Introduction to Light Scattering:

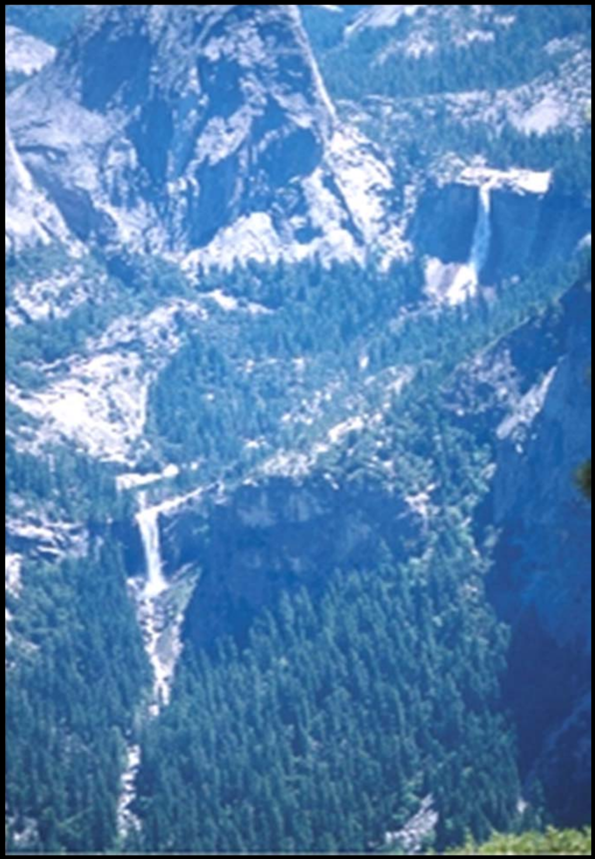
An Imaging Sciences Perspective

Lecture #19

First, lets look at some pretty pictures

Distant objects appear Bright !

Mountains



Haze

De-hazed


Bad Weather

Haze

Mist

Fog

Rain

Images Courtesy : Steve and Carol Sheldon

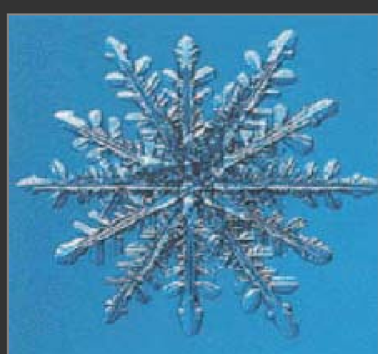
More Weather…



Non-uniform Fog



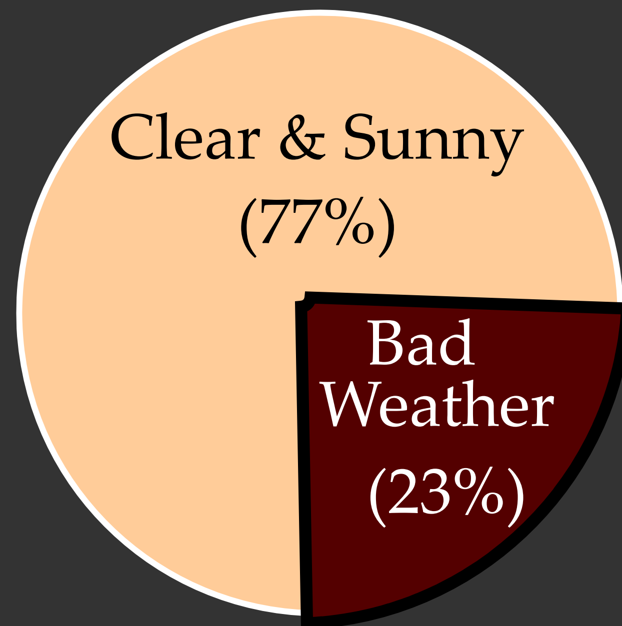
Rain Drops and Rain Streaks



Snow Flakes and Snow Streaks

How often do we see Bad Weather?

Manhattan, Every Hour, 12 Months

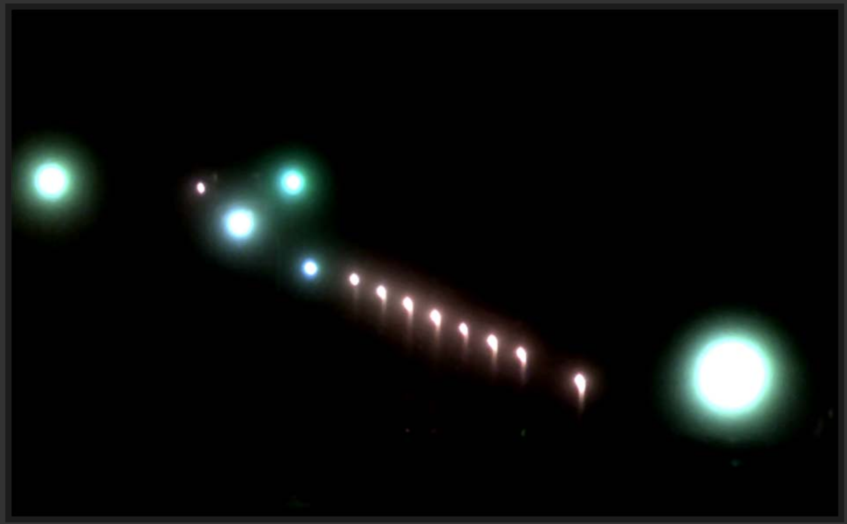


Natural illumination in Scattering Media

[Narasimhan and Nayar, 99 - 03, Schechner et al, 01, 04]

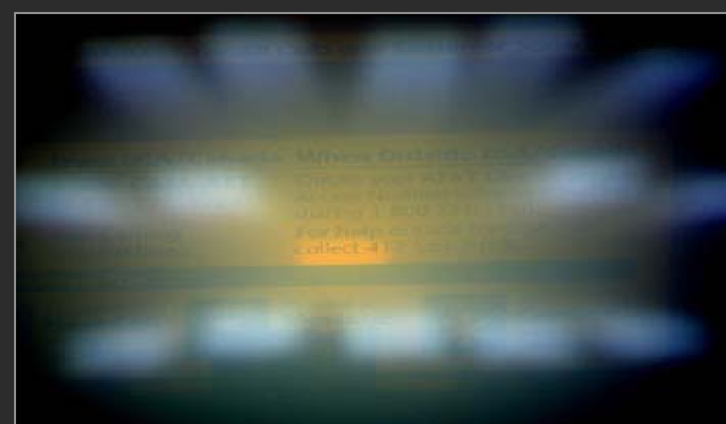
Glows of Light Sources

Mist



Fog

Active illumination in Scattering Media



[Levoy et al., Narasimhan-Nayar, Kocak-Caimi, Jaffe et al., Schechner et al., Negahdaripour et al.]

Floodlighting is Bad in Scattering Media

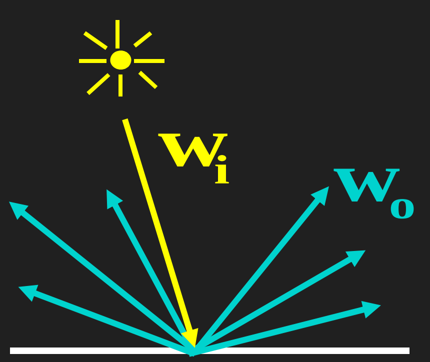



Remember Driving in Fog at Night?

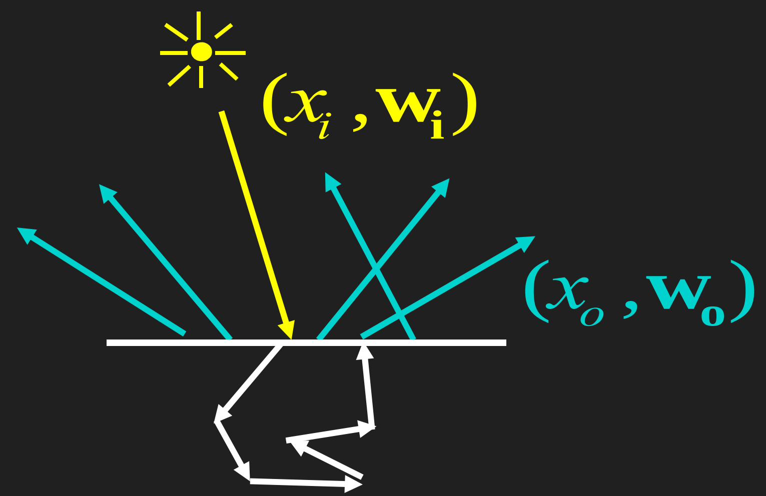
Is BRDF sufficient for Translucent Objects ?

