Measuring Material Appearance: BRDF, BSSRDF, BTF



Computer Graphics, Fall 2009

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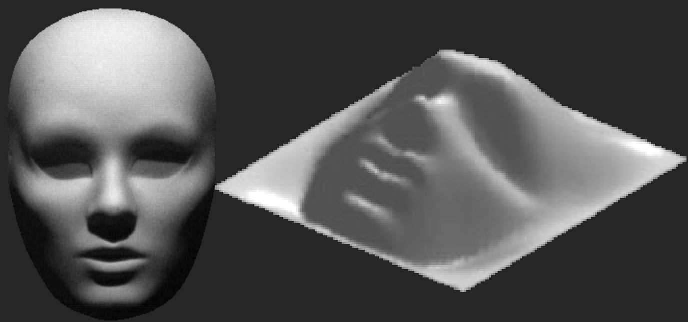
Images Courtest Ben-Ezra et al

Thanks to Steve Marschner, Shree Nayar, Ravi Ramamoorthi, Szymon Rusinkiewicz, Marc Levoy, Pat Hanrahan, Kristin Dana, Ken Perlin, Debevec, Matusik

A variety of material appearances

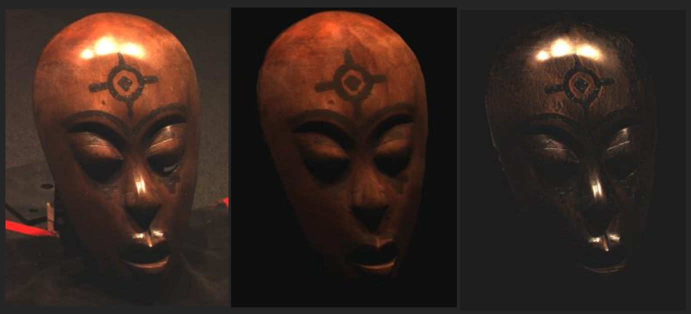
Methods Relying on Surface Reflectance



Shape from Shading

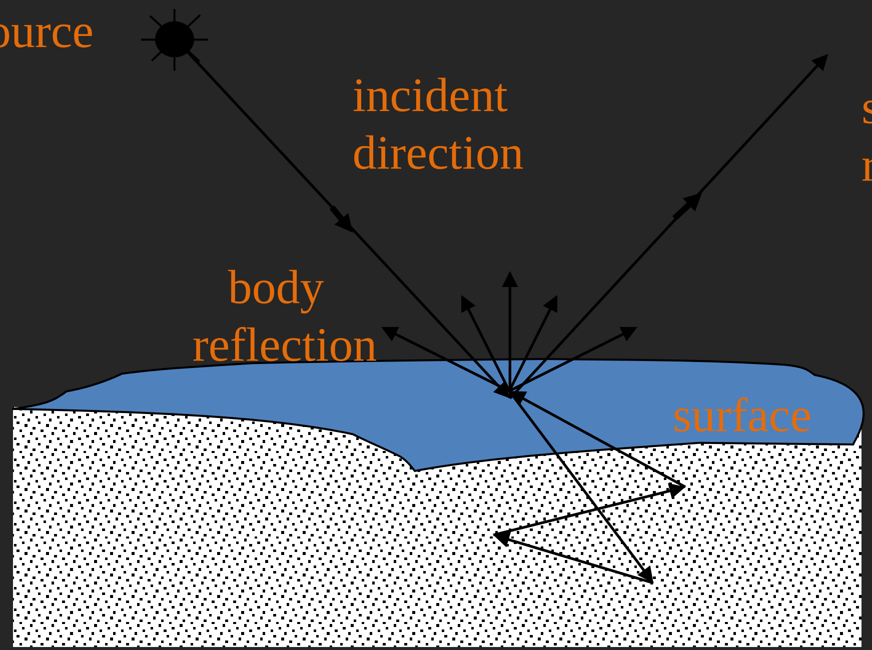
Texture Modeling

Photometric Stereo



Reflection Separation

Mechanisms of Reflection



Surface Reflection:

- Specular Reflection
- Glossy Appearance
- Highlights
- Dominant for Metals

Body Reflection:

- Diffuse Reflection
- Matte Appearance
- Non-Homogeneous Medium
- Clay, paper, etc

Image Intensity = Body Reflection + Surface Reflection

Mechanisms of Reflection

Body Reflection:

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Surface Reflection:

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- Highlights
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Many materials exhibit both Reflections:

Surface Appearance

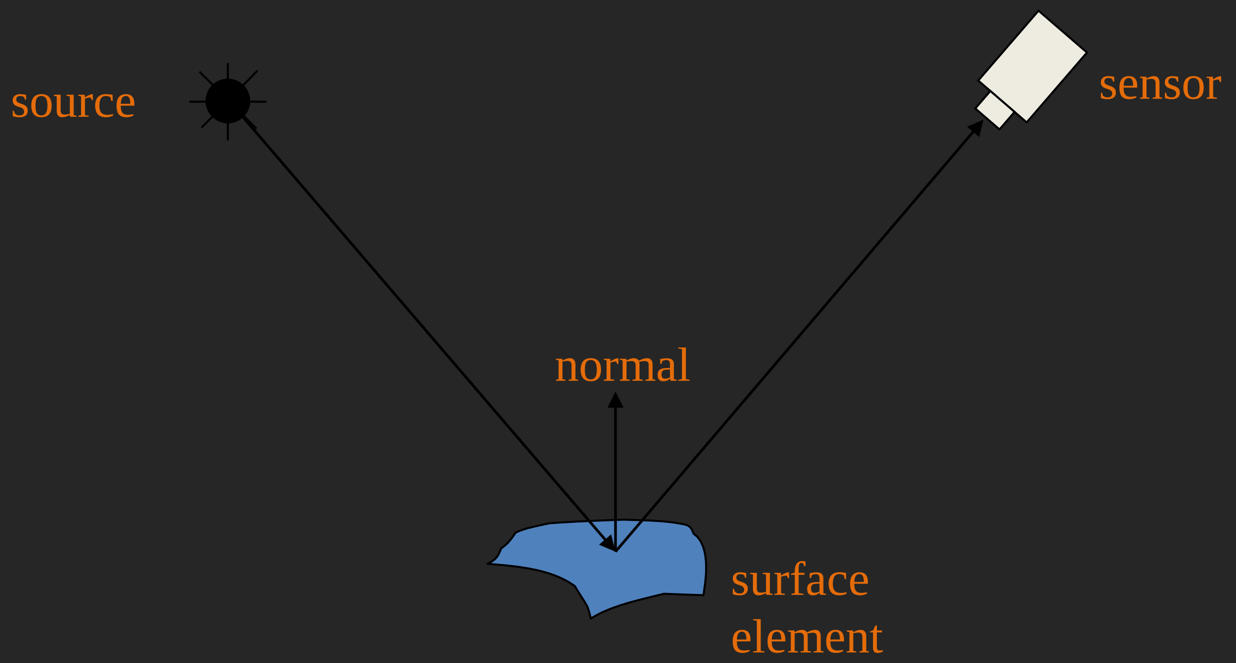
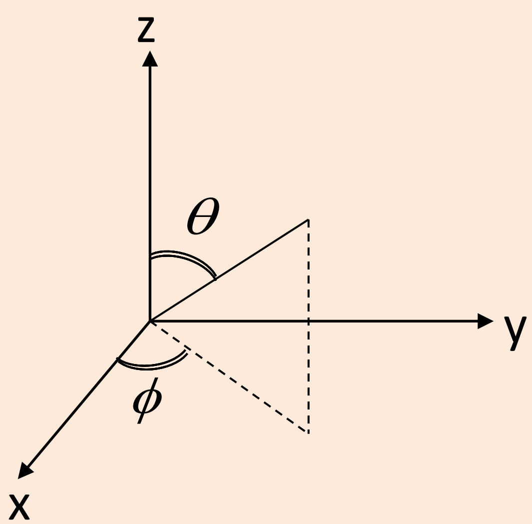
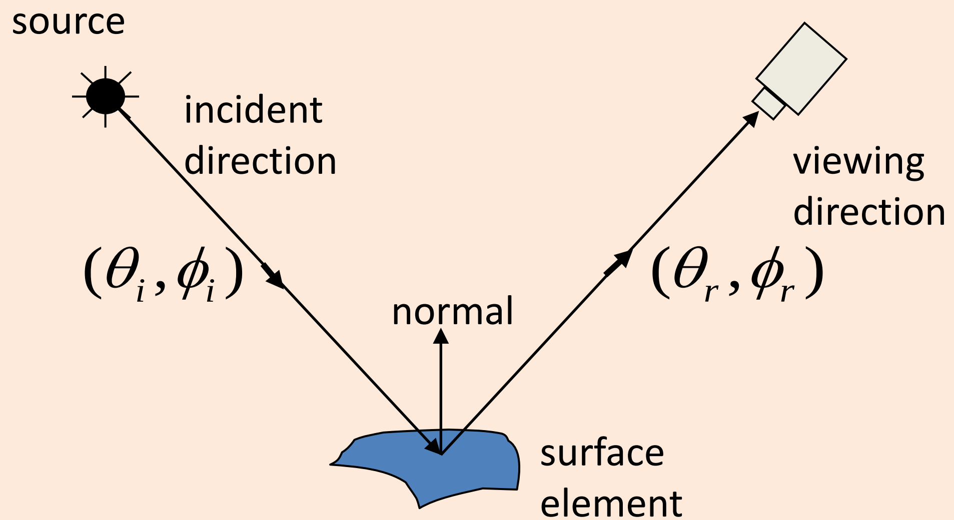


Image intensities = f (normal, surface reflectance, illumination)

Surface Reflection depends on both the viewing and illumination directions.

BRDF: Bidirectional Reflectance Distribution Function



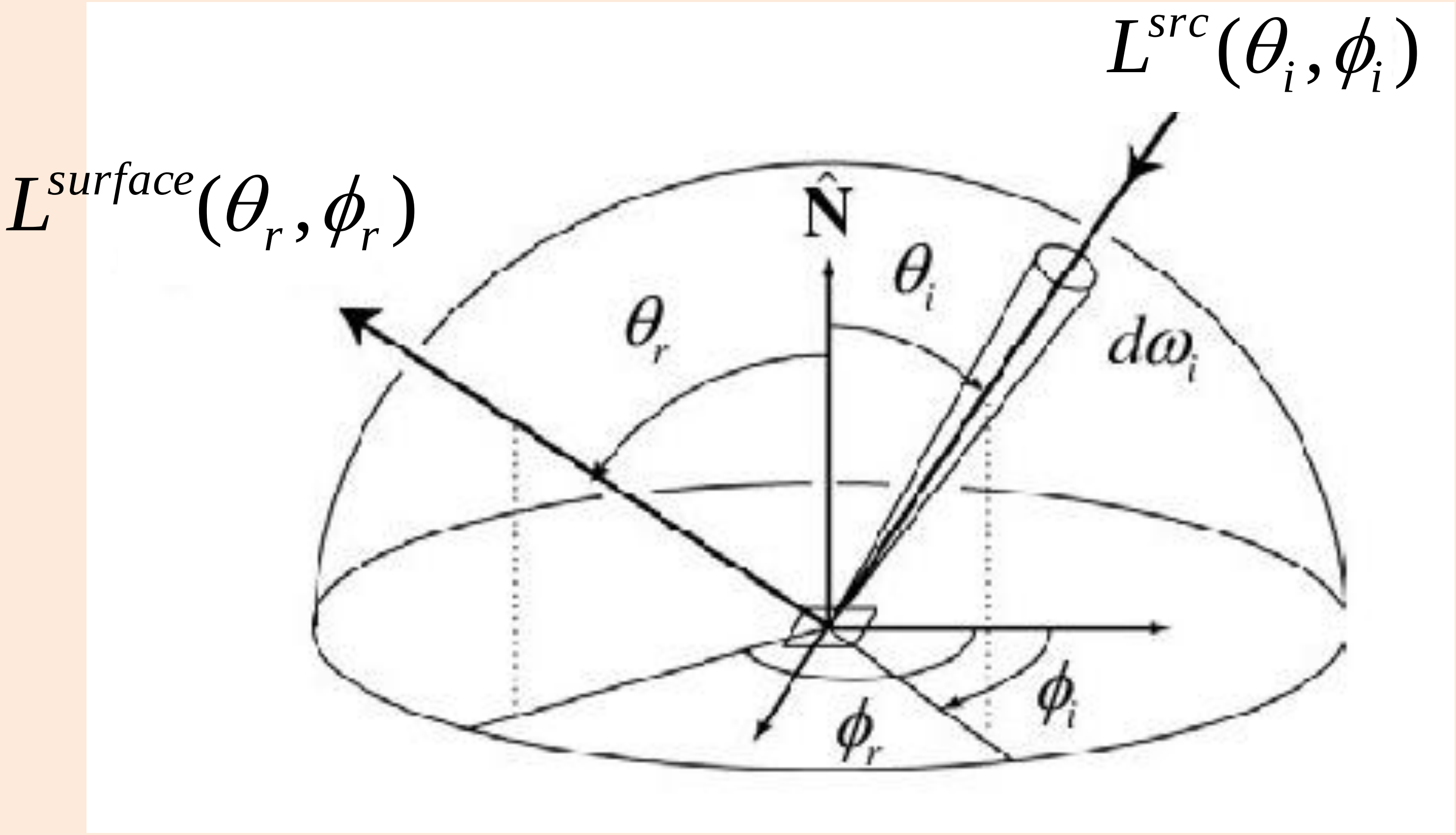


$E^{surface}(\theta_i, \phi_i)$ Irradiance at Surface in direction (θ_i, ϕ_i)

$L^{surface}(\theta_r, \phi_r)$ Radiance of Surface in direction (θ_r, ϕ_r)

$$\text{BRDF : } f(\theta_i, \phi_i; \theta_r, \phi_r) = \frac{L^{surface}(\theta_r, \phi_r)}{E^{surface}(\theta_i, \phi_i)}$$

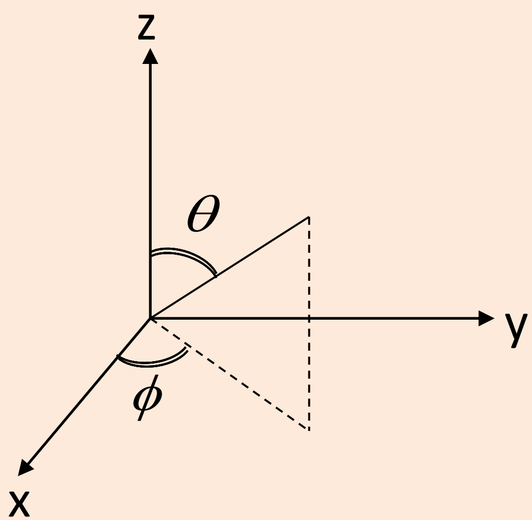
Derivation of the Scene Radiance Equation

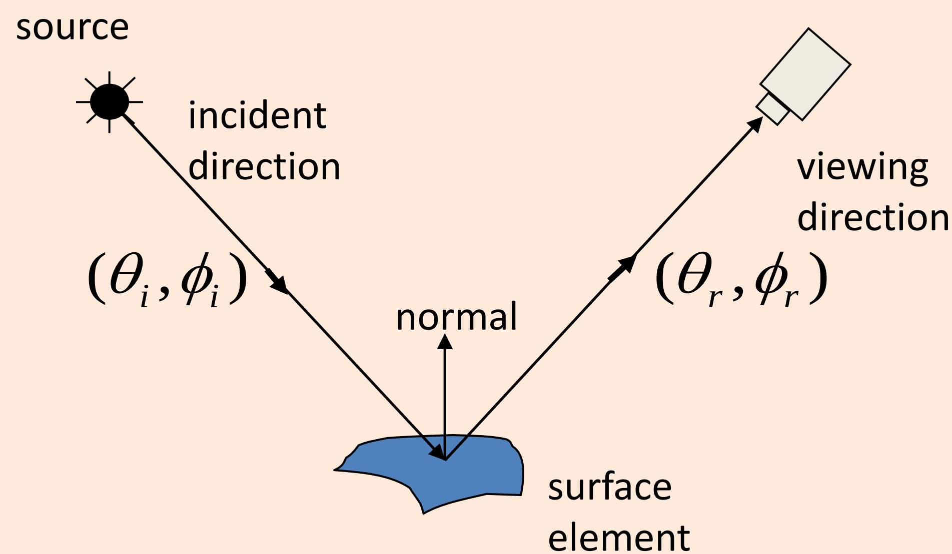


From the definition of BRDF:

$$L^{surface}(\theta_r,\phi_r) \quad = \quad E^{surface}(\theta_i,\phi_i)\, f(\theta_i,\phi_i;\theta_r,\phi_r)$$

Important Properties of BRDFs





- Rotational Symmetry:

BRDF does not change when surface is rotated about the normal.

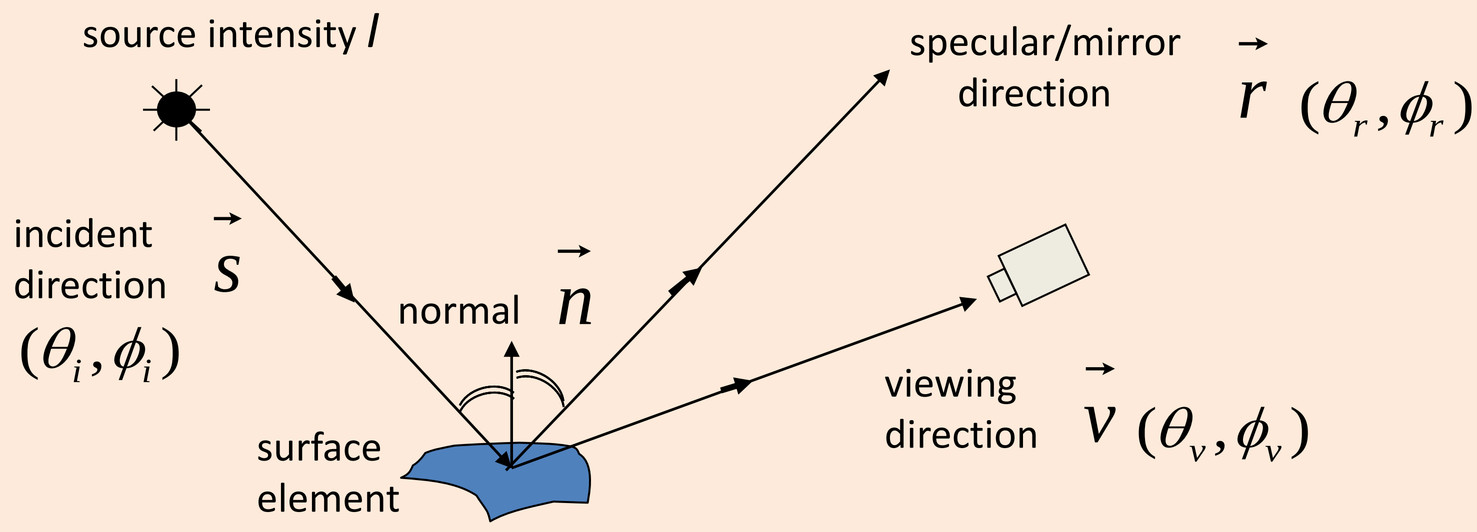
BRDF is only a function of 3 variables : $f(\theta_i, \theta_r, \phi_i - \phi_r)$

- Helmholtz Reciprocity: (follows from 2nd Law of Thermodynamics)

BRDF does not change when source and viewing directions are swapped.

$$f(\theta_i, \phi_i; \theta_r, \phi_r) \quad = \quad f(\theta_r, \phi_r; \theta_i, \phi_i)$$

Specular Reflection and Mirror BRDF



- Very smooth surface.
- All incident light energy reflected in a SINGLE direction. (only when $\vec{v} = \vec{r}$)
- Mirror BRDF is simply a double-delta function :

specular albedo

$$f(\theta_i, \phi_i; \theta_v, \phi_v) = \rho_s\ \delta(\theta_i - \theta_v)\ \delta(\phi_i + \pi - \phi_v)$$

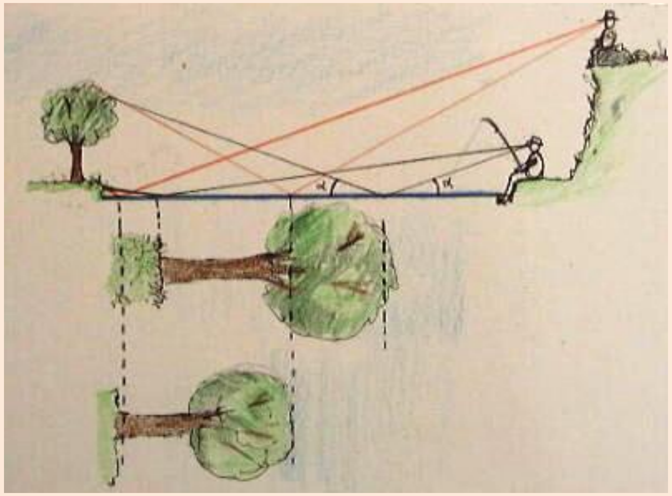
- Surface Radiance : $L = I\ \rho_s\ \delta(\theta_i - \theta_v)\ \delta(\phi_i + \pi - \phi_v)$

Specular Reflections in Nature

It's surprising how long the reflections are when viewed sitting on the river bank.

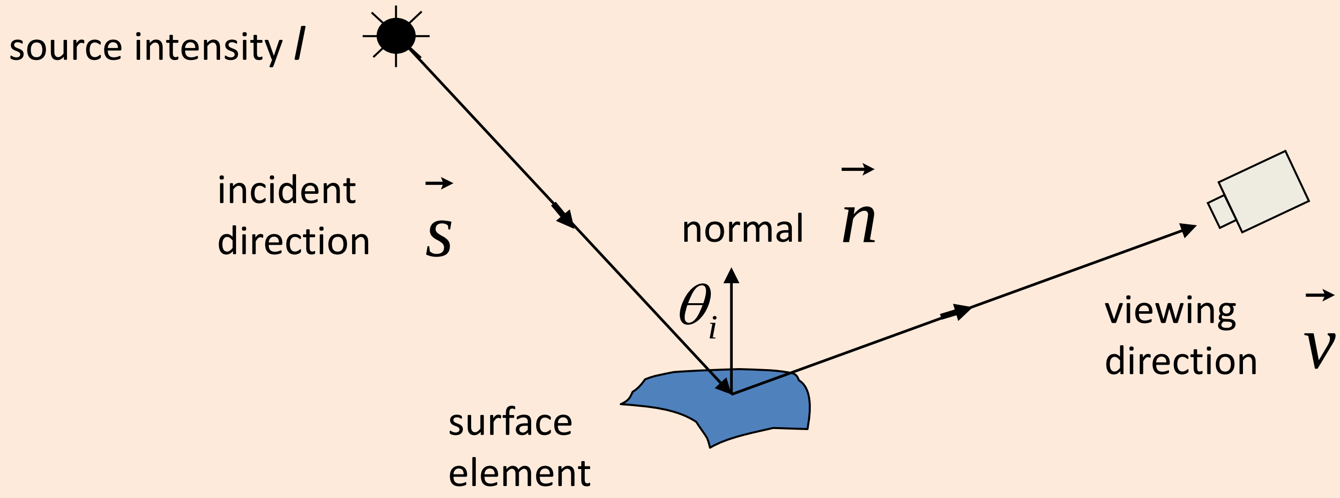
Compare sizes of objects and their reflections!

The reflections when seen from a lower view point are always longer than when viewed from a higher view point.



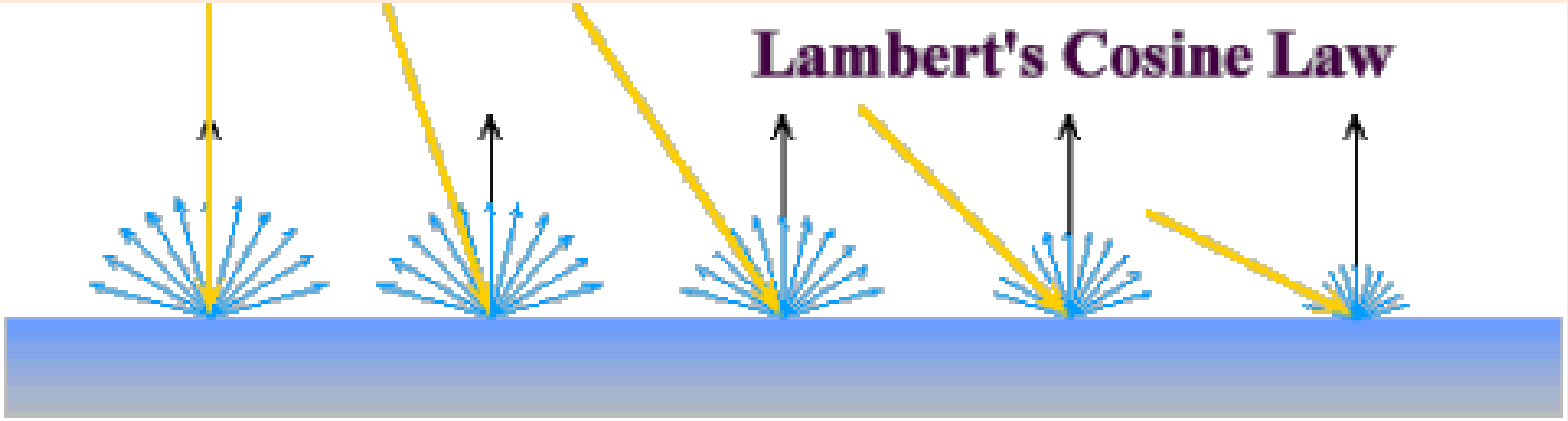
Specular Reflections in Nature

Diffuse Reflection and Lambertian BRDF



- Surface appears equally bright from ALL directions! (independent of $\vec{v}$)
- Lambertian BRDF is simply a constant : $f(\theta_i, \phi_i; \theta_r, \phi_r) = \frac{\rho_d}{\pi}$ albedo
- Surface Radiance : $L = \frac{\rho_d}{\pi} I \cos\theta_i = \frac{\rho_d}{\pi} I \; \vec{n} \cdot \vec{s}$ source intensity
- Commonly used in Vision and Graphics!

