Aesthetically-Oriented Atmospheric Scattering (AOAS)

Our aspiration to render aesthetically pleasing skies, with a sky style that can be interactively configured.

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Expressive 2019, Genoa, Italy / 06/04/2019
Motivation

Idea

Related Work

AOAS

Discussion

QA
Motivation

A Feeling

Sky is, mysterious, emotionally evocative

Movie “Amélie”
Directed by Jean-Pierre Jeunet, 2001
Motivation

A Feeling

Sky is, mysterious, emotionally evocative

Pixar “Up”
Directed by Pete Docter, 2009
Motivation

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Animated Film “The Little Prince”
Directed by Mark Osborne, 2015
Motivation

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Animated Film “Your Name”
Directed by Makoto Shinkai, 2017
Motivation

A Feeling

Sky is, mysterious, emotionally evocative

Video Game “Journey”
Developed by Thatgamecompany, 2012
We want to render these types of skies and make it interactively configurable.
Evolution of the Idea

- Impression
- Physics
- Imagination
- The Idea
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<tr>
<th>Impression</th>
<th>Gradient</th>
<th>Hue</th>
<th>Pattern</th>
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<tbody>
<tr>
<td><img src="image1" alt="Boston" />, <img src="image2" alt="Salt Lake City" />, <img src="image3" alt="Las Vegas" />, <img src="image4" alt="San Francisco" /></td>
<td><img src="image5" alt="Boston Gradient" />, <img src="image6" alt="Salt Lake City Gradient" />, <img src="image7" alt="Las Vegas Gradient" />, <img src="image8" alt="San Francisco Gradient" /></td>
<td><img src="image9" alt="Boston Hue" />, <img src="image10" alt="Salt Lake City Hue" />, <img src="image11" alt="Las Vegas Hue" />, <img src="image12" alt="San Francisco Hue" /></td>
<td><img src="image13" alt="Boston Pattern" />, <img src="image14" alt="Salt Lake City Pattern" />, <img src="image15" alt="Las Vegas Pattern" />, <img src="image16" alt="San Francisco Pattern" /></td>
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Photo Credit: Sophie photographies of Boston, Salt Lake City (left: top, bottom), Las Vegas, and San Francisco (right: top, bottom).
Evolution of the Idea

**Impression**
- Physics

**Physics**
- Evolution of the Idea
- Atmosphere Composition, etc
- Scattering Constants, Sunlight Direction etc

**Gradient**
- Stable
- Essential

**Hue**
- Dynamic
- Non-Essential

**Pattern**
- Dynamic
- Non-Essential

Scattering constants: how likely a wavelength is to be scattered by particles in the air.
Rayleigh Scattering: blue sky; Mie Scattering: sunlight halo; haze

Sunlight direction: varying atmosphere thicknesses went through by sunlight

Because of the influence of wind on droplets, clouds never stops changing
Evolution of the Idea

Impression

- Gradient
  - Atmosphere Composition, etc
  - Stable
  - Essential
  - Physically-Based

- Hue
  - Scattering Constants, Sunlight Direction etc
  - Dynamic
  - Non-Essential
  - Physically-Based to Non-Photorealistic
  - Non-Photorealistic Colors: green, yellow, ...

- Pattern
  - Cloud
  - Dynamic
  - Non-Essential
  - Physically-Based to Non-Photorealistic
  - Artistic Cloud Shape: animals, ...
  - Various Cloud Complexities
  - Ambiguity
### Evolution of the Idea

#### The Idea

Facilitate artistic iteration of sky style

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#### Gradient

- Atmosphere Composition, etc
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#### Hue

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## Evolution of the Idea

### The Idea

Facilitate artistic iteration of sky style

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<th>Transferrable</th>
<th>Immediate</th>
<th>Easy To Composite 3D Scene</th>
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### Impression

- **Physics**: Atmosphere Composition, etc
  - Stable
  - Essential
  - Physically-Based

- **Imagination**: Physically-Based to Non-Photorealistic
  - Non-Photorealistic Colors: green, yellow, ...
  - Artistic Cloud Shape: animals, ...
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### Gradient

