

Visual Appearance and Color

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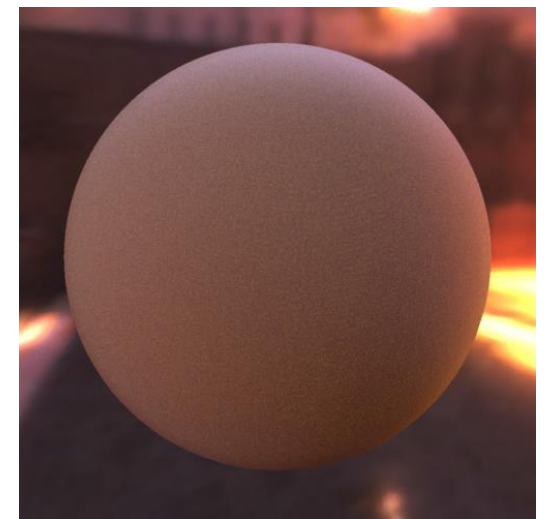
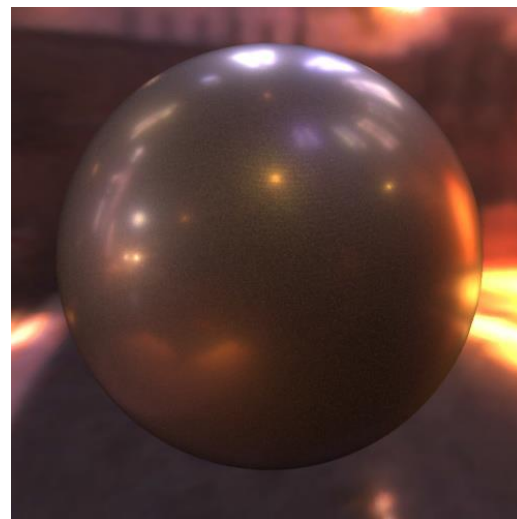
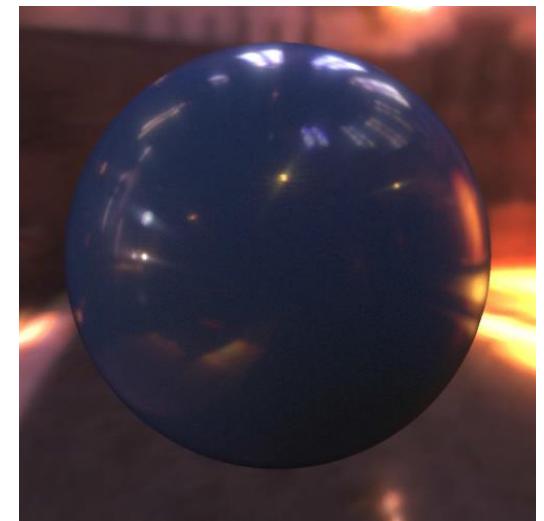
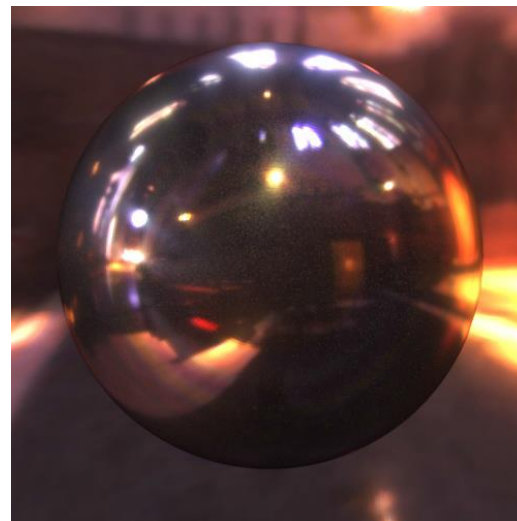
Visual Appearance

- Color due to the interaction between the lighting environment (intensity, position, ...) and the properties of the object surface and material.

LIGHT



MATERIAL



Visual Appearance: why?

- Photorealistic rendering – High fidelity reproduction of the real world



PHOTO



RENDERING

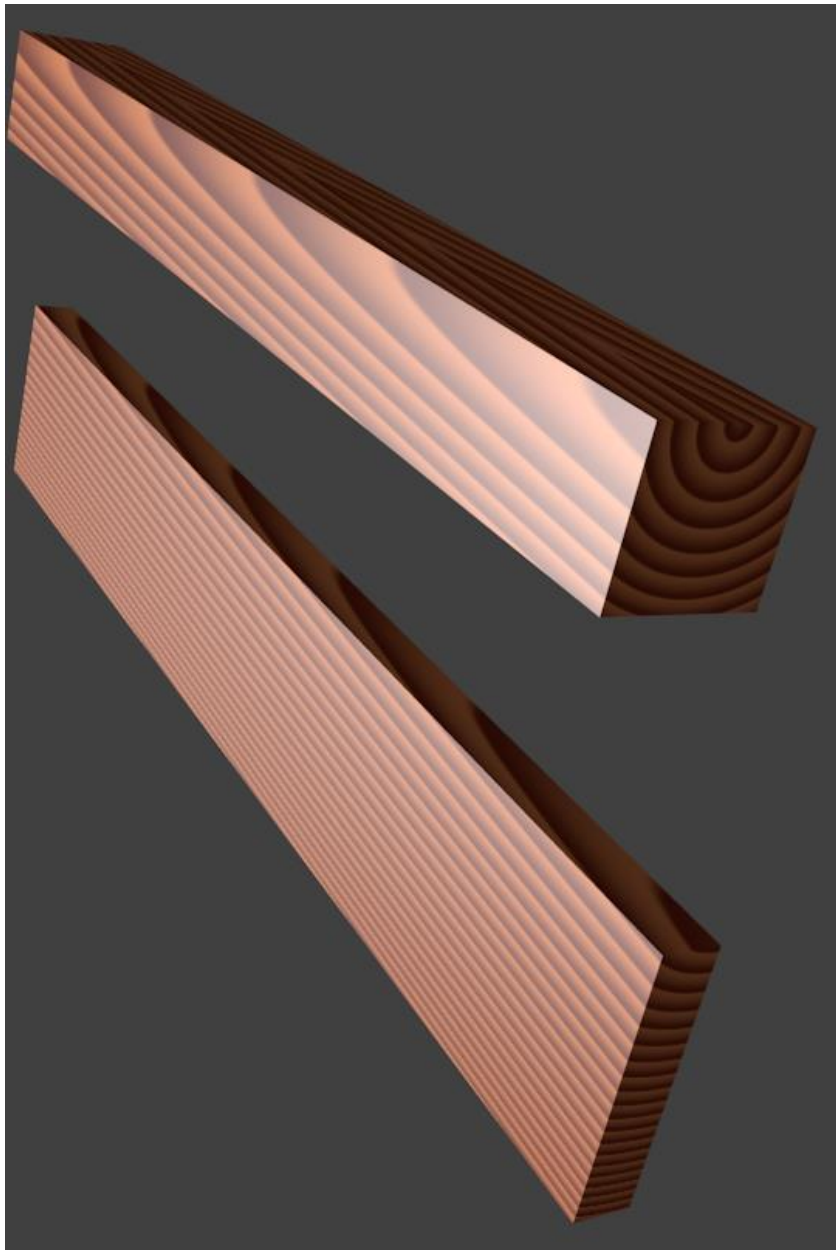
Visual Appearance: why?

- Perception – Better understanding of the details (even with a fake appearance)



Visual Appearance: why?

- To infer more cognitive data from color details

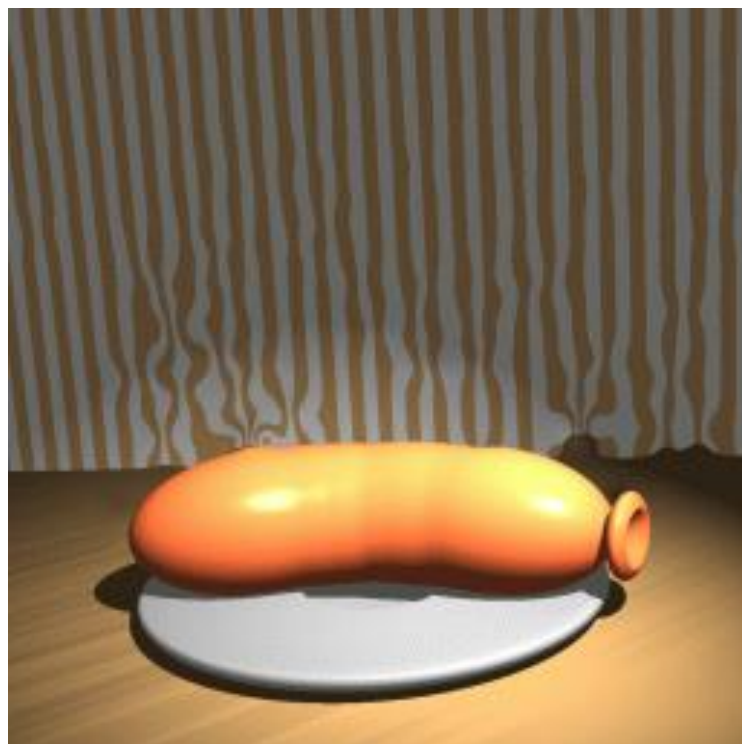


Physical-based Rendering

- Algorithms that compute images by simulating the physical behavior of light
 - Predictive simulation, photorealistic
 - But slow (simulation of physics is computationally very expensive)
 - Need accurate geometry, materials and lights

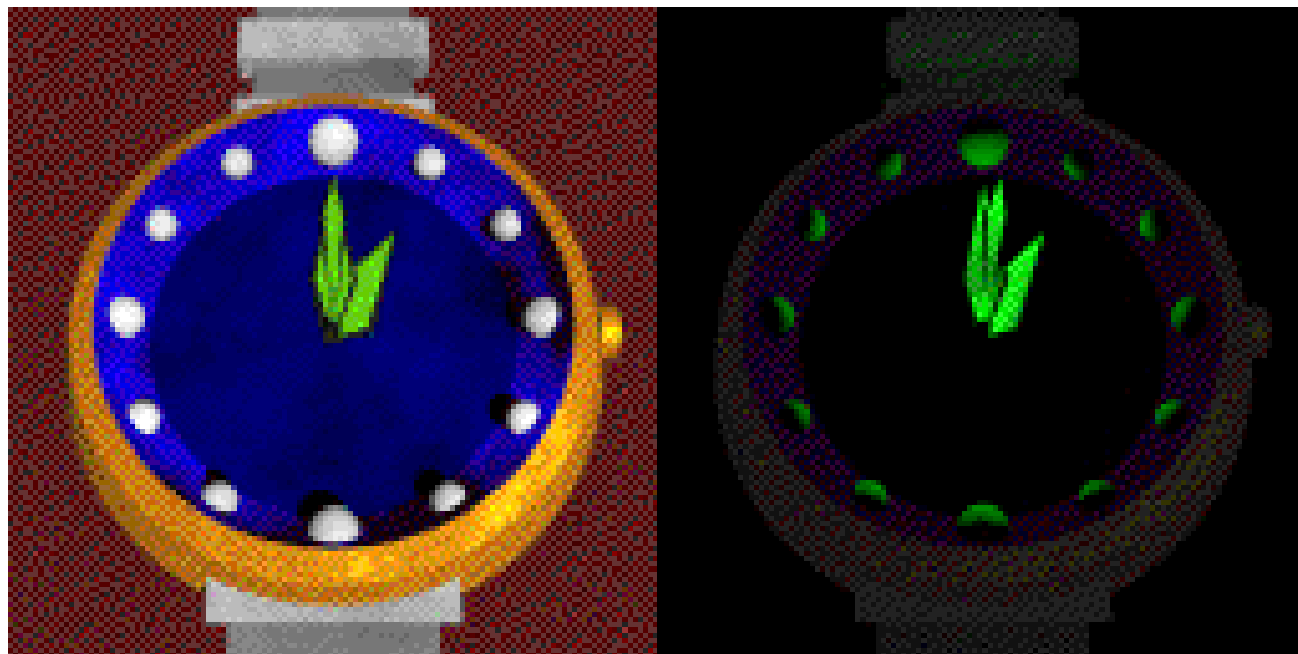
Model of light

- Geometric optics
 - Light particles travel in straight lines
 - Light particles do not interact with each other
 - Describes: emission, reflection/refraction, absorption



Model of light

- Quantum optics
 - Light particles are like any other quantum particles
 - Captures: fluorescence, phosphorescence



Model of light

- Wave optics
 - Light particles interact with each other
 - Describes: diffraction, interference, polarization



Rendering Equation

- Describe physical behavior of light in vacuum filled with objects
 - Based on geometric optics principles
 - Can be extended to describe participating media
 - Can be extended to describe wavelength and time dependency

