Introduction to Light Scattering:

An Imaging Sciences Perspective

Lecture #19
First, let's look at some pretty pictures
Distant objects appear Bright!
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?

Clear & Sunny (77%)

Bad Weather (23%)

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?

BRDF is a 4D function of viewing and illumination directions: \( f(\mathbf{w}_i, \mathbf{w}_o) \)

Jensen et al., 2001
Translucent Objects

Clouds

Milk

Koenderink and van Doorn, 2001

Illumination

Opaque (Lambertian Sphere) vs. Translucent (Cotton)
Rendering Milk

Skim Milk

Whole Milk

Diffuse BRDF

BSSRDF Model

Jensen et al., 2001
Rendering a Marble Bust

Jensen et al., 2001
Rendering Moon

Jensen et al., 2001
Computer Vision

Underwater Imaging

Optics

Medical Imaging

Satellite Imaging

Computer Graphics
Scattering in different fields

<table>
<thead>
<tr>
<th>Field</th>
<th>Years</th>
</tr>
</thead>
<tbody>
<tr>
<td>Art</td>
<td>500-600 years</td>
</tr>
<tr>
<td>Physics</td>
<td>250 years</td>
</tr>
<tr>
<td>Astrophysics/Astronomy</td>
<td>80-100 years</td>
</tr>
<tr>
<td>Atmospheric Optics</td>
<td>80-100 years</td>
</tr>
<tr>
<td>Medical Imaging</td>
<td>30 years</td>
</tr>
<tr>
<td>Remote Sensing</td>
<td>30 years</td>
</tr>
<tr>
<td>Oceanic Engineering</td>
<td>30 years</td>
</tr>
<tr>
<td>Computer Graphics</td>
<td>20 years</td>
</tr>
<tr>
<td>Computer Vision</td>
<td>5-10 years</td>
</tr>
</tbody>
</table>
The Fundamental Assumption in Vision

Assumption: We live in Vacuum!
Radiation Fog

Advection Fog

Dense Aerosols with Drizzle

Haze

Fog with Cumulus Clouds

Urban Aerosol with Moderate Rain
Driving in Bad Weather

People tend to drive fast in fog!! – Nature, 1998
## Weather Conditions and Particles

<table>
<thead>
<tr>
<th>CONDITION</th>
<th>PARTICLE TYPE</th>
<th>RADIUS ($\mu$m)</th>
<th>CONCENTRATION ($\text{cm}^{-3}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>AIR</td>
<td>Molecule</td>
<td>$10^{-4}$</td>
<td>$10^{19}$</td>
</tr>
<tr>
<td>HAZE</td>
<td>Aerosol</td>
<td>$10^{-2} \text{--} 1$</td>
<td>$10^3 \text{--} 10$</td>
</tr>
<tr>
<td>FOG</td>
<td>Water Droplet</td>
<td>$1 \text{--} 10$</td>
<td>$100 \text{--} 10$</td>
</tr>
<tr>
<td>CLOUD</td>
<td>Water Droplet</td>
<td>$1 \text{--} 10$</td>
<td>$300 \text{--} 10$</td>
</tr>
<tr>
<td>RAIN</td>
<td>Water Drop</td>
<td>$10^2 \text{--} 10^4$</td>
<td>$10^{-2} \text{--} 10^{-5}$</td>
</tr>
</tbody>
</table>

(Mie 1908, McCartney 1975)
Particle Scattering Mechanisms

(Mie 1908)

Single Scattering:

- Incident Beam
  - Size: 0.01 \( \mu m \)
  - Size: 0.1 \( \mu m \)
  - Size: 1 \( \mu m \)

Independent Scattering:

- Incident Beam
  - Distance of Separation >> Size of Particles
Multiple Scattering in the Atmosphere

Incident Beam → Particle → Phase Function
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:
  \[ \text{Phase function} \times \text{Scattering Coefficient} \]
Brightness at Distance \( d \):

\[
E(d) = E_0 \ e^{-\beta d}
\]

( Bouguer’s Law, 1729 )
Direct Transmission

Attenuation of Diverging Beams:

\[ E(d) = \frac{I_0 e^{-\beta d}}{d^2} \]  
(Allard’s Law, 1876)

Optical Thickness:

\[ T = \beta d \]

Scaled Depth
Airlight Model – First Order Scattering

Brightness due to a Path of Length $d$:

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

(Koschmeider, 1924)
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?

