



**SIGGRAPH 東京
ASIA 2024
TOKYO**

Conference | 3–6 December 2024

Exhibition | 4–6 December 2024

Venue | Tokyo International Forum, Japan

Rendering Course: Recent Advances in Photorealistic Cloth Rendering

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University of California, Santa Barbara

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University of Manchester

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Organized by



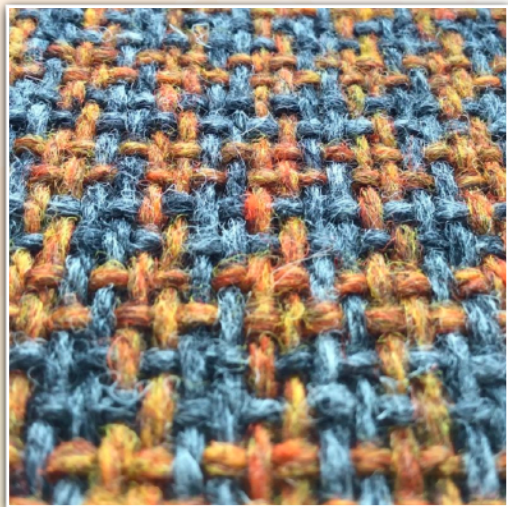
Learning Objectives

- Cloth rendering basics for beginners
- Types of cloth representations and their advantages/disadvantages
- Previous solutions
- State of the art solutions (academia and industry)

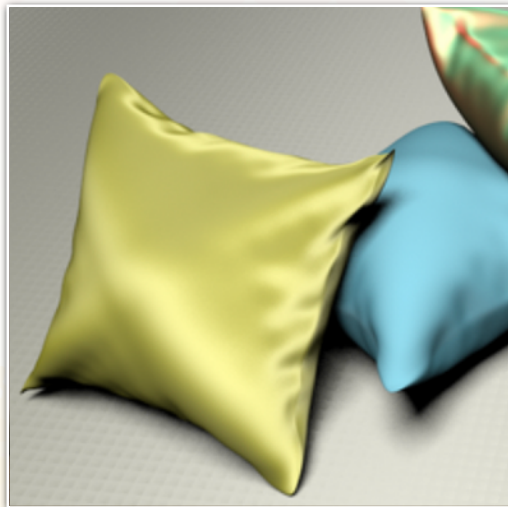
Target Audiences

- Students / Beginners
- Industrial friends
- Researchers
- Basically everyone!

Arrangements



Cloth 101

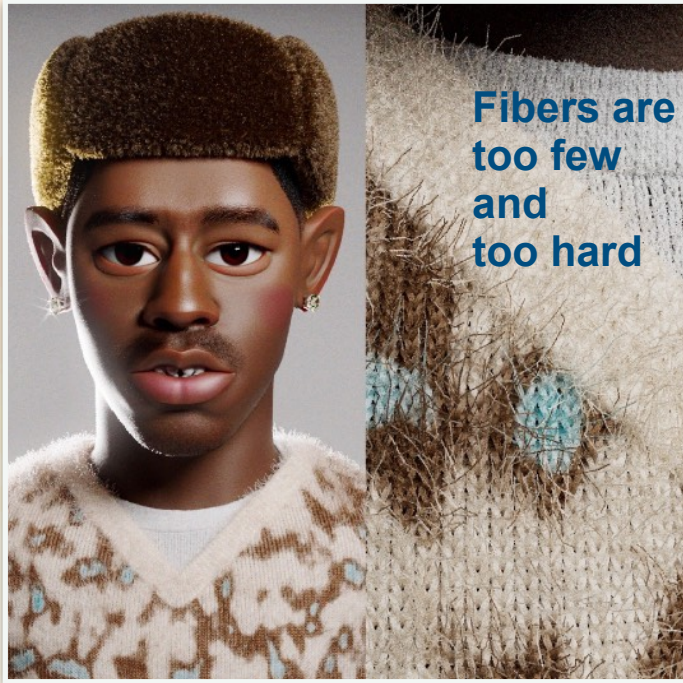


Cloth Rendering Models



Modern Cloth Rendering

Far From Photorealistic — As We Can See



By Alex Alvarado



By Pauline Boiteux

Far From Photorealistic — Cloth in Artists' Eyes

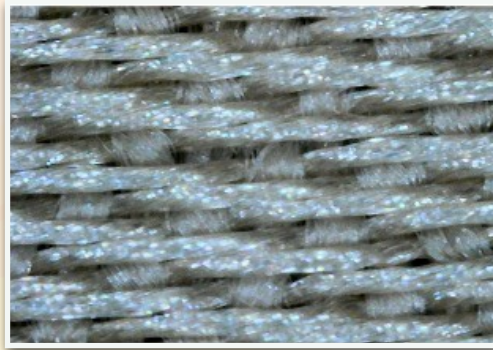
“We use 0.4 roughness,
0.3 **metallic**,
1.0 anisotropy,
a rather high **IOR**.
That’s the cloth we got,
but I really don’t know
what I am looking at.”

— An anonymous friend
from the industry



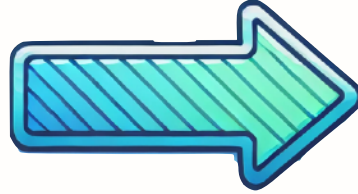
Cloth modeling & rendering by Lintex Digital Technology

Key to Cloth Rendering — Cloth Structure



Structure

Determine



**(Optical)
Property**

Cloth Structure

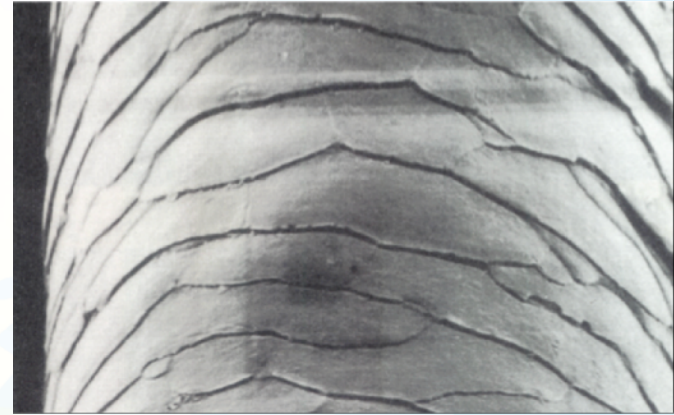
- Different levels of cloth geometry



Woven cloth



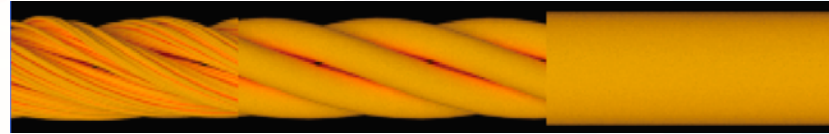
Underlying structure



Single fiber

Cloth Structure

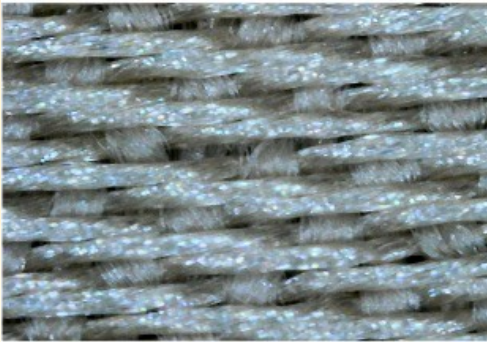
- Most common structure
- Three-level hierarchy
 - Fiber -> Ply -> Yarn



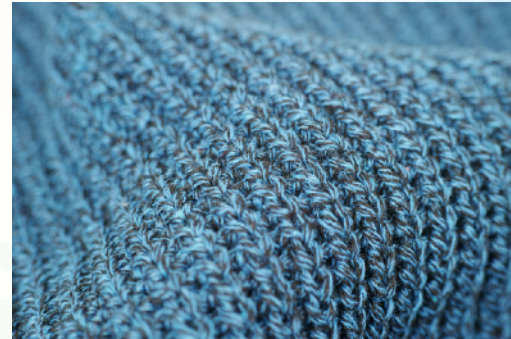
Fiber

Ply

Yarn



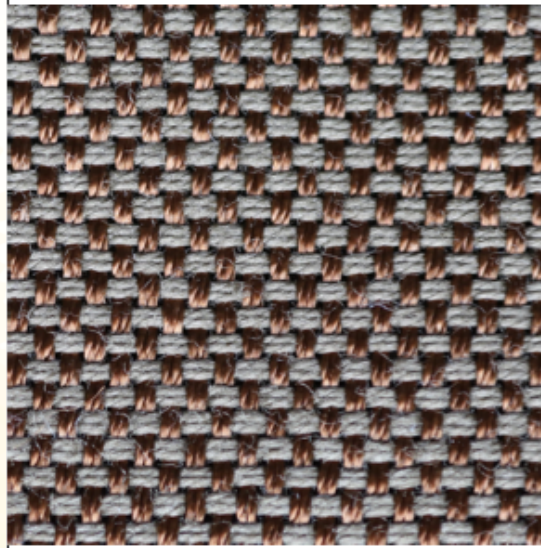
Woven cloth



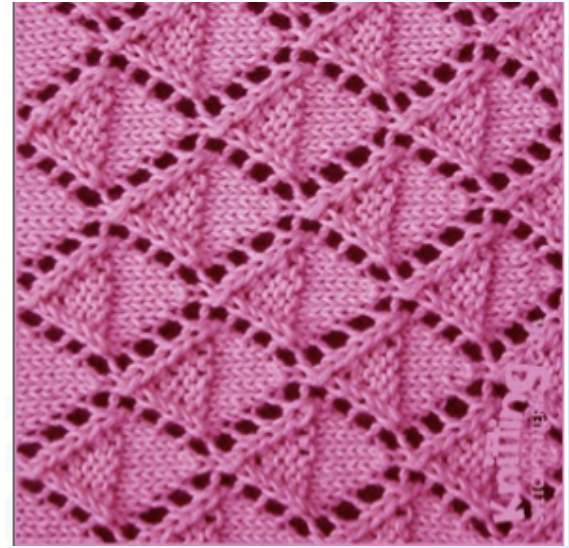
Knitted cloth

Cloth Structure

- Yarn to cloth?
- Woven or knitted



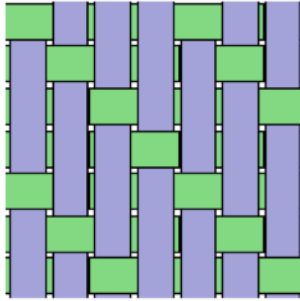
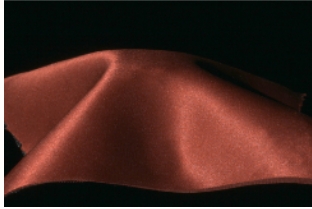
Woven



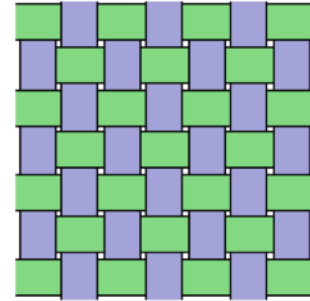
Knitted

Cloth Structure — Woven

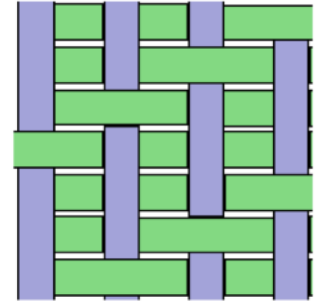
- Use repetitive patterns to define a piece of cloth
- Different patterns -> Significantly different optical properties



Satin



Plain Weave



Twill

Cloth Structure — Knitted

- More complex patterns
 - Sweater
 - Shirt
- Yarns are usually thicker (though not necessarily)
 - So, the thickness of knitted cloth matters



Sweater

Shirt

Desired Effects from Real Cloth

- Sheen



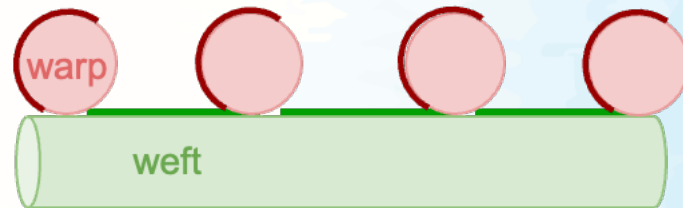
Desired Effects from Real Cloth

- Sheen
- Fly-away fibers



Desired Effects from Real Cloth

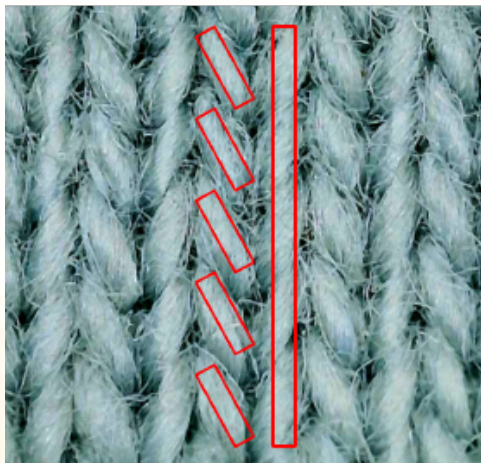
- Sheen
- Fly-away fibers
- Shadowing-masking



