Shape and Visual Appearance Acquisition for Photo-realistic Visualization

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Appearance Acquisition

- **2.1 Introduction**

Light-matter interaction. Radiometry in a nutshell. Bidirectional Reflectance Distribution Function (BRDF) and Bidirectional Surface Scattering Reflectance Distribution function (BSSRDF).

- **2.2 BRDF measurement**

Gonioreflectometer. Image-based estimation. Analytical BRDF models. BRDF factorization (texture decomposition, spherical harmonics, Haar wavelets).

- **2.3 Reflectance as N-dimensional function estimation**

Taxonomy. Plenoptic function. Light field. Reflectance Field. Bidirectional Texture Function (BTF). Reflection Transformation Imaging: polynomial (PTM) and hemispherical harmonics approximation (HSH).

- **2.4 Texture registration**

Multi-modal matching through feature-based (keypoints, lines) and statistical methods (mutual information). Statically-fixed shading problems. Color mapping strategies. Intrinsic images (brief notes).

Reflectance as N-dimensional function estimation

Taxonomy of reflectance functions

General scattering function: 14 D

$(x_i, y_i, z_i, \theta_i, \phi_i, \lambda_i, t_i, x_o, y_o, z_o, \theta_o, \phi_o, \lambda_o, t_o)$

↓ Ignore time, wavelength dependence
Assume free space

BSSRDF / 8D-RF: 8D

$(x_i, y_i, \theta_i, \phi_i, x_o, y_o, \theta_o, \phi_o)$

↓ Ignore subsurface scattering

SVBRDF / BTF / 6D-RF: 6D

$(x, y, \theta_i, \phi_i, \theta_o, \phi_o)$

↓ Ignore spatial variation

BRDF: 4D

$(\theta_i, \phi_i, \theta_o, \phi_o)$

↓ Assume isotropy

Isotropic BRDF: 3D

$(\theta_i, \theta_o, |\phi_i - \phi_o|)$

About the Taxonomy

- The general scattering functions derives from the *plenoptic function*.
- *Spatially Varying BRDF* (SVBRDF) is simply a BRDF which varies along the surface (*SVBRDF = BRDF(u,v)*)

Plenoptic Function

- The *plenoptic function P* is a function which permits to generate every image of a particular space-time chunk of a real scene. This concept was originally proposed by Adelson et al. [Adelson1991].
- It is the flow of light at all position from all directions, at a certain instant of time, i.e. a 7D function:

$$P\left(x, y, z, \theta, \phi, \lambda, t\right)$$

time

wavelength

[Adelson2011] E. H. Adelson and J. R. Bergen, "The Plenoptic Function and the Elements of Early Vision", *Computational Models of Visual Processing*, Cambridge, MA: MIT Press, 1991.

Plenoptic function

- Considering *static scene* and *ignore wavelength dependence* we obtain the 5D version of the plenoptic function:

$$P\left(\underbrace{x, y, z}_{\textbf{position}}, \overbrace{\theta, \phi}^{\textbf{direction}}\right)$$

Light Field

- The term *light field* was coined by A. Gershun [Gershun36] in his classic paper describing the radiometric properties of light in a space.
- If we assume the air to be transparent, the radiance along a ray through the empty space remains constant → we can focus on the light leaving a bounding volume of a 3D object.

[Gershun36] Gershun, A., "The Light Field',' Moscow, 1936. Translated by P. Moon and G. Timoshenko in Journal of Mathematics and Physics, Vol. XVIII, MIT, 1939, pp. 51-151.620, 2003.

Light Field

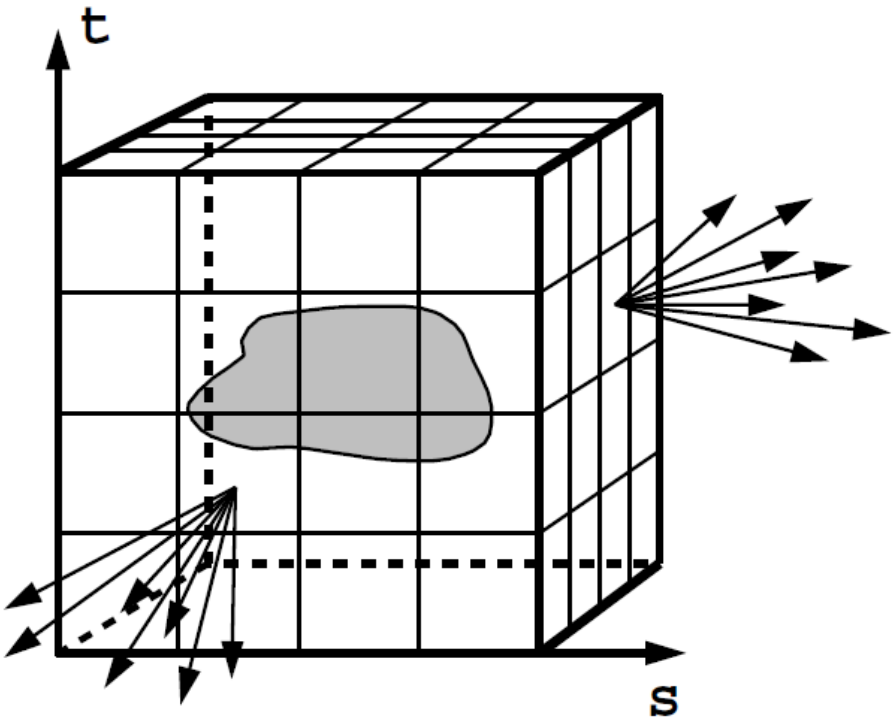
- The plenoptic function restricted to a bounding volume becomes a 4D function

$$P(u,v,\theta,\varphi)$$

- If the bounding volume coincides with the object surface, *P* corresponds to the BSSRDF with a fixed incident lighting.

Lumigraph

- The Lumigraph [Gortler1996] is a subset of the plenoptic function, i.e. a light field.
- The bounding volume used is a cube.

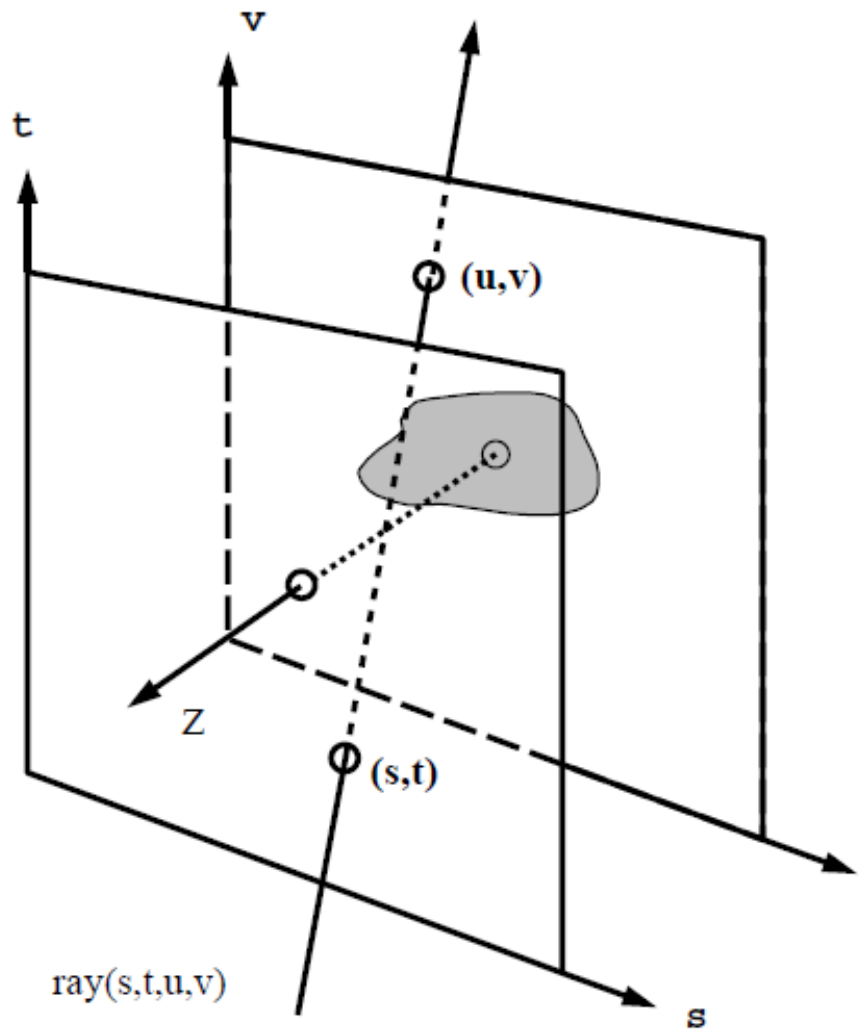


[Gortler1996] S. J. Gortler, R. Grzeszczuk, R. Szeliski, and M. F. Cohen, "The lumigraph", In *Proc. of the 23rd Conf. on Computer graphics and interactive techniques* (SIGGRAPH '96). ACM, New York, NY, USA, 43-54.