Jensen et al., 2001

BRDF is a **4 D** function of viewing and illumination directions : $f(\mathbf{w_i}, \mathbf{w_o})$



Opaque Objects



Translucent Objects

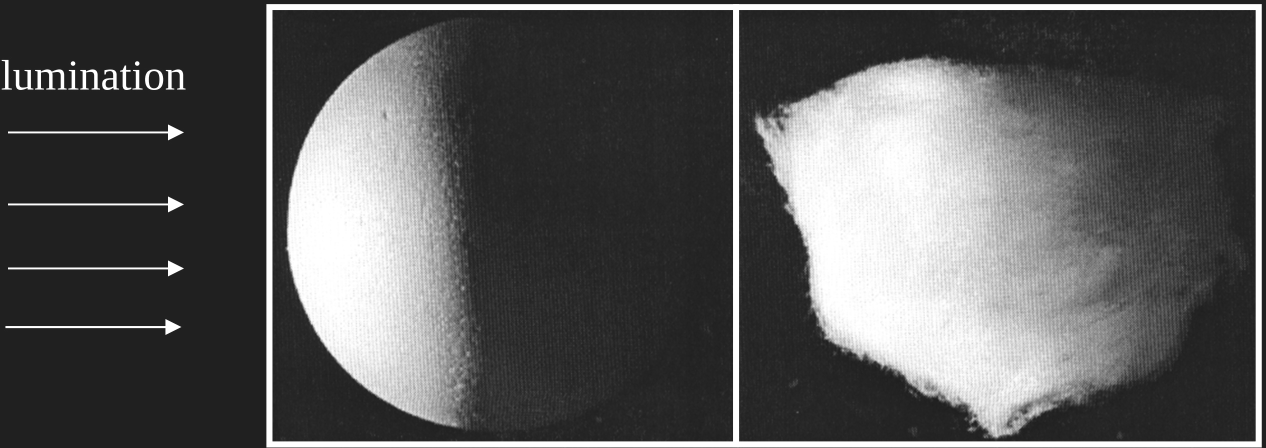
Translucent Objects

Koenderink and van Doorn, 2001

Clouds

Milk

Illumination



Opaque (Lambertian Sphere) vs. Translucent (Cotton)

Rendering Milk

Jensen et al., 2001

Skim Milk

Whole Milk

Diffuse BRDF

BSSRDF Model


RENDERED BY HENRIK WANN JENSEN - 2001


RENDERED BY HENRIK WANN JENSEN - 2001

Rendering a Marble Bust

Jensen et al., 2001

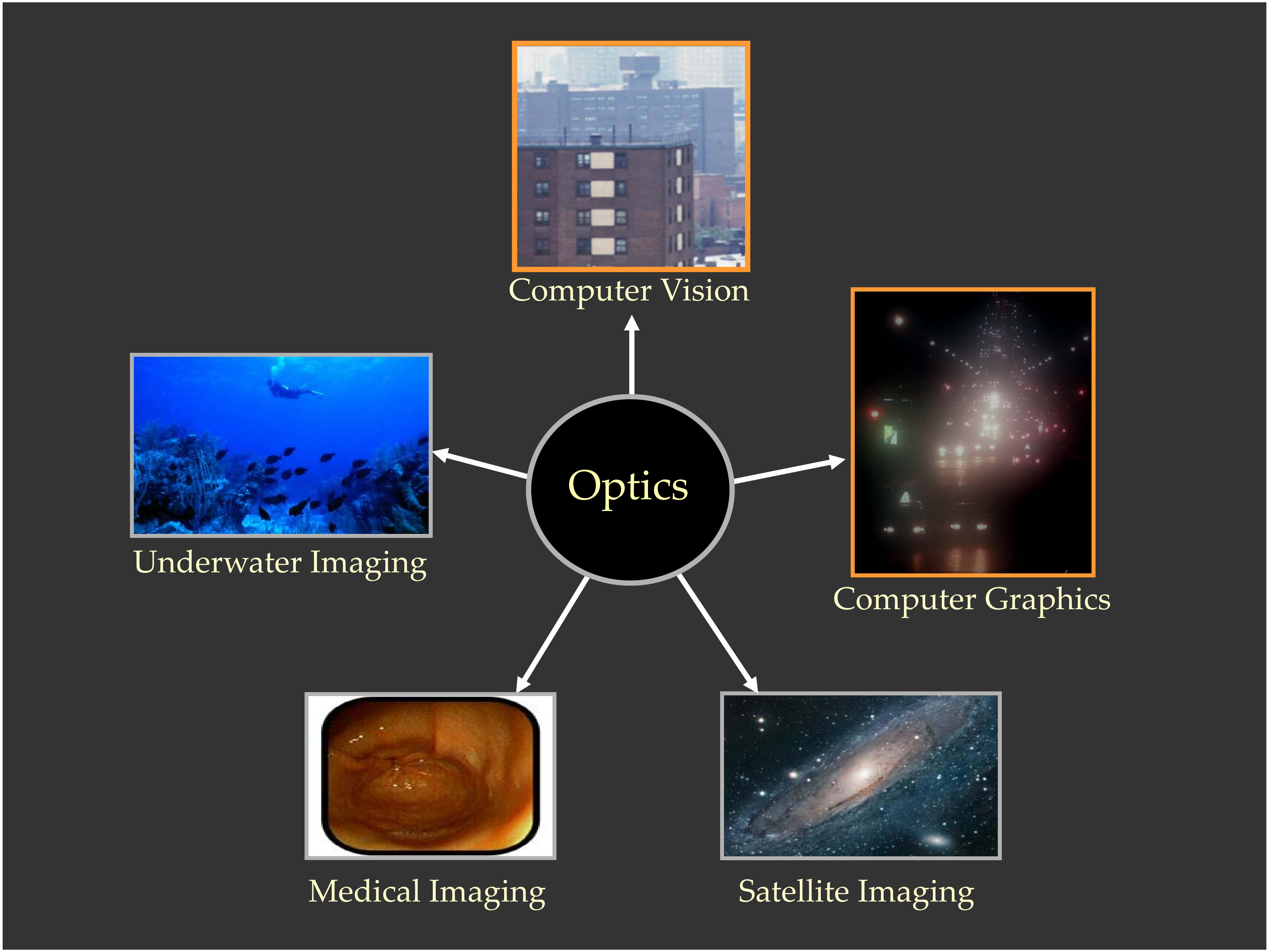
BRDF

BSSRDF Model

Full Monte Carlo Simulation of Radiative transport

Rendering Moon

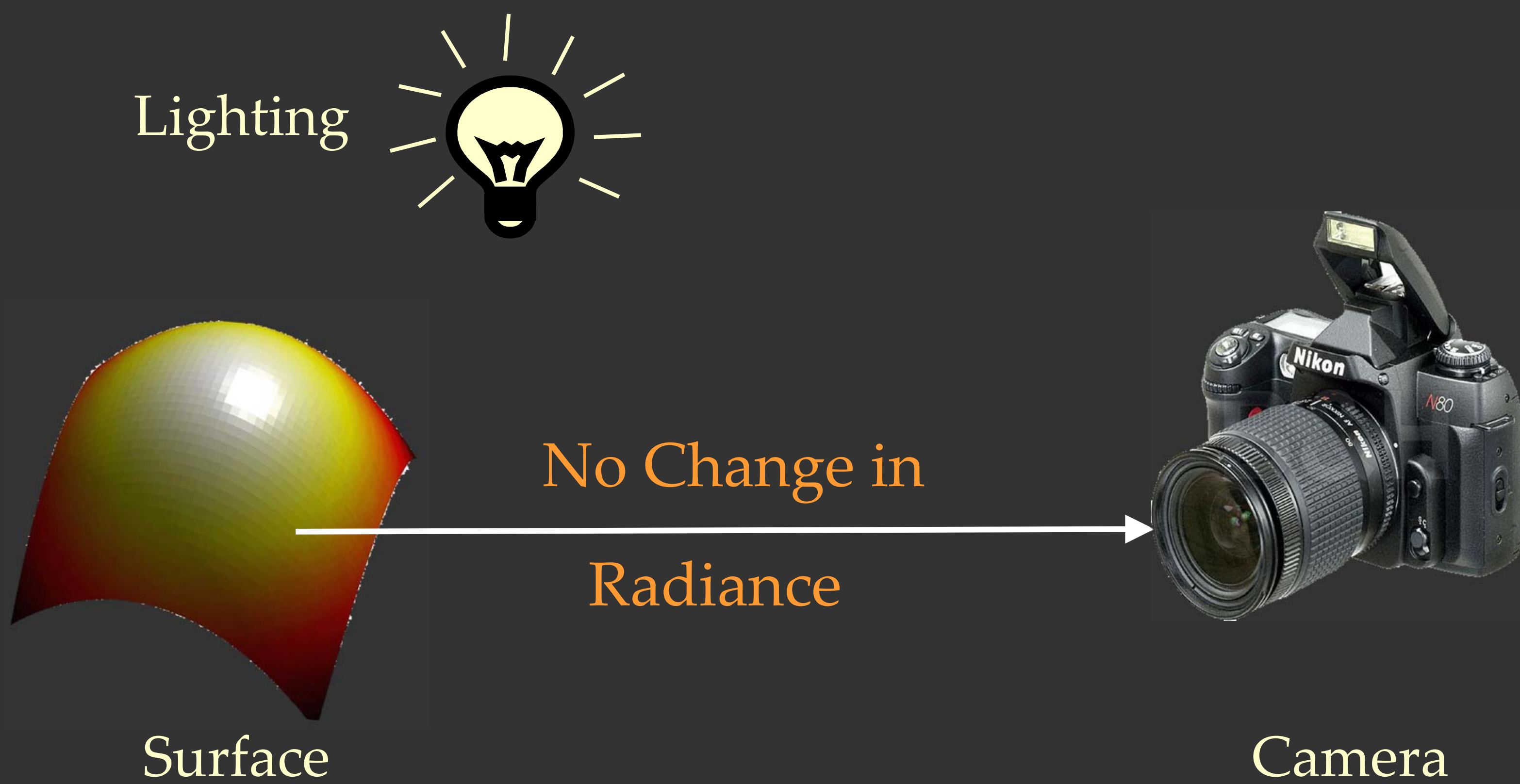
Jensen et al., 2001


Computer Vision
Underwater Imaging
Optics
Computer Graphics
Medical Imaging
Satellite Imaging

Scattering in different fields

Art -	500-600 years
Physics -	250 years
Astrophysics/Astronomy -	80-100 years
Atmospheric Optics -	80-100 years
Medical Imaging -	30 years
Remote Sensing -	30 years
Oceanic Engineering -	30 years
Computer Graphics -	20 years
Computer Vision -	5-10 years

The Fundamental Assumption in Vision



Assumption: We live in Vacuum!

