# Rendering of Wet Materials

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**Abstract.** The appearance of many natural materials is largely influenced by the environment in which they are situated. Capturing the effects of such environmental factors is essential for producing realistic synthetic images. In this work, we model the changes of appearance due to one such environmental factor, the presence of water or other liquids. Wet materials can look darker, brighter, or more specular depending on the type of material and the viewing conditions. These differences in appearance are caused by a combination of the presence of liquid on the surface and inside the material. To simulate both of these conditions we have developed an approach that combines a reflection model for surface water with subsurface scattering. We demonstrate our approach with a variety of example scenes, showcasing many characteristic appearances of wet materials.

**Keywords:** appearance, subsurface scattering, participating media, global illumination, Monte Carlo, rendering, ray tracing.

## 1 Introduction

It is well known that the appearance of materials is noticeably influenced by environmental factors. One common factor is the presence of water and other liquids, either on or within a material, leading to a "wet" appearance. For example, most rough or powdered materials, such as sand, asphalt, and clay, become darker when wet. Other materials, such as paper and cloth, become more transparent. Wet paper appears darker than dry paper under direct lighting conditions, but brighter than dry paper when illuminated from behind.

In these examples, the appearance is affected by water that has been absorbed into the material. A different situation can be observed when water is present on the surface of a material, such as water puddles on a road. The appearance of the road is changed so that it not only becomes darker but it also becomes more specular due to the smooth air-water interface.

The presence of water puddles on a road has been simulated in computer graphics by Nakamae et al. [12] for the purpose of driving simulations. They modeled water puddles using a two-layer reflection model with one layer of water above the asphalt. To account for the darkening of the road due to the presence of water, they use an empirical approach, introducing mud particles in the water and manually adjusting the diffuse and specular coefficients of the road. To simulate the transition from a dry road to a wet road with water puddles, they linearly interpolate the reflection coefficients and normal vectors of the smooth water surface and the bump-mapped asphalt. This approach made it possible to render some very convincing images. Dorsey et al. [4]

also applied an empirical approach to rendering surface water due to flow simulations, modulating the diffuse reflection depending on the wetness.

In the optics literature, there are two dominating theories regarding the appearance of wet materials, one considering a layer of water on the surface [10], and a second considering water inside the material [17]. In this paper we present a model that incorporates both of these theories, implemented in a general Monte Carlo subsurface scattering ray tracer. We find that these theories can be integrated effectively, and our results demonstrate that our model can be used to accurately simulate the appearance of wet materials.

### 1.1 Overview

The rest of this paper is organized as follows. In Section 2, we describe the two theories that explain why some materials change appearance when wet. We present our methods for rendering both surface and subsurface water effects in Section 3. In Section 4 we show our results of applying these methods to four test scenes. We discuss our results in Section 5, and in Section 6 we draw conclusions.

## 2 The Appearance of Wet Materials

There are two main reasons why materials look different when they are wet: a layer of water on the surface and a concentration of water beneath the surface. Both of these components influence the appearance of the material.

### 2.1 Water on the Surface

The presence of water on a surface (for example a puddle of water on a road) causes the surface to become specular due to the smooth air-water interface. The behavior of this interface is described by Fresnel's equations for dielectric media [3].

A thin water film on a Lambertian surface can also cause the surface to become darker [10]. The main cause for this darkening is the possibility of total internal reflection at the water-air boundary. Some of the light reflected from the Lambertian surface will be reflected back to the surface by the water-air interface. This light is then subject to another round of absorption by the surface (see Figure 1) before it is reflected again. This can lead to a sequence of multiple absorptions, resulting in a darkening of the surface.

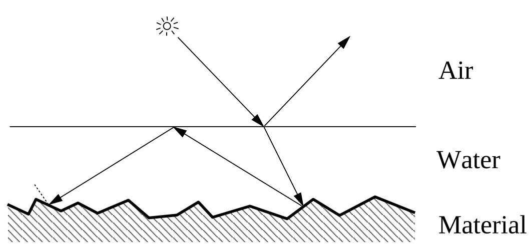



**Fig. 1.** A layer of water above the surface reflects less light due to the internal reflection at the water-air interface.

