A Fiber-Level Appearance Model For Cloth

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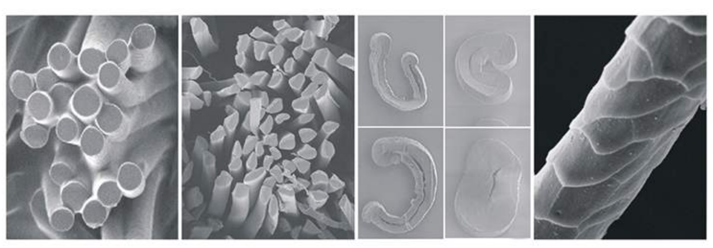
Render the Possibilities

Reproducing the appearance of cloth remains challenging due to the micro-structures found in textiles, and the complex light scattering patterns exhibited at such scales. Recent approaches have reached very realistic results, either by directly modeling the arrangement of the fibers [Schröder et al. 2011], or capturing the structure of small pieces of cloth using Computed Tomography scanners (CT) [Zhao et al. 2011]. However, existing methods either rely on manually-set parameter values, or use photographs of real pieces of cloth to guide appearance matching algorithms, often assuming certain simplifications (e.g. elliptical cross sections for fibers, or homogeneous volume density). Our model builts upon precise measured data, including geometric properties as fiber density, cross section, surface roughness or volumetric structure, as well as optical properties such as index of refraction and absorption, modeled as a function of the type and concentration of dye. We build digital replicas with the same structural and optical properties as their real counterparts, leveraging the wealth of measured, real-world data available from the textile research community, and explicitely compute light transport within them to build highly-detailed scattering functions. Then, we use the BCSDF to render the appearance of cloth as a volumetric model [Jakob et al. 2010]. Since volumetric representations of cloth present a strong structure at a sub-voxel level, we account for it by introducing in graphics a theoretical framework for *light transport in structured media*, which we adapt for the specific case of cloth. Our model is able to account for the statistical structure within a voxel, being able to match more faithfully the light transport in this special case of media, including the observable *longer-than-exponential* transmittance that cannot be predicted by the Beer-Lambert law.

Physical Properties of Fibers

Most cloth fibers are made up of dielectric materials surrounding an absorbing medium, whose shape has been traditionally modeled as a cylinder extruded from elliptical cross sections. However their actual shape differ greatly from these simplifications, and depends on the type of fiber (wool furthermore presents overlapping, tilted scales on its surface). All these features together lead to visually important reflectance features such as self occlusions or caustics, which cannot be fully simulated with current Bidirectional Curve Scattering Distribution Functions (BCSDF).



◁ ***Cross-section and structure*** *Images from textile research community, captured with a Scanning Electron Microscope (SEM) of real polyester, silk, cotton and wool fibers. Analyzing this kind of images, we manually modeled a representative set of different cross sections for each type of fiber, since it greatly affects the optical properties of cloth [Bueno et al. 2004].*

▷ *Measurements of the physical and optical properties acquired from the textile literature [Hearle and Morton 2008, Gillberg and Kemp 1981]. To render cloth, most previous works have attempted to model the optical parameters using a top-down approach, either directly defining the fiber color [Jakob et al. 2010; Schroder et al. 2011], or matching a specific appearance through optimization [Khungurn et al. 2015]. Instead, we opt for a bottom-up approach, defining fiber appearance from real-world low-level structural and chemical data. To model the absorption, we introduce the concentration of the dye used to color the fibers, including the specific ones used in industry for different types of cloth. Thus, we avoid absorption values out of the range of actual fabrics or artifacts like colored specular reflections, present in previous works.*

Type	Diameter μm	Density g/cm^3	IOR $\eta_\parallel, \eta_\perp$	$R_a\ (l)$ nm	β degrees
Polyester	10	1.39	1.73, 1.54	2.33-5 (30)	2.7-3.5
Silk	5-10	1.34	1.591, 1.538	8-9 (30)	6-7
Cotton	17-20	1.52	1.578, 1.532	12.5-15.8 (50)	14-17
Wool	24-40	1.31	1.553, 1.542	6 (40)	5

△ *Images under the microscope of a real silk thread of 3 plys, each composed by 90 fibers. The most right image shows how a single fiber has very low absorption, but the cumulative effect of each of the 90 fibers per ply gives the thread its overall yellowish color.*

Surface roughness The fibers' dielectric boundary presents roughness at nanoscopic scale [Walter et al. 2007], which prevents us from using directly the Fresnel equations. We model surface roughness following a microfacet-based approach, where the average angle β of the microfacets is modeled as a Beckmann distribution. A simple V-cavity model works well for the range of fibers shown here. The average nanofacet orientation is thus modeled as $\beta = \arctan(R_a/l)$, where R_a is the average peak-to-valley height, and l is the profile length (both in nm).