Radiation Fog

Actual Clear Day Image

Simulated Foggy Image

Advection Fog

Actual Clear Day Image

Simulated Foggy Image

Dense Aerosols with Drizzle

Actual Clear Day Image

Simulated Foggy Image

Haze

Actual Clear Day Image

Simulated Hazy Image

Fog with Cumulus Clouds

Actual Clear Day Image

Simulated Foggy Image

Urban Aerosol with Moderate Rain

Actual Clear Day Image

Simulated Foggy Image

Driving in Bad Weather

People tend to drive fast in fog!! – Nature, 1998

Weather Conditions and Particles

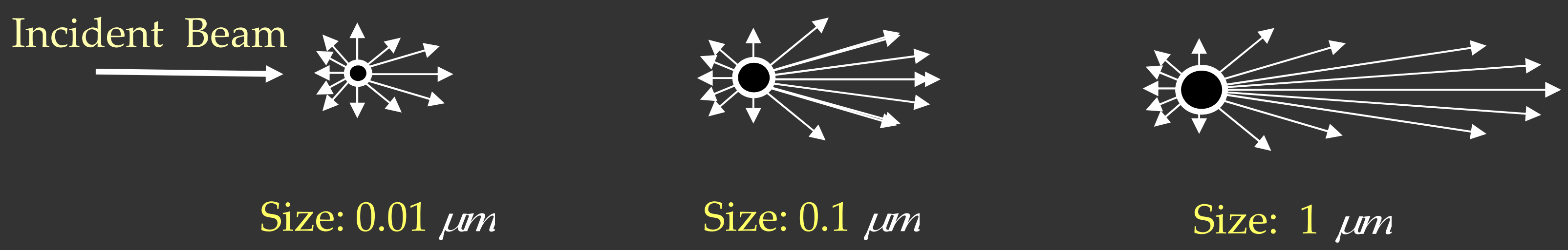
CONDITION	PARTICLE TYPE	RADIUS (μm)	CONCENTRATION(cm^{-3})
AIR	Molecule	10^{-4}	10^{19}
HAZE	Aerosol	$10^{-2} - 1$	$10^{3} - 10$
FOG	Water Droplet	$1 - 10$	$100 - 10$
CLOUD	Water Droplet	$1 - 10$	$300 - 10$
RAIN	Water Drop	$10^{2} - 10^{4}$	$10^{-2} - 10^{-5}$

(Mie 1908, McCartney 1975)

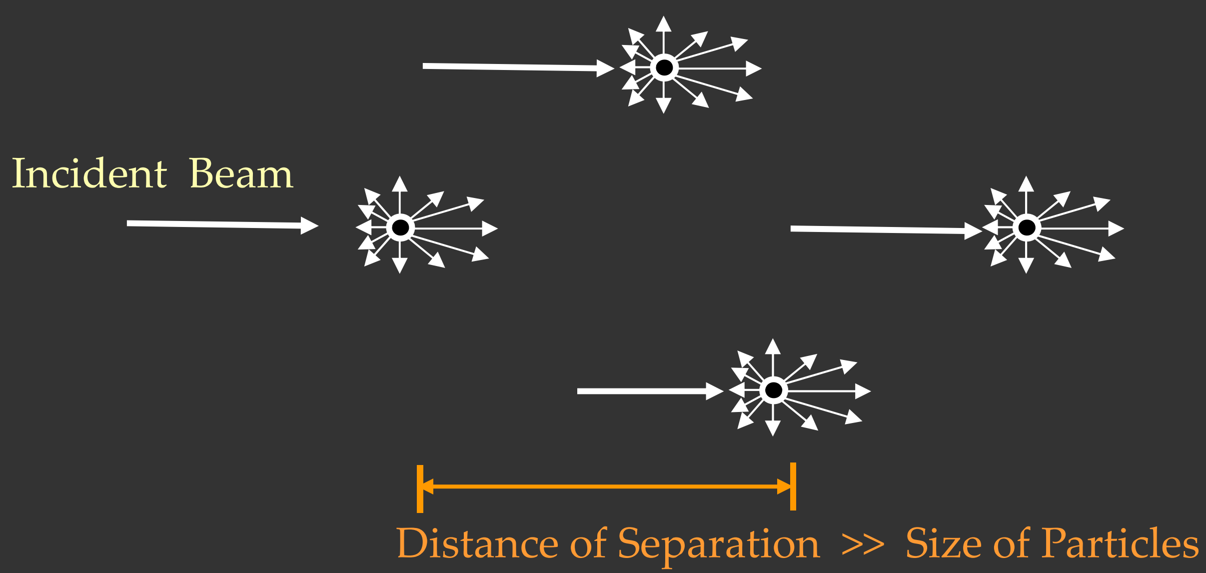
Particle Scattering Mechanisms

(Mie 1908)

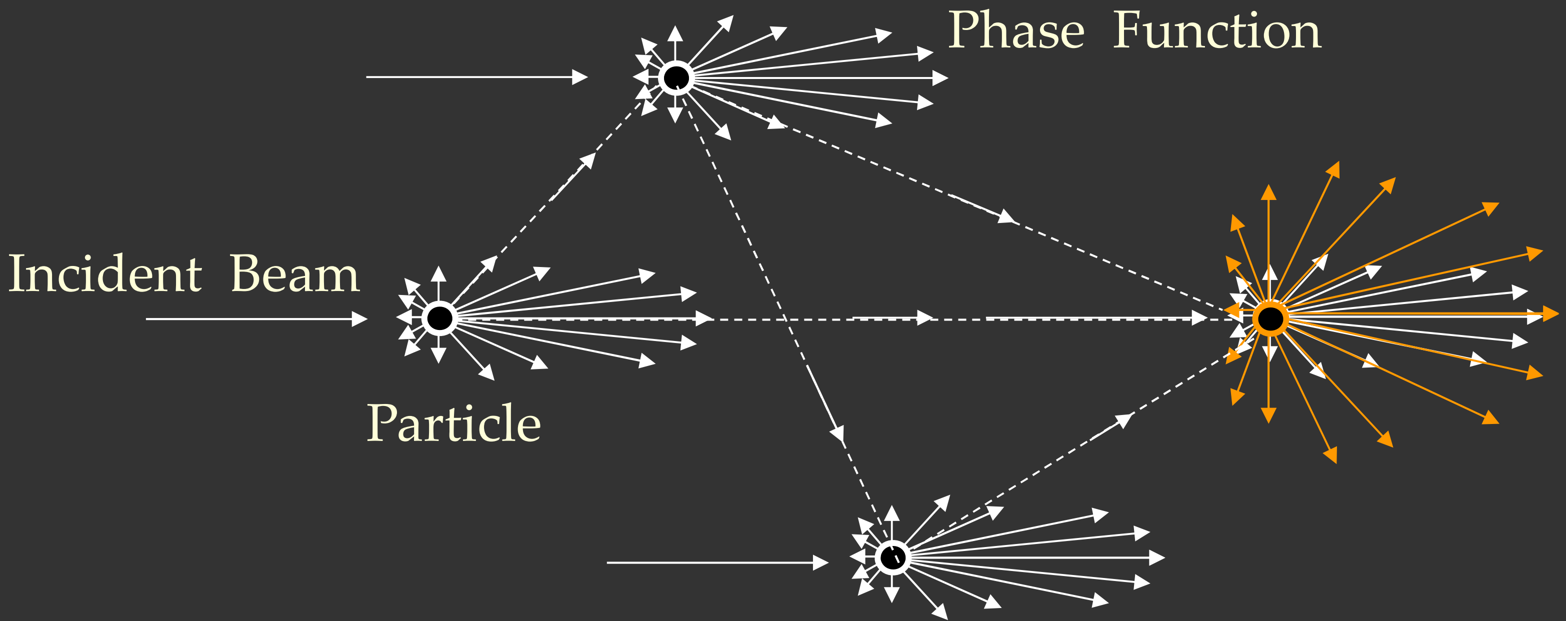
Single Scattering:



Independent Scattering:



Multiple Scattering in the Atmosphere



Properties of Scattering Media

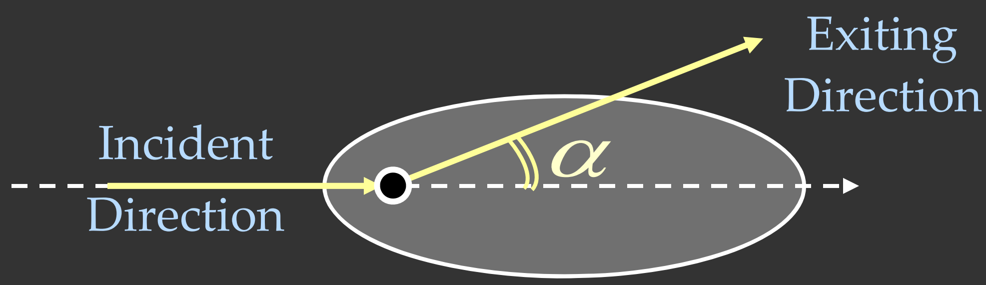
Scattering Coefficient: Fractional loss in intensity
due to scattering
per unit cross section

Absorption Coefficient: Fractional loss in intensity
due to absorption
per unit cross section

