Realistic Cloud Rendering Using Pixel Synchronization

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Introduction

Clouds are integral part of outdoor scenes

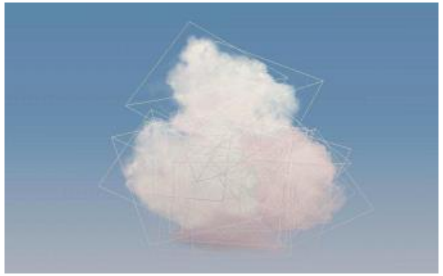
Rendering good-looking *and* fast clouds is challenging

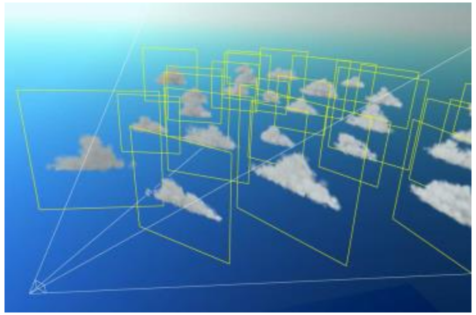
Different approaches to the problem exist

- Billboards
- Ray-marching
- Direct volume rendering (slicing)

Existing methods - Particles

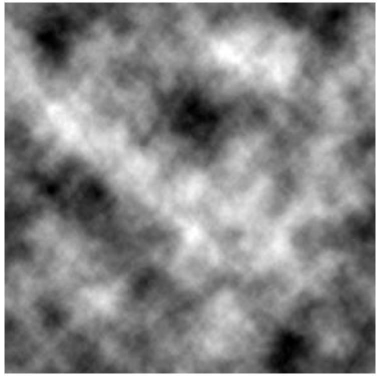
- Represents the clouds as collection of camera-facing polygons (quads)
  - Can combine simple shapes (radial fall-of textures) as well as more complex objects
  - (+) Gives good control over clouds shape and location
  - (-) Billboards are flat
  - (-) Lighting is usually precomputed, clouds are static
- Impostors are related concept
  - Pre-renders clouds into camera-facing billboards





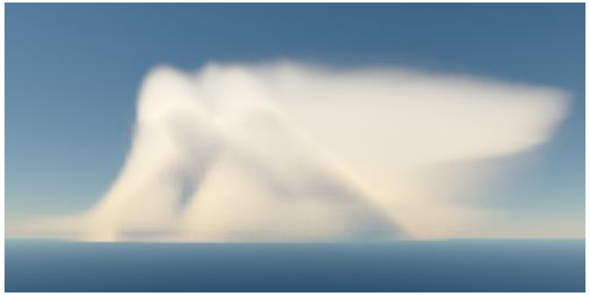
Existing methods – Ray Marching

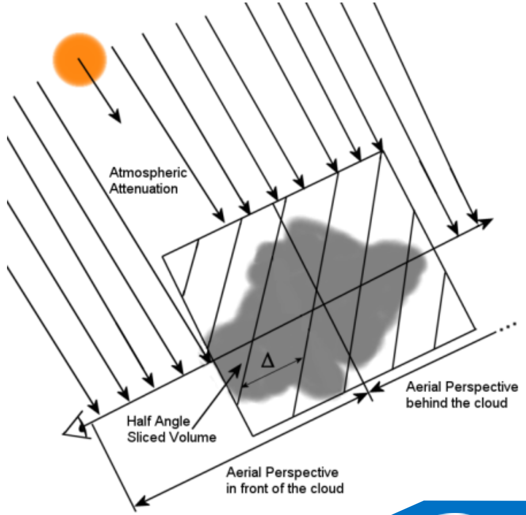
- The cloud density is represented as 3D noise
- Ray marching is performed through the volume to accumulate lighting
  - (+) Good looking result
  - (-) Control over cloud shape and location is intricate
  - (-) Many ray marching steps can be required to eliminate aliasing
  - (-) Lighting usually limited to single scattering



Existing methods – Direct Volume Rendering

- Direct volume rendering methods can be applied to render clouds
- The volume is sliced with planes; the planes are alpha-blended to get final result
- Half-angle slicing can account for occlusion by light at the same time as rendering from the camera
  - (+) Lighting can be rather sophisticated (multiple forward scattering)
  - (-) Control over cloud shape and location is intricate
  - (-) Many slicing planes can be required to eliminate aliasing



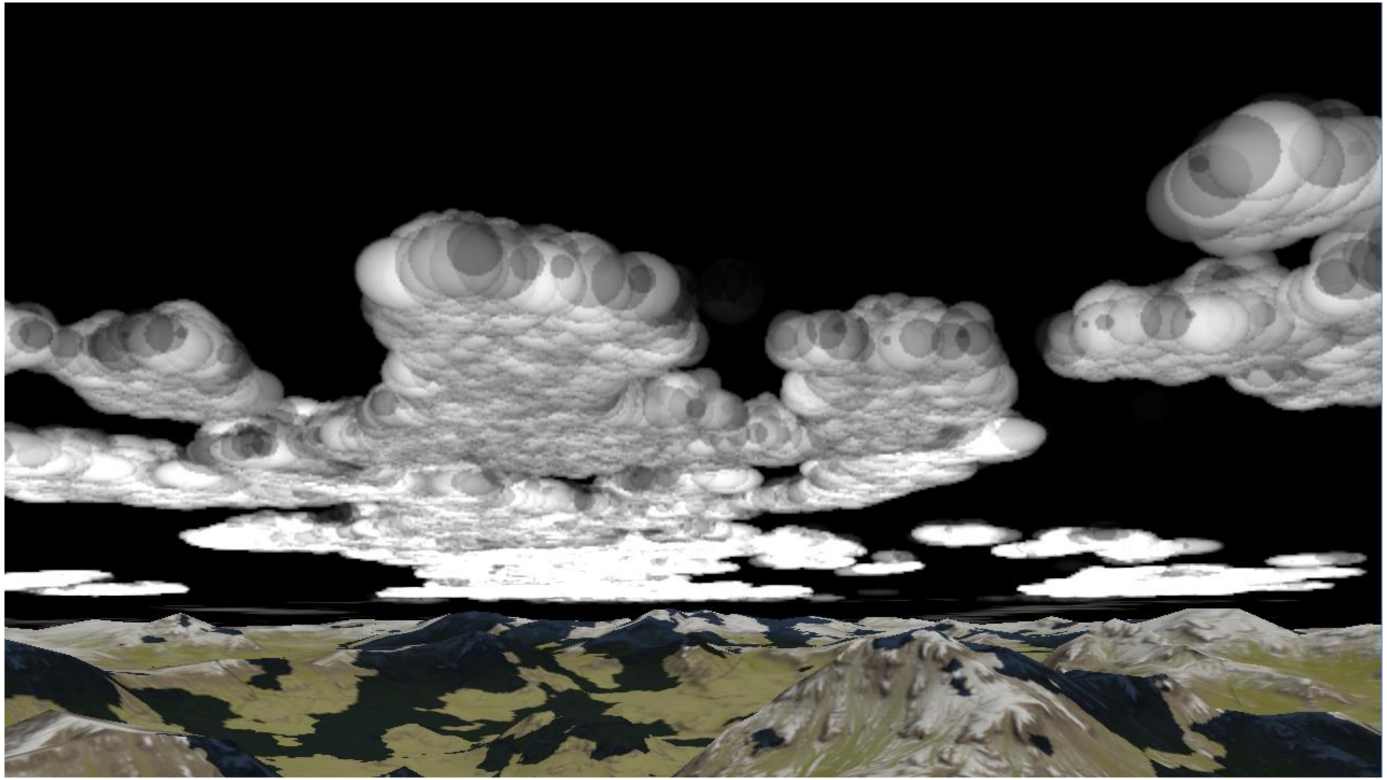

Atmospheric Attenuation
Δ
Half Angle Sliced Volume
Aerial Perspective behind the cloud
Aerial Perspective in front of the cloud

Our method

- Attempts to combine control of particle-based approaches with quality of ray marching and slicing techniques
- Key ideas:
  - Use volumetric particles representing the actual 3D-shapes
  - Use physically-based lighting
  - Pre-compute lighting and other quantities to avoid expensive computations at run time
  - Perform volume-aware blending instead of alpha blending

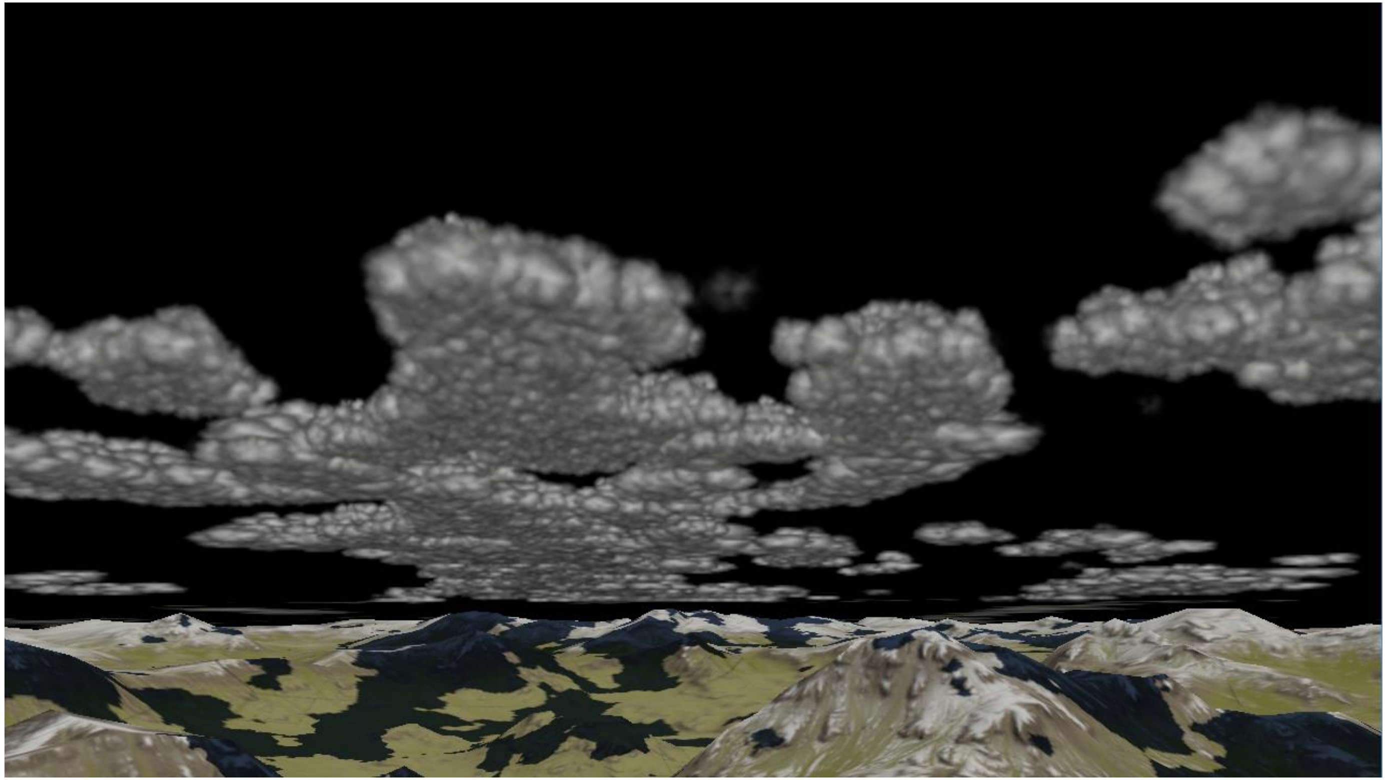
Algorithm overview

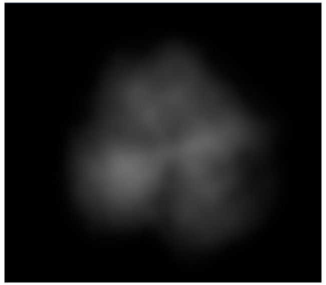
Initial step – modeling clouds with spherical particles



Algorithm overview

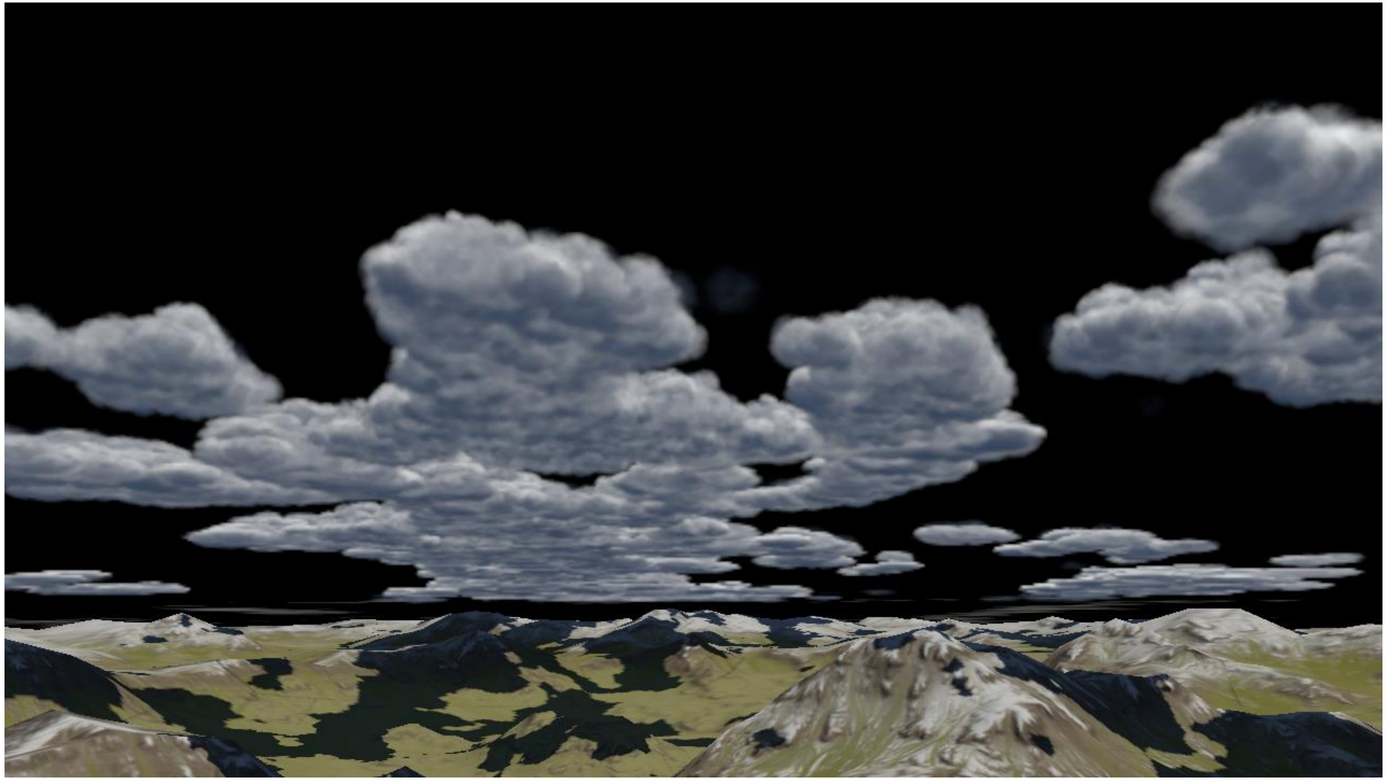
Add pre-computed cloud density and transparency