Absorption Absorption inside the fiber plays a crucial role on its appearance [Hearle and Morton 2008]. We compute the absorption coefficient μ_a [m^{-1}] based on the amount of dye and its particular absorption as $\mu_a = \kappa\varepsilon$, where κ is the dye concentration [g l^{-1}], and ε is the extinction per gram [l g^{-1} m^{-1}]. The latter is given by $\varepsilon = \varepsilon_m w^{-1}$, with ε_m the molar extinction coefficient in m [l mol^{-1} m^{-1}], and w_m the molar weight of the dye [g mol^{-1}]. We model the dye concentration κ as a function of the fibers' density ρ [g l^{-1}], and the depth of shade (DoS) ζ, as $\kappa = \rho\zeta$. The DoS ζ is a quantity used in industry for controlling the saturation of dyed cloth, which is the ratio of grams of dye to grams of fiber (ranging from 0.1% for pale shades to 4% for deep shades). We choose two of the most common dyes suitable for a very wide range of commercial fabrics, reactive and disperse.

A Structured Volumetric Model for Cloth

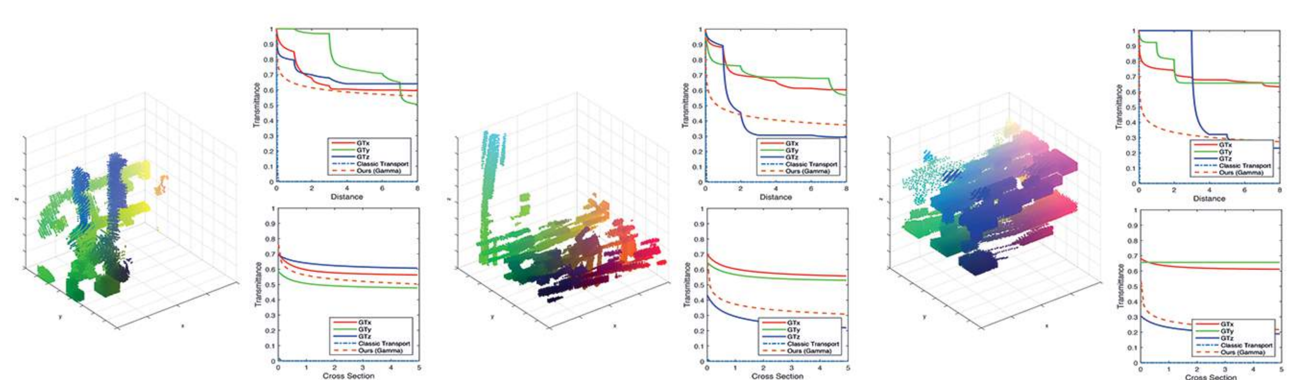
We adopt a statistical volumetric model, by voxelizing the spline-based description of the fibers. Previous works assume a uniform distribution of fibers within each voxel. However, cloth fibers form a highly-structured, non-uniform medium, which has a significant effect on light transport within the volume. We leverage advances in computational transport outside computer graphics, in fields like atmospheric sciences [Newman et al. 1995], and present a new formulation of the radiative transfer equation (RTE) which takes into account the effect of locally structured media.

Assuming a homogeneous medium with an average extinction coefficient μe, transmittance can be computed analytically from the Beer-Lambert law as $T_R(x, y) = \exp(-\mu_e \cdot d)$, with $d = |x - y|$. However, this exponential attenuation model does not hold in the presence of local spatial structure. We propose to model the effect of local structure statistically as a function of the distribution of the extinction coefficients μ_e within each differential volume [Davis and Xu 2014]; intuitively this means that locally the particles are not uniformly distributed, but forming groups. Modeling the distribution as a probabiltiy distribution function, we model the transmittance as:

$$\widehat{T_r}(\mathbf{x},\mathbf{y}) = \int_0^\infty \exp(-\mu'_e \cdot d) p(\mu'_e) d\mu'_e$$

