Scattering in Skin and Hair

70001 – Advanced Computer Graphics: Photographic Image Synthesis

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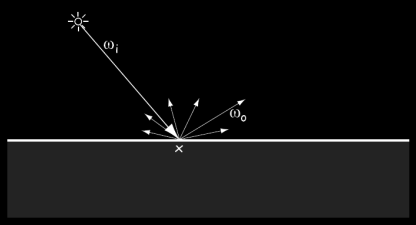
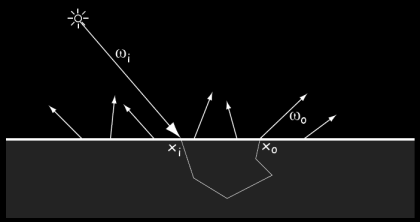
Lecture 17, Mar. 1st 2024

1

Skin subsurface (diffuse) scattering





BRDF $f_r(x, \vec{\omega}_i, \vec{\omega}_o) = \frac{dL(x,\vec{\omega}_i)}{dE(x,\vec{\omega}_o)}$

BSSRDF $S(x_i, \vec{\omega}_i, x_o, \vec{\omega}_o) = \frac{dL(x_o,\vec{\omega}_o)}{d\Phi(x_i,\vec{\omega}_i)}$

- Bidirectional surface scattering distribution function (BSSRDF), 8D function
  - 4D approximation for highly scattering materials like skin!
  - Dipole diffusion model [Jensen et al. 01]

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Skin rendering – BRDF model

3

Skin rendering with dipole diffusion

rendering with measured parameters

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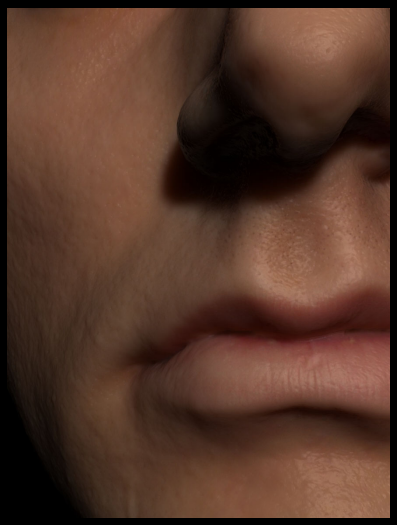
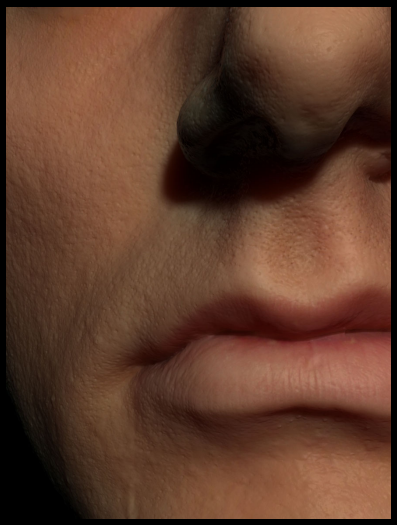
Multilayer diffusion – Donner & Jensen 05



rendering with dipole diffusion



rendering with 3 diffusion layers

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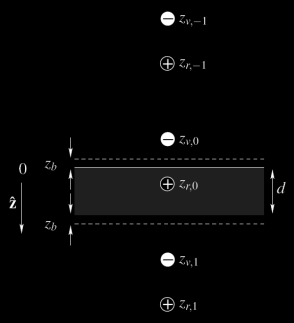
Kubelka-Munk theory



$$T_{12} = T_1 * T_2 + T_1 * R_2 * R_1 * T_2 + T_1 * R_2 * R_1 * R_2 * R_1 * T_2 + \ldots$$

$$\mathcal{T}_{12} = \frac{\mathcal{T}_1 \mathcal{T}_2}{1 - \mathcal{R}_2 \mathcal{R}_1}$$

$$\mathcal{R}_{12} = \mathcal{R}_1 + \frac{\mathcal{T}_1 \mathcal{R}_2 \mathcal{T}_1}{1 - \mathcal{R}_2 \mathcal{R}_1}$$

- Derived from geometric series formula!

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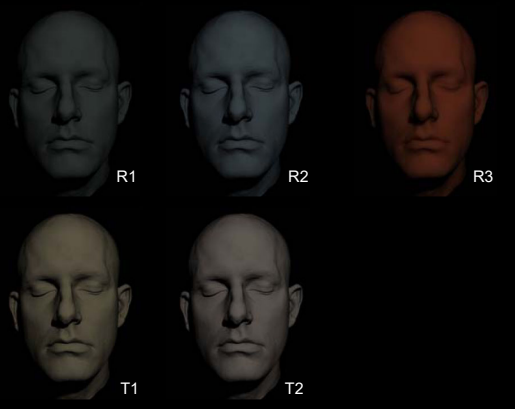
3 layer model rendering



Epidermis Dermis Bloody Dermis

- Layer params. based on tissue optics [Tuchin 2000]
- Layers combined with Kubelka-Munk theory

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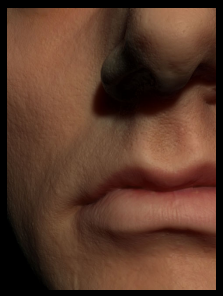
Diffusion models

[Jensen et al. 01]



[Donner&Jensen 05]

- Offline rendering with photon mapping
  - first pass scatter photons from light source
  - second pass gather photons on skin surface using diffusion kernel weights

