

Rendering Iridescent Rock Dove Neck Feathers

Weizhen Huang
University of Bonn
Bonn, Germany
whuang@cs.uni-bonn.de

Sebastian Merzbach
University of Bonn
Bonn, Germany
merzbach@cs.uni-bonn.de

Clara Callenberg
University of Bonn
Bonn, Germany
callenbe@cs.uni-bonn.de

Doekele G. Stavenga
University of Groningen
Groningen, Netherlands
d.g.stavenga@rug.nl

Matthias B. Hullin
University of Bonn
Germany
hullin@cs.uni-bonn.de

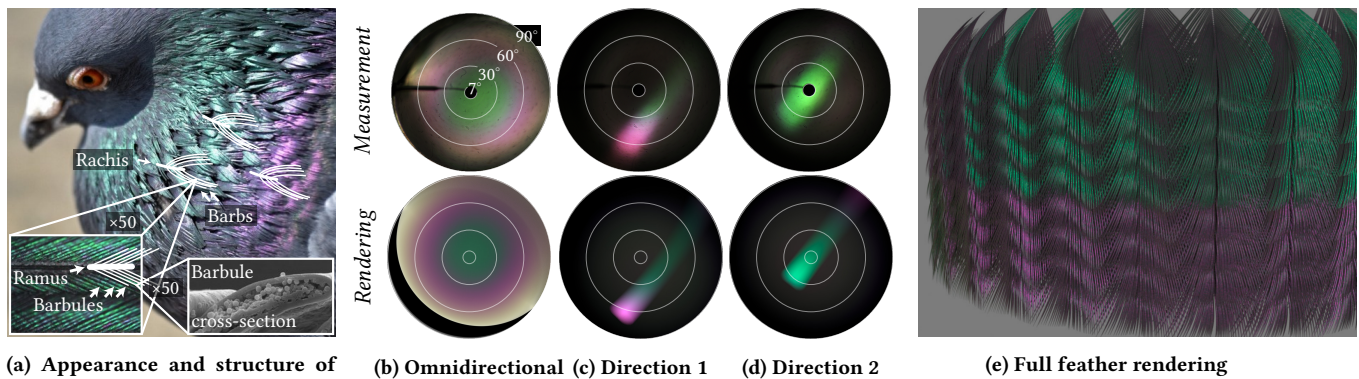


Figure 1: (a) The neck feather of the rock dove features geometric structures across a wide range of scales. (b–d) Barbules exhibit a characteristic scattering behavior due to their intricate surface and interior structure. (e) Our model covers details like milliscale roughness, thin films or mutual shadowing between barbules, closely recreates the appearance of the feather.

ABSTRACT

Bird feathers exhibit fascinating reflectance, which is governed by fiber-like structures. Unlike hair and fur, the feather geometric structures follow intricate hierarchical patterns that span many orders of magnitude in scale. At the smallest scales, fiber elements have strongly non-cylindrical cross-sections and are often complemented by regular nanostructures, causing rich structural color. Therefore, past attempts to render feathers using fiber- or texture-based appearance models missed characteristic aspects of the visual appearance. We introduce a new feather modeling and rendering framework, which abstracts the microscopic geometry and reflectance into a microfacet-like BSDF. The R, TRT and T lobes, also known from hair and fur, here account for specular reflection off the cortex, diffuse reflection off the medulla, and transmission due to barbule spacing, respectively. Our BSDF, which does not require pre-computation or storage, can be efficiently importance-sampled and readily integrated into rendering pipelines that represent feather geometry down to the barb level. We verify our approach using

a BSDF-capturing setup for small biological structures, as well as against calibrated photographs of rock dove neck feathers.

CCS CONCEPTS

• **Computing methodologies** → **Reflectance modeling**; *Rendering*.

KEYWORDS

Feather, BSDF, iridescence, rock dove

ACM Reference Format:

Weizhen Huang, Sebastian Merzbach, Clara Callenberg, Doekele G. Stavenga, and Matthias B. Hullin. 2022. Rendering Iridescent Rock Dove Neck Feathers. In *Special Interest Group on Computer Graphics and Interactive Techniques Conference Proceedings (SIGGRAPH '22 Conference Proceedings)*, August 7–11, 2022, Vancouver, BC, Canada. ACM, New York, NY, USA, 8 pages. <https://doi.org/10.1145/3528233.3530749>

1 INTRODUCTION

The creation of realistic humans and animals has always been a central challenge in computer graphics. An important factor is the rendering of hair and fur, for which various models exist [d'Eon et al. 2011; Khungurn and Marschner 2017; Marschner et al. 2003; Yan et al. 2017; Zinke and Weber 2007]. A related but much less studied problem is the rendering of bird feathers [Chen et al. 2002; Franco and Walter 2007], even though birds have played pivotal roles in famous animation works like 'For the Birds', 'Piper' (Pixar)

or ‘Rio’ (Disney). Hair and fur models can only partly be transferred to feathers, due to the more complex structure of the latter.

This work explores the rendering of the iridescent neck feathers of one of the most well-known and representative urban bird species, the rock dove (Fig. 1a). The feathers show a prominent green-purple shading, which arises from thin-film interference in the feather substructure [Yoshioka et al. 2007]. Supported by spectrally and angularly resolved measurements, we develop a comprehensive model for the accurate rendering of feathers that takes into account features across various scales (Table 1).

