BRDF-Shop: Creating Physically Correct Bidirectional Reflectance Distribution Functions

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The BRDF-Shop interface lets artists create bidirectional reflectance distribution functions through positioning and manipulating highlights on a spherical canvas.

A majority of the artists in the graphics community use one of the mainstream packages for modeling and designing a scene for 3D rendering. These packages—such as Alias' Maya, Discreet's 3ds Max, or Newtek's Lightwave—provide slider bars and numerical inputs that let the artist design the material's attributes, such as smoothness and metallic qualities.

While advanced users develop a mental mapping from numerical input to material appearance, novice users might not have a natural feel for a material's numeric parameterization. We present a novel and intuitive approach for material design through direct control of the material's bidirectional reflectance distribution function (BRDF) via a series of brush strokes. Using our system, BRDF-Shop, the artist can paint highlights onto a spherical canvas and model a physically correct BRDF. Our principal hypothesis behind this approach is that artists understand materials through the shape and position of the highlights. We propose that these brush strokes, in combination with a real-time display, allow the artist to create a BRDF with intrinsic knowledge of how the highlight will appear on a given object.

Background

BRDF is a function that gives the relation between the light reflected along an outgoing direction and the light incident from an incoming direction. We present a method that allows artists to manipulate the way incoming light reflects, and thus, we need a model to replicate the reflection behavior. Additionally, we impose the requirement of a physically correct mathematical model to make the BRDFs compatible with physically based rendering techniques.

A physically correct BRDF model must satisfy two properties. First, the BRDF must conserve energy. This means that the amount of energy leaving a material must be less than or equal to the amount of energy reaching a material. Second, the BRDF must maintain reciprocity. In other words, the BRDF must remain the same if the angles of incoming and outgoing lights' directions are interchanged. Various physically correct, mathematical models include those by Ashikhmin,[1] Lafortune,[2] and Ward.[3] From these, we chose the Ward BRDF model for our system as it has an intuitive set of parameters that makes mapping of an artist's interaction, or brush strokes, to BRDF creation relatively straightforward. The "Related Work" sidebar discusses other BRDF work and approaches.

The Ward BRDF model is the underlying model for BRDF-Shop. Equation 1 shows the formula for a specular lobe in the Ward BRDF model.

$$F(\omega_i,\omega_o) = \frac{1}{4\pi\alpha_x\alpha_y\sqrt{\cos\theta_i\cos\theta_o}}\exp\left[-2\frac{\left(\frac{\hat{h}\cdot\hat{x}}{\alpha_x}\right)^2+\left(\frac{\hat{h}\cdot\hat{y}}{\alpha_y}\right)^2}{1+\hat{h}\cdot\hat{n}}\right] \tag{1}$$

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Related Work

Related work on intuitive bidirectional reflectance distribution function (BRDF) modeling includes the perception-based experiments by Pellacini et al.[1] Using psychophysical experiments and multidimensional analysis on the results, they found that people identify with two different parameters in a BRDF: the contrast gloss and the distinctness-of-image gloss. The authors designed a simple interface of slider bars, which change the two perceptual parameters, to create different BRDFs. We complement their work by introducing a unique and more intuitive input mechanism of painting highlights.

Sloan et al. presented the idea of painting on a spherical canvas for nonphotorealistic rendering.[2] While Sloan et al. used the spherical canvas as a map from normal to color, we introduce a painting technique that will create a physically correct BRDF. This lets the user design a much wider gamut of materials, including both diffuse and metallic materials.

Kautz introduced a technique for artists to model a BRDF via manipulation of a normal distribution function (NDF).[3] The NDF is a BRDF stored as an image and indexed by the half-angle vector between the incoming and outgoing directions of light. This reparameterization of the BRDF allows an artist to design a highlight's shape by simply drawing the NDF in a paint program, but does not guarantee any physical plausibility.

Shimizu et al. presented an interface for designing automotive paints by manipulating a BRDF parameterized by aspecular angles, or the angle from the point-perfect specular reflection.[4] Their work allows the user to adjust a quadratic curve, which controls the intensity of the BRDF as a function of the aspecular angle. Additionally, their interface visualizes the resulting BRDF illuminated by environment lighting in real time. However, the work does not provide a direct painting interface for the user.

