Lec 18 - Advanced Topics in Rendering

Advanced Light Transport

- Unbiased light transport methods
    - Bidirectional path tracing (BDPT)
    - Metropolis light transport (MLT)
- Biased light transport methods
    - Photon mapping
    - Vertex connection and merging (VCM)
- Instant radiosity (VPL / many light methods)
    - 间接光表示为很多小光源

Biased vs. Unbiased Monte Carlo Estimators

- 无偏：An unbiased Monte Carlo technique does not have any systematic error
    - 无论取多少样本，期望永远是对的
- 有偏：其他情况
    - One special case, the expected value converges to the correct value as infinite #samples are used — consistent 有偏，但能收敛到无偏

Bidirectional path tracing (BDPT 双向路径追踪)

- Traces sub-paths from both the camera and the light (半路径)
- Connects the end points from both sub-paths 半路径末端互相连接，形成通路
- 好处：Suitable if the light transport is complex on the light’s side
    - 比如，光源第一跳大多是diffuse
- 缺点：Difficult to implement & quite slow 能做出来基本能自己写渲染器了

Metropolis light transport (MLT)

- A Markov Chain Monte Carlo (MCMC) application
    - 马尔可夫链帮助采样
        - 马尔可夫链：根据当前样本，根据一个概率分布，生成下一个相近的样本
    - Jumping from the current sample to the next with some PDF
- 可以做到以任意函数为pdf生成样本
- Key idea: Locally perturb an existing path to get a new path 有一个路径的情况下，可以生成相似的路径
- 好处：Very good at locally exploring difficult light paths 有了种子，就能找到更多相似的
    - Caustics, Indirect Light Source
- 缺点：
    - Difficult to estimate the convergence rate
        - Monte Carlo可以估计Variance，可以量化
    - Does not guarantee equal convergence rate per pixel
    - So, usually produces “dirty” results 看上去比较脏
    - Therefore, usually not used to render animations

Photon Mapping (光子映射)

- A biased approach & A two-stage method
- Very good at handling Specular-Diffuse-Specular (SDS) paths and generating caustics

很多种实现方法，这里是其中一种：

Photon Mapping — Approach (variations apply)

- Stage 1 — photon tracing
  - 光源出发直到diffuse，Emitting photons from the light source, bouncing them around, finally recording photons on diffuse surfaces
- Stage 2 — photon collection (final gathering)
  - 摄像机出发sub-paths,直到diffuse, Shoot sub-paths from the camera, bouncing them around, until they hit diffuse surfaces
- Calculation — local density estimation 局部光子密度估计
  - Idea: areas with more photons should be brighter
  - For each shading point, find the nearest N photons (通过树状结构实现算法，N是固定的). Take the surface area they over 面积计算，然后光子密度=光子数量/面积
  - 光子数量少：面积大，噪声大；光子数量大：模糊
- 模糊是因为有偏
  - Local Density estimation dN / dA != ΔN / ΔA 光子密度估计在数量趋向无限时才与真正光子密度相等，所以biased but consistent!