Extinction Coefficient: Scattering Coefficient + Absorption Coefficient

Phase Function

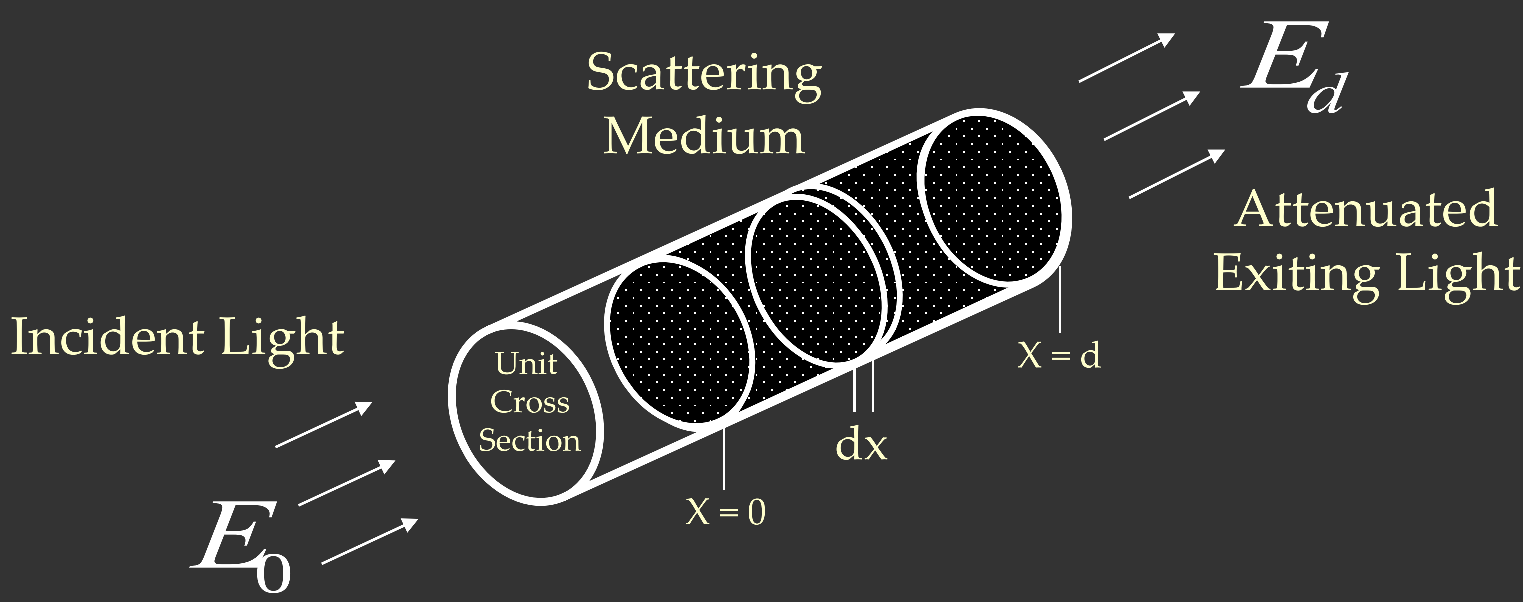
- Probability of light getting scattered in a single direction



- Phase function integrates to 1
- Light Scattered in any direction :

Phase function * Scattering Coefficient

Attenuation Model – Zeroth Order Scattering



Brightness at Distance d :

$$\boxed{E(d) = E_0 \; e^{-\beta d}}$$

(Bouguer's Law, 1729)

Scattering Coefficient

Direct Transmission

Attenuation of Diverging Beams:

$$\boxed{E(d) = \frac{I_0 \; e^{-\beta d}}{d^2}}$$

(Allard's Law, 1876)

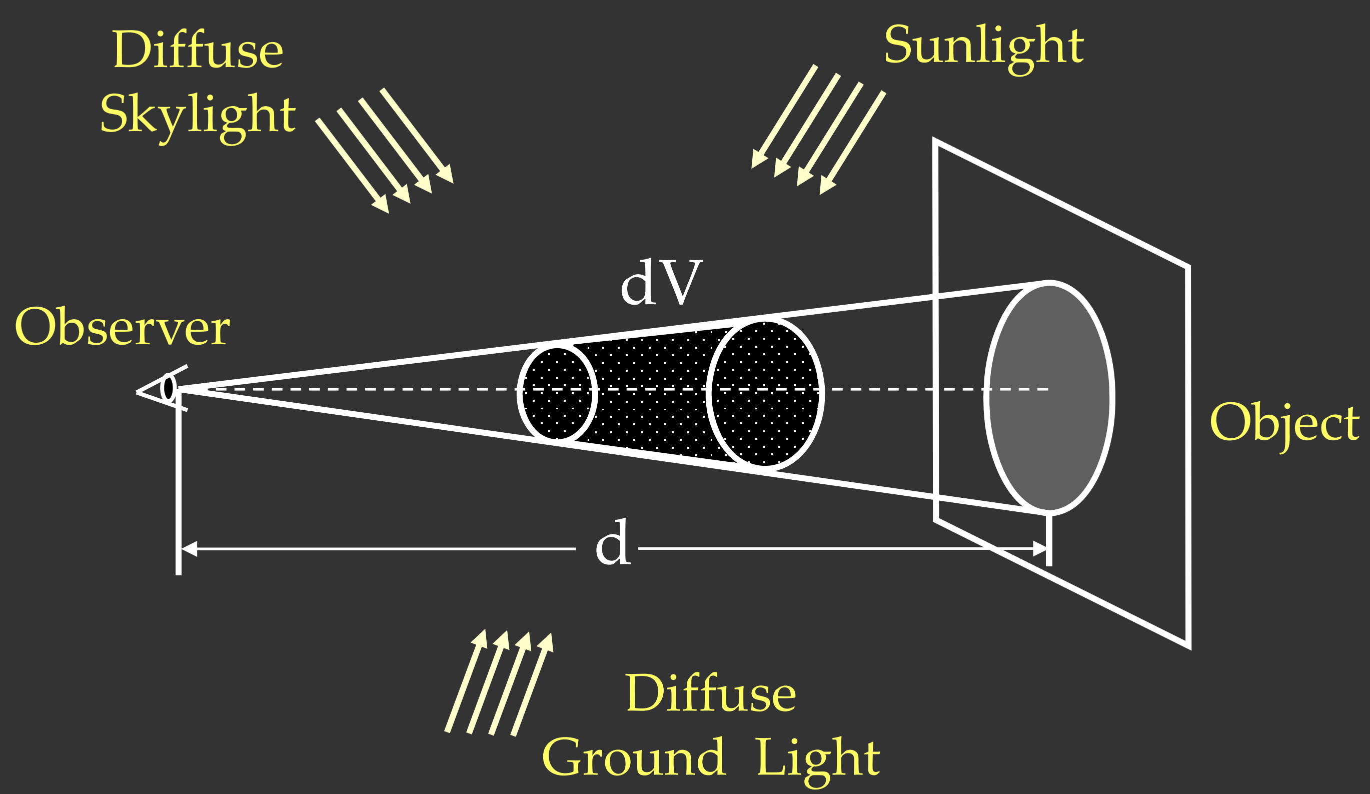
Optical Thickness:

$$T = \beta \, d$$

Scaled Depth

Airlight Model – First Order Scattering

(Koschmeider, 1924)



Brightness due to a Path of Length d :

Horizon Brightness

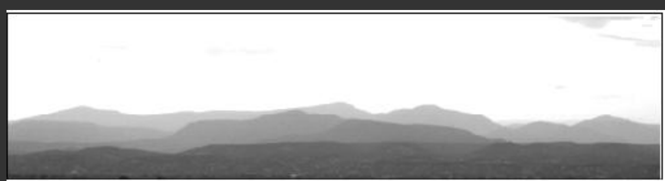
$$\boxed{E(d) = E_{\infty}\,(1 - e^{-\beta d})}$$

Distant objects appear Bright !

Mountains

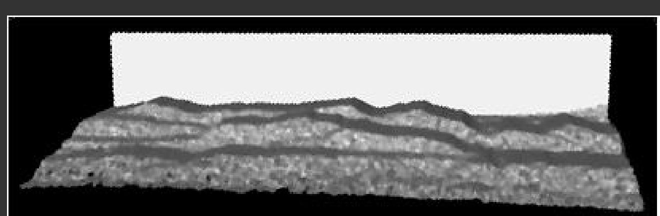
Structure from Airlight

Mountain Range



Foggy Day Image

Computed Depth Map

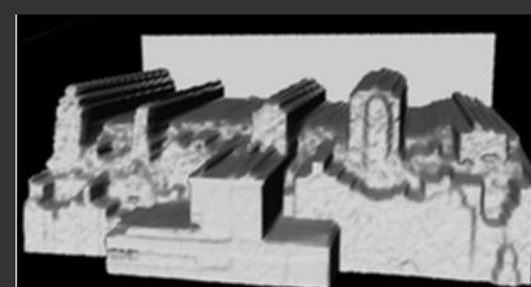


3D Structure

Urban Scene

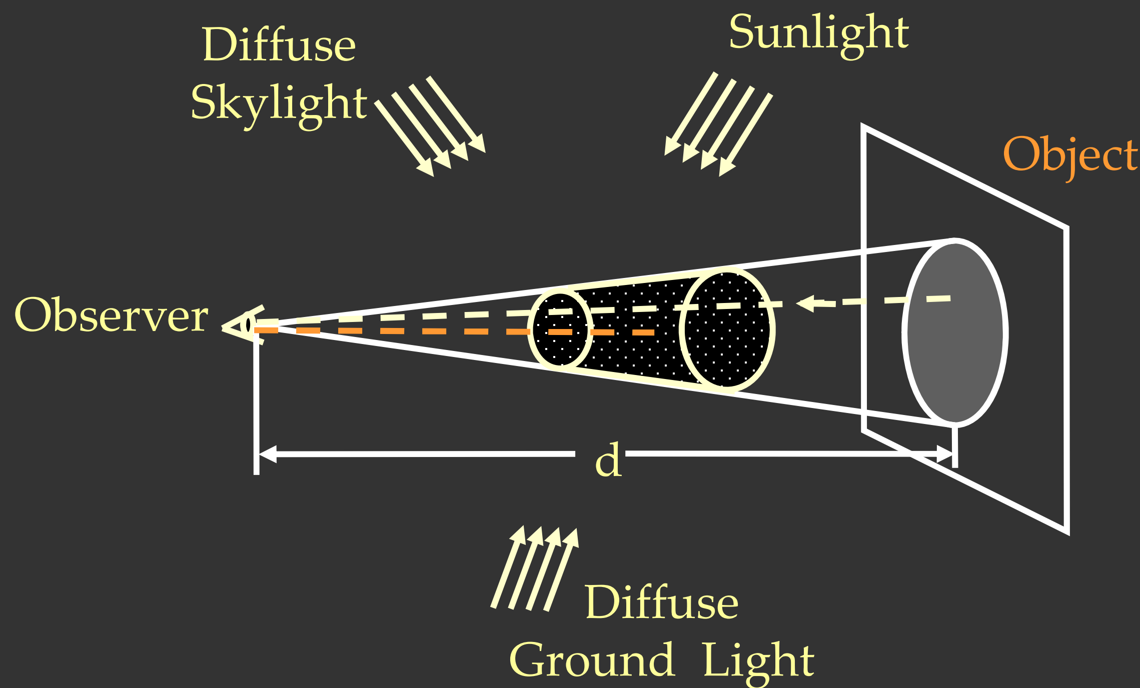
Foggy Day Image

Computed Depth Map

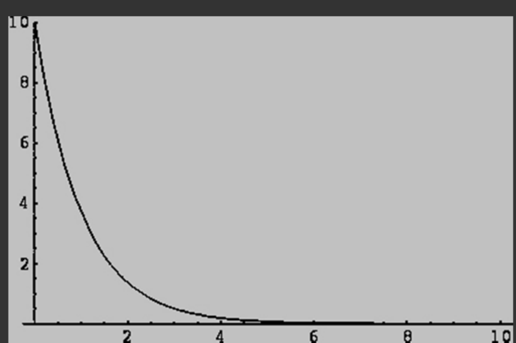


3D Structure

How does Brightness/Color vary with Distance?