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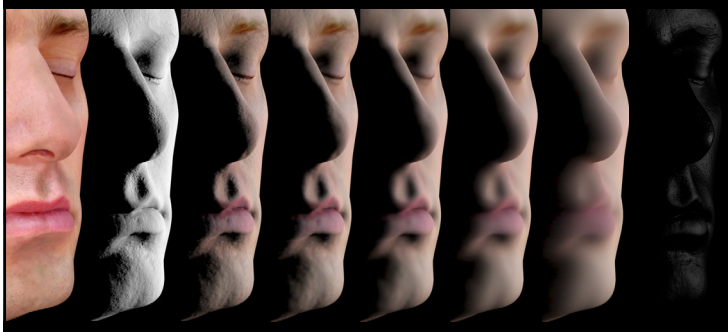
Real-time rendering [d'Eon et al. 07]



- Diffusion approximated as sum of Gaussians

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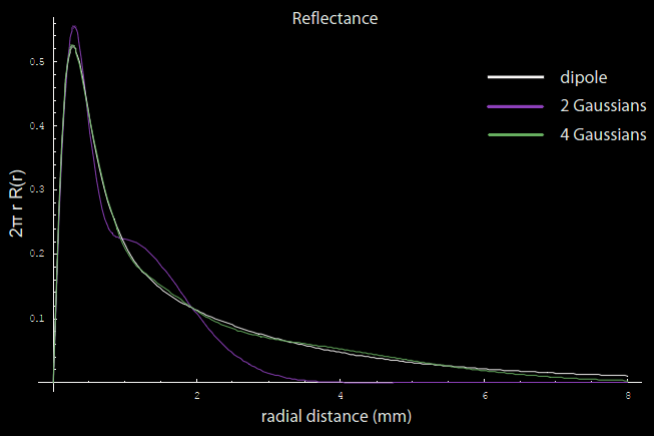
Real-time rendering [d'Eon et al. 07]



- 4 – 8 Gaussians well approximate dipole & multipole models

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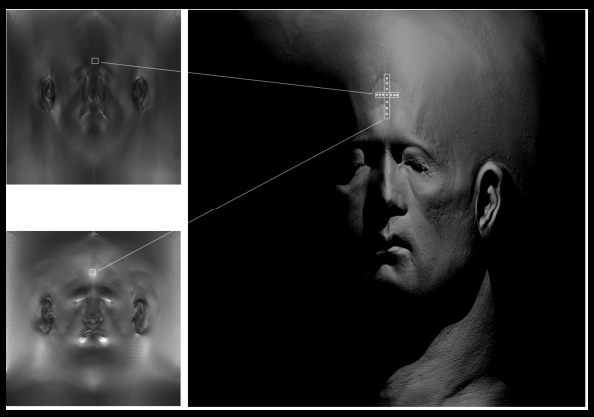
Real-time rendering [d'Eon et al. 07]



- Gaussian blur implemented in 2D texture space of GPU
- Need to account for texture distortion

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Real-time rendering [d'Eon et al. 07]

- 4 – 8 Gaussians well approximate dipole & multipole models

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Screen-space diffusion [Jimenez et al. 09]

Texture –space
[d'Eon]

Screen –space
[Jimenez]

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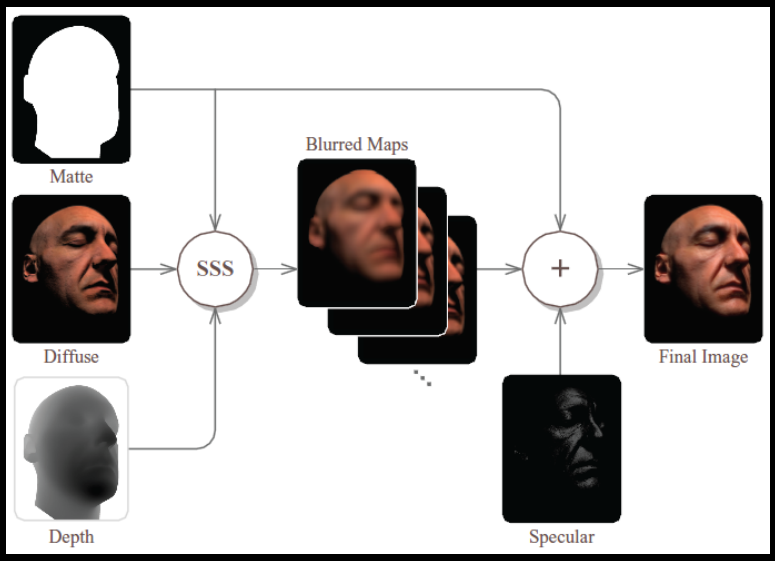
Screen-space diffusion [Jimenez et al. 09]



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Screen-space diffusion [Jimenez et al. 09]

- Efficient rendering for many faces on screen
- Choice of rendering technique in games!

