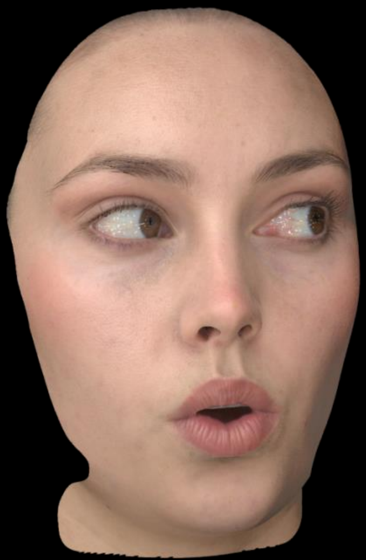
BMVC 2016 Tutorial:
Measurement Based Appearance Modelling







Abhijeet Ghosh

Imperial College London

Applications: Phorealistic Computer Graphics

Special Effects / Movies

Applications: Phorealistic Computer Graphics

Games

Other visualization applications …

Product design

AR

Architectural Visualization

Cultural Heritage

Speaker

Abhijeet Ghosh

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Senior Lecturer in Computing

Imperial College London 2012 – present

Realistic Graphics and Imaging group

EPSRC Early Career fellow

Research Assistant Professor, Graphics Lab

USC Institute for Creative Technologies 2007 – 2012

Research in Graphics and Imaging

Facial Acquisition and Reflectance

Skin micro-geometry deformation
SIGGRAPH 2015

Diffusion from spherical gradients
IEEE CG&A 2013

Facial micro-geometry
Eurographics 2013

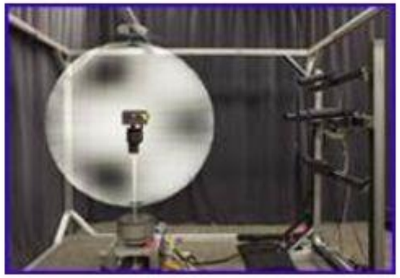
Multiview face capture
SIGGRAPH Asia 2011

Layered facial reflectance
SIGGRAPH Asia 2008

Research in Graphics and Imaging

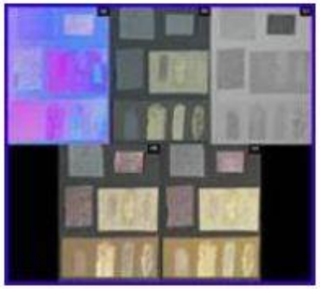
Surface Reflectometry

Mobile surface reflectometry
Computer Graphics Forum 2015



Continuous SH illumination
SIGGRAPH 2013

Circularly polarized spherical illumination
SIGGRAPH Asia 2010

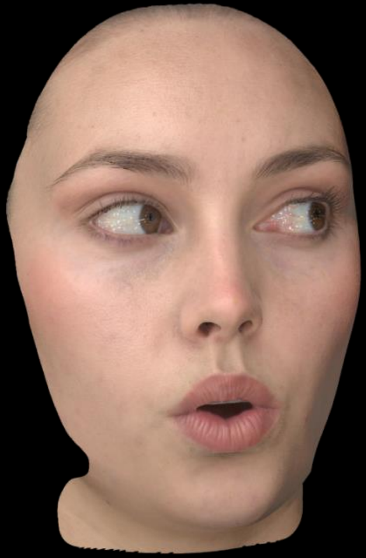


Second order statistics
EGSR 2009

Basis illumination BRDF acquisition
ICCV 2007 (Marr Prize Hon. Mention)

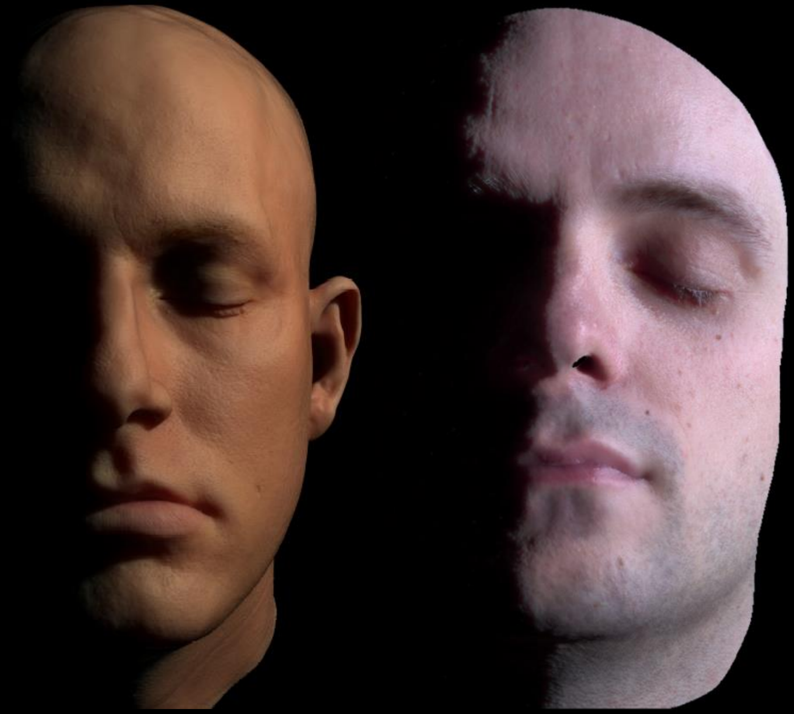
Facial Capture and Modeling

Image-
based

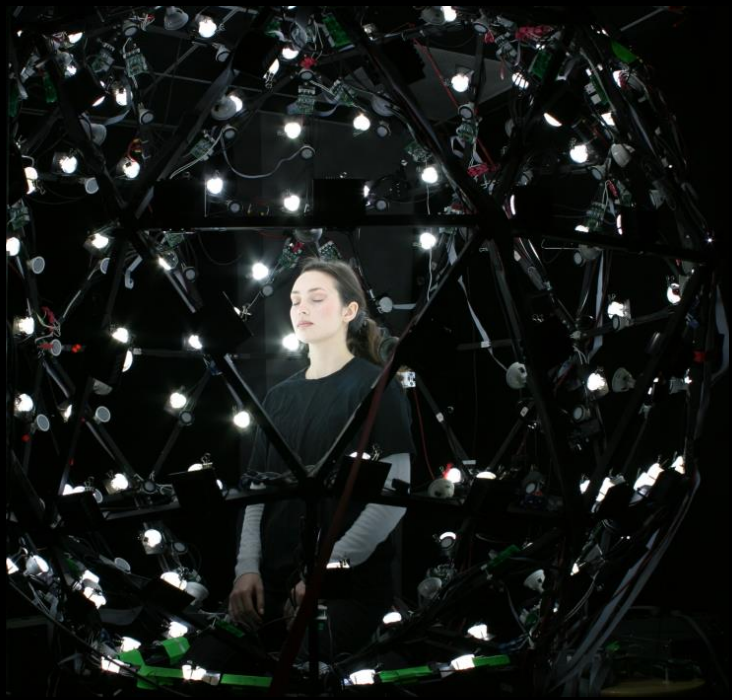


Model-
based

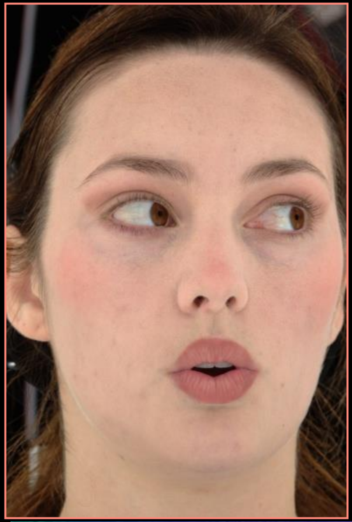
Multi-layer
skin
reflectance

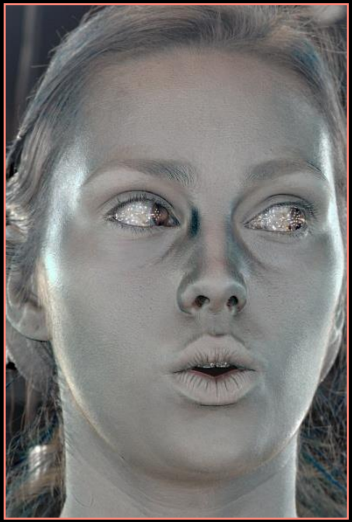


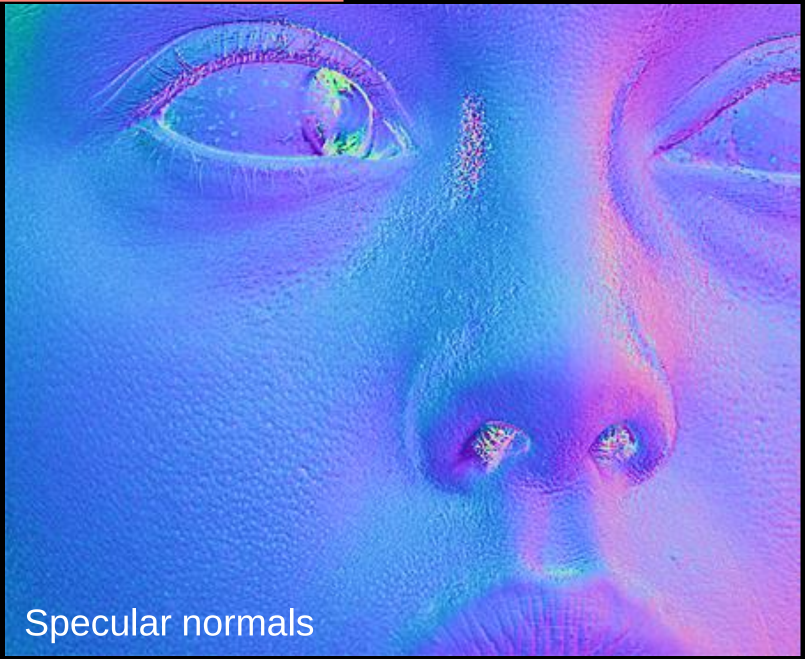
Facial capture techniques



Polarized illumination

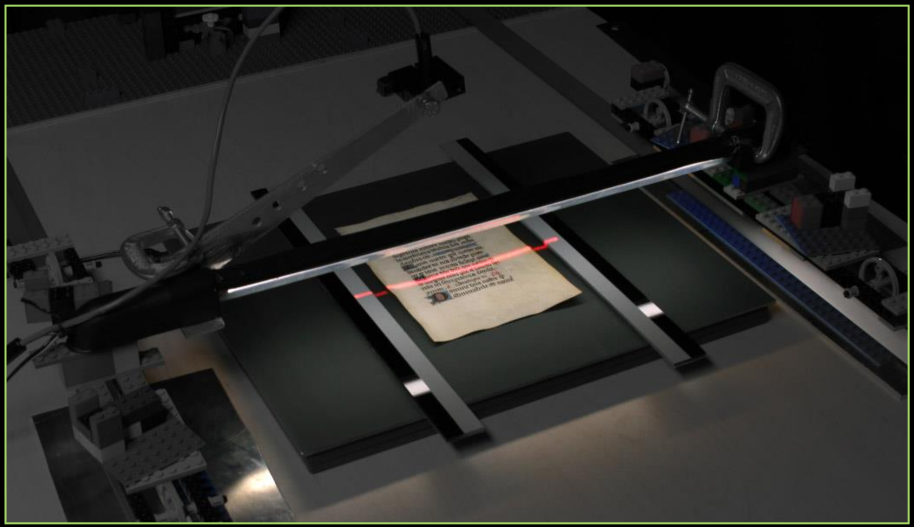






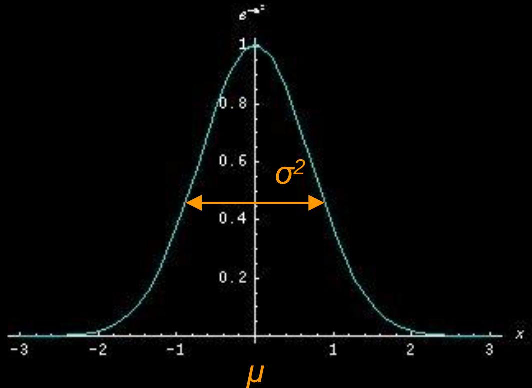
Specular normals

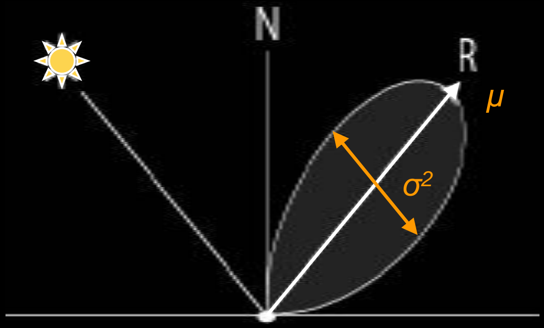
Reflectance capture techniques

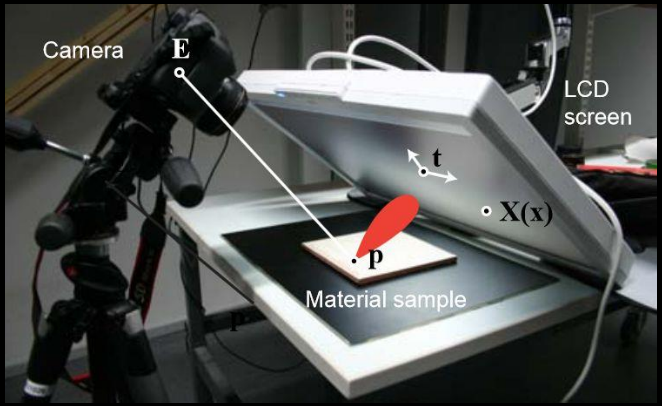


BRDF

SVBRDF







Facial Appearance Capture and Modelling

- Image based
  - Reflectance field
  - Relighting

- Model based
  - 3D geometry
  - Surface reflectance
  - Subsurface scattering

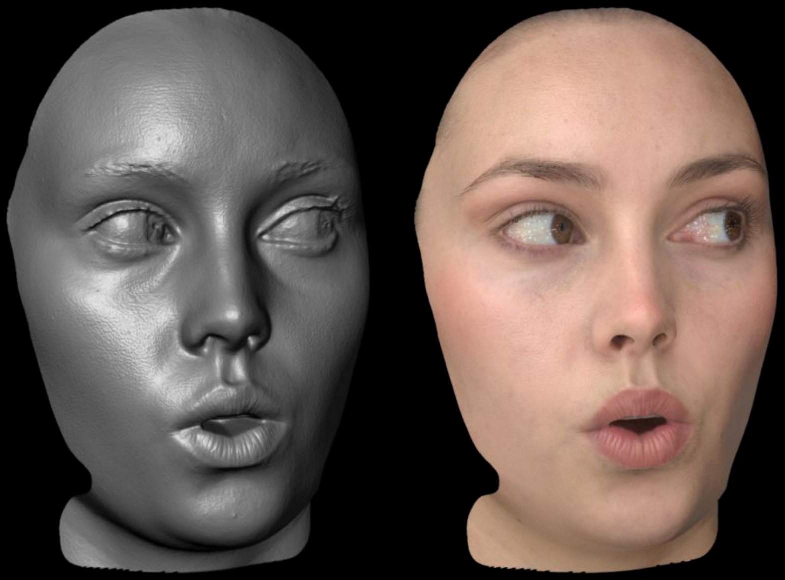
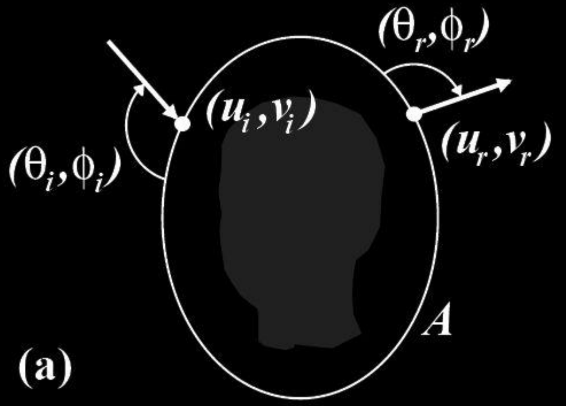


Image Based Relighting & Reflectance Field

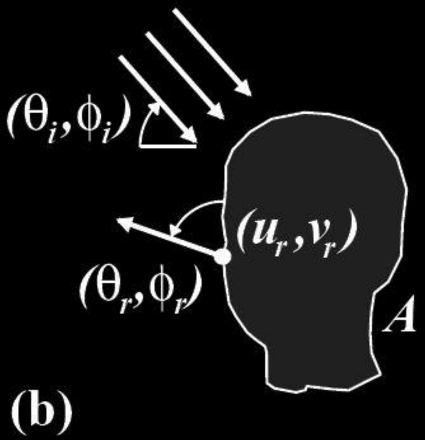
Debevec, Hawkins, Tchou, Duiker, Sarokin, and Sagar. *Acquiring the Reflectance Field of a Human Face*. SIGGRAPH 2000

Reflectance field

- 8D general case [Debevec 00]
  - 4D incident & 4D reflected light field



- 4D special case
  - Distant illumination
  - Fixed viewpoint

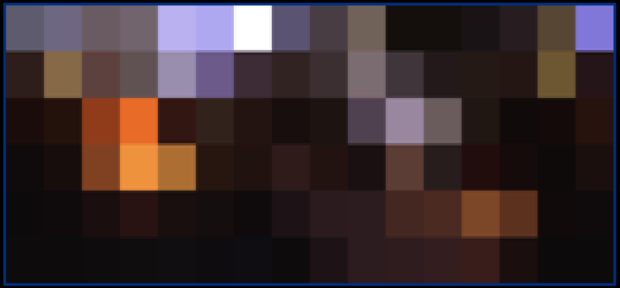



Light Stage 1:
60-second exposure

Light Stage 4D Reflectance Field

Light Stage 4D Reflectance Field

$\sum$

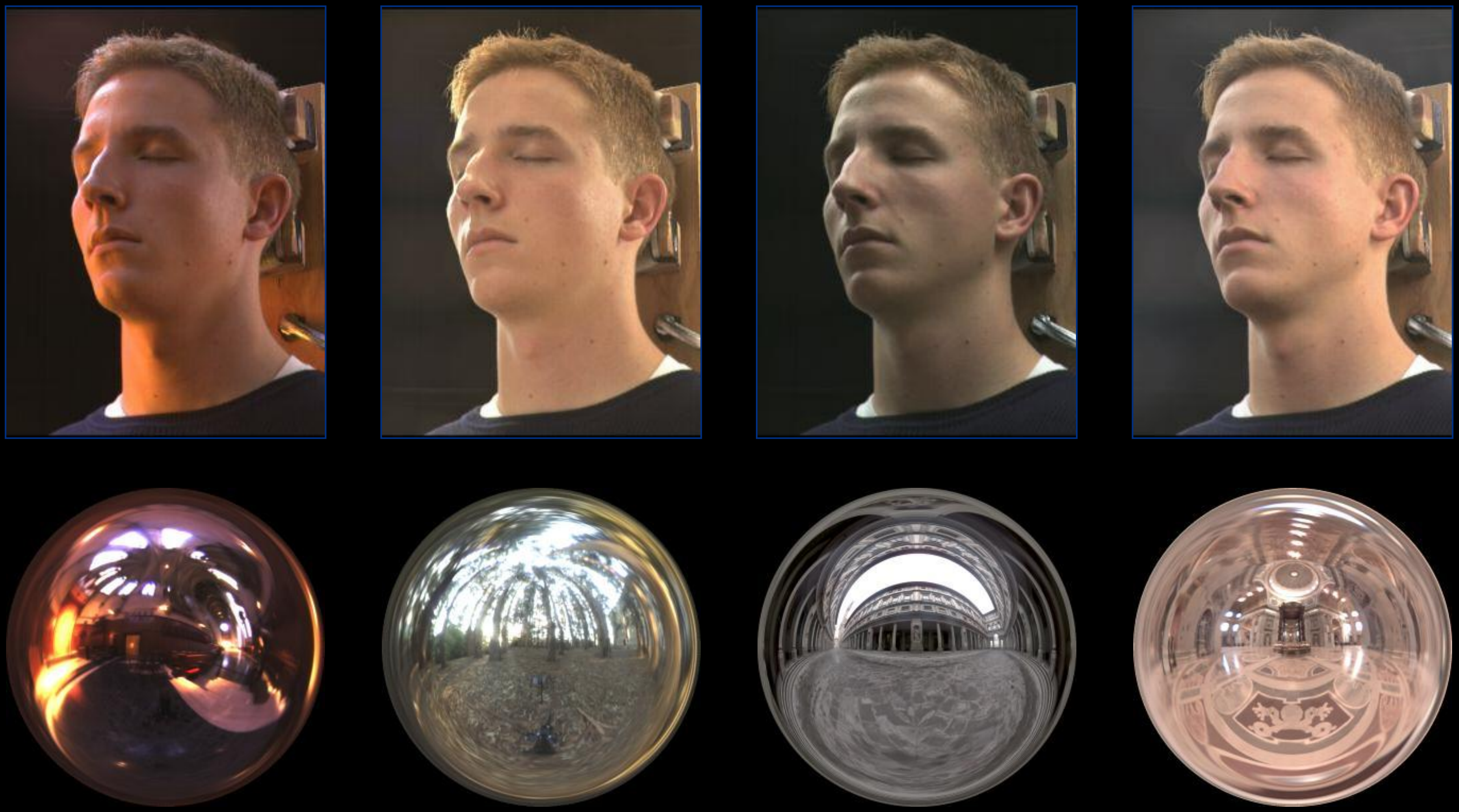


Dot product of reflectance field and light probe

Image Based Relighting

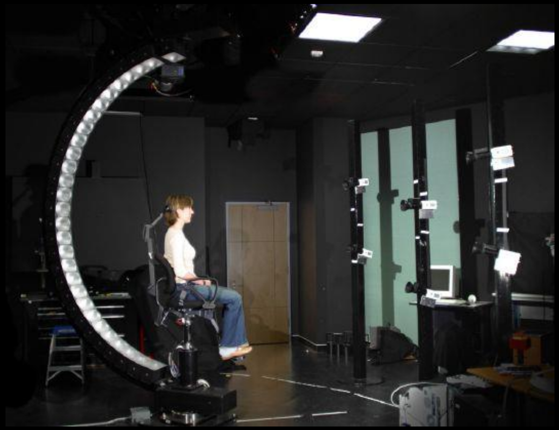
Relit result!

Image Based Relighting



Relit results

Light Stage designs for IBR



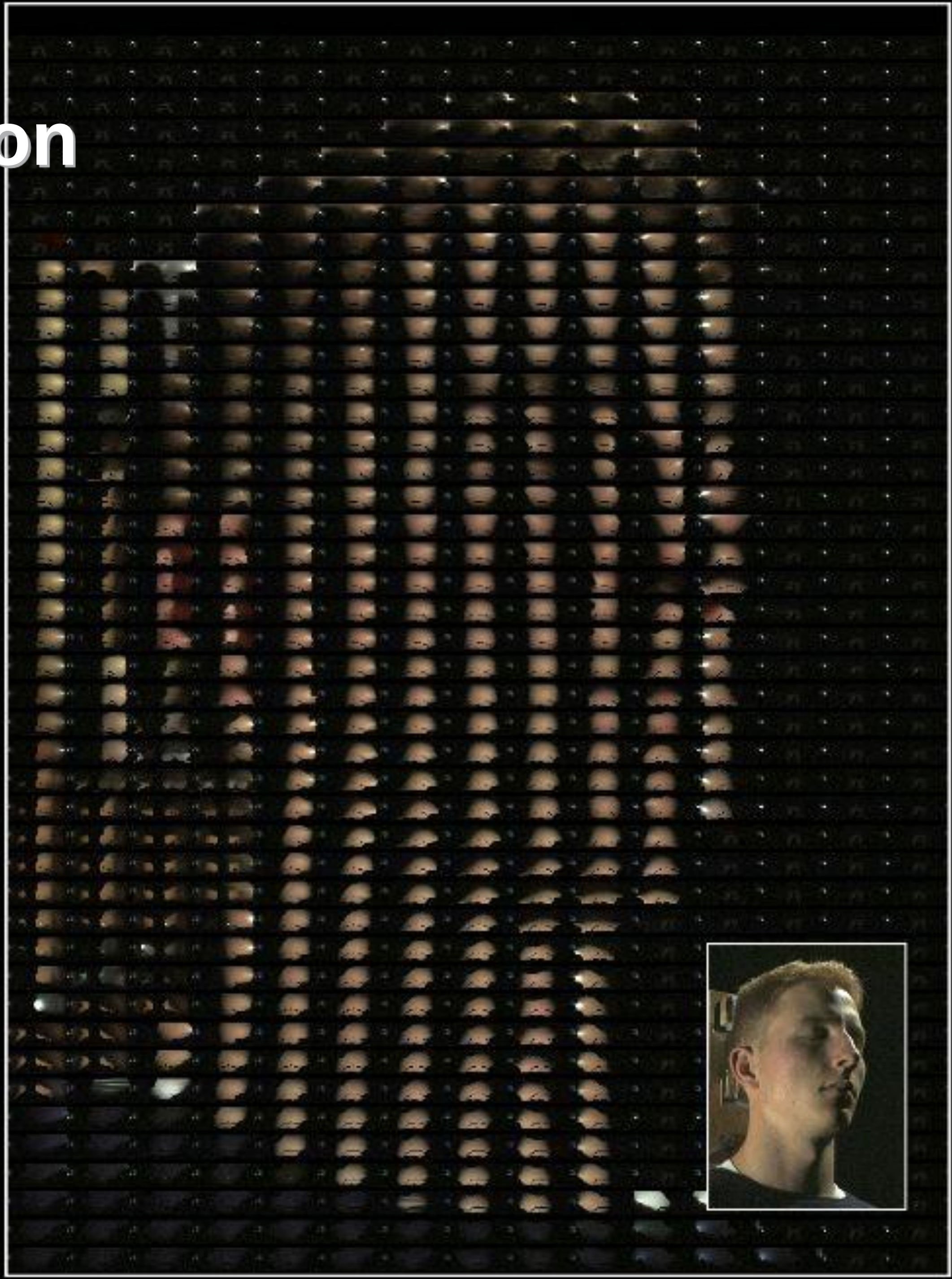
Light Stage 2

[Hawkins et al. 04]

Light Stage 5

[Wenger et al. 05]

Reflectance Function



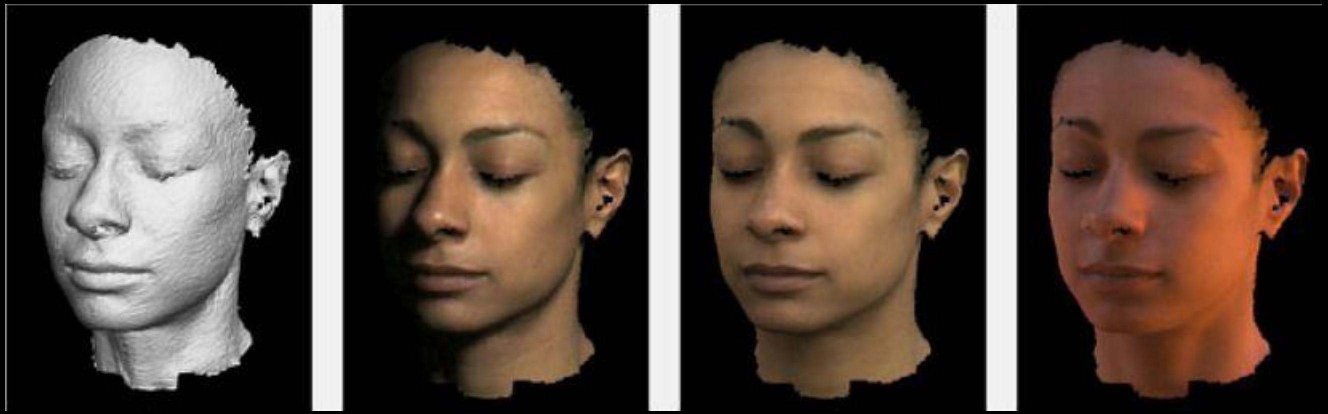
- Resampling of reflectance field

Reflectance Function

- Per-pixel light transport
  - Diffuse, specular
  - Subsurface scattering
  - Inter-reflection

Model-Based Facial Appearance! [Debevec et al. 00]

Light Stage data | Surface normal | Diffuse albedo | Specular albedo



Facial geometry

(structured light)

Facial Relighting

(Interpolated reflectance field)

Model based view interpolation!