Lumigraph

- This allows for easy parameterization, i.e. the *two parallel plane parameterization:*

$$L\left(s,t,u,v\right)$$



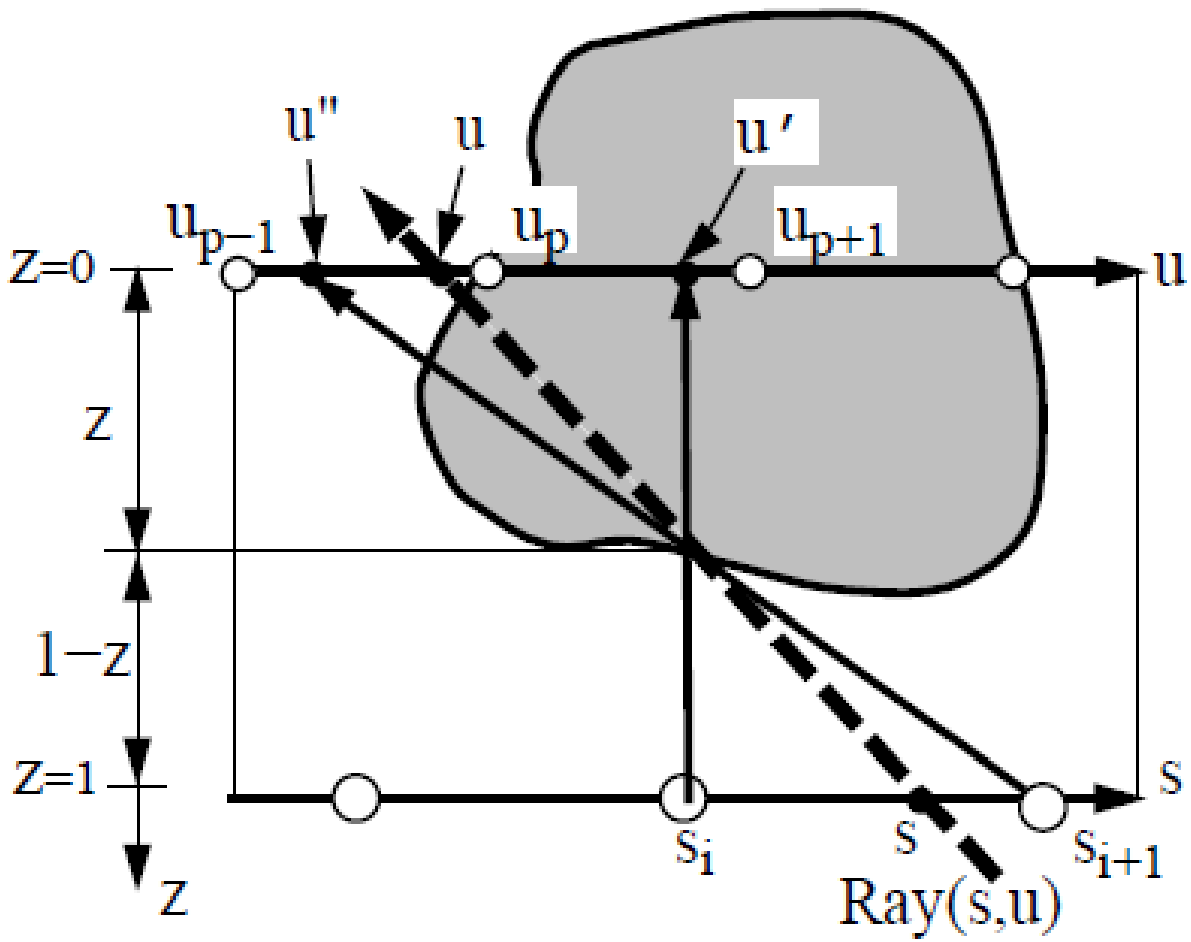
Lumigraph

- As usual, to obtain *L(s,t,u,v)* we have to find the coefficients of a basis by integrating box functions defined on the parameterization:

$$L(s,t,u,v) = \sum_i \sum_j \sum_p \sum_q x_{i,j,p,q} B_{i,j,p,q}(s,t,u,v)$$

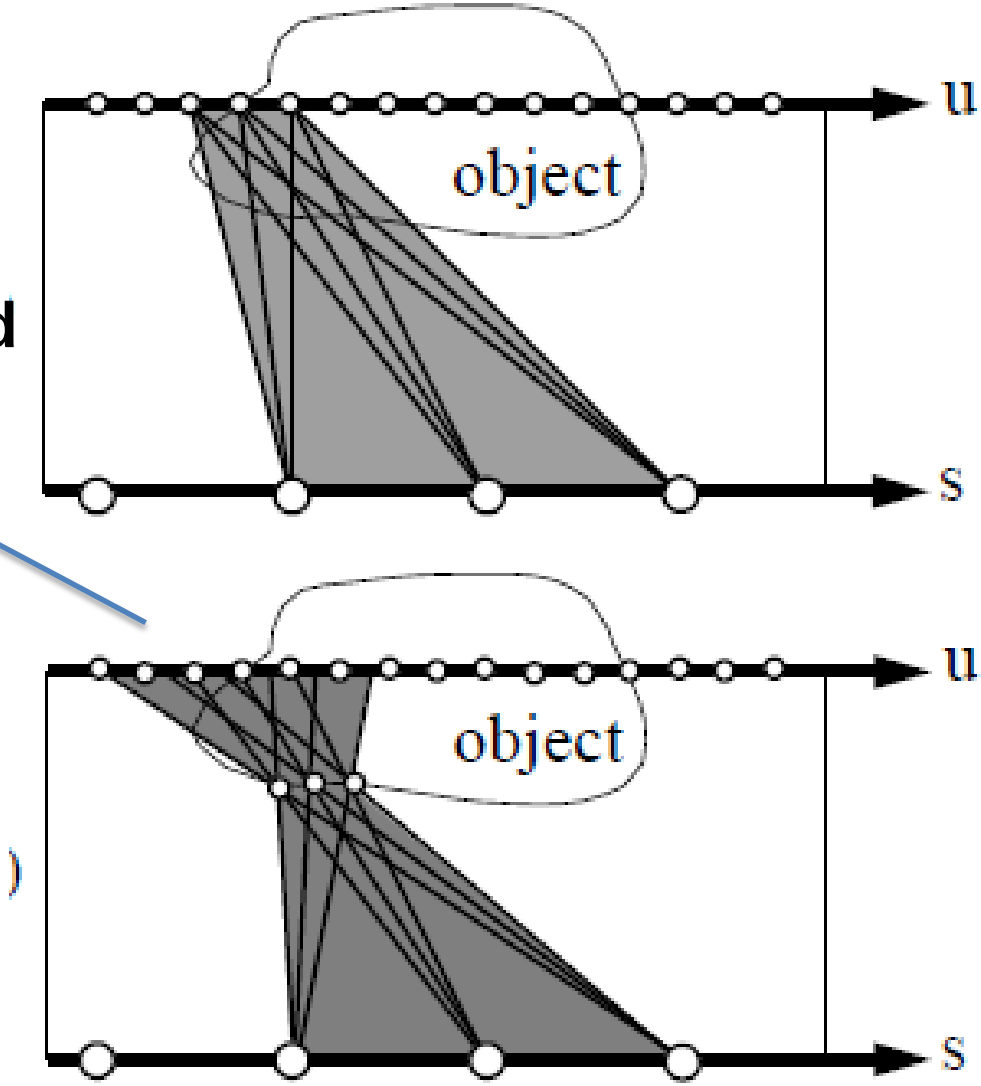
Lumigraph

- Considering a 2D Lumigraph *(s,u)*



Lumigraph – Support basis functions

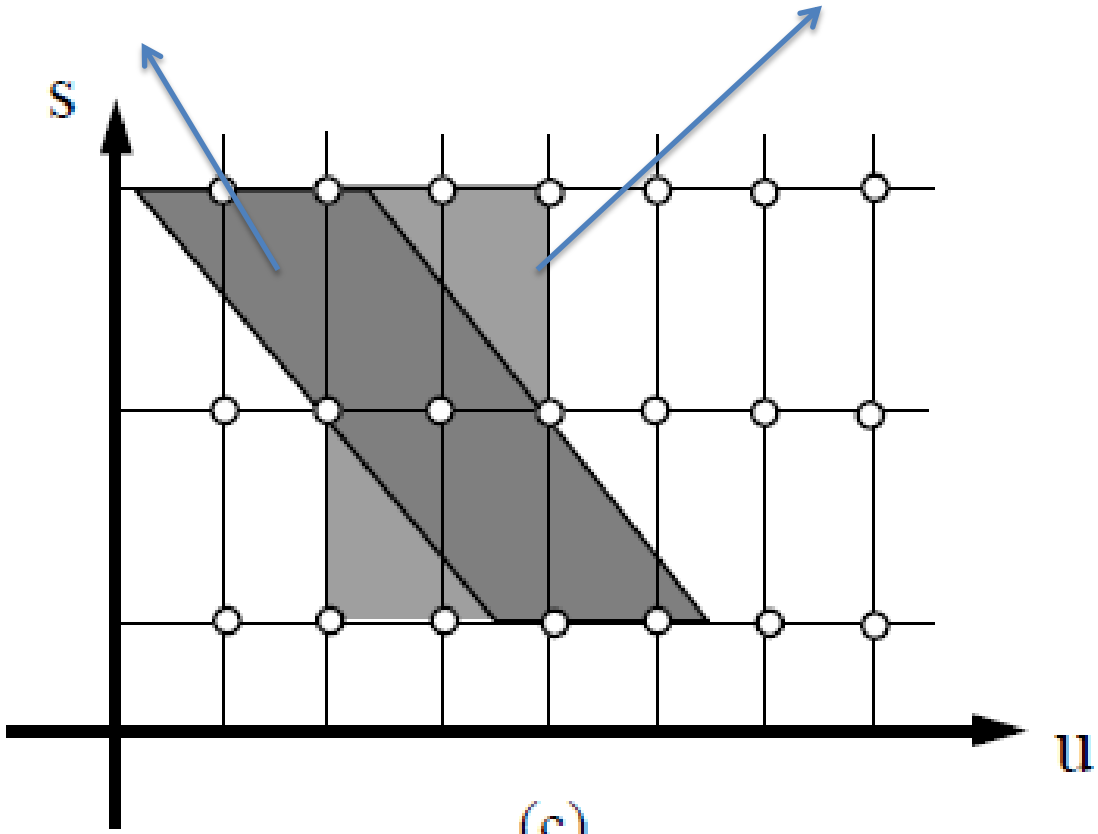
Depth corrected support



Lumigraph – depth corrected support

Depth-corrected Support in ray space

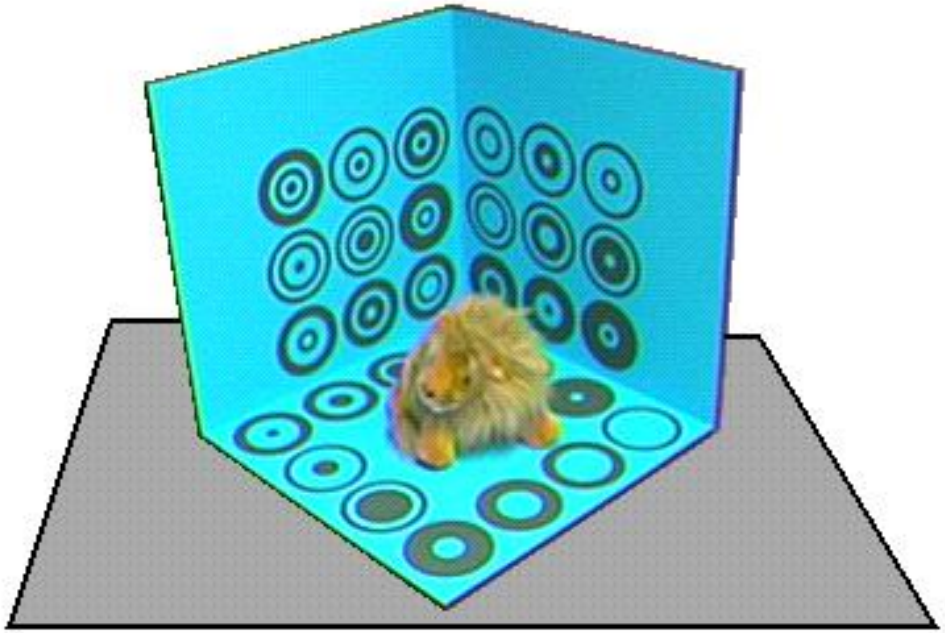
Non-corrected support in ray space



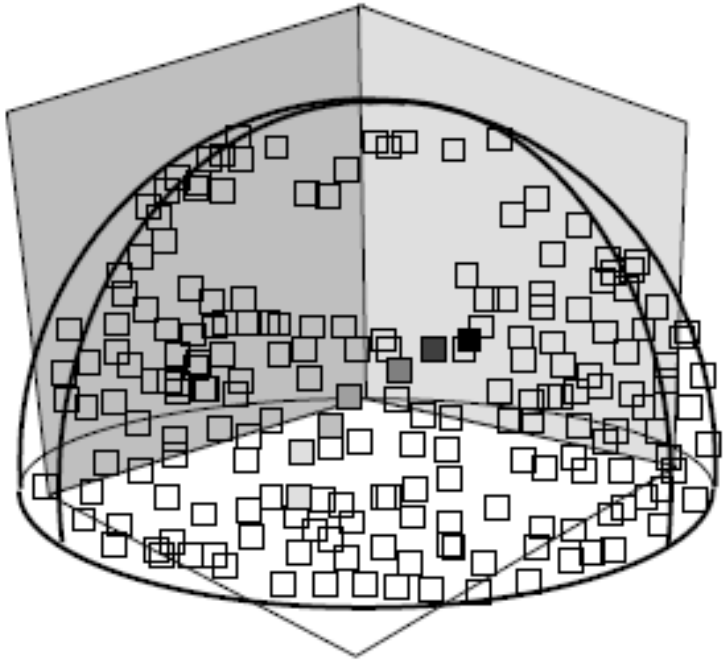
(c)

Image Acquisition

- In order to calculate the inner product, the images have to be *calibrated*



calibration setup



result

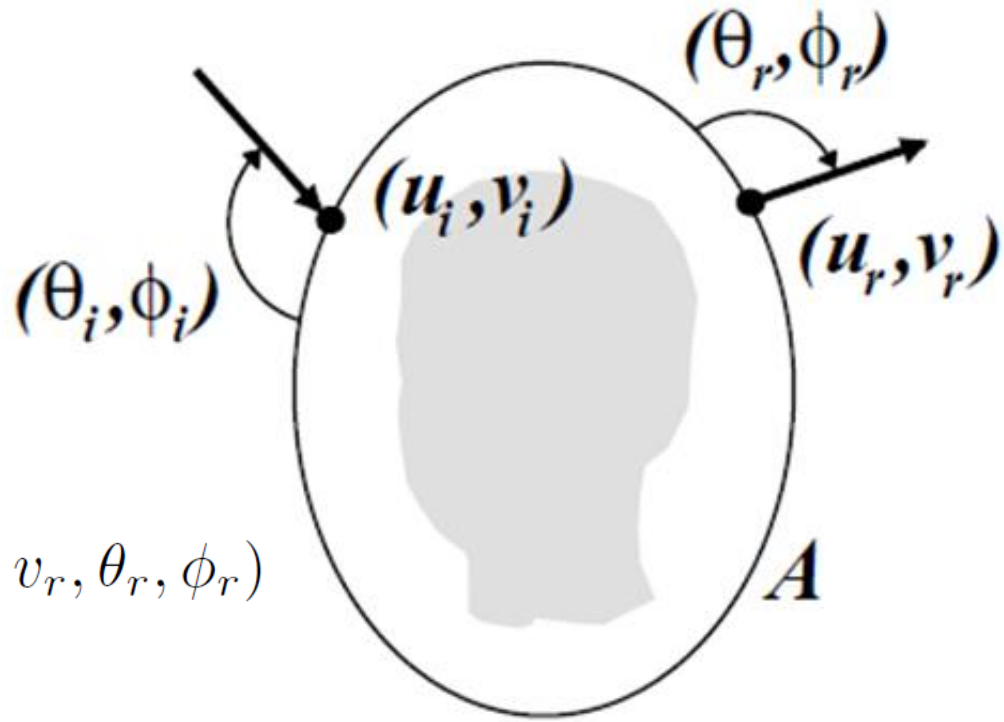
Refletance Field of an Human Face

- We will see now how to capture the reflectance field of an human face [Debevec2000] (!)
- The idea is to capture the radiant light field (4D) for different fixed illumination conditions (directional light).

[Debevec2000] Paul Debevec, Tim Hawkins, Chris Tchou, Haarm-Pieter Duiker, Westley Sarokin, and Mark Sagar, "Acquiring the reflectance field of a human face", In *Proc. of the 27th Conf. on Computer graphics and interactive techniques* (SIGGRAPH '00). ACM Press/Addison-Wesley Publishing Co., New York, NY, USA, pp. 145-156, 2000.

Reflectance Field of an Human Face

- Capturing the radiant light field for every possible incident light field give us the reflectance function *R*:



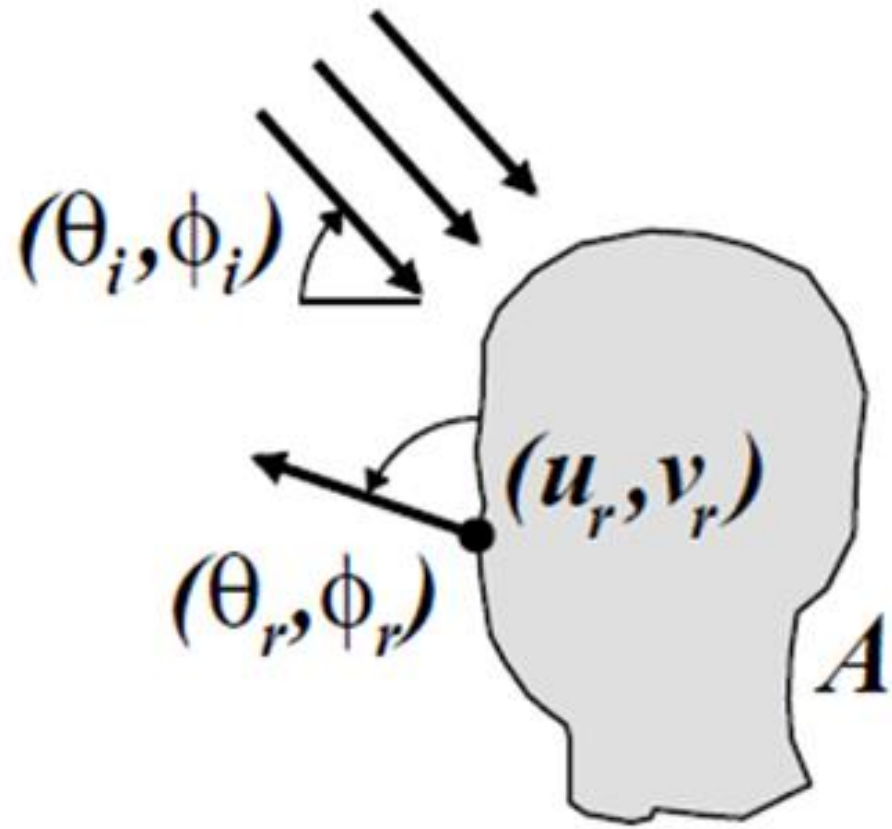
$$R_i = R_i\left(u_i, v_i, \theta_i, \phi_i\right)$$

$$R_r = R_r\left(u_r, v_r, \theta_r, \phi_r\right)$$

$$R\left(R_i, R_r\right) = R\left(u_i, v_i, \theta_i, \phi_i, u_r, v_r, \theta_r, \phi_r\right)$$

Non-local Reflectance Field (6D)

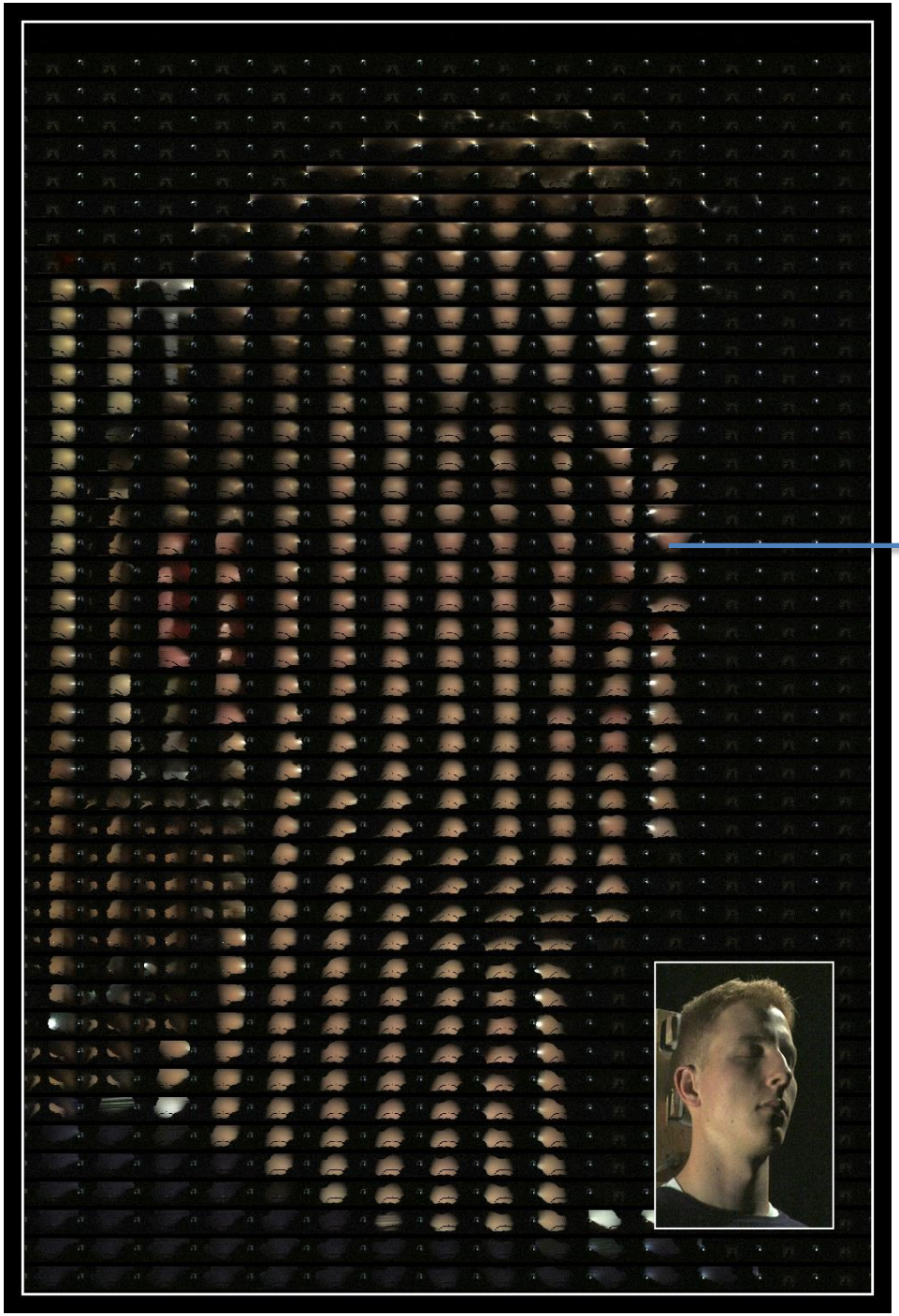
- The different incident illumination condition are assumed different directional lights.
- What is it acquired is a *non local reflectance field.*