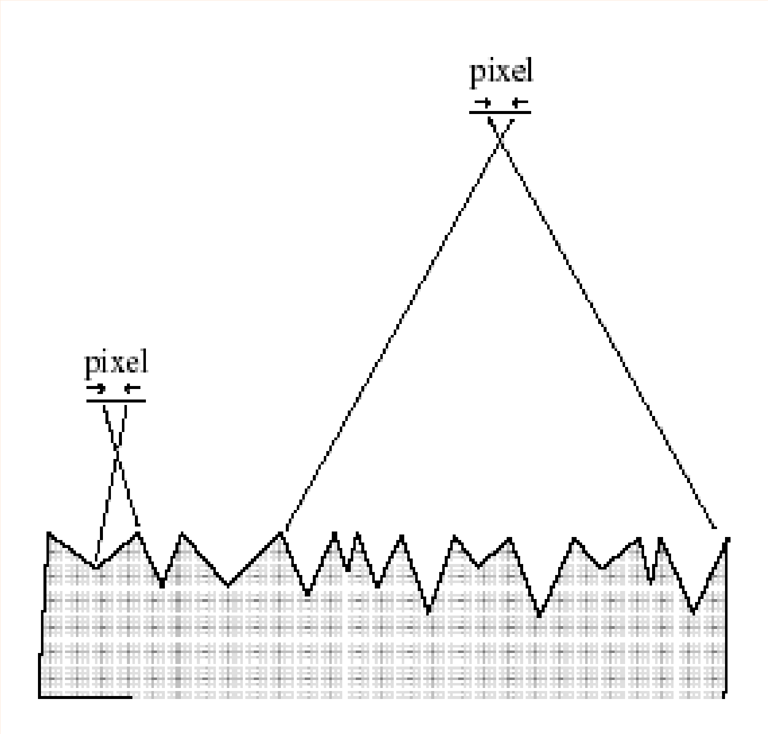
Diffuse Reflection and Lambertian BRDF

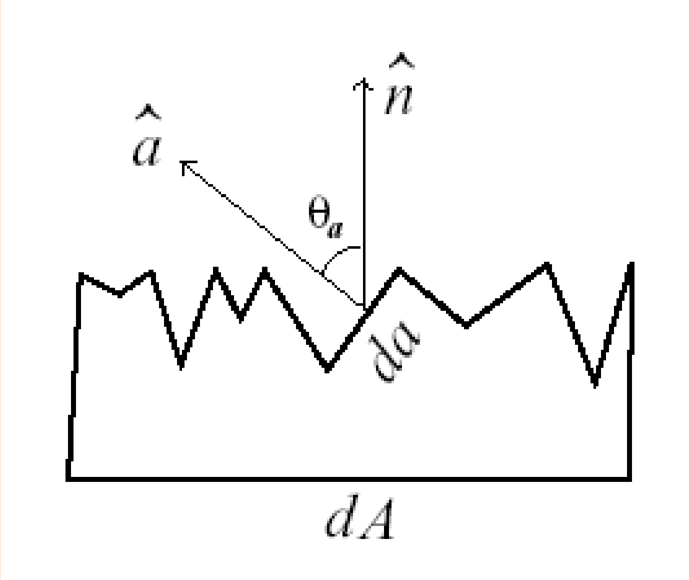


White-out Conditions from an Overcast Sky

CAN'T perceive the shape of the snow covered terrain!

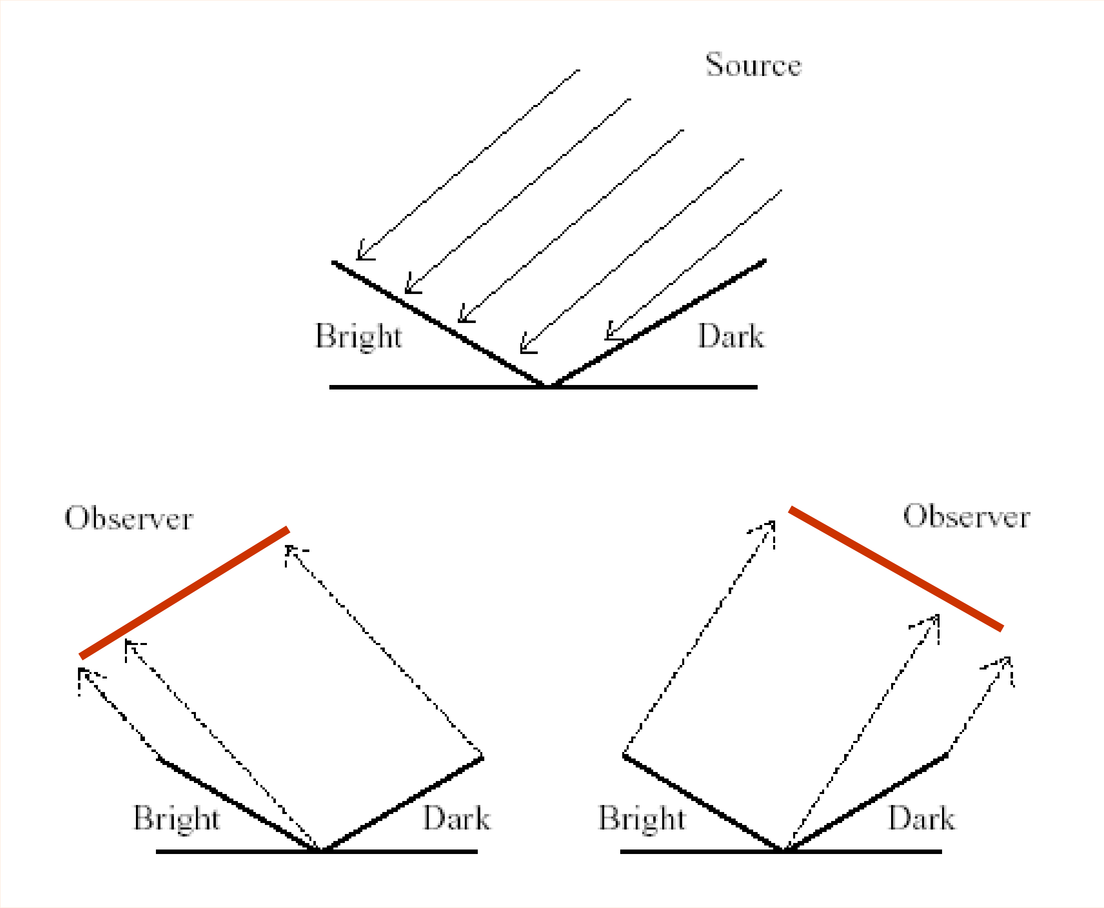
Modeling Rough Surfaces - Microfacets





- Roughness simulated by Symmetric V-groves at Microscopic level.
- Distribution on the slopes of the V-grove faces are modeled.
- Each microfacet assumed to behave like a **perfect lambertian surface.**

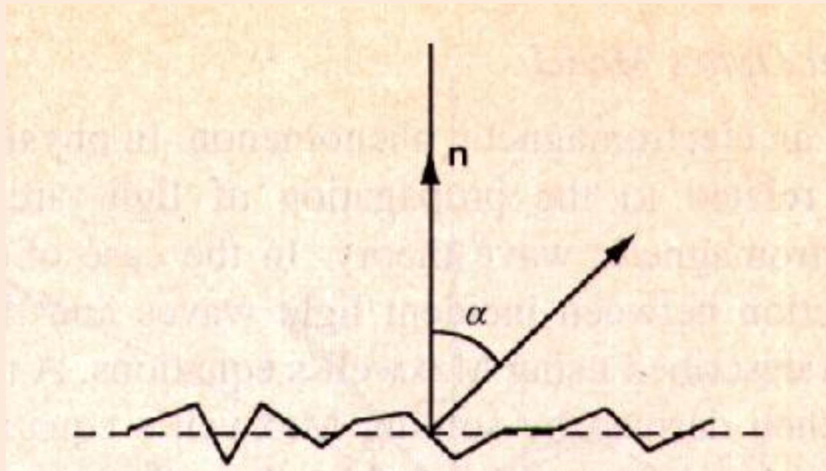
View Dependence of Matte Surfaces - Key Observation



- Overall brightness increases as the angle between the source and viewing direction decreases. WHY?

- Pixels have finite areas. As the viewing direction changes, different mixes between dark and bright are added up to give pixel brightness.

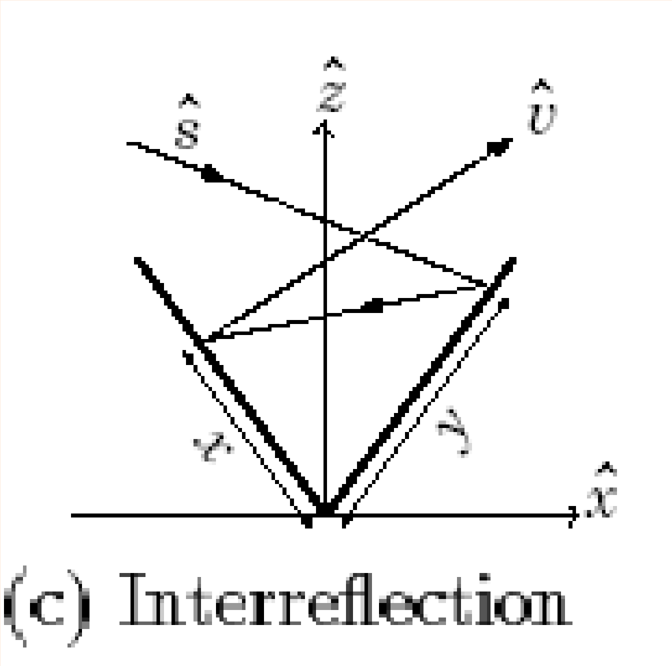
Slope Distribution Model



- Model the distribution of slopes as Gaussian.
- Mean is Zero, Variance represents ROUGHNESS.

$$\rho_\alpha(\alpha) = \frac{1}{\sqrt{2\pi\sigma_\alpha}} e^{-\frac{\alpha^2}{2\sigma_\alpha{}^2}}.$$

Oren-Nayar Model – Different Factors (contd.)



- Take into account two light bounces (reflections).
- Hard to solve analytically, so they find a functional approximation.

Oren-Nayar Model – Final Expression

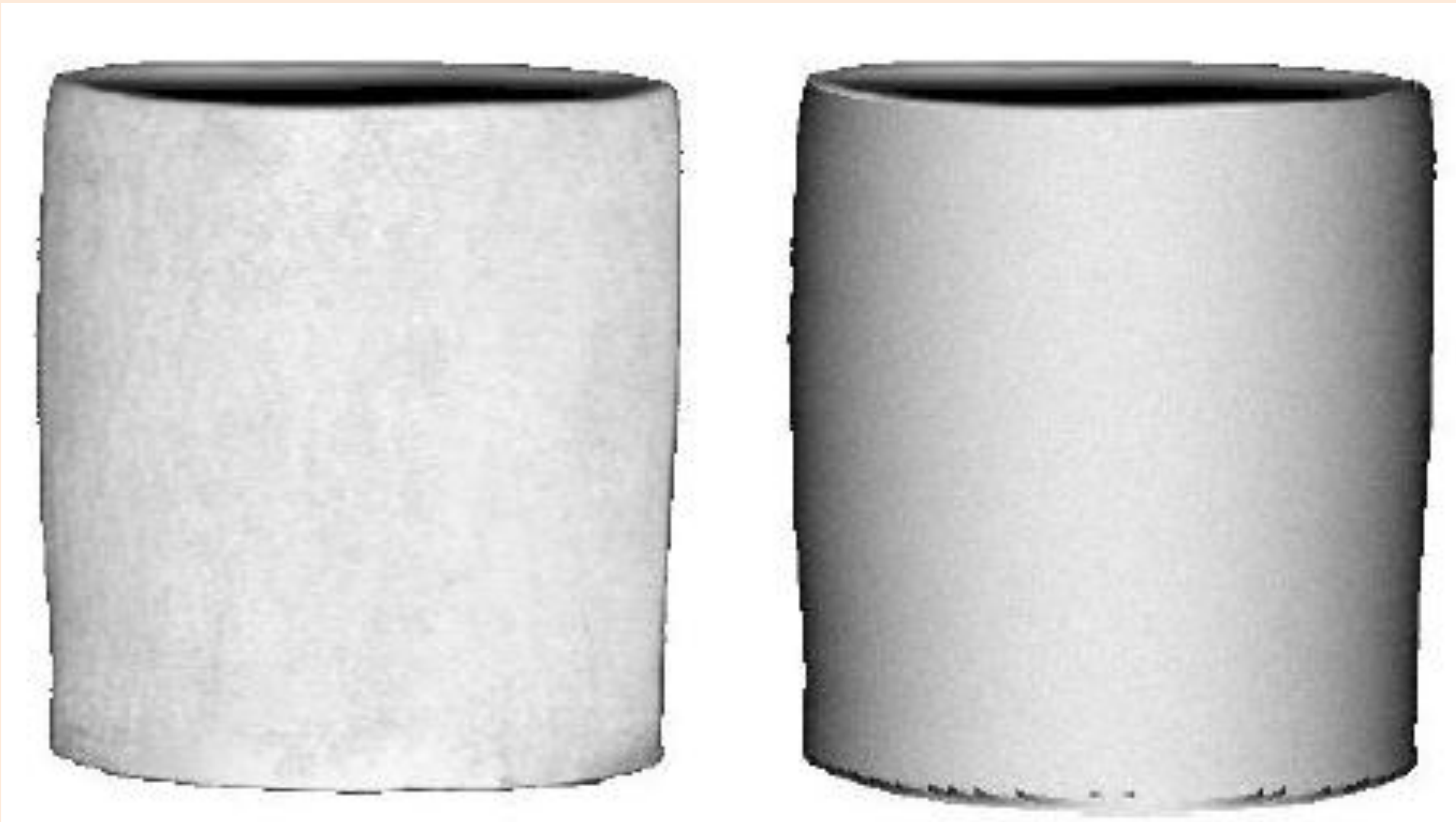
$$\boxed{L(\theta_r, \theta_i; \phi_r - \phi_i; \rho, \sigma) = \frac{\rho}{\pi} E_0 \cos\theta_i (A + B\,Max\left[0, \cos(\phi_r - \phi_i)\right] \sin\alpha \tan\beta)\,,}$$

$$A = 1.0 - 0.5\frac{\sigma^2}{\sigma^2 + 0.33}\,, \qquad \alpha = Max(\theta_r, \theta_i)$$

$$B = 0.45\frac{\sigma^2}{\sigma^2 + 0.09}\,, \qquad \beta = Min(\theta_r, \theta_i).$$

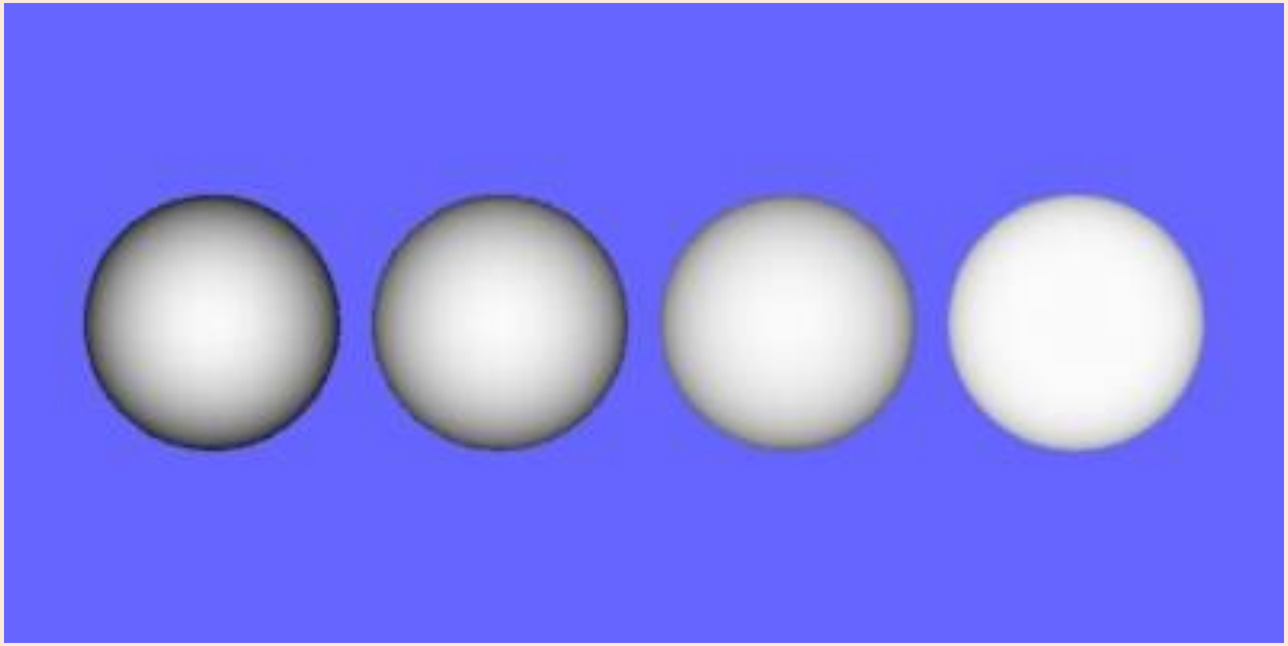
Lambertian model is simply an extreme case with roughness equal to zero.

Surface Roughness Causes Flat Appearance



Actual Vase   Lambertian Vase

Surface Roughness Causes Flat Appearance



Increasing surface roughness

Lambertian model

Valid for only SMOOTH MATTE surfaces.

Bad for ROUGH MATTE surfaces.

Rendered Sphere with Lambertian BRDF

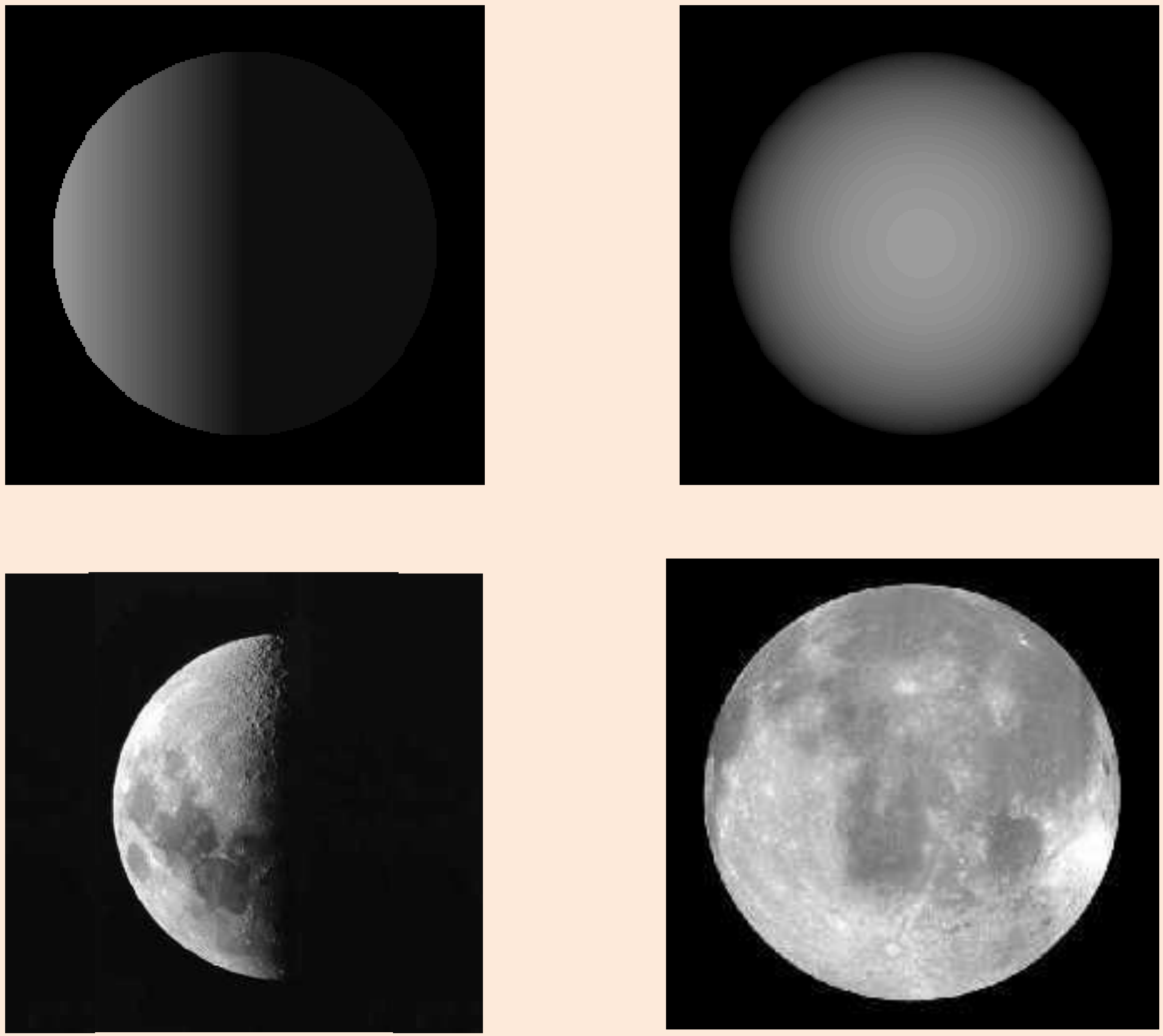
- Edges are dark (N.S = 0) when lit head-on
- See shading effects clearly.

Why does the Full Moon have a flat appearance?

- The moon appears matte (or diffuse)

- But still, edges of the moon look bright (not close to zero) when illuminated by earth's radiance.

Why does the Full Moon have a flat appearance?



Lambertian Spheres and Moon Photos illuminated similarly

Oren-Nayar Model – Main Points

- Physically Based Model for Diffuse Reflection.

- Explains view dependent appearance in Matte Surfaces

- Lambertian model is simply an extreme case with roughness equal to zero.

Comparison to Ground Truth

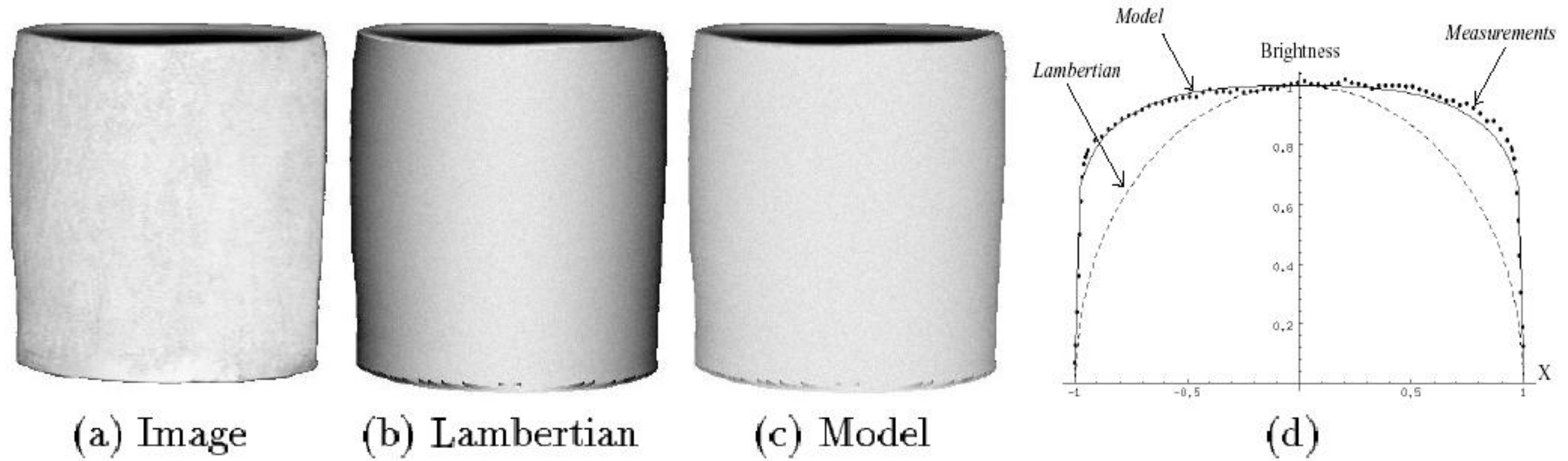


Fig. 7. (a-c) Real image of a cylindrical clay vase compared with images rendered using the Lambertian and proposed models. Illumination is from the direction $\theta_i = 0°$. (d) Comparison between image brightness along the cross-sections of the three vases.

Glossy Surfaces

- Delta Function too harsh a BRDF model
  (valid only for highly polished mirrors and metals).

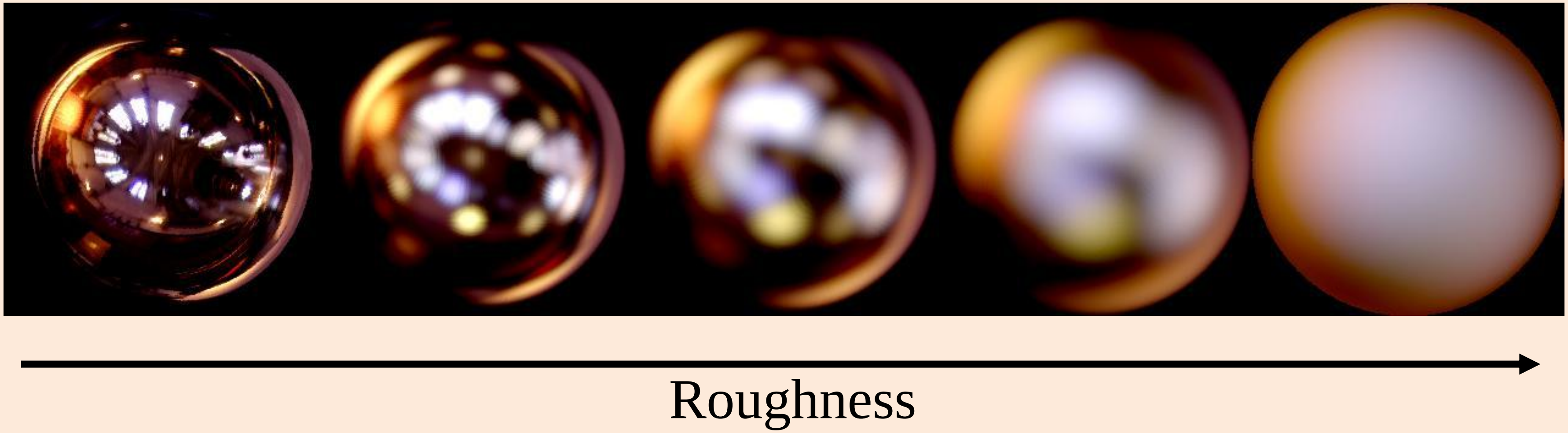
- Many glossy surfaces show broader highlights in addition to mirror reflection.