BRDF-Shop can be considered as an extension of Poulin and Fournier's work, which presented a tool for designing both material and lighting through a painting interface.[5] Their method works by the users directly selecting the point of perfect specular reflection for a Blinn highlight and their algorithm generating the corresponding directional light source. We focus only on the material design, and thus provide a wider gamut of possible BRDFs. Additionally, we provide a real-time interface to display complex objects and unknown BRDFs under environment lighting.

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where:

- ω_i, ω_o are, respectively, the normalized incoming and outgoing directions;
- $\hat{n}$ is the surface normal;
- $\hat{x}$, $\hat{y}$ are the principal directions of anisotropy;
- $\hat{h}$ is the half angle vector,

$$\hat{h} = \omega_i + \omega_o / \left\| \omega_i + \omega_o \right\|$$

- θ_i and θ_o are angles made by ω_i and ω_o with $\hat{n}$;
- α_x is the standard deviation of the surface slope along $\hat{x}$; and
- α_y is the standard deviation of the surface slope along $\hat{y}$.

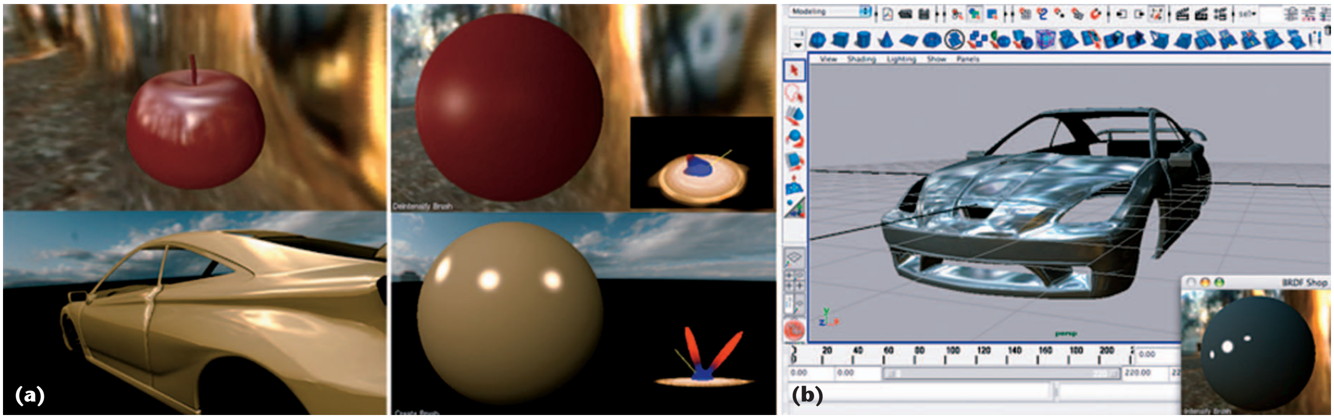
Equation 1 models the reflectance function as a Gaussian lobe. The spread of the lobe is directly related to the roughness of the material and is modeled by the parameters α_x and α_y. Inequality of these two parameters indicates an asymmetric lobe. Additionally, Ward's BRDF model will conserve energy provided the standard deviations, or α values, are below 0.2.

