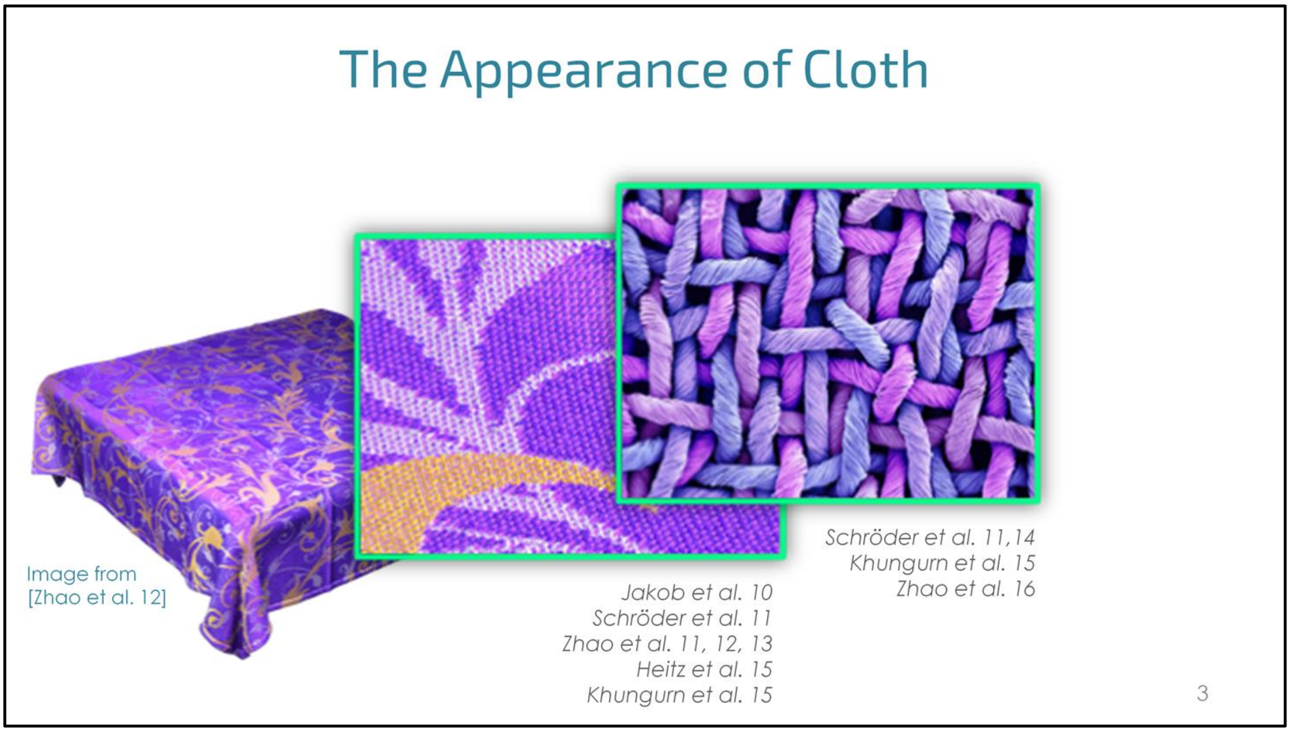
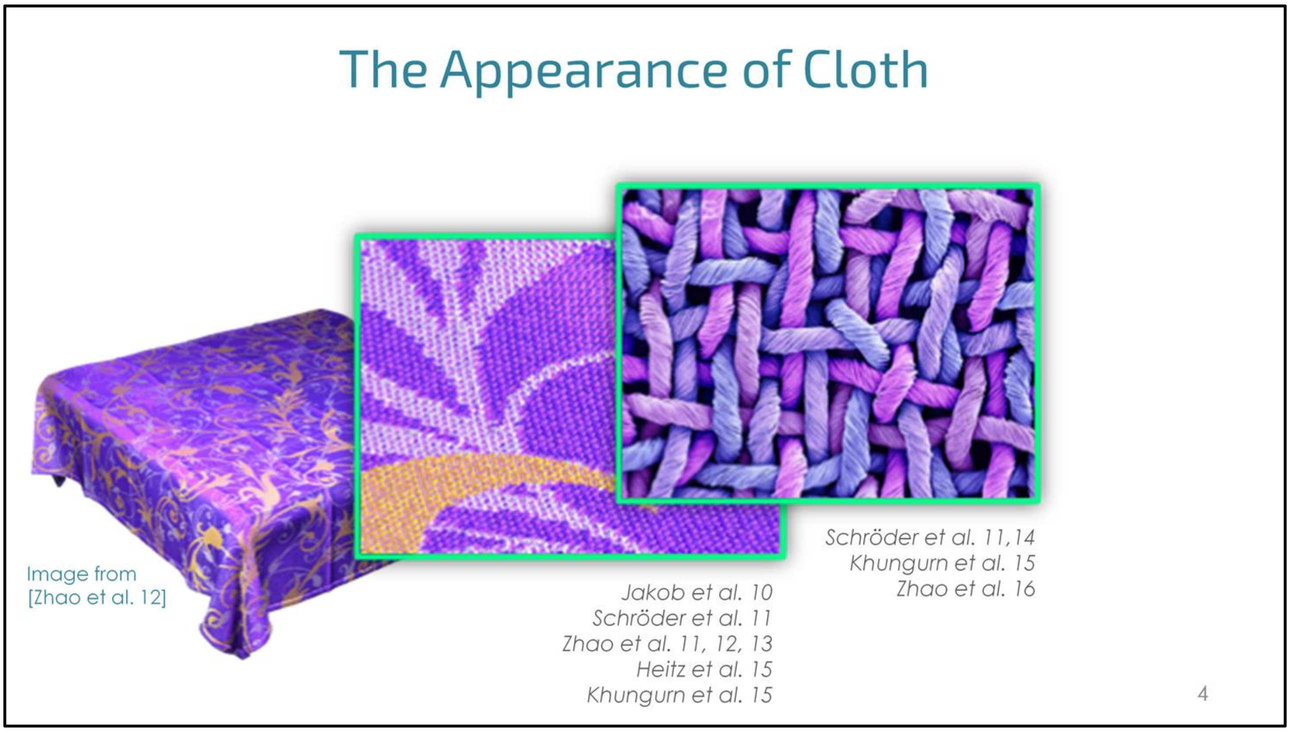
In this paper we present a novel approach to accurately modeling the appearance of cloth fibers

Creating photorealistic cloth is challenging, due to the great amount of different types of fabrics.



And specially because of the multi scale nature of cloth,
and its complex interaction with light.

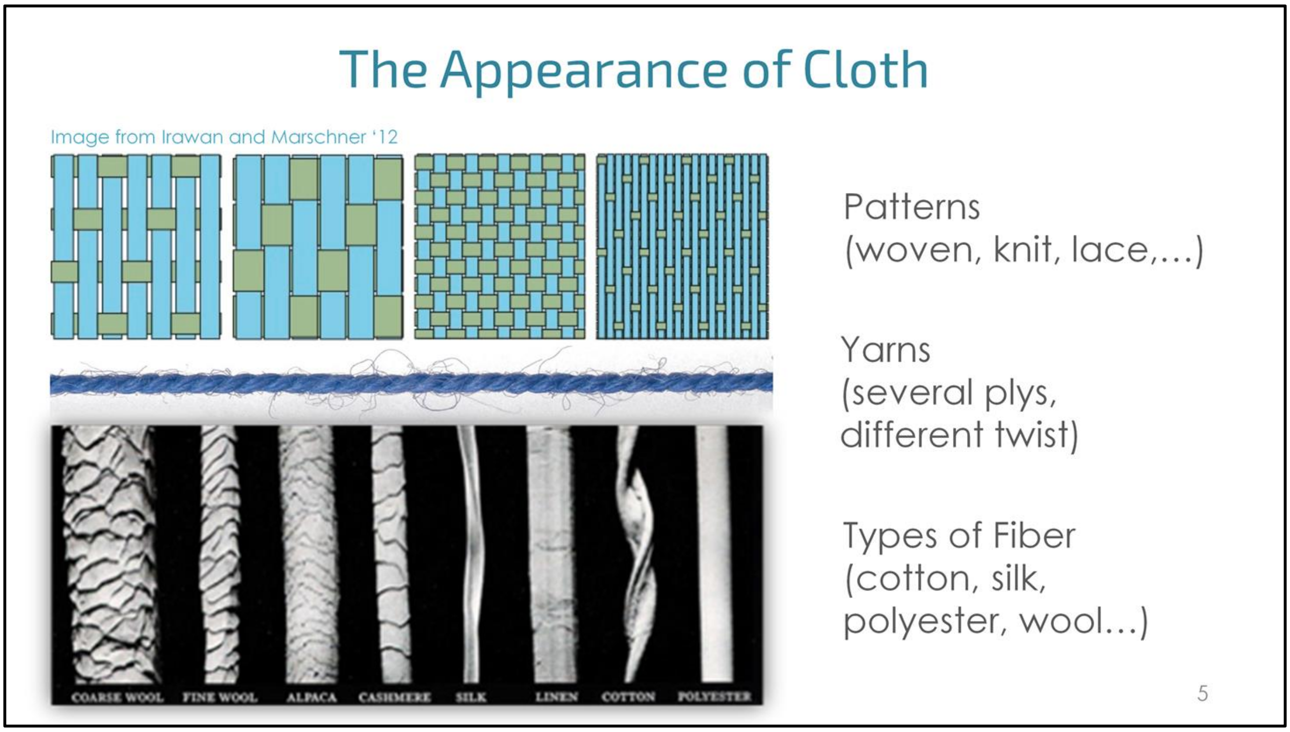
Much effort has been done to reach this level of detail to accurately modeling the appearance of cloth,
up to mesoscale,
and also at the scale of the fibers and yarns.



And this is because we know the appearance of cloth is determined by its micro-structures,

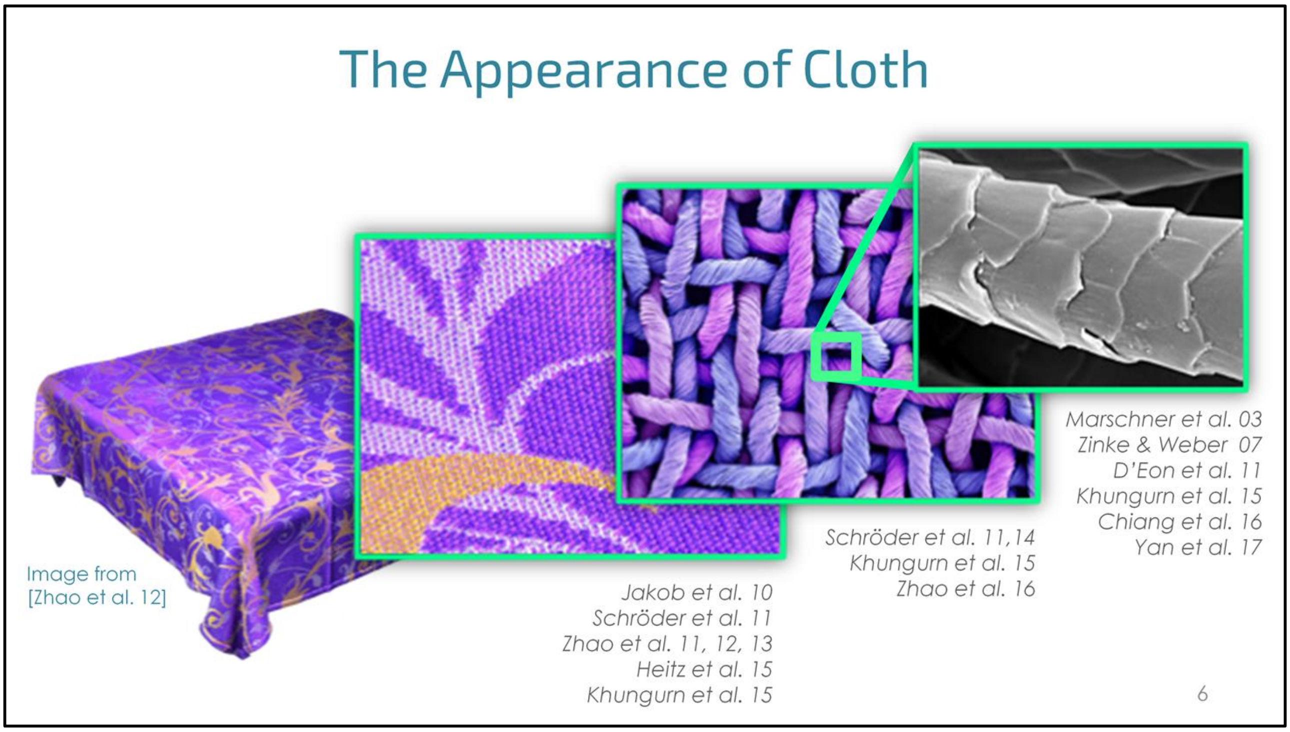
not only at close ups, but also at longer viewing distances,

where the overall apperance is the result of the cumulative effect of light scattering at the smallest building blocks.



In addition, the **structures found at different levels** can be **aggregated** in many different ways:

there are infinite types of
patterns,
yarns,
and **fibers**.



However, the **light interaction** at the **scale of fibers** has been traditionally **over simplified**.

There are **many models** but usually centered **in hair and fur**,
so they are often **disconnected** to the real properties of textile fibers and cloth manufacturing parameters.