Our main contributions are the following:

- We propose a parameterized bidirectional scattering distribution function (BSDF) for feathers, which encapsulates the statistics of microscale structures (barbule). It is completely evaluated and importance-sampled at render time.
- we apply the BSDF at milliscale (barb) by changing the local shading frame, providing rich details without having to model the microstructures explicitly.
- We incorporate iridescence in the model, alleviating the need to mix hair and iridescence shaders.
- We validate our model using one-to-one comparisons between measured and rendered BSDF as well as photographs.

2 RELATED WORK

We briefly review existing models for feather geometry and appearance, as well as previous work on reflectance measurement.

Geometry. Similar to hair geometry modeling, the majority of works model feathers as assemblies of parametric primitives, usually Bézier curves [Chen et al. 2002; Franco and Walter 2002; Streit and Heidrich 2002] or NURBS [Baron 2018]. Latest works [Baron 2018; Baron and Patterson 2019] derive a procedural feather geometry representation of curve primitives automatically from photos.

Triangulated representations are often used for texturing: [Franco and Walter 2007] generate an auxiliary mesh from the Bézier representation of their earlier work [Franco and Walter 2002] to transfer results from a pigmentation simulation back to the barb curves. Similarly, [Seddon et al. 2008] deform a Bézier patch from a scanned feather. A shader generates barb curves along the patch, which can be controlled by bio-inspired attributes painted on the patch.

Our model is based on barb curves with associated normal vector at each vertices, representing the local barbule orientation. To our knowledge, [Baron et al. 2021a,b] are the only ones also adapting the shading frame between barb and barbule.

Rendering. When rendering feathers in larger scales, bidirectional texture function (BTF) are often used without looking into its substructures [Chen et al. 2002; Franco and Walter 2007]. For more geometric detail, hair models [d’Eon et al. 2011; Marschner et al. 2003] are alternatively applied to barbs [Haapaoja and Genzwürker 2019; Leaning and Fagnou 2010], ignoring finer structures such as

Table 1: The four characteristic scales of our model.

Name	Scale	Feature
Macro	>20 mm	Feather
Milli	0.3 mm	Barb
Micro	40 μ m	Barbule
Nano	550 nm	Thin film

barbules. However, according to [Harvey et al. 2013], the feathers’ milliscale features also contribute to optical scattering. Recently, [Baron et al. 2021a,b] demonstrate a new rendering technique that take into account milliscale features by procedurally rendering the substructures while still applying hair shading models.

None of the above works deal with iridescence. Iridescence in bird feathers is well understood by the ornithology community; however, their simulation is mostly restricted to nanoscales with basic approaches such as thin-film interference simulation [Okazaki 2019] and finite-difference time-domain modeling [Wilts et al. 2014]. Only one heavy ray-tracing simulation on feather barbules [McCoy et al. 2018] is performed with a commercial tool for optical system prototyping FRED [Harvey et al. 2015]. These methods are not well suited for integration in a renderer.

We instead propose a feather-specific BSDF, which models the barbule reflectance statistically.

Measurements. There are mainly two approaches to acquire BxDFs. [Baron et al. 2021a; Chen et al. 2002; Khungurn et al. 2015] adopt an image-based approach, matching the simulation with a few photographs. Alternatively, [Khungurn and Marschner 2017; Yan et al. 2015] use a gonireflectometer with motorized robotic arms. The reflectance can be sampled at high angular resolution, moving either the light source or the sensor. In particular, [Harvey et al. 2013] take multiple photographs of a complete feather using a spherical gantry; these photos are then fused to visualize the BRDF.

Our image-based approach uses the setup by [Stavenga et al. 2009]. It is closely related to the setups in [Ghosh et al. 2007; Khungurn and Marschner 2017] regarding the application of a nonplanar reflector. Our setup allows direct and efficient BSDF acquisition with a digital camera, and is especially suitable for measuring microscale features such as feather barbules and insect wing scales.

3 BACKGROUND

This section provides an introduction of the feather geometry, the mechanisms behind the color production and the measurement setting for the BSDF. Table 2 lists an overview of the symbols.

3.1 Feather Geometry

A bird feather is a multi-scale structure (Fig. 1a). The hair-like structures that are normally seen with bare eyes are barbs that branch from the rachis. A barb, in turn, has numerous side branches: the barbules, which overlap and together form a rather flat surface. The barbule has a distinctly non-cylindrical cross-section and may, depending on species, comprise thin film coatings, multilayer stacks or photonic crystals (Fig. 2). In this paper, we investigate rock dove neck feathers (Fig. 2c), which exhibit thin film structure.

3.2 The Colors of Bird Feathers

Mainly two mechanisms contribute to the color of birds: pigments and structures [Stoddard and Prum 2011]. *Pigmentary colors* originate from pigments that absorb light in selective wavelength ranges. A virtually universal pigment in bird feathers, absorbing in a very broad wavelength range, is melanin, which also exists in human hairs. *Structural colors*, on the other hand, originate from regular organized micro- and nanostructures of keratin and melanosomes, reflecting light in restricted wavelength ranges. Structural colors