- Surfaces are not perfectly smooth – they show micro-surface geometry (roughness).

- Example Models : Phong model

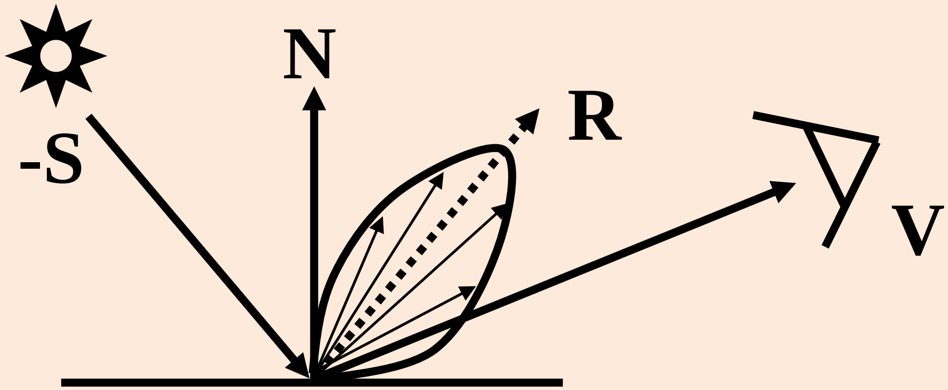
  Torrance Sparrow model

Blurred Highlights and Surface Roughness



Phong Model: An Empirical Approximation

- How to model the angular falloff of highlights:



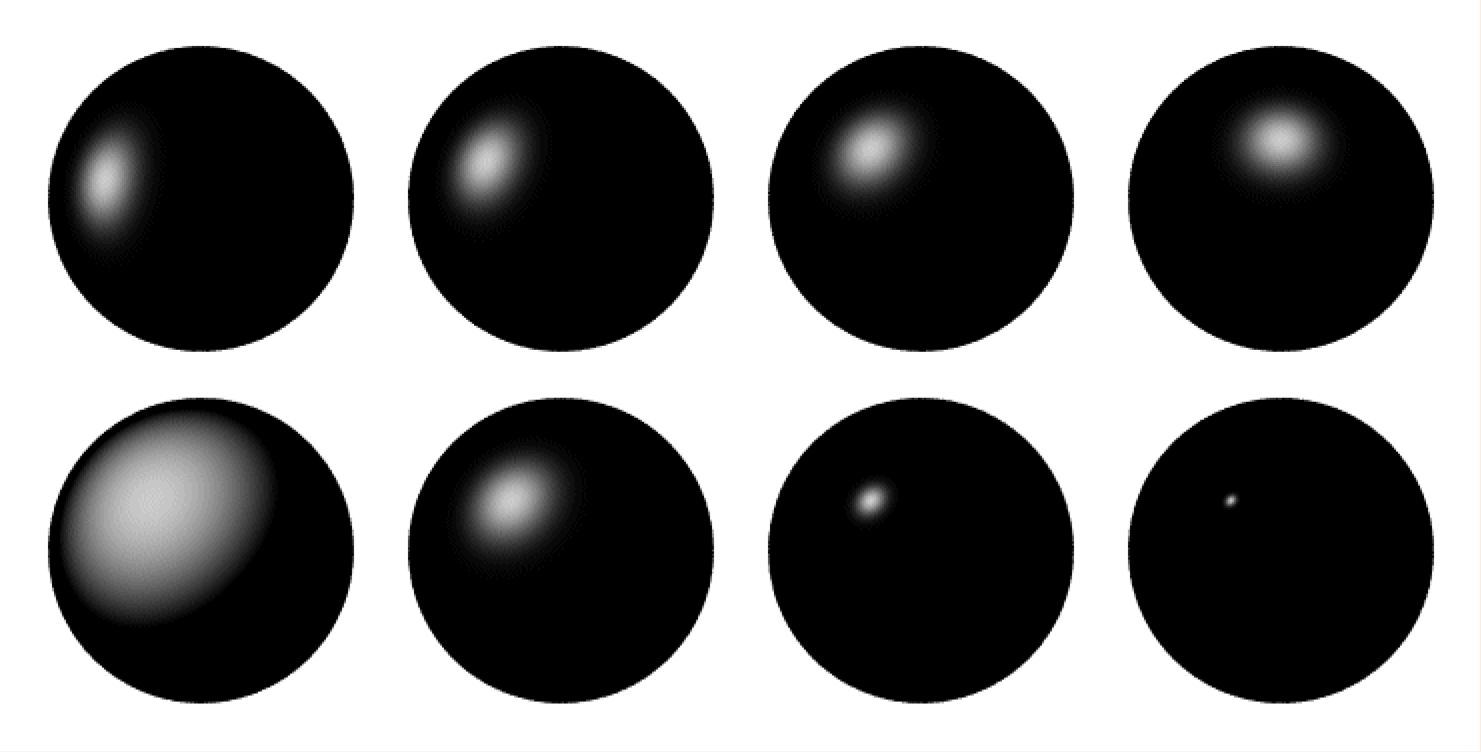
$$L = I\ \rho_s\ (R.E)^{n_{shiny}}$$

Phong Model

- Sort of works, easy to compute
- But not physically based (no energy conservation and reciprocity).
- Very commonly used in computer graphics.

Phong Examples

- These spheres illustrate the Phong model as *lighting direction* and n_{shiny} are varied:



Those Were the Days

- "In trying to improve the quality of the synthetic images, we do not expect to be able to display the object exactly as it would appear in reality, with texture, overcast shadows, etc. We hope only to display an image that approximates the real object closely enough to provide a certain degree of realism."

  – Bui Tuong Phong, 1975

Summary of Surfaces and BRDFs

Smooth → Rough

Specular ↓ Diffuse

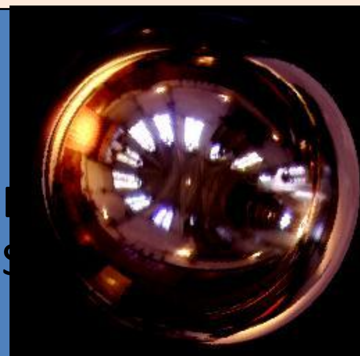
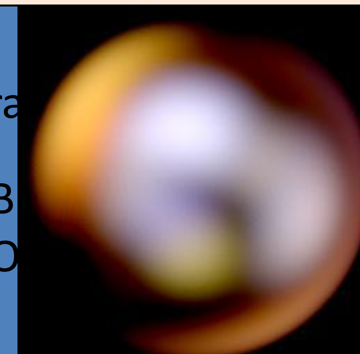
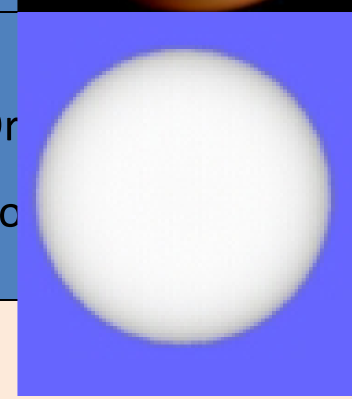
	Smooth	Rough
Specular	Mirror BRDF Delta Function Speck of reflection	Torrance-Sparrow BRDF Broader Highlights Off-specular lobe
Diffuse	Lambertian BRDF No view dependence	Oren-Nayar BRDF Models view dependence

Many surfaces may be rough and show both diffuse and surface reflection.

Summary of Surfaces and BRDFs

Smooth → Rough

Specular ↓ Diffuse

	Torra F B O 
La No e 	Or Mo ence 

Many surfaces may be rough and show both diffuse and surface reflection.

Measuring BRDFs

Why bother modeling BRDFs?

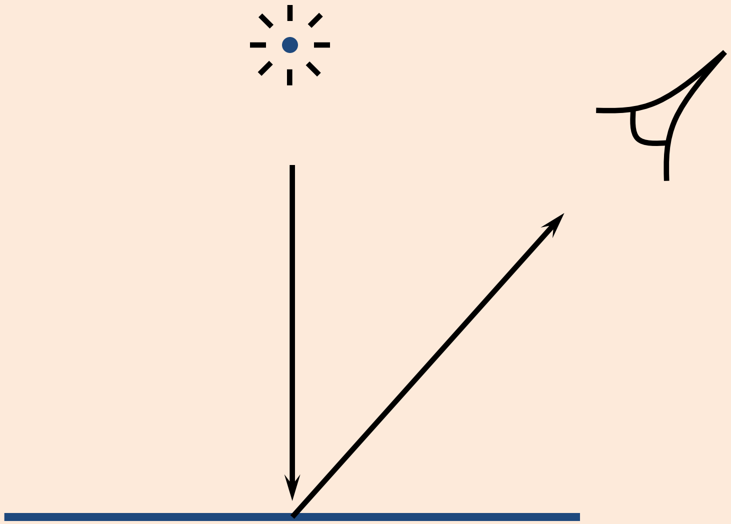
Why not directly measure BRDFs?

- True knowledge of surface properties
- Accurate models for graphics

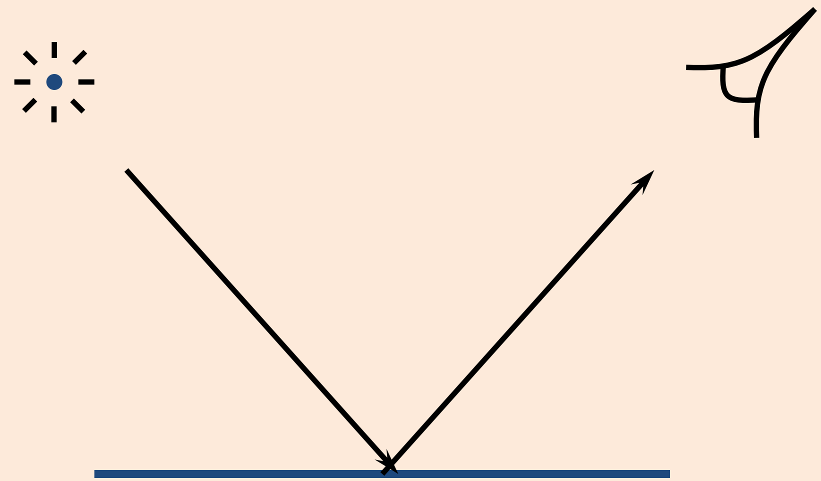
Measuring BRDFs

- A full BRDF is 4-dimensional
- Simpler measurements (0D/1D/2D/3D) often useful
- Lets start with simplest and get more complex

Measuring Reflectance



0º/45º
Diffuse Measurement



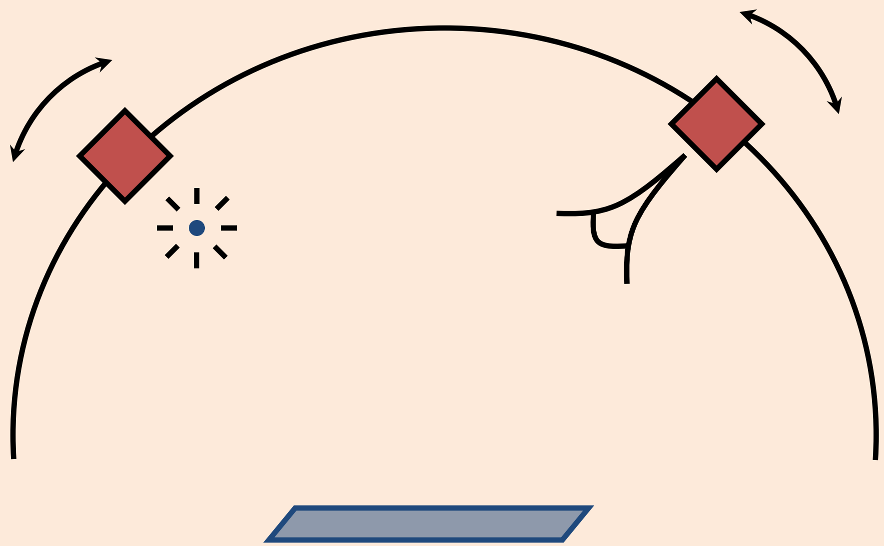
45º/45º
Specular Measurement

Gloss Measurements

- Standardized for applications such as paint manufacturing
- Example: “contrast gloss” is essentially ratio of specular to diffuse
- “Sheen” is specular measurement at 85°

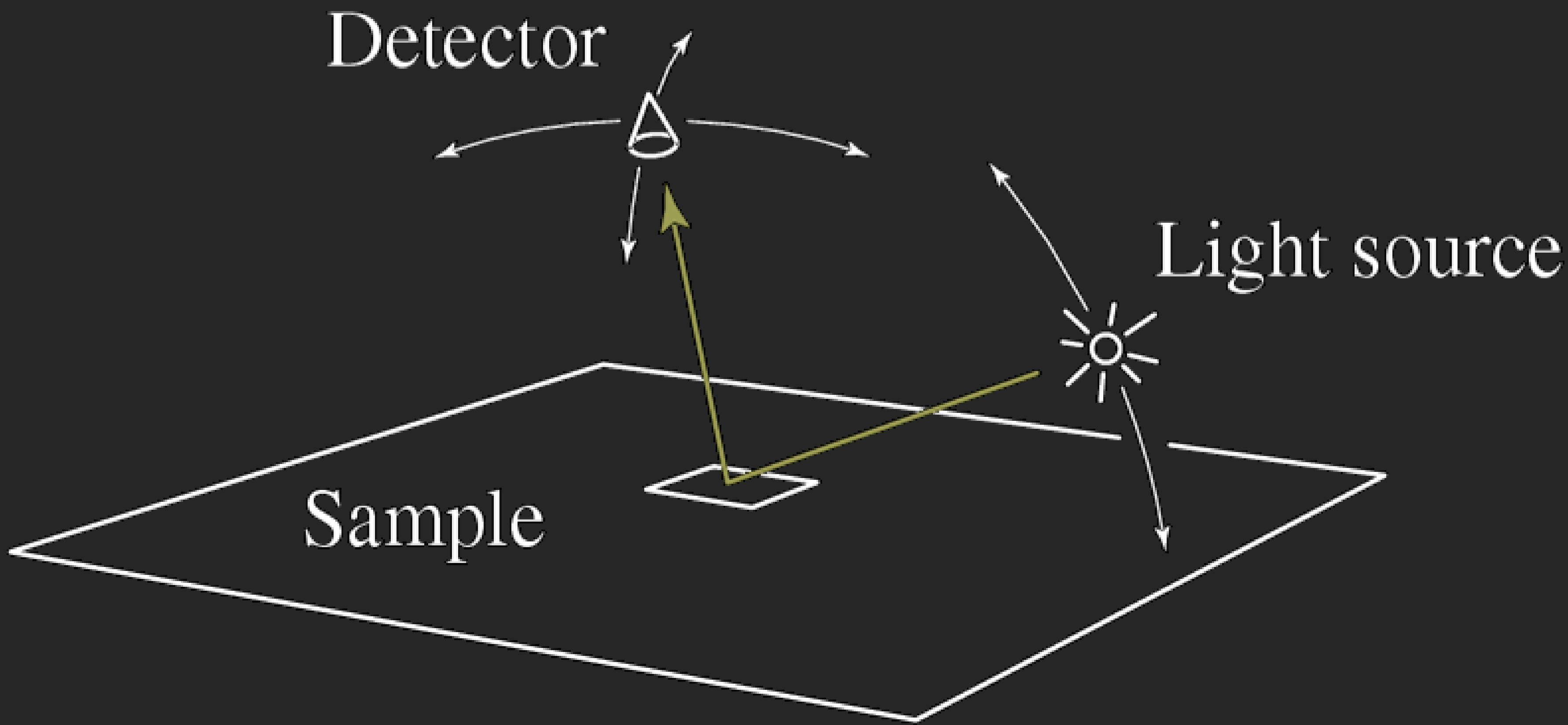
BRDF Measurements

- Next step up in complexity: measure BRDF in plane of incidence (1- or 2-D)



Gonioreflectometers

- Three degrees of freedom spread among light source, detector, and/or sample



Gonioreflectometers

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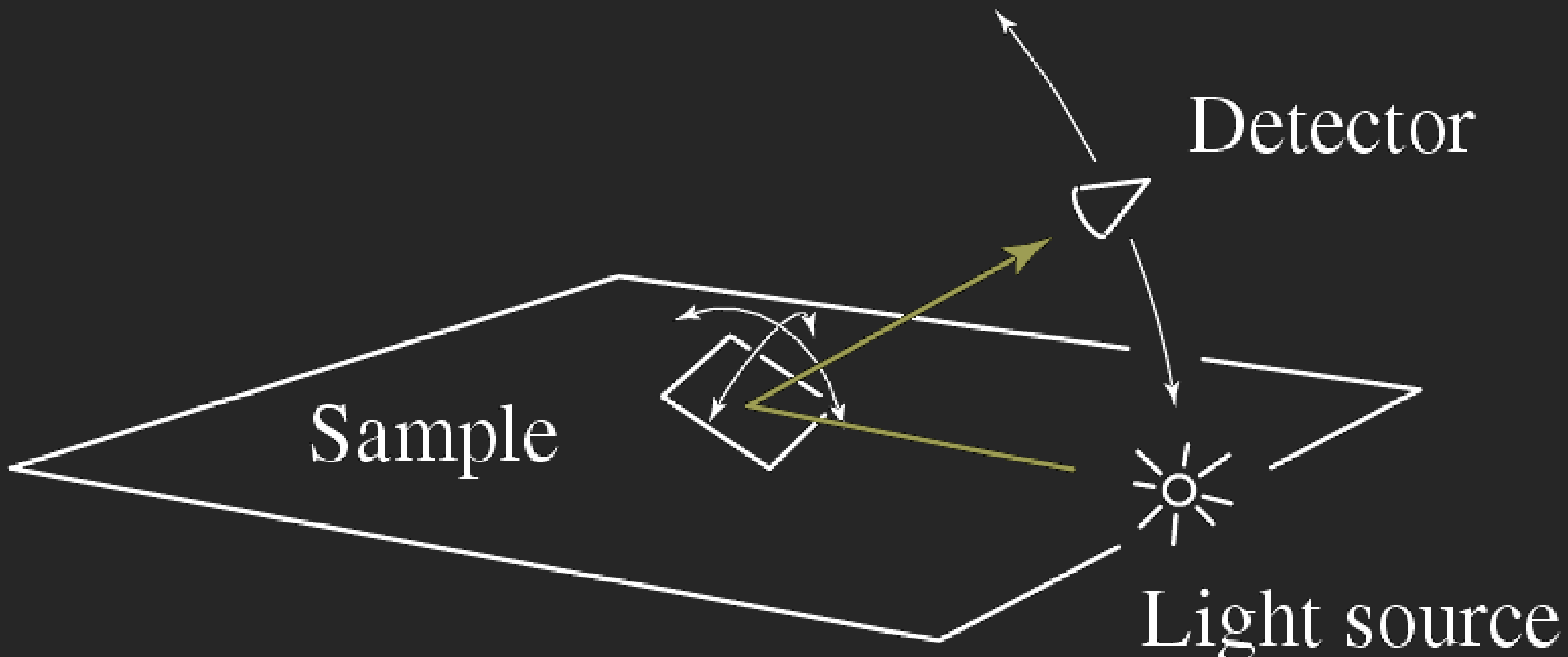


Gonioreflectometers

- Can add fourth degree of freedom to measure anisotropic BRDFs

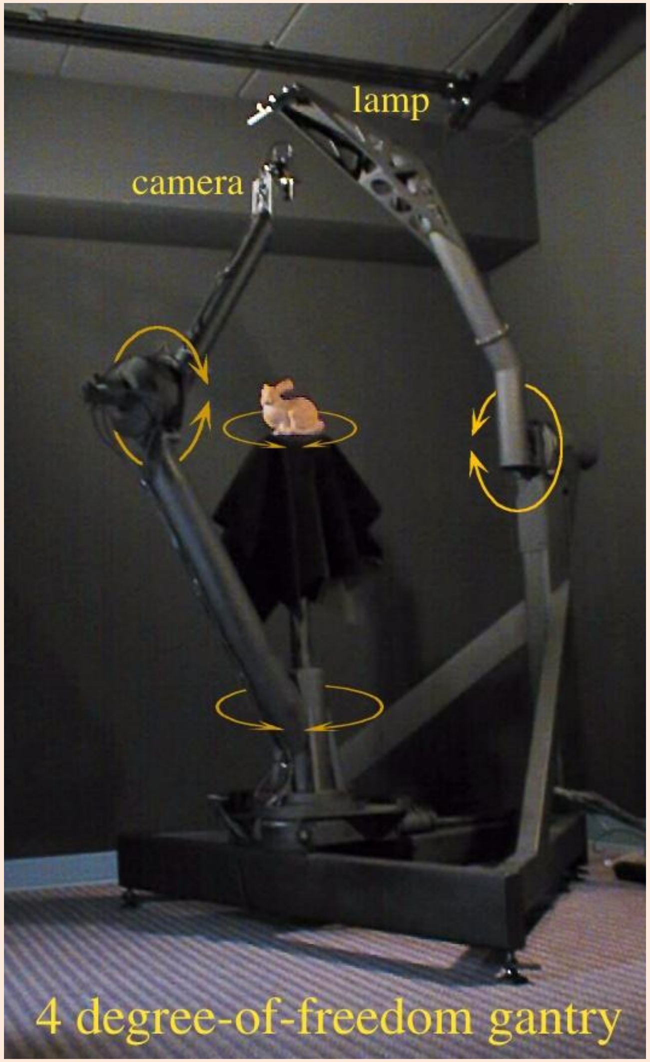
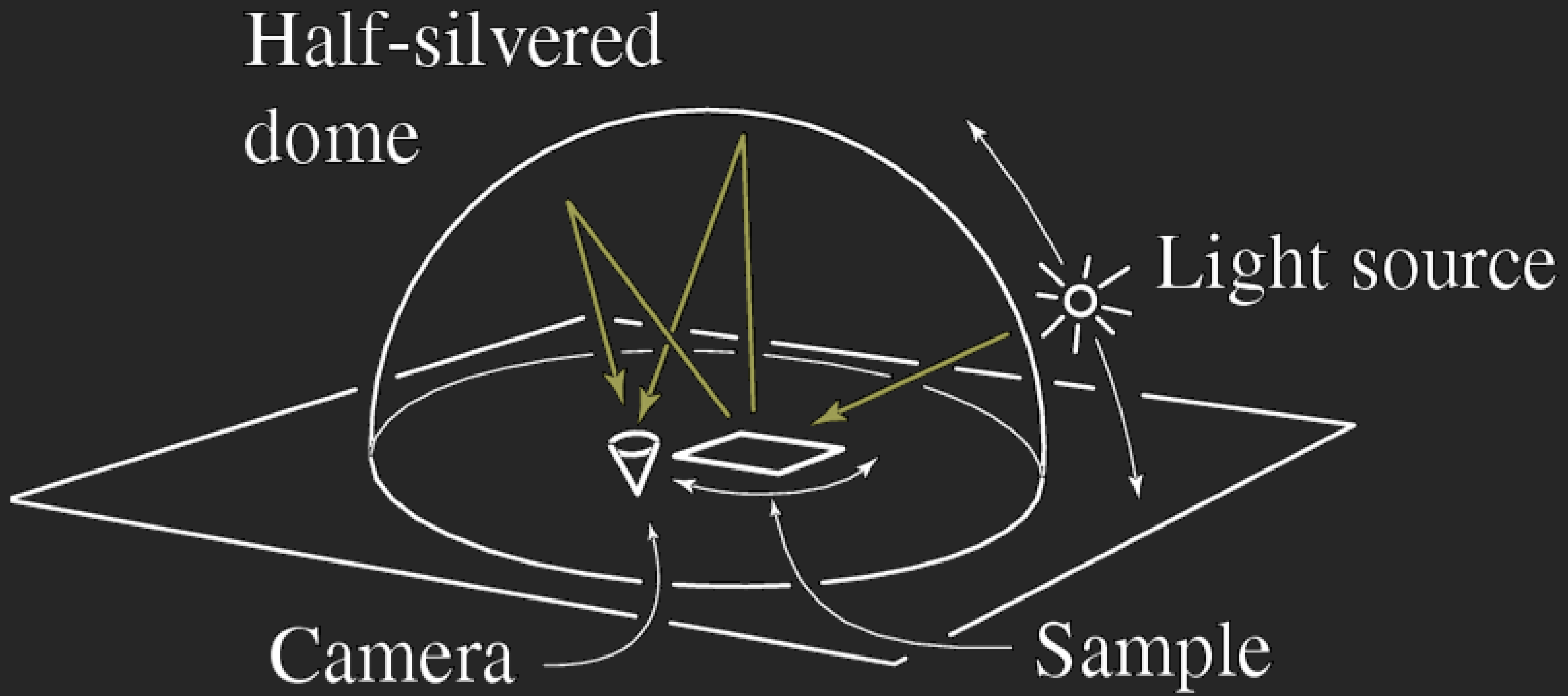


Image-Based BRDF Measurement

- Reduce acquisition time by obtaining larger (e.g. 2-D) slices of BRDF at once
- Idea: Camera can acquire 2D image
- Requires mapping of angles of light to camera pixels