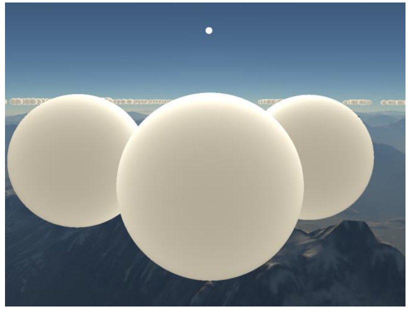




Algorithm overview

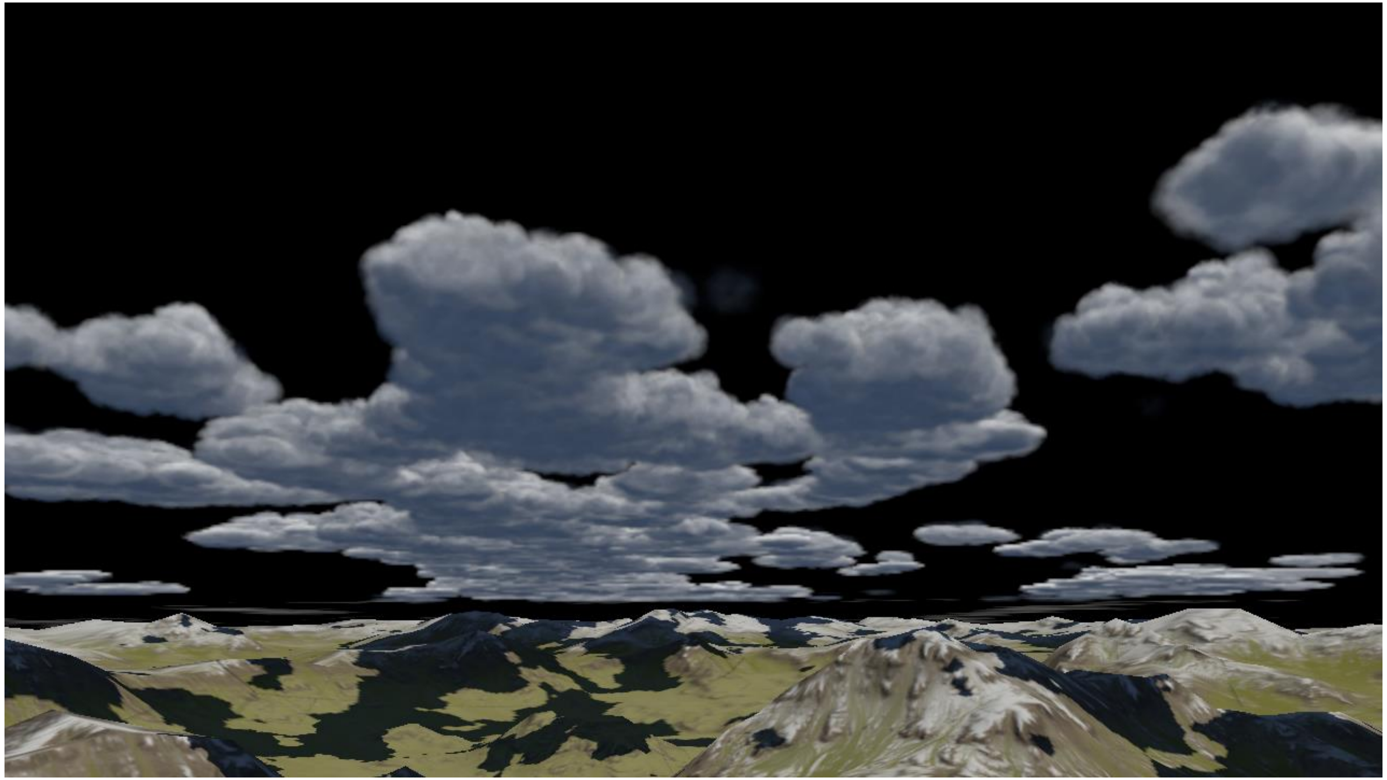
Add pre-computed light scattering





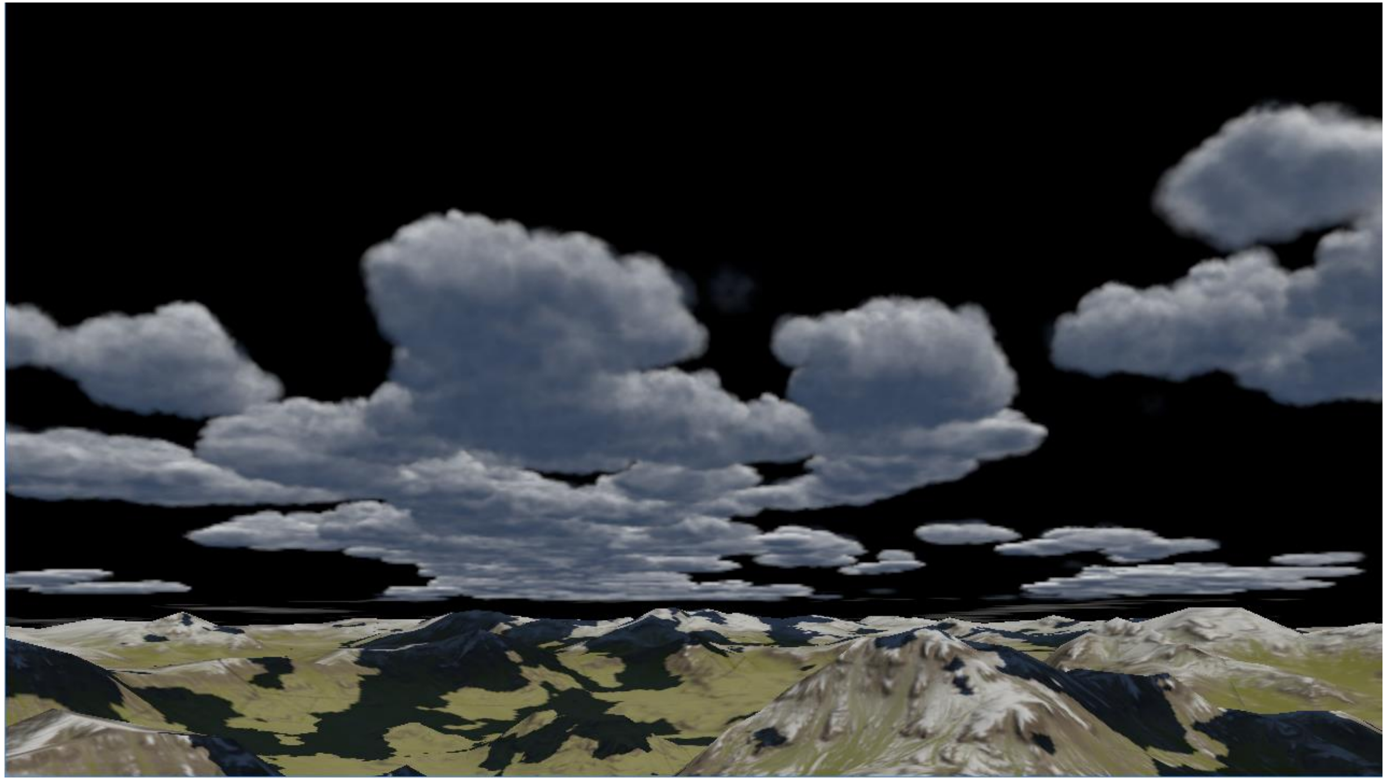
Algorithm overview

Add light occlusion



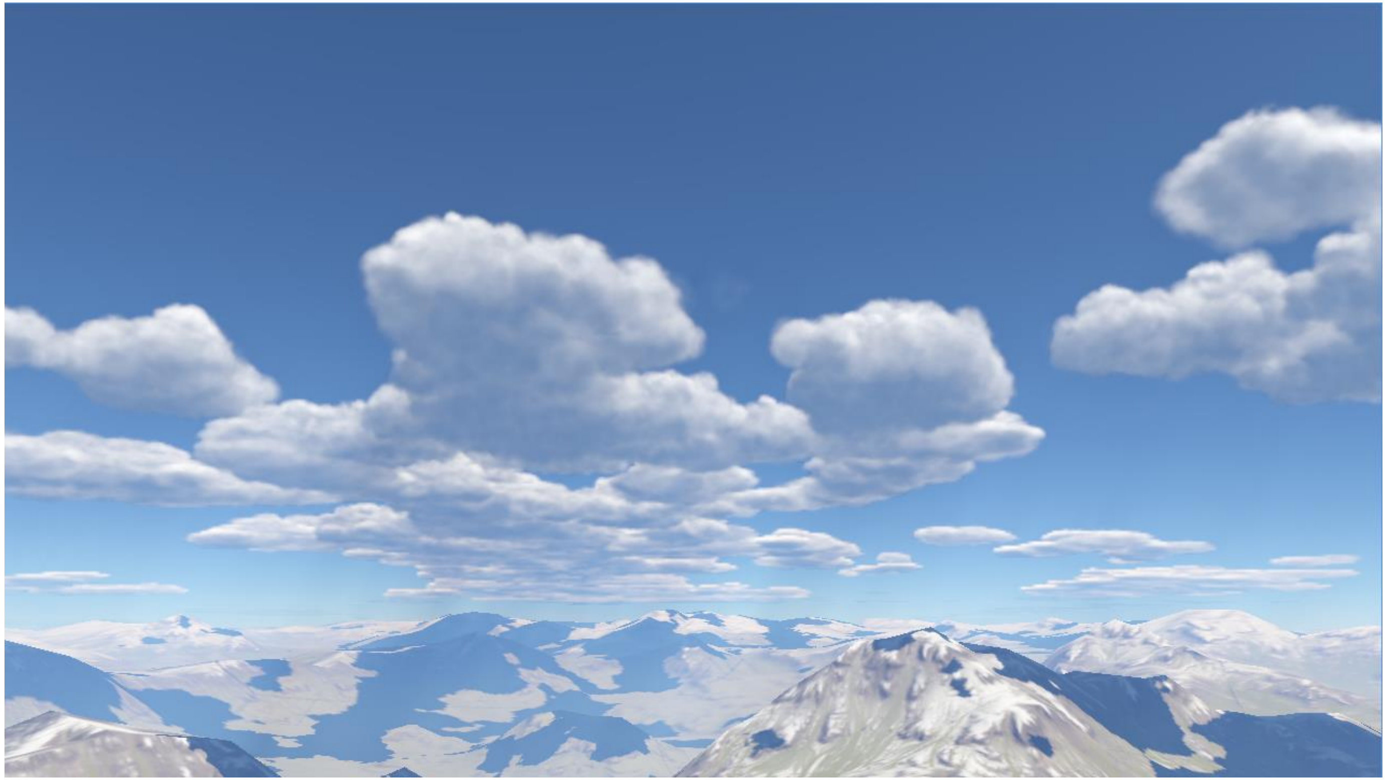
Algorithm overview

Add volume-aware blending (enabled by Pixel Sync)



Algorithm overview

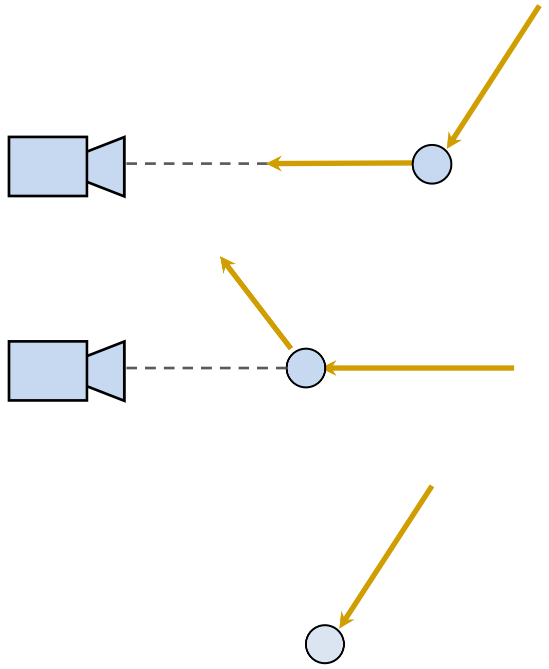
Add light scattering



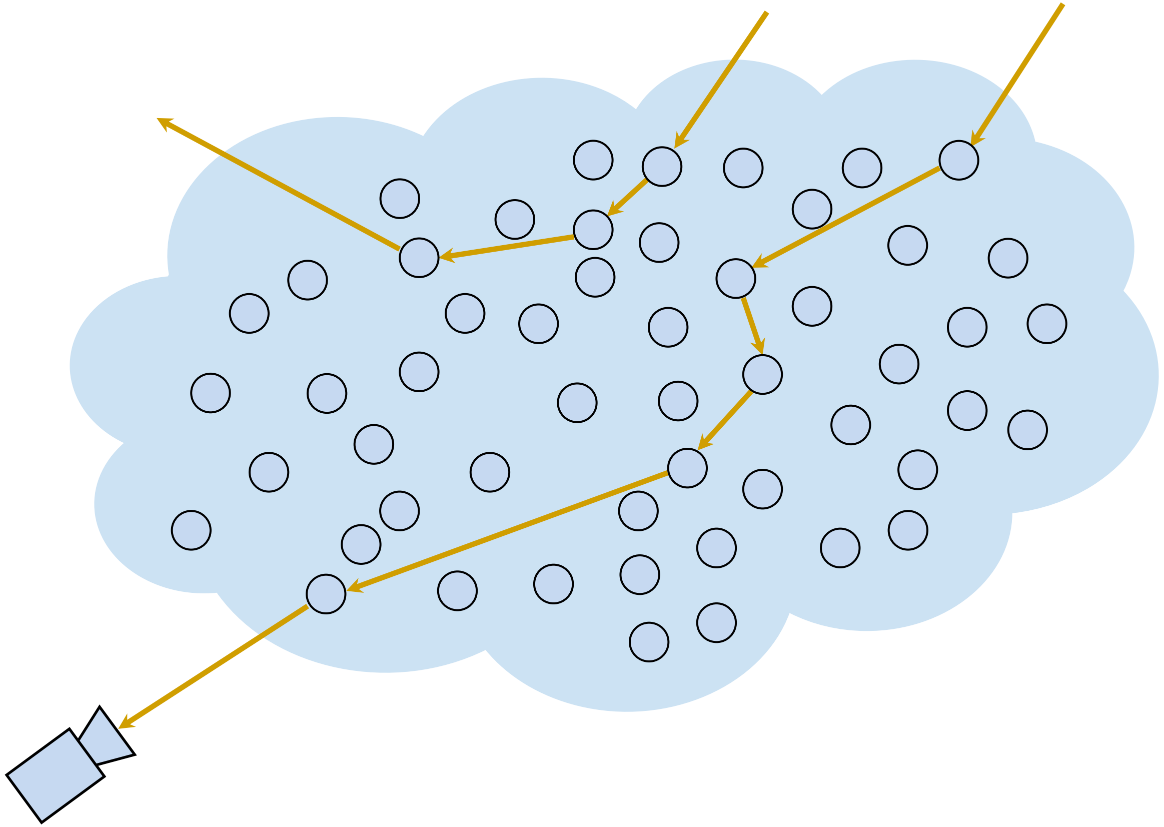
Scattering physics

Light interacts with the tiny (2-8 µm) particles distributed in the cloud:

- A photon can be scattered
  - In-scattering is scattering in the view direction
  - Out-scattering is scattering out of the view direction
- Absorbed



Scattering physics



Scattering physics

Optical depth integral

Light gets attenuated while it travels through the cloud

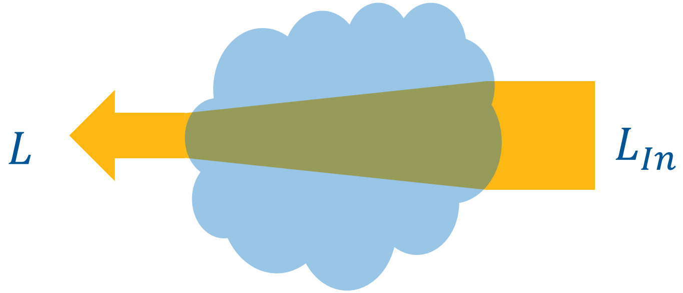
Since there is no absorption, only out-scattering attenuates the light

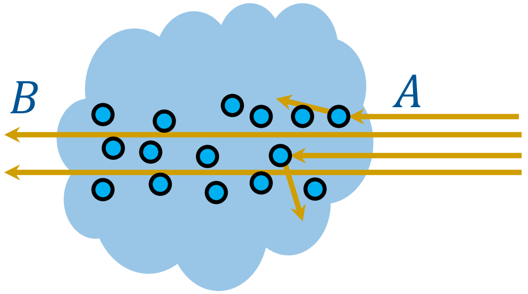
Optical depth is the amount of scattering matter on the way of light:

$$T(\mathbf{A} \to \mathbf{B}) = \int_{\mathbf{A}}^{\mathbf{B}} \beta(\mathbf{P})\, ds$$

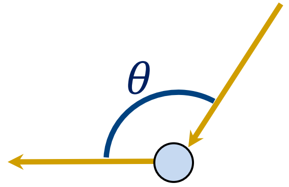
Transmittance through the cloud is the fraction of light survived out-scattering:

$$L = e^{-T(\mathbf{A}\to\mathbf{B})} \cdot L_{In}$$





Scattering physics

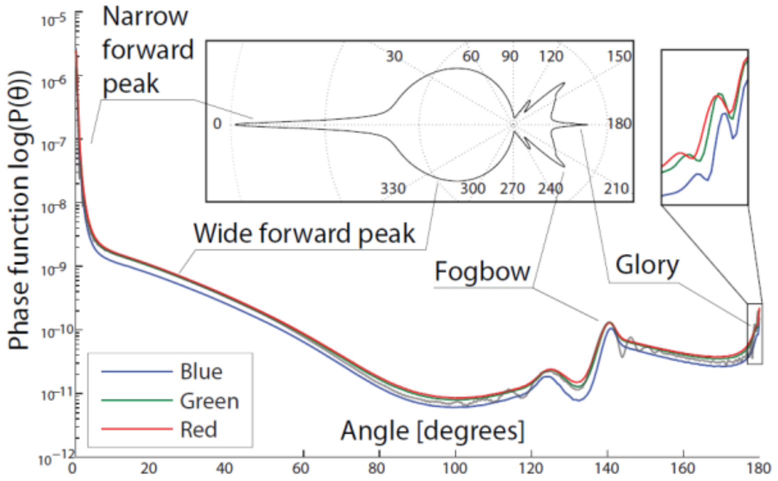


In clouds, absorption is negligible and almost all the light is scattered

- The clouds color is defined by the scattered light

Phase function defines direction of a photon after scattering event

- The phase function of cloud particles exhibit strong forward peak
- Almost all light is scattered in forward direction



Scattering physics

Single-scattering integral:

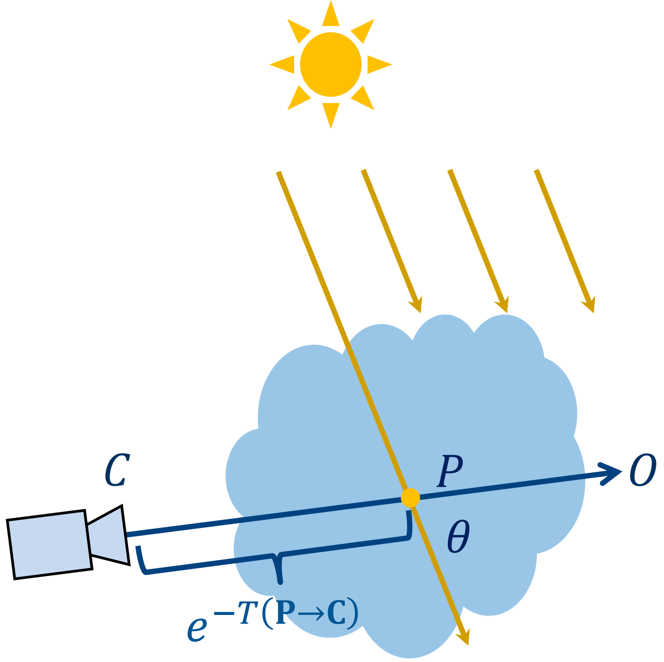
$$L_{In} = p(\theta) \int_{\mathbf{C}}^{\mathbf{O}} e^{-T(\mathbf{P}\rightarrow\mathbf{C})} \beta(\mathbf{P})\, L(\mathbf{P})\; ds$$

$L(\mathbf{P})$ is the light intensity at point P

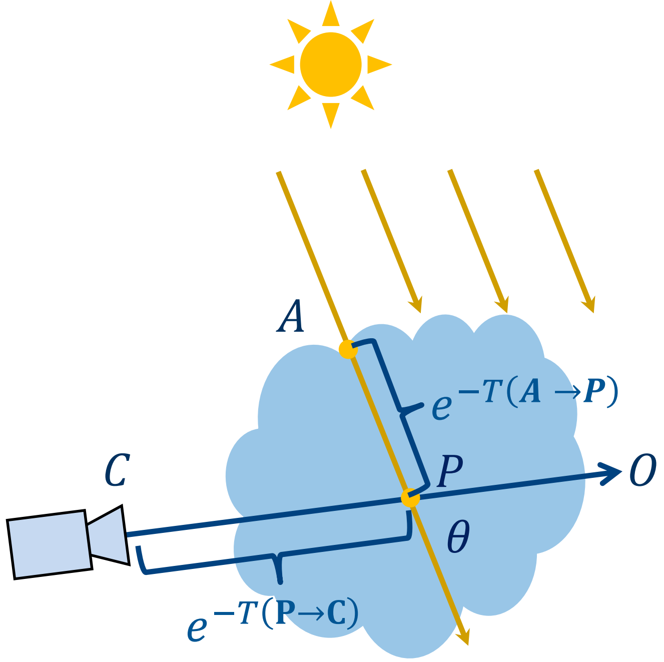
$\beta(\mathbf{P})$ is the scattering coefficient at point P