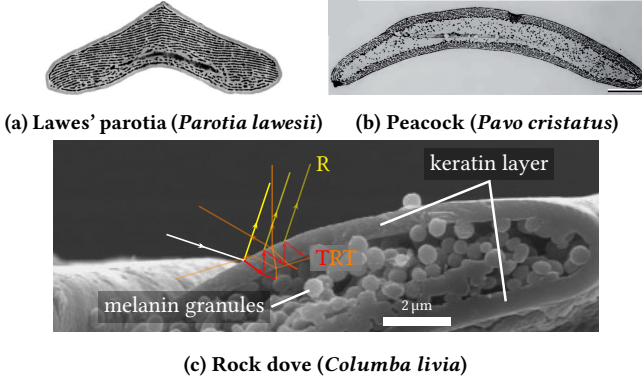


Figure 2: Various mechanisms of structural color in barbules. (a) Transmission electron microscopic (TEM) image of a male Lawes' parotia breast feather barbule, showing multilayer structure [Stavenga et al. 2011a]. (b) TEM image of the transverse cross-section of a peacock tail feather barbule, showing 2D photonic crystal structure [Freyer and Stavenga 2020]. (c) Scanning electron microscopic (SEM) image of the transverse cross-section of a rock dove neck feather barbule with thin-film structure [Nakamura et al. 2008] (©2008 The Physical Society of Japan), overlaid with annotations demonstrating the R and TRT components (Section 3.3).

are generally directional and more brilliant than pigmentary colors. Many birds combine pigmentary and structural coloration.

Rock Dove Neck Feather Barbule Colors. Rock dove neck feather barbules (Fig. 2c) exhibit a special two-color iridescence caused by thin-film interference from the upper keratin layer [Nakamura et al. 2008; Okazaki 2019; Yoshioka et al. 2007]. The feathers located on the upper part of the neck have an average keratin thickness of 595 nm [Yin et al. 2006] and look green at normal incidence. With only slight variation of the illumination or viewing angle though, the color can very suddenly change from green to purple; the purple feathers on the lower part of the neck, with a mean keratin thickness of 530 nm, turn green at an oblique angle. This angle-dependence of color is demonstrated in Fig. 3. Below the keratin layer, the

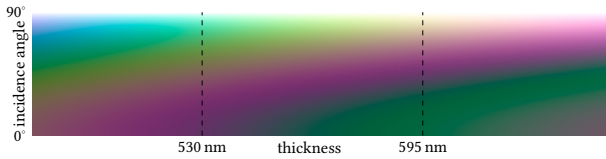


Figure 3: Simulated color of a thin keratin film in air as a function of thickness and incidence angle (illuminant D65).

barbules feature randomly arranged melanin granules, with minor and almost constant reflectance in the visible wavelength range. They mainly decrease the color saturation.

3.3 The Physics of Thin Films

Thin-film interference occurs when light is reflected from the upper and lower boundary of the film, causing difference in optical paths

Table 2: Important notations used in this work

Symbol	Definition
η	Index Of Refraction
λ	Wavelength
$I_{R,TRT}$	Reflectance, similar to Fresnel term, Eqs. (2) and (3)
$L_{i,o}(\omega_{i,o}, \lambda)$	Incoming / outgoing spectral radiance
$S(\omega_i, \omega_o, \lambda)$	Bidirectional Scattering Distribution Function
$\omega_{i,o}$	Incoming / outgoing unit vectors
ω_m	Barbule normal vector, Fig. 7b
$\vec{n}$	Barb plane normal vector, Fig. 8
θ/ϕ	Longitudinal/azimuthal parametrization of ω , Fig. 7b
$\phi_{0,1}$	Lower (ϕ_0) and upper (ϕ_1) bound of the azimuth
b	Ellipse semi-minor axis, Fig. 7b
r_θ	Radius of the longitudinal circular arc, Fig. 7b
θ_d	Circular arc opening angle, Section 4.1, Fig. 7b
D, D_θ, D_ϕ	Normal Distribution Function, Section 4.1
$G(\omega_i, \omega_m, \omega_o)$	Masking and shadowing term, Section 4.1
H	Barbule spacing, Fig. 8
$\Delta h(\phi), \Delta h'(\phi)$	Projected length of elliptical arc, Fig. 8
h, l	Azimuthal / longitudinal offset, Fig. 9

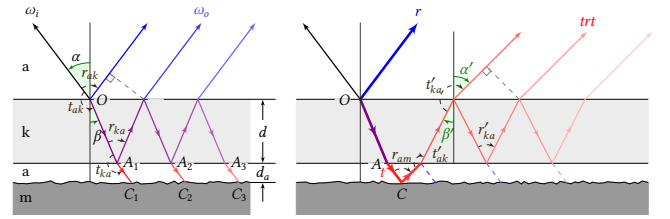


Figure 4: Thin-film interference. The keratin layer (k) is surrounded by two air layers (a), beneath these layers lies the randomly dispersed melanin granules (m), which we model as a diffuse surface. Left: thin-film reflection (blue arrows) amounts to the R component. Right: thin-film reflection (blue) plus TRT component (red), the thick rays on the right summarize the respective thin rays on the left. The components after the blue dashed lines are ignored due to their negligible contribution.

