Blind Recovery of Spatially Varying Reflectance from a Single Image

Kevin Karsch David Forsyth
University of Illinois

Extract spatially-varying, specular materials from a single image

Extract spatially-varying, specular materials
from a single image

Extract spatially-varying, specular materials
from a single image


LuxRender
20


LuxRender
20

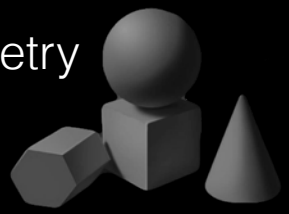

LuxRender
20

Image Formation

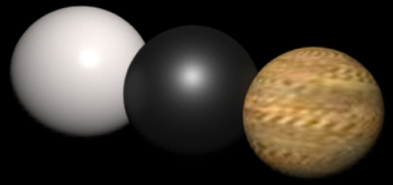
Image Formation

Camera parameters

Geometry



Materials



Light sources

Image Formation

Camera parameters

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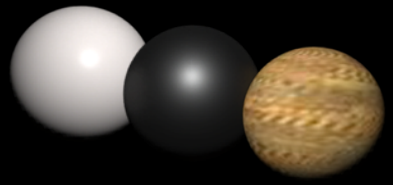

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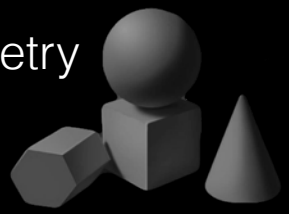

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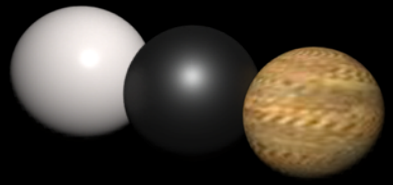


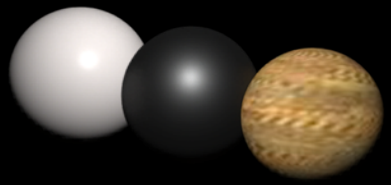
Light sources

Inverse Rendering

Camera parameters

Geometry

Materials



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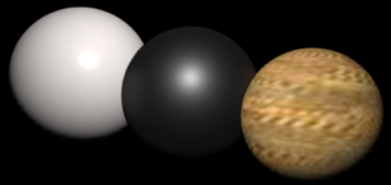

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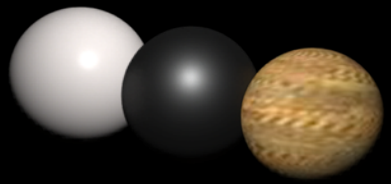

Light sources

Intrinsic Image Model

Image

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Reflectance (R)

•

Shading (S)

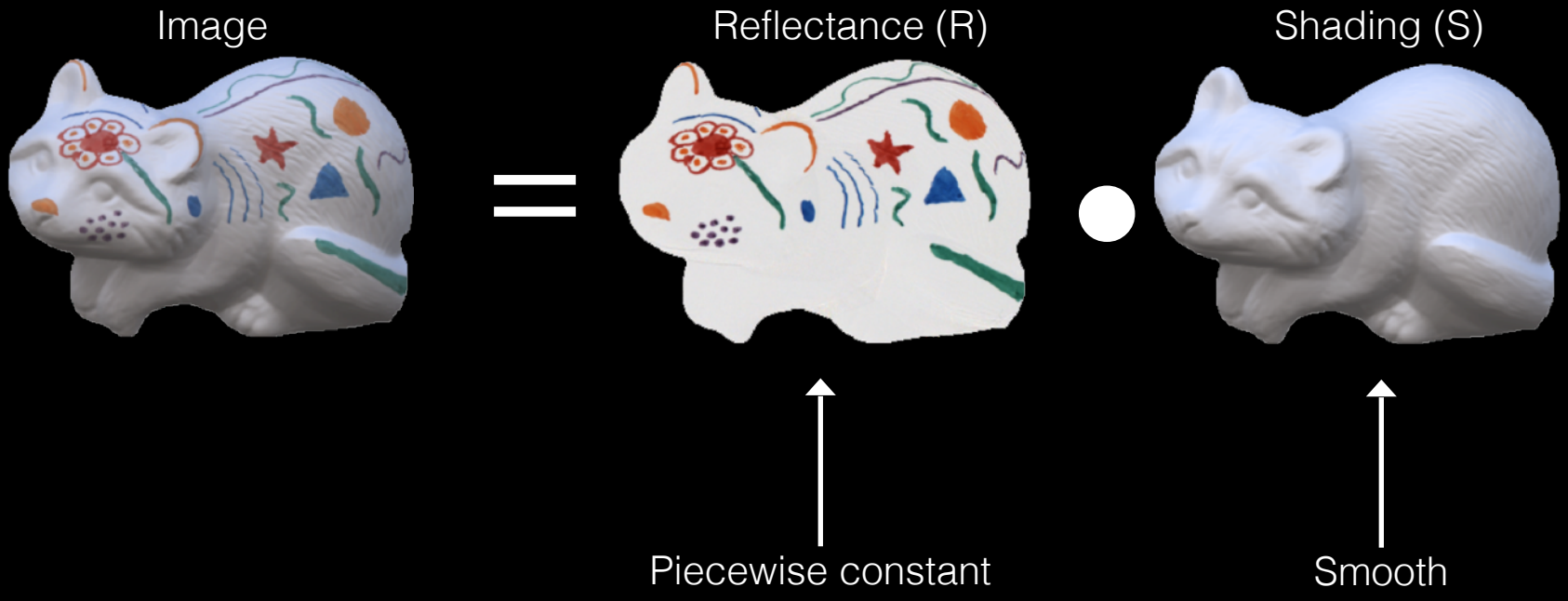
Images from Jon Barron

Intrinsic Image Model

Piecewise constant

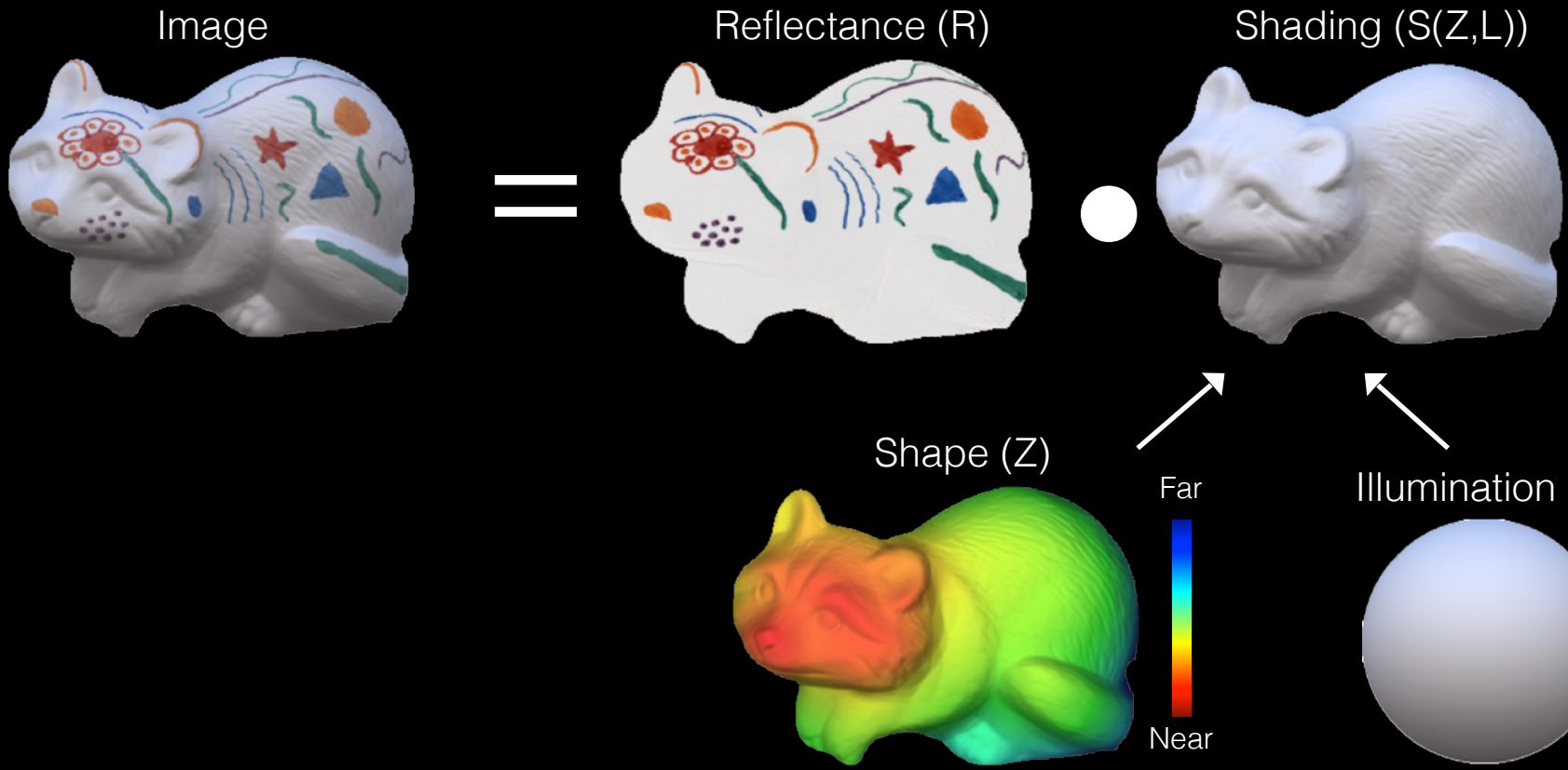
Images from Jon Barron

Intrinsic Image Model



Images from Jon Barron

SIRFS Model [Barron and Malik]



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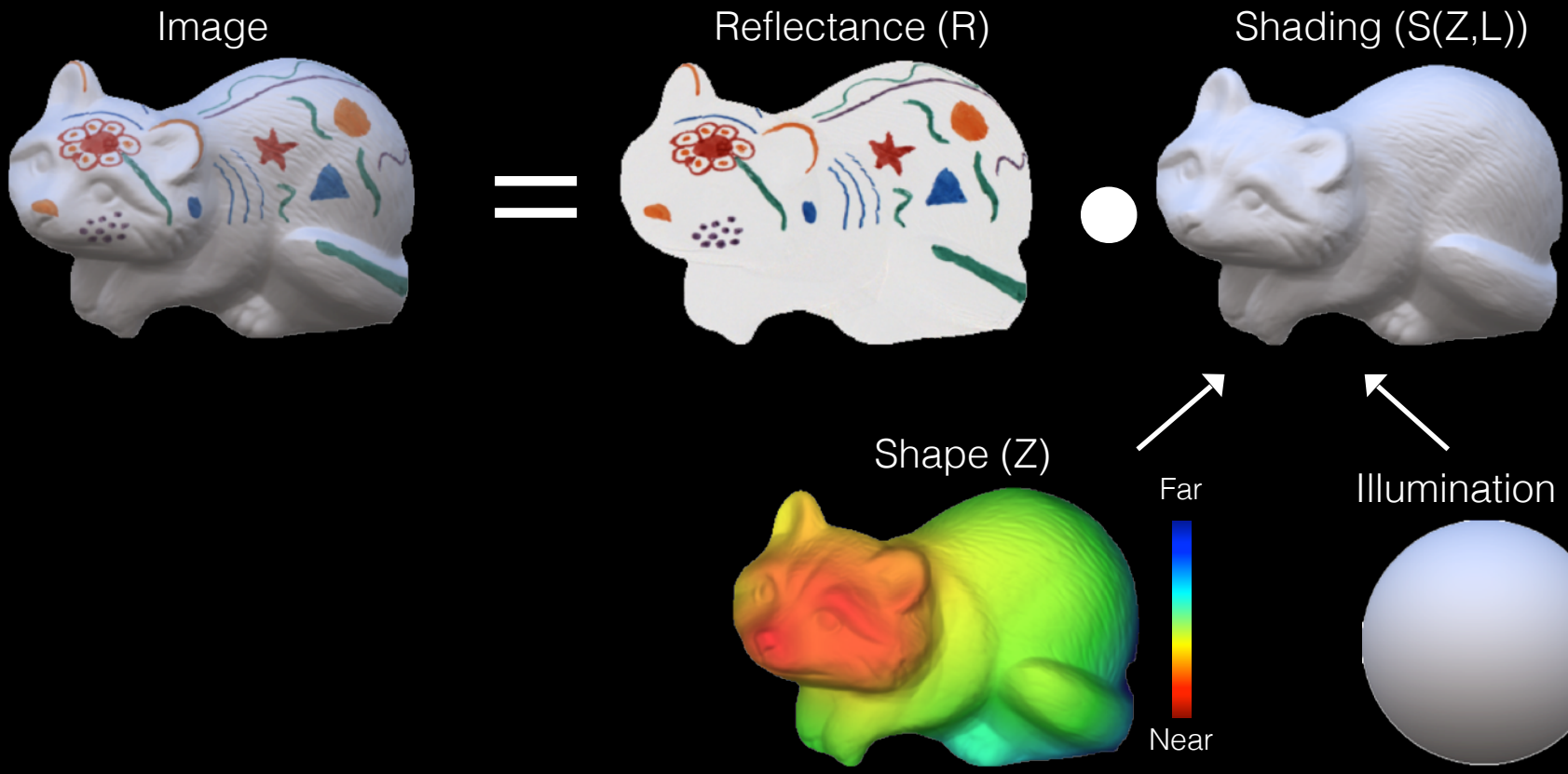