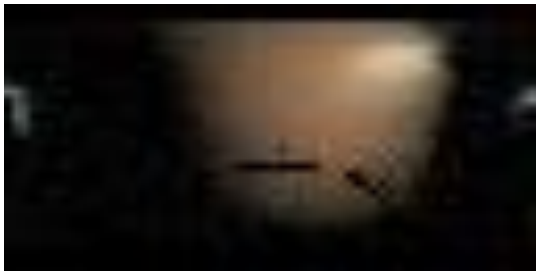
$$R\left(R_i, R_r\right) = R\left(\theta_i, \phi_i, u_r, v_r, \theta_r, \phi_r\right)$$

Acquisition Device

- The light stage used to acquire the reflectance field is shown in figure.
- The light moves as a spiral (2048 directions are sampled)
- Multiple views are acquired simultaneously



$$R_{xy}(\theta, \phi)$$



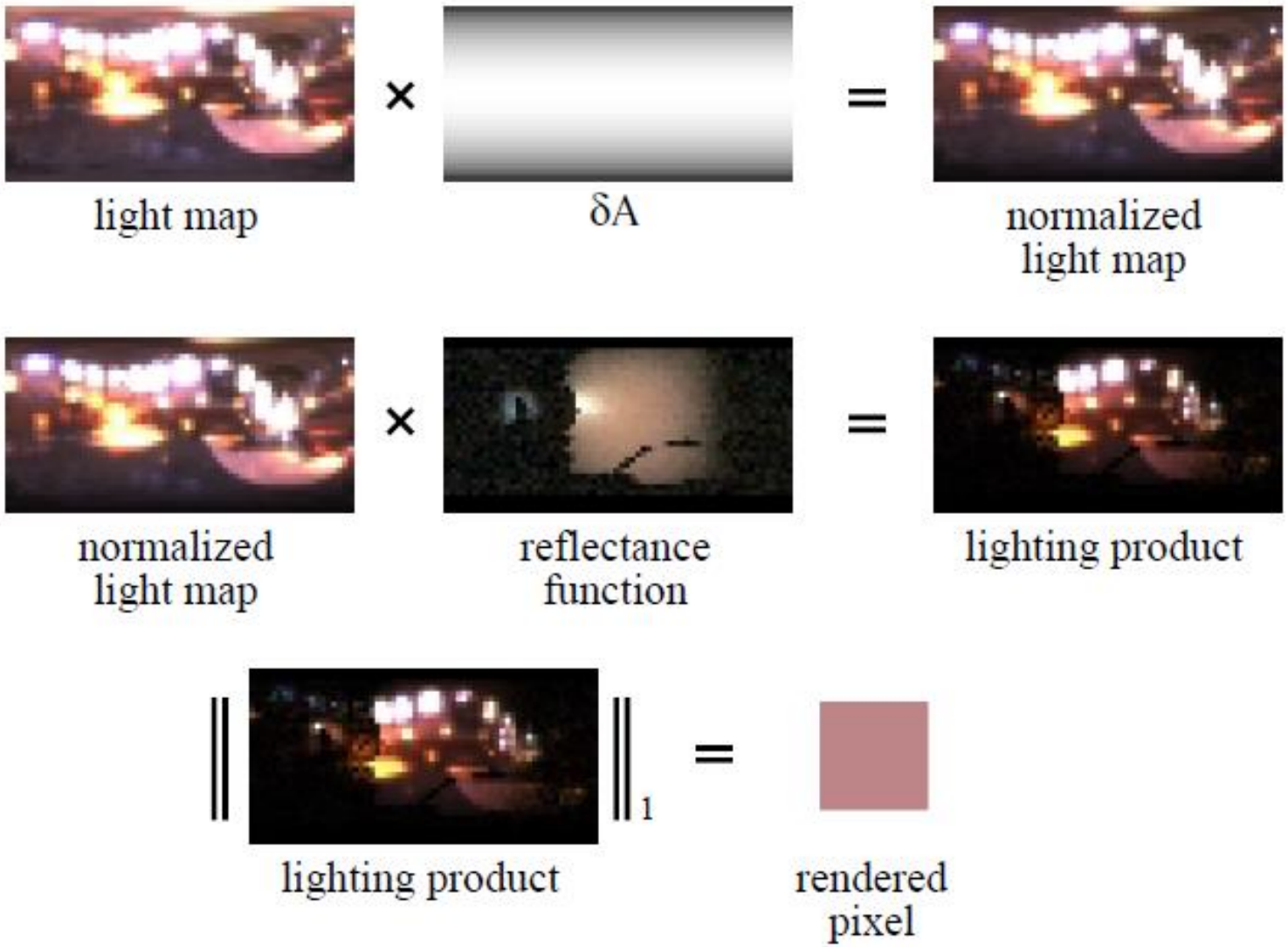
64 x 32 directions

Generate a New Image

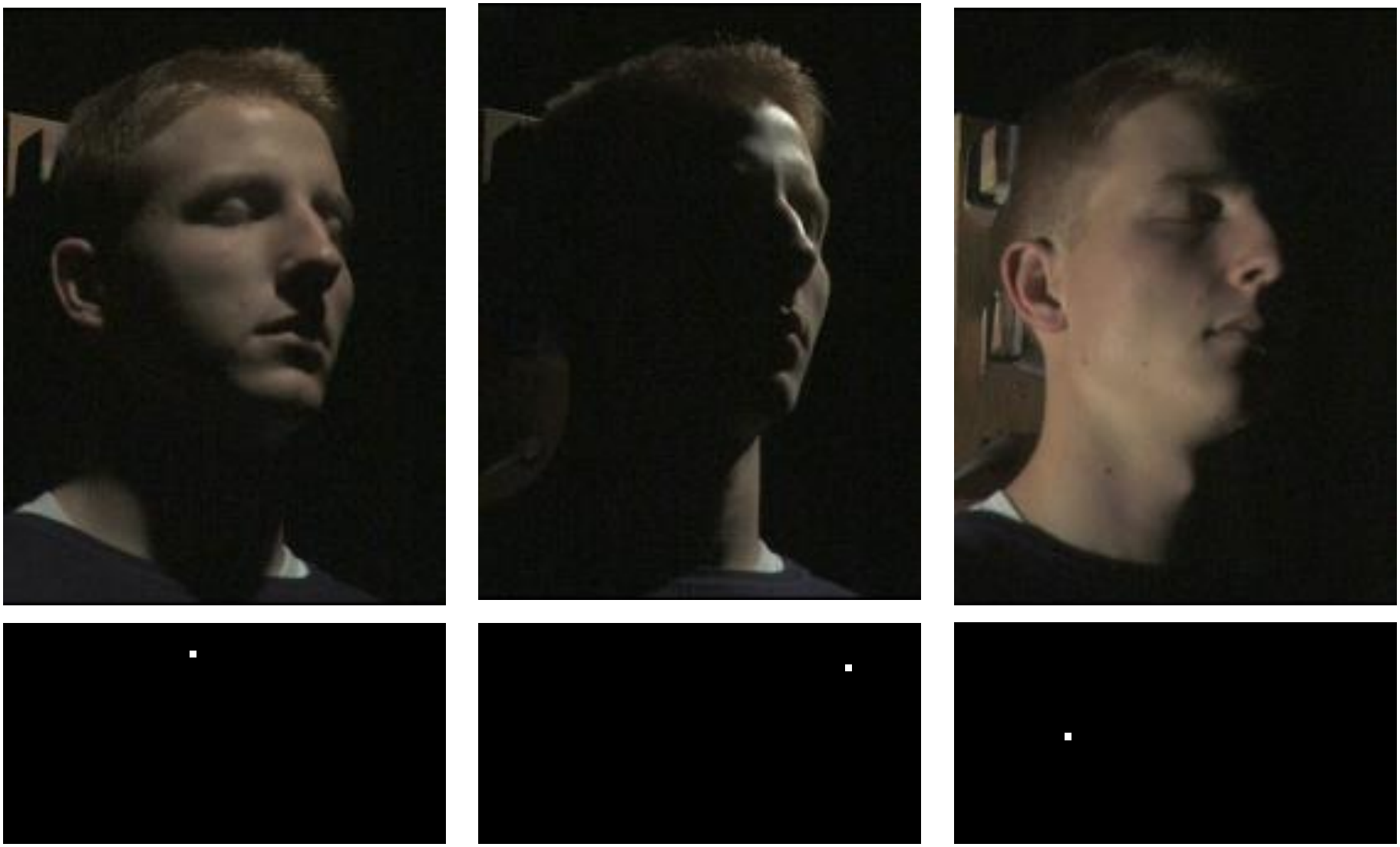
- The new image under a combination of the original light sources is:

$$L(x, y) = \sum_{\theta, \phi} R_{xy}(\theta, \phi) L_i(\theta, \phi)$$

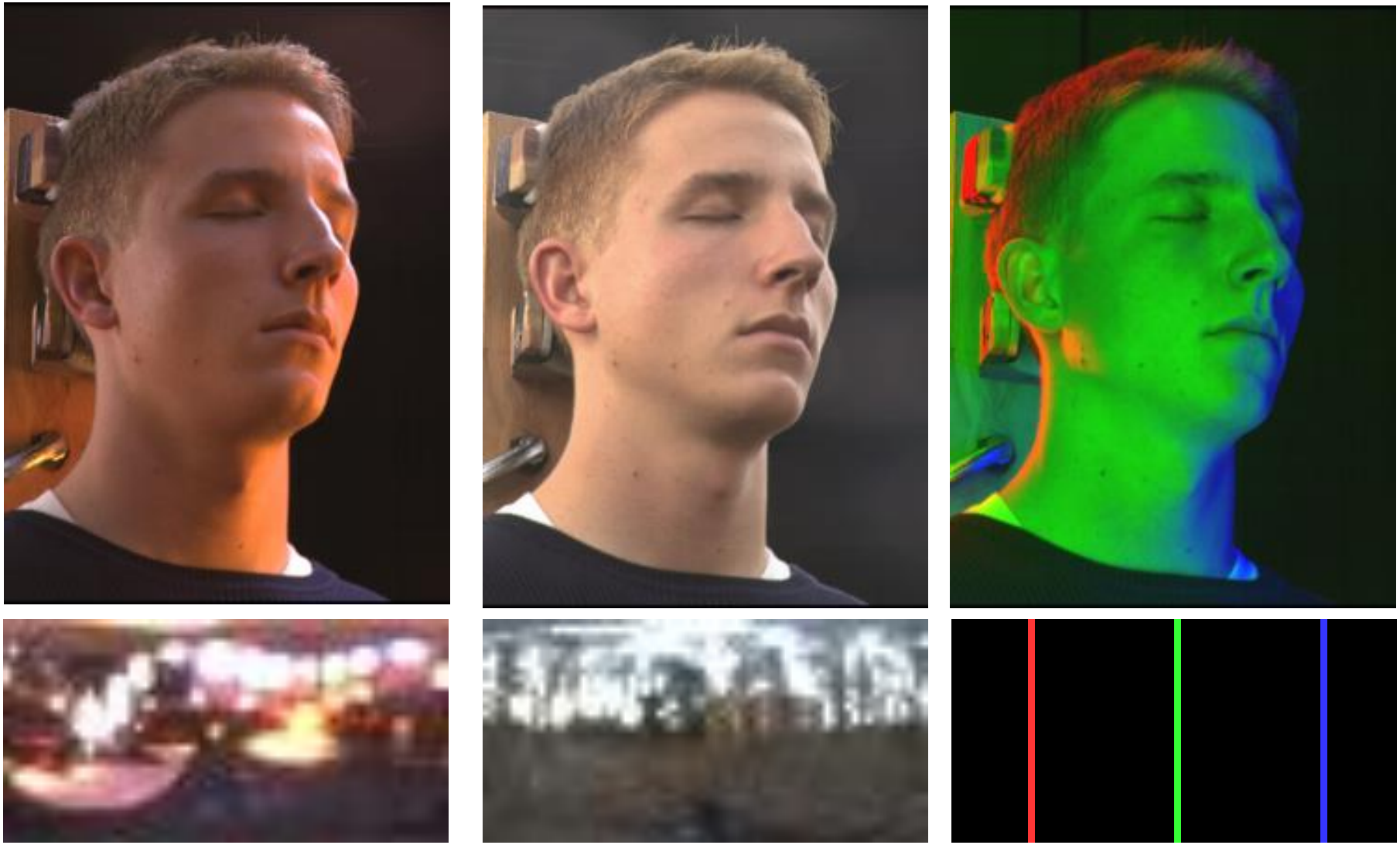
Reflectance Field of an Human Face



Examples – illumination basis

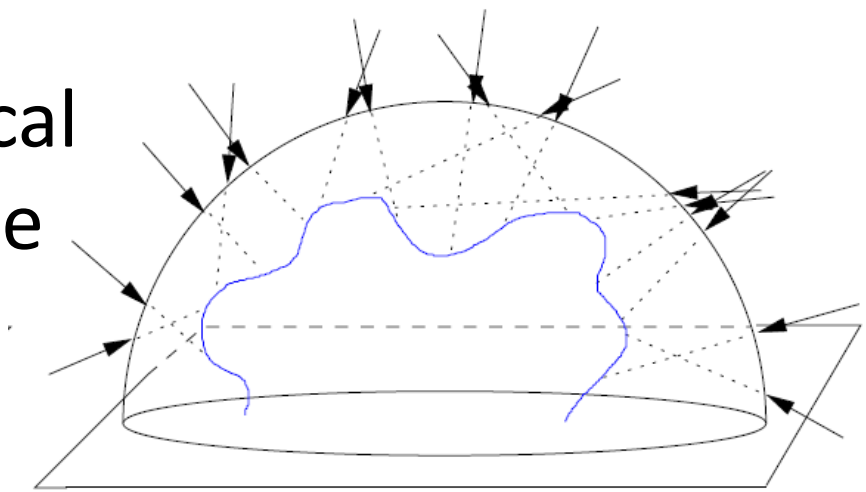


Changing the lighting environment Examples



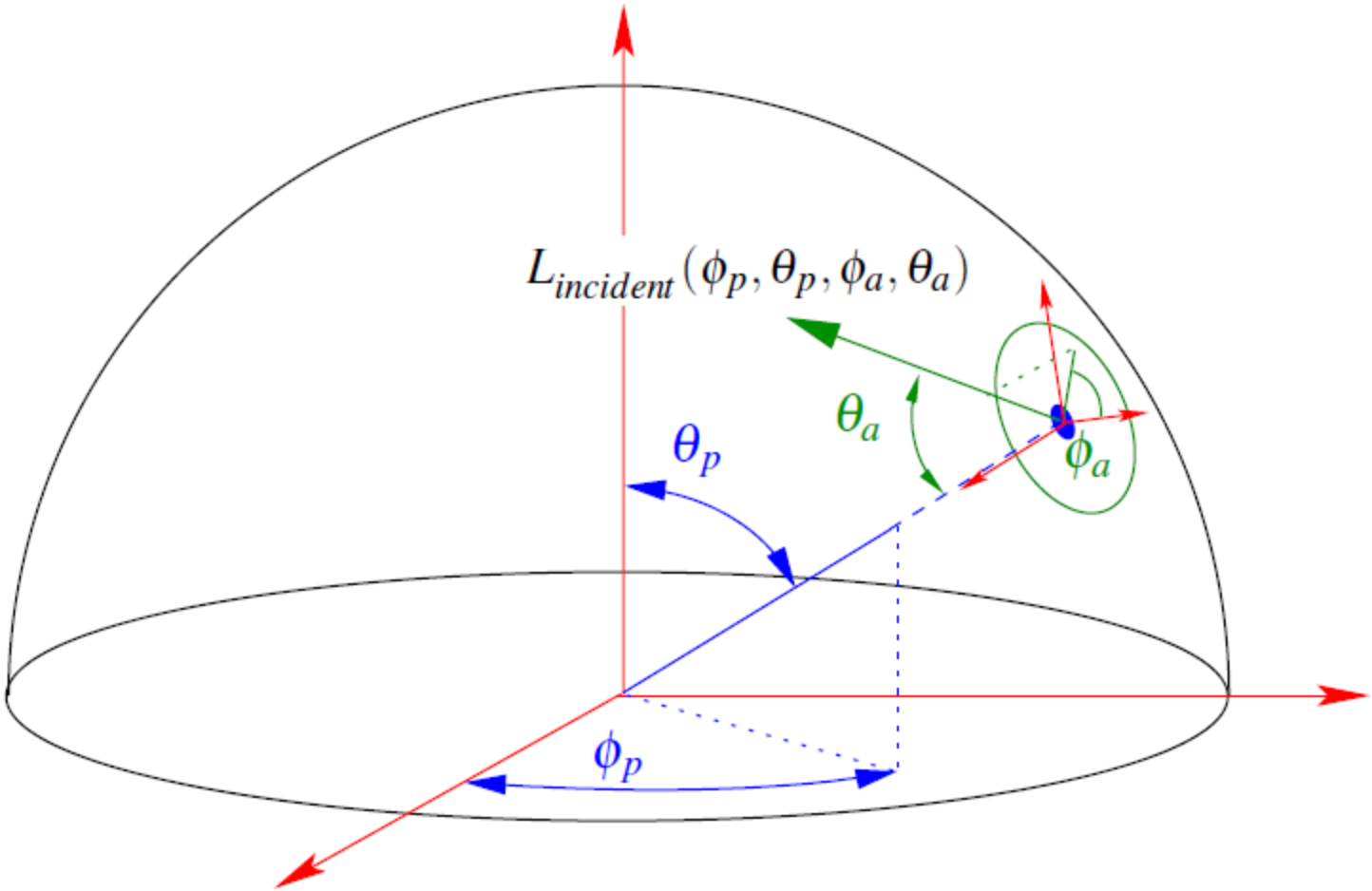
Reflectance Field (6D)

- We will see now another way to acquire a 6D reflectance field [Masselus2003]
- The idea is to use a spherical surface to parameterize the incident light field.



Vincent Masselus, Pieter Peers, Philip Dutré, and Yves D. Willems "Relighting with 4D incident light fields", ACM SIGGRAPH 2003 Papers (SIGGRAPH '03). ACM, New York, NY, USA, pp. 613-620, 2003.

6D Reflectance Field



Vincent Masselus, Pieter Peers, Philip Dutré, and Yves D. Willems "Relighting with 4D incident light fields", ACM SIGGRAPH 2003 Papers (SIGGRAPH '03). ACM, New York, NY, USA, pp. 613-620, 2003.