(Fig. 4). The path difference $\mathcal{D}$ results in a phase shift $\Delta\psi = \frac{2\pi\mathcal{D}}{\lambda}$ of the light, with λ being the wavelength. We denote r_{ak} (t_{ak}) as the Fresnel reflection (transmission) coefficient at the air-keratin interface and r_{ka} (t_{ka}) as that at the keratin-air interface (Fig. 4 left), and derive the complex thin-film reflection/transmission coefficients r and t via Airy formula [Belcour and Barla 2017; Yeh 2005]

$$r = r_{ak} + \frac{t_{ak}r_{ka}t_{ka}e^{i\Delta\psi}}{1 - r_{ka}^2e^{i\Delta\psi}}, \quad t = \frac{t_{ak}t_{ka}}{1 - r_{ka}^2e^{i\Delta\psi}}, \quad (1)$$

where $\Delta\psi = \frac{2\pi\mathcal{D}}{\lambda} = \frac{4\pi d\eta_k \cos\beta}{\lambda}$ holds for both reflection and transmission, with the index of refraction (IOR) of keratin η_k and the film thickness d . The intensity reflectance is then given by

$$I_R = |r|^2. \quad (2)$$

We call this reflection the *R component*.

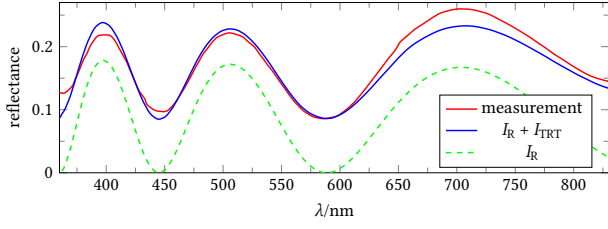


Figure 5: Reflectance spectra of a green barbule as measured with an MSP (red, calibrated with a spectralon), and simulated with (blue) or without (green) the background component.

We measure the reflectance spectra of a $10 \times 10 \mu\text{m}^2$ spot from normal incidence with a microspectrophotometer (MSP) [Vukusic and Stavenga 2009]. Fig. 5 shows the observed wavelength-dependent reflectance and the simulated R component. Evidently, this component alone cannot sufficiently describe the barbule reflectance behavior, as total destructive interference appears at some wavelengths. There is clearly a background component, which is resulted from the light transmitted through the keratin layer, reflected on the melanin layer, then transmitted back through the keratin layer. We call this the *TRT component*, it is illustrated in Fig. 4 (right), and is similarly computed as

$$I_{\text{TRT}} = \left| \frac{t_{\text{am}} t'_{\text{ak}} t'_{\text{ka}}}{1 - (r'_{\text{ka}})^2 e^{i\Delta\psi'}} \right|^2, \quad (3)$$

where r_{am} is the Fresnel reflection coefficient at the air-melanin interface, and the phase shift $\Delta\psi' = \frac{4\pi d \eta_k \cos \beta'}{\lambda}$. The superscript ' takes account of the possibility that the incoming and outgoing directions are non-symmetric. After reflecting on the randomly distributed melanin granules, we do not expect the R and the TRT components to interfere; thus, we simply add their intensities Eq. (2) and Eq. (3) together. Due to the melanin layer's low reflectance of only 5% [Yin et al. 2006], we neglect all subsequent components that involve interaction with the melanin layer. This choice is validated by the similarity of the blue curve to the measurement in Fig. 5.

3.4 Measuring with an Imaging Scatterometer

Above analyses apply to flat thin films; however, the keratin film in a barbule is curved, as shown in Fig. 2c. We deploy the measurement setting designed by [Stavenga et al. 2009], called *imaging scatterometer* (Fig. 6), to measure the influence of the barbule geometry on the reflectance. The resulting far-field scattering image is called a *scatterogram*, which captures the hemispherical reflectance from the sample simultaneously via a digital camera. Examples are shown in Figs. 1b to 1d. The long, pointed, black object at 9 o'clock is the occlusion from the glass micropipette holding the sample. The white circles indicate various scattering angles of ϑ .

We implement in Mitsuba 2 [Nimier-David et al. 2019] a hemispherical sensor looking from all directions at the sphere origin. This delivers equivalent images as scatterograms.

4 MODELING

In accordance with the SEM image, the scatterograms in Figs. 1c and 1d show reflection into a wide solid angle. In particular, the

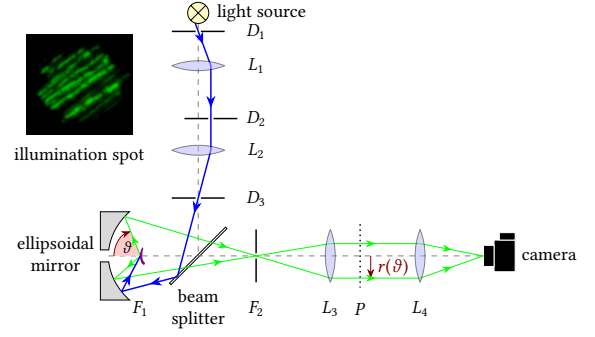


Figure 6: Diagram of the imaging scatterometer. A narrow beam (blue) from a xenon lamp is focused through diaphragms $D_{1,3}$, lenses $L_{1,2}$, the beam splitter together with an ellipsoidal reflector on the sample (purple). Light scattered by the sample into the hemisphere is focused at the second focal point F_2 and delivered to a camera (Canon EOS 30D). D_2 controls the incident angle. Inset: Near-field image of a green barb, showing illumination spot of our scatterograms, about $120 \times 120 \mu\text{m}^2$, covering ~ 30 barbule cells.

iridescent pattern stretches in one diagonal direction, which is the transversal direction of the barbule. In the longitudinal direction, i.e. along the barbule axis, the angular span is much smaller. Besides, the green color in Fig. 1c has a lower intensity than purple; this is caused by the edges of the barbules (denoted by the blue arrows in Fig. 7a), since a surface with a larger curvature reflects the same amount of light to a broader angle. Thus, we model the longitudinal barbule profile to be a small circular section, and the azimuthal profile to be an elliptical section with a larger angular span (Fig. 7).

