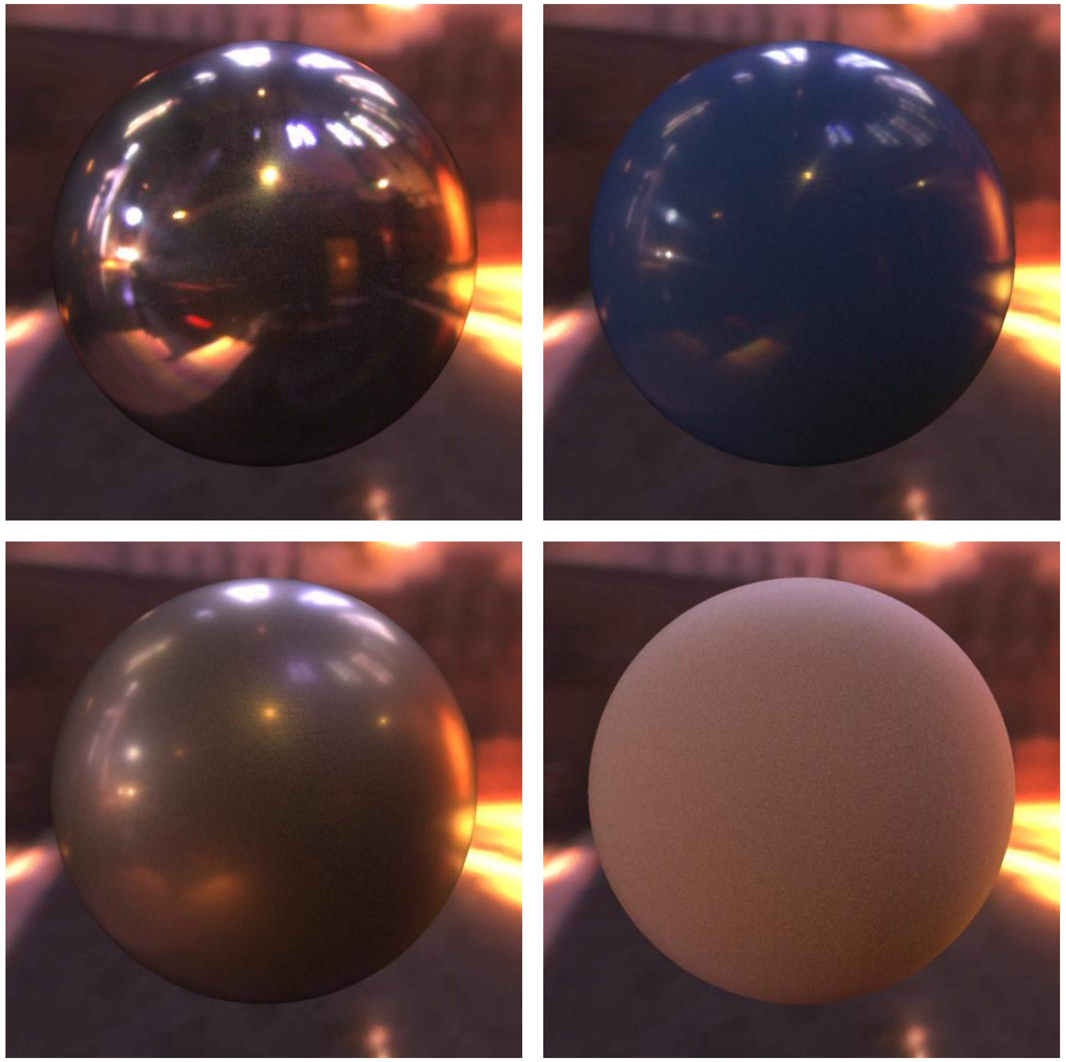
Visual Appearance and Color

Gianpaolo Palma

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

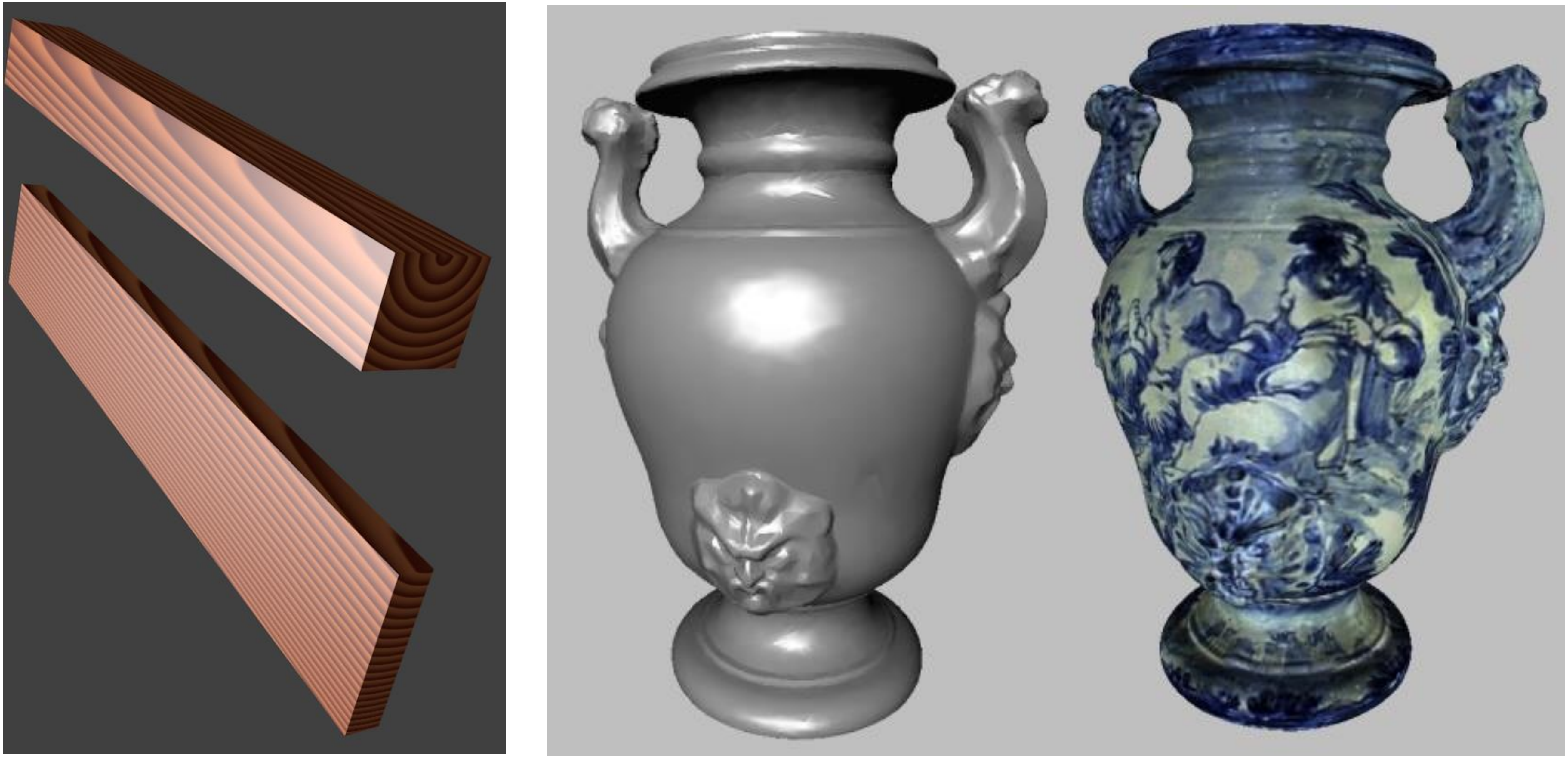
PHOTO RENDERING

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

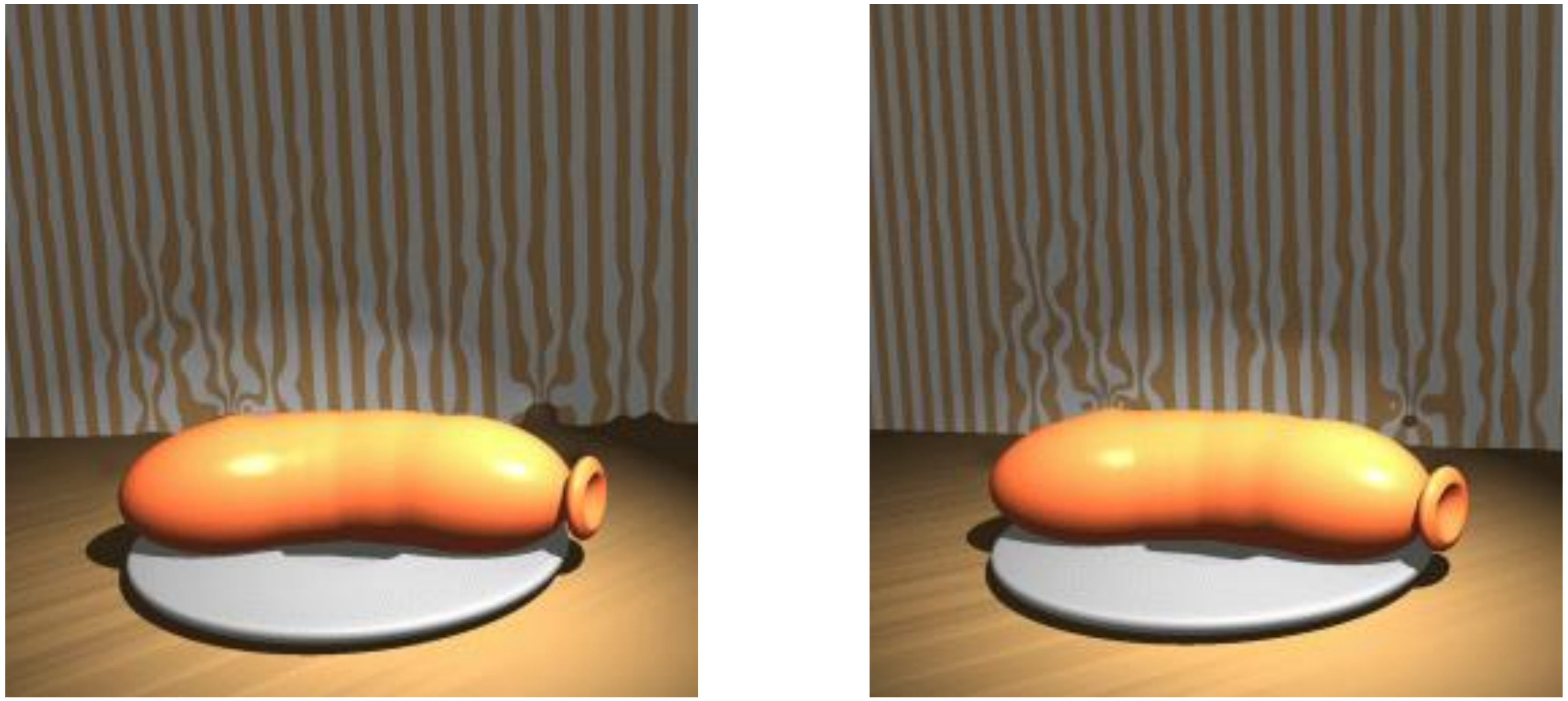


Physical-based Rendering

- 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

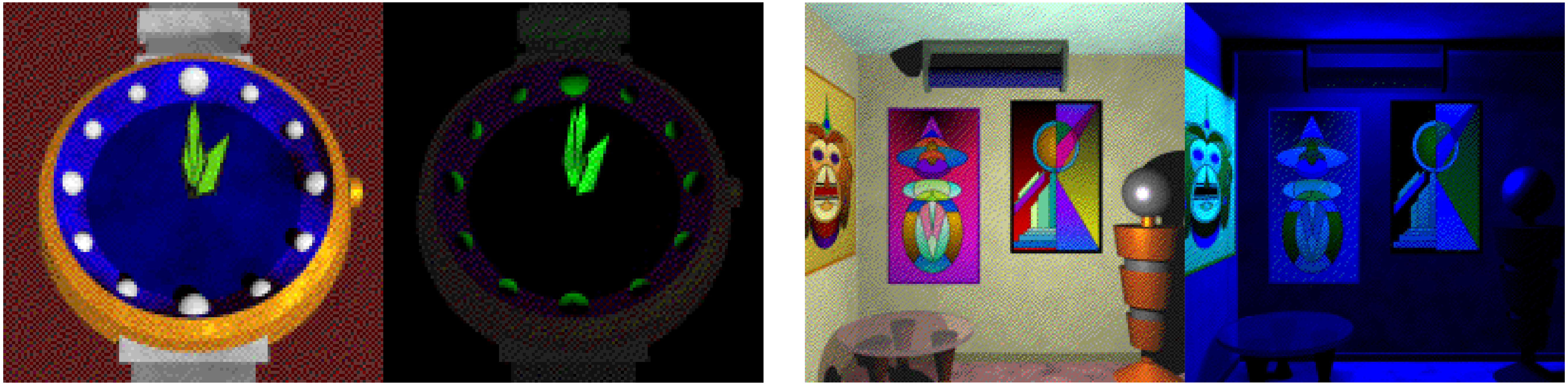
Model of light

- 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

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

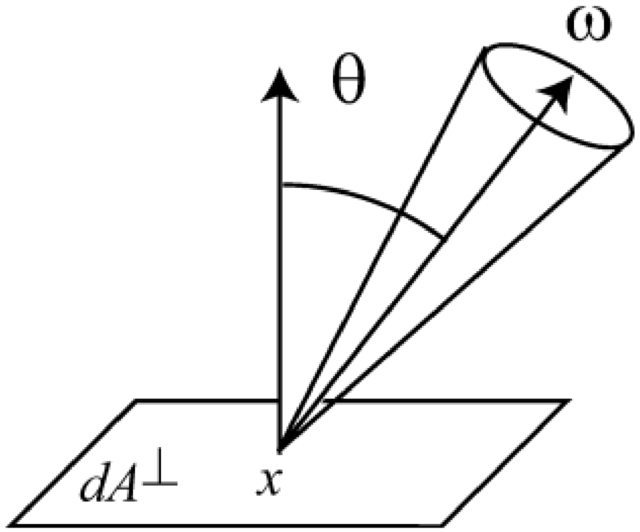
