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# Interactive Rendering of Optical Effects in Wet Hair

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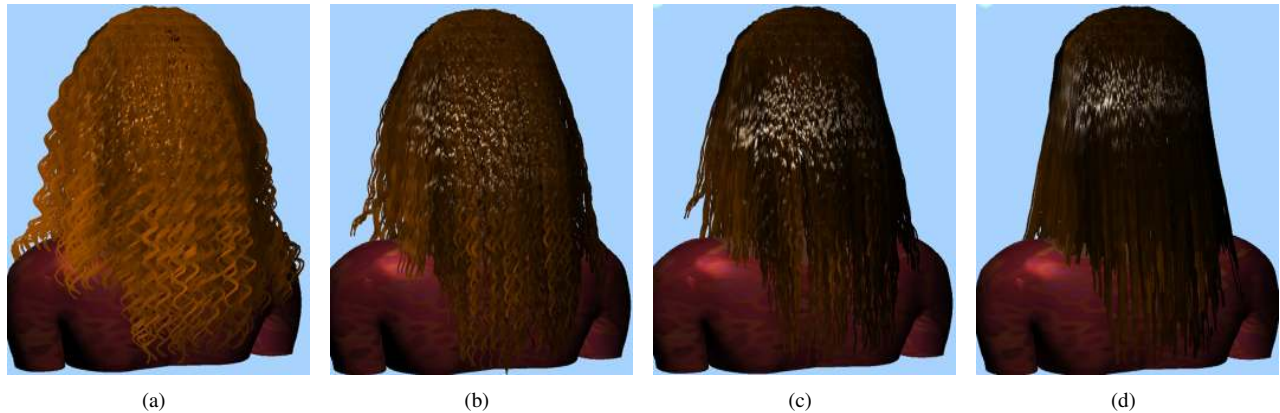


Figure 1: A sequence of images showing variations in the optical effects in a hairstyle with increase in wetness. Subfigure (a) shows a dry hairstyle with the usual self-shadow and specular highlights. The other three figures show changes in these effects for wetness  $w = 0.3, 0.6, 0.8$  respectively.

## Abstract

Visually, wet hair is easily distinguishable from dry hair because of the increased highlights and intense darkening displayed by them. It is therefore essential for realism to capture these characteristics under certain real world conditions. In this regard we propose a model for rendering wet hair at interactive rates. We start by analyzing the physical aspect behind this special effect in hair and then present a model for incorporating the variations in visual appearance of the hair due to presence of water. For simulating the increased specularities because of the water layer on hair, we present a parameter controlled Gaussian-based model. To simulate darkening in hair, for outer hair we consider total internal reflection at water-hair interface as dominant and propose a probabilistic approach to determine the amount of light absorbed. For inner hair, we consider that increase in opacity due to water results in stronger self-shadow and propose a model that updates the opacities based on water content and accumulates them to calculate the self-shadow term. By pre-processing and optimising our algorithm both for the self-shadow in dry hair and the special effects due to water presence, we can get visually pleasing results at interactive rates. Furthermore, the model is highly versatile and can easily be adaptable to other liquids and hair styling products.

**Keywords:** Wet Hair Rendering, Self-Shadow, Hair Simulation, Interactive Rendering.

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## 1 Introduction

Since its introduction in the graphics world around 20 years back, hair rendering has been an intriguing research topic. The challenges involved have been an important driving force towards this research and are being successfully dealt with to produce some innovative techniques. As a result, approaches for simulating the most prominent effects in hair like anisotropic reflections and self-shadows have now become matured enough and can produce convincing hair images very effectively. Furthermore, the dedicated effort along with the availability of advanced graphics accelerators has resulted in overcoming computational speed barrier facilitating real-time rendering of these effects.

Moreover, with the growing demands of simulating new effects in graphics applications for increased realism, it is now becoming evident to focus on other special effects related to hair as well. In this regard, one of the interesting effects that we encounter everyday is wet hair and hair influenced by styling products. The presence of these external products not only changes the hairstyle geometrically but also redefines its dynamical and optical behaviour. Though the basic complexities in each of the tasks for simulating wet hair still remain the same as those for dry hair, it is the additional complexities arising due to water presence that makes each of them even more challenging, and require special methodology. Here we focus on one such methodology for simulating the optical variations.

As can be observed in Figure 2, visually the appearance of wet hair is very different from dry hair, mainly because of more complex light interaction due to the presence of water. Similarly to other materials, wet hair displays increased specularities and increased darkness in presence of water. Physically, as highlighted by [Jensen et al. 1999], the water on a surface results in increased specularities due to formation of a smooth air-water interface and increased darkening due to total internal reflection at the water-air interface.

Additionally, for some material because of absorption of water in the material there is more scattering of light resulting in darker appearance of the material.