An example of masking

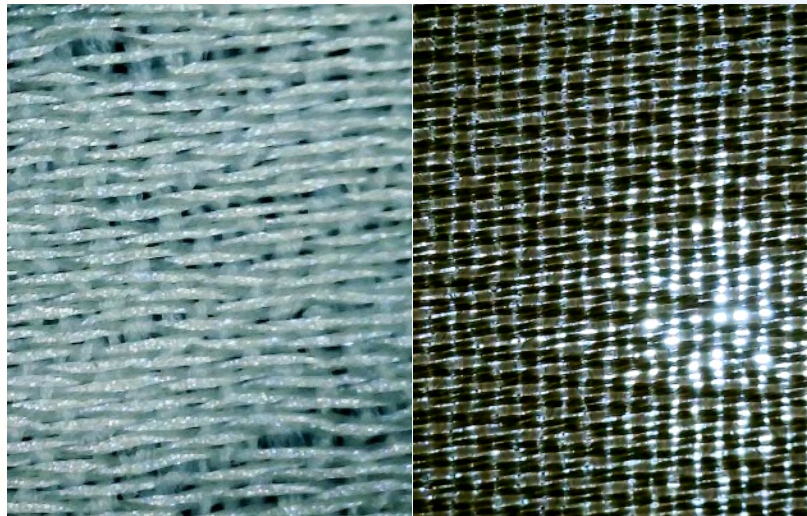
Desired Effects from Real Cloth

- Sheen
- Fly-away fibers
- Shadowing-masking
- Anisotropy



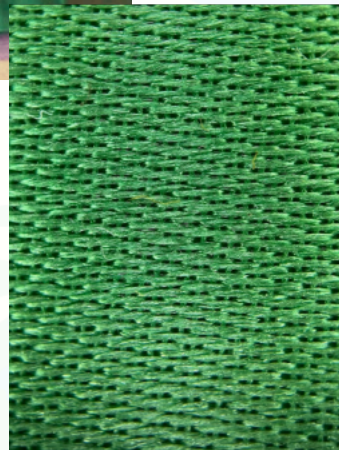
Desired Effects from Real Cloth

- Sheen
- Fly-away fibers
- Shadowing-masking
- Anisotropy
- Transparency

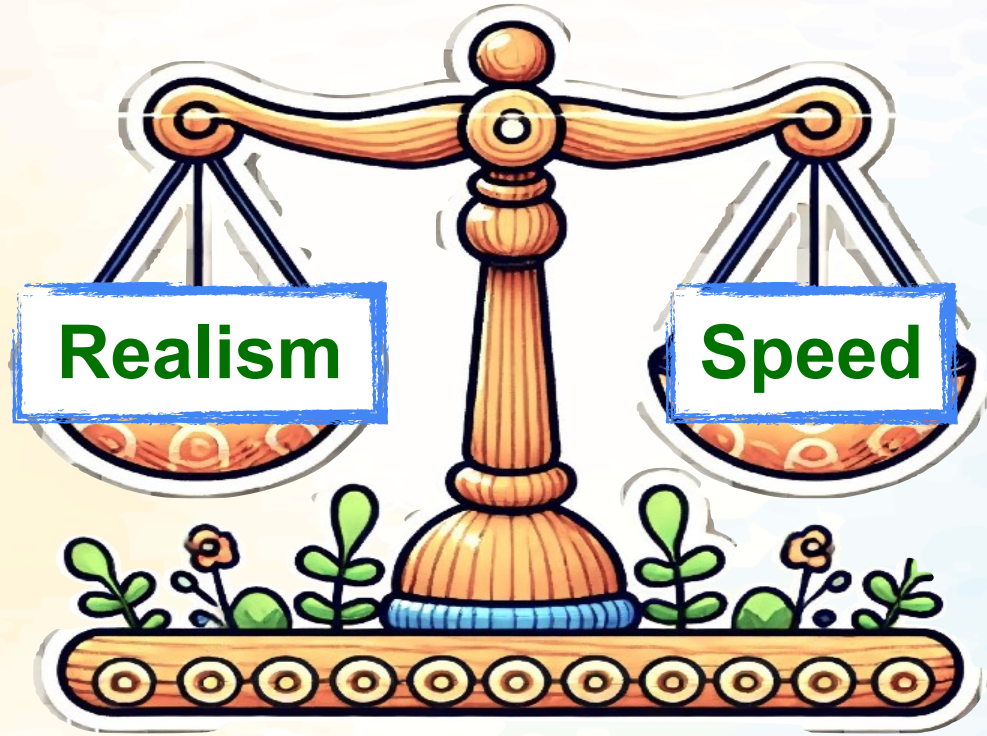


Desired Effects from Real Cloth

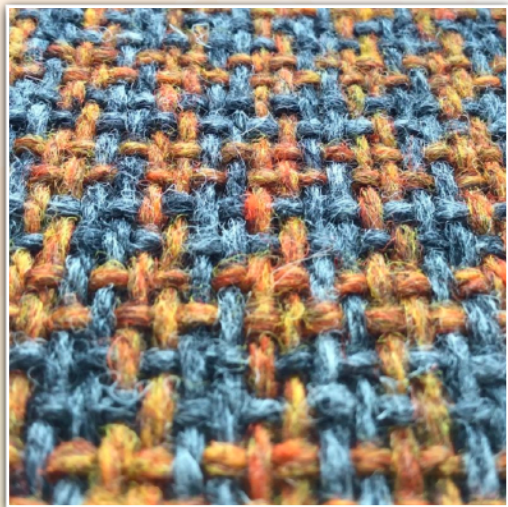
- Sheen
- Fly-away fibers
- Shadowing-masking
- Anisotropy
- Transparency
- Detail / Variation



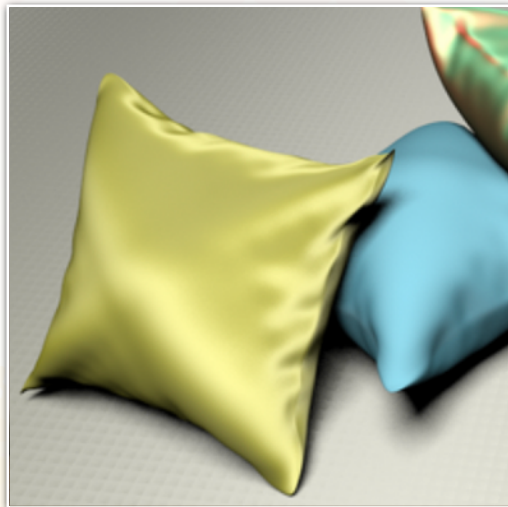
Key Challenge — The Tradeoff Between ...



Next Part



Cloth 101

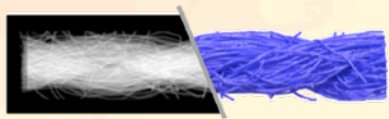


Cloth Rendering Models



Modern Cloth Rendering

Previous Cloth Rendering Models



Fiber geometry



Rendering

Micro-appearance methods



Surface geometry



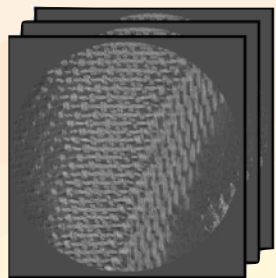
Rendering

Surface-based methods

Volumetric Representation

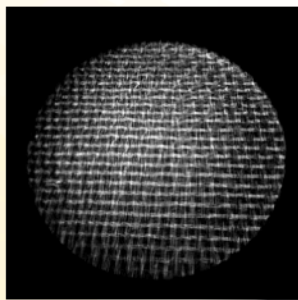


Input

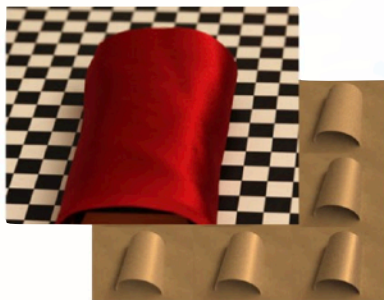


Micro CT Images

Real Cloth



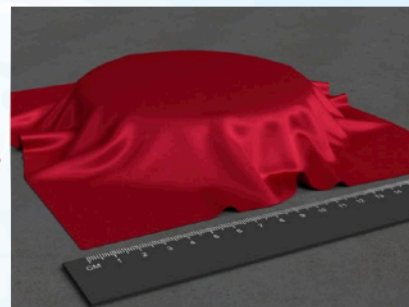
Reconstructed Density Field
and Orientation Field



Appearance Matching



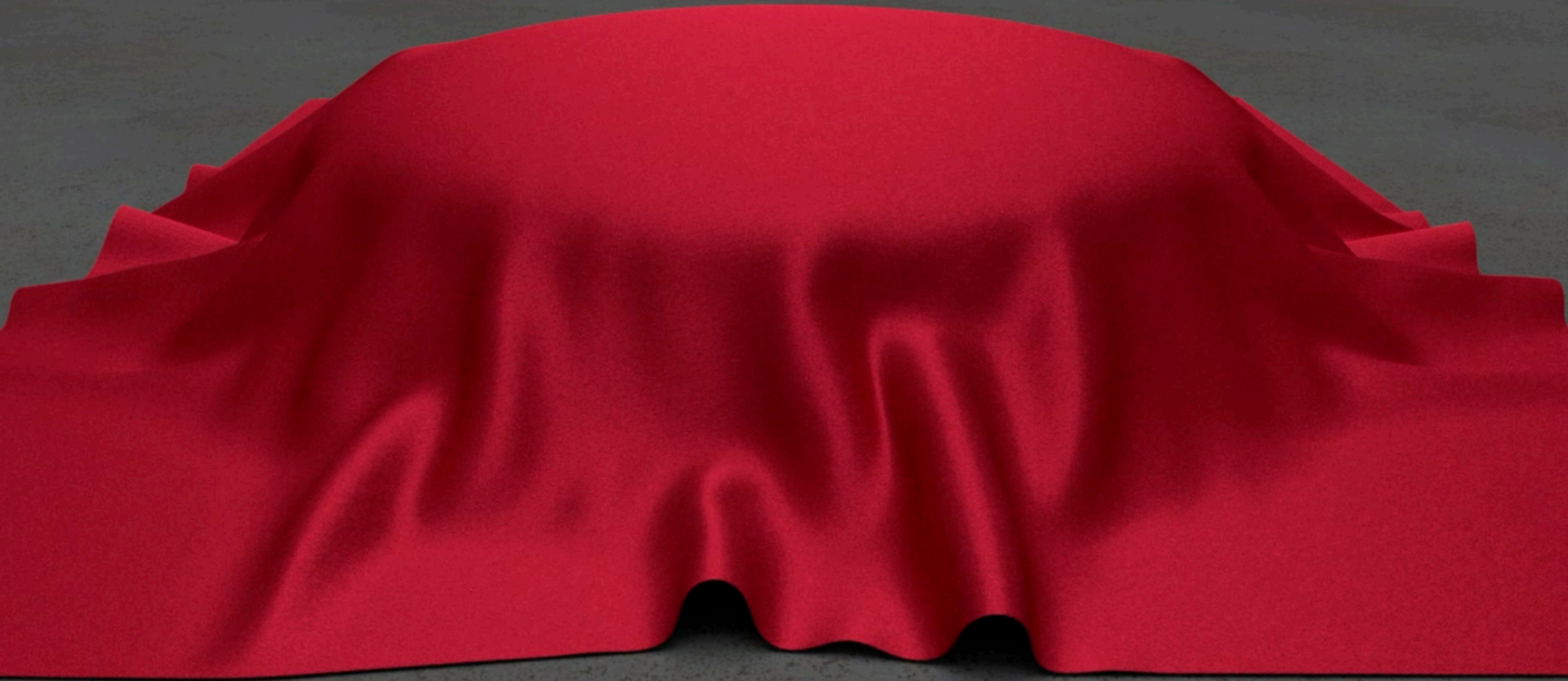
Output



Rendered Results

Virtual Cloth

[Zhao et al. 2011]



[Zhao et al. 2011]

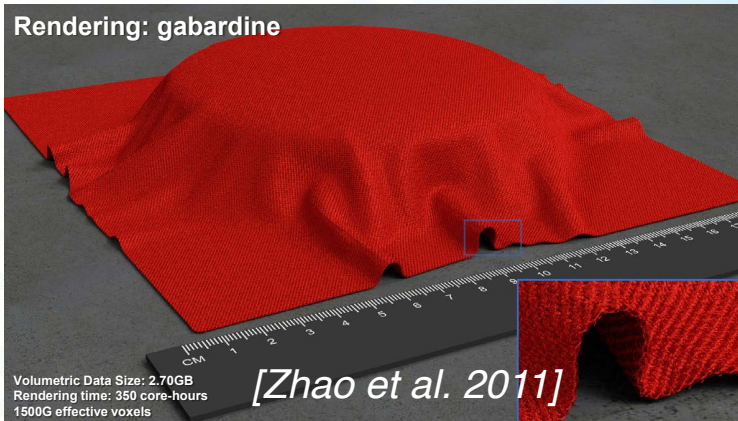
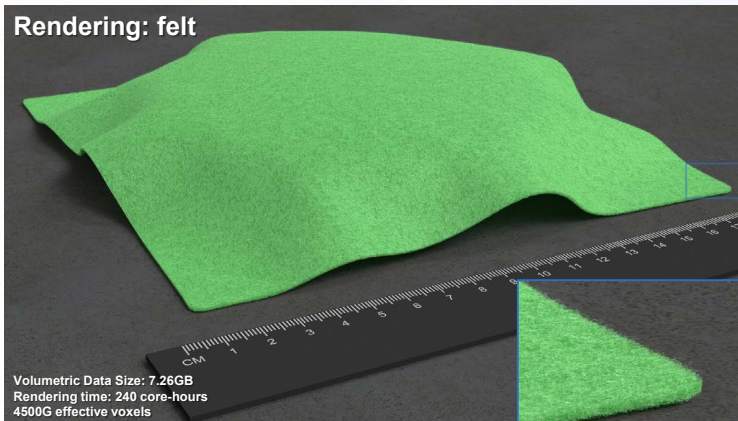
Satin / environment lighting