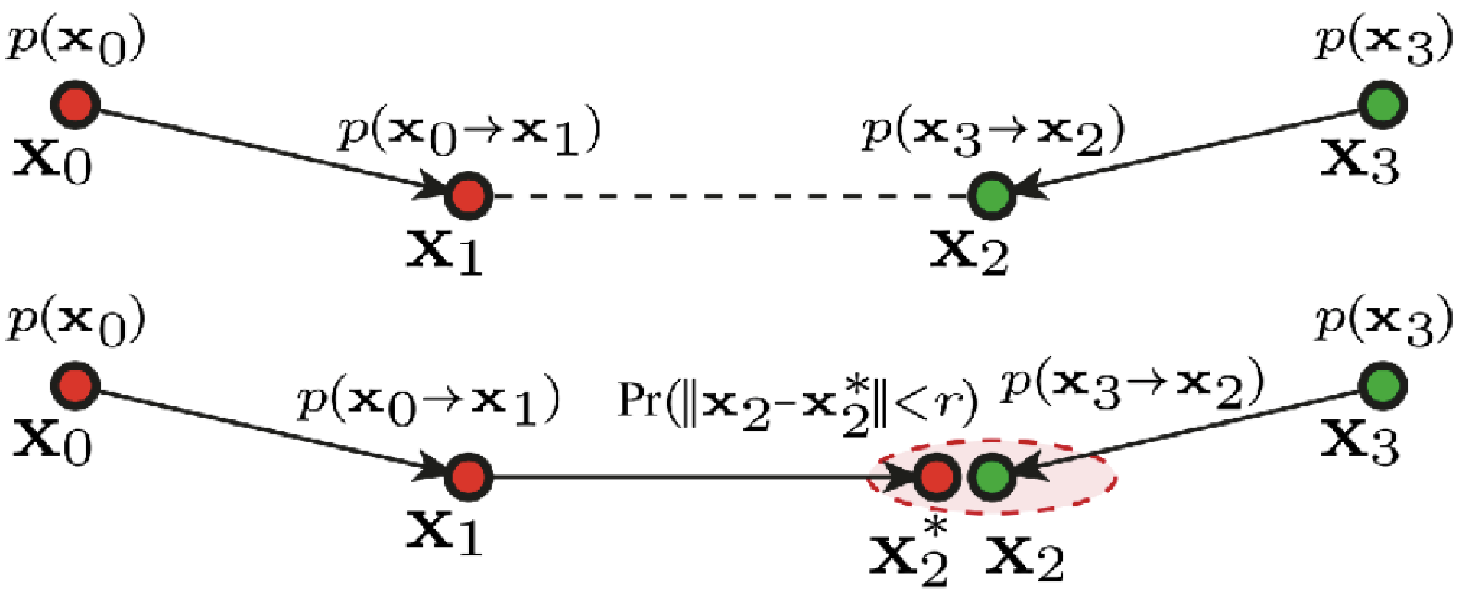
有偏和无偏的实用辨别方法：

- 在渲染中：Biased有偏 == blurry模糊
- 一致的Consistent == not blurry with infinite #samples

如何理解 (un)biased render？ - 知乎

Vertex Connection and Merging (VCM)

- A combination of BDPT and Photon Mapping
- Key idea: Let's not waste the sub-paths in BDPT if their end points cannot be connected but can be merged, but Use photon mapping to handle the merging of nearby "photons"



- 比如，x_2和x_2^* 在同一个面上，但是没有重合，按照BDPT，这种就是浪费
- 但是VCM决定利用这种情况，把其中一半光路转化成光子，进行Photon Mapping一样的计算

Instant Radiosity (IR)

- aka many-light approaches 很多光源的方法
- Key idea: Lit surfaces can be treated as light sources 被照亮的表面就像是光源
- 模拟从光源发出光线，打到的地方相当于二级光源。如果此时Sample某个场景点的颜色，那么遍历这些二级光源，叠加计算即可
- Shoot light sub-paths and assume the end point of each sub-path is a Virtual Point Light (VPL), Then Render the scene as usual using these VPLs
- Pros: fast and usually gives good results on diffuse scenes
- Cons:
  - Spikes will emerge when VPLs are close to shading points
  - Cannot handle glossy materials

工业界：Path Tracing，不高端，但可靠

Advanced Appearance Modeling

Appearance → Material → BRDF

Non-surface models

- Participating media
- Hair / fur / fiber (BCSDF)
- Granular material

Surface models

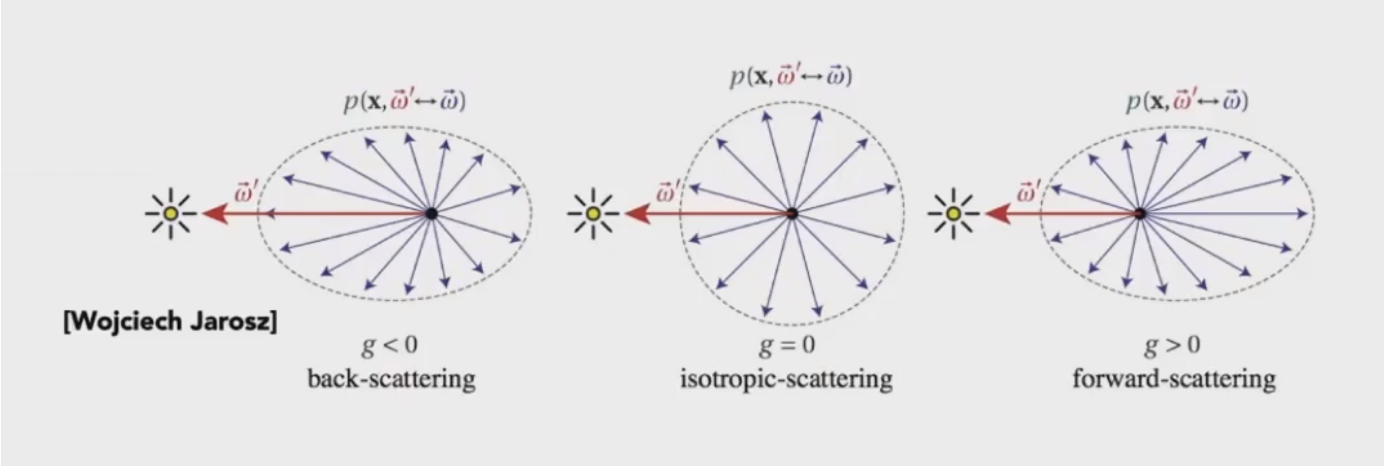
- Translucent material (BSSRDF)
- Cloth
- Detailed material (non-statistical BRDF)

Procedural appearance

Non-Surface Models

Participating Media (散射介质)：Fog, Cloud ...