- Irradiance: power per unit area
    - Measured in Watts/meter^2

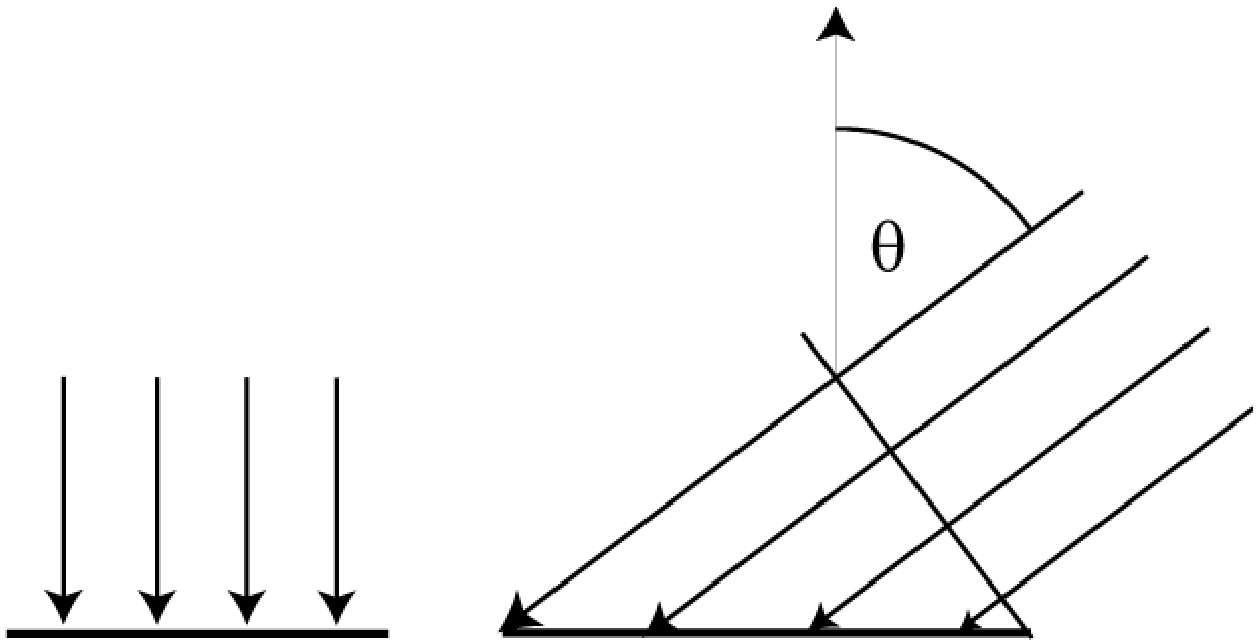
$$E = \frac{d\Phi}{dA}$$

Radiance

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

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



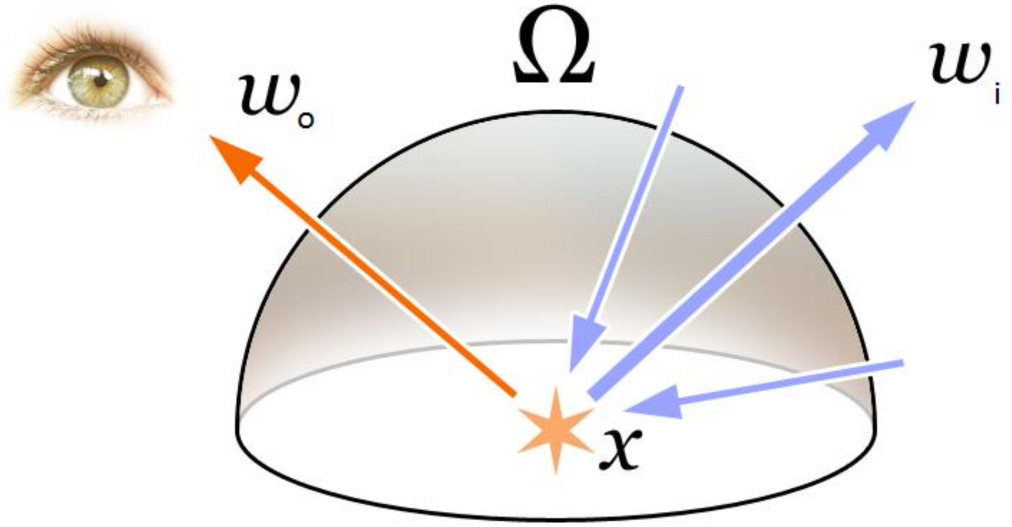


Rendering Equation

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

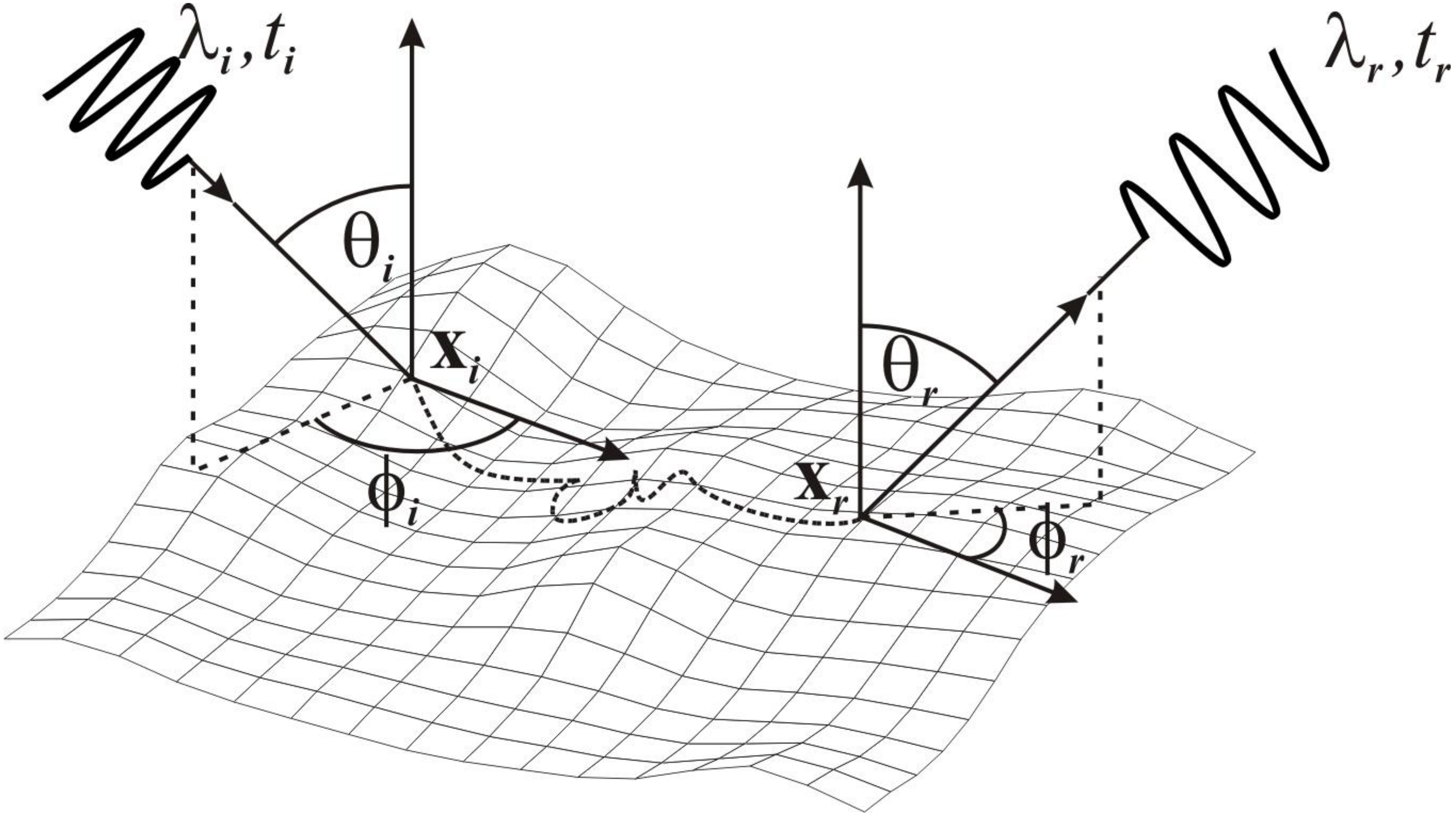
$$L(\mathbf{x} \rightarrow \vec{\omega}_o) = L_e(\mathbf{x} \rightarrow \vec{\omega}_o) + L_r(\mathbf{x} \rightarrow \vec{\omega}_o)$$