Volumetric Representation

Extremely realistic
(models every single
fiber and different
kinds of cloth)

Requires **CT scan**
data for
preprocessing

Large data size (TB),
long rendering times
(hundreds of hours)



Accelerated Volume Representation

- Main idea: Volume subdivided into coarse grids, with the statistical optical behavior within each grid averaged

Reduces storage,
enabling larger fabrics
rendering

No near-field

Rendering is still not
efficient enough



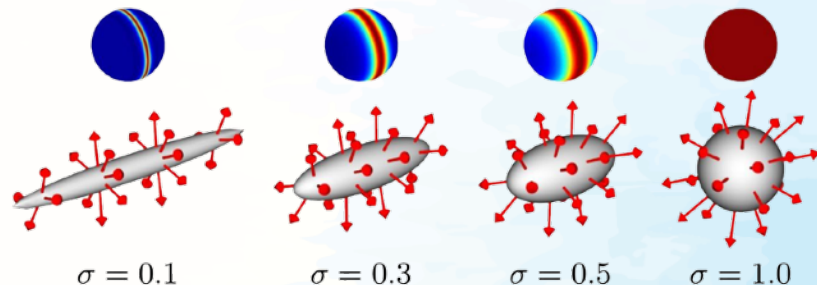
[Schröder et al. 2011]

Volumetric Cloth Shading Models

- How to shade the volume cloth data:



Micro-flake Model
[Jakob et al. 2010]



SGGX
[Heitz et al. 2015]

A more abstract mathematical description
Efficient and still realistic

Fiber-level Geometry Modeling

Modeling the fiber geometry using control parameters

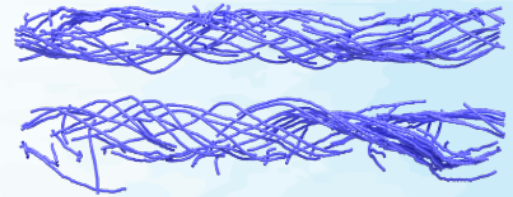
- Twist, density, migration, fly-away fibers



All fibers
in untied plies



Regular fibers



Flyaway fibers

Importance for realism

Fiber-level Geometry Modeling

Extremely realistic

No special data required. (Such as CT scans)

Large data size (TB),
long rendering times

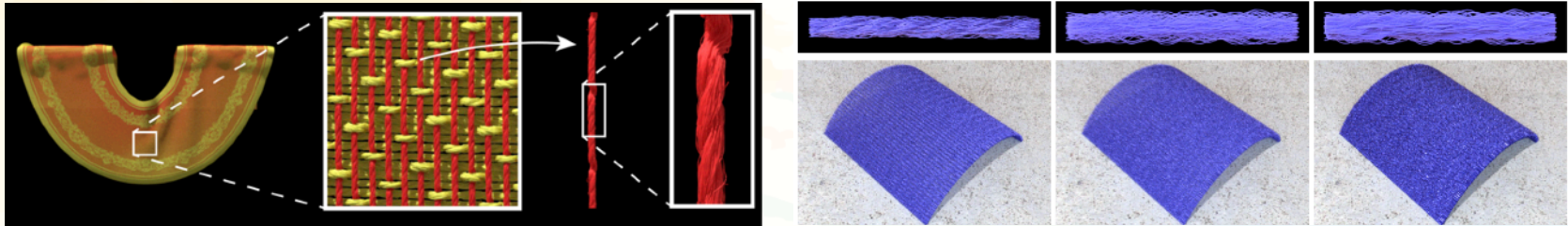
Difficult to match the
real world



[Zhao et al. 2016]

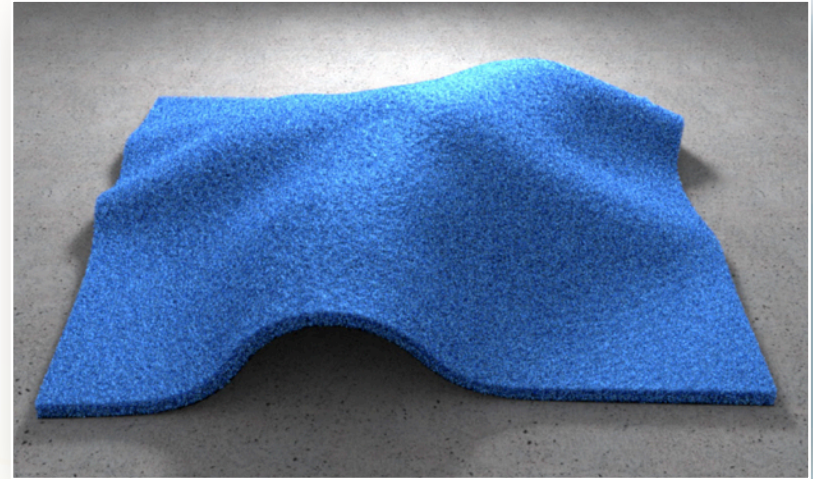
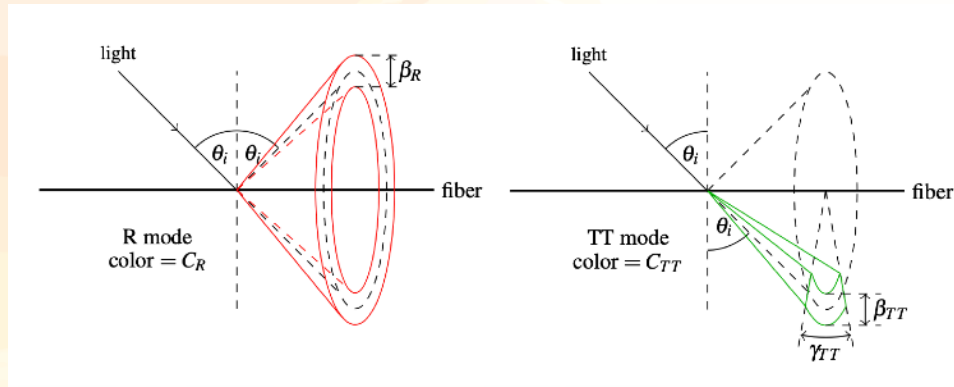
Procedural Fiber-level Geometry Representation

- **Difficulty:** Converting procedural models into data-driven formats negates their compactness and makes them impractical for rendering.
- **Solution: Semi-implicit volumetric description** computes material properties on demand, treating cloth as an anisotropic medium.
- **Pros:** Efficient rendering with **reduced memory usage**, enabling practical handling of large procedural cloth models.
- **Cons:** Rendering inefficiency, still need to ray trace fiber-level geometry.



[Luan et al. 2017]

Micro-appearance Methods - Shading



[Khungurn et al. 2015]

Micro-appearance Methods

Accurate and realistic!

Memory and time
inefficient

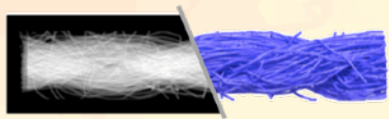


[Zhao et al. 2016]



[Khungurn et al. 2015]

Cloth Rendering Models



Fiber geometry



Rendering

Micro-appearance methods



Surface geometry

+texture maps
+normal
+tangent



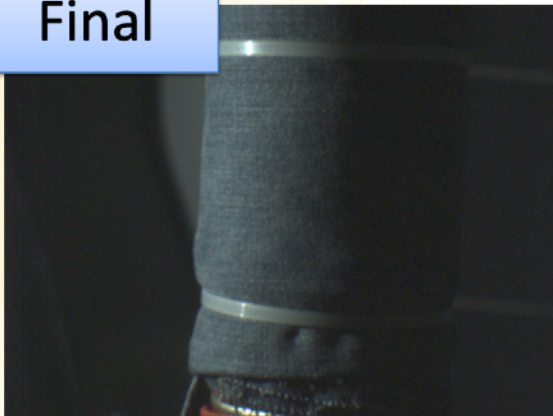
Rendering

Surface-based methods

Industry

- Diffuse Cloth

Final



Diffuse



Specular



[Hable 2010]

Industry

- Shiny Cloth

Rim Lobe



Inner Lobe



Remaining Diffuse



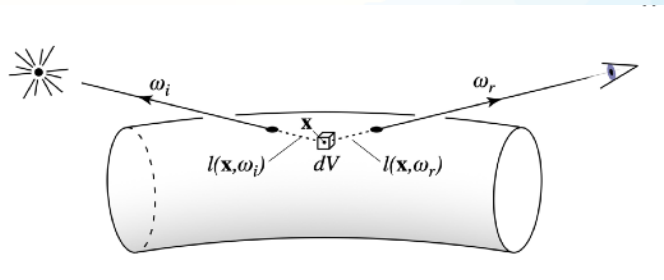
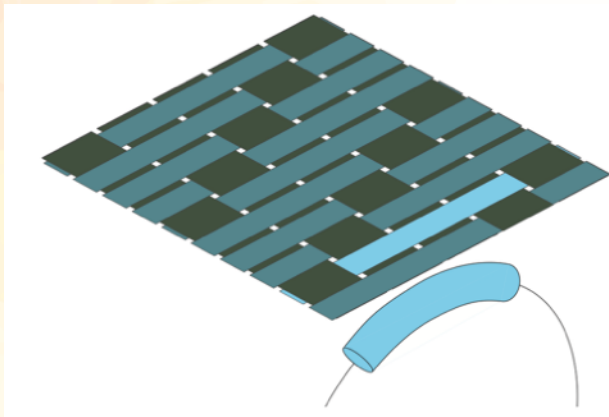
Rendering Result



[Hable 2010]

Surface-based Methods

- Surface geometry + pattern parameters (uv tangent directions)
- Simulate the BCSDF on surface



[Irawan et al. 2012]

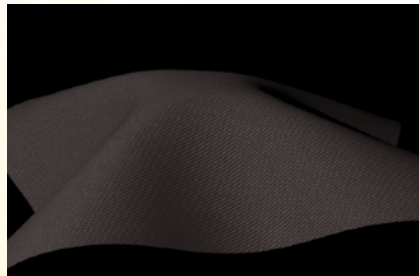
Surface-based Methods

- Matching (**surface reflectance only**)

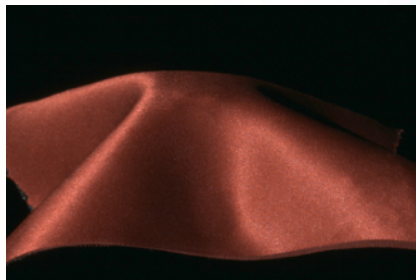
Photo



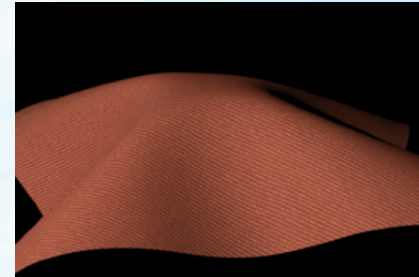
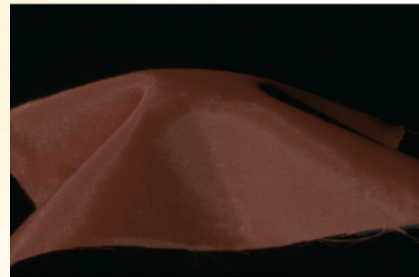
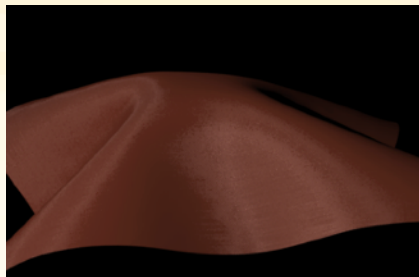
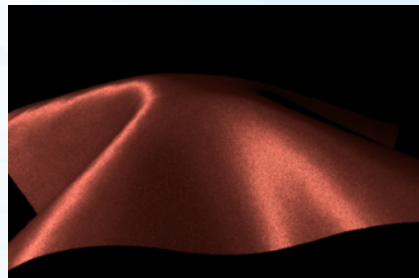
Match