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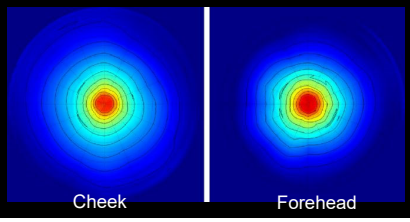
Measuring facial subsurface scattering

- LED probe [Weyrich et al. 06]
  - special contact device with spatial light sensors for diffusion
  - one measurement over entire region
  - dipole diffusion fit



[Weyrich et al. 06]

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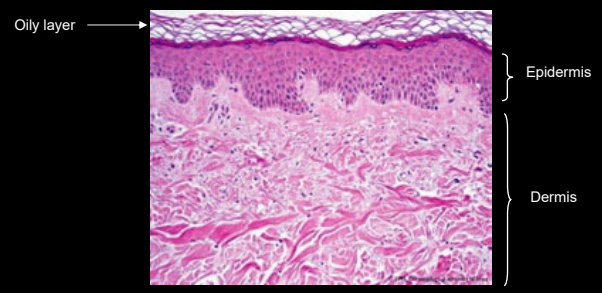
Skin - layered media



Skin diagram
(courtesy University of Iowa)

- Skin layered heterogeneous scattering media
- Single layer diffusion not sufficient!

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Practical Modeling and Acquisition of Layered Facial Reflectance – [Ghosh et al. 08]

ACM SIGGRAPH Asia 2008

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Aim

- Seek to bridge gap in measurement and modeling
  - parameters of multi-layer model
  - data driven modeling of multiple layers
- Fast acquisition for live subjects in natural expressions
  - few seconds!

Rendering with measured data

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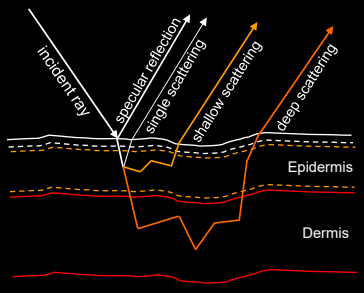
Approach

- Model skin reflectance as combination of different layers
  - specular reflection
  - single scattering
  - shallow multiple scattering
  - deep multiple scattering



Skin reflectance model

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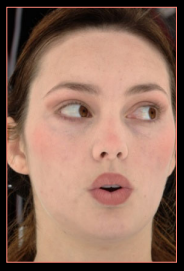
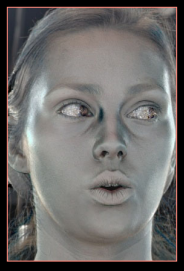
Polarization based reflectance separation

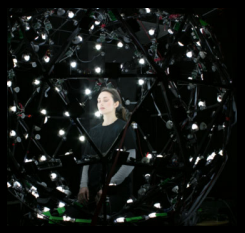

Parallel pol.

-

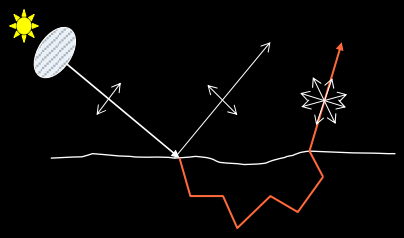

Cross pol.

=


Pol. preserving


[Ma et al. 2007]
[Alexander et al. 2010]

- Polarization difference imaging
  - Parallel and cross pol. states



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Exploiting polarization


(a) front-lit, parallel polarized

-


(b) front-lit, cross polarized

=


(c) specular reflection + single scattering

- Separating single and multiple scattering

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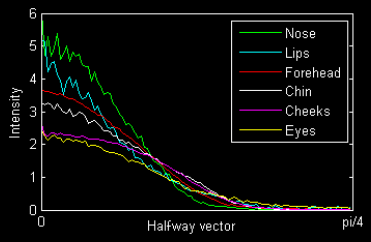
Specular reflection

- Cook-Torrance micro-facet BRDF model
- separate distributions for different regions of the face

measurement

CT BRDF-fit

segmentation



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Single scattering

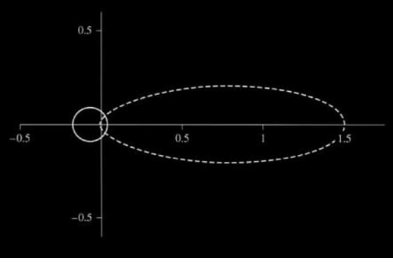
- Polarization preserving non-specular scattering
- Hanrahan & Krueger BRDF model
- Heney-Greenstein phase function fit to backscattering

$$p_{HG}(\cos\theta) = \frac{1 - g^2}{4\pi\ (1 + g^2\ - 2g\cos\theta)^{3/2}}$$

  - θ is the angle between ω & ω'
  - g → [-1, 1], g > 0 forward scatting

measurement

CT + HK BRDF fit



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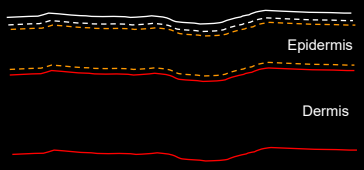
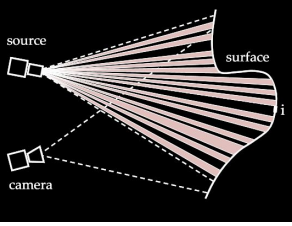
Modeling multiple scattering

- Model skin as a 2 layer scattering medium
  - epidermis (~ 0.5mm) and dermis



- Direct-indirect separation [Nayar et al. 06]
  - illumination frequency determines separation

Direct-indirect separation [Nayar et al. 06]



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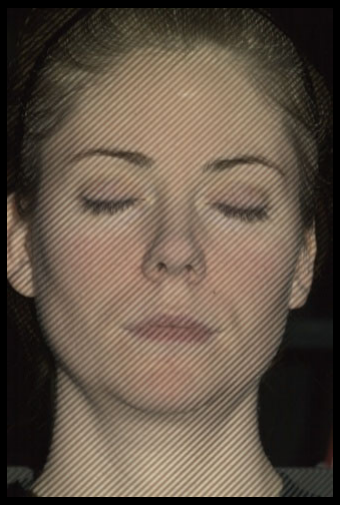
Modeling multiple scattering