Decisions when Simulating Cloth Appearance

Modeling Cloth Structure

Geometric Representations

Light Scattering Models

Model Parameters Definition

7

So, simulating cloth appearance remains very challenging in practice,
and there are several key decissions that need to be taken.

Those decissions are mainly:
How to model the structure of cloth
Which geometric representation choose
Which light scattering models use
And
How to define the parameters of the model.

Modeling Cloth Structure

Much progress to **reach very small scales:**

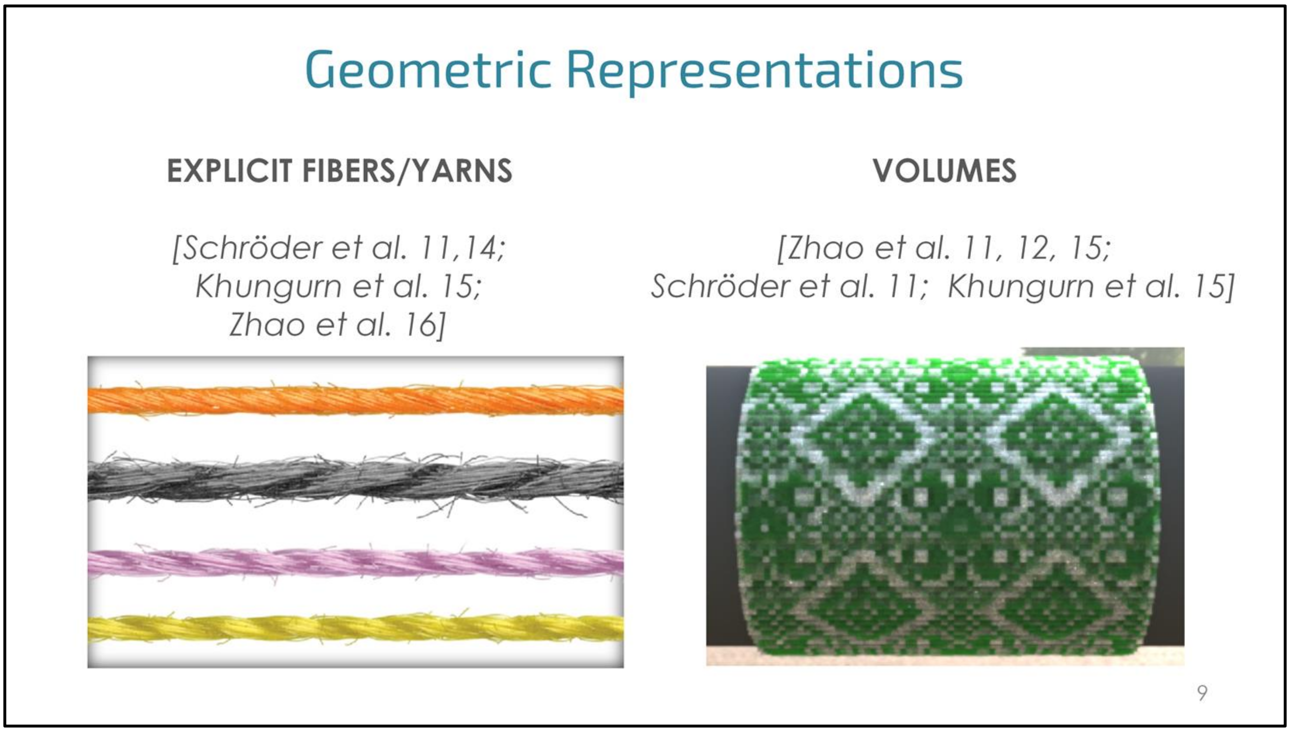
8

As said, much progress has been done to reach very small scales

[click] Either by procedurally modeling the fibers and yarns, like the work from Schroder and colleagues

[click] Or capturing cloth volumes, like the works from Zhao et al.

Both produce very realistic results,
but the former requires costly acquisition devices,
like micro CT scanners, for capturing small volumetric pieces of cloth.



Either if we generate or capture the cloth,

[click] Cloth can be represented by explicit fibers or yarns

[click] or as voxel aggregates,
later rendered as heterogeneous participating media.

A recent work from Khungurn and colleagues demonstrated that both approaches can offer similar quality.

Light Scattering Models

microflake phase function
*[Jakob et al. 10 ;
Zhao et al. 11;
Heitz et al. 15]*

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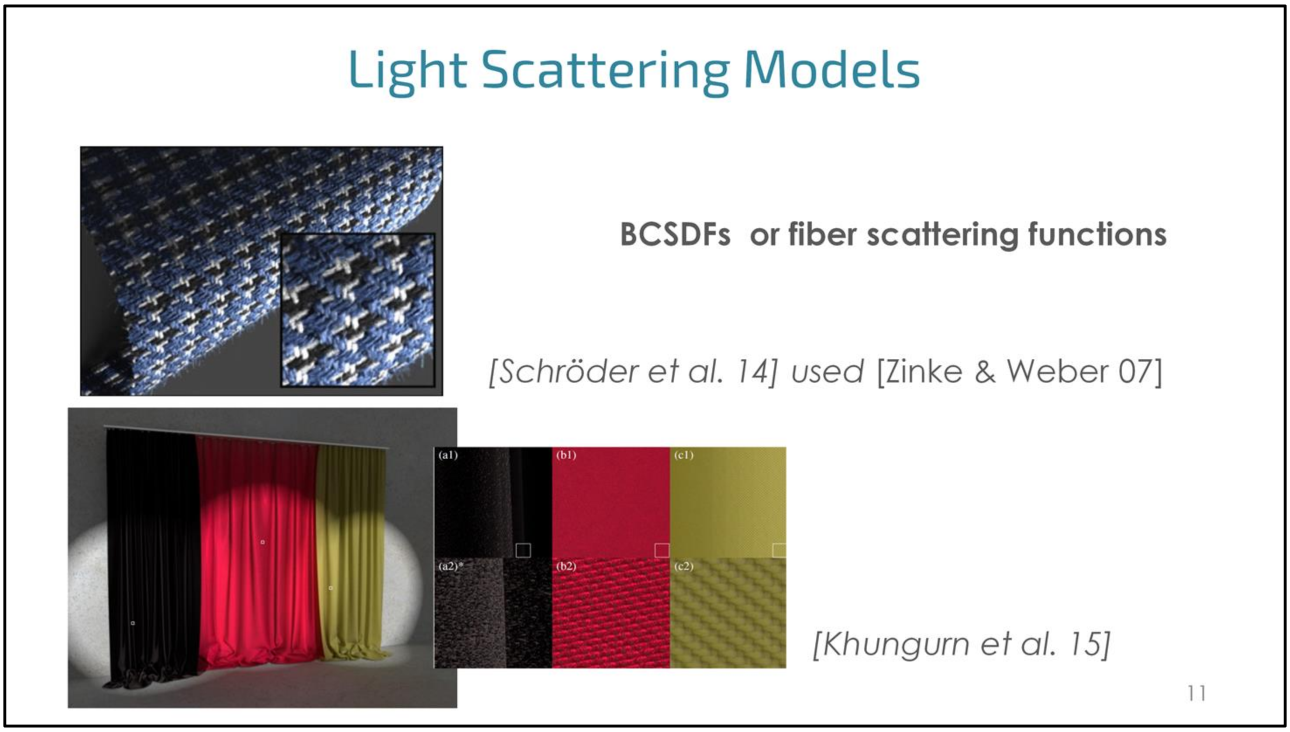
Another important choice is the light scattering used to render the cloth

A common approach is to use anisotropic phase functions like the microflake model or derived ones.

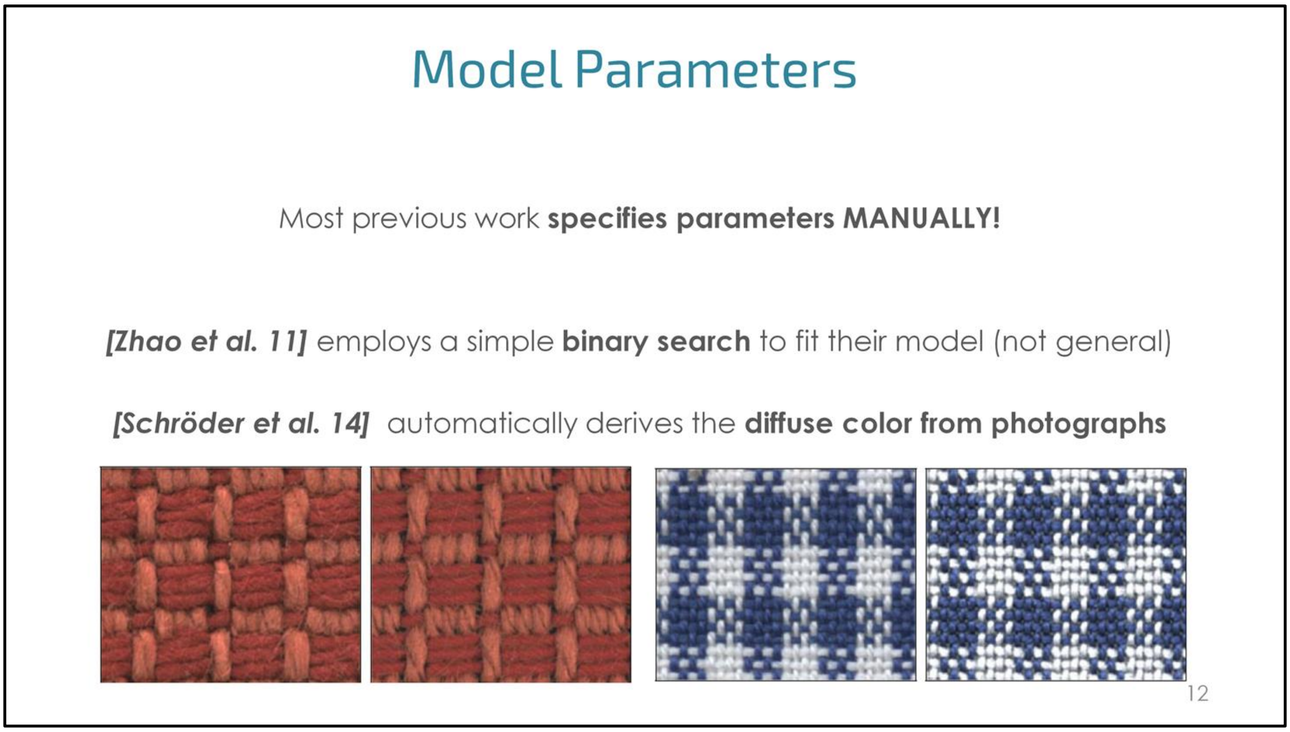
But the same work from Khungurn and colleagues already showed it’s not suitable for reproducing the appearance of cloth,
specially at grazing angles.



On the other hand, fiber scattering models or BCSDFs can be used instead.

Schroder used the model of scattering from filaments, from Zinke and Weber
Khungurn and other subsequent works used a simplified version.

Or we can even use any fiber scattering model,
even those used for hair, like d’Eon and colleagues.



Another decission when modeling cloth is how to specify the paramters of the models.

[click] Most previous work specifies the parameters manually

[click] Others like Zhao and colleagues use a binary search to fit their model, but it’s not general enough

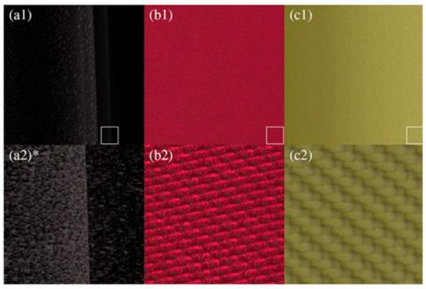
[click] The inverse-engineering approach by Schroder et al. only obtains the diffuse color from photographs,
requiring many other parameters to be set manually

Model Parameters

[Khungurn et al. 15]

Rely on **image-based optimization** to fit model parameters

Fiber scattering model over simplified to ease the process



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And the most recent approach in that sense is presented by Khungurn and colleagues,
who rely **on image-based optimization to fit** model parameteres.

It's relevant to note that **this work demonstrated**…
that using **an accurate fiber scattering model is crucial** for reproducing the appearance of cloth.

Open Problems

Light Scattering Models over simplified

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So, summarizing, one of the **common problems**
is the use of **over simplified scattering models**.

Some of these models are very powerful in image based optimization pipelines, where the ultimate goal is to fit renders to photographs.

But they are not suitable when aiming for a bottom-up approach.