Photo



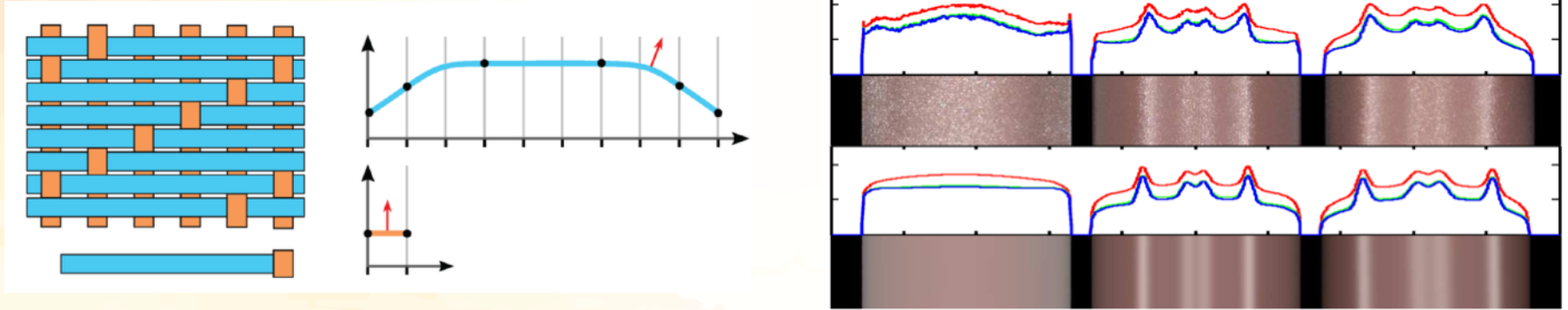
Match



[Irawan et al. 2012]

Surface-based Methods

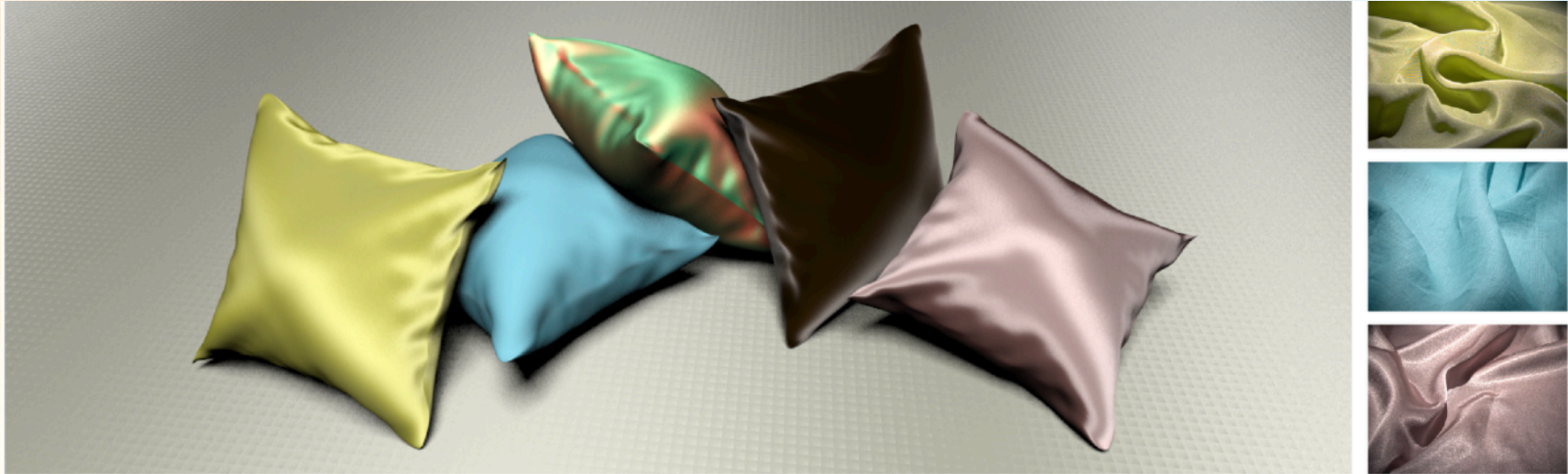
- Define the cloth as parameters
- Average the contribution (far-field only)



[Sadeghi et al. 2013]

Surface-based Model - Micro-cylinder

- Far-field only (no details)
- Surface reflectance only



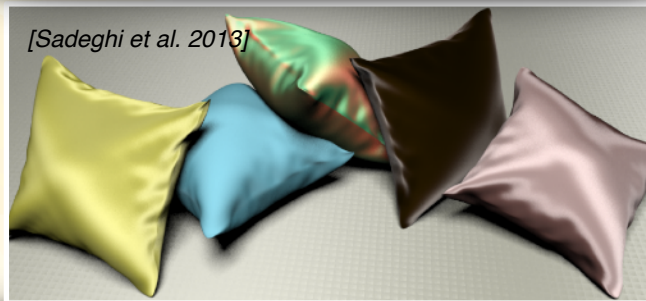
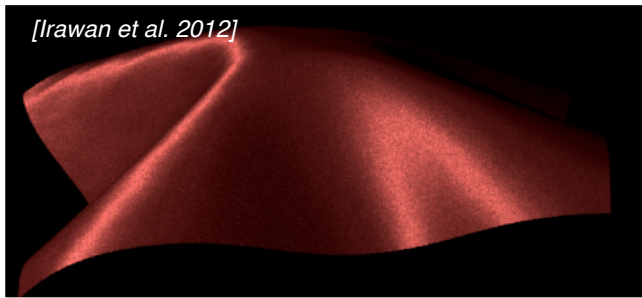
[Sadeghi et al. 2013]

Surface-based Methods

Memory and time
efficient!

Not real enough

Only surface
reflectance



[Jin et al. 2022]

Real-time Fiber-level Cloth Rendering

- Simplify fiber geometry while preserving the details
- Level-of-detail Rendering
- Focus on the Knitted Cloth

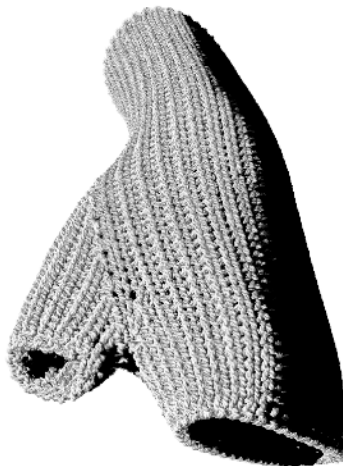
Core Fibers



LoD



Self-shadows



Ambient Occlusion



[Wu et al. 2017]

Real-time Fiber-level Cloth Rendering

Real-time Rendering

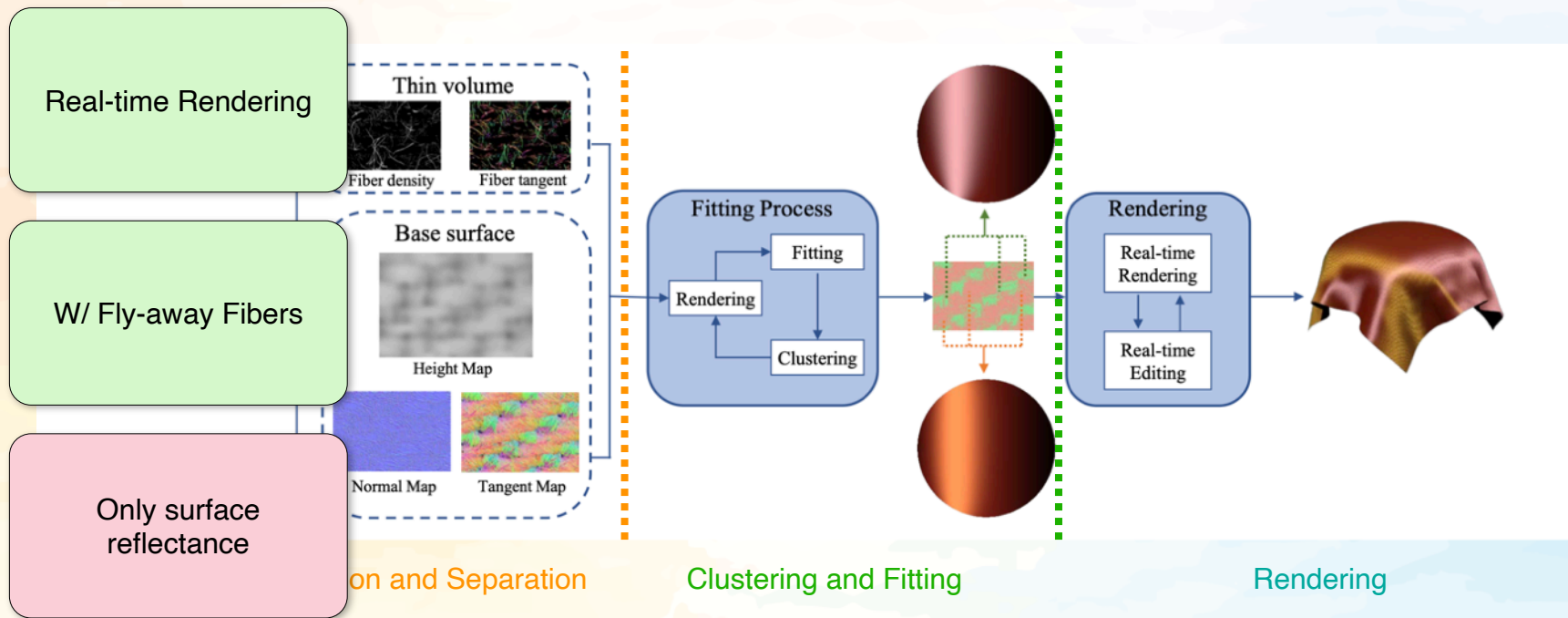
Fiber-level Details

Not Focusing on the
Cloth Shading Model



[Wu et al. 2017]

Hybrid Cloth Rendering Method



[Xu et al. 2017]

Ideal Rendering Model

- Accurate / realistic (physically-based)
- Memory efficient
- Fast to render, better real-time
- General to render all types of cloth

Reduce #fibers!

Aggregate the
appearance!

Appearance Aggregation

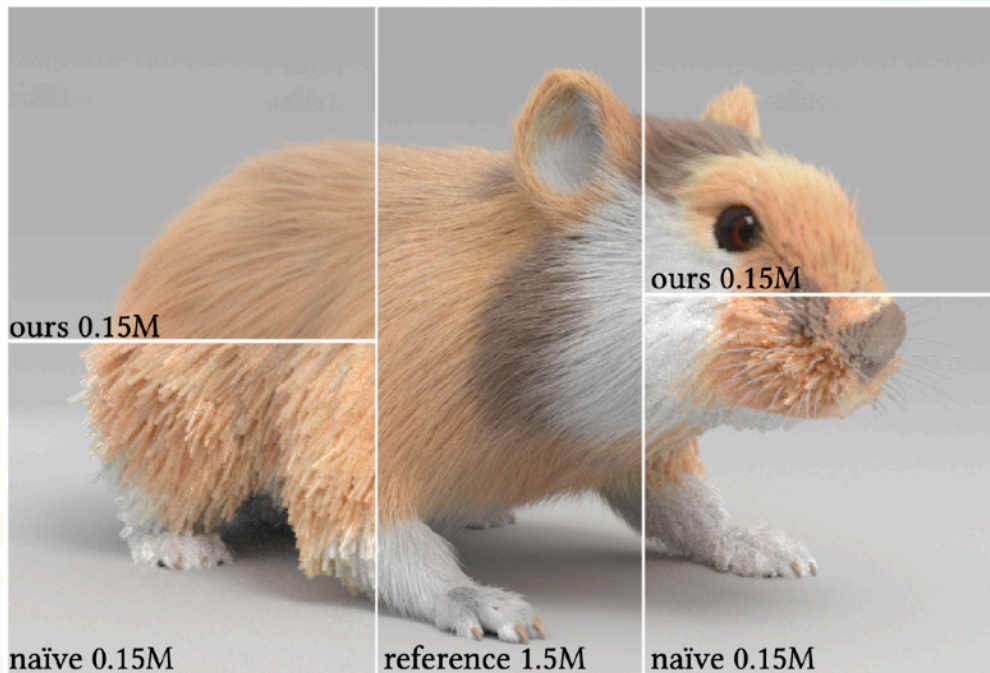
Ours:
#fibers 109.0 k



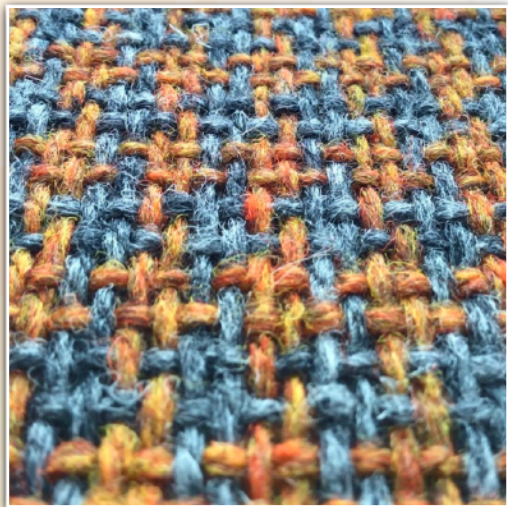
Level of details (LOD)

Why Aggregation?

