Aesthetically-Oriented Atmospheric Scattering (AOAS)

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

Yang Shen (Sophie) / Originate, Dopamine Animatic
Ian Mallett / University of Utah
Konstantin Shkurko / University of Utah

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

THE UNIVERSITY OF UTAH

Originate

Dopamine Animatic

Layout

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

A Feeling

Sky is, mysterious, emotionally evocative

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

Motivation

A Feeling

Sky is, mysterious, emotionally evocative

Animated Film "Your Name"
Directed by Makoto Shinkai, 2017

Motivation

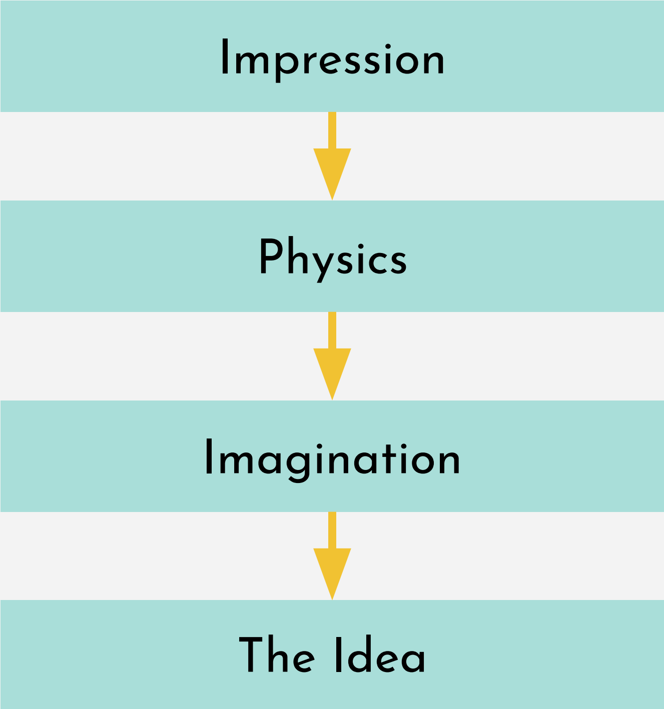
A Feeling

Sky is, mysterious, emotionally evocative

Video Game "Journey"
Developed by Thatgamecompany, 2012

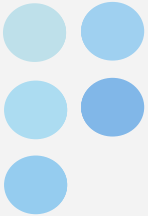
We want to render these types of skies and make it interactively configurable.

Evolution of the Idea



Evolution of the Idea

Impression | **Gradient** | **Hue** | **Pattern**



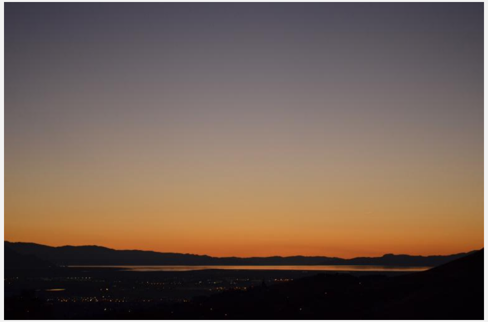


Photo Credit: Sophie photographies of Boston, Salt Lake City (left: top, bottom), Las Vegas, and San Francisco (right: top, bottom).

Evolution of the Idea

Impression

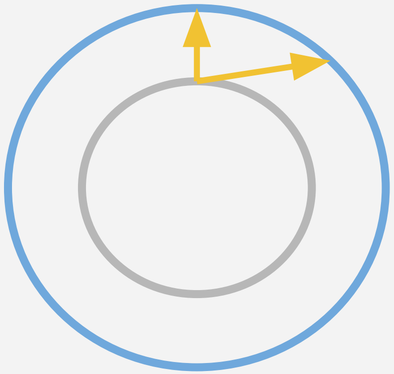
Physics

Gradient

Atmosphere Composition, etc

Stable

Essential



Hue

Scattering Constants, Sunlight Direction etc

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

Pattern

Cloud

Dynamic

Non-Essential

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

Evolution of the Idea

Impression	Gradient	Hue	Pattern
Physics	Atmosphere Composition, etc	Scattering Constants, Sunlight Direction etc	Cloud
	Stable	Dynamic	Dynamic
	Essential	Non-Essential	Non-Essential
Imagination	**Physically-Based**	**Physically-Based to Non-Photorealistic**	**Physically-Based to Non-Photorealistic**
		Non-Photorealistic Colors: green, yellow, …	*- Artistic Cloud Shape: animals, …* *- Various Cloud Complexities* *- Ambiguity*

Evolution of the Idea

	Gradient	Hue	Pattern
Impression	Gradient	Hue	Pattern
Physics	Atmosphere Composition, etc	Scattering Constants, Sunlight Direction etc	Cloud
	Stable	Dynamic	Dynamic
	Essential	Non-Essential	Non-Essential
Imagination	Physically-Based	Physically-Based to Non-Photorealistic	Physically-Based to Non-Photorealistic
		Non-Photorealistic Colors: green, yellow, …	*- Artistic Cloud Shape: animals, …* *- Various Cloud Complexities* *- Ambiguity*
The Idea	**Facilitate artistic iteration of sky style**		

Evolution of the Idea

	Gradient	Hue	Pattern
Impression			
Physics	Atmosphere Composition, etc	Scattering Constants, Sunlight Direction etc	Cloud
	Stable	Dynamic	Dynamic
	Essential	Non-Essential	Non-Essential
Imagination	Physically-Based	Physically-Based to Non-Photorealistic	Physically-Based to Non-Photorealistic
		Non-Photorealistic Colors: green, yellow, …	*- Artistic Cloud Shape: animals, …* *- Various Cloud Complexities* *- Ambiguity*

The Idea

Facilitate artistic iteration of sky style

Transferrable **Immediate** **Easy To Composite 3D Scene**

Evolution of the Idea

	Gradient	Hue	Pattern
Impression			
Physics	Atmosphere Composition, etc	Scattering Constants, Sunlight Direction etc	Cloud
	Stable	Dynamic	Dynamic
	Essential	Non-Essential	Non-Essential
Imagination	Physically-Based	Physically-Based to Non-Photorealistic	Physically-Based to Non-Photorealistic
		Non-Photorealistic Colors: green, yellow, …	*- Artistic Cloud Shape: animals, …* *- Various Cloud Complexities* *- Ambiguity*

The Idea

Facilitate artistic iteration of sky style

Transferrable	Immediate	Easy To Composite 3D Scene
Physically-Based ⟷ **Non-Photorealistic**	**Real-Time**	

Evolution of the Idea

The Idea

Physically-Based ⟷ Non-Photorealistic

Real-Time

Easy To Composite 3D Scene

Gradient
Hue
Pattern

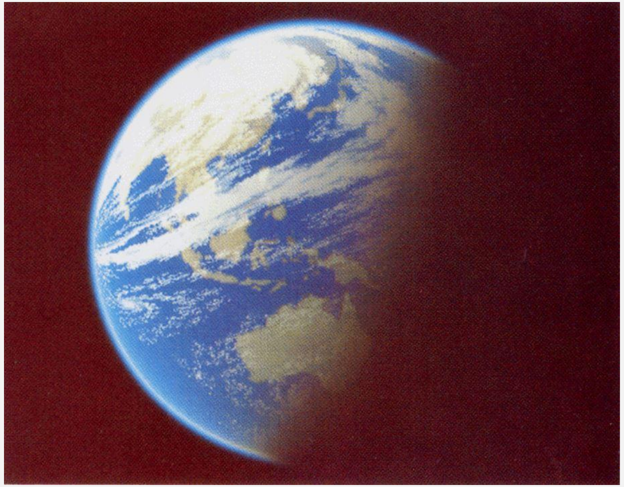
Hue
Pattern

Related Work

Physically-Based		Non-Photorealistic		Real-Time	Easy To Composite 3D Scene
Sky	Cloud	Sky	Cloud		
NSTN93	Per85		RP05	ONe04	BN08
	Per02		ERWS12	ONe05	DYN02
				SFE07	Val15
				DYN02	

Related Work

Physically-Based		⟷	Non-Photorealistic		Real-Time	Easy To Composite 3D Scene
Sky	Cloud		Sky	Cloud		
NSTN93						



Display the earth from the outer space [NSTN93]

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:

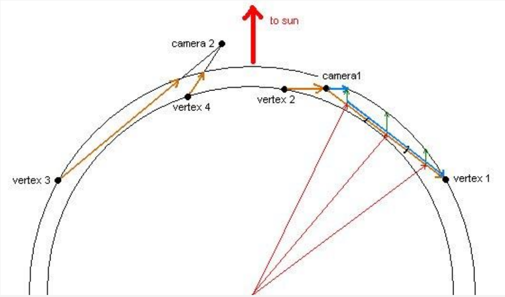
- Did not achieve real-time performance in its implementation on an IRIS Indigo Elan

For the easy-to-compute scattering equations of Rayleigh and Mie Scatterings, we choose these single scattering equations to render the **physically-based sky**.

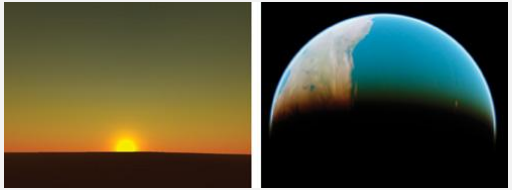
Related Work

Physically-Based ⟷ **Non-Photorealistic**

Physically-Based		Non-Photorealistic		Real-Time	Easy To Composite 3D Scene
Sky	Cloud	Sky	Cloud	ONe04	
NSTN93				ONe05	



Lookup tables with four channels for Rayleigh and Mie Scatterings [ONe04]



Physically-accurate atmospheric scattering [ONe05]

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.

Related Work

Physically-Based		Non-Photorealistic		Real-Time	Easy To Composite 3D Scene
Sky	Cloud	Sky	Cloud		
NSTN93				ONe05	**BN08**
				SFE07	

Aerial perspective [BN08]

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:

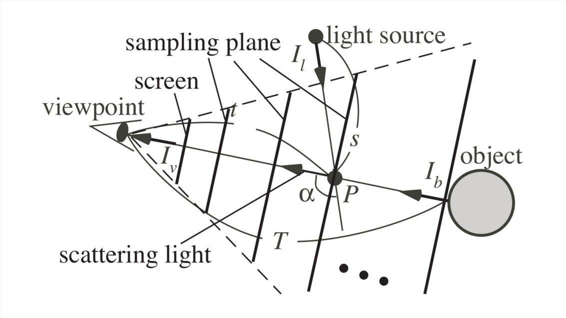
- high performance on modern GPU
- multiple-scattering effects with any static 3D scene on the ground
- dynamic aerial perspective

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

Physically-Based			Non-Photorealistic		Real-Time	Easy To Composite 3D Scene
Sky	Cloud		Sky	Cloud		
NSTN93					ONe05	**DYN02**



Calculation of atmospheric scattering of light [DYN02]

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

Pros:

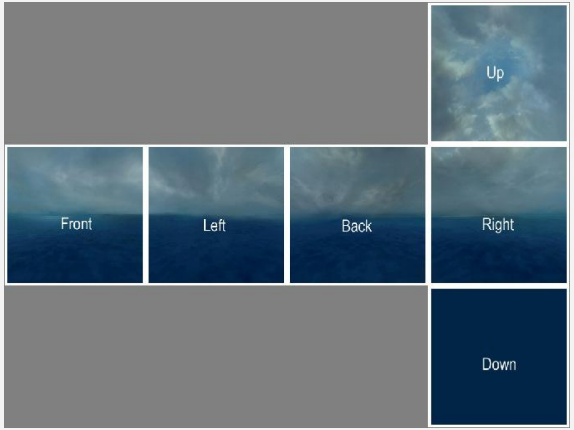
- Dynamic scene exploration in real-time made possible with lookup tables storing scattering intensities and attenuation ratios as functions of altitude, view direction, and the sun direction.

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

Related Work

Physically-Based		Non-Photorealistic		Real-Time	Easy To Composite 3D Scene
Sky	Cloud	Sky	Cloud		
NSTN93		**Val15**		ONe05	**Val15**
				Val15	



Sky texture for Skybox [Val15]

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

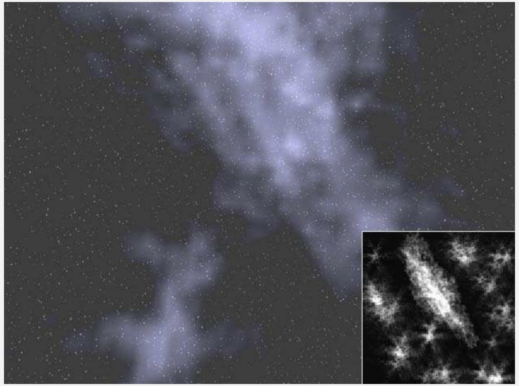
Cons:

- 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.

