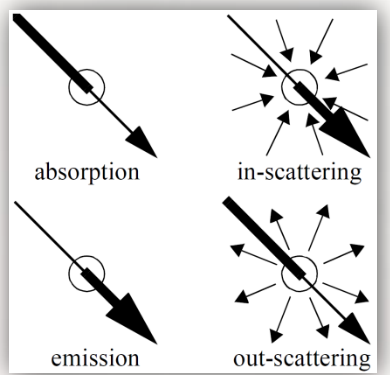
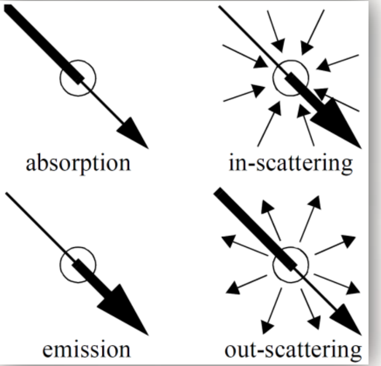


Properties – medium composition

- Main property – medium (particle) density



- Main property – medium (particle) density
- Derived characteristics:
  - σ_e – emission coefficient [m^{-1}]
  - σ_a – absorption coefficient [m^{-1}]
  - σ_s – scattering coefficient [m^{-1}]
  - σ_t – extinction coefficient ($\sigma_a + \sigma_s$)
  - $e^{-\sigma}$ dependency ($\sigma = 2 \approx 13.6\%$ transmittance)



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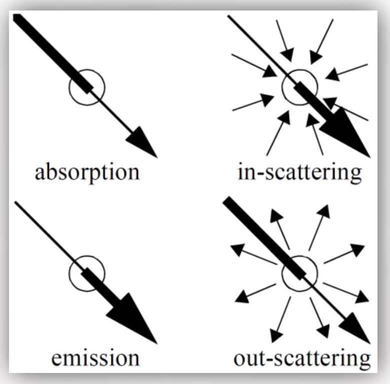
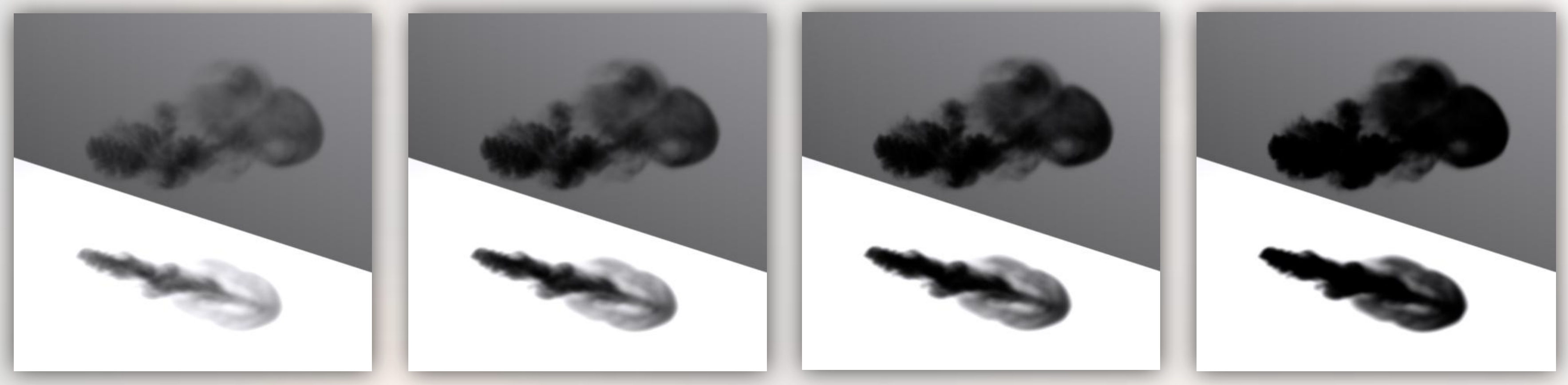


$\sigma_a=5$ $\sigma_a=10$ $\sigma_a=15$ $\sigma_a=30$



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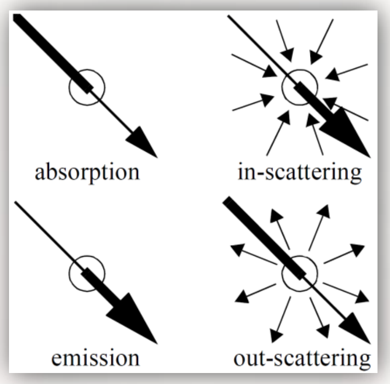

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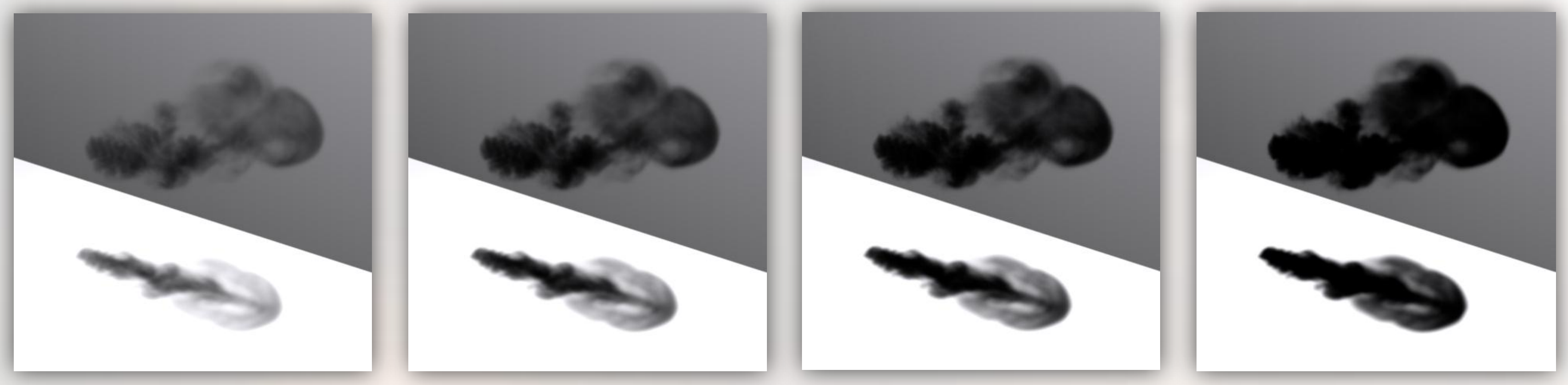
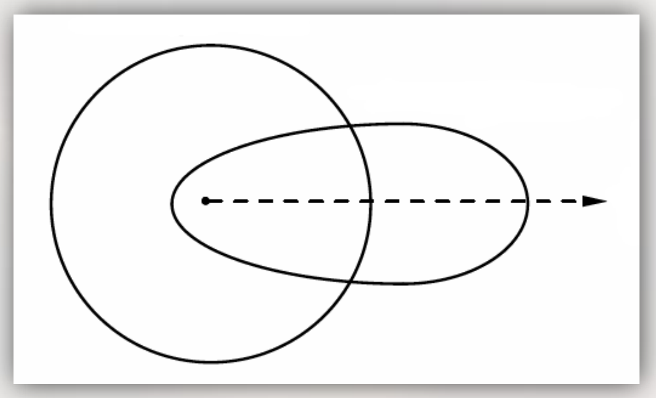
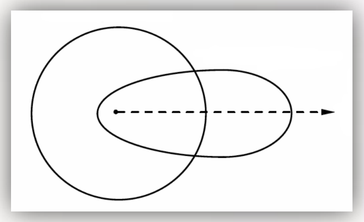