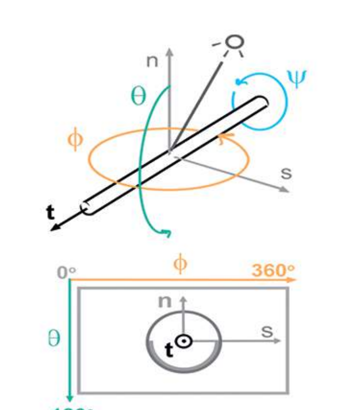
By extensively analyzing histograms of the concentration in cloth voxels, we observed that a gamma distribution $\Gamma(\alpha, \beta)$, with parameters $\alpha = \mathrm{Mean}(\mu_e)^2\,\mathrm{Var}(\mu_e)^{-1}$ and $\beta = \mathrm{Mean}(\mu_e)\,\mathrm{Var}(\mu_e)^{-1}$ its well the distribution of concentrations at each voxel. By using the moment generating function of the gamma distribution, the expression of transmittance has a closed form solution as:

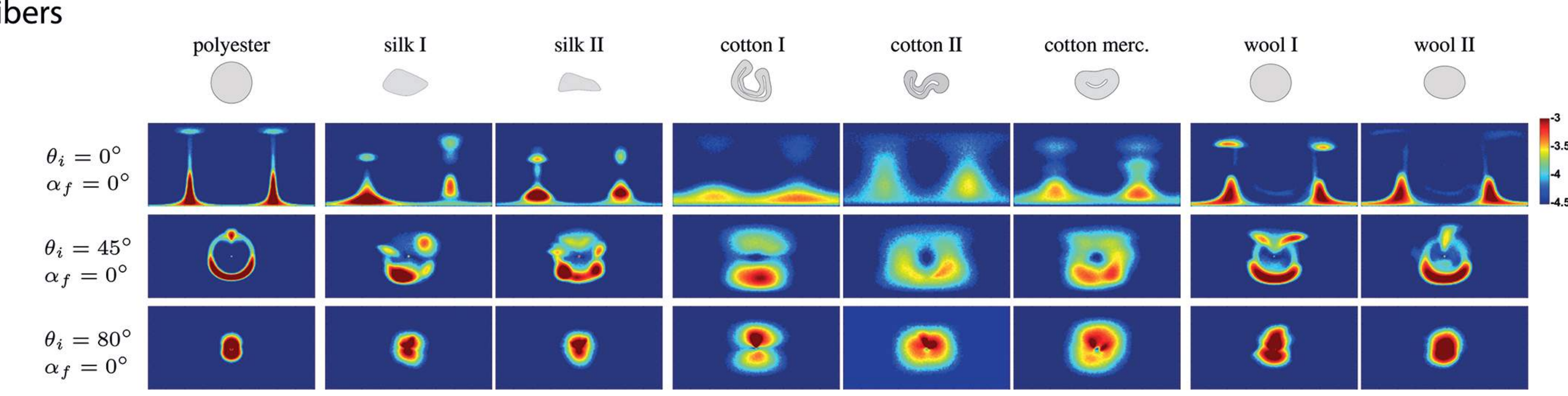
$$\widehat{T_r}(\mathbf{x},\mathbf{y}) = \left(1 + \frac{\overline{\sigma_e}(\omega_o) \cdot d}{\beta}\right)^{-\alpha}$$



△ *Three example voxels of cloth that exhibit strong structure due to the fibers (color codes position in space, for better depiction of the volumetric structure). Both previous work (classic transport) and ours consider the voxel to be statistically invariant, but previous work models the distribution of particles as uniform, which significantly overstimates thee extinction along the volume for all, but very small particles (in our case fiber segments) cross section (bottom plots). This results in a exponential energy decay with distance (top plots). On the other hand, our method models the structure within the voxel by accounting the distribution of different extinction coefficients in the volume. This allows us to better model the total extinction of the voxel for the full range of particles cross sections (bottom plots), matching the longer-than-exponential extinction with distance in the actual volume (top plots). The ground truth transmittance GTx, GTy and GTz is computed using explicit tracing in the volume along the x, y and z axes, respectively.*