$T(\mathbf{P} \rightarrow \mathbf{C})$ is the optical thickness of the media between points P and C

$p(\theta)$ is the phase function



Scattering physics



Light is also attenuated in the cloud before it reaches the scattering point:

$L(\mathbf{P}) = L\ e^{-T(A \to P)}$

L is the light intensity outside the cloud

Let's now look at our integral:

$$\int_{\mathbf{P}}^{\mathbf{C}} \beta(\mathbf{P})\, ds$$

$$\int_{\mathbf{A}}^{\mathbf{P}} \beta(\mathbf{P})\, ds$$

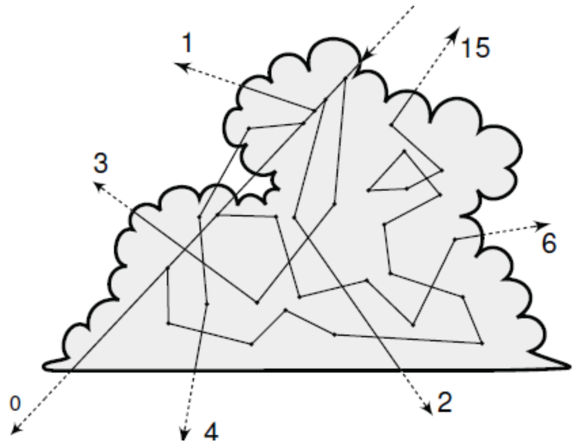
$$L_{In} = p(\theta) \int_{\mathbf{C}}^{\mathbf{O}} e^{-T(\mathbf{P} \to \mathbf{C})} \beta(\mathbf{P}) L\ e^{-T(A \to P)}\, ds$$

Scattering physics

In clouds, a photon is usually scattered multiple times before it leaves the clouds

This multiple scattering is crucial to cloud appearance and cannot be ignored

- In contrast, air is much more optically thinner media thus single scattering models produce convincing results



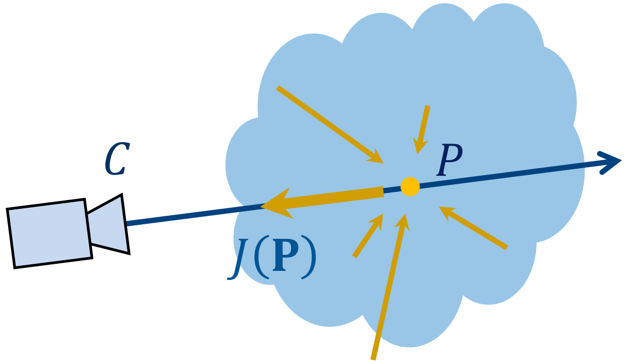
Scattering physics

Multiple scattering

$$L = p(\theta)\int_{\mathbf{C}}^{\mathbf{O}} e^{-T(\mathbf{P}\rightarrow\mathbf{C})}\,\beta(\mathbf{P})\,J(\mathbf{P})\;ds$$

$$J(\mathbf{P}) = \int_{\mathbf{\Omega}} L\,p(\theta)d\omega$$

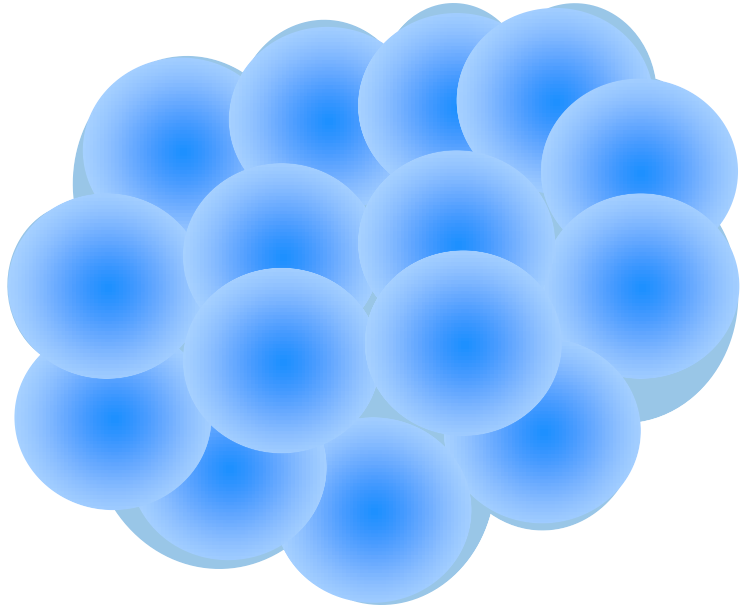
$\mathbf{\Omega}$ is the whole set of directions



Pre-computed lighting

The idea main idea is to

- Precompute physically-based lighting for simple shapes
- Construct clouds from these simple shapes
- The term **Particle** will now refer to these basic shapes (not individual tiny droplets)



Pre-computing optical depth

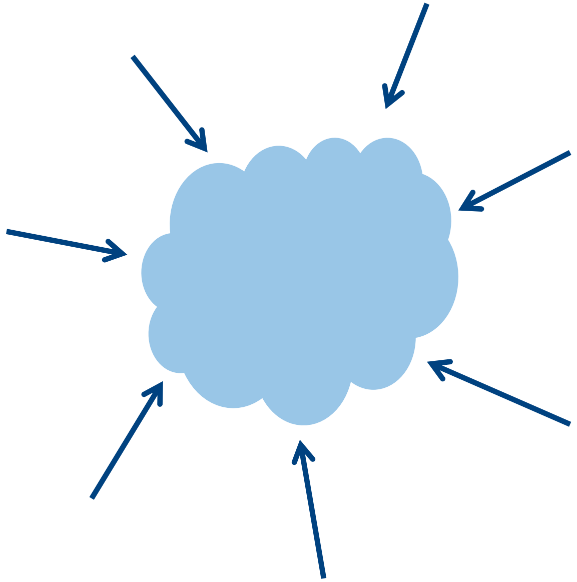
$$T(\mathbf{A} \to \mathbf{B}) = \int_{\mathbf{A}}^{\mathbf{B}} \beta(\mathbf{P})\, ds$$

Typical way to evaluate optical depth is ray marching

- Impractical to do in real-time

For a known density distribution, the integral can be evaluated once and stored in a look-up table for all possible viewpoints and directions

- No ray marching at run-time
- Fast evaluation for the price of memory

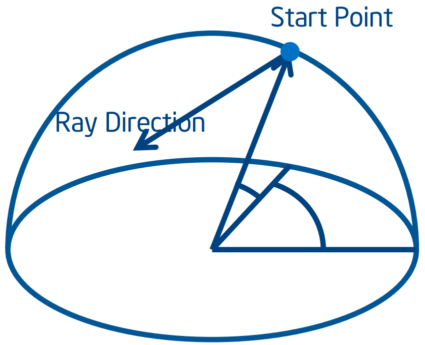


Pre-computing optical depth

$$T(\mathbf{A} \to \mathbf{B}) = \int_{\mathbf{A}}^{\mathbf{B}} \beta(\mathbf{P})\, ds$$

Parameterization

- We need to describe all start points on the sphere and all directions
- Two angles describe start point on the sphere
- Two angles describe view direction
- 4D look-up table is required

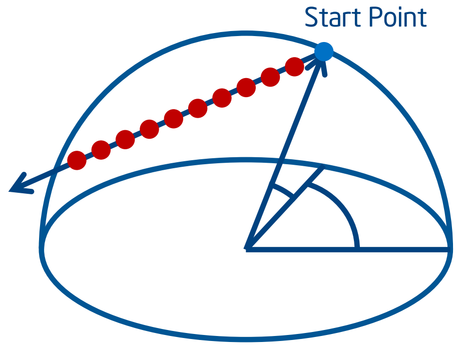


Pre-computing optical depth

$$T(\mathbf{A} \to \mathbf{B}) = \int_{\mathbf{A}}^{\mathbf{B}} \beta(\mathbf{P})\, ds$$

Integration

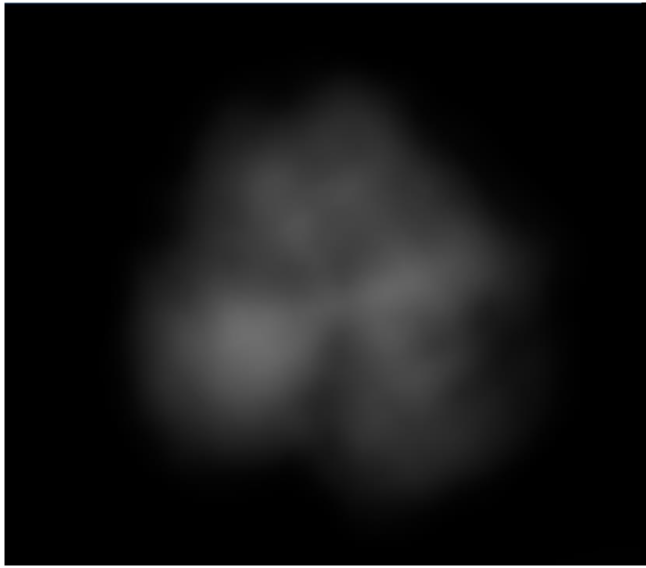
- Integration is performed by stepping along the ray and numerically computing optical thickness
  - Cloud density at each step is determined through 3D noise
- 4D look-up table is implemented as 3D texture
  - For look-up, manual filtering across 4th coordinate is necessary



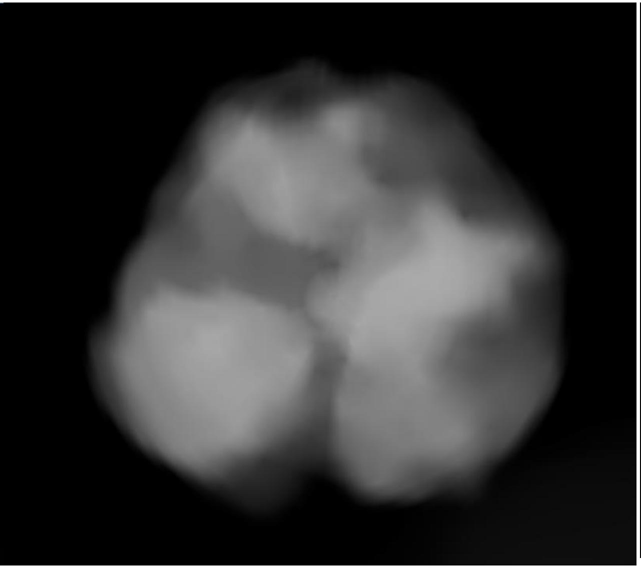
Pre-computing optical depth

3D Noise generation

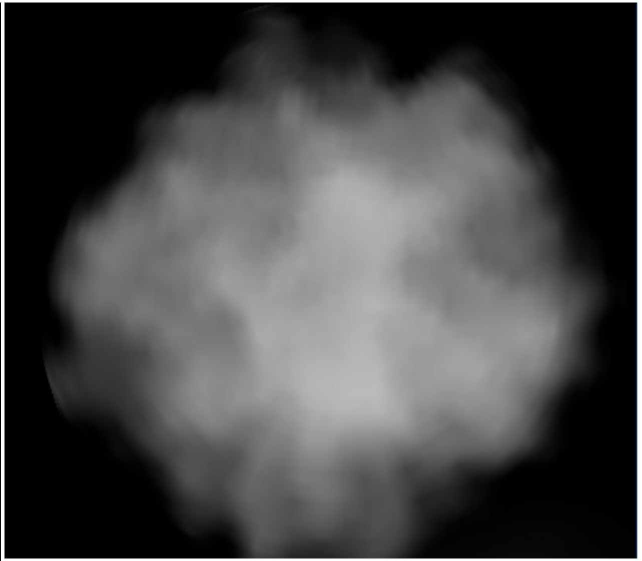
Radial falloff+3D noise



Thresholding



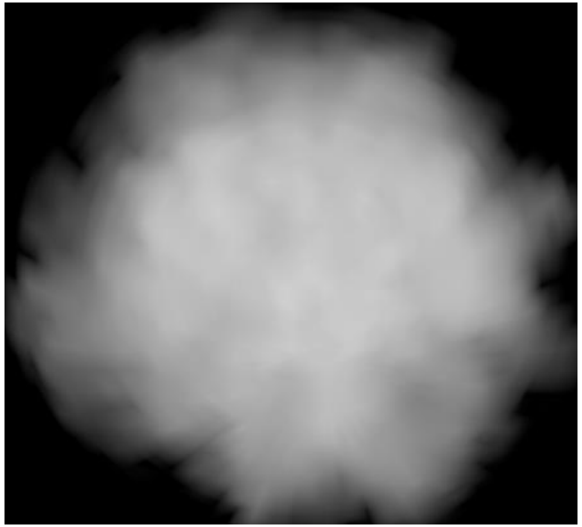
Pyroclastic style

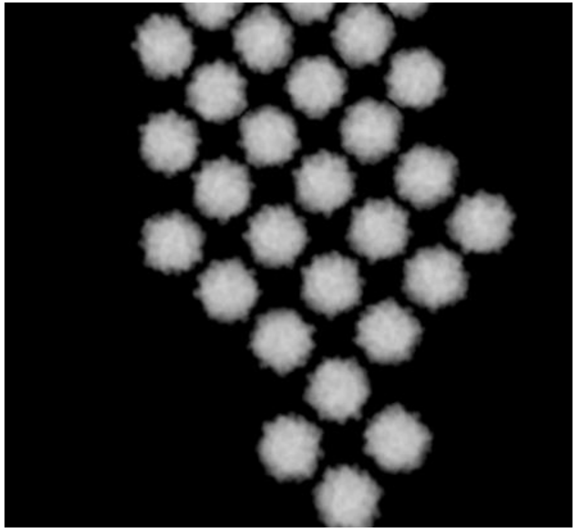


Pre-computing optical depth

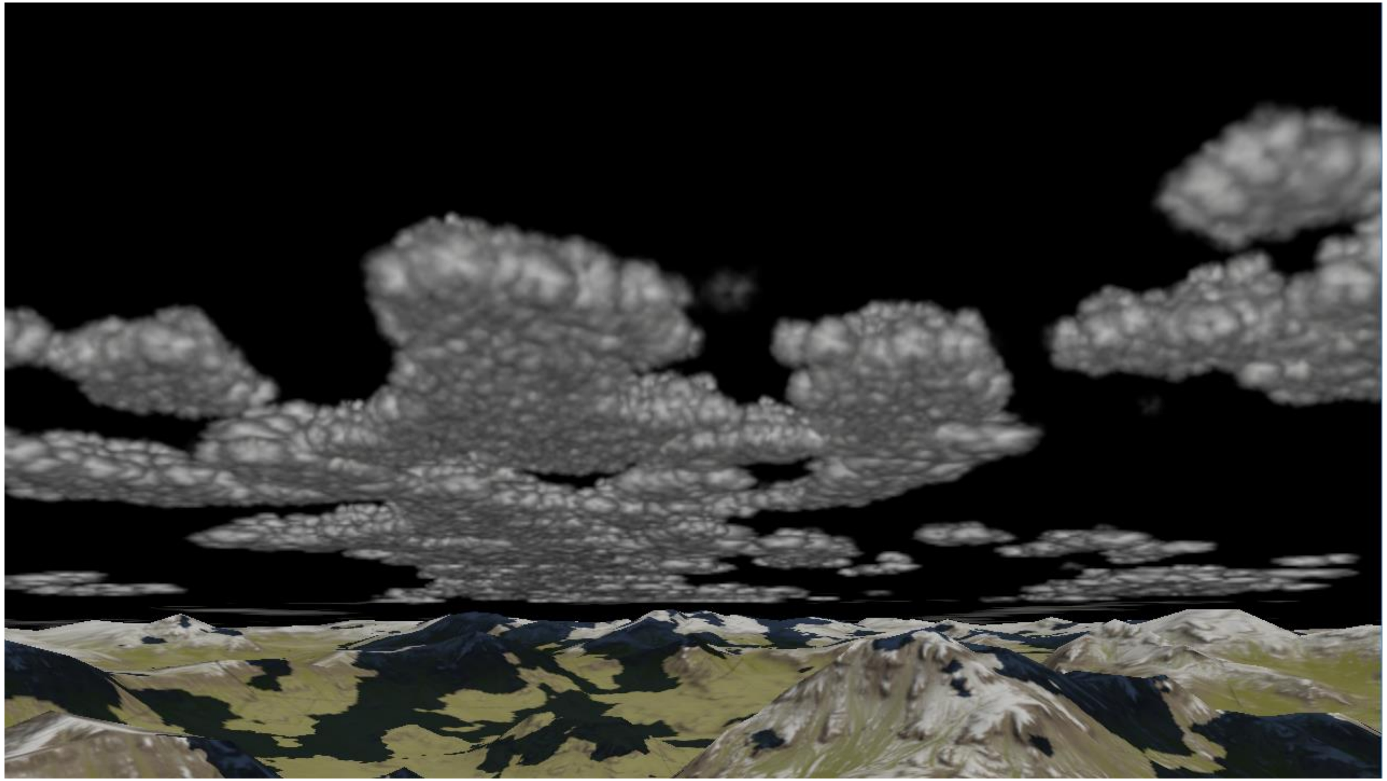
Resolution

- 32x64x32x64 look-up table
- Interpolation artifacts can be visible from close look-ups
- OK from distance





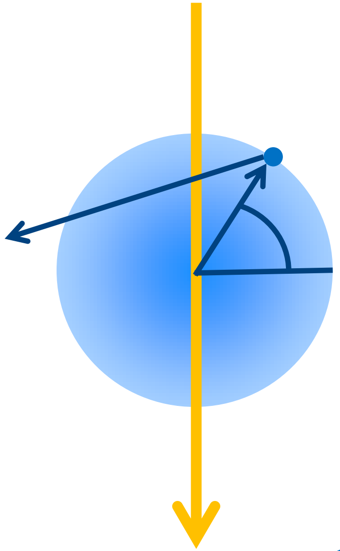
Pre-computing optical depth



Pre-computing scattering

- Let's consider spherically symmetrical particle
- Any start point on the sphere can be described by a single angle
- View direction is described by two angles
- Thus 3 parameters are necessary to describe any start point and view direction -> 3D look-up table

$$L = \int_{\mathbf{C}}^{\mathbf{O}} e^{-T(\mathbf{P}\to\mathbf{C})}\, \beta(\mathbf{P}) \left(\int_{\mathbf{\Omega}} L\, p(\theta) d\omega \right) ds$$



