CS6630: Realistic Image Synthesis

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determining how much light falls on a flat surface not in shadow is trivial, and even for curved surfaces this is not difficult, but economically determining exactly what regions of the scene are in shadow is a very difficult problem.

Figure 3 — An assembly of planes which make up a cardboard model of a building

Figure 4 — Another view of the building

Figure 5 — A higher angle view of the building. The calculation time for this picture was about 30 minutes.

Point by point shading techniques yield good graphic results but at large computational times. These techniques are docile, require the minimum of storage and enable easily coded graphical experimentation. Figures 3, 4, and 5 are examples of point by point shading. Referring to Figure 6, the technique generating these pictures was as follows:

1. Determine the range of coordinates of the projection of the vertex points.
2. Within this range generate a roster of spots (Pi) in the picture plane, reproject these spots one at a time to the eye of the observer and generate the equation of the line of sight to that spot.
3. Determine the first plane the line of sight to a particular spot pierces. Locate the piercing point (Pi) in space. Ignore the spots that do not correspond to any point on the object.
4. Determine whether the piercing point is hidden from the light source by any other surface. If the point is hidden from the light source (for example P2) or if the surface the piercing point is on is being observed from its shadow side, mark on the roster spot the largest allowable plus sign Hs. If the point in space is visible to the light source (for example Px) draw a plus sign with dimension Hj as determined by Equation 1.

This method is very time consuming, usually requiring for useful results several thousand times as much calculation time as a wireframe drawing. About one half of this time is devoted to determining the point to point correspondence of the projection and the scene. In order to minimize calculation time for point by point shading and maintain resolution, techniques were developed to determine the outline of cast shadows. Outlining shadows has the advantage that all regions of dissimilar tones on the picture plane are outlined. Even when projected shadows are delicate, and symbols spacing is large, the shadows are specified and the discontinuity in tone is emphasized.

The strategy for point by point determination of shadow boundaries is as follows: (Referring to Figure 7)
Whitted 1980
Recursive ray tracing
Cook, Porter, Carpenter 1984
Distribution Ray Tracing
Figure 8. Simulated Cube with Two Wall Subdivisions and Linear Interpolation Over each Element (Patch).

Values for front wall (~p seen):

Goral et al. 1984
Radiosity method
Hanrahan et al. 1991
Hierarchical radiosity
Lischinski et al. 1993
Discontinuity meshing
Sillion et al. 1991
Nondiffuse radiosity
Hanrahan and Lawson 1992
RenderMan shading language
Kajiya 1986
The Rendering Equation; path tracing
Figure 10.3: A comparison of bidirectional and standard path tracing. The test scene contains a spotlight, a floor lamp, a table, and a large glass egg. Image (a) was computed with bidirectional path tracing, using the power heuristic with to combine the samples for each path length. The image is 500 by 500 with 25 samples per pixel. Image (b) was computed using standard path tracing in the same amount of time (using 56 samples per pixel).
Veach and Guibas 1997
Markov Chain Monte Carlo (Metropolis Light Transport)
Kelemen et al. 2002
Primary sample space MCMC
Cline et al. 2005

“Energy Redistribution” with non-ergodic MCMC
Walter et al. 1997 • Jensen 1996
Density estimation (Photon Mapping)
Keller 1997

Virtual point lights (Instant Radiosity)
Walter et al. 2005
LightCuts
This results in an effective optical depth
\[ t' = \frac{t}{1-D} \]
for the very small values of \( D \) for which the approximation was valid. This reduces to the classical result. When \( D \) approaches 1 (i.e., a solid packing of scattering particles), the effective optical depth approaches infinity, as would be expected. Note that this extension is particularly nice in that it only alters the value of the input parameter to the brightness function but does not otherwise alter the properties of that function.

5.2 Shadowing Effect

The scattering function was derived from considering the volume of two cylinders for entering and exiting rays of light. At that time it was mentioned that there was a small overlap between the cylinders \( V_{\text{in}} \) and \( V_{\text{out}} \) which was neglected. This overlap actually becomes quite significant when \( L = E \) (i.e., \( p = p_0 \)). The two cylinders, in fact, coincide and the entire volume is erroneously counted twice. This geometrical situation will yield a brighter observed intensity than that predicted by the simple model. The correct value will be produced by counting only...
Jensen and Christensen 1998
Volumetric photon mapping
Figure 7: The Cornell box, Cars, and Lighthouse scenes. Render times are shown as (minutes:seconds). For both the fixed and adaptive gathering approaches our method produces noise-free results while conventional photon mapping suffers from significant noise, especially around distant light sources.
Pauly et al. 2000
Metropolis in volumes
Diffuse:

Ambient:

mirror

\[ D = \text{Beckmann function with} \]
\[ \begin{align*}
& w_{ml} = 0.4 \\
& m_1 = 0.4 \\
& w_{m1} = 0.2 \\
& d = 0.0 \\
& R_d = \text{the bidirectional reflectance of copper for normal incidence} \\
& I_{ia} = 0.01 \cdot I_i \\
& R_a = R_d
\end{align*} \]

Note that two values for the rms slope are employed to generate a realistic rough surface finish. The specular reflectance component has a copper color. The copper vase in Figure 6b does not display the plastic appearance of the vase in Figure 6a, showing that a correct treatment of the color of the specular component is needed to obtain a realistic nonplastic appearance.