Power and Irradiance

- Power: energy per unit time
 - Measured in Watts = Joules/sec

$$\Phi = \frac{dQ}{dt}$$

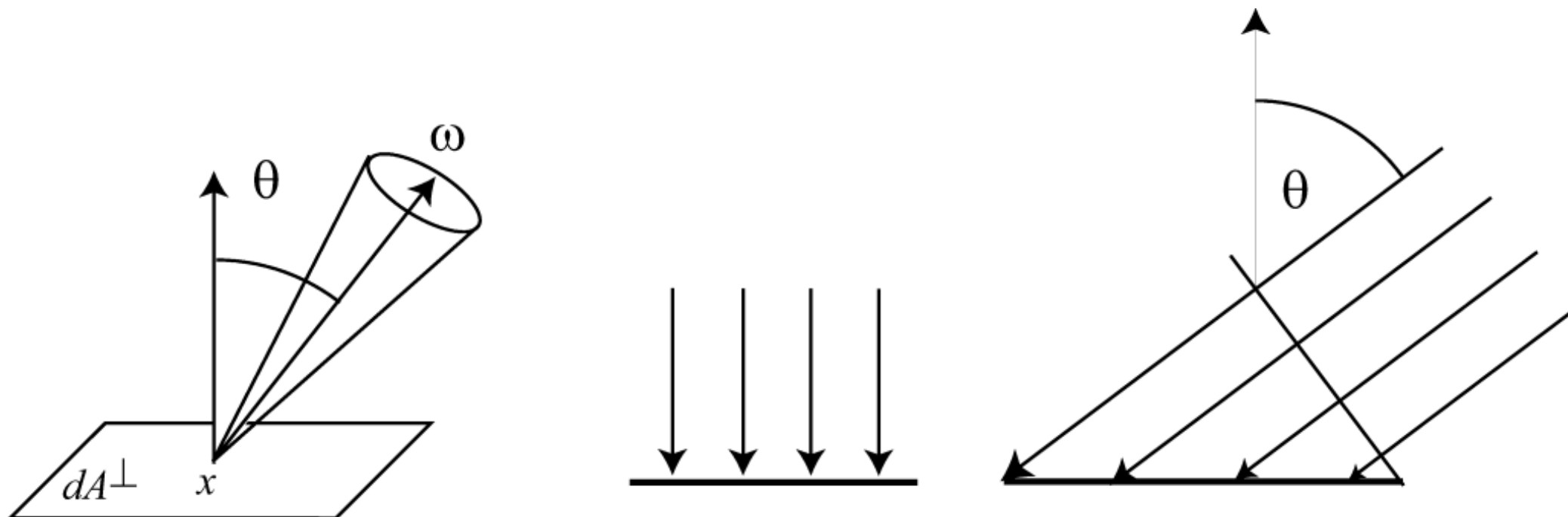
- Irradiance: power per unit area
 - Measured in Watts/meter²

$$E = \frac{d\Phi}{dA}$$

Radiance

- Power per unit projected area and solid angle
 - Depends on position and direction

$$L(\mathbf{x} \rightarrow \Omega) = \frac{d^2 \Phi}{dA^\perp d\vec{\omega}_\Omega} = \frac{d^2 \Phi}{dA \cos \theta d\vec{\omega}_\Omega} = \frac{dE}{\cos \theta d\vec{\omega}_\Omega}$$

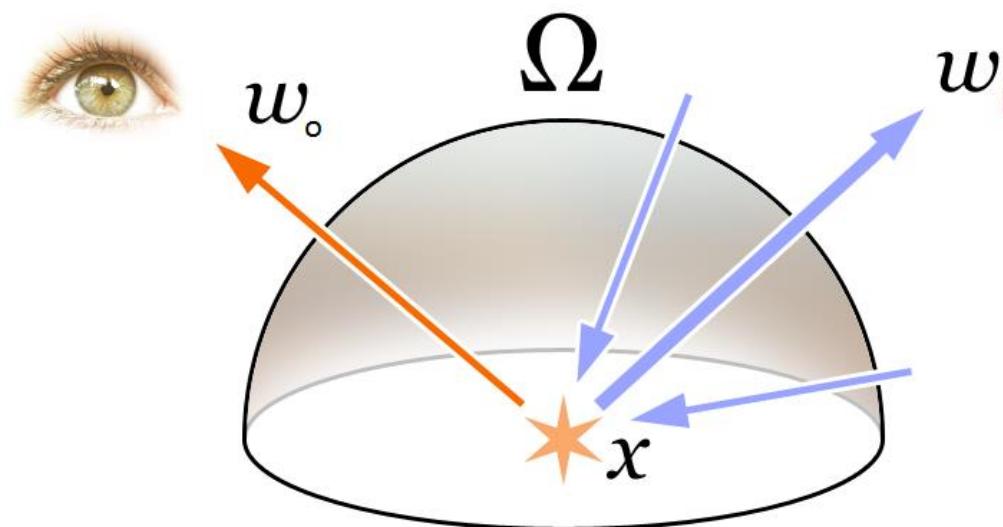


Rendering Equation

- The outgoing radiance is the sum of emitted and reflected radiance

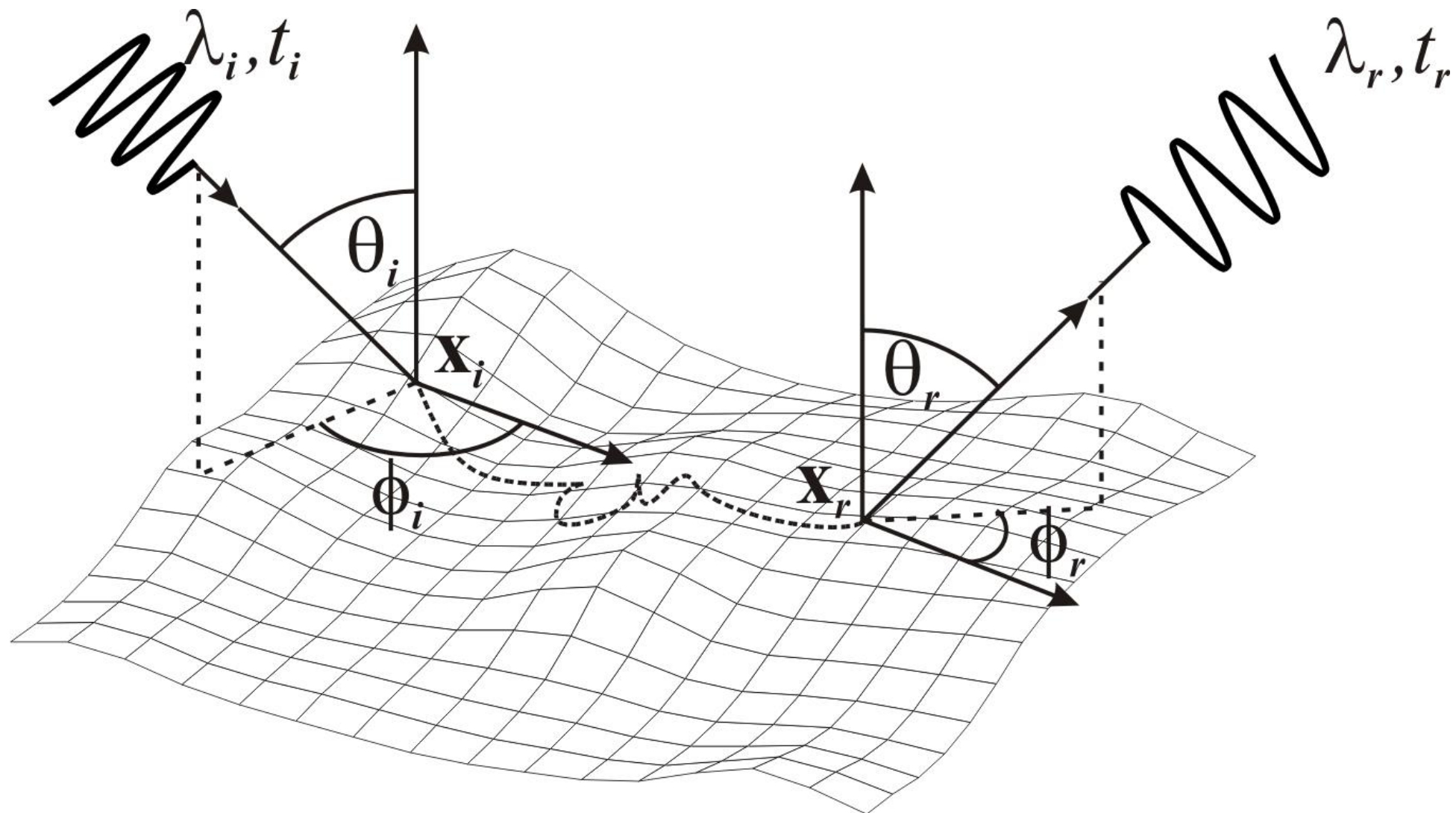
$$L(\mathbf{x} \rightarrow \vec{\omega}_o) = L_e(\mathbf{x} \rightarrow \vec{\omega}_o) + L_r(\mathbf{x} \rightarrow \vec{\omega}_o)$$

$$L_r(\mathbf{x} \rightarrow \vec{\omega}_o) = \int_{\vec{\omega}_i \in \Omega} L(\mathbf{x} \leftarrow \vec{\omega}_i) f(\mathbf{x}, \vec{\omega}_i \rightarrow \vec{\omega}_o) (\vec{\omega}_i \cdot \vec{\mathbf{n}}) d\vec{\omega}_i$$



Reflectance Scattering Function

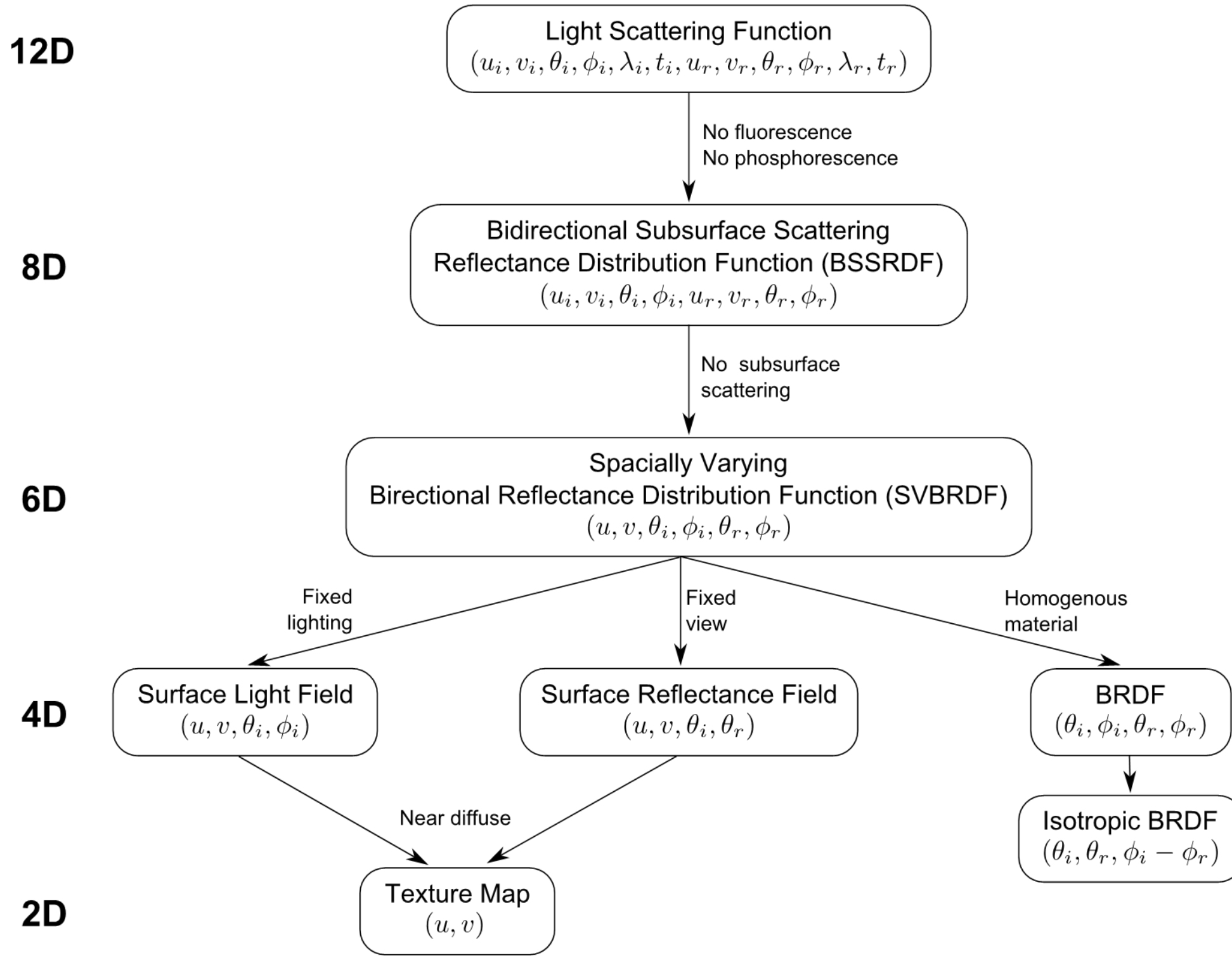
- 12D function
(Light and view direction, incident and outgoing surface point, wavelength, time)