Ward's BRDF Measurement Setup

- Collect reflected light with hemispherical mirror

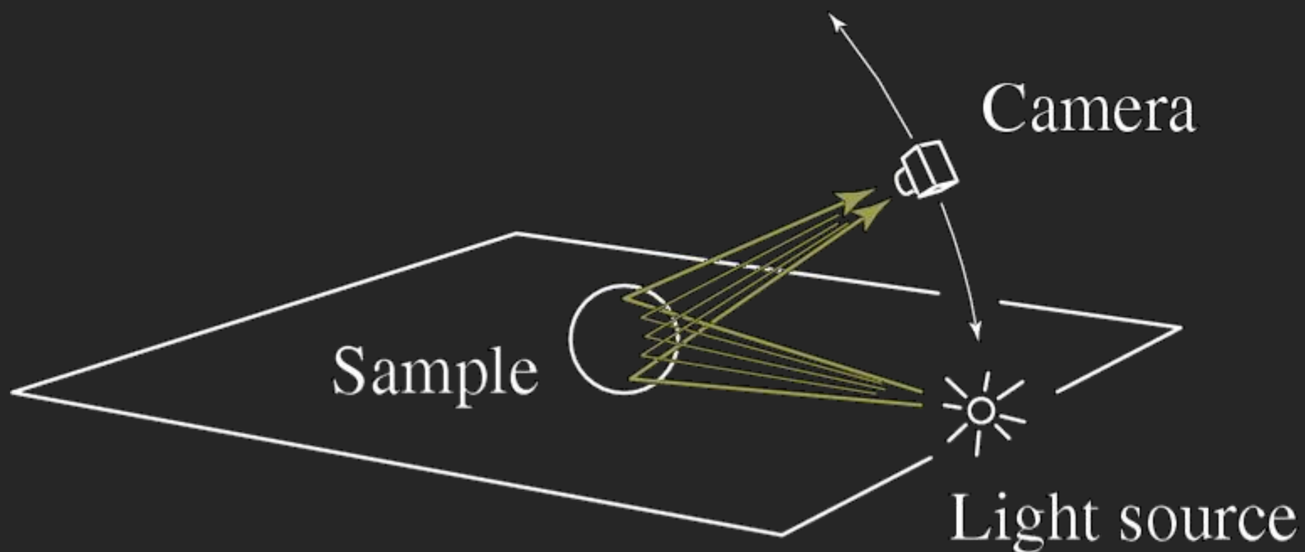


Ward's BRDF Measurement Setup

- Result: each image captures light at all exitant angles

Image-Based BRDF Measurement

- For uniform BRDF, capture 2-D slice corresponding to variations in normals (Marschner et al)



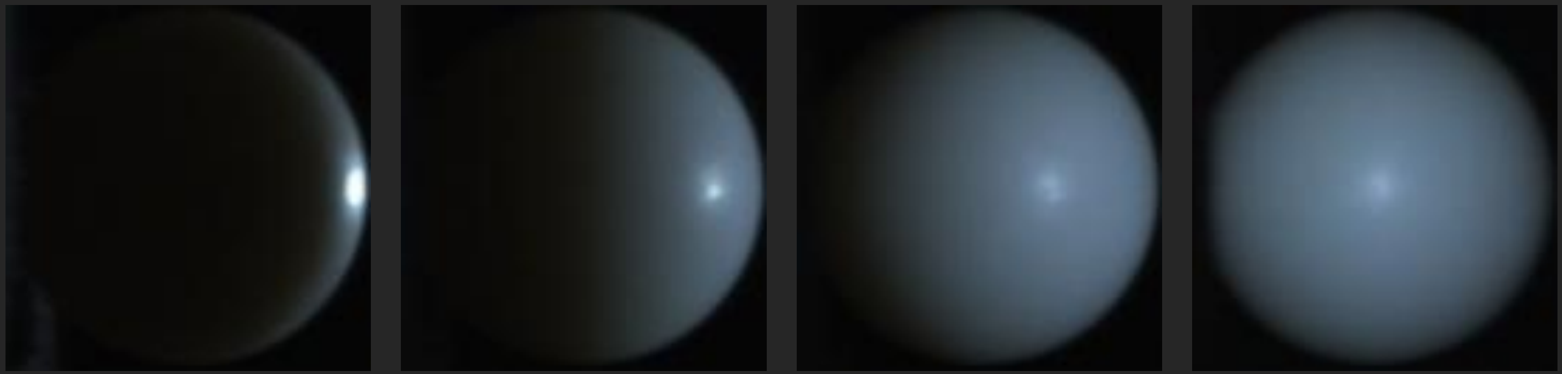
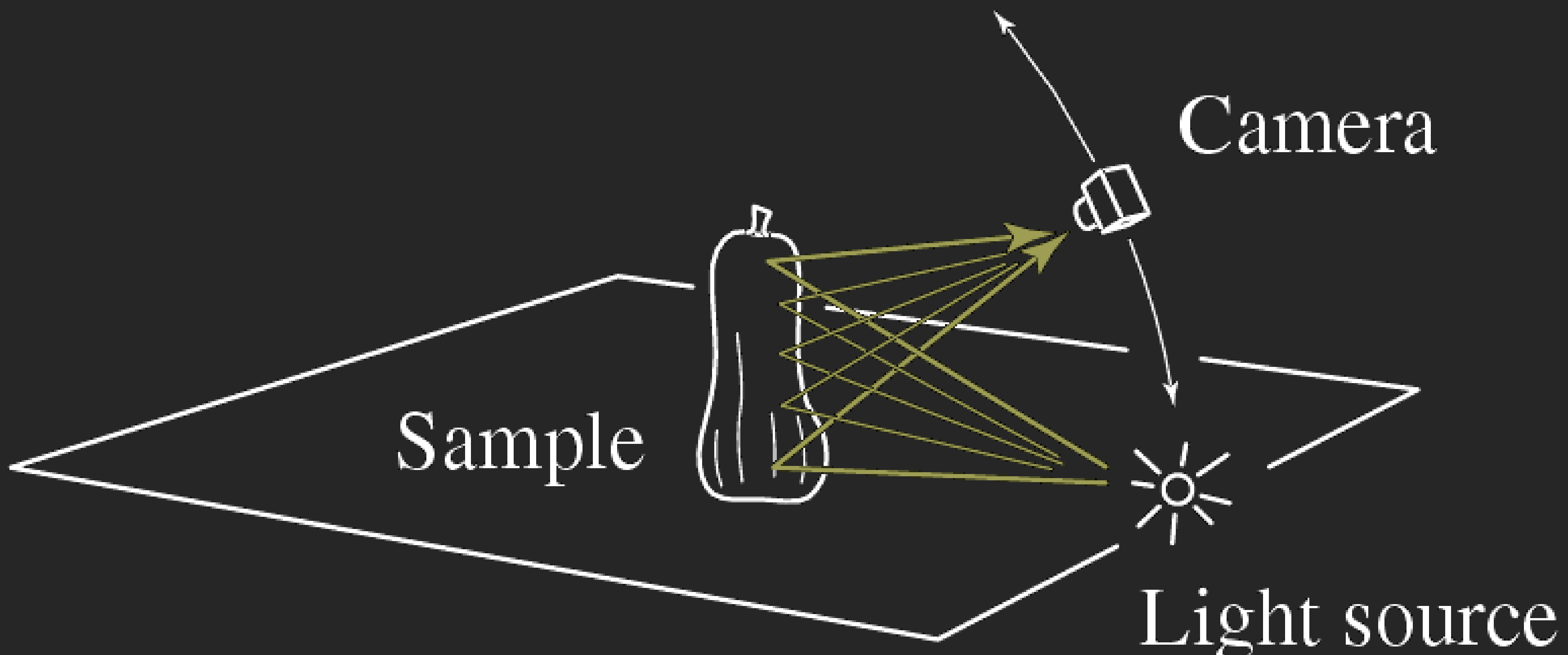


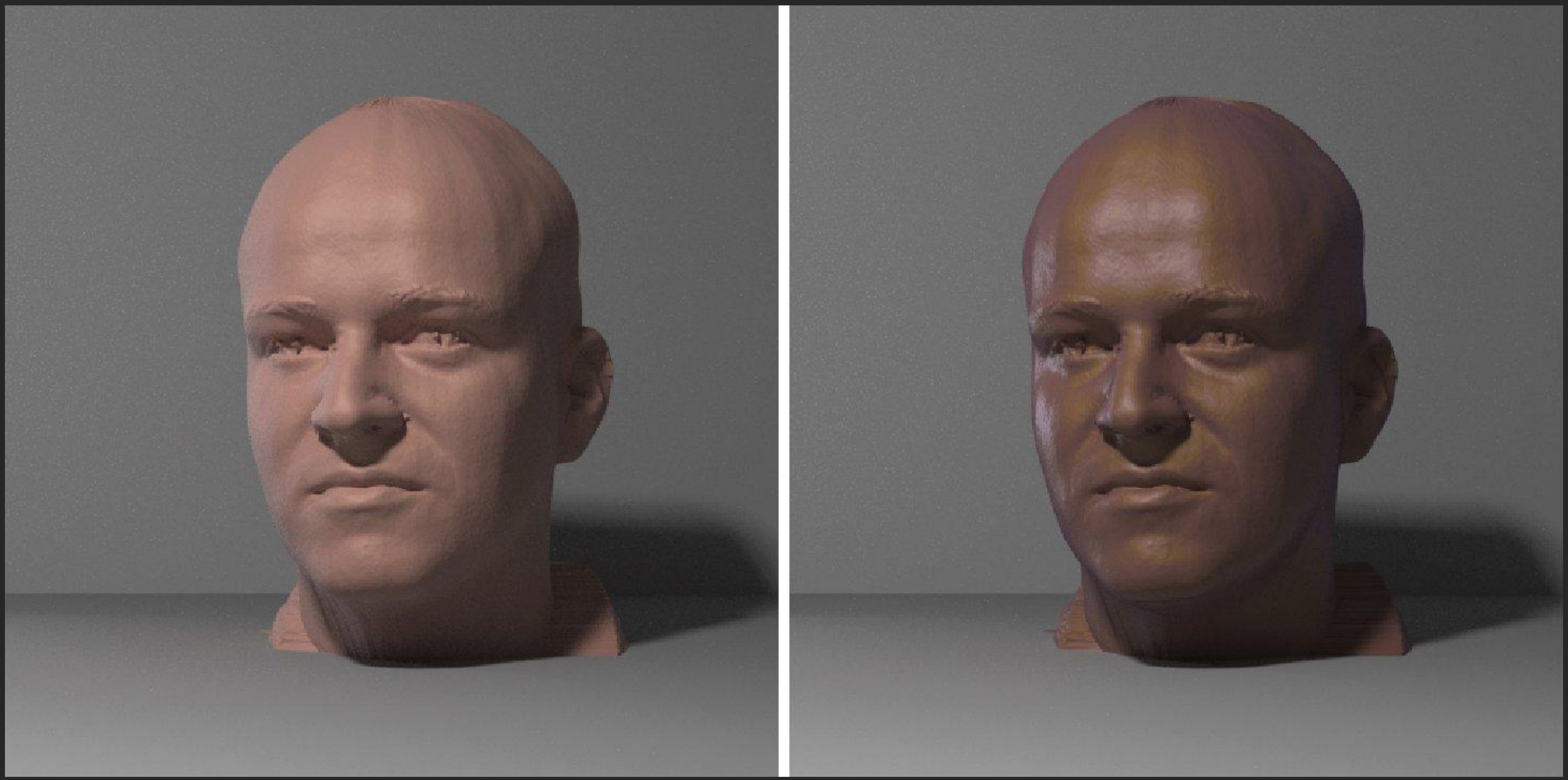
Image-Based BRDF Measurement

- Any object with known geometry



Marschner et al.

Image-based measurement of skin



Marschner et al. 2000

Measurement

- Light Source
  - Hamamatsu SQ Xenon lamp
    - Stable emission output
    - Continuous and relatively constant radiation spectrum

Measurement

SIGGRAPH2005

- Turntable
  - Kaidan MD-19
  - Computer-controlled
- Dark Room
  - Walls painted with flat black paint
- Spherical Samples

Calibration

SIGGRAPH2005

- Geometric calibration
  - Contact digitizer
    - Faro Arm
  - Intrinsic & extrinsic camera parameters
  - Sphere center & radius
  - Light Position
    - parameterized on a circle in 3D

Measurement

SIGGRAPH2005

- 20-80 million reflectance measurements per material
- Each tabulated BRDF entails 90x90x180x3=4,374,000 measurement bins

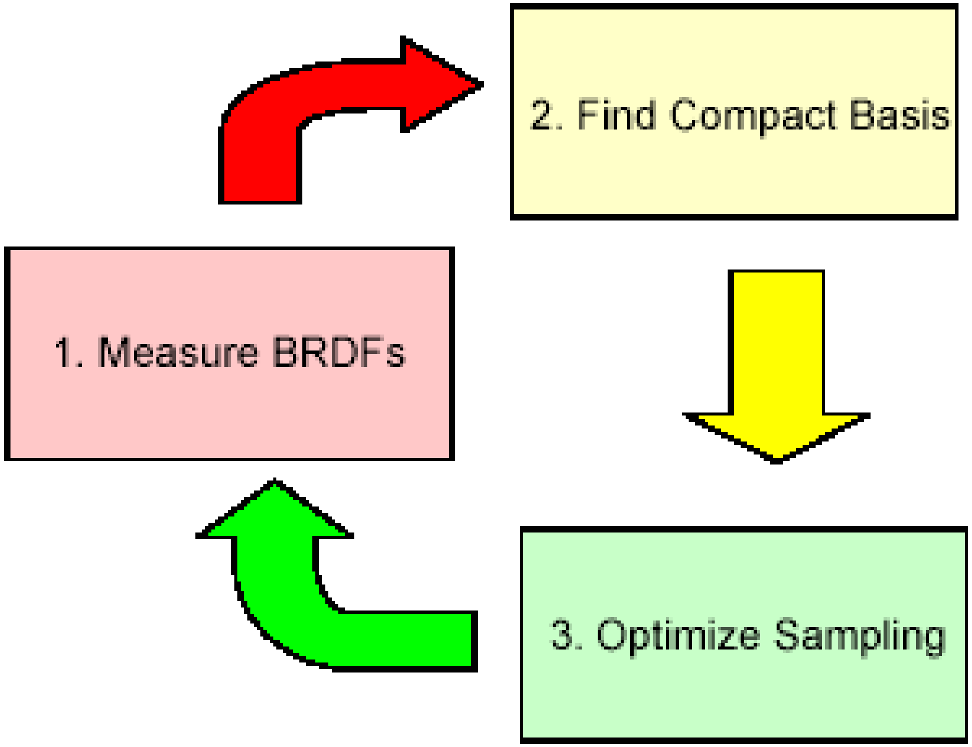
Rendering from Tabulated BRDFs

SIGGRAPH2005

- These BRDFs are immediately useful
- Direct renderings from measurements

Nickel Hematite Gold Paint Pink Felt

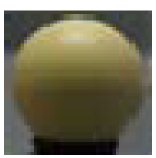
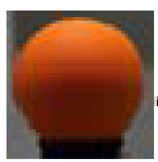
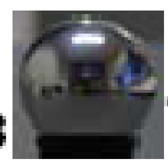
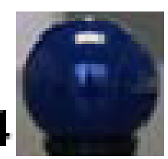
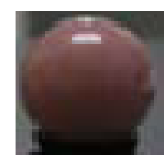
Measurement Process



Linear Combinations of BRDFs (LCB)

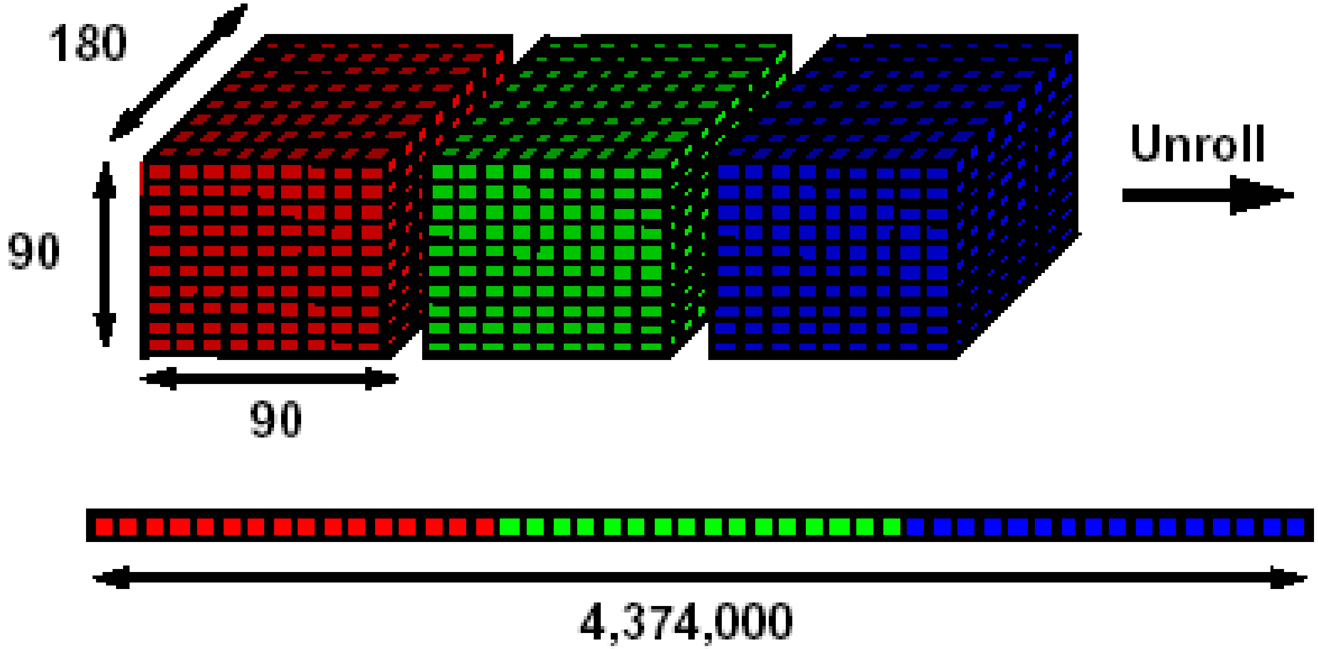
SIGGRAPH2005

- Can we find a linear combination of our existing BRDFs that match any new one?
- Requires only estimating 100 coefficients for source BRDFs
- Compute a set of 800 constraints that allow estimating these 100 coefficients robustly

α_1  + α_2  + α_3  + α_4  + …= 

BRDFs as Vectors in High Dimensional Space

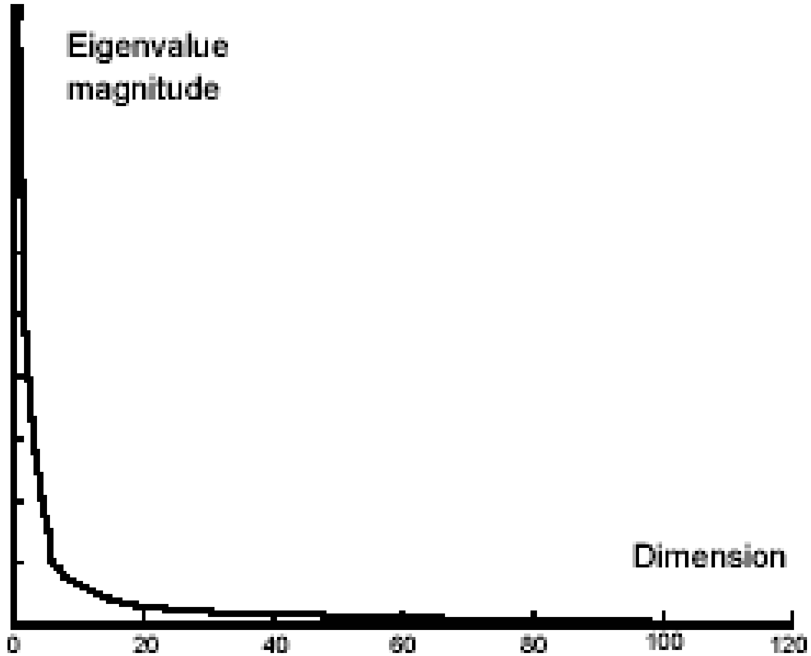
- Each tabulated BRDF is a vector in 90x90x180x3 =4,374,000 dimensional space



Linear Analysis (PCA)

SIGGRAPH2005

- Find optimal linear basis for our data set
- 45 components needed to reduce residue to under measurement error

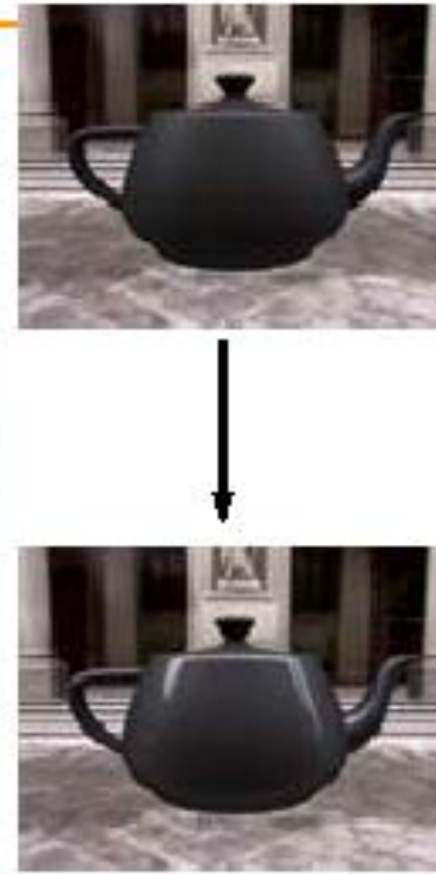


Navigation Results

SIGGRAPH2005

Adding Silver Trait

Navigation Results



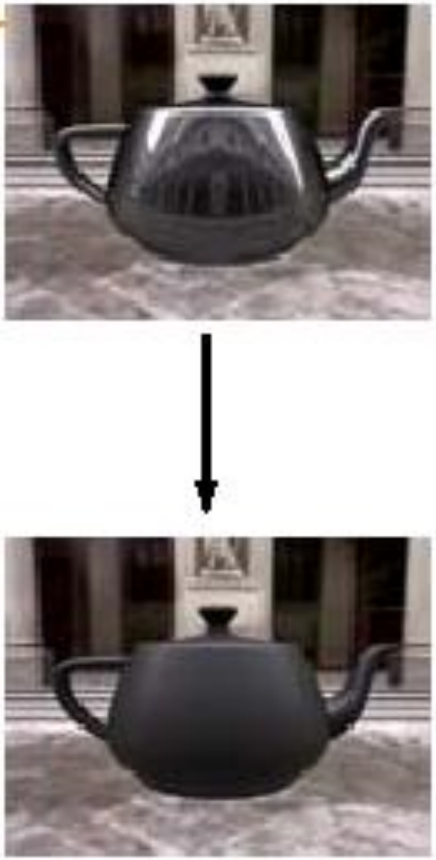
Adding Specular Trait

Navigation Results

SIGGRAPH2005

Adding Metallic Trait

Representing Physical Processes



Steel Oxidation

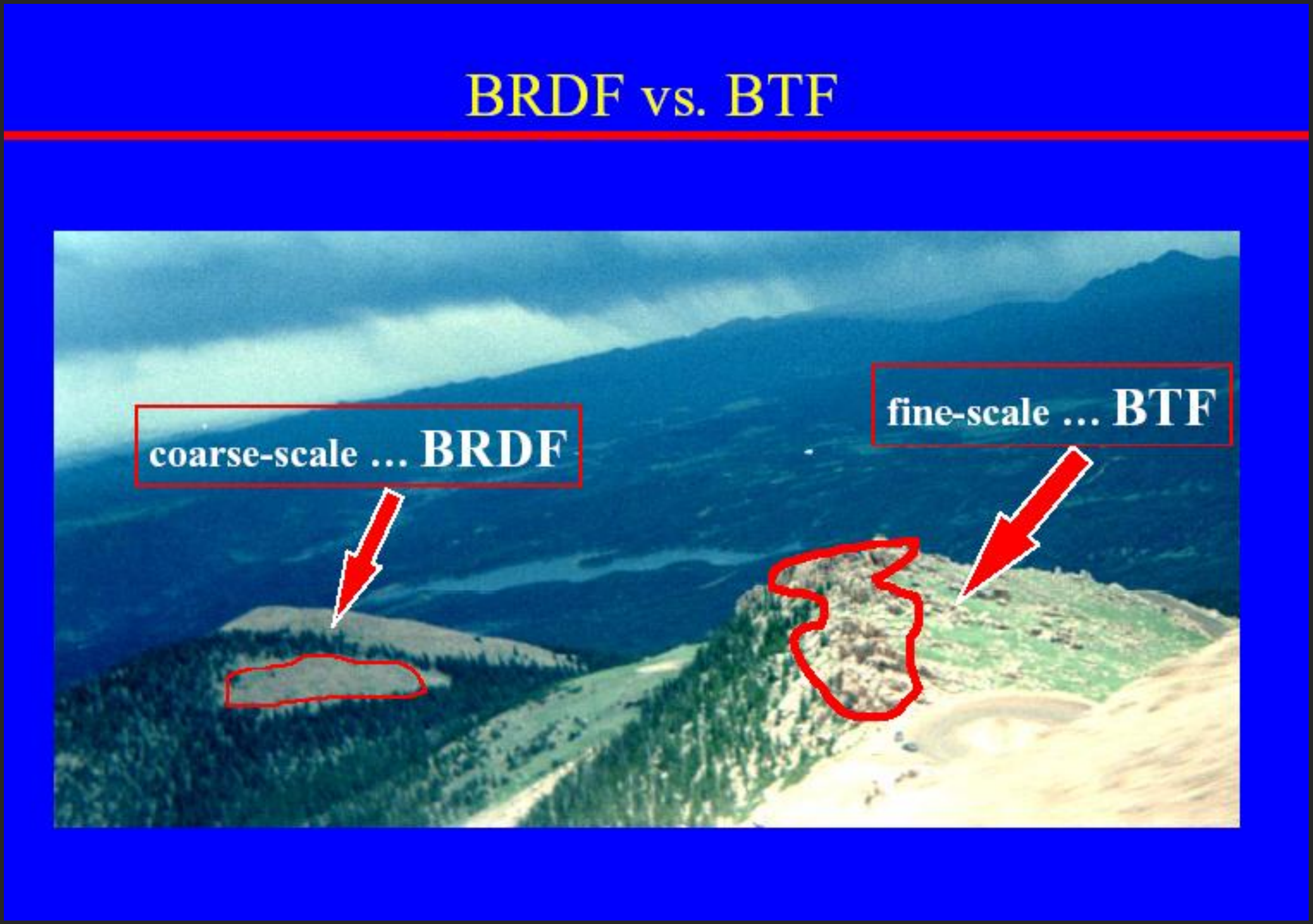
Next Step in the Appearance Food Chain

Textures

Spatially Varying BRDFs

CURET Database – [Dana, Nayar 96]