Open Problems

Light Scattering Models over simplified

Model Parameters Definition. Disconnection with real properties

Lack of bottom up definition

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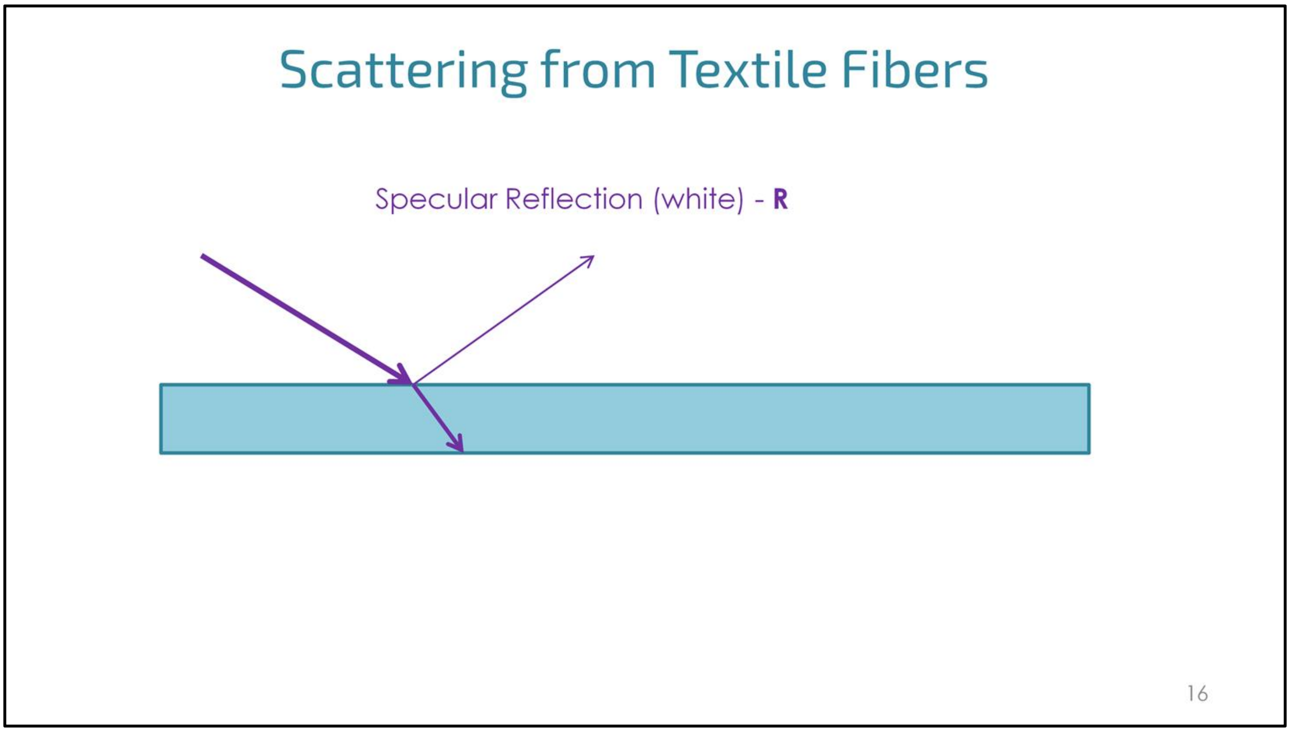
Another common issue is the fact that parameters are set manually or require costly optimizations.

[click] Also, there is no direct relationship between the parameters used in rendering and the actual properties of the fibers
or the fabrication parameters.

This paper focuses on developing a light scattering model from that perspective, relying on actual physical and optical measurements of real textile fibers,

That is, it represents a first attempt for a bottom-up definition of cloth appearance.

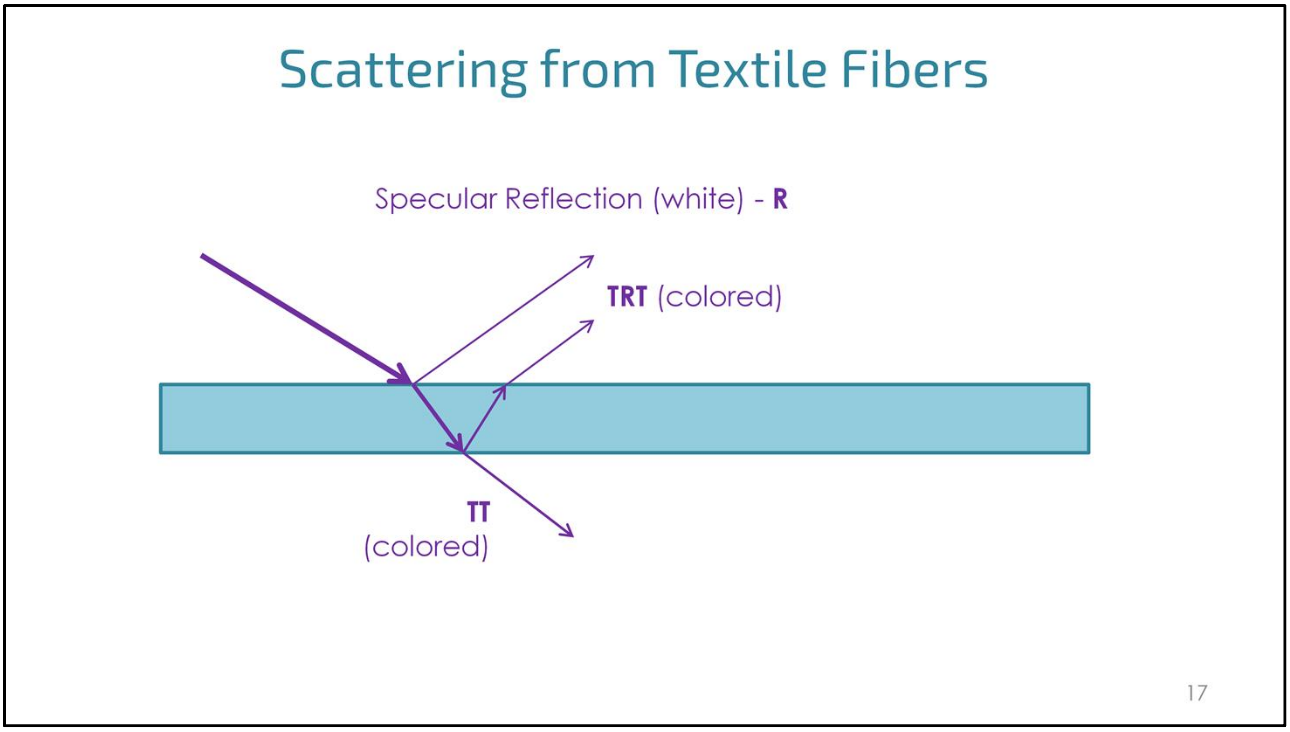


First, let’s see how **light interacts with cloth fibers** [click]

When a beam of light **hits the surface** of the fiber, **part is reflected**,
and that’s the specular reflection, often called R.

This is determined by the **index of refraction** and the **surface roughness**,
and both properties are **different for each type of fiber**.

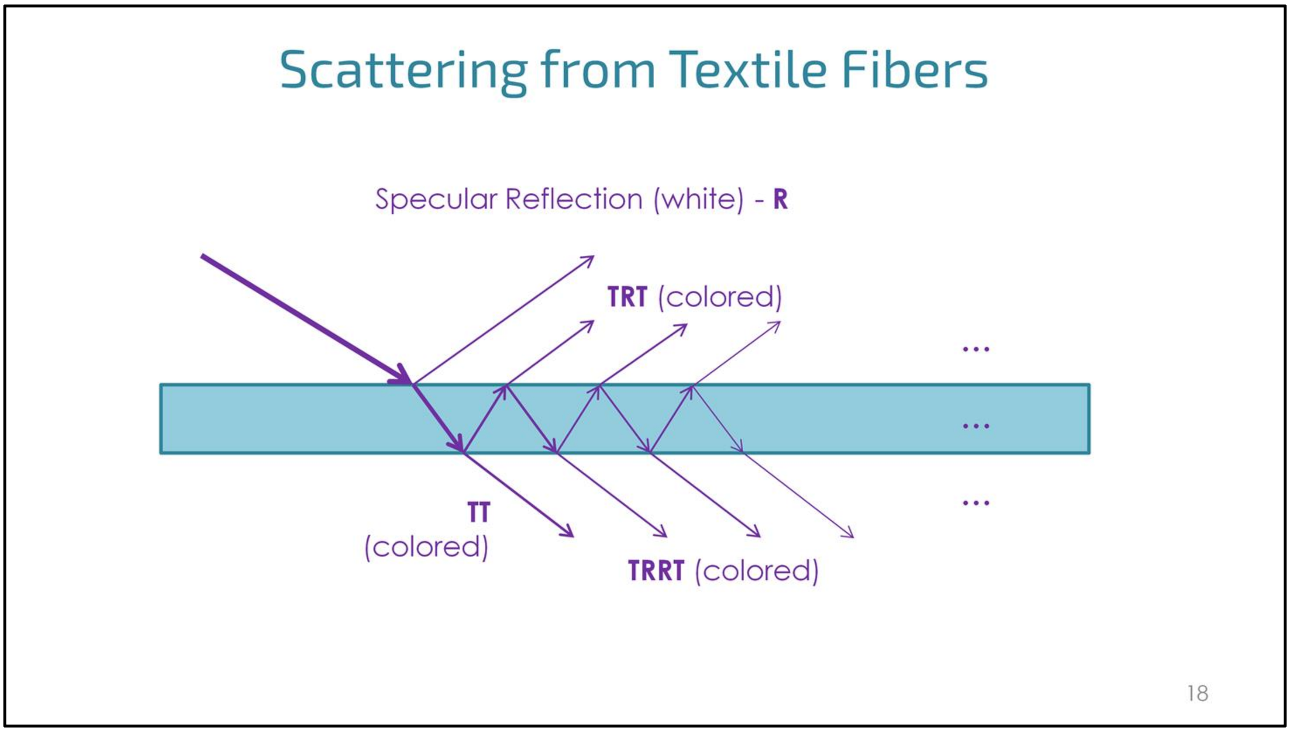
Instead, current models **have the index of refraction fixed at 1.55**
and control the **shape of the lobes ad-hoc.**



After the first bounce, light travels straight inside the fiber,
and part of it goes out, attenuated due to absorption inside the fiber.

This lobe is called TT (from transmittance transmittance)

At this point and for the next bounces,
all the light coming out from the fiber is colored due to absorption.

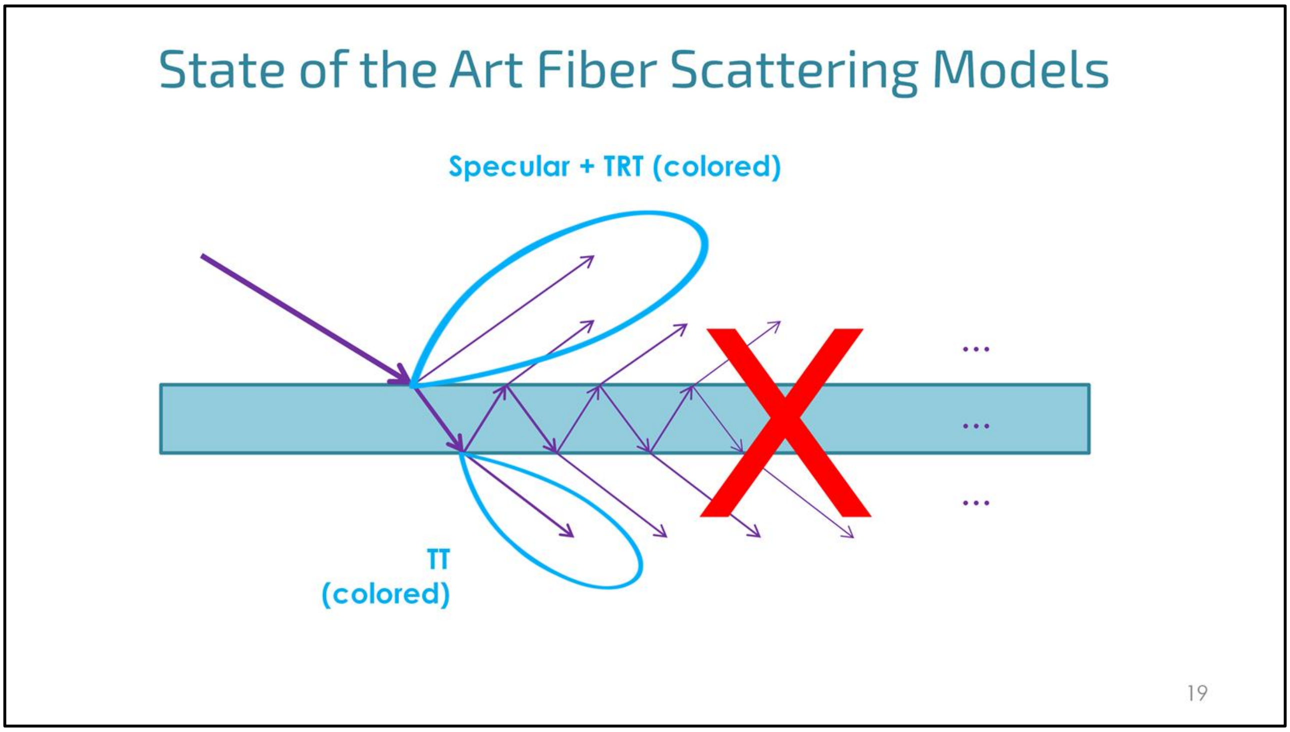


Then, part of the light keeps inside the fiber, after several internal reflections.

Those subsequent lobes are called TRT, TRRT, TRRRT, and so on.