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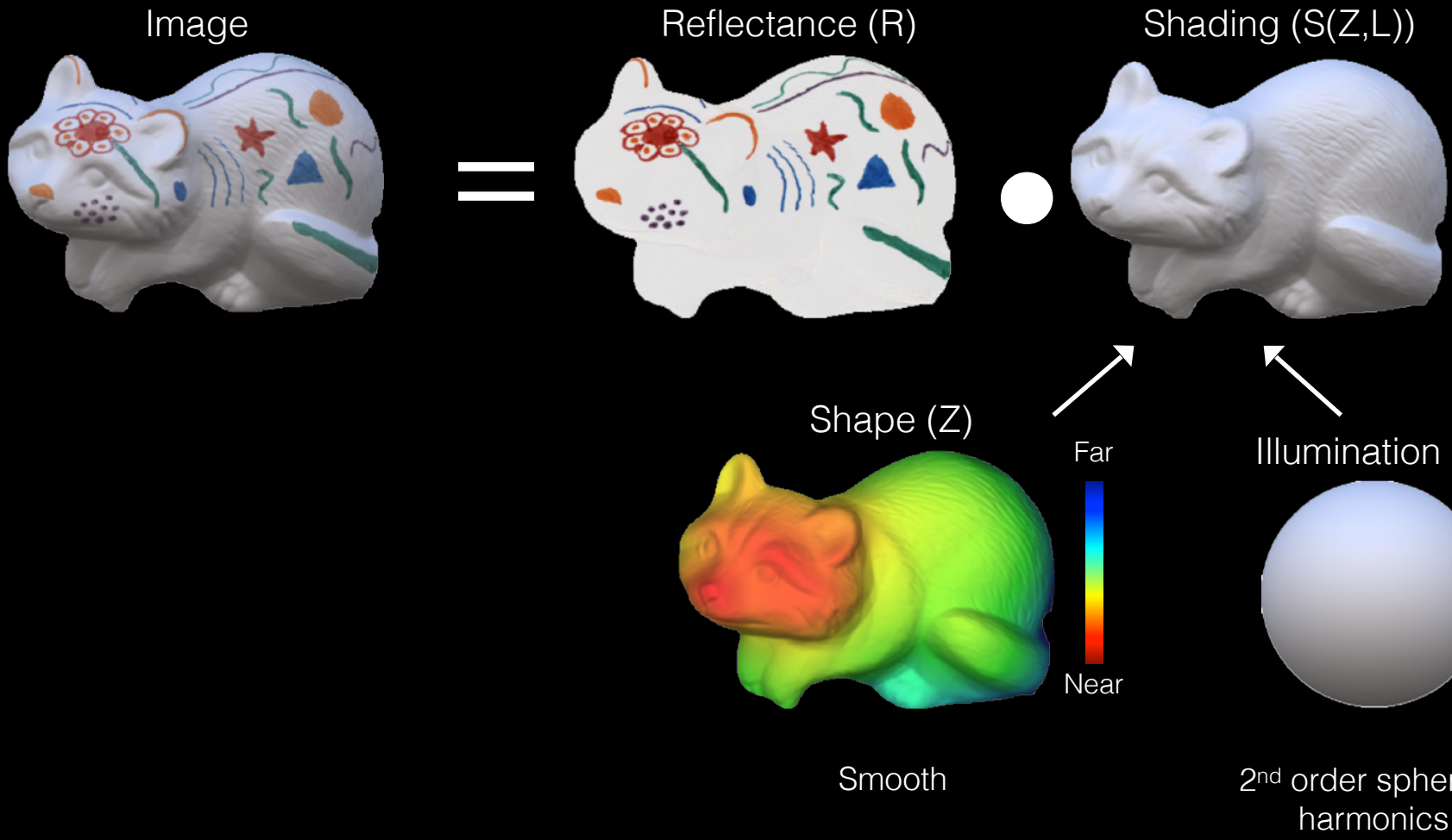

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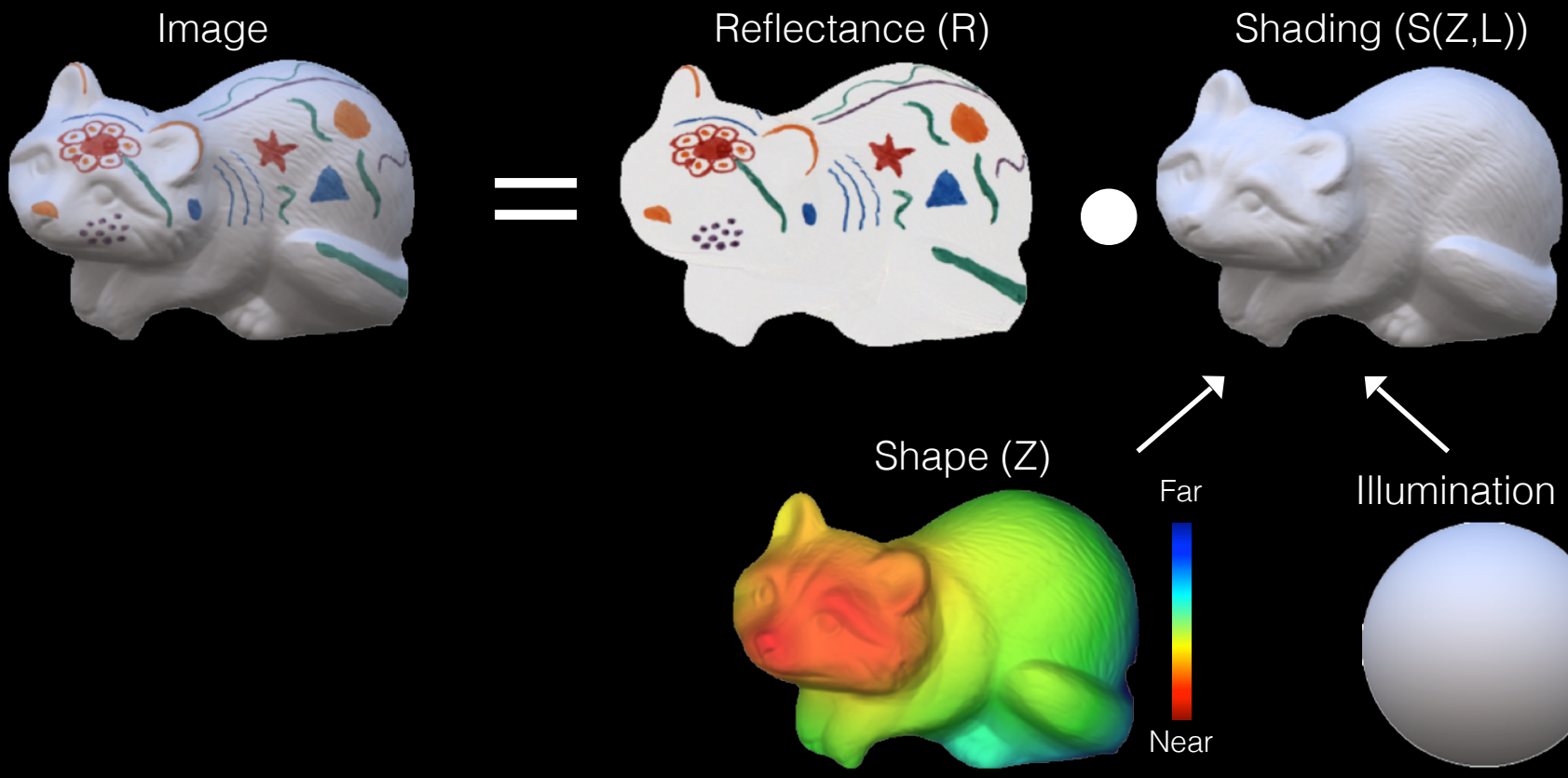

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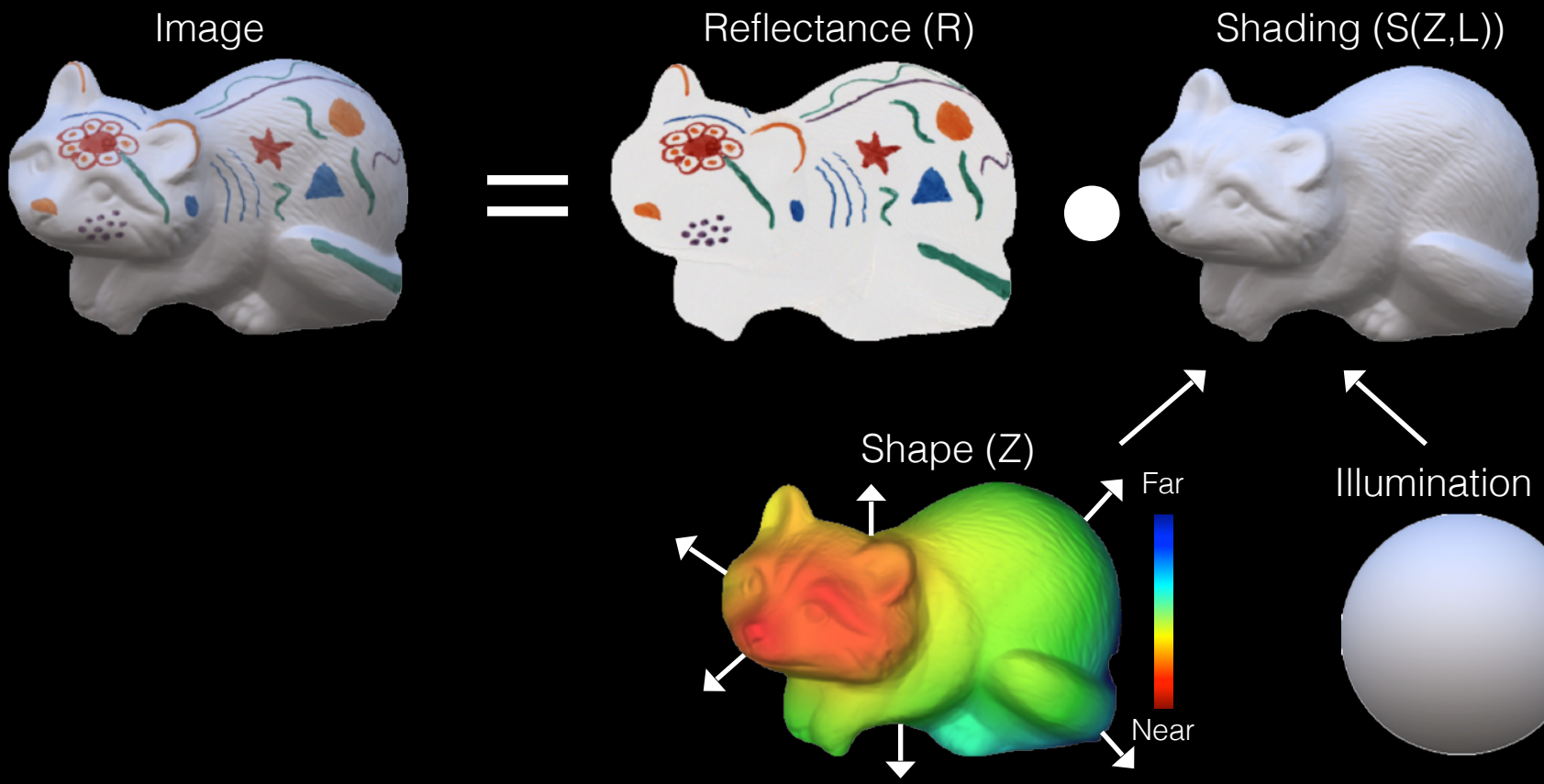