- More particle types → linear combination of coefficients

- Phase function
  - Describes directional distribution of scattered light
  - Equivalent of BRDF for surfaces (probability density)
  - Denotes scattering anisotropy (equivalent of diffuse vs. glossy surfaces)





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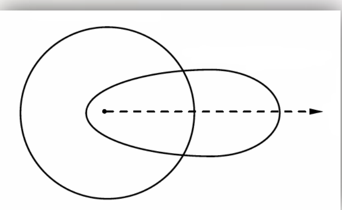
- We recognize Rayleigh and Mie (light) scattering

Uniform:

$$p_{\mathrm{uni}}(\theta) = \frac{1}{4\pi}$$



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Uniform:

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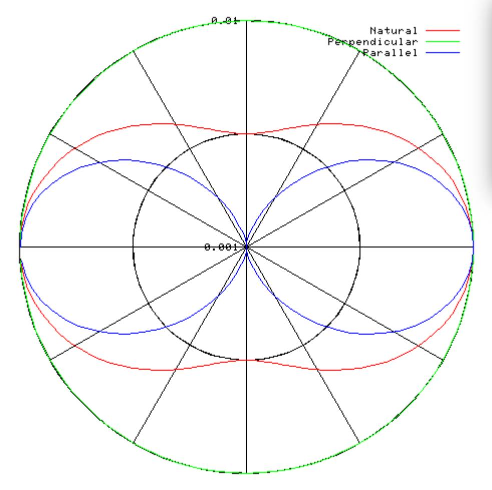
Rayleigh (λ^{-4}-dependent):

$$p_{\mathrm{ray}}(\theta) = \frac{3}{4}(1 + \cos^2(\theta))$$



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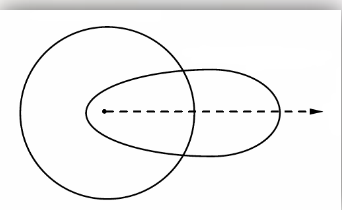

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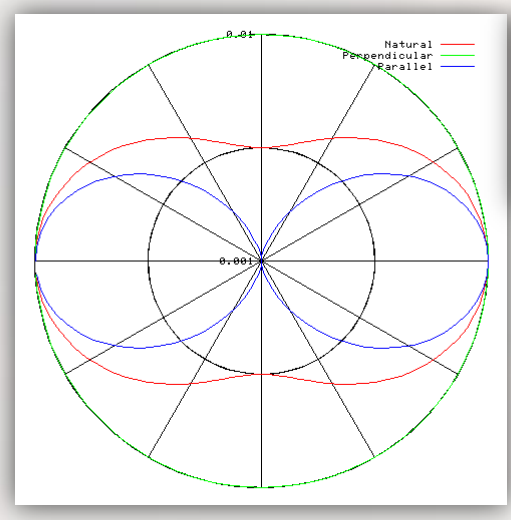

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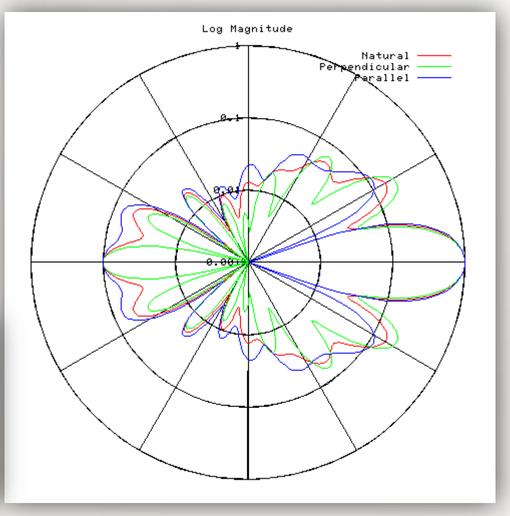

Mie (Henyey-Greenstein approximation):

$$p_{\text{hg}}(\theta, g) = \frac{1}{4\pi} \frac{1-g^2}{(1+g^2-2g\cos(\theta))^{3/2}}$$

- Albedo – efficiency of a single scattering event
  - Defined as: 100 * σ_s / (σ_a + σ_s) [%]
  - Mean number of scattering events depends on it

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Strongly homogeneous

Strongly inhomogeneous

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- Medium anisotropy (sundogs, parhelia)

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- Shape complexity

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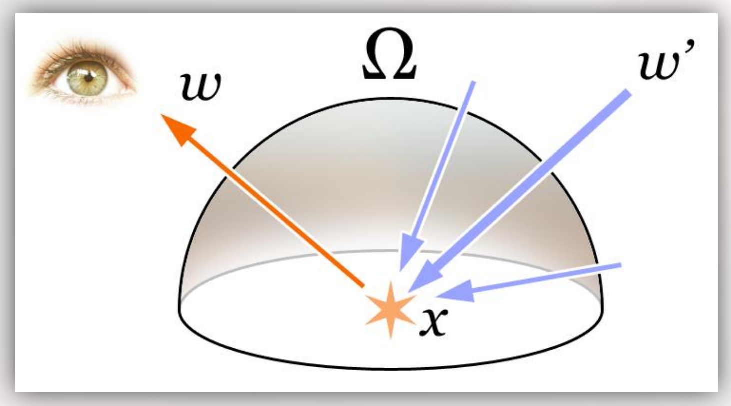
- Standard (areal) RE

$$L_o(x,\vec{\omega}) = L_e(x,\vec{\omega}) + \int_{2\pi} f_r(x,\vec{\omega}',\vec{\omega}) L_i(x,\vec{\omega}')(-\vec{\omega}'\cdot\vec{n})d\vec{\omega}'$$