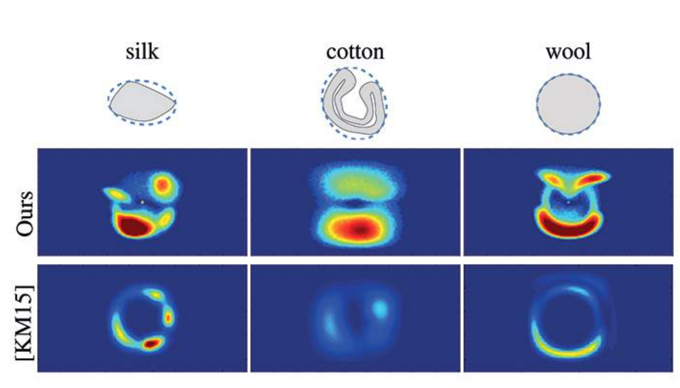
Light Scattering from Fibers





△ ***Left, top:*** *spherical coordinates and local frame defined for the fiber, aligned along the t axis.* ***Left, bottom:*** *illustration of coordinate system and shape of lobes observed in the scattering plots; circle in the middle is the reflection cone under illumination angle $\omega_i = \{0°, 45°\}$.* ***Right:*** *Outgoing field of the BCSDF for a set of cloth fibers with under varying illumination setups, with false color depicting radiance in logarithmic space. From left to right: polyester, silk, cotton and wool, each with several different cross-sections (top), equalized in diameter for visualization purposes. Each fiber is softly dyed ($\zeta = 0.1\%$). Note that the cross section of mercerised cotton (cotton merc.), which is a typical treatment of this fiber to gain luster, is very different from untreated cotton. From top to bottom, the incident light varies from perpendicular direction to near grazing illumination angle $\theta i = 0°, -45°, -80°$ respectively, and $\varphi_i = 0°$, and the fiber is rotated along its tangent direction by $\psi = 0°$ and 90°.*

△ *Effect in our model of the DoS ζ used to dye the fibers, in particular, the scattering of a silk fiber (see cross-section on the inset on the left) lit from $\omega_i = \{0°, 45°\}$ with an orange dye with a different ζ parameter, from left to right, from very a pale to a very deep DoS (μ_a = 5.08, 40.46 and 84.68 mm^{-1}). While the reflection cone remains uncolored (specular reflection), it can be seen how the colored lobes increase in saturation when the amount of dye increases. Since the silk fibers are thin, note also that the refraction lobe remains sofly colored even for deeply dyed fibers (right).*



◁ *Comparison between our BCSDFs (top) and the results predicted by Khungurn and Marschner's elliptical fiber model [2015] (bottom), for fibers of silk, cotton and wool, illuminated by a beam of light with incoming direction $\theta_i = 45°$. We use the best physical fit of Khungurn and Marschner's model, by setting the same or closest fiber parameters - roughness, bounding ellipse and diameter, cuticle slope, etc.- to match the fiber's real parameters (bounding ellipses are rotated accordingly). As shown, the elliptical cross section is unable to capture the complexity of realistic fiber reflectances.*

△ *Volumetric rendering of a scarf using the anisotropic micro-flake phase function [Jakob et al. 2010] (with std. dev. 0.05) (left) vs one of our phase functions of polyester fibers (right). Apart from the fact that our polyester phase function is directly related with the real properties of the cloth, it presents richer anisotropic highlights than the micro-flake counterpart.*

Vizualizing slices of the computed BSDFs for a set of fibers of polyester, silk, cotton and wool, the reflectance of each fiber presents clear differences. While the BCSDF in polyesteris rotation-invariant and exhibits uniform high-frequency lobes due to sharp reflection and caustics on the cone of reflection, other fibers (specialy natural ones) yield much heterogeneous and anisotropic scattering profiles, highly dependent on the cross-section and the incident light direction ω_i. Silk for instance exhibits sharp, highly anisotropic caustics due to its flat irregular shape. Instead, cotton presents wider lobes due to its higher surface roughness, its inside hole, and the multiple self-intereflections within the fiber boundaries, specially in the case of non-mercerized fibers. Finally, the reflectance of wool is more similar to perfect cylindrical fibers (e.g. polyester) due to the low eccentricity of its cross section, but presents a set of high-frequency anisotropies due to the irregular cuticle variation along the longitudinal axis. In addition, the depth of shade has a strong impact on appearance. As we increase the amount of dye, the saturation in transmitted components affected by transport inside the fiber (scattering orders higher than one) increases. Moreover, the effect of higher-order scattering (e.g. order 3) gets dimmer due to higher absorption resulting in more energy losses.

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