Pre-computing scattering

Intermediate 4D table is used to store radiance for every point in the sphere

For each scattering order:

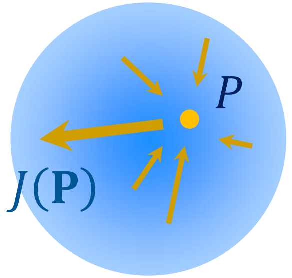
1. Compute $J(\mathbf{P})$ for every point and direction inside the sphere by integrating previous order scattering

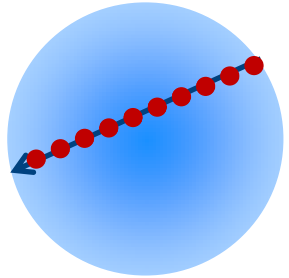
$$J_n = \int_{\Omega} L_{n-1}(\omega) p(\theta) d\omega$$

2. Compute current order inscattering by numerical integration of J_n:

$$L_n = \int_{C}^{O} e^{-T(\mathbf{P}\to\mathbf{C})} \beta(\mathbf{P}) J_n(\mathbf{P}) ds$$

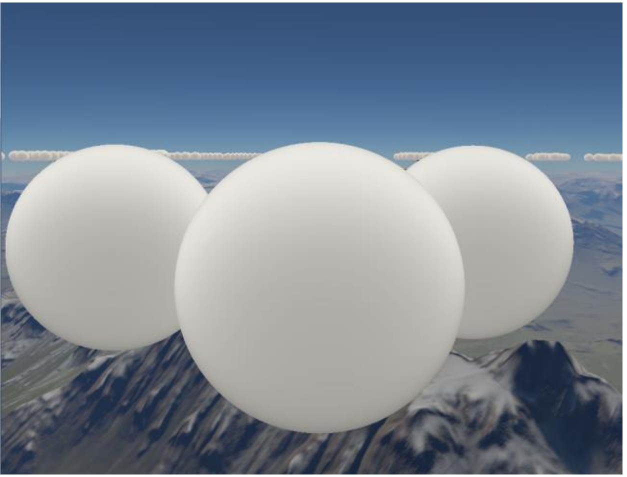
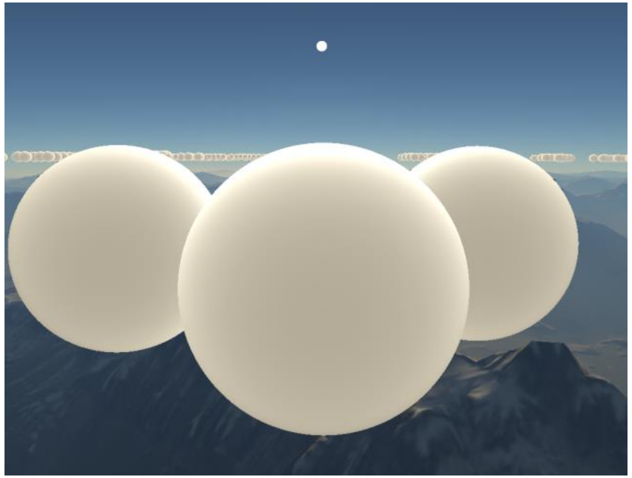
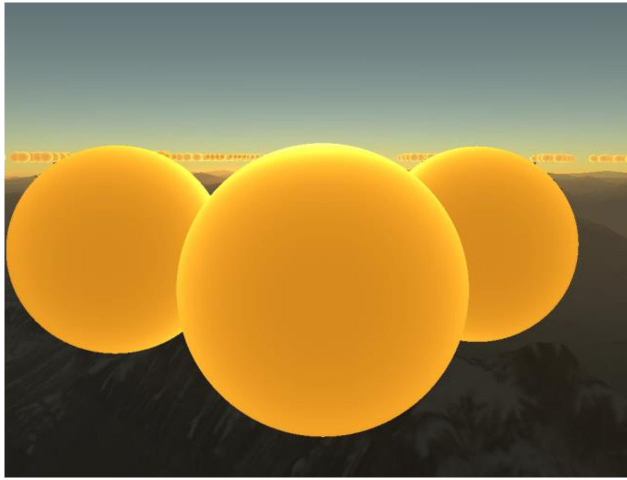
3. Add current scattering order to the total look-up table





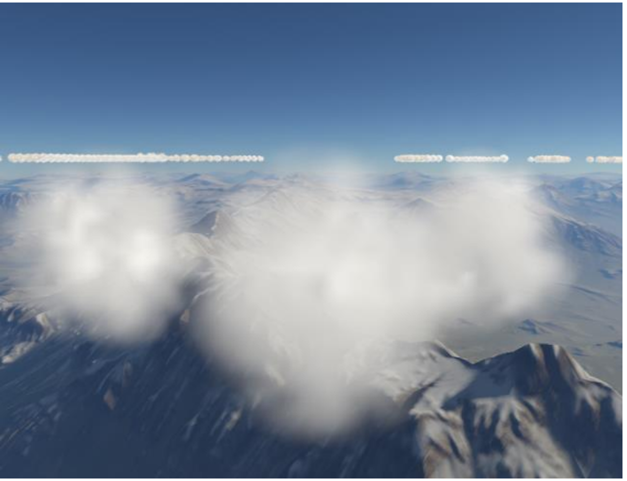
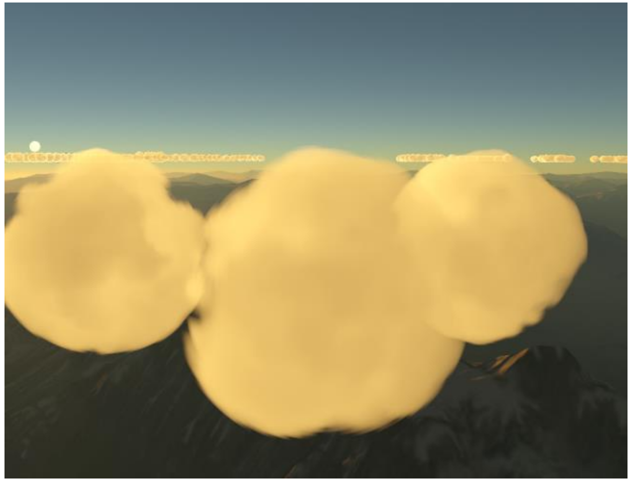
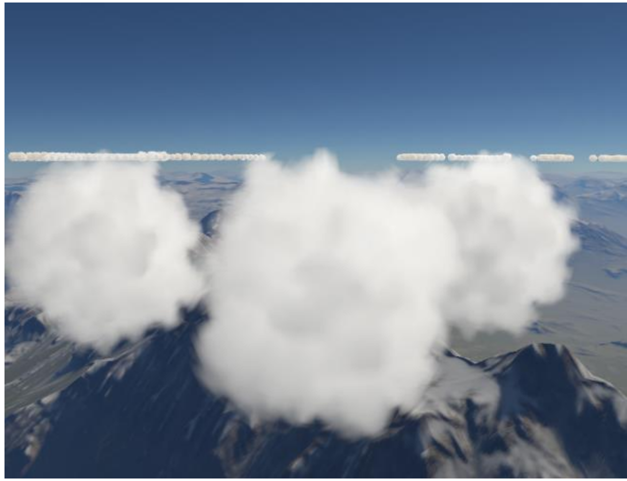
Pre-computing scattering

Pre-computed scattering for different light orientations

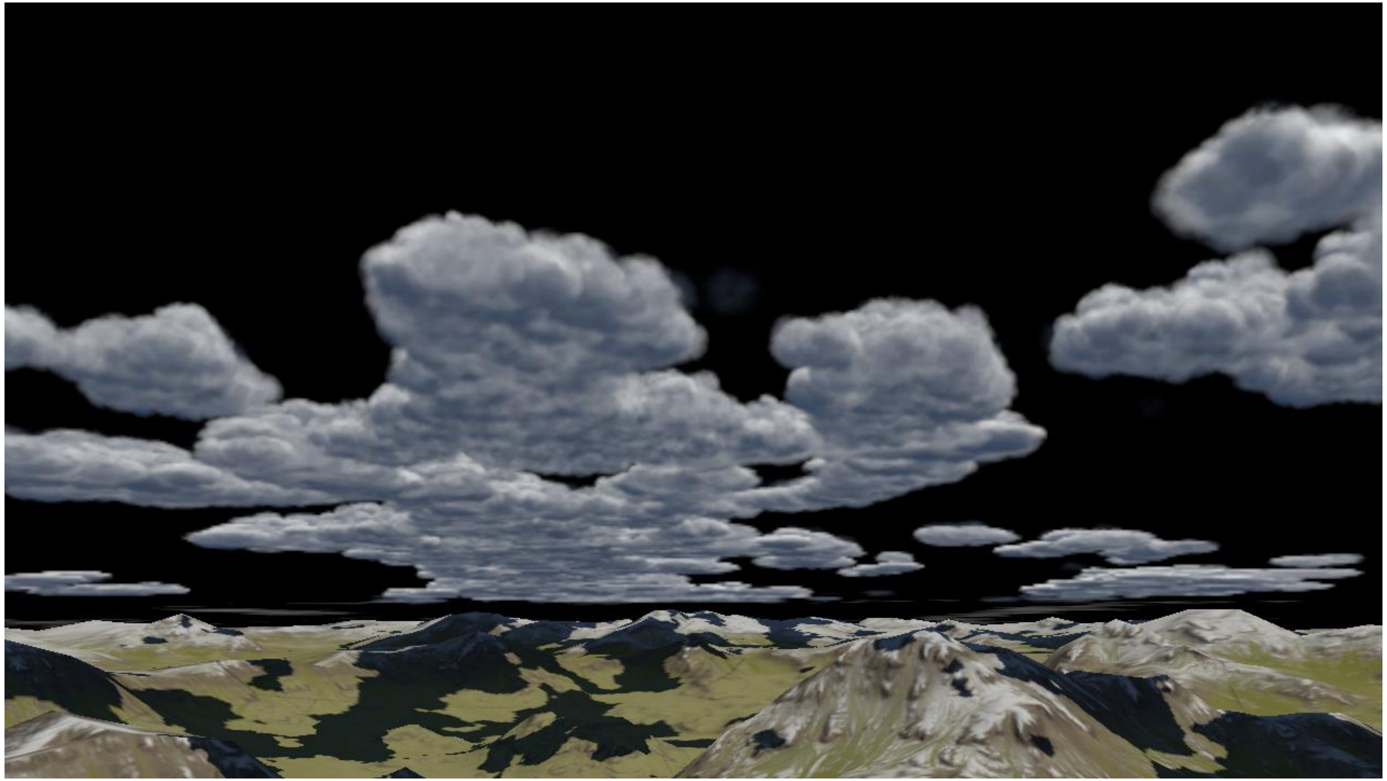




Pre-computing scattering

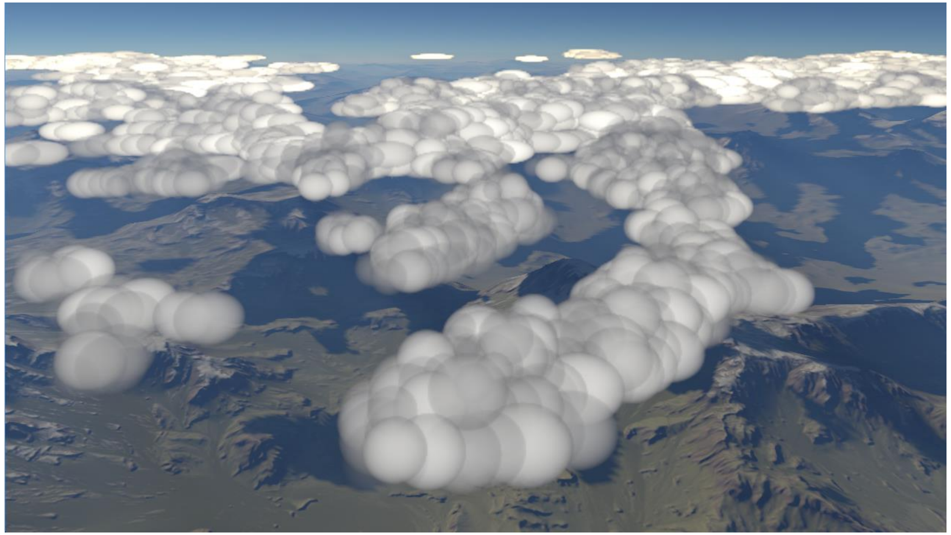
Combining pre-computed lighting and pre-computed cloud density