- At any point as light travels through a participating medium, it can be (partially) absorbed and scattered. （部分）吸收和散射
- 散射：Use **Phase Function(相位函数)** to describe the angular distribution of light scattering at any point x within participating media. 规定如何散射



- 如何渲染Rendering:
  - Randomly choose a direction to bounce
  - Randomly choose a distance to go straight
  - At each 'shading point', connect to the light

散射介质也有可能是巧克力酱、手

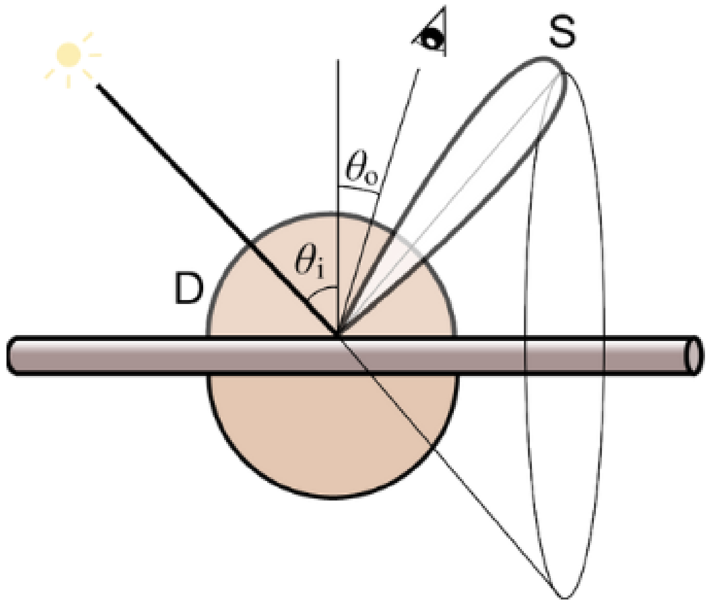
Hair Appearance

关键点：光线和曲线的作用

- 有两种高光：无色 & 有色高光，如何形成？
  - 无色高光
  - 有色高光

Kajiya-Kay Model：简单模型

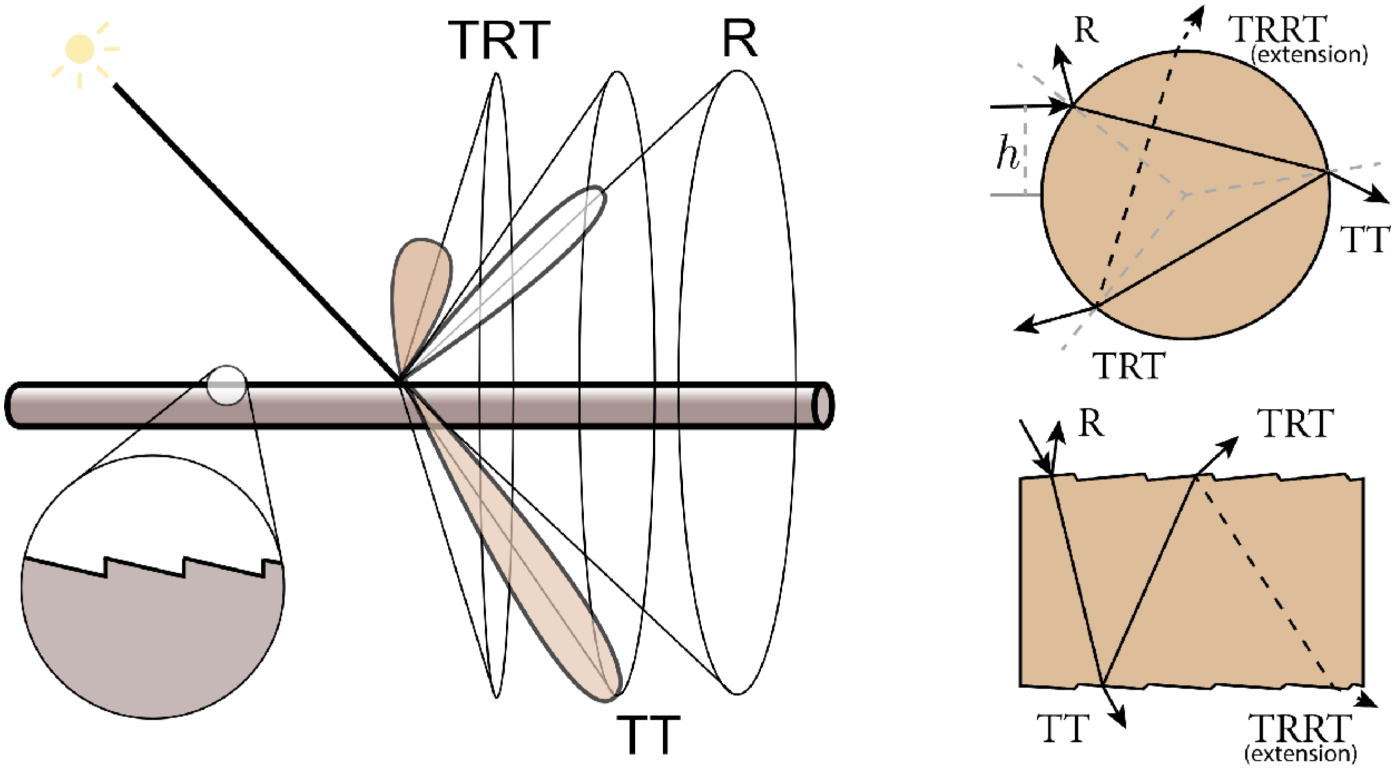
- 一根光线，打到圆柱（头发）上，散射出一个圆锥上，同时向四面八方散射，像是Diffuse+Specular想加
- 效果不好，很假