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



Reflectance Scattering Function

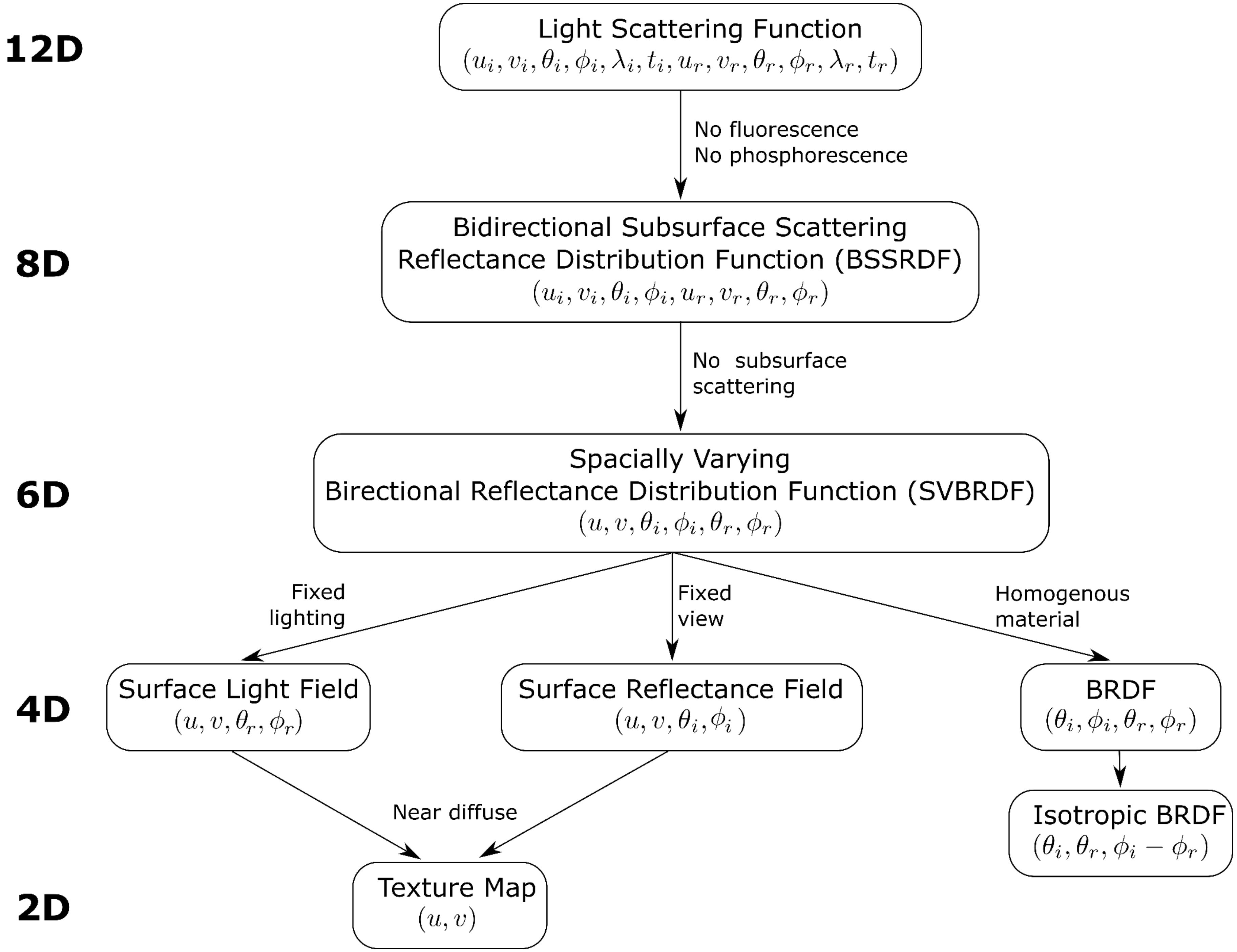
- 12D function
  (Light and view direction, incident and outgoing surface point, wavelength, time)



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



12D

Light Scattering Function
$(u_i, v_i, \theta_i, \phi_i, \lambda_i, t_i, u_r, v_r, \theta_r, \phi_r, \lambda_r, t_r)$

No fluorescence
No phosphorescence

8D

Bidirectional Subsurface Scattering Reflectance Distribution Function (BSSRDF)
$(u_i, v_i, \theta_i, \phi_i, u_r, v_r, \theta_r, \phi_r)$

No subsurface scattering

6D

Spacially Varying Birectional Reflectance Distribution Function (SVBRDF)
$(u, v, \theta_i, \phi_i, \theta_r, \phi_r)$

Fixed lighting

Fixed view

Homogenous material

4D

Surface Light Field
(u, v, θ_r, ϕ_r)

Surface Reflectance Field
(u, v, θ_i, ϕ_i)

BRDF
$(\theta_i, \phi_i, \theta_r, \phi_r)$

Isotropic BRDF
$(\theta_i, \theta_r, \phi_i - \phi_r)$

Near diffuse

2D

Texture Map
(u, v)

Reflectance Scattering Function

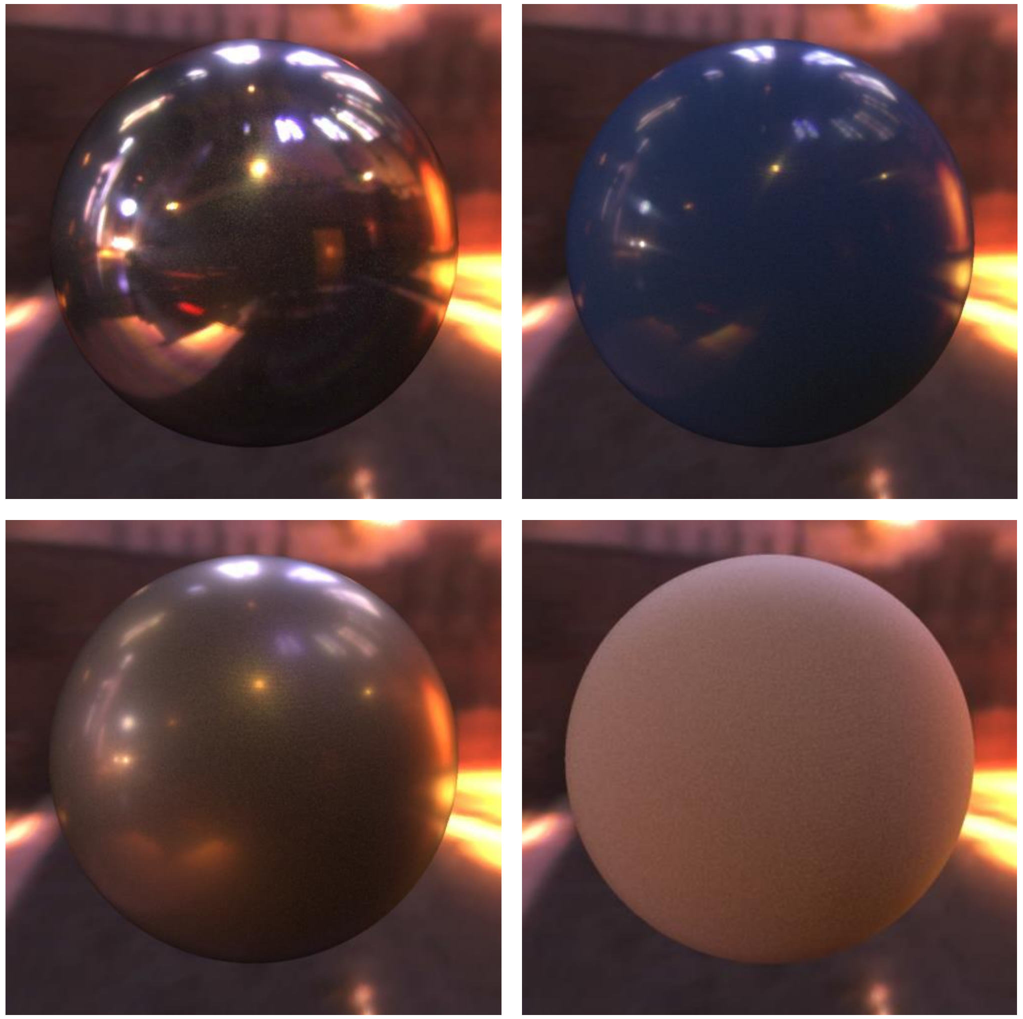
- BSSRDF (8D)
  - No fluorescence (no wavelength change)
  - No Phosphorescence (zero time light transport)
  - Subsurface scattering (translucent material)

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?

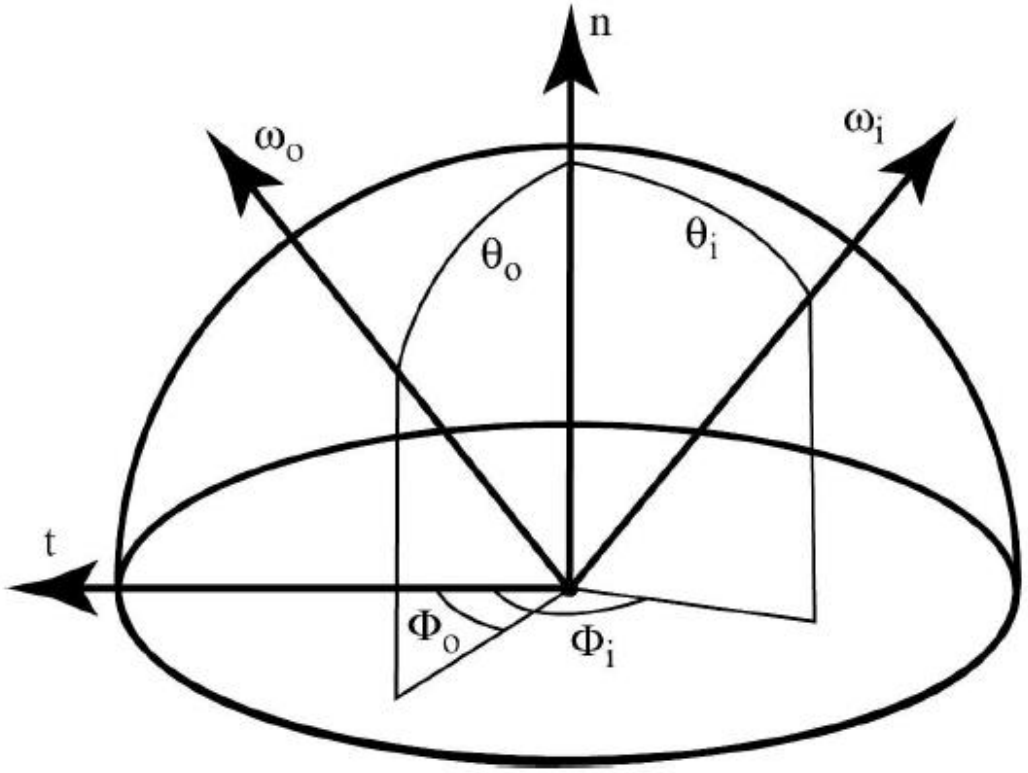
- BSSRDF and BRDF
  - Model-based rendering
  - Explicit geometry
  - Modeling or acquisition of the appearance
  - Global illumination algorithm
  - More precise but computational heavy

- 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

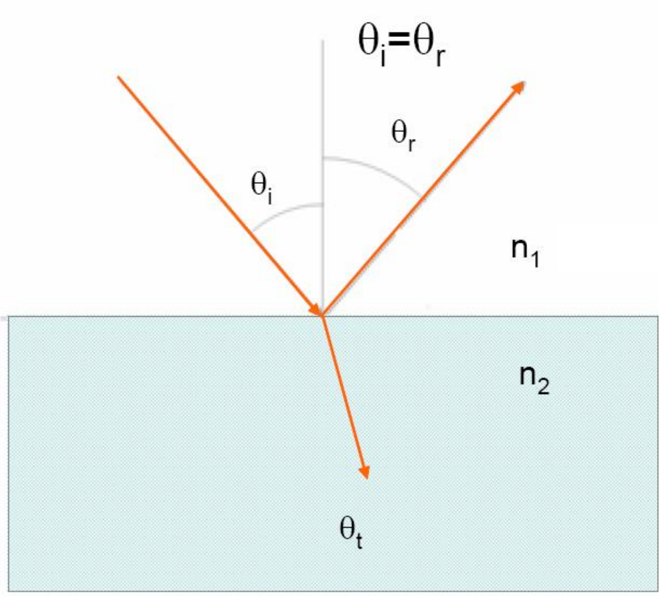
- General model to approximate the form of the BRDF (diffuse and specular reflection, off-specular scattering, backscattering)

- 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 (Rayleight criterion)