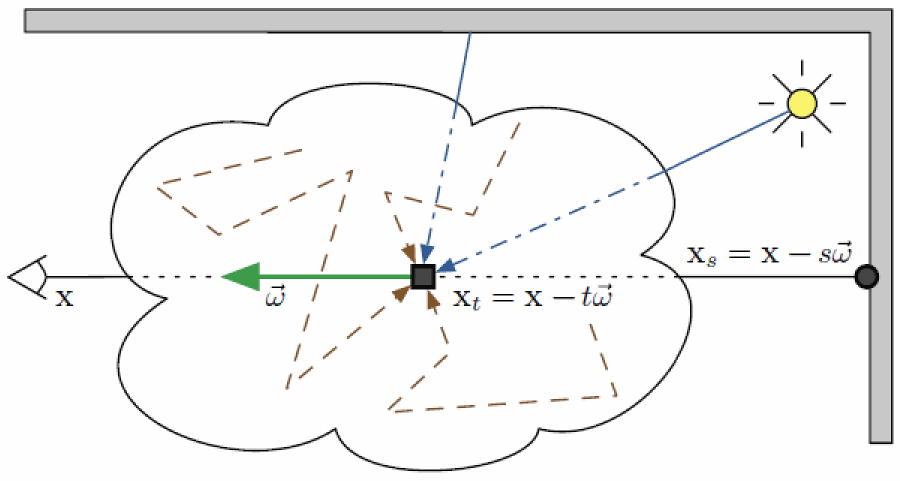
Volume rendering equation

- Standard (areal) RE

$$L_o(x,\vec{\omega}) = L_e(x,\vec{\omega}) + \int_{2\pi} f_r(x,\vec{\omega}',\vec{\omega}) L_i(x,\vec{\omega}')(-\vec{\omega}'\cdot\vec{n})d\vec{\omega}'$$

- Volume RE, directional formulation

$$L(x,\vec{\omega}) = \int_0^s T_r(x \leftrightarrow x_t)\sigma_s(x_t)L_i(x_t,\vec{\omega})dt + T_r(x \leftrightarrow x_s)L(x_s,\vec{\omega})$$



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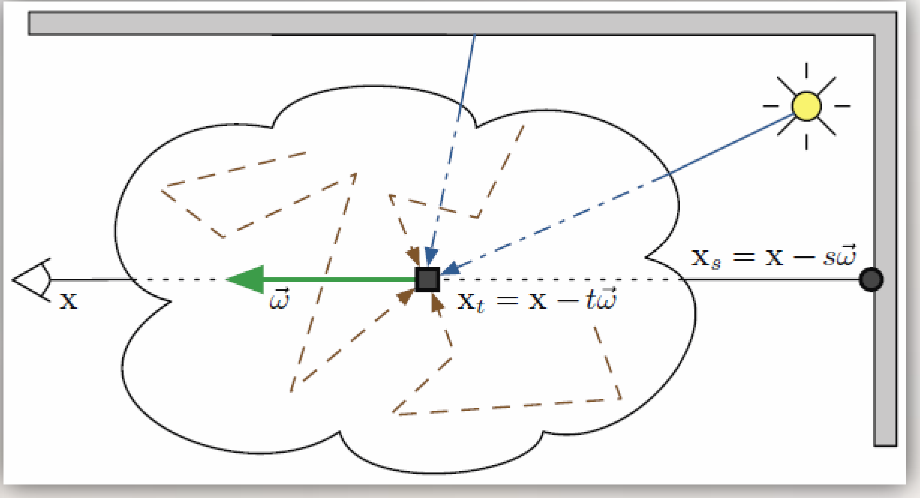
$$L_i(x,\vec{\omega}) = \int_{4\pi} p(x,\vec{\omega}',\vec{\omega})L(x,\vec{\omega}')d\vec{\omega}'$$

$$\tau(x \leftrightarrow x') = \int_x^{x'} \sigma_t(u)du$$

$$T_r(x \leftrightarrow x') = e^{-\tau(x \leftrightarrow x')}$$

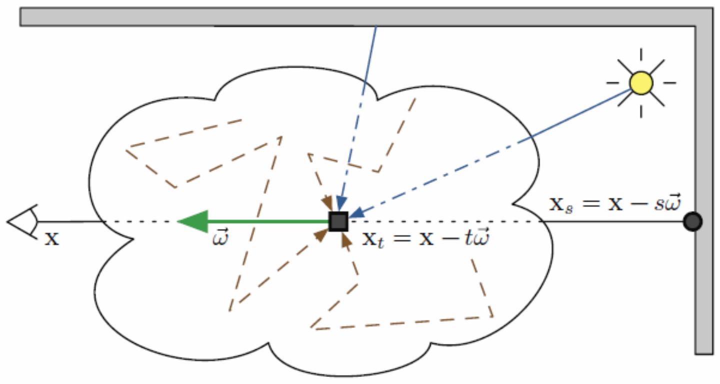


- Standard (areal) RE
- Volume RE, directional formulation

$$L(x,\vec{\omega}) = \int_0^s T_r(x \leftrightarrow x_t)\sigma_s(x_t)L_i(x_t,\vec{\omega})dt + T_r(x \leftrightarrow x_s)L(x_s,\vec{\omega})$$

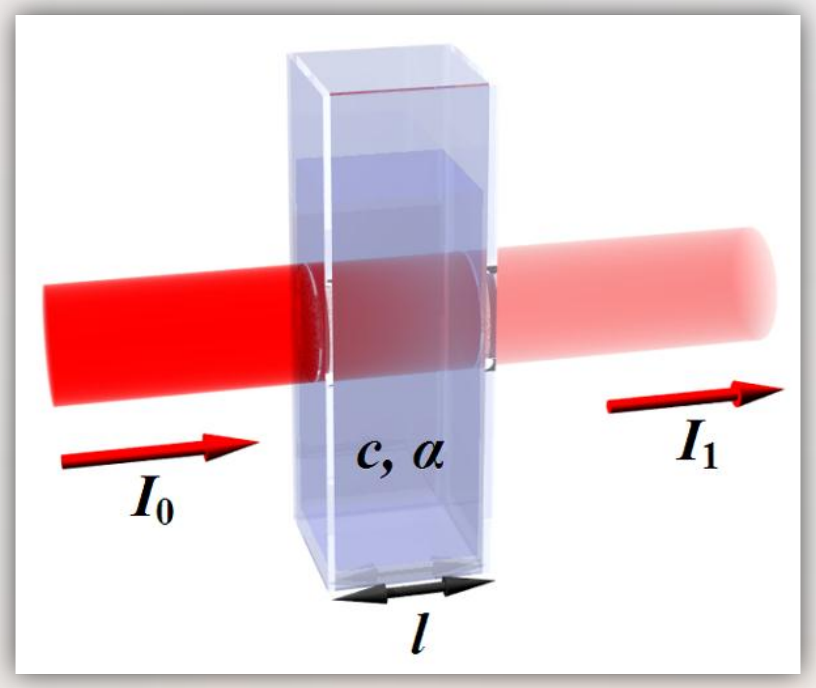
- Volume RE, differential formulation (energy transport equation)