Related Work

Physically-Based		↔	Non-Photorealistic		Real-Time	Easy To Composite 3D Scene
Sky	Cloud		Sky	Cloud		
NSTN93				**RP05**	ONe05	Val15



Night sky (contrast applied) with 128x128 galaxy texture (inset) [RP05]

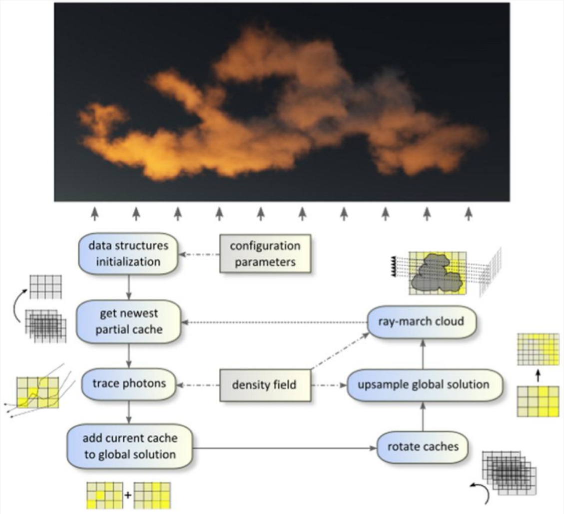
Roden and Parberry render dynamic clouds with customized shapes by blending cloud textures [RP05].

Cons:

- Difficult to customize cloud shape because its derived from real world pictures

Related Work

Physically-Based		Non-Photorealistic		Real-Time	Easy To Composite 3D Scene
Sky	Cloud	Sky	Cloud		
NSTN93			**ERWS12**	ONe05	Val15
				ERWS12	



Algorithm overview [ERW12]

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

Related Work

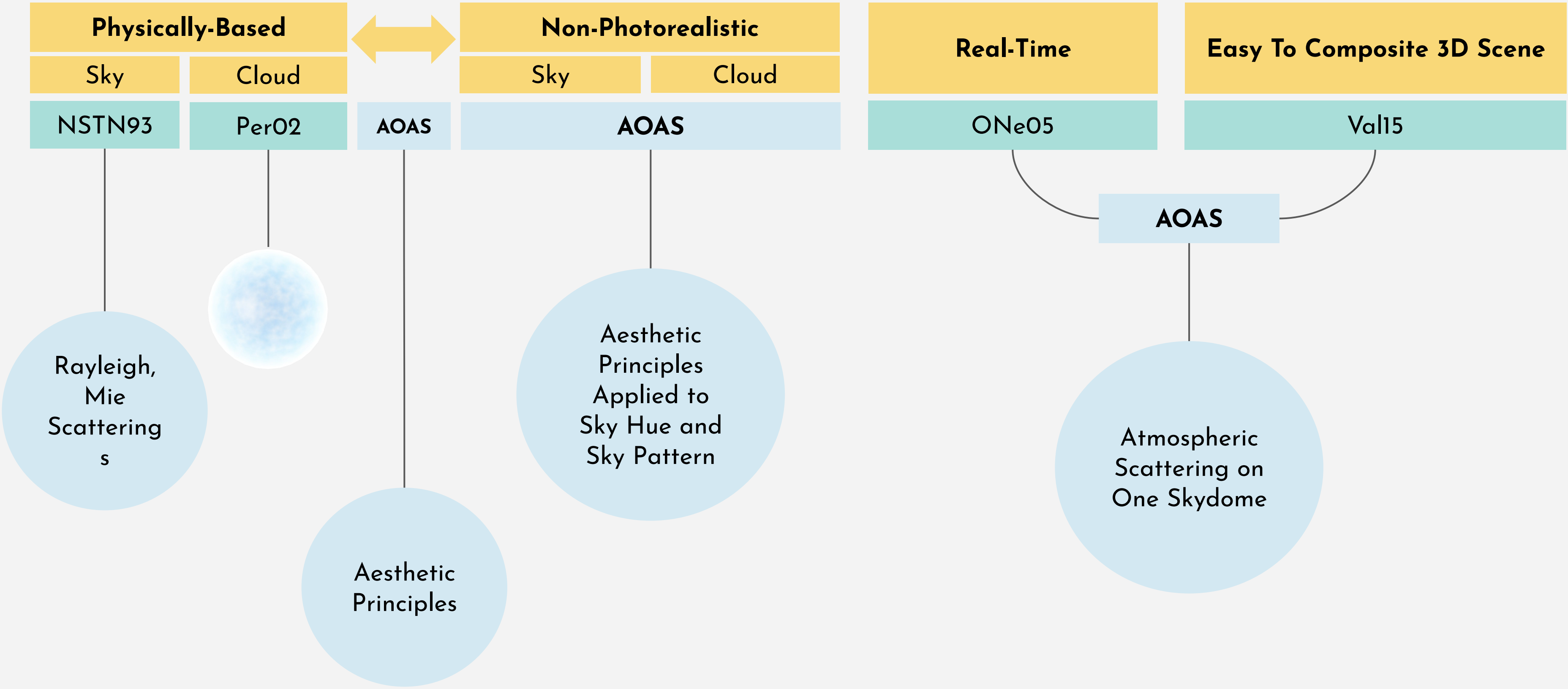
Physically-Based		Non-Photorealistic		Real-Time	Easy To Composite 3D Scene
Sky	Cloud	Sky	Cloud		
NSTN93	**Per85**			ONe05	Val15
	Per02				

An image synthesizer [Per85]

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

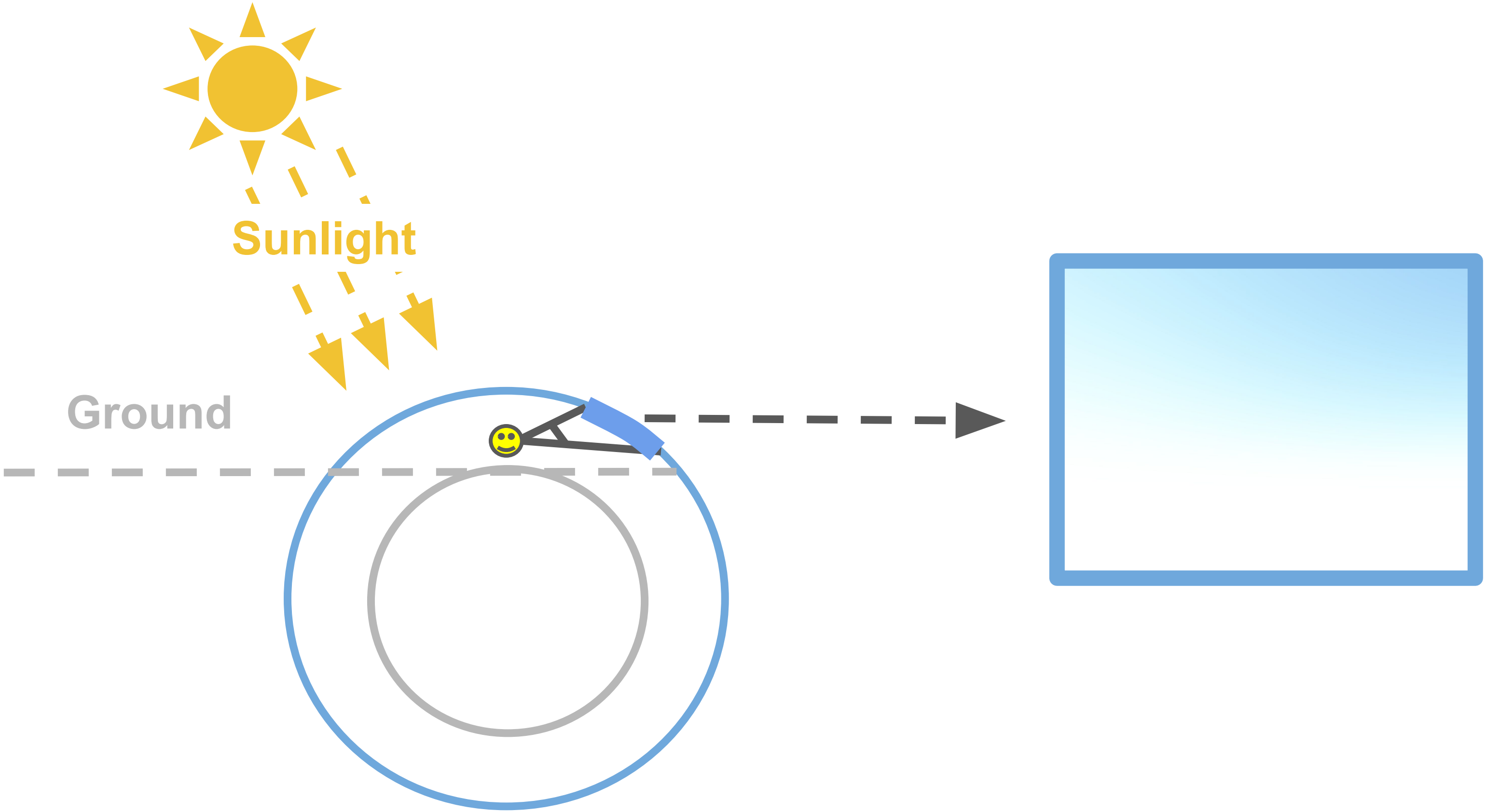
Perlin Noise can potentially support designing artistic clouds of arbitrary shape without noticeable performance penalties.

AOAS


Physically-Based
Sky
Cloud
NSTN93
Per02
Rayleigh, Mie Scatterings
AOAS
Aesthetic Principles
Non-Photorealistic
Sky
Cloud
AOAS
Aesthetic Principles Applied to Sky Hue and Sky Pattern
Real-Time
ONe05
Easy To Composite 3D Scene
Val15
AOAS
Atmospheric Scattering on One Skydome

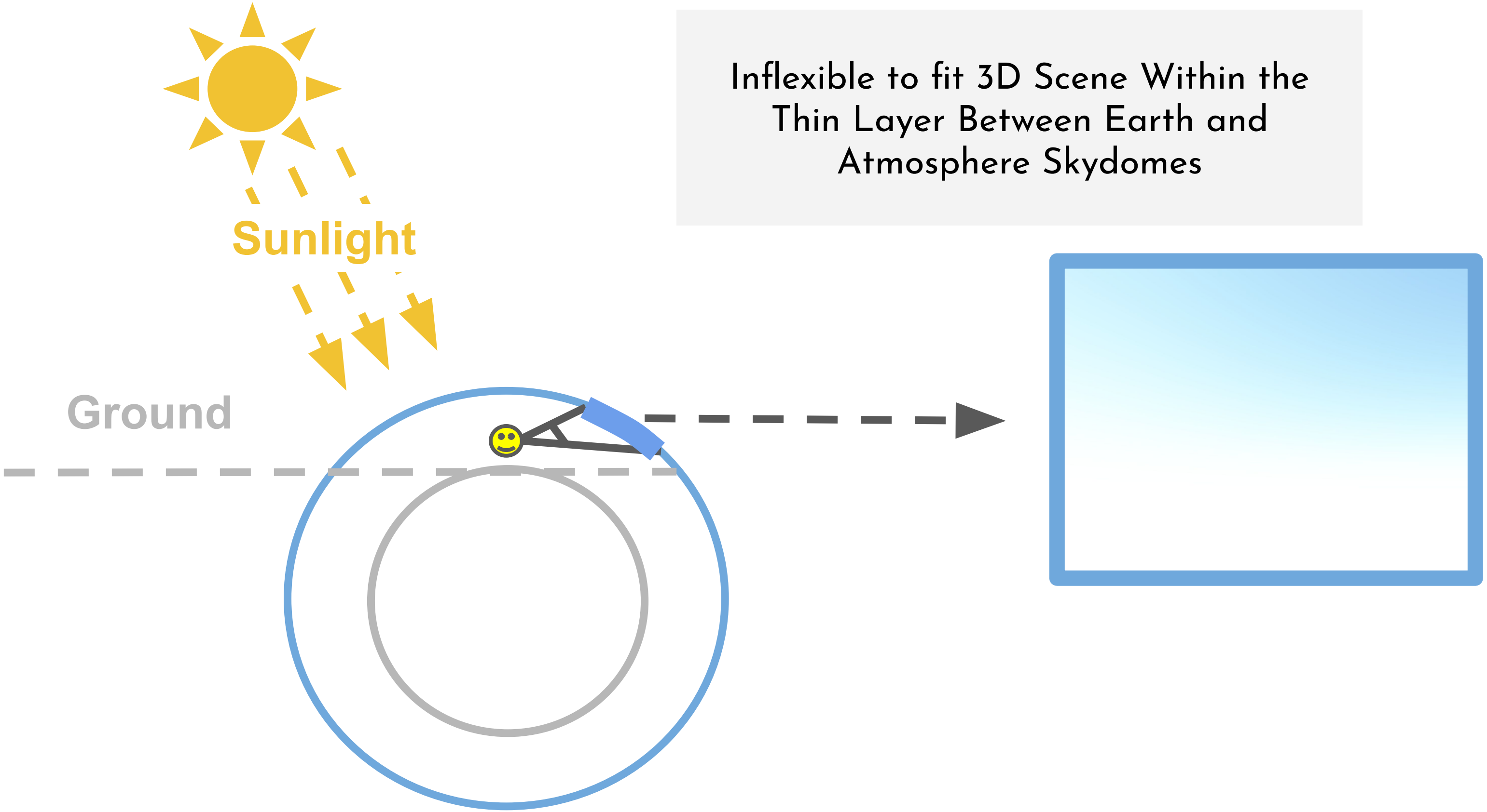
LIVE DEMO AVAILABLE!