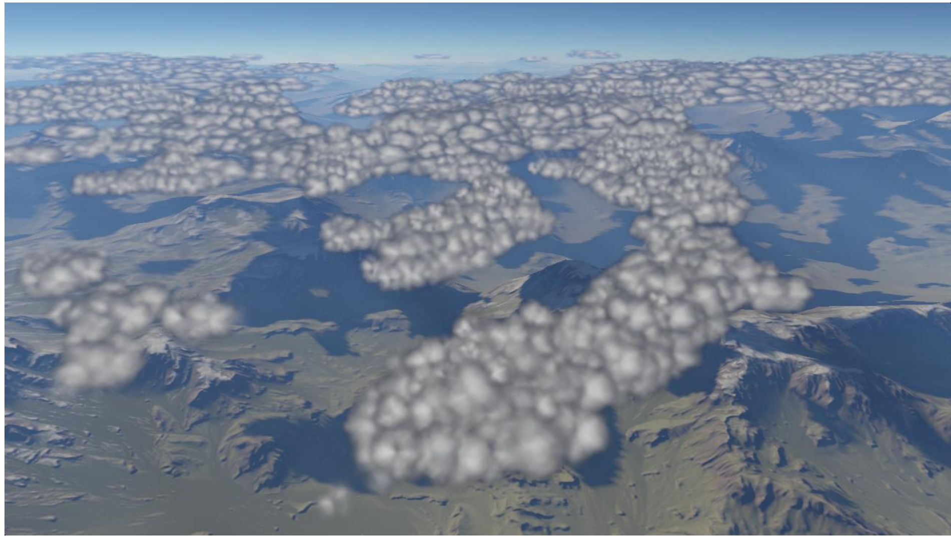




Pre-computing scattering

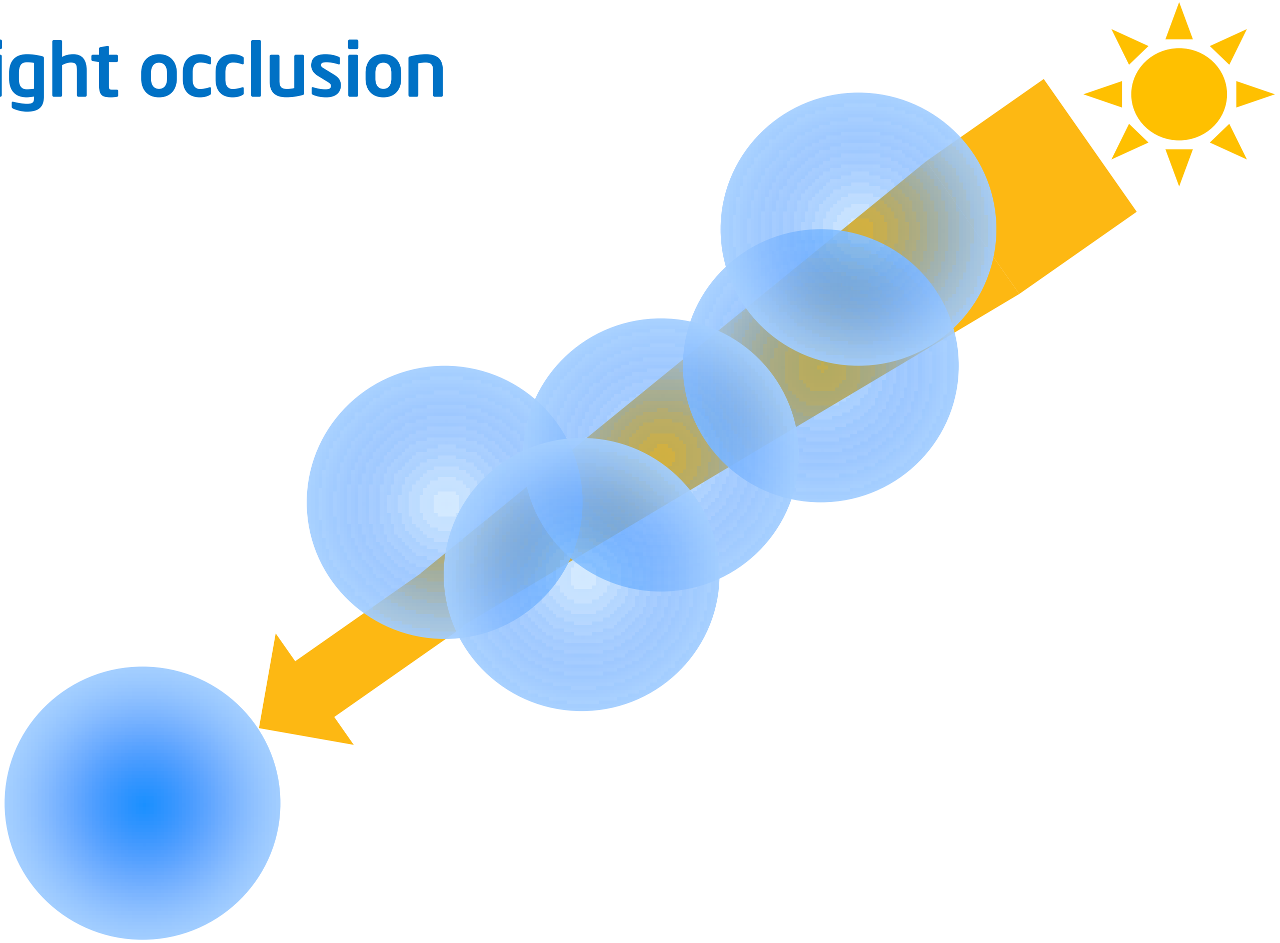


Compositing clouds





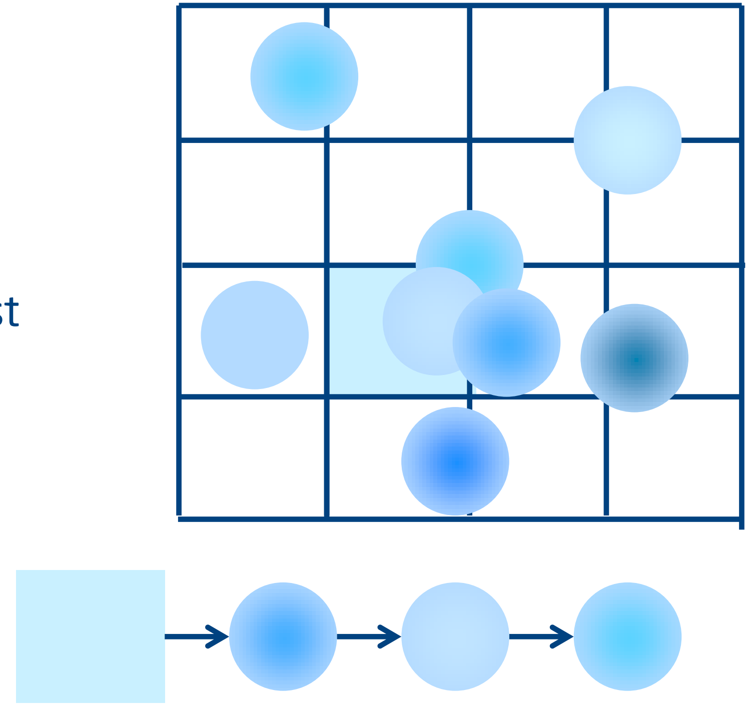
Computing light occlusion



Computing light occlusion

Tiling

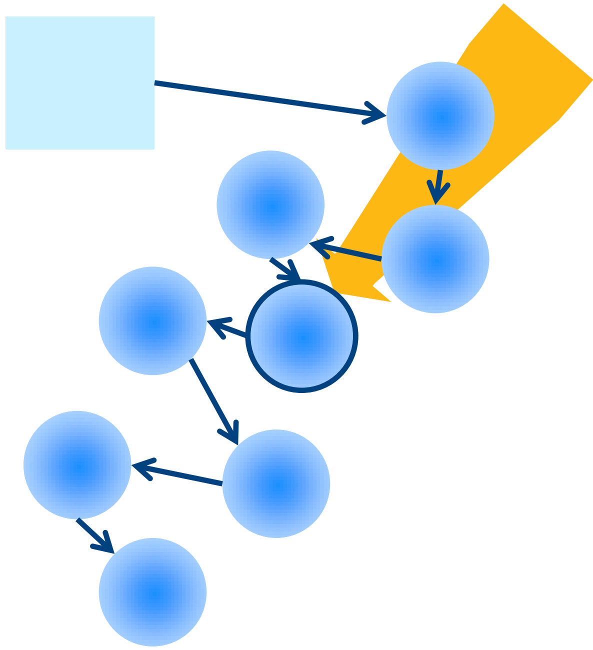
- The scene is rasterized from the light over the tile grid
  - One tile is one pixel
- Each particle is assigned to the tile
  - Screen-size buffer is used to store index of the first particle in the list
  - Append buffer is used to store the lists elements
- Pixel Shader Ordering is used to preserve original particle order (sorted from the light)



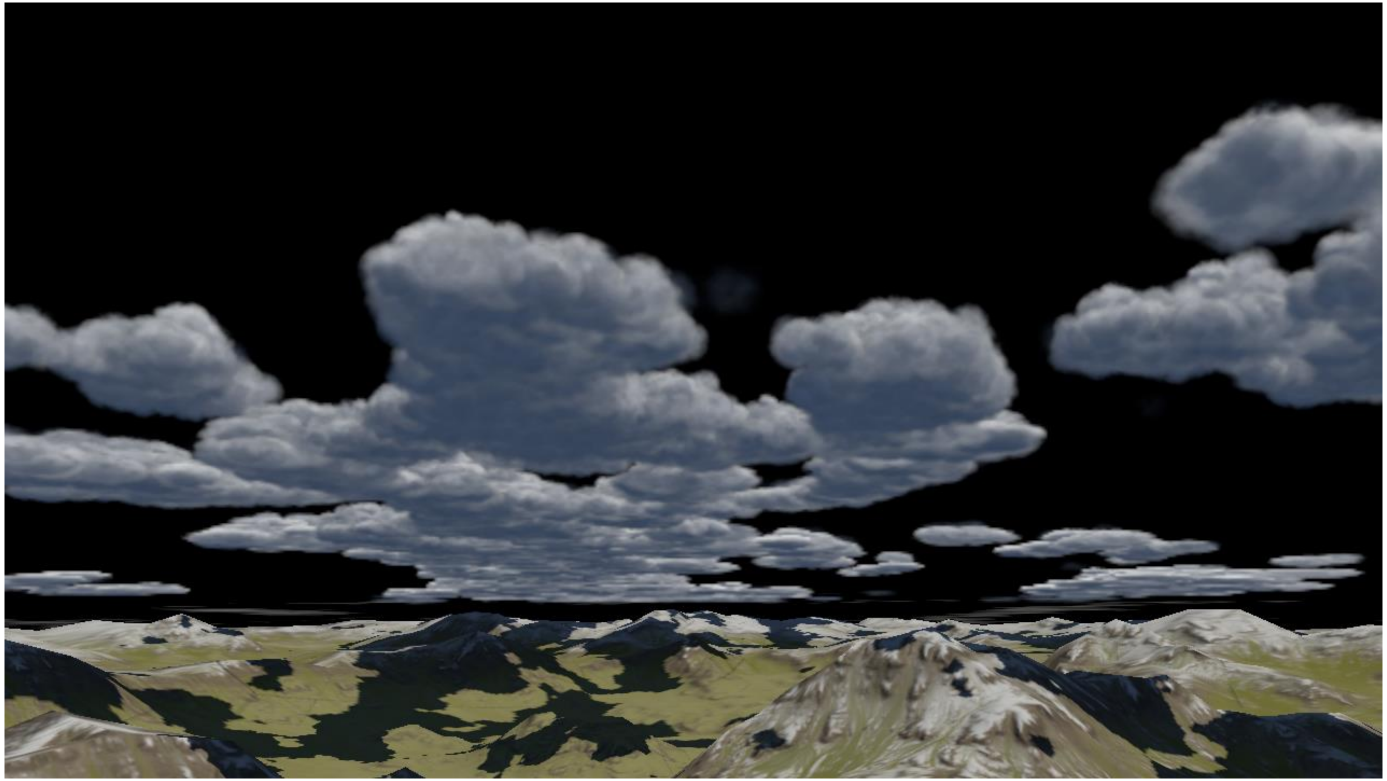
Computing light occlusion

Traversing lists

- Processing is done by the compute shader
- Each particle finds a tile it belongs to
- The shader then goes through the list of the tile and computes opacity of particles on the light path
- Since particles are ordered from the light, the loop can be terminated as soon as current particle is reached
- The loop can also be terminated when total transparency reaches threshold (0.01)
- Early exit gives up to 2x speed-up for opacity calculation stage

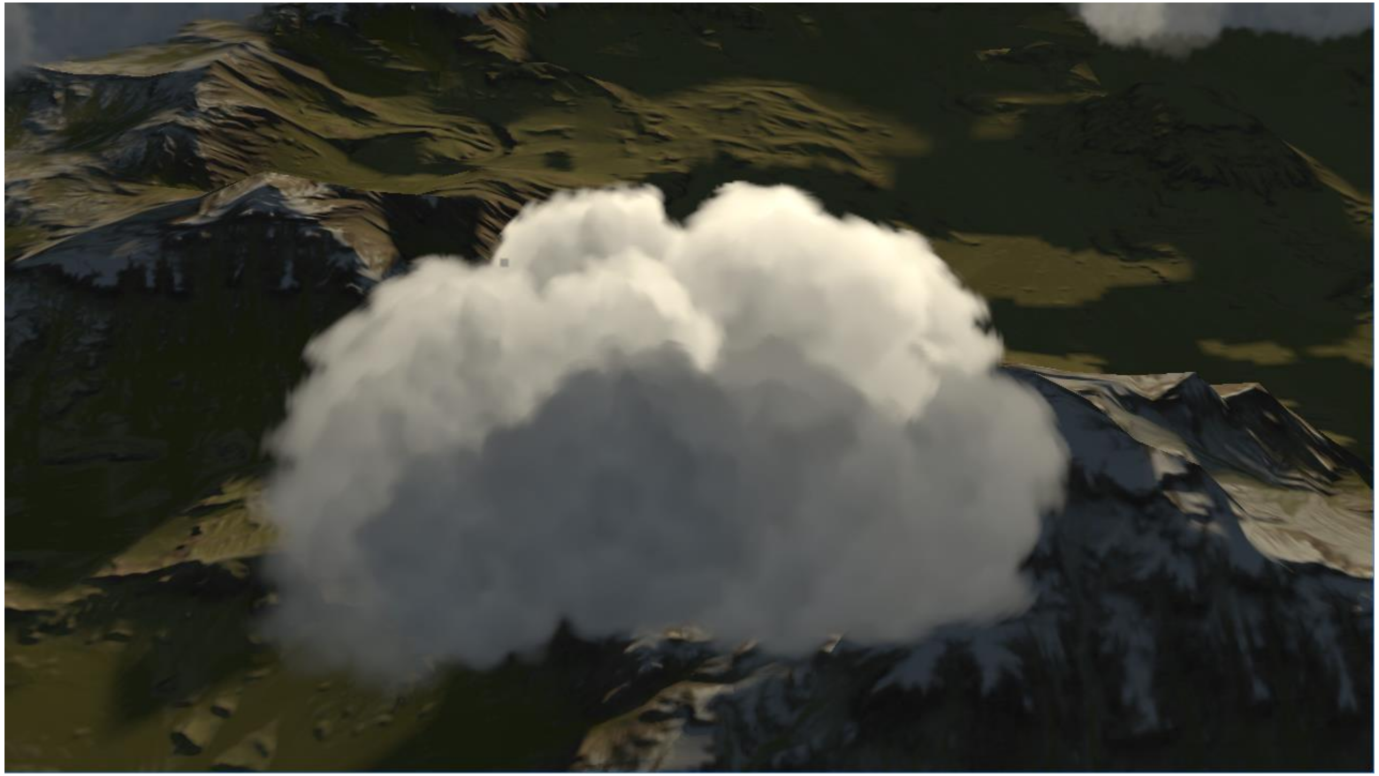


Computing light occlusion



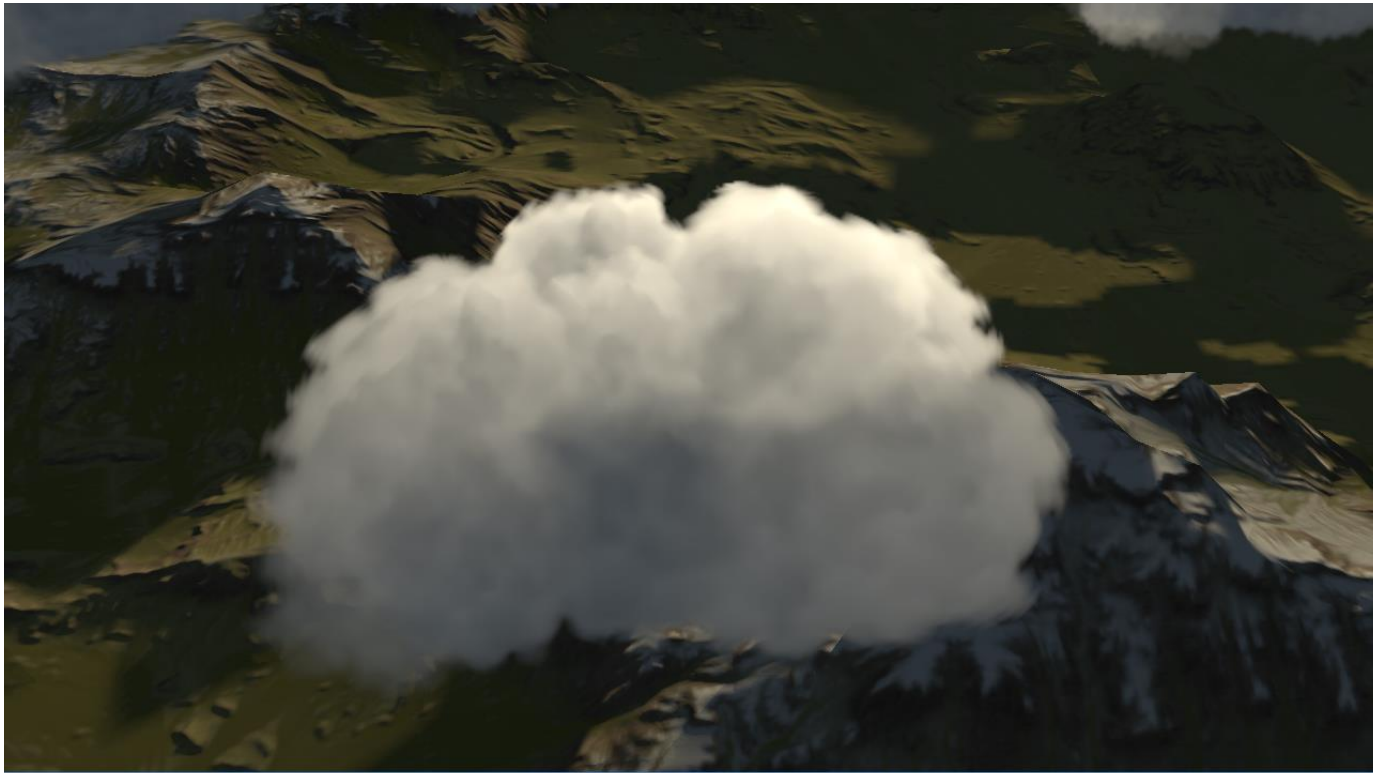
Volume-aware blending

No Pixel Sync – Conventional Alpha Blending



Volume-aware blending

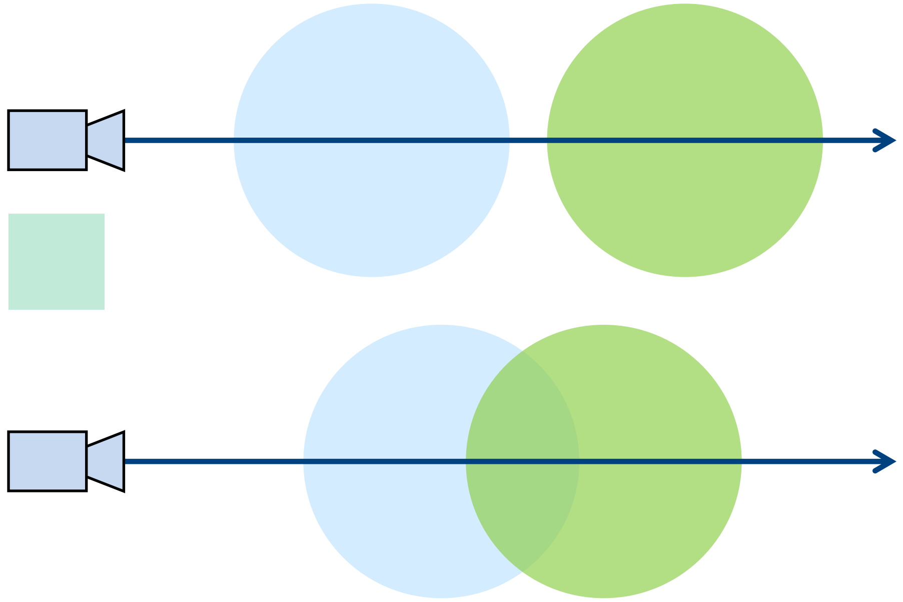
Pixel Sync – Volume-Aware Blending



Volume-aware blending

Blending volumetric particles

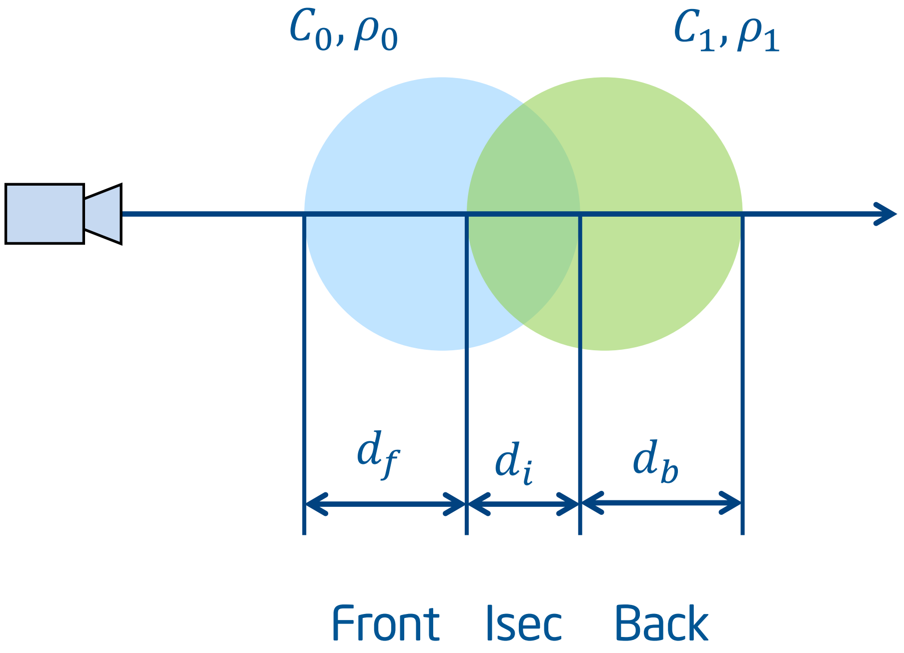
- If particles do not overlap, blending is trivial
- How can we correctly blend overlapping particles?