Due to the relatively large IOR of keratin (~ 1.55 [Leertouwer et al. 2011]), we assume that light travels a relatively small tangential length before contributing to the reflectance, so that the film can be treated as locally flat when computing interference. Thus, we only consider influence of the barbule curvature on the angular span of the reflectance. More discussions on interference from curved thin films can be found in our supplementary document.

In the following subsection, we derive a new reciprocal BSDF.

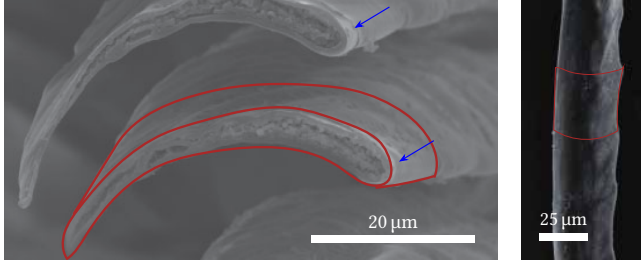
4.1 Elliptical BSDF

The BSDF $S(\omega_i, \omega_o, \lambda)$ describes the relationship between the incoming radiance L_i and the outgoing radiance L_o

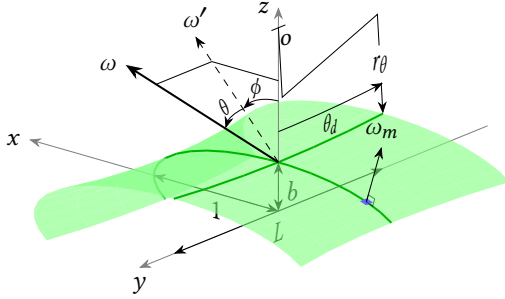
$$L_o(\omega_o, \lambda) = \int L_i(\omega_i, \lambda) S(\omega_i, \omega_o, \lambda) \langle \omega_i, \vec{n} \rangle d\omega_i, \quad (4)$$

where $\vec{n}$ is the normal vector of the overlapping barbule plane (Fig. 8), and $S(\omega_i, \omega_o, \lambda) = S_R + S_{\text{TRT}} + S_T$ sums up the R, TRT and T lobes. This formulation complies with the well-known rendering equation, yet differs from the formulations of fiber scattering models [Marschner et al. 2003; Xia et al. 2020; Yan et al. 2017], where $\cos \theta_i$ instead of $\langle \omega_i, \vec{n} \rangle = \cos \theta_i \cos \phi_i$ is used. This is because their radiance is defined per unit length, while ours is defined per area.

Traditionally, the scattering distribution function S is divided further into the product of the longitudinal scattering function M and the azimuthal scattering function N . However, as argued



(a) SEM images of iridescent dove barbules. Left: cross-section view. The blue arrows indicate the edge of the barbules with a large curvature. Right: front view. Images adapted from [Nakamura et al. 2008], ©2008 The Physical Society of Japan.



(b) A saddle-like unit barbule cell. ω stands for incident, outgoing or normal direction, it is parameterized by spherical angles θ and ϕ , where θ is the angle between ω and the $x-z$ plane and ϕ is the angle from the z axis to the projection of ω onto the $x-z$ plane (ω'). $\omega = [\sin \phi \cos \theta, \sin \phi, \cos \phi \cos \theta]^T$.

Figure 7: SEM image and model of a unit barbule cell.

by [d'Eon et al. 2014], separating S causes significant artifacts at grazing angles. We propose to separate the normal distribution function (NDF) instead, similar to microfacet models.

NDF. A barbule can be considered a periodic structure consisting of an array of saddle-like unit barbule cells, as indicated by the red outlines in Fig. 7a. We model the exposed front surface (Fig. 7b), where the transversal cross-section is represented by an elliptical arc with semi-major axis 1 and semi-minor axis b , and the longitudinal cross-section is represented by a circular section with a radius r_θ and an arc length of $2r_\theta\theta_d$.

The overlapping barbules form a plane (“barb plane”) (Fig. 8) which is the $x-y$ plane of the barbule coordinate system rotated by angle μ around the y axis. The distance between adjacent barbules is denoted as H . The NDF in azimuthal direction is

$$D_\phi(\phi_m) = \frac{1}{H\kappa(\phi_m)} = \frac{b^2}{H} \left(\sin^2 \phi_m + b^2 \cos^2 \phi_m \right)^{-\frac{3}{2}}, \quad (5)$$

where $\kappa(\phi_m)$ is the curvature at $\phi = \phi_m$, $\phi_m \in [\phi_0, \phi_1]$. Dividing by H ensures that $\int D_\phi(\phi_m) \cos(\phi_m + \mu) d\phi_m \leq 1$. The NDF in longitudinal direction is

$$D_\theta(\theta_m) = \frac{1}{2 \sin \theta_d}. \quad (6)$$

Combining Eqs. (5) and (6), we obtain

$$D(\omega_m) = D_\theta(\theta_m) D_\phi(\phi_m) (\cos \theta_m)^{-1} = \frac{b^2}{2H \sin \theta_d \cos \theta_m} \left(\sin^2 \phi_m + b^2 \cos^2 \phi_m \right)^{-\frac{3}{2}}. \quad (7)$$

Eq. (7) satisfies $\int D(\omega_m) \langle \omega_m, \vec{n} \rangle d\omega_m = 1$.