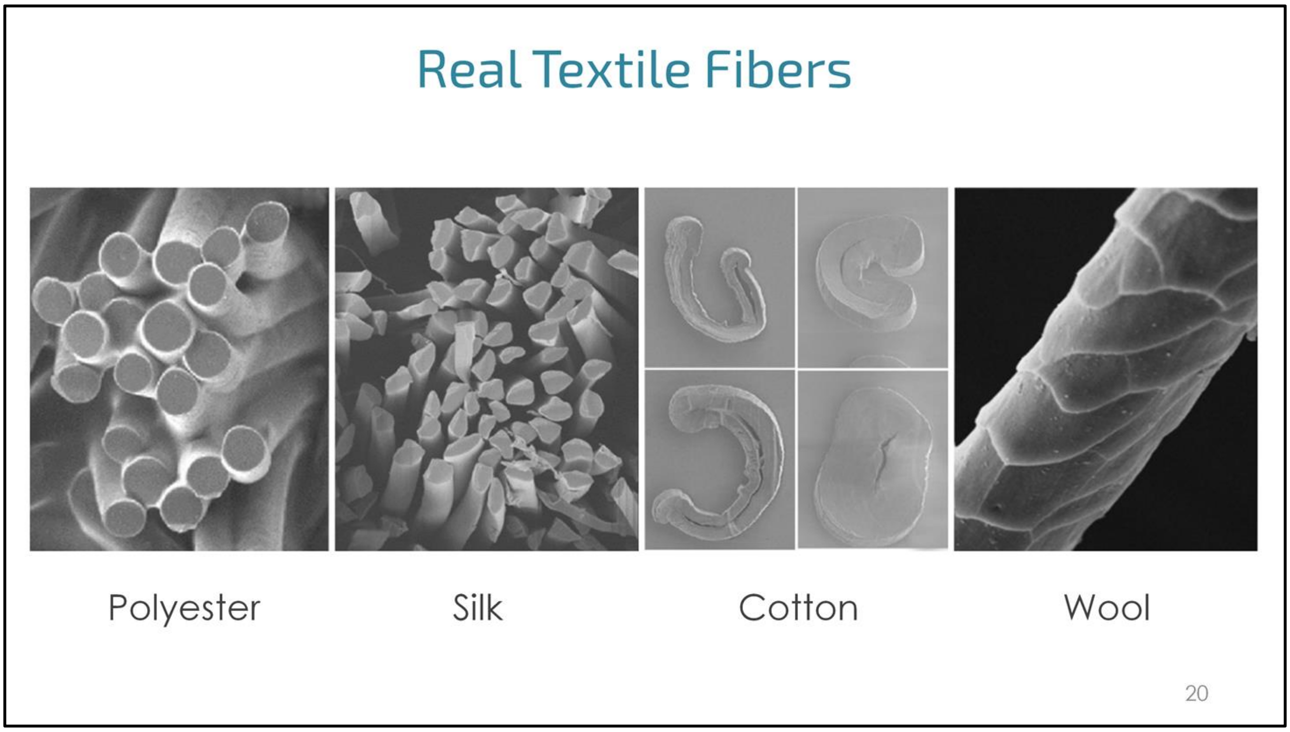
Here, the amount of light that exits the fiber at each bounce,
that is, the shape and the color of each lobe,
are determined by:
the **shape and thickness** of the fiber,
its **density**,
and specially, by the **amount of dye inside**.

Again, previous models usually employ an absorption coefficient that does not relate
to the real properties of the fibers,
and that is often set ad-hoc.



Actually, some recent models are even more simplified,
for instance, grouping R and TRT lobes into a single colored lobe,
[click] or neglecting further bounces than TT.

Again, note that this is done intentionally
in order to fit well in image-base optimization pipelines.



Anyway, most of the assumptions don’t hold when looking at real fibers,
and they are not valid when aiming for a bottom up approach.

In addition, a widely used assumption,
common to every method,
is to consider that fibers are perfect cylinders.

Instead, real fibers show much more complex shapes,
as we can see in these electron microscope pictures.

Parameters of the model

Fibers cross section

Surface Roughness (R_a, l)

IOR

Type of dye (molar extinction coefficient)

Depth of Shade

Diameter (μm)

Density (g/cm^3)

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Instead, our model takes into account the **shape of the fibers** and their **particular cross-sections**,
as well as **optical properties** such as the surface roughness and the index of refraction particular to each fiber type.

Parameters of the model. Properties of Textile Fibers

Type	Diameter μm	Density g/cm^3	IOR $\eta_{\|\|}, \eta_{\perp}$	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 (50)	5

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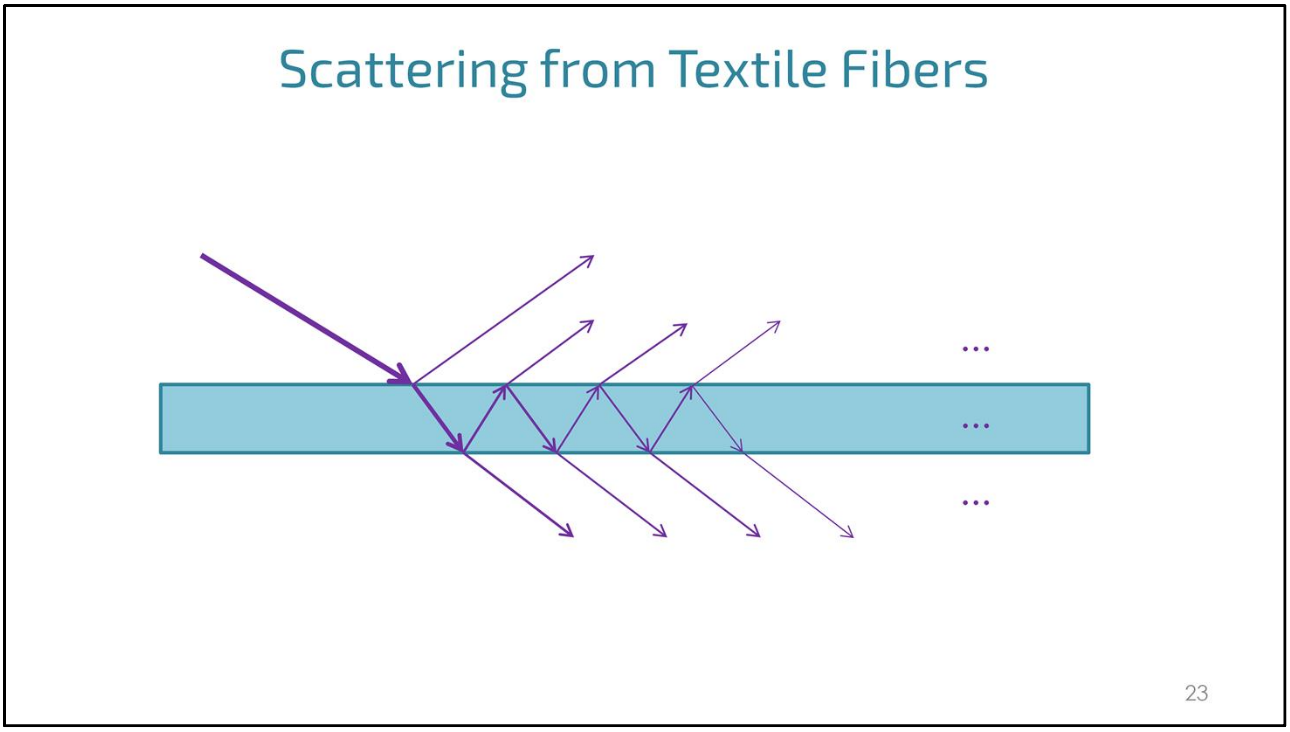
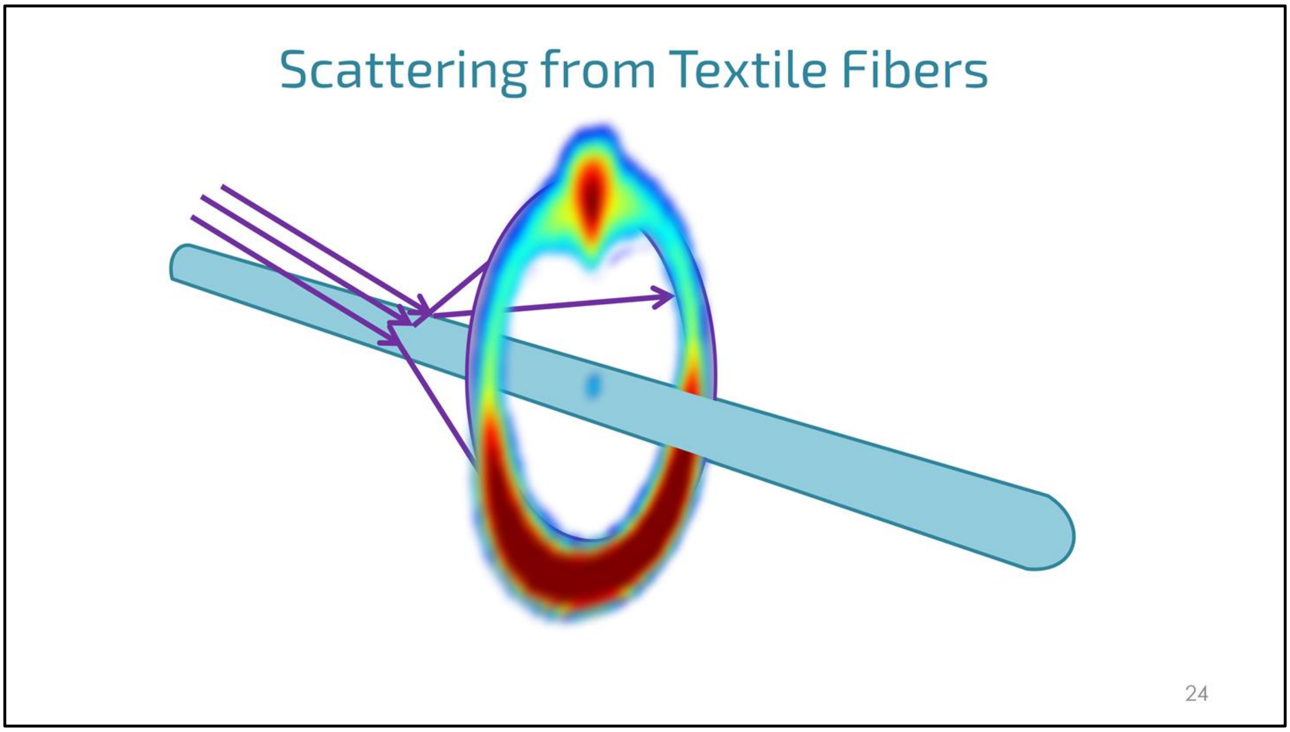
So we model the most common fiber types:
polyester, silk, cotton and wool,
using measurements available from the textile research community, listed in this table.



With this data, we built replicas of the fibers,
and then we relied on brute force monte carlo simulations
(like many others did in the past),
to capture the full reflectance field of the fibers, the 4D function called BCSDF.

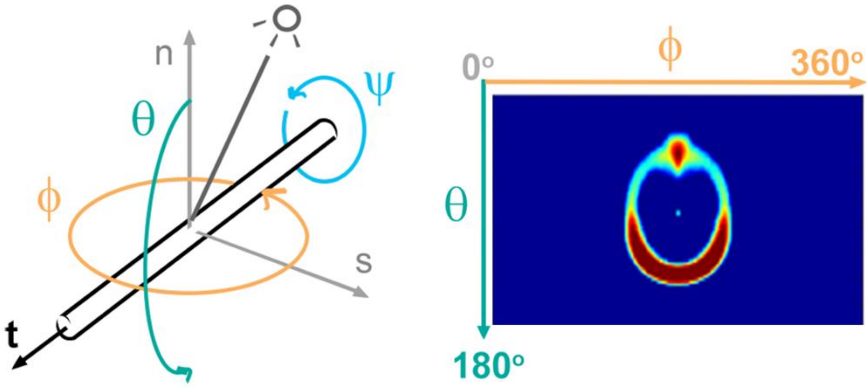
As previous approaches, we assume a far field model, where light enters and exits at the same longitudinal point.

Our model was implemented in Mitsuba renderer.



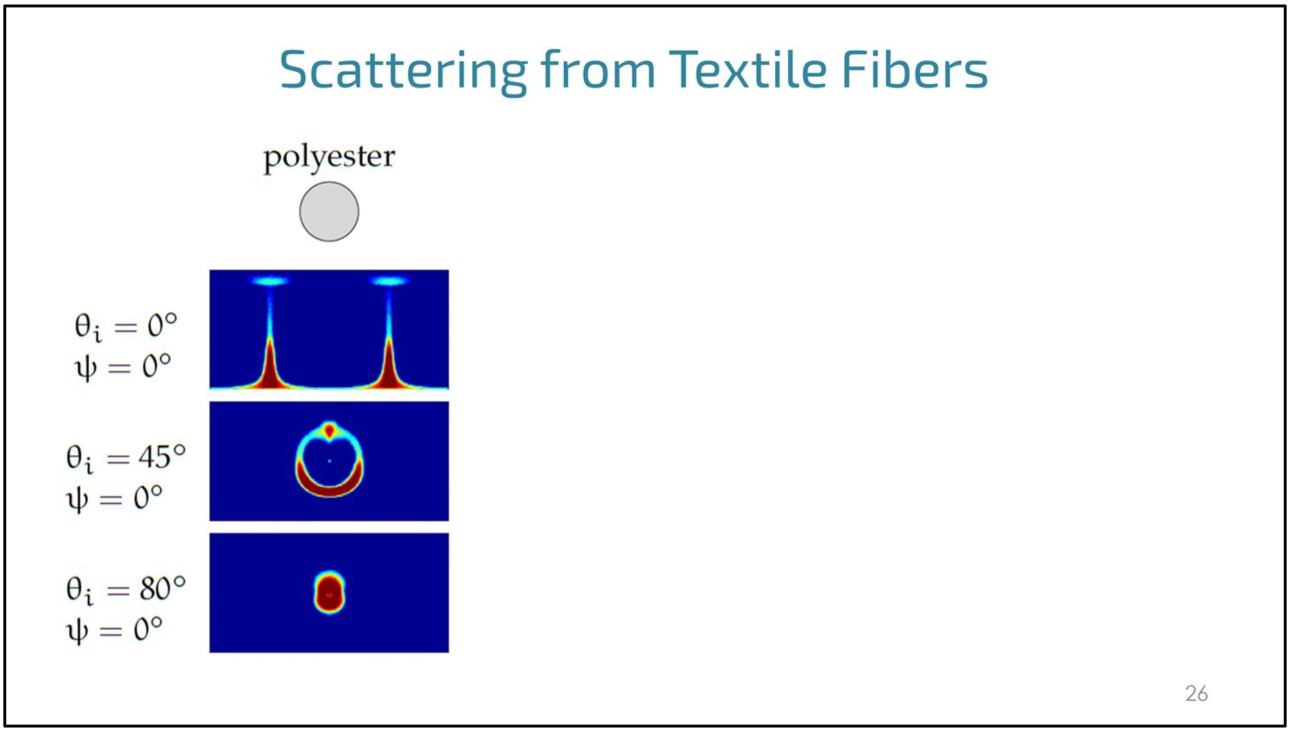
Back to the fiber, if we look at how light scatters there, it always follows this sort of conical shape,
usually called CONE OF REFLECTION.