- Snell’s law
  - Directionality of transmission and reflection



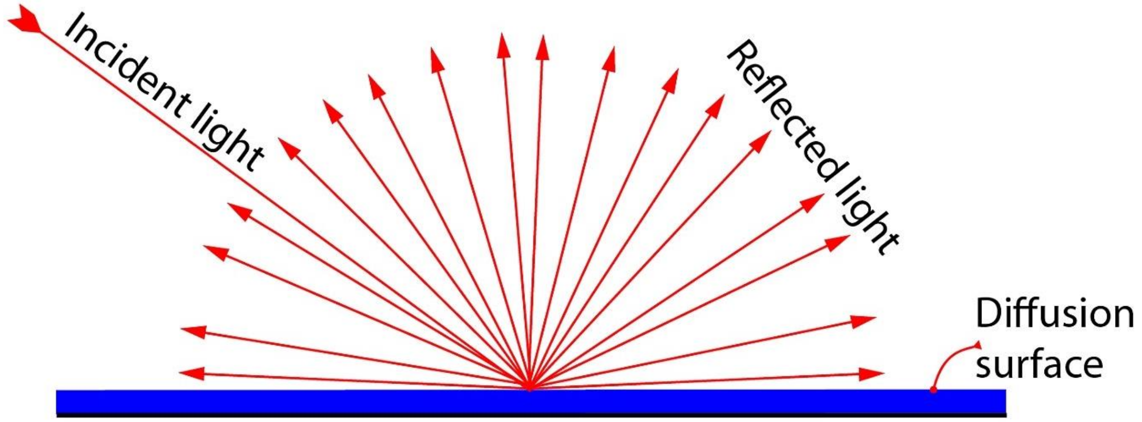
- Fresnel’s equation
  - Fraction of light reflected
  - Schlick’s approximation

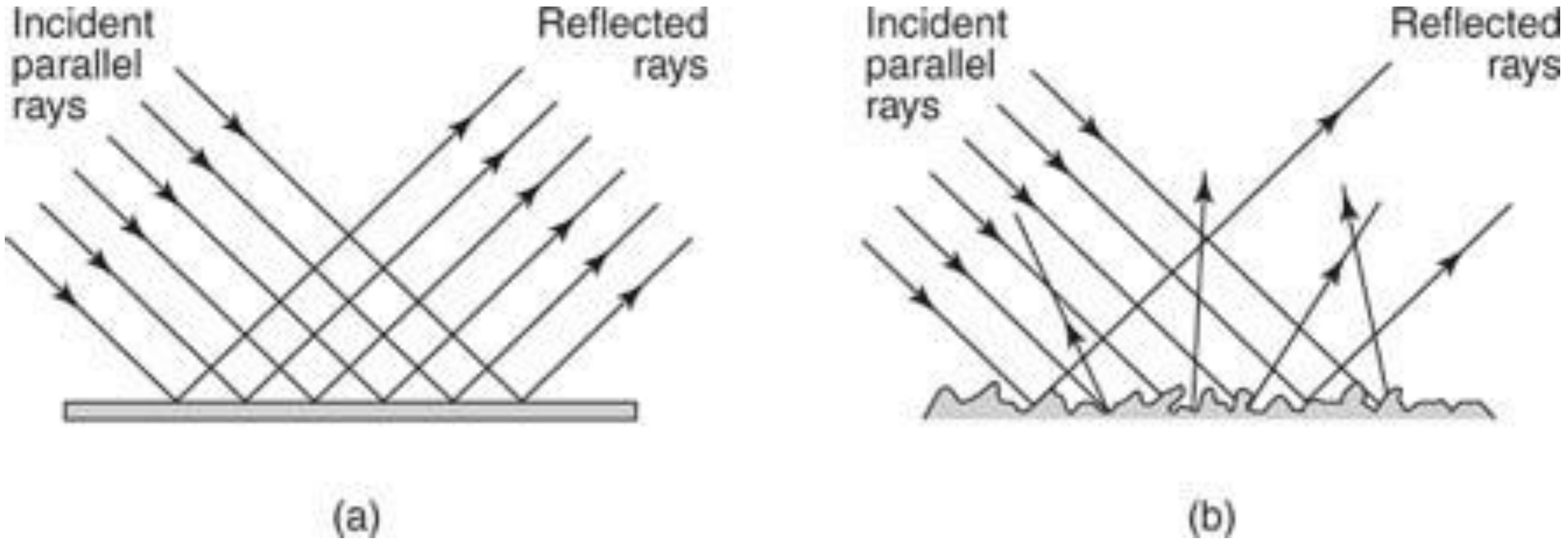
$$F(\theta) = F(0) + (1 - \cos\theta)^5 (1 - F(0))$$

Lambertian BRDF

- Light is reflected equally in all directions

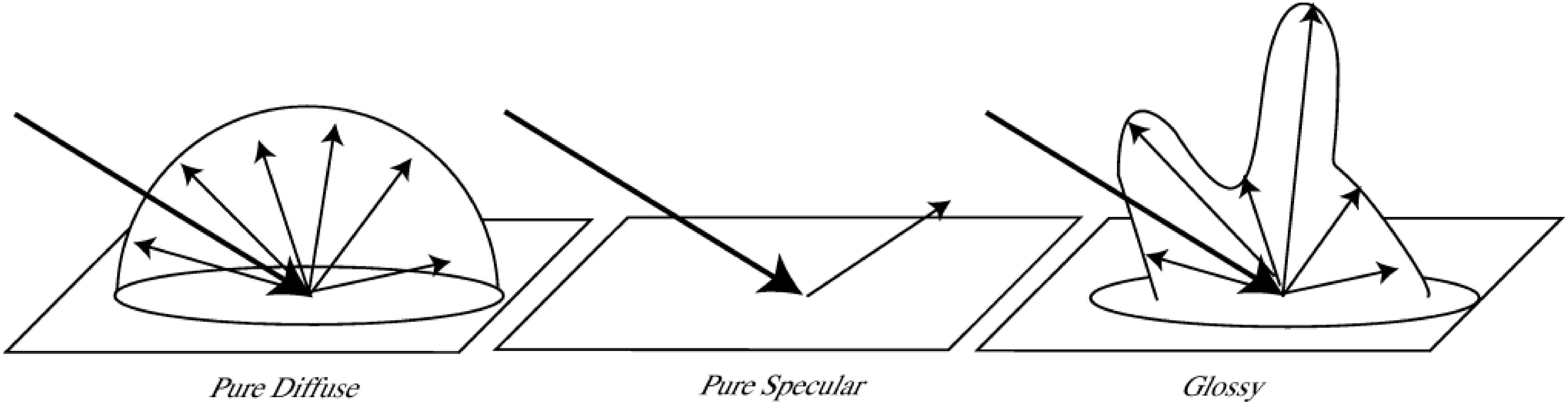
$$f(\mathbf{x}, \vec{\omega}_i \to \vec{\omega}_o) = \frac{\rho_d}{\pi}$$