BRDF-Shop

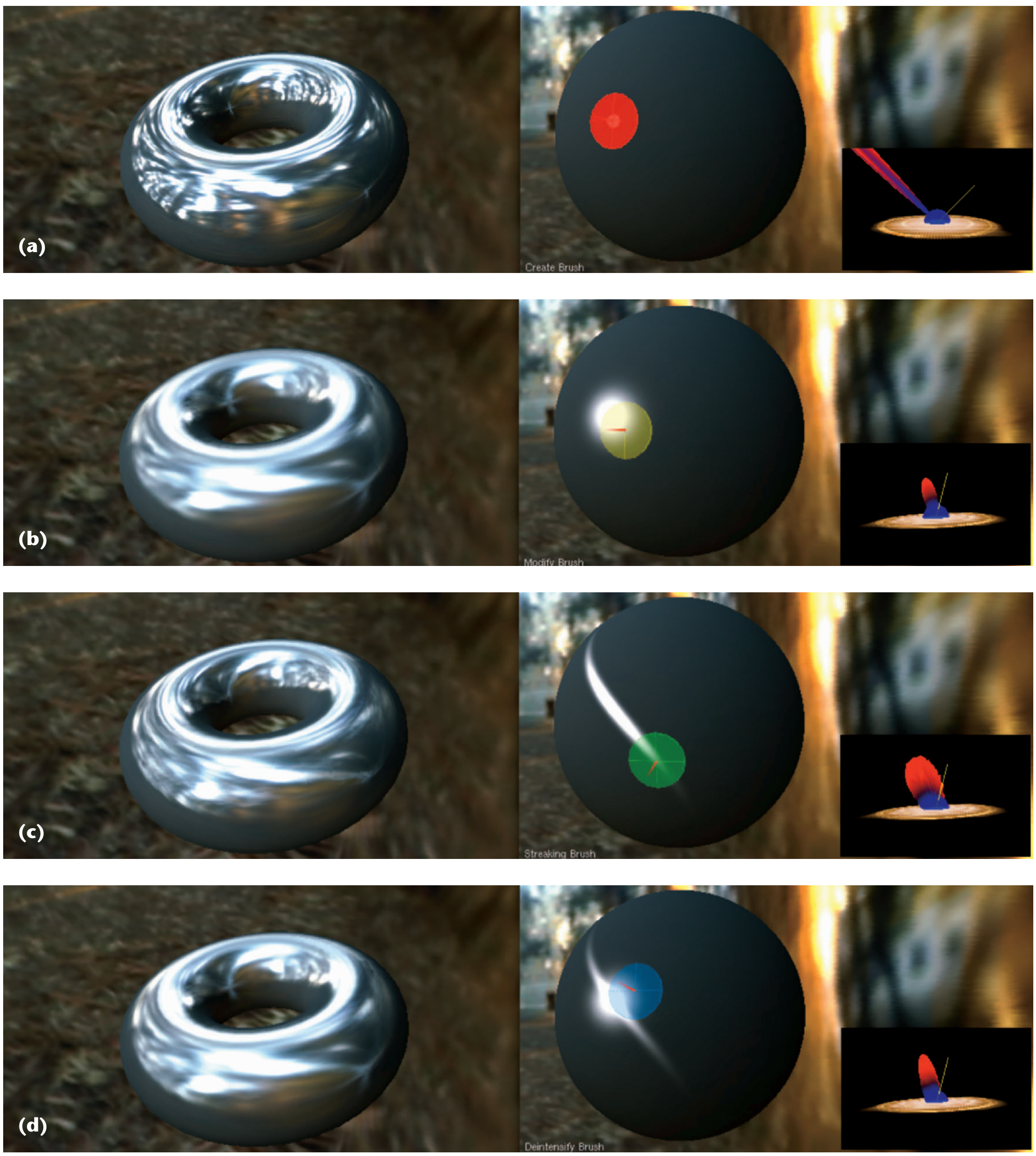
We have two principal goals for BRDF-Shop. First, BRDF-Shop must provide a mechanism for creating BRDFs in a manner that is both artistic and intuitive. Second, BRDF-Shop must support interactive feedback to provide a clearer understanding of the behavior of the created BRDF. We meet both criteria by providing a simple and straightforward interface that requires an extended Ward BRDF model and a novel, efficient mapping of user interaction to parameters of this model.

Interface and interaction

The interface layout of BRDF-Shop consists of a spherical canvas on the right, a graph of the BRDF on the lower right, and a naturally lit object on the left, as Figure 1a shows on the next page. Following Fleming et al.'s demonstration that people understand BRDFs better when illuminated by natural lighting, we use a natural environment to light an arbitrary mesh and our spherical canvas.[4] However, we approximate the environment light for the canvas through a single-point light source. The single light source locates the brightest location of the environment, which could represent the sun or another key light source. We use a spherical canvas with a single-point light source, because an arbitrary mesh with complex environment lighting could easily cause confusion in designing a BRDF. For instance, a single BRDF lobe on an arbitrary mesh could actually create multiple highlights, thereby making the highlight painting less intuitive. However, we also show an object with the created BRDF illuminated through full environment lighting, instead of a single light source approximation, thereby giving the artist feedback of how the



1 The BRDF-Shop interface consists of (a) a spherical canvas, where the artist can directly paint highlights and design a unique BRDF, and simultaneously and in real time inspect the designed BRDF on a complex model rendered under environment lighting. Additionally, (b) we adapted the interface for Maya allowing fast integration in a production environment.