Scattering from Textile Fibers



25

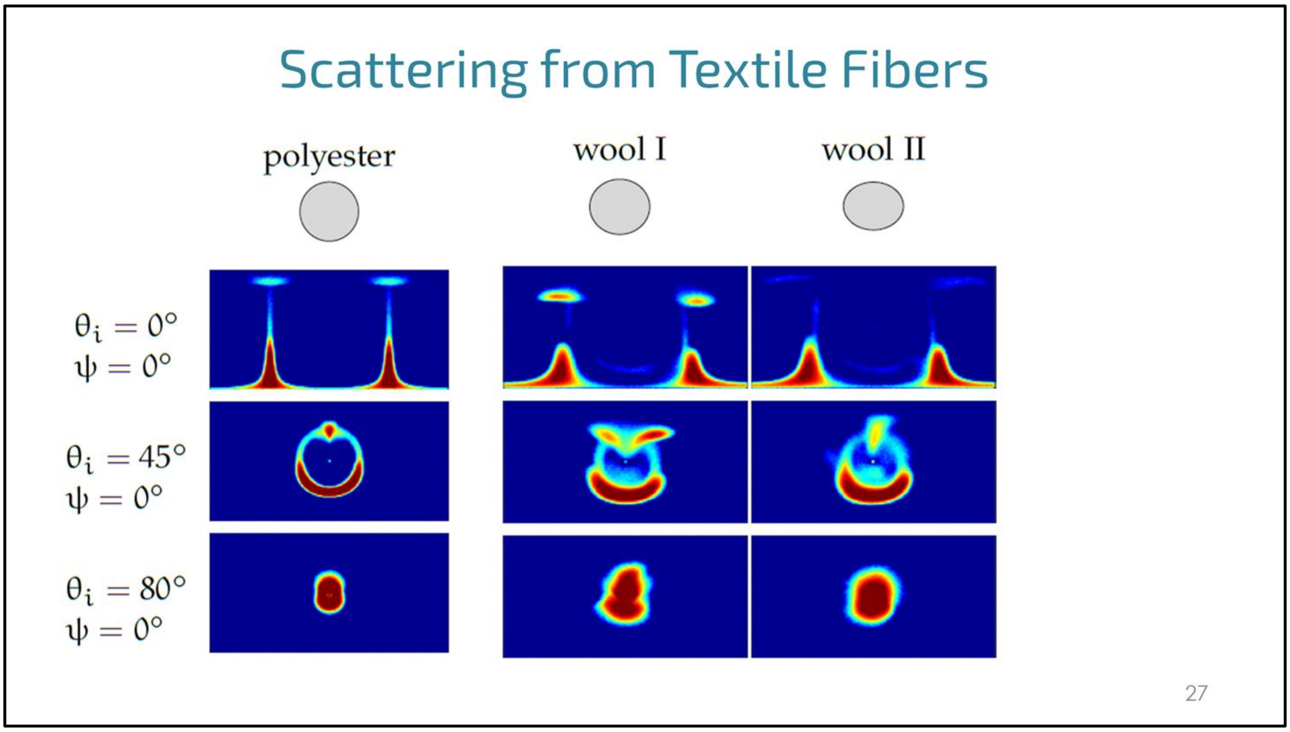
With the previous image in mind,
here we see the local frame of the fiber…
…to better understand the images shown along this presentation, of the slices of the BCSDFs.



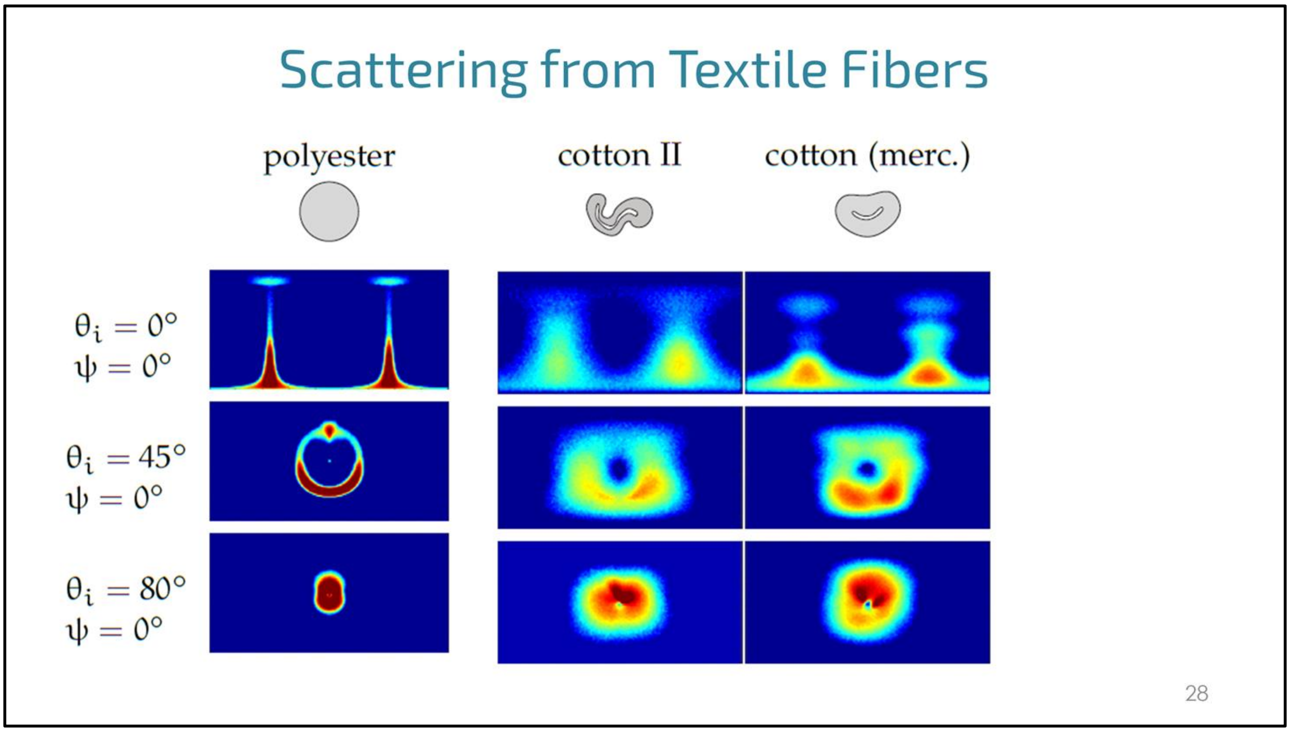
Let’s start by the polyester, which is pretty smooth and its cross-section is almost a perfect cylinder.

Note that this are already our simulated phase functions.

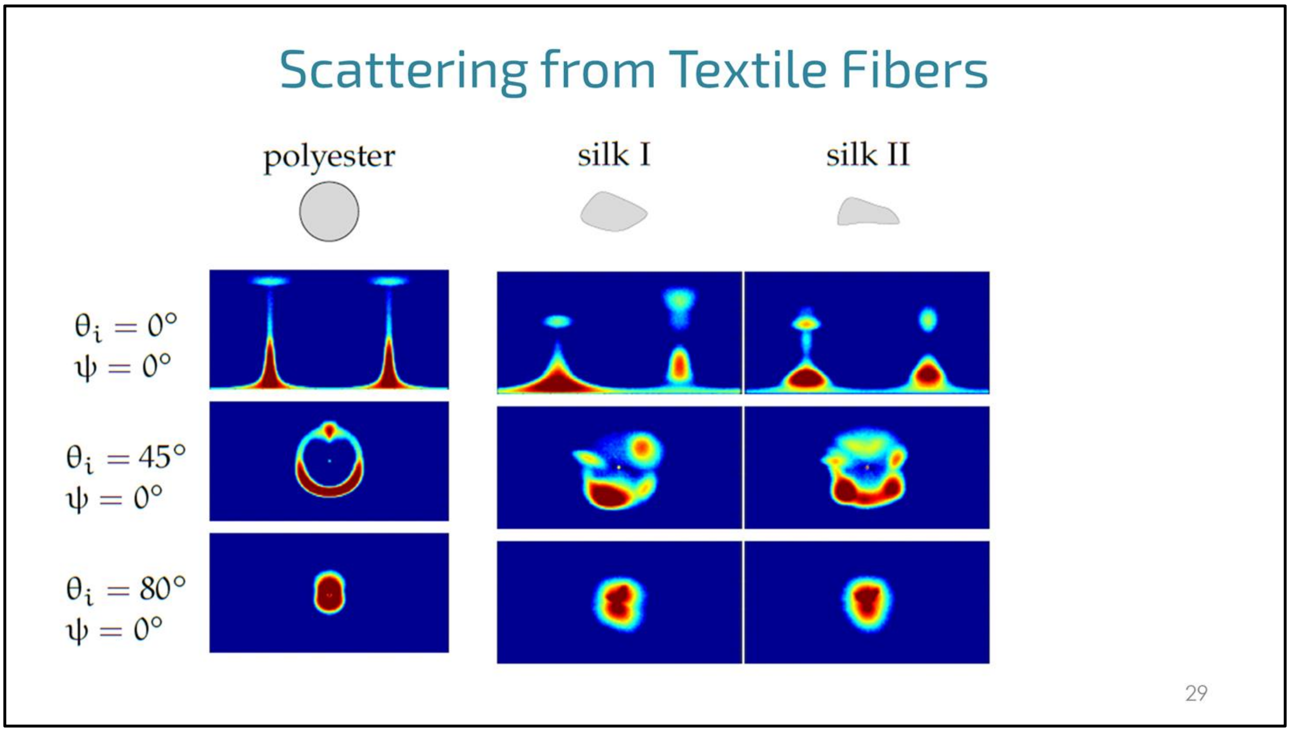
We could consider the polyester as the easiest to fit by current models,
since it can have a pretty cylindric cross section.



However, when looking at the scattering from wool,
even if the cross-section shape remains pretty regular,
the cuticle tilts present in the surface generate more anisotropies,
difficult to handle with current models.



This becomes much more prominent for other natural fibers like cotton,
either completely raw on the left, with a pretty random shape,
or treated for a better luster through mercerization.



And the differences become even more visible when the roughness of the fiber is not as high as cotton,
like in the case of silk.

In this case, the reflectance field is much more anisotropic,
presenting multiple lobes along the cone of reflection.

Parameters of the model. Absorption

[Hearle & Morton 08] **scattering** inside the fiber is **neglectable**

absorption is mostly due to the **dye** used
(natural fibers are uncolored)

Types of dye used:

reactive (cotton, wool, silk)
disperse (polyester)

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So now, let’s take a look at the paramteres of the model.

Here, it’s important to mention to facts:

First, that the **scattering is neglectable** inside the fiber.

And second, that **natural fibers are uncolored**,
so it´s the **dye** used the **main responsible** for the **color and saturation** of the cloth.

We model two types of dye, that cover the most common fabrics:
Reactive dyes, often used for cotton, wool and silk
And **disperse dyes**, more suitable for polyester fibers.

Parameters of the model. Absorption

Absorption coefficient $\mu_a = \kappa\ \varepsilon$

where

κ = dye concentration, in [g l^{-1}]

ε = extinction per gram, in [l $g^{-1} m^{-1}$]

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So, the absorption coefficient depends on
the dye concentration
and
the extinction per gram

Parameters of the model. Absorption

Extinction per gram $\boldsymbol{\varepsilon} = \boldsymbol{\varepsilon_m} \mathbf{w_m}^{-1}$

Where $\boldsymbol{\varepsilon_m}$ = molar extinction coefficient, in *[l mol^{-1} m^{-1}]*

$\mathbf{w_m}$ = molar weight, in *[g m^{-1}]*

>> Particular to each type of dye!

32

Where the extinction per gram is simply the product of
the molar extinction coefficient
and
the molar weight of the dye.