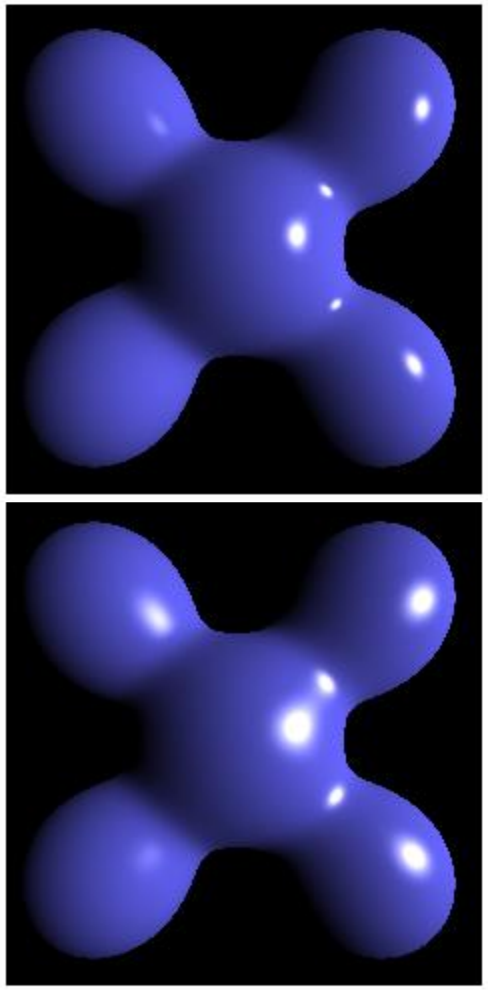


Specular and Glossy BRDF

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



Phong and Blinn Models



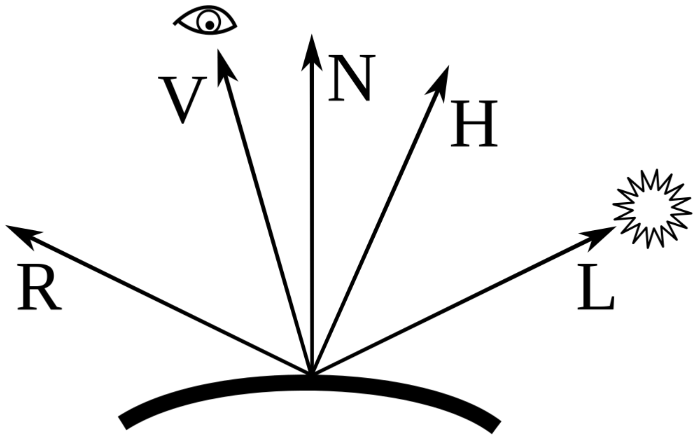
- Phong

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

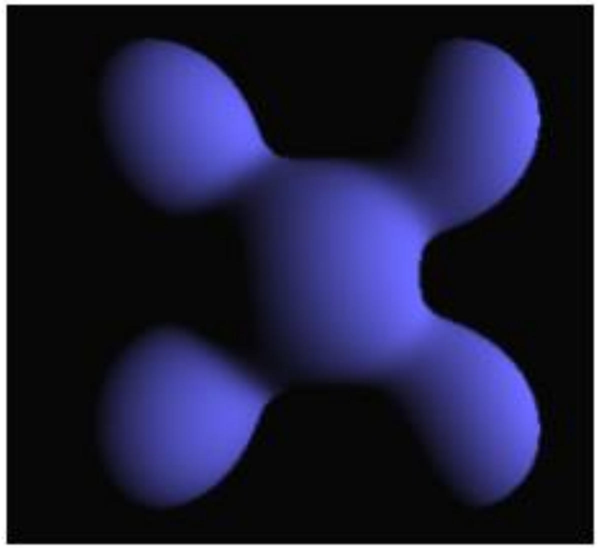
- Blinn-Phong

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

- Issues
  - Non reciprocal
  - Non energy conserving

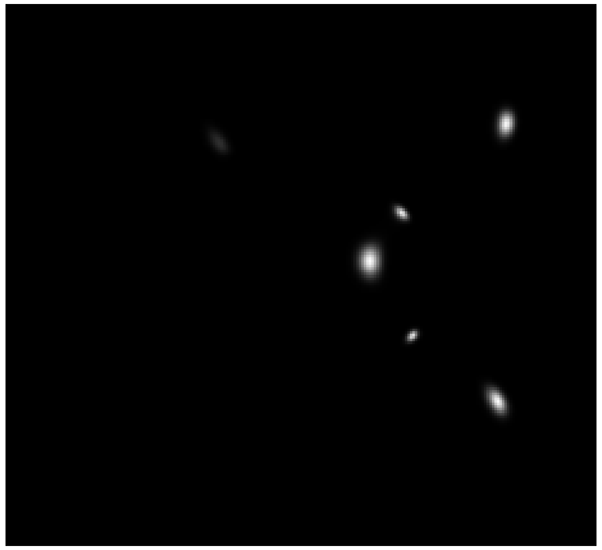


Phong Model



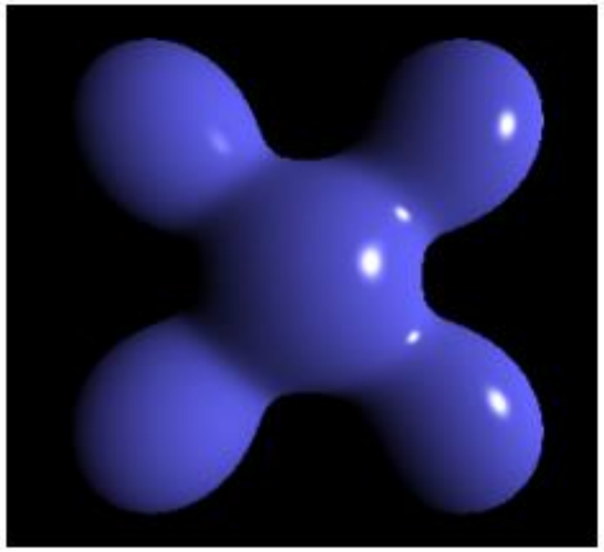
DIFFUSE

+

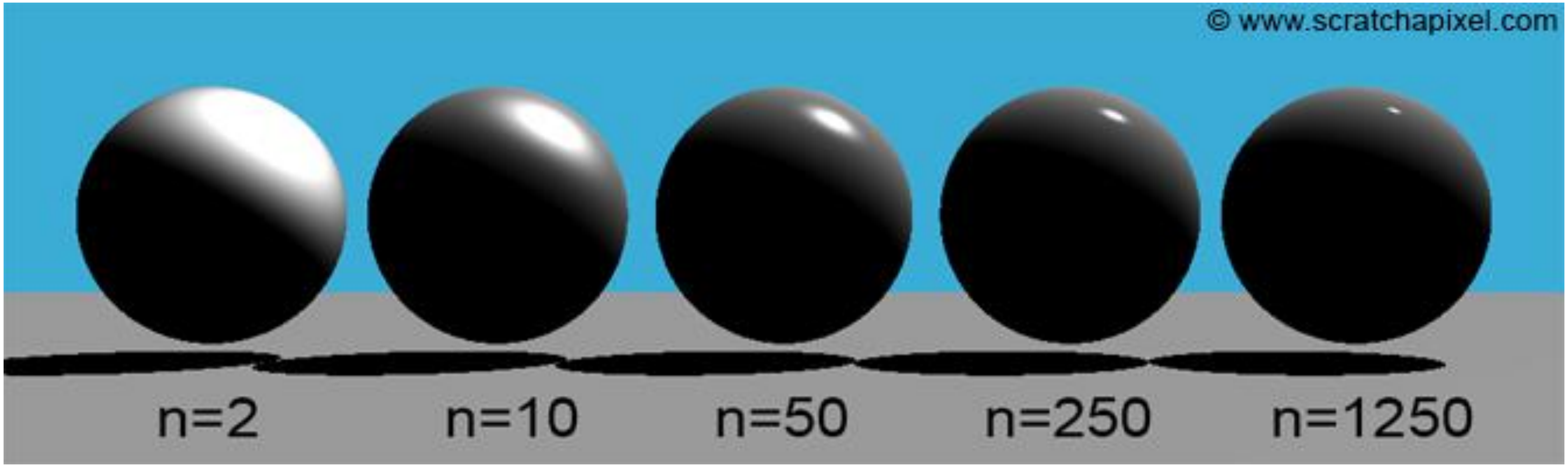


SPECULAR

=



FINAL APPEARENCE



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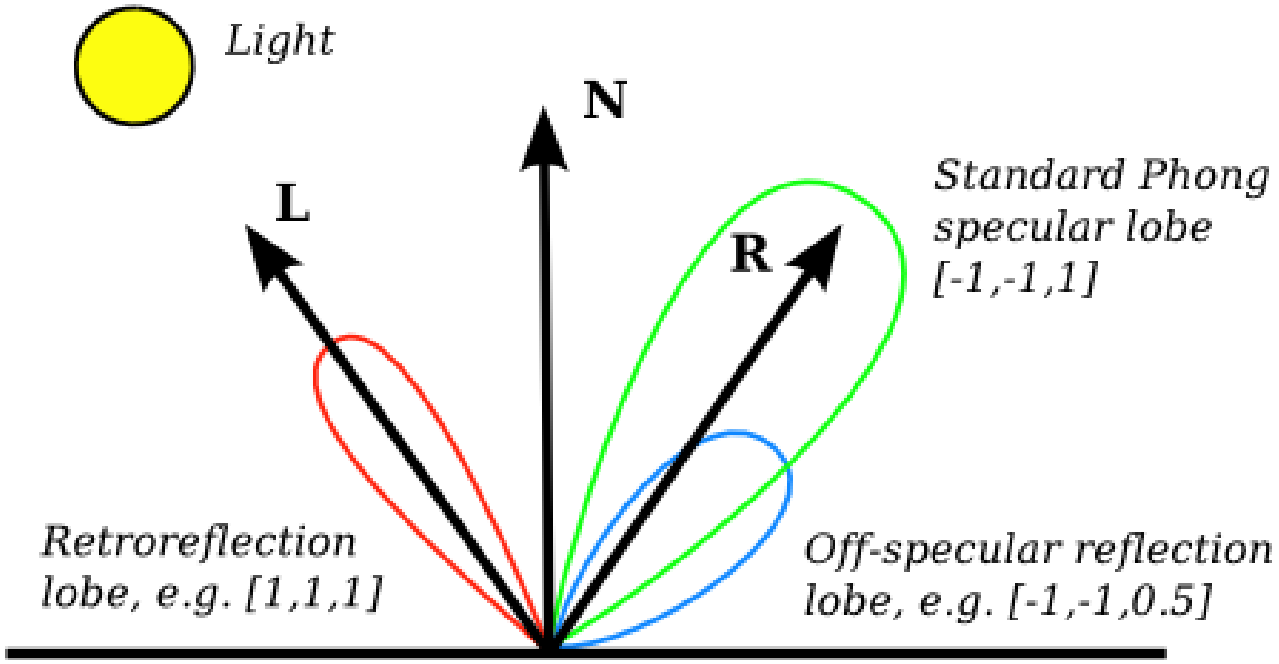
Lafortune Model

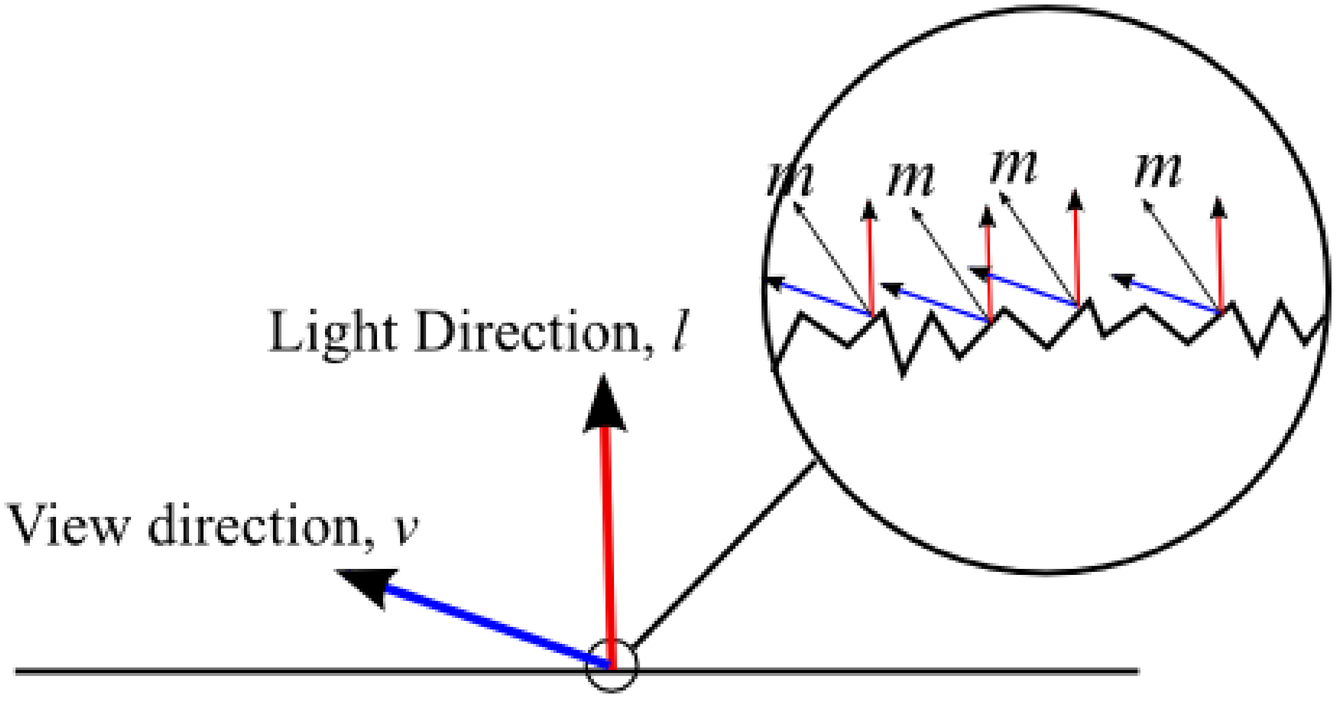
$$f(\mathbf{x}, \vec{\omega}_i \rightarrow \vec{\omega}_o) = f(\mathbf{x}, \vec{\mathbf{u}} \rightarrow \vec{\mathbf{v}}) = \rho_s (C_x u_x v_x + C_y u_y v_y + C_z u_z v_z)^n$$

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



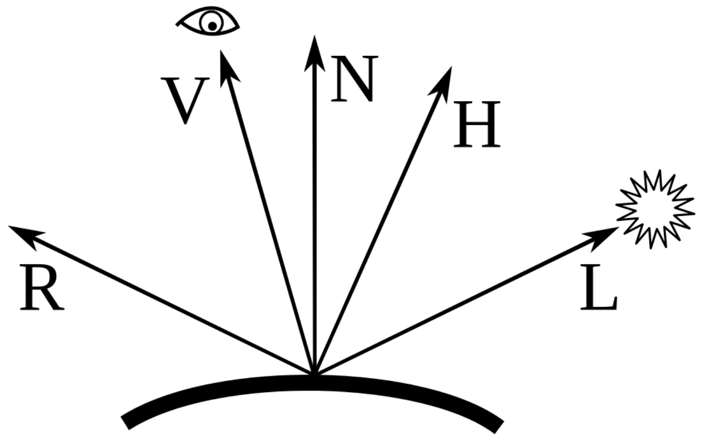
Physical based model

- 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

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

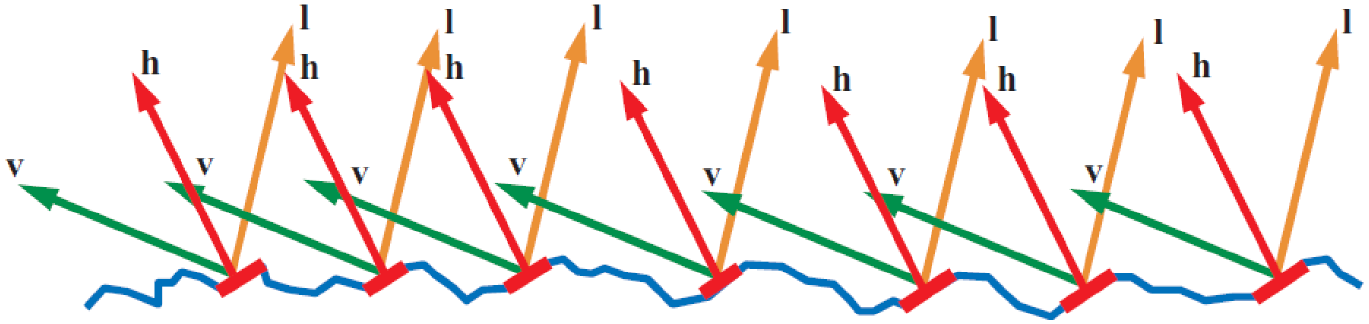


- Fresnel reflectance F
- Shadowing-masking function G
  - Percentage of the microfacets with normal equals to H are not shadowed or masked
- Microfacet normal distribution function D
  - Concentration of microfacets which are oriented thus that they could reflect light from l into v