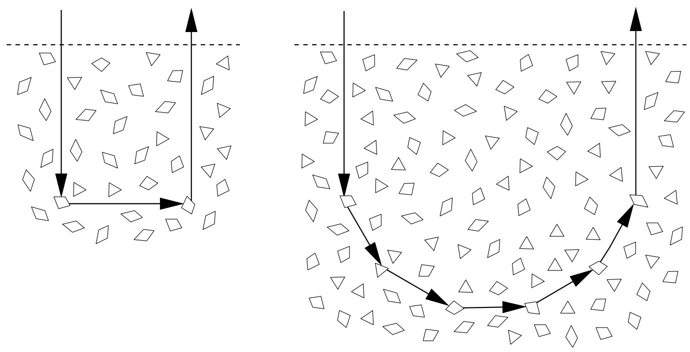



**Fig. 2.** After many scattering events, the shortest path a photon can take to leave the surface (a) with 90 degree average scattering angle and (b) with 30 degree average scattering angle. (Redrawn from [2].)

### 2.2 Water Beneath the Surface

The presence of water beneath the surface is another important factor influencing the appearance of a material. For rough or powdered materials, such as sand or clay, the water can usually enter regions previously filled with air. This changes the scattering properties of the material and makes the scattering more directional in the forward direction [17]. The main reason for this is that the index of refraction of water is higher than that of air and most often closer to that of the material. This again means that a ray of light entering the material will be refracted less due to the lower relative index of refraction. On a larger scale, this can be seen as a change in the scattering properties of the material, where the average scattering angle is reduced such that the scattered light diverges less from the previous ray. As illustrated in Figure 2, the influence of this reduced scattering angle on a ray of light is that it on average it undertakes a larger number of scattering events before leaving the surface. This increases the total amount of light that is absorbed, and the overall effect is a reduction in the reflectivity of the material.

## 3 Rendering Wet Materials

We use a combined surface and subsurface model to capture the appearance of wetness in and on a material. The surface model is used to simulate the interaction of light with a thin film of water or other liquid on the surface. The subsurface model is used to simulate the scattering properties of the material, and how they are changed by the presence of absorbed wetness.

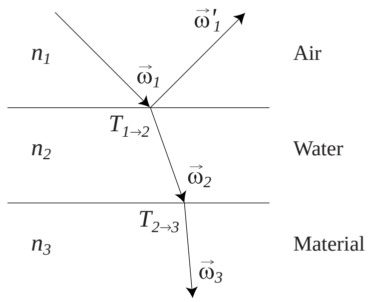



**Fig. 3.** Computing the light transmitted through a thin liquid film.

### 3.1 A Two-Layer Surface Reflection Model

To simulate the presence of a thin film of liquid on a surface, we use a two-layer reflection model. This model takes into account the interaction of light with both the air-liquid interface and the liquid-material interface (see Figure 3). By using Fresnel's equation [3] we can compute the amount of light transmitted through each layer:

$$T_{1\to2} = \left(\frac{n_1}{n_2}\right)^2 (1 - F_{1-2}(\vec{\omega}_1, n_1, n_2)) \quad (1)$$

and

$$T_{2\to3} = \left(\frac{n_2}{n_3}\right)^2 (1 - F^k_{2-3}(\vec{\omega}_2, n_2, n_3)), \quad (2)$$

where $n_1$, $n_2$, and $n_3$ are the indices of refraction of air, the liquid, and the material respectively. $\vec{\omega}_2$ is the refracted direction into the liquid as given by Snell's law. $F_{1-2}$ and $F_{2-3}$ are the amount of reflected light at the air-liquid and the liquid-material interface respectively. The Fresnel term for the liquid-material interface is raised to a constant $k$. We use $k$ as a simple technique for simulating surface roughness. A value of $k$ larger than 1 increases the amount of light transmitted into the material — in particular for light entering the material at non-grazing angles.

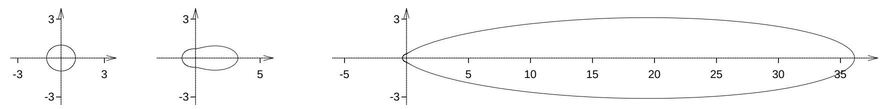
The radiance leaving a surface, $L_o$, is computed as the sum of the reflected radiance, $L_r$ and the transmitted radiance, $L_t$:

$$L_o(x, \vec{\omega}_1) = L_r(x, \vec{\omega}'_1) + L_t(x, \vec{\omega}_2)\,, \quad (3)$$

where $\vec{\omega}'_1$ is the direction of the reflected ray. Using Equations 1 and 2, we compute the transmitted radiance:

$$L_t(x, \vec{\omega}_2) = \left(\frac{n_1}{n_3}\right)^2 (1 - F_{1-2}(\vec{\omega}_1, n_1, n_2))(1 - F^k_{2-3}(\vec{\omega}_2, n_2, n_3))L_s(x, \vec{\omega}_3)\,, \quad (4)$$

where $L_s$ is the radiance due to subsurface scattering, and $\vec{\omega}_3$ is the refracted direction of the light as it enters the material. When light intersects the surface from the inside, we apply Equation 4 in reverse. Note that in this case there is the possibility of total internal reflection. For the shadow rays in the subsurface scattering simulation, we use Equation 4 to compute the amount of light entering the material at the point where the shadow ray intersects the medium. This assumes that the light source is distant compared to the optical thickness of the material.




(a) (b) (c)

**Fig. 4.** Polar plots of the Henyey-Greenstein phase function. (a) $g_1 = g_2 = w = 0$, (b) $g_1 = 0.5$, $g_2 = 0.2$, $w = 0.5$, (c) $g_1 = 0.8$, $g_2 = 0.1$, $w = 0.8$.

### 3.2 Representing the Materials

Materials rendered with subsurface scattering are considered as participating media. The parameters controlling the appearance of participating media are the scattering coefficients, the absorption coefficients and the phase function. In a non-homogeneous medium these parameters can have different values depending on the position within the medium.

A number of different phase functions are available for different types of media. For the materials we consider here, the phase function is not known. One can assume that the sources of scattering (grains, cracks, air-bubbles, etc.) are larger than the wavelength of light [1] and thus the individual scattering events can be described reasonably well with Mie scattering [11]. Instead of simulating each scattering event, we use the empirical Henyey-Greenstein phase function [8] to approximate the accumulated effect of Mie scattering. To have control of both back scattering and forward scattering, we use the two-term Henyey-Greenstein phase function:

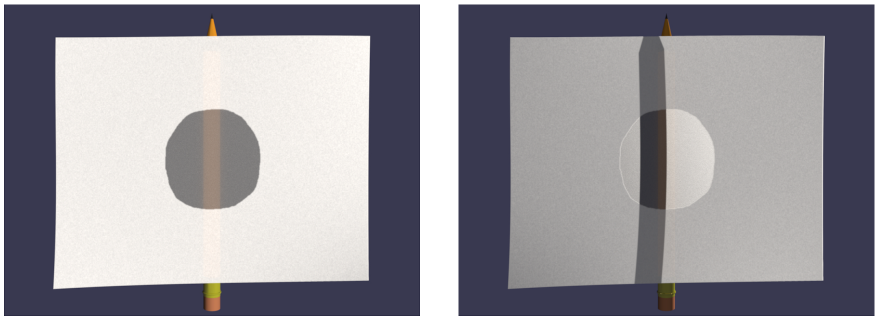
$$f(cos\theta, g_1, g_2, w) = w \frac{1 - g_1^2}{(1 - 2g_1 \cos\theta - g_1^2)^{1.5}} + (1-w) \frac{1 - g_2^2}{(1 - 2g_2 \cos\theta + g_2^2)^{1.5}} \,, \quad (5)$$

where $\theta$ is the angle between the current direction and the scattered direction. $g_1 \in [0, 1]$ controls forward scattering, $g_2 \in [-1, 0]$ controls backward scattering, and $w$ is the weight of the forward scattering lobe relative to the backward scattering lobe. Figure 4 illustrates three configurations of the Henyey-Greenstein phase function.

## 4 Results

We have implemented the wetness model in a global illumination renderer. For the simulation of subsurface scattering we have implemented two techniques: Monte Carlo path tracing [15] and the volume photon map [9, 5]. For our results we have used the path tracing approach where practical. Even though this is slower than the photon map approach it has the advantage that the error from the subsurface scattering is visible only as noise.

All our results were rendered using a dual processor (Pentium II 400 MHz) PC running Linux, at a resolution of 1024x768. We supplied wetness functions and material parameters to all objects in our test scenes using a combination of hand-painted textures and procedural 3D functions [14].



(a) (b)

**Fig. 5.** Wet Paper: (a) light source in front of the paper, (b) light source behind the paper.

### 4.1 Wet paper

Our first test scene demonstrates a wet spot on a piece of paper. The paper is modeled using an extruded Bezier patch with a thickness of 0.8 mm.