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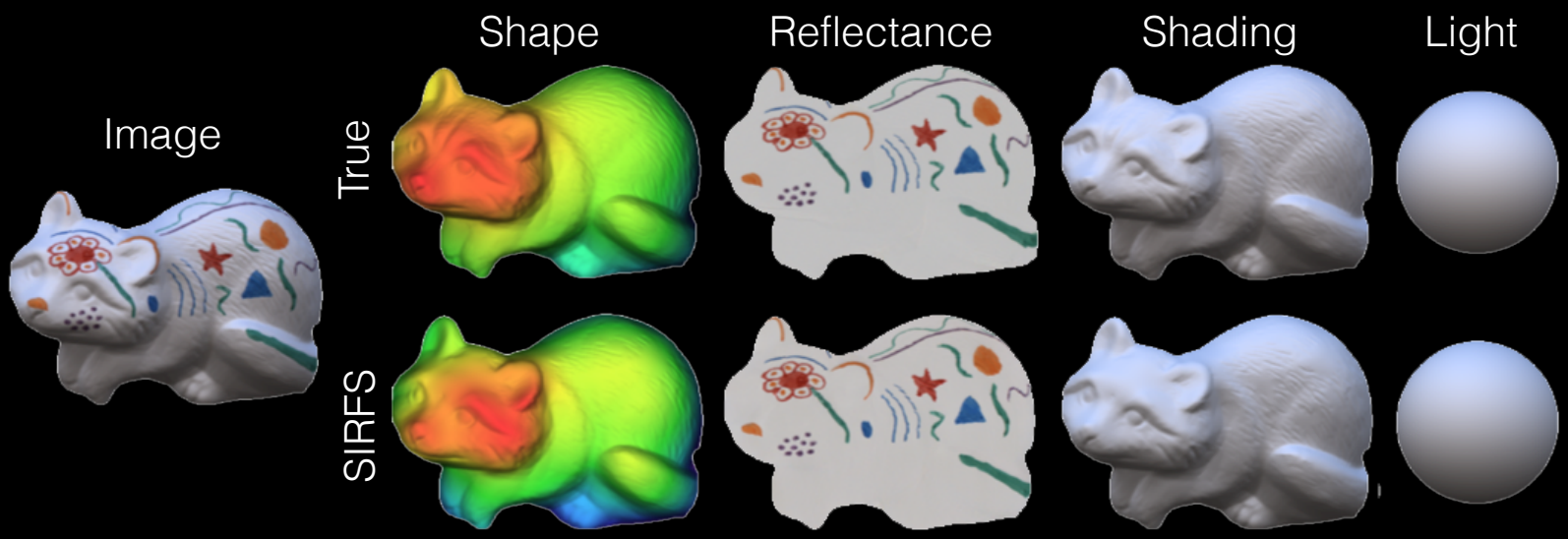
SIRFS Diffuse Material Estimates




LuxRender
20


LuxRender
60
45
15
30
20


No specular estimates!

Beyond Diffuse Material Estimation

Beyond Diffuse Material Estimation

- Disclaimer: blind, single image methods!

Beyond Diffuse Material Estimation

- Disclaimer: blind, single image methods!
- Many others outside of this category:
  - Known lighting
    - [Oxholm and Nishino ’12, ’14]
  - Known geometry
    - [Lombardi and Nishino ’12, Chen and Koltun ’13]
  - Multiple images
    - [Yu et al. ’99, Goldman et al. ‘10, Kong et al. ’14]
  - User input
    - [Bousseau et al. ‘09, Karsch et al. ’11]
  - Many more

Beyond Diffuse Material Estimation

- Why are we stuck on diffuse?
  - Diffuse isn't completely solved
  - Lack of data
  - Parameterization
  - Estimation

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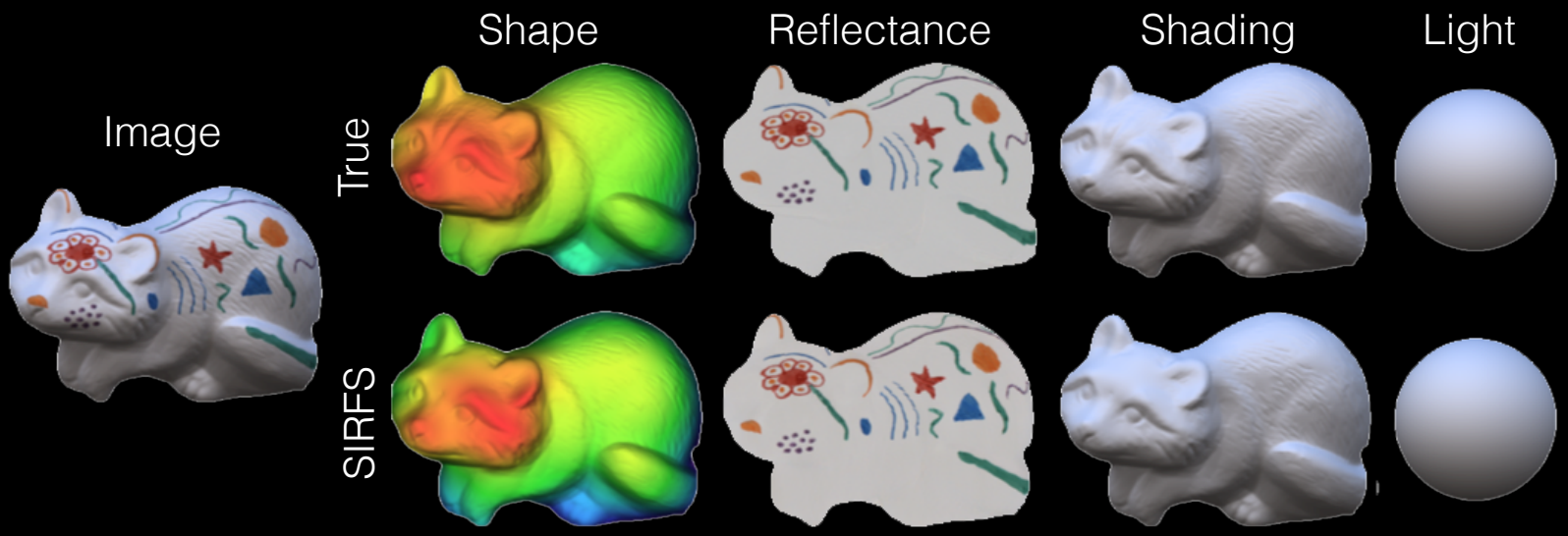
State-of-the-Art Diffuse Material Estimates

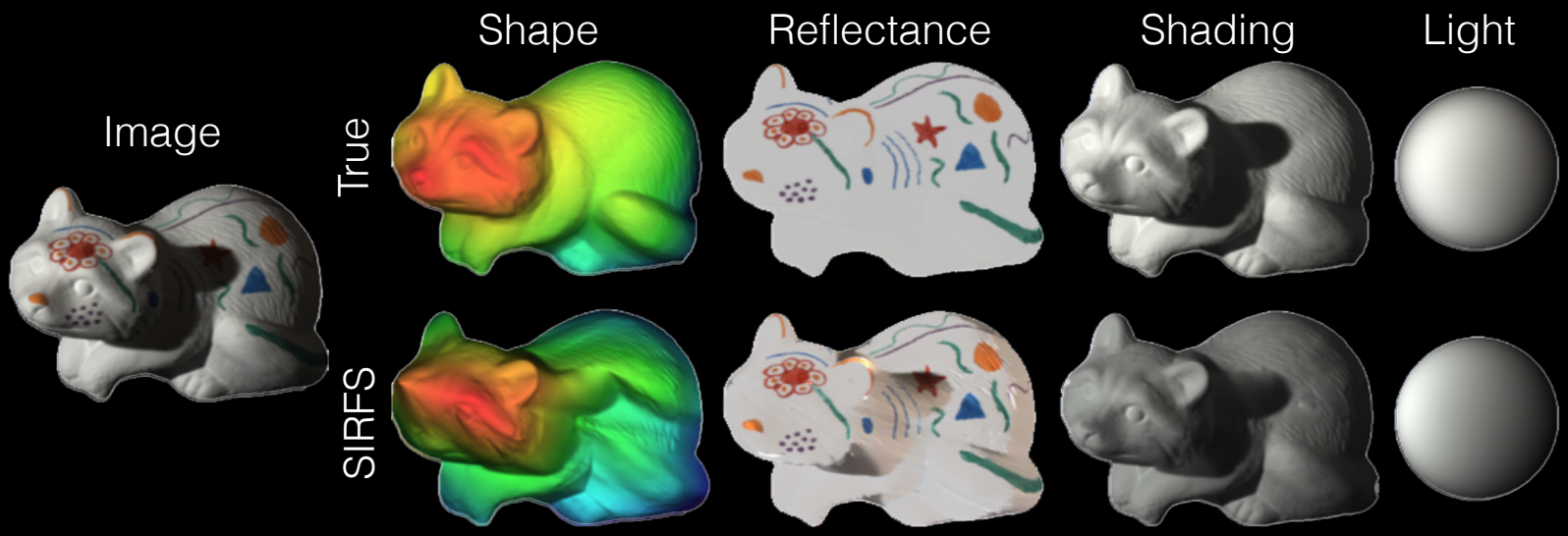
[Barron and Malik]



- Cast shadows, global illumination not modeled
- 2.5D Geometry
- Orthographic scenes
- Better priors?