- Cross-polarized separation
  - width 1.2 mm
  - approx. separate epidermal & dermal scattering!



high frequency shifted stripes - phase 1

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Modeling multiple scattering

- Cross-polarized separation
  - width 1.2 mm
  - approx. separate epidermal & dermal scattering!

high frequency shifted stripes - phase 2

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Modeling multiple scattering

- Cross-polarized separation
  - width 1.2 mm
  - approx. separate epidermal & dermal scattering!

high frequency shifted stripes - phase 3

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Modeling multiple scattering

- Cross-polarized separation
  - width 1.2 mm
  - approx. separate epidermal & dermal scattering!

high frequency shifted stripes - phase 4

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Modeling multiple scattering

- Cross-polarized separation
  - width 1.2 mm
  - approx. separate epidermal & dermal scattering!
  - measurement of scattering albedo
  - still need estimate of translucency or diffuse mean free path (spatial spread of light)

shallow scattering

(max - min)

deep scattering

(2*min)

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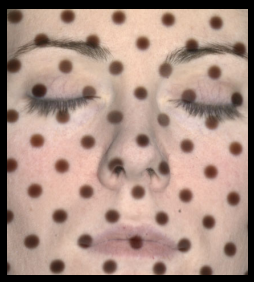
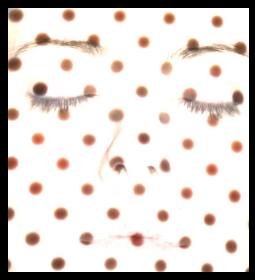
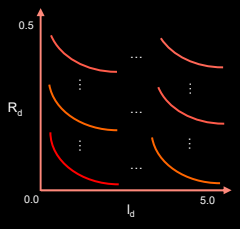
Estimating scattering



exposure bracketing

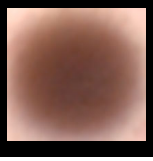


2 f-stops



- Circular black dot pattern for observing spatially varying SSS
- 2D LUT for translucency estimation
  - Monte Carlo simulation for LUT

forehead



mouth

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Rendering comparison

single layer + specular

layered rendering

photograph

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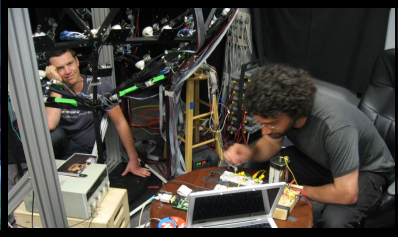
Avatar (2009)



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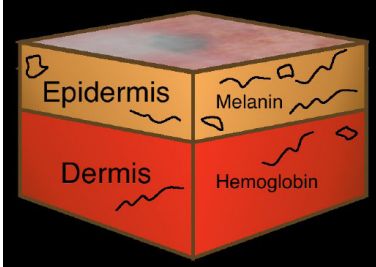
Spectral 2 layer model: Donner&Jensen06



Epidermis absorption:

$$\sigma_a^{epi}(\lambda) = C_m(\beta_m \sigma_a^{em}(\lambda) + (1-\beta_m)\sigma_a^{pm}(\lambda)) + (1-C_m)\sigma_a^{baseline}$$

Melanin type $\beta_m \in [0,1]$ and concentration $C_m \in [0,1]$

Dermis absorption:

$$\sigma_a^{derm}(\lambda) = C_h(\gamma \sigma_a^{oxy}(\lambda) + (1-\gamma)\sigma_a^{deoxy}(\lambda)) + (1-C_h)\sigma_a^{baseline}$$

Hemoglobin oxygenation $\gamma = 0.7$ and concentration $C_h \in [0,1]$

- Based on bio-physical parameters of melanin and hemoglobin concentrations in skin

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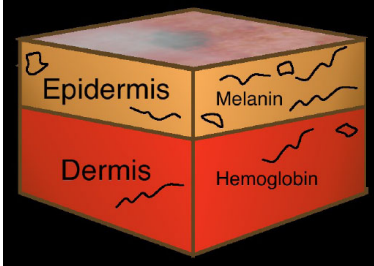
Spectral 2 layer model: Donner&Jensen06



Epidermis absorption:

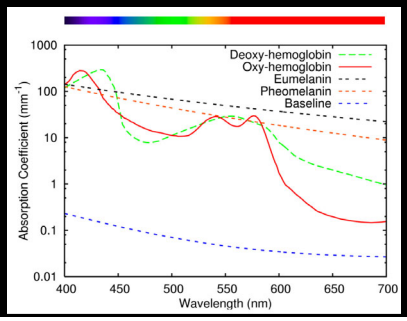
$$\sigma_a^{epi}(\lambda) = C_m(\beta_m \sigma_a^{em}(\lambda) + (1-\beta_m)\sigma_a^{pm}(\lambda)) + (1-C_m)\sigma_a^{baseline}$$

Melanin type $\beta_m \in [0,1]$ and concentration $C_m \in [0,1]$

Dermis absorption:

$$\sigma_a^{derm}(\lambda) = C_h(\gamma \sigma_a^{oxy}(\lambda) + (1-\gamma)\sigma_a^{deoxy}(\lambda)) + (1-C_h)\sigma_a^{baseline}$$