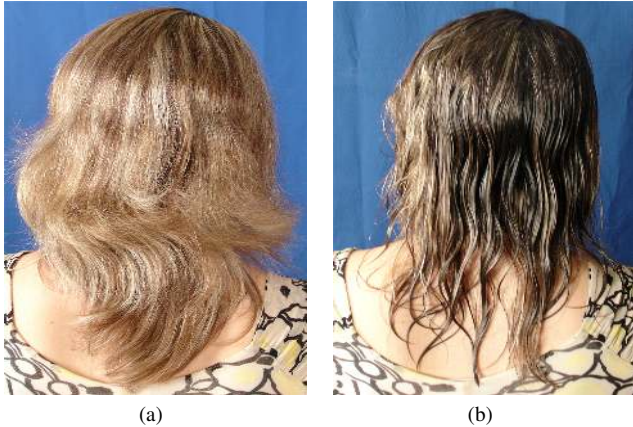


Figure 2: Comparing real appearances: The wet hair (right) appear much shinier and darker in comparison to the dry hair (left).

The appearance of wet hair is in fact owing to all these three interactions of light at the air-water-hair interfaces. The hair surface, which is usually rough due to presence of cuticles resulting in higher diffused component of light, is smoothed because of the water layer. The water has a lower diffuse component and so most of the reflected light from the air-water interface in fact appears as the specular component. The reflectivity is increased so much that it even reflects the low frequency light from the environment, making its subtle glossy appearance more prominent. The light that is transmitted through the water surface is trapped between the water-hair and water-air interface and gets absorbed due to multiple total internal reflections. Furthermore, because of its porous nature, hair absorbs water which technically increases the opacity of the hair resulting in more absorption of light and thus stronger self-shadowing. The increased absorption of light within hair means that the colored component of the highlights arising because of the traversal through the hairs is reduced, which additionally results in the colorless reflected specular component to be more dominant. An overview of light behaviour on interaction with wet hair is given in Figure 3.

Surprisingly, not much attention has been paid to rendering of wet hair and usually an empirical model has been chosen to address this issue. In this paper we state a partial physical model that takes into consideration changes in appearance of hair because of both the water on the hair strand surface as well as the water inside the hair strands. Our main contributions are:

- A parameter controlled local model for simulating increase in intensity and sharpness of specular highlights at the air-water interface.
- A probabilistic model for computing the amount of light absorbed due to Total Internal Reflection and simulating the consequent darkening.
- A model for considering increased light absorption and scattering due to water absorption in hair to simulate stronger self-shadowing in them.

The rest of the paper is organised as follows: In section 2 we look at some of the related work. In section 3, we shortly state the modeling and animation approach and rendering considerations for our wet hair simulation, followed by the description of our wet hair

rendering model in section 4. In section 5 we look at some results along with the performance issues, followed by a discussion on various conditions that can influence the appearance of hair with liquids or styling products. We finally conclude in section 6.

## 2 Related Work

This section gives an overview of the different techniques developed for dry hair rendering, followed by a brief background to rendering of wet objects and then a look at the related work on wet hair simulation.

### 2.1 Hair Rendering

The immense challenges that lie in formulating a rendering model for hair have been quite motivating for a number of researchers. To a good extent they have been successful and developed techniques for both local highlights and global self-shadow in hair. In [Kajiya and Kay 1989] an empirical model for anisotropic highlights in hair was presented and has been widely used and extended by other researchers. Another lighting model for fast rendering has been proposed in [Anjyo et al. 1992]. [Marschner et al. 2003] presents a physical model based on scattering for simulating significant effects not predicted earlier, mainly multiple highlights and variation in scattering with rotation about the hair axis. This has been then approximated for interactive purposes in [Gupta and Magnenat-Thalmann 2005].

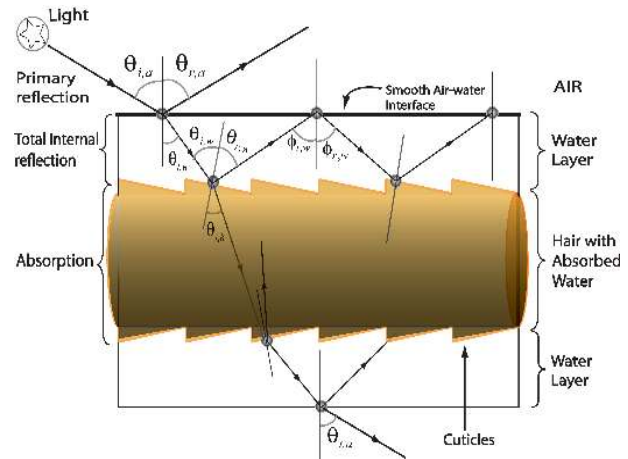


Figure 3: Light propagation on interaction with wet Hair.