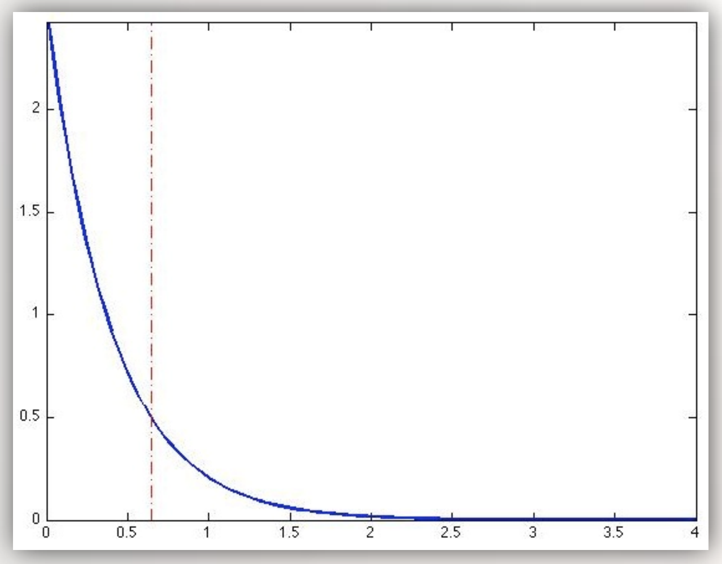
$$\frac{dL(x,\vec{\omega})}{dx} = -\sigma_t L(x,\vec{\omega}) + \sigma_a L_e(x,\vec{\omega}) + \sigma_s \int_{4\pi} L(x,\vec{\omega}')p(x,\vec{\omega}',\vec{\omega})d\vec{\omega}'$$



- Defines relation of medium composition to its light attenuating properties

$$T_r = e^{-\sigma_t l}$$





Beer-Lambert-Bouguer law

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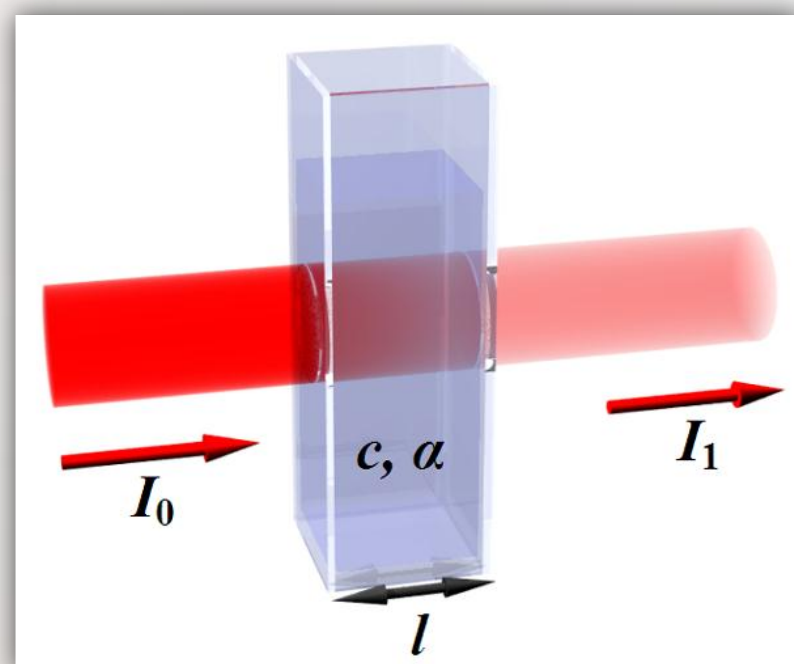

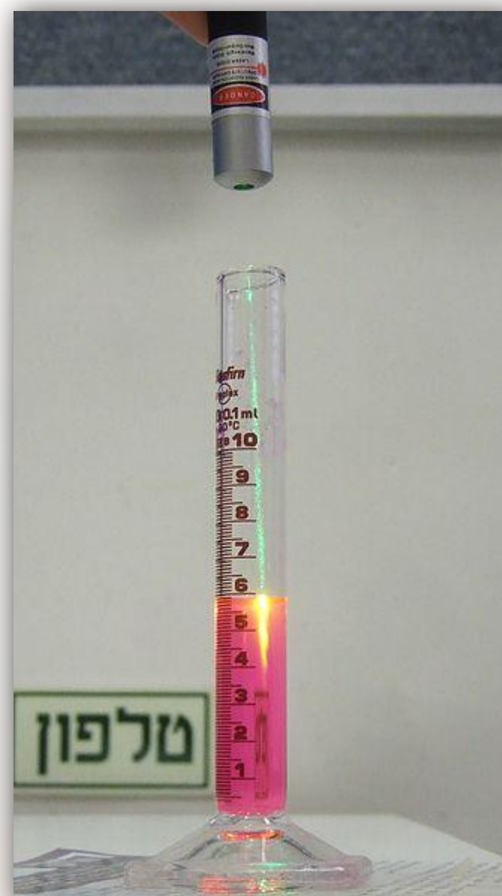

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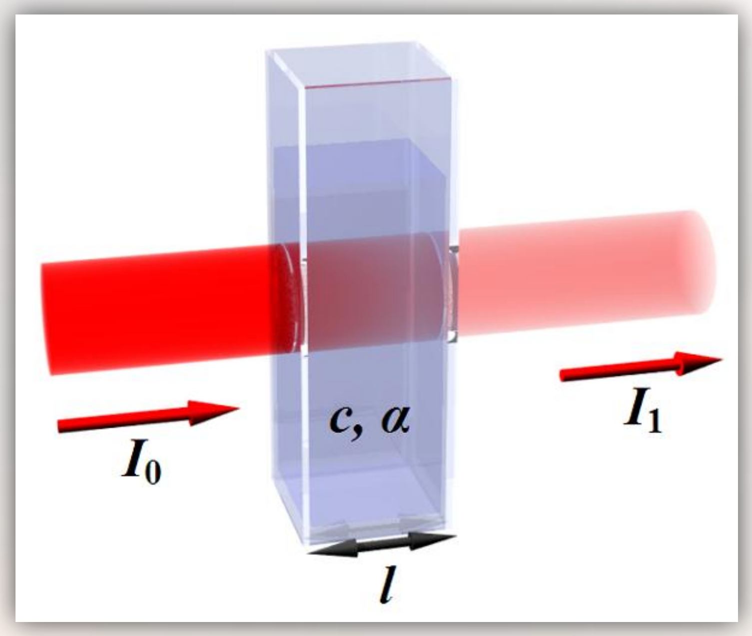
$$T_r = e^{-\sigma_t l} \qquad dI_x = -\sigma_t I_x dx$$