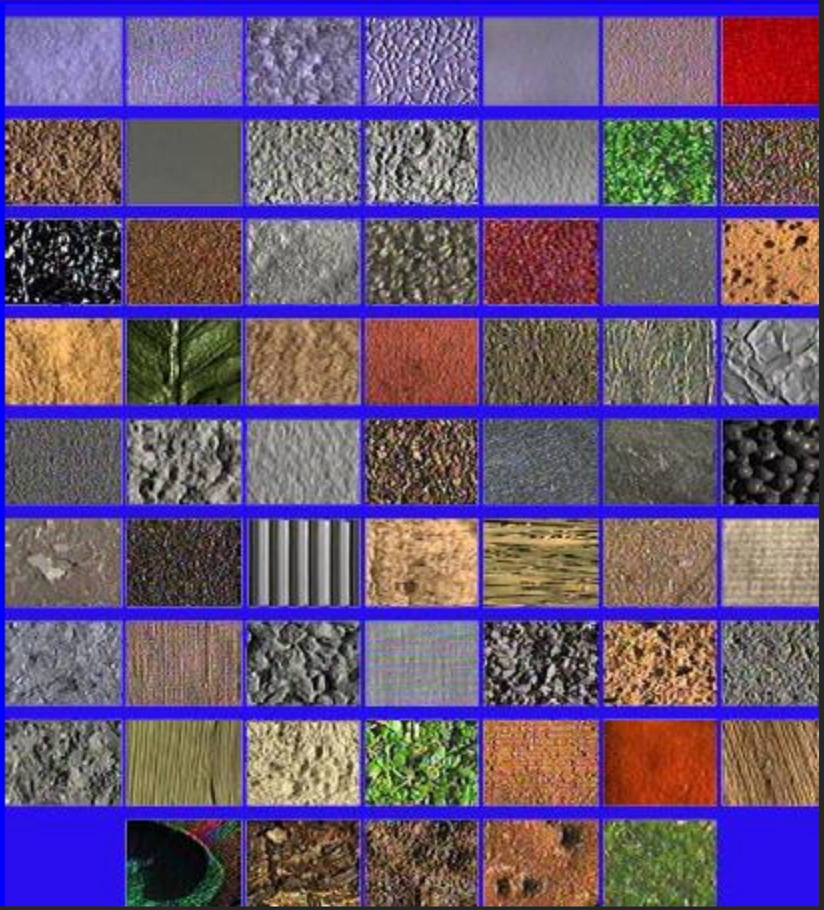
Few slides about BTF here – from Kristin Dana's slides



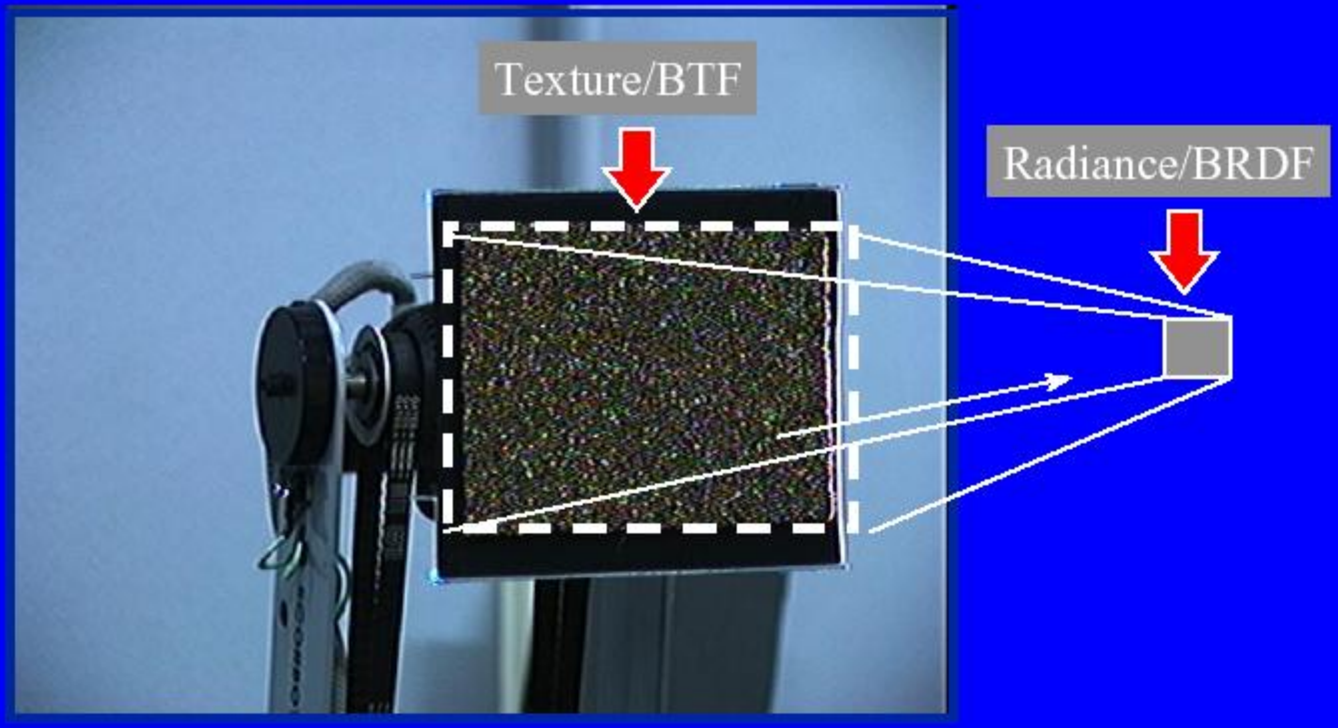
Samples for Measurements

61 samples:

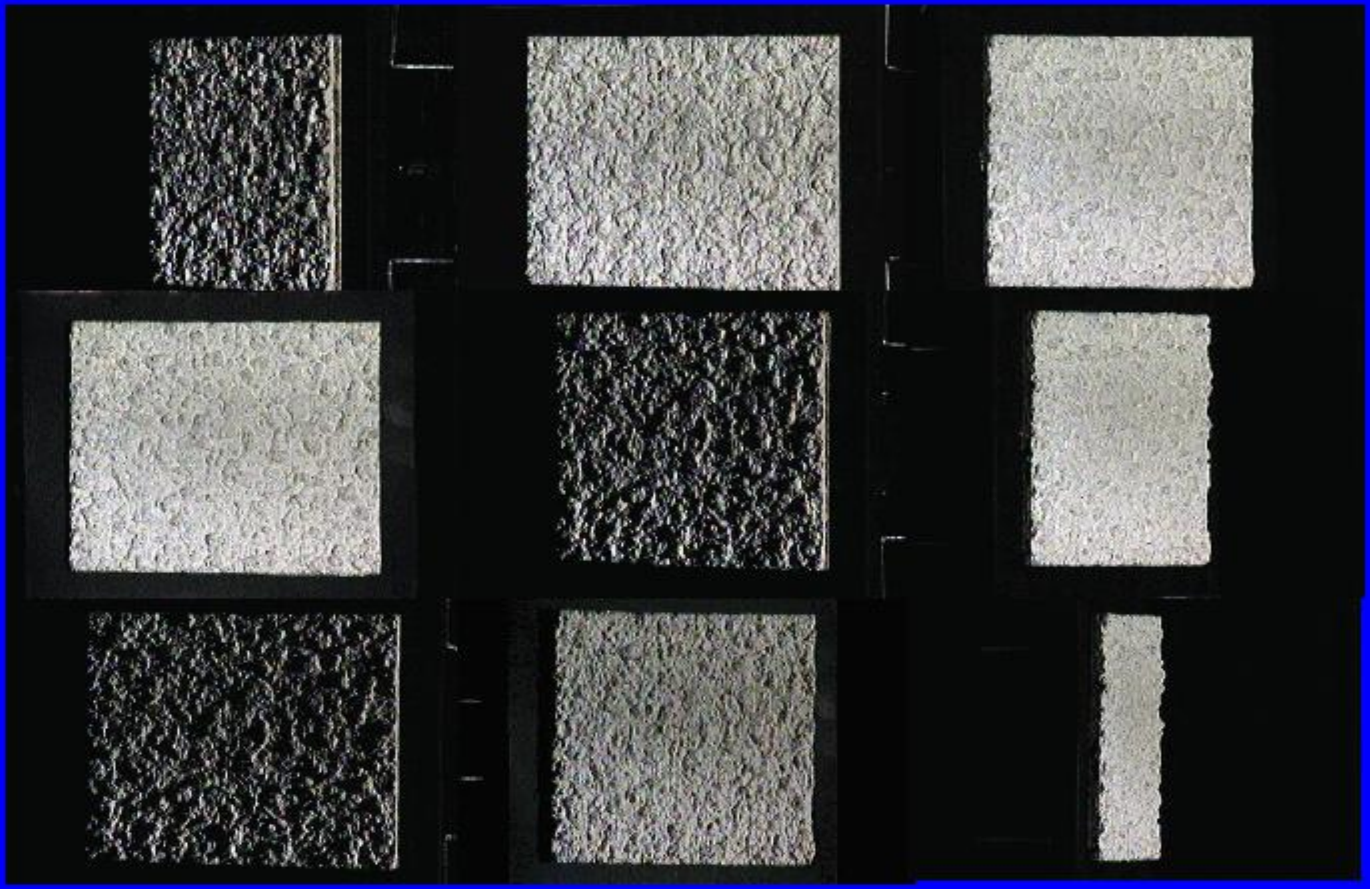
- *specular* (foil, artificial grass)
- *diffuse* (brick, plaster)
- *natural* (fur, moss)
- *man-made* (velvet, leather)
- *isotropic* (bread, concrete)
- *anisotropic* (corn husk, wood)



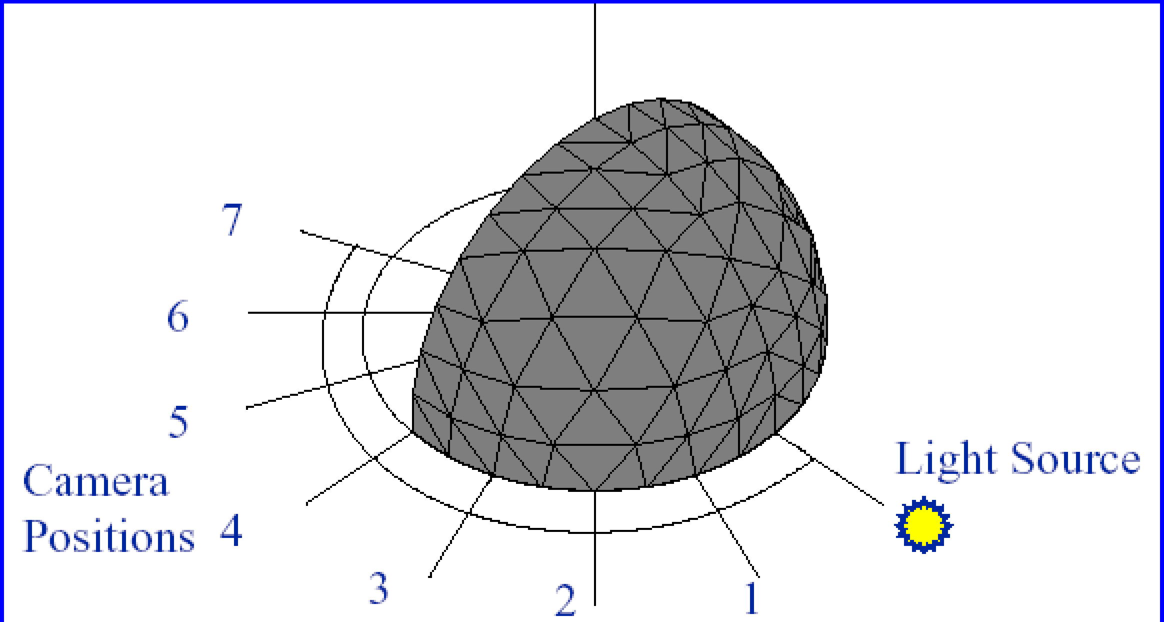
Measurement Methods



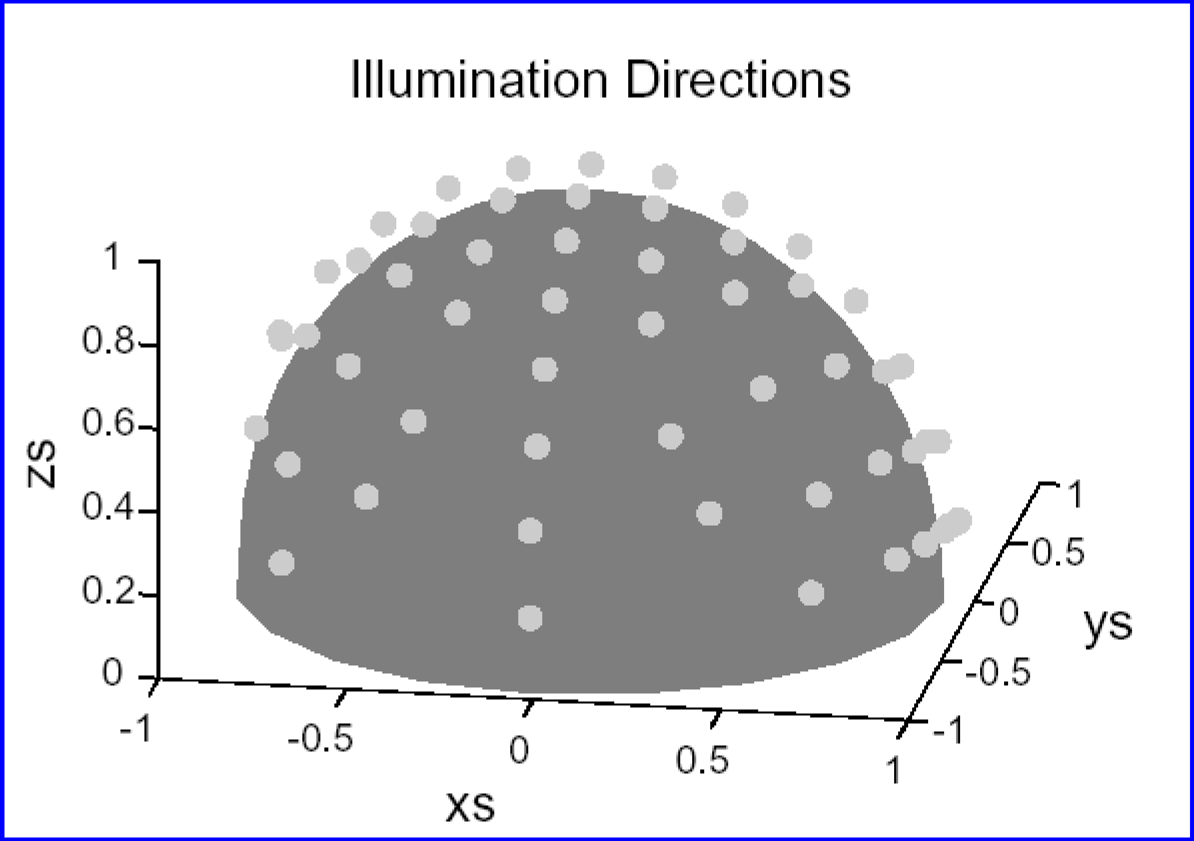
Example images



Measurement Methods

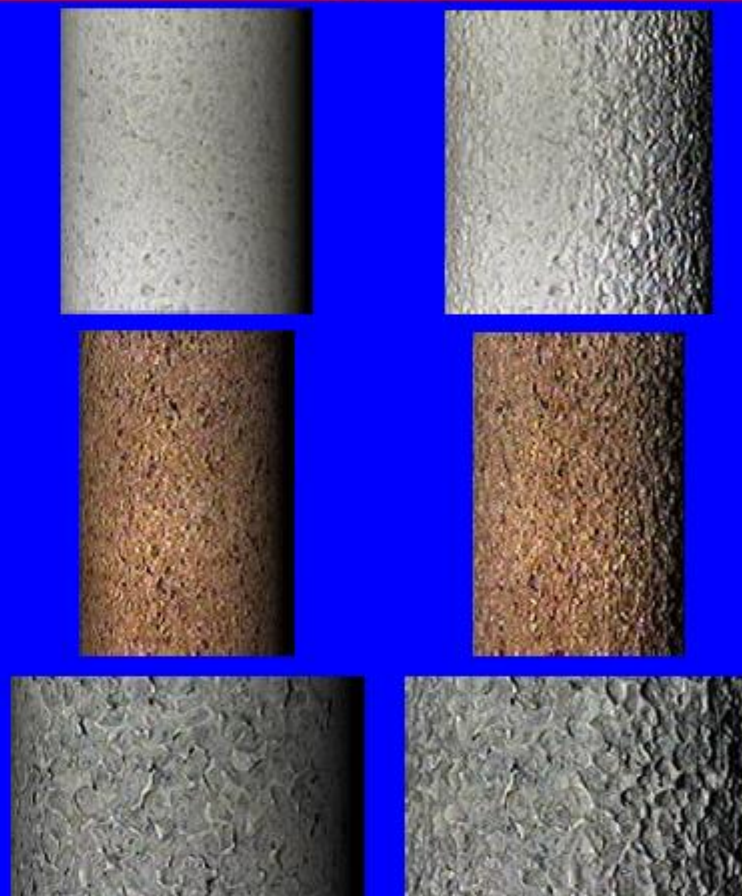


Measurement Methods



Texture-mapping using BTF

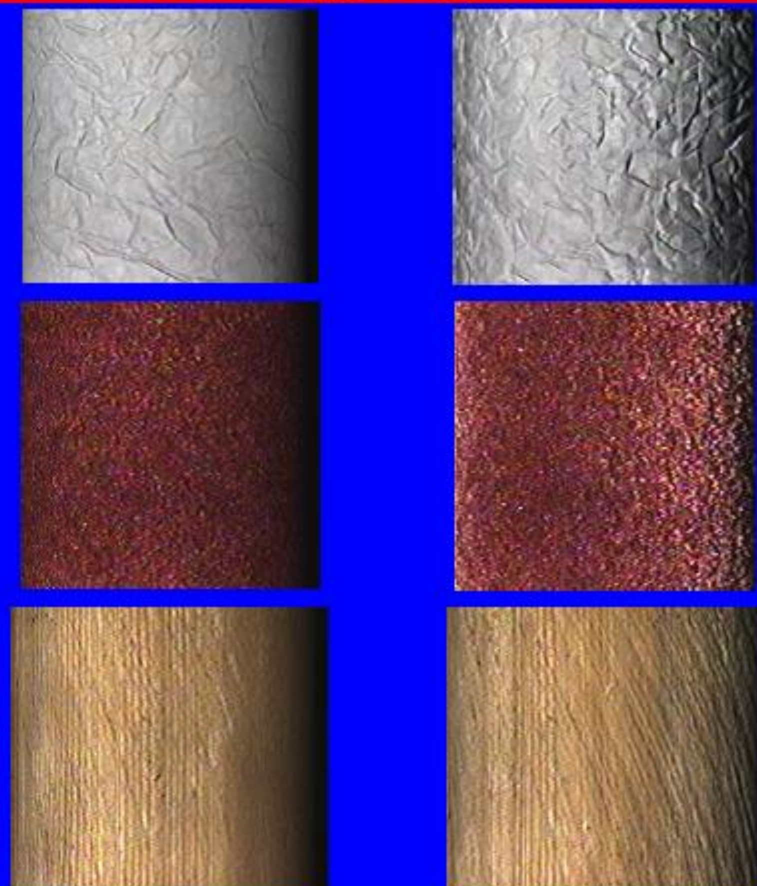
standard
texture-mapping



texture-mapping
with the BTF

Texture-mapping using BTF

standard texture-mapping



texture-mapping with the BTF

Next Step in the Appearance Food Chain

Why bother about measuring patches or spheres?

Why not measure the scenes themselves directly?

- Change only lighting (for Relighting)
- Change only viewpoint (Light Fields)
- Change both lighting and view point

Debevec et al. Siggraph 2000

VIDEO and DEMO for relighting

Time-Varying BRDFs

Bo Sun

Kalyan Sunkavalli

Ravi Ramamoorthi

Peter Belhumeur

Shree Nayar

Columbia University

Materials Change with Time

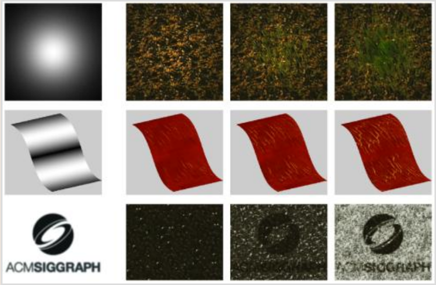
Previous Work

- Time-Varying Spatial Albedo Patterns

[J. Dorsey et al., 96]

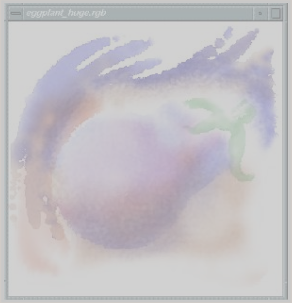
[J. Dorsey et al., 99]

[J. Lu et al., 05]



[S. Enrique et al., 05]

- Paints, Wet Surfaces and Dust



[C. J. Curtis., 97]

[J. W. Jensen et al., 99]

[E. Nakamae et al., 96]

[S. Hsu et al., 96]