For self-shadow, the research has quite matured with a lot of approaches available. Since the early work by [Lokovic and Veach 2000] in which for each pixel of the shadow map a transmittance function is stored at all possible depths rather than a single depth and is then compressed by piece-wise linear approximation, a number of more efficient and faster techniques have come up [Kim and Neumann 2001][Koster et al. 2004][Mertens et al. 2004][Bertails et al. 2005][Gupta and Magnenat-Thalmann 2005]. Storing the transmittance function as opacity maps was the idea implemented in [Kim and Neumann 2001], which was later accelerated by using Graphics hardware for real time rendering by [Koster et al. 2004]. A statistical approach for storing hair density was discussed in [Mertens et al. 2004] which quite efficiently simulated self-shadows in animated hair. In [Bertails et al. 2005] another approach is presented in which the hair volume is always aligned in the light direction which makes it easy to accumulate the hair density for computing transmittance function. The computations

are portable and can be accelerated by parallelization. Yet another self-shadowing model was highlighted in [Gupta and Magnenat-Thalmann 2005], in which both absorption and scattering was considered for light attenuation. Moreover, the refinement technique introduced was quite efficient for updating shadows in animated hair.

## 2.2 Wet Objects and Surfaces

In the quest of realism, rendering of wet objects realistically plays an important role, as has been highlighted in [Lekner and Dorf 1988][Nakamae et al. 1990][Dorsey et al. 1996][Jensen et al. 1999]. One of the initial work in rendering wet surfaces was done by in [Lekner and Dorf 1988] in which an optical model was presented for computing the probability of darkening of surfaces taking into account polarization at the interfaces. For enhancing realism in driving simulations [Nakamae et al. 1990] proposes an empirical approach for simulating transition from wet to dry by varying the specular and diffuse coefficient. They also presented a two layered reflection model for simulating puddles on a road using ray tracing and even considered scattering and absorption for muddy puddles. An important contribution towards a physical model for wet material rendering was made in [Jensen et al. 1999] which introduced a two surface model taking into account the Fresnel reflection and transmission at the interfaces and also proposed a sub-surface scattering model for water absorbing materials that produced very realistic results. However, these ray tracing and sub-surface scattering renderers for wet surfaces are computationally expensive and cannot be applied for interactive wet hair rendering.

## 2.3 Simulating Wet Hair

To the best of our knowledge, the earliest work in this regards has been presented in [Bruderlin 2000] where a clumping approach for wet fur is discussed. Based on certain parameters, two types of clumps on the fur are created; one that are at fixed predefined areas, and the other ones at areas that can be moved on the model. Also, work on wet hair has been stated in [Ward et al. 2004], though their main contribution was for modeling wet hair for which they proposed a dual skeleton system. For rendering both the model approximated the lighting equation and parameterized the opacity and specularity based on water content, and used them for changing the visual appearance of hair. The minimum and maximum values of these parameters were obtained empirically and the other values were computed by linear interpolation.

The underlying basis for our model is the optimized rendering approach discussed in [Gupta and Magnenat-Thalmann 2005] for dry hair which also takes the advantage of the free-form deformation based animation technique presented in [Volino and Magnenat-Thalmann 2004]. We have successfully extended the model to adapt to water presence and, based on its content, efficiently simulate the variations in optical effects.

## 3 Approach Overview

As previously noted, the presence of water modifies the geometry, dynamical behaviour and the optical appearance of the hair. Though our main emphasis is on rendering of wet hair, we realise that for realistic simulation of the effect we need to take into consideration the geometrical and dynamic changes as well. We present a simple approach for modifying the geometry and consequently updating the mechanical model. We then introduce our optimized approach for rendering wet hair, considering the issues raised by wetness.

## 3.1 Modeling and Animation

When wet, close hair strands stick together due to bonding nature of water resulting in lesser volume and even in formation of clumps. Also the curls in the hair seem to relax and hair become more straight. For simulating these changes in physical appearance we consider a simple geometric modification model. For decreasing the volume we consider a parameterized variable based on which the hair gets attracted towards the head center. The variable based on water content controls the volume of hair which goes on decreasing until the hair are on a sphere that bounds the head.

For clumping strands, determining close by hair strands at runtime could be computationally expensive and not suitable when interactive rates are required. To get this effect at fast speed we define a set of guide hairs already at pre-processing and relate the rest of the hair to them. In order to do this, we first store the hair roots based on their position in the lattice voxels and then for a given set of neighboring voxels we define a guide hair, which is usually the longest hair in the set. The rest of the hair in those voxels are set as the child hair and follow their parent guide hair. In addition, we also define a local weight for each of the hair vertices of the strands in the set that controls the distance of it from the guide hair corresponding vertices. As the wetness is increased the hair vertices tend to get attracted towards their parent guide hair's vertices resulting in formation of clumps. Defining a local parameter also gives us the advantage of simulating localised wetness effect, as we can decrease the distance between vertices only for the effected region. In order to speed up the performance we can also use a hybrid model, with both textured strips and individual strands, for hair representation. The strips can easily represent clumps by decreasing their width and tapering it as it gets further from the root.