2 Illustration of the different brushes and their effect on the BRDF. On the left, a real-time rendering with environment lighting on a torus, and on the right, the spherical canvas with a single-point light-source approximation for the environment: (a) creation of a new highlight with the create brush; (b) the modify brush, which adjusts the roughness of the highlight; (c) the streaking brush, which pulls a highlight in the direction of the brush; and (d) the deintensify brush, which adjusts the distribution of energy between multiple lobes.

BRDF will look in a globally illuminated scene on a complex mesh.

We provide a small set of brushes for quick and intuitive development of highlights. The create brush (see Figure 2a) creates a high-frequency, circular highlight on the spherical canvas. The modify brush (see Figure 2b) adjusts the size of an existing highlight on the canvas and thereby controls the roughness of the material. The streaking brush (see Figure 2c) extends a highlight to any given orientation and thus controls the direction of anisotropy for the material. The intensify brush and the deintensify brush (see Figure 2d) modify the albedo, or reflectance value, of a highlight, and thereby shift the distribution of energy between multiple highlights and the diffuse component.

To provide the artist sufficient creative freedom, we use an extended Ward BRDF model and show a novel mapping between brush strokes and the parameters of the BRDF model. Although we provide a painting metaphor, the actual highlights on the canvas are created by rendering the canvas geometry with the underlying BRDF.

Extended Ward BRDF model

Using the original Ward BRDF model, as Equation 1 shows, we can only place highlights around the point of perfect specular reflection. In our interface, we want to provide the artist with the flexibility to place a highlight at any point on the spherical canvas. We attain such capability by multiplying the outgoing vector, ω_o, by the transformation matrix, $\boldsymbol{R}$. Derivation of matrix $\boldsymbol{R}$ is given in the "Creating circular highlights" section.

We also extend the model to support the design of materials with multiple reflection lobes, thus we propose Equation 2 as our BRDF model:

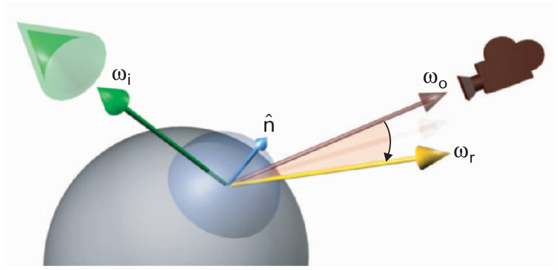
$$f(\omega_i,\omega_o)=\frac{\rho d}{\pi}+\sum_{k=1}^{\#\,\text{lobes}}\rho_{s_k}\cdot F_k(\omega_i,\boldsymbol{R}_k\omega_o) \tag{2}$$

The parameter ρ_d represents the diffuse albedo for the material and ρ_{sk} represents the specular albedo for the kth lobe. F_k represents Ward's BRDF model, as presented in Equation 1, for the kth lobe, where each lobe has a set of unique, defining parameters. This includes the transformation matrix, $\boldsymbol{R}$, and the α_x, α_y values. For energy conservation, we maintain the constraint that the sum of all the albedos, ρ, must be less than or equal to one.

Mapping brush strokes to BRDF lobes

BRDF-Shop consists of multiple brushes that let the artist quickly paint highlights on a spherical canvas and create lobes in the BRDF. The following will explain our mapping between highlights and lobes.

Creating circular highlights. When the highlights appear mostly circular on the spherical canvas, and when illuminated by a single-point light source, we simply refer to them as circular highlights. Because the underlying surface can be rotated and not affect the BRDF, the lobes that represent the circular highlights are isotropic. When α_x and α_y are equal in Equation 1, we get a circular, symmetric Gaussian lobe and the highlight becomes circular on the spherical canvas.