Model-Based Facial Appearance

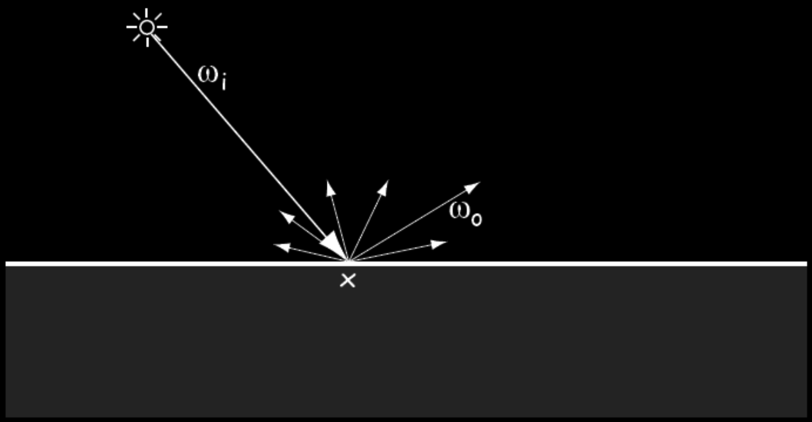
- Dense measurements [Weyrich et al. 06]
  - 16 cameras, 150 lighting directions
  - commercial face scanner for geometry
  - specular BRDF, single layer subsurface scattering

LED Sphere

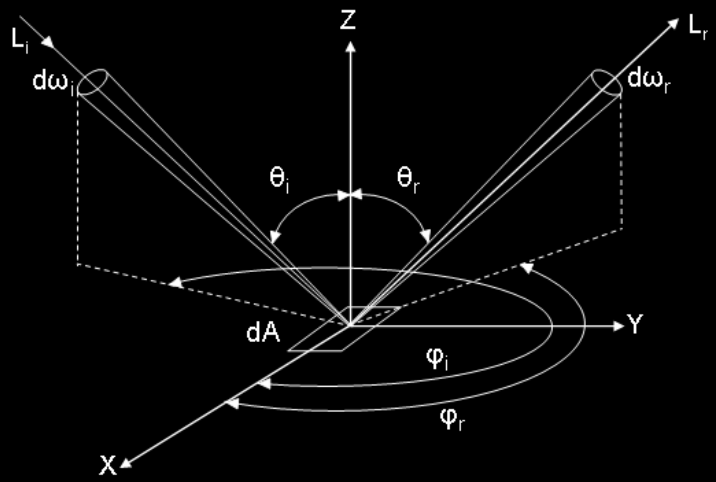
Viewpoint freedom!

Face renderings

Skin surface (specular) reflectance

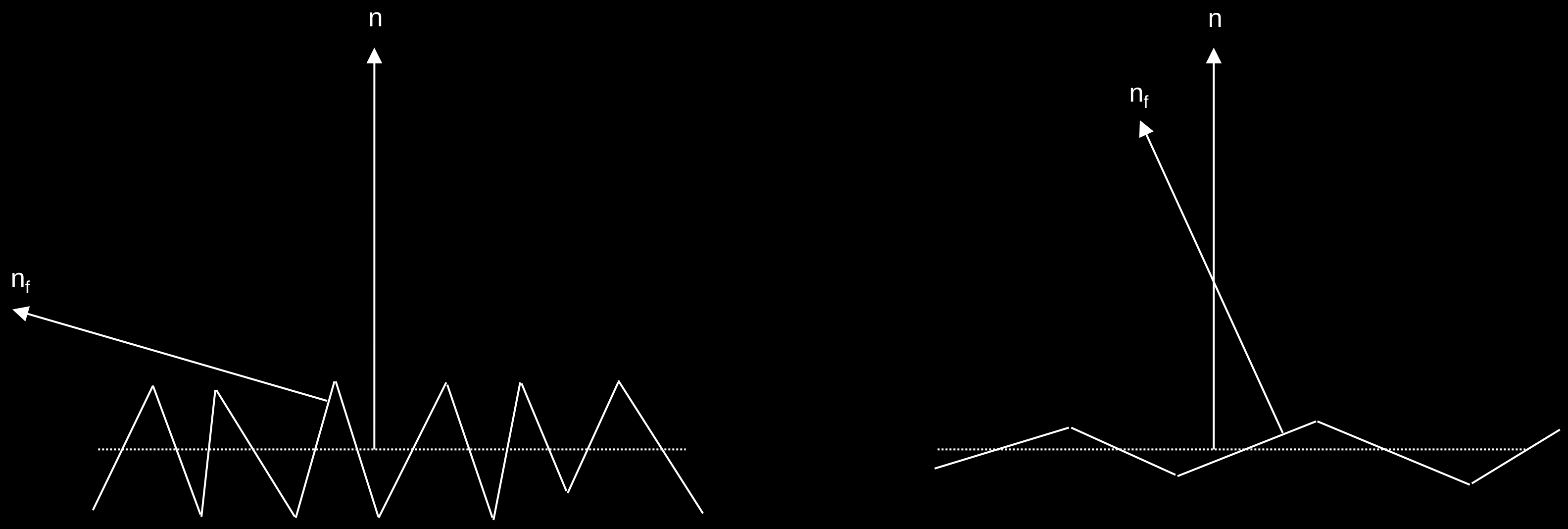


BRDF $f_r(x, \vec{\omega}_i, \vec{\omega}_o) = \frac{dL(x,\vec{\omega}_i)}{dE(x,\vec{\omega}_o)}$



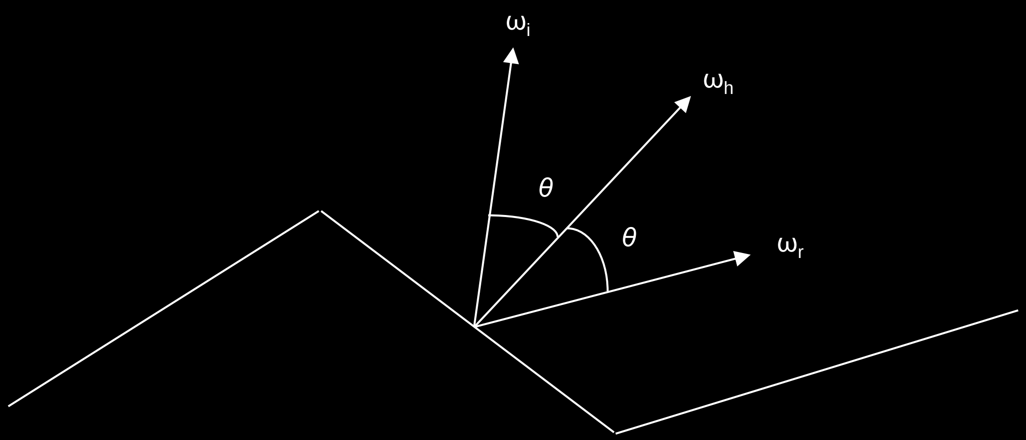
- Bidirectional reflectance distribution function (BRDF), 4D function
  - 3D for isotropic materials like skin
  - Microfacet model

Microfacet Models



- Rough surfaces modeled as a collection of microfacets
  - each face a perfect specular reflector
  - distribution of faces described statistically

Cook-Torrance Model



- $$f_r(\omega_r, \omega_i) = \frac{D(\omega_h)\, G(\omega_r, \omega_i)\, F_r(\omega_h)}{4\,(n \cdot \omega_i)\,(n \cdot \omega_r)}$$

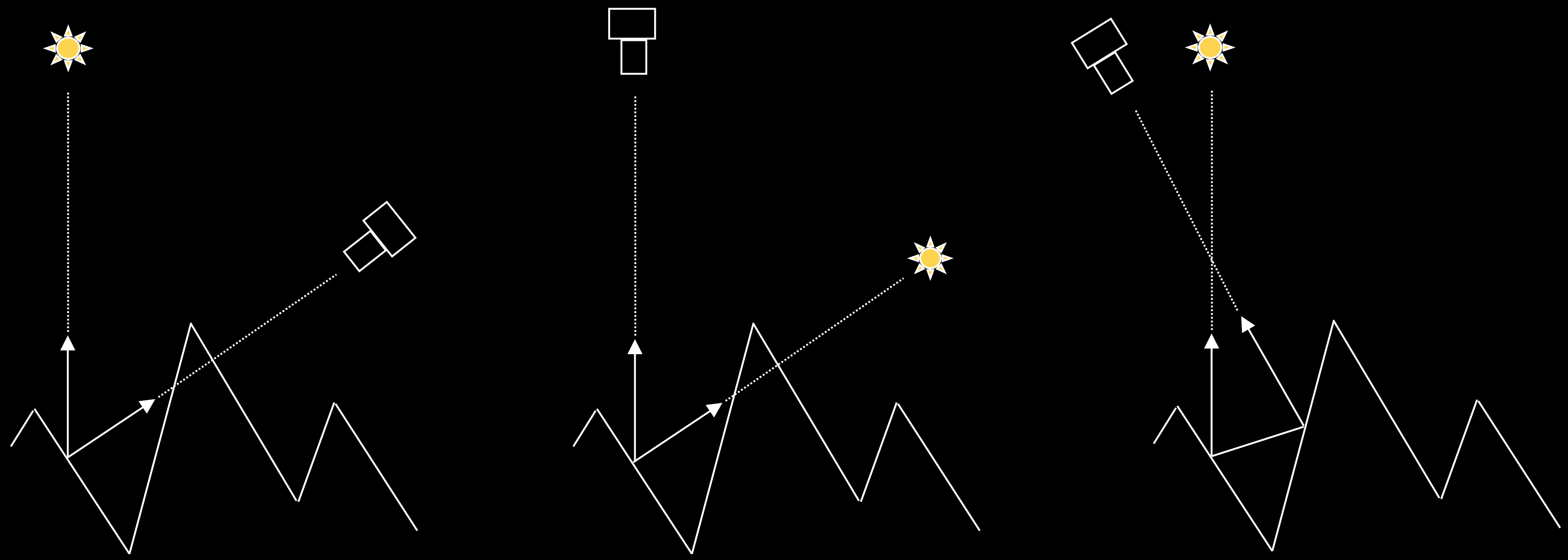
  - D, the distribution term
  - G, the geometric term
  - F, the Fresnel term

Cook-Torrance Model

- $D(\omega_h) = \dfrac{\exp-[\tan\delta/m]^2}{m^2 \cos^4\delta}$ Beckman distribution
  - δ, angle between n and ω_h
  - m, root-mean-square slope of microfacets

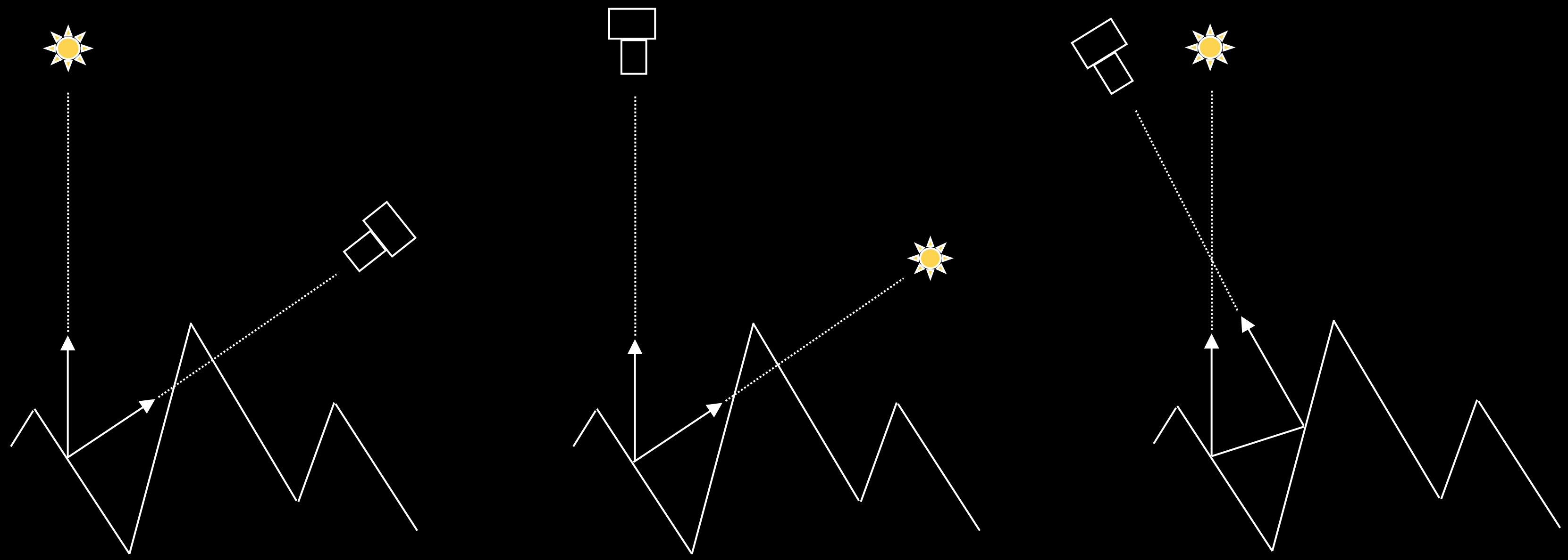
- $D(\omega_h) = \dfrac{(s + 2)}{2\pi} (n \cdot \omega_h)^s$ Blinn microfacet distribution
  - Replace Gaussian with a cosine lobe
  - Normalization term $(s + 2)/ 2\pi = \int_\Omega (n \cdot \omega_h)^s \cos\theta_h \, d\omega_h$

Geometric effects



- Geometric effects of microfacets
  - masking
  - shadowing
  - interreflections

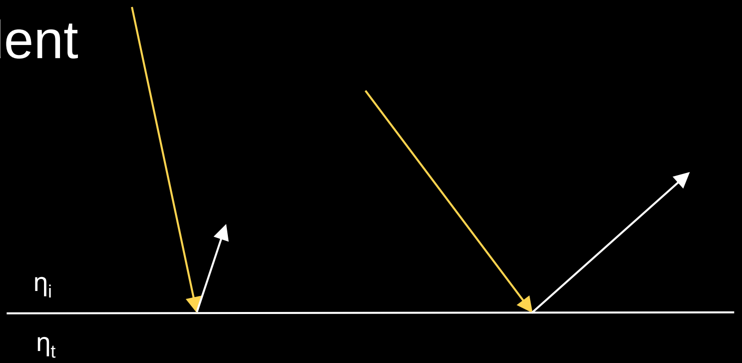
Geometric effects



- $G(\omega_r, \omega_i) = \min\left\{1, \dfrac{2\,(n \cdot \omega_h)\,(n \cdot \omega_r)}{(\omega_r \cdot \omega_h)}, \dfrac{2\,(n \cdot \omega_h)\,(n \cdot \omega_i)}{(\omega_r \cdot \omega_h)}\right\}$
    - V-shaped grooves

Fresnel Reflectance

- Reflection from a surface is view dependent



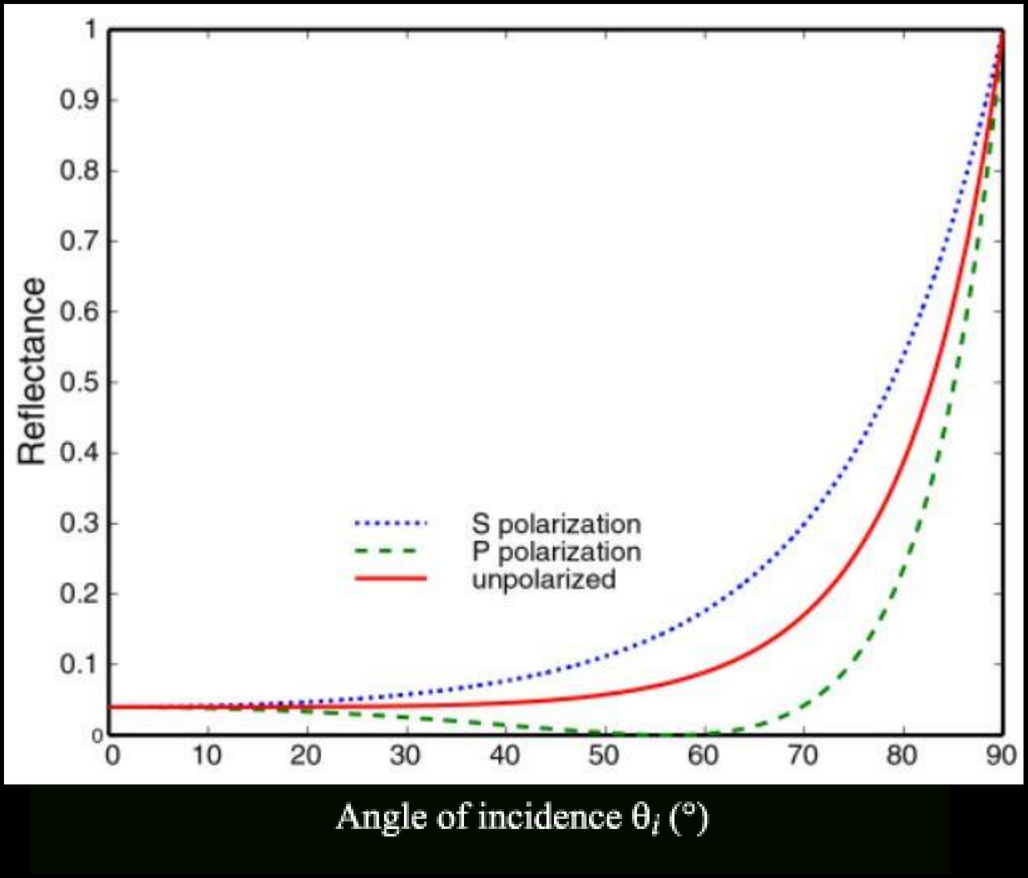
- Fresnel equations
  - Maxwell's equations at smooth surfaces
  - index of refraction and polarization!
  - Dielectrics vs metals

- Approx. using Schlick's formula:

$$R(\theta) = R_0 + (1 - R_0)(1 - \cos\theta)^5$$

  - reflectance at normal incidence R_0
  - No need for index of refraction

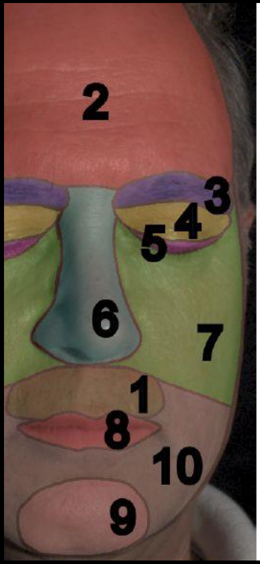
Fresnel

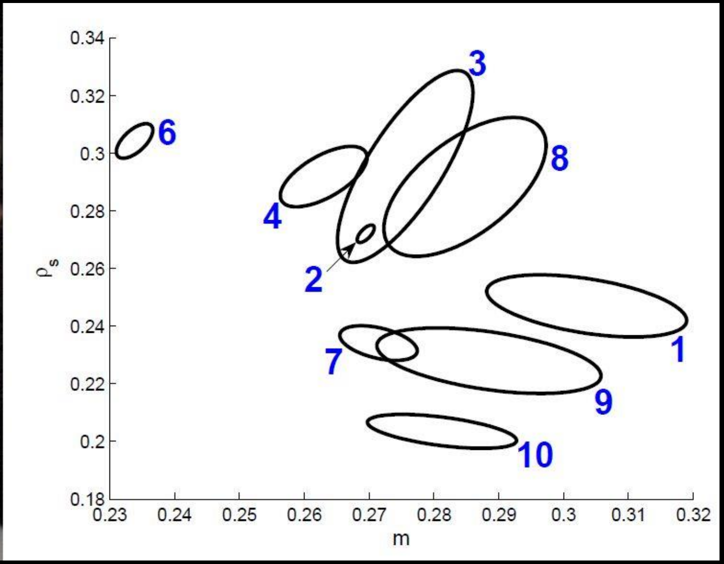


- Schlick formula approximates red curve for unpolarized reflectance
- Well suited for dielectrics like skin!