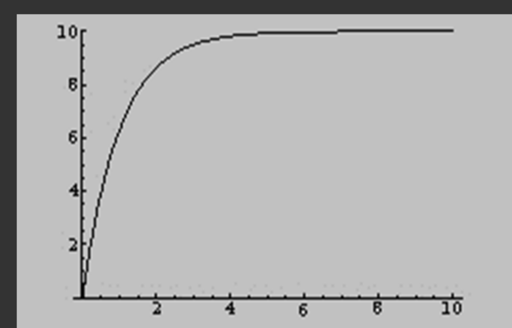
Color



Distance

Attenuation

Color



Distance

Airlight

Contrast Degradation in Bad Weather

Irradiance = **Attenuation** + **Airlight**

$$E(d) = E_\infty \, \rho e^{-\beta d} + E_\infty (1 - e^{-\beta d})$$

Depth (d), **Horizon Brightness** (E_∞), **Reflectance** (ρ), **Scattering Coefficient** (β)

Contrast between Iso-Depth points, $P^{(1)}$ and $P^{(2)}$:

$$C_{12} \stackrel{\Delta}{=} \frac{E^{(1)} - E^{(2)}}{E^{(1)} + E^{(2)}} = \frac{\rho^{(1)} - \rho^{(2)}}{\rho^{(1)} + \rho^{(2)} + 2(e^{\beta d} - 1)}$$

Contrast Decay : Exponential in Scene Depth

Depth Edges vs. Reflectance Edges

Mild Fog

Depth Edge

Denser Fog

Reflectance Edge

Normalized SSD of Reflectance Edge Neighborhood

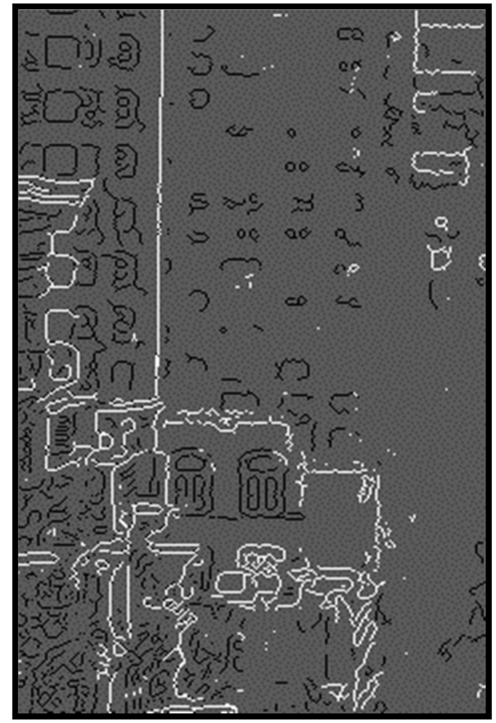
$$(\square - \square)^2 \ll (\square - \square)^2$$

Normalized SSD of Depth Edge Neighborhood

Edge Classification from Weather Changes

Mild Fog

Denser Fog



Edge Classification

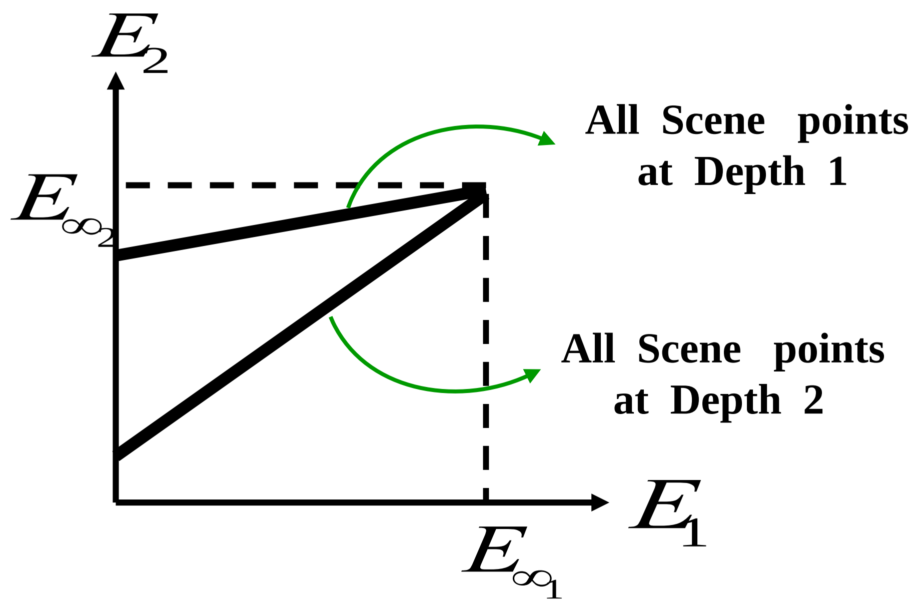
Reflectance Edge :

Depth Edge :

Scene Structure from Weather Changes

Irradiance E_1 under β_1 versus Irradiance E_2 under β_2 : **Linear**

$$\boxed{E_2} = \frac{E_{\infty_2}}{E_{\infty_1}} e^{-(\beta_2-\beta_1)d} \boxed{E_1} + E_{\infty_2}\left(1 - e^{-(\beta_2-\beta_1)d}\right)$$



Scaled Depth : $(\beta_2-\beta_1)\,d = \ln\dfrac{E_{\infty_1}-E_1}{E_{\infty_2}-E_2} + \ln\dfrac{E_{\infty_1}}{E_{\infty_2}}$

Gray World: Contrast Restoration and Structure

Misty Image (3:00pm)

Misty Image (4:00pm)

Deweathering

3D Visualization

Contrast Restoration and 3D Structure

Mild Fog, 5 PM

Dense Fog, 5:30 PM

Computed Depth Map (20 levels)

Contrast Restored Image

Defogging Videos

Foggy Video

Defogged Video

Histogram Equalized Video

Scattering and Wavelength

Rayleigh's Law :

constant

$$\beta = \frac{k}{\chi}$$

(0 – 4)

Smaller the particles, larger the dependence on wavelength

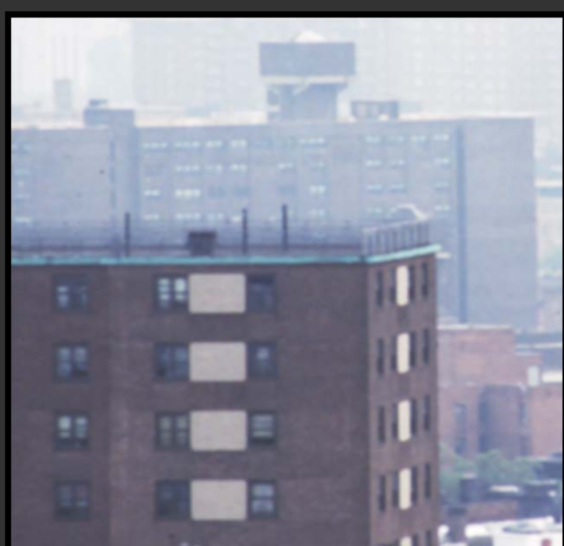
Blue skies through pure air (small particles)

Fog looks greyish (whitish) – larger water droplets.

Clear Day from Hazy Days

Unknown Hazy Conditions

Time: 3:00 PM



Time: 3:30 PM

Deweathering →

Computed Clear Day Image

(Narasimhan et. al, IJCV 2002)