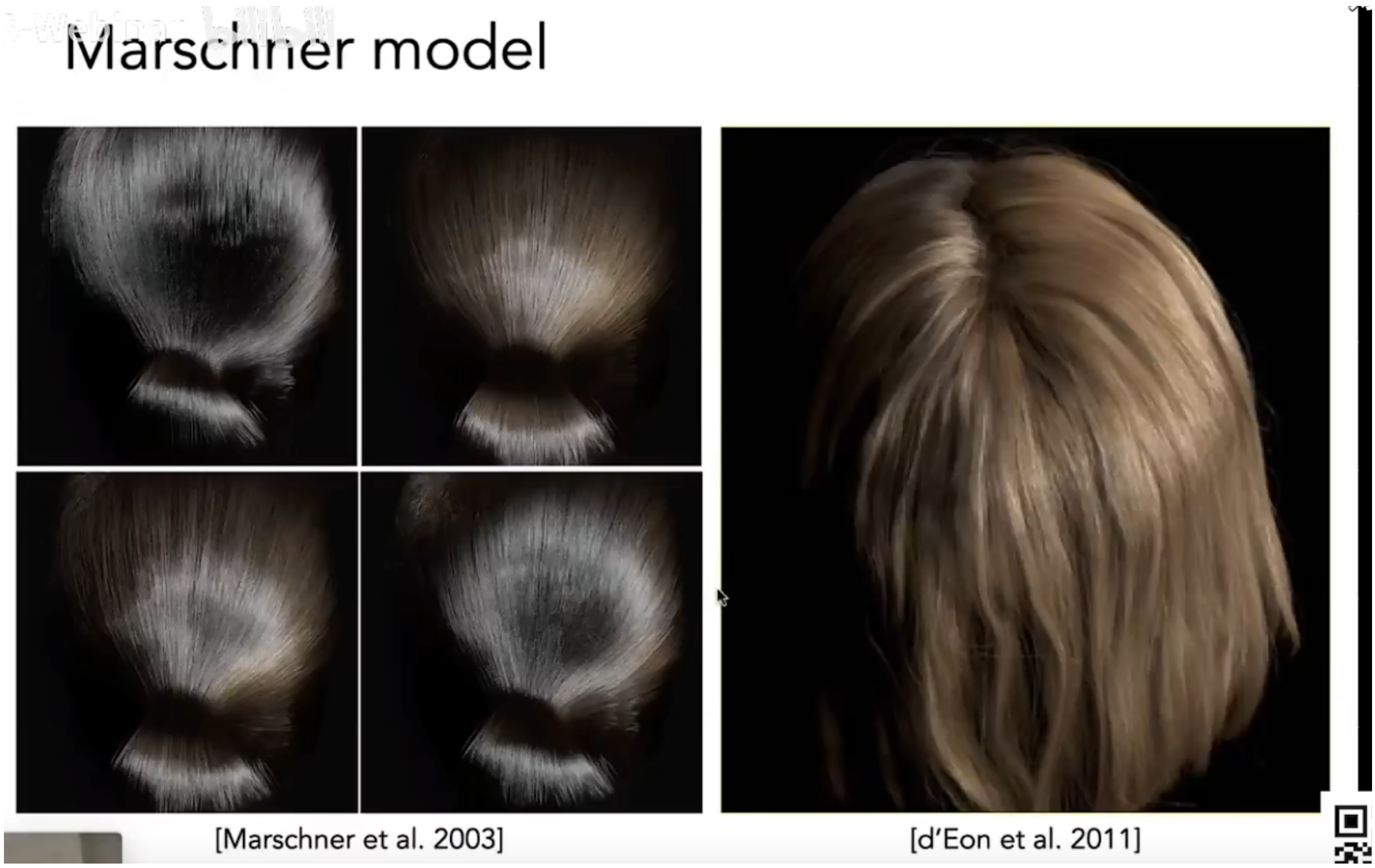


Marschner Model：广泛使用

- 把头发看作Glass-like cylinder，有色素，会吸收能量
- 3 types of light interactions: R, TT, TRT (R: reflection, T: transmission)
- possible extension: TRRT
- 一部分直接反射（R）
- 一部分穿进头发，再穿出（TT）
- 一部分穿进，内部反射，再穿出TRT
- 效果不错

