A Production Friendly Hair Shading System

Figure 1: *Rendering results using our ~~developed~~ hair shading system from different lighting and viewing directions.* Update Images?

Abstract

Rendering hair in motion pictures is a very important and challenging task. Despite huge advancements in research on physically based hair rendering, hair rendering is still a challenge in movie industry mainly because physically based shading models lack artist control. This lack of control is extremely undesirable and is one of the main reasons that ~~many~~ production work so far have used ad hoc shaders which are ~~more~~ art-directable. We show why physically based shading models fail to satisfy production needs for artist controls and introduce a novel approach to produce ~~art~~-directable shading models from existing physically based models. /easily

? you produce shading models?

?

We have applied our approach to hair rendering and implemented an art-directable hair shading system that is based on the physical properties of hair. By performing a user study, we show that our novel shading system makes it easier for artists to obtain a desired appearance compared to physically based and ad hoc shaders. Our shader has been integrated to Walt Disney Animation Studio's production pipeline and is being used in the production of upcoming feature animated ~~movie~~ Rapunzel.

CR Categories: I.3.7 [Computer Graphics]: Three-Dimensional Graphics and realism—Color, shading, shadowing, and texture

Keywords: Hair shading, artist control, single scattering, multiple scattering

1 Introduction

this

Almost all characters in ~~the~~ a movie have some kind of hair or fur on their bodies. Besides our eyes are sensitive to the appearance of hair and we can observe subtle inaccuracies in their appearance. Hair appearance have been shown to be one of the most important features of avatar personalization [Ducheneaut et al. 2009].

change

Hair rendering is challenging because it requires capturing the exact behavior of light scattering events inside the hair volume which are very complex and computationally expensive. Although there has been huge advancements in research on physically based hair rendering, it is still a challenging process in movie industry. The main drawback of using physically based shaders in movie industry is their lack of artist control. This lack of control is extremely undesirable and is the main reason that many production work so far has have used ad hoc shaders which are ~~more~~ much art-directable. However, ad hoc shaders fail to capture the details in light scatterings inside the hair volume and break under different lighting conditions.

We show why physically based shaders, in general and specifically in the context of hair rendering, fail to satisfy the controllability required in the movie industry and present a novel approach that can produce approximate art-directable shading models based on the available physically based models. We have applied our approach to hair rendering and implemented a novel hair shading model that produces results based on the physical properties of hair fibers and handles different lighting conditions while giving full control over all visually important aspects of the hair appearance to the artists.

By performing a user-study we show that using our novel shading model, artists can achieve a desired appearance easier and faster compared to a physically based hair shader and an ad hoc hair shader which had been previously used in Walt Disney Animation Studio.

Our novel approach for creating artist-friendly shading models is not limited to hair rendering and it is applicable to a large number of shading models in the field of appearance modeling and photo-inspired rendering. Our approach can enhance the art-directability of shading models in movie and game industry. Our shader has been battle tested, integrated to our studios production pipeline, and is being used in the production of the feature animated ~~movie~~ Rapunzel.

same as abstract!?

?

2 Related Work

+ your related work is other work that is production friendly

In research community, there have been extensive efforts to capture the exact behavior of light scattering by human hair fibers. The first prominent work in the field of hair rendering is the classical model of Kajiya and Kay [1989]. Since then, researchers have investigated the scattering of light by hair fibers both in the case of single scattering [Goldman 1997; Kim 2002; Marschner et al. 2003] and multiple scattering [Moon and Marschner 2006; Zinke and Weber 2006; Moon et al. 2008; Zinke et al. 2008]. For a survey on hair rendering please refer to [Ward et al. 2007]. These methods are concerned with physical correctness of the results and they do not consider the controllability of the hair shading model. One exception is the model of Goldman [1997] which includes some basic artist controls.

But matching a desired appearance, by tweaking the physically based parameters (e.g. absorption coefficient, and index of refraction) is a time-consuming and tedious task [Zinke et al. 2009; Bonneel et al. 2009]. There has been some effort to estimates the values of those physically based parameters by analyzing a single photograph [Zinke et al. 2009; Bonneel et al. 2009]. These methods enable artists to render hair with similar appearance to a photograph reference. However, they do not provide any artist control for further adjustments. Besides, they can only produce results which we already have a photograph reference of. Therefore, they cannot produce super-natural appearances which is sometimes needed in movie production.

different term?

art-directable ⇒ artist-directable

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Beside working physically based shading models, there has been some work on implementing ad hoc shaders in movie and game industry [references?]. These shaders have more intuitive and easy-to-understand controls and they can produce supper-natural looking appearances. However, they break down under different lighting conditions and they fail to produce physically plausible appearances which inversely affects the believability of the characters.

Image based capturing methods? Artist control papers?

3 Motivation and Paper Organization

put in intro

In an upcoming feature animated movie, Rapunzel, the main character has long blond hair with super-natural properties. The hair plays an important role in the movie and is basically a character by itself. Therefore, the appearance of hair is critical in this ~~movie~~ and artists needed to have full control over it. Because of supper-natural properties of the hair and the photo-inspired look ~~of the~~ movie, artists needed the ability to deviate from the photo-realistic hair appearance as they desire.

Our goal was to design and implement an efficient hair shading model which can produce physically plausible results consistent with the photo-inspired look of the movie, is robust under different lighting situations, and satisfies the needs of production for artist controls. In next Section 4 we define these artist control needs and explain why physically based shading models, in general and specifically in hair rendering context, fail to satisfy these needs.

out line starts in new paragraph

Figure 2: *Some visual development art references for the movie Rapunzel. The hair appearance is very critical in the movie and the whole look of the movie is photo-inspired. Pictures from http://disneyanimation.com © Disney.*

In Section 5 we present our novel approach for producing art-directable shading models based on available physically based models. In section 6 we show how we ~~applied~~ apply our novel approach to hair rendering. We proceed by presenting some results in Section 7. The results of our user-study is summarized in Section 8. We end by presenting some performance measurements in Section 9 and in conclusion Section 10.

4 Production Needs for Artist Controls

put in intro

Artist control over the behavior of shading modules is critical in movie production. Art directors usually have specific comments about the appearance of characters and how they want to modify the appearances. It is very important that artists have tools with enough controls that enables them to apply the required modifications. [more about artist control?].

It is important to note that there is no universal "artist friendly" system. Different artists have different needs and concerns over the final appearance. These concerns vary over time, are different between production departments, and between individuals. It is impossible to satisfy the needs of all artists in one shading model.

However, there are some simple criteria which are required in movie production and usually physically based shaders fail to satisfy these criteria. We describe these requirements and explain why physically based models fail to satisfy them:

4.1 Intuitive Control Parameters

Shading models used in movie production should have intuitive control parameters. Artists need to know which parameters they should modify to get a desired appearance ~~Besides~~ Since, changes in final appearance caused by those modifications should be predictable for the artists.

In the physically ~~based world~~, appearance of materials ~~are being~~ is determined by ~~the~~ material properties (e.g. index of refraction, reflectance coefficients, absorption coefficient, etc). These properties usually have very complex and unintuitive effects on the final appearance. Manually finding parameters to obtain a desired appearance is a very time consuming and sometimes even impossible task [Zinke et al. 2009].