Perceive Sky from Ground



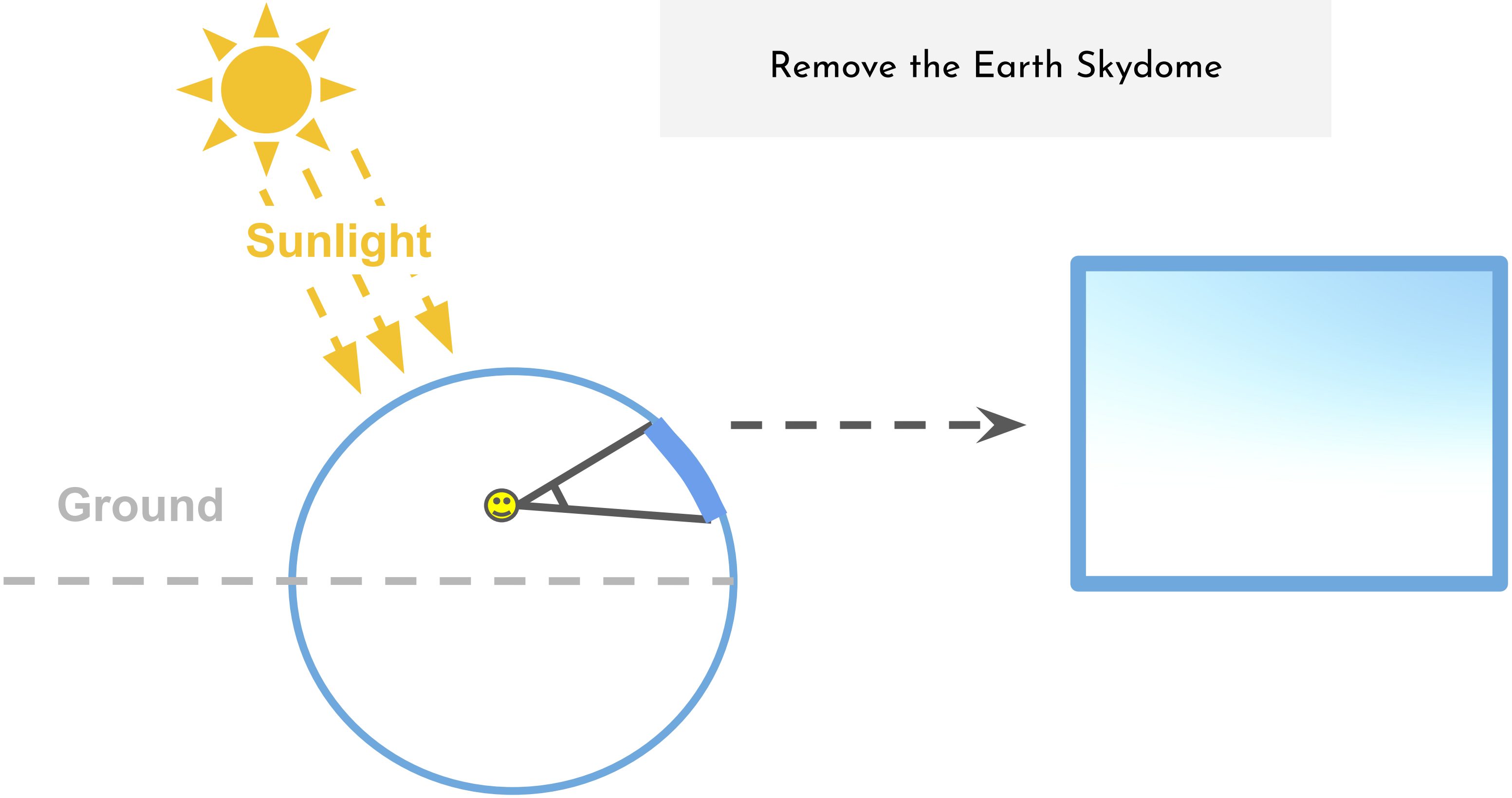
Problem of Geometric Representation in Rendering

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



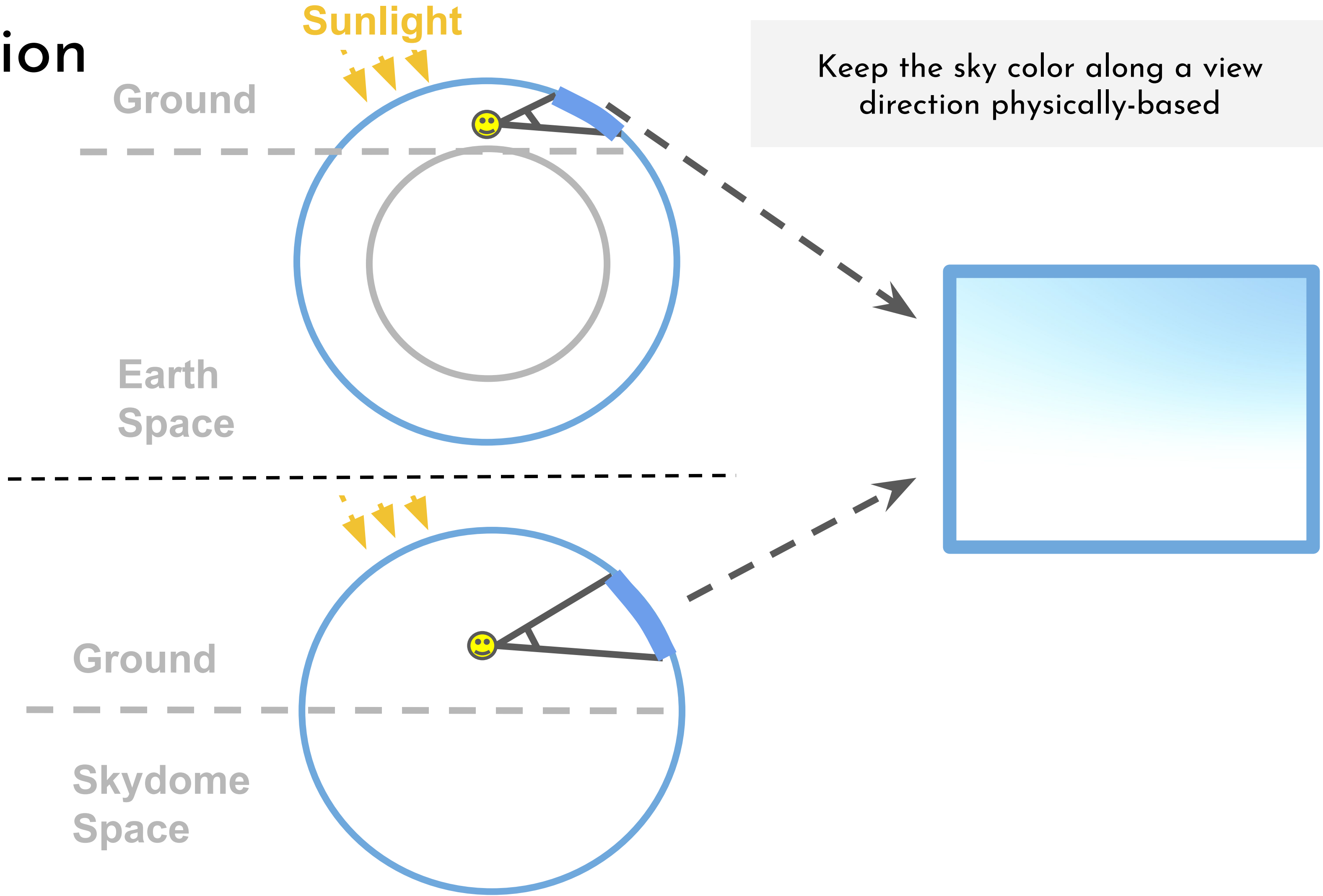
A Solution

Remove the Earth Skydome

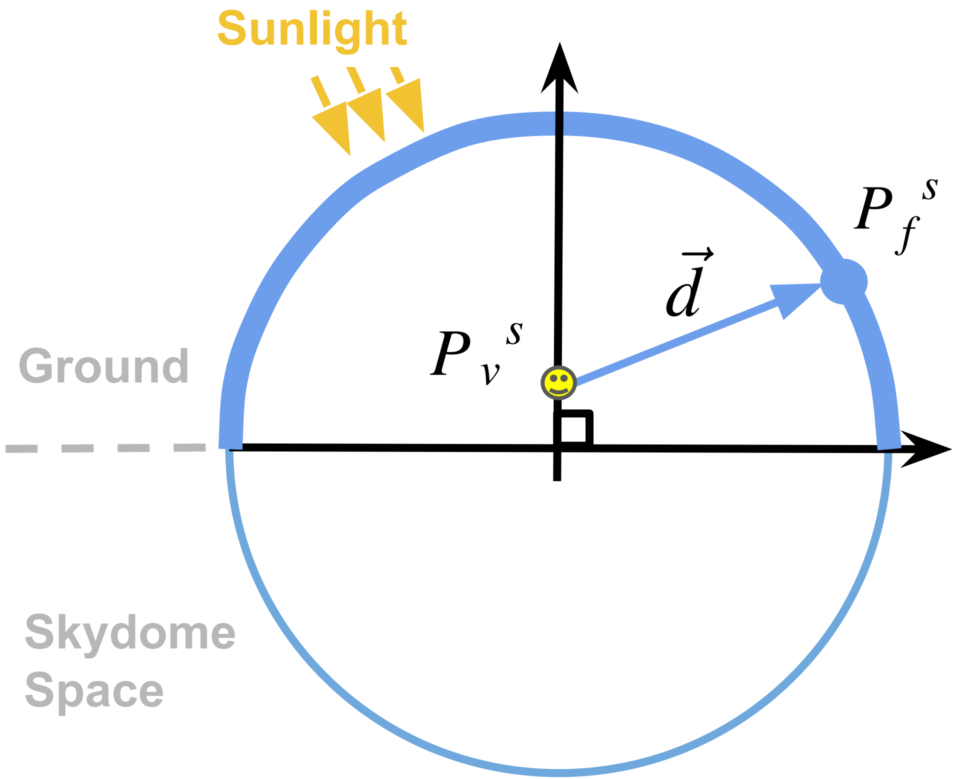


A Solution

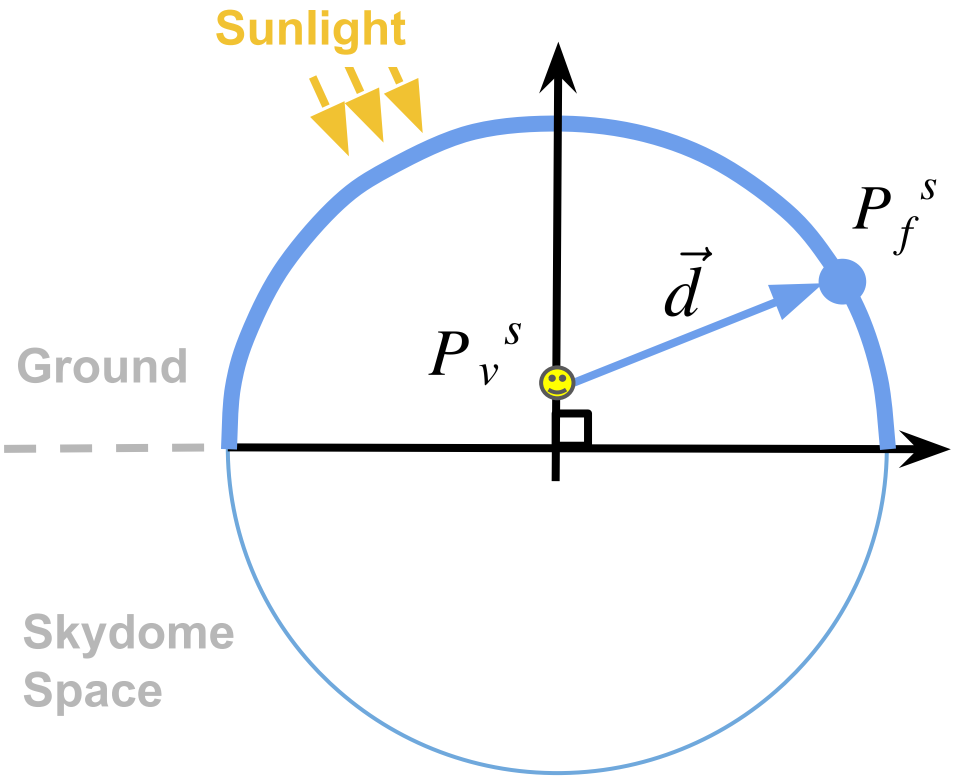
Keep the sky color along a view direction physically-based



How to Calculate the Sky Color along a View Direction?