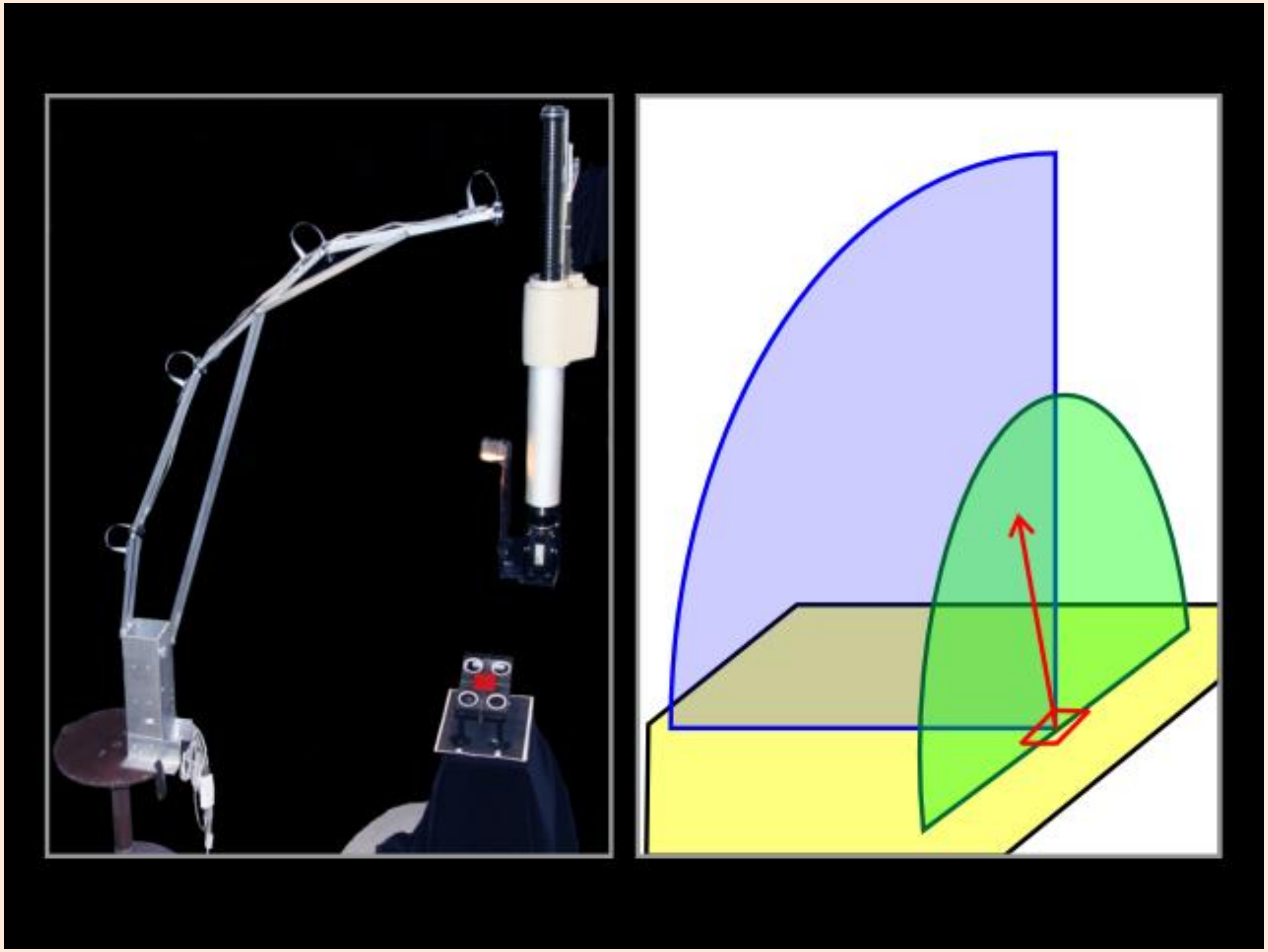
Our Goals

- Efficient TVBRDF Acquisition

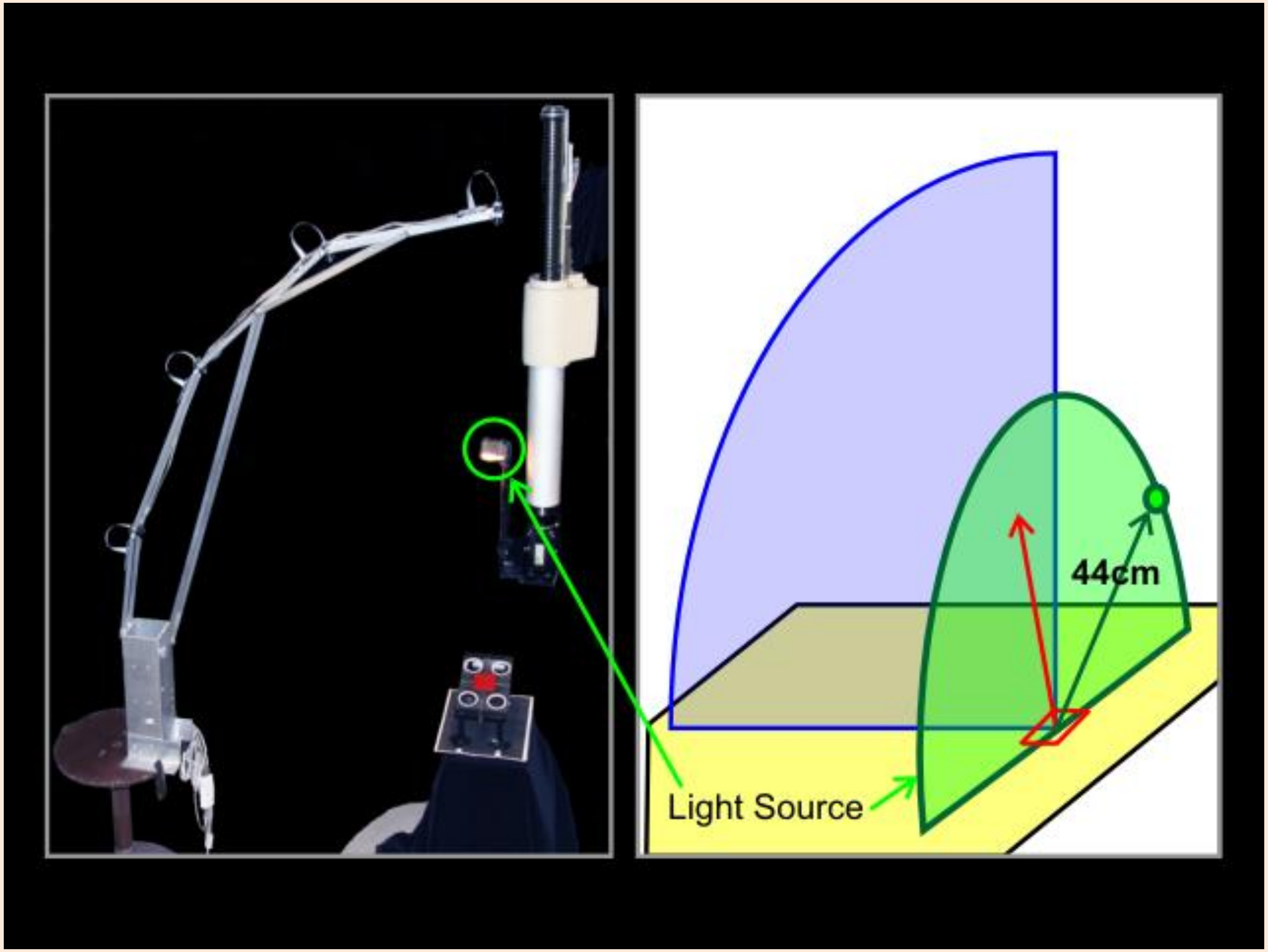
- Underlying Temporal Trend Analysis

- Developing Analytic TVBRDF Models

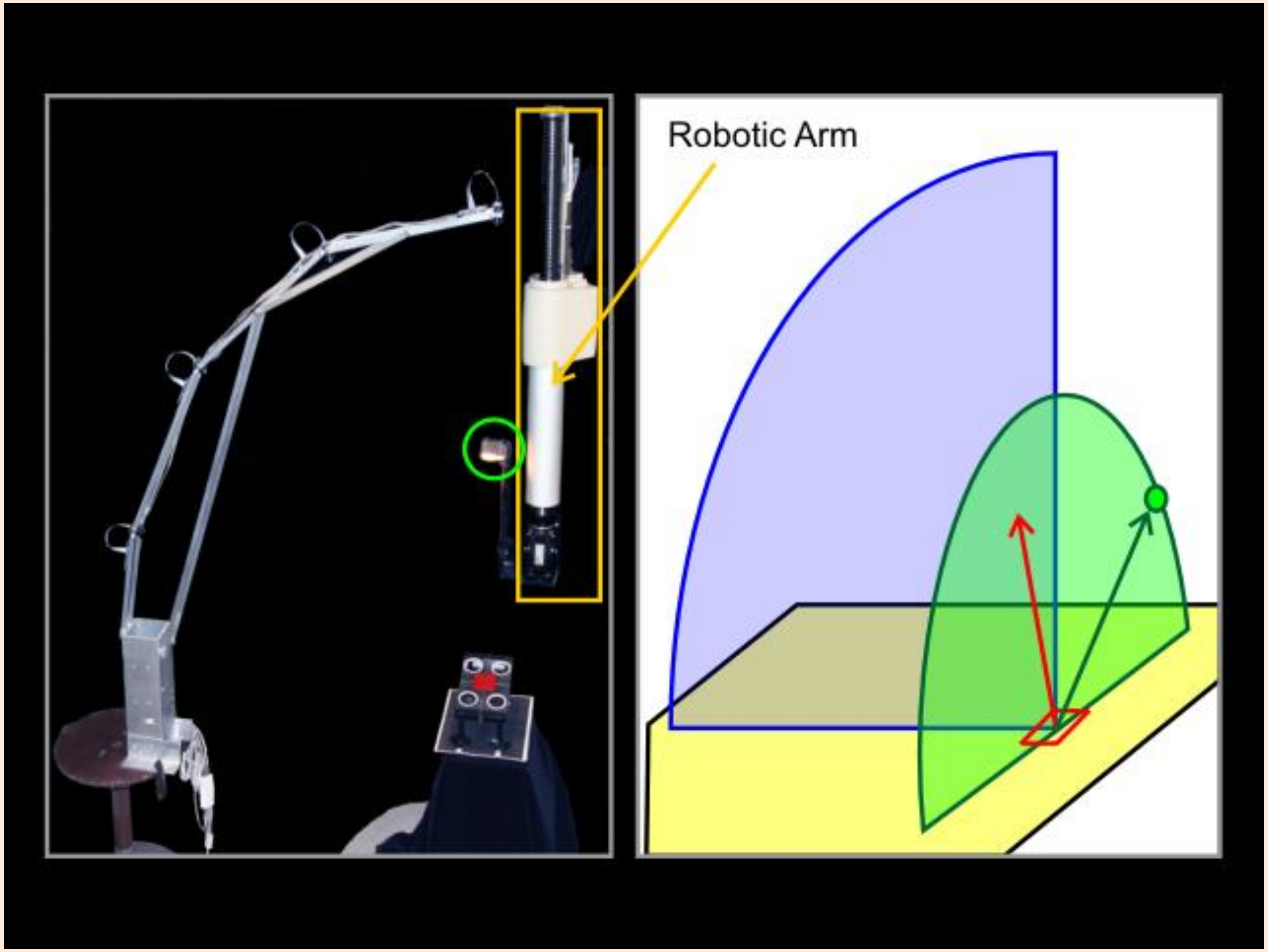
Acquisition System



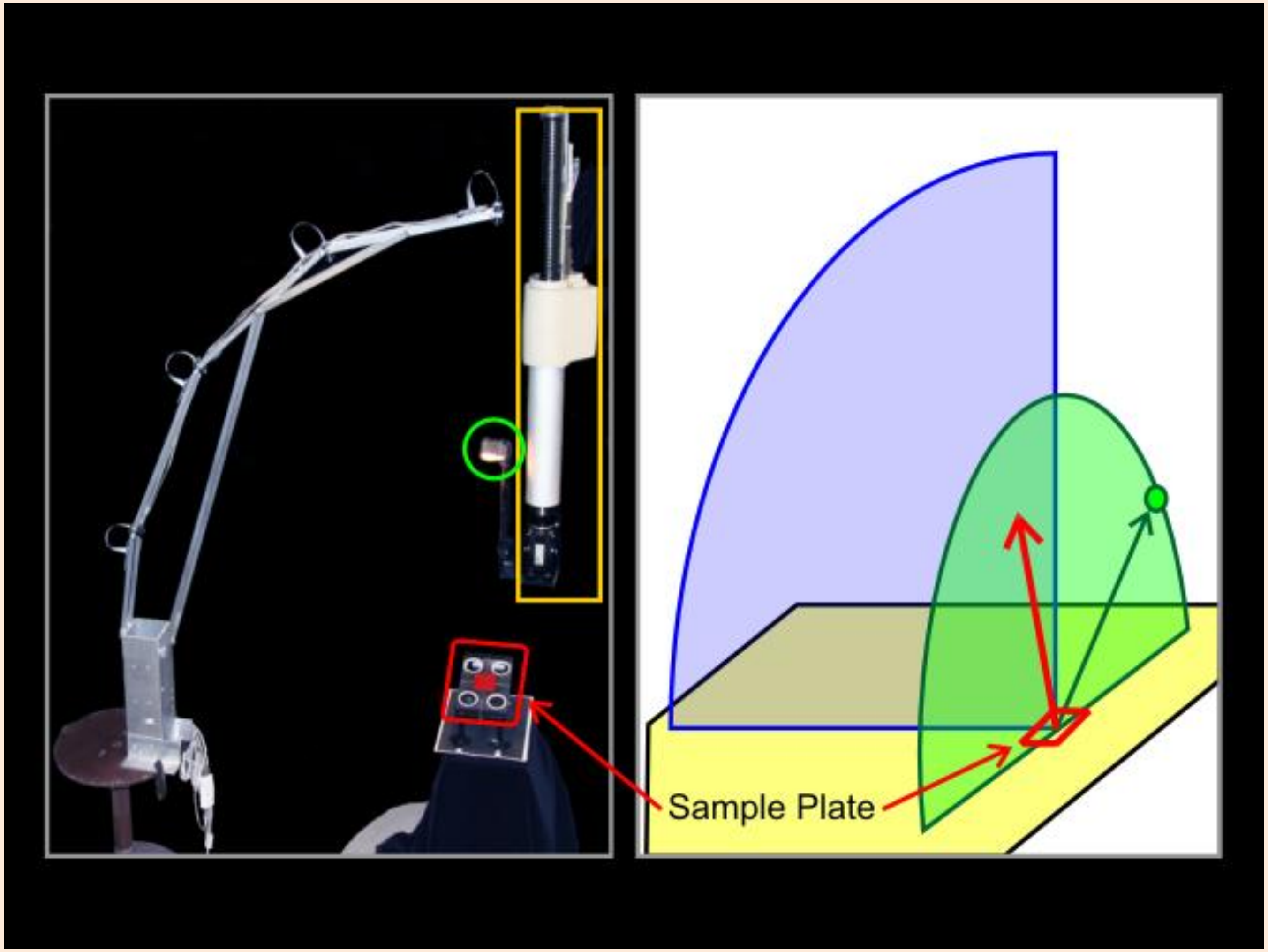
Acquisition System



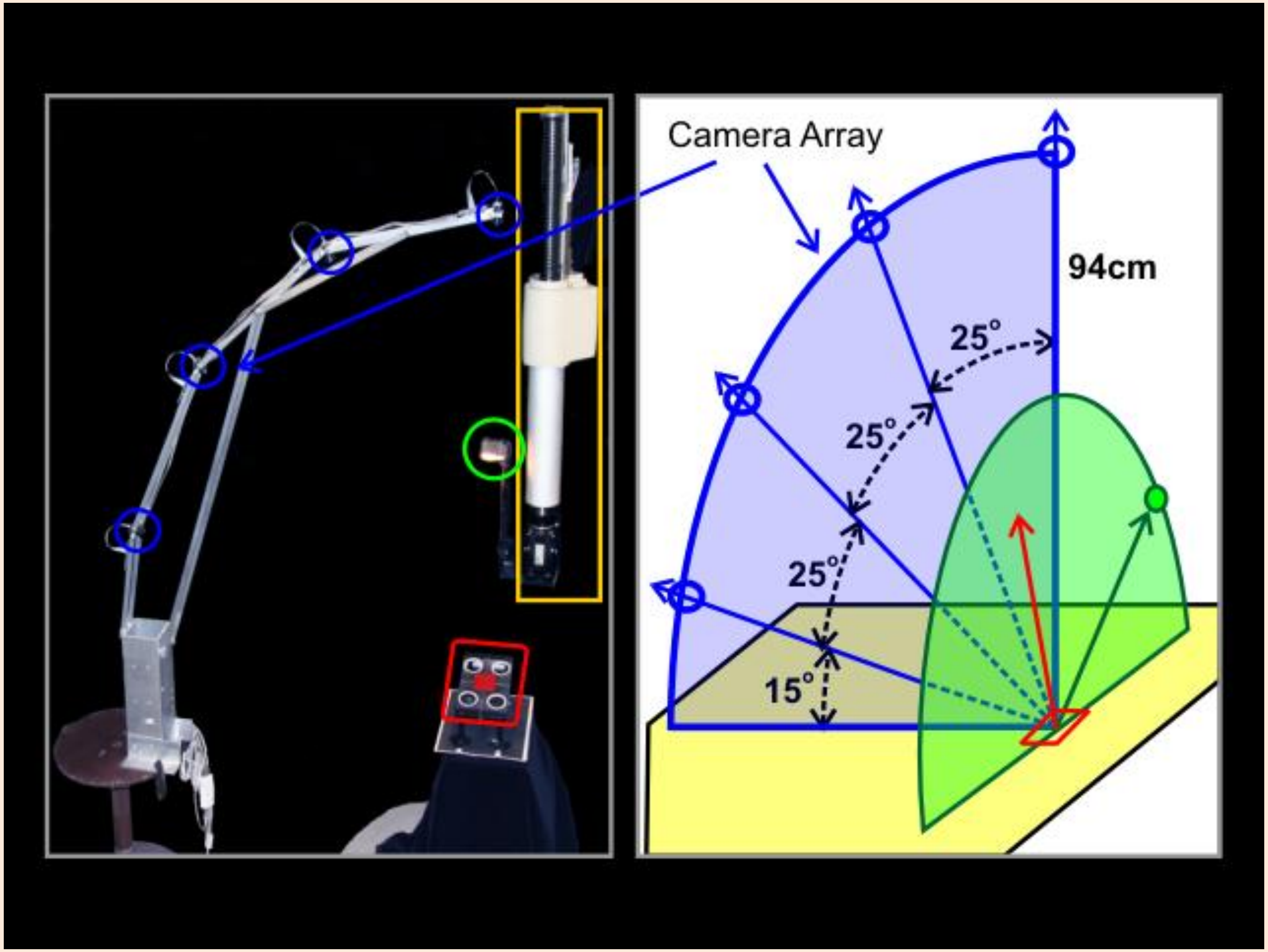
Acquisition System



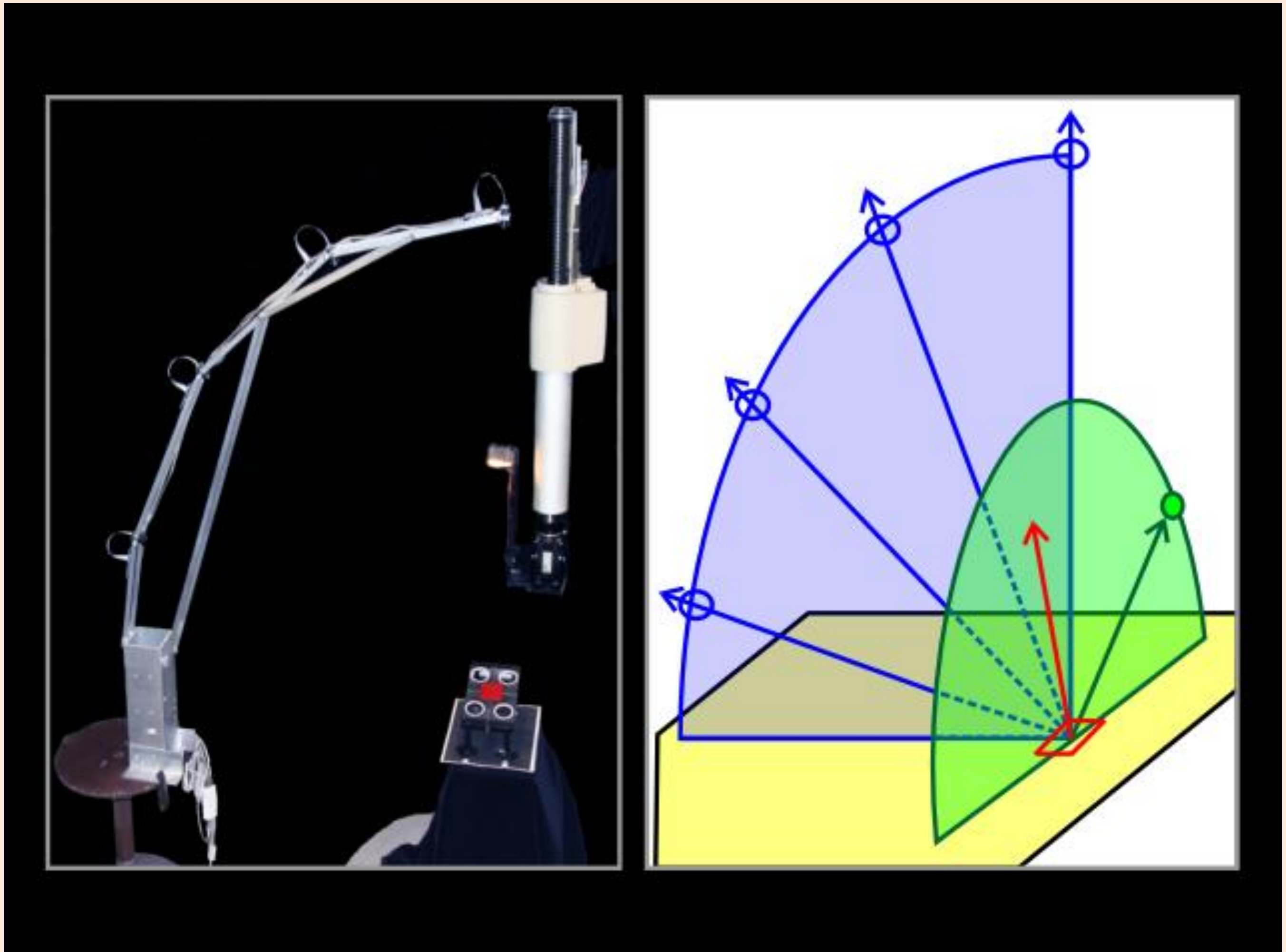
Acquisition System



Acquisition System

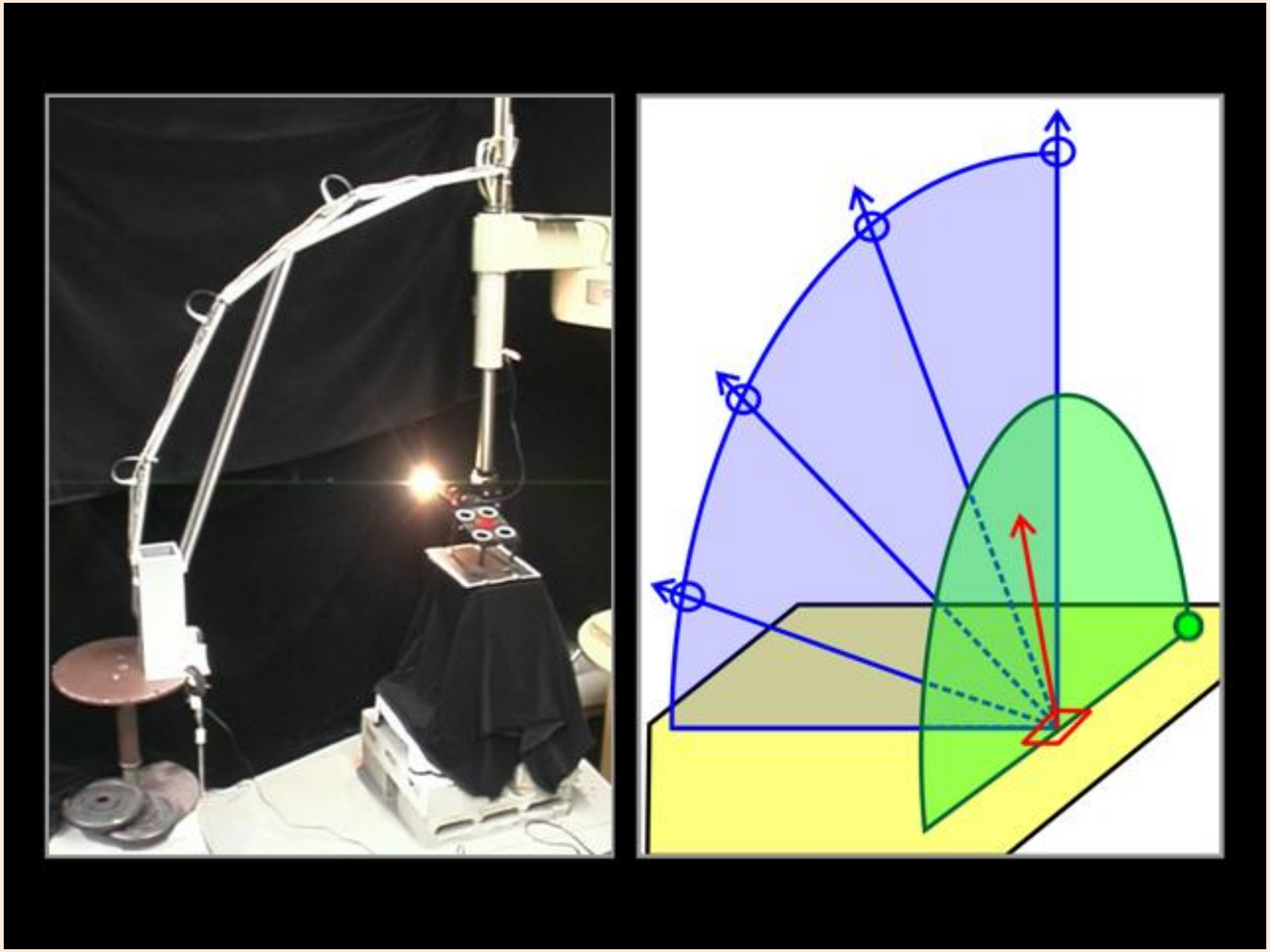


Acquisition System



millisec exposures

Acquisition - Sampling



TVBRDF Samples

Paints	Wet Surface	Dust	Misc.
Crayola Watercolor Blue Red Green Purple Orange Light Green Yellow **Krylon Spray Paint** Flat / White Satin / Green Glossy / Blue Glossy / Blue Satin / Dove-Teal **Rust-Oleum Spray** Flat / Yellow **Daler-Rowney Oil** Prussian Green Prussian Red Light Green Cadmium Yellow	**Fabrics** Alme Grey Blue Idemo Beige Ingebo Dark Red Pink Denim Beige Cotton Orange Cotton Pink Cotton **White Plaster** **Cement** **Terracotta Clay**	**Joint Compound** Electric Red Paint Satin / Red Spray Satin / Dove-Teal Flat / Yellow Spray Almas Red Fabric Green Grey Paint **Household Dust** Electric Red Paint Satin / Red Spray Satin / Dove-Teal Flat / Yellow Spray Almas Red Fabric Green Grey Paint	**Chocolate Melting** **Red Wine on Fabric**

11 samples and three time-varying effects

TVBRDF Samples

Paints	Wet Surface	Dust	Misc.
Crayola Watercolor Blue Red Green Purple Orange Light Green Yellow **Krylon Spray Paint** Flat / White Satin / Green Glossy / Blue Glossy / Blue Satin / Dove-Teal **Rust-Oleum Spray** Flat / Yellow **Daler-Rowney Oil** Prussian Green Prussian Red Light Green Cadmium Yellow	**Fabrics** Alme Grey Blue Idemo Beige Ingebo Dark Red Pink Denim Beige Cotton Orange Cotton Pink Cotton **White Plaster** **Cement** **Terracotta Clay**	**Joint Compound** Electric Red Paint Satin / Red Spray Satin / Dove-Teal Flat / Yellow Spray Almas Red Fabric Green Grey Paint **Household Dust** Electric Red Paint Satin / Red Spray Satin / Dove-Teal Flat / Yellow Spray Almas Red Fabric Green Grey Paint	**Chocolate Melting** **Red Wine on Fabric**

41 samples and three time-varying effects

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41 samples and three time-varying effects

TVBRDF Samples

Paints	Wet Surface	Dust	Misc.
Crayola Watercolor	**Fabrics**	**Joint Compound**	**Chocolate Melting**
Blue	Alme Grey Blue	Electric Red Paint	**Red Wine on Fabric**
Red	Idemo Beige	Satin / Red Spray	
Green	Ingebo Dark Red	Satin / Dove-Teal	
Purple	Pink Denim	Flat / Yellow Spray	
Orange	Beige Cotton	Almas Red Fabric	
Light Green	Orange Cotton	Green Grey Paint	
Yellow	Pink Cotton		
Krylon Spray Paint	**White Plaster**	**Household Dust**	
Flat / White	**Cement**	Electric Red Paint	
Satin / Green	**Terracotta Clay**	Satin / Red Spray	
Glossy / Blue		Satin / Dove-Teal	
Glossy / Blue		Flat / Yellow Spray	
Satin / Dove-Teal		Almas Red Fabric	
Rust-Oleum Spray		Green Grey Paint	
Flat / Yellow			
Daler-Rowney Oil			
Prussian Green			
Prussian Red			
Light Green			
Cadmium Yellow			