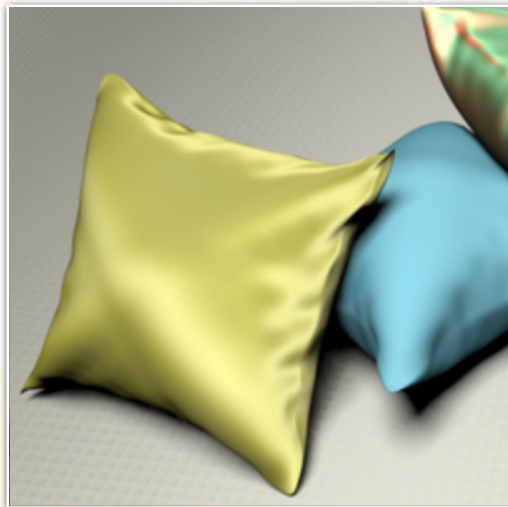
- Use fewer fibers w/ **original fibers'** appearance **✗**
 - Drier, harder and brighter!
- Use fewer fibers w/ **aggregated** appearance **✓**
 - Realistic!



Outline



Cloth 101

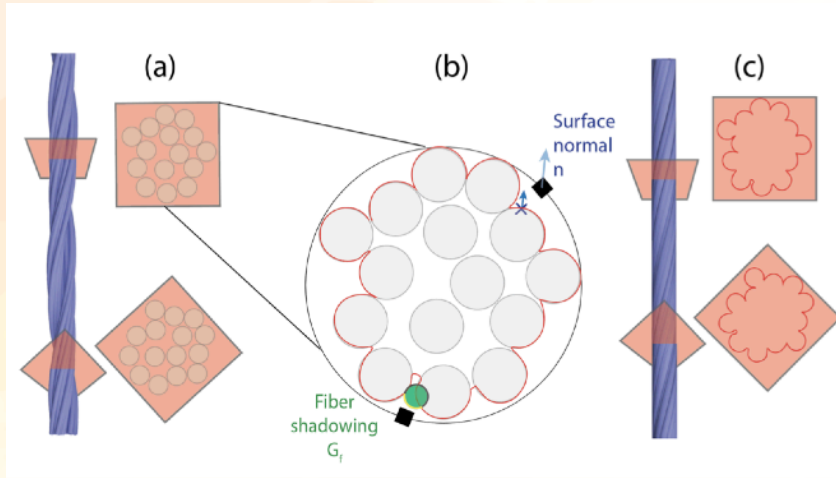


Cloth Rendering Models

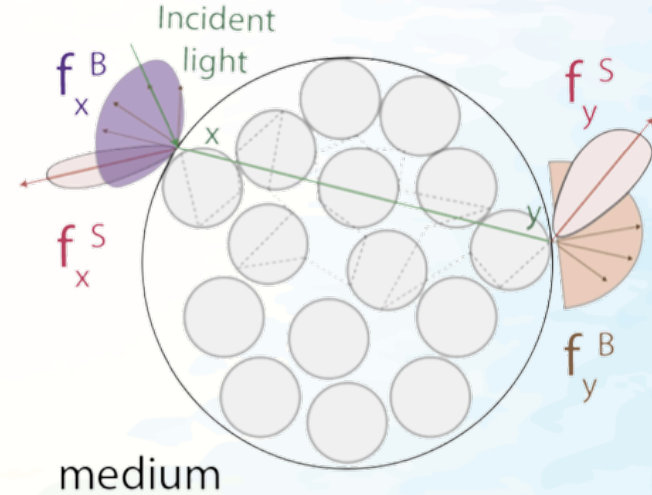


Modern Cloth Rendering
(Recent 5 Years)

Ply-based Cloth Model



Ply geometry with fiber silhouette



medium

Ply-based shading model

[Montazeri et al. 2020]

Ply-based Cloth Model

(a) Yarn curves



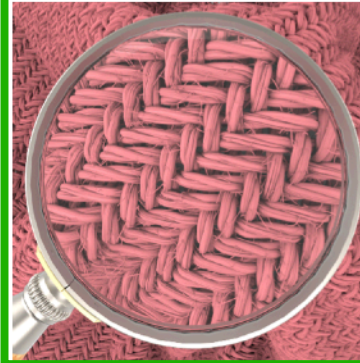
(b) Ply curves



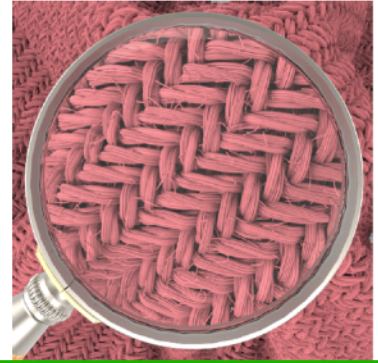
(c) Fiber details



(d) Flyaway



(e) Fiber-based



Ply-based Cloth Model

Photo

Ours

Photo

Ours

Fast rendering!

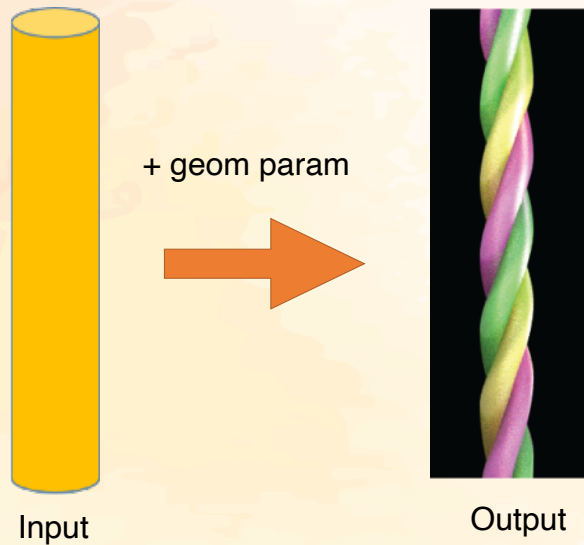
Artist driven

Inefficient for multi-ply

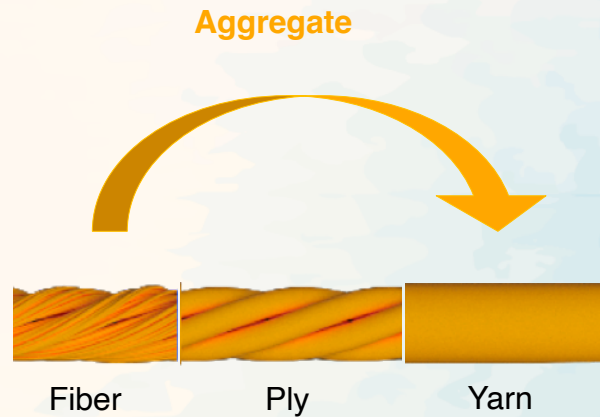
Frontlit close-up

Backlit close-up

Yarn-based Cloth Model



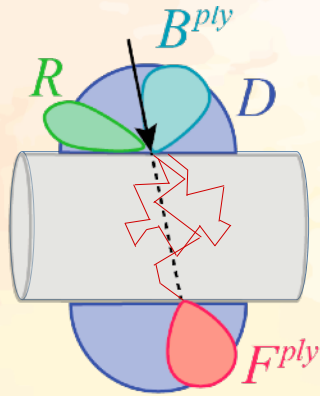
Geometric representation



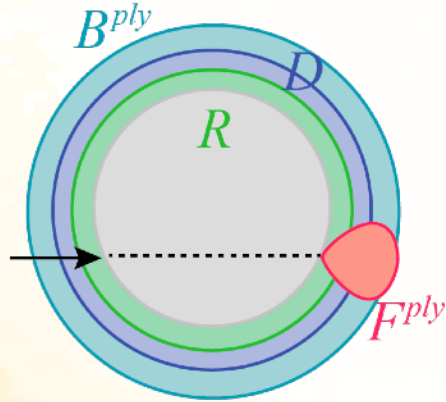
Shading

[Zhu et al. 2023]

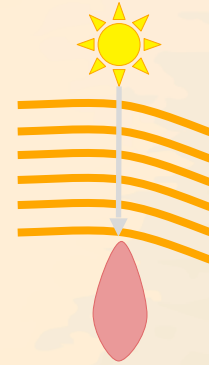
Ply-level Shading Model — Aggregating Fibers



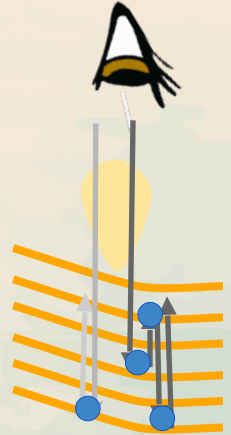
longitudinal



azimuthal



Forward scattering



Backward scattering

Extended dual scattering



Ref



Ours



Ref

Different Density



Ours



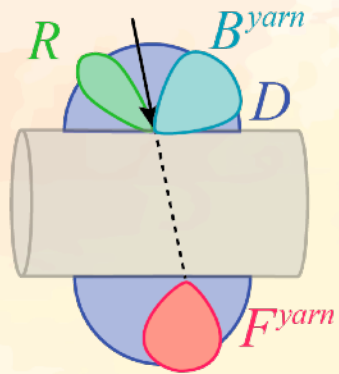
Ref

Different Twist

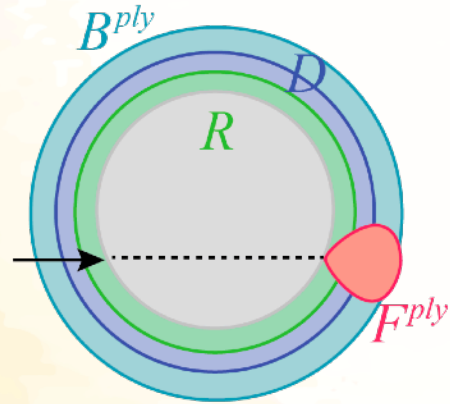


Ours

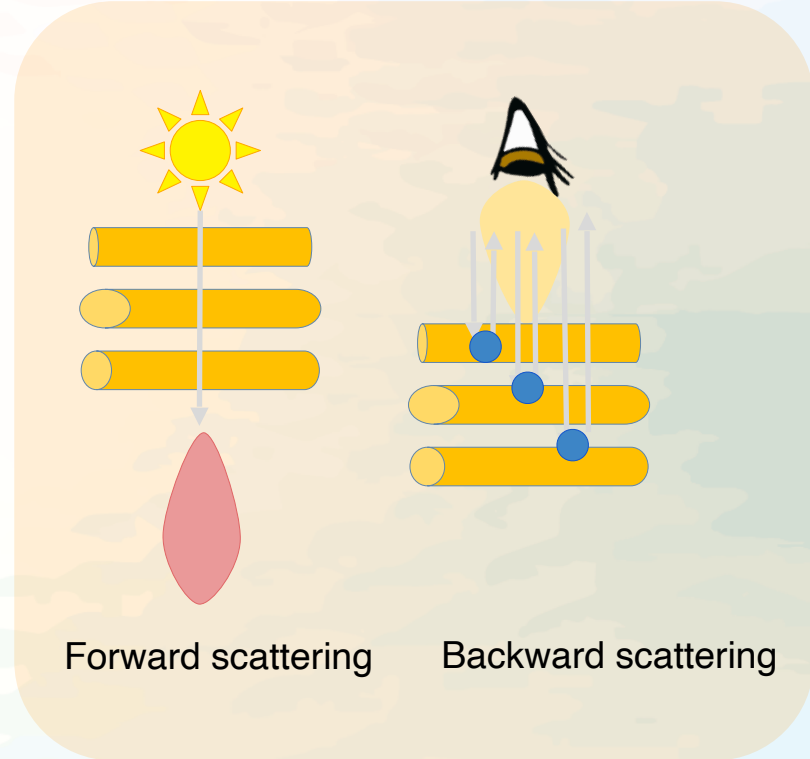
Yarn-level Shading Model — Aggregating Plies