Figure 7 shows vases made of a variety of materials. In every case, the specular and diffuse components have the same color (i.e., \( R_d = F_0 = \lambda \)). The lighting conditions for all of the vases are identical to the lighting conditions for Figures 6a and 6b. The six metals were generated with the same parameters used for Figure 6b, except for the reflectance spectra. The six nonmetals were generated with the following parameters:

<table>
<thead>
<tr>
<th>Material</th>
<th>( s_d )</th>
<th>( m_2 )</th>
<th>( w_{ml} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>Carbon</td>
<td>0.3</td>
<td>0.7</td>
<td>0.40</td>
</tr>
<tr>
<td>Red Rubber</td>
<td>0.4</td>
<td>0.6</td>
<td>0.30</td>
</tr>
<tr>
<td>Obsidian</td>
<td>0.8</td>
<td>0.2</td>
<td>0.15</td>
</tr>
<tr>
<td>Lunardust</td>
<td>0.0</td>
<td>1.0</td>
<td>not used</td>
</tr>
<tr>
<td>Army Olive</td>
<td>0.3</td>
<td>0.7</td>
<td>0.50</td>
</tr>
<tr>
<td>Ironox</td>
<td>0.2</td>
<td>0.8</td>
<td>0.35</td>
</tr>
</tbody>
</table>

Figure 8 shows a watch made with a variety of materials and surface conditions. It is illuminated by a single light source. The outer band of the watch is made of gold, and the inner band is made of stainless steel. The pattern on the links of the outer band was made by using a rougher surface for the interior than for the border. The LEDs are standard red 640 nanometer LEDs, and their color was approximated by using a color with the same dominant wavelength.

Conclusions

1. The specular component is usually the color of the material, not the color of the light source. The ambient, diffuse, and specular components may have different colors if the material is not homogeneous.

2. The concept of bidirectional reflectance is necessary to simulate different light sources and materials in the same scene.

3. The facet slope distribution models used by Blinn are easy to calculate and are very similar to others in the optics literature. More than one facet slope distribution function can be combined to represent a surface.

4. The Fresnel equation predicts a color shift of the specular component at grazing angles. Calculating this color shift is computationally expensive unless an approximate procedure or a lookup table is used.

5. The spectral energy distribution of light reflected from a specific material can be obtained by using the reflectance model together with the spectral energy distribution of the light source and the reflectance.
Walter et al. 2007
Microfacet transmission model
Jakob et al. 2010
Anisotropic volume media
Stam 1995
Diffusion for light transport
Figure 9: A simulation of subsurface scattering in a marble bust. The marble bust is illuminated from behind and rendered using:

- **a**– the BRDF approximation, in 2 minutes;
- **b**– the BSSRDF approximation, in 5 minutes;
- **c**– a full Monte Carlo simulation, in 1250 minutes.

Notice how the BSSRDF model matches the appearance of the Monte Carlo simulation, yet is significantly faster. The images in **d–f**– show the different components of the BSSRDF:

- **d**– single scattering term,
- **e**– diffusion term,
- **f**– Fresnel term.

Highly scattering materials (such as milk and skin).

A particularly interesting aspect of the BSSRDF simulation is that it is able to capture the smooth appearance of the marble surface. In comparison the BRDF simulation gives a very hard appearance where even tiny bumps on the surface are visible (this is a classic problem in realistic image synthesis where objects often look hard and unreal).

For the marble we used synthetic scattering and absorption coefficients, since we wanted to test the difficult case when the average scattering albedo is 0.5 (here the contribution from diffusion and single scattering is approximately the same). Figure 9 demonstrates how the sum of both single scattering and the diffusion term is necessary to match the Monte Carlo simulation.

Figure 10 contains three renderings of milk. The first rendering uses a diffuse reflection model; the others use the BSSRDF model and our measurements for skim milk and whole milk. Notice how the diffuse milk looks unreal and too opaque compared to the BSSRDF images, even though multiple scattering dominates and the radiant exitance due to subsurface scattering is very diffuse. It is interesting that the BSSRDF simulations are capable of capturing the subtle details in the appearance of milk, making the milk look more bluish at the front and more reddish at the back. This is due to Rayleigh scattering that causes shorter wavelengths of light to be scattered more than longer wavelengths.

Skin is a material that is particularly difficult to render using methods that simulate subsurface scattering by sampling ray paths through the material. This is due to the fact that skin is highly scattering (typical albedo is 0.95) and also very anisotropic (typical average cosine of the scattering angle is 0.85). Both of these properties mean that the average number of scattering events of a photon is very high (often more than 100). In addition skin is very translucent, and it cannot be rendered correctly using a BRDF (see Figure 11). A complete skin model requires multiple layers, but a reasonable approximation can be obtained using just one layer. In Figure 11 we have rendered a simple face model using the BSSRDF and our measured values for skin (skin1). Here we also used the Henyey-Greenstein phase function \( g = 0.85 \) as the estimated mean cosine of the scattering angle. The skin measurements are from an arm (which is likely more translucent than skin on the face), but the overall appearance is still realistic considering the lack of spatial variation (texture). The BSSRDF gives the skin a soft appearance, and it renders the color bleeding in the shadow region below the nose. Here, the absorption by blood is particularly noticeable as the light that scatters deep in the skin is redder. For this simulation the diffusion term is much larger than the single scattering term. This means that skin reflects light fairly diffusely, but also that internal color bleeding is an important factor. The BRDF image was rendered in 7 minutes, the BSSRDF image was rendered in 17 minutes.

### 6 Conclusion and Future Work

In this paper we have presented a new practical BSSRDF model for computer graphics. The model combines a dipole diffusion approximation with an accurate single scattering computation. We have shown how the model can be used to measure the scattering properties of translucent materials, and how the measured values can be used to reproduce the results of the measurements as well as synthetic renderings. We evaluate the BSSRDF by sampling the incoming light over the surface, and we demonstrate how this technique is capable of capturing the soft and smooth appearance of translucent materials.

In the future we plan to extend the model to multiple layers as well as include support for efficient global illumination.
d’Eon and Irving 2011
Advanced diffusion models