Masking and Shadowing. Diffraction often arises from regularly aligned microstructures. However, the barbule spacing is rather large and irregular, and from Figs. 1a and 5 it is obvious that the most prominent source of iridescence is the thin film. Thus, we apply geometrical optics when considering shadowing and masking.

In previous literature, the correlation between the height and slopes is usually ignored in the geometry term [Smith 1967], so that each normal direction has a certain probability to be visible, independent of the incident and outgoing angles. In our case, however, the relationship between the height and slopes is known, so that each ω_m is either always visible or always invisible, depending on $\omega_{i,o}$. When sampling from or evaluating the NDF, we check on-the-fly if there is an intersection of ω_i or ω_o with the two adjacent barbules. The visibility term $G(\omega_i, \omega_m, \omega_o)$ is either exactly 1 when there is no intersection, or 0 if at least one intersection exists. This term is *reciprocal*. Figure 8 illustrates the visible sections from both ω_i and ω_o in purple. Multiple interreflections are ignored.

S_R : Thin-film reflection. For the R lobe, ω_m coincides with the half-vector between ω_i and ω_o , acting as small mirrors. Consider the differential flux $d\Phi_m$ incident on the differential surface oriented with normal direction ω_m . From the definition of the radiance

$$d\Phi_m = L_i(\omega_i, \lambda) \langle \omega_i, \omega_m \rangle d\omega_i dA(\omega_m). \quad (8)$$

The differential area of the surface with orientation ω_m is

$$dA(\omega_m) = D(\omega_m) d\omega_m A, \quad (9)$$

where A is the projected area of a unit barbule cell onto the barb plane. The outgoing flux is

$$d\Phi_o = I_R(\omega_i, \omega_o, \lambda) d\Phi_m. \quad (10)$$

The differential outgoing radiance over the projected area A_o is

$$dL_o(\omega_o, \lambda) = \frac{d\Phi_o}{d\omega_o A_o}. \quad (11)$$

Combining above equations and the half-angle mapping $d\omega_m = \frac{d\omega_o}{4\langle \omega_m, \omega_o \rangle}$ yields

$$dL_o(\omega_o, \lambda) = \frac{I_R(\omega_i, \omega_o, \lambda) L_i(\omega_i, \lambda) D(\omega_m) A d\omega_i}{4A_o}. \quad (12)$$

The ratio between the projected areas in normal and outgoing directions is

$$\frac{A}{A_o} = \frac{HL}{\cos \theta_o \Delta h(\phi_o) L} = \frac{H}{\cos \theta_o H \cos(\phi_o + \mu)} = \frac{1}{\langle \omega_o, \vec{n} \rangle}, \quad (13)$$

where $\Delta h(\phi)$ is the projected length in direction ϕ (Fig. 8), and L is the length of a barbule cell along the z axis. The value of L is irrelevant as it is canceled out in the equation. Comparing with Eq. (4) and adding the term G , we acquire the BSDF for the R lobe

$$S_R(\omega_i, \omega_o, \lambda) = \frac{I_R(\omega_i, \omega_o, \lambda) D(\omega_m) G(\omega_i, \omega_m, \omega_o)}{4\langle \omega_i, \vec{n} \rangle \langle \omega_o, \vec{n} \rangle}, \quad (14)$$

which is exactly the form of a microfacet BRDF.

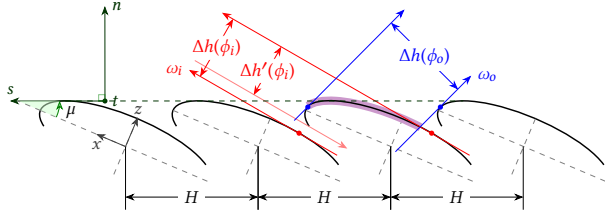
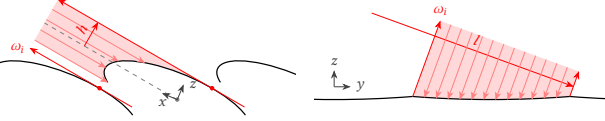


Figure 8: Transverse cross-section of a barb plane.

Figure 9: Uniform sampling of h and l .

S_T : *Transmission through barbule spacing*. At some angles, part of the light rays do not hit the barbule surface (Fig. 8), causing $\int D_\phi(\phi_m) \cos(\phi_i - \phi_m) d\phi_m < \cos(\phi_i + \mu)$. In practice, we always sample from the valid projected length, denoted as $\Delta h'(\phi_i)$. The rays that do not hit the barbule surface is propagated without changing its direction and intensity, giving the T lobe

$$S_T(\omega_i, -\omega_i, \lambda) = 1 - \frac{\Delta h'(\phi_i)}{\Delta h(\phi_i)}. \quad (15)$$

S_{TRT} : *Background component*. As seen in Fig. 2c, the melanin granules scatter the light into even wider angles. We model the melanin layer as a diffuse surface due to its irregular distribution. The BSDF for the TRT component is

$$S_{TRT}(\omega_i, \omega_o, \lambda) = \frac{\rho(\omega_i, \omega_o, \lambda)}{\pi}, \quad (16)$$

where

$$\rho(\omega_i, \omega_o, \lambda) = \frac{1}{A_i} \iint I_{TRT}(\omega_i, \omega_m, \omega_o) dh dl \quad (17)$$

is the reflectance averaged over the illuminated projected area A_i . h, l are the azimuthal and longitudinal offsets seen from the illumination direction, respectively (Fig. 9). Since ω_m is a function of h and l , the above equation is impractical to solve analytically. We compute the integral implicitly by randomly picking h and l at each evaluation.