Specially, in the context of hair rendering, current complex physically-based shading models have many unintuitive control parameters [Zinke et al. 2009; Bonneel et al. 2009]. These unintuitive parameters make it really hard and time-consuming, even for trained artists, to guess the shader parameter values in order to get a desirable appearance [Mihashi et al. 2003]. There are some automated methods to estimate the values of these control parameters from photograph references [Zinke et al. 2009; Bonneel et al. 2009]. But these methods wont work for hairs that have non-physical appearance. Besides, even after finding the correct physical values, it is really hard to predict the results of any changes to the parameter values. Small changes can make a huge difference on the final appearance. None of these works address the problem of art-directability despite its importance in movie production.

(0.03, 0.07, 0.15) (0.15, 0.2, 0.3)

put #'s here

Figure 3: *Final hair colors for different RGB absorption coefficients (from left to right) (0.03,0.07,0.15), (0.15,0.2,0.3), (0.2,0.3,0.5), and (0.3,0.6,1.2). Coming up with appropriate values for absorption coefficient to get a desired hair color is not intuitive. Image is taken from [Zinke et al. 2009] with permission.*

For instance, hair color is ~~being~~ determined by absorption coefficients which are the measure of wave-length based attenuation of light as it passes through the hair medium. It is not intuitive to set the values of absorption coefficients to set the hair color. ~~Besides,~~ The final hair color (especially for light-colored hair) also depends on the number of light scattering events inside the hair volume. That makes predicting the final color of hair from the ~~values of~~ absorption coefficients even more complex and unintuitive. Figure 3 shows some hair rendering results and their corresponding absorption coefficient values.

An intuitive control parameter for changing the color of hair would be a simple color variable that has direct impact on the color of hair. As an example of unsuccessful try, a physically based shader at our studio has a input color parameter for setting the hair color. This color variable gets translated into absorption coefficients and will get used in the physically based computations. This translation between color space and absorption coefficient space is not accurate and results in unintuitive behaviors. See Figure 4.

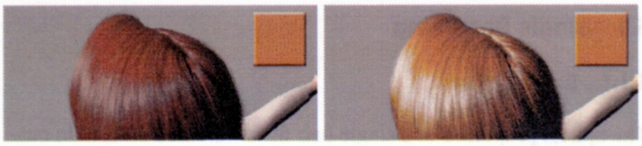


Figure 4: *Comparison between changing the input color parameters (colors inside the boxes) in a physically based shader in our studio which results in an unintuitive final color (left) and in our new shader which results in intuitive final hair color (right).*

Beside having intuitive behavior, control parameters should have intuitive names. Technical terms taken from the computer graphics literature are not artist-friendly and in some cases can be ambiguous and even misleading for artists.

repetition

~~Control parameter names should be easy to understand~~ for artists. Terms like azimuthal and longitudinal should be replaced with more appropriate terms. ~~Also, the names should be consistent with what artists are used to work with.~~ ~~(e.g. we used~~ the term *Scale* ~~for~~ represent~~ing~~ the intensity or brightness of each component to be consistent with other shaders). ~~Besides, the names should be non-ambiguous. For example, we found out that~~ the term *Highlight* (which is being widely used in literature) is ambiguous for some artists because it gets confused by the process of dying ones hair.

repetition should

We came up with a list of artist friendly terms in the context of hair shading by brainstorming with our lighting and look-development artists. we have listed these terms in Appendix A. We hope these terms become common vocabulary for artists and researchers in the future.

list them here!

4.2 Decoupled Control Variables

use "Parameters"

an

From artist's point of view, changes to one visually distinct feature (e.g. brightness of primary highlight, color of the secondary highlight) should not affect other visually distinct features. This is critical because in many cases art directors ask for a change in a one feature and expect the rest of the appearance to remain unchanged.

not always?

Since physically based controls are the material properties, they are inherently interconnected: Changing physically based properties will affect all visually distinct features of the final appearance at the same time. Therefore, modifying part of the appearance will affect all other components as a whole. As an extreme example, changing the index of refraction of hair will change almost all visual features of the hair appearance at the same time. Changing index of refraction will affect the color, intensity, and position of different highlights which is very undesirable. See Figure 5 (top row) for a visualization of these effects.

In general, "energy conservation" forces any physically based scattering function to integrate to a value less than one. Therefore, if an artist makes one of the subcomponents of the scattering function very large other subcomponents have to become smaller. A related example in context of hair rendering is changing the longitudinal width of different highlights. Changing the width of highlights will reduce their intensity due to energy conservation. By widening a highlight the energy gets distributed over a larger area and that will decrease the observed intensity of the highlight. See Figure 5 middle row for a visualization of these effects. These coupled behaviors reduce art-directability and are very undesirable. In contrast, an artist friendly control parameter for changing the width of a highlight should keep the color, intensity, and position of the highlight intact. See Figure 5 bottom row.

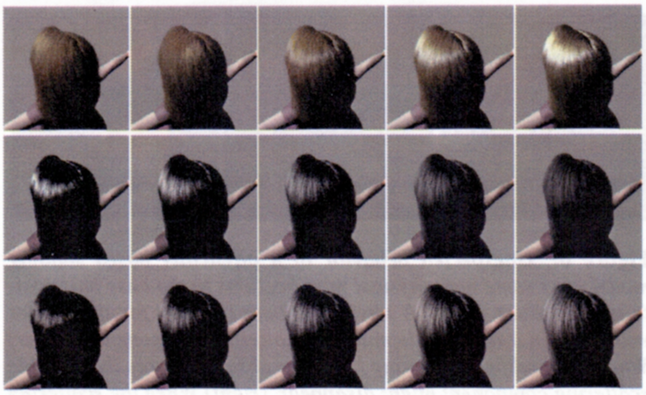


Figure 5: *Comparison between coupled and decoupled control parameters. (top row) Changing the "Index of Refraction" in a physically based shader affects all visual components of the appearance at the same time and is an example of coupled control parameter. (middle row) Increasing the width of a highlight in a physically based shader will reduces its intensity. This coupled behavior is undesirable from artists point of view. (bottom row) An example of decoupled control parameter for changing the width of a highlight which will not affect any other aspects of the highlight.*

4.3 Ability to Produce Supernatural Appearances

Physically based models follow the rules of physics and cannot produce non-physical results. But in movie production, many times art directors are interested in appearances which are not feasible in real world. One example is Rapunzel's hair that has a supernatural glowing properties in some scenes of the movie. In movie production the ability to deviate from photo-realistic appearances is required.

physically based

It is important to note that in movie production, not all the shaders produce photo-realistic appearances. Physically accurate shaders only work if all other shading modules are physically accurate. A mixture of physically based shaders with non-physically based shaders will result in the undesirable uncanny valley experience. In movie production, not all shaders are physically based, therefore, having a completely accurate hair shader will not produce consistent results with the rest of the environment and the results will not look believable.