Reflectance Scattering Function

- No mathematical formulation
- Measurement impractical
- Simplification by constrains on the set of possible reflectance effects
 - Phosphorescence
 - Fluorescence
 - Subsurface scattering
 - Specular scattering
 - Backscattering
 - Diffuse scattering

Reflectance Scattering Function



Reflectance Scattering Function

- BSSRDF (8D)
 - No fluorescence (no wavelength change)
 - No Phosphorescence (zero time light transport)
 - Subsurface scattering (translucent material)



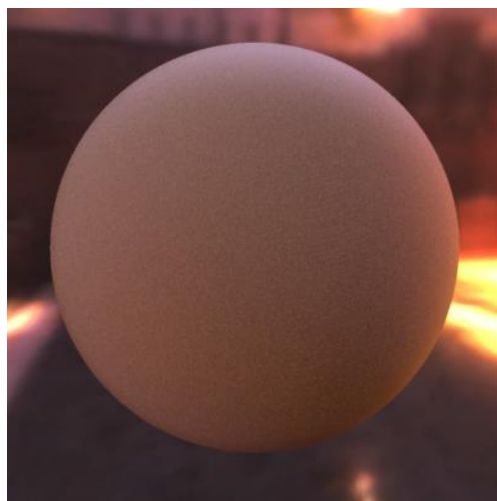
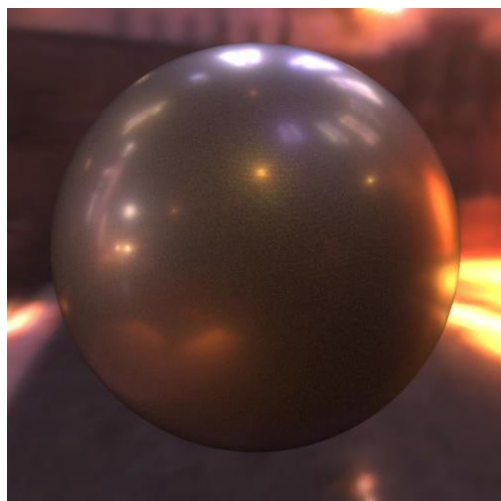
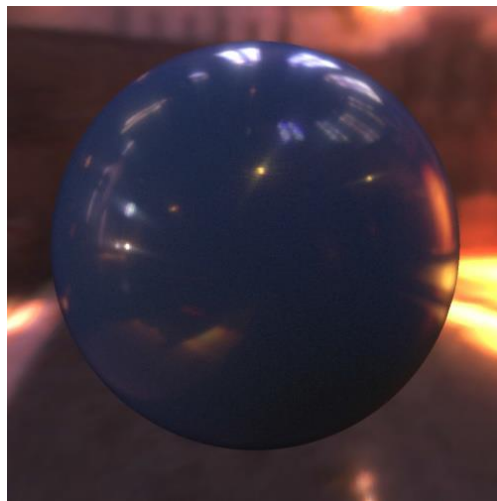
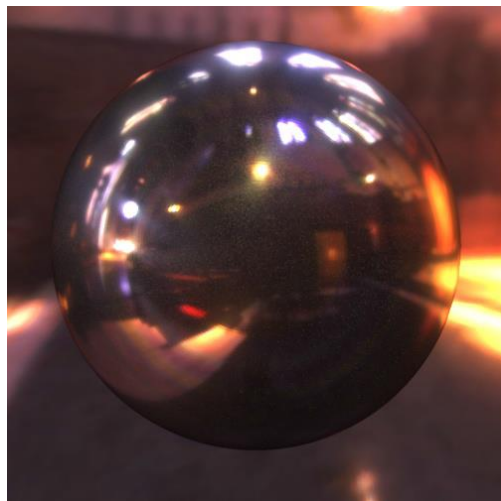
Reflectance Scattering Function

- SVBRDF (6D)
 - No Subsurface scattering (translucent material)
 - Opaque material (reflection on the same place)
 - Spatially varying glossy material



Reflectance Scattering Function

- BRDF (4D)
 - No spatially varying
 - Uniform material



Reflectance Scattering Function

- Light Field (4D)
 - Amount of light faring in every direction through every point in space (simplified plenoptic function)
 - Fixed lighting condition and variable view direction
 - Spatially varying
 - Image-based rendering (no geometry)
- Surface Reflectance Field (4D)
 - Fixed view position and variable light direction
 - Spatially varying
 - Image-based relighting (RTI)
 - Implicit geometry
 - No spatially varying
 - Uniform material

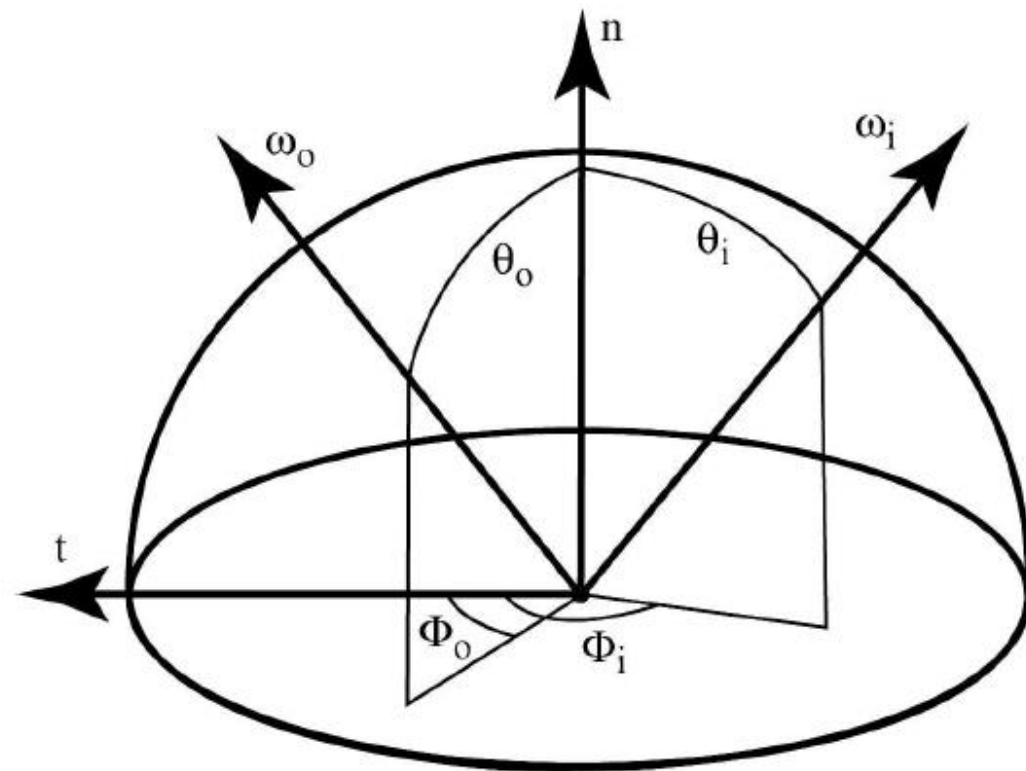
Visual Appearance: how to use?

- BSSRDF and BRDF
 - Model-based rendering
 - Explicit geometry
 - Modeling or acquisition of the appearance
 - Global illumination algorithm
 - More precise but computational heavy
- Light Field and Reflectance Field
 - Image based rendering
 - Set of photos (“interpolation”)
 - No geometry or “implicit” geometry
 - Realistic rendering but trade-off between data and precision

BRDF

$$f(\mathbf{x}, \vec{\omega}_i \rightarrow \vec{\omega}_o) = \frac{dL(\mathbf{x} \rightarrow \vec{\omega}_o)}{dE(\mathbf{x} \leftarrow \vec{\omega}_i)} = \frac{dL(\mathbf{x} \rightarrow \vec{\omega}_o)}{L(\mathbf{x} \leftarrow \vec{\omega}_i) \cos \theta d\vec{\omega}_i}$$

- Spatially varying (Heterogeneous materials)
- 6D Anisotropic



BRDF

- Properties

- Energy conservation $\int_{\Omega} f(\mathbf{x}, \vec{\omega}_i \rightarrow \vec{\omega}_o) \cos \theta d\vec{\omega}_i \leq 1$

- Helmholtz reciprocity $f(\mathbf{x}, \vec{\omega}_i \rightarrow \vec{\omega}_o) = f(\mathbf{x}, \vec{\omega}_o \rightarrow \vec{\omega}_i)$

- Simplification $f(u, v, \theta_i, \phi_i, \theta_o, \phi_o)$

- Isotropic material 5D $f(u, v, \theta_i, \theta_o, \phi_i - \phi_o)$

- Homogeneous materials 4D $f(\theta_i, \phi_i, \theta_o, \phi_o)$

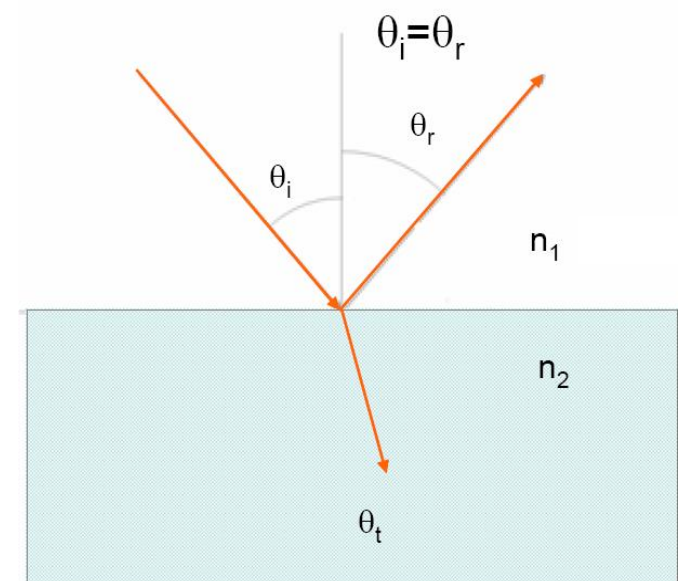
- Homogeneous and isotropic material 3D $f(\theta_i, \theta_o, \phi_i - \phi_o)$

BRDF Models

- General model to approximate the form of the BRDF (diffuse and specular reflection, off-specular scattering, backscattering)
- Smooth surface
 - Maxwell's equation, Snell's law, Fresnel's equation
- Empirical Model
 - Function controlled by few parameters related to the observed effects
- Analytical Model
 - Physical principles applied to the surface microstructure (physical based rendering)

Smooth Surface

- Surface flat and infinite when viewed at the scale of wavelength of light (Rayleigh criterion)
- Snell's law
 - Directionality of transmission and reflection
- Fresnel's equation
 - Fraction of light reflected
 - Schlick's approximation

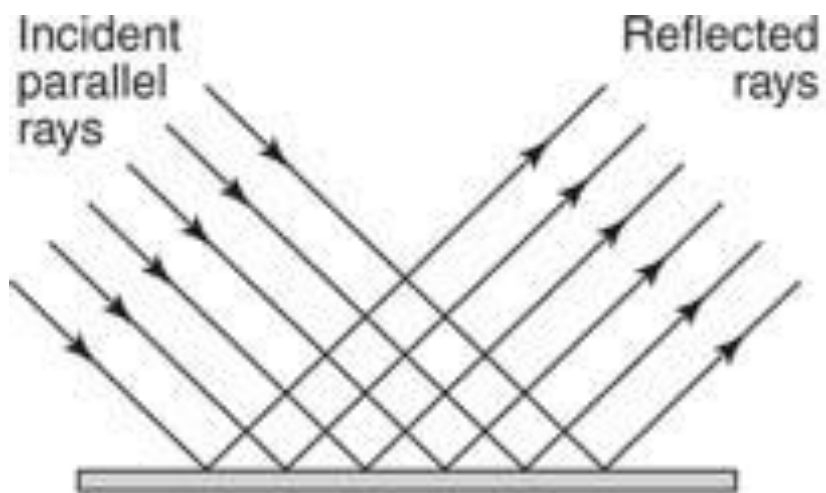
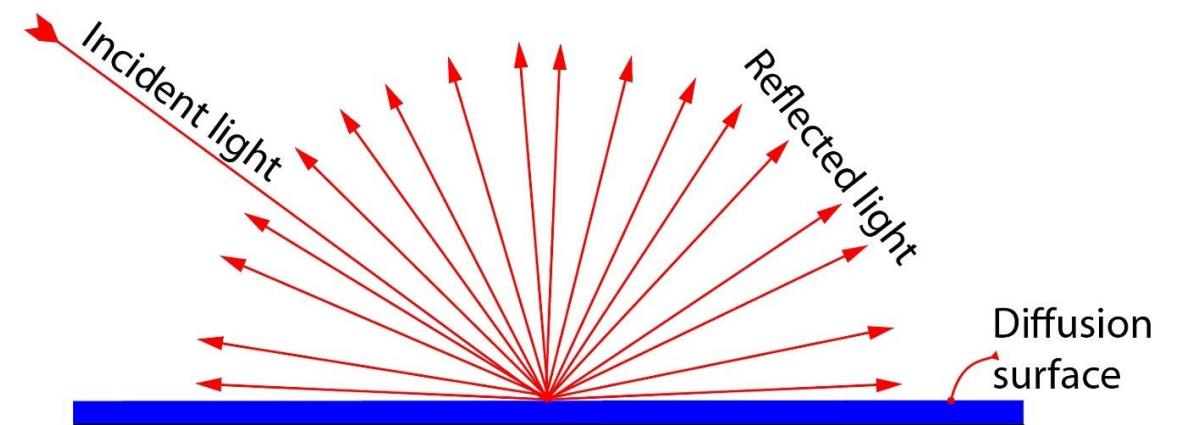