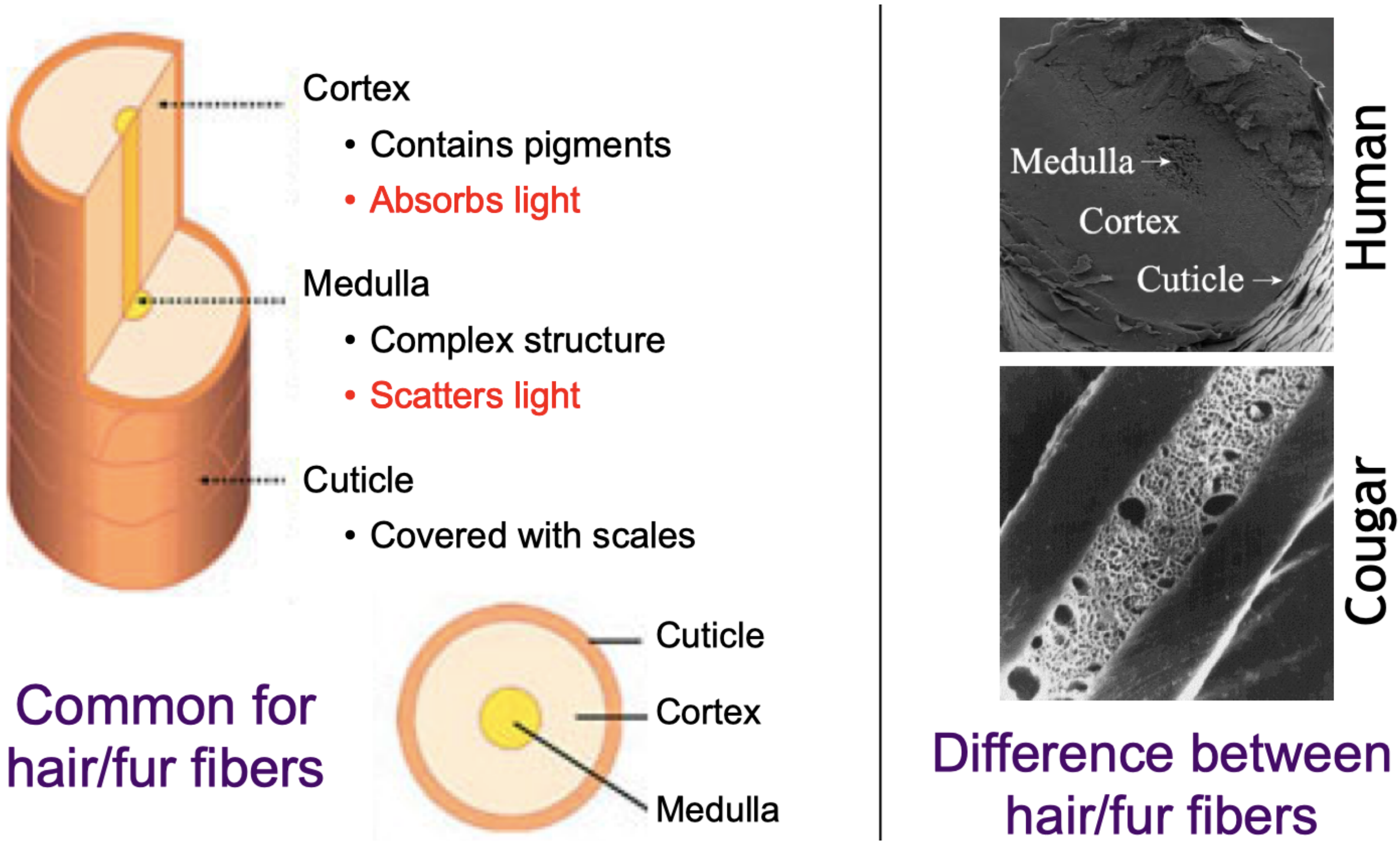
- 只是单次散射





Fur Appearance

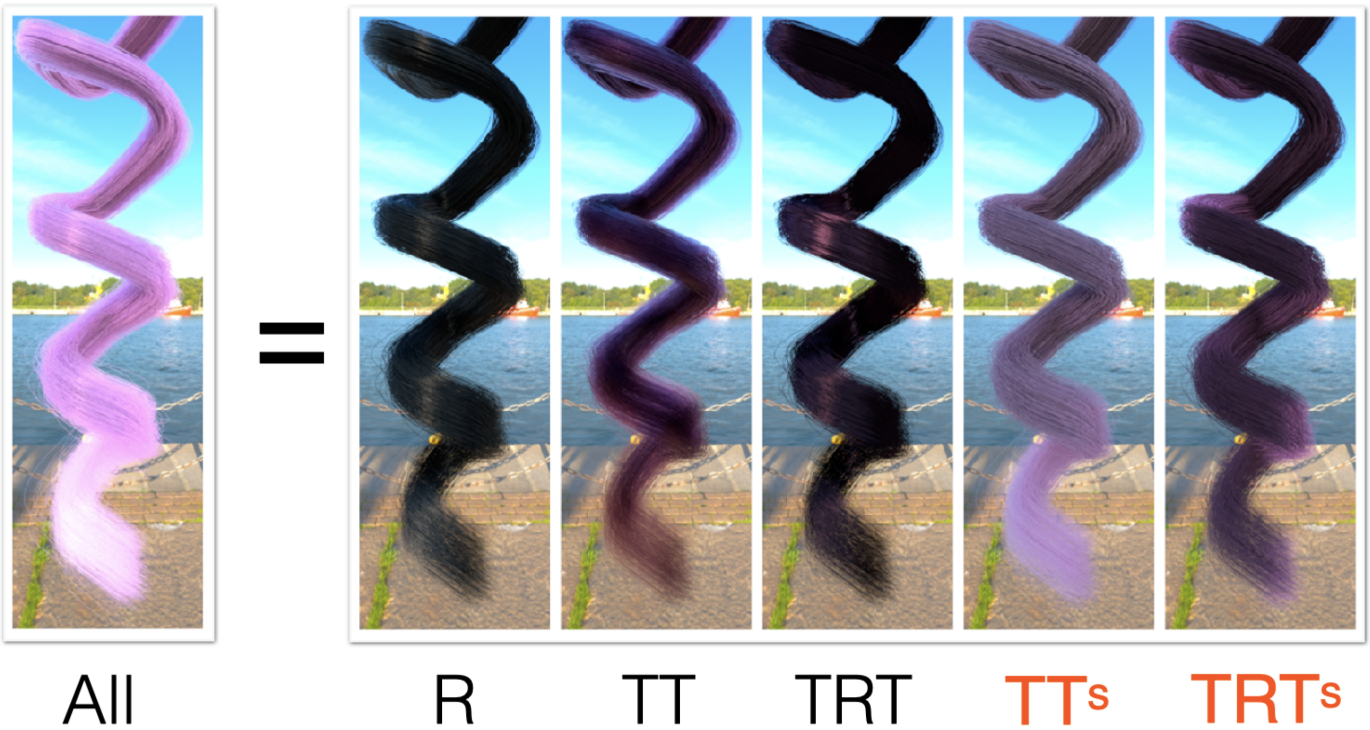
不能直接把头发模型用到动物毛发上，两者有差别



动物毛发髓质(Medulla)很大，头发忽略了不明显，但是动物毛发忽略之后很明显

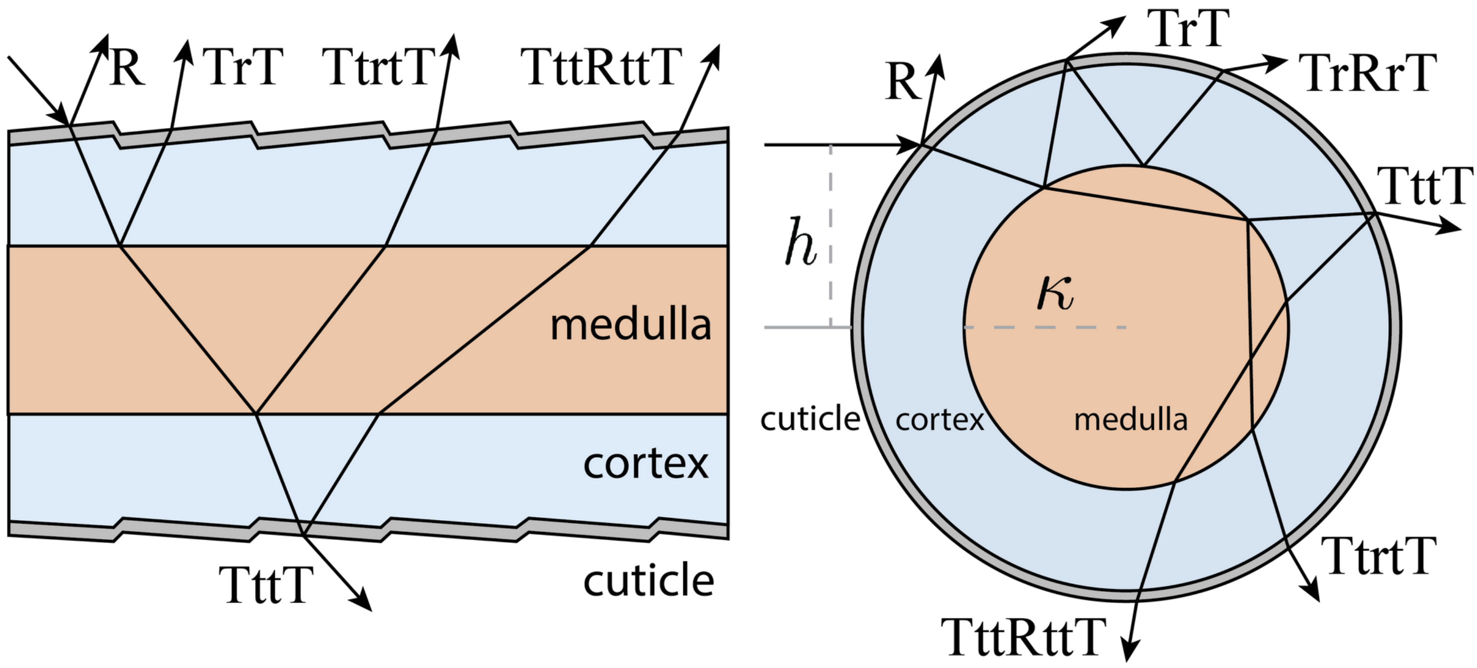
Double Cylinder Model：描述了头发和髓质的双层结构

- R，TT，TRT
- TTs，TRTs：经过髓质，被散射过的光



应用：

- [War for the Planet of the Apes. 2017 movie] (2018 Oscar Nominee for Best Visual Effects)
- [The Lion King (HD). 2017 movie] (2019 Oscar Nominee for Best Visual Effects)



Granular Material 颗粒状材质

Can we avoid explicit modeling of all granules?