The wet spot is created by modulating the phase function from the dry value $g_1 = 0.05$, $g_2 = -0.05$ and $w = 0.2$ to the wet value $g_1 = 0.8$, $g_2 = -0.1$ and $w = 0.1$. This change makes the forward scattering much stronger, and this is the reason for the different appearance of the wet spot.

We rendered two versions of the paper scene: Figure 5(a) has the light source at the same side of the paper as the observer. As a result, the wet spot looks darker than the dry surrounding area. This is due to the fact that light striking the wet spot is scattered in the forward direction (away from the observer), while more light hitting the dry paper is scattered back toward the eye. Another observation is the increased translucency of the wet spot that can be observed by the fact that the pencil behind the paper is visible through the wet spot but not through the dry part of the paper. This, again, is due to increased forward scattering in the wet region. In Figure 5(b) we moved the light source behind the paper. This changes the appearance of the paper significantly. Due to the stronger forward scattering, the wet spot is brighter than the surrounding dry area.

For both paper scenes we used Monte Carlo path tracing using up to 1600 subsurface samples. Rendering the images took 110 and 190 minutes respectively. The high albedo of the paper ($\approx 0.85$) makes multiple scattering important, and it is the main reason why we used this relatively high number of sample rays.

### 4.2 Beach Scene

Our second test scene is a rock on a sandy beach. The model consists of 730,000 triangles, and we use subsurface scattering to render both the rock and the beach. We used procedural textures to control the scattering and absorption parameters of the rock and the sand. The wetness in this scene was modeled using a sum of turbulence functions simulating the water left from the four previous waves. Based on the wetness we changed the forward scattering from $0.1$ to $0.8$ for the rock and from $0.2$ to $0.7$ for the sand.

We rendered four different images of the beach scene. Figure 6(a) shows a completely dry version of the scene. Both the rock and the sand look light and diffuse.

In Figure 6(b) we have rendered the beach scene after applying the wetness function. Notice how the sand and the lower part of the rock look much darker.

To investigate the relative contribution of the surface model and the subsurface model, we rendered the beach scene from Figure 6(b) again but with water covering all of the rock. The result is shown in Figure 6(c). Note that the top of the rock does not look significantly darker. The main difference is at grazing angles, where the rock is more specular due to the smoother air-water interface. The main result of the presence of water on the rock is that it has a glazed appearance. Our final rendering of the beach scene is shown in Figure 6(d). Both the sand and the rock are completely wet and, as a result, much darker.

We rendered these images using Monte Carlo path tracing with approximately 500 subsurface samples. The rendering time was from 180 minutes for the dry scene to 300 minutes for the completely wet scene. The increase in rendering time for the wet material is mainly caused by the increased number of subsurface samples (as shown in Figure 2). The rendering time for this scene was largely due to the procedural 3D textures used for the stone material and the wetness function.

### 4.3 Spilled Cognac

Our last test scene shows a glass of cognac spilled on a wood table. The cognac glass is modeled as a surface of revolution clipped to form three separate dielectric interfaces: air-glass, air-cognac and cognac-glass. The wood table is rendered with subsurface scattering. A 2D texture map was used to control the absorption and scattering coefficients for the wood. This is similar to the way a 2D texture would be used to control the color of a surface-based wood material. By using a 2D texture for subsurface scattering, we assume that the scattering and absorption coefficients are constant in the direction orthogonal to the table. This is a reasonable approximation considering that most of the scattering happens close to the surface.

The wet area is another 2D texture map projected into the table and used for the subsurface samples. Since cognac is a colored liquid, we used the wetness function to modulate not only the phase function parameters but also the scattering and absorption coefficients. Note that we did not change the scattering and absorption coefficients to make the material look darker; the darkening is caused only by the change to the phase function. We used a bump map based on the wetness map to modify the normals at the edge of the spilled cognac. This mainly affects the highlights on the spilled cognac, but nonetheless adds to the impression that a liquid is present *on* the surface.

For the cognac scene we used the photon map approach [9] since Monte Carlo path tracing is too inefficient for sampling the caustic below the cognac glass. Note that this caustic as well as the rest of the indirect illumination of the table is due to photons stored in the volume photon map. Since the photons are stored in the wood medium and not just on the wood surface, we have to use more photons than for a surface-based approach. We used two million photons for this scene. The image was rendered with 4 samples per pixel in 28 minutes. The background is blurry due to a lens simulation.

## 5 Discussion and Future Work

A legitimate criticism of our approach is that we did not directly compare the predictions of our model with experiment. The predictions of our model and the influence of measured material parameters should be checked carefully.