$$F(\theta) = F(0) + (1 - \cos \theta)^5 (1 - F(0))$$

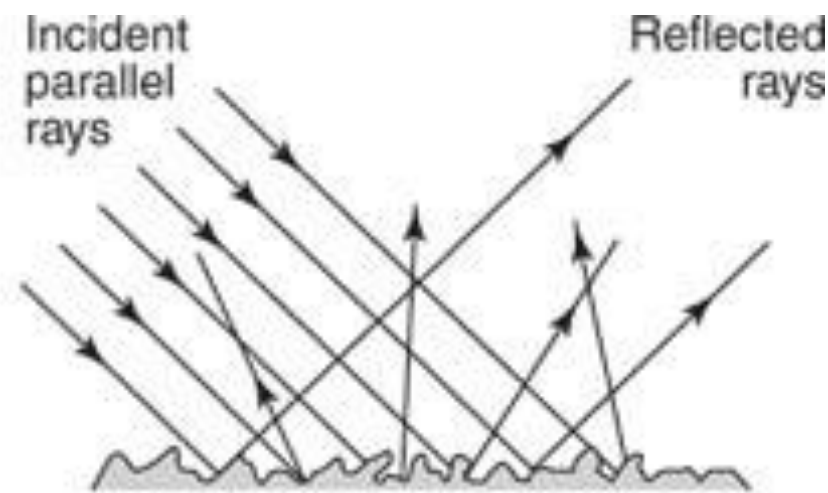
Lambertian BRDF

- Light is reflected equally in all directions

$$f(\mathbf{x}, \vec{\omega}_i \rightarrow \vec{\omega}_o) = \frac{\rho_d}{\pi}$$



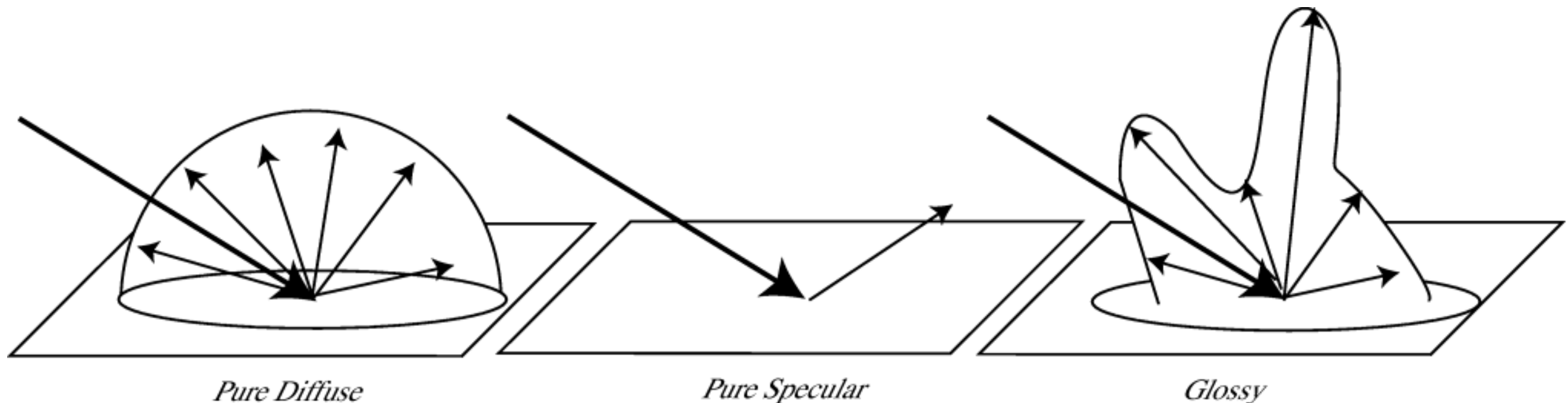
(a)



(b)

Specular and Glossy BRDF

- Specular BRDF
 - Light is reflected only in one direction
- Glossy BRDF
 - Light is reflected in many directions unequally



Phong and Blinn Models

- Phong

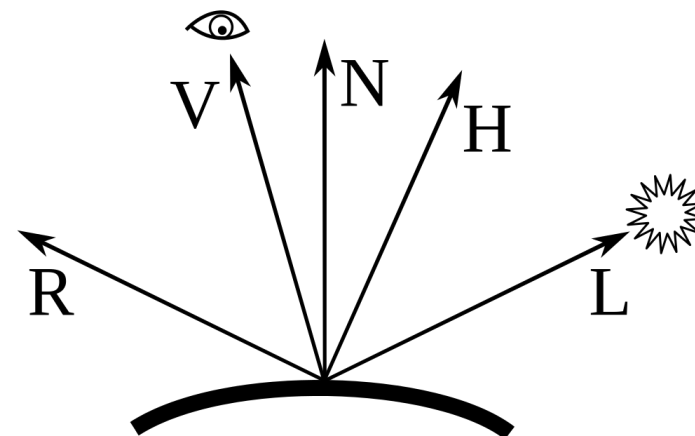
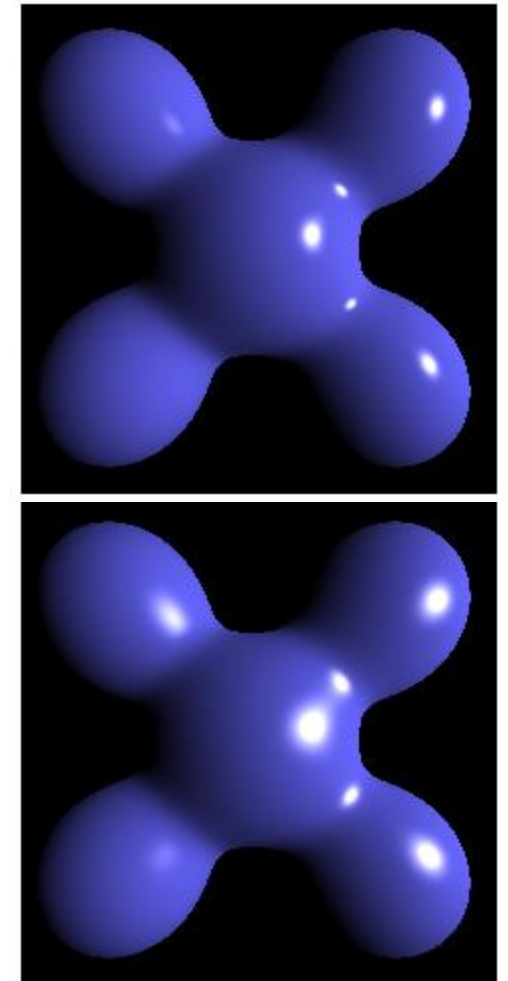
$$f(\mathbf{x}, \vec{\omega}_i \rightarrow \vec{\omega}_o) = k_d + k_s (R \cdot \vec{\omega}_o)^n$$

- Blinn-Phong

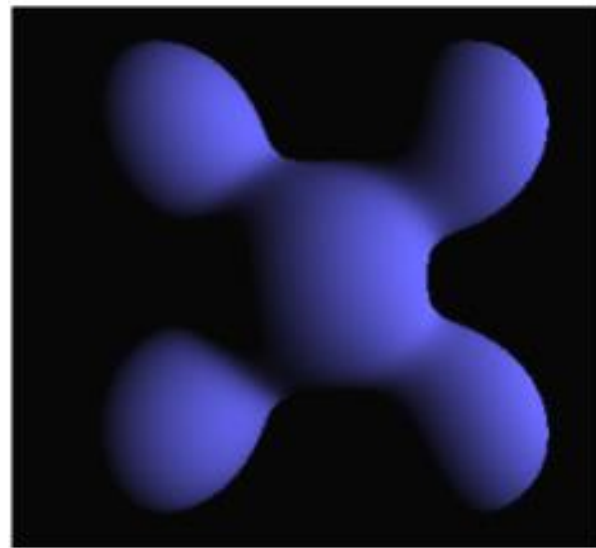
$$f(\mathbf{x}, \vec{\omega}_i \rightarrow \vec{\omega}_o) = k_d + k_s (N \cdot H)^n$$

- Issues

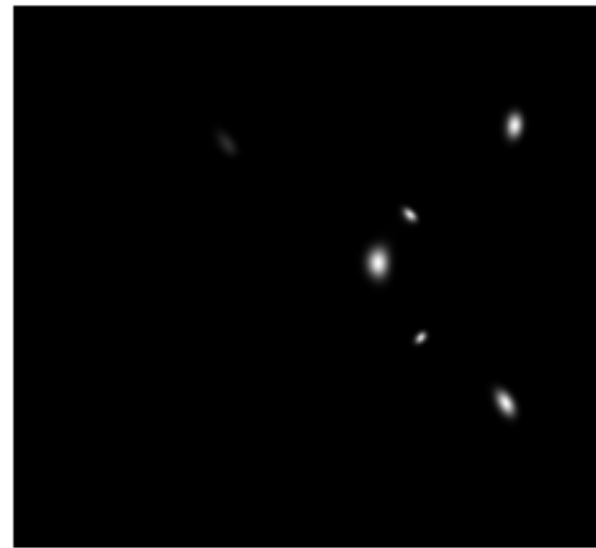
- Non reciprocal
- Non energy conserving