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### Pattern

- **Cloud**: Physically-Based to Non-Photorealistic
- Dynamic
- Non-Essential
Evolution of the Idea

Impression

Physics

Imagination

The Idea

Facilitate artistic iteration of sky style

Transferrable

Immediate

Easy To Composite 3D Scene

Physically-Based ↔ Non-Photorealistic

Real-Time

Gradient
- Atmosphere Composition, etc
- Stable
- Essential
- Physically-Based

Hue
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Evolution of the Idea

The Idea

Physically-Based <-> Non-Photorealistic

Real-Time

Easy To Composite 3D Scene

Gradient Hue Pattern

Hue Pattern
### Related Work

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<td>Per85</td>
<td>ERWS12</td>
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- Sky: Physically-Based
- Cloud: Physically-Based
- RPO5: Real-Time
- ONe05: Real-Time
- ERWS12: Real-Time
- BNO8: Easy To Composite 3D Scene
- DYN02: Easy To Composite 3D Scene
- SFE07: Easy To Composite 3D Scene
- Val15: Easy To Composite 3D Scene
Nishita et al. proposed **scattering equations** based on Rayleigh and Mie Scatterings; display the Earth from the outer space; basis of more recent academic work on sky color simulation on modern GPU shaders with two pros.

**Pros:**
- Accurately simulate physically-based sky with single scattering
- High computational performance via evaluated optical depth

**Cons:**
- Did not achieve real-time performance in its implementation on an IRIS Indigo Elan

For the easy-to-compute scattering equations of Rayleigh and Mie Scatterings, we choose these single scattering equations to render the **physically-based sky**.
O’Neil describes CPU algorithm based on Nishita et al.’s scattering equations [ONe04], with lookup tables of optical depth in [ONe04], and math approximation in [ONe05].

**Pros:**
- **ONe05:** eliminates the necessity of lookup tables, reducing calculation overheads

**Cons:**
- Rely on two concentric spheres to represent the earth and its atmosphere - tricky and inconvenient to transform the 3D scene into the thin layer between the two spheres

We choose O’Neil’s math approximation of optical depth [ONe05], to for the **real-time performance** it brings in with physically-correct sky appearance.
Bruneton and Neyret render visible ground and atmosphere to a screen-space quad [BN08]. Each quad fragment is shaded by sampling pre-calculated 3D textures, proposed by Schafhitzel et al [SFE07], along the view ray. The texture stores scattering integrals of the multiple-scattering equations, an extension of Nishita et al.'s single-scattering formulation.

Pros:
- high performance on modern GPU
- multiple-scattering effects with any static 3D scene on the ground
- dynamic aerial perspective

Cons:
- Not easy to composite 3D scene: impossible for interactive scene exchange because scene structure is taken into account for physically-correct appearance of ground colors, shadows and light shafts
Related Work

Dobashi et al. render physically-based sky based on Rayleigh and Mie Scattering as well [DYN02].

Pros:
- Dynamic scene exploration in real-time made possible with lookup tables storing scattering intensities and attenuation ratios as functions of altitude, view direction, and the sun direction.

Cons:
- Memory intensive for the reliance on the texture memory - not a better alternative than [ONe05] to solely render sky
- Not intuitive for artist to composite 3D scene with screen-space quad as the geometric representation for sky rendering
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The Skybox technique renders any sky style in real-time with any 3D scene. Sky appearance is rendered on skybox or skydome with pre-baked texture.

Pros:
- Easy to composite 3D scene
- Real-time
- Low memory overhead

Cons:
- Time consuming for interactive style configuration

For the flexibility of composite with 3D scenes and low memory overhead, we choose Skybox technique for *compositing with 3D scenes*. Between skydome and skybox, we choose the former for its smoother surface.
Roden and Parberry render dynamic clouds with customized shapes by blending cloud textures [RP05].

**Cons:**
- Difficult to customize cloud shape because it's derived from real-world pictures.

Night sky (contrast applied) with 128x128 galaxy texture (inset) [RP05]
Elek et al. simulate light transport within clouds at a low computational cost by utilizing a temporally-coherent illumination caching process and a novel representation of angular distribution of illumination within clouds [ERW12].