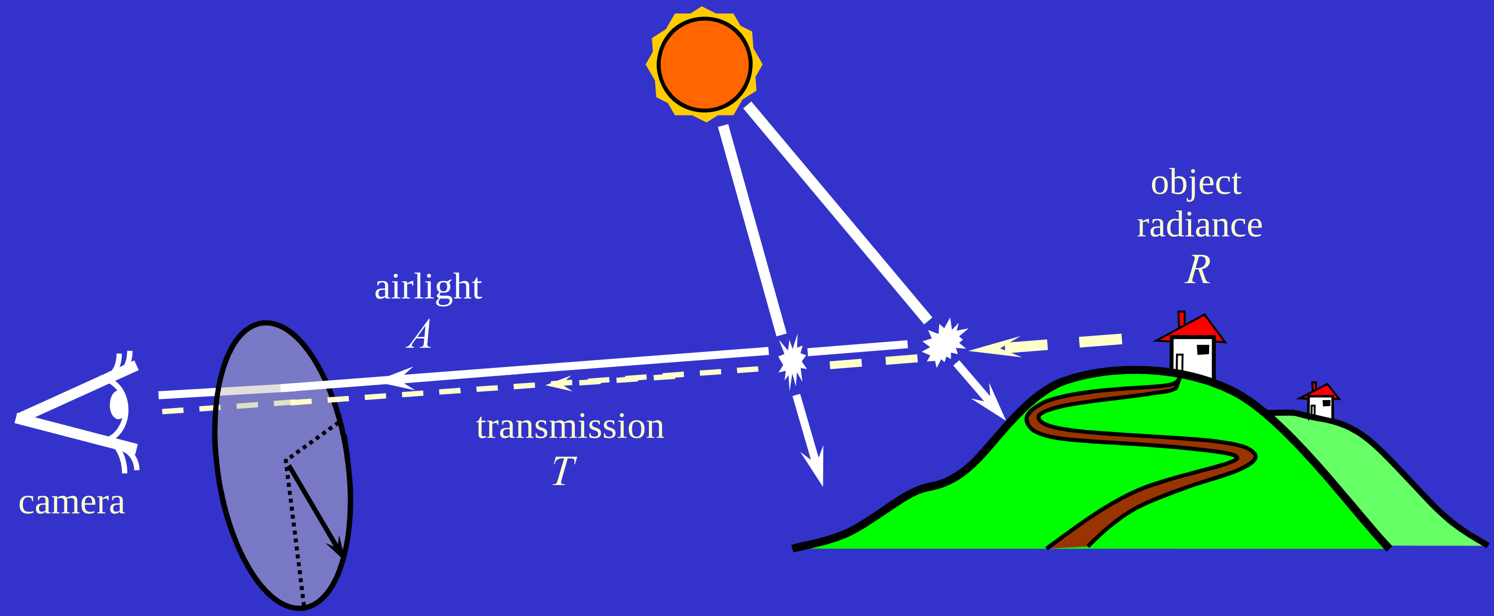
Clear Day from Hazy Day : Using Polarizing Filters

Haze

De-hazed

Airlight is Partially Polarized

Model



2 input images:

$$I_{||} = T/2 + A_{||}$$

$$I_{\perp} = T/2 + A_{\perp}$$

transmission $T = R\, e^{-\beta z}$

airlight $A = A_{\infty}\left(1\text{-}e^{-\beta z}\right)$

polarization degree $p \equiv \dfrac{A_{\perp} - A_{||}}{A_{\perp} + A_{||}}$

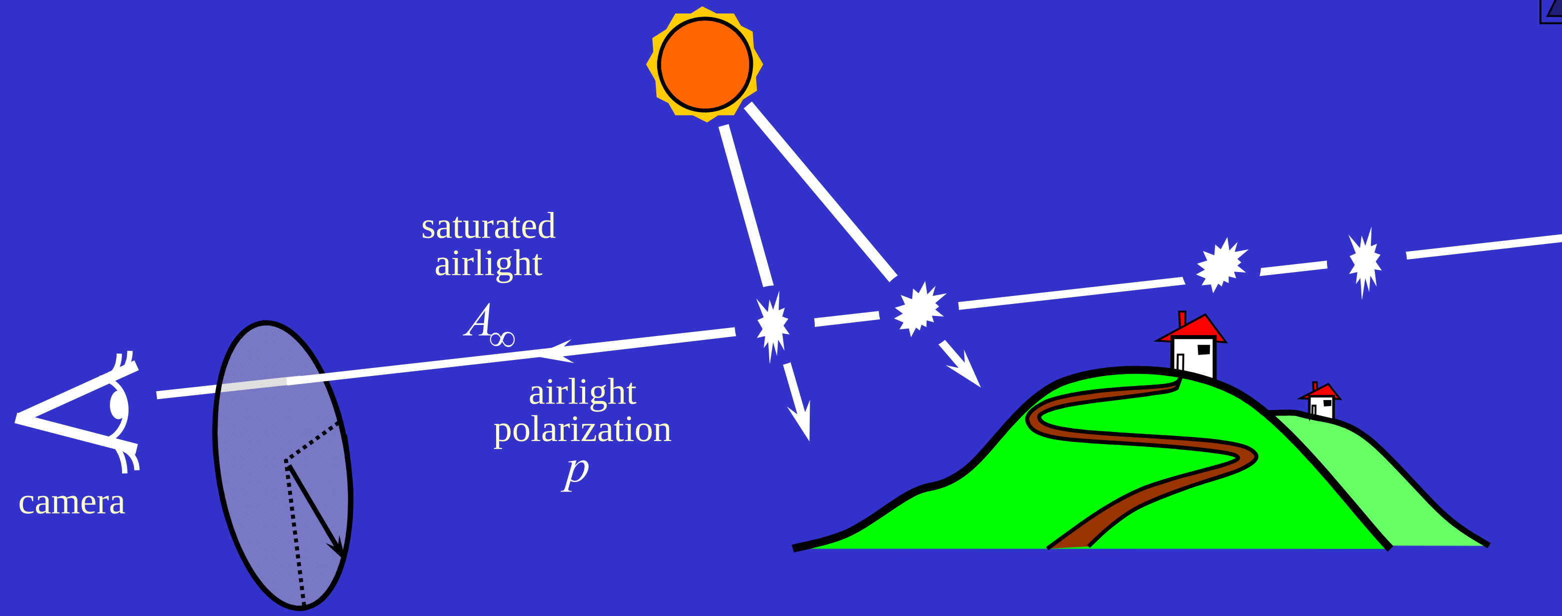
Recovery

depth $e^{-\beta z} = 1 - \dfrac{\boxed{(I_{\perp} - I_{||})/p}}{A_{\infty}}$

radiance $R = \dfrac{(I_{\perp} + I_{||}) - \boxed{(I_{\perp} - I_{||})/p}}{e^{-\beta z}}$

for known p, A_{∞}

Model



2 input images:

$$\boldsymbol{I}_{\parallel} = T/2 + \boldsymbol{A}_{\parallel}$$

$$\boldsymbol{I}_{\perp} = T/2 + \boldsymbol{A}_{\perp}$$

---

transmission $T = R\, e^{-\beta z}$

airlight $A = A_\infty \left(1 - e^{-\beta z}\right)$

polarization degree $p \equiv \dfrac{\boldsymbol{A}_{\perp} - \boldsymbol{A}_{\parallel}}{\boldsymbol{A}_{\perp} + \boldsymbol{A}_{\parallel}}$

Recovery

depth $e^{-\beta z} = 1 - \dfrac{(I_{\perp} - I_{\parallel})/p}{A_\infty}$

radiance $R = \dfrac{(I_{\perp} + I_{\parallel}) - (I_{\perp} - I_{\parallel})/p}{e^{-\beta z}}$