41 samples and three time-varying effects

TVBRDF Samples

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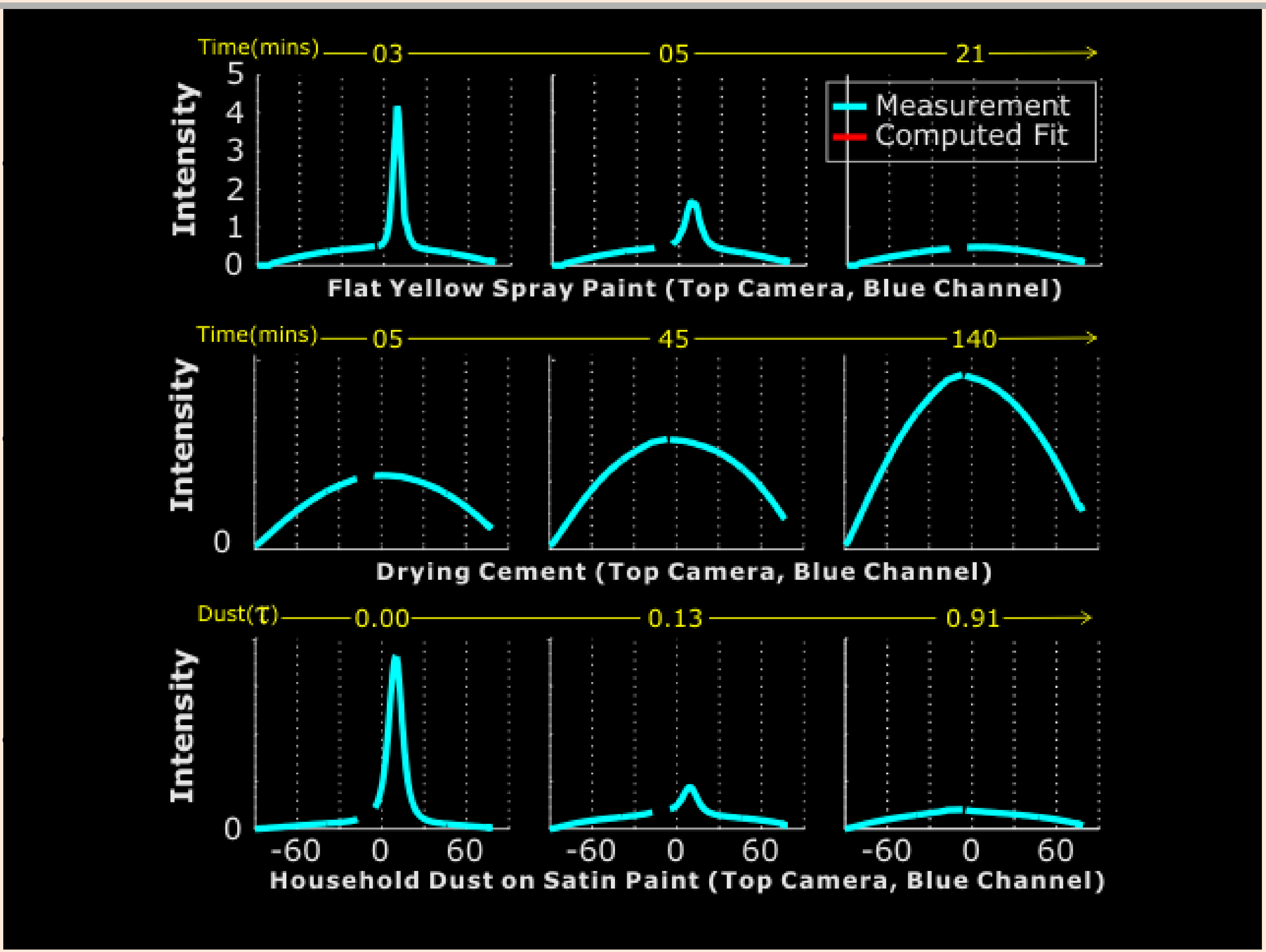
11 samples and three time-varying effects

Measurement

Top C

Top C

Top C



Analytic BRDF Functions

- The Oren-Nayar diffuse model

$$\boxed{\rho_d(\omega_i, \omega_o; \sigma_d, K_d^{r,g,b})}$$

- The Torrance-Sparrow specular model

$$\boxed{\rho_s(\omega_i, \omega_o; \sigma_s, K_s)}$$

- The Blinn's dust model

$$\boxed{\rho(\tau) = (1 - T_1(\tau)) \cdot \rho_{dust} + T_2(\tau) \cdot \rho_d + \rho_s(\sigma_s, K_s)}$$

Data Fitting

Top C

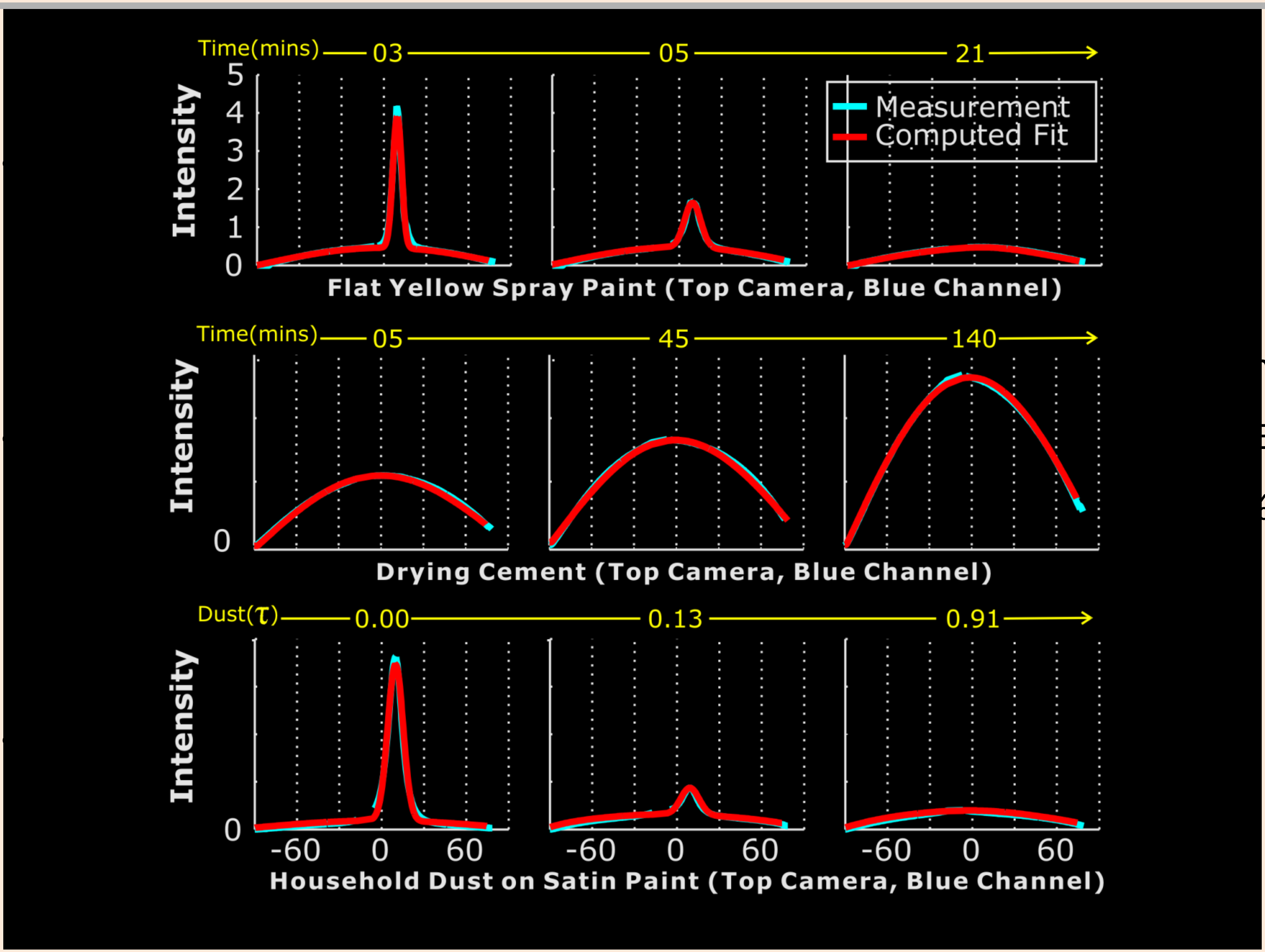
Top C

Top C

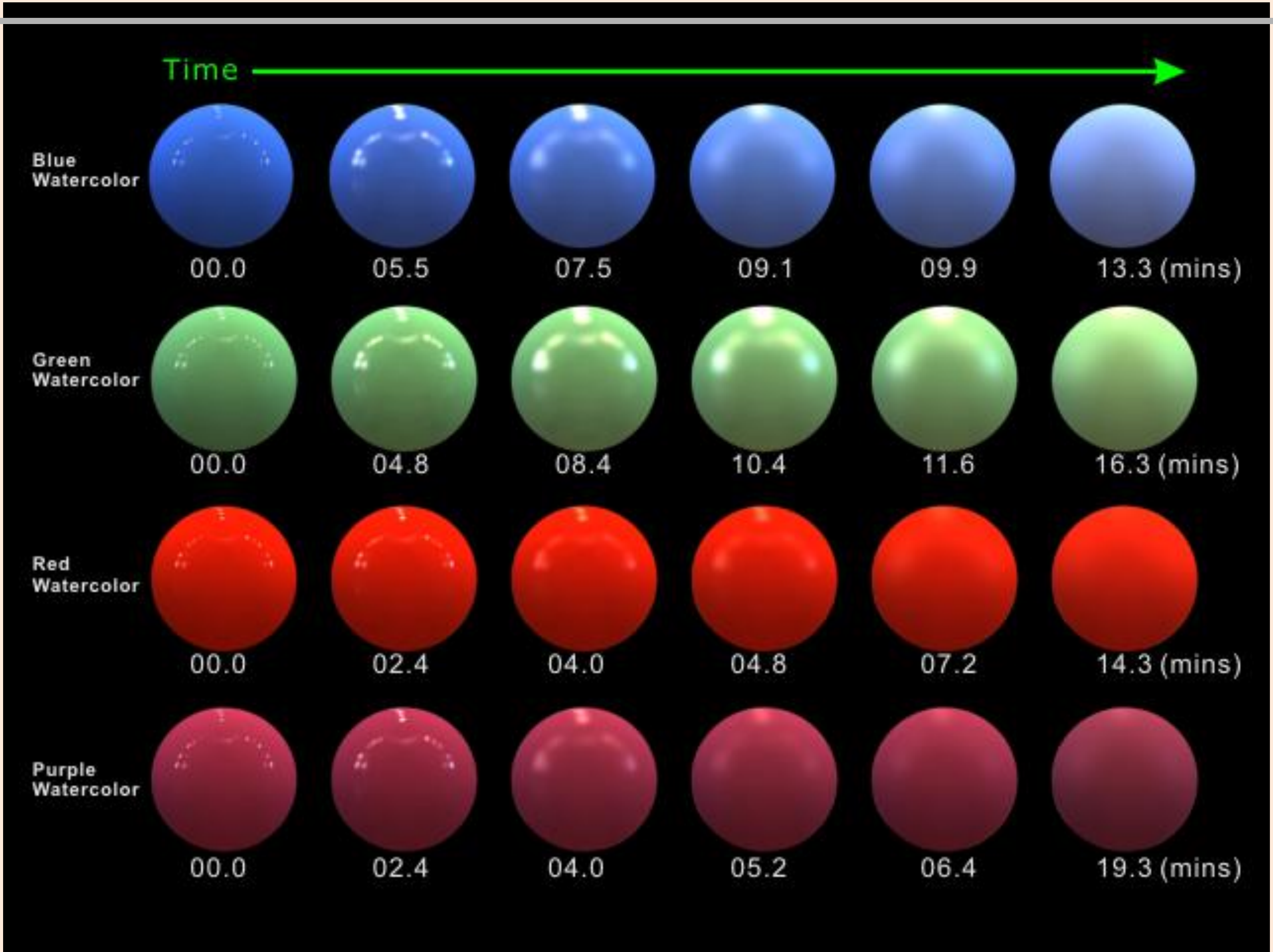
mum

Error

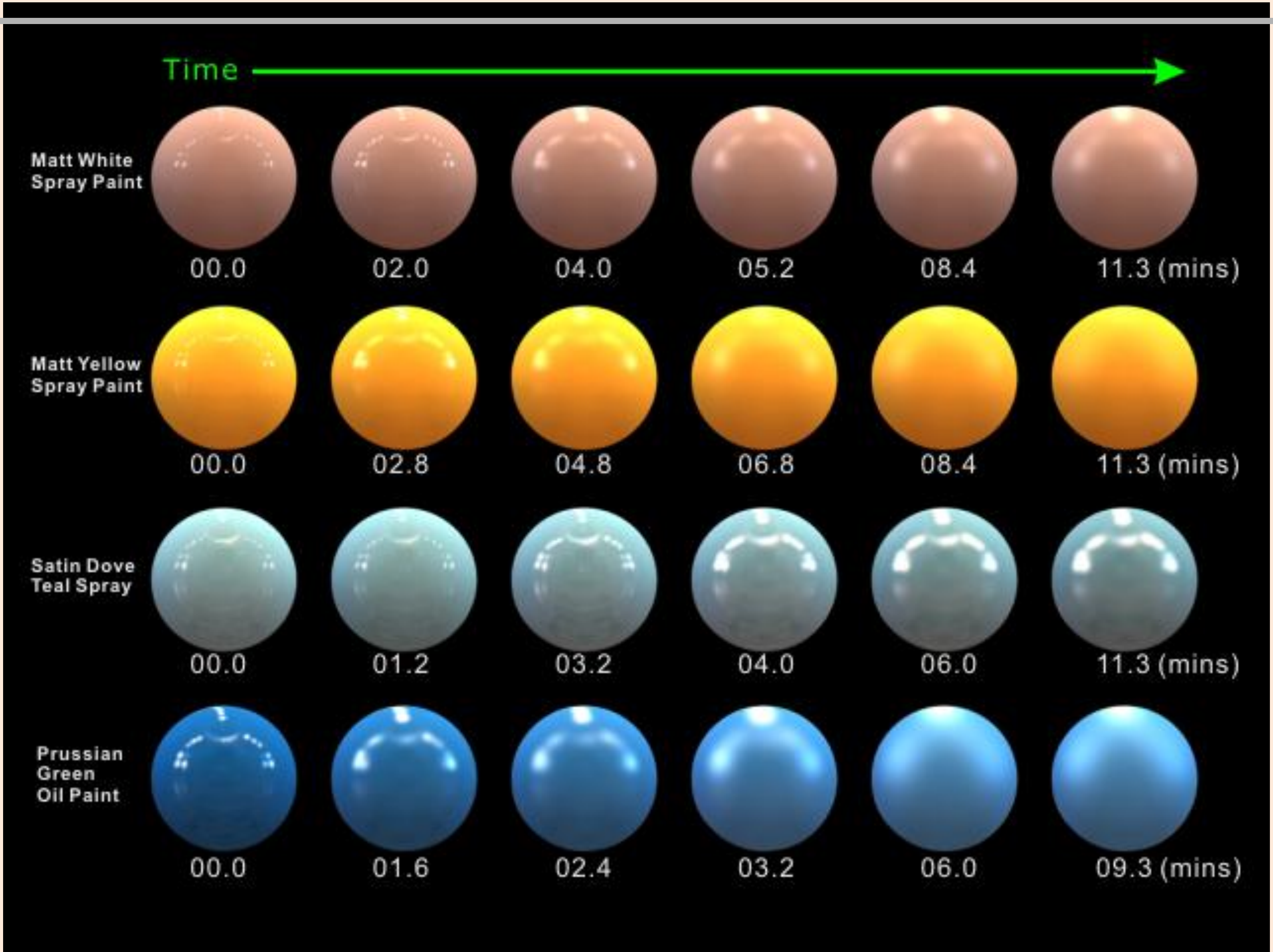
%



TVBRDF Database



TVBRDF Database



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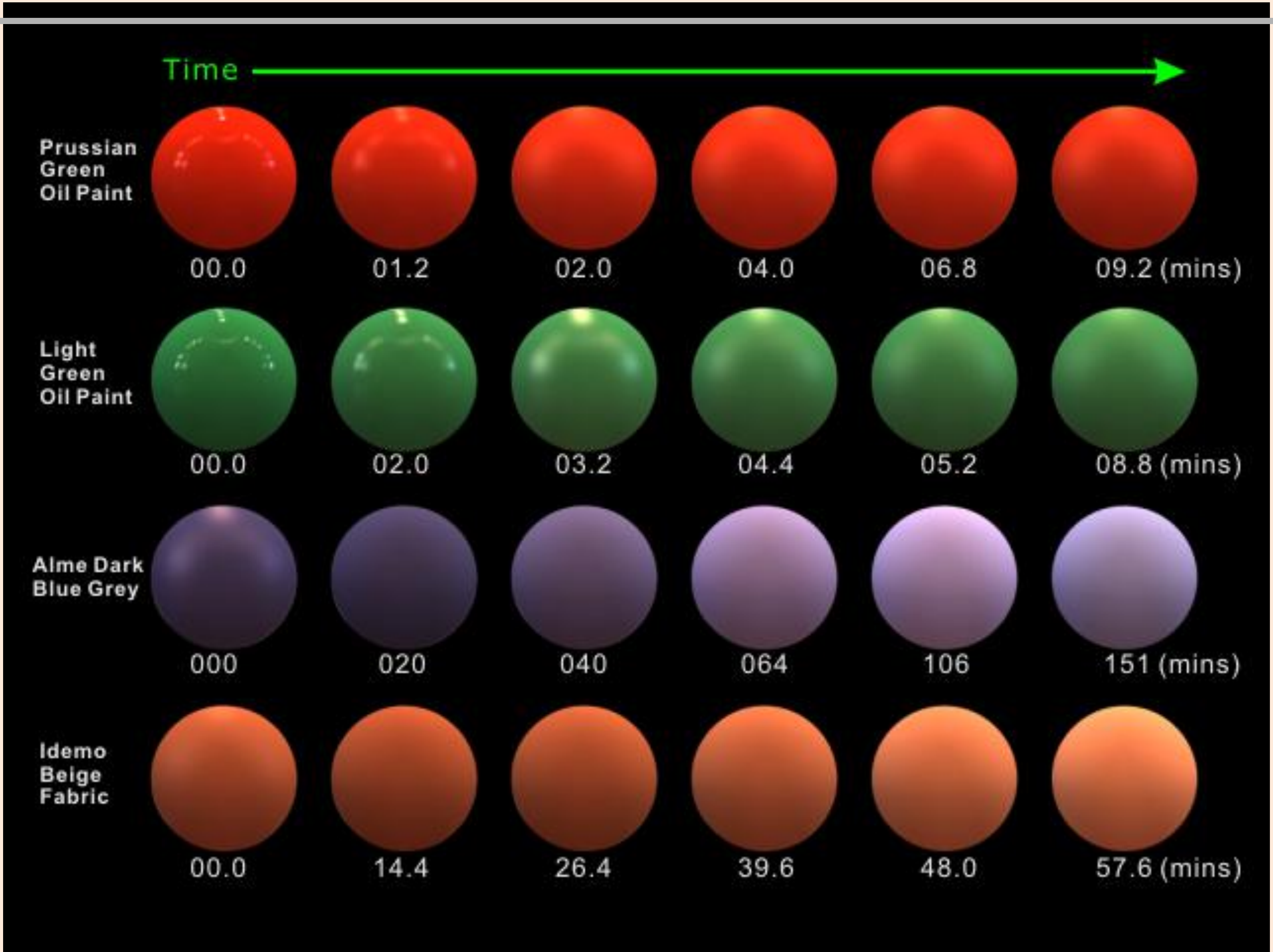

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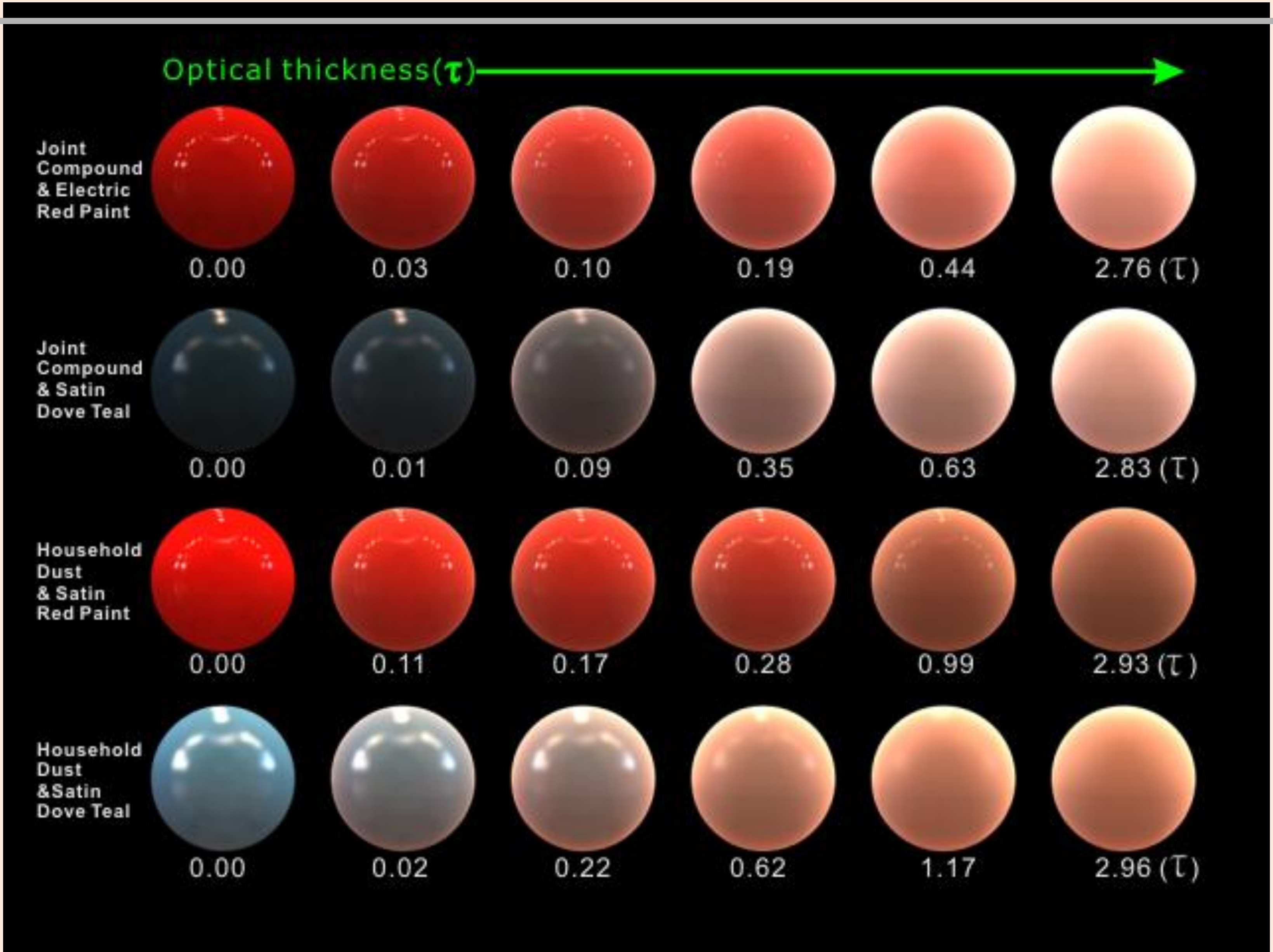
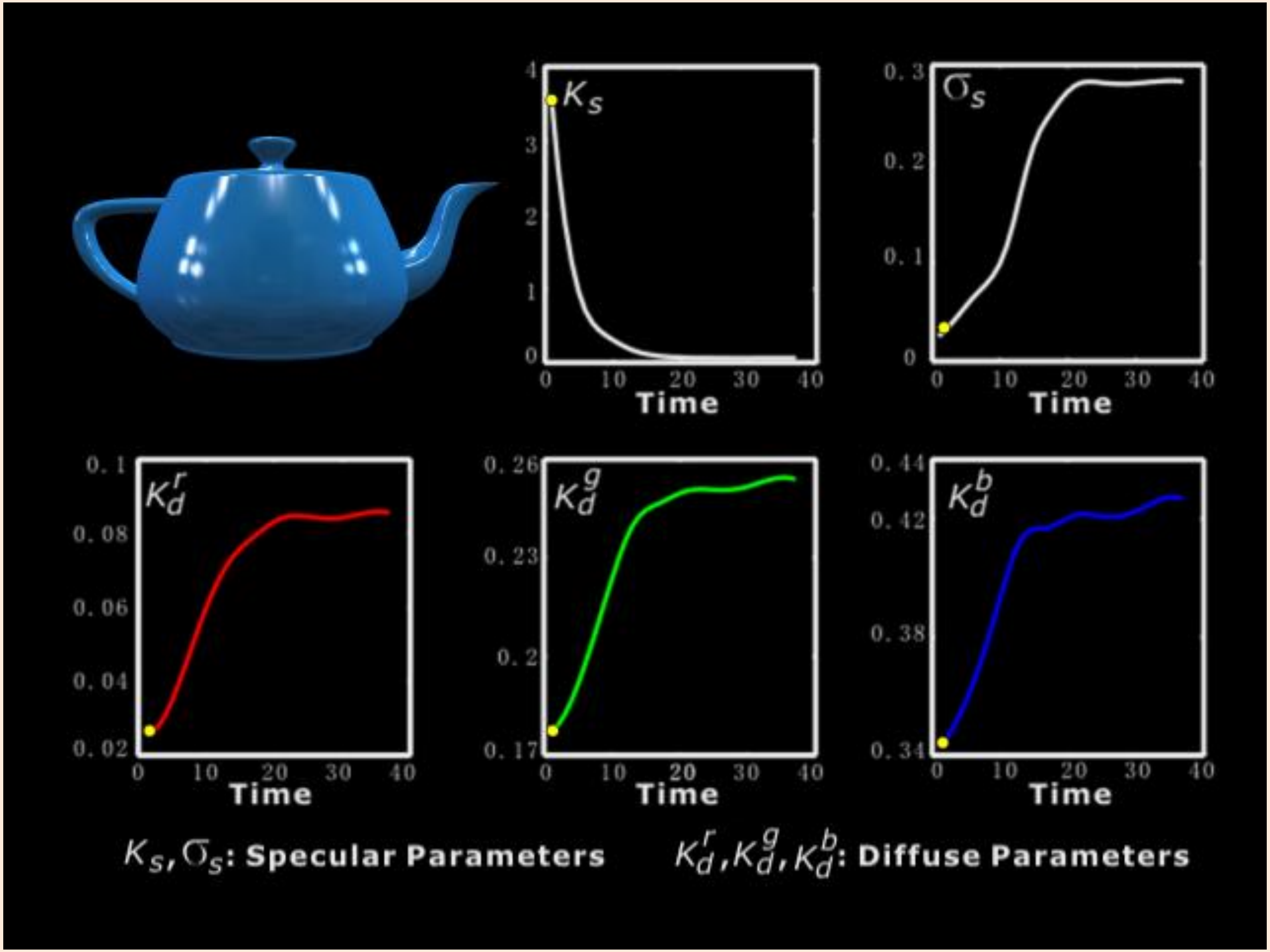