- Yes with procedural definition.

目前还没有很好的渲染优化

Surface Models

Subsurface Scattering 次表面散射, BSSRDF

Translucent: 不仅仅是半透明，光线在内部还会有折射，比如玉石，水母，牛奶，人耳

物理上：Subsurface Scattering 次表面散射

- Visual characteristics of many surfaces caused by light exiting at different points than it enters
- Violates a fundamental assumption of the BRDF → BSSRDF

BSSRDF: generalization of BRDF; exitant radiance at one point due to incident differential irradiance at another point: $S\left(x_i, \omega_i, x_o, \omega_o\right)$ 进来和出去的点不一定一样

Generalization of rendering equation: integrating over all points on the surface and all directions 对表面其他地方进入的光线也要考虑，过于复杂

$$L\left(x_o, \omega_o\right)=\int_A \int_{H^2} S\left(x_i, \omega_i, x_o, \omega_o\right) L_i\left(x_i, \omega_i\right) \cos \theta_i \mathrm{d} \omega_i \mathrm{d} A$$

→ Dipole Approximation [Jensen et al. 2001]: Approximate light diffusion by introducing two point sources. 用两个光源模拟次表面散射

BSSRDF: Application

- 真实的皮肤
- https://cgelves.com/10-most-realistic-human-3d-models-that-will-wow-you/

Cloth: Fiber

布：A collection of twisted fibers! 由纤维缠绕而成

- 每一根纱线是由纤维缠绕而成
- 每一股毛线是由纱线缠绕而成
- 规模很恐怖

Render as Surface

- Given the weaving pattern, calculate the overall behavior
- Render using a BRDF，根据不同的织法，给不同的BRDF
- 但是布料并不仅仅是表面，天鹅绒那样的效果无法展现

Render as Participating Media

- Properties of individual fibers & their distribution -> scattering parameters
- 空间中分布的体积→细小的格子，对每个格子里布料的性质进行采样，转化成对光线的渲染 （像对云的渲染那样）计算量很恐怖