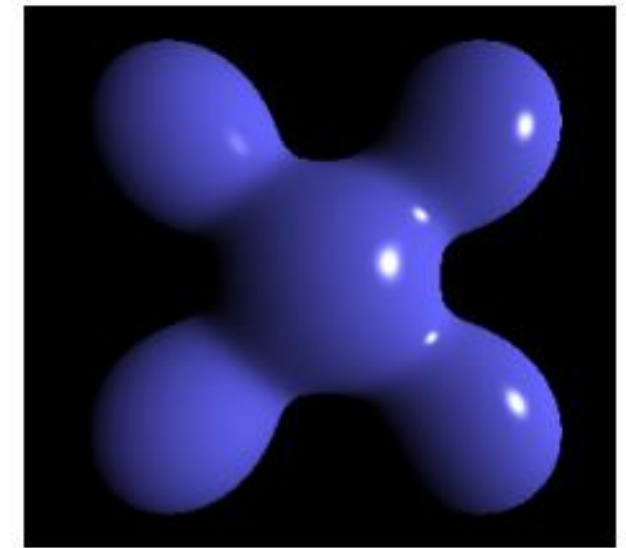
Phong Model



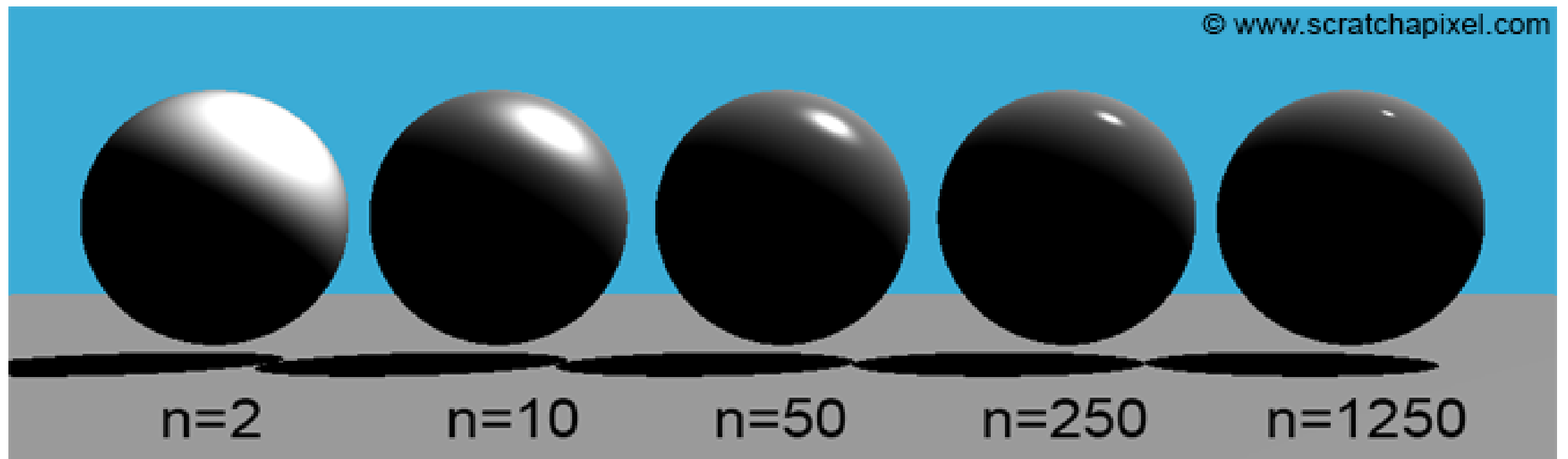
DIFFUSE



SPECULAR



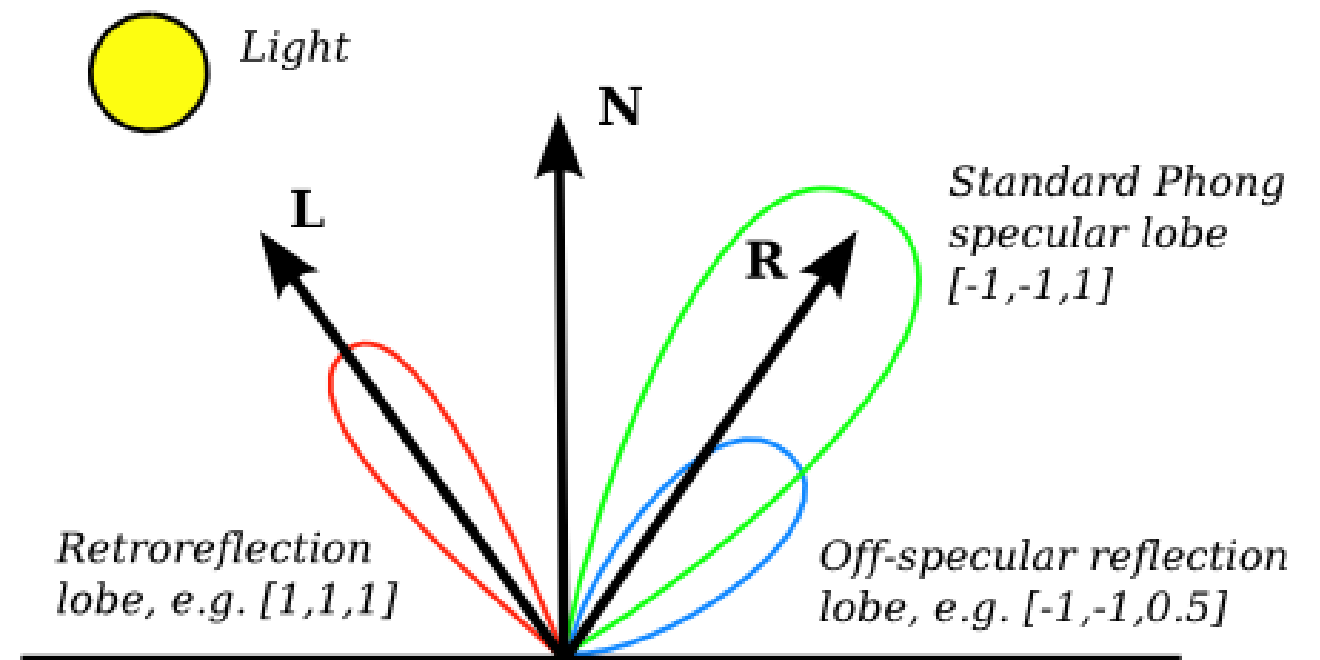
FINAL APPEARENCE



Lafortune Model

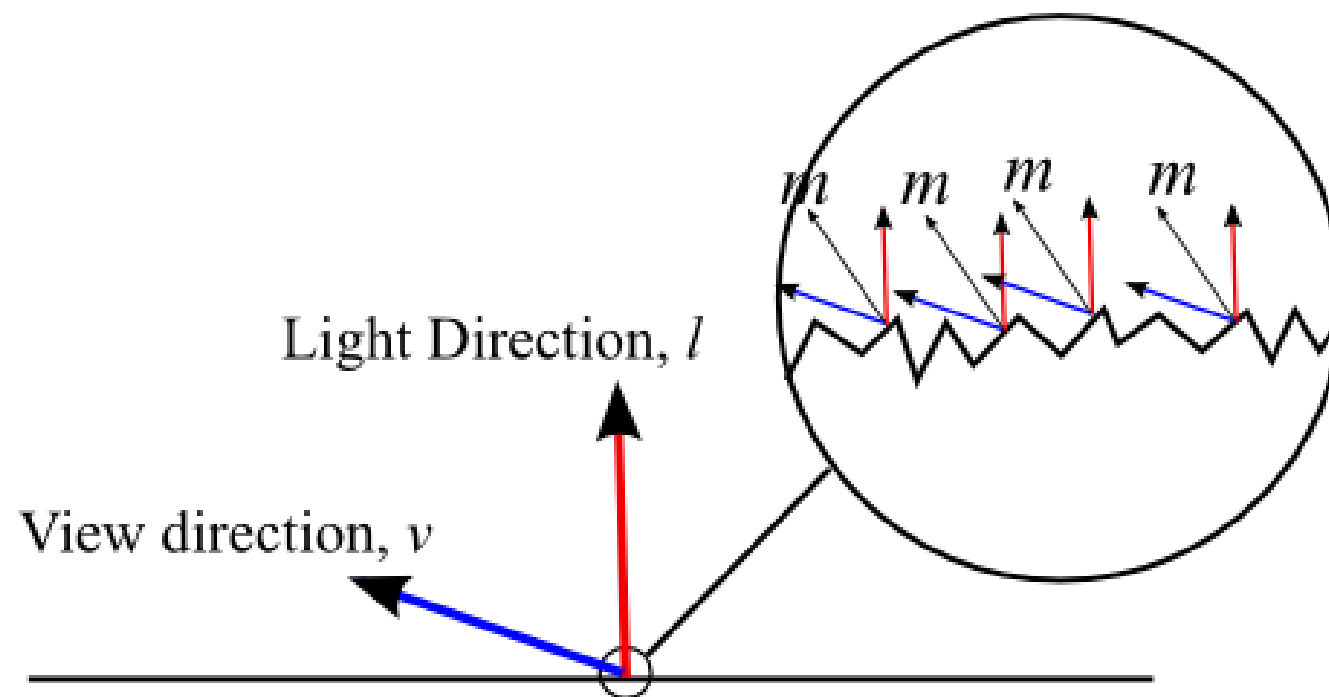
$$f(\mathbf{x}, \vec{\omega}_i \rightarrow \vec{\omega}_o) = f(\mathbf{x}, \vec{\mathbf{u}} \rightarrow \vec{\mathbf{v}}) = \rho_s (C_x u_x v_x + C_y u_y v_y + C_z u_z v_z)^n$$

- Definition of lobes around any axes
- By appropriate normalization, a lobe conserves energy and obeys reciprocity
- Mechanism to model backscattering



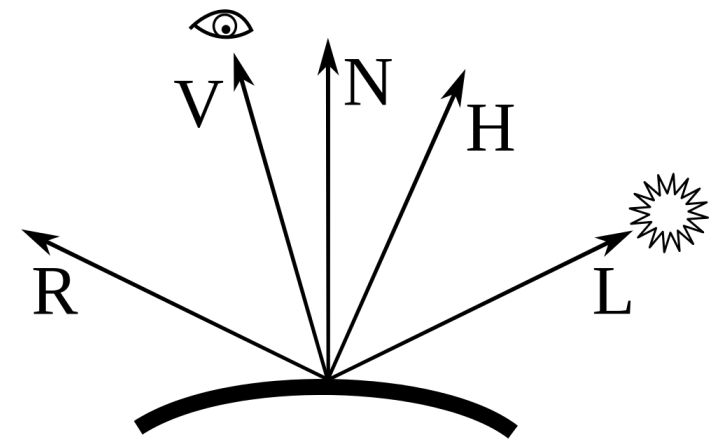
Physical based model

- Microfacet theory
 - Surface is composed of many micro-facets and each micro-facet will only reflect light in a single direction according to their normal



Physical based model

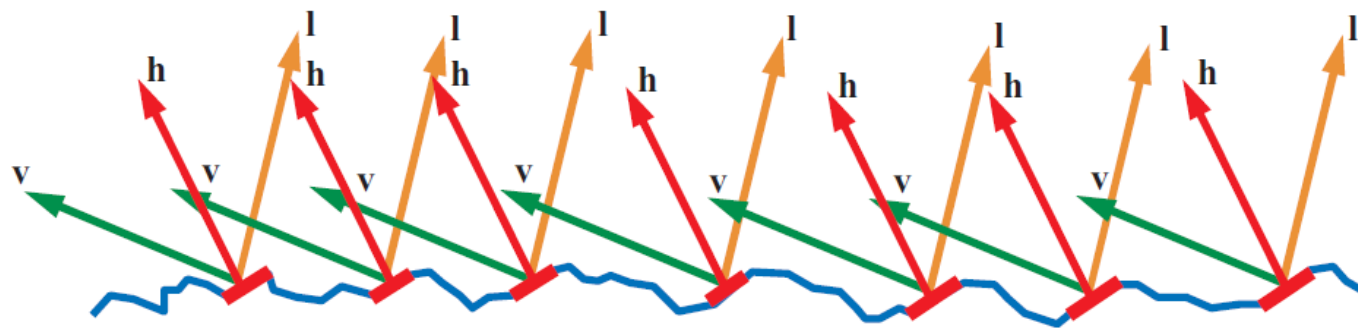
$$f(\vec{l} \rightarrow \vec{v}) = \frac{F(\vec{l}, \vec{h})G(\vec{l}, \vec{v}, \vec{h})D(\vec{h})}{4(\vec{n} \cdot \vec{l})(\vec{n} \cdot \vec{v})}$$



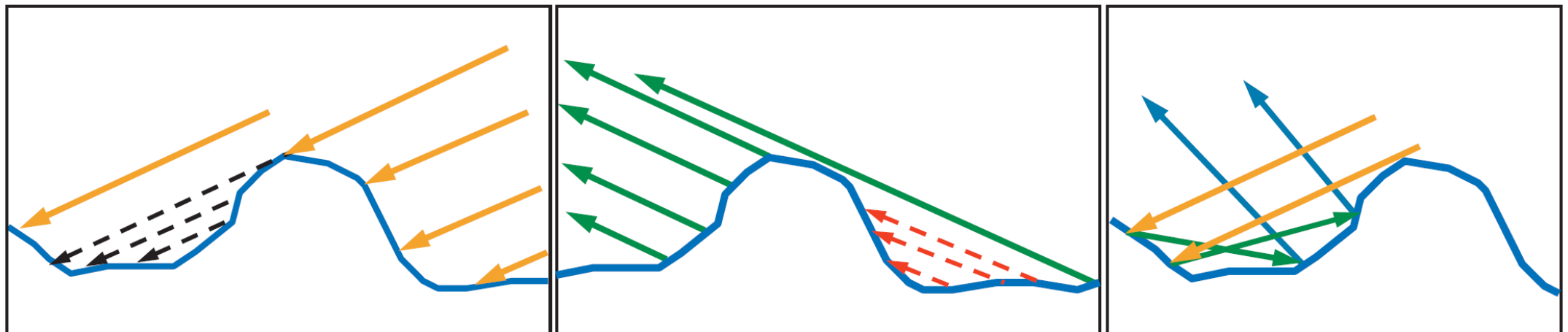
- Fresnel reflectance F
- Shadowing-masking function G
 - Percentage of the microfacets with normal equals to \vec{H} are not shadowed or masked
- Microfacet normal distribution function D
 - Concentration of microfacets which are oriented thus that they could reflect light from \vec{l} into \vec{v}

Physical based model

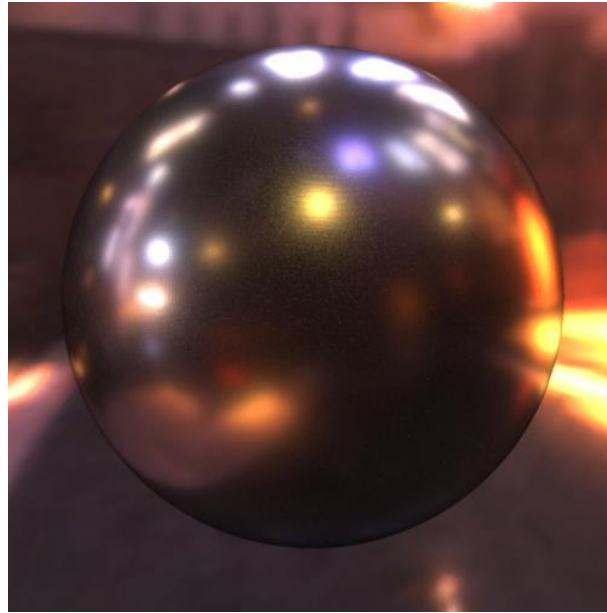
- The product of function D and G gives the concentration of active microfacets, that reflects light from l to v
- Shadowing-masking function G