Volume-aware blending

Blending volumetric particles

- Suppose we have two overlapping particles with color and density C_0, ρ_0 and C_1, ρ_1
- Back:
  - $T_{Back} = e^{-\rho_1 \cdot d_b \cdot \beta}$
  - $C_{Back} = C_1 \cdot (1 - T_{Back})$
- Front:
  - $T_{Front} = e^{-\rho_0 \cdot d_f \cdot \beta}$
  - $C_{Front} = C_0 \cdot (1 - T_{Front})$
- Intersection:
  - $T_{Isec} = e^{-(\rho_0+\rho_1) \cdot d_i \cdot \beta}$
  - $C_{Isec} = \frac{C_0\rho_0 + C_1\rho_1}{\rho_0+\rho_1}(1 - T_{Isec})$



Volume-aware blending

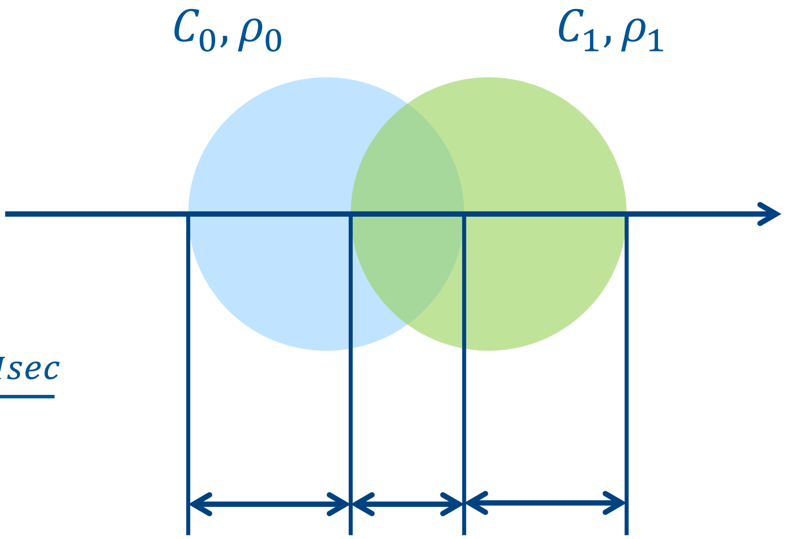
Blending volumetric particles

- Final color and transparency:

$$T_{Final} = T_{Front} \cdot T_{Isec} \cdot T_{Back}$$

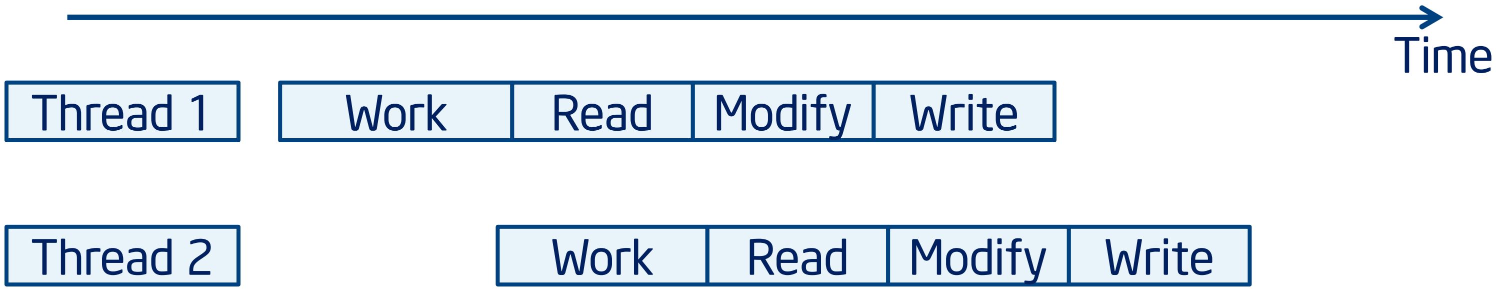
$$C_{Final} = \frac{C_{Front} + C_{Isec} \cdot T_{Front} + C_{Back} \cdot T_{Front} \cdot T_{Isec}}{1 - T_{Final}}$$

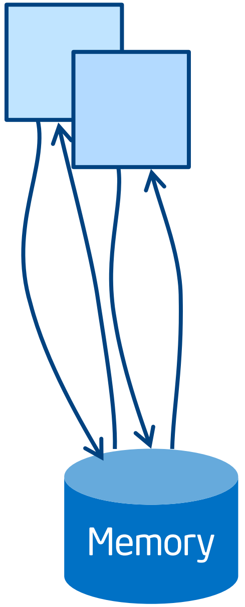
- Division by $1 - T_{Final}$ because we do not want alpha pre-multiplied color



Volume-aware blending

- DirectX does not impose any ordering on the execution of pixel shader
  - Ordering happens later at the output merger stage
- If two threads read and modify the same memory, result is unpredictable

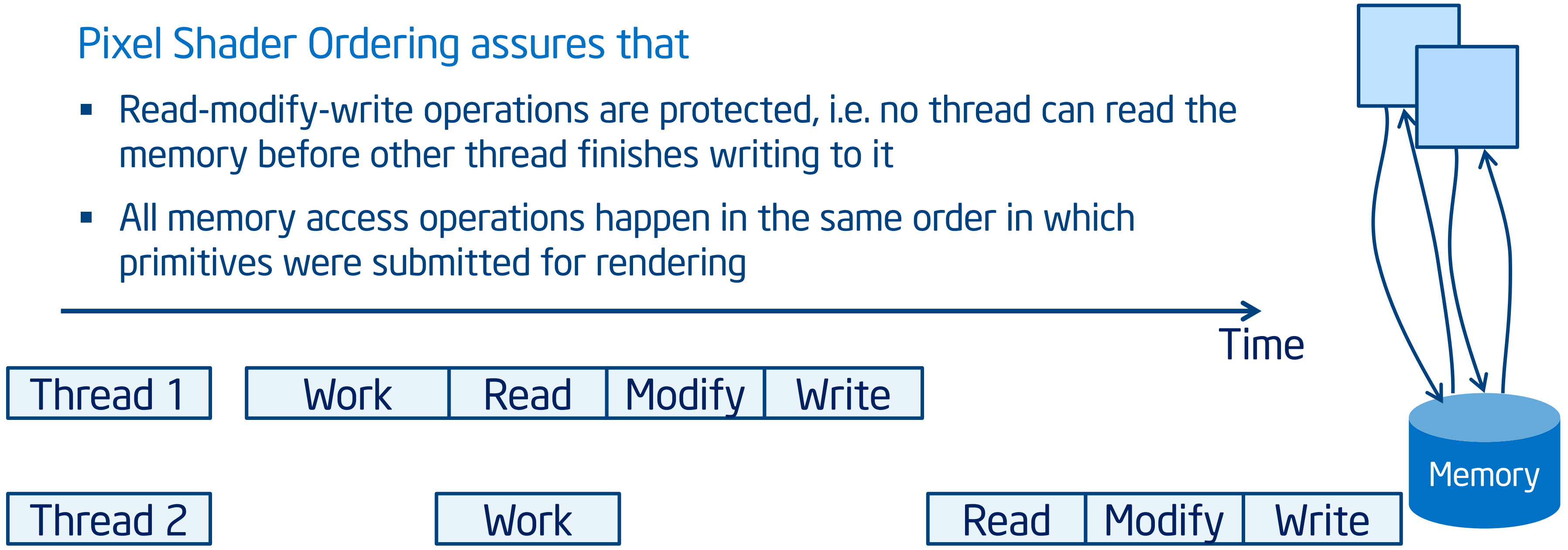




Volume-aware blending

Pixel Shader Ordering assures that

- Read-modify-write operations are protected, i.e. no thread can read the memory before other thread finishes writing to it
- All memory access operations happen in the same order in which primitives were submitted for rendering



Volume-aware blending

Enabling pixel shader ordering

```
#include "IntelExtensions.hlsl"
...
void YourPixelShader(...)
{
     IntelExt_Init();
     ...
     IntelExt_BeginPixelShaderOrdering();
     // Access UAV

}
```

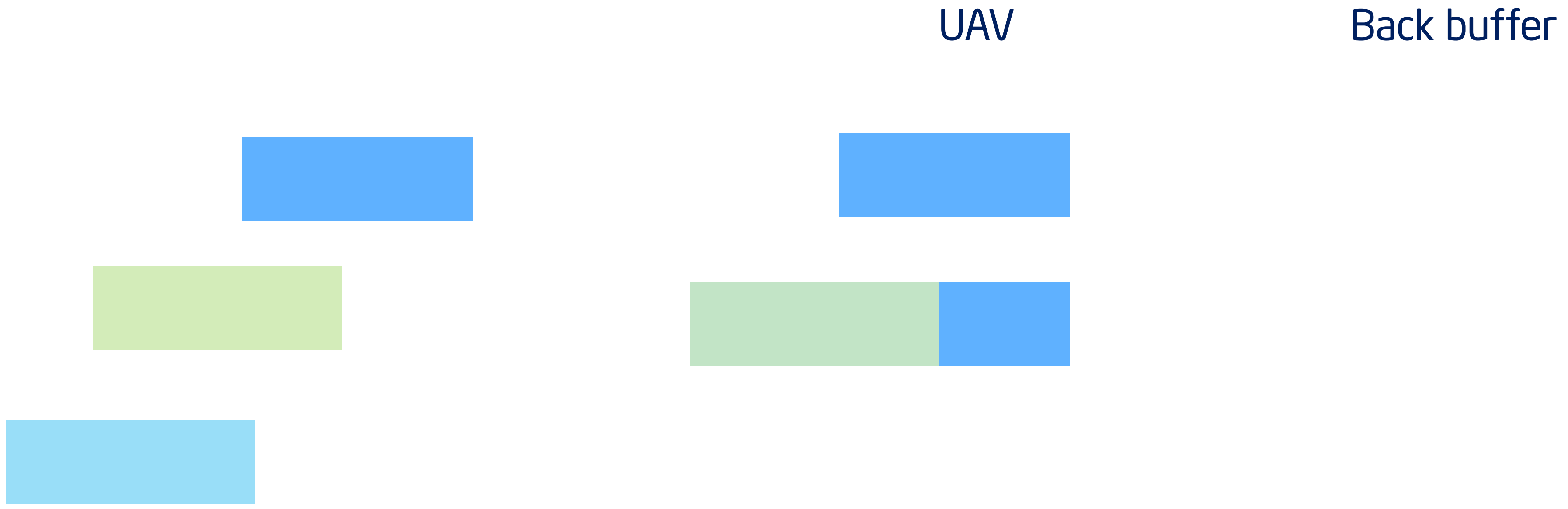
Volume-aware blending

Blending volumetric particles - Implementation

- Pixel Shader Ordering must be enabled
- Color, density and min/max extent of the current particle are stored in the UAV buffer
- Each new particle is tested against the currently stored
  - If new particle is in front of the current, the current is blended into the back buffer and replaced with the new one
  - If new particle overlaps with the current, they are blended and stored
  - Particles need to be sorted

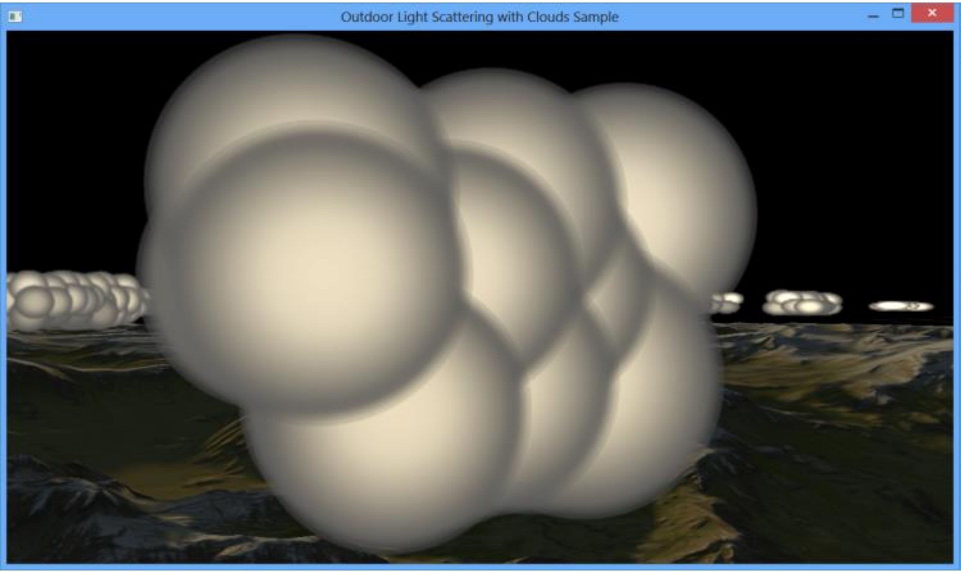
Volume-aware blending

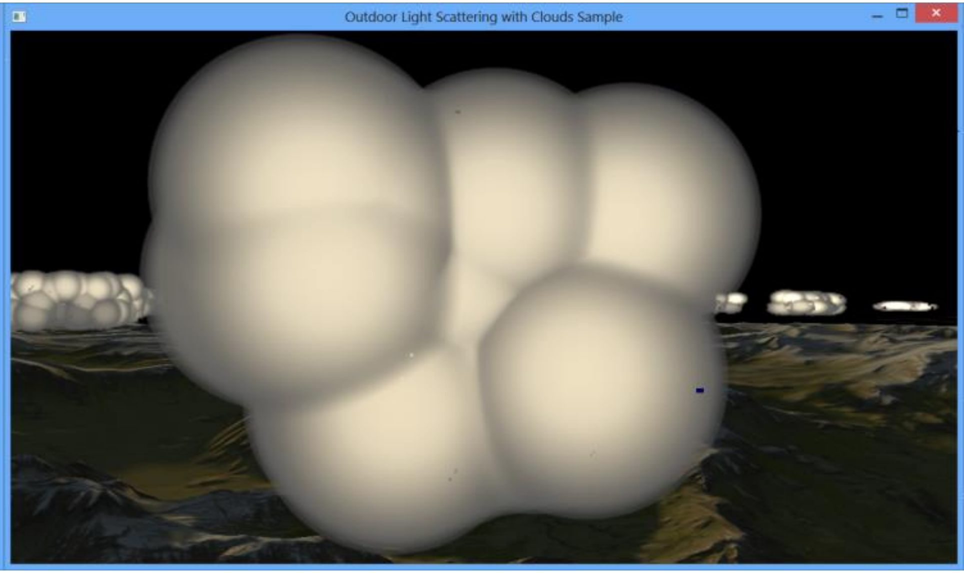
Blending volumetric particles - Implementation



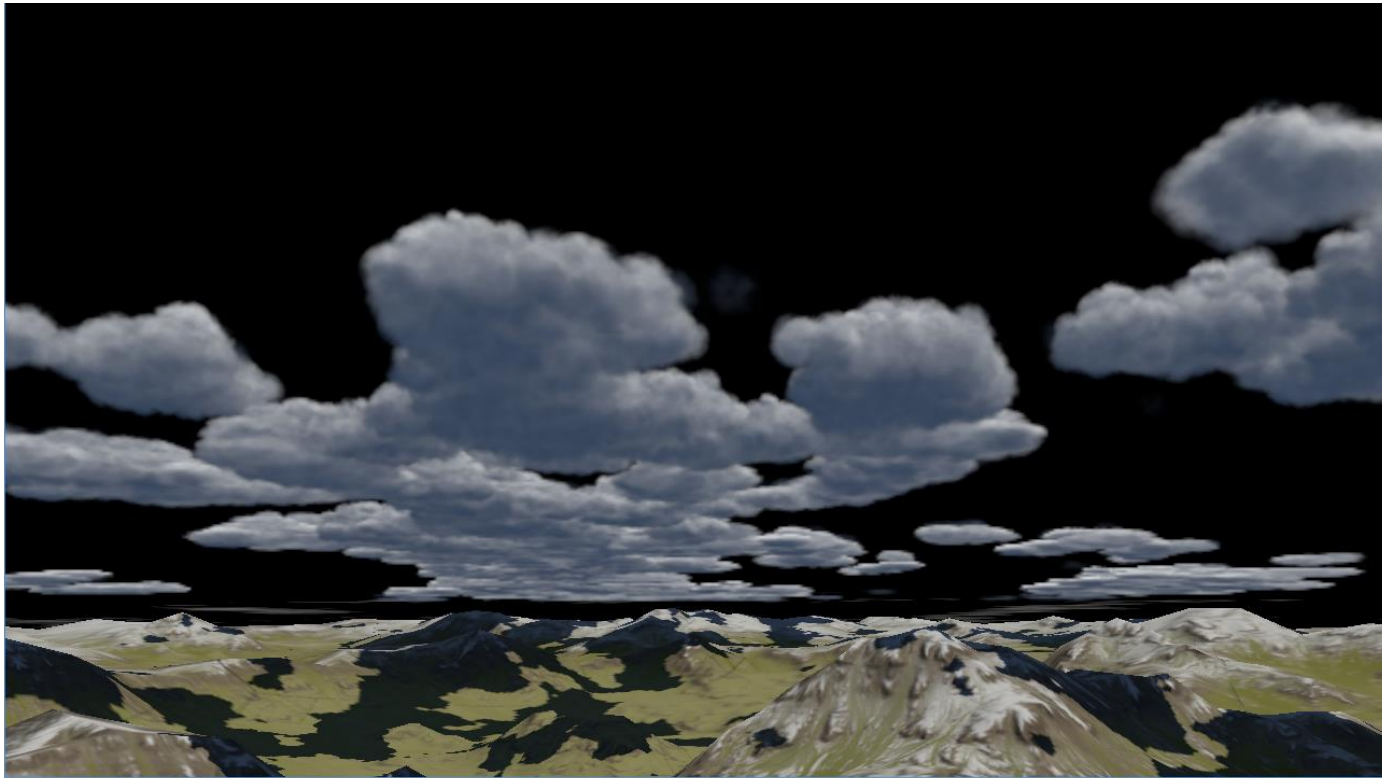
Volume-aware blending

Blending volumetric particles – comparison with traditional blending





Volume-aware blending



Rendering

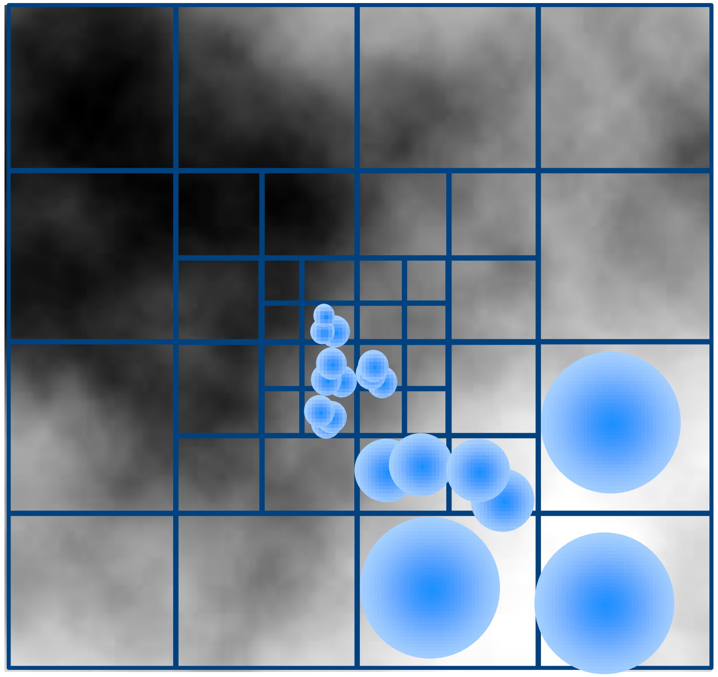
Low-resolution rendering

- To improve performance, particles are rendered to a low-resolution buffer
- Bilateral filtering is then performed to upscale to original resolution and preserve edges