State-of-the-Art Diffuse Material Estimates

[Barron and Malik]



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Ground Truth Material Datasets

BRDF Datasets

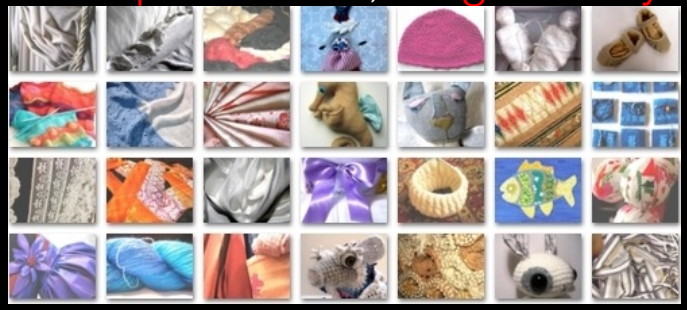
[Matusik et al. 03, Dana et al. '99]

Full BRDF, no geometry

Material Recognition Datasets

[Sharan et al. '14]

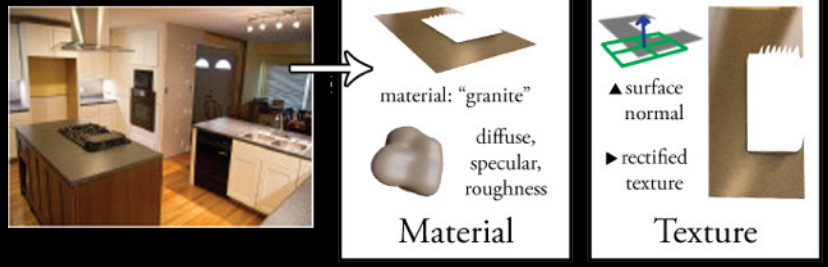
Non-parametric, no geometry



OpenSurfaces

[Bell et al. 14]

Real data, flat geometry



MIT Intrinsic Image Dataset

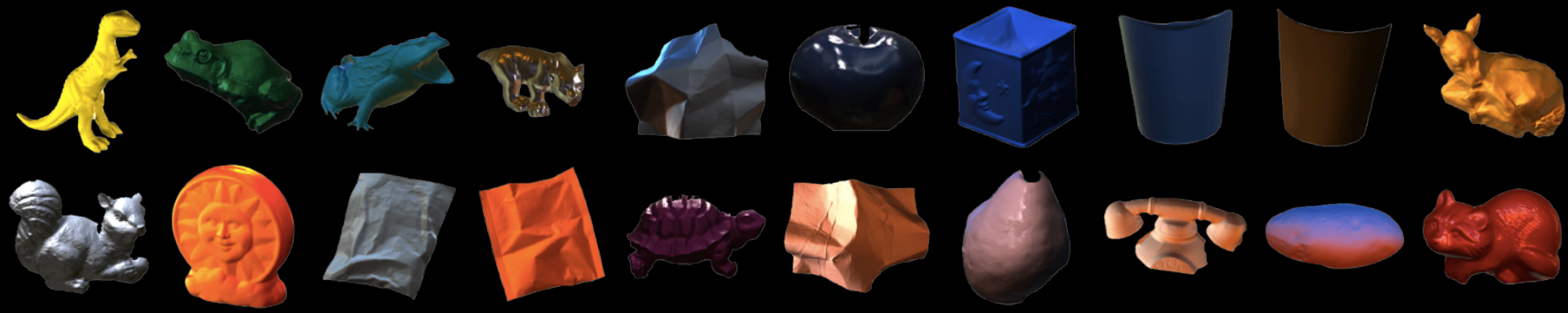
[Grosse et al. 09]

Real data, diffuse only

Ours

Full BRDF, synthetic data

Measured BRDF + Geometry Dataset



Render measured materials onto measured geometry

+ Real materials: MERL BRDF Dataset
+ Real geometry: MIT Intrinsic Image Dataset
+ Real, image-based lighting: SIBL Archive

– Object-level
– Synthetic

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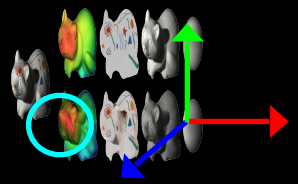
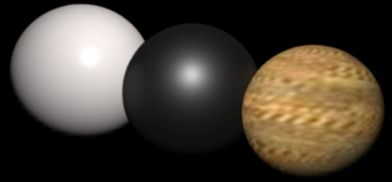
How to parameterize a scene?

Camera parameters



Geometry

Materials



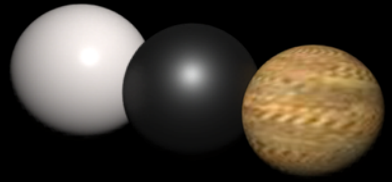
Light sources

How to parameterize a scene?

Camera parameters
- Orthographic
- Perspective
  - f, cx, cy, …

Geometry

Materials



Light sources

How to parameterize a scene?

Camera parameters
- Orthographic
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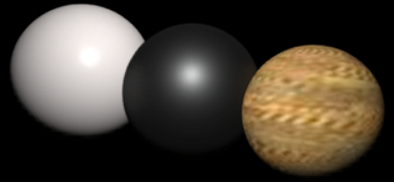
  - f, cx, cy, …

Geometry
- 2.5D
- 3D

Materials



Light sources

How to parameterize a scene?

Camera parameters
- Orthographic
- Perspective
  - f, cx, cy, …

Geometry
- 2.5D
- 3D

Materials
- BRDF
- DS-BRDF
- Microfacet model

Light sources

How to parameterize a scene?

Camera parameters
- Orthographic
- Perspective
  - f, cx, cy, …

Geometry
- 2.5D
- 3D

Materials
- BRDF
- DS-BRDF
- Microfacet model

Light sources
- Spherical harmonics
- Image-based
- Physical

How to parameterize a scene?

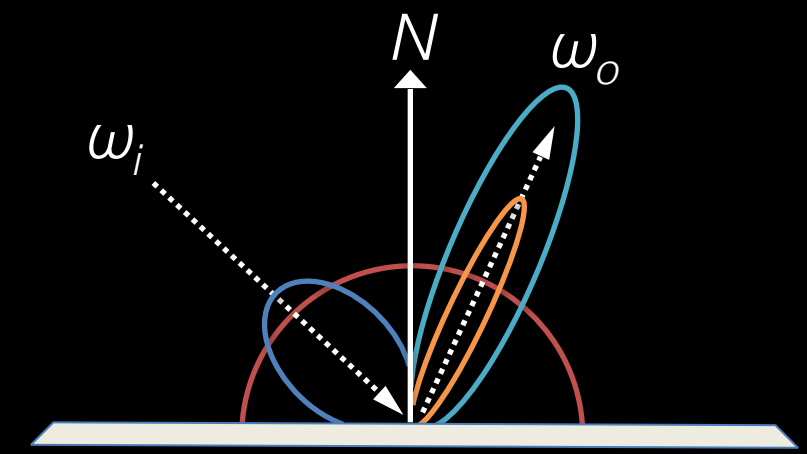
Camera parameters
- Orthographic
- Perspective
  - f, cx, cy, …

Geometry
- 2.5D
- 3D

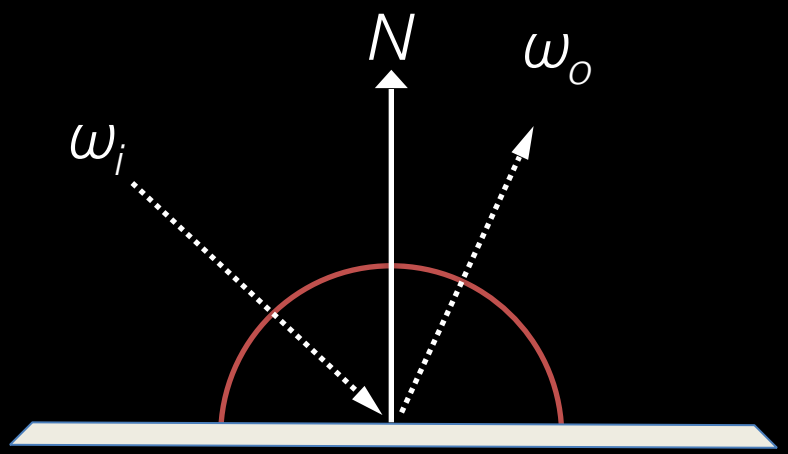
Materials
- BRDF
- DS-BRDF
- Microfacet model

Light sources
- Spherical harmonics
- Image-based
- Physical
- Hybrid

Material Parameterization

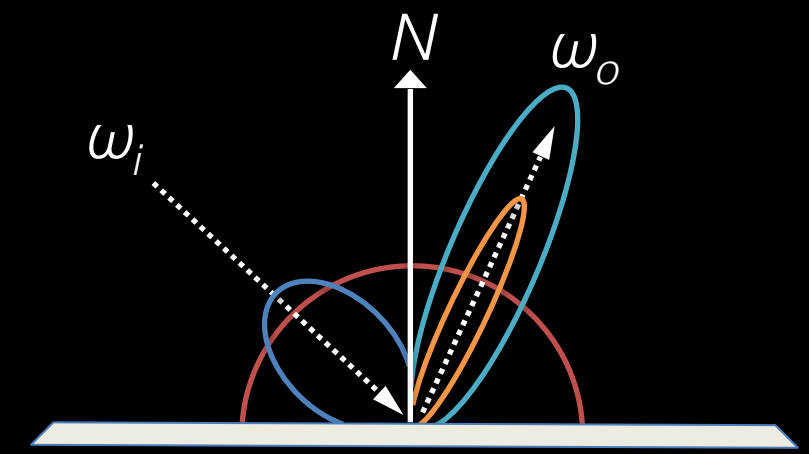


Full BRDF (4D function, multiple lobes)



Diffuse model (single diffuse lobe)

Material Parameterization



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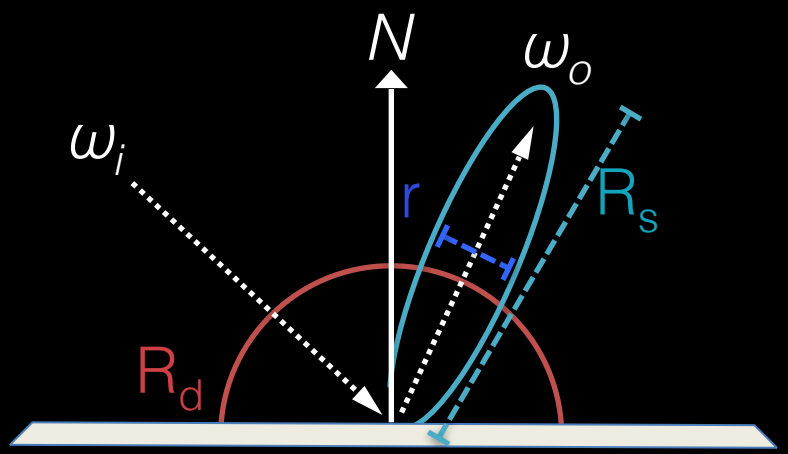
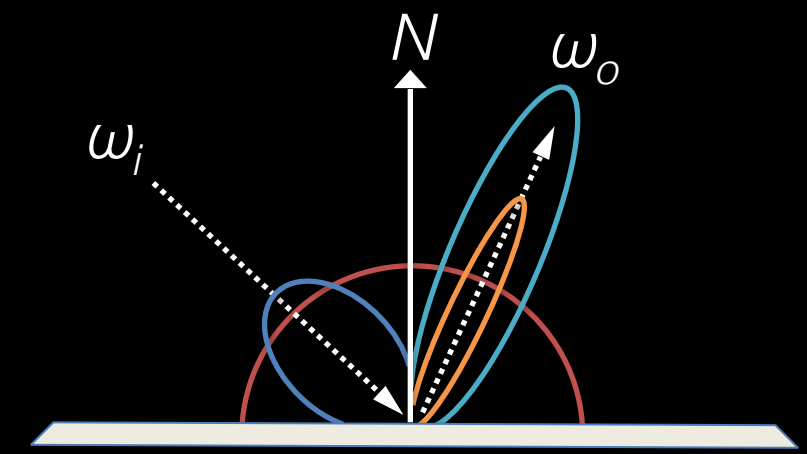


Our model (Diffuse + specular lobe)