Parameters of the model. Absorption

Usual ranges of extinction coefficient ε :

Reactive dyes *(cotton, silk, wool)*	0.005 - 0.016	$[l\ mg^{-1}\ cm^{-1}]$
Disperse dyes *(polyester)*	0.045 - 0.246	$[l\ mg^{-1}\ cm^{-1}]$

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These properties are very particular for each type of dye.

Although they can vary among different kinds of dye of the same type,
Values are usually in the ranges shown here,
and that's what we used for the simulations.

Parameters of the model. Absorption

Dye concentration $\kappa = \rho\, \zeta$

Where

ρ = fibers density, in *[g l^{-1}]*

ζ = Depth of Shade (DoS)

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Last, the dye concentration is determined by:

the density of the fibers, in grams per liter,

and the depth of shade

Parameters of the model. Absorption

ζ = Depth of Shade (DoS)

Ratio grams of dye to grams of fiber.

Commonly used in industry.
Controls the saturation of dyed cloth.

Pale shades:	**0.1 %**
Deep shades:	**4 %**

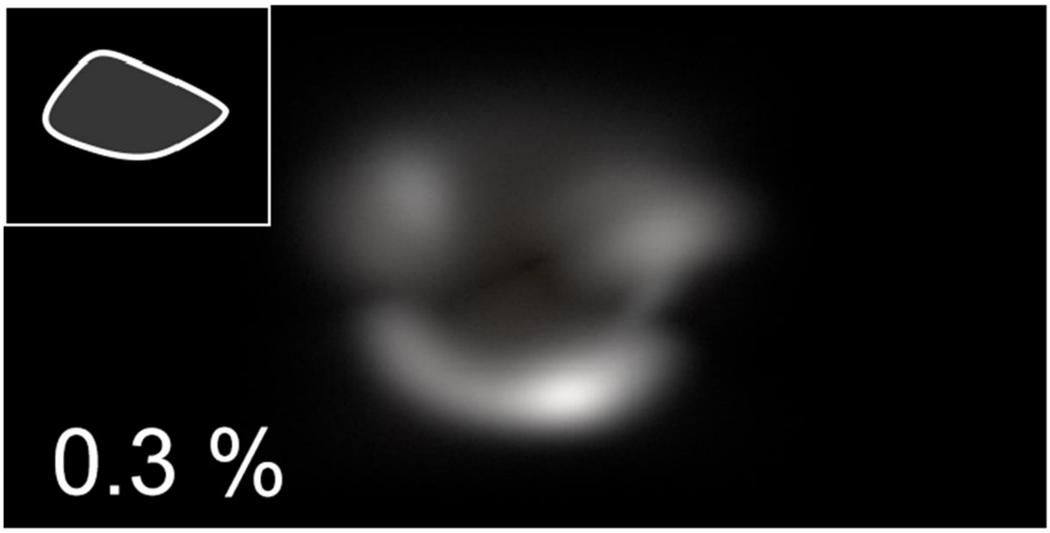
35

The depth of shade is a parameter widely used in industry to control the saturation of dyed cloth
and it’s the **ratio grams of dye to grams of fiber**.

Again, the usual ranges are from
0.1% for pale shades
to 4% for very deep shades

But its use depends on the fiber type,
the properties of the yarns,
the type of garment, etc.

Parameters of the model. Absorption



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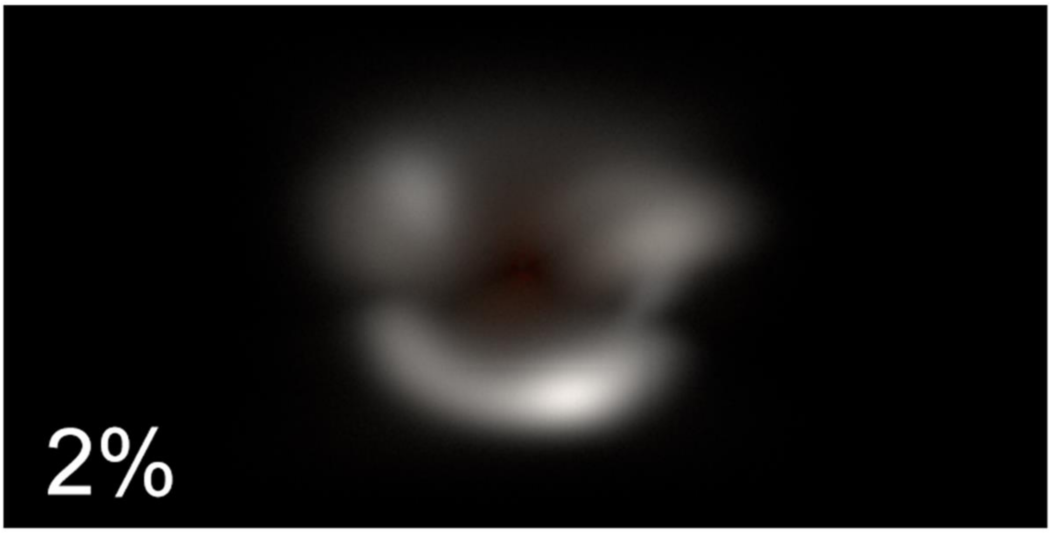
This is an example of a slice of one of our BCSDFs

In particular a silk fiber, with the cross section shown in the inset on the left

This is for different Depth of shades, or Dye concentrations, **from pale**

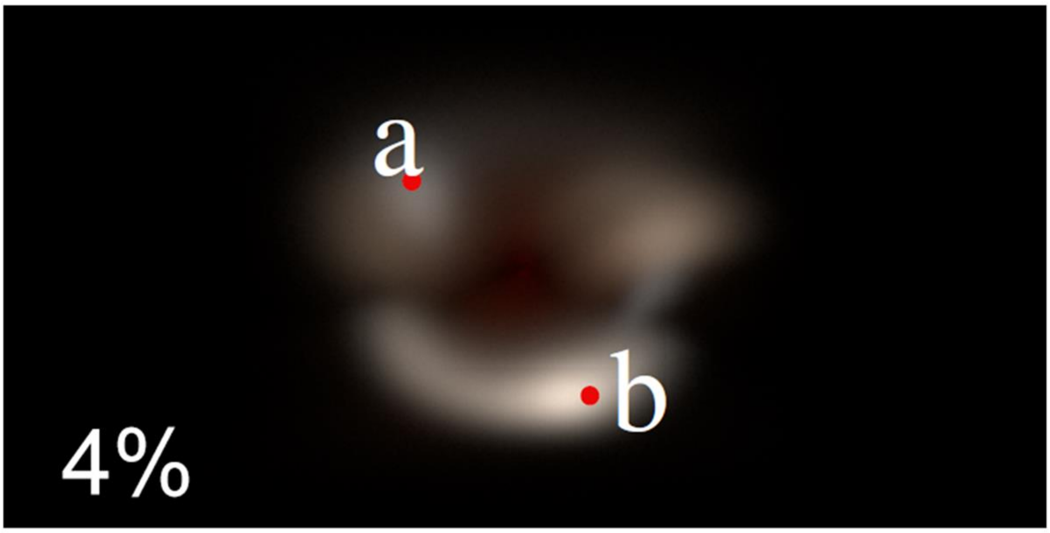
Parameters of the model. Absorption



37

To intermediate

Parameters of the model. Absorption



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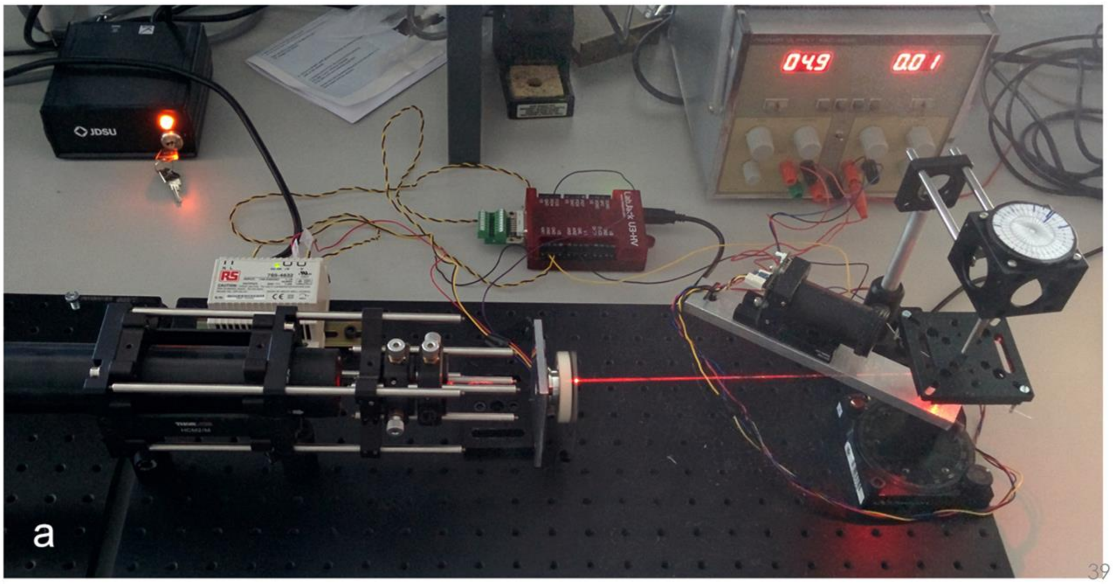
To very deep shades.

Not that the saturation is still subtle at this scale,
but the cumulative effect of hundreds of fibers is very visible at larger scales,
as we'll see later.

Validation

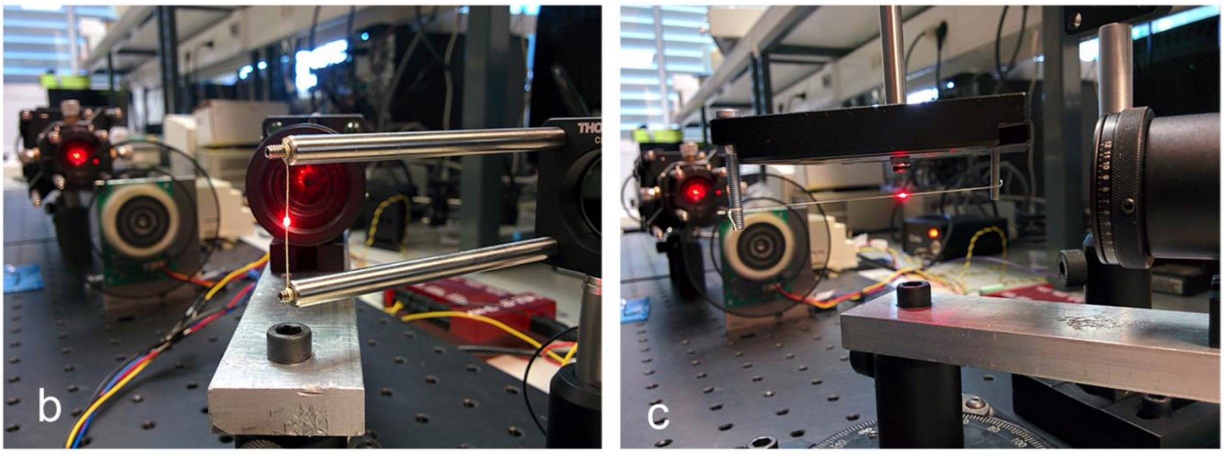


39

Once we defined the model and captured the BCSDFS,
we validated our results with real yarns,
acquired from one of the biggest sweing yarn manufacturers worldwide.