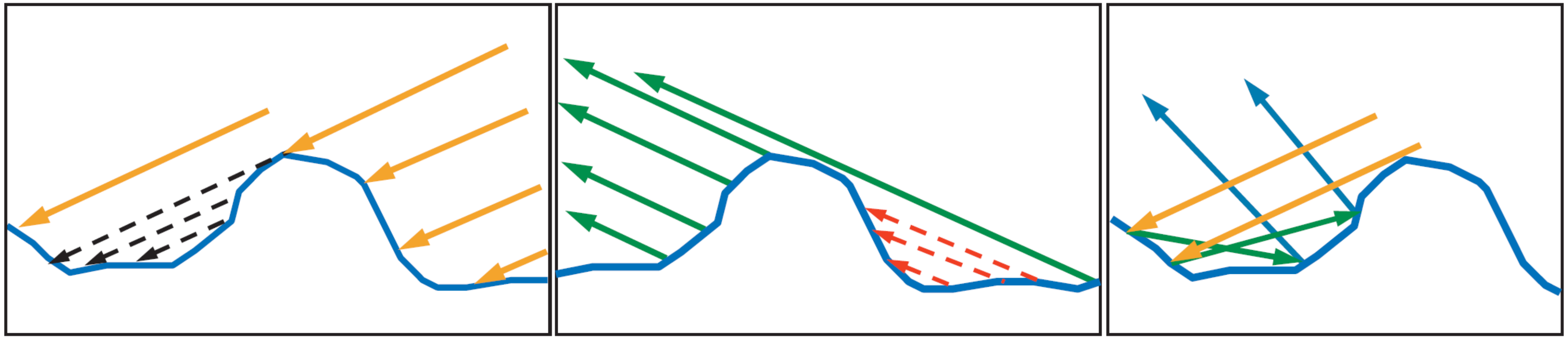
Physical based model

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

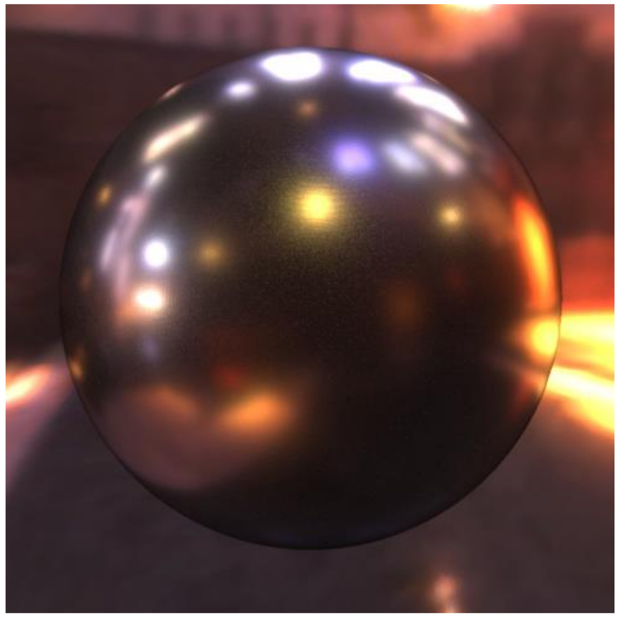
- Shadowing-masking function G



- 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

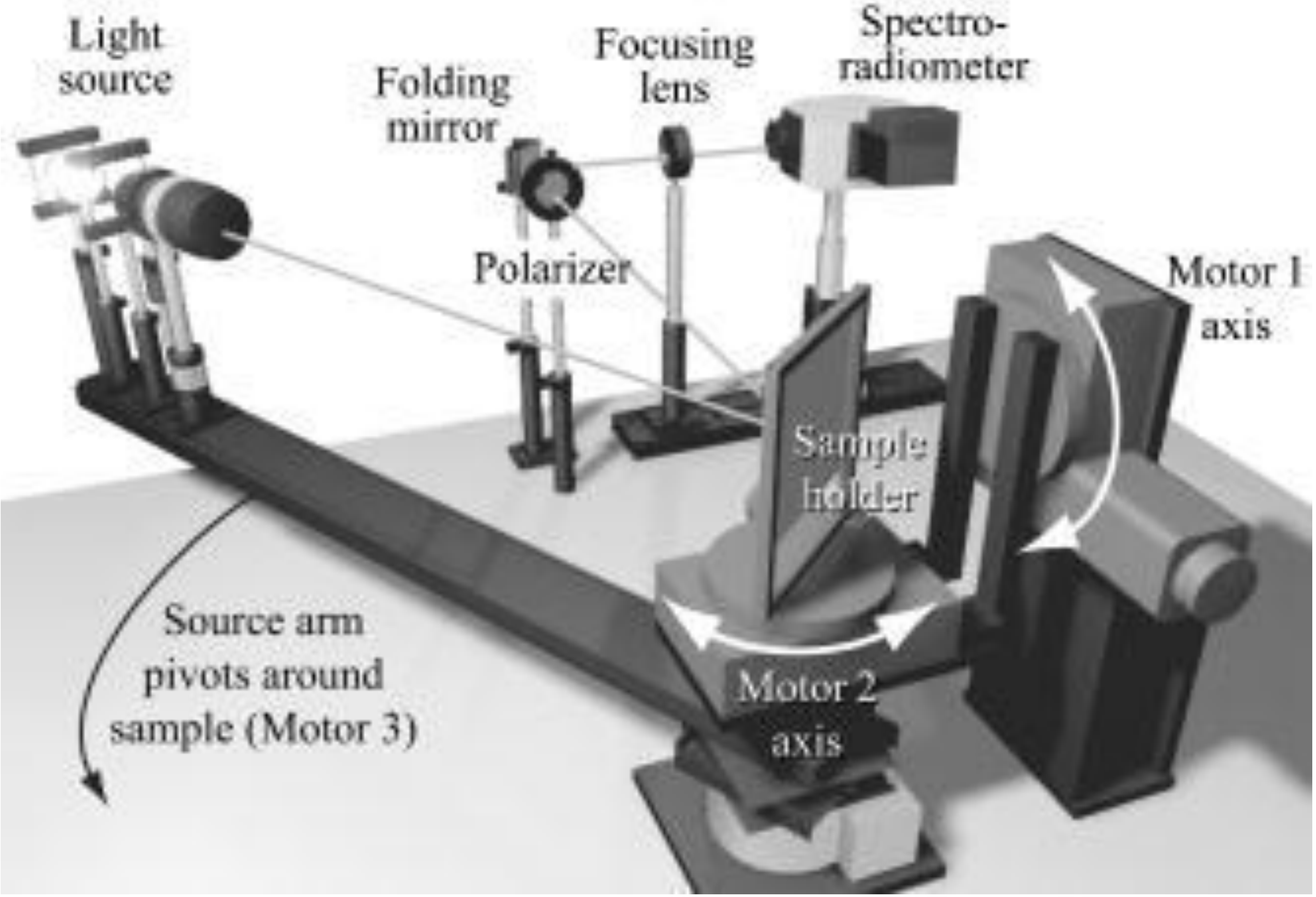
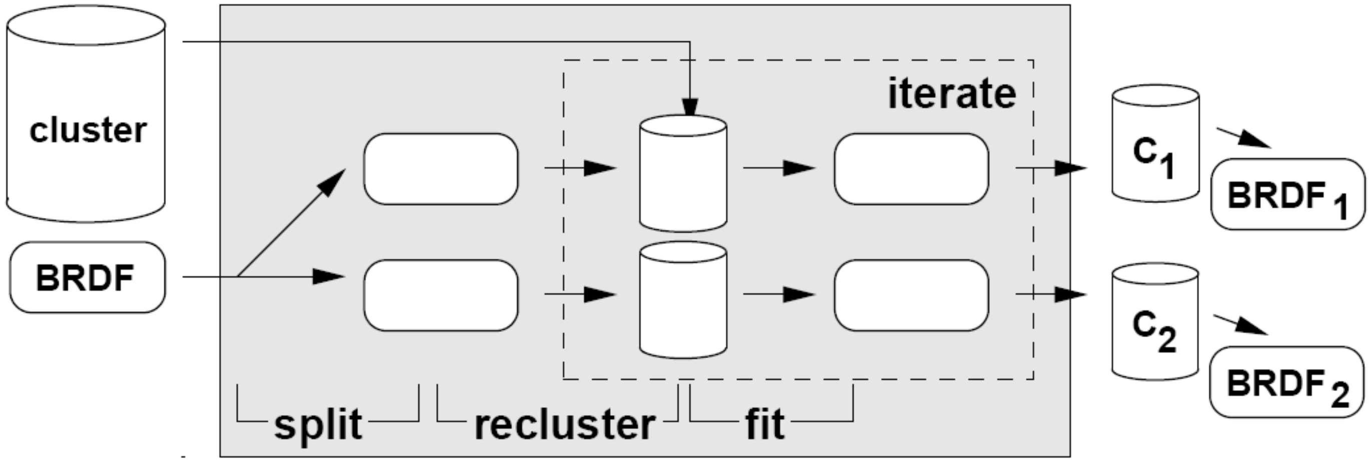


Image-based measurements

[Lensch et al., TOG 03]