Material Parameterization



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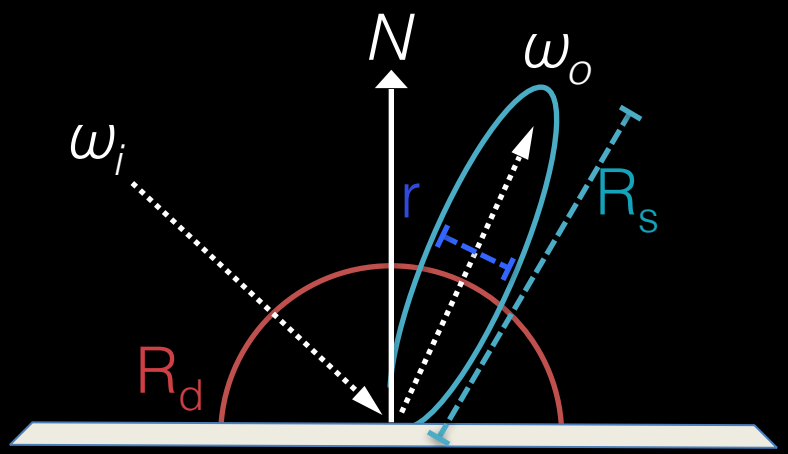
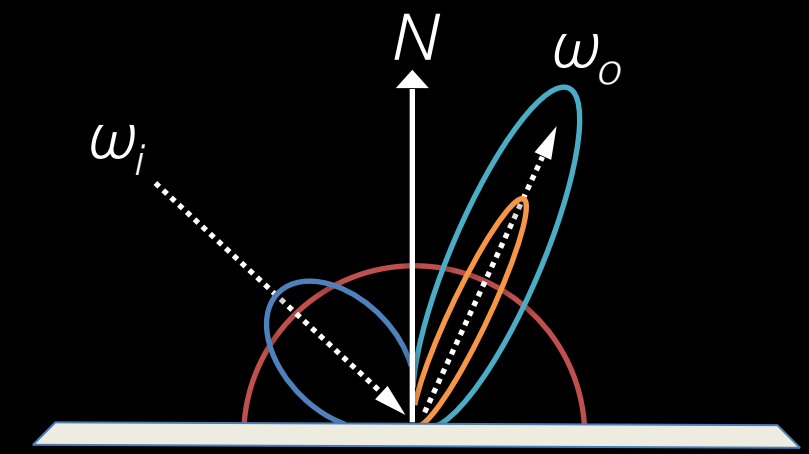


Our model (Diffuse + specular lobe)

- Isotropic substrate model [Pharr and Humphreys 10]
  - Models 1-lobe specularities
  - Approximates Fresnel (Schlick)

Material Parameterization



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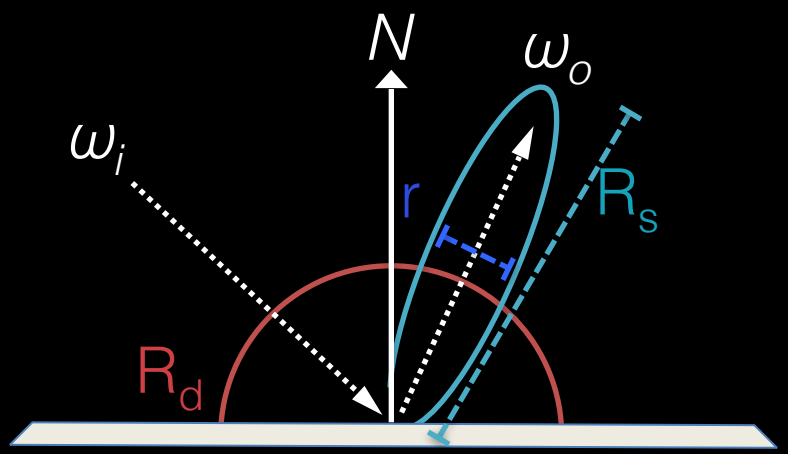


Our model (Diffuse + specular lobe)

- Isotropic substrate model [Pharr and Humphreys 10]
  - Models 1-lobe specularities
  - Approximates Fresnel (Schlick)
- Low order (5 parameters)
  - RGB diffuse reflectance (R_d)
  - Monochrome specular reflectance (R_s)
  - Isotropic lobe size (r)

Illumination Parameterization

Image-based light

Spherical harmonics (2nd order)

Illumination Parameterization

Image-based light

SH (2^{nd} order) + Mix of S^2 Gaussians

Illumination Parameterization

Image-based light

SH (2^{nd} order) + Mix of S^2 Gaussians

- Hybrid of spherical harmonics and distant area sources
  - Parallels between Nishino's DS-BRDF

Illumination Parameterization

Image-based light

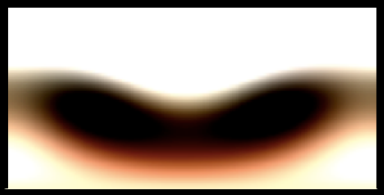
SH (2^{nd} order) + Mix of S^2 Gaussians

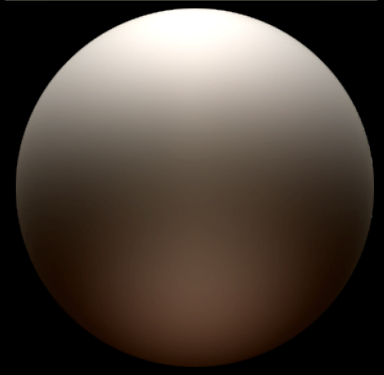
- Hybrid of spherical harmonics and distant area sources
  - Parallels between Nishino's DS-BRDF
- Compromise between # parameters and spatial frequency
  - 27 parameters (9 per channel) for 2^{nd} order SH
  - 6 parameters per Gaussian (total parameters = 27 + 6k)

Parameter Comparison

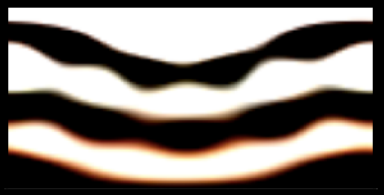
IBL
6048 parameters

2nd order SH
27 parameters

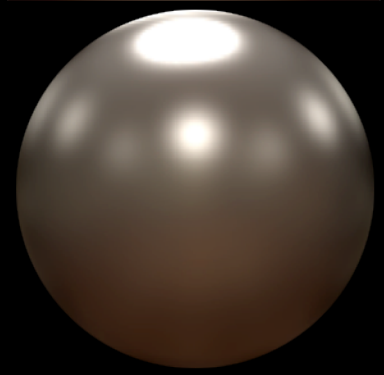




5th order SH
108 parameters



20th order SH
1323 parameters



Hybrid model
87 parameters

Rendered Comparison

	Measured BRDF + Image-based light	Our material model + Image-based light	Our material model + our light model
Blue rubber			
Bronze aluminum			

Beyond Diffuse Material Estimation

- Why are we stuck on diffuse?
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  - Estimation

Estimation

- Retinex, SIRFS, …, ours
  - All are underconstrained, continuous optimization problems
  - Differences lie in priors and parameterization

Retinex Optimization

Image

=

Reflectance (R)

•

Shading (S)

$$\underset{R}{\text{argmin}} \sum_{i}^{\text{pixels}} ||\nabla R_i - t(\nabla I_i)||$$

$$t(x) = \begin{cases} x & x > \text{threshold} \\ 0 & \text{otherwise} \end{cases}$$

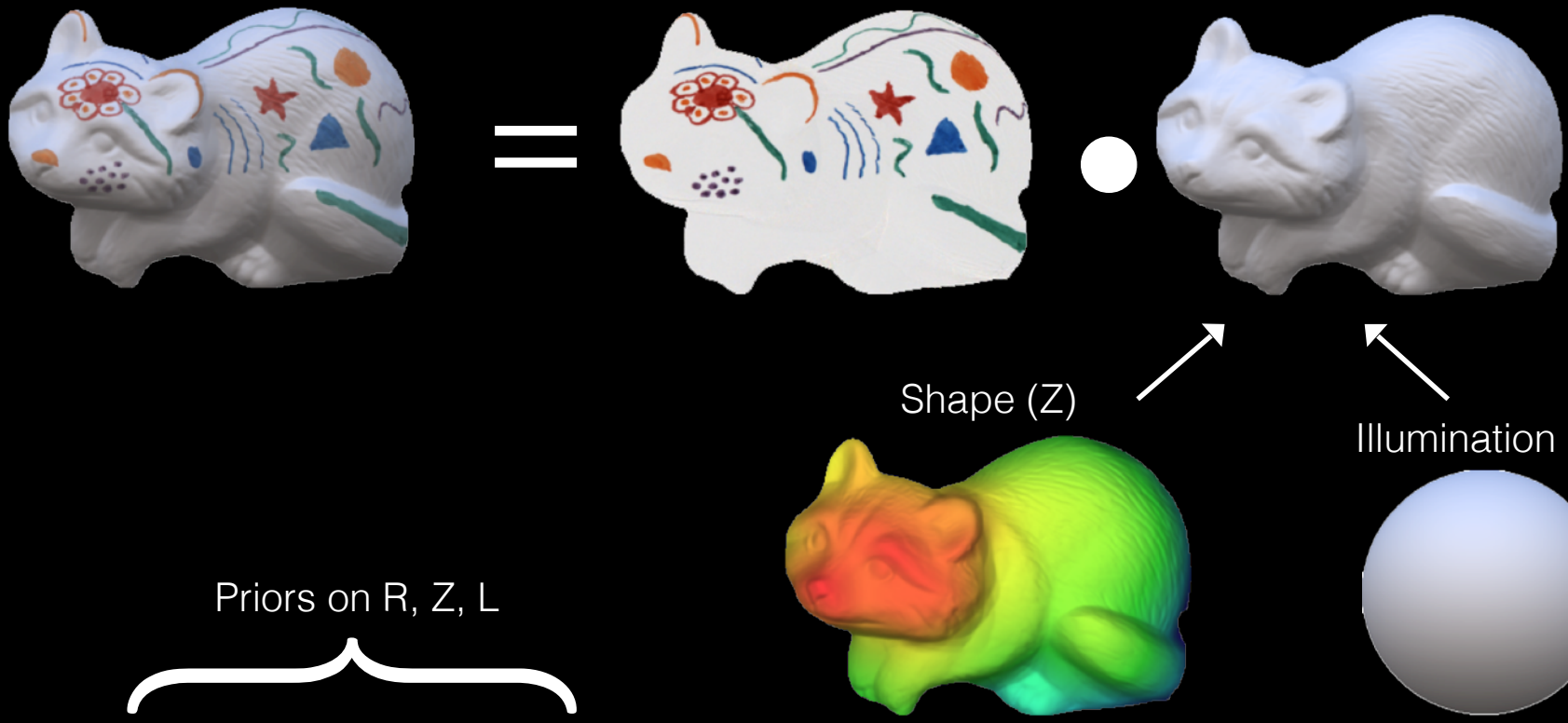
$$S = \frac{I}{R}$$

Prior on R

$$\underset{R}{\text{argmin}} \; g(R)$$

$$\text{subject to } I = R \cdot S$$

SIRFS Model [Barron and Malik]



Priors on R, Z, L

$$\underset{R,Z,L}{\operatorname{argmin}} \; g(R) + f(Z) + h(L)$$

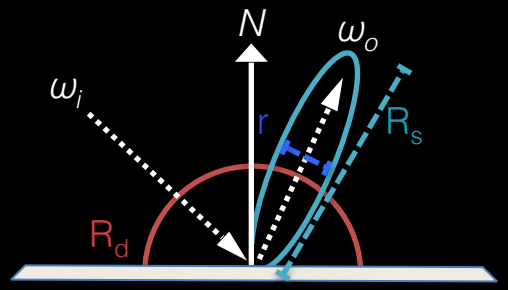
$$\text{subject to } I = R \cdot S(Z, L)$$