4.2 Implementation

In this section, we provide the implementation details of our model, including geometry modeling using the software package Houdini and rendering with Mitsuba 2 using scalar_spectral variant.

Geometry Modeling. In Houdini, we model a feather as a collection of barb curves (Fig. 10a), as in usual feather grooming pipelines [Haapaoja and Genzwürker 2019]. The vertices with their normal directions and other customizable parameters are exported as a .ply file. The geometry is read by a custom feather shape plugin in Mitsuba 2, which generates barb primitives (Fig. 10b). The BSDF described in Section 4.1 is applied on these barb primitives, the local shading frame coincides with the local barb plane (Figs. 8 and 10b).

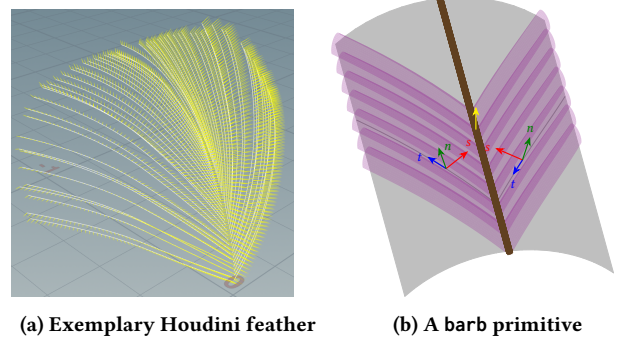


Figure 10: Explicit geometry in Houdini (a) and implicit geometry in Mitsuba 2 (b). The barb curves are represented by vertex chains (white in a) with assigned vertex normals in yellow. Our barb primitives are modeled as an extrusion of a circular arc (gray). Barbules (purple) and ramus (brown) are illustrative only, their geometry is not modeled in the primitive. s, t and n form the local shading coordinate system.

Importance Sampling. Our sampling strategy is similar to [d'Eon et al. 2013]: first, the azimuthal offset h and the longitudinal offset l are uniformly sampled (Fig. 9), then one of the three lobes is chosen proportional to their energy. The probability density function (PDF) for the R lobe is computed the same as in micro-facet models, whereas that for the TRT lobe is the same as for a diffuse surface. The complete sampling procedure is stated in Algorithm 1.

ALGORITHM 1: Importance Sampling Barbule BSDF

Output: pdf, ω_o , sample value
sample valid h and l and compute $\omega_m(h, l)$;
calculate $I_R(\omega_i, \omega_m)$ according to Eq. (2);
sample ω_o^{TRT} from the cosine-weighted upper hemisphere around $\vec{n}$;
 $\omega_o^{TRT} \leftarrow \text{sgn}(\omega_m, \omega_o^{TRT})$;
calculate $I_{TRT}(\omega_i, \omega_m, \omega_o^{TRT})$ according to Eq. (3);
generate uniform random sample $\xi \sim [0, I_R + I_{TRT} + \Delta h_i / \Delta h'_i - 1]$;
if $\xi < I_R$ **then** /* choose R lobe */
| $\omega_o = \text{reflect}(\omega_i, \omega_m)$; pdf = $0.25 I_R D(\omega_m) / \langle \omega_i, \vec{n} \rangle$;
else if $\xi < I_R + I_{TRT}$ **then** /* choose TRT lobe */
| $\omega_o = \omega_o^{TRT}$; pdf = $I_{TRT} |\omega_o \cdot z| / \pi$;
else /* choose T lobe. */
| $\omega_o = -\omega_i$; pdf = $\Delta h_i / \Delta h'_i - 1$;
end
if sample position visible from ω_o **then**
| pdf /= $I_R + I_{TRT} + \Delta h_i / \Delta h'_i - 1$;
| sample value = $(I_R + I_{TRT} - 1) \Delta h'_i / \Delta h_i + 1$;
else
| reject sample;
end

5 RESULTS AND COMPARISON

In this section, we compare our rendered results with the measurements. The source code is available at https://github.com/RiverIntheSky/dove_neck.