? don't understand

As an example in context of hair rendering, if art director wants to modify the base hair scattering functions and deviates them from the physically based settings, undesirable side effects might occur. For instance, if the modified scattering function is energy absorbent, the multiple scattering component (which is very important in hair color perception) might disappear. On the other hand if the scattering function is energy producing, then the multiple scattering component will blow up! See Figure 6. These results, which are consistent with the rules of physics, are extremely undesirable from artists' point of view. Artists expect consistent behavior from the shading modules even after deviating from the real world.

repetition you said this before.

what is blow up?

5 Our Approach

The reason that physically based shading models fail to provide intuitive artist controls is that physically based scattering functions (f_s) are defined over the domain of material properties (e.g. index of refraction, reflectance coefficients, absorption coefficient, etc):

$$f_s = f(\omega_i, \omega_r, \sigma_a, \nu, ...) \tag{1}$$

~~I would not use~~

Figure 6: *Unexpected behavior of a physically based shading model after some non-physical modifications to the base hair scattering functions. (left) A physically based setting for the shader will result in a reasonable multiple scattering component. (center) When the modified scattering functions absorbs energy the multiple scattering component might disappear. (right) When the scattering functions produces energy, the multiple scattering component might blow up!*

These physically based parameters affect the final appearance in a complex way and are not intuitive for artists. They also affect the appearance of the material as a whole and in most cases affect all visually separate components at the same time. Besides, the underlying physical calculations on these parameters, force the final appearance to be physically based.

Our goal is to reproduce a pseudo scattering function f'_s that approximates f_s, but is defined on a different domain of parameters which have intuitive visual meanings to the artists, and ~~are~~ separate ~~for~~ all visually meaningful components. We refer to these intuitive, decoupled, and meaningful parameters as *Degrees of Freedom* (DoF). [Another name?]

how about "control parameters"? (CP)

$$f'_s = f(\omega_i, \omega_r, \{DoF\}) \approx f_s \tag{2}$$

To approximate f'_s from f_s, we propose the following steps:

1. Examination: Examine the exact behavior of physically based scattering function f_s over the domain of material properties.
2. Decomposition: Decompose the behavior of f_s into visually separate and meaningful scattering sub-functions f_{s_i}. Defining meaningful subcomponents is subjective and should be done with the help of end users of the system (i.e. artists).
3. Defining DOFs: for each sub-component f_{s_i}, define meaningful and decoupled degrees of freedom DoF_{ij}. These DOFs define qualities like color, intensity, size, shape, and position. This step is also subjective and should be done with brainstorming with the artists that will use the system.
4. Reproduction: Create pseudo scattering functions f'_{s_i} that approximate the qualitative behavior of decomposed scattering functions f_{s_i} over the domain of DoF_{ij}.
5. Combining: Combine the approximated pseudo scattering functions f'_{s_i} to get one pseudo scattering function f'_s. Final pseudo scattering function f'_s approximates f_s and is defined over the domain of meaningful degrees of freedom DoF_{ij}.

seems like the hard part

See Figure 7 for a schematic of our approach applied to hair shading.

6 Applying Our Method to Hair Shading

In this section we explain how we have applied our 5 step~~s~~ process to hair shading. We explain single scattering and multiple scattering components separately in the following two subsections.

6.1 Single Scattering

6.1.1 Examination

The optical properties of a single hair fiber were first studied in cosmetic science [Stamm et al. 1977; Bustard and Smith 1991; Robbins 1994]. In computer graphics, ~~literature~~ the prominent work on single scattering properties of hair fibers is the work by Marschner et al. [2003].

According to these studies, single scattering has three main subcomponents: 1) The light that reflects off the surface of hair (aka primary highlight), 2) light that has transmitted through the hair medium (aka Transmission highlight), 3) light that has been internally reflected off the inner surface of the hair (aka secondary highlight). We will refer to these components as R, TT, and TRT respectively. ~~See~~ (Figure 8 left)

Due to the presence of tilted cuticles, these three components will be reflected ~~off the fiber~~ in 3 different angles around the hair fiber, forming ~~which will form~~ 3 different cones. The R component has the color of the light source and usually appears as a white bright highlight. The TT component appears in back lighting situations and is the bright halo around the hair. The TRT component appears above the primary highlight and has the color of the hair. This component contains some randomized looking sharp peaks that are basically caustics formed as light passes through the hair fibers. Their randomized appearance is due to the fact that hairs have elliptical cross sections and are oriented randomly.

Marschner et al. [2003] showed that one can decompose the scattering function of hair fibers into three longitudinal function $M(\theta)$ and three azimuthal functions $N(\phi)$. See Figure 8 for a qualitative visualization of these six functions. Marschner et al. [2003] defined the final hair scattering function f_s as:

$$f_s(\theta, \phi) = \sum_X M_X(\theta) N_X(\phi) / \cos^2\theta \tag{3}$$

where $X \in \{R, TT, TRT\}$ represents different sub-components.

which is the "original paper"?

In the original paper the longitudinal scattering functions $M_X(\theta)$ have been modeled as three unit-integral, zero-mean Gaussian functions. The variance of these Gaussian functions represents the longitudinal width of each highlight.

$$M_X(\theta) = g(\beta_X^2, \theta_h - \alpha_X) \tag{4}$$

where g is a unit-integral, zero-mean Gaussian function and β^2 represents the variance of the lobe and α_X represents its longitudinal shift.

They have calculated each azimuthal scattering function assuming that the hair fibers have circular cross sections. We refrain from mentioning the calculations here and refer the interested reader to the ~~original paper~~ [2003]. What is important for our purpose is that those computations will result in qualitatively similar results for different hair materials. See Figure 8.

Similar to what?

Due to the eccentricity of the human hair fibers, the number, intensity, and the azimuthal direction of the glints varies based on the orientation of hair. However, since we are only concerned about the final visual impact of the glints, we assume that glints are two sharp peaks with the same intensity that are always coming back toward the incoming light direction. We add a random shift to them to get label each row with the name of the component

Text & Symbols need to be larger!