- Microfacet normal distribution function D



BRDF Models Comparison



REFERENCE

BLINN-PHONG



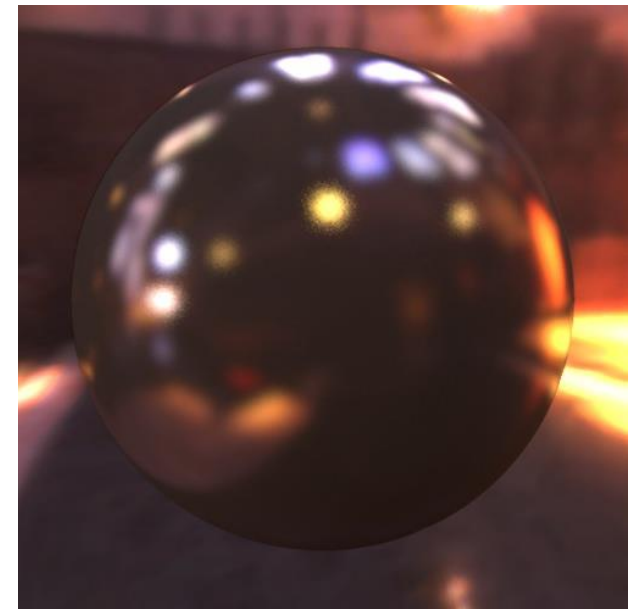
0.191

LAFORTUNE



0.123

COOK-TORRANCE



0.114

BRDF Measurement

- Acquiring outgoing radiance for each point from different view direction and by lighting the point from different light direction
 - Store the data in tabular form
 - Non-linear minimization to fit a parametric models to the acquire data

Gonioreflectometer

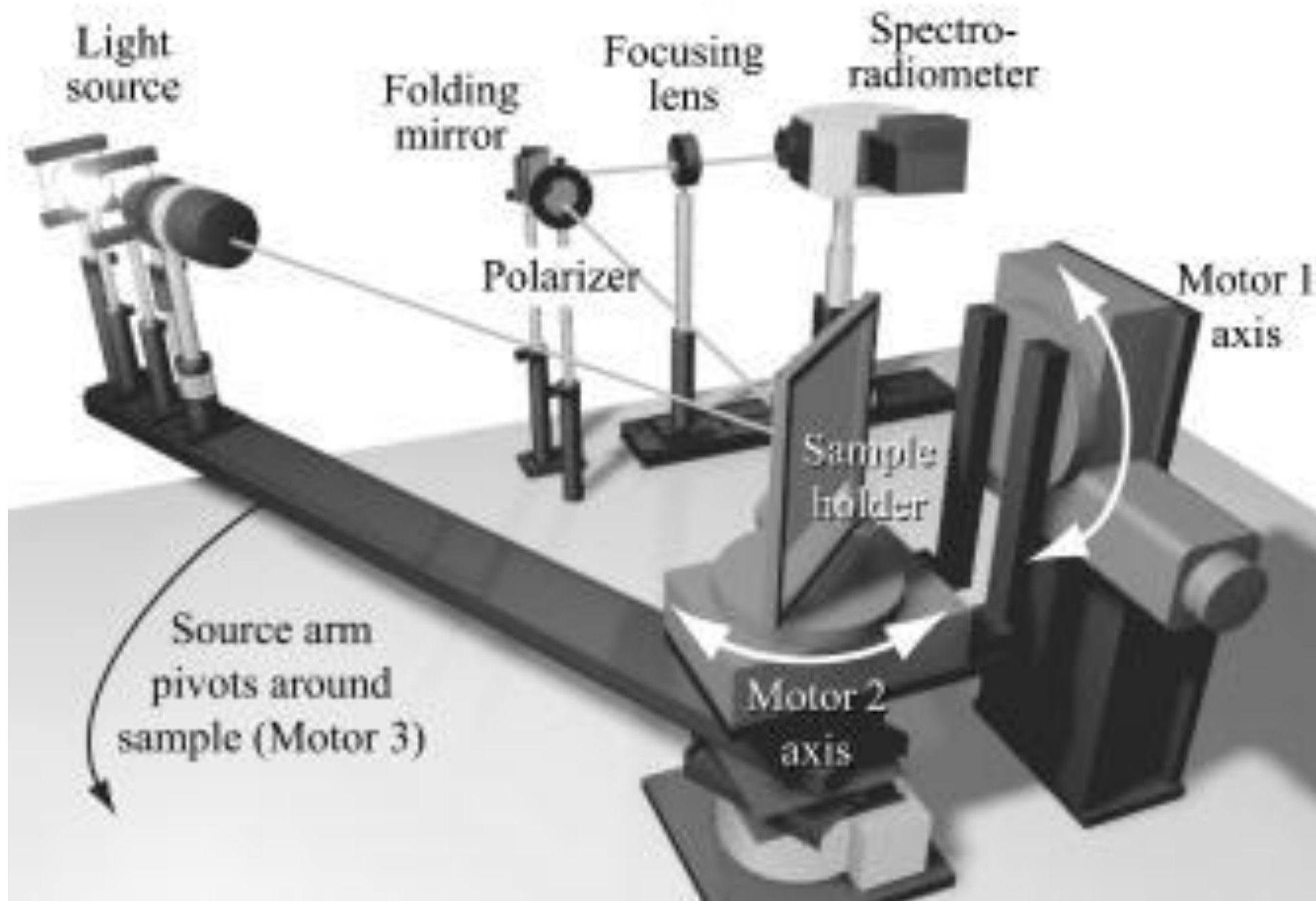


Image-based measurements

[Lensch et al., TOG 03]

- Image-based acquisition in a dark room with a single light
- Automatic identification of the main materials

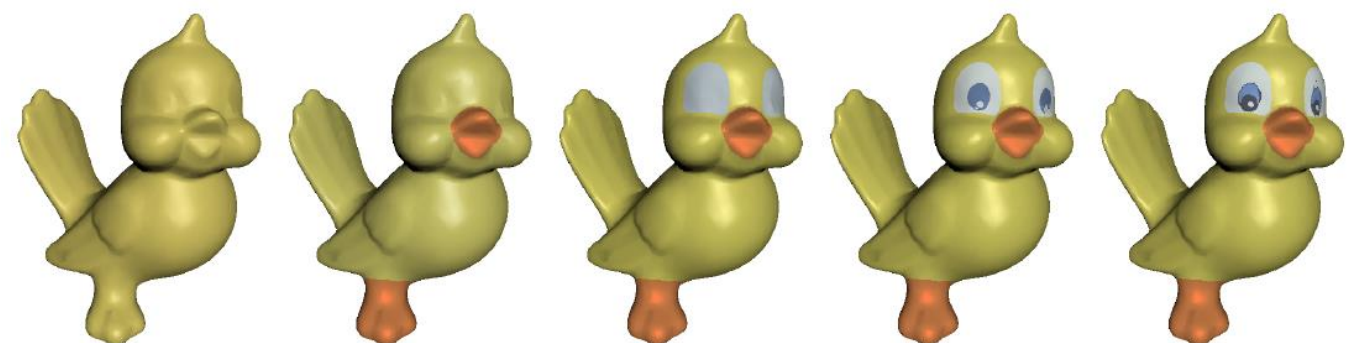
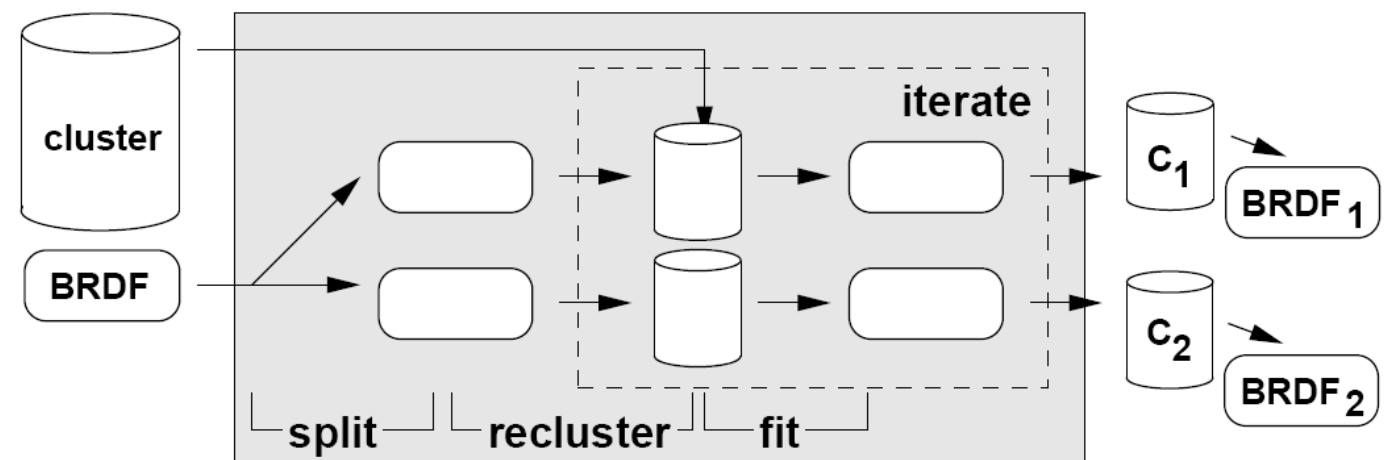
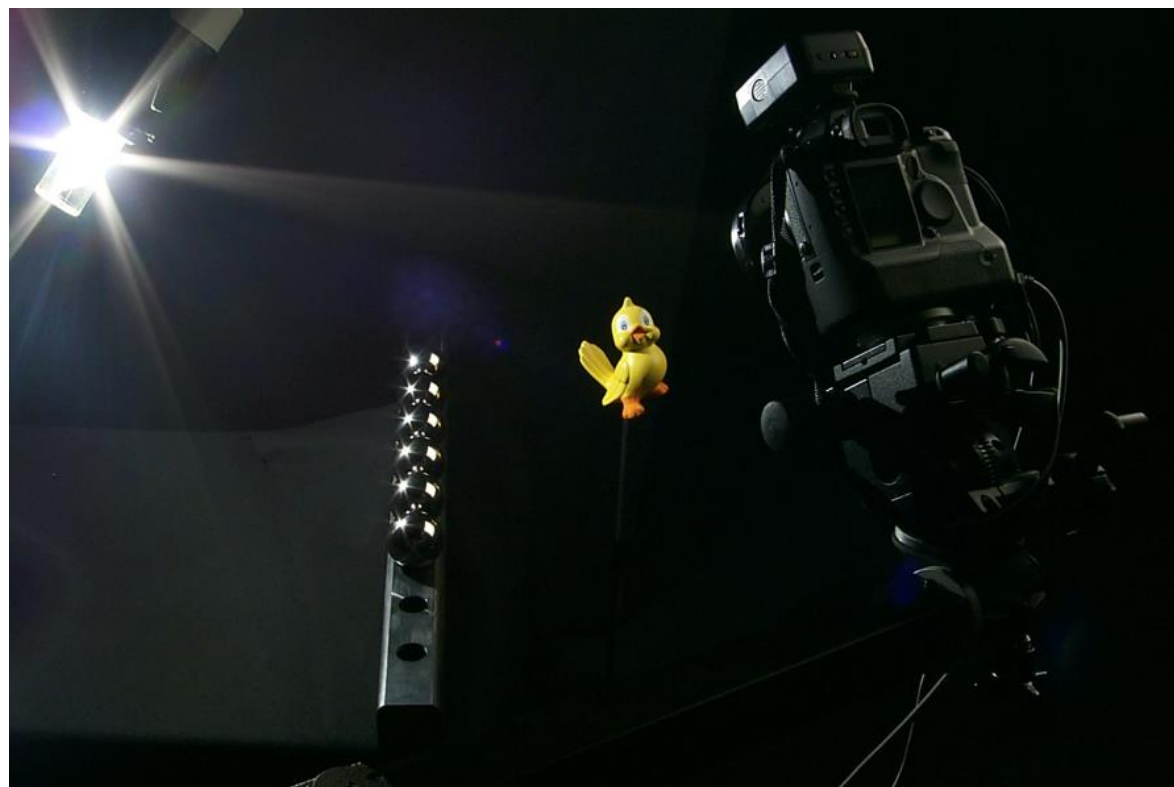
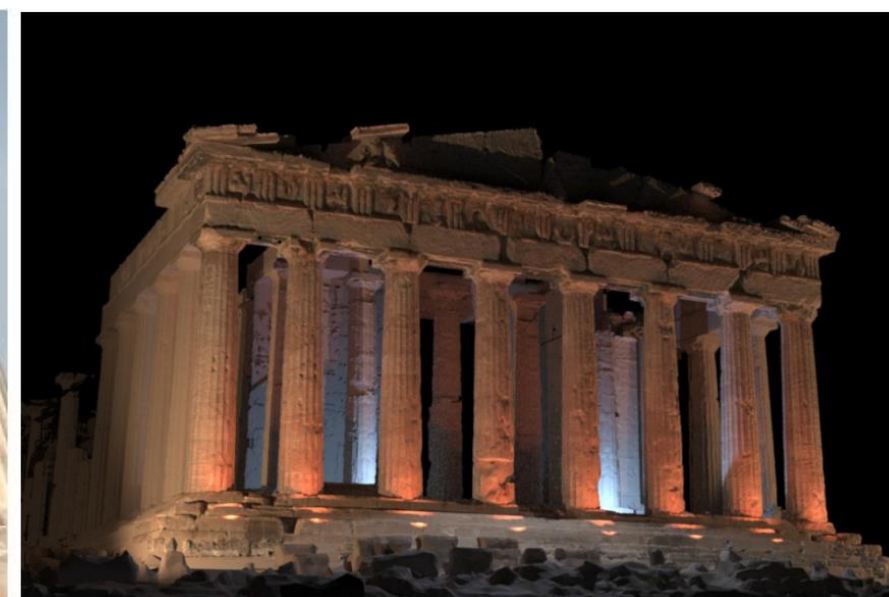