How to Calculate the Sky Color along a View Direction?

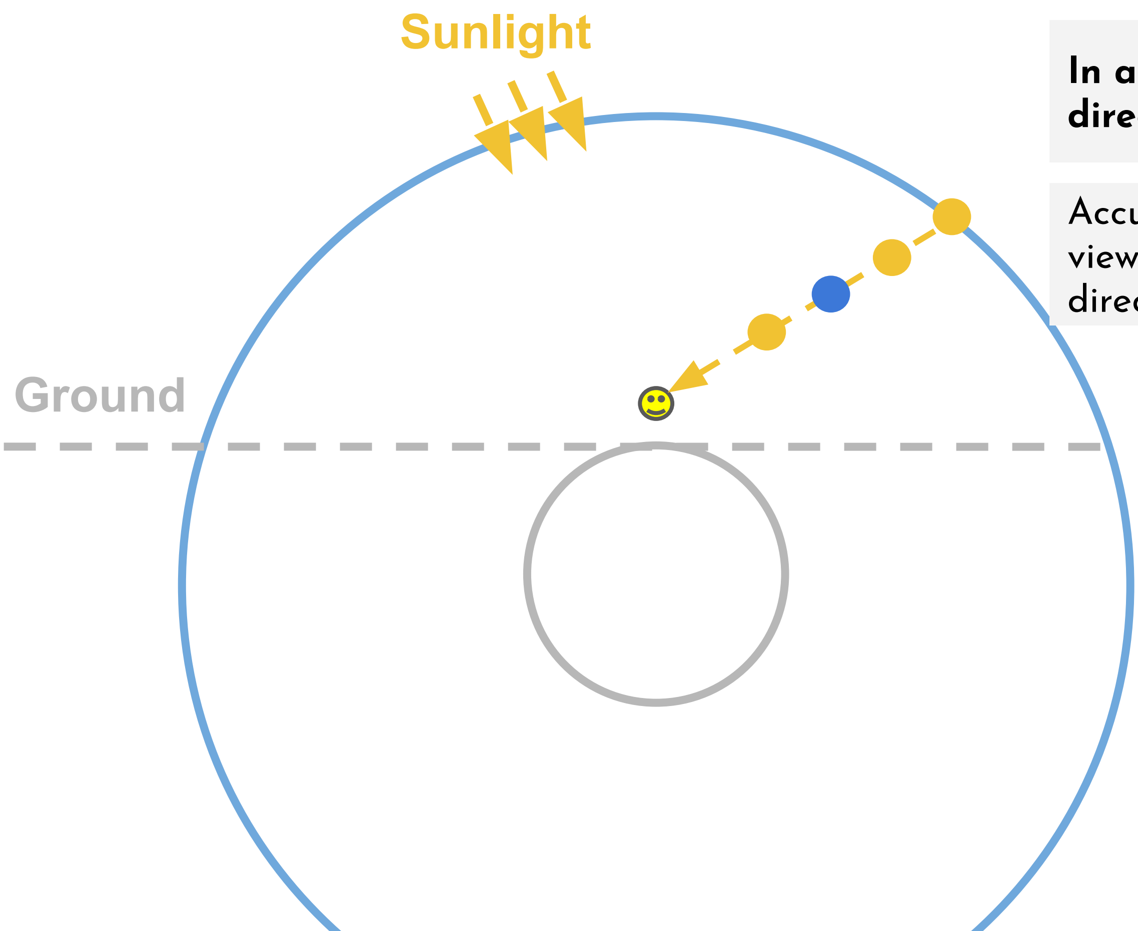


Physically-Based Atmospheric Scattering: In-Scattering

O'Neil Optimization: Optical Depth Approximation with Surface Fitting

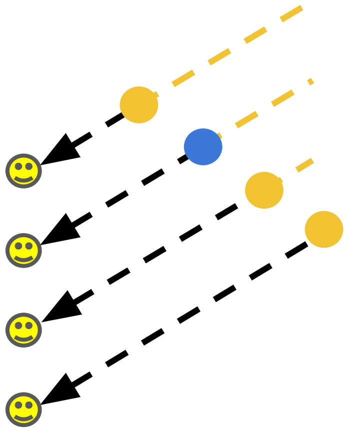
AOAS: Simplified Geometric Representation of Sky from Two Skydomes to One

Physically-Based Atmospheric Scattering

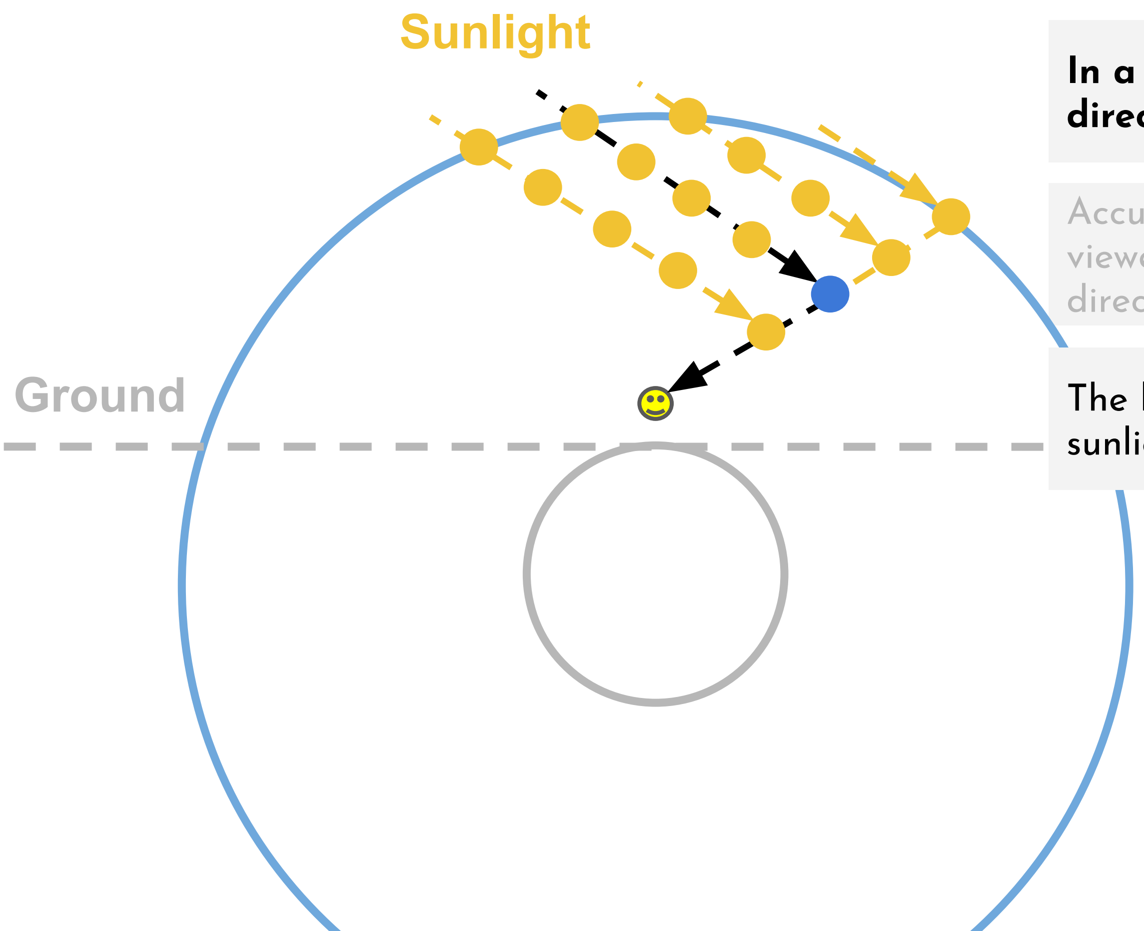


In a nutshell, sky color along a view direction is:

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



Physically-Based Atmospheric Scattering

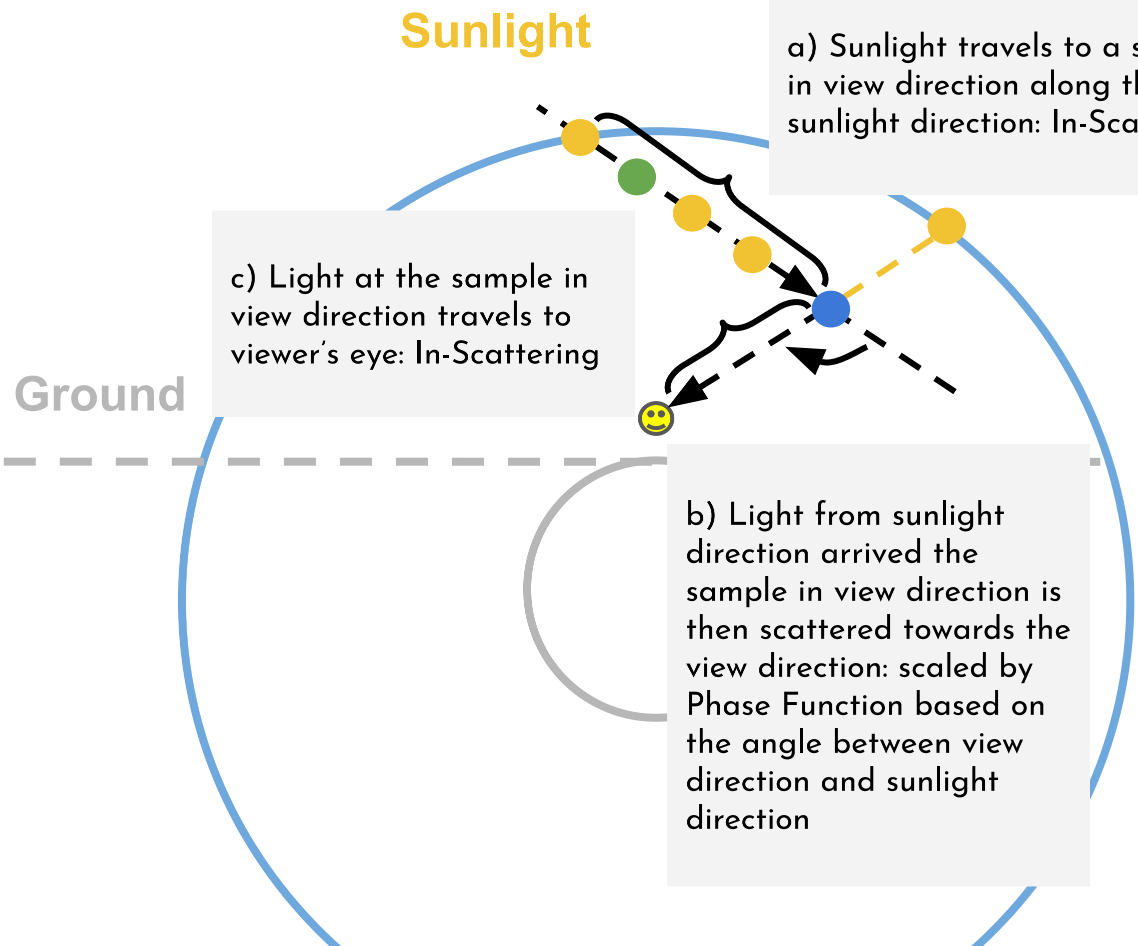


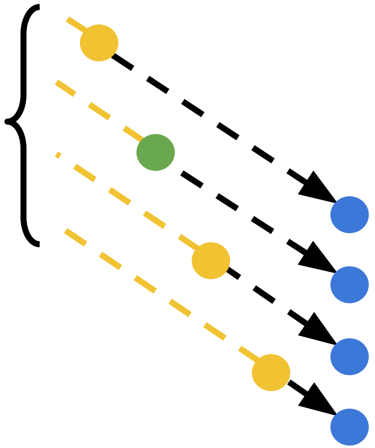
In a nutshell, sky color along a view direction is:

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.