With the presence of water the hair tend to get heavier and there elasticity is increased, thus overall changing its dynamic behaviour. The final animation involves a more damped motion of the hair with collision being more prominent between group of hair strands rather individual strands and in this aspect our FFD model can easily be adapted for hair under wet condition. The FFD lattice containing the hair volume adaptively gets adjusted to the modified geometry. The changes in the mechanical behaviour of the lattice are incorporated by changing the mass of each of its node and the stiffness of springs connected with each of the lattice cells, based on the water content. For more control over the motion of the wet hair strands, the deformation coefficient for each of the vertices of the hair strand is also parameterized in terms of water amount as:

$$\delta = 1.0 - \exp\left(\frac{((1.0 - 0.45 \times w) \times \lambda)^2}{\lambda_0^2}\right) \quad (1)$$

where  $\lambda$  is the distance of a hair vertex from the root along the hair curve, and  $\lambda_0$  is the "typical" hair length from the root that does not deform significantly and defines the bending stiffness of hair near its root.  $w$  is the wetness with a values between 0 and 1, which is further scaled by 0.45, considering the fact that hair can absorb approximately 45% of its own weight of water [L'oreal 2007].

## 3.2 Rendering

In order to simulate the effect of wetness on the appearance of hair, we present a model that takes into account the optical variations both locally and globally. The increase in the specularity of the hair is considered as a local effect dependent on the amount of light reflected and transmitted at the air-water interface. The behaviour of the highlight with the viewing and the light direction is quite similar to the behaviour of dry hair and that is why we adapt the existing local illumination model to work for wet hair. As the diffuse component of water is much smaller in comparison to its specular component, presence of a smooth water layer increases the specular



reflectivity of the hair surface resulting in increase in the intensity of the highlight. This change in the intensity due to the water surface is incorporated by varying parameters of the Gaussian function as well as by modifying the Fresnel term at the air-water interface.

The remaining part of the light, after it is strongly reflected from the air-water interface, is transmitted into the water. On the water-hair interface the light ray is again reflected as well as further transmitted into the hair volume. The interactions of the reflected light in between water-hair and water-air interface, and of the transmitted light within wet hair volume, contribute to hair darkening. In our model the darkening of hair is in fact simulated as both local and global effect.

We consider that for the hair lying on the outside, the dominating factor for the darkness is the total internal reflection. This turns out to be a local effect as the water layer on the surface of the hair is very thin. To accurately solve for the total internal reflection effect in wet hair turns out to be computationally expensive. In fact what we want to compute is that how much light entering at a point on the water surface is trapped between the water-air and water-hair interface and is eventually absorbed. We compute this based on a simple probabilistic approach similar to [Lekner and Dorf 1988]. By computing the total probability of a light to undergo total internal reflection we can actually get a measure of the amount of light getting absorbed. For simplicity we compute the probability by considering that only the light incident at critical angle or greater on the water-air interface is reflected back due to total internal reflection to the hair surface as shown in Figure 5(a).

For the inner set of hair we consider it to be more affected by the global self-shadow which, as earlier mentioned, becomes stronger due to water content in hair. We use a model that takes into consideration the increase in opacity of hair by in fact calculating the increase in hair density based on the water amount. Similarly to as in dry hair, in wet hair the attenuation in transmitted light is related to this density of the wet hair encountered by the light ray. This requires formulating the transmittance function taking into account the renewed opacity due to the water that eventually results in increased absorption and scattering of the light, and defines the self-shadow component within the hair.

## 4 Rendering Wet Hair

The local changes in highlight intensities are incorporated via the modification of the Gaussian-based illumination model while the lattice-based approach for both animation and rendering allows easy acquisition of the initial dry hair data which is then efficiently used by our technique for simulating darkening of hair under influence of water.

### 4.1 Enhanced Highlight Intensity

The change in the appearance of the reflectance of hair, on transition from dry to wet condition, arises mainly because wet hair reflects more light in comparison to dry one. This is because of the smoothing of the hair surface due to the water layer that is accounted for by decreasing the cuticle angle distribution parameter for the hair strands. In our illumination model this parameter is the standard deviation for the Gaussian function. Also from the physical aspect, in our model we need to modify the Fresnel function in the specular highlight term as well. Our Gaussian-based specular term is given by:

$$I_s(p) = \rho_s \times \frac{G_r(\alpha_x) \times F_r(\eta, \vec{H}, \vec{V})}{\cos^2(\theta_d)} \quad (2)$$

where  $\rho_s$  is specular coefficient,  $\vec{V}$  and  $\vec{H}$  are the viewing and the halfway vector and  $\theta_d$  is the difference angle between incident and

reflected light directions. The refraction index ratio  $\eta$  for the air-hair interface in the Fresnel reflection function  $F_r$ , which controls the amount of light reflected from hair, is replaced by that function for the air-water interface in case of presence of water. Unlike in Kajiyama et al. [Kajiyama and Kay 1989] where for all light and viewer configuration we get a uniform intensity highlight, the use of Fresnel term in our model is essential for providing a non-uniform specular highlight as perceived in real hair, for the varying the light and viewer configuration. This means using our model a stronger highlight is achieved when the light and viewing angle are at grazing angles. The Fresnel term is usually a complex function, but for fast and easy implementation we utilize the approximate Fresnel function from Schlick [Schlick 1994] given as:

$$F_r(\eta, \vec{h}, \vec{v}) = f(\eta) + (1 - f(\eta)) \times (1 - (\vec{V} \bullet \vec{H}))^5 \quad (3)$$

$$f(\eta) = \frac{(\eta-1)^2}{(\eta+1)^2}, \eta = \eta_{water} \text{ for water surface}$$