Particle generation

Cell grid

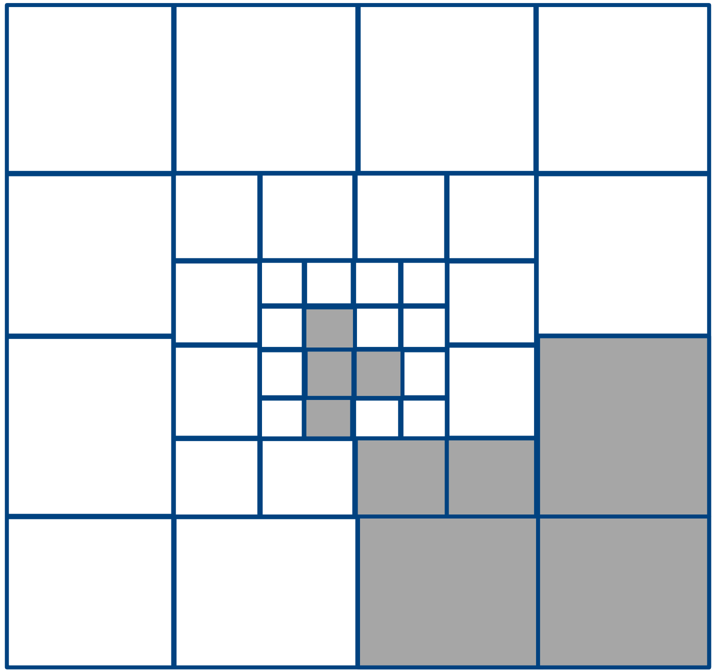
- Organized as a number of concentric rings centered around the camera
- Particles in each next ring have twice the size of the inner ring
- Each cell contains several layers of particles
- Density and size of particles in each cell are determined by the noise texture



Particle generation

Steps:

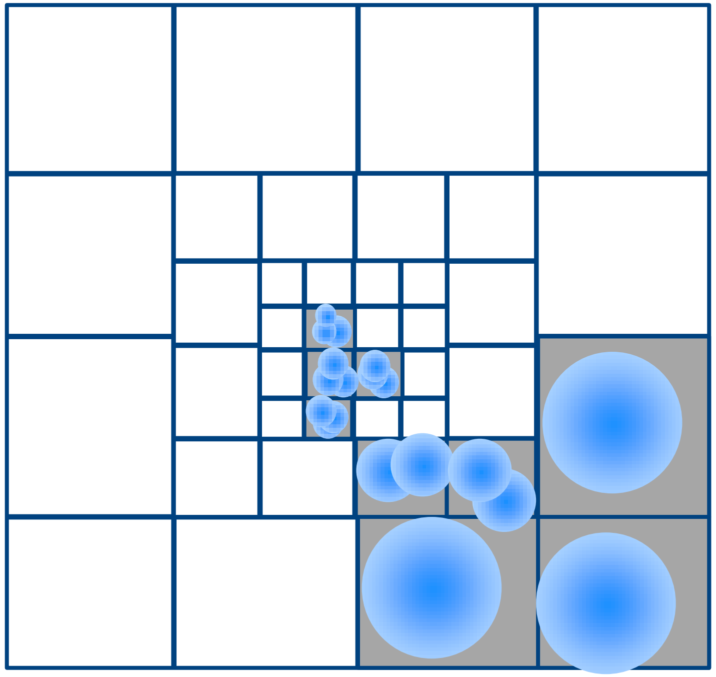
- Process cell grid and create a list of valid (non-empty) cells
    - One compute shader thread processes one cell
    - Append buffer is used to store indices of valid cells



Particle generation

Steps:

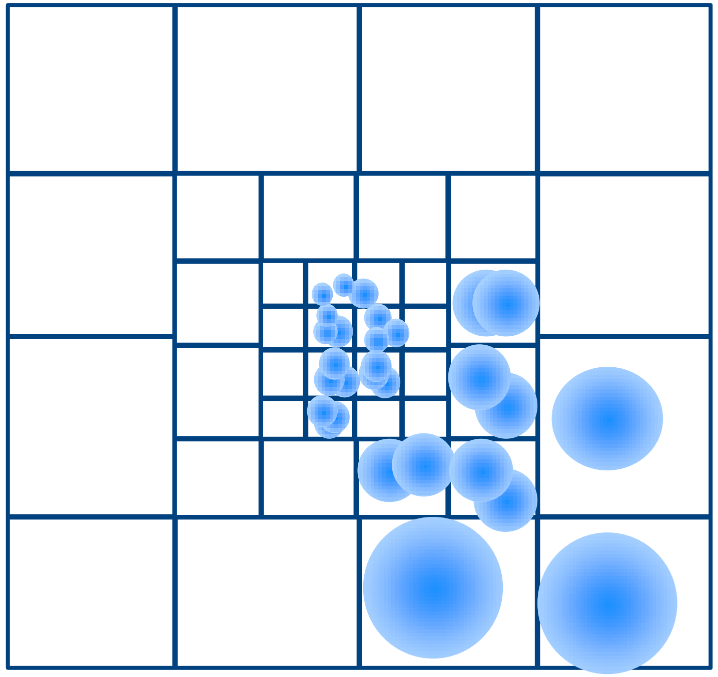
- Process each valid cell and create a list of valid particles in each cell
    - Use DispatchIndirect() to execute the required number of threads on GPU
    - One thread processes one valid cell and generates several particles



Particle generation

Animation:

Clouds are animated by changing particle size and transparency



Particle Rendering

Particle ordering

- Particles must be rendered in back to front order
  - Sorting on the GPU is very expensive
- We can sort cells on the CPU
  - Not all cells contain actual particles
- Solution:
  - Output particles only for valid cells
  - Use stream-out to preserve order
  - Process 32 particles by one GS thread

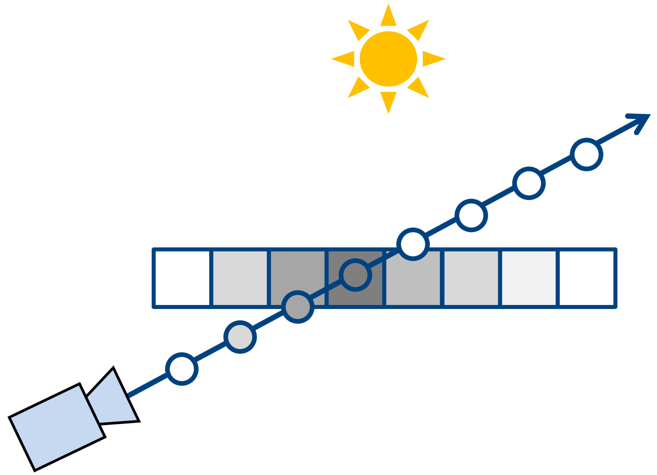
Particle Rendering

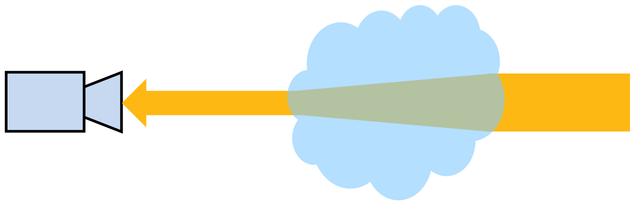
Particle processing

- DispatchIndirect() is used to execute CS computing light opacity for each valid particle
- DispatchIndirect() is used to execute CS computing visibility for each valid particle

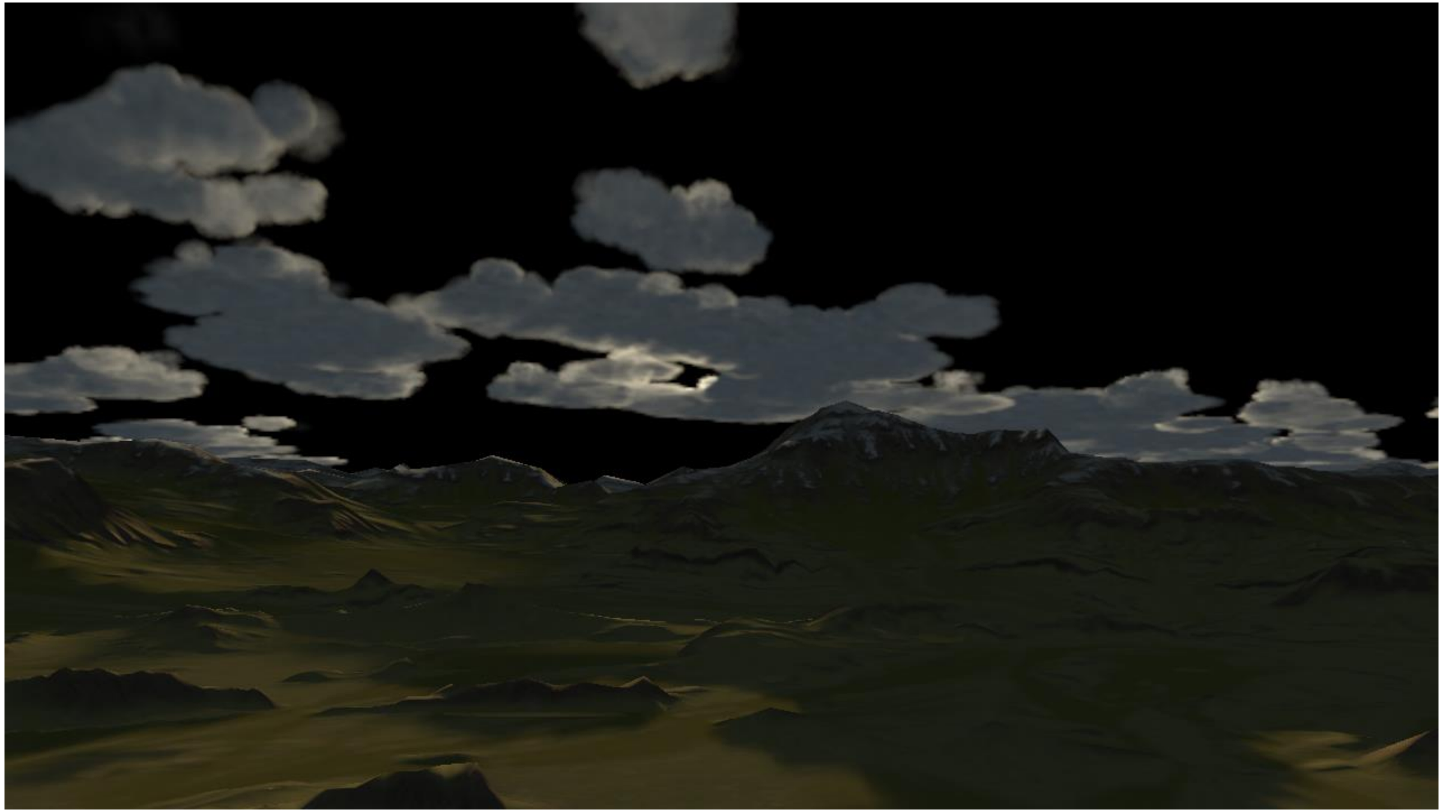
Integration with light scattering technique

- Cloud density texture is rendered from light
- At each ray marching step, it is determined if a point is above or under the cloud (clouds are assumed to have constant altitude)
- If point is under the clouds, the cloud density texture is sampled to get the occlusion by clouds
- Cloud transparency and distance to clouds in screen-space are used to attenuate scattering along view rays

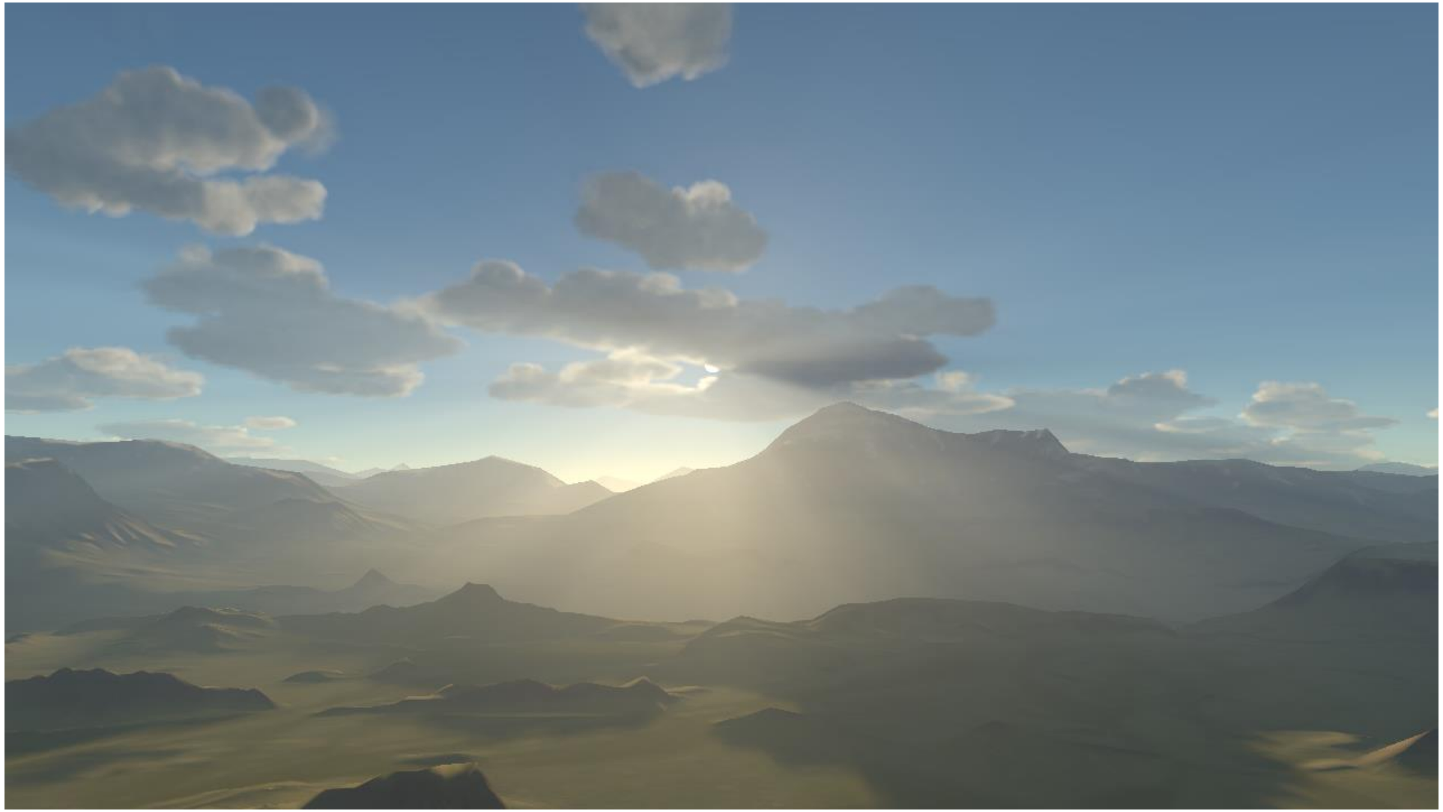




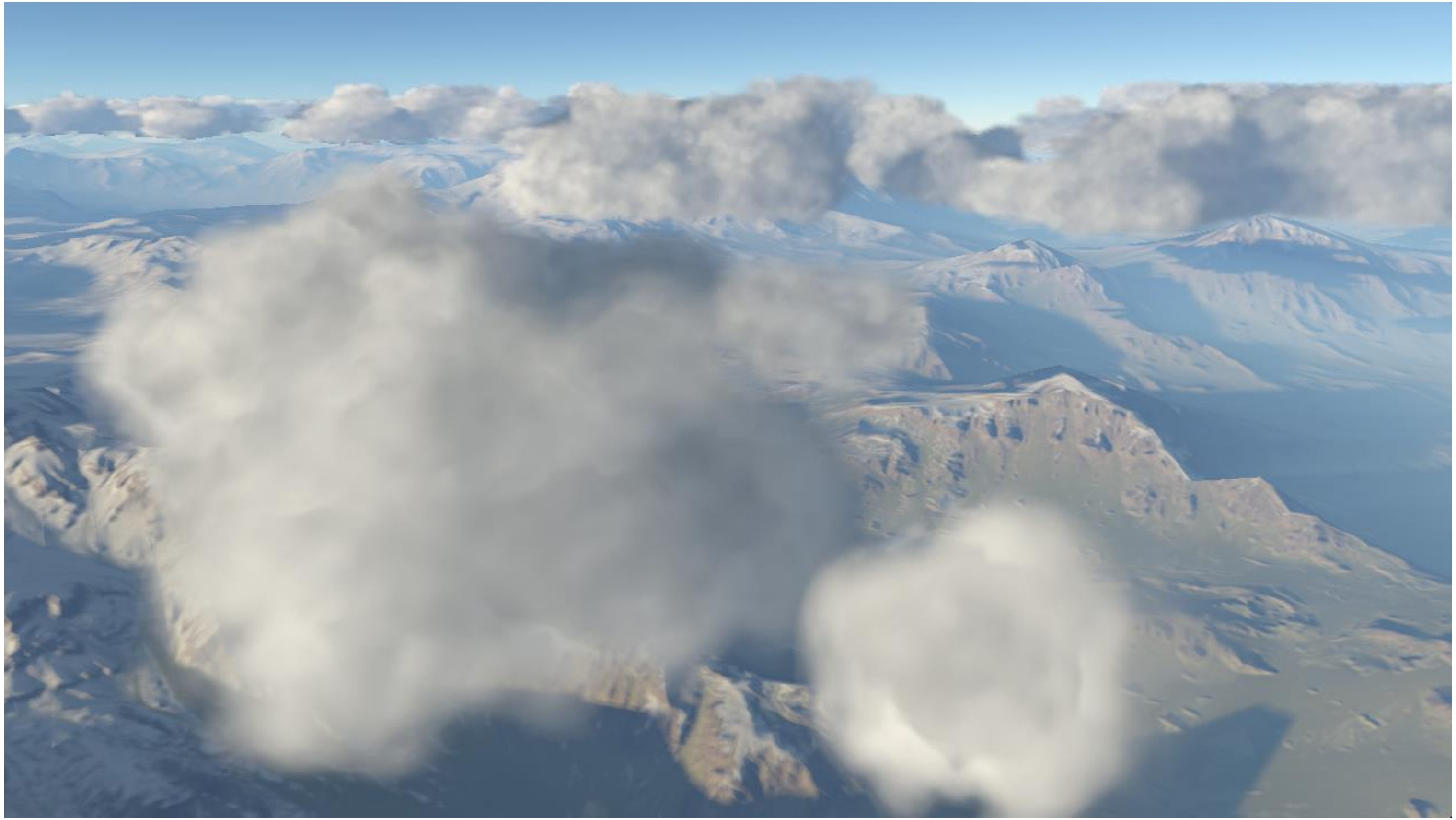
Integration with light scattering technique