**Pros:**
- Physically-based cloud covering most cloud types
- Simulate custom cloud shape with density field

**Cons:**
- Expensive to simulate custom cloud shape if too many density field is used

Algorithm overview [ERW12]
Although Perlin Noise is not designed for cloud rendering, it captures the random patterns in clouds and can be computed efficiently / asynchronously [Per85; Per02].

Perlin Noise can potentially support designing artistic clouds of arbitrary shape without noticeable performance penalties.
Aesthetic Principles Applied to Sky Hue and Sky Pattern
Perceive Sky from Ground
Problem of Geometric Representation in Rendering

Inflexible to fit 3D Scene Within the Thin Layer Between Earth and Atmosphere Skydomes
A Solution

Remove the Earth Skydome

Sunlight
A Solution

Keep the sky color along a view direction physically-based
How to Calculate the Sky Color along a View Direction?

![Diagram showing the relationship between sunlight and the sky color calculation]

- \( P_v \): Point on the ground
- \( P_f \): Point on the sky dome
- \( \vec{d} \): Vector from \( P_v \) to \( P_f \)

The diagram illustrates how to calculate the sky color along a view direction based on the sunlight and the position on the ground and sky dome.
How to Calculate the Sky Color along a View Direction?

- Physically-Based Atmospheric Scattering: In-Scattering
- O’Neil Optimization: Optical Depth Approximation with Surface Fitting
- AOAS: Simplified Geometric Representation of Sky from Two Skydomes to One
Physically-Based Atmospheric Scattering

In a nutshell, sky color along a view direction is:

Accumulation of lights scattered to the viewer’s eye from samples in the view direction.
Physically-Based Atmospheric Scattering

In a nutshell, sky color along a view direction is:

Accumulation of lights scattered to the viewer’s eye from samples in the view direction.

The light at each sample is scattered from sunlight direction.

Ground

Sunlight
Physically-Based Atmospheric Scattering

Sunlight

a) Sunlight travels to a sample in view direction along the sunlight direction: In-Scattering

c) Light at the sample in view direction travels to viewer’s eye: In-Scattering

b) Light from sunlight direction arrived the sample in view direction is then scattered towards the view direction: scaled by Phase Function based on the angle between view direction and sunlight direction

In-Scattering between two samples:

Remaining light; exponential of the negative of:

Out-Scattering: away light; proportional to:

Optical Depth: average atmospheric density; stable in Rayleigh and Mie Scatterings; 
expensive
Optical depth of a sample towards a direction to the outer atmosphere is approximated in terms of altitude and vertical angle.

Surface fitting of optical depth of Rayleigh (Top) and Mie Scatterings (Bottom).
Optical depth of a sample towards a direction to the outer atmosphere is approximated in terms of altitude and vertical angle.

Surface fitting of optical depth of Rayleigh (Top) and Mie Scatterings (Bottom).
O’Neil Input Parameters

- $\vec{d}$: View direction of the viewer in Earth space
- $P_v$: Position of the viewer in Earth space
- $P_i$: Position of ray-marching sample in Earth space

Pre-defined variables:

- Sunlight direction
- Ray marching step
AOAS: Directly Ray Marching in Skydome Space Isn’t Possible to Obtain Vertical Angle for the Same Altitude
AOAS: Directly Ray Marching in Skydome Space Isn’t Possible to Obtain Vertical Angle for the Same Altitude. Hence, affect the input parameters.
AOAS: Transform to Earth Space

**Assumption:** Shared Apex Direction of the Viewer in Skydome and Earth Spaces

**Observation:** Shared View Direction

**Viewer Position**

\[ P_v = P_v^s + r \cdot \frac{P_v^s - O}{\|P_v^s - O\|} \]

**View Direction**

\[ \vec{d} = \frac{P_f^s - P_v^s}{\|P_f^s - P_v^s\|} \]

**Position of Ray-Marching Sample in Earth space**

\[ P_i = P_{i-1} + t \cdot \vec{d}, \quad P_0 = P_v \]
AOAS: One Skydome Overview

Sunlight
Ground
Apex Direction
Earth Space

Sunlight
Ground
Apex Direction
Skydome Space
AOAS: Additional Benefits of One Skydome

Sky color and distribution perceived by the viewer stays invariant of the scaling transformation of the atmosphere skydome.