Hemoglobin oxygenation $\gamma = 0.7$ and concentration $C_h \in [0,1]$



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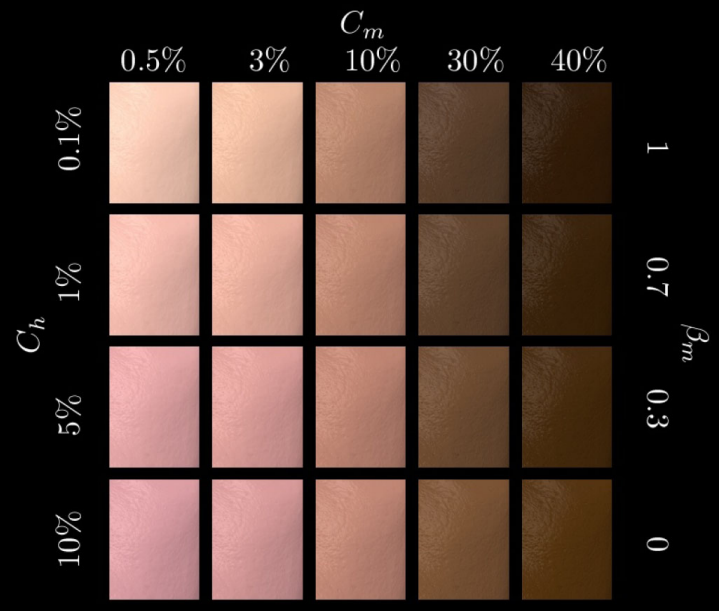
Spectral 2 layer model: Donner&Jensen06



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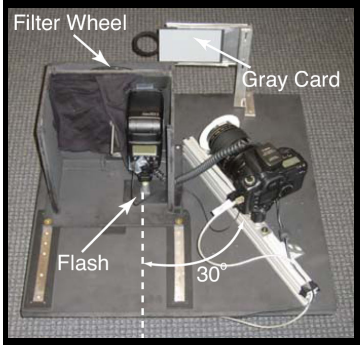
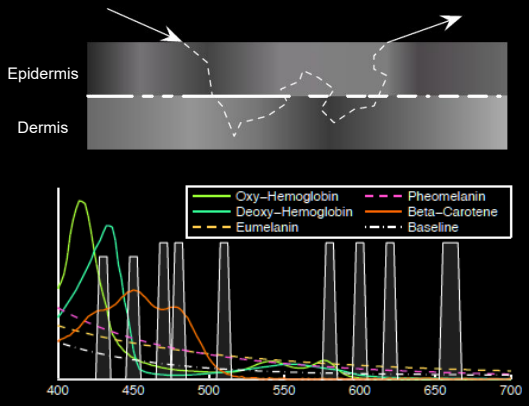
Measuring spectral parameters– Donner et al. 08





- Multi-spectral imaging
- Inverse rendering for parameters: melanin, hemoglobin & inter layer absorption

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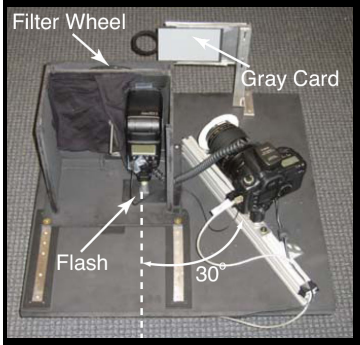
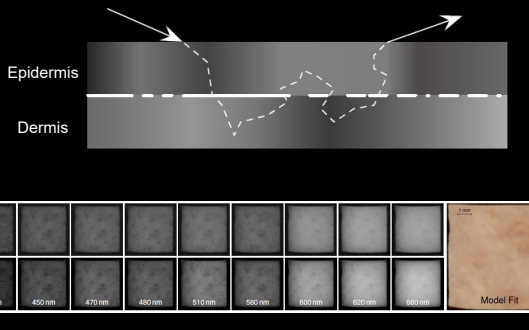
Measuring spectral parameters– Donner et al. 08





- Multi-spectral imaging
- Inverse rendering for parameters: melanin, hemoglobin & inter layer absorption

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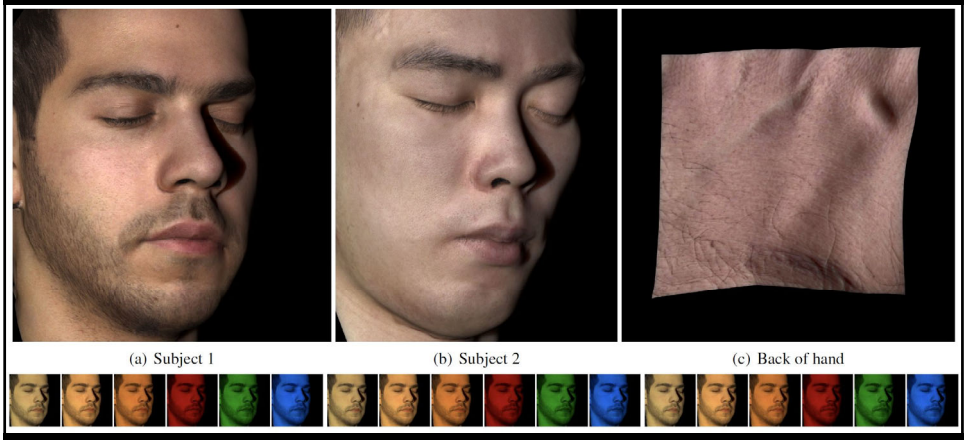
Practical spectral measurement of skin – Gitlina et al. 2020