for known p, A_∞

Scattering from Near-Field Sources






Scattering from Near-Field Sources



Loss of contrast



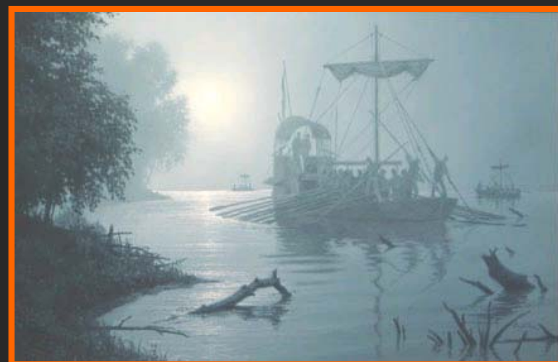
Scattering from Near-Field Sources



Loss of contrast   Dimming and blur



Scattering from Near-Field Sources

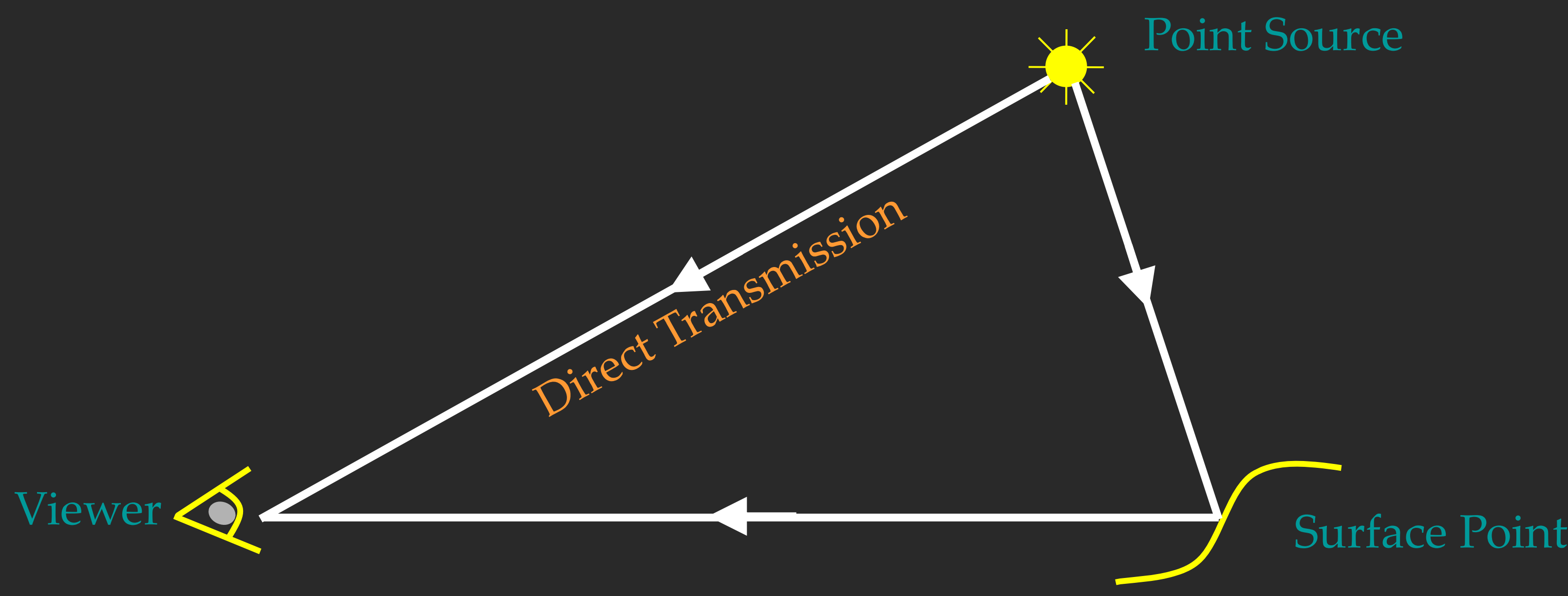

Lost of contrast

Dimming and blur

Glows

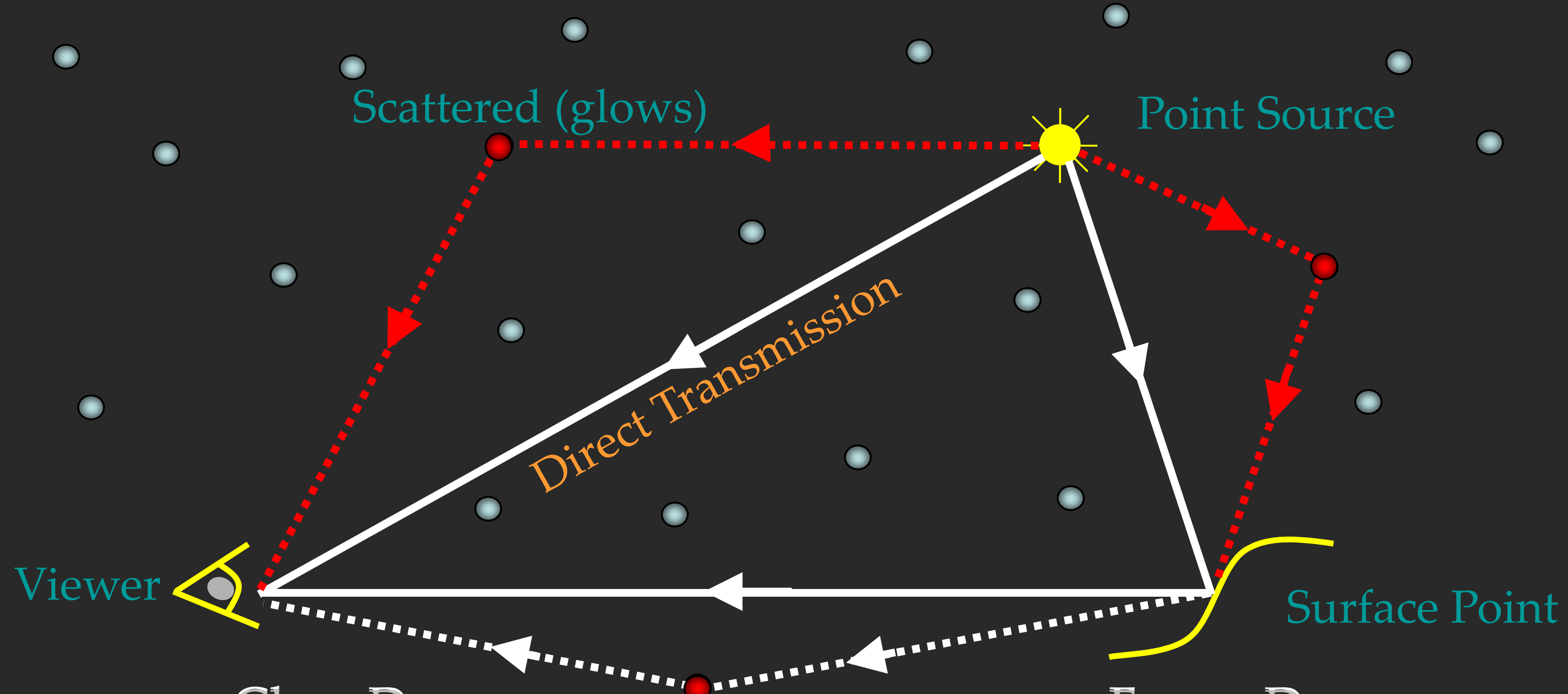


Light Transport in Clear Day



Near-Field Divergent Sources

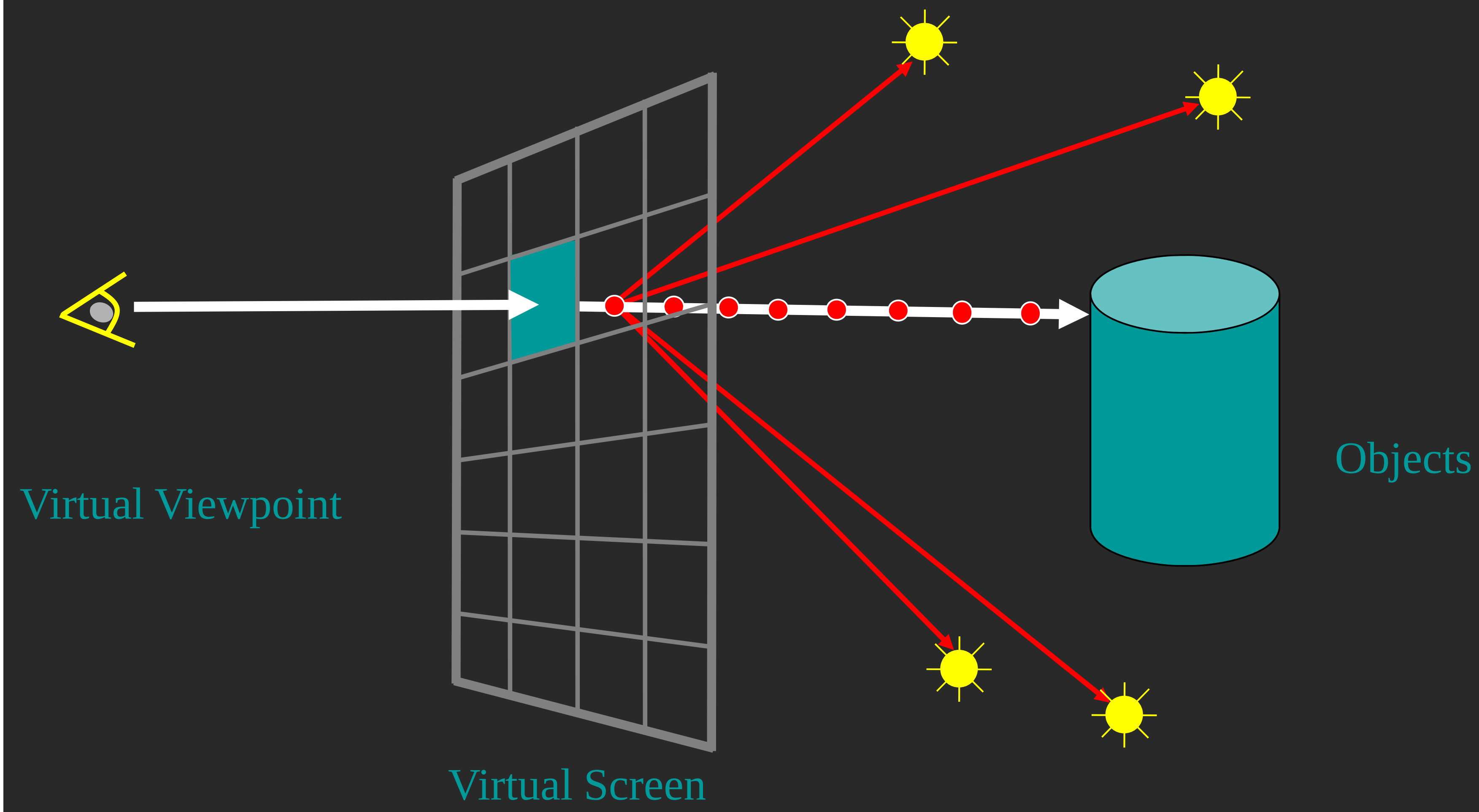
Light Transport in Scattering Media