Sky color and distribution perceived by the viewer stays invariant of the scaling transformation of the atmosphere skydome. Skies within the same column share the same viewer position in skydome space, which is different between columns. **Top to bottom:** tall, regular, and short skies. All skies share the same sunlight direction - from skydome center to the yellow quad.
Physical sky is already very beautiful.

But..

Let’s explore more to render beyond physical appearance!
Based on our observations, we believe that the non-stable characteristics of the sky create an opportunity for artistic expression.

More specifically, we believe that specifying non-photorealistic values for the sky hue and the sky pattern can generate artistically driven sky styles, however the sky gradient must remain physically-based to make the sky recognizable.

Despite this constraint, a variety of imaginative artistic styles are achievable.
Aesthetic Principles

Artistic Color: Hue

Ambiguity: Pattern

Custom Cloud Shape: Pattern
Aesthetic Principles

Artistic Color:

Any color for scattering constant
Aesthetic Principles

Artistic Color:

Custom Sunlight Direction
Aesthetic Principles

Ambiguity: Perturb View Direction
Ambiguity: Perturb View Direction

Perturbing the view direction. The sky color along the view direction towards fragment \( P_{f'}^s \) (solid blue arrow) is obtained by the unperturbed sky color of another fragment \( P_f^s \) (red arrow). \( P_{f'}^s \) (dashed arrow) is a random fragment from a neighborhood of \( P_f^s \) with configurable size \( l_{pt} \).
Aesthetic Principles

Custom Cloud Shape

Perlin noise for cloud complexity
Aesthetic Principles

Custom Cloud Shape

Indicate cloud shape with points and splines
MUSEUM OF FINE ARTS, BOSTON.
Winnie-the-Pooh: Exploring a Classic.
2019 1.
Style Config Example: Winnie-the-Pooh
Style Config Example: Winnie-the-Pooh
Style Config Example: Winnie-the-Pooh

Three points to indicate smiley clouds for fragments of the Earth skydome
Style Config Example: Winnie-the-Pooh

Heart spline to indicate heart clouds for fragments of the Earth skydome
Style Config Example: Winnie-the-Pooh
Style Config Example: Winnie-the-Pooh
Style Config Example: Winnie-the-Pooh
Style Config Example: 3D Futuristic City

Explore sky style for 3D model in Blender Game Engine
Style Config Example: 3D Futuristic City

Explore sky style for 3D model in Blender Game Engine
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Explore sky style for 3D model in Blender Game Engine
Contribution

Simplify Geometric Representation to Leverage of Flexibility of Skydome in Compositing with any 3D Scene

Essential and Non-Essential Characteristics of Sky

- Essential: sky gradient
- Non-essential: sky hue, pattern

Aesthetic Principles: Vary Non-Essential Characteristics to Create Artistic Style from Physically-Based Style

- Non-photorealistic scattering constants for sky hue
- Sunlight direction for sky hue
- Ambiguity for sky pattern
- Cloud complexity for sky pattern
- Custom cloud shape for sky pattern
Discussion

Future Work:

Open Source
Global Illumination
Qualitative Artistic Evaluation

Create Computer Art:

Combine Physically-Based Technique and Aesthetic Principles?
Thank you for the attention! Any questions?

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More Explanations
Physically-Based Atmospheric Scattering

Rayleigh Scattering

Mie Scattering

Mie Scattering, larger particles

Direction of incident light

Rayleigh Scattering

Mie Scattering

From overhead, the Rayleigh scattering is dominant, the Mie scattered intensity being projected forward. Since Rayleigh scattering strongly favors short wavelengths, we see a blue sky.

Observer

When there is large particulate matter in the air, the forward lobe of Mie scattering is dominant. Since it is not very wavelength dependent, we see a white glare around the sun.