Physically-Based Atmospheric Scattering





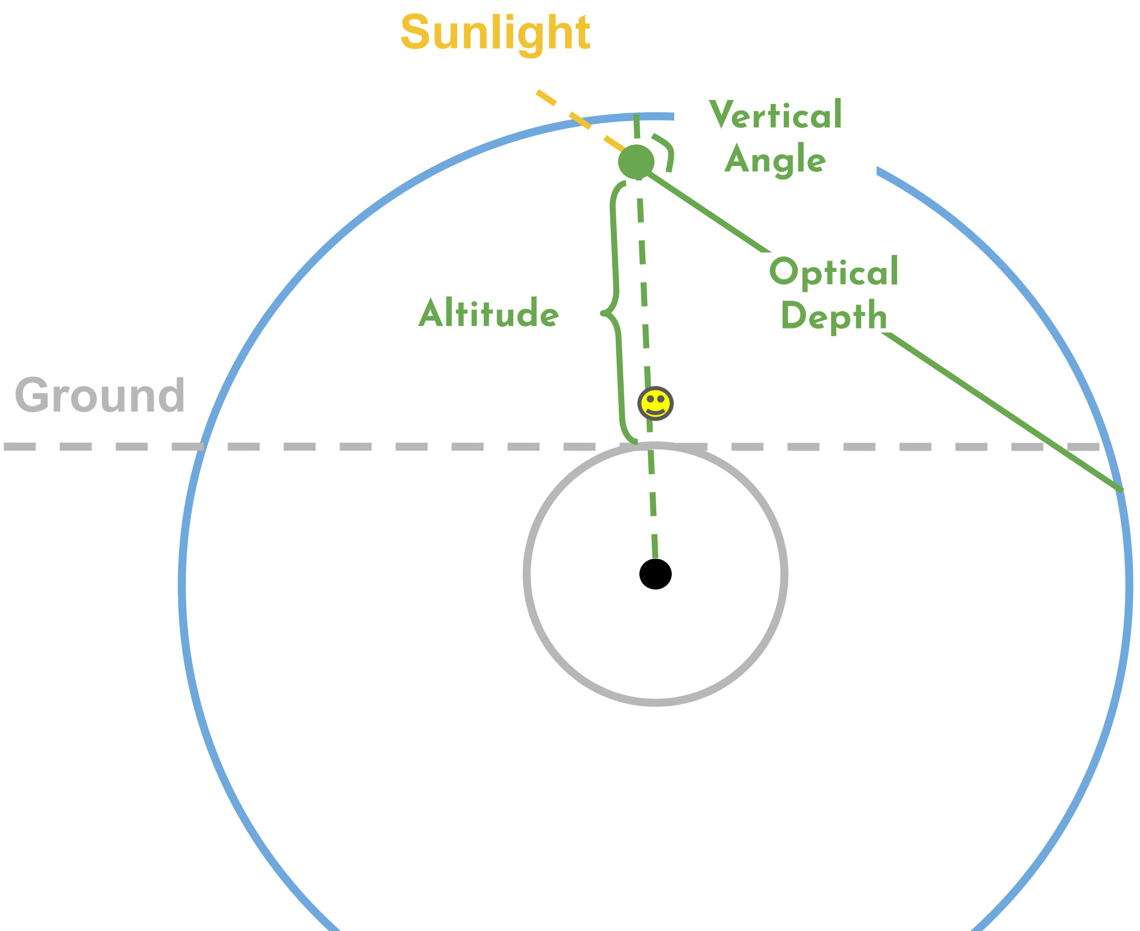
In-Scattering between two samples:

Remaining light; exponential of the negative of:

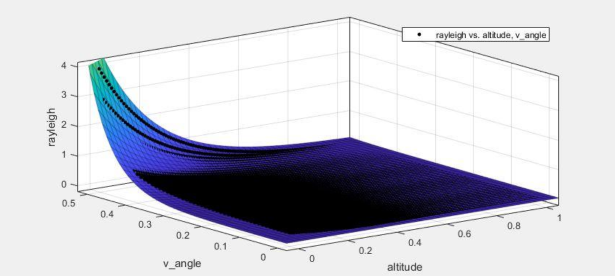
Out-Scattering: away light; proportional to:

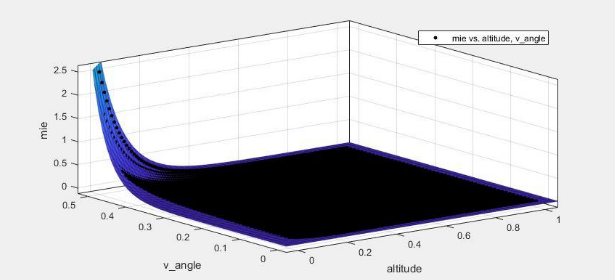
Optical Depth: average atmospheric density; stable in Rayleigh and Mie Scatterings; **expensive**

O’Neil Optimization



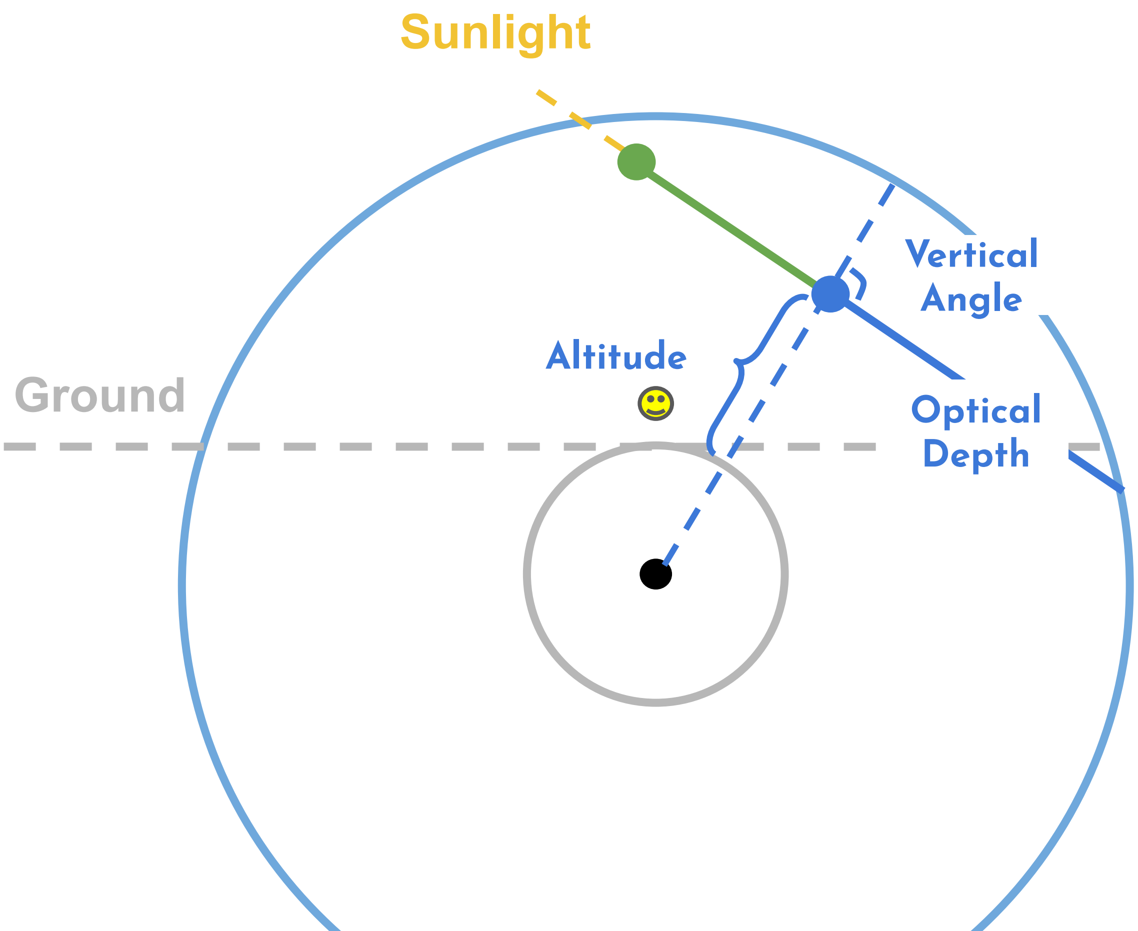
Optical depth of a sample towards a direction to the outer atmosphere is approximated in terms of altitude and vertical angle.



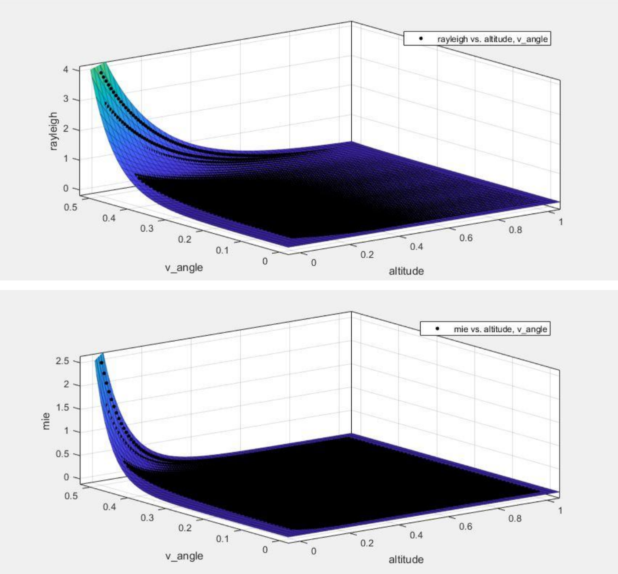


Surface fitting of optical depth of Rayleigh (Top) and Mie Scatterings (Bottom).

O'Neil Optimization

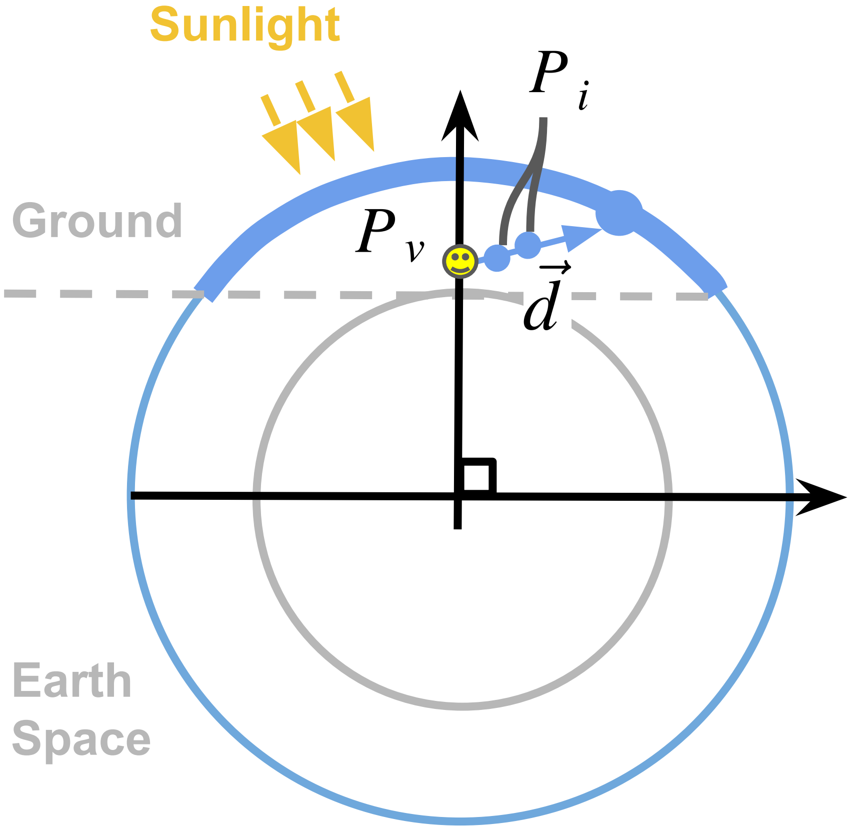


Optical depth of a sample towards a direction to the outer atmosphere is approximated in terms of altitude and vertical angle.