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



cluster

BRDF

iterate

split

recluster

fit

c_1

BRDF_1

c_2

BRDF_2

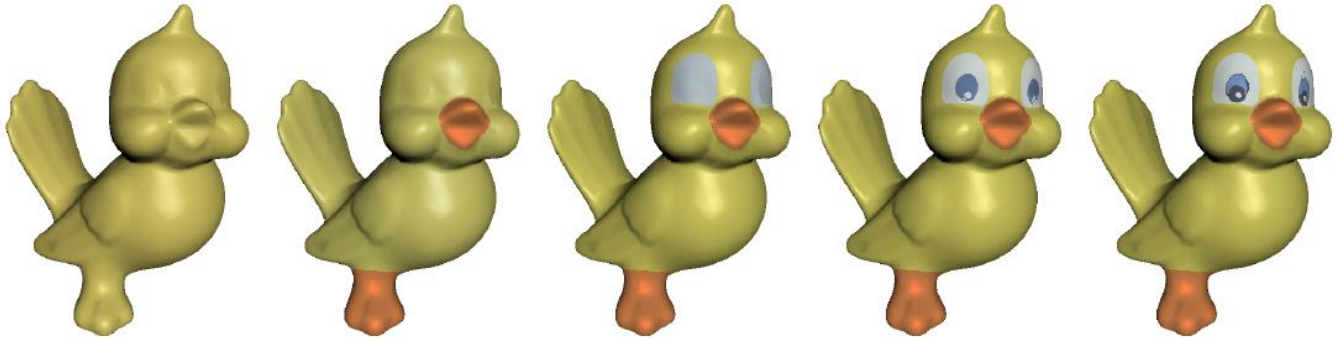


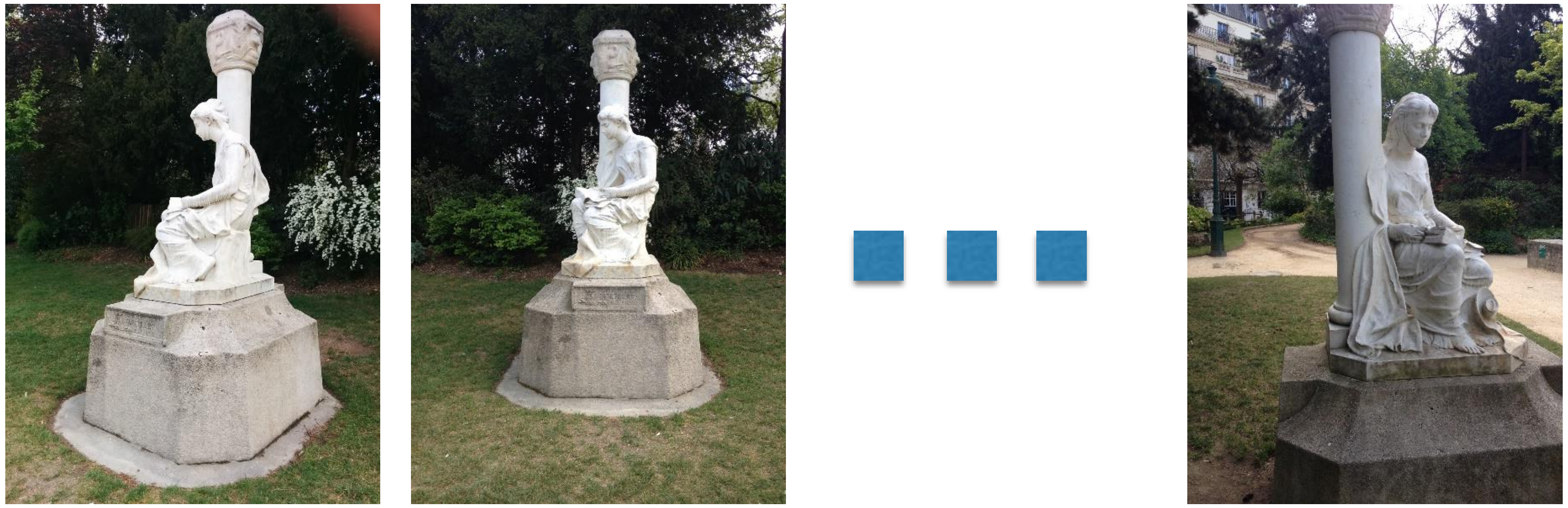
Image-based measurements

[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

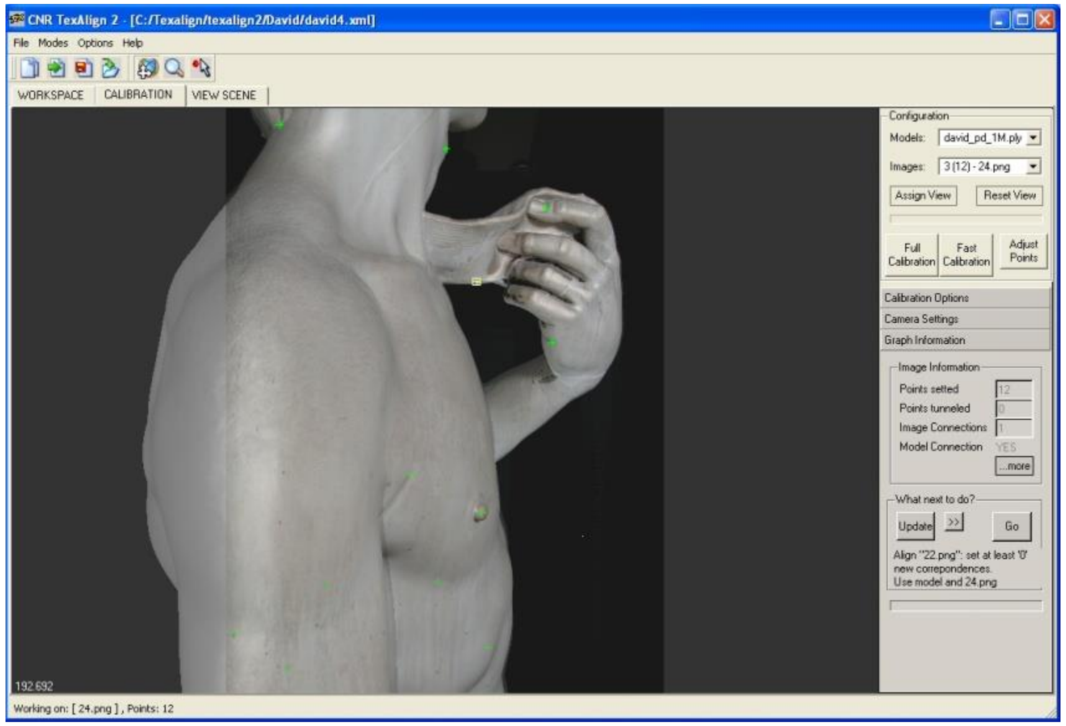
$$\min_{P} \|PX - x\|^2$$

    - 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)



Models: david_pd_1M.ply
Images: 3 (12) - 24.png
Points setted 12
Points tunneled 0
Image Connections 1
Model Connection YES
Align "22.png": set at least '0' new correpondences.
Use model and 24.png
192.692
Working on: [24.png], Points: 12

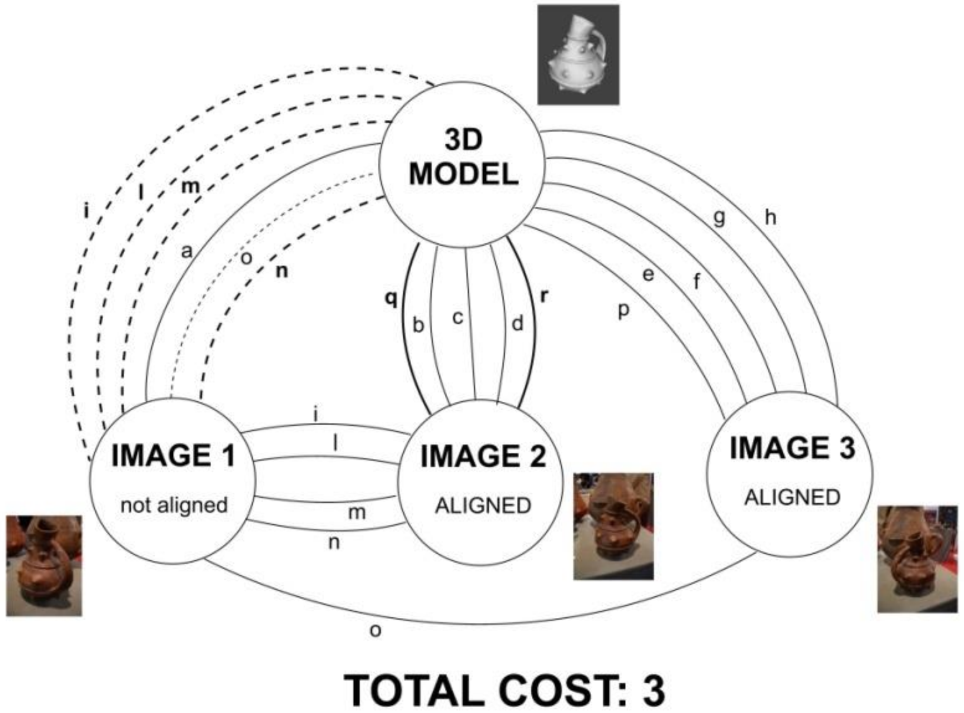


Image-to-Geometry Registration

[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

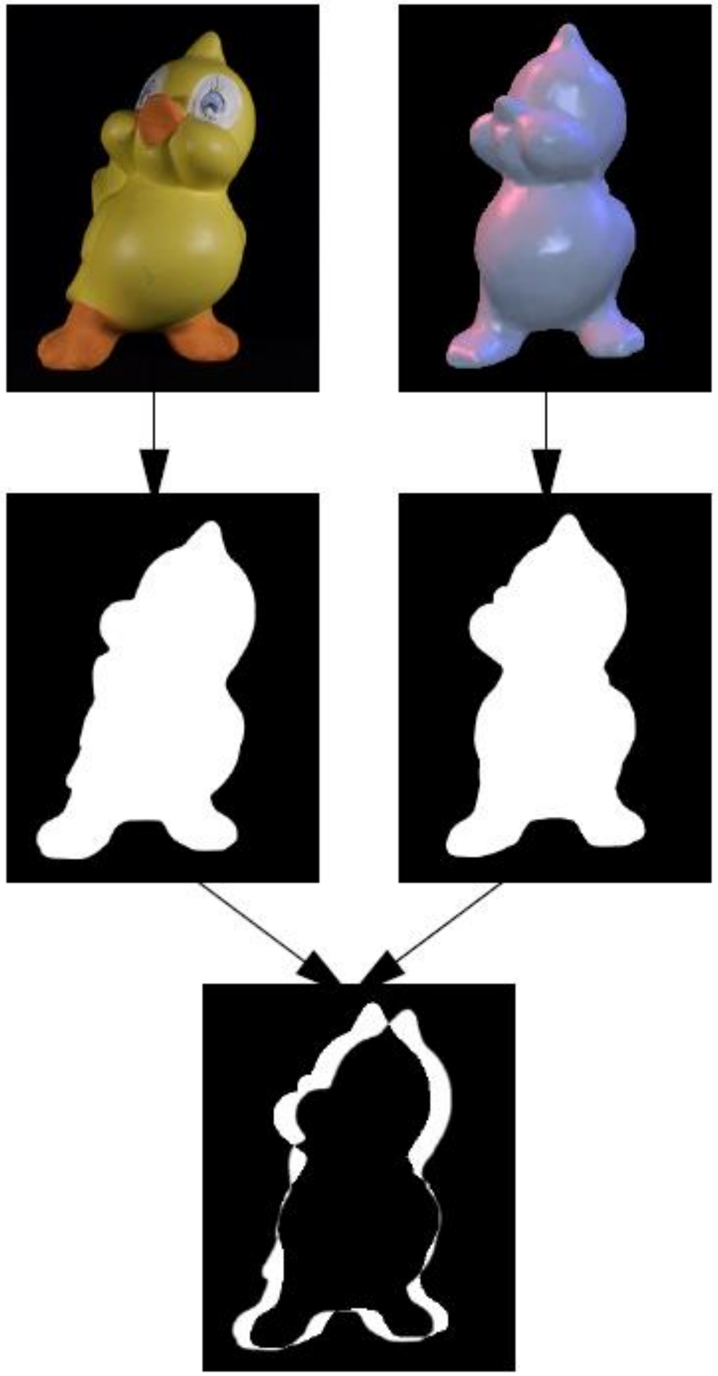


Image-to-Geometry Registration

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

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

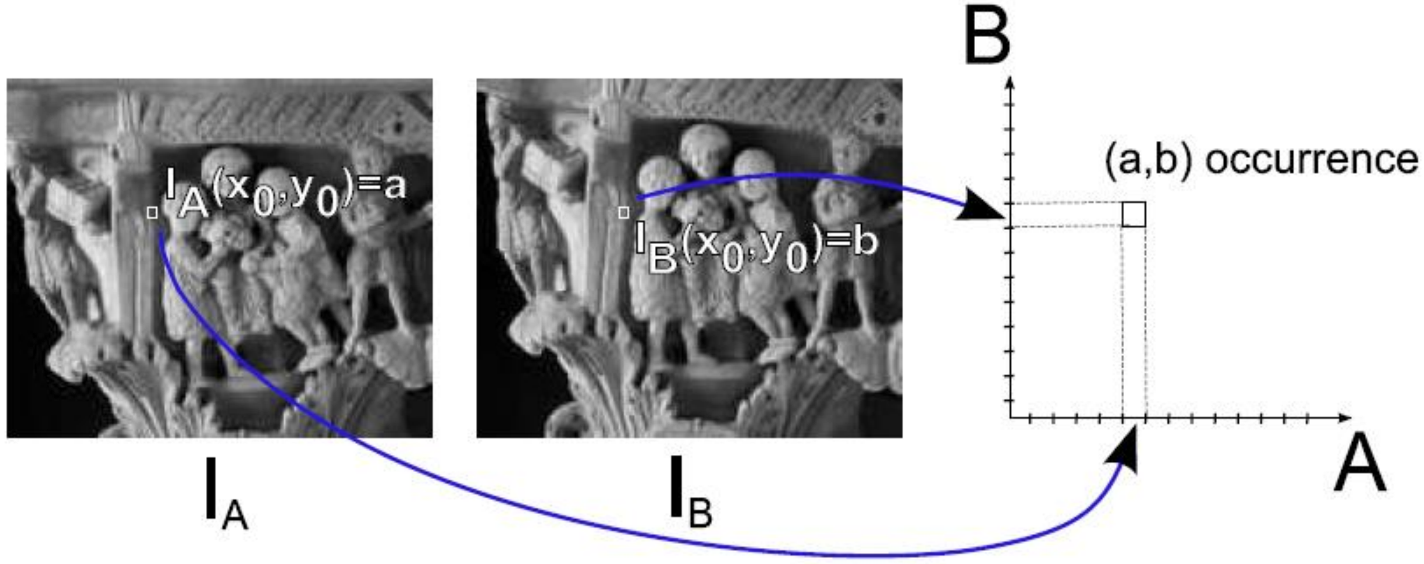
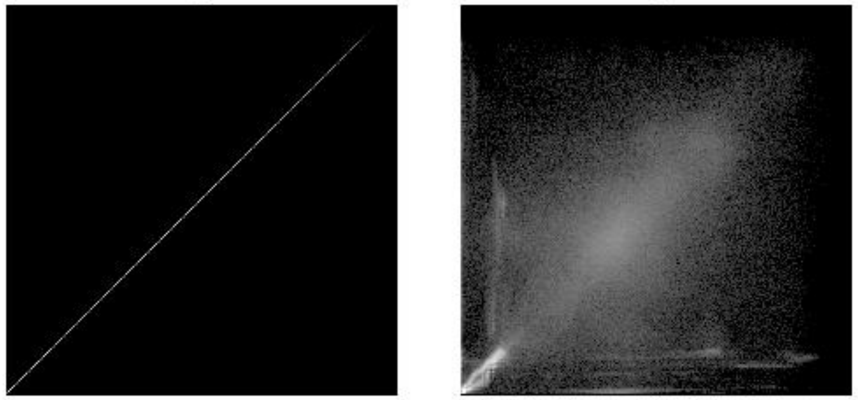