Our Model

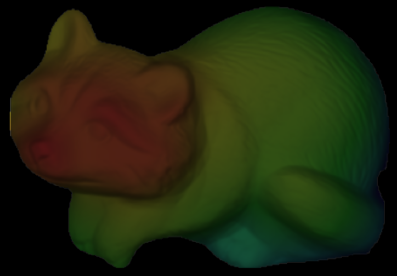
Image

≈

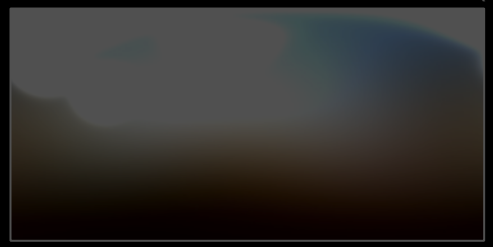
Material (R_d, R_s, r)



Shape (Z)



SH+Gaussian Illumination (L)

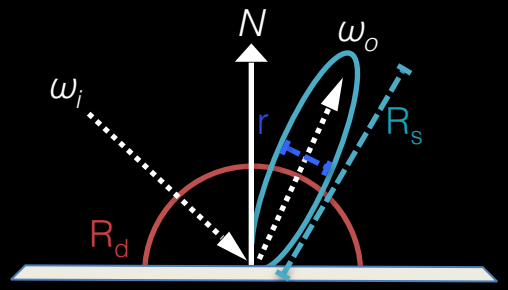


Our Model

Image

≈

Material (R_d, R_s, r)



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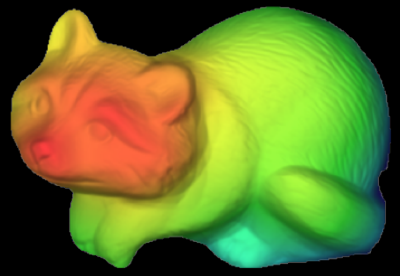

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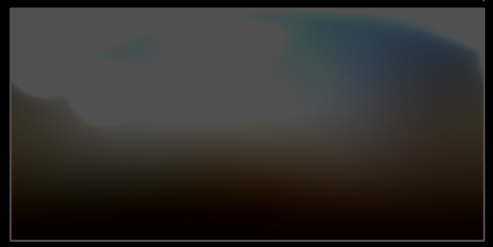

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Image

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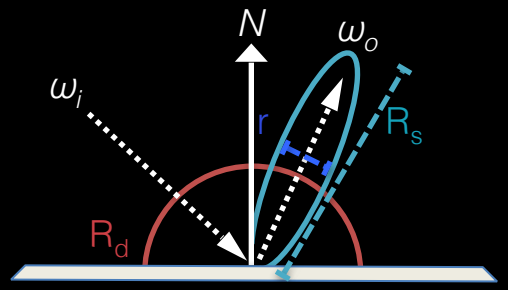
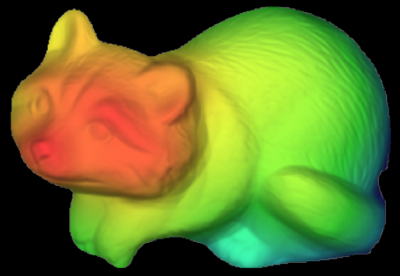
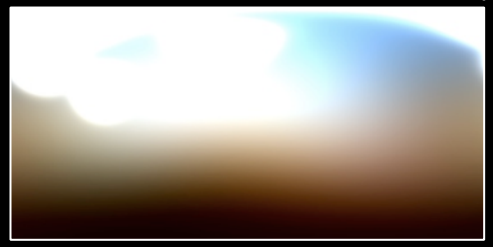


Shape (Z)



SH+Gaussian Illumination (L)



Our Model

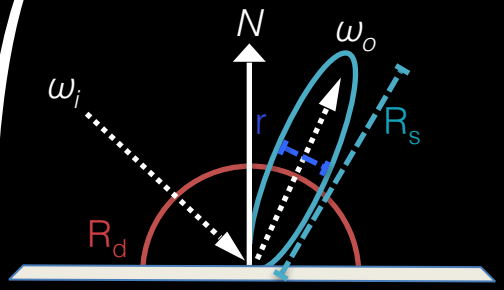
Image

≈

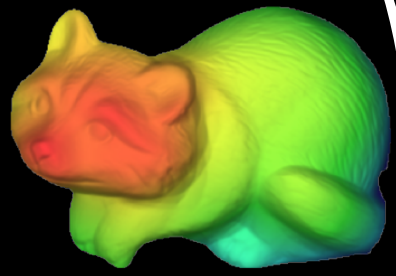
Non-linear
rendering function

$\hat{p}$

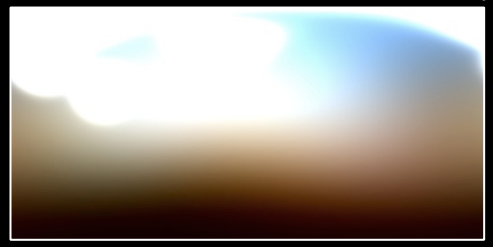
Material (R_d, R_s, r)



Shape (Z)



SH+Gaussian Illumination (L)



Our Model

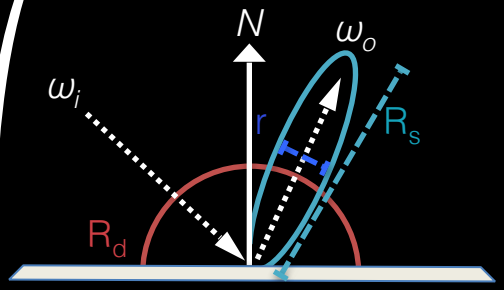
Image

$\approx$

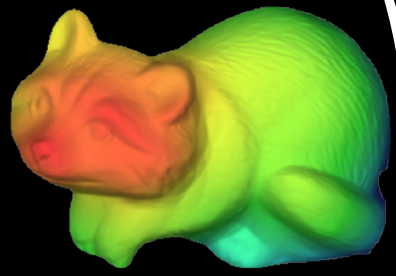
Non-linear rendering function

$\hat{\rho}$

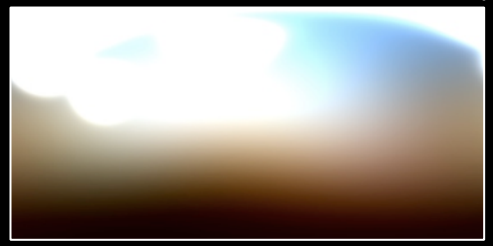
Material (R_d, R_s, r)



Shape (Z)



SH+Gaussian Illumination (L)



$$\underset{R_d,R_s,r,Z,L}{\operatorname{argmin}} \quad g(R_d, R_s, r) + f(Z) + h(L)$$

Our Model

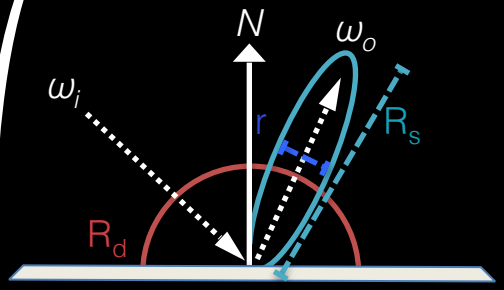
Non-linear rendering function

Image

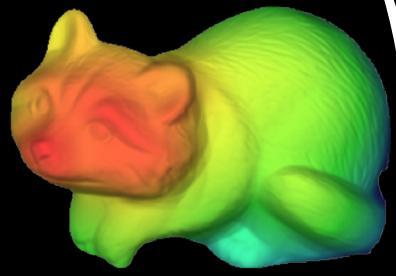
$\approx$

$\hat{\rho}$

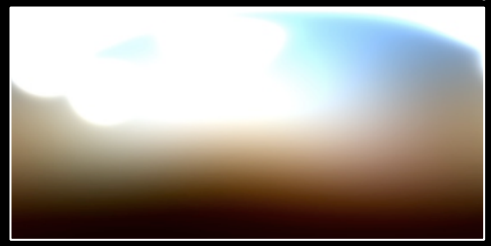
Material (R_d, R_s, r)



Shape (Z)



SH+Gaussian Illumination (L)



$$\underset{R_d,R_s,r,Z,L}{\operatorname{argmin}} \quad g(R_d, R_s, r) + f(Z) + h(L) + ||I - \rho(R_d, R_s, r, Z, L)||$$

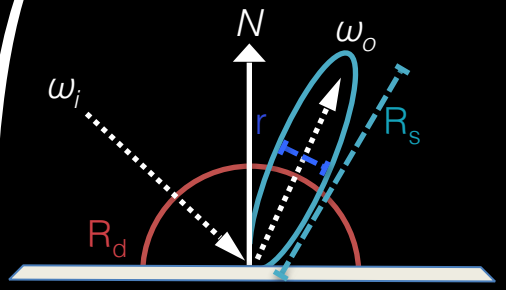
Our Model

Non-linear rendering function

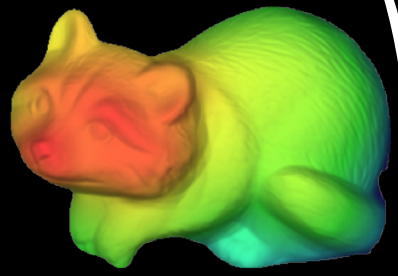
Image

$\approx$ ρ

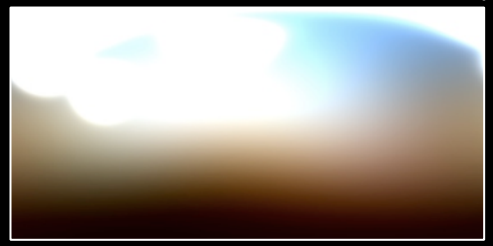
Material (R_d, R_s, r)



Shape (Z)



SH+Gaussian Illumination (L)



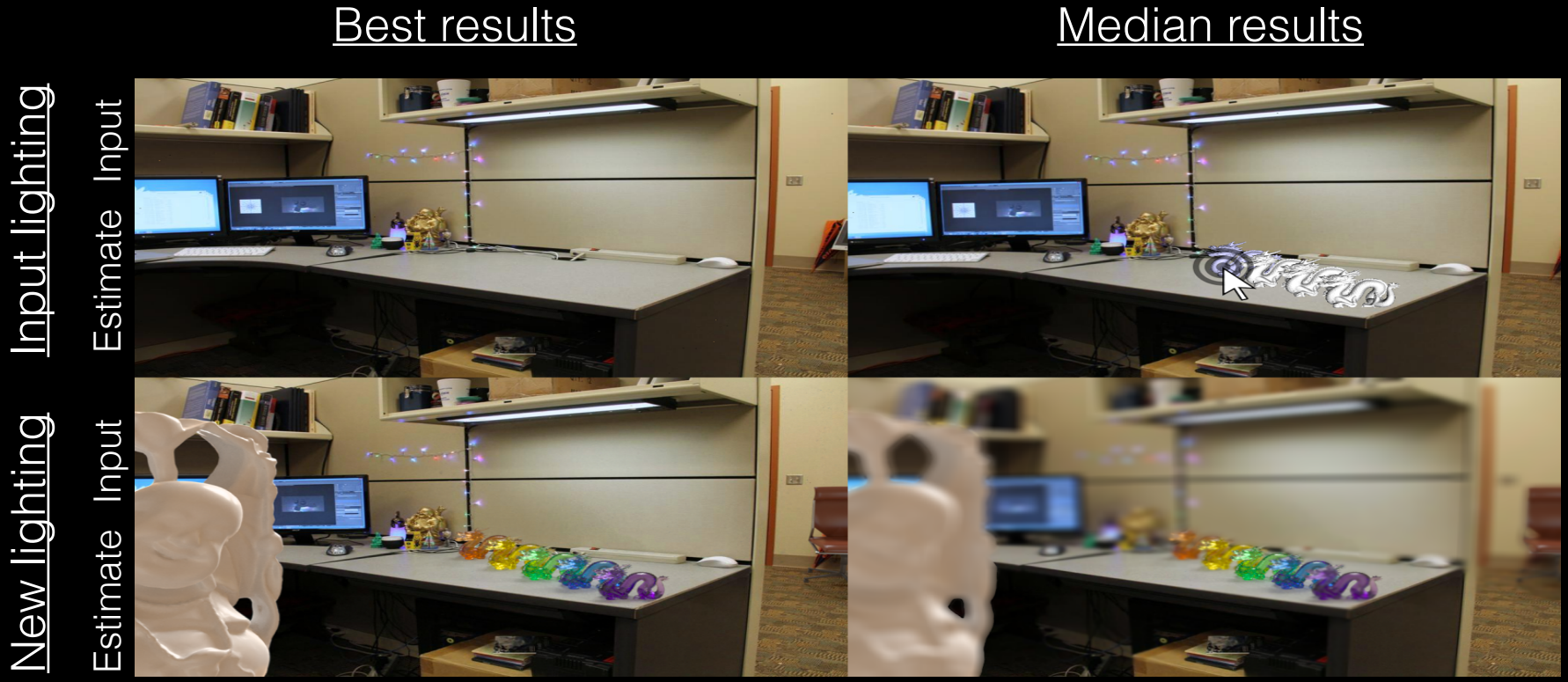
Data driven material and lighting priors