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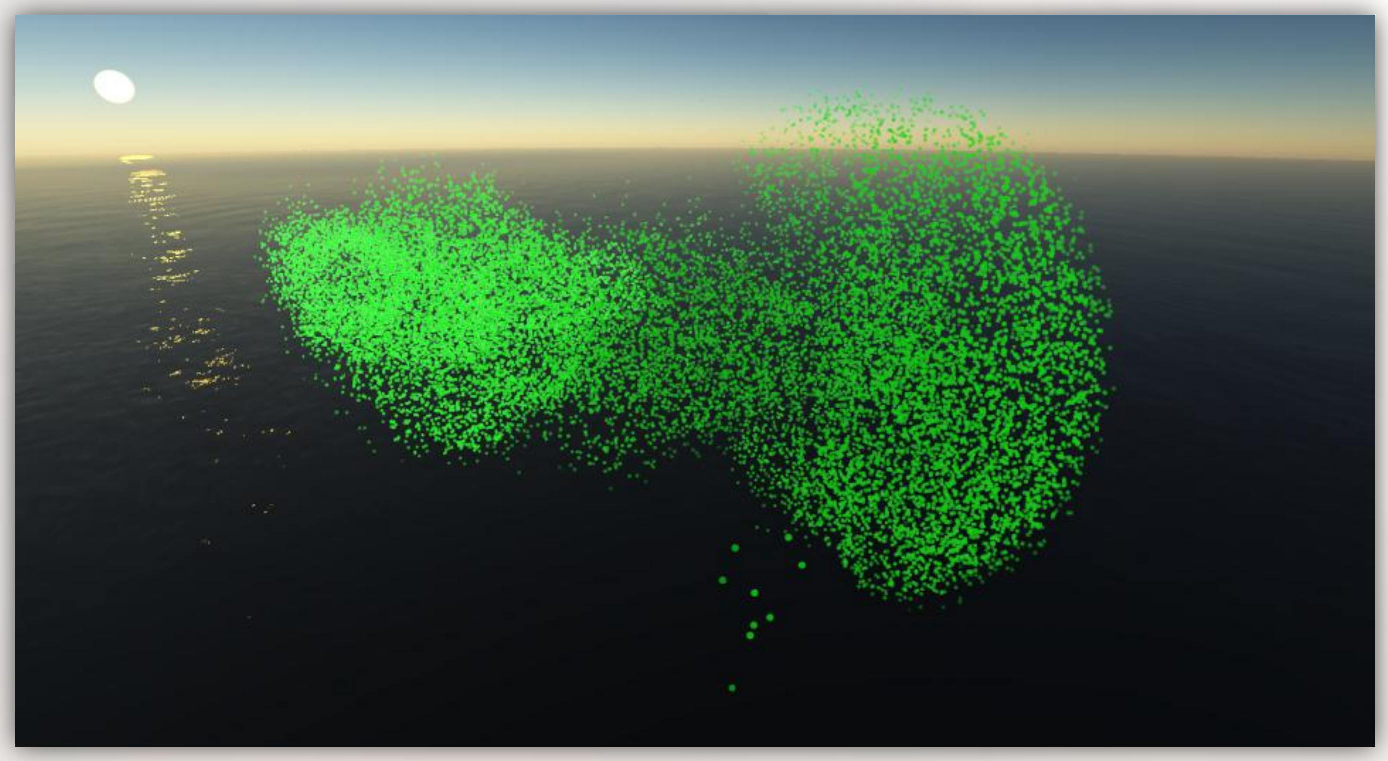
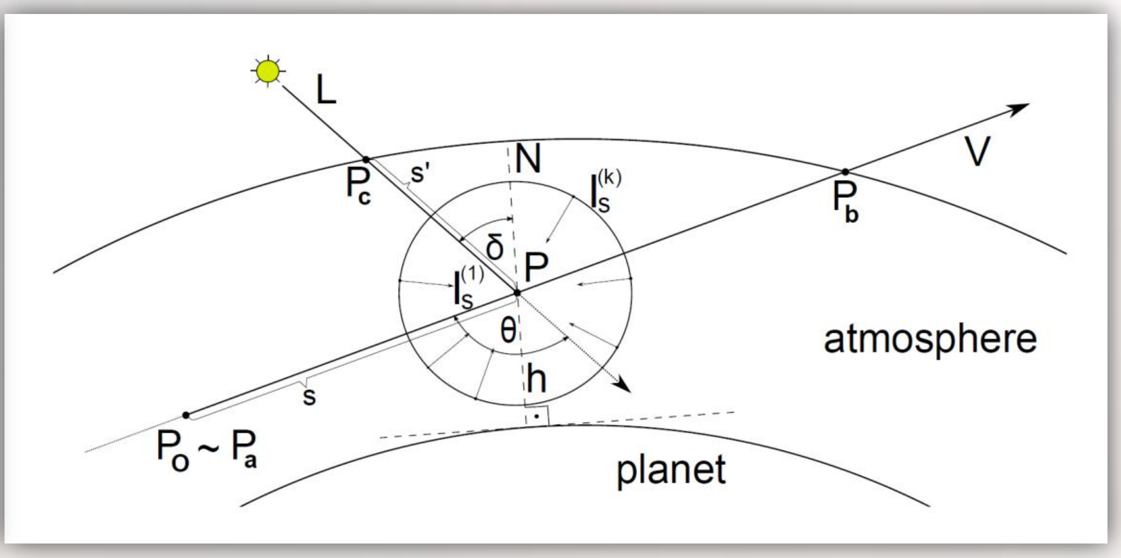
- 3D density grids
  - Pros: accuracy, easy detail representation, fast evaluation
  - Cons: large storage space needed (esp. animations), difficult manipulation (editing), HDR media problems



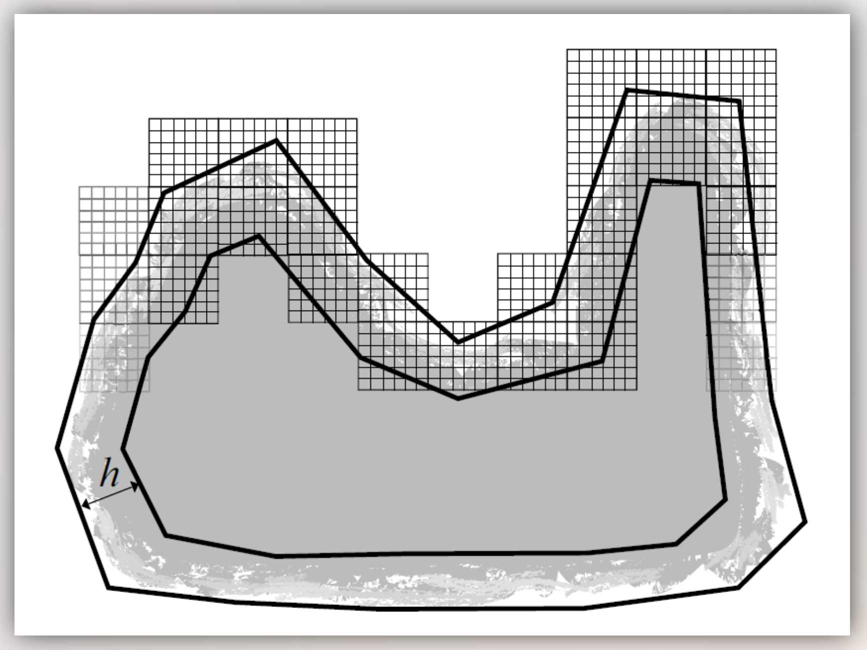
- 3D density grids
- Point sets
  - Pros: adaptive, plausible storage space requirements, easier manipulation (editing), 1:1 particle simulation correspondence
  - Cons: slower evaluation, less obvious interpolation scheme



- 3D density grids
- Point sets
- Analytically defined
  - Pros: no storage space required, (usually) very fast evaluation, allow precomputation (if low DoF), instant medium properties changes
  - Cons: limited to simple shapes/situations