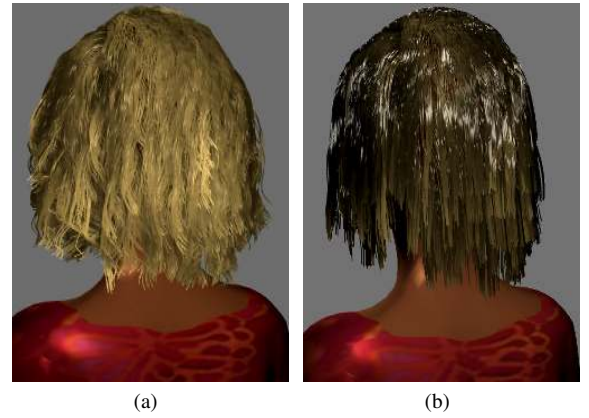


Figure 4: Presence of water causes change in reflectance of hair resulting in increase in specular highlight intensity and sharpness.

In addition, the intensity of the reflected light is varied by modifying the specular coefficient based on the percentage of water. The energy conserving Gaussian function  $G_r$  in equation 2 for dry hair is defined to capture the anisotropic reflection as:

$$G_r = \frac{1}{2\sqrt{\pi}\alpha_x} \times \exp\left(\frac{-2 \times ((\vec{H} \bullet \vec{T})/\alpha_x)^2}{1 + \vec{H} \bullet \vec{N}}\right) \quad (4)$$

where  $\alpha_x$  defines the cuticle angle distribution or roughness parameter and controls both the increase in intensity of the highlight as well as its sharpness. The roughness parameter is related to wetness as  $\alpha_{wet} = \alpha_{dry} \times (1.0 - c \times w)$ , where  $c$  is a constant. Defining change in roughness parameter like this quite effectively captures the variations in the highlight. For computation purpose, since hair strands do not have a single defined normal, we replace the normal vector by better defined tangent vector for the strands using this simple trigonometric relation:  $\vec{H} \bullet \vec{N} = \sqrt{1 - (\vec{H} \bullet \vec{T}) \times (\vec{H} \bullet \vec{T})}$ .

### 4.2 Lattice Based Approach for Darkening

To simulate darkening of inner hair due to absorption we first voxelise the hair volume and compute the density of the voxels based on the amount of segments in it. This step is performed at pre-processing for the dry hair and the variations in densities with water content are computed at runtime. Additionally, for outer hair,

where the total internal reflection is dominant, we cover the original lattice with another set of voxels to represent water on the surface as in figure 5(b), and then make probabilistic computation for the absorption of the trapped light.

#### 4.2.1 Probabilistic approach for Surface Absorption

The light trapped between the water-hair and water-air interface undergoes multiple reflections at the two interfaces and is absorbed with some probability as shown in Figure 5(a). The fraction of transmitted light through the air-water interface into the water is given by  $(1 - F_r)$  where  $F_r$  is the Fresnel equation for reflection given in equation 3. For our probabilistic model this defines the probability of the light ray penetrating the water layer. At the water-hair interface the probability of light transmitted into hair volume  $F_t$  is again defined by equation 3, but with  $f(\eta) = \frac{4\eta}{(\eta+1)^2}$  where  $\eta = \frac{\eta_{hair}}{\eta_{water}}$ . The amount of light thus reflected from hair surface is  $(1 - F_t)$ . If now the probability of light getting totally internally reflected is  $p$ , then the fraction of light reflected at the water-air interface is  $(1 - F_r)(1 - F_t)p$ .

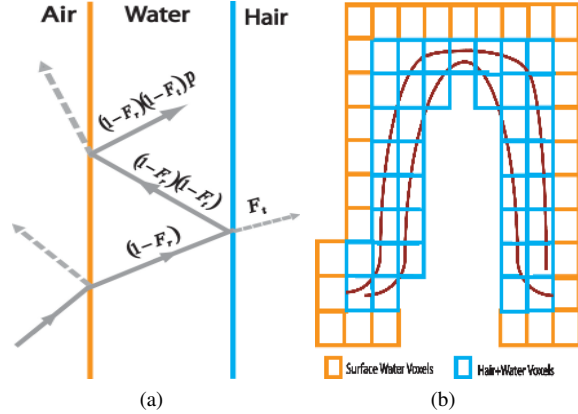


Figure 5: The probability computation (left) as the light interacts with water-hair and hair-water interfaces, and our optimized lattice (right) showing the outer cells for the probability computation, and the inner cells that contain both hair and water used for computing increased self shadowing.

