Refractions, Reflections and Caustics: Basic Concepts

Lecture #15

Thanks to Henrik Jensen, John Hart, Ron Fedkiw, Pat Hanrahan, Rahul Swaminathan, Ko Nishino
Reflection and Refraction

Reflection

Vertex Normal N

Refraction

Air

Water

α

β
Snell’s Law

- $\alpha$ Incoming = $\alpha$ Reflected
- $\sin(\alpha)/\sin(\beta) = \text{Refractive Index}$ (material dependent)
- Refractive index inversely proportional to speed of light (Huygens Principle)

<table>
<thead>
<tr>
<th>Material</th>
<th>Refractive Index</th>
</tr>
</thead>
<tbody>
<tr>
<td>Air</td>
<td>1.0003</td>
</tr>
<tr>
<td>Water</td>
<td>1.333</td>
</tr>
<tr>
<td>Glycerin</td>
<td>1.473</td>
</tr>
<tr>
<td>Immersion Oil</td>
<td>1.515</td>
</tr>
<tr>
<td>Glass (Crown)</td>
<td>1.520</td>
</tr>
<tr>
<td>Glass (Flint)</td>
<td>1.656</td>
</tr>
<tr>
<td>Zircon</td>
<td>1.920</td>
</tr>
<tr>
<td>Diamond</td>
<td>2.417</td>
</tr>
<tr>
<td>Lead Sulfide</td>
<td>3.910</td>
</tr>
</tbody>
</table>
Snell's Law and Refractive Index Effects

\[ n_1 < n_2 \]

- Incident Ray
- Normal
- Air
- Refracted Ray
- Water
- Interface

\[ n_1 > n_2 \]

- Incident Ray
- Normal
- Air
- Refracted Ray
- Water

Figure 3
Light Refraction Through Glass and Water

Figure 4
Virtual Image Observed by Refraction

Eye

Incoming Light Rays

Image Seen by Eye

Actual Position of Fish

Figure 6
Image Formation with a Convex Lens

Figure 5
Reflection
Reflections From the Surface of Water

Smooth Water Surface

Wavy Water Surface

Figure 1
Reflection from Convex and Concave Surfaces

Outside Spoon Bowl

Inside Spoon Bowl

Figure 4
Experiment

Reflections from a shiny floor

From Lafortune, Foo, Torrance, Greenberg, SIGGRAPH 97
Really starts to be noticeable at less than 10-15° from the surface.
Fresnel Reflectance

Metal (Aluminum)

Dielectric (N=1.5)

Gold  $F(0)=0.82$
Silver  $F(0)=0.95$

Glass  $n=1.5  F(0)=0.04$
Diamond  $n=2.4  F(0)=0.15$

Schlick Approximation  $F(\theta) = F(0) + (1-F(0))(1-\cos\theta)^5$

CS348B Lecture 10  Pat Hanrahan, Spring 2002
Fresnel Term

- Fresnel Term as found in text books is
  \[ F = \frac{1}{2} \left( \frac{\sin^2(\alpha - \beta)}{\sin^2(\alpha + \beta)} \right) + \tan^2(\alpha - \beta) \cdot \tan^2(\alpha + \beta) \]

- Returns good results for strong reflecting water surfaces
Approximated Fresnel Term

- $F_0 = \frac{(N-1)^2}{(N+1)^2}$ is a minimum of incoming light parallel to the normal of the surface.

- $F_\alpha = F_0 + (1 - \cos(\alpha))^5 \times (1 - F_0)$ is a value between 0 and 1 depending on the angle between the incoming ray and the surface normal.

- e.g. $F_{90} = 1$, if the incoming ray is parallel to the surface, all light is reflected.
Designed to reflect all light eventually to Observer.
Anti-reflective Coatings

- Reduce unwanted, stray reflections
- Use material coatings on glass to reduce reflection and maximize transmission.
- Take advantage of destructive light interference.

“One of the most significant advances made in modern lens design, whether for microscopes, cameras, or other optical devices, is the improvement in antireflection coating technology.”
Anti-reflective Coatings

Magnesium fluoride very commonly used on Lenses, Microscopes
Refractions or Reflections?
Refractions or Reflections Confusion

Why do you see shiny roads when they are diffuse and are not wet?

Why do you see apparent reflections in deserts?

Where else do you see apparent reflections?