Facial specular BRDF

- Spatially varying fits of specular albedo and roughness over various facial regions
  - Cook-Torrance [Weyrich 06]



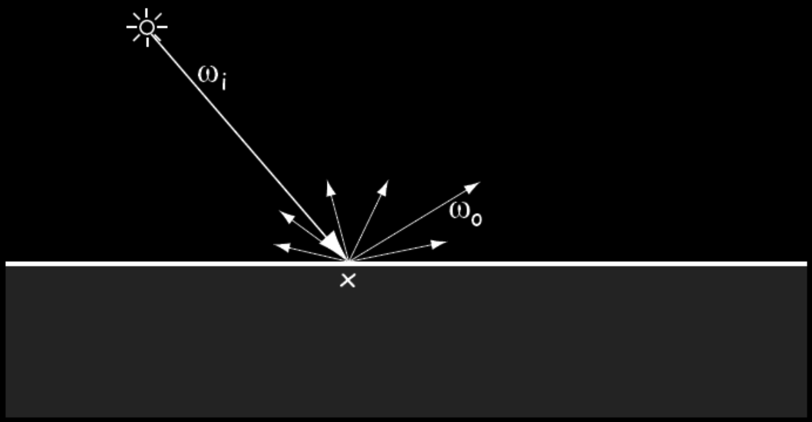


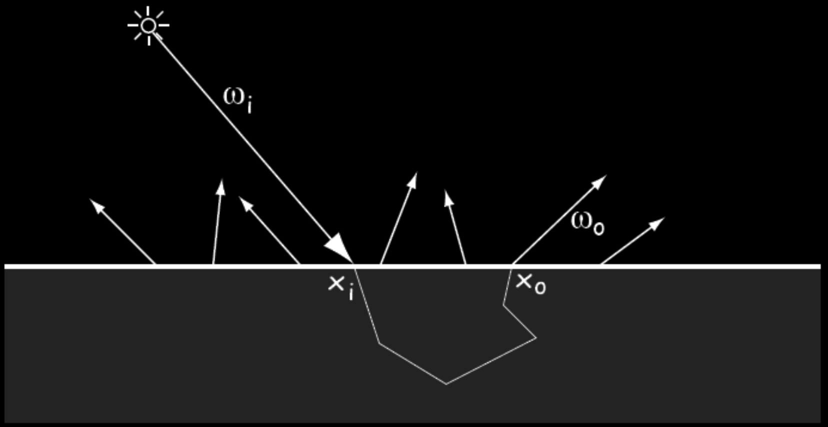
Photograph

Spatially varying BRDF

Uniform BRDF

Skin subsurface (diffuse) scattering



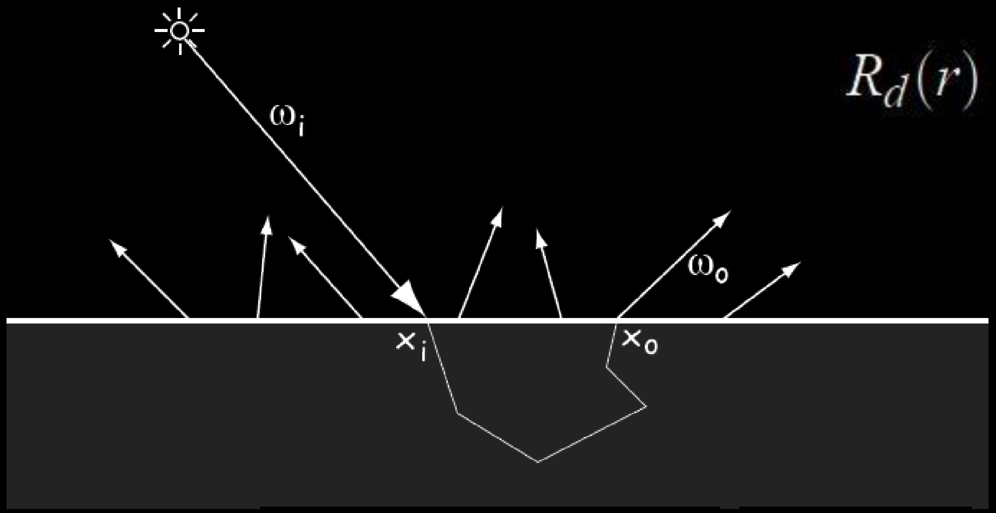


BRDF $f_r(x, \vec{\omega}_i, \vec{\omega}_o) = \frac{dL(x,\vec{\omega}_i)}{dE(x,\vec{\omega}_o)}$

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]

Diffuse BSSRDF [Jensen et al. 01]

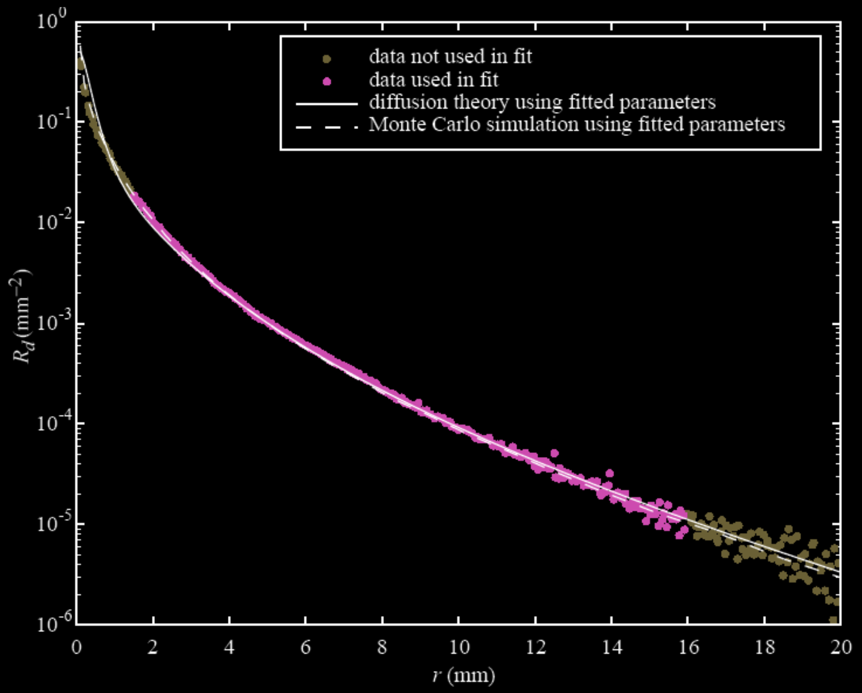


$$R_d(r) = \frac{\alpha'}{4\pi}\left\{z_r\left(\sigma_{tr} + \frac{1}{d_r}\right)\frac{e^{-\sigma_{tr} d_r}}{d_r^2} + z_v\left(\sigma_{tr} + \frac{1}{d_v}\right)\frac{e^{-\sigma_{tr} d_v}}{d_v^2}\right\}$$

BSSRDF $S_d(x_i, \omega_i, x_o, \omega_o) \approx R_d(x_i, x_o)$

- $R_d(x_i, x_o)$ models isotropic Gaussian-like diffusion between points x_i and x_o
  - Dipole model for homogeneous semi-infinite medium
  - Sum of two Gaussian like fall-offs

Diffuse BSSRDF [Jensen et al. 01]



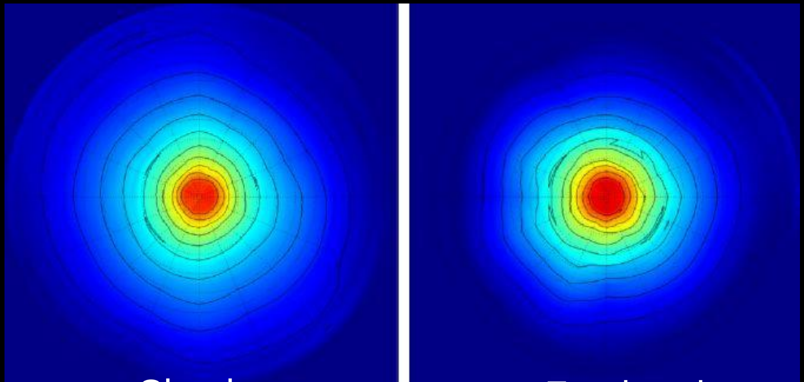
$$R_d(r) = \frac{\alpha'}{4\pi}\left\{z_r\left(\sigma_{tr}+\frac{1}{d_r}\right)\frac{e^{-\sigma_{tr}d_r}}{d_r^2}+ z_v\left(\sigma_{tr}+\frac{1}{d_v}\right)\frac{e^{-\sigma_{tr}d_v}}{d_v^2}\right\}$$

- $R_d(x_i, x_o)$ models isotropic Gaussian-like diffusion between points x_i and x_o
  - Two parameters, albedo and translucency (diffuse mean free path in mm)

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]



Cheek Forehead

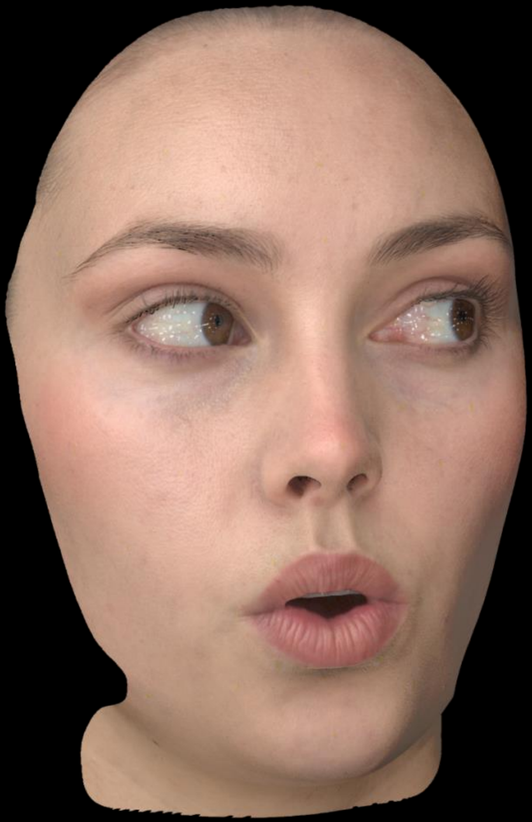
Measuring facial subsurface scattering

- phase-shifted stripes [Tariq et al. 06]
  - inverse rendering for dipole diffusion parameter fitting
  - 40 phase shifts time consuming

Rapid acquisition of geometry and reflectance

Photograph

Geometry

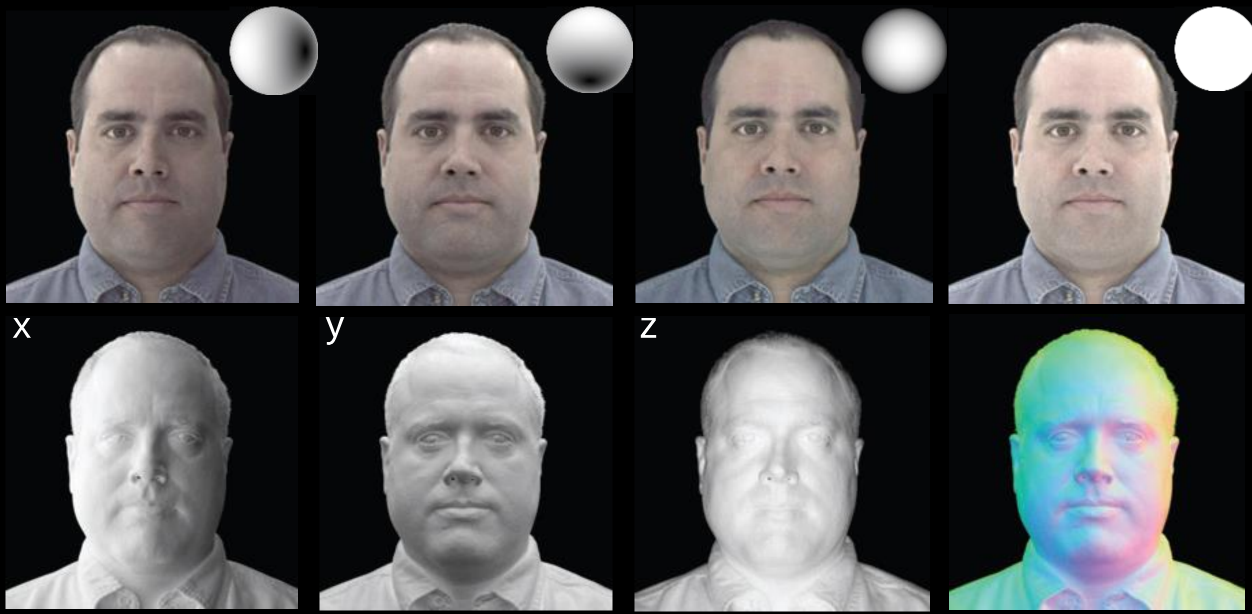


Rendering

[Alexander et al. 2010]

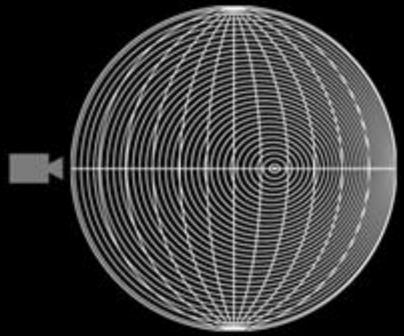
Spherical gradient illumination

[Ma et al. 2007]



LED sphere

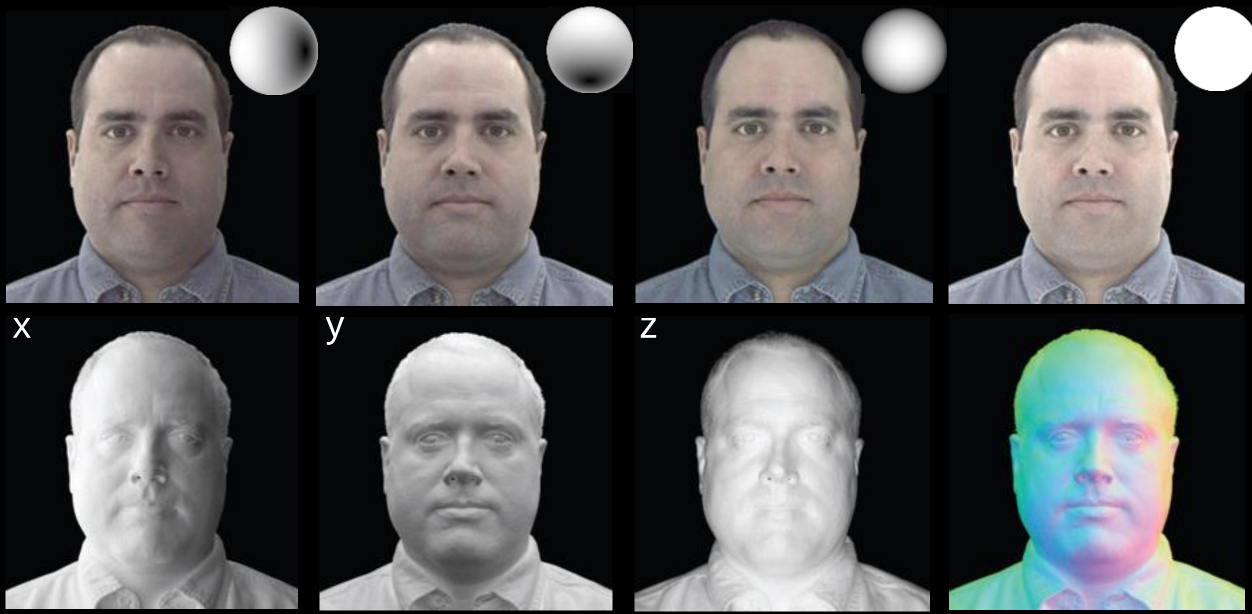
- Polarization for diffuse/specular separation
  - separate diffuse & specular normals
  - albedo maps

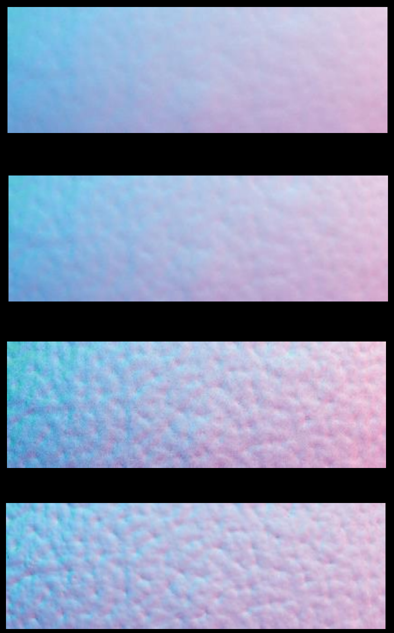


Linear polarization pattern

Spherical gradient illumination

[Ma et al. 2007]

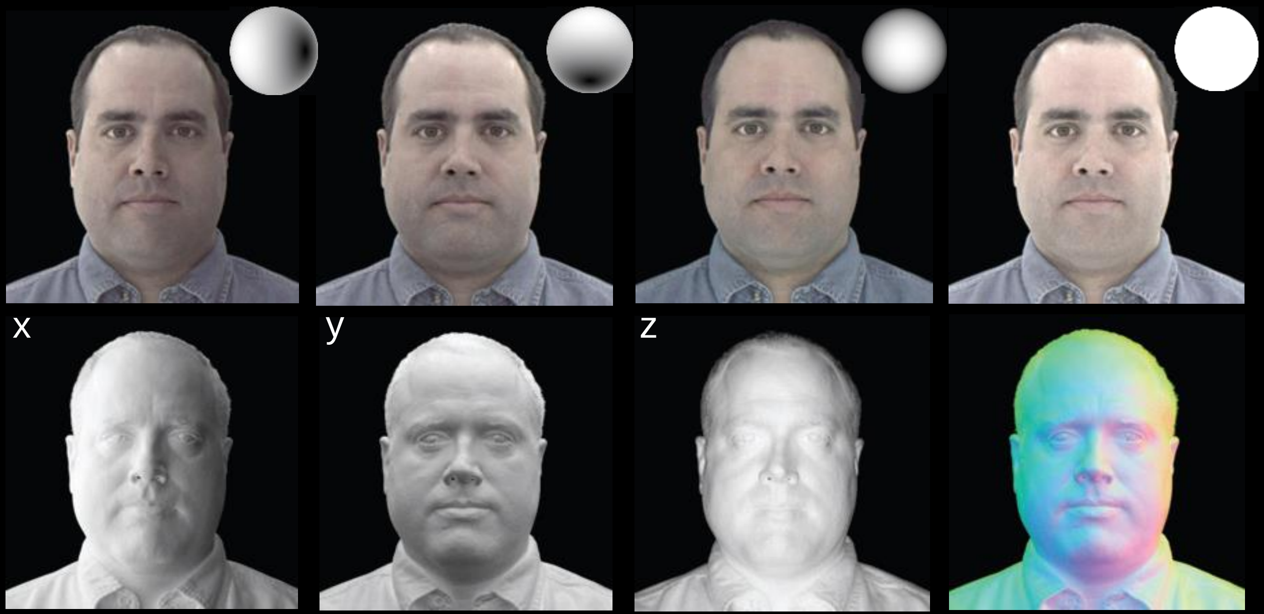


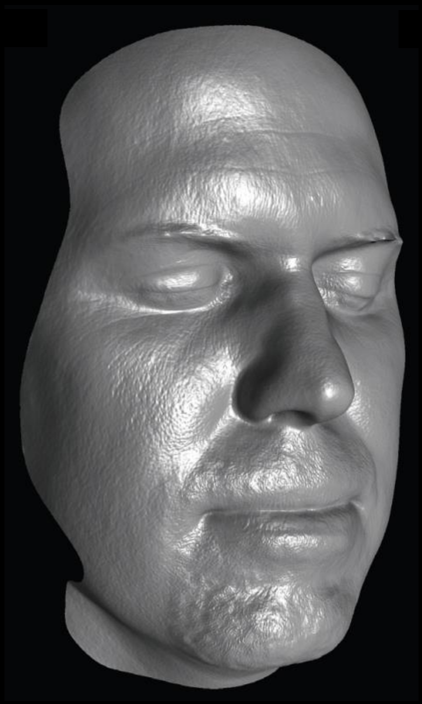


- Polarization for diffuse/specular separation
  - separate diffuse & specular normals
  - albedo maps

Spherical gradient illumination

[Ma et al. 2007]



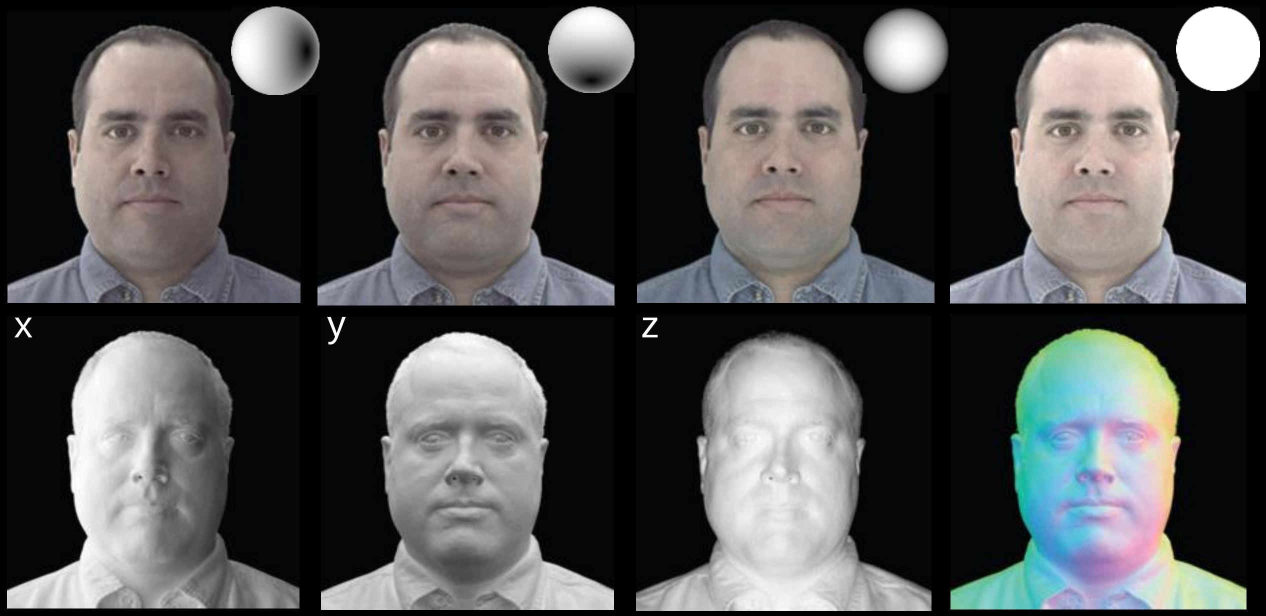


High res. geometry

- Polarization for diffuse/specular separation
  - separate diffuse & specular normals
  - albedo maps
  - structured light for base geometry

Spherical gradient illumination

[Ma et al. 2007]

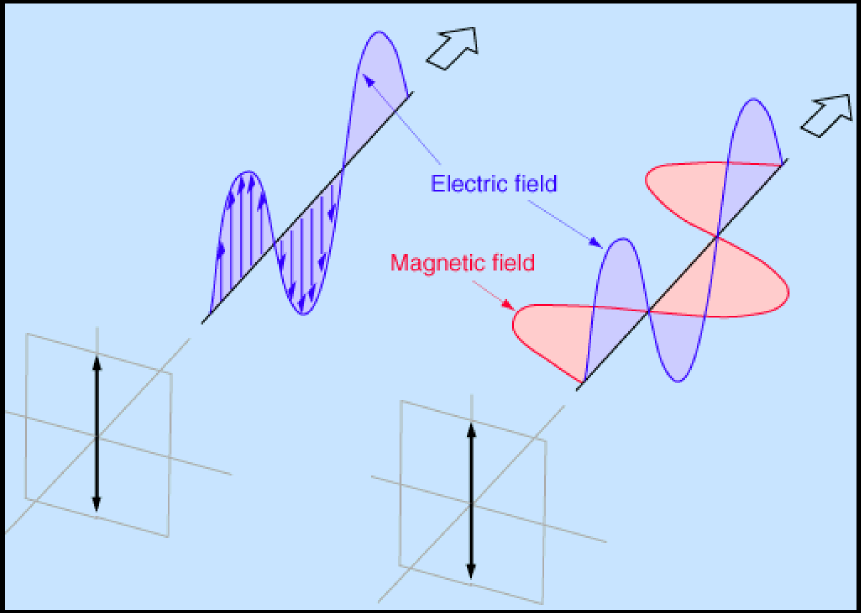


Hybrid normal rendering

- Polarization for diffuse/specular separation
  - separate diffuse & specular normals
  - albedo maps
  - structured light for base geometry

Polarization

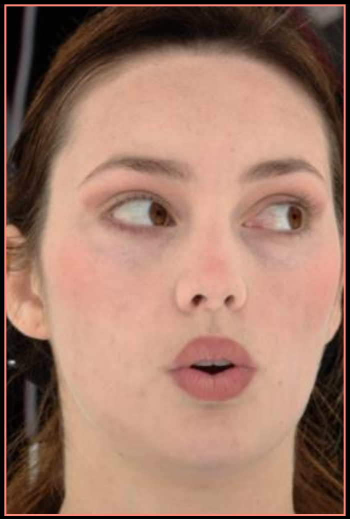
- Light a transverse electromagnetic wave
  - natural state un-polarized
  - electric field randomly oriented
- Linear polarization
  - electric field in fixed plane



Polarization based reflectance separation

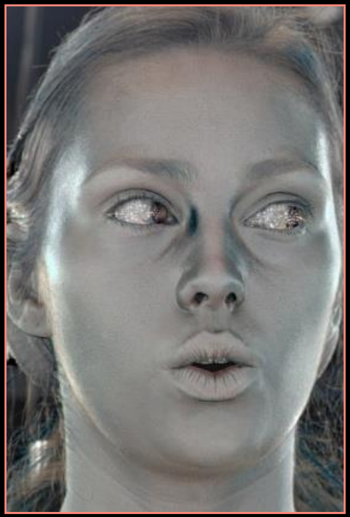
Parallel pol.

-

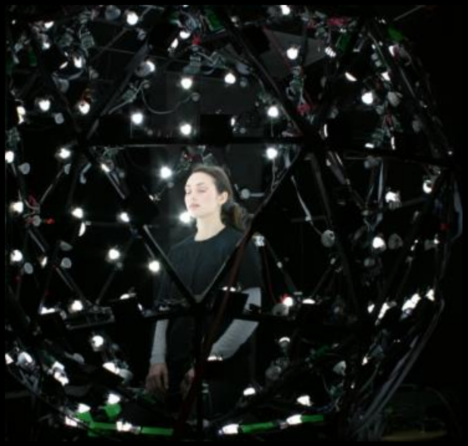


Cross pol.