$$\underset{R_d,R_s,r,Z,L}{\operatorname{argmin}} \quad g(R_d, R_s, r) + f(Z) + h(L) + ||I - \rho(R_d, R_s, r, Z, L)||$$

Shape should be smooth and perpendicular at boundary

Input and rendering can have some errors (models aren't perfect)

Material Estimation Results



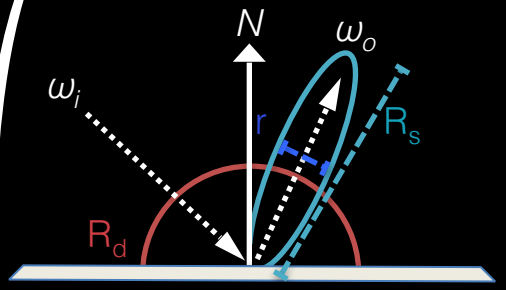
Our Model (Spatially-Varying Materials)

Image

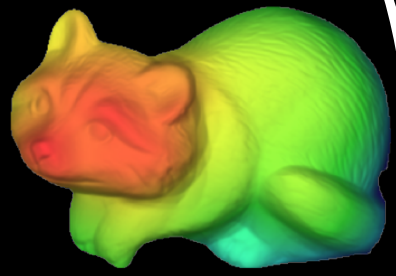
$\approx$

ρ

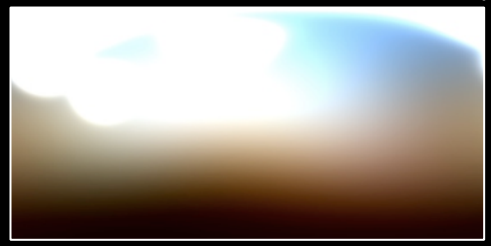
Material (R_d, R_s, r)



Shape (Z)



SH+Gaussian Illumination (L)



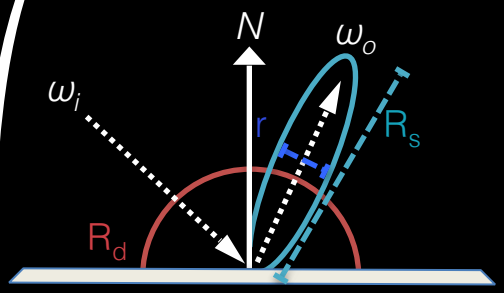
$$\underset{R_d,R_s,r,Z,L,m}{\operatorname{argmin}} \left[\sum_{i=1}^{k} g(R_d^i, R_s^i, r^i) + p(m_i)\right] + f(Z) + h(L) + ||I - \sum_{i=1}^{k} m_i \rho(R_d^i, R_s^i, r^i, Z, L)||$$

Our Model (Spatially-Varying Materials)

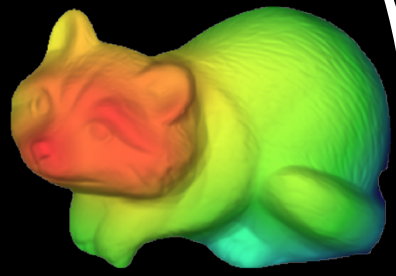
Image

$$\approx \sum_{i=1}^{k} m_i \rho$$

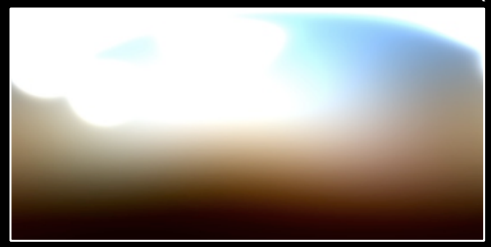
Material (R_d^i, R_s^i, r^i)



Shape (Z)



SH+Gaussian Illumination (L)



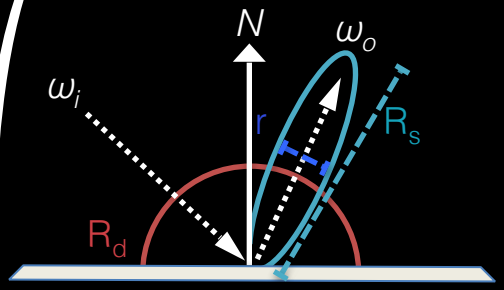
$$\underset{R_d,R_s,r,Z,L,m}{\operatorname{argmin}} \left[\sum_{i=1}^{k} g(R_d^i, R_s^i, r^i) + p(m_i)\right] + f(Z) + h(L) + ||I - \sum_{i=1}^{k} m_i \rho(R_d^i, R_s^i, r^i, Z, L)||$$

Our Model (Spatially-Varying Materials)

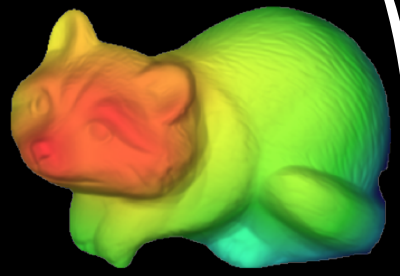
Image

$$\approx \sum_{i=1}^{k} m_i \rho \left(\right.$$

Material (R_d^i, R_s^i, r^i)



Shape (Z)



SH+Gaussian Illumination (L)

$\left. \right)$

Prior on spatial mixing weights
(smooth over space except at image edges)

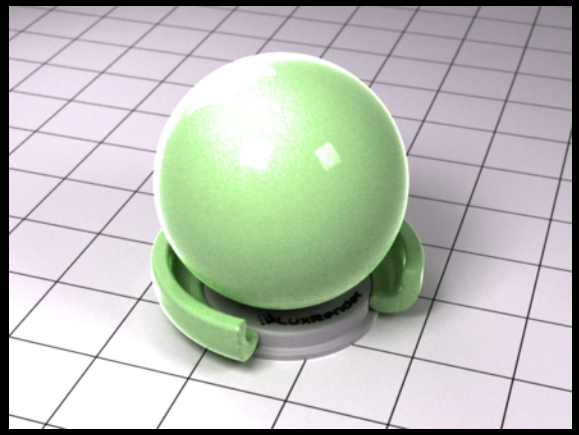
Image formation model is a linear combination [Goldman et al. '10]

$$\underset{R_d, R_s, r, Z, L, m}{\operatorname{argmin}} \left[\sum_{i=1}^{k} g(R_d^i, R_s^i, r^i) + p(m_i) \right] + f(Z) + h(L) + ||I - \sum_{i=1}^{k} m_i \rho(R_d^i, R_s^i, r^i, Z, L)||$$