Image-based measurements

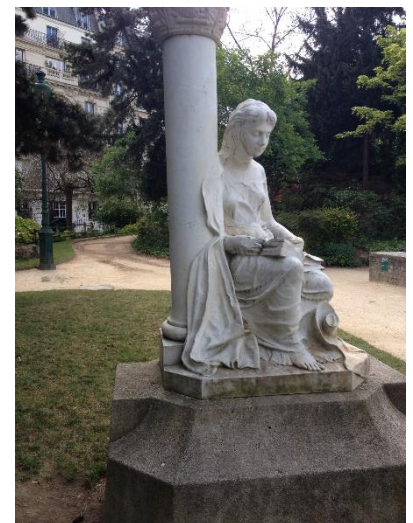
[Debevec et al., 2004]

- Acquisition of complex scene under natural illumination condition
- BDRF measurement of a set of representative samples.
- Assign the BRDF using a small set of photo under natural illumination



Perceived Color

- The simplest approximation of the appearance is just a simple color for point
- Even if some 3D scanner return color information, this data has low quality
- Solution: ad-hoc photographic campaign and projection on the 3D geometry



Perceived Color Reprojection

- Inverse projection, transferring the color from the images to the 3D surface
- Issues
 - Align each photo to the 3D models (camera calibration)
 - How to reproject the color on the 3D surface
 - How to select the most correct color

Image-to-Geometry Registration

- Estimate for each photo the pin-hole camera model parameters (intrinsic and extrinsic parameters w.r.t. the reference system of the 3D models)
- Manual method - Selection of 2D-3D (x , X) correspondences and non-linear minimization algorithm

$$\min_P \|PX - x\|^2$$

- Automatic method

Image-to-Geometry Registration

[Franken et al., 2005]

- Select pairs of correspondences (2D-to-3D, 2D-to-2D) to compute the camera parameters
- Graph of correspondences to infer new 2D-to-3D pairs and to help the user to complete the registration
- Manual selection (possible inaccuracies, time-consuming)

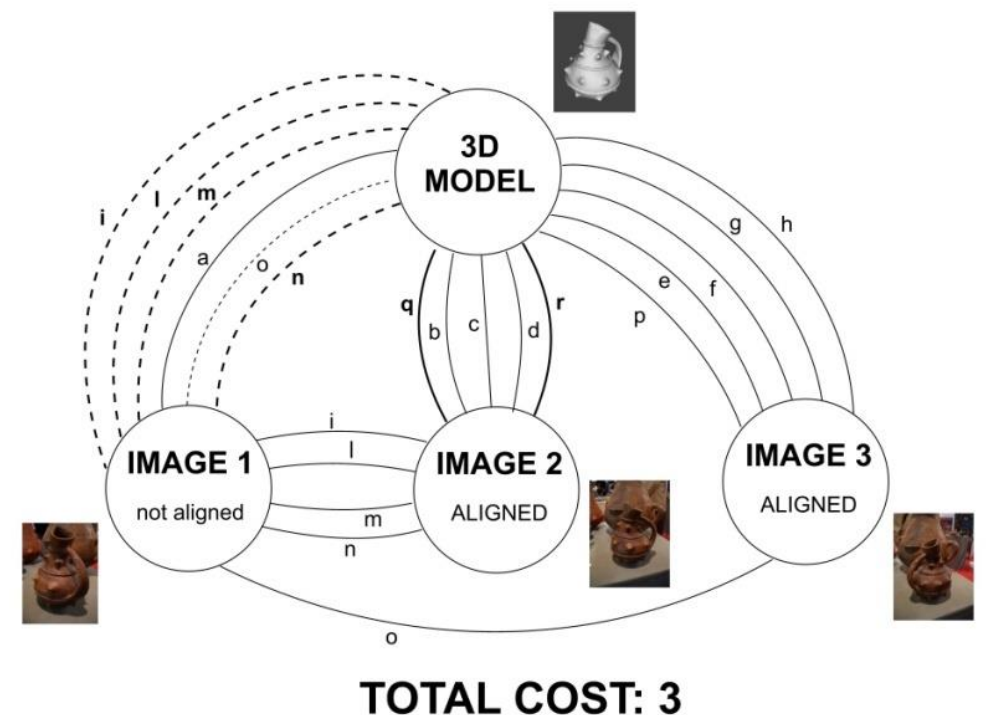
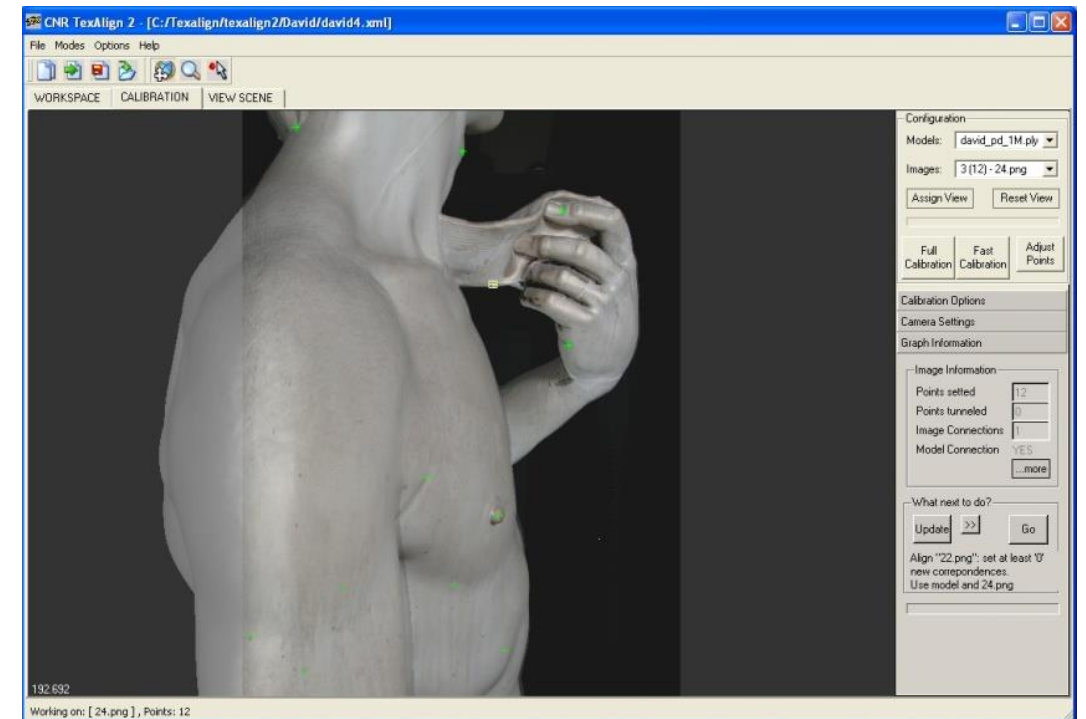


Image-to-Geometry Registration

[Lensch et al., GM 01]

- Compute the silhouette on image
- Render the 3D model and compute the silhouette
- Compute the pixels covered by just one silhouette
- Greedy iteration, by small rotation, until silhouette matching error is below a threshold
- Limitation
 - Silhouette extraction
 - All object visible in each image

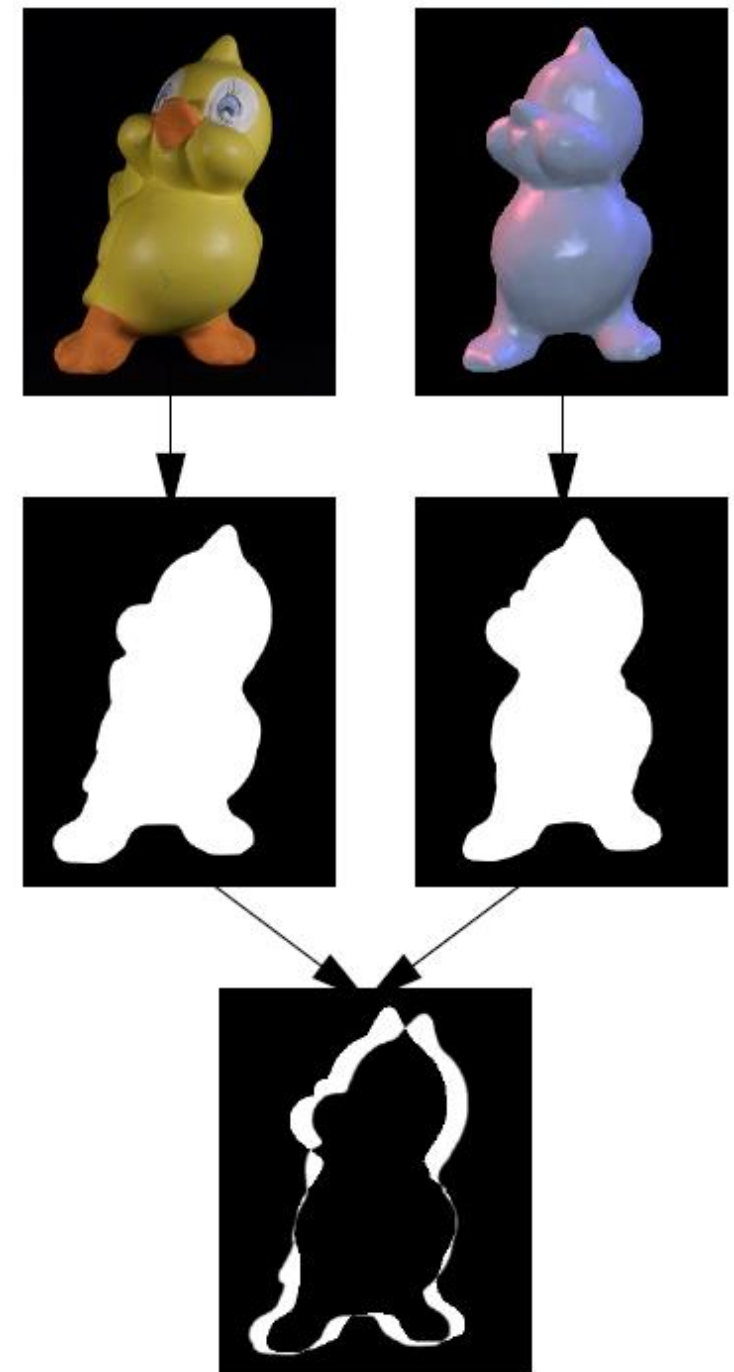


Image-to-Geometry Registration

- Mutual Information

The amount of information about a random variable B that a random variable A contains

$$M(I_A, I_B) = \sum_{(a,b)} p(a, b) \log \left(\frac{p(a, b)}{p(a)p(b)} \right)$$