- 3D density grids
- Point sets
- Analytically defined
- Combined
    - Pros: possible good detail/storage space ratio
    - Cons: more complicated manipulation



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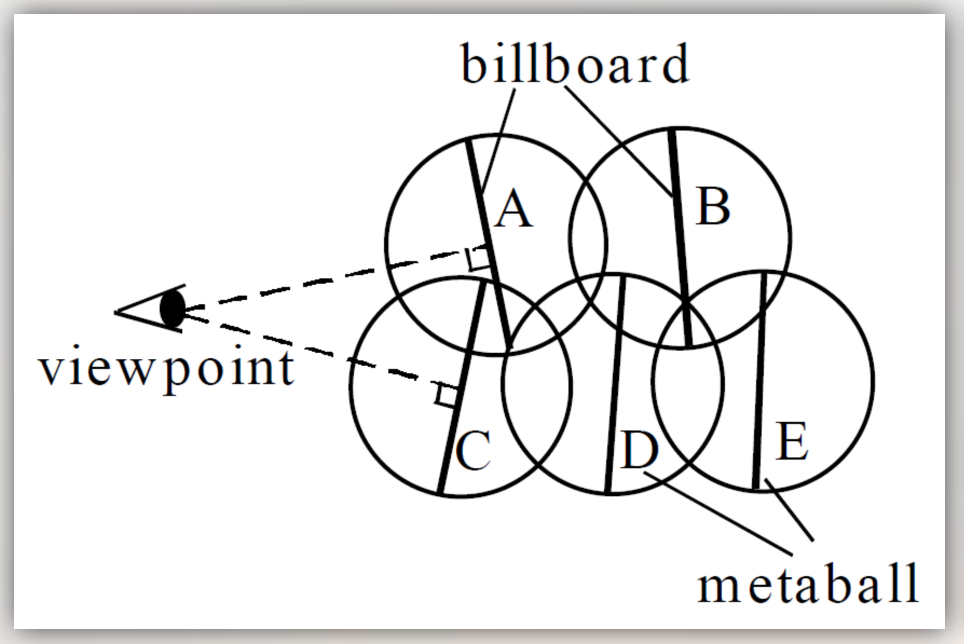

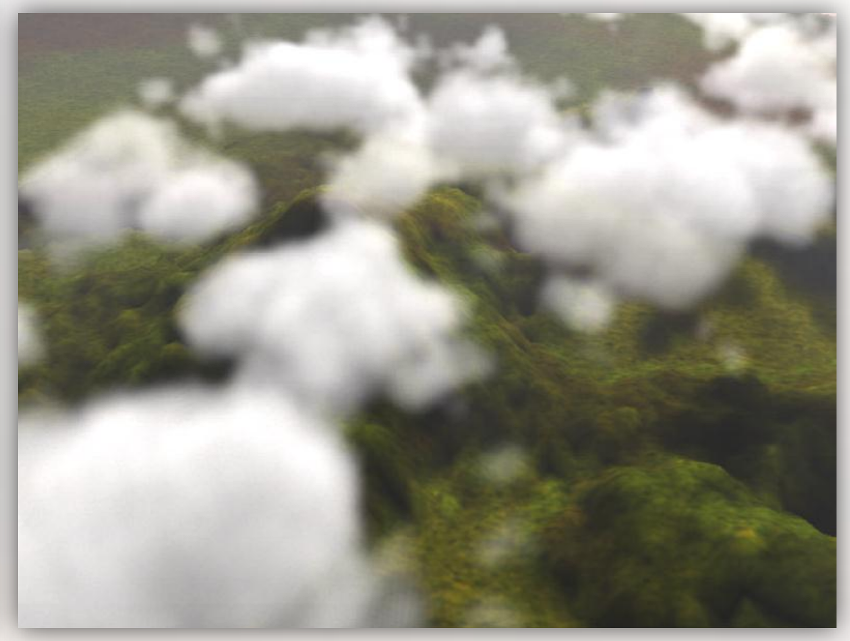

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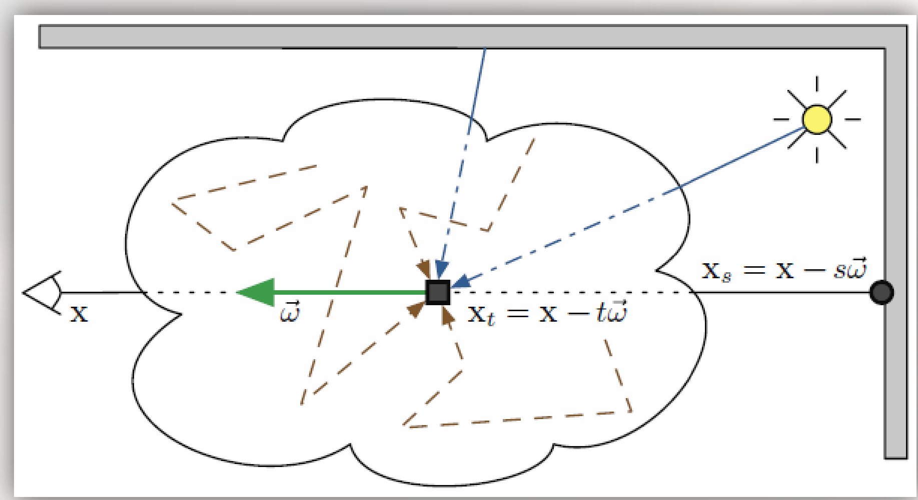
- Similar to areal PT, solves directional VRE by generating random walks in the medium

$$L(x,\vec{\omega}) = \int_0^s T_r(x \leftrightarrow x_t)\sigma_s(x_t)L_i(x_t,\vec{\omega})dt + T_r(x \leftrightarrow x_s)L(x_s,\vec{\omega})$$