=

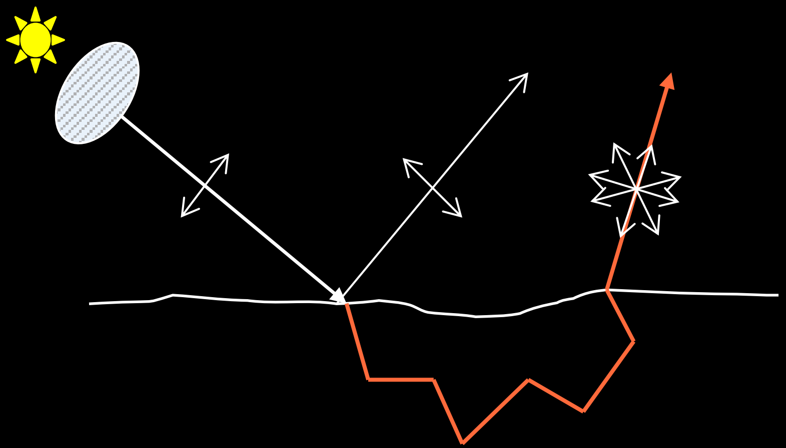


Pol. preserving

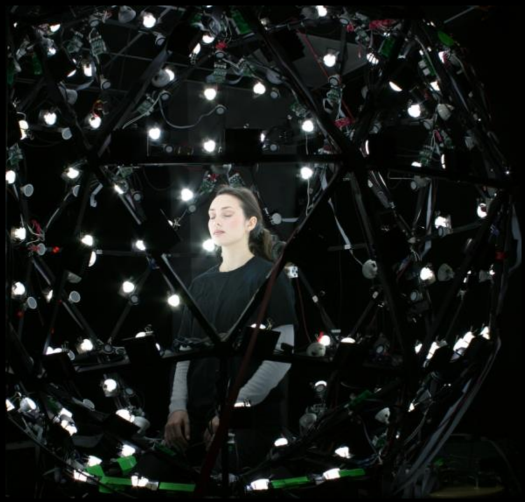


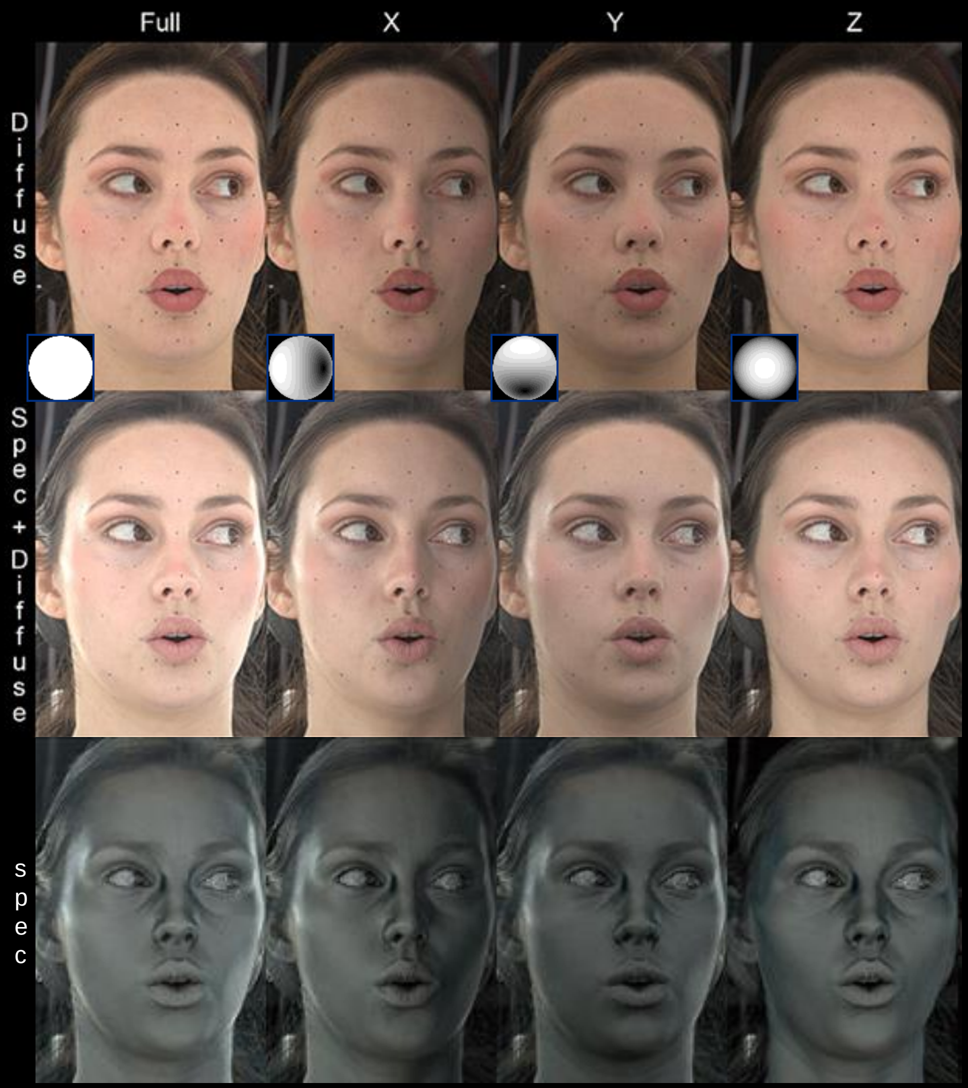
[Ma et al. 2007]
[Alexander et al. 2010]

- Polarization difference imaging
  - Parallel and cross pol. states

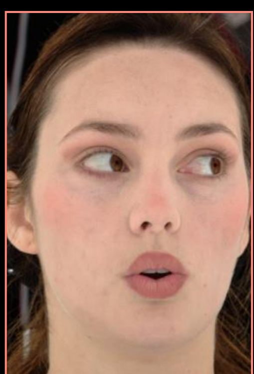


Polarized spherical gradients

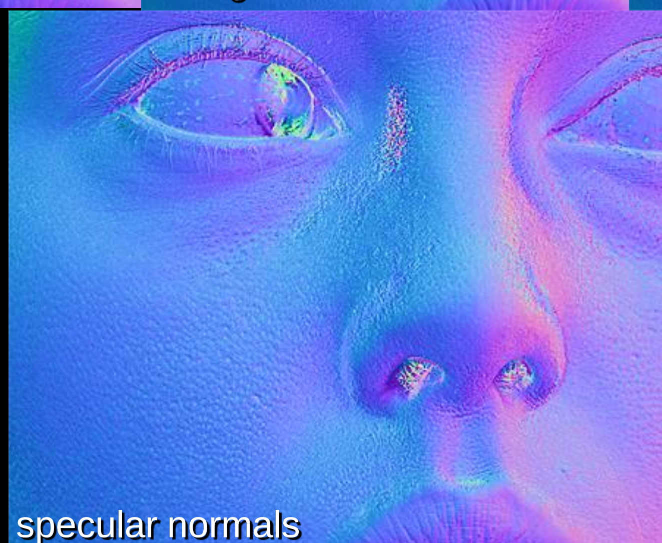




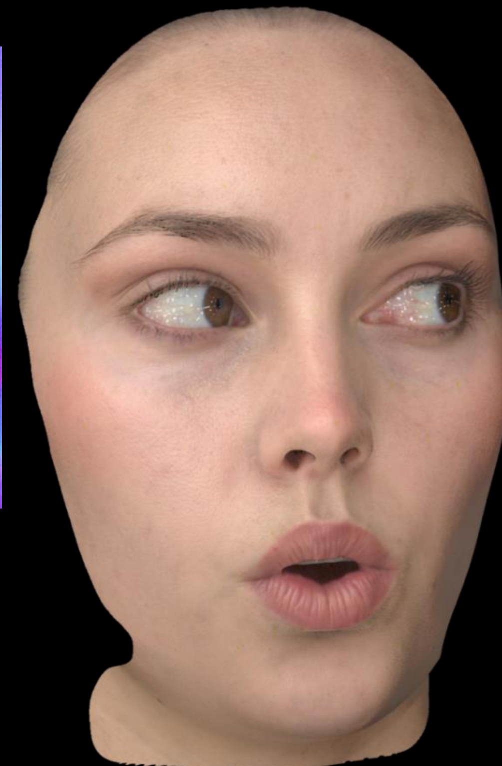
Polarized spherical gradients



diffuse albedo



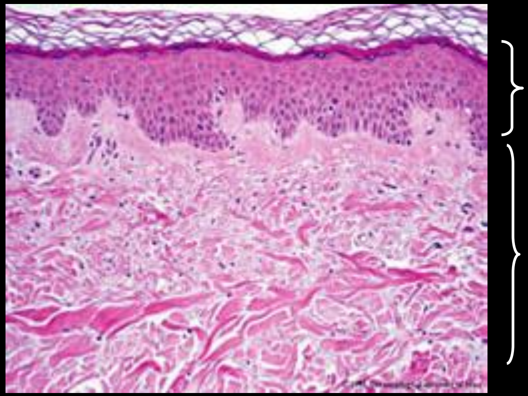
specular albedo



Hybrid normal rendering

Skin Reflectance

Photograph



Skin diagram

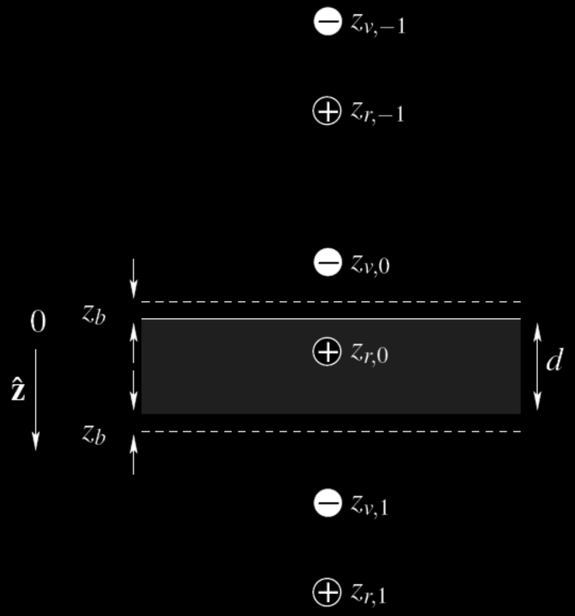
(courtesy University of Iowa)

Diffusion models

Single layer diffusion [Jensen et al. 01]

Multi-layer model
[Donner&Jensen 05]

Multipole model – Donner&Jensen 05

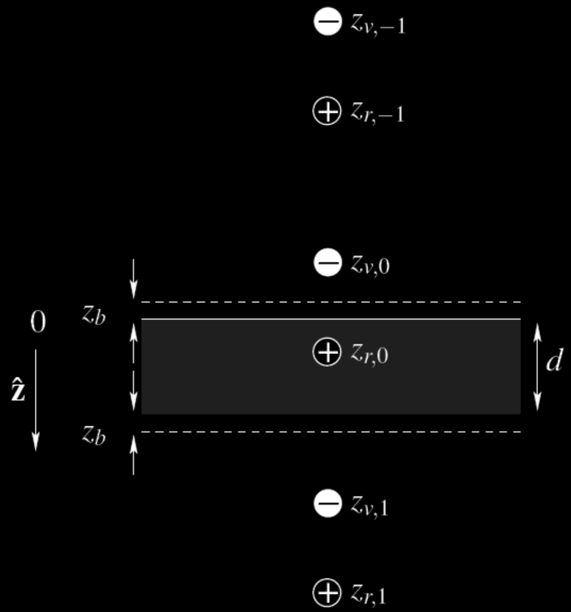


$$R(r) = \sum_{i=-n}^{n} \frac{\alpha' z_{r,i}(1+\sigma_{tr} d_{r,i}) e^{-\sigma_{tr} d_{r,i}}}{4\pi d_{r,i}^3} - \frac{\alpha' z_{v,i}(1+\sigma_{tr} d_{v,i}) e^{-\sigma_{tr} d_{v,i}}}{4\pi d_{v,i}^3}$$

$$T(r) = \sum_{i=-n}^{n} \frac{\alpha'(d - z_{r,i})(1+\sigma_{tr} d_{r,i}) e^{-\sigma_{tr} d_{r,i}}}{4\pi d_{r,i}^3} - \frac{\alpha'(d - z_{v,i})(1+\sigma_{tr} d_{v,i}) e^{-\sigma_{tr} d_{v,i}}}{4\pi d_{v,i}^3}$$

- Multipole models reflectance and transmissions through thin layers more accurately than dipole model
- More accurate for epidermal scattering

Kubelka-Munk theory

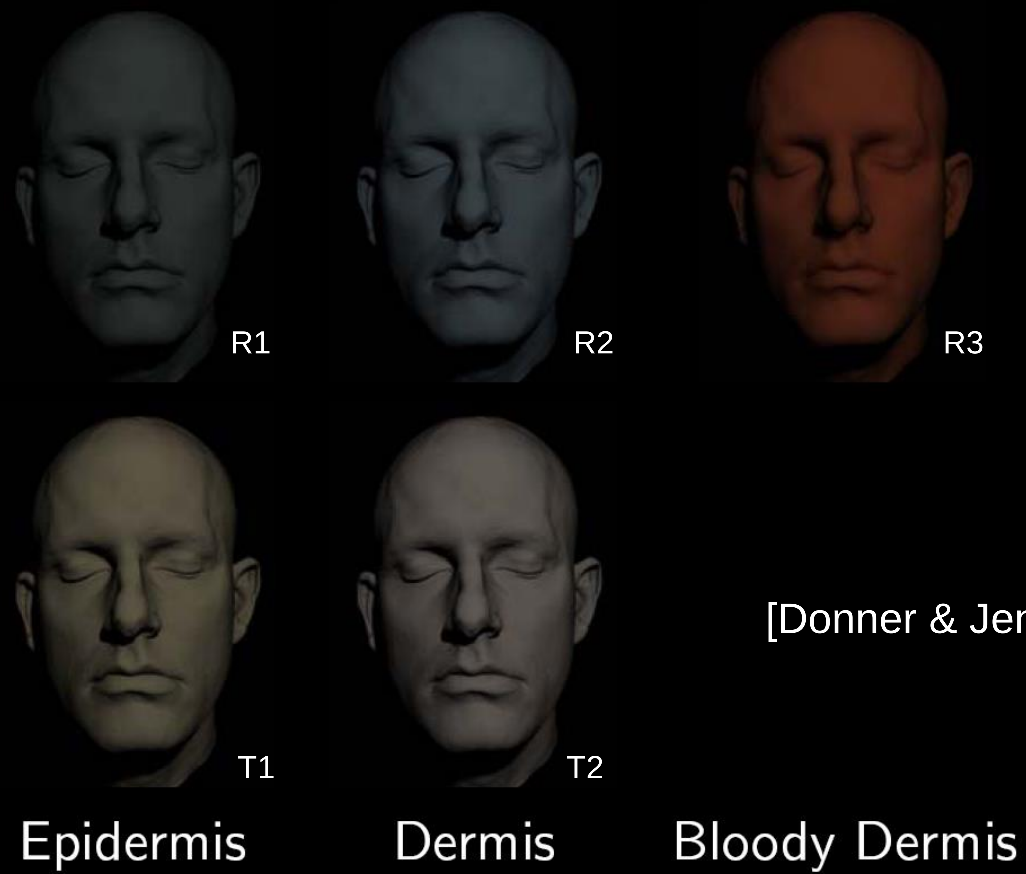


$$T_{12} = T_1 * T_2 + T_1 * R_2 * R_1 * T_2 + T_1 * R_2 * R_1 * R_2 * R_1 * T_2 + \dots$$

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

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

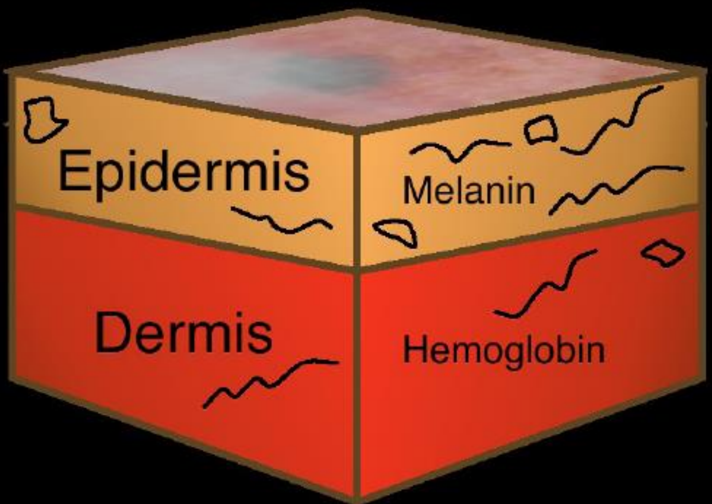
3 layer model rendering



[Donner & Jensen05]

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

Spectral 2 layer model: Donner&Jensen06



Epidermis absorption:

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

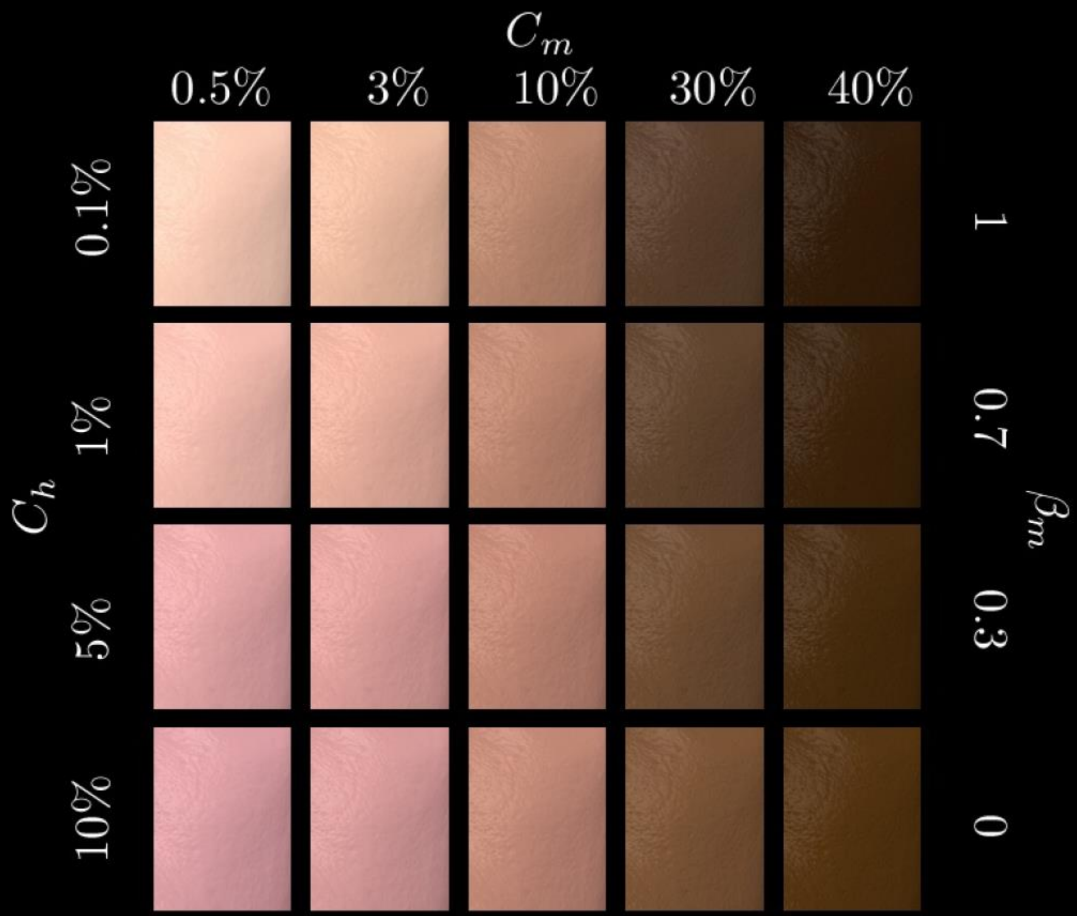
Melanin type $\beta_m \in [0,1]$ and concentration $C_m \in [0,1]$

Dermis absorption:

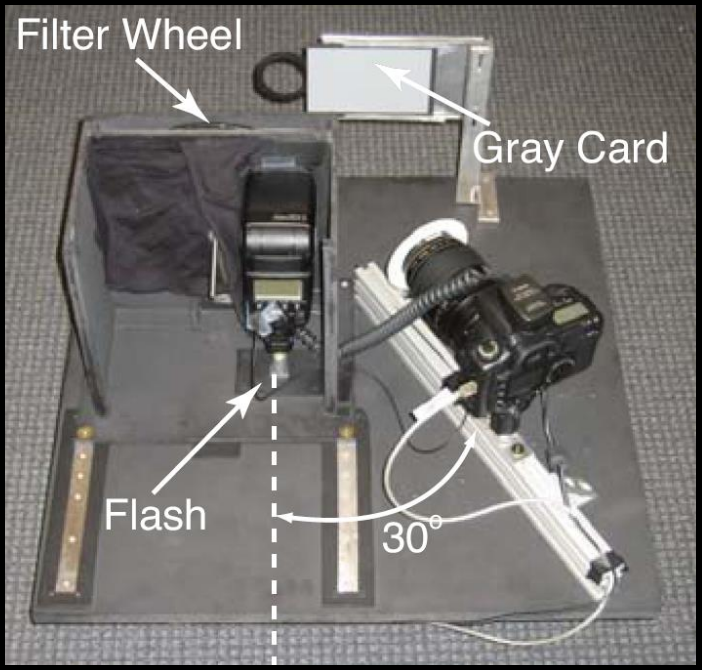
$$\sigma_a^{derm}(\lambda) = C_h(\gamma \sigma_a^{oxy}(\lambda) + (1-\gamma)\sigma_a^{deoxy}(\lambda)) + (1-C_h)\sigma_a^{baseline}$$

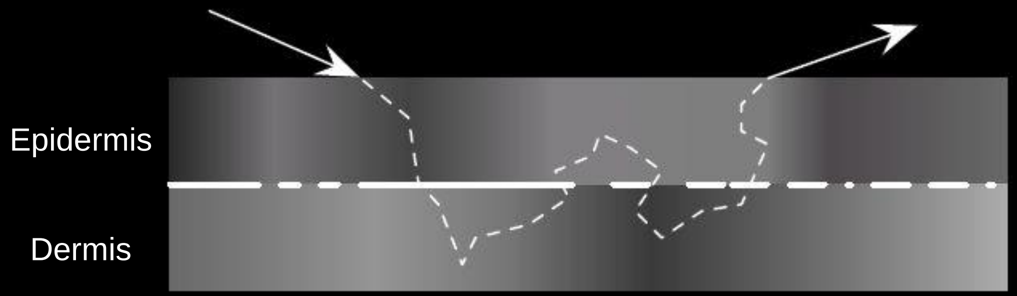
Hemoglobin oxygenation $\gamma = 0.7$ and concentration $C_h \in [0,1]$

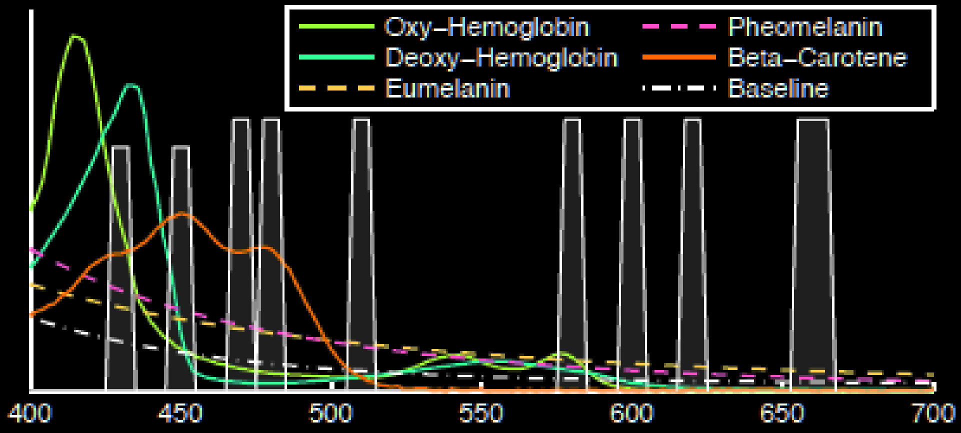
Spectral 2 layer model: Donner&Jensen06



Measuring spectral parameters– Donner et al. 08

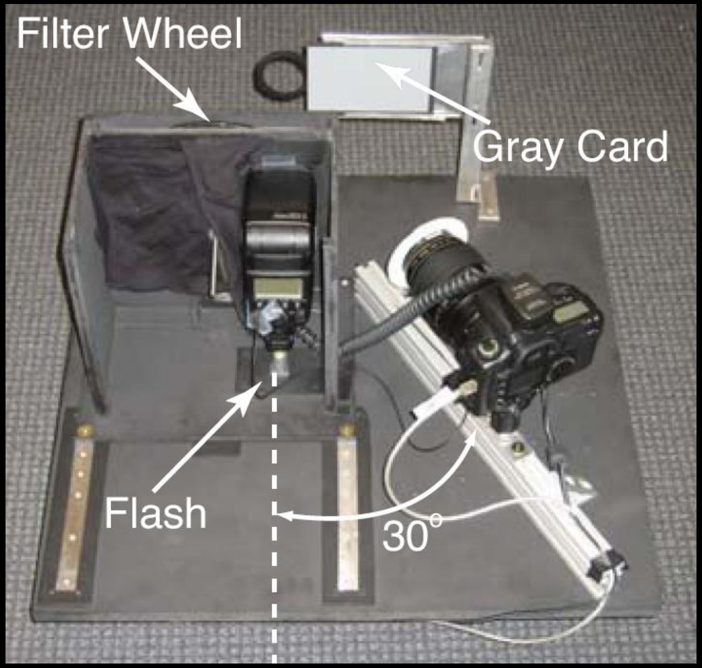


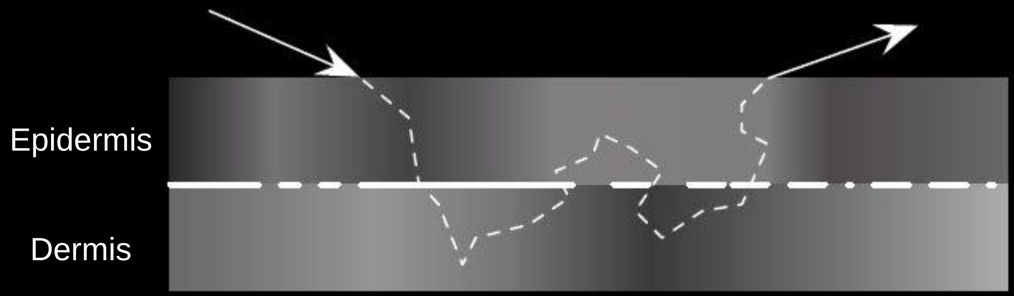


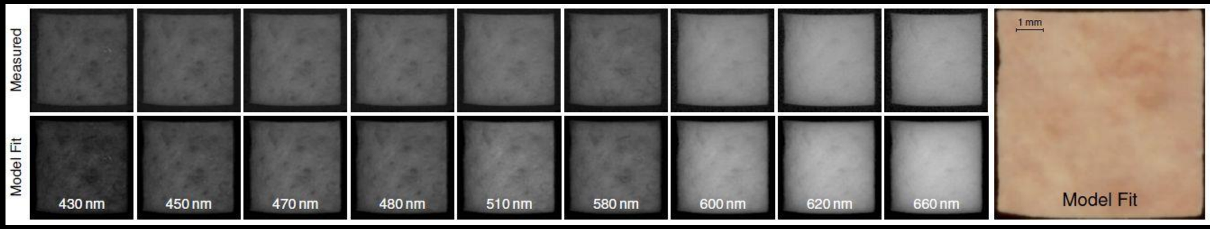


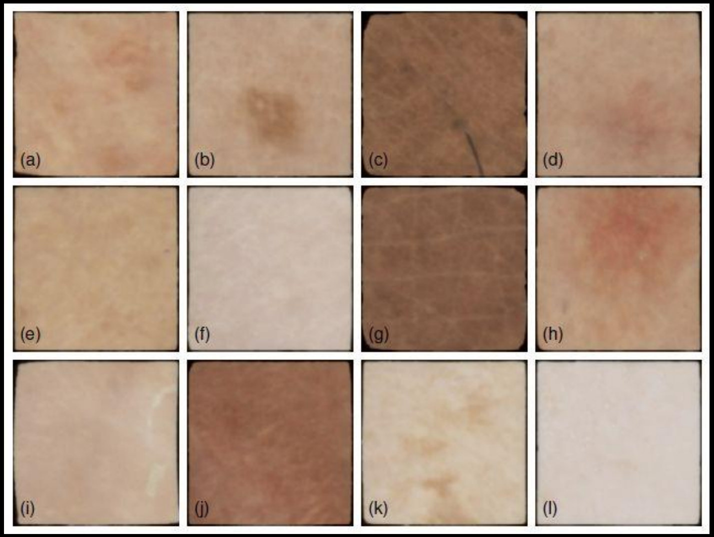
- Multi-spectral imaging
- Inverse rendering for parameters: melanin, hemoglobin & inter layer absorption