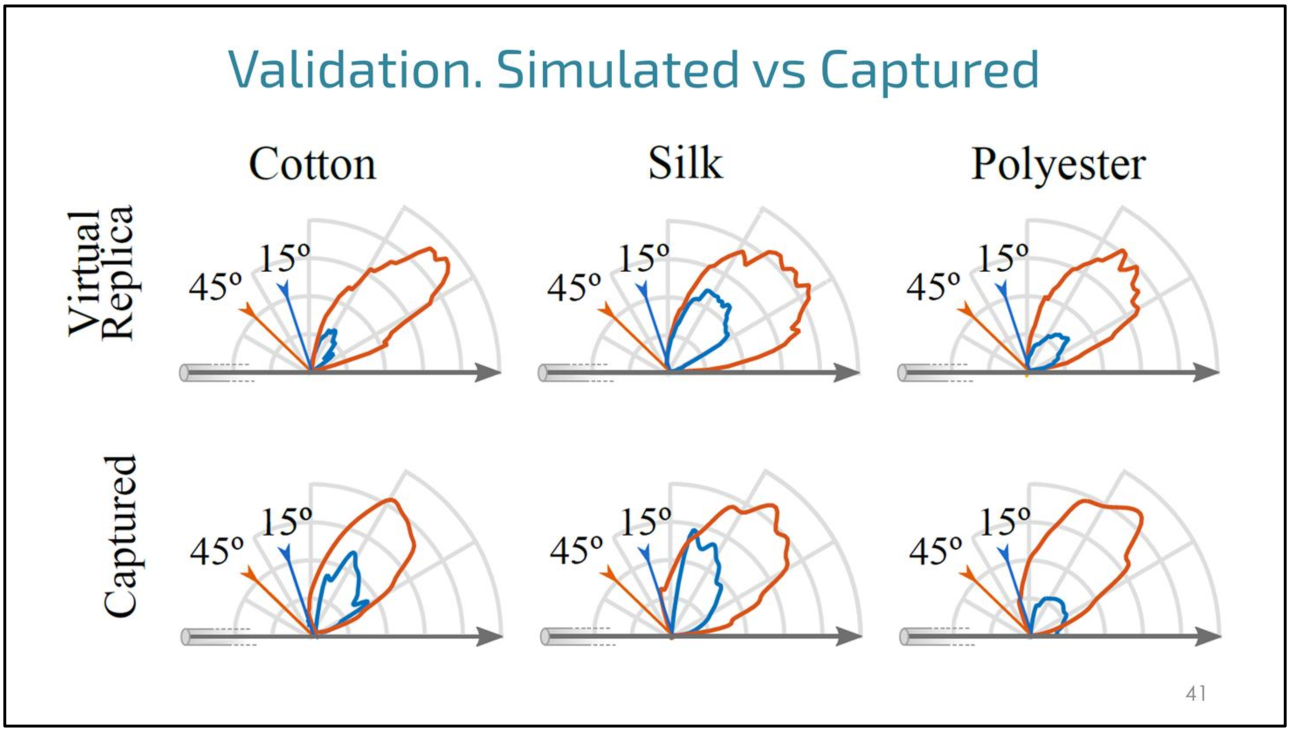
We built this setup at the optics laboratory…

Validation



40

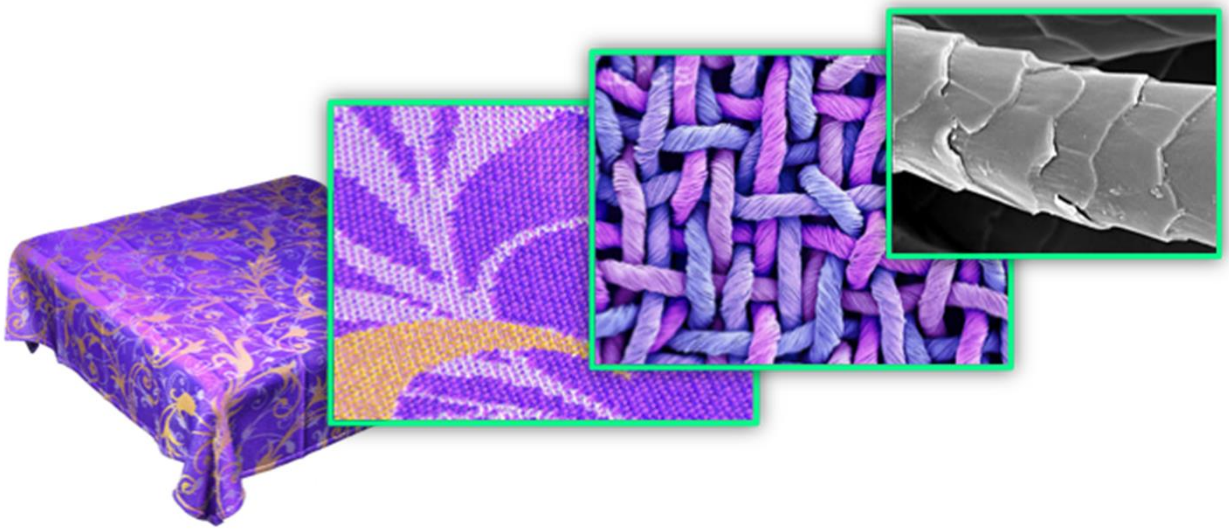
and took radiance samples in the azimuthal plane, on the left,
and the longitudinal plane, on the right.



The plots here show the real radiance acquired along the longitudinal plane ,
[click] and the scattering captured from the virtual replicas, rendered using our model.

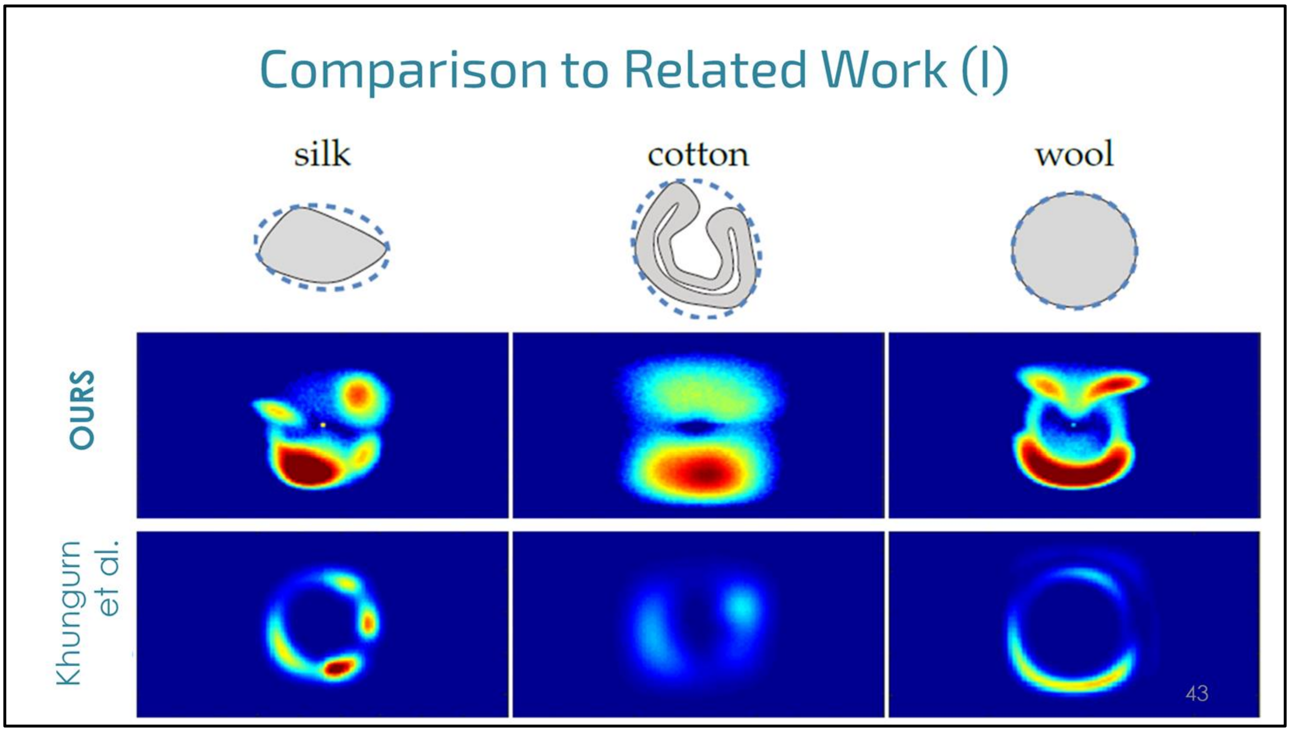
Although there are many variables involved,
the overal shape, orientation and size of the lobes are matched by our model.

Results



42

Finally, we’re going to see some results of our model, bottom to top scales.



In this examples we can see directly what happens
when we manually fit the parameters of the state of the art model on the bottom row
to our model on the top row.

Parameters were set as close as possible,
including manually setting the cross section as the bounding ellipse of our characteristic cross sections.

And we can see that the multiple lobes present in our model cannot be reproduced.

Comparison to Related Work (II)

d'Eon et al. | **OURS** | Khungurn et al.

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This is also visible at the yarn scale.

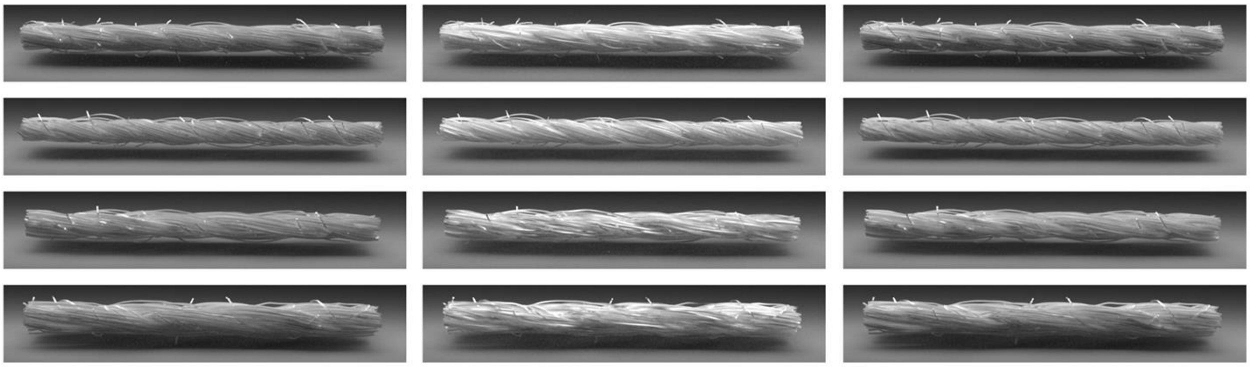
In this case the fibers are represented explicitely by splines.

These are numerical fits of some of the most recent fiber models.
d'Eon and Khungurn, fitted to ours.

First for cotton….

Comparison to Related Work (II)

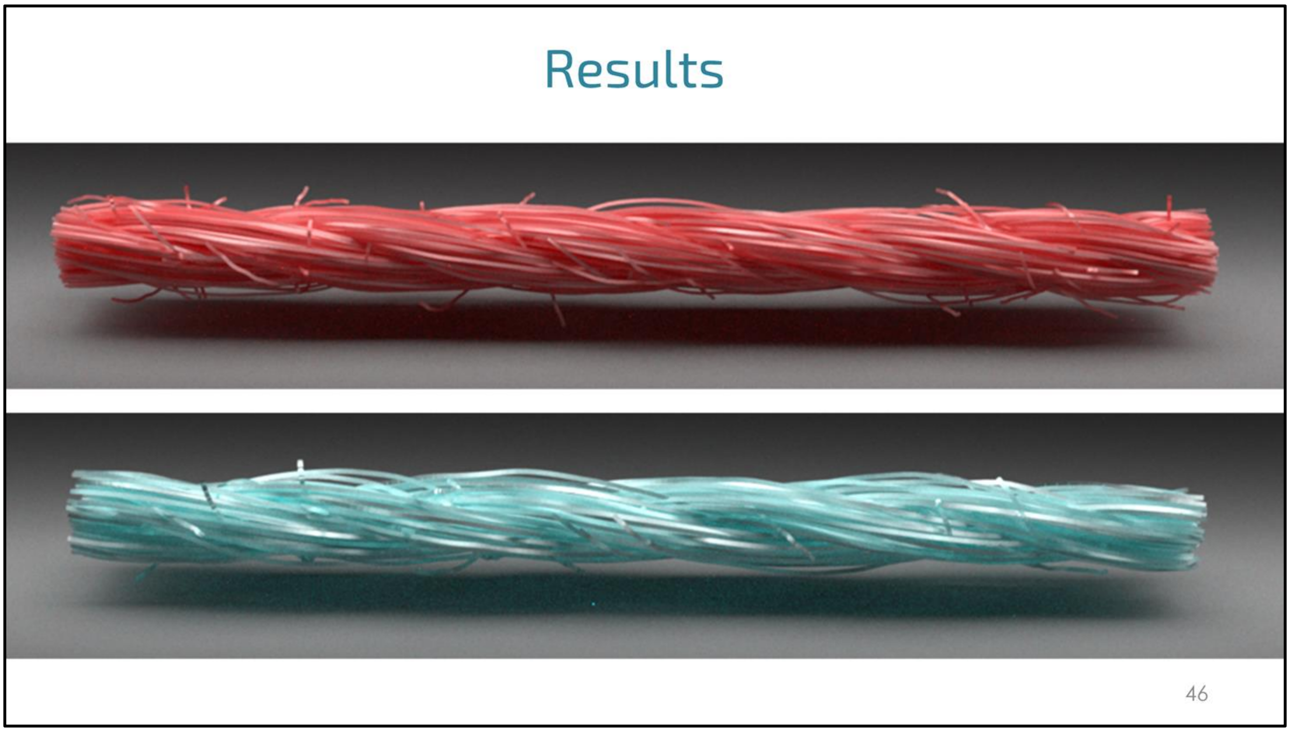
d'Eon et al. | **OURS** | Khungurn et al.



45

…then for silk, where differences are more evident.

The models are unable to reproduce the highlights of individual fibers,
that come from the anisotropic lobes of the BCSDFs,
and tend to homogeneize and over smooth the look of the yarn,
when the optimization finally converges.



These are more renderings of yarns.

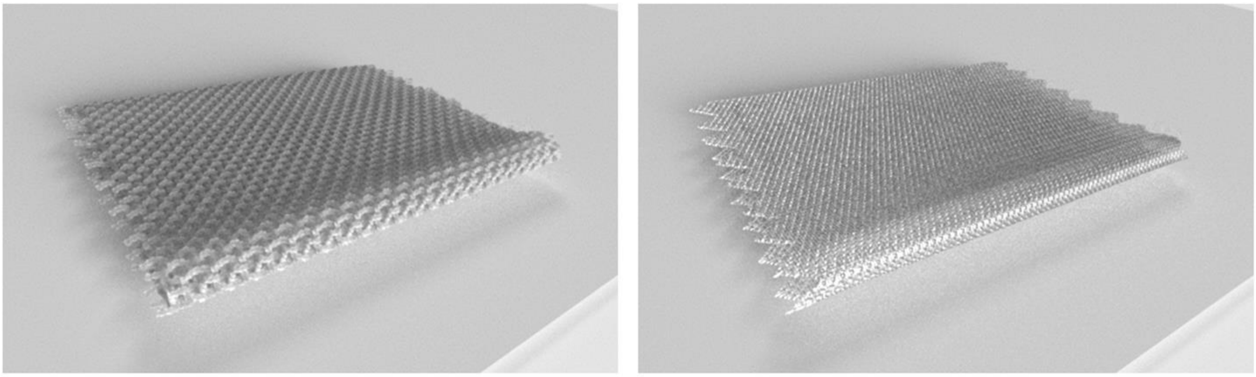
At this viewing distance, the overall look of the yarn is pretty diffuse.
[click] however, at closer views, everything becomes more shiny.