6D Reflectance Field

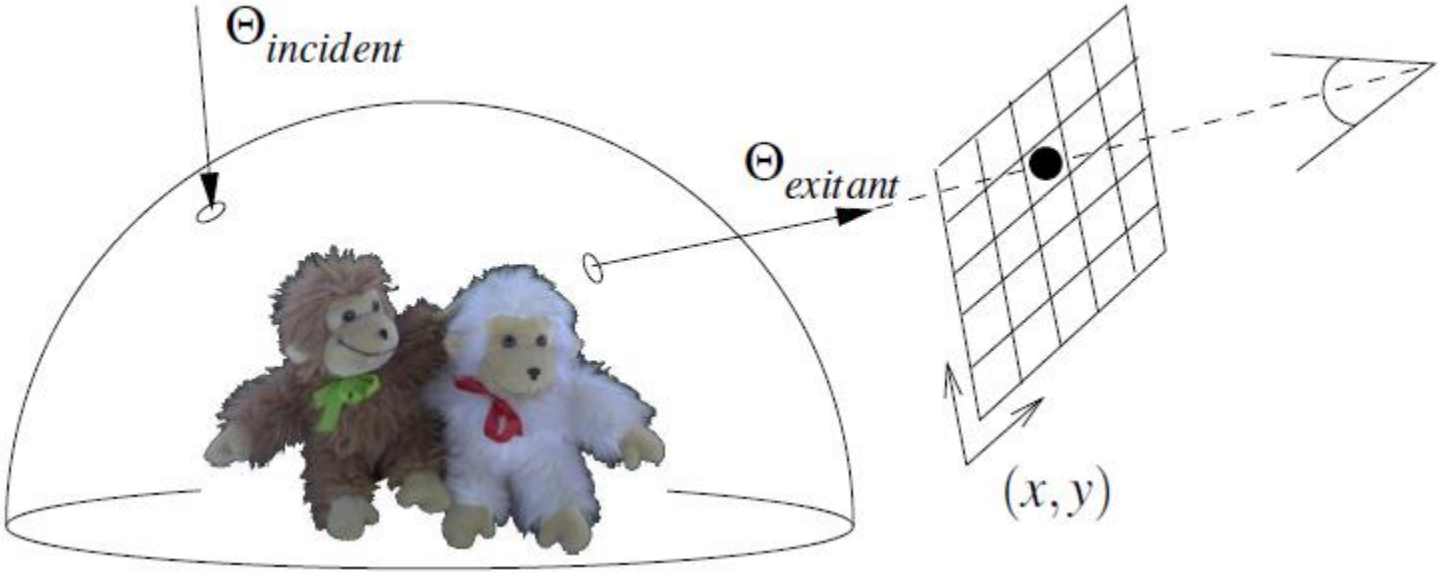
$$\text{ILF } L \rightarrow L\left(\theta_p, \phi_p, \theta_a, \phi_a\right) = L\left(\Theta_I\right)$$

Reflectance Field (8D)

$$\text{REFLECTANCE FIELD } R \rightarrow R\left(\Theta_I, \Theta_E\right)$$

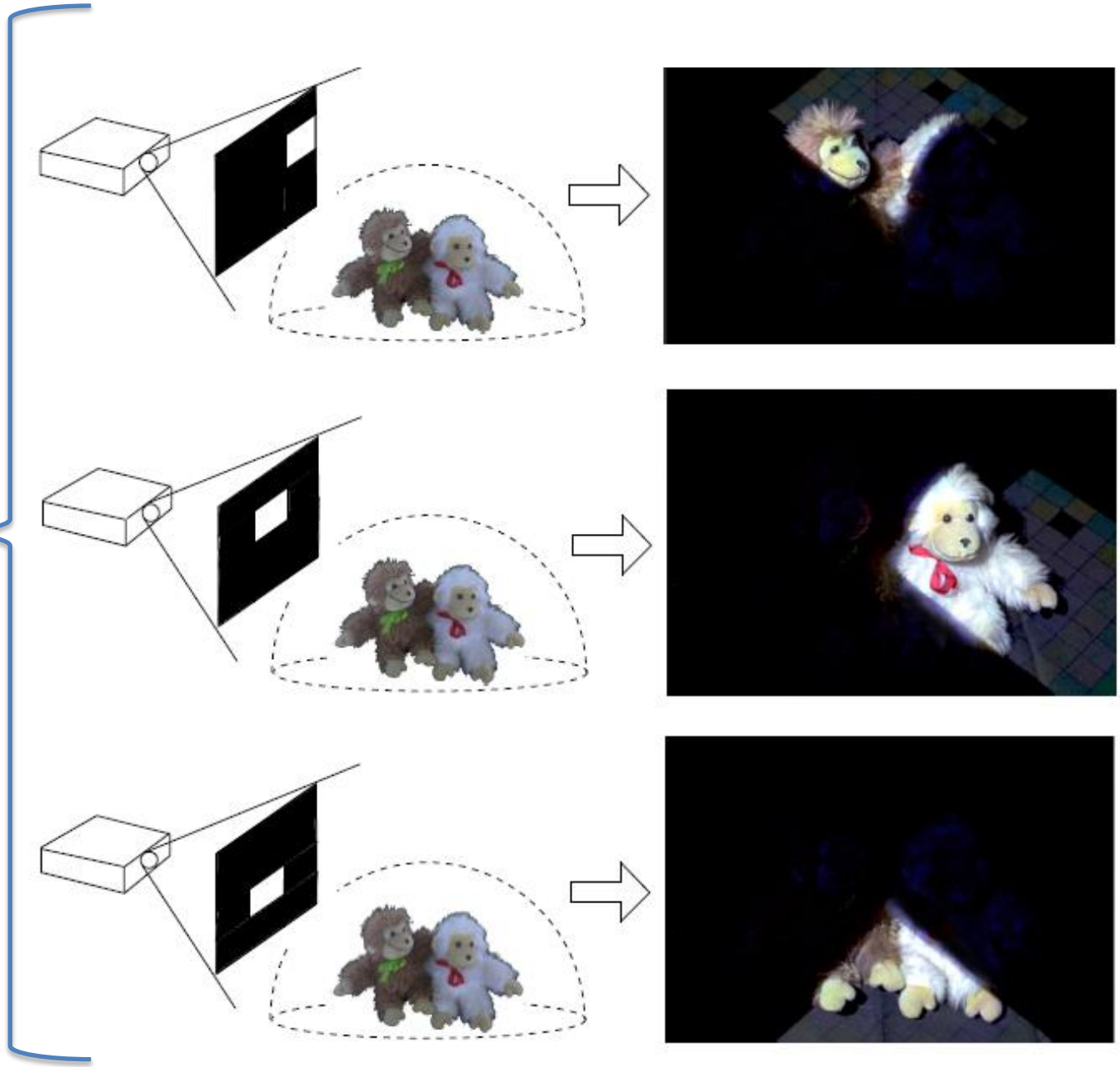
6D Reflectance Field

Exitant light field is restricted to the image plane → $L_E(x,y)$ (fixed camera view) → 6D Reflectance Field



$$R(\theta_p, \phi_p, \theta_a, \phi_a, x, y) = R(\Theta_I, x, y)$$

Light basis to estimate the 6D Reflectance Field



Results

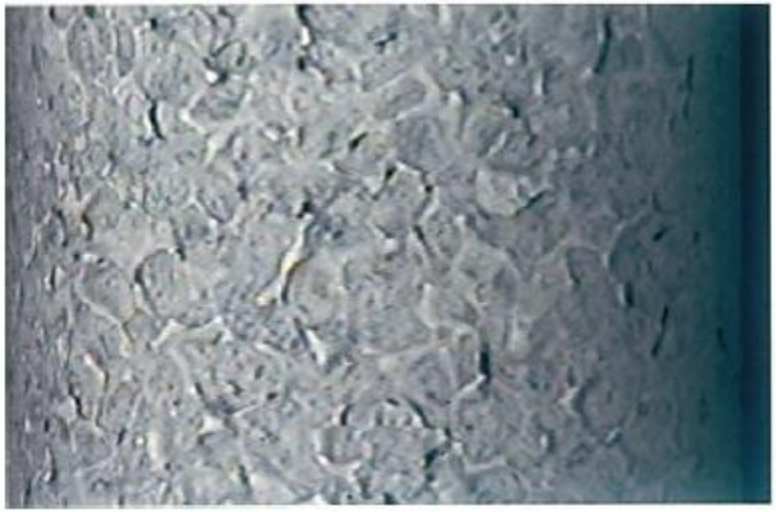
Original Image

Relighted Images

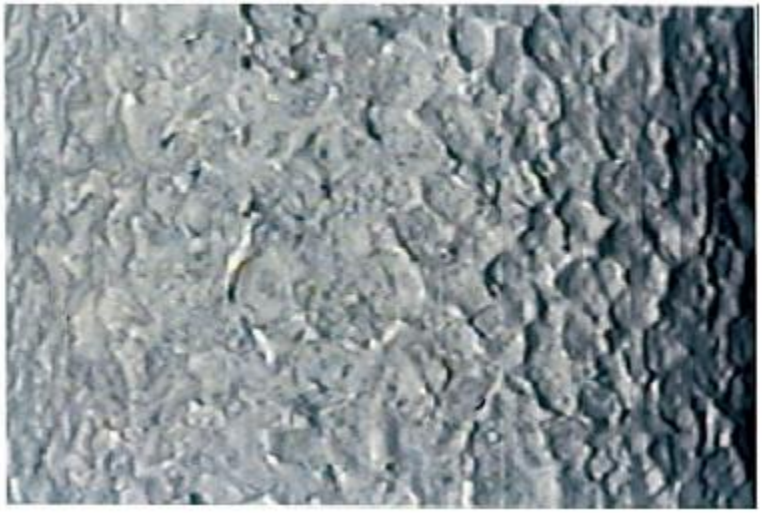
Bidirectional Texture Function (BTF)

- A surface patch of material (a small image, a *texture*) is acquired using approaches similar to the ones for BRDF.
- From each view, a set of photographs in different lighting conditions is acquired → many compression scheme have been proposed.
- *It is not a SVBRDF (!)* → it includes *self-shadowing* and *inter-reflections* effects due to the microstructure of the material.
- Useful to account for the *fine scale* of a material.