- Diffuse
- Skylight
- Sunlight
- Object
- Observer
- Attenuation
- Color vs. Distance
- Airlight
- Color vs. Distance
Contrast Degradation in Bad Weather

<table>
<thead>
<tr>
<th>Irradiance</th>
<th>=</th>
<th>Attenuation + Airlight</th>
</tr>
</thead>
<tbody>
<tr>
<td>$E(d)$</td>
<td></td>
<td>$E_\infty \rho e^{-\beta d}$ + $E_\infty (1-e^{-\beta d})$</td>
</tr>
</tbody>
</table>

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

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

Contrast Decay: Exponential in Scene Depth
Depth Edges vs. Reflectance Edges

Mild Fog

Normalized SSD of Reflectance Edge Neighborhood

\[ (\square - \square)^2 \]

Denser Fog

Normalized SSD of Depth Edge Neighborhood

\[ (\square - \square)^2 \ll (\square - \square)^2 \]

Depth Edge

Reflectance Edge
Edge Classification from Weather Changes

Mild Fog  Denser Fog

Edge Classification

Reflectance Edge: ---
Depth Edge: ----
Scene Structure from Weather Changes

Irradiance $E_1$ under $\beta_1$ versus Irradiance $E_2$ under $\beta_2$: Linear

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

Scaled Depth: $$(\beta_2 - \beta_1) d = \ln \frac{E_{\infty_1} - E_1}{E_{\infty_2} - E_2} + \ln \frac{E_{\infty_1}}{E_{\infty_2}}$$
Gray World: Contrast Restoration and Structure

Misty Image (3:00pm)

Misty Image (4:00pm)

3D Visualization

Dewathering
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:

\[
\beta = \frac{k}{\lambda} \quad \text{constant} \quad (0 - 4)
\]

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

Dewathering

Time: 3:30 PM

Computed Clear Day Image

( Narasimhan et. al, IJCV 2002)
Clear Day from Hazy Day: Using Polarizing Filters

Airlight is Partially Polarized
Model

2 input images:

\[ I_\parallel = T/2 + A_\parallel \]
\[ I_\perp = T/2 + A_\perp \]

transmission \( T = R e^{-\beta z} \)

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

polarization degree \( p \equiv \frac{A_\perp - A_\parallel}{A_\perp + A_\parallel} \)

Recovery

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

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

for known \( p, A_\infty \)
Model

2 input images:

\[ I_{\parallel} = \frac{T}{2} + A_{\parallel} \]
\[ I_{\perp} = \frac{T}{2} + A_{\perp} \]

transmission \( T = Re^{-\beta z} \)

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

polarization degree \( p \equiv \frac{A_{\perp} - A_{\parallel}}{A_{\perp} + A_{\parallel}} \)

Recovery

depth \( e^{-\beta z} = 1 - \frac{(I_{\perp} - I_{\parallel})}{A_\infty} \)

radiance \( R = \frac{(I_{\perp} + I_{\parallel}) - (I_{\perp} - I_{\parallel})}{p e^{-\beta z}} \) for known \( p, A_\infty \)
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
- Scattered (glows)
- Point Source
- Direct Transmission
- Surface Point
- Viewer

Inclusions: Scattered light (glows) and different lighting conditions.
Complexity of Rendering Scattering Media

Virtual Viewpoint

Virtual Screen

Objects
Complexity of Rendering Scattering Media

Virtual Viewpoint

Virtual Screen

Objects
Complexity of Rendering Scattering Media

Virtual Viewpoint

Virtual Screen

Objects
Complexity of Rendering Scattering Media

Virtual Viewpoint

Virtual Screen

Objects

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

1.9 Trillion Calculations
3.0 GHz CPU?
NEXT CLASS

Multiple Scattering in Vision and Graphics