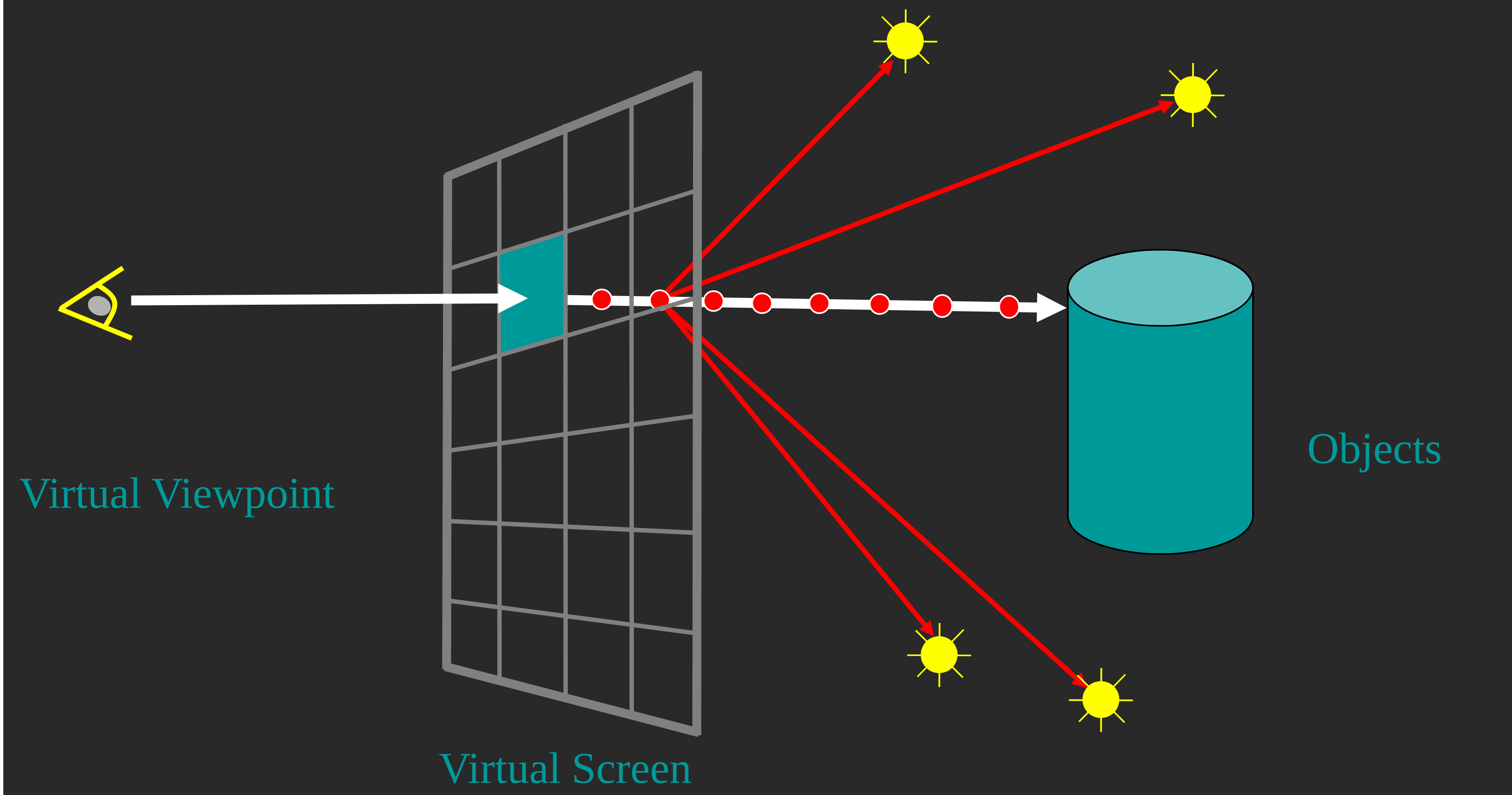
Clear Day

Foggy Day

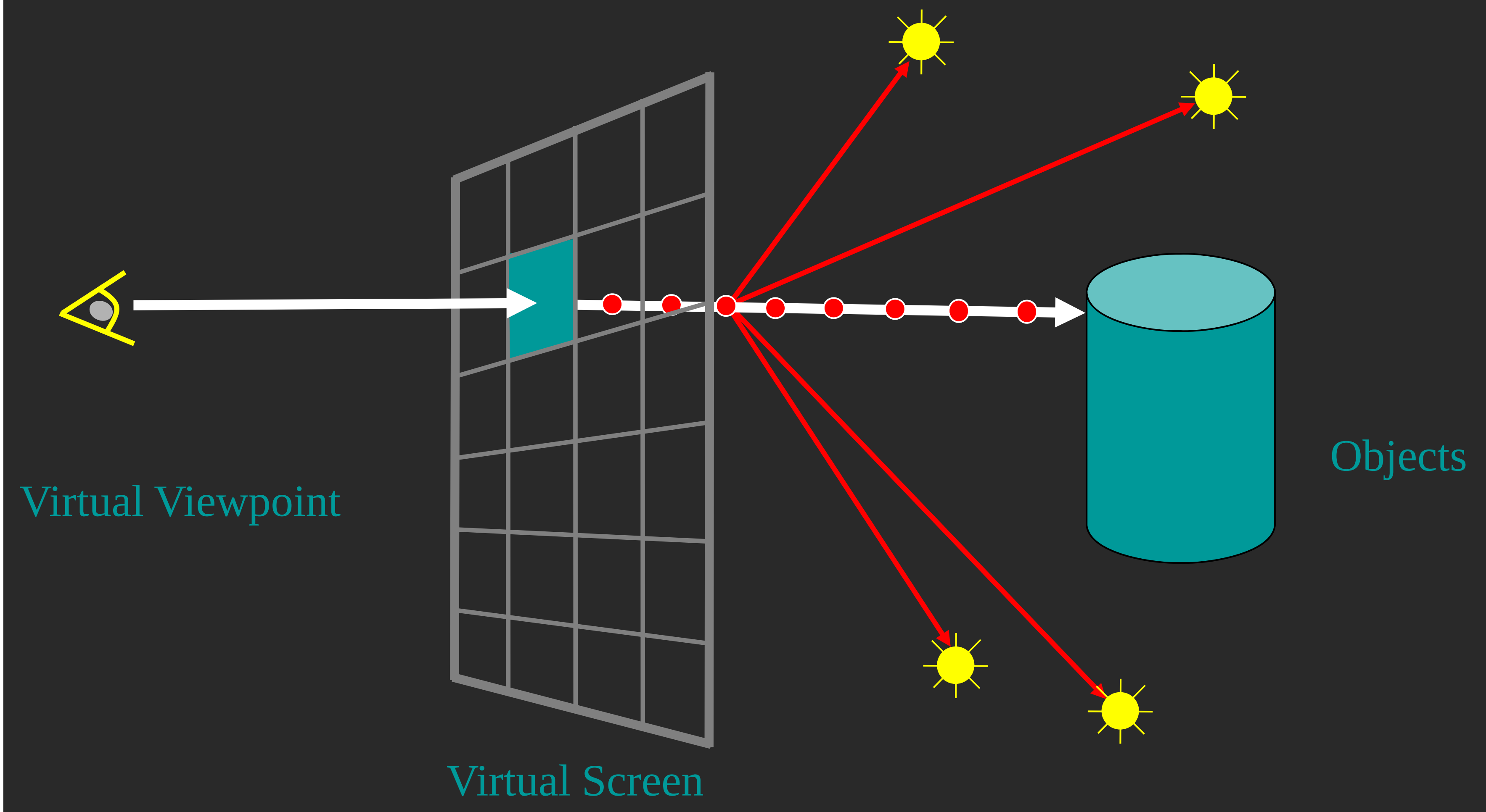
Complexity of Rendering Scattering Media



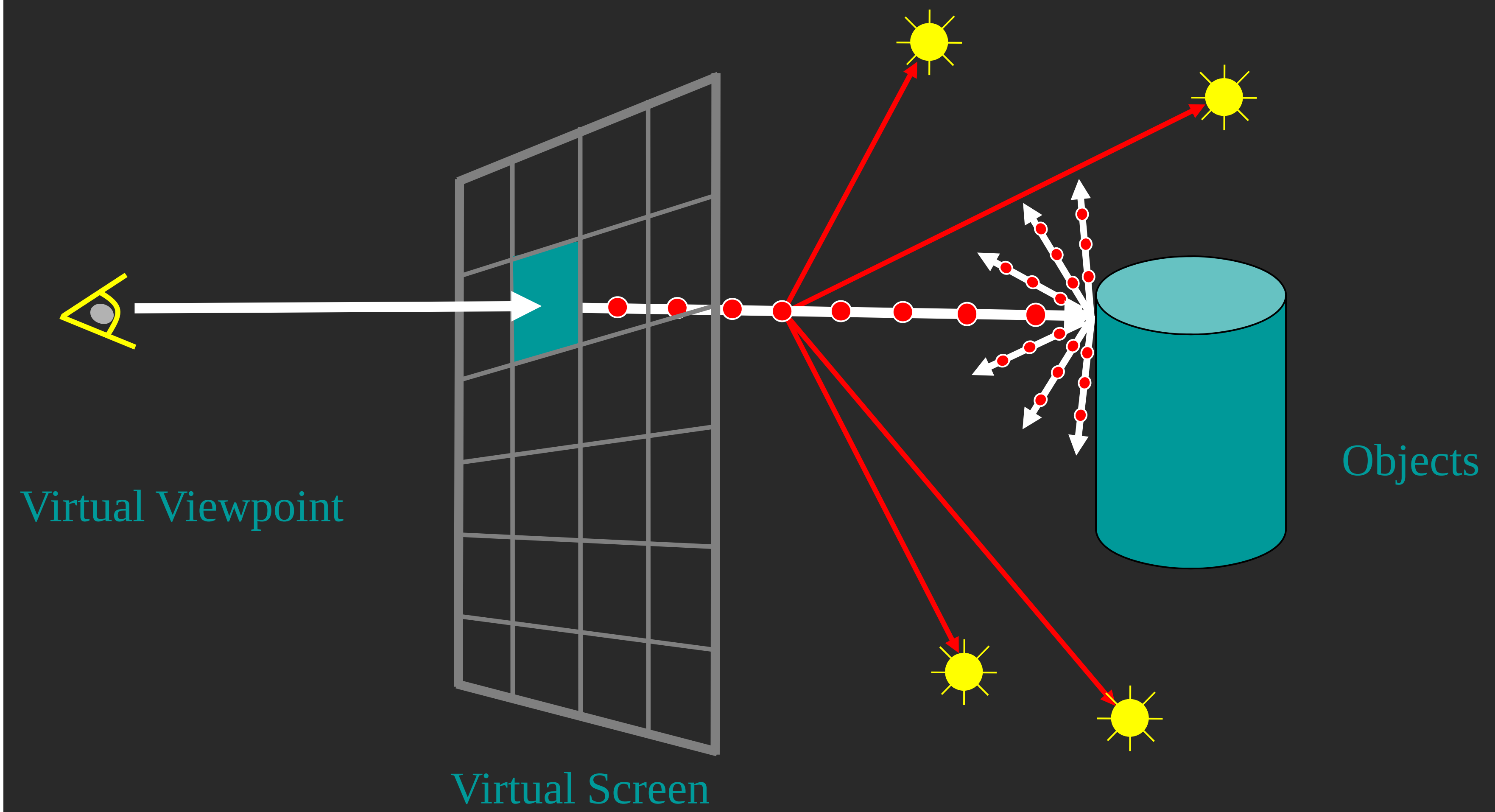
Complexity of Rendering Scattering Media



Complexity of Rendering Scattering Media



Complexity of Rendering Scattering Media



640×480 (image) $\times$ 4 (lights) $\times$ [50 (steps) + 100 (directions) $\times$ 50 (steps)] $\times$ $30\sqrt[3]{1000}$ (intersect) = ?

1.9 Trillion Calculations

3.0 GHz CPU?

NEXT CLASS

Multiple Scattering in Vision and Graphics