The red one is made of cotton fibers,
the blueish one is made of silk.

We can see how even individual cotton fibers can have pretty visible hightlights.

This effect can be captured by our scattering model,
where each fiber exhibits independent highlights,
instead of having an average model where all fibers would look exactly the same.

Comparison to Related Work (III)



Cotton Silk

OURS

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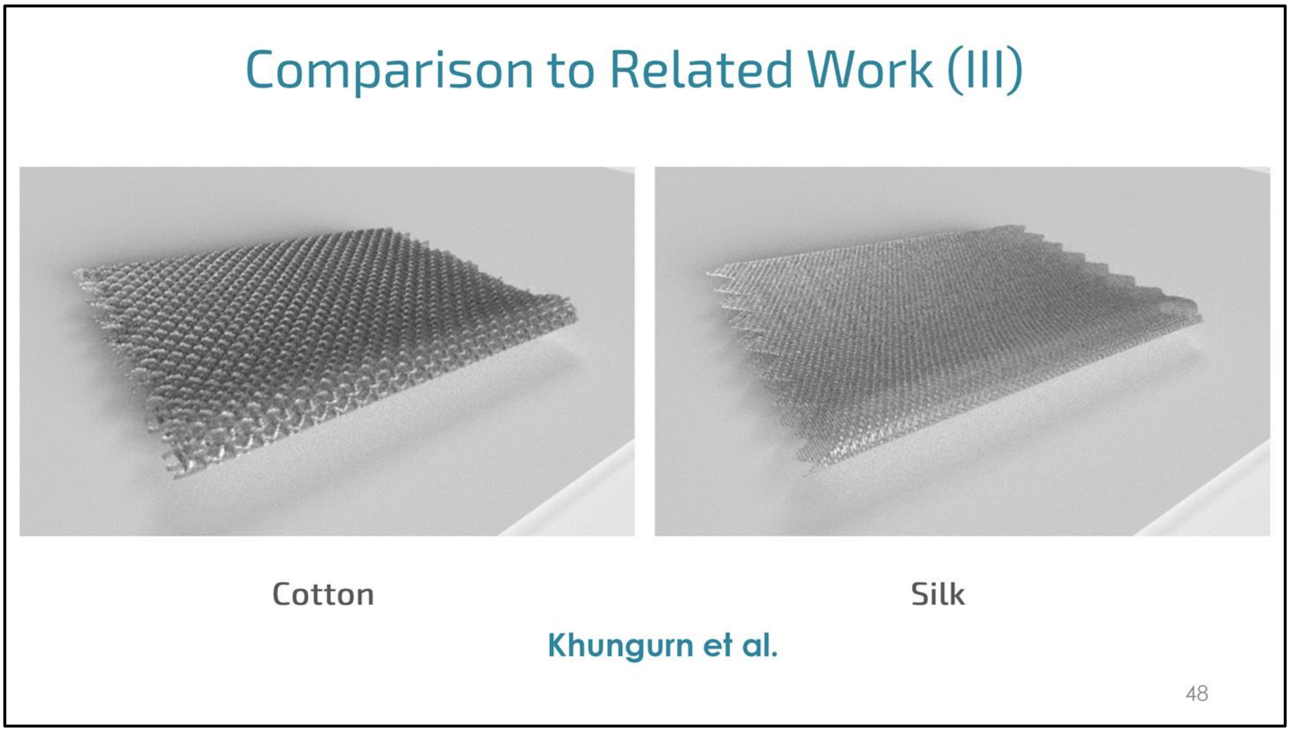
The same effect can be noticed from longer distances,
for pieces of cotton and silk.

These are renderings using our model



and these are using Khungurn’s model numerically fitted to ours.

At bigger scales, we can illustrate the effect that fiber type has on the overall look of the cloth.

Let's take a look at what happens when we change the fibers of a piece of cloth like this.

We use here a voxelized representation,
and rendered using volumetric path tracing together with our fiber scattering model.

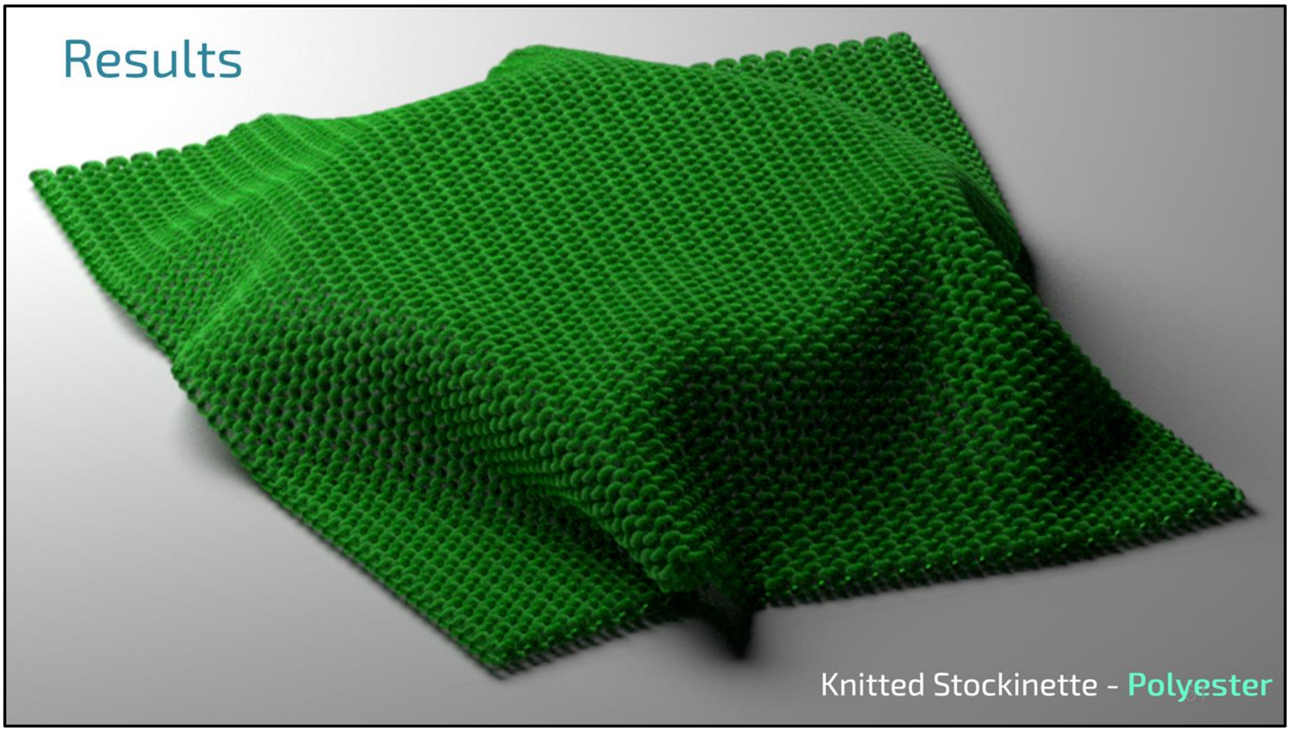
This first image is wool,

And this is cotton,
that looks brighter brighter due to its smaller fiber radius.

It also presents a slightly more diffuse look than wool,
due to the high roughness of the surface of the cotton fibers
and the multiple bounces of light that occur due to its complex and messy cross section, as we have seen.

Note that we keep the same knit pattern to better appreciate the differences.
In this case a stockinette knitting pattern.

Also note that some of combinations can look weird,
since not every type of fiber is suitable for any weaving or knitting pattern.



This is the same but with polyester.

The look is much more saturated than in previous cases,
due to the typical dyes used for polyester…
…and its low surface rouhgness.

And finally, silk, whose appearance is soft but shiny,
due to the anisotropic light transport that occurs within it’s triangular-ish cross section.

Results

Cotton	Silk	Polyester
Knit Garter	Woven Satin	Knit Garter
Reactive	Reactive	Disperse

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To finish, this is a result of volumetric pieces of cloth,
each with a different fiber type that suits each kind of pattern,
and colored with their appropiate dyes.

Conclusions

First fiber scattering model based on **real fiber parameters**.

Key features:

Cross section shape depending on fiber type

Absorption by **dye** type and concentration

Measured **real** parameters

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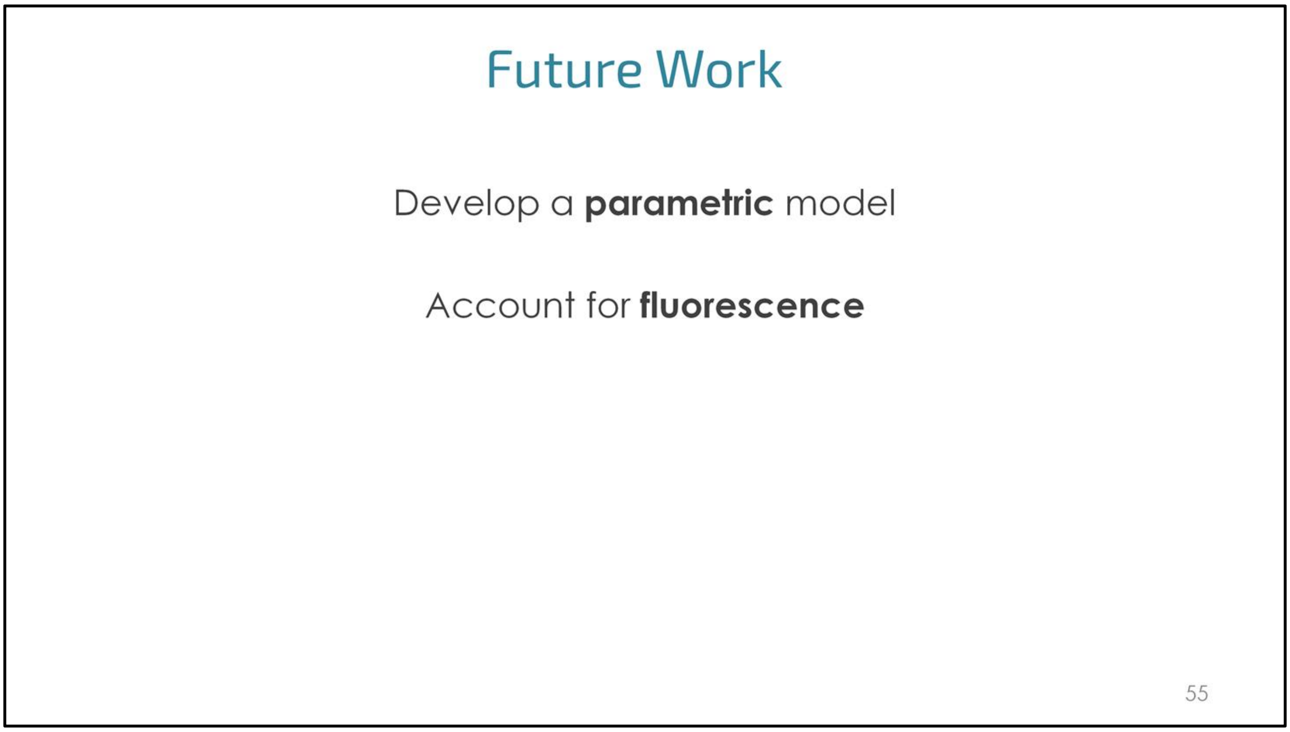
So, wrapping up, this is the first model based on parameters of real cloth fibers,
taking into account the shape of the cross section of the fibers,
and other physical and optical properties
like the surface roughness or index or refraction.

It controls the color and saturation of the cloth through physically based dying parameters,
instead of using generic optical thickness parameters that are not linked to any real property.

It is also suitable for any cloth representation,
either volumes and explicit fibers,
and it represents the first step towards a forward bottom up approach for defining cloth appearance,
which could be of help for a better synergy between computer graphics and textile research and manufacturing processes.



As future avenues of work:

[click] We would like to develop a **parametric** model, extending this also to more different types of fibers, dyes, etc

[click] Account for **fluorescence**, present in many real garments

Future Work

Develop a **parametric** model

Account for **fluorescence**

Account for **washing** and **chemical treatments** (mercerization)

Further explore the effect of **wave optics**

Measure the effect of the **far field** scattering model

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[click] Account for **washing** and **chemical treatments,**
like mercerization, which is a process that increases the luster of the fibers

[click] Further explore the effect of **wave optics.** In this sense, we´re specially interested in modeling **iridiscence**

[click] And finally, it would be interesting to measure the effect of the **far field** scattering model on the appearance at close-up views.

An Appearance Model for Textile Fibers

Carlos Aliaga[1]
Miguel A. Otaduy[2]
Carlos Castillo[2]
Jorge López-Moreno[2]
Diego Gutiérrez[1]
Adrián Jarabo[1]

1 Graphics and Imaging Lab
2 Universidad Rey Juan Carlos

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