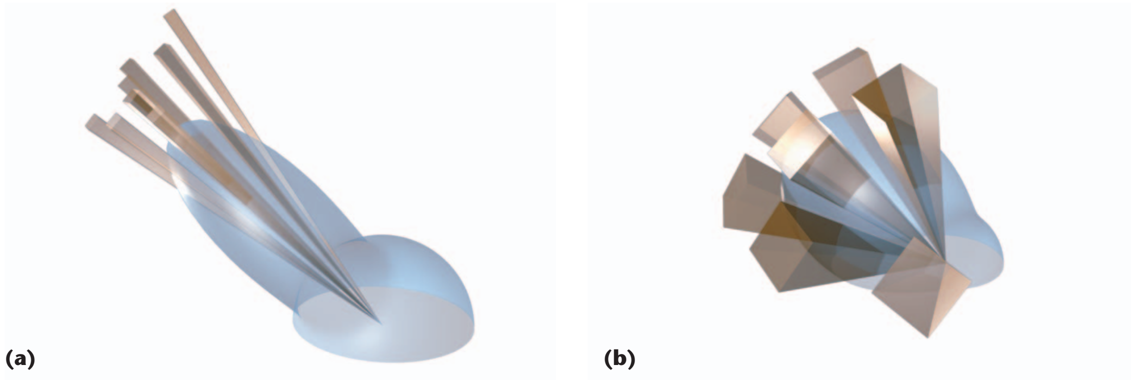
3 Illustration of various directions.

Artists using BRDF-Shop can place the highlight at any position on the spherical canvas. BRDF-Shop computes the transformation matrix proposed in our extended Ward BRDF model to place the highlight at the desired position. We derive the transformation matrix by first determining the mirror reflection direction, ω_r, of the incoming direction of light, ω_i, at the center of the painted highlight. Next, we rotate the outgoing direction of light at the center of the highlight, ω_o, to align it with ω_r. This rotation becomes our transformation matrix, $\boldsymbol{R}$, for the extended Ward BRDF lobe; Figure 3 shows the different vectors.

Split lobes and reciprocity. By rotating the outgoing direction, we lose reciprocity in our BRDF. However, creating an additional lobe with the inverse of the transformation matrix, $\boldsymbol{R}$, can easily rectify the problem. Lafortune first suggested the split lobe approach for his BRDF model.[2] The result of a split lobe is a double highlight for a single-point light source, which is plausible in some grooved metals.[1] Figure 1a shows an example of a split lobe in the BRDF-Shop interface. However, since split lobes are not common in nature, we provide a snapping mechanism that suggests where the artist could create a highlight without making a split lobe. We also allow artists to disable the use of split lobes if they want to generate a physically impossible BRDF.

Adjusting roughness. A surface's roughness controls the highlight's diffuseness and the lobe's shape. In the Ward BRDF model, this is modeled by the parameters α_x and α_y. If α_x and α_y are equal, the highlight will remain circular on the spherical canvas lit by a point light source, or the BRDF will remain isotropic. However, if the values differ, the highlight takes on a streaking shape, or becomes anisotropic. The mapping of brush strokes to these values is critical for our interface, as it allows the strokes to feel natural, as if the artist truly has control over the highlight.

In an approach similar to Poulin and Fournier,[5] we determine the necessary exponent to raise the cosine of the angle between ω_r and ω_o to some threshold, γ, where ω_o is the outgoing direction of the spherical canvas to the camera at the current brush position. In other words, we are taking the inverse of the Phong BRDF,[6] at the current brush position, to find the exponent that produces γ. Empirically, a value of 0.8 for γ provides the most intuitive results. We then use the relationship of Phong expo-