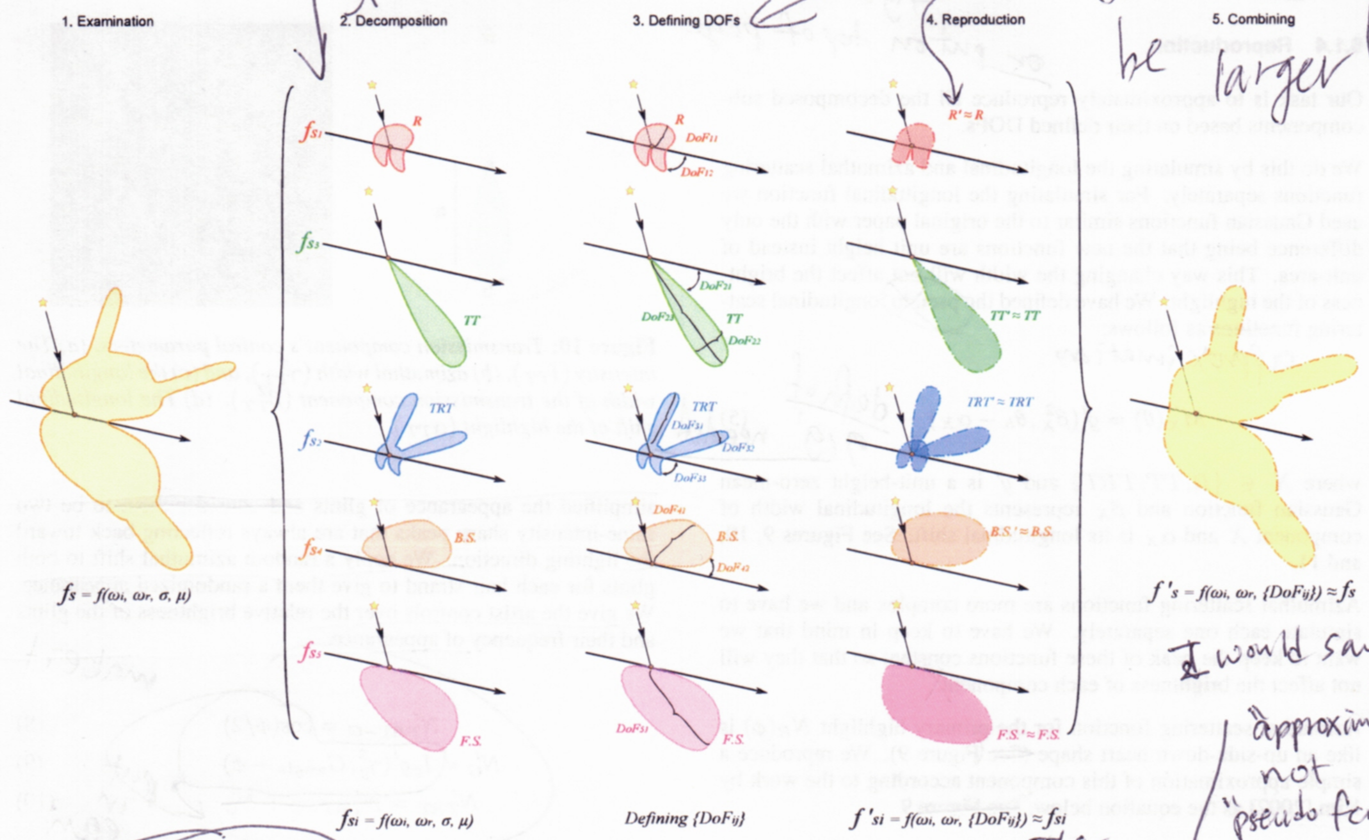


Figure 7: *A schematic schematic of our approach applied to the context of hair rendering. ~~From left to right.~~ The first column shows the physically based hair scattering function f_s. Second column shows decomposed scattering functions f_{s_i}. In the third column, meaningful degrees of freedom DoF_{ij} are being defined for each subcomponent. In the forth column, new pseudo scattering functions f'_{s_i} are being introduced to approximate each f_{s_i} functions. These functions are being defined over the domain of DoF_{ij}. ~~At~~ In the last column, all of these pseudo functions are ~~being~~ combined to give us the final pseudo scattering function f'_s that approximates f_s.*

fourth

I would say "approximations" not "pseudo fcns"

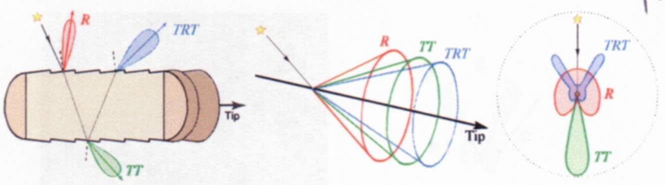


Figure 8: *Single scattering sub-component: R, TT, and TRT (left) shows different paths that light can take after intersecting a hair fiber. (center) three longitudinal cones that will contain single scattering subcomponents. (right) Qualitative visualization of azimuthal scattering functions.*

the randomized appearance. This very simplified model for glints produces visually acceptable results.

6.1.2 Decomposition

All three subcomponents mentioned in last section are visually meaningful and separate entities. TRT component contains the secondary highlight and the glints so we decompose TRT to two smaller subcomponents: glints and secondary highlight excluding the glints.

So we will have the following separate and meaningful subcomponents for the single scattering:

1. R component
2. TT component
3. TRT component excluding Glints
4. Glints

reduce spacing

This step is subjective and could be done differently. [explain more]

For example!

6.1.3 Defining DOFs

Defining decoupled degrees of freedom for each component means defining qualities like color, intensity, size, shape, and position of each decomposed component. Our team of artists came up with the following DOFs.

1. R : Color, intensity, longitudinal position, longitudinal width
2. TT : Color, intensity, longitudinal position, longitudinal width, azimuthal width
3. TRT - Glints : Color, intensity, longitudinal position, longitudinal width
4. Glints: Color, intensity, frequency of appearance

This step is subjective and could be done differently. [explain more]

How ~~What~~ does each DoF affect the final appearance?

Fig 9, 10, 11 ← combine to one figure

or put on top of page

6.1.4 Reproduction

Our task is to approximately reproduce all the decomposed subcomponents based on their defined DOFs.

We do this by simulating the longitudinal and azimuthal scattering functions separately. For simulating the longitudinal function we used Gaussian functions similar to the original paper with the only difference being that the new functions are unit height instead of unit-area. This way changing the width will not affect the brightness of the highlight. We have defined the ~~pseudo~~ longitudinal scattering ~~functions~~ as follows:

approximations

$$M'_X(\theta) = g'(\beta^2_X, \theta_h - \alpha_X) \tag{5}$$

def of g, g' needed

where $X \in \{R, TT, TRT\}$ and g' is a unit-height zero-mean Gaussian function and β_X represents the longitudinal width of component X and α_X is its longitudinal shift. See Figures 9, 10, and 11.

Azimuthal scattering functions are more complex and we have to simulate each one separately. We have to keep in mind that we want to keep the peak of these functions constant so that they will not affect the brightness of each component~~s~~.

The Azimuthal scattering function for the primary highlight $N_R(\phi)$ is like an up-side-down heart shape ~~(See~~ Figure 9). We reproduce a simple approximation of this component according to the work by Kim [2002] as the equation below. ~~See Figure~~ 9

$$N_R(\phi) = \cos(\phi/2) \quad 0 < \phi < \pi \tag{6}$$

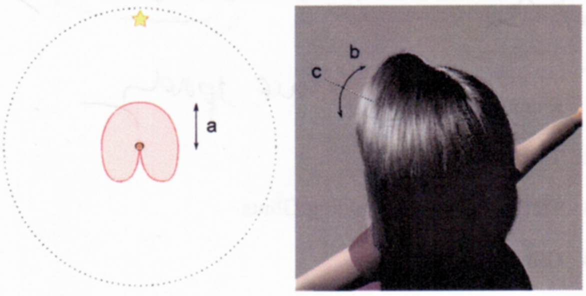


Figure 9: *Primary highlight's control parameters. (a) The intensity (I_R) and (b) the longitudinal width of the primary highlight (β^2_R). (c) The longitudinal shift of the highlight (α_R).*

With this approximation we are ignoring the Fresnel term for simplicity.