Taking into consideration a similar interaction multiple times, we compute the total probability of absorption at the two interfaces which gives us an infinite sum:

$$P = (1 - F_r)[(F_t + F_t(1 - F_t)p + F_t(1 - F_t)^2p^2 + \dots)] \quad (5)$$

which consecutively can be written as:

$$P = \frac{(1 - F_r)F_t}{1 - p(1 - F_t)} \quad (6)$$

Usually, a number of factors account for computing the probability of reflection at water-hair interface ( $p$ ), and their contributions give rise to complex transmission equations that are computationally expensive. For simplicity and fast simulation we consider all light to be reflected at the interface for angles greater than critical angles. Since this is related to the refractive index ratio of the surface, we use  $p = f(\eta)$  with  $\eta = \frac{\eta_{air}}{\eta_{water}}$ .

The absorption probability  $P$  is computed for each of the vertices of the outer voxels that represents the water layer. The final contribution of each of these voxels towards absorption of light due to water on the surface is the average of probability values computed for each of that voxel's vertices.

#### 4.2.2 Strong Self-Shadowing

To compute the contribution of wetness to self-shadow in hair, we need to perform three updates in our lattice-based model as the hair change from dry state to wet state. The first modification is related to direct increase in voxel opacity as the wetness is increased. The modified opacity of the voxel is determined by the weighted sums of the hair and water opacities in the voxel. Considering the facts, as mentioned earlier that the hair can absorb approximately 45% of its own weight of water, and that the opacity of water is related to its refractive index, we calculate the new opacity of the cell as:

$$O_{wet} = (O_{dry} + 0.45 \times w \times O_w) \quad (7)$$

where  $w$  is the wetness and  $O_w$  is the opacity of water which is related to its refractive index as  $(\eta_{water} - 1)$ .

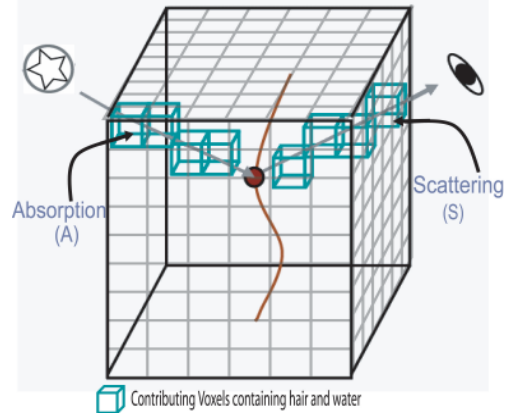


Figure 6: Accumulating voxels for computation of the absorption and scattering term, and the combined shadow contribution to the hair vertex after the opacities of the voxels are modified based on water content.

The second update is due to the modified geometry, which requires re-computation of intermediate cells that the transmitted light encounters before reaching the hair, and then the viewer after being scattered. Based on the newly calculated opacities for the voxels, the absorption term is computed to get the amount of light reaching the hair vertex, and further attenuation of light due to scattering towards the viewer is computed. The third update is of the contribution of the parent voxel to the hair vertex because of the change in position within the cell, which is obtained by tri-linearly interpolating the values at the 8 corners of this voxel. Following these updates, the final shadow contribution to the hair vertex is given by:

$$I_n(p) = A(p, \vec{L}) \times S(p, \vec{L}, \vec{V}) \quad (8)$$

where  $A(p, \vec{L})$  is the absorption term for hair vertex  $p$  and is computed by accumulating the opacities of the voxels in light direction  $\vec{L}$ , and  $S(p, \vec{L}, \vec{V})$  is the scattering term computed by considering a phase function that defines the directionality of the scattering, and the opacities of all the voxels in the viewing direction  $\vec{V}$ .

## 5 Results

For all the results presented in this paper we have made rendering computations using a lattice size  $128 \times 128 \times 128$ , with the underlying mechanical model containing 100 attachments and 400 springs built on 343 lattice nodes. At pre-processing for the dry hair, the hair density in each voxel is computed for rendering, along with

defining the mechanical behaviour to all the springs for animation, which are then updated at runtime for wet hair. All implementations are made on a workstation equipped with an Intel P4, 3.4GHz processor with a 2 GB RAM and a NVIDIA GeForce 6800 graphics board. Our computation algorithm is written in standard C++ and rendering is done using the OpenGL API and Cg shading language.

The shadow contribution  $I_n(p)$  and the absorption probability  $P$  corresponding to each vertex are passed to the vertex shader. The diffuse and specular components,  $I_d(p)$  and  $I_s(p)$ , are computed in the vertex shader and the final fragment color is then computed as:

$$C(f) = I_s(f) \times C_{hair}^s + I_d(f) \times (1 - P) \times I_n(f) \times C_{hair}^d \quad (9)$$

where  $C_{hair}^d$  and  $C_{hair}^s$  are the colors defined for the hair and the highlight respectively. The color of the highlight, which is usually visible as blended color of the hair and the light, is also parameterized with the wetness and tends to become more colorless with increasing wetness.