Surface fitting of optical depth of Rayleigh (Top) and Mie Scatterings (Bottom).

O'Neil Input Parameters



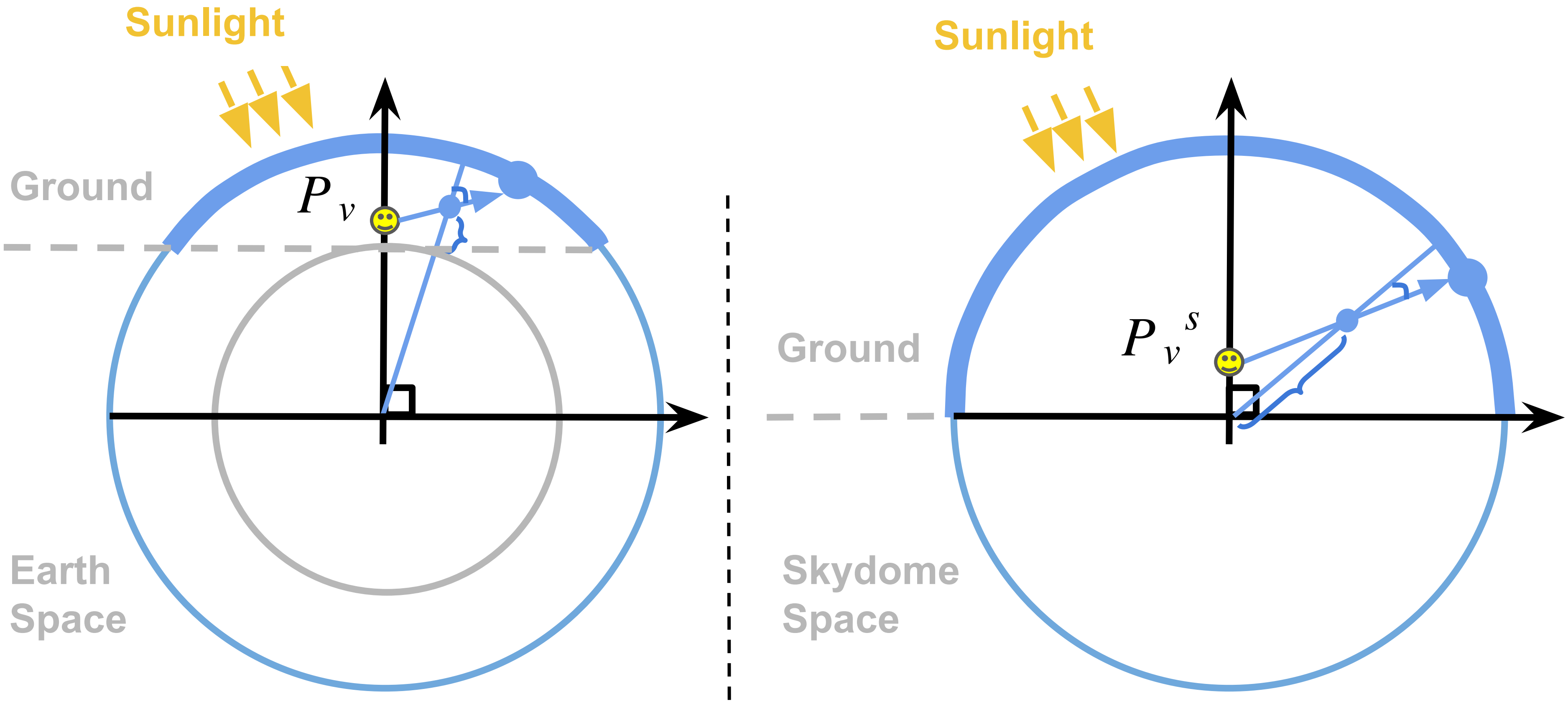
$\vec{d}$	View direction of the viewer in Earth space
P_v	Position of the viewer in Earth space
P_i	Position of ray-marching sample in Earth space

Pre-defined variables:

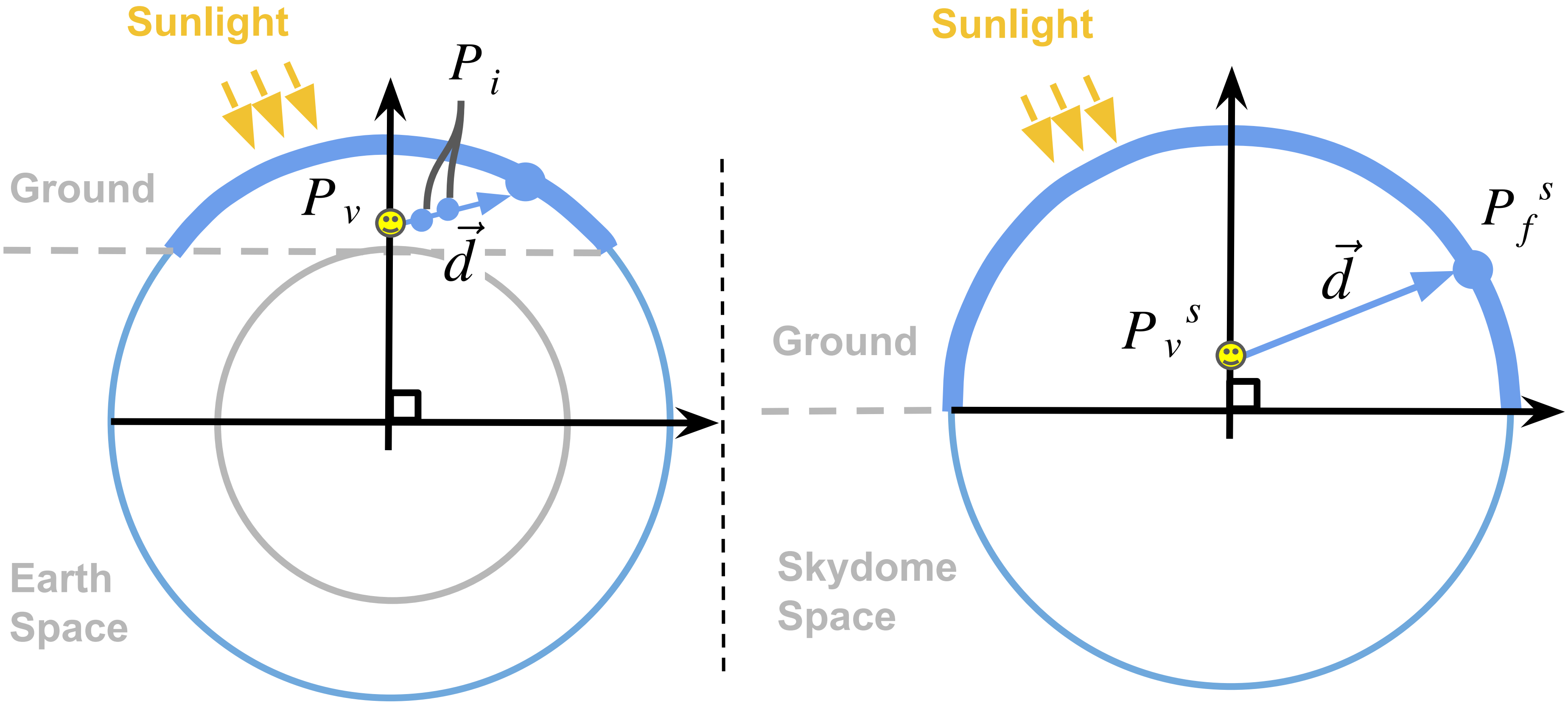
Sunlight direction

Ray marching step

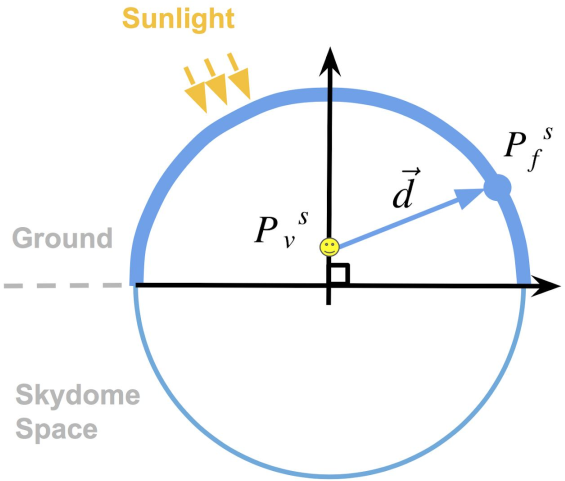
AOAS: Directly Ray Marching in Skydome Space Isn't Possible to Obtain Vertical Angle for the Same Altitude

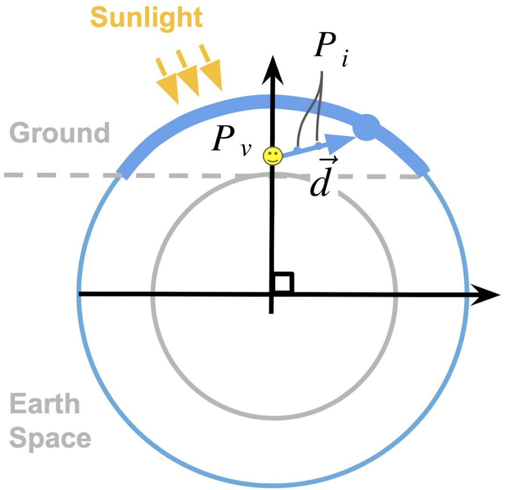


AOAS: Directly Ray Marching in Skydome Space Isn't Possible to Obtain Vertical Angle for the Same Altitude. Hence, affect the input parameters



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

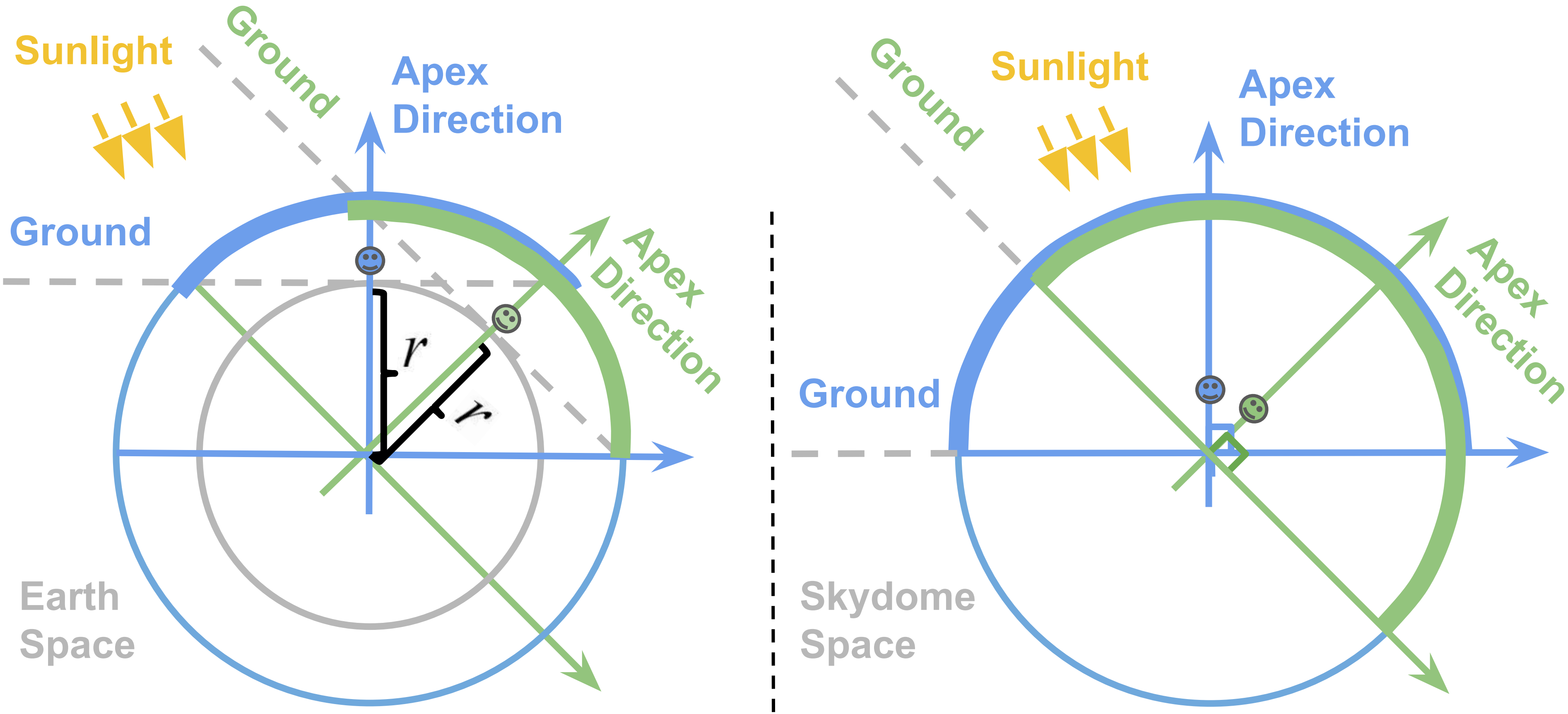
$$\vec{d} = \frac{P_f^s - P_v^s}{\left\|P_f^s - P_v^s\right\|}$$