BTF example



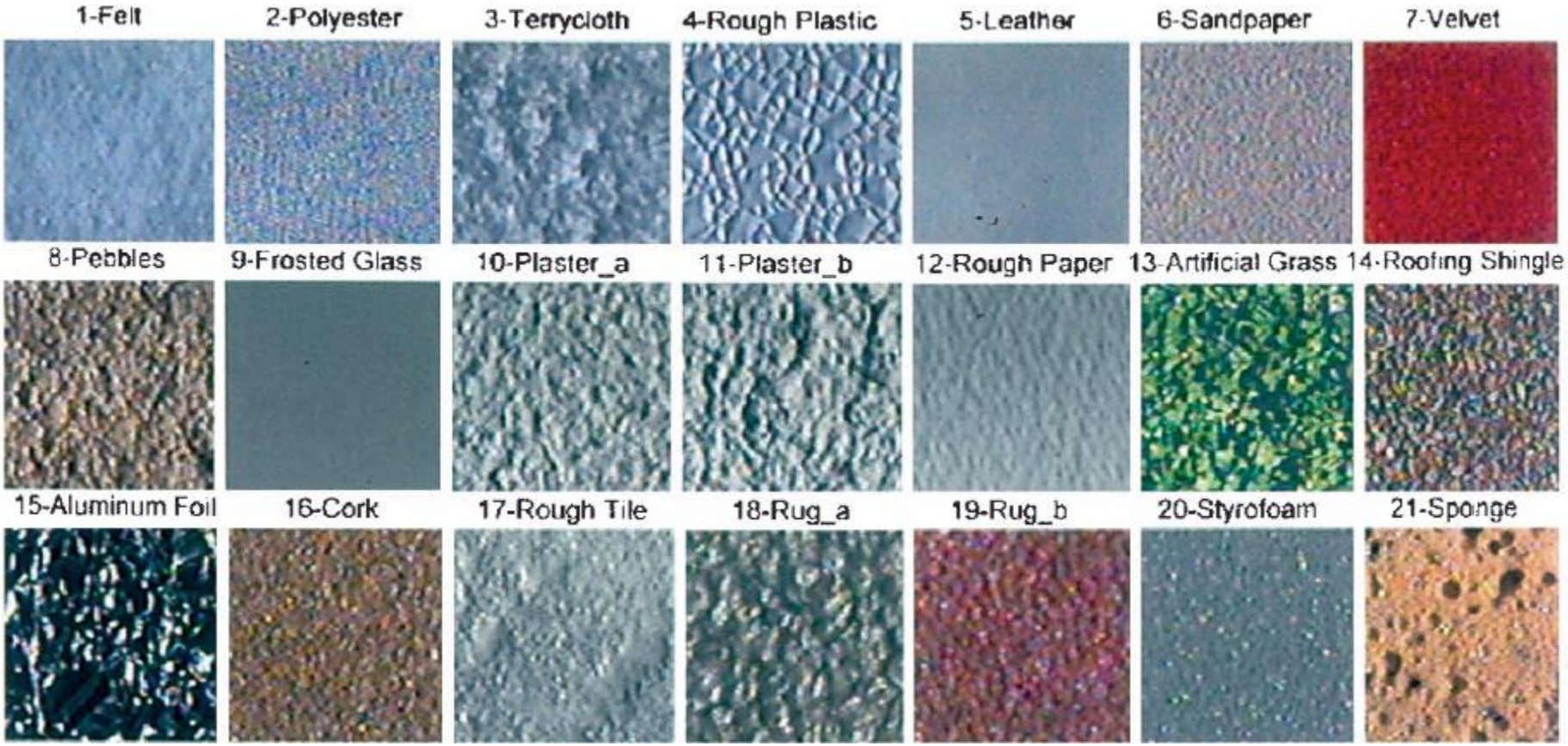
Cylinder + Texture



Cylinder + BTF

From:
Kristin J. Dana, Bram van Ginneken, Shree K. Nayar, and Jan J. Koenderink, "Reflectance and texture of real-world surfaces", *ACM Trans. Graph.* 18, 1 (January 1999), pp. 1-34, 1999.

BTF database



From:
Kristin J. Dana, Bram van Ginneken, Shree K. Nayar, and Jan J. Koenderink, "Reflectance and texture of real-world surfaces", *ACM Trans. Graph.* 18, 1 (January 1999), pp. 1-34, 1999.

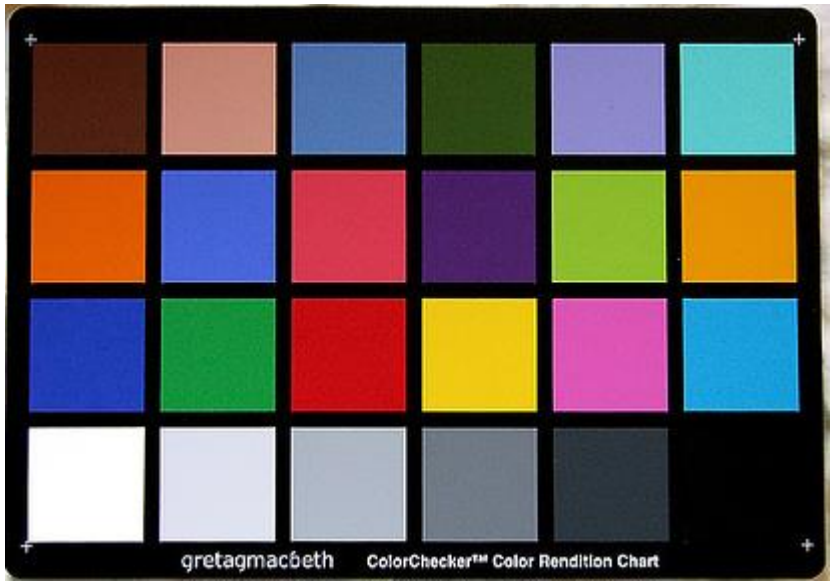
Made BRDF Acquisition More Practical

- One of the main challenge of current research in the field
- One of the most effective idea is the *pocket reflectometry* of Ren et al. [Ren2011]

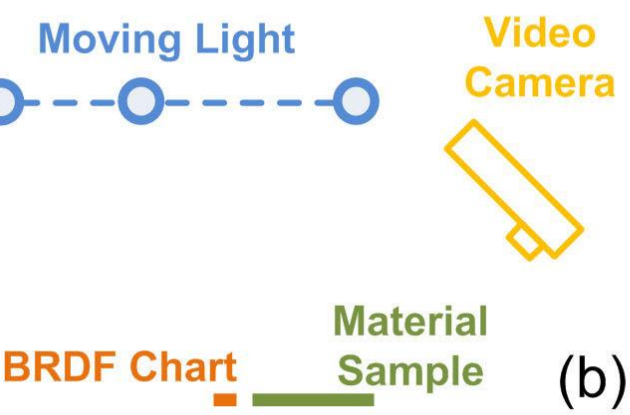
[Ren2011] Peiran Ren, Jiaping Wang, John Snyder, Xin Tong, and Baining Guo, "Pocket reflectometry", ACM Trans. Graph. 30, 4, Article 45 (July 2011).

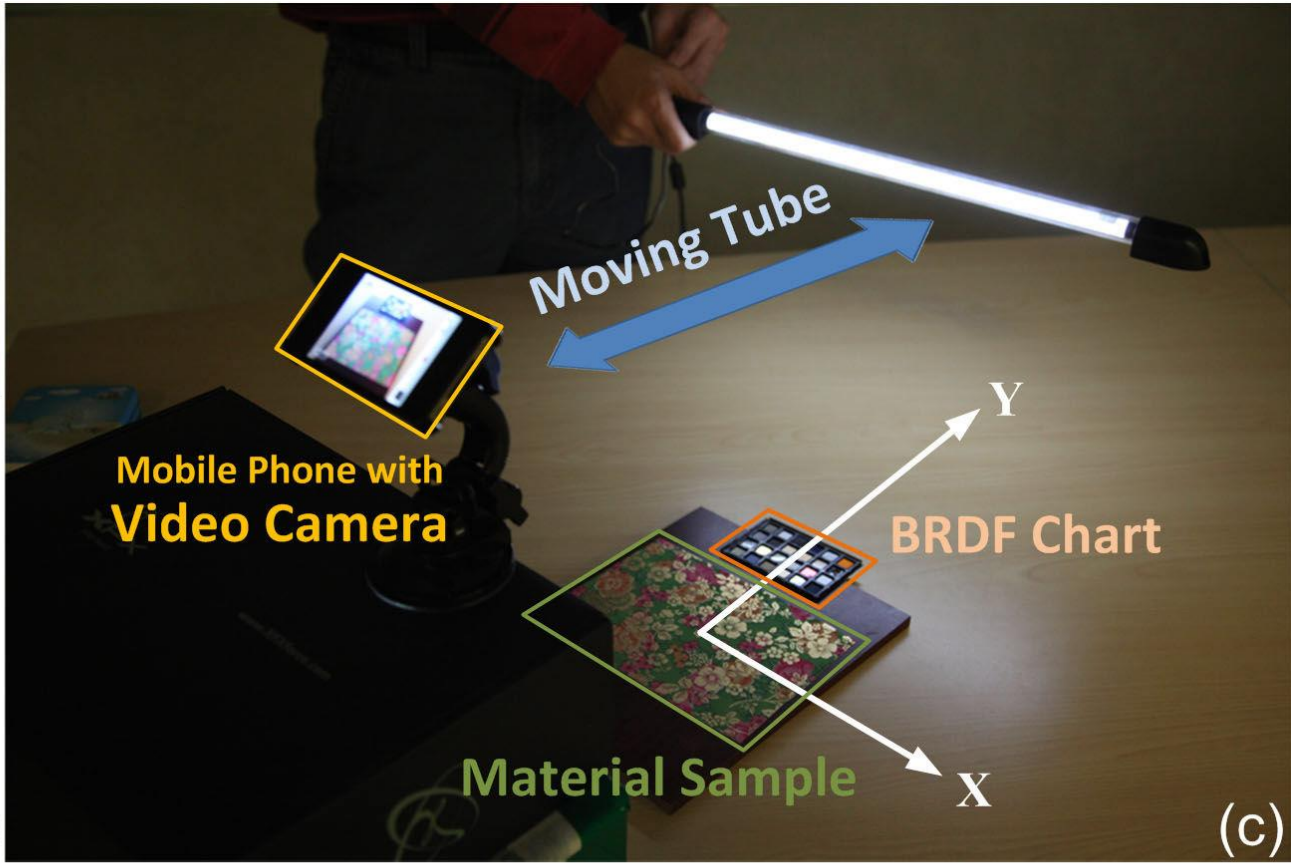
Pocket Reflectometry

- Mimic the *color calibration of a camera*
  - Known color target (Gretag Macbeth)
  - The color target is in the photograph
  - The color are remapped according to the known color