Measuring spectral parameters– Donner et al. 08









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

Layered Facial Reflectance

[Ghosh et al. 2008]

specular reflection

single scattering

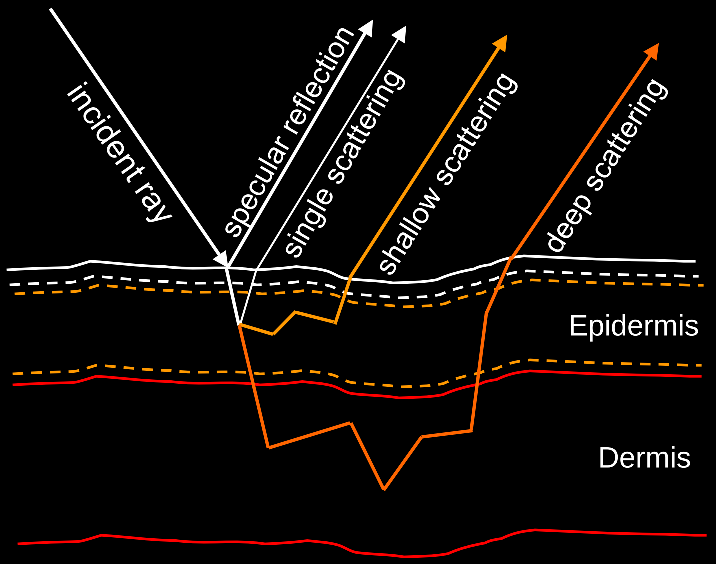
shallow scattering

deep scattering

layered rendering

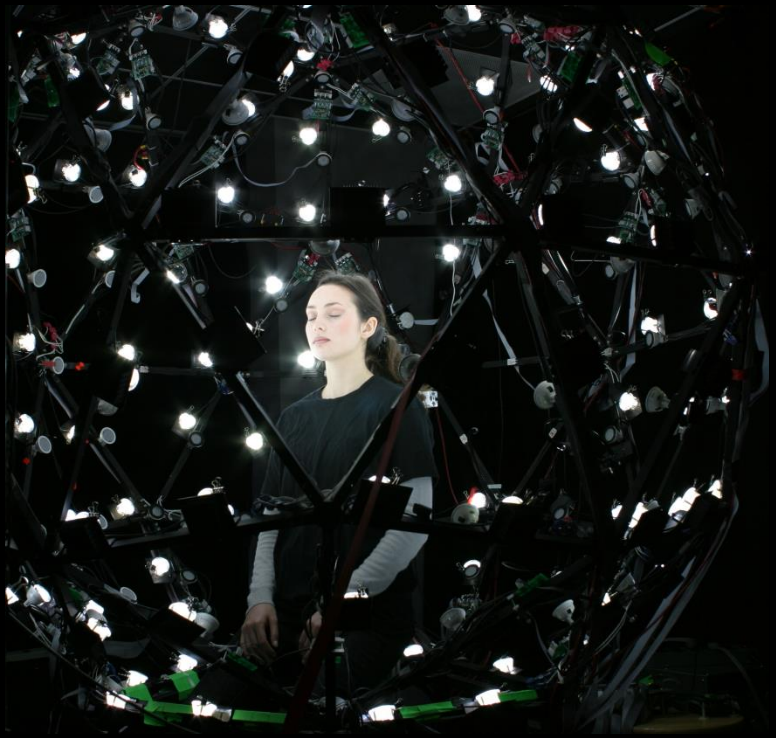
Approach

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

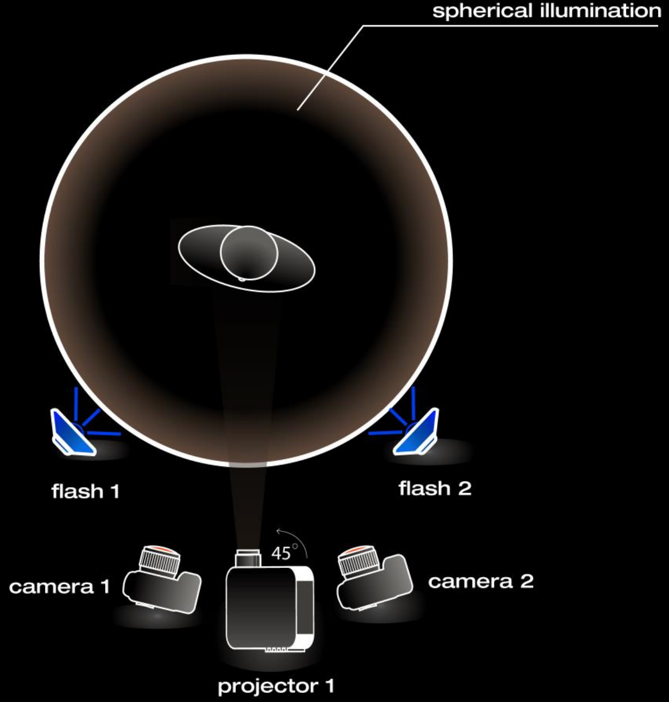


Skin reflectance model

Acquisition setup



LED sphere



- Canon 1D Mark III digital SLRs
- LCD projector vertically polarized
- LED sphere with linear polarizers (similar to [Ma et al. 07])

Measured components

(a) specular albedo

(b) front lit,
parallel polarized

(e) shallow
scattering

+

(d) = (e) + (f)

(c) diffuse albedo

(d) front lit,
cross polarized

=

(f) deep
scattering

Exploiting polarization

(a) front-lit, parallel polarized

-

(b) front-lit, cross polarized

=

(c) specular reflection + single scattering

- Separating single and multiple scattering

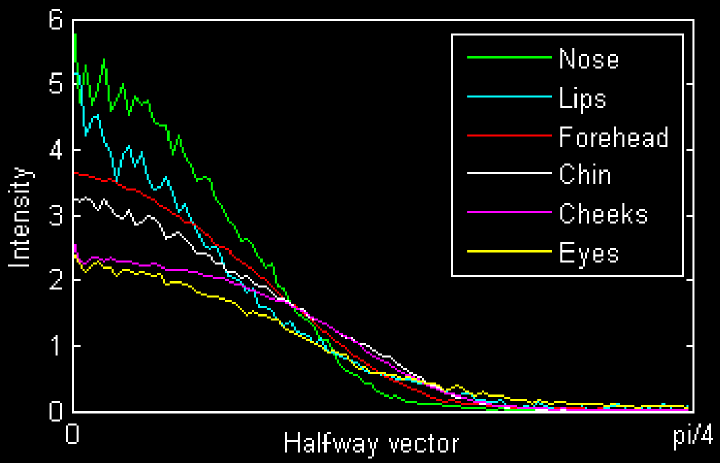
Specular reflection

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

measurement

CT BRDF-fit

segmentation



Single scattering

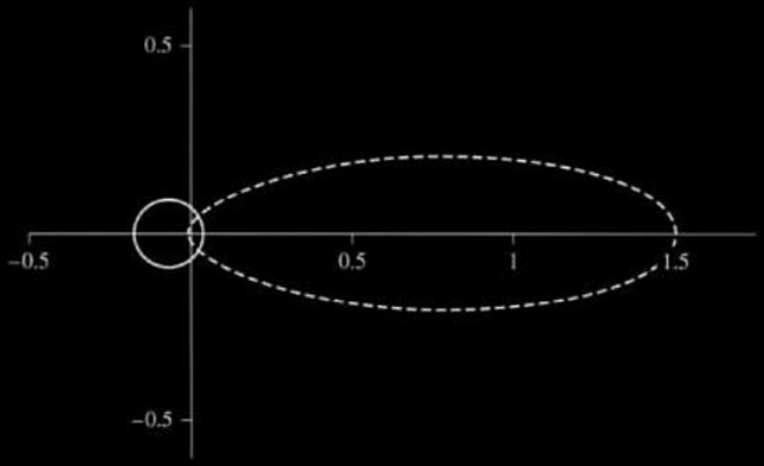
- Polarization preserving non-specular scattering
- Hanrahan & Krueger BRDF model
- Heney-Greenstein phase function fit to backscattering

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

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

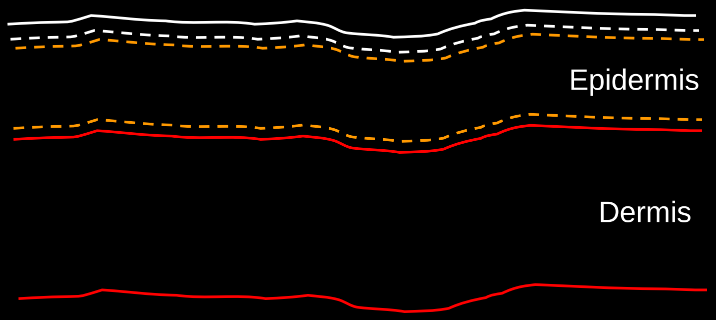
measurement

CT + HK BRDF fit



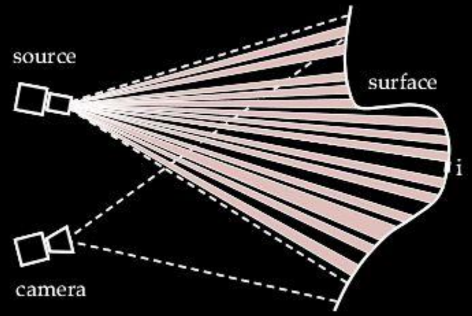
Modeling multiple scattering

- 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]



Modeling multiple scattering

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

high frequency shifted stripes - phase 1

Modeling multiple scattering

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

high frequency shifted stripes - phase 2

Modeling multiple scattering

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

high frequency shifted stripes - phase 3

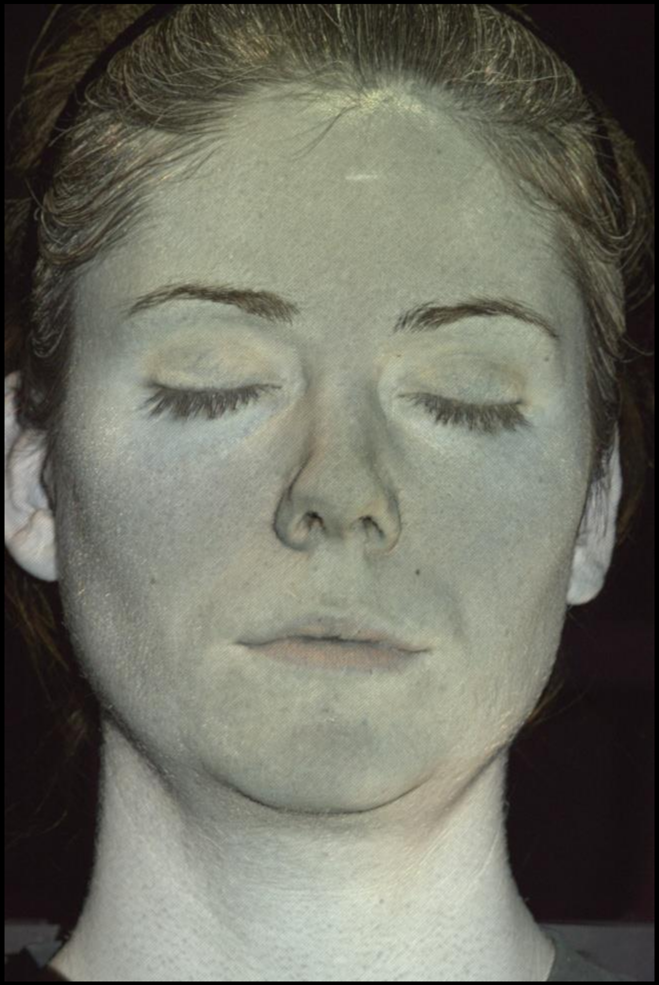
Modeling multiple scattering

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

high frequency shifted stripes - phase 4

Modeling multiple scattering

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



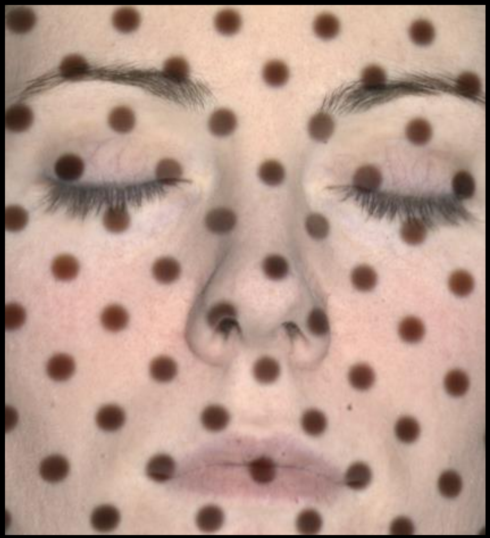
shallow scattering

(max - min)

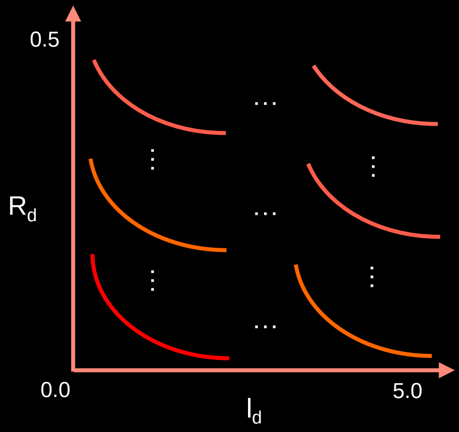
deep scattering

(2*min)

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

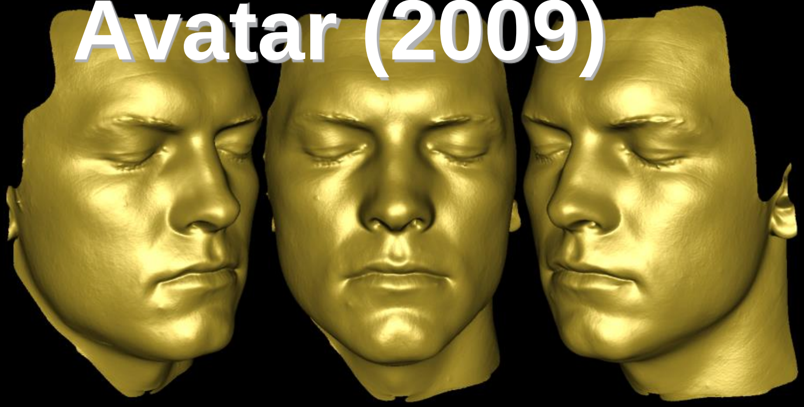
Rendering comparison

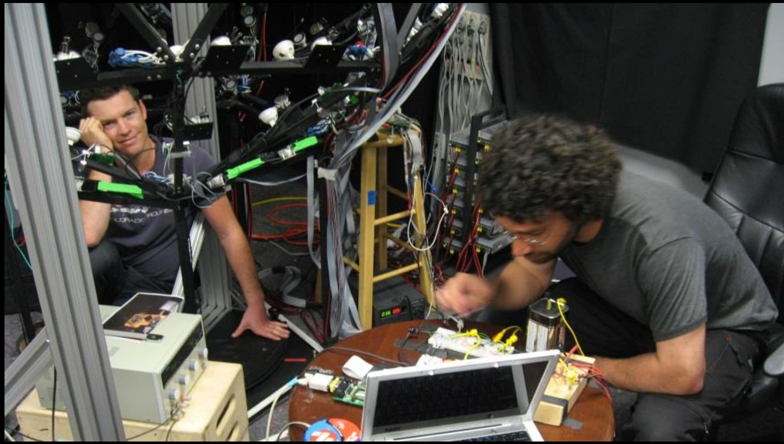
single layer + specular

layered rendering

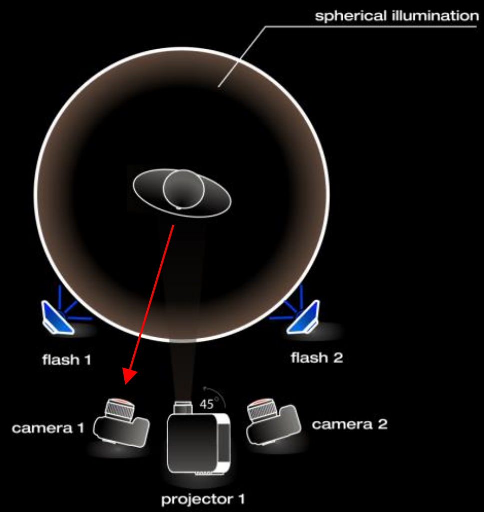
photograph

Avatar (2009)

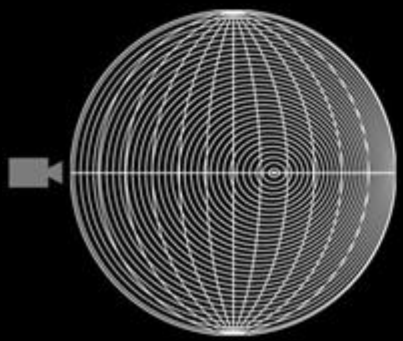




Fixed viewpoint acquisition

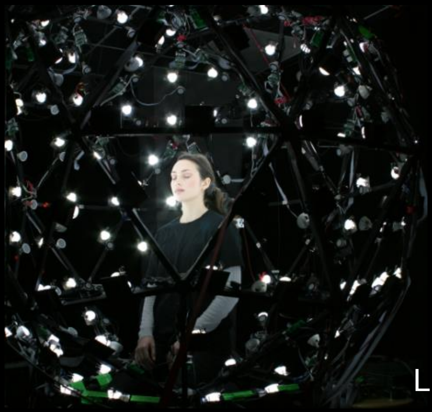


Linear polarization



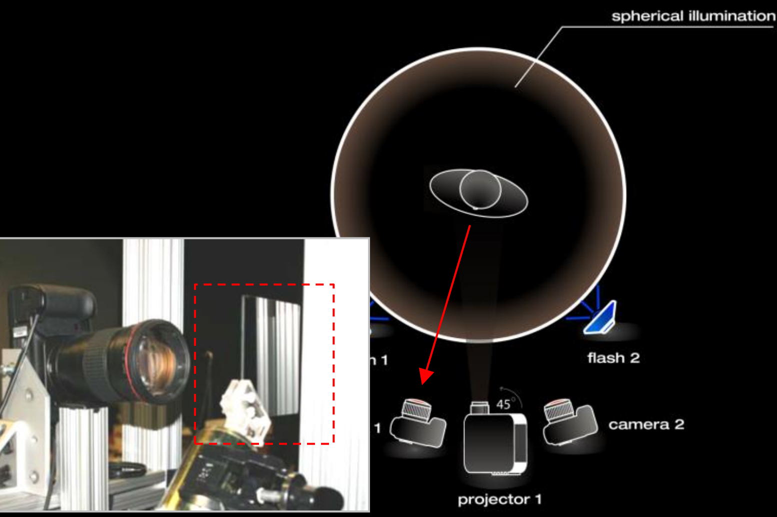
Linear polarization pattern [Ma et al. 07]

(side view)



LED sphere

Fixed viewpoint acquisition



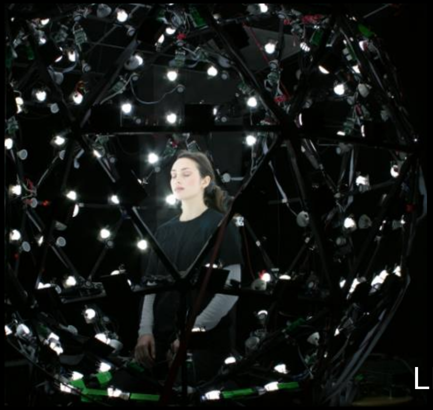
Linear polarization

frontal scan

right side

left side

manual rotation for
side-to-side scans

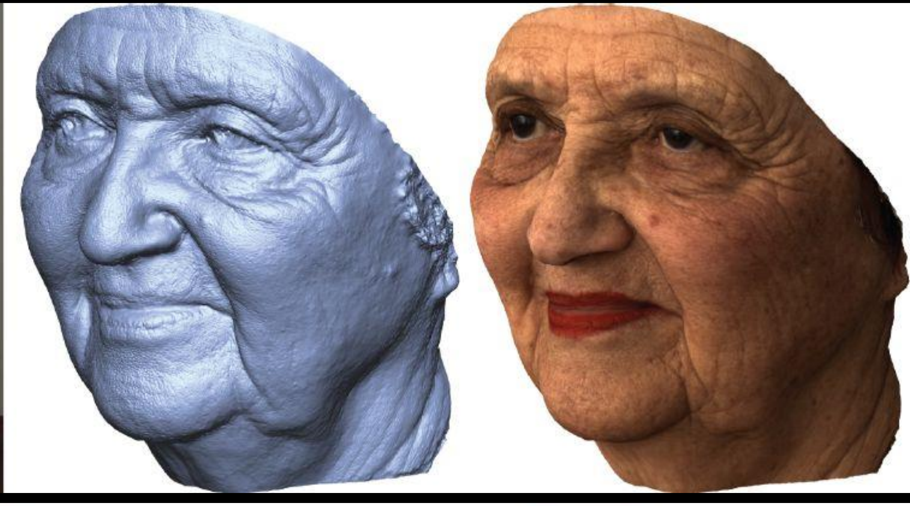


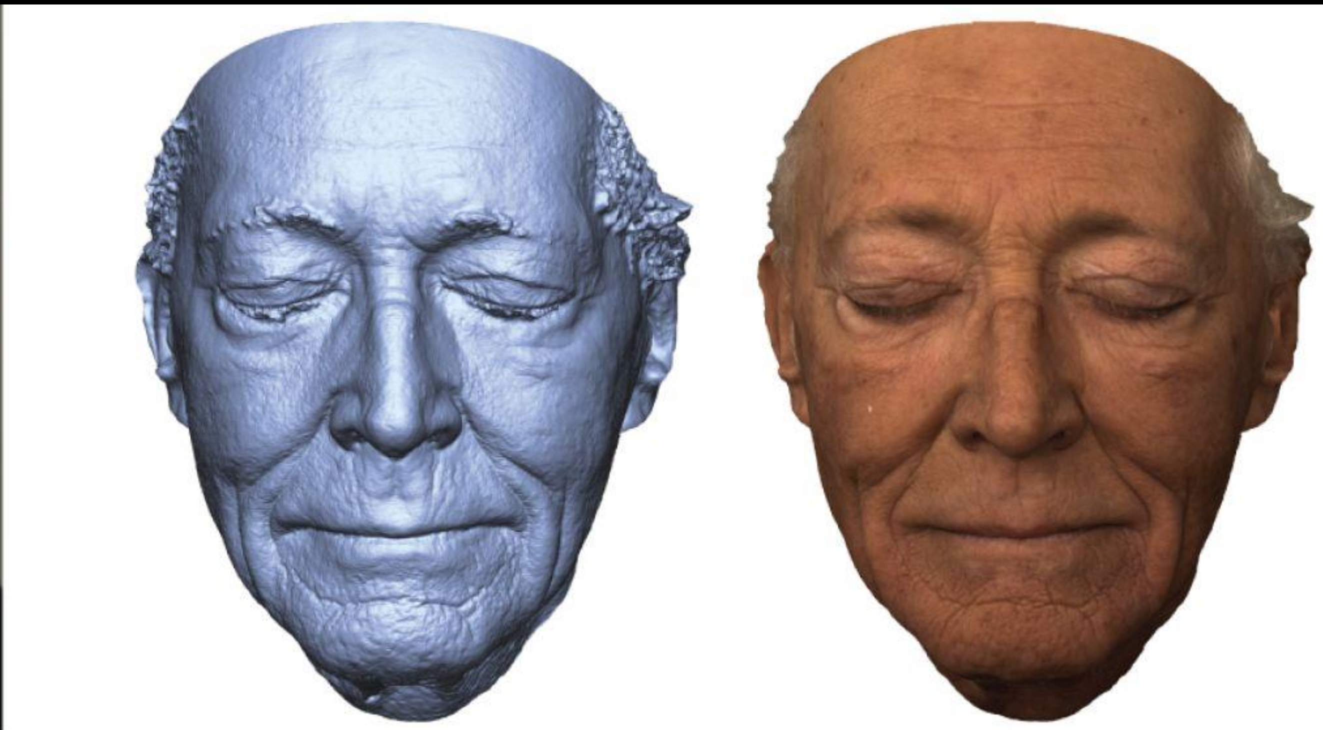
LED sphere

Passive Multiview Capture

[Beeler et al. 2010]