Do you see reflections above objects???
Reflection at the Critical Angle

Figure 9

- Refracted Light Waves
- Reflected Light Waves
- Total Internal Reflection
- Air
- Aqueous Medium
- \( n(2) > n(1) \)
Mirage and Looming Artifacts

Cool Air

Warm Air

Virtual Image

Observer sees the virtual image of palm tree.
Looming Image
Observer sees the virtual image of an inverted ship.

Warm Air
(b)

Cool Air

Figure 7
Total Internal Reflection in Fiber Optics

Figure 7

Individual Glass Fibers

Internal Light Wave Reflections

Fiber Optic Light Pipe

Used in Endoscopy, Communications
Water Drops: Refractions + Reflections
A Drop and its Environment.

World in a drop
Shapes of falling drop

Shapes of falling drop
Refraction and Reflection
Refraction

\[ \theta_r = 2(\pi - \theta_n) + 2 \sin^{-1}\left(\frac{\sin(\theta_n)}{\mu}\right) \]

\[ \phi_r = \pi + \phi_n . \]
Geometric mapping

fov=165 degrees

\[ \rho = ma \sin \theta_n , \quad \phi = \phi_n . \]
Experiments: Refraction

Experimental setup

Calculated corners are in green
Photometry of Refraction

\[ L_r(\hat{n}) = (1 - k(i))^2 L_e(\hat{r}) . \]
Plot of Transmitted Radiance
Experiment: Photometry of Refraction

Experimental Setup

Rendered  actual image  difference image
Reflection

\[ \theta_s = 2\theta_n - \pi \]
\[ \phi_s = \pi + \phi_n. \]
Photometry of Reflection

\[ L_s(\hat{n}) = k(i)L_e(\hat{s}) \]
Reflection vs. Refraction

\[ L(\hat{n}) = (1 - k(i))^2 L_e(\hat{r}) + k(i) L_e(\hat{s}) \]
Rendering a Rain drop

Environmental Illumination

Rendering a Drop
World in a Rain Drop

Low Library

Pupin Hall
Tired of water drops?

Wait, there’s more...
Rainbows: Refractions + Reflections + Wavelength of Light
Rainbow Features

- Secondary bow colors reversed
- Darker sky between
- Supenumerary arcs
- Light sky under primary rainbow
Visible Light Wavelength Dispersion

Equilateral Dispersing Prism

Figure 8

White Light

Separated or Dispersed Wavelengths

Red

Orange

Yellow

Green

Blue

Purple
Can you see rainbows during midday?
Why are there two rainbows?

Are there only two rainbows?
Why the color pattern?

The colors of the secondary rainbow are reversed from the primary bow, and the secondary bow is twice as broad.

Violet light is bent more and comes out higher from the droplet. It appears at the bottom of the rainbow since violet light from lower droplets strikes your eye.

The red light from droplets higher in the sky reaches your eye.

Red

Violet
top of secondary bow since it comes to the eye from higher drops.
Bright Sky under and Dark above the Rainbow

Photo by Ben Lanterman taken immediately after a heavy rainstorm when the air was quite saturated at 4PM.
Lowest drops which double reflect to the eye.

Highest drops which single reflect to the eye.

Secondary rainbow angle
51°

42°

Observer

Dark sky

Primary rainbow angle

Light sky

Anti-solar point
Caustics: Bunching up
Reflections or Refractions
• What is wrong with this rendering?
With caustics
Looking at Water

- Light is reflected and refracted at the same time
- There is a light pattern on the ground (Caustics)
• Shafts of light and caustics:
Caustics by Refraction

- Light is refracted by the water surface
- Some spots are stronger illuminated than others
Light rays through a water surface

Bright areas caused by bunching of refracted rays
Water-filled glass spheres to focus or condense candlelight onto small areas
Lighting Effects

Hard Shadows

Soft Shadows

Caustics

Indirect Illumination

CS348B Lecture 1

Pat Hanrahan, Spring 2002
Create nice pictures with translucent objects and render nice effects on diffuse surfaces.
Caustics in Cornell Box
Modeling and Animating Water Surfaces
Caustics by Reflections
Reflections and Caustics: Catadioptric Imaging + Refractions/Reflections and Caustics: Photon Mapping

Lecture #16

Thanks to Henrik Jensen, John Hart, Ron Fedkiw, Pat Hanrahan, Rahul Swaminathan, Ko Nishino