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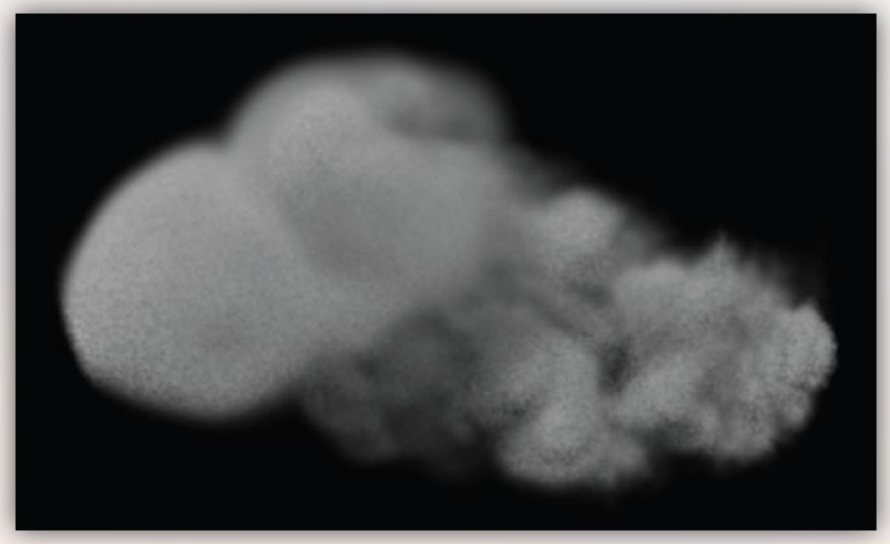
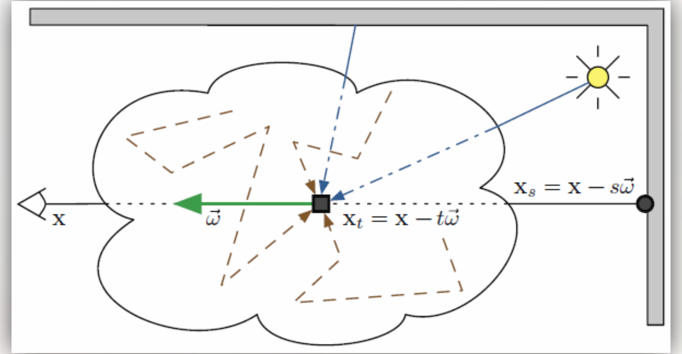
- Evaluation
  - Pros: simplicity, not limited to any PMa range, unbiasedness
  - Cons: speed (in certain cases almost pathological), high variance

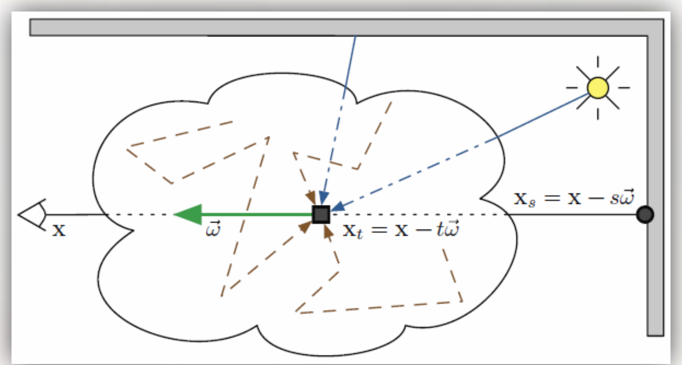


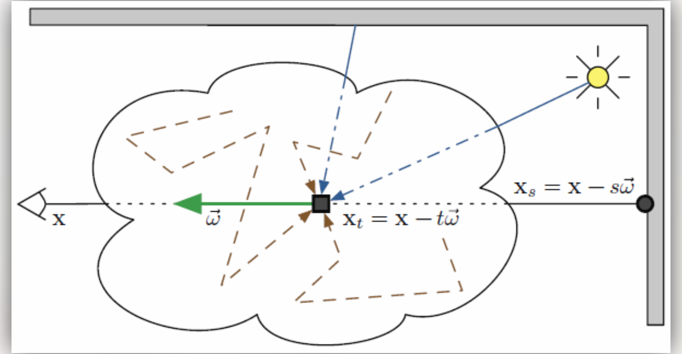
- Choose randomly
  - Pros: unbiasedness
  - Cons: awful efficiency



- Choose randomly
- Taking into account extinction

$$\int_0^{d_{next}} \sigma_t(s)\, ds = -\ln(1-\xi)$$





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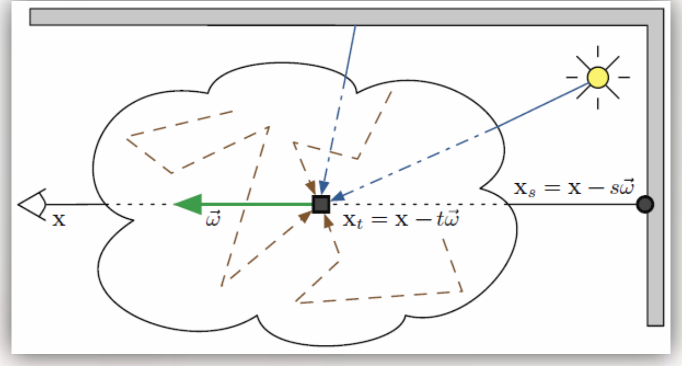
  - Ray marching
    - Pros: simplicity
    - Cons: low efficiency, biasedness



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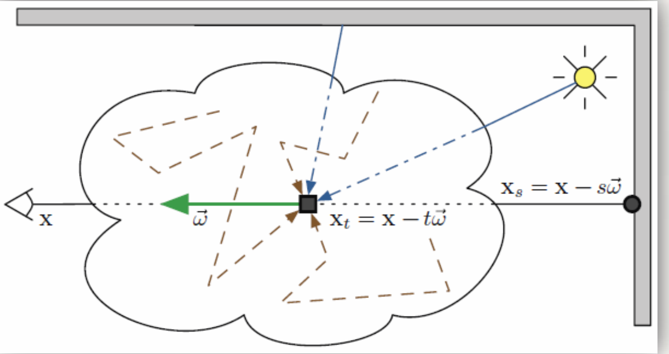
  - Woodcock tracking
    - Increment *x* by $-\ln(1-\xi_1)/\sigma_{s_M}$ until $\sigma_s(x)/\sigma_{s_M} < \xi_2$

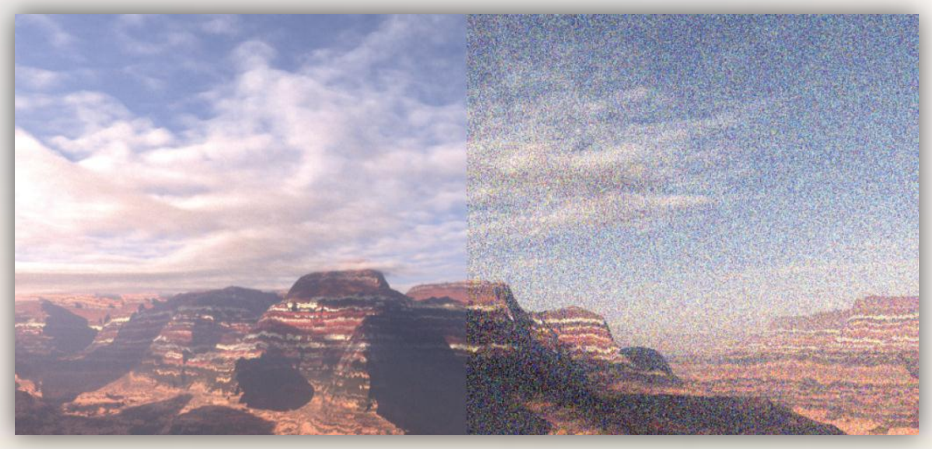
Rendering strategies – event location generation



- Choose randomly
- Taking into account extinction

$$\int_0^{d_{next}} \sigma_t(s)\, ds = -\ln(1-\xi)$$

  - Ray marching
  - Woodcock tracking
    - Increment *x* by $-\ln(1-\xi_1)/\sigma_{s_M}$ until $\sigma_s(x)/\sigma_{s_M} < \xi_2$
    - Pros: fast (using adaptive kD-tree scheme), unbiasedness
    - Cons: slightly more complicated