4 **BRDF importance sampling with prefiltered environment map. As the frequency of the BRDF decreases, we use larger, averaged areas of the environment map, via prefiltering, to sample the convolution of the BRDF and environment. (a) A higher frequency BRDF uses narrow samples focused around the peak highlight direction. (b) A lower frequency BRDF uses wider samples more evenly distributed around the hemisphere.**

nents to standard deviations, or the α values (see http://radsite.lbl.gov/mgf/mgfhtml/stanprac.html), to derive the final result shown in Equation 3:

$$\alpha = \frac{\sqrt{2}\log(\omega_r \cdot \boldsymbol{R}\omega_o)}{\log\gamma} \tag{3}$$

Streaking highlights. Streaking highlights, as shown in Figure 2c, are examples of directional anisotropic reflection. The most common instance of a streaking highlight occurs with brushed metal, where the grooves in the material cause the light to reflect in an elongated fashion. These streaks can occur in any direction for a given material, so we handle this by rotating the $\hat{h}$ vector around the normal. The rotation is calculated from the angle between the tangent vector on the surface and the direction vector of the brush position, both with respect to the peak highlight position. Additionally, the artist will adjust the roughness by manipulating only the parameter α_x. Because we are rotating with respect to the tangent vector, the artists will feel as if they are extending the highlight and rotating it around the center of the highlight.

Implementation

Our implementation of BRDF-Shop consists of all the brushes and mappings as described in the previous sections along with a real-time rendering interface to show the resulting materials. For rendering, we use a multiple pass approach. In the first pass, we display the diffuse lobe of the BRDF through spherical harmonic environment map rendering.[7] In the subsequent passes, we render each lobe created by the artist. However, our rendering technique differs for the canvas and for the object mesh.

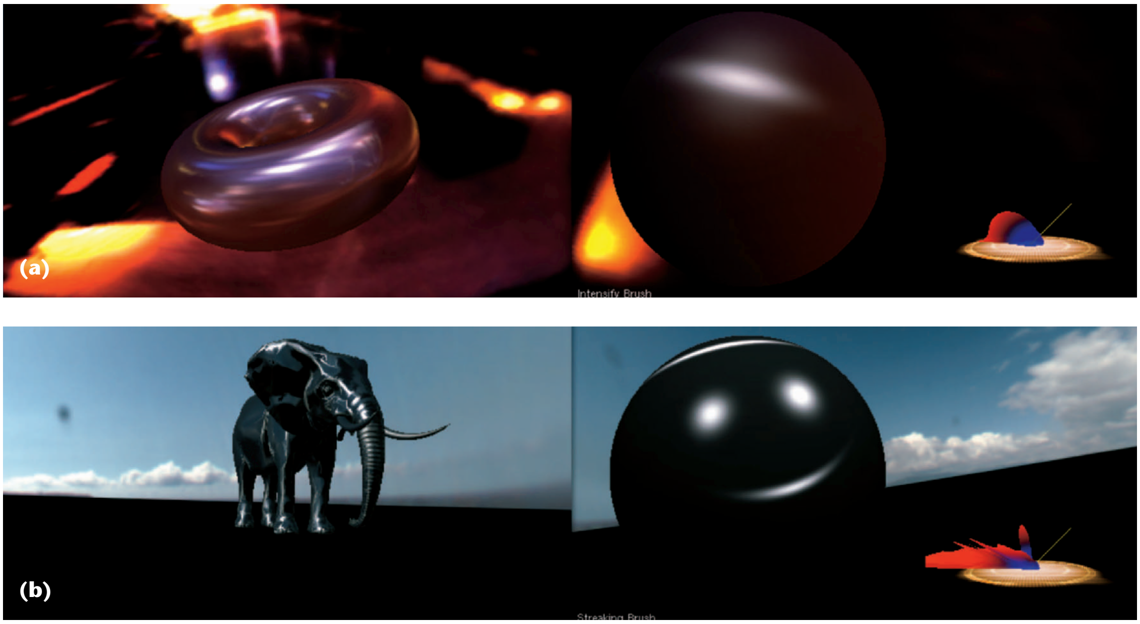
In rendering the lobes on the spherical canvas, we approximate the environment by a single-point light source at the brightest location in the environment. We evaluate Equation 2 in the GPU for every visible pixel of the spherical canvas. In rendering the lobes on the arbitrary mesh, we carry out integration of the environment at every visible pixel of the mesh.