Image A Image B



$\mathcal{H}(A,A)$ $\mathcal{H}(A,B)$

Image-to-Geometry Registration

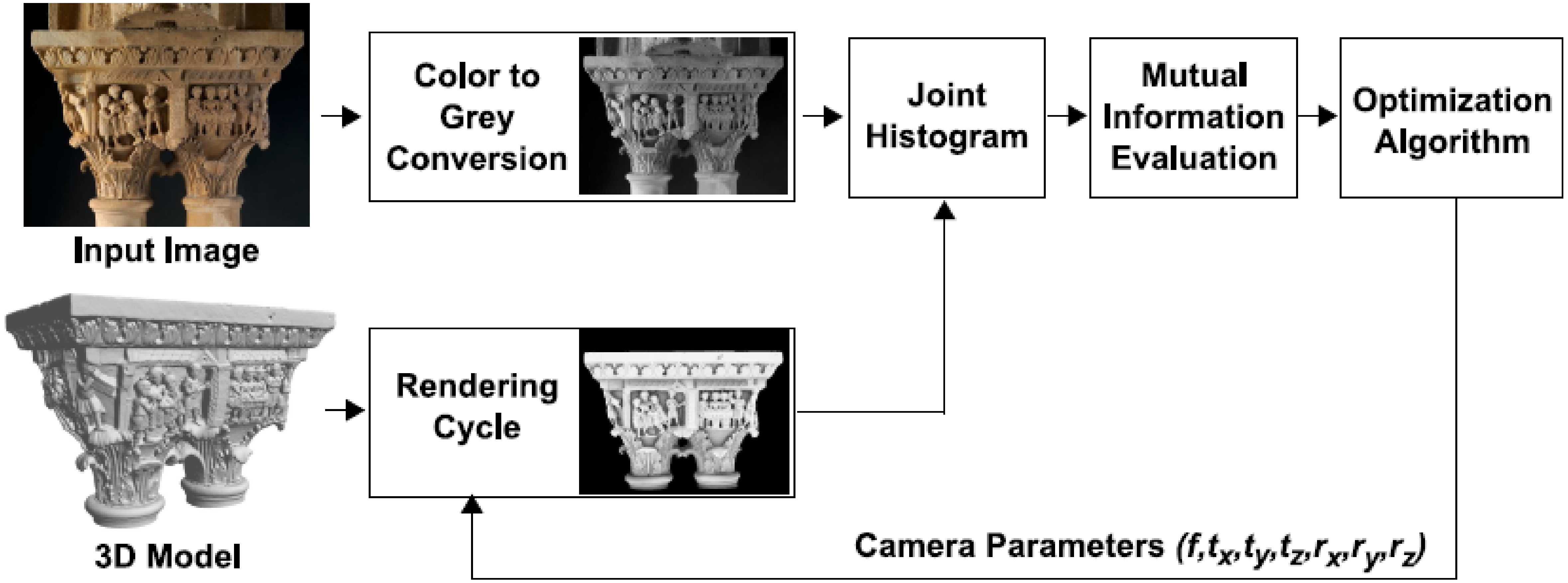
[Corsini et al., PG 09]

- 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



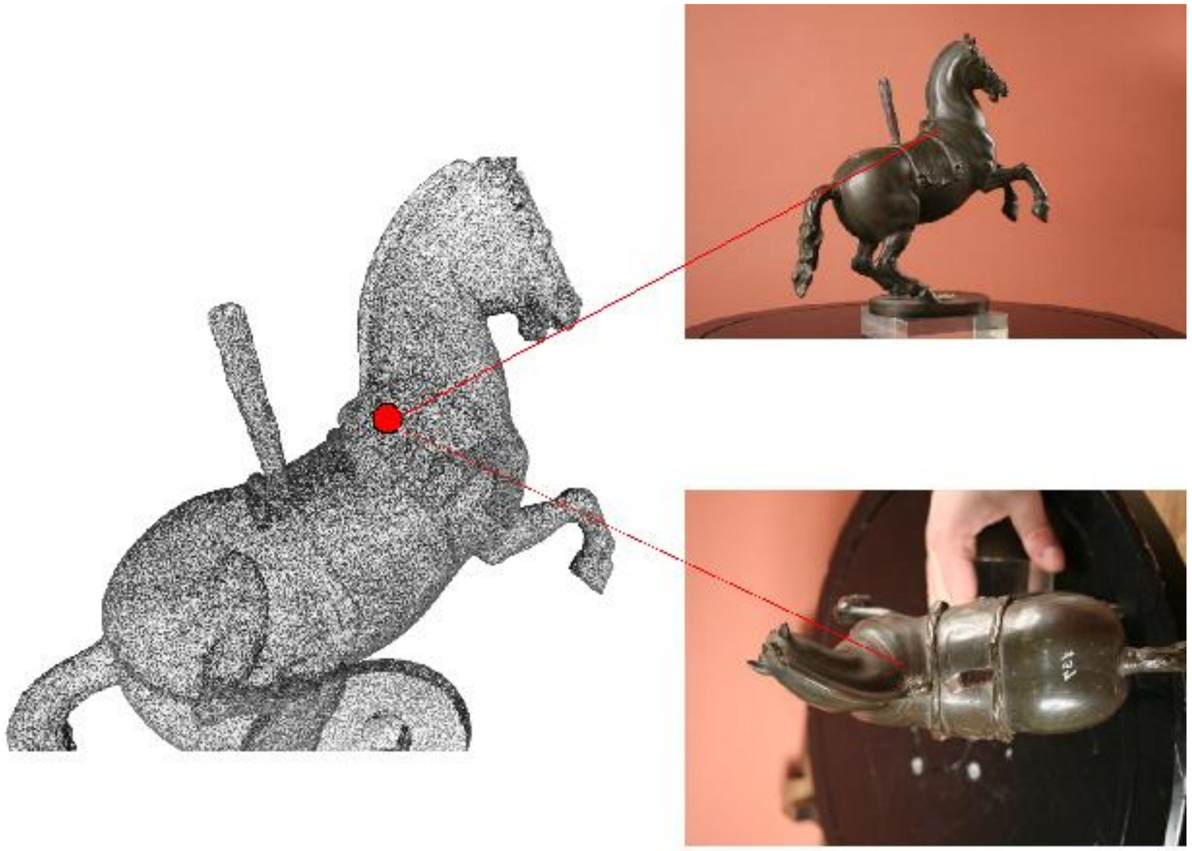
Encoding of the Color

- 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

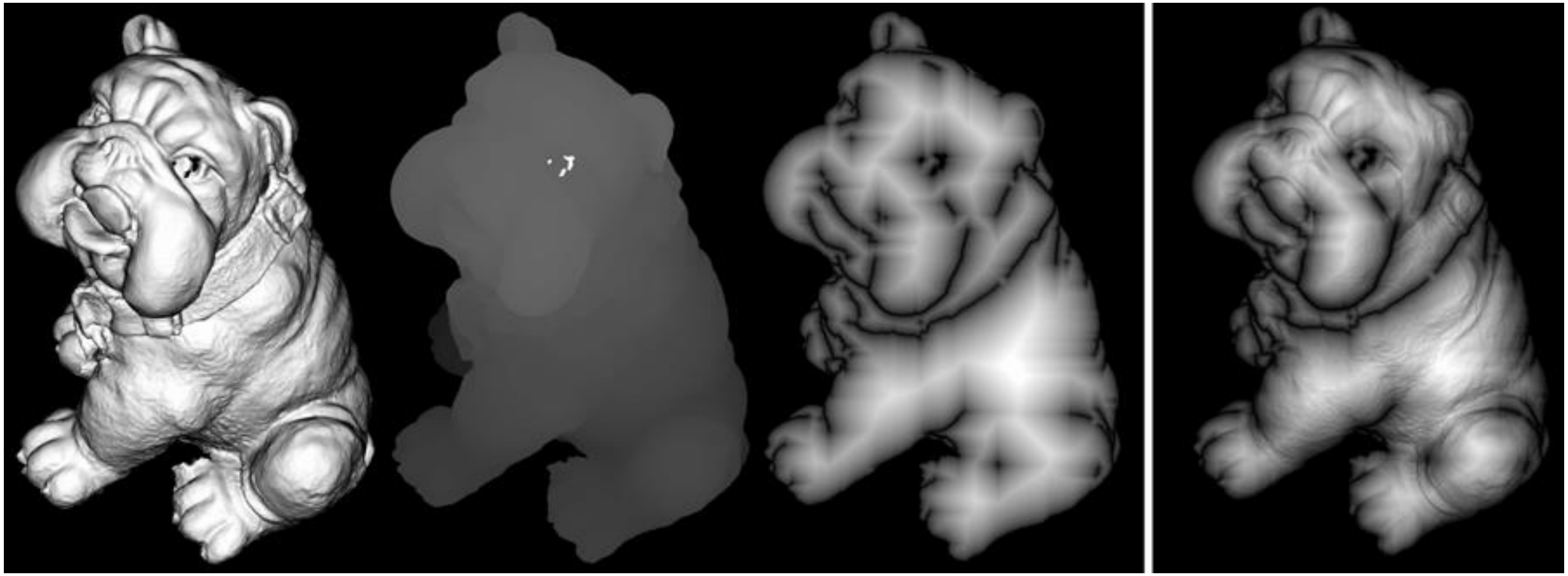
[Callieri et al., VMV 03]

- 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

- Weyrich, Tim, et al. "Principles of appearance acquisition and representation." *Foundations and Trends® in Computer Graphics and Vision* 4.2 (2009): 75-191.
- Hoffman, Naty. "Background: physics and math of shading." *Physically Based Shading in Theory and Practice* 24.3 (2013): 211-223.
- Lensch, Hendrik, et al. "Image-based reconstruction of spatial appearance and geometric detail." *ACM Transactions on Graphics (TOG)* 22.2 (2003): 234-257.
- Debevec, Paul, et al. "Estimating surface reflectance properties of a complex scene under captured natural illumination.“
- Franken, Thomas, et al. "Minimizing user intervention in registering 2D images to 3D models." *The Visual Computer* 21.8 (2005): 619-628.
- Lensch, Hendrik PA, Wolfgang Heidrich, and Hans-Peter Seidel. "A silhouette-based algorithm for texture registration and stitching." *Graphical Models* 63.4 (2001): 245-262.
- Corsini, Massimiliano, et al. "Image-to-Geometry Registration: a Mutual Information Method exploiting Illumination-related Geometric Properties." *Computer Graphics Forum*. Vol. 28. No. 7, 2009.
- Callieri, Marco, Paolo Cignoni, and Roberto Scopigno. "Reconstructing Textured Meshes from Multiple Range RGB Maps." *VMV*. 2002.
- Callieri, Marco, et al. "Masked photo blending: Mapping dense photographic data set on high-resolution sampled 3D models." *Computers & Graphics* 32.4 (2008): 464-473.