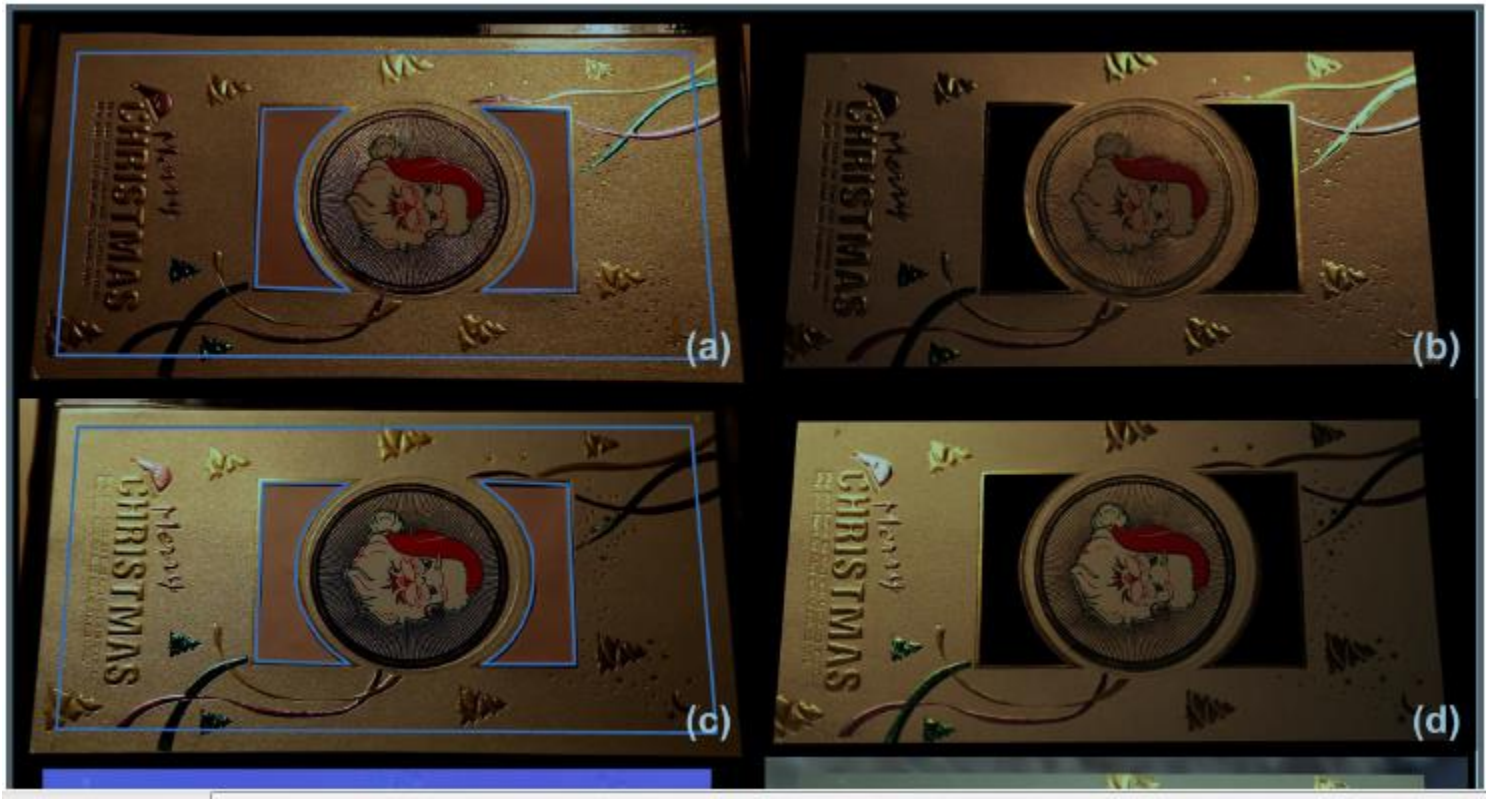


Pocket Reflectometry





Pocket Reflectometry



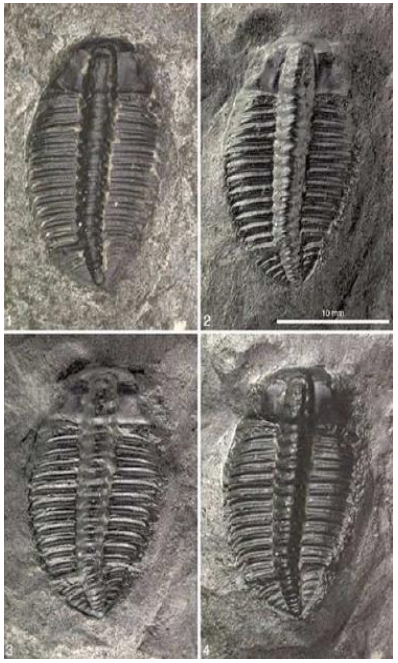
Let's see some results..

Polynomial Texture Maps (PTM)

- Image-based Lighting technique for the acquisition of appearance (Malzbender et al. – HP laboratories)
- Relightable images are the final product
- Motivations:
  - Three-dimensional illusion is high
  - Viewer’s understanding is improved
  - Rendering is not complex
  - Acquisition setup is cheap

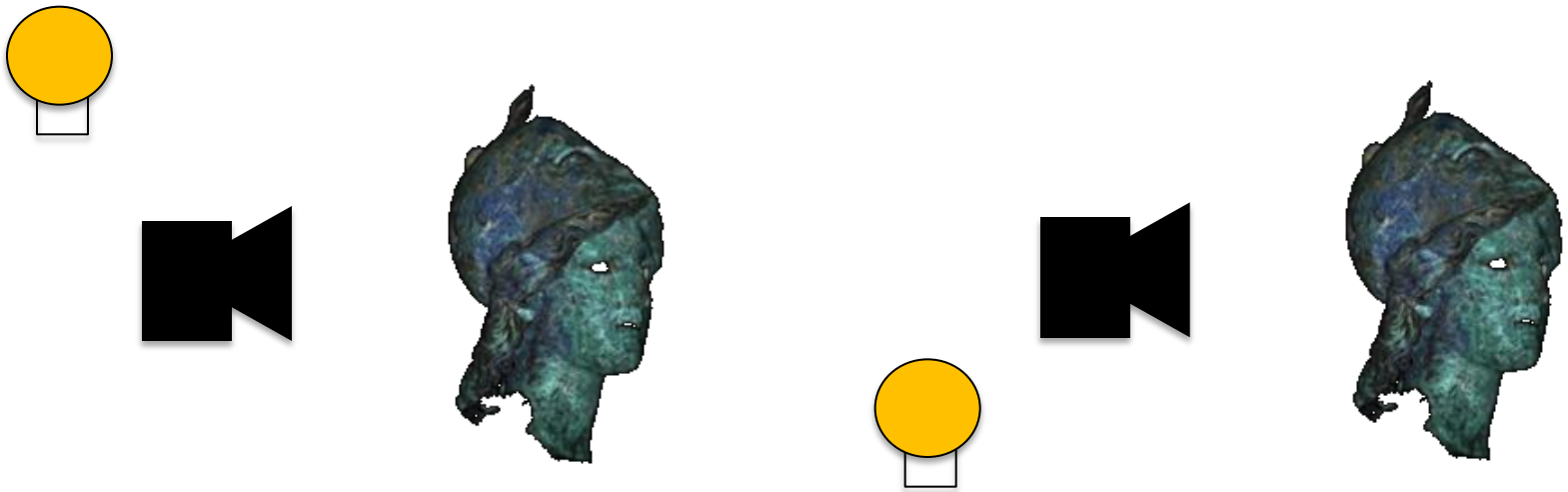
PTM in Cultural Heritage

- Inspection of cuneiform epigraphy (Malzbender et al. 2000)
- In Paleontology, to provide noticeable improvement in imaging of low color contrast, high relief fossils (Hammer et al. 2002)
- To reveal fine details of concoidal knapping fractures on ancient stone tools (Mudge 2004 et al.)
- To provide additional information about the surface of oil paintings (Padfield et al. 2005)
- To build a “virtual exihibition” of the large numismatic collections of the Hospice of Grand St. Bernard (Mudge et al. 2005)



Polynomial Texture Maps

- A set of images in controlled light conditions is acquired but *the camera is fixed*
- The idea is to evaluate per-pixel a function that given the light directions returns the color of the image



Acquisition device

- Devices designed for small objects
  - Illumination dome composed by multiple lights on known positions
  - Illumination dome is hardware controlled
- Reduce to an arc section to make less cumbersome

Acquisition devices by HP Labs

PTM of large objects

Polynomial Texture Map

- Distant light is assumed (directional light)
- Bi-quadratic polynomial is used to model the per-pixel reflectance functions ***L(.)***

$$
\begin{aligned}
L(l_u, l_v, x, y) &= a_o(x,y) + a_1(x,y)l_u + a_2(x,y)l_v + \\
&+ a_3(x,y)l_u l_v + a_4(x,y)l_u^2 + a_5(x,y)l_v^2
\end{aligned}
$$

$$
\left.
\begin{aligned}
R_f(l_u, l_v, x, y) &= L(l_u, l_v, x, y)R(x,y) \\
G_f(l_u, l_v, x, y) &= L(l_u, l_v, x, y)G(x,y) \\
B_f(l_u, l_v, x, y) &= L(l_u, l_v, x, y)B(x,y)
\end{aligned}
\right\} \textbf{LRGB PTM}
$$

From PTM to RTI

- Recently, a generalization of PTMs called Reflectance Transformation Images (RTI) has been proposed
- Some of the results in this direction has been presented at VAST 2009 conference
  - **Prabath Gunawardane et al. "Optimized Image Sampling for View and Light Interpolation"**

From PTM to RTI

- A first step has been to replace the bi-quadratic polynomials with other, more complex, functions
  - Spherical or hemi-spherical harmonics (HSH)
  - Adaptive polynomials of high degree
- Another goal has been to remove the fixed viewpoint limitations (i.e. multi-view RTI)

PTM - Demo

- Let’s see a live demo (!)

Normal Unsharp Masking (NUM)

Standard Rendering

NUM Rendering

Thanks for the attention.

Question ?