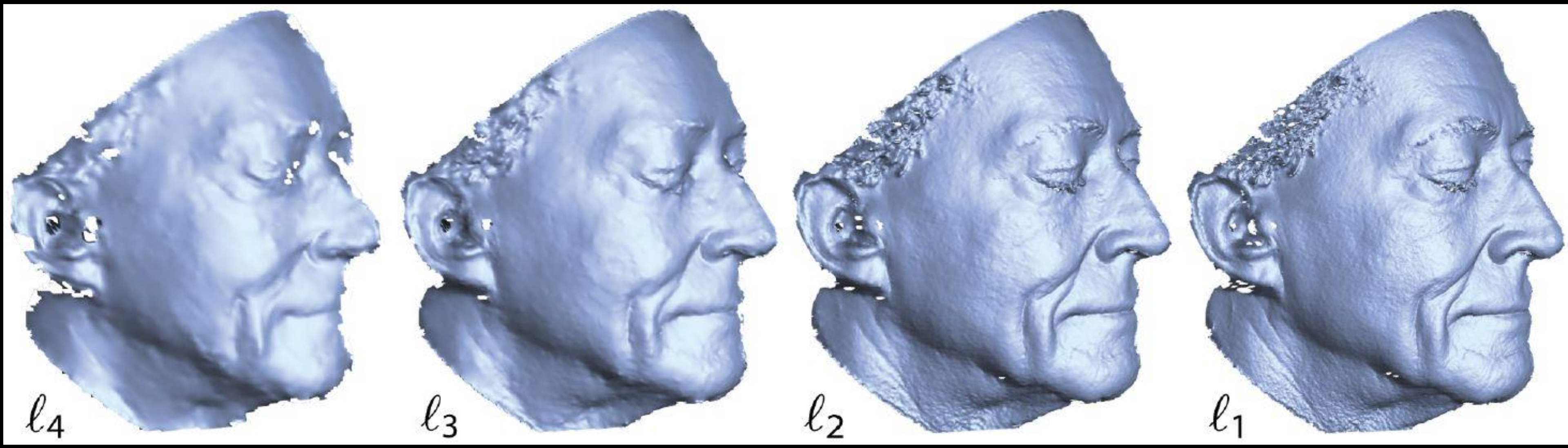
7 cameras



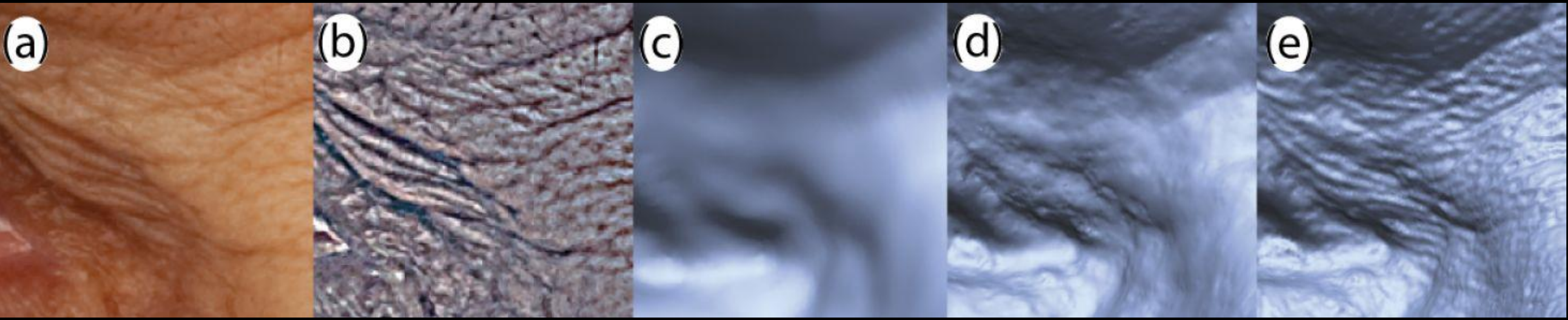


Passive Multiview Capture

[Beeler et al. 2010]



Multiscale geometric refinement



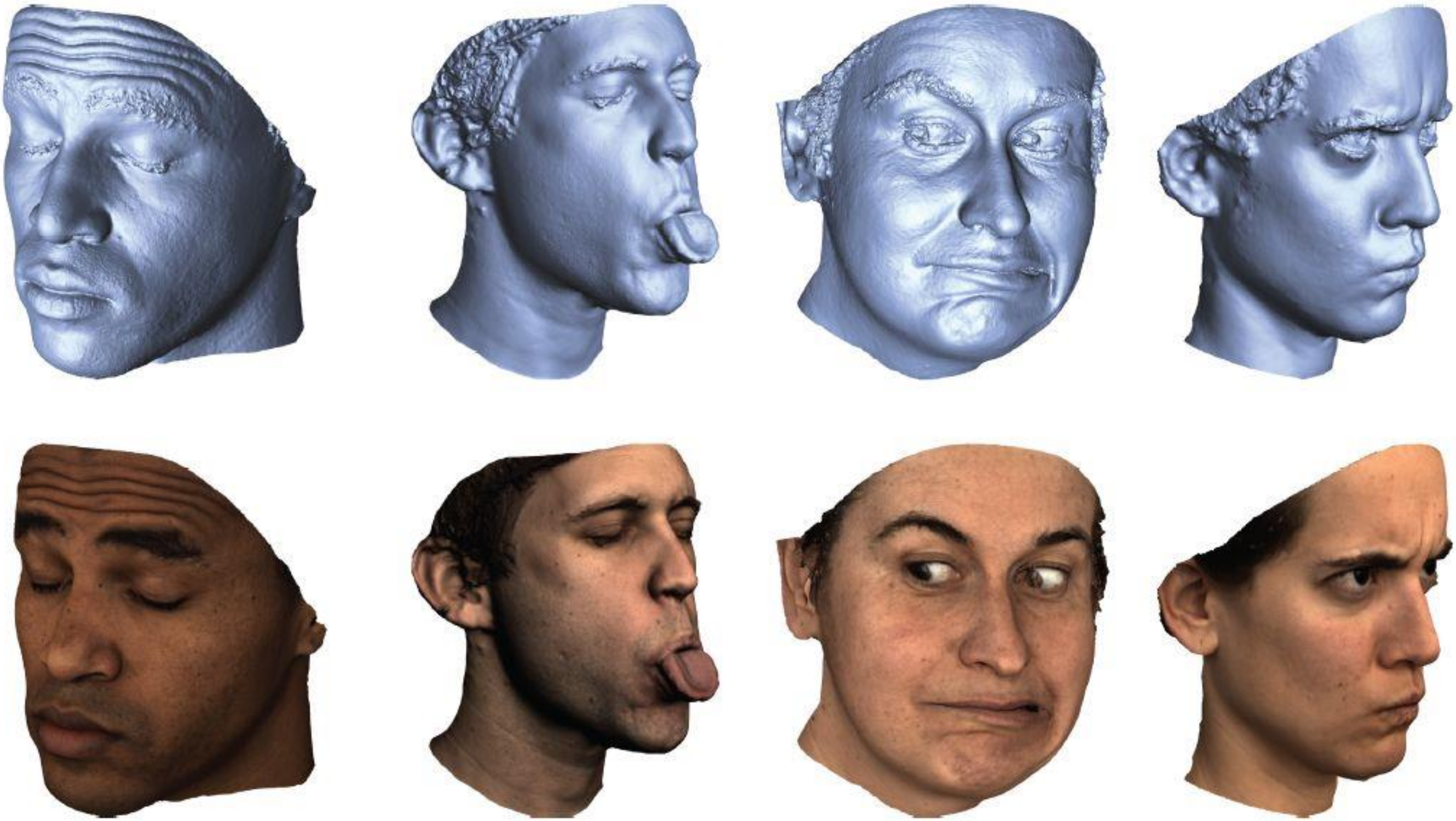
Diffuse texture

high-pass filtering (meso-structure)

Mesoscopic augmentation ("dark is deep" emboss)

Passive Multiview Capture

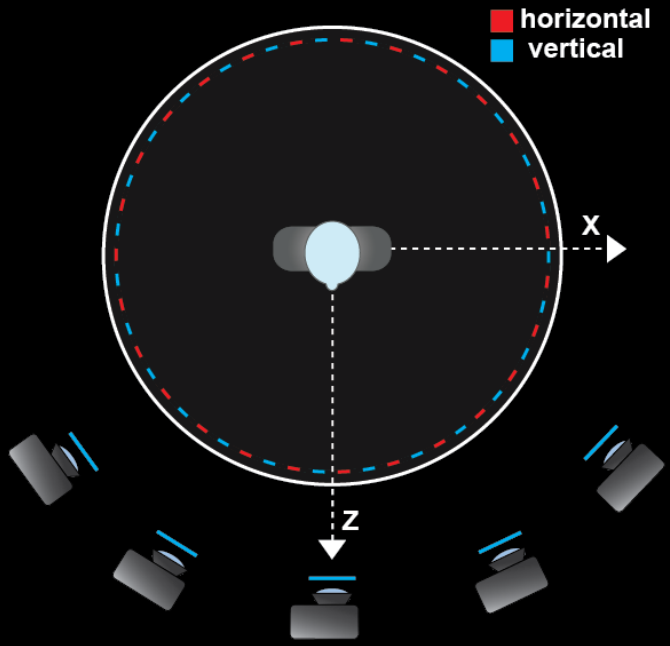
[Beeler et al. 2010]



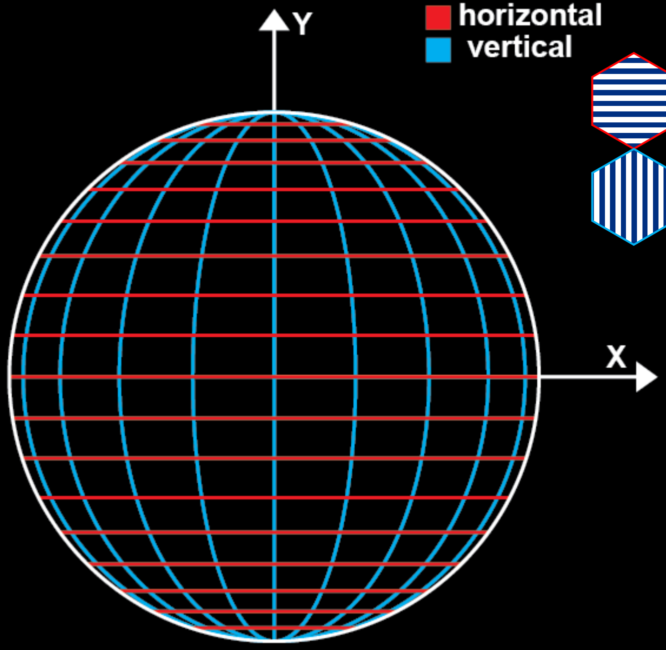
Multiview Polarization for Face Capture

[Ghosh et al. 2011]

Acquisition setup



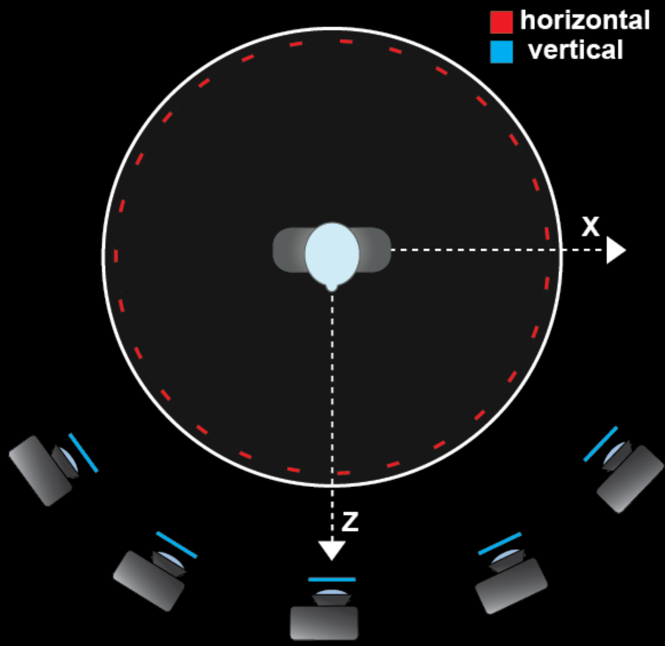
Multiview setup (top-view)



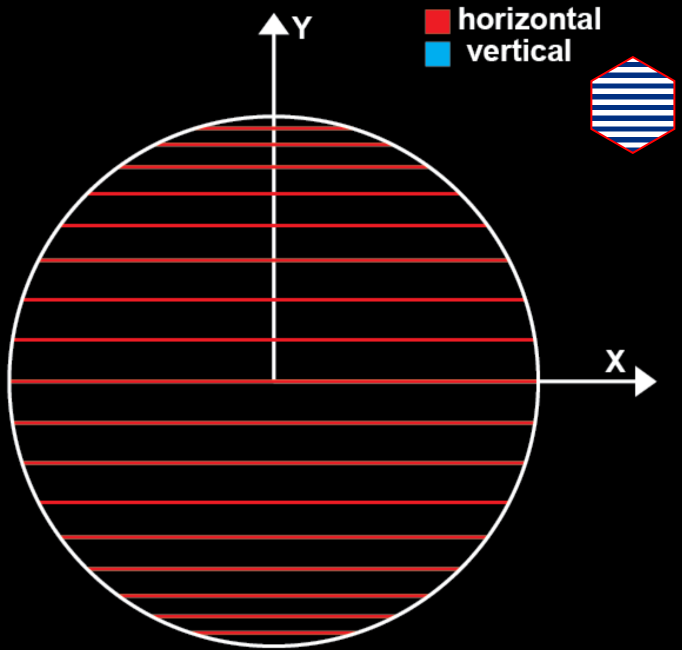
Lines of latitude-longitude

linear polarization

Cross polarization



Multiview setup (top-view)

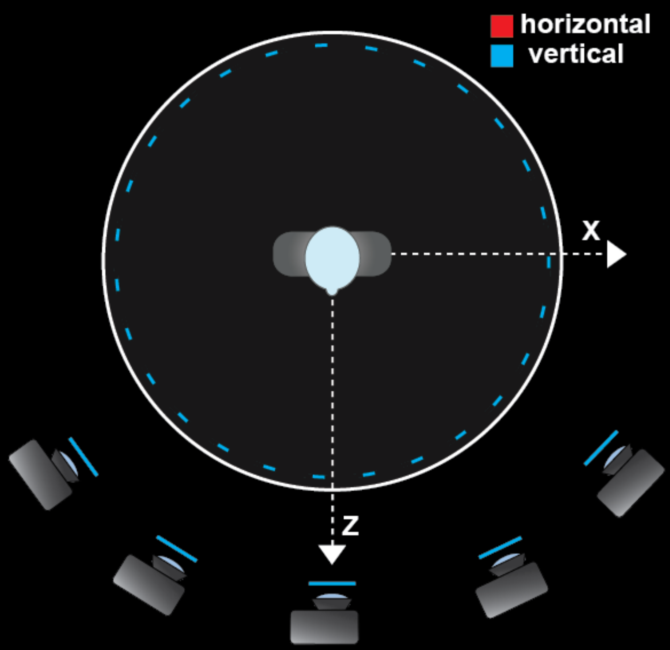


Lines of latitude

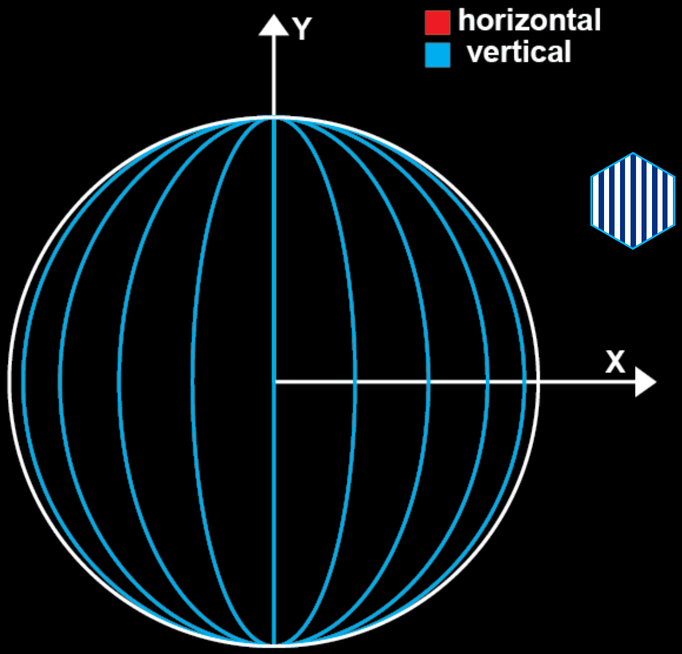
linear polarization

Diffuse

Parallel polarization



Multiview setup (top-view)

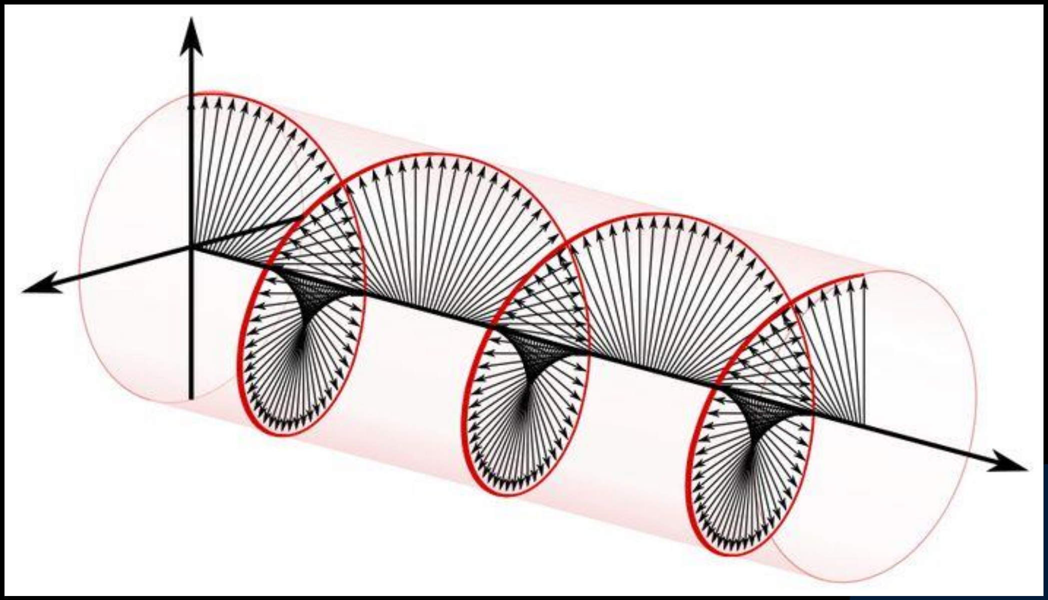


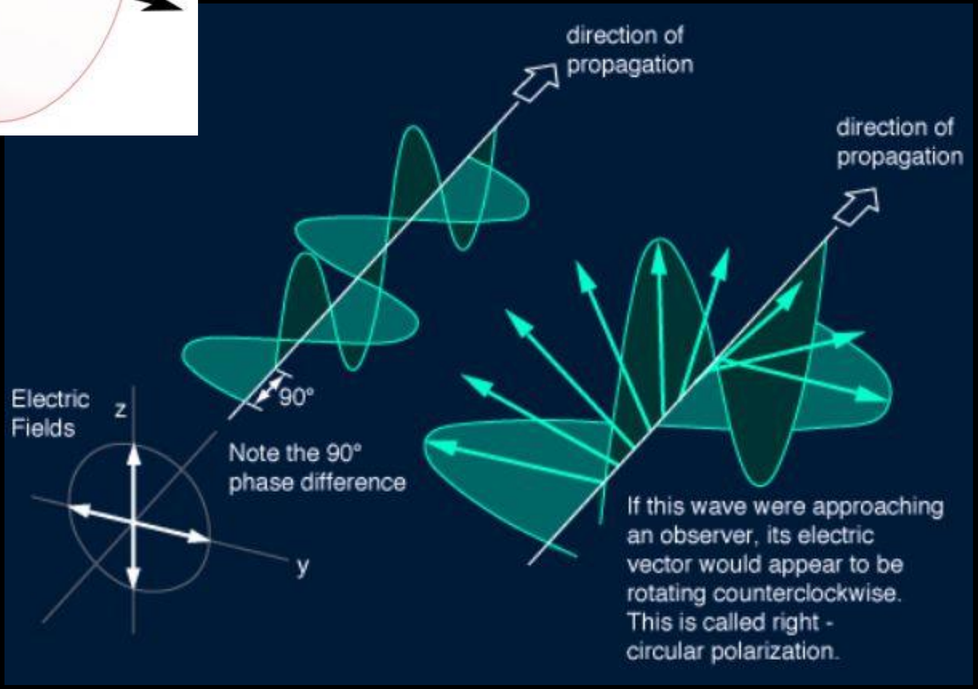
Lines of longitude

linear polarization

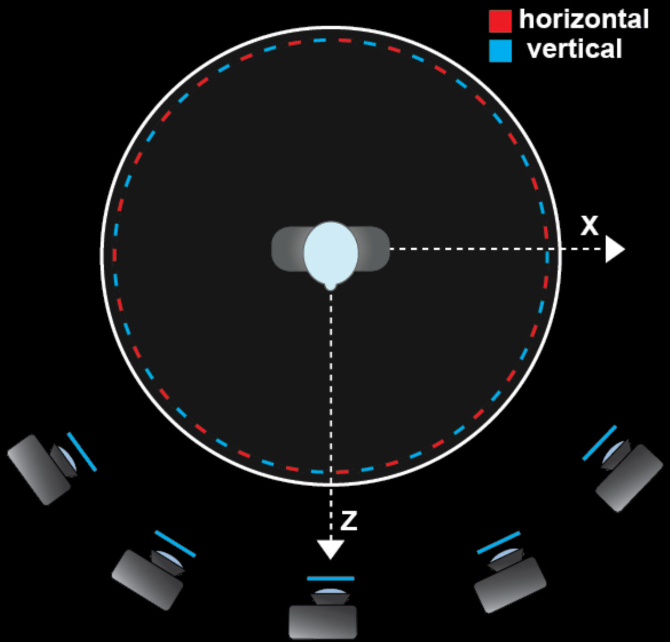
Diff. + Spec.