The Azimuthal scattering function of the transmission component N_{TT} (Fig 10) is a sharp forward directed lobe, ~~and~~ We simply reproduce it as a sharp Gaussian with unit height and controllable azimuthal width ~~as follows:~~

$$N_{TT} = g'(\gamma^2_{TT}, \pi - \phi), \tag{7}$$

where γ_{TT} is the azimuthal width of the transmission component. ~~See Figure 10.~~

For the secondary highlight we have more control parameters because of ~~the presence of~~ glints. As ~~we~~ described earlier, we ~~have~~

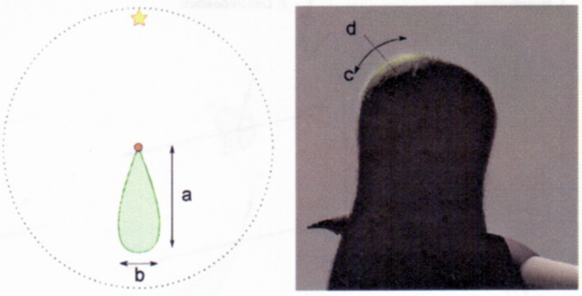


Figure 10: *Transmission component's control parameters. (a) The intensity (I_{TT}), (b) azimuthal width (γ^2_{TT}), and (c) the longitudinal width of the transmission component (β^2_{TT}). (d) The longitudinal shift of the highlight (α_{TT}).*

simplified the appearance of glints ~~and consider them~~ to be two same-intensity sharp peaks that are always reflecting back toward the lighting direction. We apply a random azimuthal shift to both glints for each hair strand to give them a randomized appearance. We give the artist controls over the relative brightness of the glints and their frequency of appearance.

make it one eqn

$$N'_{TRT-G} = \cos(\phi/2) \tag{8}$$

$$N'_G = I_g g'(\gamma^2_g, G_{angle} - \phi) \tag{9}$$

$$N'_{TRT} = \cancel{N'_{TRT-G} + N'_G} \tag{10}$$

put in eqn

Here, I_g is the relative ~~intensity~~ of glints to the intensity of secondary highlight, γ_g is the azimuthal width of the glints and G_{angle} is the half of the angle between two glints. For simulating the effect of eccentricity on the glints we use a random variable to rotate the glints by up to ±45° for each hair strand. See Figure 11.

does it mean rotate ϕ?, why is rotation not in eqns?

[rewrite]

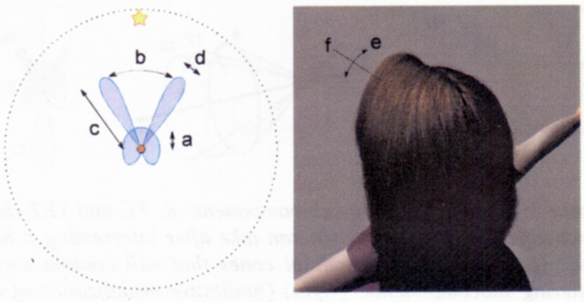


Figure 11: *Secondary highlight's control parameters: (a) The intensity of the secondary highlight (I_{TRT}). (b) The angle between the glints (G_{angle}). The (c) relative intensity (I_g), and (d) sharpness of the glints (γ^2_g). (e) The longitudinal width of the secondary highlight (β^2_{TRT}). (f) The longitudinal shift of the highlight (α_{TRT}).*

To embed the control for color and brightness of each component we simply multiply the each one by a scalar variable and a color variable.

$$f'_X = C_X I_X M'_X(\theta) N'_X(\phi) \tag{11}$$

where $X \in \{R, TT, TRT\}$ and C_X and I_X are the color and intensity of component X respectively.

Why is I_X not part of C_X? C_X normalized somehow?

[Explain expressions?]

6.1.5 Combining

To combine the results we have to basically add all the components together and divide by the cos^2 which accounts for the projected solid angle of the specular cone [2003].

authors

$$f'_s = \sum_X f'_X / \cos^2(\theta) \tag{12}$$

6.2 Multiple Scattering

Considering multiple scattered light is critical for correct perception of hair color, especially for light colored hair [Moon and Marschner 2006; Zinke and Weber 2007]. For capturing the exact behavior of the multiple scattered light one needs more elaborate methods like brute force path tracing [Zinke et al. 2004], photon mapping [Moon and Marschner 2006; Zinke and Weber 2006], or other grid based approaches [Moon et al. 2008]. Path-tracing approaches are computationally expensive and their results converge very slowly. Photon-mapping and grid-based approaches are faster than path-tracing methods but are still relatively expensive. Also These methods require ray-tracing capabilities are costly for production.

Another class of methods try to approximate the multiple scattering component by considering the physical properties of human hair fibers. The most prominent work in this category is the Dual Scattering model [Zinke et al. 2008]. This method is very fast and accurate, and with some simplifications it can be used in production very efficiently without ~~the use of any extra data structures and any ray-tracing steps.~~ [Sadeghi and Tamstorf 2008] [Our technical report from Disney]

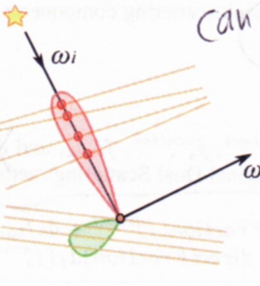
I would avoid citing this since it reveals who you are

Here we explain how we have applied our approach to the multiple scattering component.

6.2.1 Examination

The Dual Scattering method approximates the multiple scattering function as a combination of two components: global multiple scattering and local multiple scattering.

Global multiple scattering at any point is dependent on the orientations of all the hairs between the light source and that point. It computes the forward scattering transmittance and spread of the light that reaches the shading point from all light sources. Global multiple scattering will be computed for different points separately.



can you visualize like fig12,

Figure 12: *Dual scattering method separates the multiple scattering component into global multiple scattering and local multiple scattering.*

Local multiple scattering is only dependent on the longitudinal inclination of the hair strand at the shading point, and assumes that all the surrounding hairs around the shading region have the same orientation and that there are infinite number of them. Local multiple scattering can be pre-computed for all the longitudinal inclination angles. [verify?]