longitudinal



azimuthal





Ref



*[Zhu et
al. 2023]*



Ref

Different Density



*[Zhu et
al. 2023]*

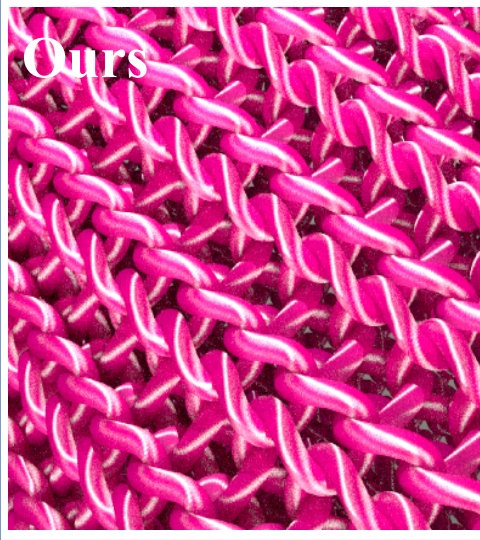


Ref

Different Twist

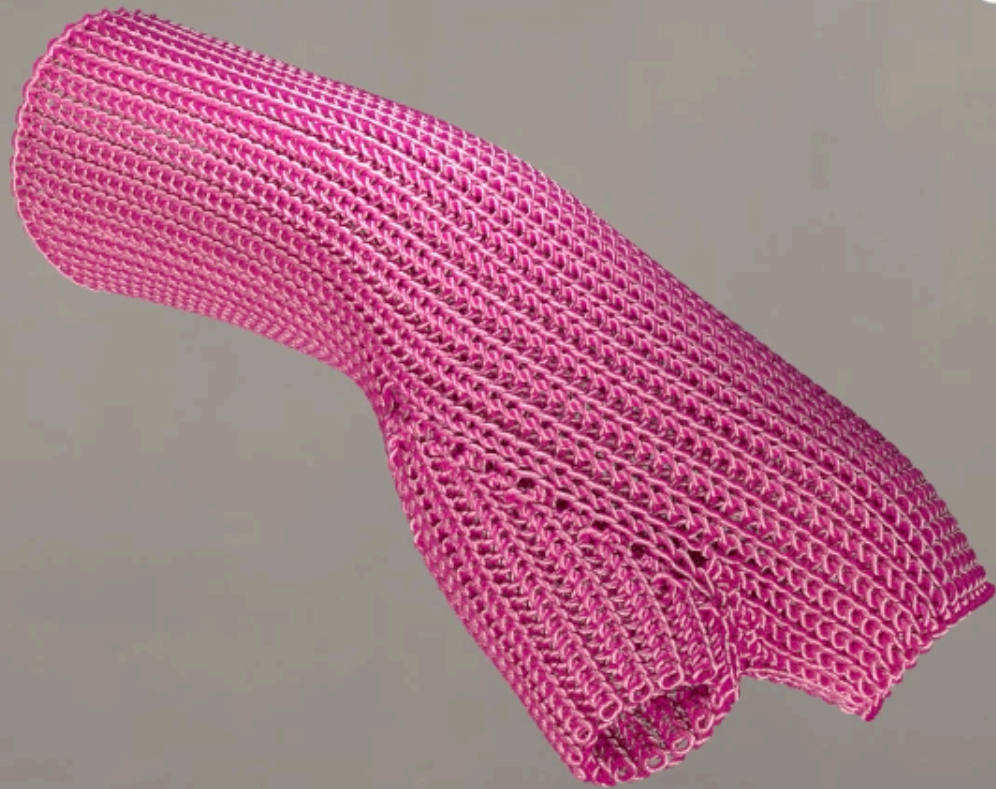


*[Zhu et
al. 2023]*



Ref

Ours

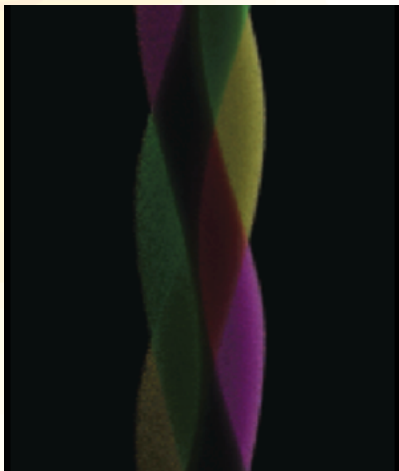


Yarn-based Cloth Model

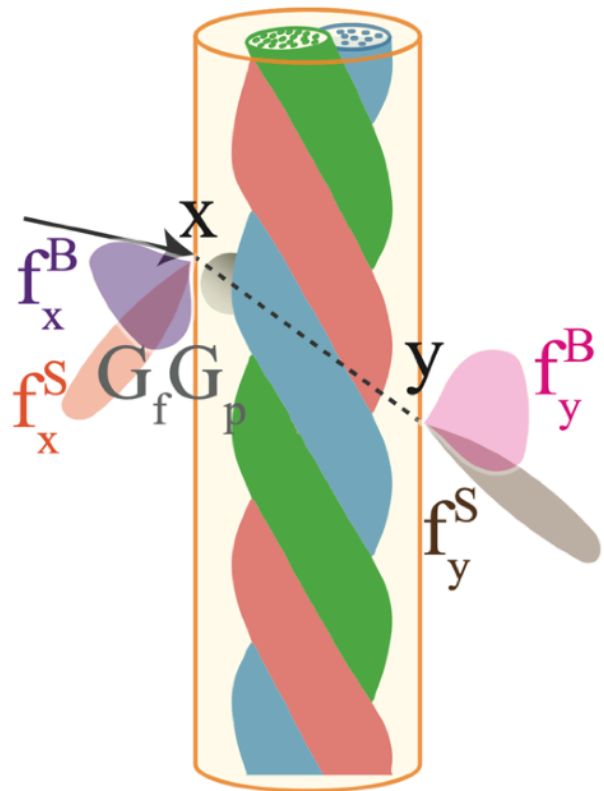
Complete shading remake

- Sampled secondary ray, and
- (More) physically-based shading (rather than dual scattering)

Previous



[Khattar et al. 2024]



New

Conclusion

Accurate!

Fast rendering!

Memory efficient!

Physically-based!

General model!

Easy to edit!

Can we do better in
performance?

Overview

- State-of-the-art surface-based cloth model
 - Realistic appearance modeling
 - Level of detail
 - Precomputation-based
 - Neural-based
- Cloth appearance reconstruction
 - Differentiable rendering
 - Generative AI
 - Data-driven reconstruction

Overview

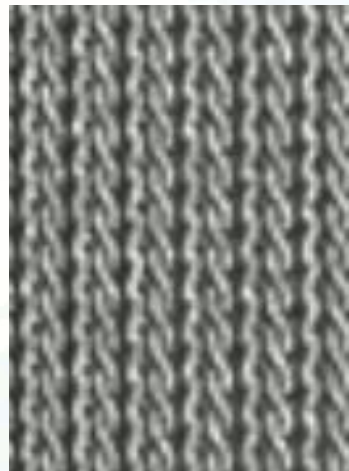
- State-of-the-art surface-based cloth model
 - **Realistic appearance modeling**
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Surface-based cloth model

- Advantages:
 - Strikes a balance in **realism**, **storage** and **performance**
 - Easier for **reconstruction**
- State-of-the-art example:
 - *A realistic surface-based cloth rendering model [Zhu et al. 2023]*

Surface-based cloth model

- *A realistic surface-based cloth rendering model [Zhu et al. 2023]*
 - **Realism:** Accounts for complex visual effects.
 - **Asymmetric reflection highlight**



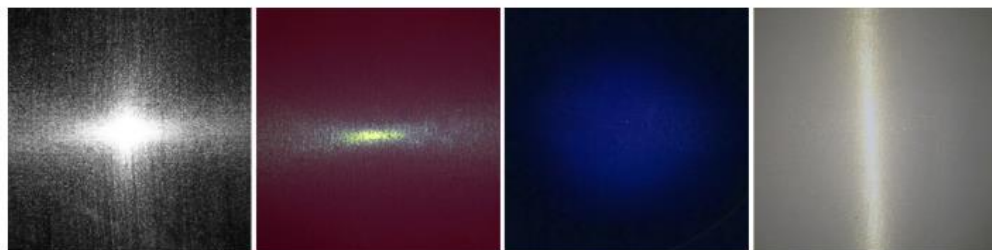
Photo

Render

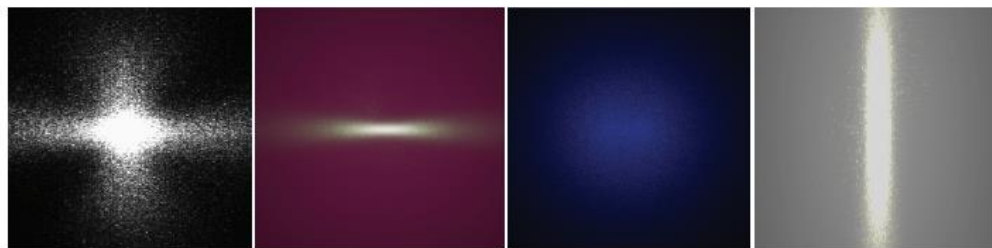
Surface-based cloth model

- *A realistic surface-based cloth rendering model [Zhu et al. 2023]*
 - **Realism:** Accounts for complex visual effects.
 - **Cross shaped transmission highlight**

Photo



Render



Surface-based cloth model

- *A realistic surface-based cloth rendering model [Zhu et al. 2023]*
 - **Realism:** Accounts for complex visual effects.
 - **Transparency**



Render

Surface-based cloth model

- *A realistic surface-based cloth rendering model [Zhu et al. 2023]*
 - Yarn-level geometric maps + yarn-level shading

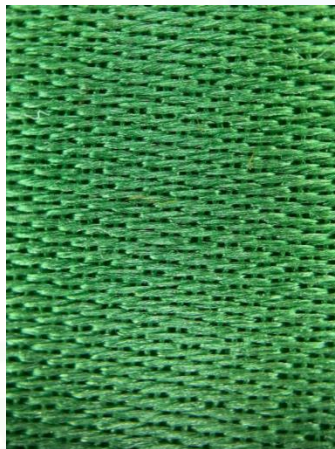


Photo reference

Surface-based cloth model

- *A realistic surface-based cloth rendering model [Zhu et al. 2023]*
 - Yarn-level geometric maps + yarn-level shading



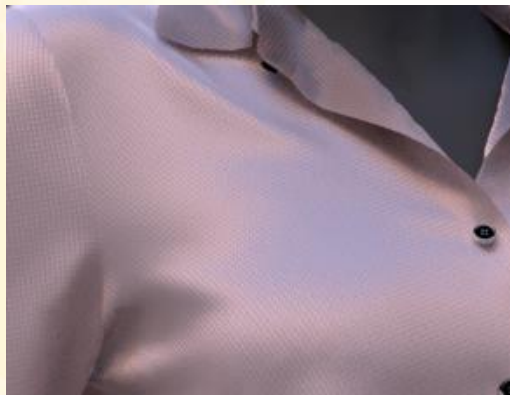
Photo



Render w/ [Zhu et al. 2023]

Surface-based cloth model

- *A realistic surface-based cloth rendering model [Zhu et al. 2023]*
 - **Realism:** Procedural noise for irregularity.



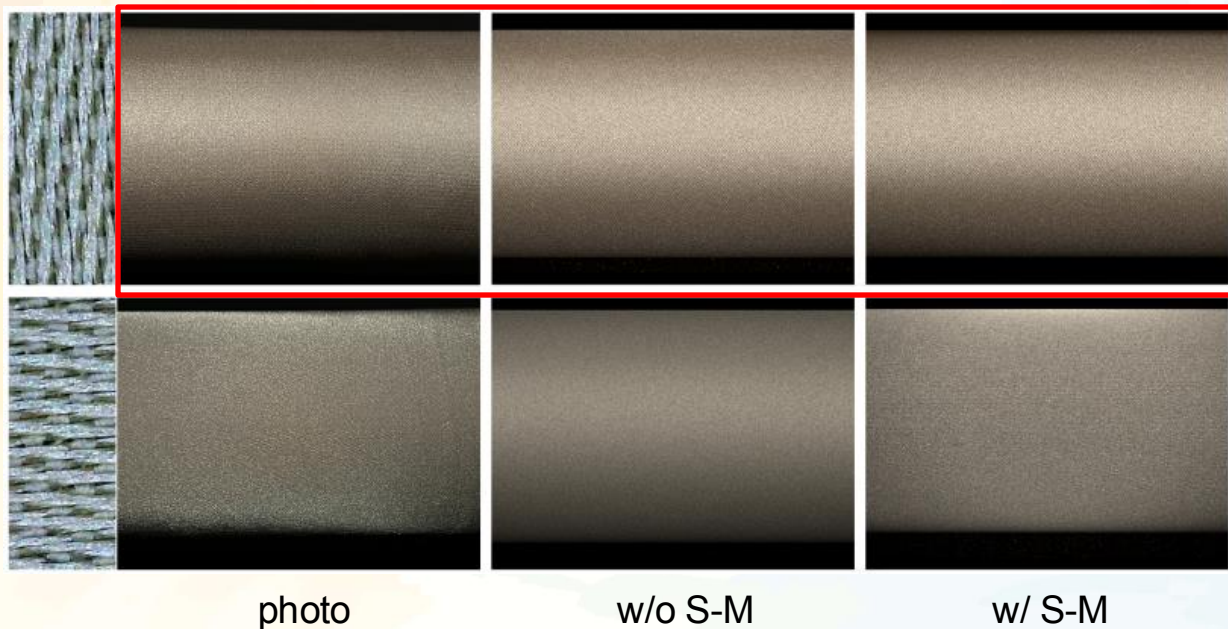
w/o noise



w/ noise

Surface-based cloth model

- A realistic surface-based cloth rendering model [Zhu et al. 2023]
 - **Realism: Shadowing and masking**, considering per-pixel effective area.



Surface-based cloth model



Photo



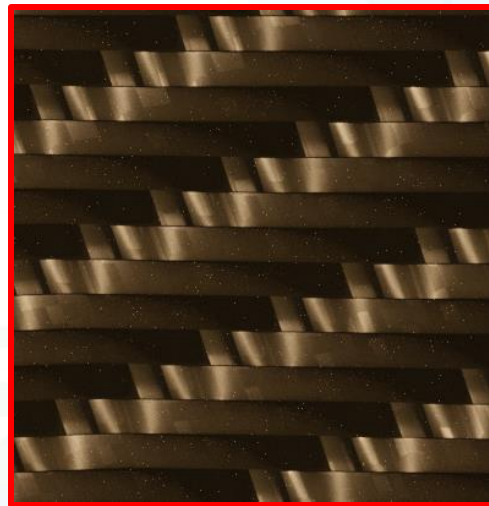
Render w/ [Zhu et al. 2023]

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Cloth Level-of-Details

- Multi-scale problem
 - Diffuse from far away but very sparkly close up
 - Requires high SPP (samples-per-pixel) to resolve such sparkles



Cloth Level-of-Details

- Multi-scale problem
 - **1K** SPP. For real-time applications we need to reduce it to **1** SPP.