Circular polarization – rotational symmetry

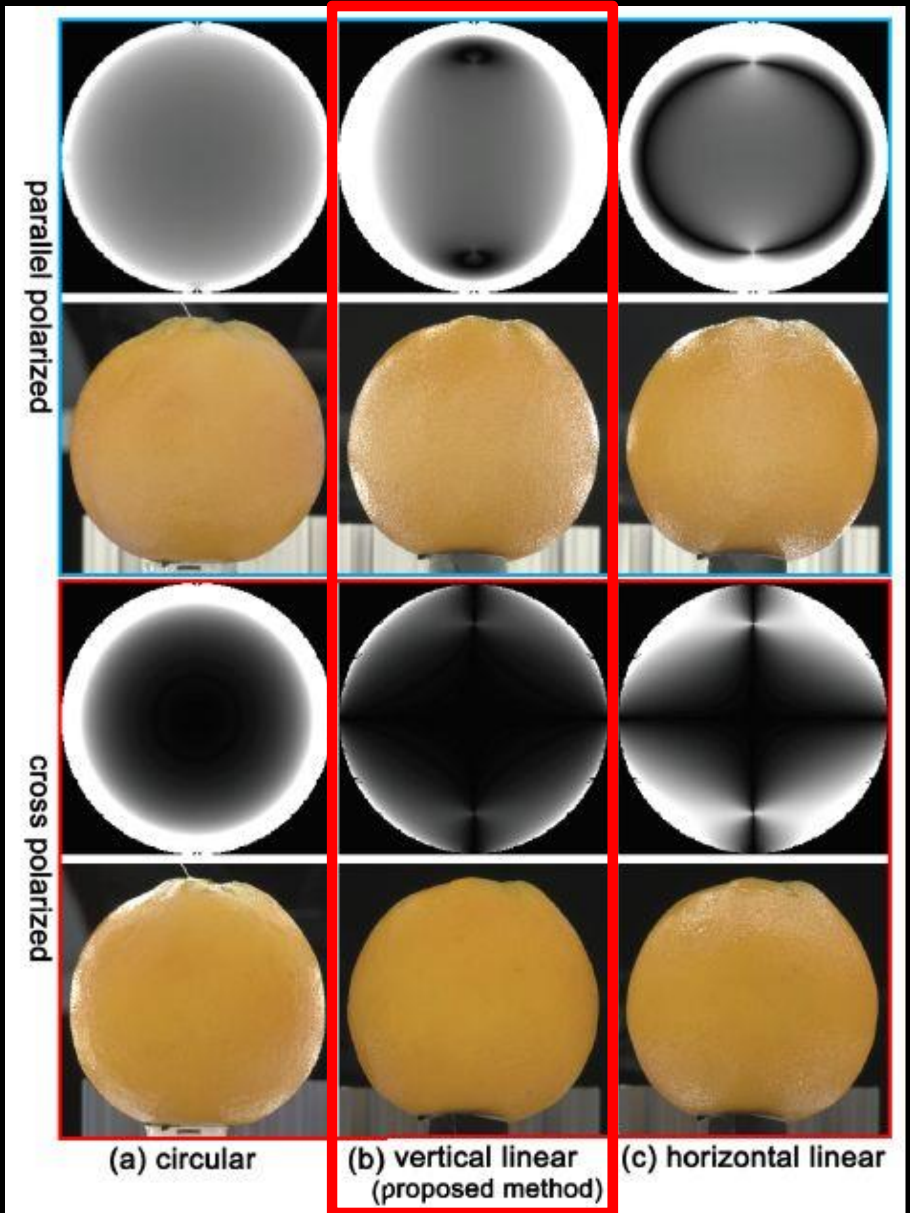




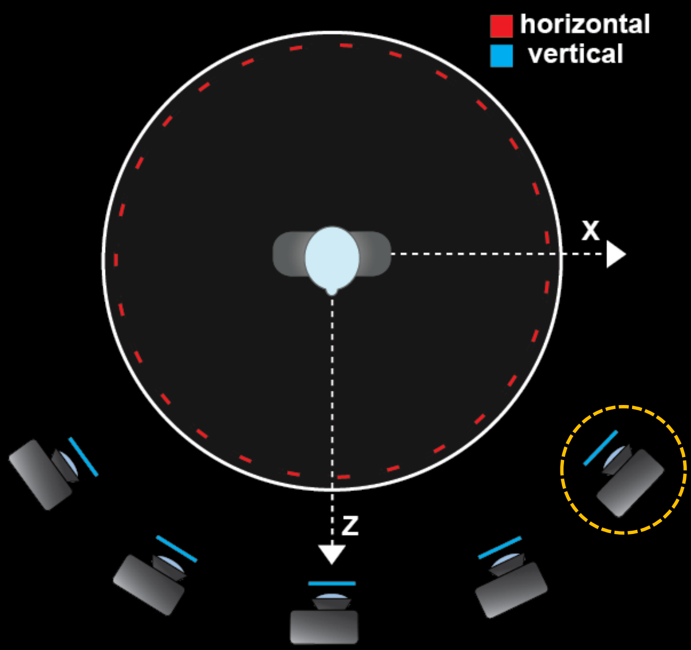
Multiview polarization



Multiview setup (top-view)

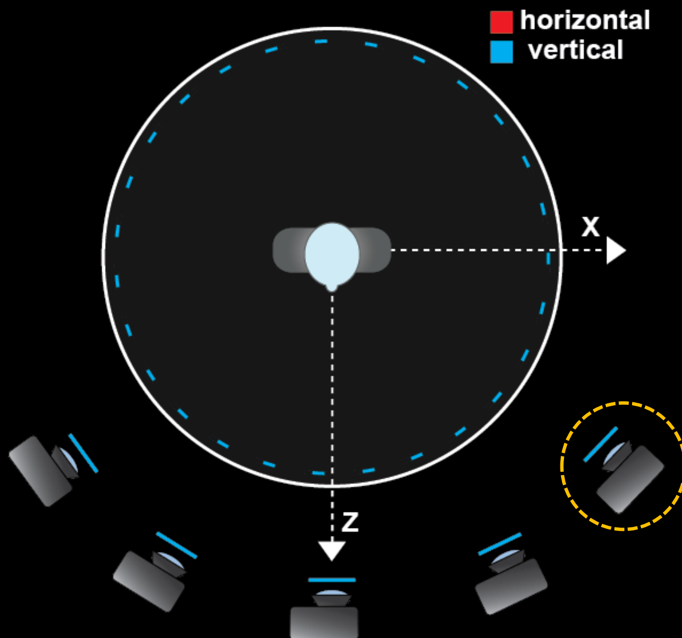


Cross polarization



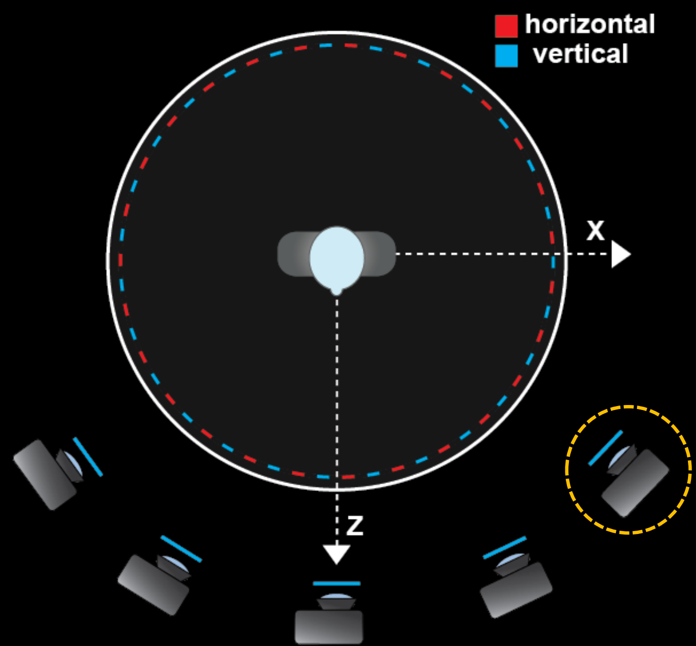
Multiview setup (top-view)

Parallel polarization



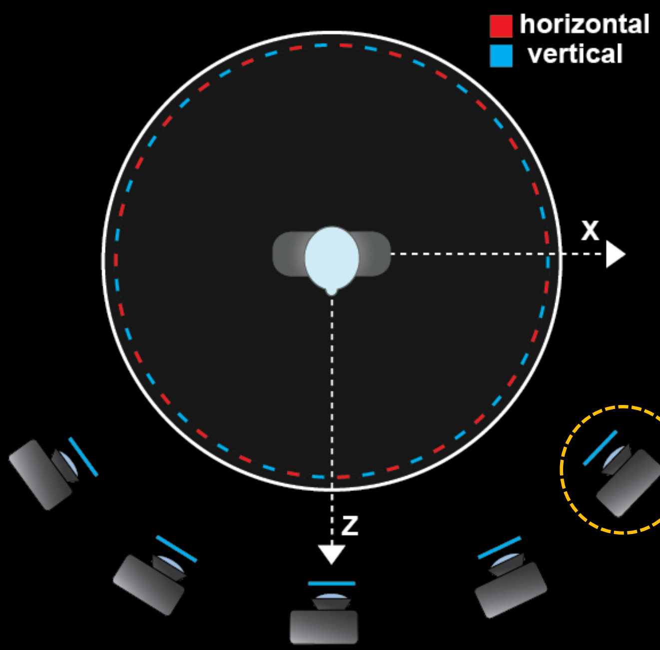
Multiview setup (top-view)

Polarization diff.



Multiview setup (top-view)

Specular normal



Multiview setup (top-view)

Multiview stereo

diffuse albedo

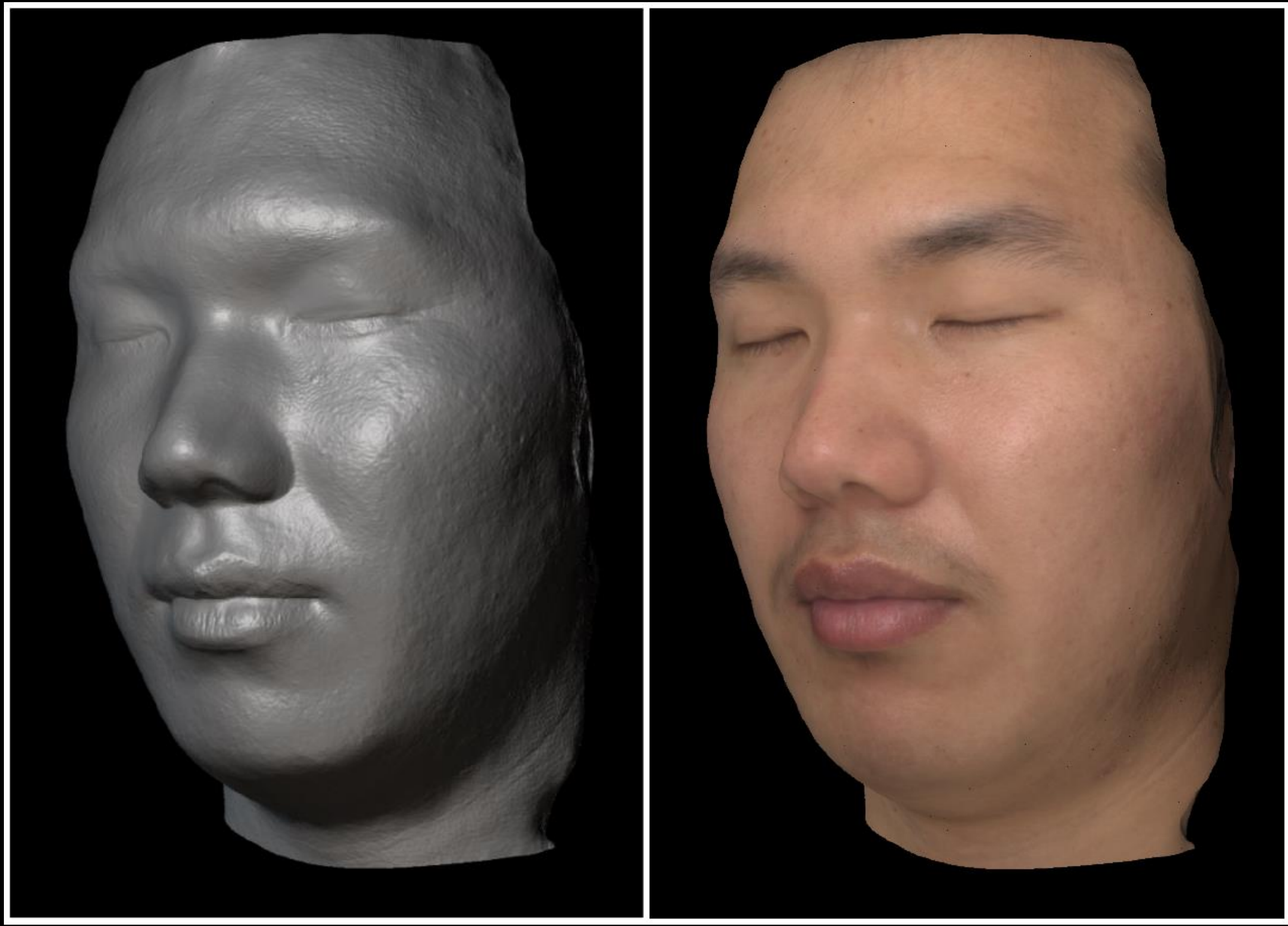
specular albedo

specular normal

five viewpoints

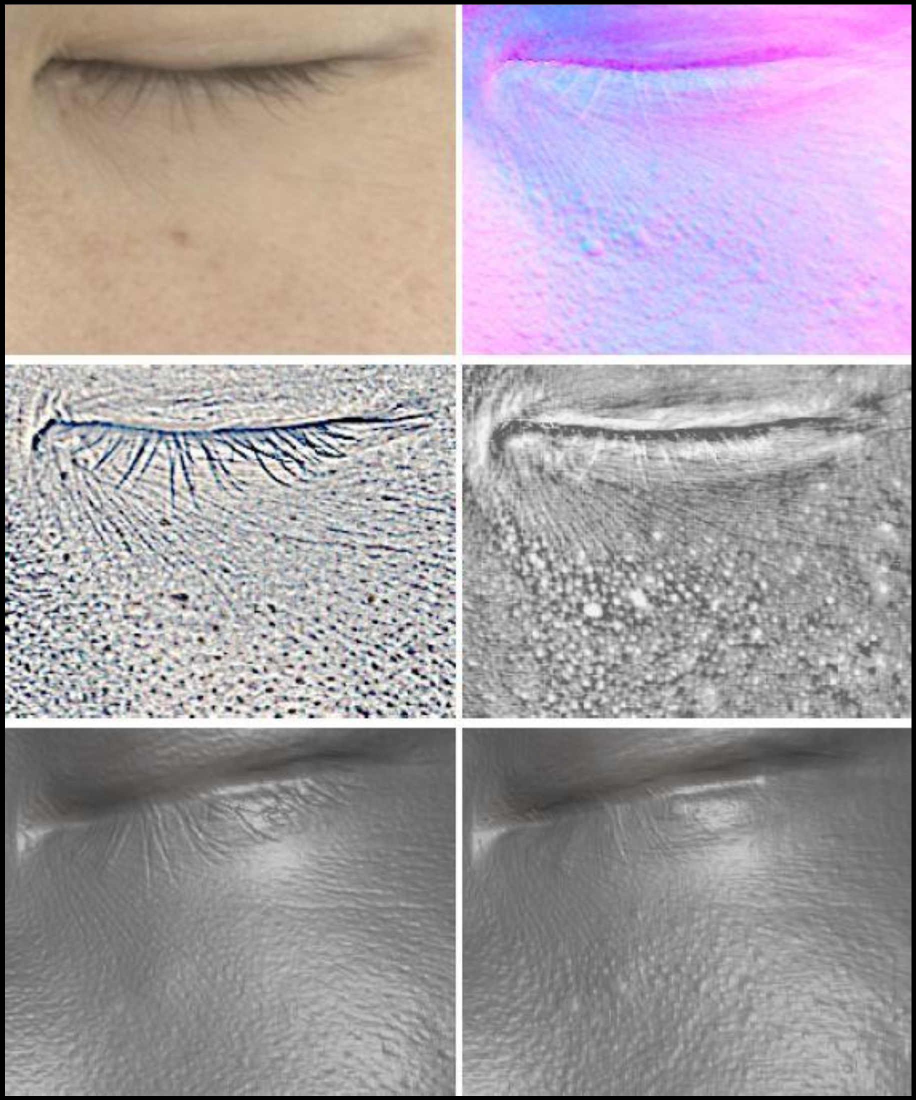
Facial rendering

4K x 4K
Rendering

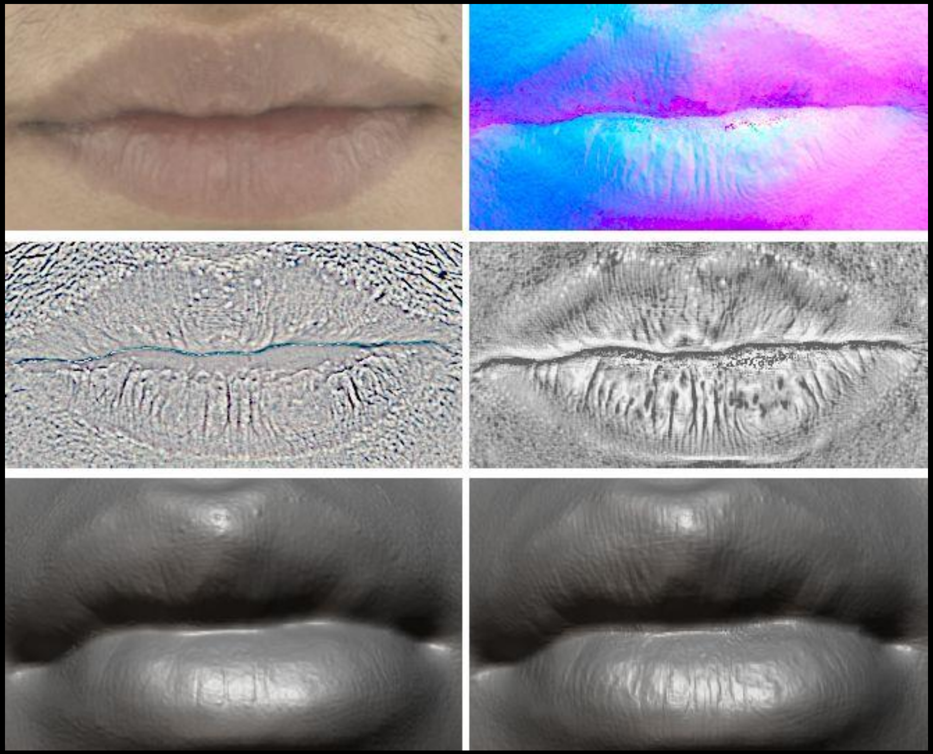


geometry rendering

Polarization vs texture for mesostructure



[Beeler et al. 10] [Ghosh et al. 11]



[Beeler et al. 10] [Ghosh et al. 11]

Presidential scanning- Smithsonian/USC 2014

President Barak Obama scanned with portable light-stage for multi-view capture with polarized spherical gradient illumination

Presidential scanning- Smithsonian/USC 2014

President Barak Obama scanned with portable light-stage for multi-view capture with polarized spherical gradient illumination

Face Close-up

Mesostructure 4K displacement maps [Ghosh et al. 2011]

Photograph

Microstructure

16K displacement maps

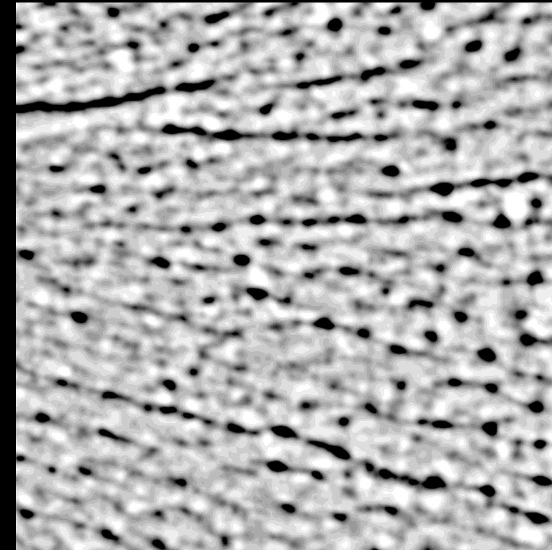
Facial Microgeometry

[Graham et al. 2013]

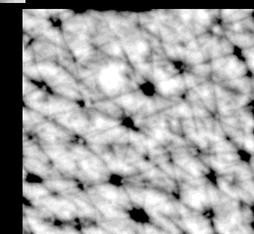
16K x 16K Rendering

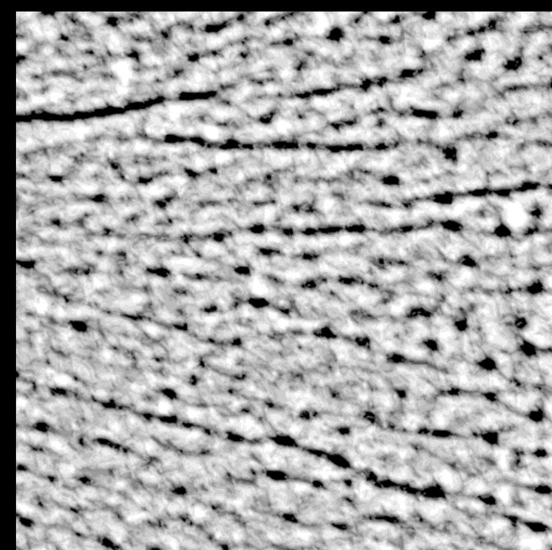
Approach

- Constrained texture synthesis!
  - microstructure digitized from skin samples
  - 10 micron resolution
  - microscale reflectance measurement
  - Image analogies for synthesis



4K displacement maps



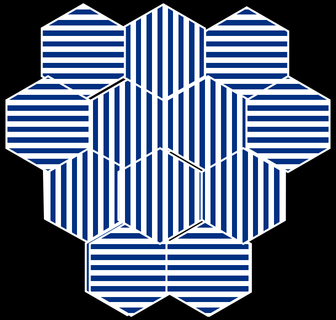


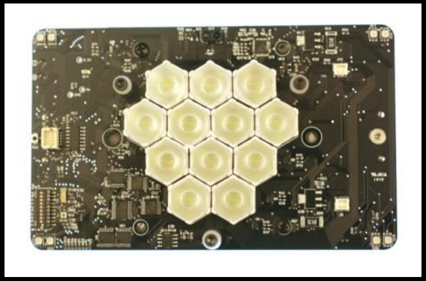
16K displacement maps

Recording skin microstructure

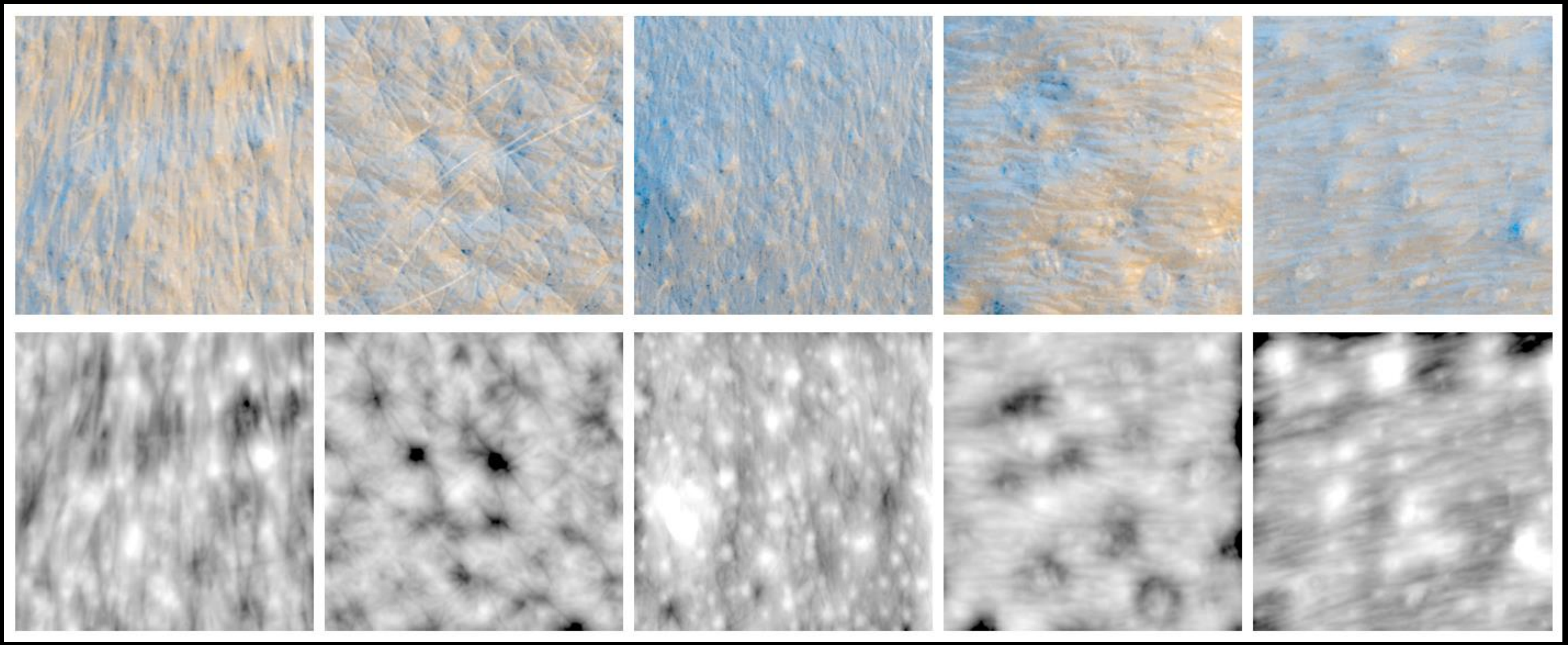
- 12-light dome
  - Canon 1DMark III camera with a Canon 100mm macro lens
  - 24mm by 16mm aperture ~ 8 microns resolution
  - each light produces either of two linear polarization conditions

Setup 1

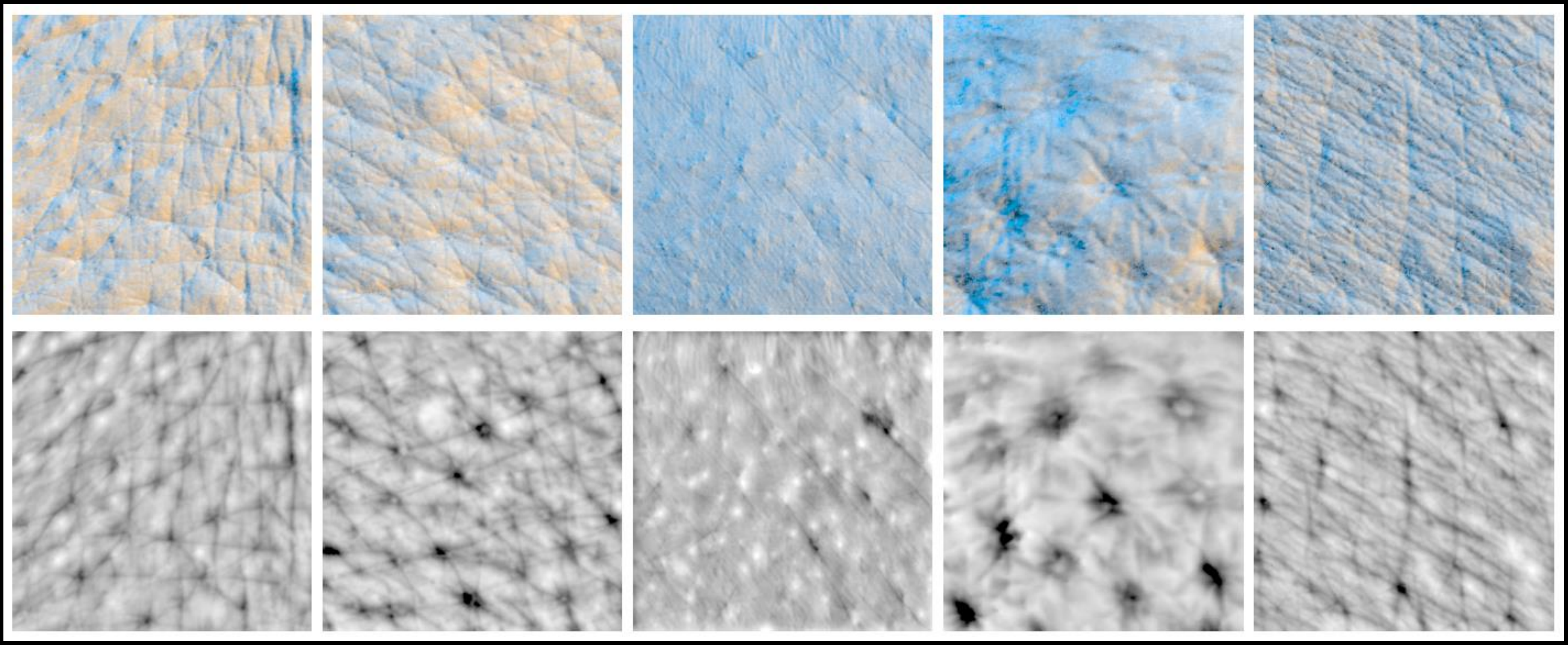




Male subject



Female subject



Forehead Temple Cheek Nose Chin

BRDF Fitting

- Cook-Torrance BRDF model for specular + single scattering [Ghosh et al. 08]
  - Skin protrudes through metal aperture resulting in sufficient normal variation
  - Two lobes of the Beckmann distribution