Here is the pseudo code of dual scattering model directly taken from [Zinke et al. 2008]. Term $f_{back}^{scatter}$ has been introduced in [~~Sadeghi and Tamstorf 2008~~] as a slight correction to the original method. why?. what is 2k? put in table

```
// Pre-compute $\bar{A}_b(\theta)$ and $\bar{\Delta}_b(\theta)$ from $f_s$ for $0 < \theta < \pi$

F($T_f$, $\bar{\sigma}_f^2$, directFraction)

    // Backscattering for direct and indirect lighting
    $f_{back} \Leftarrow 2\bar{A}_b(\theta) g(\theta_h - \bar{\Delta}_b(\theta), \bar{\sigma}_b^2(\theta))/(\pi \cos^2 \theta)$
    $f_{back}^{scatter} \Leftarrow 2\bar{A}_b(\theta) g(\theta_h - \bar{\Delta}_b(\theta), \bar{\sigma}_b^2(\theta) + \bar{\sigma}_f^2(\theta))/(\pi \cos^2 \theta)$

    // Longitudinal functions for direct and indirect lighting
    $M_X \Leftarrow g(\theta_h - \alpha_X, \beta_X^2)$
    $M_X^G \Leftarrow g(\theta_h - \alpha_X, \beta_X^2 + \bar{\sigma}_f^2)$

    // Azimuthal functions for indirect lighting
    $N_X^G(\theta, \phi) \Leftarrow \frac{2}{\pi} \int_{\pi/2}^{\pi} N_X(\theta, \phi') d\phi'$

    // Single scattering for direct and indirect lighting
    $f_s^{direct} \Leftarrow \sum M_X N_X(\theta, \phi)$
    $f_s^{scatter} \Leftarrow \sum M_X^G N_X^G(\theta, \phi)$

    $F^{direct} \Leftarrow directFraction(f_s^{direct} + d_b f_{back})$
    $F^{scatter} \Leftarrow (T_f - directFraction) d_f (f_s^{scatter} + \pi d_b f_{back}^{scatter})$

    // Combine the direct and indirect scattering components
    return $(F^{direct} + F^{scatter}) \cos \theta_i$
```

remove italics

all notations are consistent with the original paper [Zinke et al. 2008] except the appearance of new term $f_{back}^{scatter}$ [Sadeghi and Tamstorf 2008]. [Should we name/explain every single term here?]

no, just explain the new term.

The Dual Scattering model will produce a very good approximation for a given physically based BRDF. However, there is no control over its behavior. The color and intensity of the multiple scattered light is being directly calculated from the single scattering components f_s^{direct}.

since

6.2.2 Decomposition

Decomposing the dual scattering component into meaningful components is not as straightforward as of the single scattering component. To find meaningful components, we visualized all the terms involved in the computation of the final result of the model (~~See~~ Figure13) and asked our artists to chose the ones that have intuitive meanings to them. The result was the following two components: [explain better]

1- f_{back} and $f_{back}^{scatter}$. These two components represent the light that goes into the hair volume and comes back to the surface. f_{back} computes this for direct illumination and $f_{back}^{scatter}$ computes this for indirect illumination. We referred to these two quantities as the Backscattering component (B.S.).

2- $f_s^{scatter}$. This term computes the light that scatters forward and maintains its forward directionality inside the hair volume. This component is very important in back lit situations. We referred to this component as Forward Scattering component (F.S.).

↑ which pictures in the figure do these refer to?

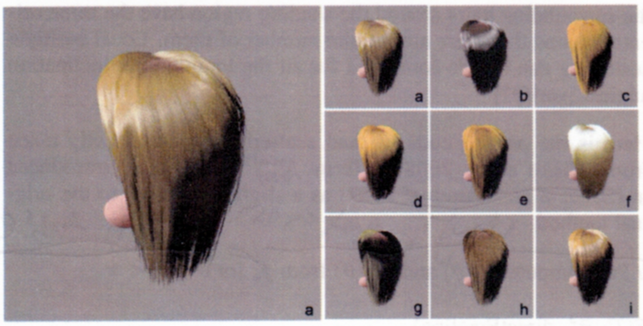


Figure 13: *Dual scattering method's (a) final result and different terms involved in the computation including (b) single scattering component* (f_s), *(c) average backscattering attenuation* (A_b), *(d) local multiple scattering for direct ~~light~~ lighting* (f_{back}), *(e) local multiple scattering for indirect~~ed~~ lighting* ($f_s^{scatter}$), *(f) average backscattering spread* (S_b), *(g) single scattering for indirect lighting* ($f_s^{scatter}$), *(h)* $F^{scatter}$, *and (i)* F^{direct}. *Re-render?*

what are these?

6.2.3 Defining DOFs

Now we need to define degrees of freedom like the color, intensity, size, shape, and position of these components. All of these components already have computed colors and intensities etc. By overriding these values with artist defined values, we will loose a lot of details in the appearance of those components.

FIGURE?

Therefore, we decided to provide adjustment control parameters for modifying these components.

Backscattering components are basically two Gaussian functions and appear as ~~a~~ very smooth *multiple-scattering highlights*. Our team of artists defined 4 adjustment control parameters for f_{back} and $f_{back}^{scatter}$: Color Adjust, Intensity Adjust, Longitudinal Shift Adjust, Longitudinal Width Adjust. Setting all these control parameters to their default values results in the original results of the dual scattering model.

For the Forward Scattering component $f_s^{scatter}$ we have defined 2 control parameters: Color Adjust, and Intensity Adjust.

[explain more]

6.2.4 Reproduction

For reproducing the dual scattering results we used the original algorithm and replaces the single scattering component f_s^{direct} with our pseudo scattering function f_s' and embedded the defined artist controls into the f_{back} and $f_{back}^{scatter}$ and $f_s^{scatter}$ components.

However, replacing the physically based scattering function of f_s^{direct} with the non-physically based model f_s' can cause problems in the dual scattering model. The main problem is that if f_s' can produce energy (i.e. its integration is larger than 1) then the multiple scattering part (correctly) goes to infinity. Also if the f_s' absorbs a lot of energy (i.e. the integration of the BRDF is very small) then we do not get any contributions in the multiple scattering components. Figure 6 shows the effect of these radical changes in multiple scattering which are caused by subtle changes in the components of f_s'.

We solved this problem by doing all the computations of the multiple scattering component on the normalized version of the single scattering components f_s^N:

shouldn't it be f'^{norm}_s?

$$f'^{norm}_s = \frac{f'_s}{\int_\Omega f'_s(\theta,\phi)d\theta d\phi} \tag{13}$$

where Ω is the full sphere around the shading point.

Here is the revised version of the pseudo code for reproducing the results of dual scattering with embedding artist controls: Modifications to the physically based version are highlighted in blue)

put in table, side by side with previous table

```
// Pre-compute $\bar{A}_b(\theta)$ and $\bar{\Delta}_b(\theta)$ from $f'^{norm}_s$ for $0 < \theta < \pi$

F($T_f$,$\bar{\sigma}_f^2$, directFraction)

    // Backscattering for direct and indirect lighting
    $f_{back} \Leftarrow 2\bar{A}_b(\theta)g(\theta_h - \bar{\Delta}_b(\theta) + \beta_{Back}, \bar{\sigma}_b^2(\theta) + \alpha_{Back})$
        $/(\pi \cos^2\theta)$
    $f_{back}^{scatter} \Leftarrow 2\bar{A}_b(\theta)g(\theta_h - \bar{\Delta}_b(\theta) + \beta_{Back}, \bar{\sigma}_b^2(\theta) + \bar{\sigma}_f^2(\theta) + \alpha_{Back})$
        $/(\pi \cos^2\theta)$

    // Apply the artist controls to the $f_{back}$ and $f_{back}^{scatter}$
    $f_{back} \Leftarrow C_{Back} I_{Back} f_{back}$
    $f_{back}^{scatter} \Leftarrow C_{Back} I_{Back} f_{back}^{scatter}$

    // Longitudinal functions for direct and indirect lighting
    $M'_X \Leftarrow g'(\theta_h - \alpha_X, \beta_X^2)$
    $M_X^G \Leftarrow g'(\theta_h - \alpha_X, \beta_X^2 + \bar{\sigma}_f^2)$

    // Azimuthal functions for indirect lighting
    $N_X^G(\theta,\phi) \Leftarrow \frac{2}{\pi}\int_{\pi/2}^{\pi} N'_X(\theta,\phi')d\phi'$

    // Single scattering for direct and indirect lighting
    $f_s^{direct} \Leftarrow \sum M'_X N'_X(\theta,\phi)$
    $f_s^{scatter} \Leftarrow \sum M_X^G N_X^G(\theta,\phi)$

    // Apply the artist controls to $f_s^{scatter}$
    $f_s^{scatter} \Leftarrow C_{Forward} I_{Forwrd} f_s^{scatter}$
```