Position of Ray-Marching Sample in Earth space

$$P_i = P_{i-1} + t \cdot \vec{d},$$
$$P_0 = P_v$$

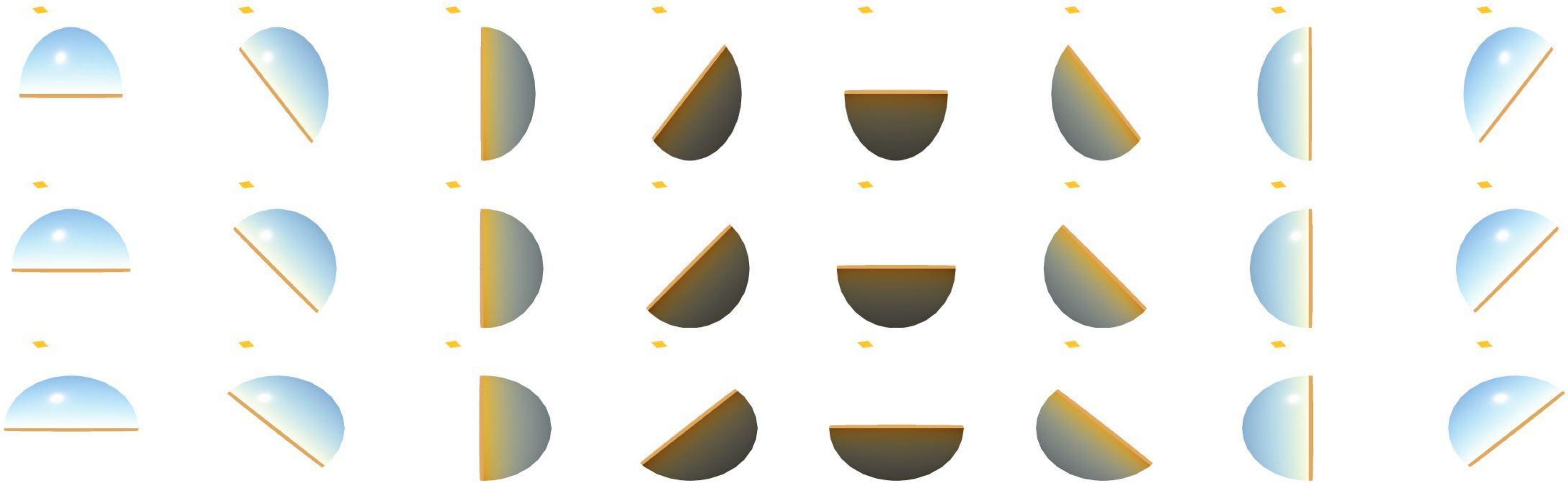
Input Parameters

AOAS: One Skydome Overview



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!

Aesthetic Principles

	Gradient	Hue	Pattern
Impression			
Physics	Atmosphere Composition, etc	Scattering Constants, Sunlight Direction etc	Cloud
	Stable	Dynamic	Dynamic
	Essential	Non-Essential	Non-Essential
Imagination	Physically-Based	Physically-Based to Non-Photorealistic	Physically-Based to Non-Photorealistic
		Non-Photorealistic Colors: green, yellow, ...	*- Artistic Cloud Shape: animals, ...* *- Various Cloud Complexities* *- Ambiguity*

- 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

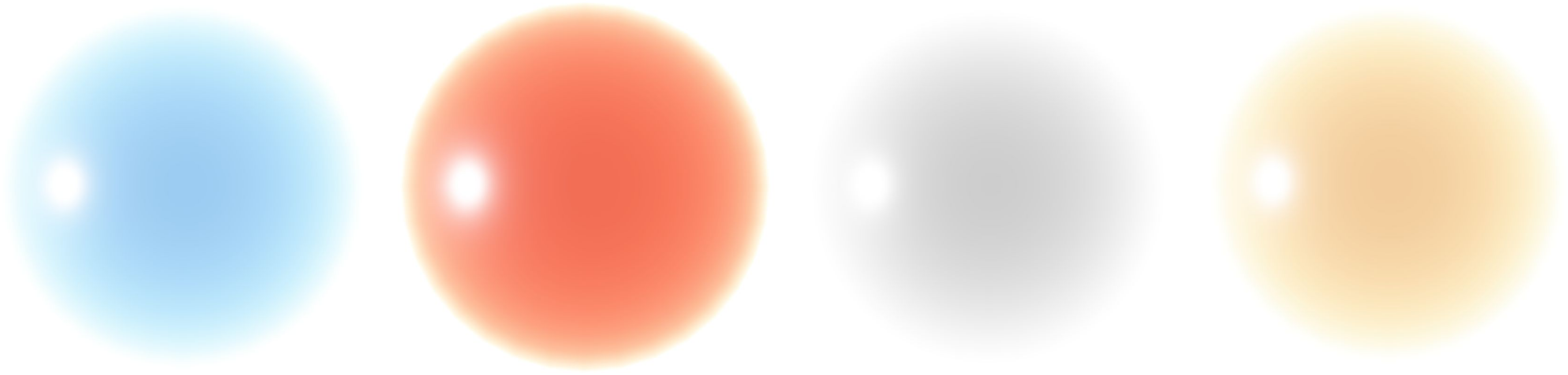
Ambiguity: Pattern

Custom Cloud Shape: Pattern

Aesthetic Principles

Artistic Color:

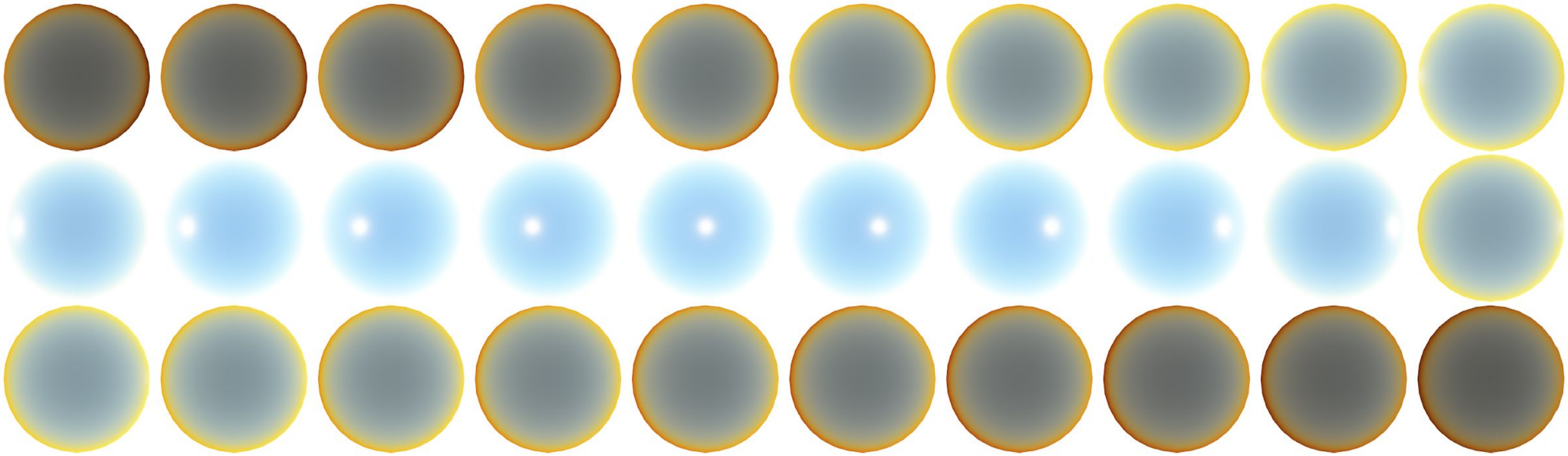
Any color for scattering constant



Aesthetic Principles

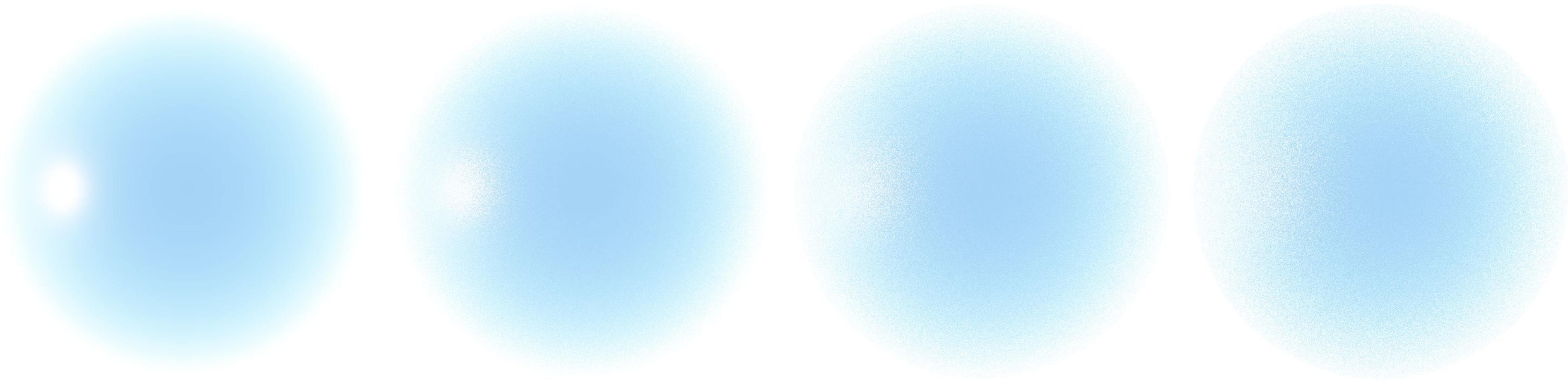
Artistic Color:

Custom Sunlight Direction

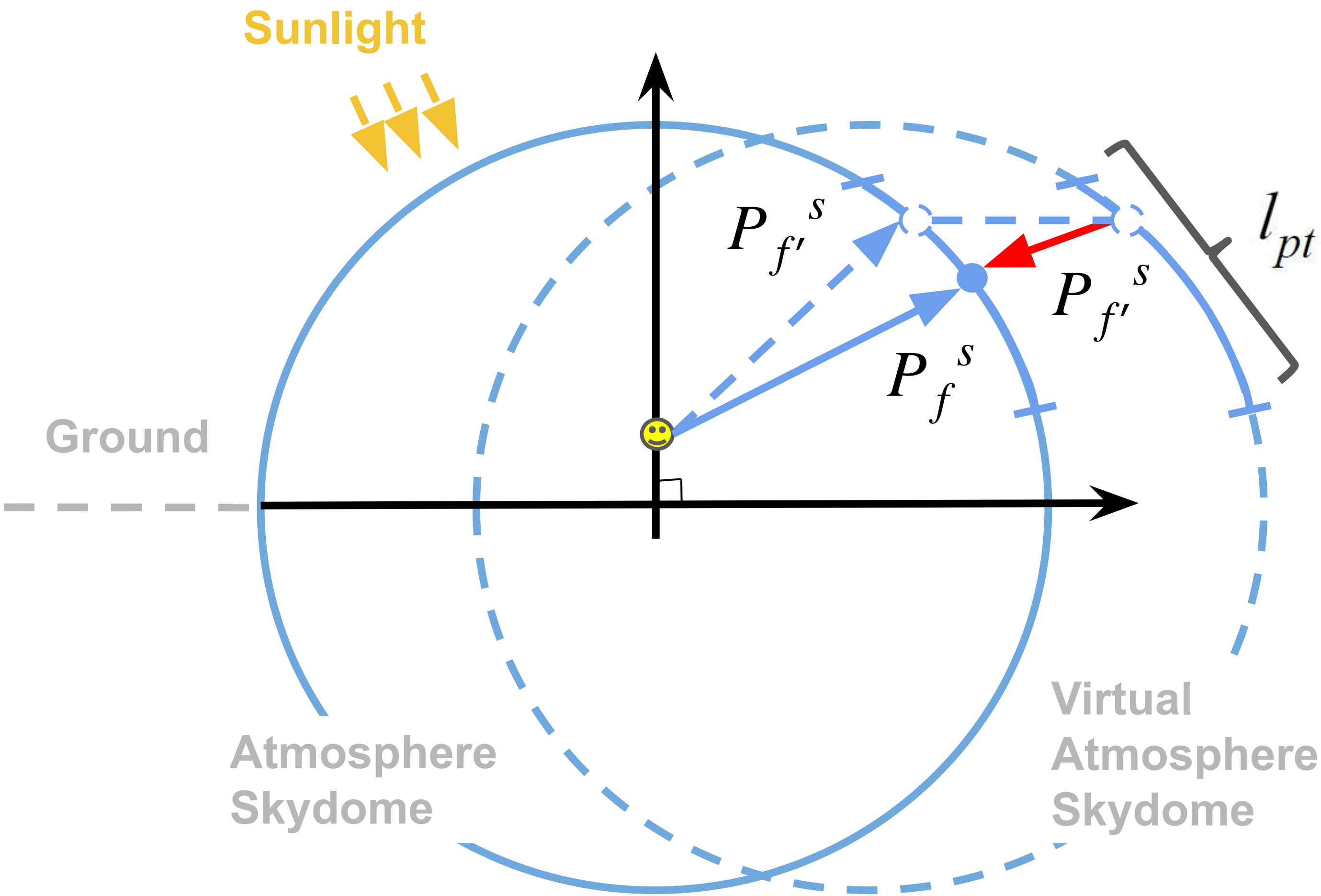


Aesthetic Principles

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 $P_{f'}^s$ 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

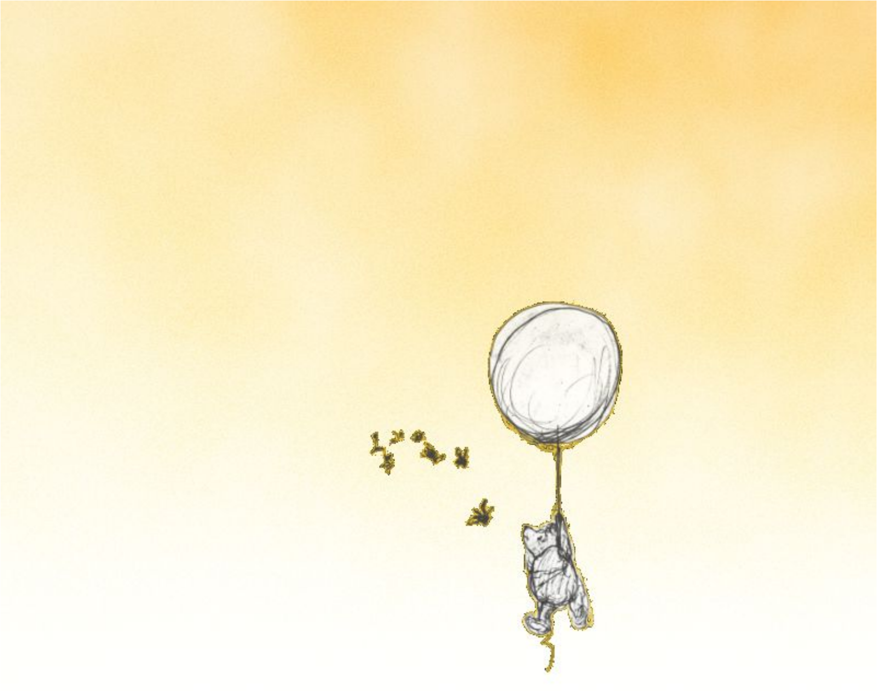
Style Config Example: Winnie-the-Pooh

Poster.
MUSEUM OF FINE ARTS, BOSTON.
Winnie-the-Pooh: Exploring a Classic.
2019 1.

Style Config Example: Winnie-the-Pooh

Poster. MUSEUM OF FINE ARTS, BOSTON. Winnie-the-Pooh: Exploring a Classic. 2019 1.

Style Config Example: Winnie-the-Pooh



Poster. MUSEUM OF FINE ARTS, BOSTON. Winnie-the-Pooh: Exploring a Classic. 2019 1.

Style Config Example: Winnie-the-Pooh

Three points to indicate smiley clouds for fragments of the Earth skydome

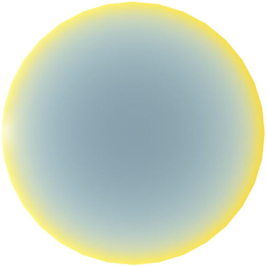
Poster. MUSEUM OF FINE ARTS, BOSTON. Winnie-the-Pooh: Exploring a Classic. 2019 1.

Style Config Example: Winnie-the-Pooh

Heart spline to indicate heart clouds for fragments of the Earth skydome

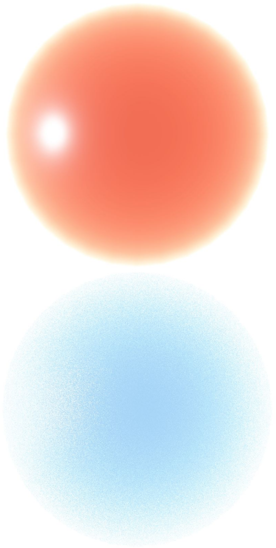
Poster. MUSEUM OF FINE ARTS, BOSTON. Winnie-the-Pooh: Exploring a Classic. 2019 1.

Style Config Example: Winnie-the-Pooh



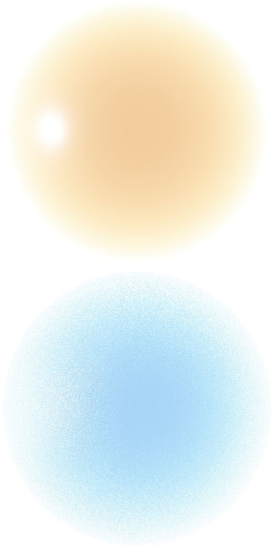
Poster. MUSEUM OF FINE ARTS, BOSTON. Winnie-the-Pooh: Exploring a Classic. 2019 1.

Style Config Example: Winnie-the-Pooh



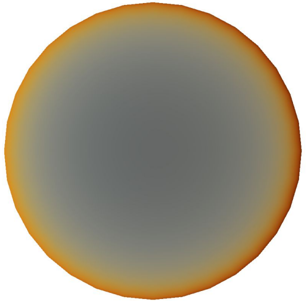
Poster. MUSEUM OF FINE ARTS, BOSTON. Winnie-the-Pooh: Exploring a Classic. 2019 1.

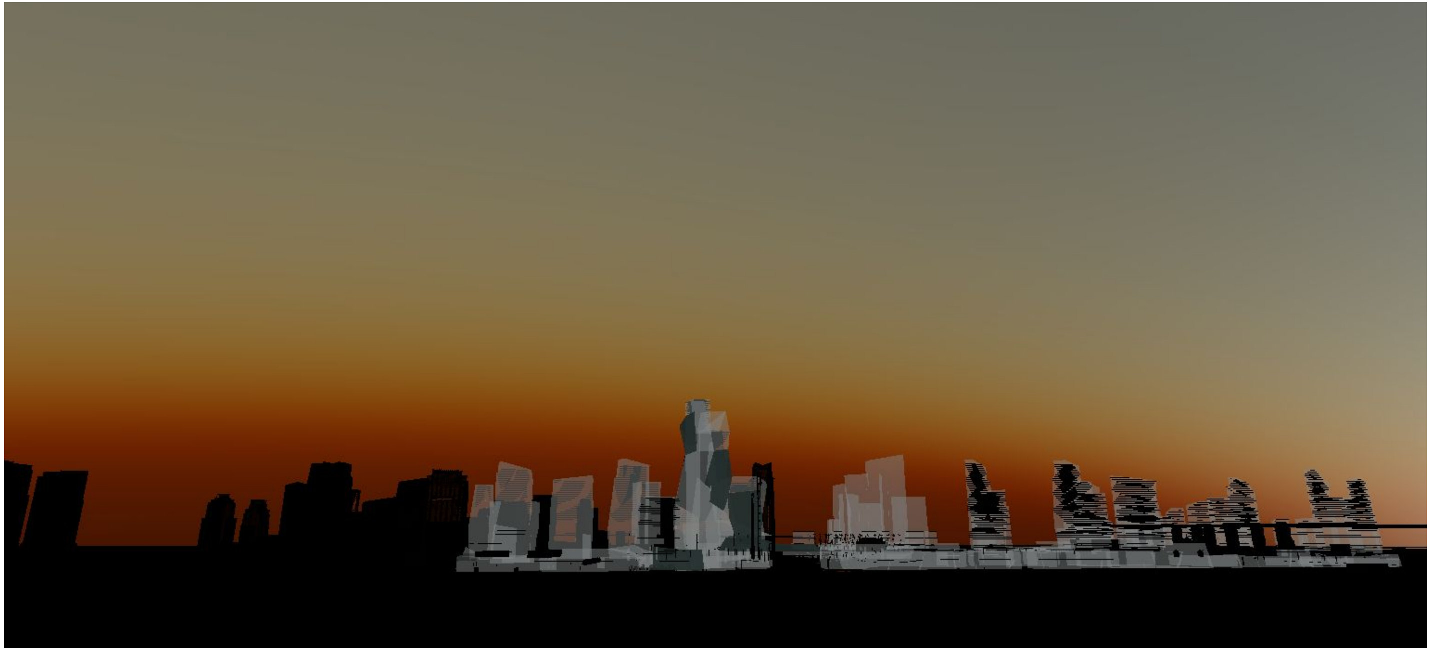
Style Config Example: Winnie-the-Pooh



Poster. MUSEUM OF FINE ARTS, BOSTON. Winnie-the-Pooh: Exploring a Classic. 2019 1.

Style Config Example: 3D Futuristic City



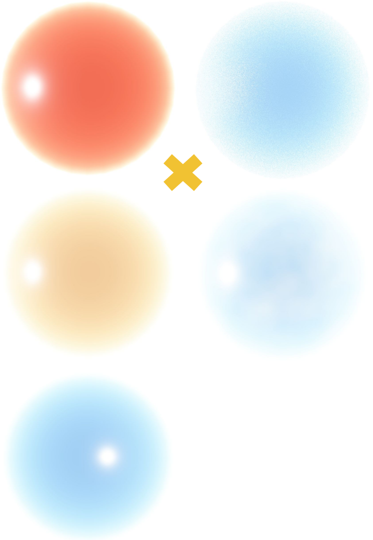


Explore sky style for 3D model in Blender Game Engine

Style Config Example: 3D Futuristic City

Explore sky style for 3D model in Blender Game Engine

Style Config Example: 3D Futuristic City



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?

Yang Shen (Sophie)

Software Engineer, Originate

Founder, Dopamine Animatic, Originate 20% Time

Member, Cambridge Innovation Center

Former MS Student on Computer Graphics, University of Utah

Cambridge, MA, USA

https://www.csyang.com

Ian Mallett

PhD Student, Utah Graphics Lab, University of Utah

Salt Lake City, UT, USA

https://geometrian.com

Konstantin Shkurko

PhD Candidate, Utah Graphics Lab, University of Utah

Salt Lake City, UT, USA

http://www.cs.utah.edu/~kshkurko/

More Explanations

Physically-Based Atmospheric Scattering