Skin patch

BRDF Fitting – Subject 1

Light 1

Light 2

Photograph

Rendering

BRDF fits at different scales

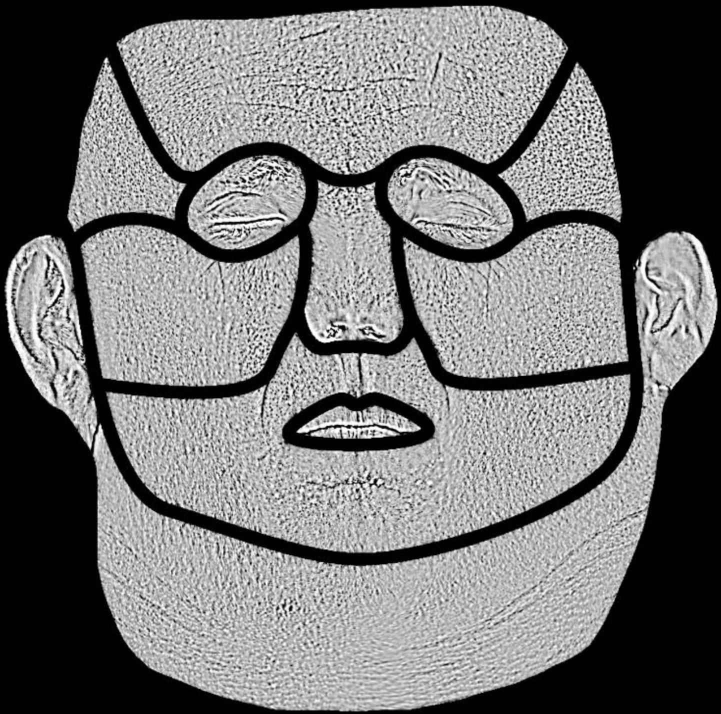
Meso-scale	Subject 1	Subject 2
Forehead	m1=0.250, m2=0.125, w=0.85	m1=0.250, m2=0.125, w=0.80
Temple	m1=0.225, m2=0.125, w=0.80	m1=0.225, m2=0.150, w=0.70
Cheek	m1=0.275, m2=0.200, w=0.60	m1=0.225, m2=0.150, w=0.50
Nose	m1=0.175, m2=0.100, w=0.65	m1=0.150, m2=0.075, w=0.80
Chin	m1=0.250, m2=0.150, w=0.35	m1=0.300, m2=0.225, w=0.15

Micro-scale	Subject 1	Subject 2
Forehead	m1=0.150, m2=0.050, w=0.88	m1=0.150, m2=0.050, w=0.60
Temple	m1=0.150, m2=0.075, w=0.55	m1=0.175, m2=0.050, w=0.80
Cheek	m1=0.150, m2=0.125, w=0.60	m1=0.100, m2=0.075, w=0.50
Nose	m1=0.100, m2=0.075, w=0.80	m1=0.100, m2=0.050, w=0.50
Chin	m1=0.125, m2=0.100, w=0.90	m1=0.150, m2=0.050, w=0.75

Data preparation

Mesostructure Scan

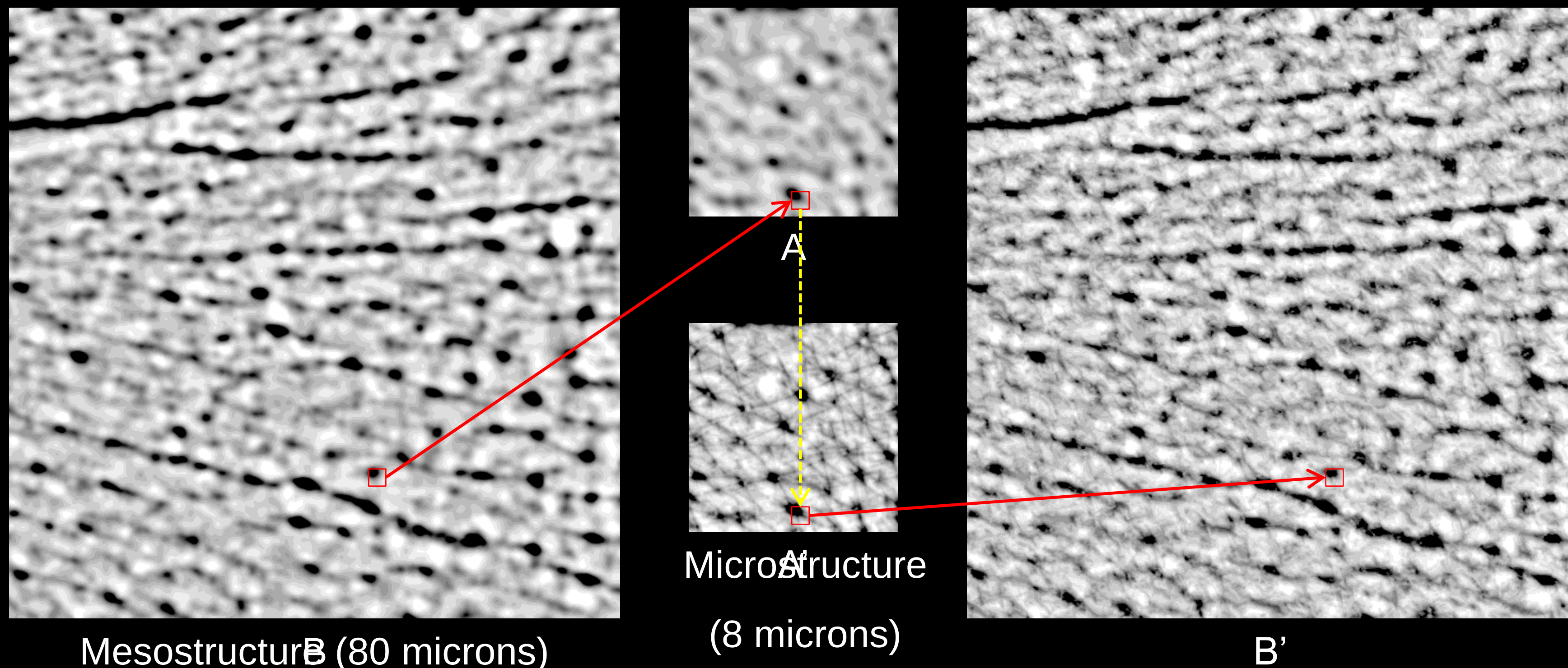
Normal Map



Displacement Map

Image Analogies (texture synthesis)

[Hertzmann et al. 01]



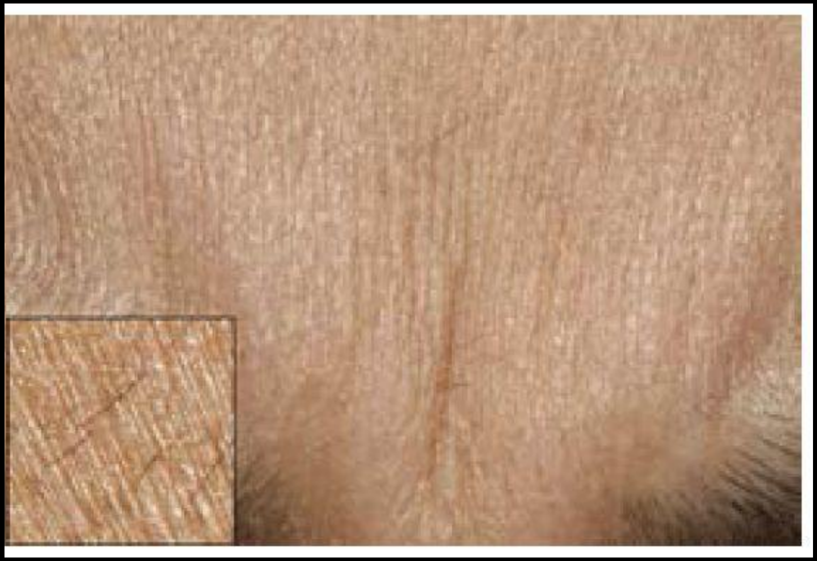

16K x 16K
Rendering

Microgeometry Deformation

[Nagano et al. 2015]

Mesostructure

Static microgeometry



Photograph

Microgeometry Deformation

[Nagano et al. 2015]

Mesostructure

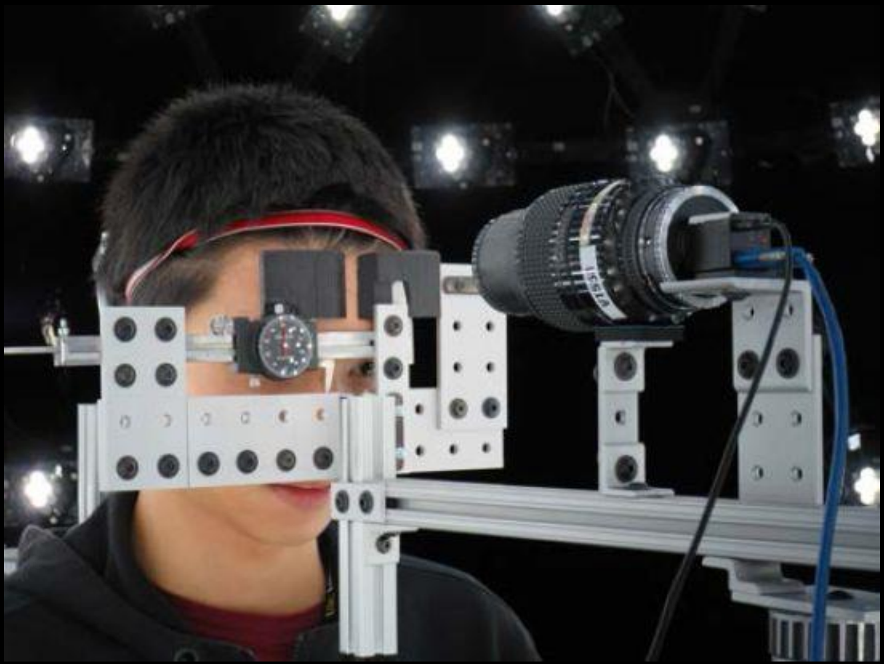
Static microgeometry

Deformed microgeometry

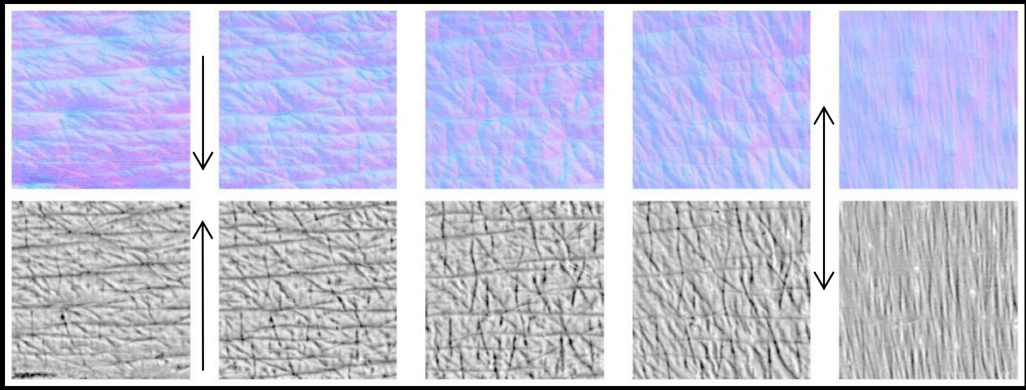
Photograph

Microgeometry Deformation

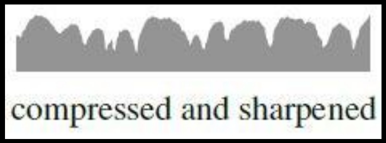
[Nagano et al. 2015]

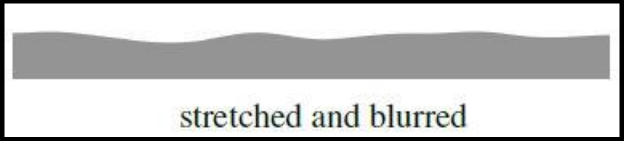


Skin patch deformation scanning



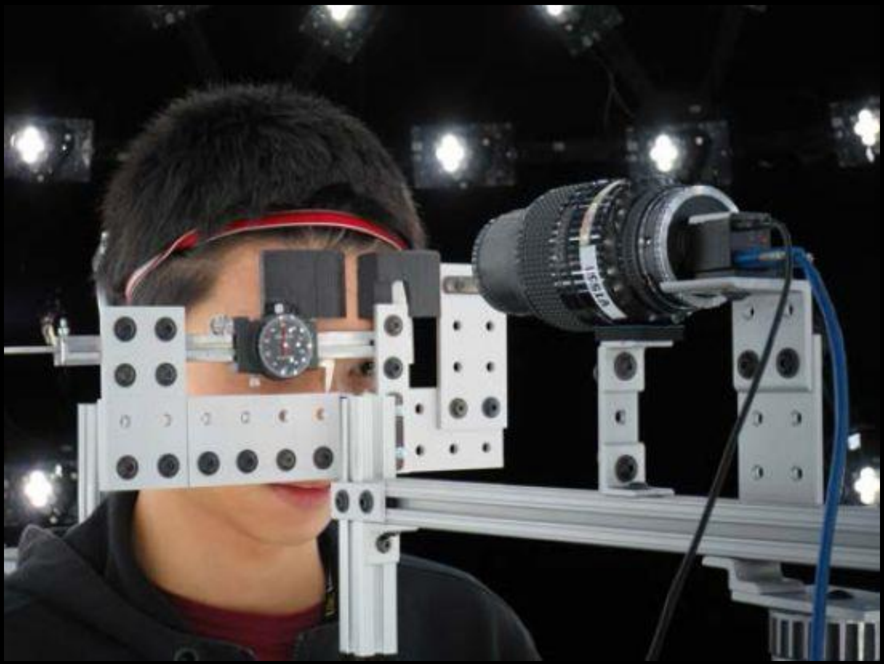
Compression Neutral Stretch



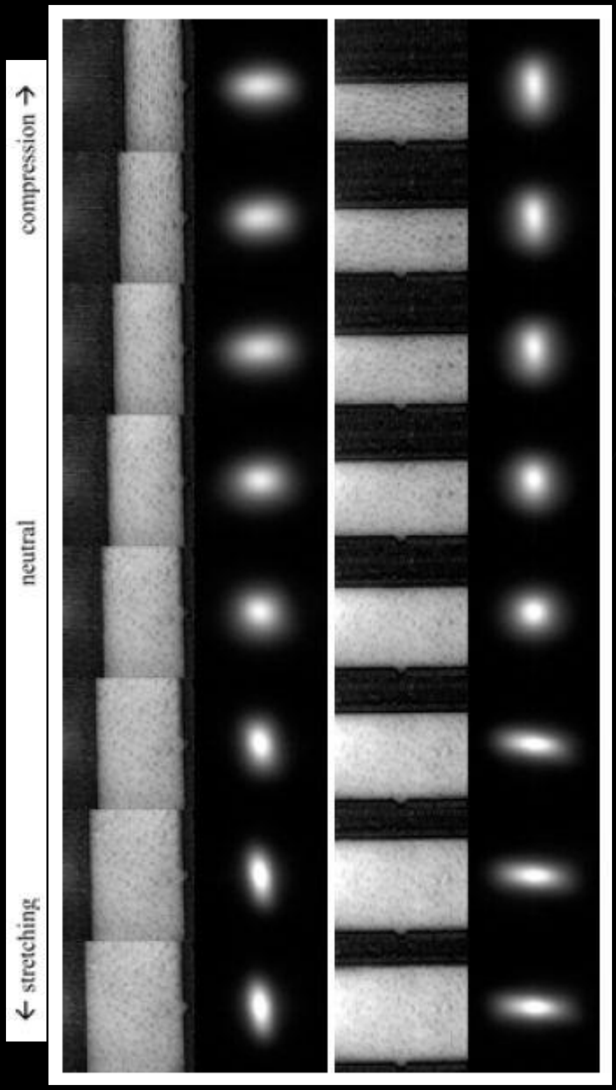


Microgeometry Deformation

[Nagano et al. 2015]



Skin patch deformation scanning

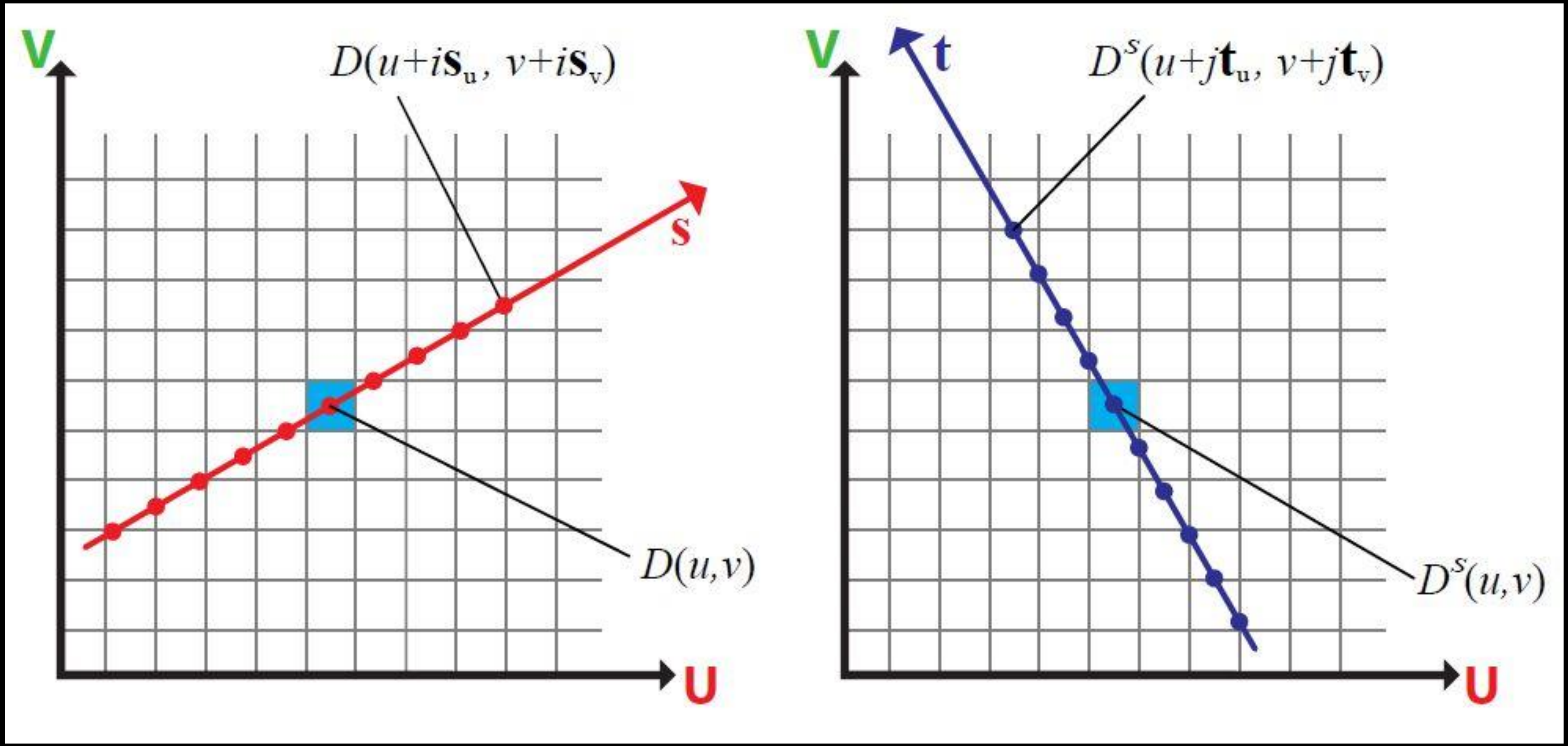


Horizontal Vertical

- Anisotropic normal distribution under compression and stretch!

Microgeometry Deformation

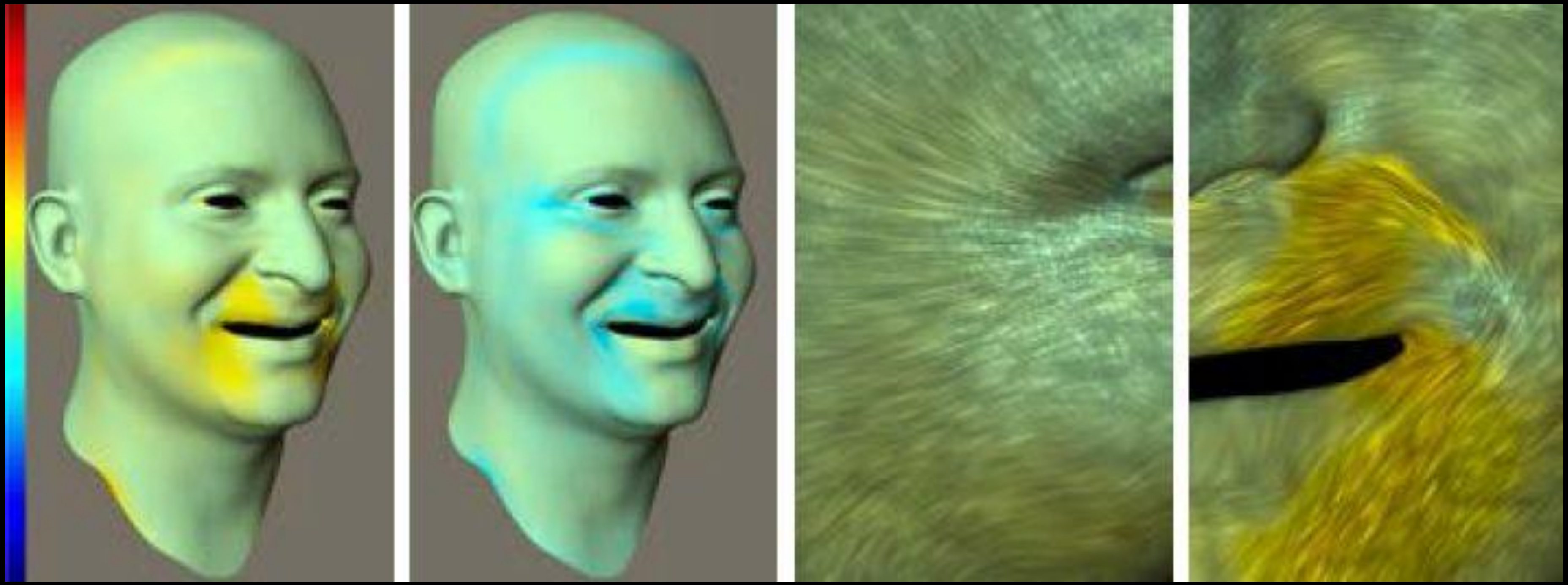
[Nagano et al. 2015]



- Blur of static microgeometry along direction of stretch
- Sharpening along direction of compression
- 1D separable kernel approximations for GPU filtering

Microgeometry Deformation

[Nagano et al. 2015]



Strain magnitude

Strain directions

- Blur of static microgeometry along direction of stretch
- Sharpening along direction of compression
- 1D separable kernel approximations for GPU filtering

Microgeometry Deformation

[Nagano et al. 2015]

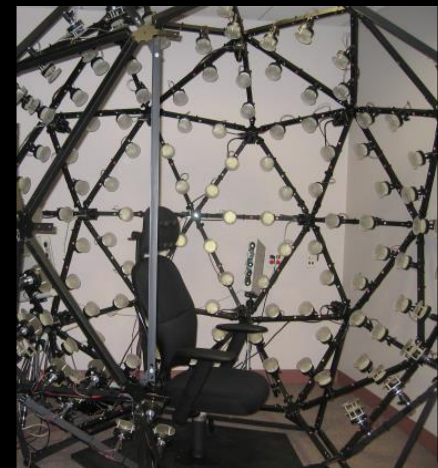
Specular only

Rendering

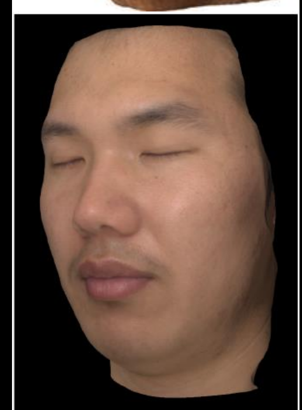
Photograph

Facial appearance recap …









Thank You

- Questions?

- Resume at 3pm
- Material appearance capture & modelling