Temporal Trends

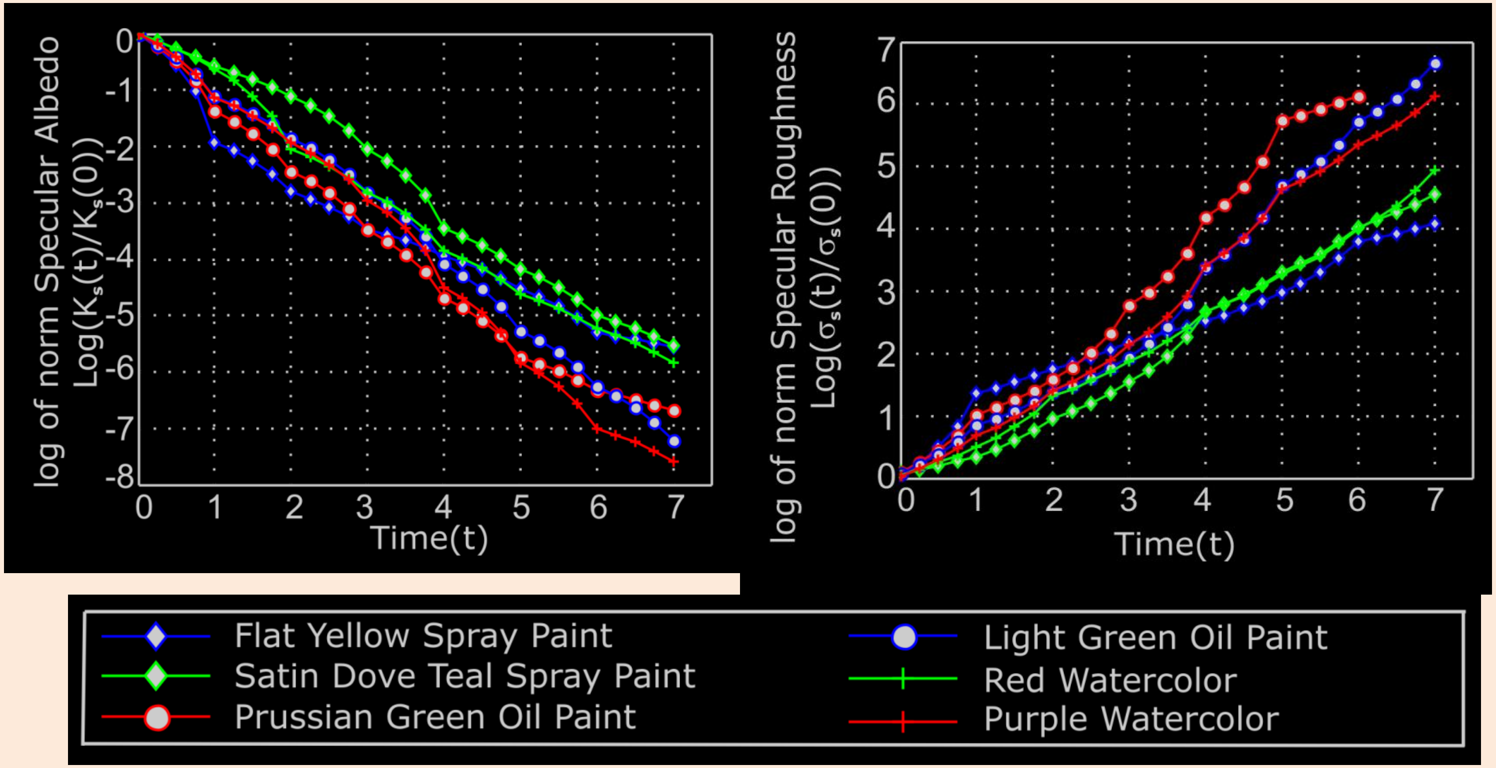


Time-Varying Phenomena

- Paints drying on smooth surfaces
- Water drying on rough surfaces
- Dust accumulation

Paints

- Exponential fall-off of specular albedo and roughness
- Diffuse color shifts in a dichromatic plane



Paints

- Exponential fall-off of specular albedo and roughness
- Diffuse color shifts in a dichromatic plane

$$K_s(t) = (K_{s,wet} - K_{s,dry}) \cdot e^{-\lambda t} + K_{s,dry}$$

$$\sigma_s(t) = \frac{\sigma_{s,wet} \cdot \sigma_{s,dry}}{(\sigma_{s,dry} - \sigma_{s,wet}) \cdot e^{-\lambda t} + \sigma_{s,wet}}$$

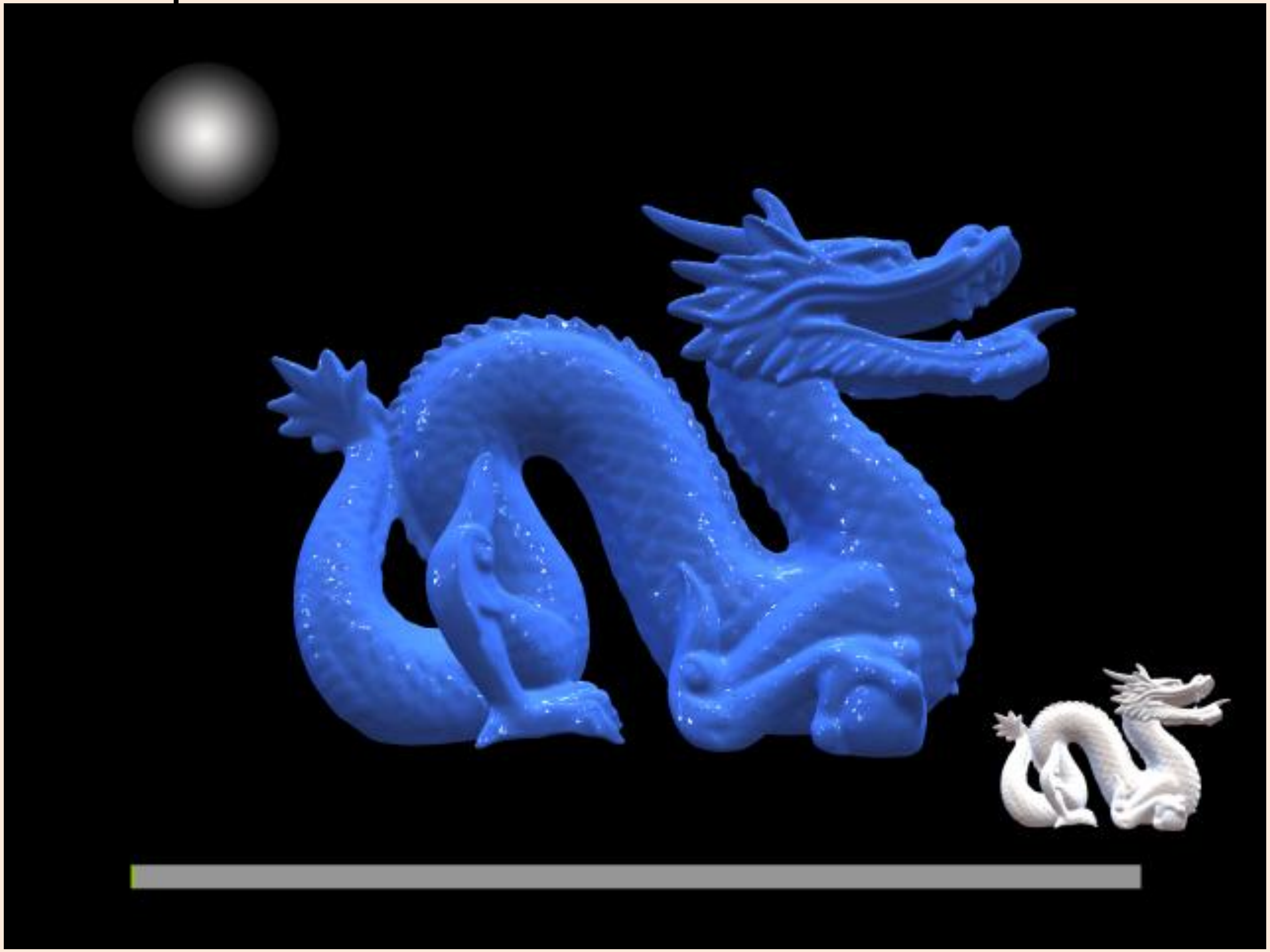
Paints

- Exponential fall-off of specular albedo and roughness
- Diffuse color shifts in a dichromatic plane

$$\boxed{\rho_d(t) = \alpha(t) \cdot \rho_{d,surface} + \beta(t) \cdot \rho_{d,surface}}$$

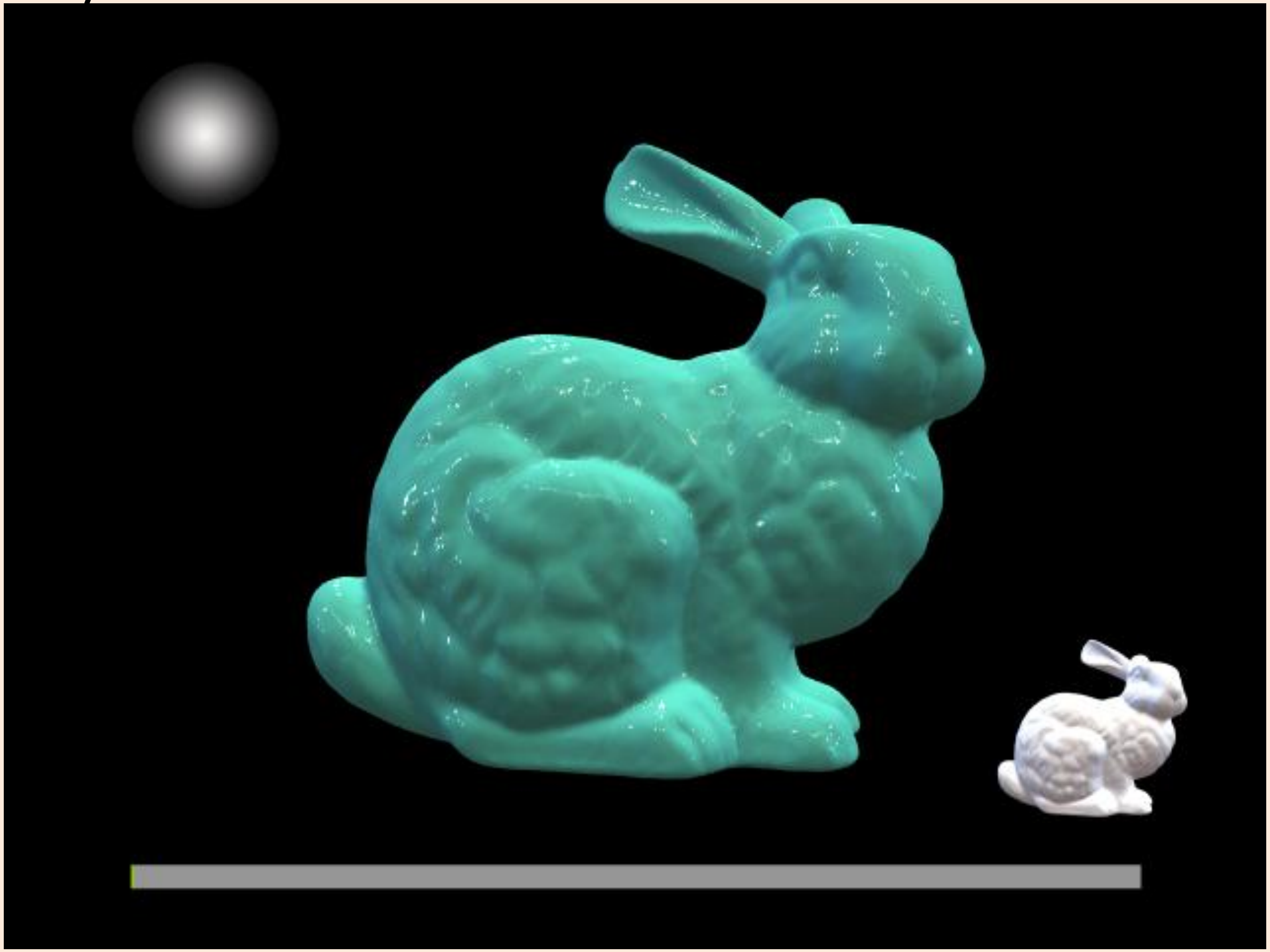
Paints – Spatial Variations

Captured Blue Watercolor on White Surface



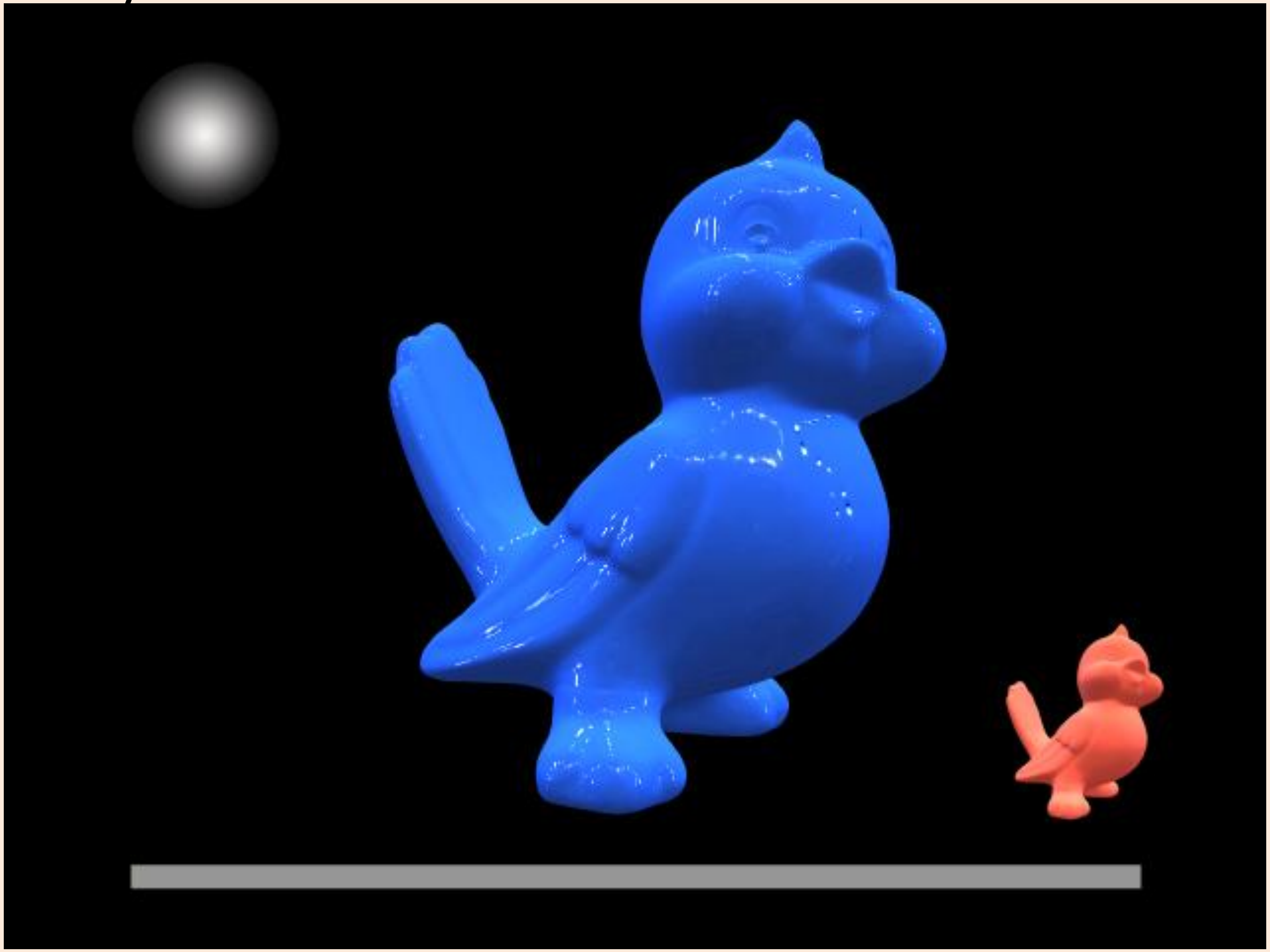
Paints – Effects Transfer

Synthesized Green Watercolor on White Surface



Paints – Effects Transfer

Synthesized Blue Watercolor on Red Surface



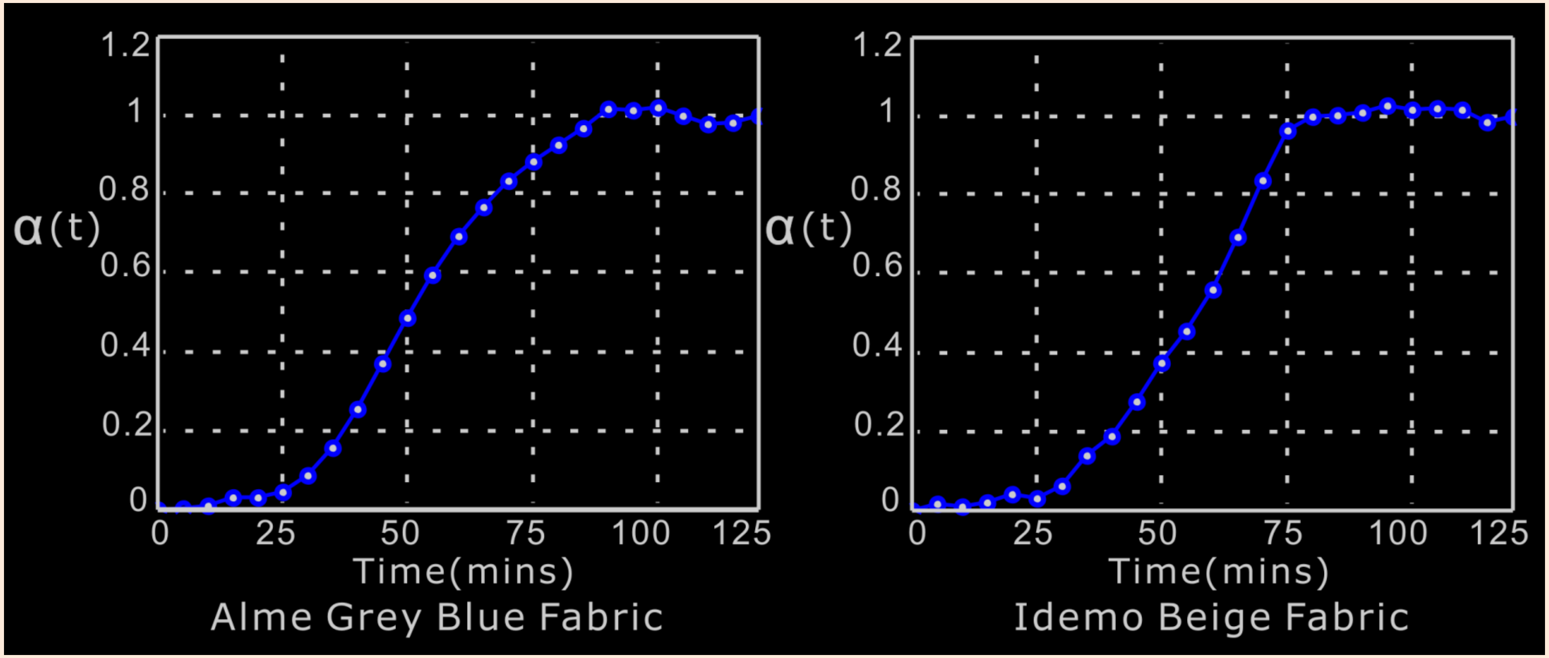
Wet Surfaces

- Diffuse color shifts on a straight line
- Sigmoidal change of surface intensity

$$\boxed{\rho_d(t) = \alpha(t) \cdot \rho_{d,dry} + (1 - \alpha(t)) \cdot \rho_{d,wet}}$$

Wet Surfaces

- Diffuse color shifts on a straight line
- Sigmoidal change of surface intensity

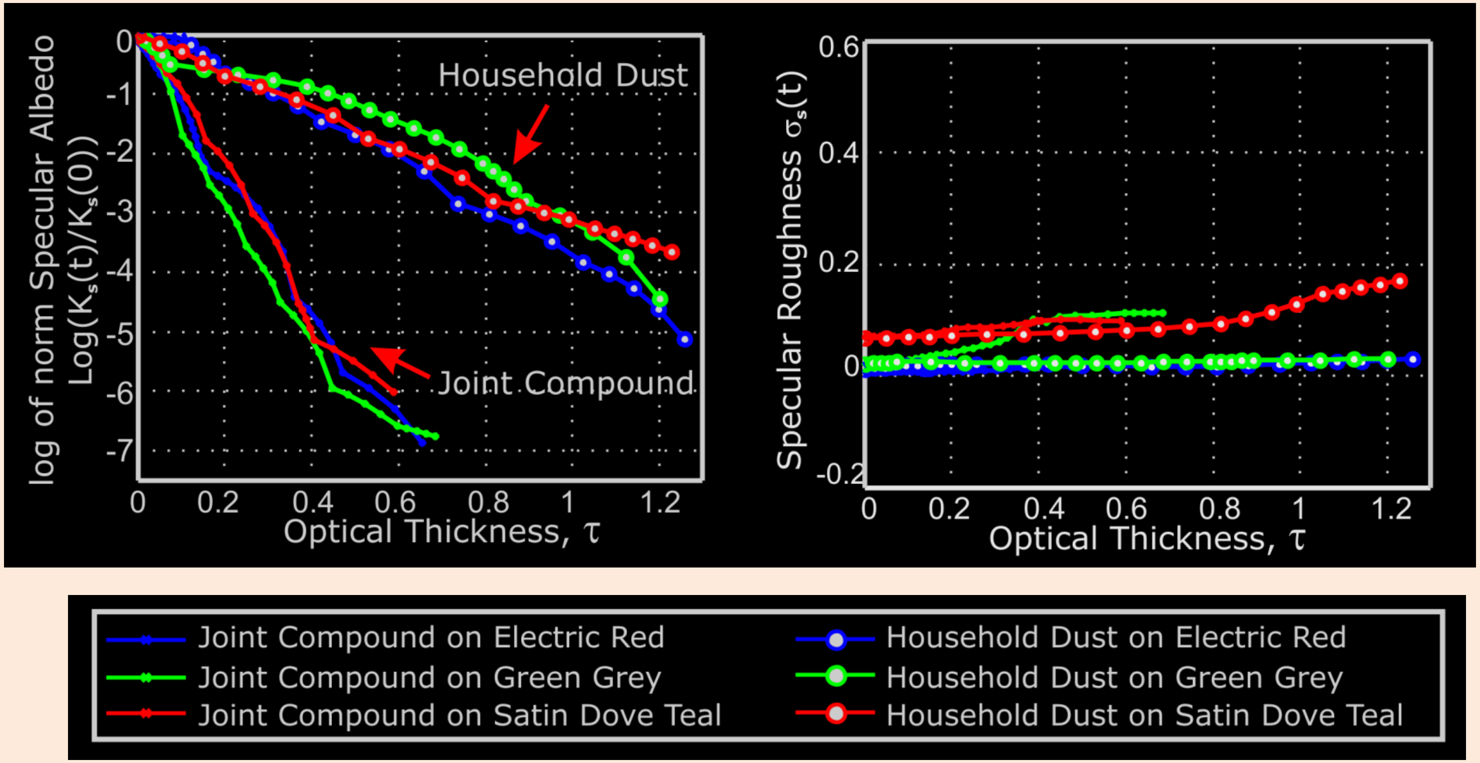


Time-Varying Phenomena

- Paints drying on smooth surfaces
- Water drying on rough surfaces
- Dust accumulation

Dust

- Analysis generalizes to other BRDF models
- Exponential fall-off of specular highlights



Dust

- Analysis generalizes to other BRDF models
- Exponential fall-off of specular highlights

$$\boxed{\rho(\tau) = (1 - T(\tau)) \cdot \rho_{dust} + T(\tau) \cdot \rho_d + e^{-\lambda\tau} \cdot \rho_s}$$

$$\rho(\tau) = (1 - T_1(\tau)) \cdot \rho_{dust} + T_2(\tau) \cdot \rho_d + \rho_s(\sigma_s, K_s)$$

Dust – Final Example