Render as Actual Fibers

- Render every fiber explicitly!
- 计算量更恐怖

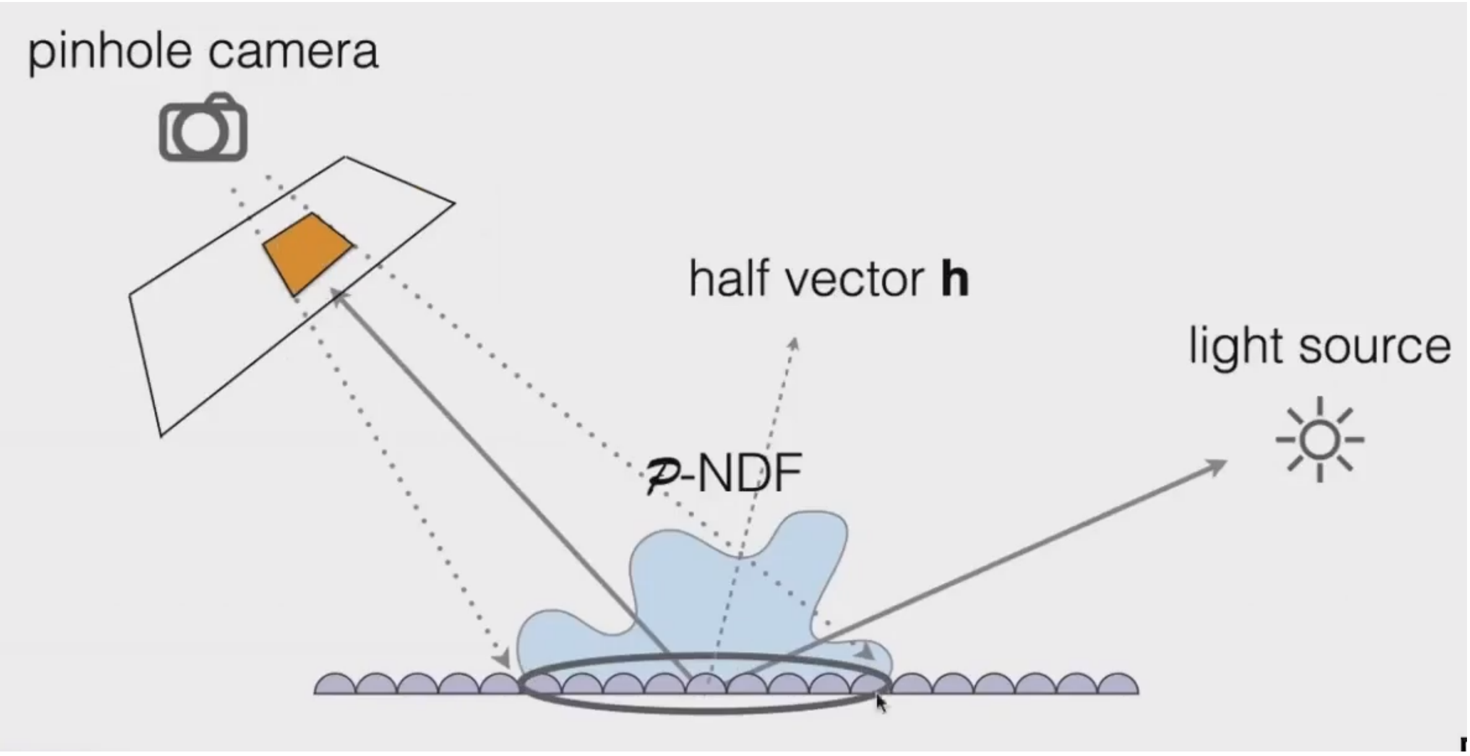
Detailed Appearance

Not looking realistic, 因为表面无噪太过完美

回顾Microfacet BRDF

- Surface = Specular microfacets + statistical normals
- 法线分布(NDF)用了正态分布，其实没有那么完美
- 把法线分布改的复杂一点，就会获得更复杂的结果
- 法线贴图200k x 200k，获得很好的效果，但是运算量爆炸（甚至一张图要一个月）
- 这是因为在法线分布复杂的情况下，很难建立valid的光线通路（光源→表面→摄像机）

Solution: BRDF over a pixel



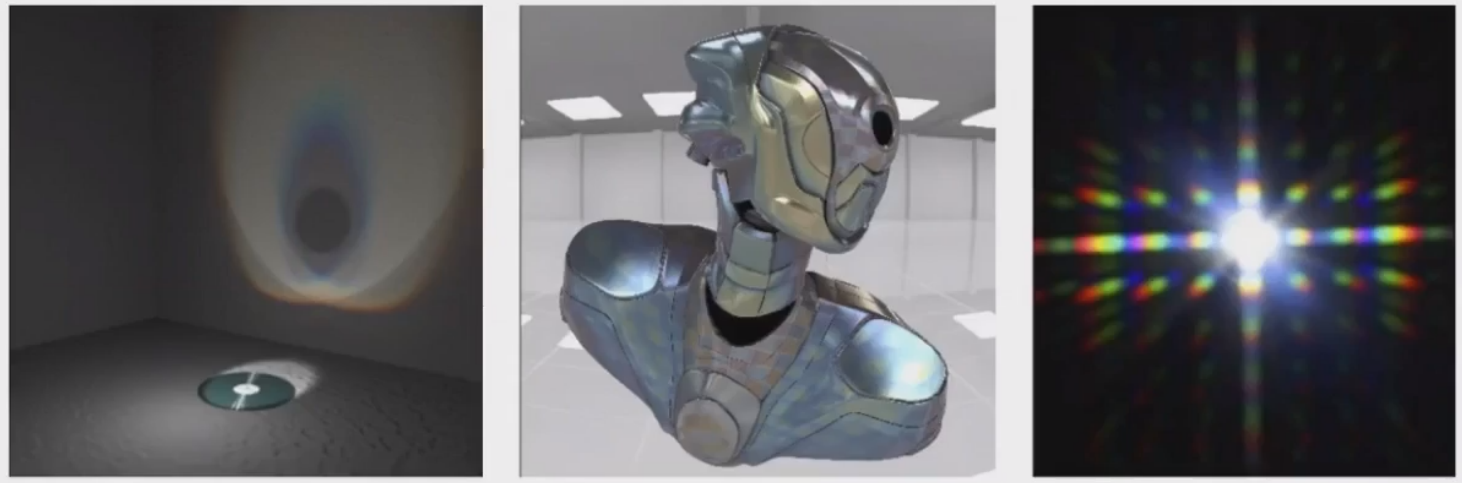
- 一个像素对应了一块微表面，把整块范围内的各向法线分布整合起来获得（P-NDF），以此简化计算
- 小范围的P-NDF会有很多奇妙的样子

Application:

- Detailed / Glinty Material
- 海绵波光粼粼的效果

Recent Trend: Wave Optics

当物体小到和光线波长相当的时候, 不可忽略光的波动性



compact disk (CD) [Cuypers 11]　metallic film [Laurent 17]　phone screen [Toisoul 17]

- 波动光学计算BRDF
  - 结果与几何光学类似，但不连续（干涉导致），不同波长也不一样

Procedural Appearance 程序化生成材质

- Explicitly or Implicitly 不一定需要真的生成，可以查询

问题：三维模型，三维材质，存储量爆炸

Can we define details without textures?

- Yes! Compute a noise function on the fly.
- 3D noise -> internal structure if cut or broken
- Thresholding (noise -> binary noise)

Complex noise functions can be very powerful.

- Perlin Noise
  - 生成地形
  - 木头的三维生成
- ...

Houdini: 程序化生成材质(Explicitly)