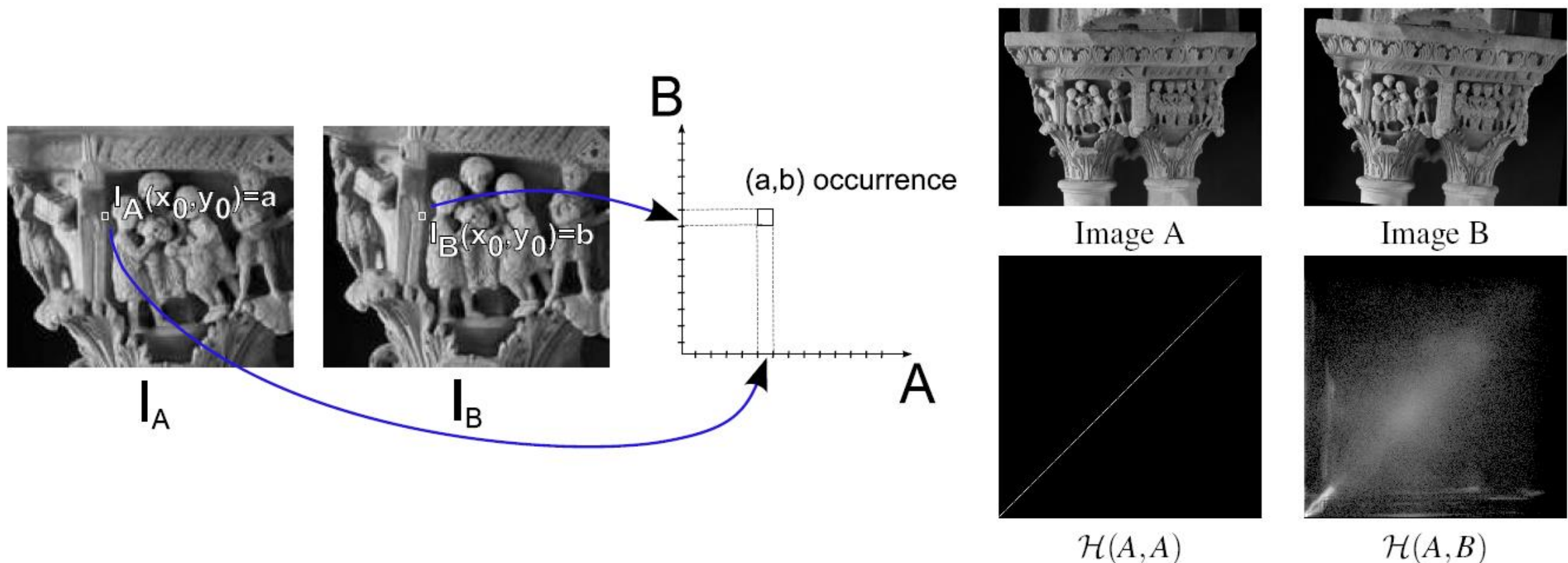


Image-to-Geometry Registration

[Corsini et al., PG 09]

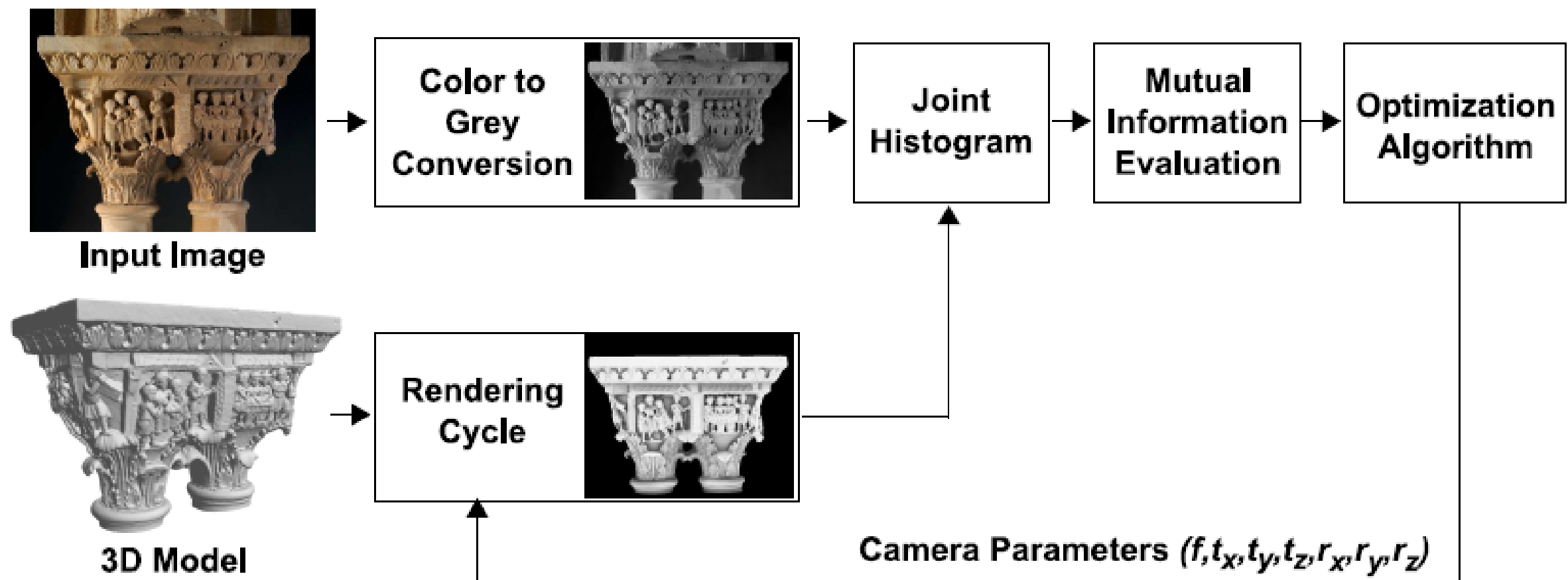
- Correlate the shading variations on the image with a particular rendering of the 3D model using the Mutual Information
 - Normal map
 - Ambient occlusion
 - Reflection map
 - Combined version



Image-to-Geometry Registration

[Corsini et al., PG 09]

- Algorithm overview



Encoding of the Color

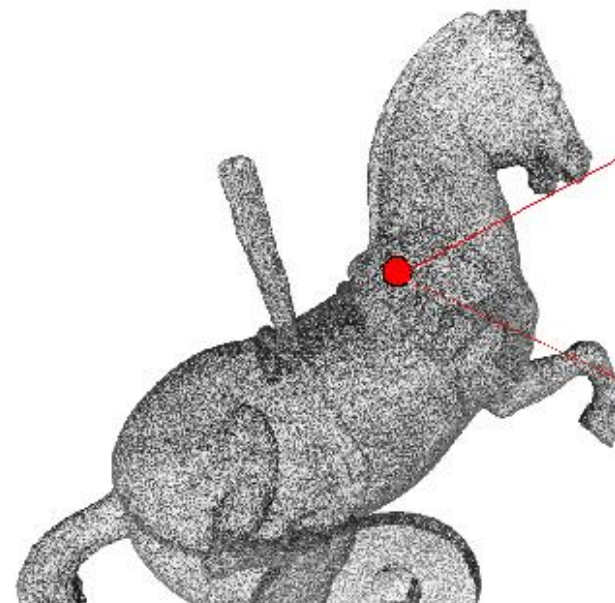
- Texture
 - Compute a texture parametrization



- Per-vertex color
 - Store the color for each vertex
 - Inside the triangle the color is obtained with barycentric interpolation

Color Integration

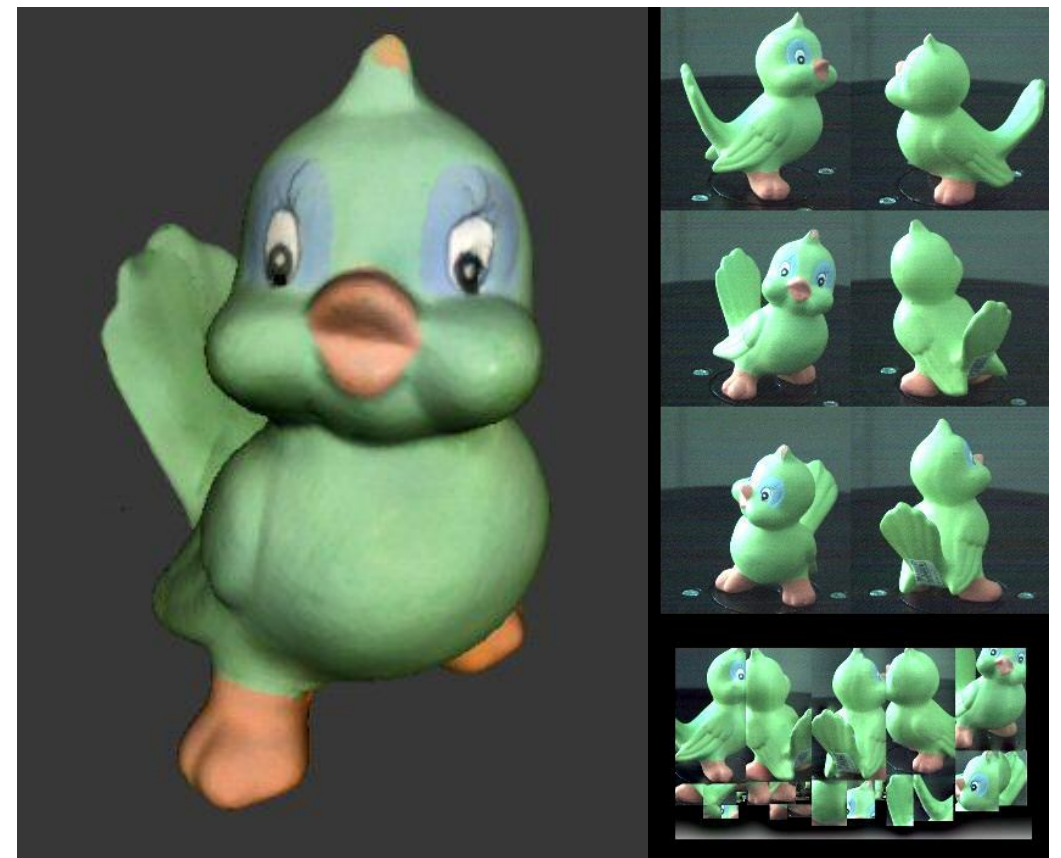
- How to select the most correct color
 - Select the right color among different images
 - Dealing with discontinuities between images that cover adjacent area
 - Reducing the illumination-related artifact (shadows, highlight)



Automatic Texture Mapping

[Callieri et al., VMV 03]

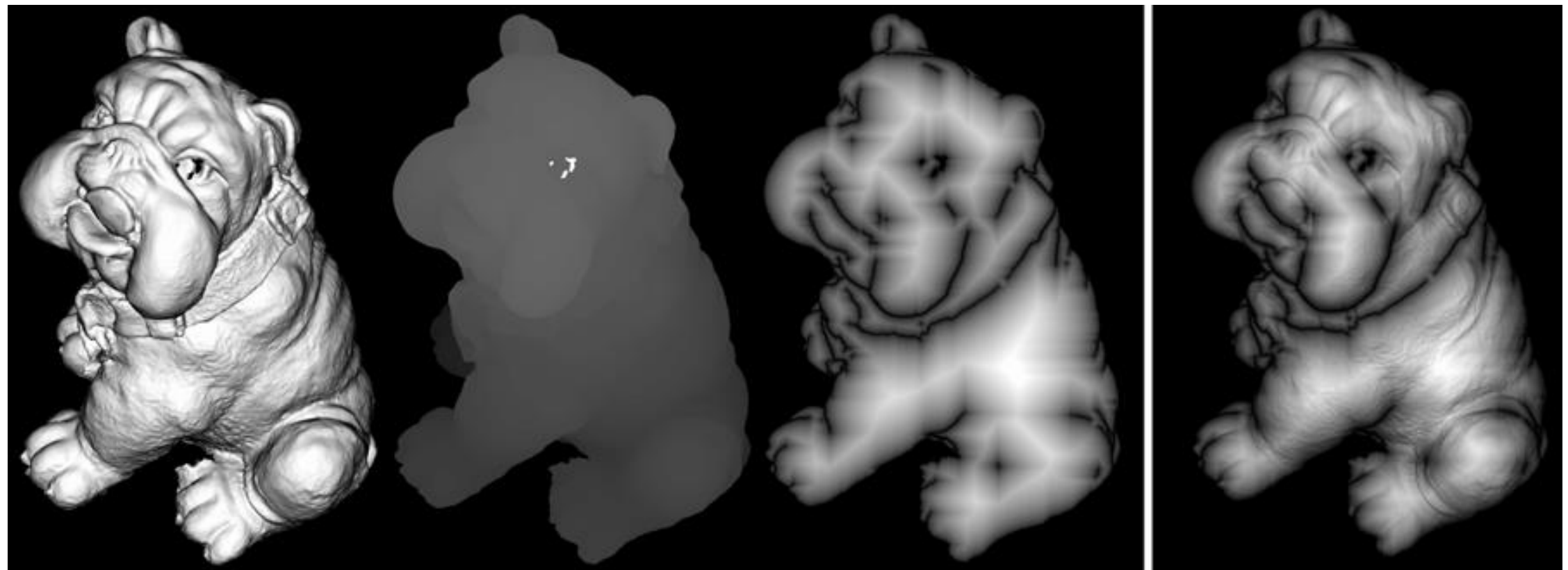
- For each area, the better (orthogonal) photo is chosen
- Mesh is split according to the photo allocation and parametrized using perspective projection
- From photos, the used area is cut and packed in the texture
- Color discordances on borders are corrected



Color Blending

[Callieri et al., C&G 08]

- Classify the quality of each pixel to compute the weighting blending
- Compute multiple masks for each images (View angle, depth, distance from border, stencil, focus, etc.)
- Compose the mask and use result as per-pixel weighting factor



References

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