Integration is done in the GPU by quasi-Monte Carlo quadrature with importance sampling of each BRDF lobe. Monte Carlo samples are generated from a precalculated Halton quasirandom number sequence. We use the importance sampling equations presented by Ward,[3] even though they have been proven not to be a correct solution.[8] However, as mentioned by Walter, the original Ward importance sampling equations provide a close solution that are more visually pleasing with less samples. For GPU optimization, we store the random values as precalculated log, cosine, and sine values. Additionally, we vectorize each importance sample calculation by computing four sample rays at the same time. We also use approximately eight samples per pixel per BRDF lobe. We prefilter the environment map,[9] via hardware accelerated mip mapping, when importance sampling the lower frequency BRDF, as in Figure 4. Using this approximation, the artist gets a clearer understanding of how the object will appear in a globally illuminated scene.

We demonstrate BRDF-Shop in Figure 5, and the supplemental videos are available online at http://opac.ieeecomputersociety.org/opac?year=2006&volume=26&issue=1&acronym=cga. We obtained the results in all the images and the supplemental video using an Apple G5 2.5-GHz processor with an Nvidia 6800 GT graphics card. As shown in Figure 1b, we also tightly integrated BRDF-Shop into Alias' Maya, via a series of plug-ins, to provide artists with the capabilities of our interface in a familiar development environment.

Discussion

We chose the Ward Gaussian model for representing BRDFs—instead of other newer models, such as Lafortune's or Ashikhmin's model, due to the intuitiveness of the parameters. Our interface is driven by the underlying BRDF model, and the choice of model is crucial to the flexibility of our interface. Our initial implementation of BRDF-Shop actually used Lafortune's model. The generality of the model made it effective in mapping circular highlights at arbitrary positions to Lafortune lobes. However, mapping streaking highlights to Lafortune lobes is difficult. To our knowledge, most reflectance data, which exhibit a streaking highlight, are fit with multiple circular-shaped highlights that are close togeth-



5 Physically correct BRDFs created using BRDF-Shop. (a) Torus in Grace Cathedral with a combination of a streaking highlight and a low-frequency circular highlight. (b) Elephant shape with a BRDF containing multiple split lobes rendered under an open sky. The happy face on the canvas results from the reflection highlights due to a single-point light source.

er and resemble a streak. Lafortune does suggest a mechanism for creating streaking highlights from a single lobe, but this technique is rarely used in data fitting. Additionally, we found that the lobes resulting from his suggested mechanism were not well behaved and made our interface less intuitive.

We also pursued Ashikhmin's microfacet model as a means to model the painted BRDF. The model seemed to best fit our ideology, as it can create a physically plausible BRDF with given knowledge of the microfacets. However, the model requires an expensive integration process to retrieve the BRDF model based on the microfacet distribution equation. Additionally, we considered Ashikhmin's anisotropic Phong model,[10] but we found the use of a rotation matrix to move the highlight caused unexpected BRDFs with this model.

We did not use a data fitting technique, based on least-square-error minimization, due to its computational complexity. While this technique might provide the artist with similar control over a BRDF, such techniques are not likely to provide a perfect fit and, with current algorithms, would not return the results in real time.

Conclusions and future work

Our work illustrates a novel method for designing BRDFs through an artistic perspective. Even though work has been done in creating perceptually based BRDF modelers, we present the first tool that provides an intuitive painting mechanism to create physically correct BRDFs. Our novel method for creating new BRDFs has applications in several industries. For instance, the automobile industry could design the reflectance of their vehicles through an artistic perspective. Due to physical correctness, the generated BRDFs could be translated into real-world materials. Likewise, material designers for the computer graphics industry could approach BRDF creation less numerically and more artistically, which could decrease the learning curve of 3D graphics design. In our informal tests with graphics artists, the artists found the program quite intuitive. However, a formal user study should be conducted with graphics artists to see if they have a clear understanding of material appearance through circular and streaking highlights. ■

Acknowledgments

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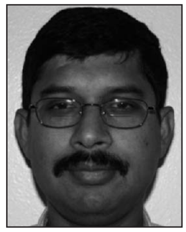

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