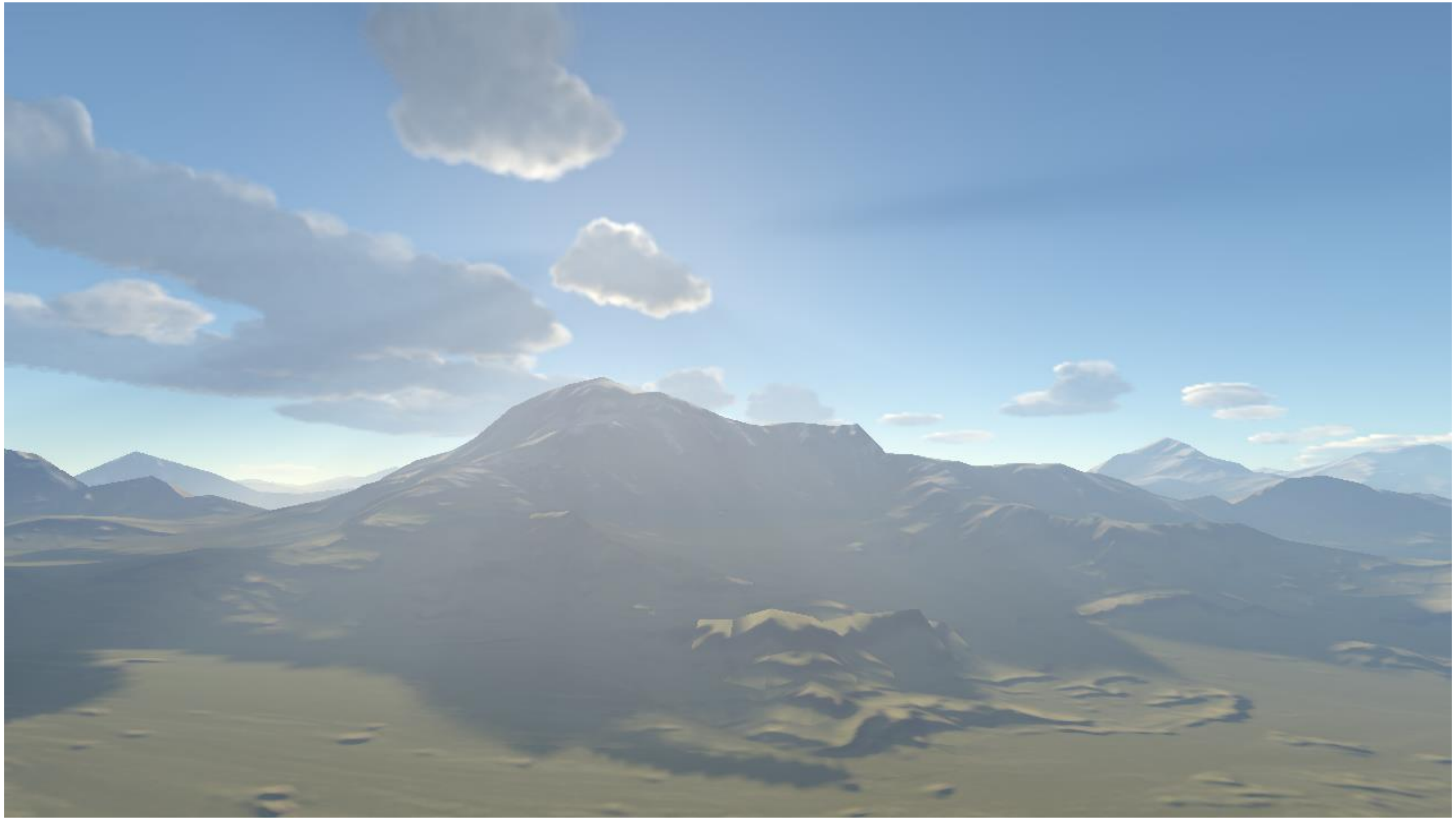
Integration with light scattering technique



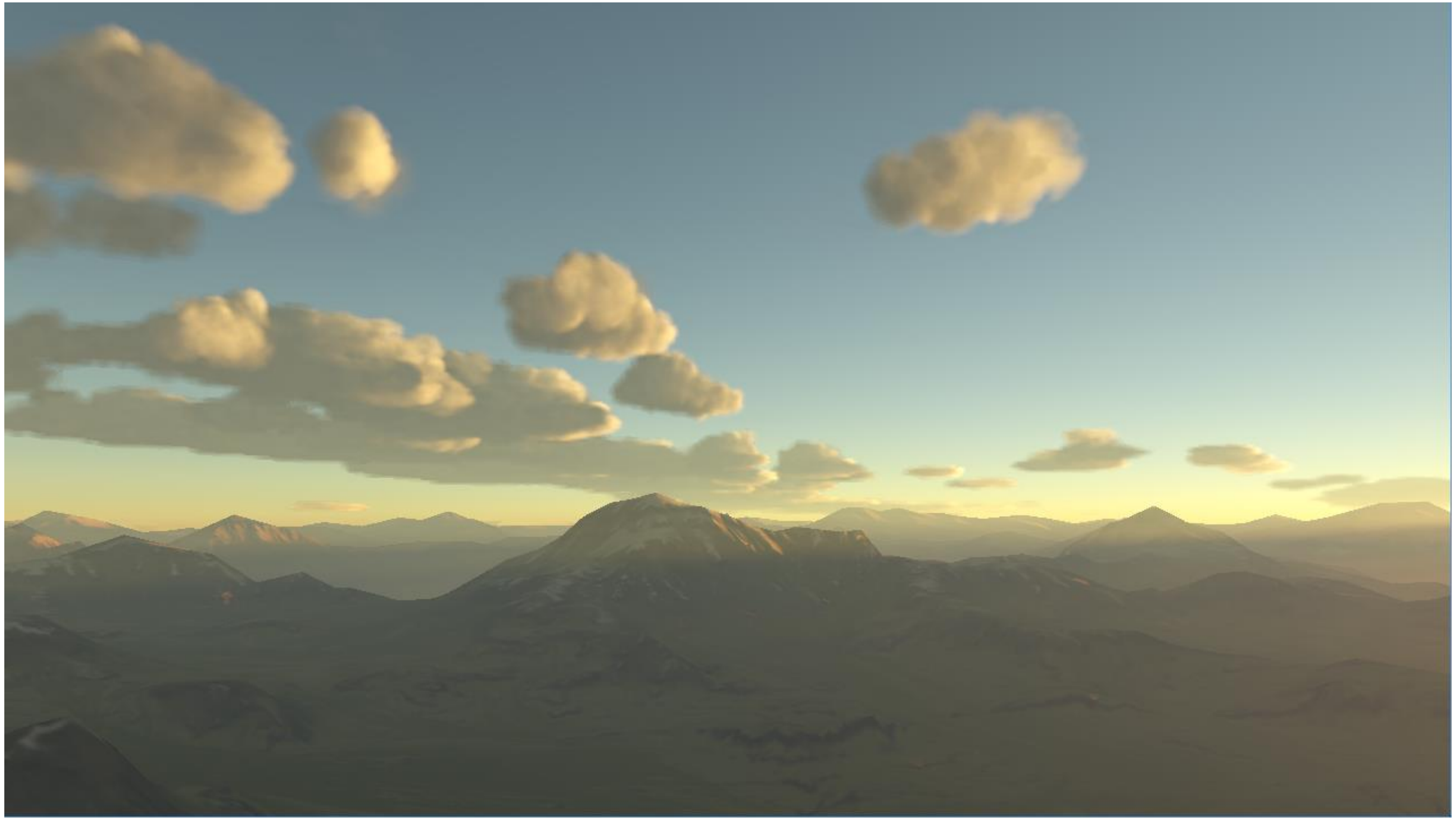
Results



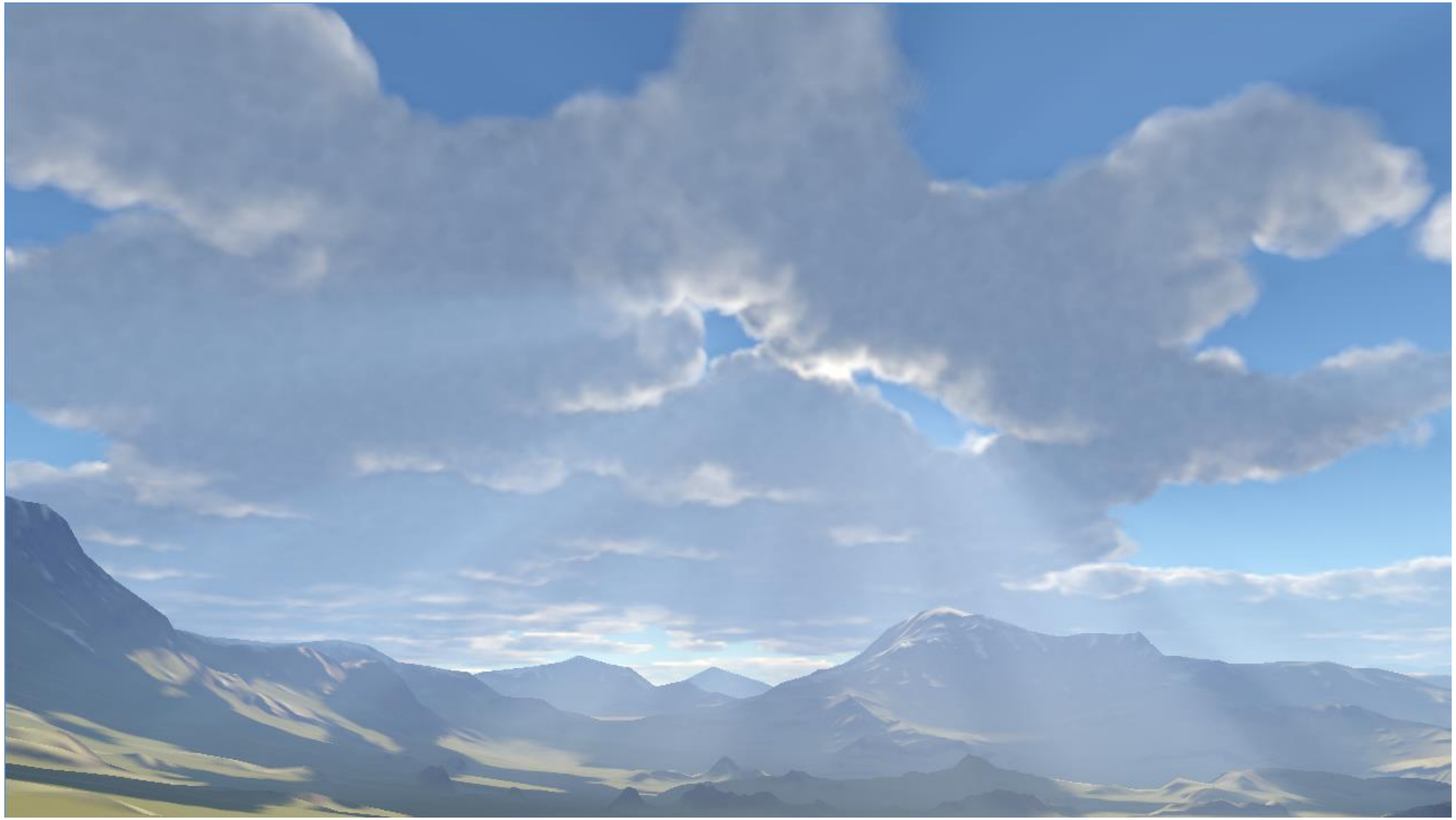
Results



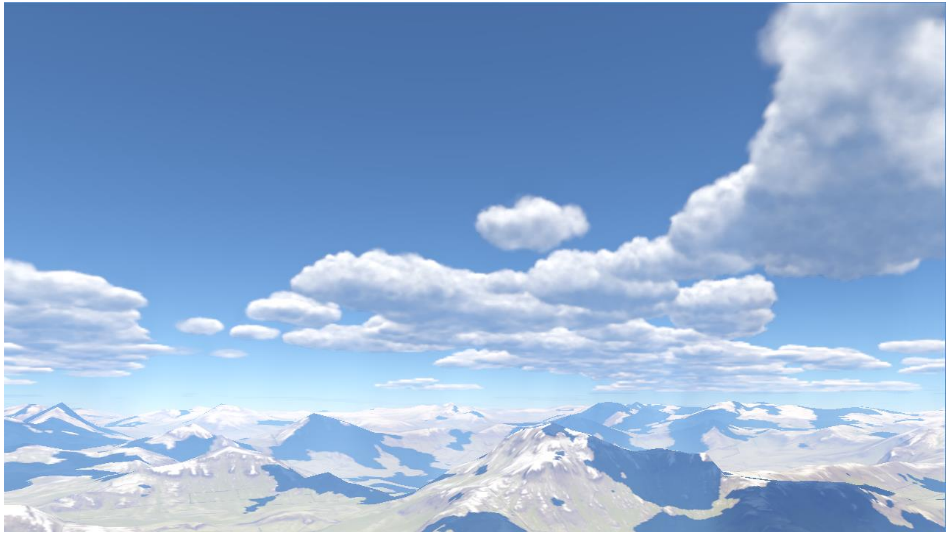
Results



Results



Results



Performance

Pre-computation

Computing optical depth integral takes less than 100 ms

- Switching between different noise generation methods can be done at run time

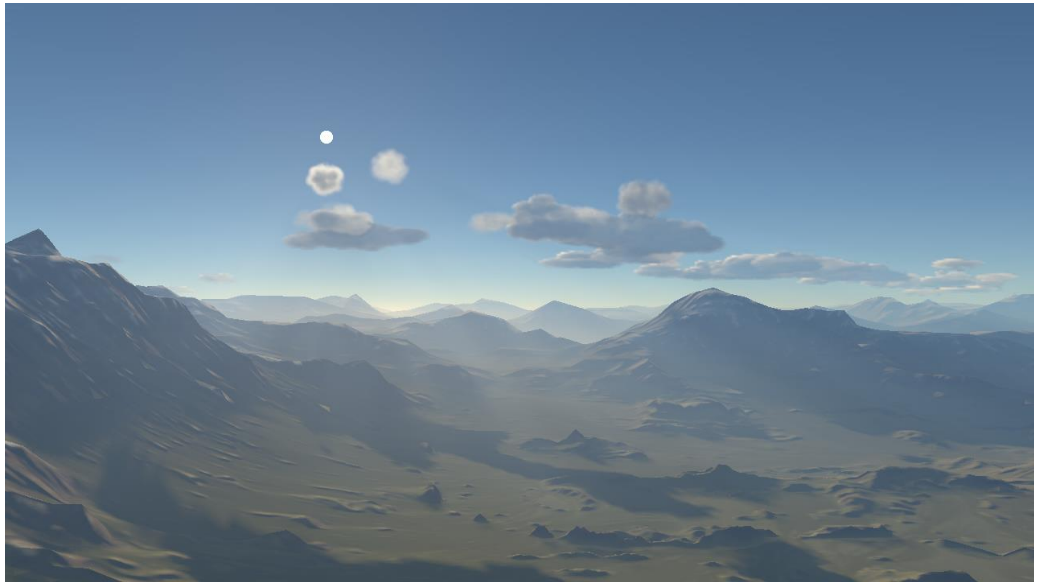
Pre-computing scattering requires several minutes

- Final look-up table is only 1 MB and thus can be distributed with the application

Performance

3.5 ms on Iris Pro 5200, 1280x720

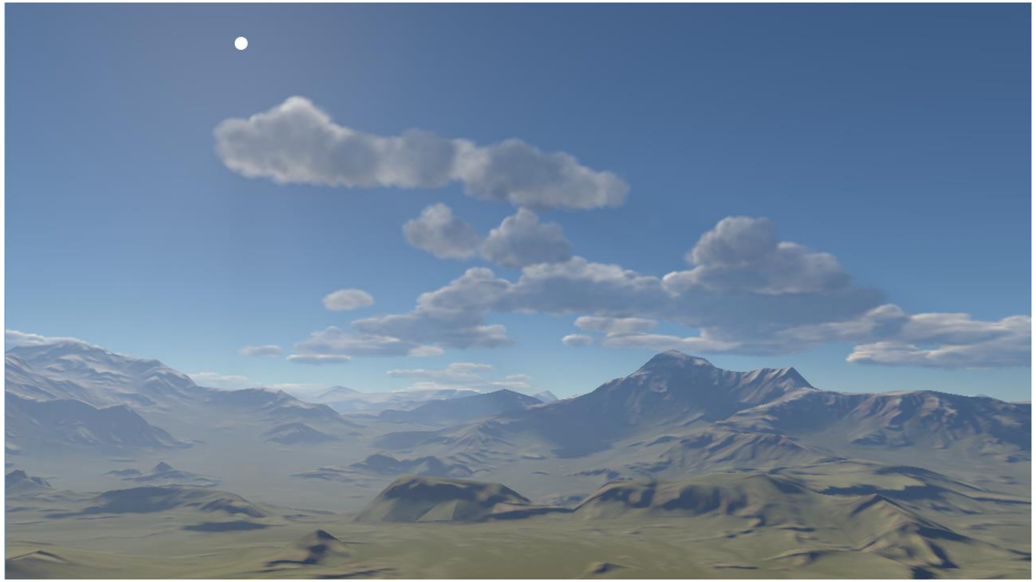
Grid size: 136x136x4x4; Half resolution rendering



Performance

12 ms on Iris Pro 5200, 1280x720

Grid size: 136x136x4x4; Half resolution rendering



Questions?

Thank You

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