Photo



Render w/ [Zhu et al. 2023]

120.2 FPS (8.3 ms/frame)

▼ Graphs

	0.300		Diffuse Weight
0.025	0.190	0.120	Specular Reflecta
	0.400		Specular Roughne
	0.000		Ply Twist Angle
	0.000		Ply Flattening
0.000	0.000	0.000	Flyaway Sheen Co
	0.050		Flyaway Thicknes
	0.500		Flyaway Roughne:
	0.000		Texture Rotation
1000.000	1000.000		Texture Scale
	0		SAT Mode

Ply Normal Texture: C:\Users\matthiang\

Texture info: 256x256 (RGBA32Float)



Remove texture

Ply Tangent Texture: C:\Users\matthiang\

Texture info: 256x256 (RGBA32Float)



Remove texture

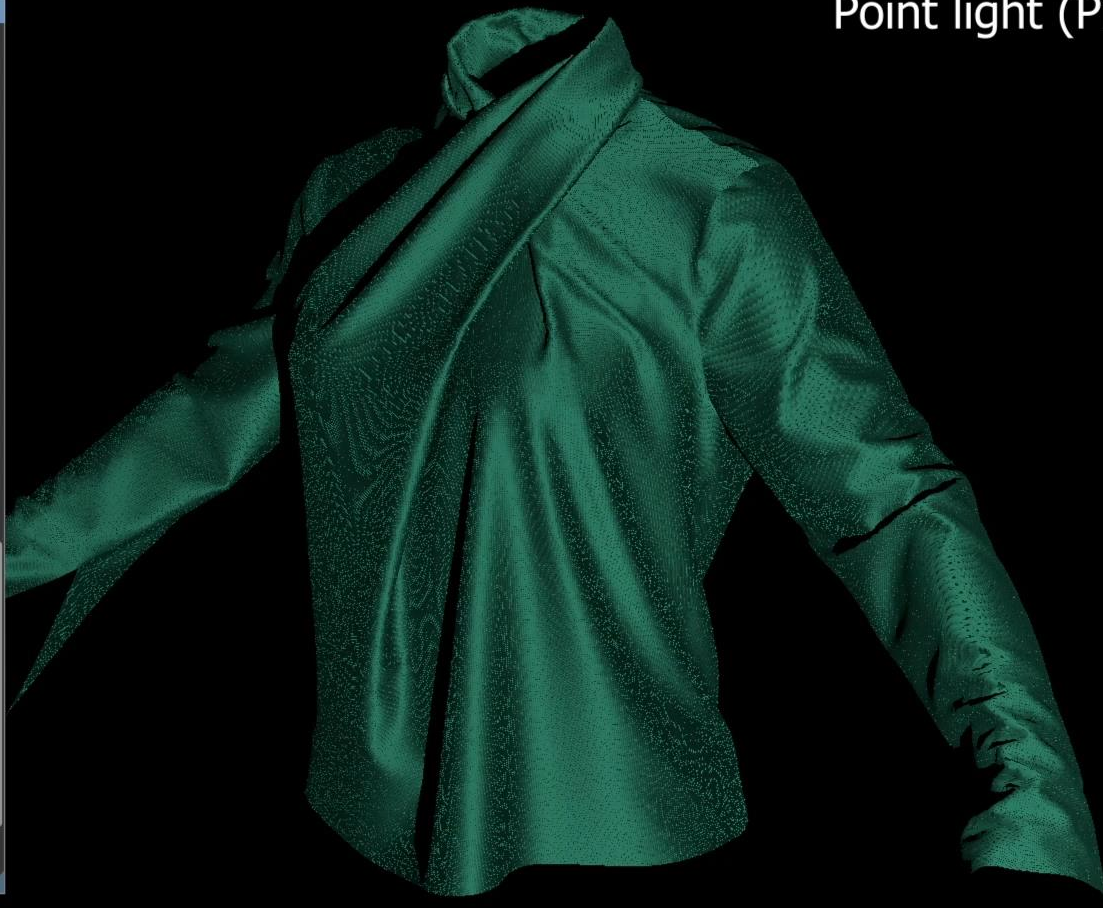
Spline ID Texture missing!

Spline UV Texture missing!

► Grid volumes

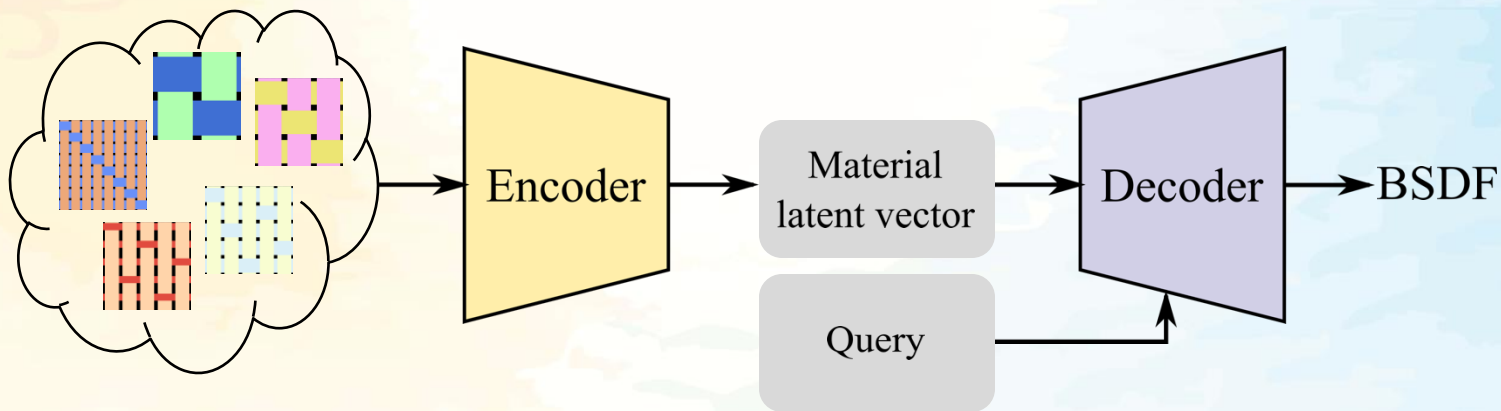
► Statistics

Point light (Previous)



Cloth Level-of-Details

- *Real-time neural woven fabric rendering [Chen et al. 2024]*
 - **Encoder** takes in a woven material (geometric maps + shading parameters)
 - **Decoder** takes in a query (viewing + lighting + footprint) and returns BRDF value



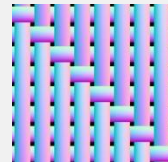
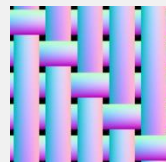
Cloth Level-of-Details

- *Real-time neural woven fabric rendering [Chen et al. 2024]*
 - **Encoder** is **universal**
 - Improvement over NeuMIP [] which is trained per-material
 - Data set: 7 patterns, 475 materials.

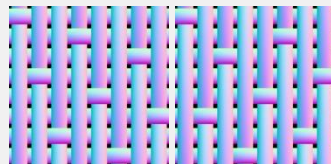
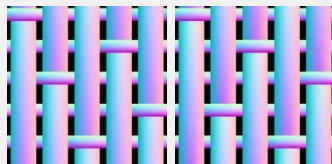
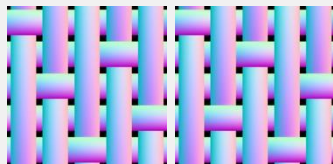
Plain



Twill

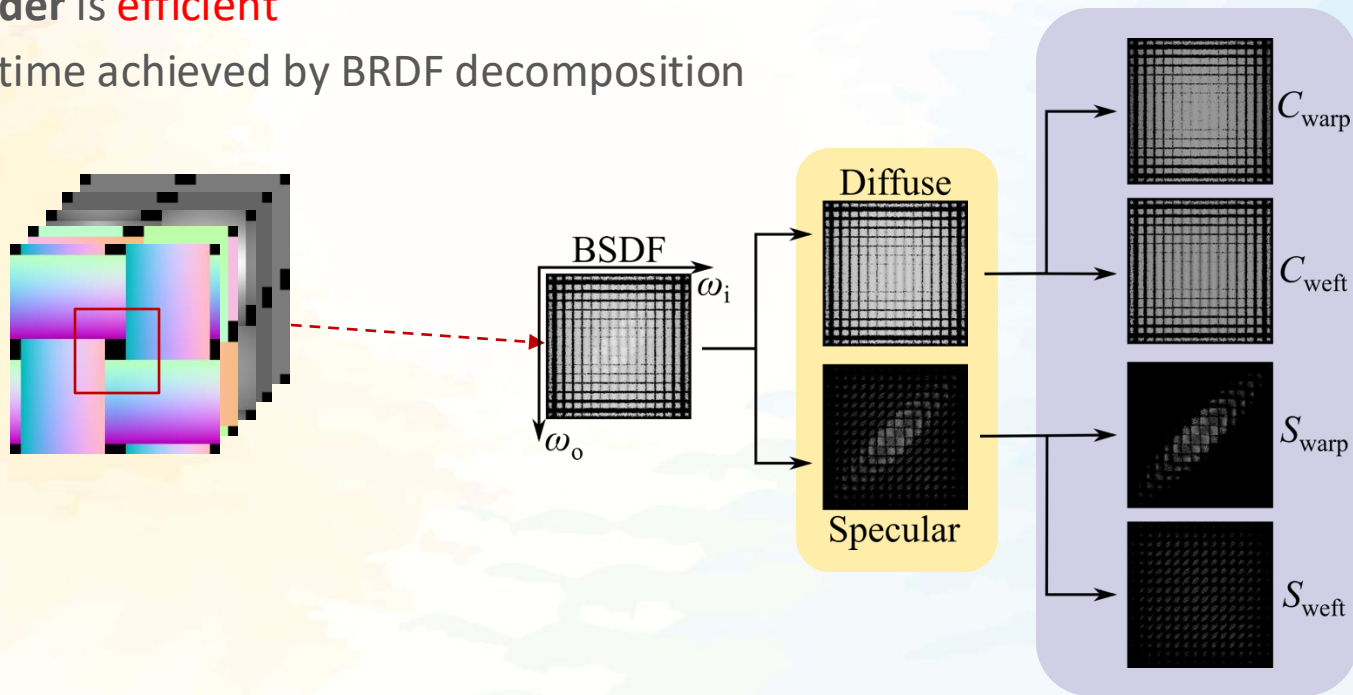


Satin



Cloth Level-of-Details

- *Real-time neural woven fabric rendering [Chen et al. 2024]*
 - **Decoder** is **efficient**
 - Real-time achieved by BRDF decomposition



Cloth Level-of-Details

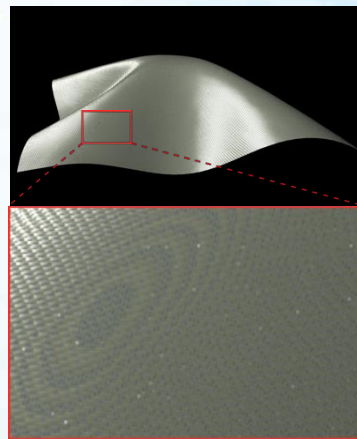
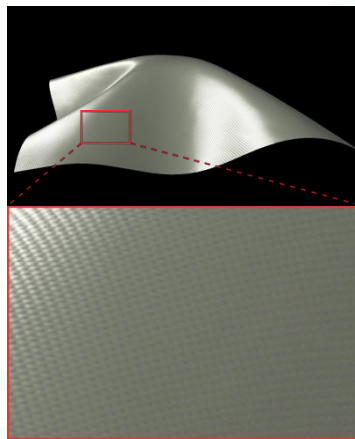
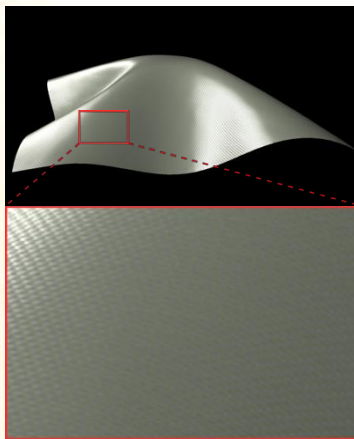
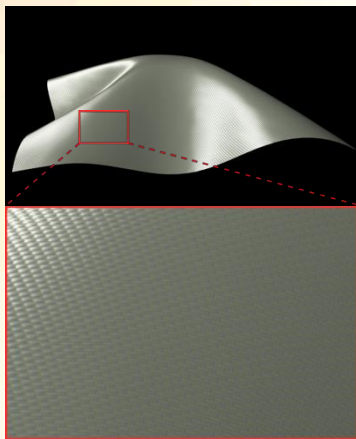
- *Real-time neural woven fabric rendering [Chen et al. 2024]*

GT
1177.6 ms

Ours
17.2 ms

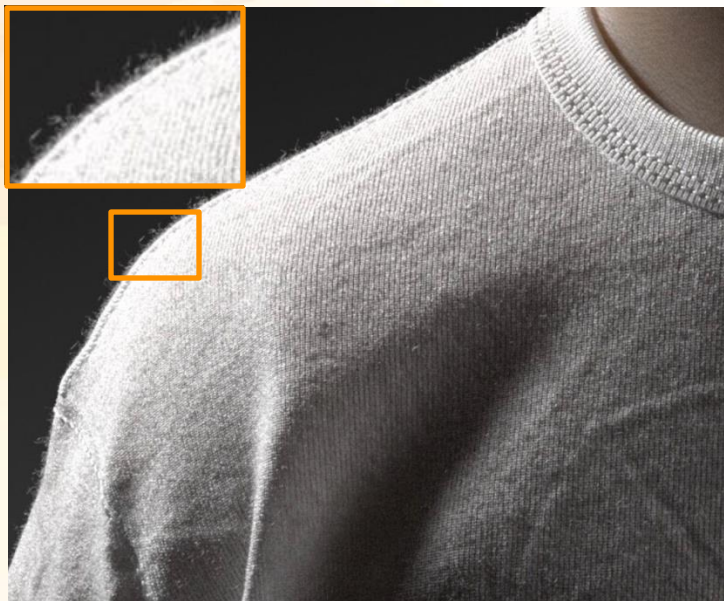
NeuMIP
9.6 ms

Single-scale, 4 SPP
18.4 ms



Limitations

- Flyaways, irregularity and non-repeating features.