- Similar to areal radiosity, solves energy transport equation

$$\frac{dL(x,\vec{\omega})}{dx} = -\sigma_t L(x,\vec{\omega}) + \sigma_a L_e(x,\vec{\omega}) + \sigma_s \int_{4\pi} L(x,\vec{\omega}')p(x,\vec{\omega}',\vec{\omega})d\vec{\omega}'$$

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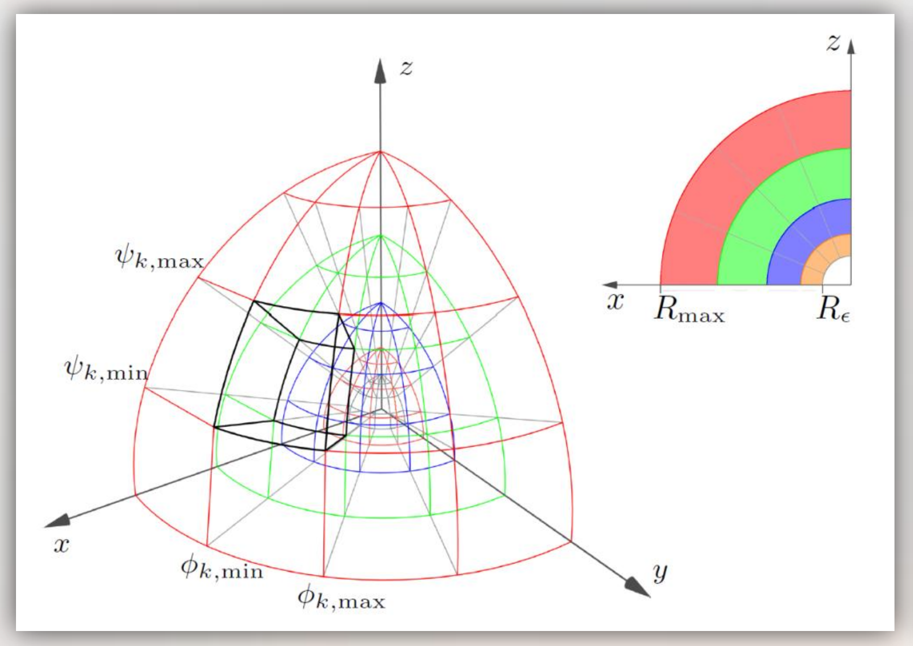
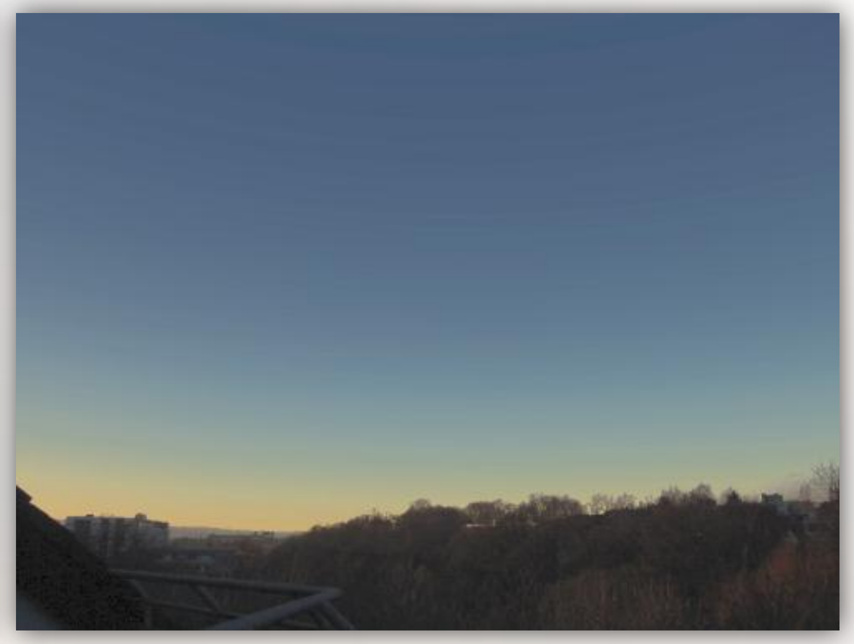
  - Pros: (theoretically) unbiased, linear scaling with number of scattering orders, computes energy state of the entire scene
  - Cons: rather slow, high storage requirements, problems with inhomogeneous media and additional objects in scene





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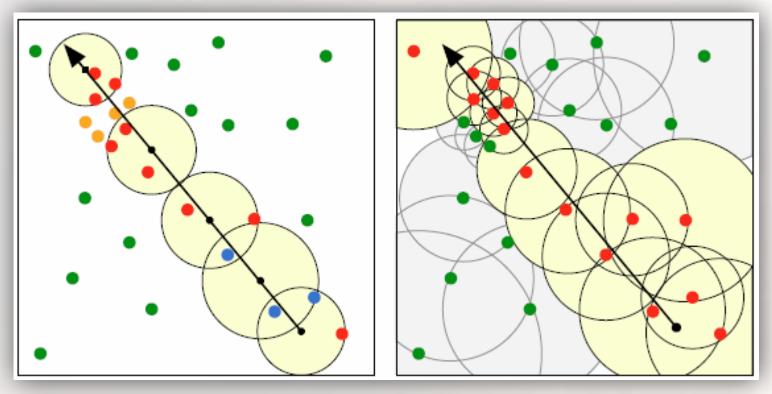
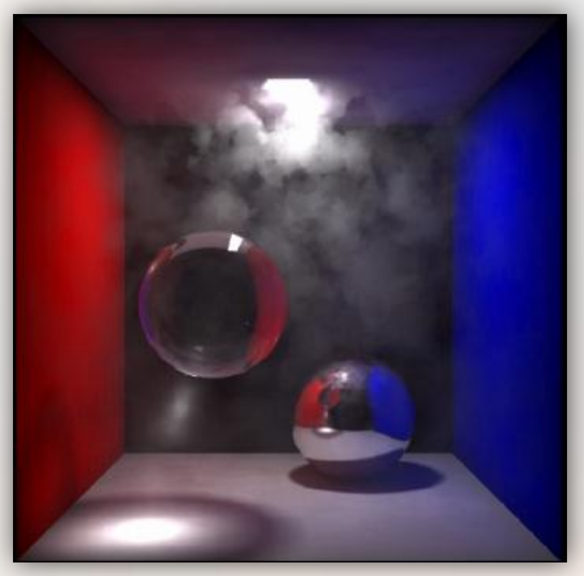


- Once again, similar to areal PM
  - Generates random walks in the medium, stores photon on each scattering event
  - Gathering more complicated → beam radiance estimate
- Evaluation – widely used
  - Pros: fast, easy extension from B-rep renderers, robust
  - Cons: biasedness, necessary storage of photons




End (part I)