- Optimal measurement and modeling complexity
- Suitable for full facial capture

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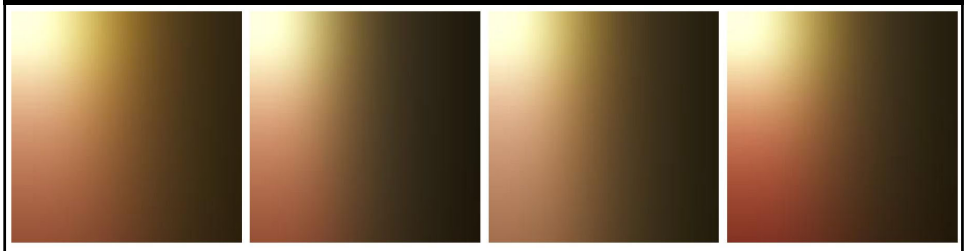
4D spectral skin model – Gitlina et al. 2020



- C_m and C_h the primary melanin and hemoglobin concentration parameters
- Melanin blend-type β_m and epidermal hemoglobin fraction C_{he} two additional parameters

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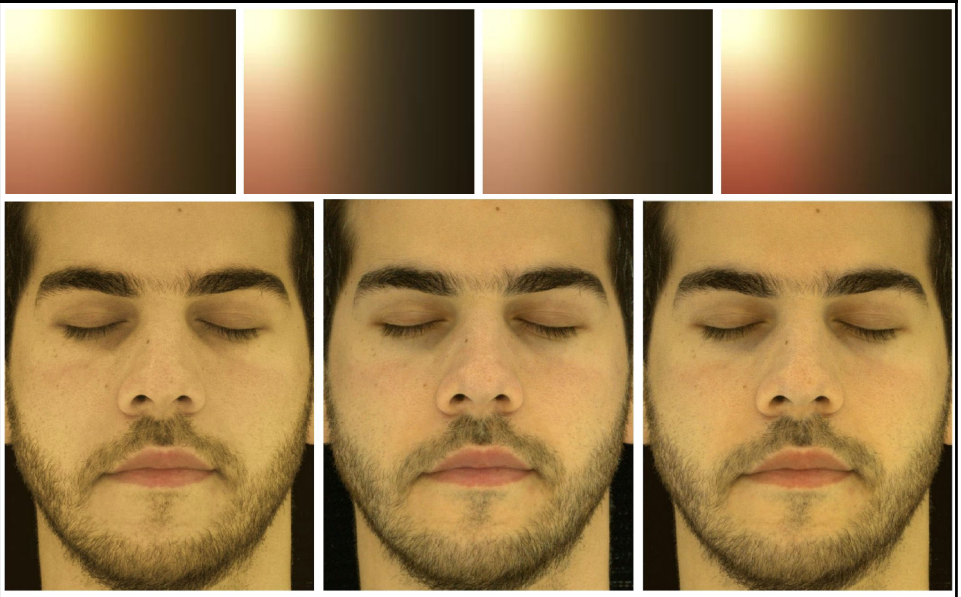
4D spectral skin model – Gitlina et al. 2020



(a) 2D model (b) Photograph (c) 4D model

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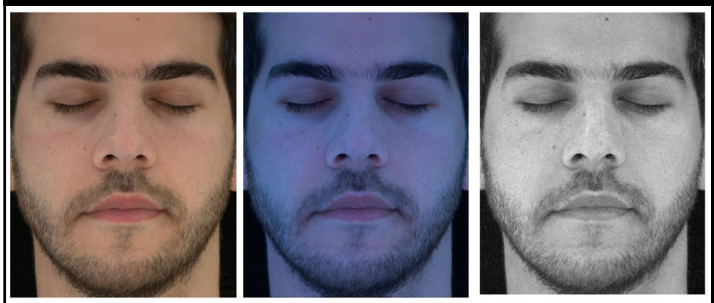
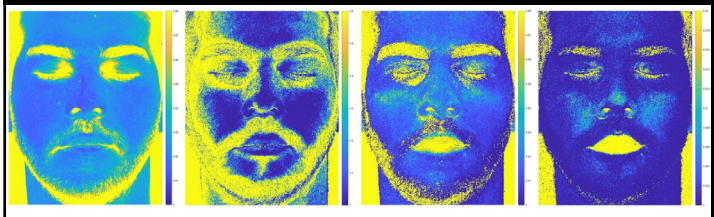
Practical spectral measurement



(a) $D65'$ (b) $D65'$+ blue (f) synth. blue isol.

- Broadband white (D65) light + narrowband blue light measurement
- Pure response to blue light (f) computed from (a) and (b)



(a) C_m (b) β_m (c) C_h (d) C_{he}

- 4D LUT search for chromophore parameters based on the RGB + synthetic blue measurements (a, f)

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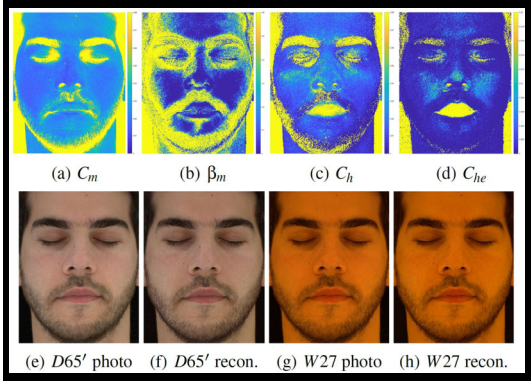
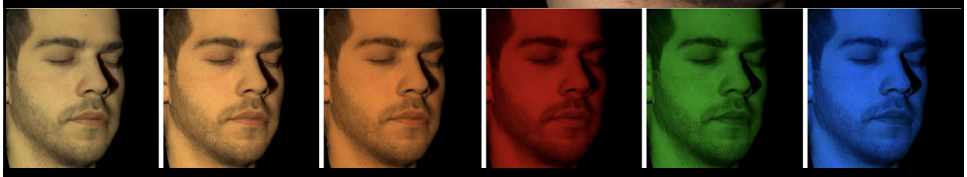
Practical spectral measurement