We have captured the prominent variations in optical effects as hair goes from dry to wet state for different hairstyles. Figure 1 shows a sequence of image under varying wetness. As we can see from the results in first two sub-figures, even with a small degree of wetness, the wet hair are distinguishable from the dry hair, as evident from increased specularity and the darkening. The later three images show varying degree of wetness. Notice how the specular highlight varies. With increase in wetness the highlight becomes stronger and sharper. In addition, the characteristic of wet hair to reflect more colorless light in comparison to the colored light in dry hair is also nicely captured. The darkening optical effect in hair with varying wetness is also noticeable. For low wetness, the total internal reflection from the outer hair surface, which is independent of wetness, is more dominant for darkening, while for higher wetness the increased absorption and scattering results in stronger self-shadowing and consequently increased darkening. In Figure 4 another short curly hairstyle shows that highlights at the curls which are not so visible in dry hair, become more prominent and sharp when the hair gets wet.

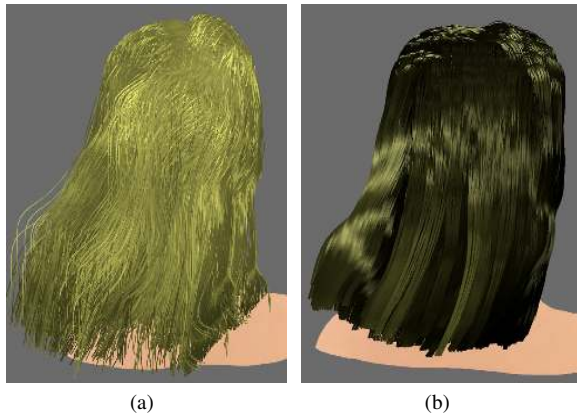


Figure 7: Optical effect variations, geometric modifications and changes in dynamical behaviour of dry and wet hair.

Also we display the various components of our wet hair rendering model in Figure 10. The figure shows a highly curly hairstyle in a dry state (Figure 10(a)) followed by a sequence of images under varying wetness and refractive index. The figure also shows the effect of the outer layer (Figure 10(b)) that results in darkening due to surface absorption. The effect of inner layer, representing hair volume with water, on the self-shadow and on the hair appearance is shown in Figure 10(c). Both the parameters, the wetness and

refractive index control the amount of darkening and intensity of highlights as can be noticed in Figure 10(d).

The convincingness of our results is also because of the geometric modifications that occurs when wetness is enabled. Notice the decrease in volume of hair and the formations of clumps as the wetness is increased. Furthermore, when rendering animated wet hair, the mechanical properties are updated at runtime so as to simulate the increased dragging motion in presence of water. Figure 7 shows the difference in motion behaviour of dry and wet hair.

## 5.1 Performance

The hairstyle in Figure 1 consists of around 150K vertices and its simulation runs at a speed of 3-4 fps under wet condition while for the curly hairstyle in Figure 10 containing around 120K hair vertices the rendering speed for is 4-5 fps. The two hairstyles when dry and animated, are rendered at around 5 fps and 6 fps respectively. The updation of the data for rendering from dry to wet state, including that for geometric and mechanical model modifications, takes around 3 seconds and 2-3 seconds respectively. Once the data is updated, in addition to the usual computation for calculating and accumulating cell densities for wet hair, only probability computation for total internal reflection is performed during the runtime. In Figure 8, we list the rendering times for different hairstyles under both dry and wet conditions, and the corresponding transition times.

Hairstyle	# of Vertices	Dry Hair (sec)	Transition Time (sec)	Wet Hair (sec)
Long Curly (Fig.1)	150K	0.203	3.1	0.252
Short Curly (Fig.4)	70K	0.125	1.9	0.144
Long Hair (Fig.7)	90K	0.136	2.1	0.161
Curly (Fig.9&10)	120K	0.166	2.4	0.206

Figure 8: Rendering times in seconds for different hairstyles in dry and wet conditions.

The use of a lattice model also facilitates localised wetting of hair, which is sometimes required for certain application, like virtual hairdresser. Once the area to be affected is realised, the parameters and opacities of the voxels only in that region are modified and probability computation is done related to region. This results in reduction of the transition time and also better performance of the application.

## 5.2 Discussion

One effect to notice is that when hair gets wet the shape changes from a volume to a more surface like appearance and the self-shadow becomes less prominent. This happens because the lateral depth in the hair decreases and the average accumulated density tends to be uniform resulting smoother appearance. On the contrary, as the volume decreases, the number of lattice voxels with significant hair density is also reduced which implies faster traversal of the data structure for final shadow color computation.

Our model, though not entirely physical, takes into consideration the various interactions of the light at the interfaces of the 3 mediums. As a result our model can also be utilized for other liquids and hair styling products ( $hsp$ ) besides water. Usually,  $hsp$  result in stronger shine and more darkening in hair than the same amount of water. In context of our model, hair styling products with higher refractive index ( $\eta_{hsp} > 1.48 > \eta_{water}$ ) will reflect more at air- $hsp$  interface resulting in stronger highlight.