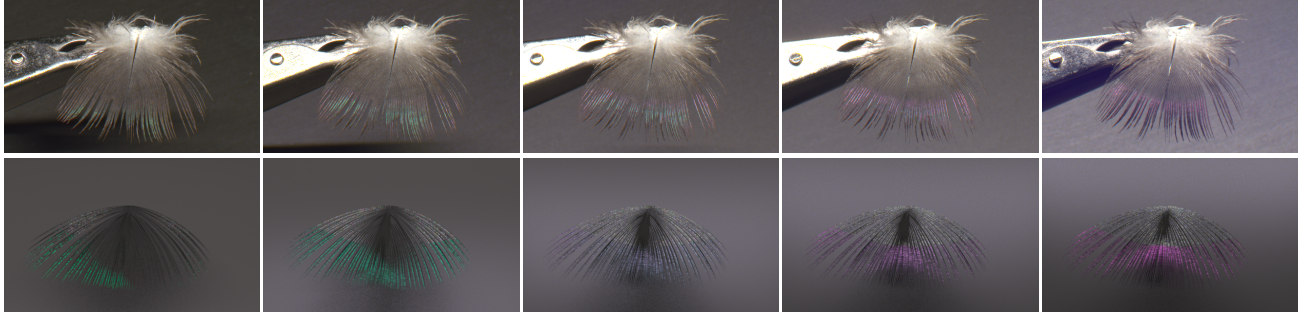


Figure 11: Comparison between calibrated photographs (top) and renderings with comparable light and view (bottom). The only linear light source (illuminant E) has inclination angles range from 0° to 60° from left to right. The non-iridescent parts of the barbs (invisible on the neck since feathers are overlapping) are approximated with a thicker film.

5.1 Comparison with Scatterograms

Rock dove neck feathers were collected from a frozen dove. We removed one green barb from a neck feather and investigated the scattering with the scatterometer. The colors are not calibrated.

In Figs. 1b to 1d, the scatterograms are compared with our BSDF renderings. The parameters are manually chosen to fit the scatterograms: $b = 0.25$, $\phi_0 = -0.37$, $\phi_1 = 2.64$, $H = 1.25$, $d = 590$ nm, $\theta_d = 0.0785$, $\mu = -0.35$. We conduct an ablation study of the effect of each of those parameters in the supplementary document.

In Fig. 1b (top), the sample is illuminated omnidirectionally by removing diaphragm D_2 , which we replicate in the renderer with a constant emitter. The green color in the inner ring indicates the reflectance around normal incidence, whereas oblique incidence angles (the middle ring) produce purple color. At grazing angles, the reflectance approaches 1; as a result, the barbule looks yellowish and bright. These characteristics are all predicted in Fig. 3 and reproduced in Fig. 1b (bottom). The darker region in the lower-left part of the scatterogram is also present in our rendering, which is due to the inclination of the local barb plane. We believe that the reflectance in this region does not fall off completely because of random perturbations of the barbule orientations: they do not align perfectly to a flat surface on a larger scale. We choose not to model the randomness in the BSDF term, but rather to add a random noise in the orientation μ of the unit barbule cells when exporting the barb curve geometry, as the influence of these perturbations is also visible on a macroscopic level (Fig. 11).

In Figs. 1c and 1d, the scatterograms (top row) were illuminated from an angular aperture of about 16° ; for the renderings (bottom row), we achieve an equivalent illumination with a disk area light. The stretching in the transversal direction, the transition between green and purple, and the lower intensity in the upper-right part are all well captured in the rendering. The large round background is the TRT component; its color is mostly brownish due to the reflectance of the melanin granules; however, there are also faint iridescent colors in the background. More precisely, the color is purple near the center and green near the periphery, exactly the reversed order as the R component. This is because when the reflected color is green, the transmitted color would be its complement, which is purple and vice versa. Our TRT lobe model follows this behavior. Also, the

diffuse assumption of the melanin layer seems appropriate, as both scatterogram and rendering show similar intensity gradients that turn almost invisible toward the outer ring.

5.2 Comparison with Photographs

We further measure a rock dove neck feather in a calibrated appearance scanner TAC7 [X-Rite 2021]. The device contains several radiometrically calibrated cameras and light sources. We use a camera observing the feather from 45° inclination and a series of light inclination angles. The resulting images in Fig. 11 are HDR-combined, calibrated and converted to linear sRGB. The renderings are obtained by modeling a similar scene in Mitsuba 2, with the feather geometry coarsely matched against the real sample. The color shifting, the glints and the irregularities are well reproduced.

5.3 Performance

Figure 1e shows a scene with 256 overlapping feathers (including 1032192 barb primitives), rendered with 256 samples per pixel and a resolution of 1024×768 . The image took 8.3 min to render, $2.1\times$ slower than rendering the identical geometry with plain thin films implemented by [Belcour and Barla 2017].

6 CONCLUSION AND FUTURE WORK

In this paper we have presented a novel framework for rendering feathers. We measure the BSDF of a feather barb from several illumination angles with a scatterometer, based upon which we design a parameterized BSDF. It is straightforward to sample and compatible with existing rendering pipelines for feathers.

Although the transversal cross-section is restricted to be elliptical in our work, the same idea could be applied to barbules of other shapes. In fact, any convex cross-section with C^2 continuity has a continuous curvature and produces a continuous NDF. This amounts to changing D_ϕ in Eq. (5). Roughness in the cortex is not a part of our model, as the barbule surface is very smooth. A modification in the NDF can be applied to achieve roughness if needed.

Our work only focuses on rendering the barbules, as their reflectance is the most prominent on rock dove feathers. For some birds, the structural colors instead originate from a sponge-like

structure of the ramus [Parnell et al. 2015; Stavenga et al. 2011b; Tinbergen et al. 2013] which is currently not considered by our model and could be covered in future work. Another potential extension would be the combination of iridescent and non-iridescent barbules, the latter ones being sometimes more opaque and possibly in need of further shading lobes.

As the measuring device was originally only designed for observational purposes, the colors are not properly calibrated. In the future, a full spectral calibration and an automated parameter fitting procedure could make the model more accurate and versatile.

ACKNOWLEDGMENTS

This work was supported by the European Research Council under ERC Starting Grant “ECHO” (802192).

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