Spectral reconstruction of skin under given illumination



PBRT rendering with heterogenous subsurface scattering

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Rendering Hair

- Anisotropic reflection [Kajiya-Kay 89]
- Single scattering BRDF model [Marschner et al. 03]
  - Dark hair
- Multiple scattering
  - Light colored hair
  - Photon Mapping [Moon and Marschner 06]

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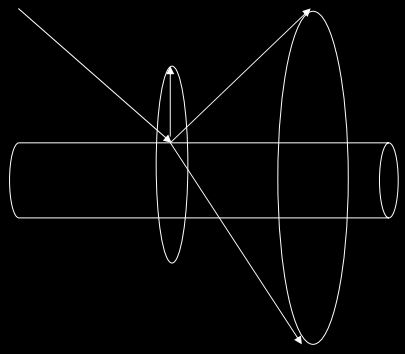
Anisotropic reflection in hair [Kajiya-Kay 89]



- Specular reflection on cylindrical hair fiber results in a cone of reflection directions
  - Ill-defined surface normal, instead surface tangent employed

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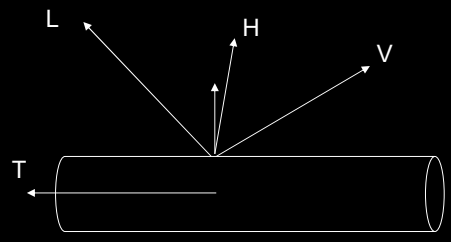
Anisotropic reflection in hair [Kajiya-Kay 89]



$$\cancel{\text{dot}(N,H)^{specularity}}$$

$$\sin(T,H)^{specularity} = \sqrt{1-\text{dot}(T,H)^2}^{specularity}$$

- Specular reflection on cylindrical hair fiber results in a cone of reflection directions
  - Ill-defined surface normal, instead surface tangent employed
- Diffuse modelled with Lambertian

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Rendering hair with Kaija-Kay

Kajiya-Kay

Photograph
(dark hair)

- Anisotropic specular reflection + diffuse
- Standard in many games and animation softwares

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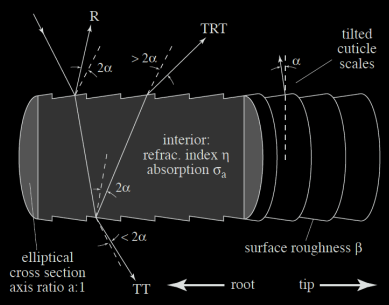
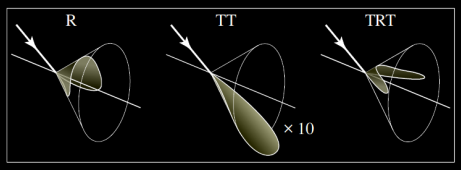
Single Scattering in Hair





- Biophysically based model [Marschner et al. 03]

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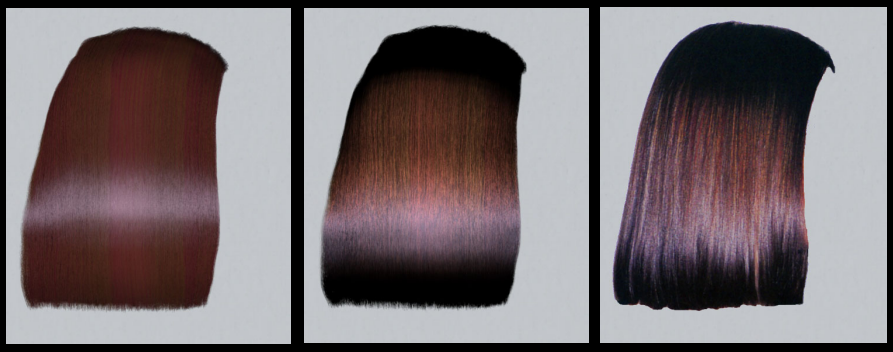
Single Scattering in dark hair



Kajiya-Kay
(diffuse + specular)

[Marschner 03]
(R + TT + TRT)

Photograph
(dark hair)

- Primary highlight R (white) – specular reflection
- Secondary highlight TRT (brown) – single scattering

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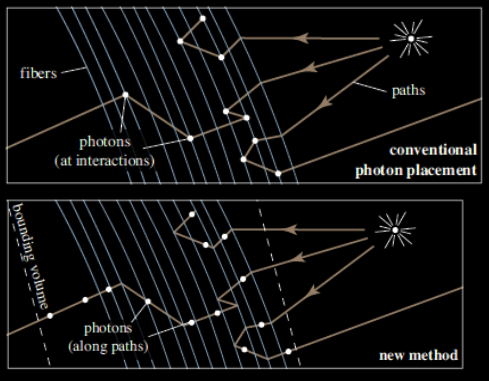
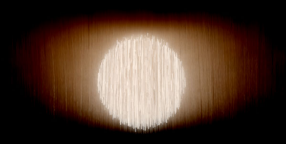
Multiple Scattering in light hair