Here, $I_{Forward}$, and I_{Back} are control parameters for Adjusting the intensity values and $C_{Forward}$, and C_{Back} are control parameters for adjusting the color values of forward scattering, and backscattering components respectively. In addition, β_{Back} and α_{Back} are control parameters for adjusting the longitudinal shift and the longitudinal width of back scattering components.

needs to be 6.2.5

6.3 Combining

Combining ~~the~~ f_s^{direct}, $f_s^{scatter}$, f_{back}, and ~~the~~ $f_{back}^{scatter}$ ~~are~~ is done according to the original Dual Scattering method:

```
$F^{direct} \Leftarrow directFraction(f_s^{direct} + d_b f_{back})$
$F^{scatter} \Leftarrow (T_f - directFraction)d_f(f_s^{scatter} + \pi d_b f_{back}^{scatter})$

// Combine the direct and indirect scattering components
return $(F^{scatter} + F^{scatter})\cos\theta_i$
```

easier to put in table? and combine 6.2.4, 6.2.5 into one section called "reproduction & combining"?

The final result of the shader is the result of the dual scattering method since it includes the single scattering components as well.

change background to white? black?

I can see aliasing?. Can you do hi-res renders?.

Figure 14: *Visualizing main components of the shader separately. (a) Final shading result. (b) Single scattering component. (c) Forward scattering component. (d) Backscattering component. Find a nicer render and show its AOV images here*

6.4 Relation between Single Scattering and Multiple Scattering

part of the "decoupling" theme

Multiple scattering computations are based on the single scattering functions. There is an inherent relationship between these two components since multiple scattering is basically the effect of many single scattering events.

However, this relation might be troublesome in movie production. For example when an art director request a change on the appearance of the single scattering (e.g. color of the primary highlight) and he want to keep every thing else untouched. If the artist changes the single scattering components it will affect the multiple scattering component.

We have provided the ability to break the link between single and multiple scattering by having two sets of parameters for single scattering components. One of these sets will feed into the computations of multiple scattering and one will be used as the parameters of the single scattering. These two sets are linked together by default but artist has the ability to break this link at any point.

I like this section, good. ok! !!

7 Rendering Results

We have implemented out our novel hair shading system in RenderMan and it has been fully integrated into Walt Disney Animation Studios's production pipeline. It is currently being used in the production of upcoming feature animated ~~movie~~ Rapunzel. Figure 15 shows some frames from the teaser of the movie that is using our hair shader.

Figure 15: *Some frames from the teaser that shows long blond hair of Rapunzel (preferably back lit and front lit), short brown hair and goatee of Flenn, and white fur/hair of horsey*

Figure 1 shows Rapunzel's head model rendered with our hair shader from different viewing angles and lighting setups. Figure 15 (b) shows Rapunzel's long blond hair in a back lit situation. Figure 15 (c) shows medium length and short brown hair rendered using our shader. And Figure 15 (a) shows long white hair and short white fur rendered using the same shader.

Figure reffig:comparison shows a reproduction of Penny ~~model~~ from BOLT ~~movie~~ rendered using both our new shader and the original shader of the movie. Our new shader is capable of re producing previous results.

Figure 17 shows an art reference (left) and a matching rendering (right) using our new shader. These are actual production art references and rendering responses from artists during the production of the movie. It is important to note that in this case, art directors were not looking for an exact match between the rendering result and the art reference image and rather the overall look and feel of the rendering results were important.

Figure 17: *Painting art reference and a matched rendering using our new hair shader. Faces have been been taken out intentionally.*

8 Artist Controllability User Study

To evaluate the usability of our shader (which we will refer to as the New Shader) we organized a user study in our studio. Our goal was to compare our novel shader to an ad hoc hair shader and a physically based shader. We chose the ad hoc hair shader which had been used in the production of BOLT movie (which we will refer to as the Production Shader). We also chose the physically based hair shader that was formerly written for the production of Rapunzel movie (which we will refer to as the Research Shader).

8.1 Setup

We gathered a total of 13 look-development and lighting artists with different amount of experience from our studio and grouped them

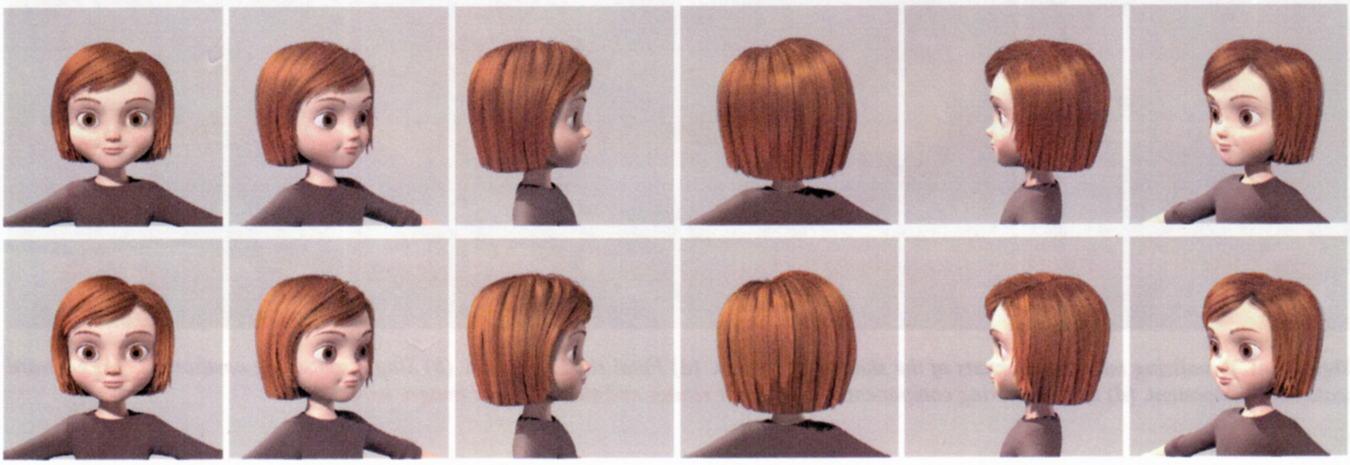


Figure 16: *Re-renderings of Penny character from BOLT movie using the (top row) original hair shader used in BOLT movie, and (bottom row) our new hair shader.*

into 3 groups. We assigned one of the shaders to each group of artists and trained them on using the assigned shader. New shader was assigned to 6 artists, Research shader were assigned to 4 artists, and Production Shader were assigned to 3 artists.