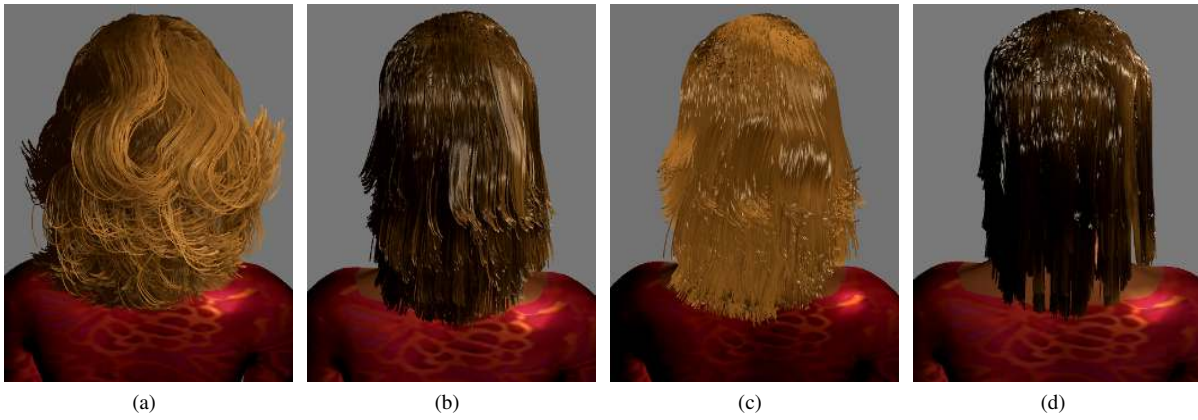


Figure 10: A sequence of images showing different components of our wet hair rendering model: (a) Shows a curly hairstyle with self-shadow in dry state, (b) Shows all the optical effects in wet hair for  $\eta = 1.3$  and  $w = 0.65$ : increased highlight and darkening due to total internal reflection (TIR) at the surface as well as stronger self-shadow due to opacity increase of the hair strands as they absorb water, (c) Shows just the TIR component that is computed at the outer layer, and (d) Shows the change in appearance as the refractive index value is increased to  $\eta = 1.5$  and wetness to  $w = 0.85$ .

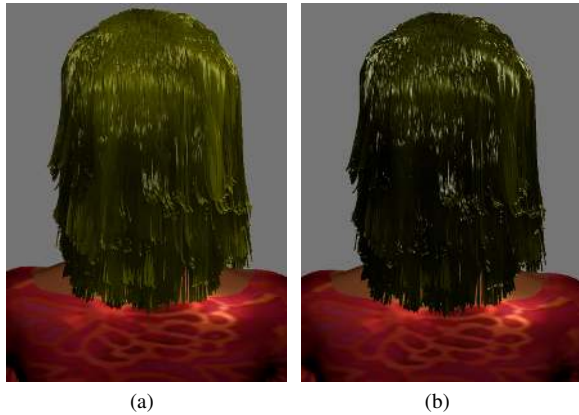


Figure 9: (a) Shows optical effects in hair with water,  $\eta_{water} = 1.33$ , and (b) Shows the effects in presence of a hair styling product with  $\eta_{hsp} = 1.5$ , for same value of  $w = 0.7$ .

Although lesser transmission of light already implies more darkening, our proposed model also captures it due to increased probability of total internal reflection. For larger values of refractive index the probability of light getting total internal reflected at  $h_{sp}$ -air interface,  $p$  increases, thereby increasing the absorption probability  $P$  and resulting in more darkening. Furthermore, presence of liquid with higher refractive index means increase in opacities and thus stronger self-shadowing. Figure 9 compares the visual appearance of a long curly hairstyle, with left image containing water ( $\eta_{water} = 1.33$ ) and right image containing a hair styling product ( $\eta_{hsp} = 1.5$ ), for the same value of  $w = 0.7$ .

## 6 Conclusion and Future Work

In this paper we have proposed an efficient way of rendering wet hair at interactive rates. The presented method considers both the visually perceived variations in optical appearance of the hair, increased specularity and increased darkening, as it changes from dry to wet state. The increase in specularity is simulated by a parameterized Gaussian-based local model. For darkening, we propose a

model in which for outer hair the total internal reflection is considered to be the prime reason for darkening, while for inner hair, the strong self-shadowing due to increase in hair opacity is dominant. The model performs fast updates when wetness is varied and then runs the simulation at interactive rates.

One of the areas where we feel the results can be improved is by consideration of the low frequency light contribution of the environment on the wet hair appearance. As mentioned earlier, the glossiness of the hair is perceived because it reflects its environment, which becomes more prominent when hair is wet. Furthermore, we plan to utilize the model’s capabilities for enhancing visualization in a hairdresser application. We are also working on a more accurate approach for modeling and animation of wet hair for overall increasing the realism of our simulations.

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