Limitations

- Precomputation-based approach [Zhu et al. 2024]
 - No interactive editing.
- Neural-based approach [Chen et al. 2024]
 - No importance sampling. Limited by network representation ability.

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Cloth appearance reconstruction

- Hot topic in many fields that involve full-body digital avatar such as AR/VR.
- The ultimate goal:
 - *Rapid and automatic appearance reconstruction from sparse in-the-wild sensor data that can be rendered under novel geometric deformation, with a novel viewport and under novel lighting conditions, while support appearance editing, all in real-time framerate.*



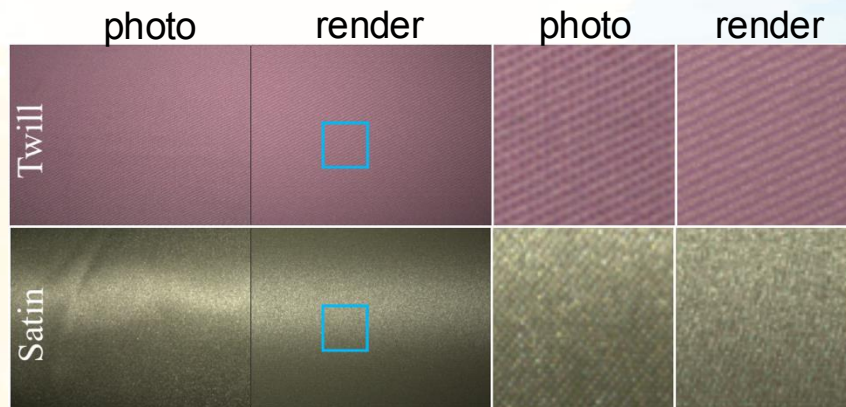
Photo



Render w/ [Zhu et al. 2023]

Differentiable rendering

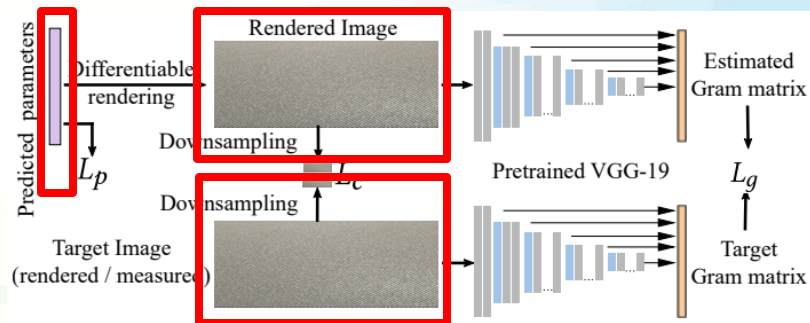
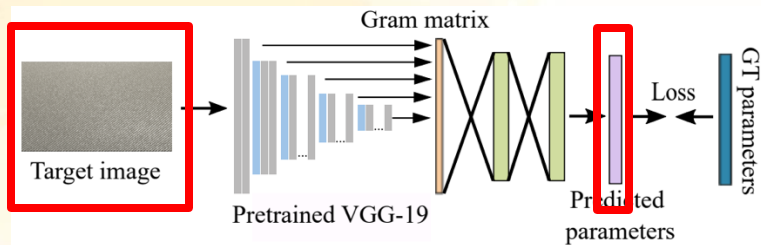
- Auto material parameters estimation from a photograph using gradient decent.
- Most effective with scene parameters known
 - [Jin et al. 2022] Simple rig to measure light, camera and geometry



[Jin et al. 2022]

Differentiable rendering

- Subject to local minimums
 - [Jin et al. 2022] Two-stage estimation
 - Initialization w/ an MLP
 - Optimization w/ differentiable rendering



Generative AI

- Diffusion excels at image-to-image translation
- Material reconstruction as intrinsic image decomposition

Input image



Albedo



Normal



Irradiance



Roughness



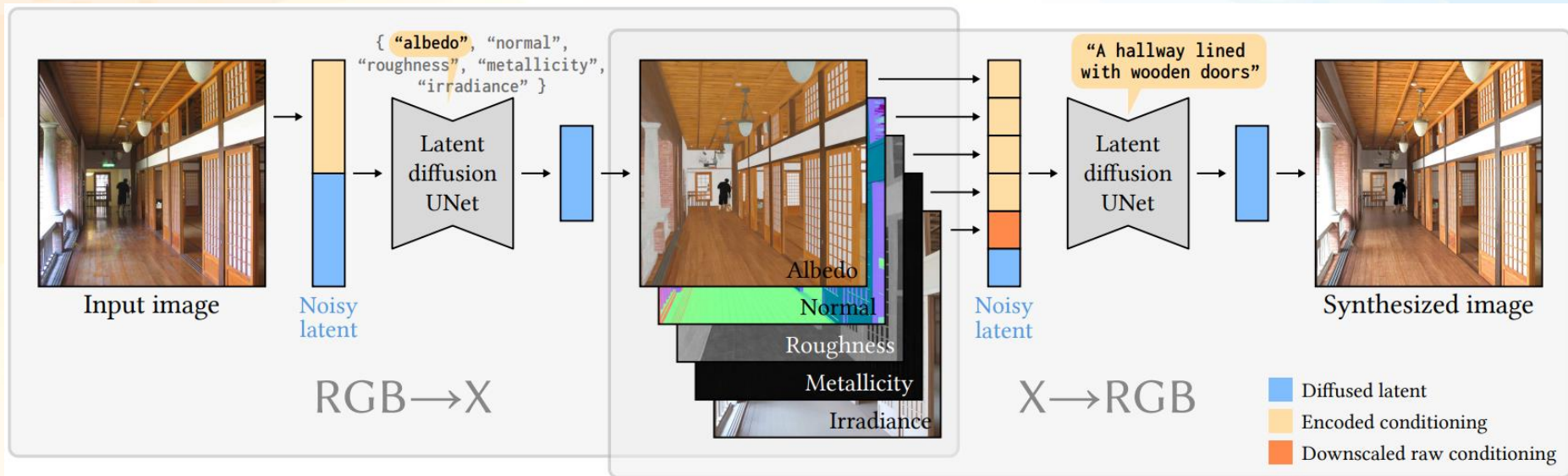
Metallicity



RGB $\leftrightarrow$ X [Zheng et al. 2024]

Generative AI

- RGB→X: reconstruction
- X→RGB: rendering



$RGB \leftrightarrow X$ [Zheng et al. 2024]

Generative AI

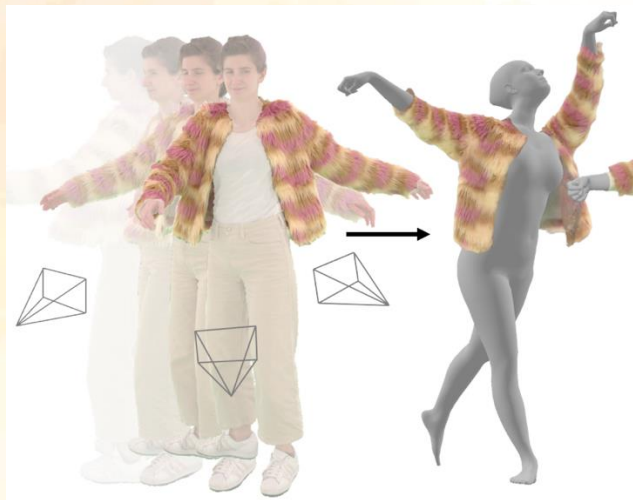
- Conditional editing via a text prompt
- Limitations: primarily 2D. No novel pose or novel view.



RGB↔X [Zheng et al. 2024]

Data-driven reconstruction

- 3D Gaussian splatting.
- Data-driven. Novel-view synthesis. Good at volumetric appearance for fabrics.



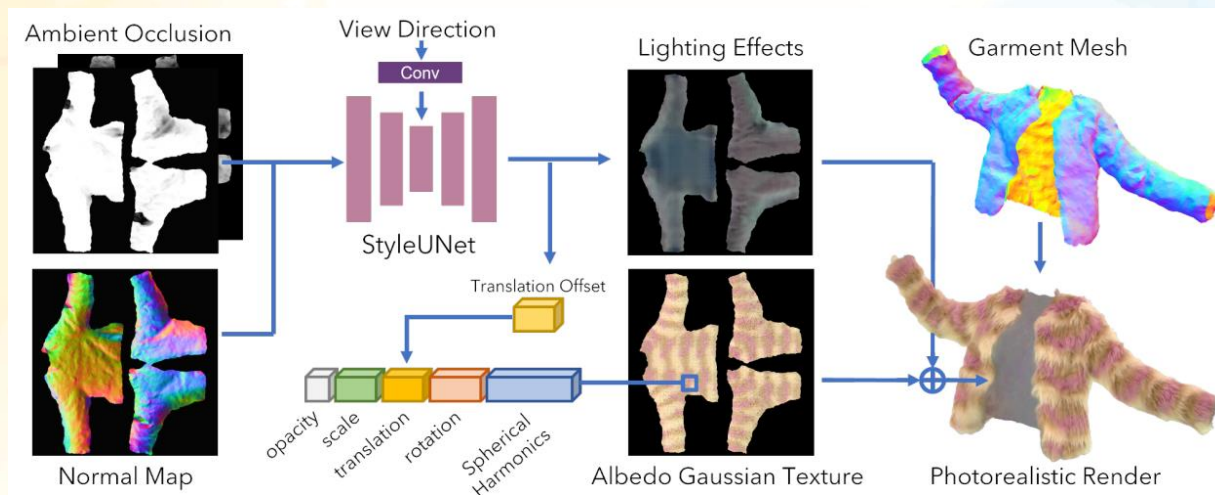
Gaussian Garments [Rong et al. 2024]



PhysAvatar [Zheng et al. 2024]

Data-driven reconstruction

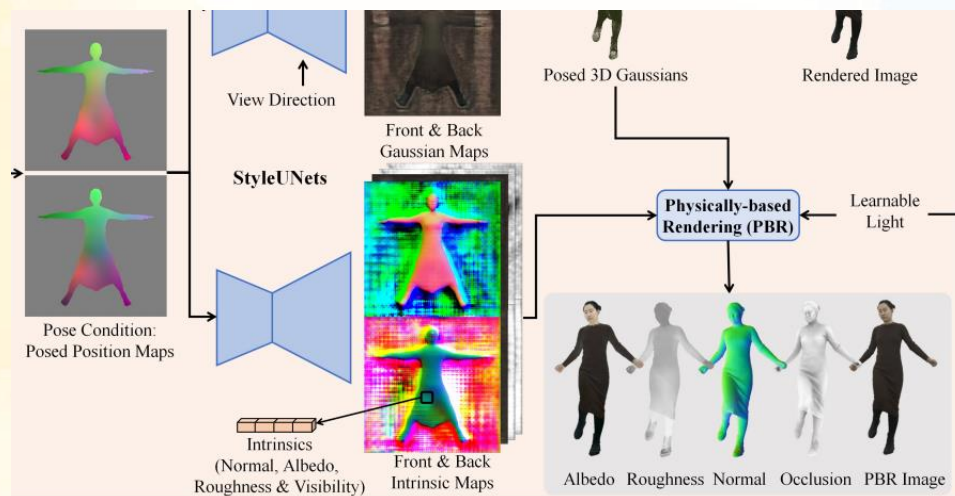
- Generalize to novel pose
 - Learning **pose-dependent 3DGS parameter offsets** using local geometric info from multi-view **video** sequences.



Gaussian Garments [Rong et al. 2024]

Data-driven reconstruction

- Generalize to novel pose and novel lighting.
 - Learning **pose-dependent *intrinsic maps*** using local geometric info from multi-view **video** sequences.



[Li et al. 2024]

Data-driven reconstruction

- Limitations:
 - Lots of data. Slow reconstruction.
 - Not easy for editing.
 - Visual quality is not thoroughly analyzed.

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