For performing our user study, we illuminated a natural hair wig from 9 different directions and gathered 9 photo references. See Figure 18 top row.

~~virtually~~ we virtual hairmodel

We ~~groomed a hair~~ model similar to our photo shoot wig reference. We placed the hair model in a ~~CG~~ scene which contained 9 lights with the same position, orientation and intensity as the ones used in our photo shoot setup.

Afterwards, we provided 4 of the photo references to each group of artists and asked them to tweak the parameters of the their assigned shader and come up with a fixed set of parameter values that match the appearance of all 4 given photo references. Because of artists' busy schedule we limited the time of user study to 4 hours.

8.2 Results

After the user study we used the submitted shader parameters of each artist to rendered all 9 lighting directions. You can see one of the best results of each groups in Figure 18. We anonymized the rendering results and asked the Rapunzel's art director, a lighting artist, and a look development artist to grade the renderings. They had different criteria for grading the pictures. The ~~F~~ollowing Tables summarizes their criteria and their submitted grades for each hair shader:

Shader	Avg.	Min	Max	Std Dev
New	6.83	4	9	1.72
Production	5.67	3	8	2.52
Research	3.75	3	5	0.96

Table 1: *Evaluation by Rapunzel's Art-Director with focus on the overall results*

combine tables 1, 2, 3

8.3 Discussion

It is interesting to note that the physically based shader gained the least average and maximum grades among all 3 shaders. It is mainly due to the lack of artist control in physically based shaders. Using

Shader	Avg.	Min	Max	Std Dev
New	6.00	4	9	1.79
Production	5.67	4	8	2.08
Research	4.25	2	6	1.71

Table 2: *Evaluation by a lighting artist with focus on matching the photograph references*

Shader	Avg.	Min	Max	Std Dev
New	4.17	1	7	2.14
Production	3.33	1	6	2.52
Research	2.75	1	4	2.75

Table 3: *Evaluation by a look-dev artist with focus on hair appearance*

the Research shader the artist could get physically feasible results but they could only match one of the photo references and not all of them at the same time. In most cases, the front lit view and the side lit view renderings appeared to be different hair materials. See Figure 19. This shows that in movie production, artist control can be more important than physical accuracy of the rendering results.

~~how? they look same to me!~~

front?

side?

new

research

Figure 19: *Comparing the one result of ~~new~~ your shader (top row) with a result of research shader (bottom row). Due to lack of control, artists were not able to match the hair appearance in both front lit case (left) and side lit case (right).*

which pictures are these a closeup of?

The Production shader fails to simulate the physically based properties of hair like capturing the secondary highlight, and the bright transmission component. Also, in most cases, it fails to capture the vari-

is this a closeup of fig 18?. you should say and specify which images put labels like this

use black background ~~grey~~, white text

photo ref

new shader

~~Research shader~~

~~product shader~~

Production ~~research~~ shader

~~Zinke et al?~~

research shader?

Figure 18: *Rendering results with highest matching scores using different shaders. Top to bottom: Photographs, the new shader, ad hoc shader, physically based shader.*

see? even I am confused...

show closeup.

ation in lighting inside the hair volume and it tends to give a flat appearance to the hair. But even with these limitations, it has recieved higher scores than the Research shader. This is because it has more artist controls than the Research shader.

Our New shader, on the other hand, has been able to produce physically feasible results while it gives artists enough control to enable them to match different viewing directions at the same time. It has received the largest average and maximum grades in all 3 evaluations. However, as noted from the minimum grade columns, artists can do poorly with any of the shaders.

9 Performance

At the end we measured the performance of all 3 shaders used in our user study. All measurements ~~are~~ were done for the front lit image of the user study in 1K resolution. We have used the instances of each shader with the highest scores for the performance measurements.

Our ~~developed~~ new shader is around 3.3 times faster than the Production shader and 1.5 times faster than the Research shader. This is a significant improvement especially in movie production where ~~only~~ even a one percent improvement means saving hundreds of hours of computation. the Research shader consumes 1.6 times more memory than our shader and the Production shader uses 1.3 times more memory.

Shader	User Time	Real Time	Memory
New	320.3 sec	1101.0 sec	1284.18 MB
Research	500.3 sec	1745.0 sec	2023.18 MB
Production	1077.0 sec	3911.7 sec	1686.26 MB

Table 4: *Performance measurements. which time column should be removed? Memories usages includes the hair geometry beside the memory used by the shaders right? Rasmus?*

10 Conclusion

directable

We have addressed the problem of art-directability of physically-based shading models in movie production. We have introduced a novel approach for creating approximate art-diractable shading models based on the physically based models. We have applied our method to hair shading and implemented a hair shading model. We show that our new shading model is more controllable than a physically based shading model and produces more realistic results label figures

front? side?

new shader

product

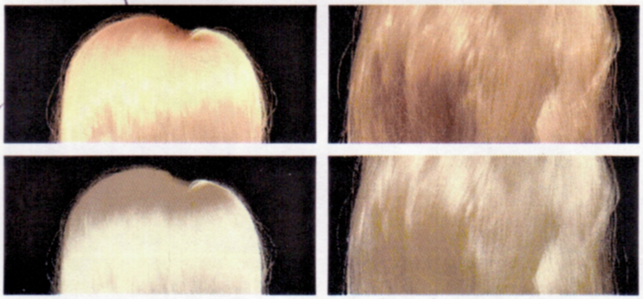


Figure 20: *Comparing ~~the~~ one result of the new shader (top row) with a result of the production shader (bottom row). All images are close ups of front lighting image. Left) Unlike the new shader, the Production shader fails to correctly produce the secondary highlight. Right) The Production shader fails to capture the depth of the hair volume and scattering details while the new shader catches these lighting details.*

no reference to this in text...

than an ad hoc shader which had been used in our studio.

[Conclude better!]

Limitations! Future work!

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A Artist Friendly Names

~~This is the list of artist friendly terms for the context of hair rendering which are result of many brainstorming sessions with our lighting and look-development artists in our studio. We hope that they become a common vocabulary for researchers and artists in the future.~~

Technical Term	Artist Friendly Term
Primary Highlight	Specular Component
Secondary Highlight	Subspecular Component
Transmission Highlight	Transmission Component
Color	Color
Intensity	Scale
Longitudinal Width	Roughness
Longitudinal Position	Angular Offset
Azimuthal Width	Spread

Table 5: *Technical terms and their corresponding artist-friendly terms for single scattering parameters.*

put in same table

Technical Term	Artist Friendly Term
Backscattering	Hair Volume Diffuse
Forward Scattering	Hair Volume Transmission

Table 6: *Technical terms and their corresponding artist friendly terms for multiple scattering parameters.*

say what other materials you think could be easily converted to be artist-friendly