Our results indicate that subsurface scattering is the most significant reason why materials are darker when wet. Water present on the surface of a material simply adds a "glazed" appearance. This observation is based on our assumption of how the phase function changes when water is applied to the material. We have been adjusting the phase function parameters to make the images look convincing. It would be very interesting if real measurements of phase function parameters were available for dry and wet materials in order to verify the results.

Real measurements would also be helpful for the absorption and scattering coefficients. For these parameters we also selected values to make the images look convincing.

Measuring the parameters for subsurface scattering is difficult, especially for non-homogeneous materials. An alternative to using measured data would be the use of a virtual gonio-reflectometer [18]. The main difficulty with this approach would be in modeling of the volumetric structure of the material.

A virtual gonio-reflectometer could also be used to compute a BRDF approximation for the subsurface scattering, similar to the approach of Hanrahan and Krueger [7]. We have not used this approach since we wanted to test the validity of the theories for wet materials without being limited by the BRDF. Moreover, the use of only a BRDF precludes the simulation of non-homogeneous materials with three-dimensional wetness functions.

One open issue that still needs to be addressed is the rendering of wet materials that are not dielectric. In our implementation, we use Fresnel's formula for dielectric surfaces. In contrast, the problem with conducting materials, such as metals, is that they are opaque. Consequently, subsurface scattering is less likely to occur. For conducting materials with a structure where subsurface scattering does occur, it will be primarily due to reflection rather than refraction. Therefore, a change in the index of refraction of the surrounding medium will have little effect.

It would also be interesting to combine the rendering of wet materials with actual simulations of the patterns due to the flow of water over surfaces [4].

We use a simple non-adaptive ray marching technique for integration inside a non-homogeneous medium. Making this ray marcher adaptive could reduce the number of evaluations of the functions controlling the behavior of the medium. This could have a large impact on the rendering times in particular when we use the costly turbulence function [14] to control the material structure.

## 6 Conclusion

We have presented a model that incorporates two theories for rendering wet materials: two-layer surface reflection and subsurface scattering. We have shown that not only do each of these theories produce convincing results, but they can be used in conjunction effectively. Our experiments have found the consideration of water inside the material to have the most dramatic effect. Using a full subsurface scattering simulation allowed us to render objects with translucency. Not only were we able to achieve the characteristic darkening of thick wet materials, but we were also able to render the increased translucency of thin materials caused by the absorption of water.

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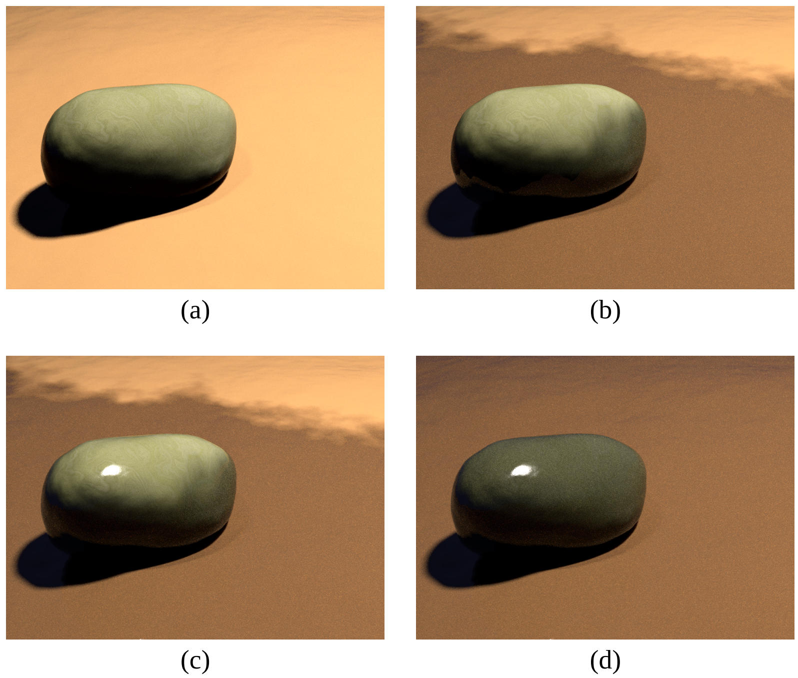


**Fig. 6.** Rock on sandy beach with different wetness functions. (a) dry, (b) mixed wet and dry, (c) water covering the rock and (d) completely wet.

**Fig. 7.** Cognac spilled on wood table.