Anisotropic scattering

- TT paths dominant in light hair!
  - Light scatters sideways more than along hair strands
- Photon Mapping [Moon and Marschner 06]
  - 6D KD-tree

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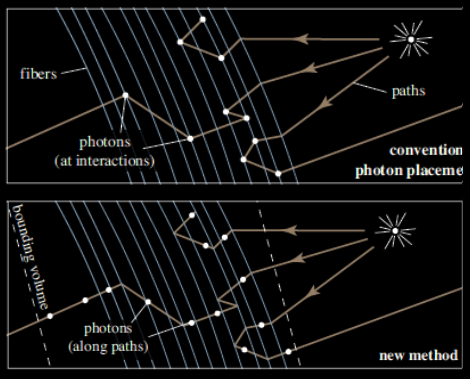
Multiple Scattering in light hair



- Photon Mapping [Moon and Marschner 06]
  - 6D KD-tree
- Photons stored for scattering paths instead of hair surface points
  - more efficient for rendering with fewer photons

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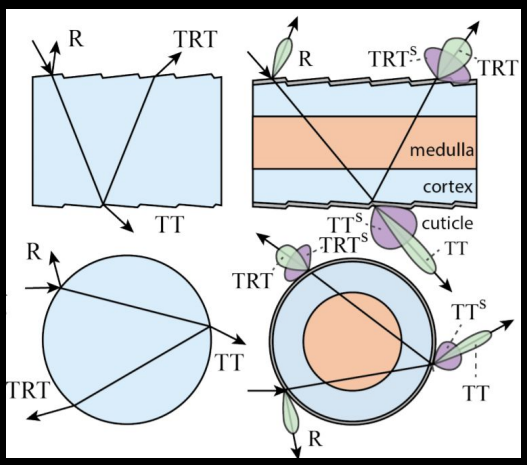
Scattering in Fur vs Hair

Hair scattering



Fur scattering

- Thick medulla inside fur fiber spreads all scattering distributions much more than in hair fibers [Yan et al. 17]

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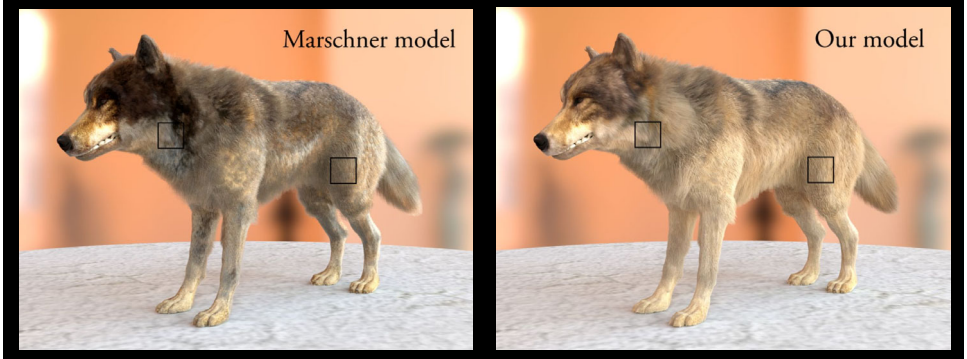
Scattering in Fur vs Hair



Hair scattering

Fur scattering

- Thick medulla inside fur fiber spreads all scattering distributions much more than in hair fibers [Yan et al. 17]

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Scattering in Fur vs Hair

Hair scattering

Fur scattering

- Thick medulla inside fur fiber spreads all scattering distributions much more than in hair fibers [Yan et al. 17]

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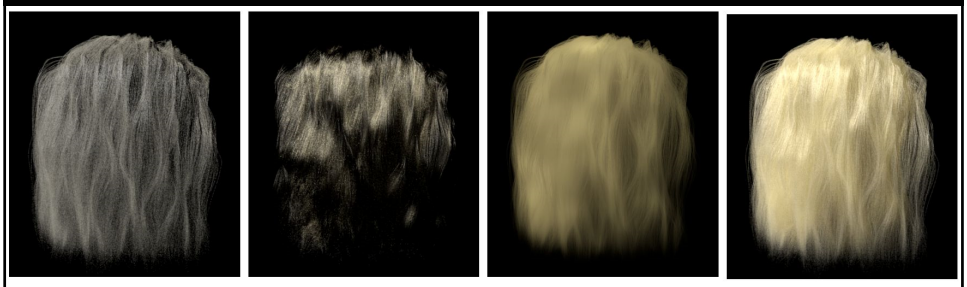
Rendering scattering in Fur



(a) Local illum. component S_c (b) Unscattered component S_{ds} (c) Scattered component S_{ss} (d) Our full model

- For rendering - scattering split into local and global components [Yan et al. 17]
- Global scattering very low frequency – dipole diffusion approximation!

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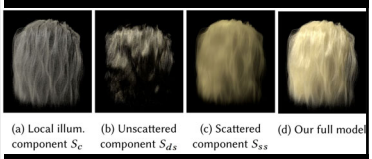
Rendering scattering in Fur

(b) Ours 42spp, 5.1min (c) Path traced 4096spp, 256min



(a) Local illum. component S_c (b) Unscattered component S_{ds} (c) Scattered component S_{ss} (d) Our full model

- For rendering - scattering split into local and global components [Yan et al. 17]
- Global scattering very low frequency – dipole diffusion approximation!

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