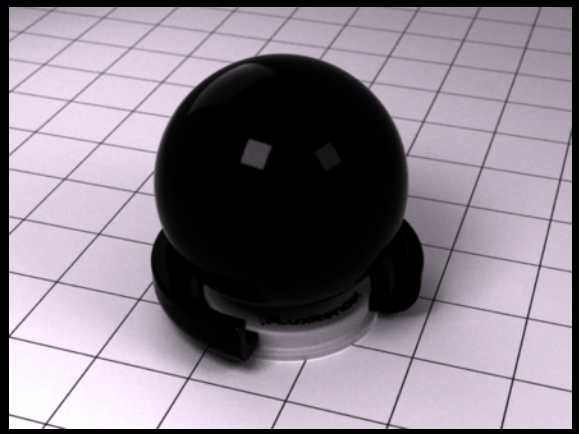
Real-world Results

Input

Material 1



Material 2

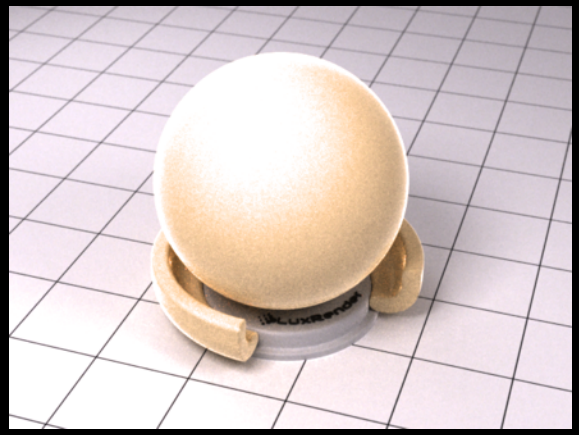


Mixing weights

Real-world Results

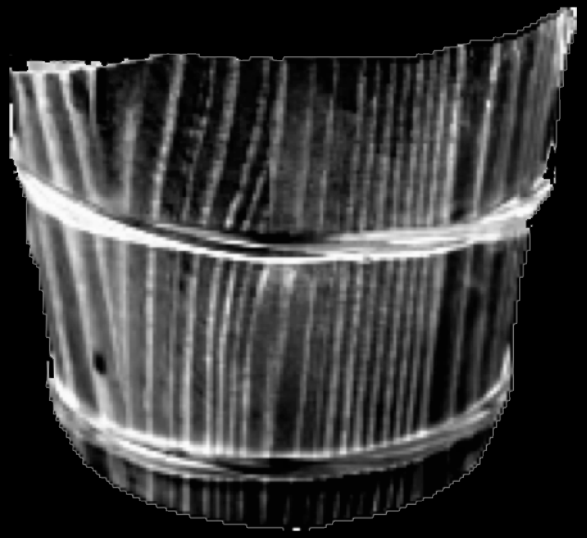
Input

Material 1



Material 2

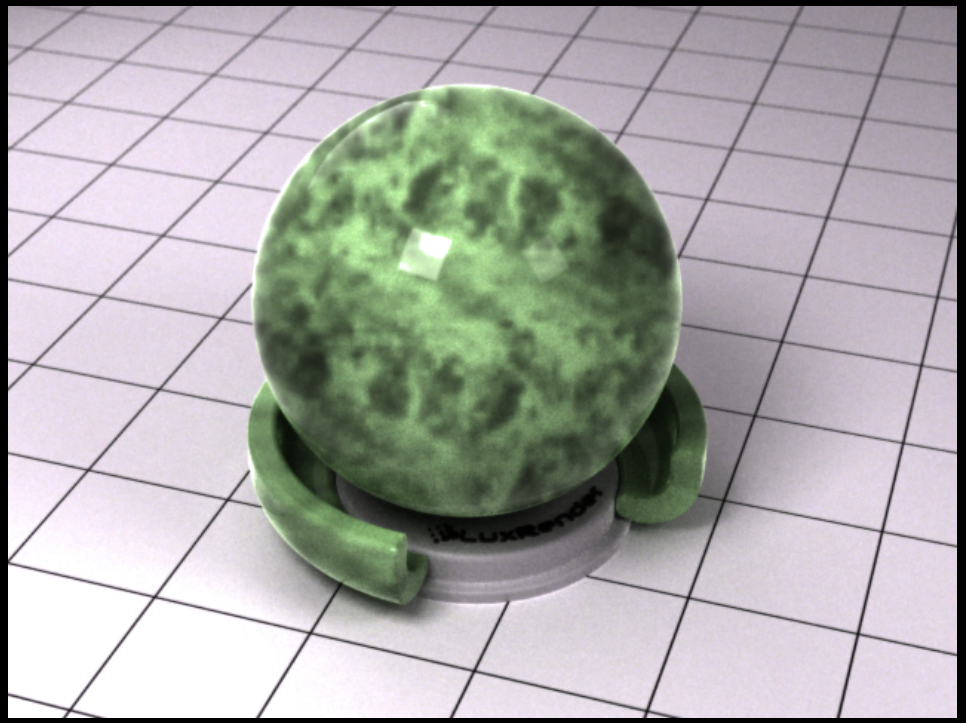
Mixing weights



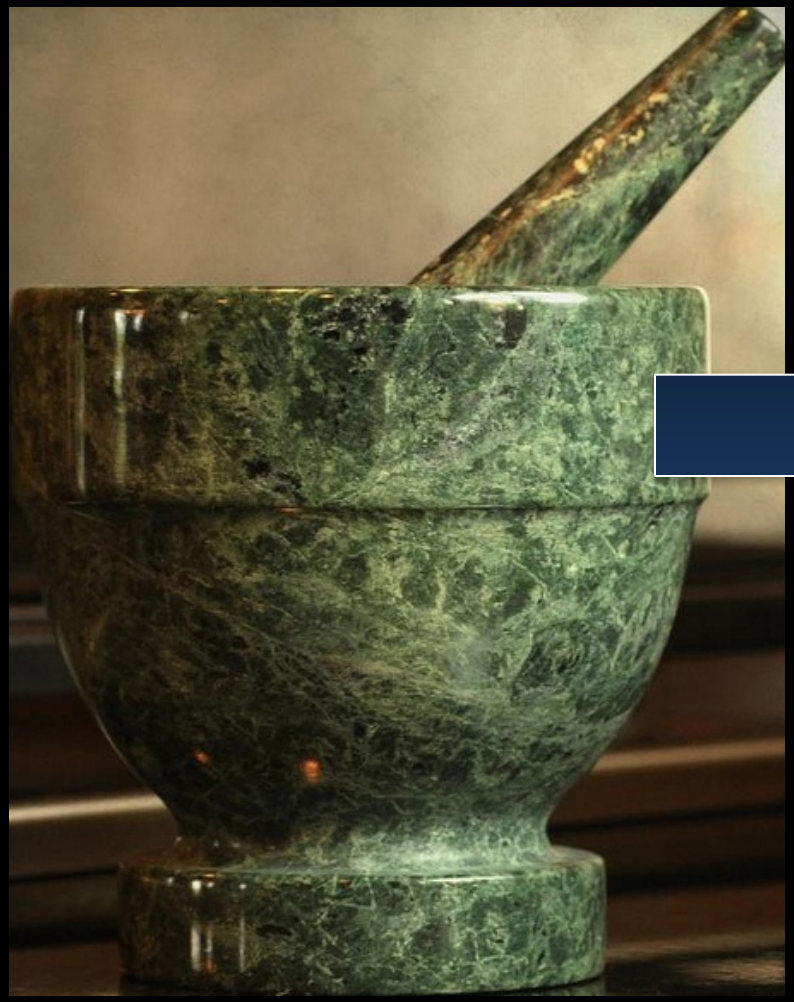
Applications: Graphics Meets Vision

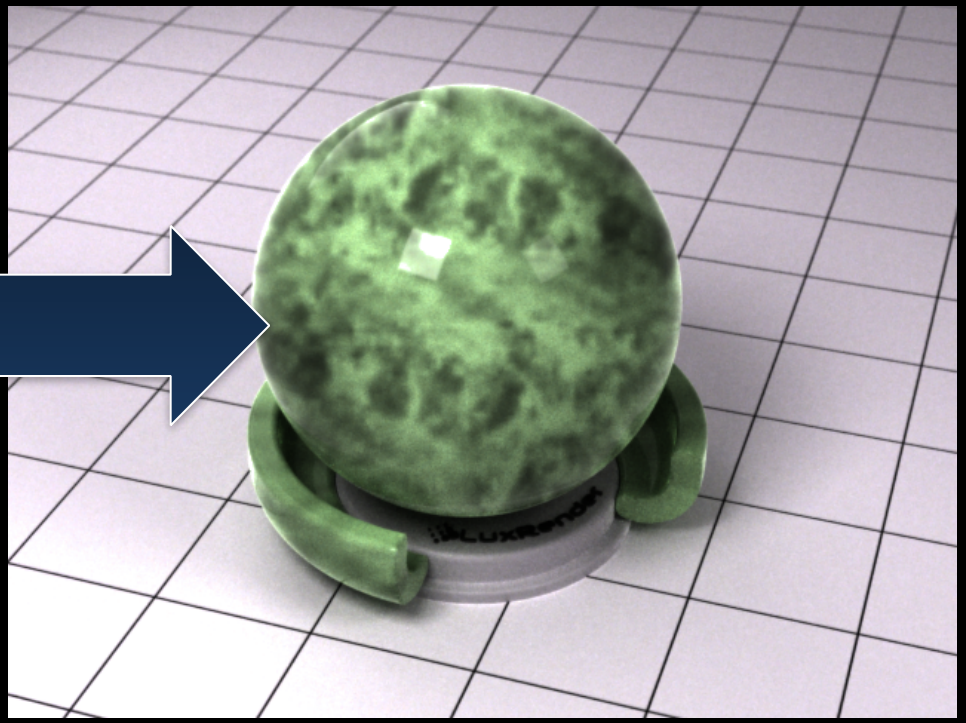
- Material transfer
- Material classification
- Material synthesis / composition

Material Transfer

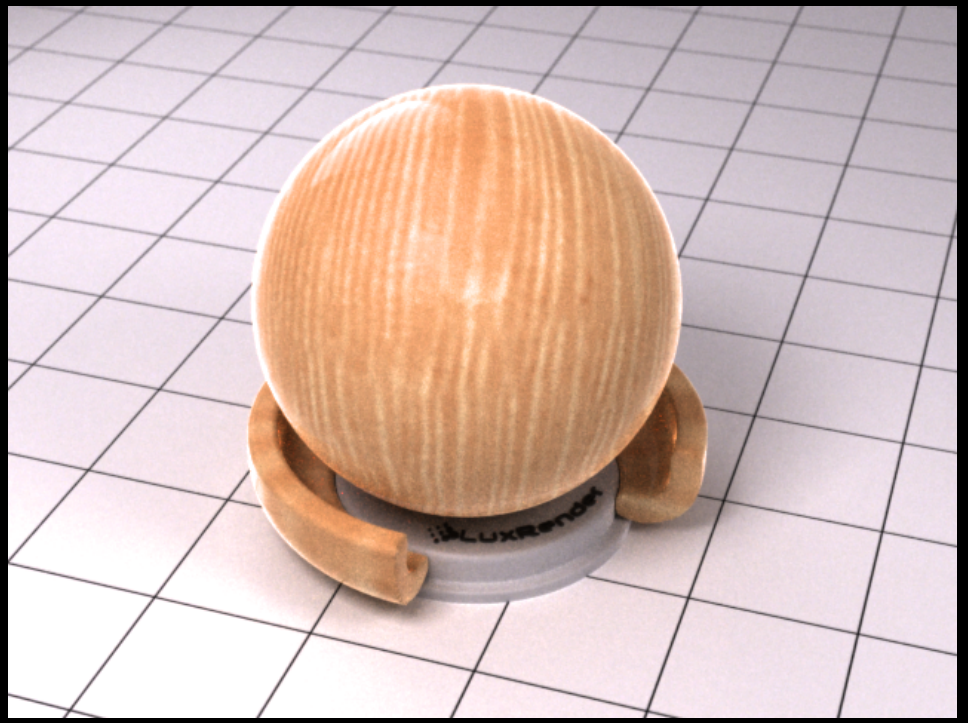


Material Transfer

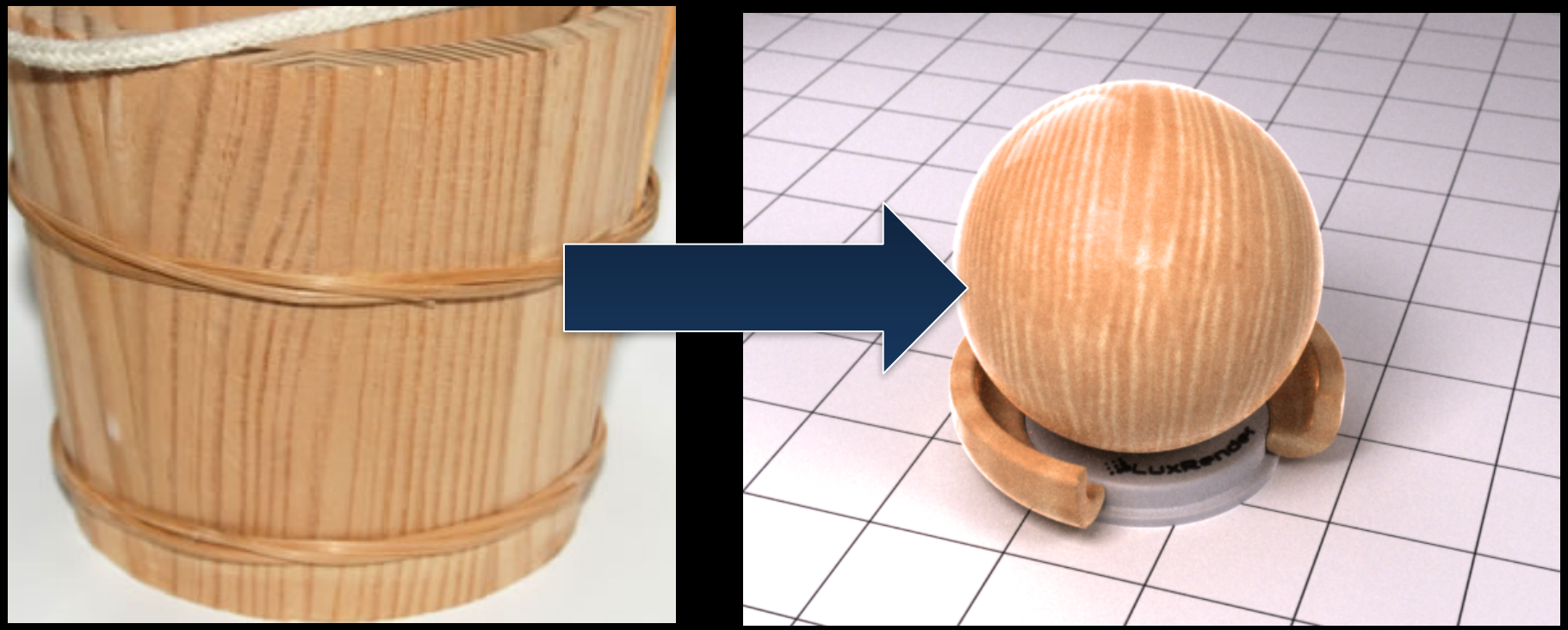




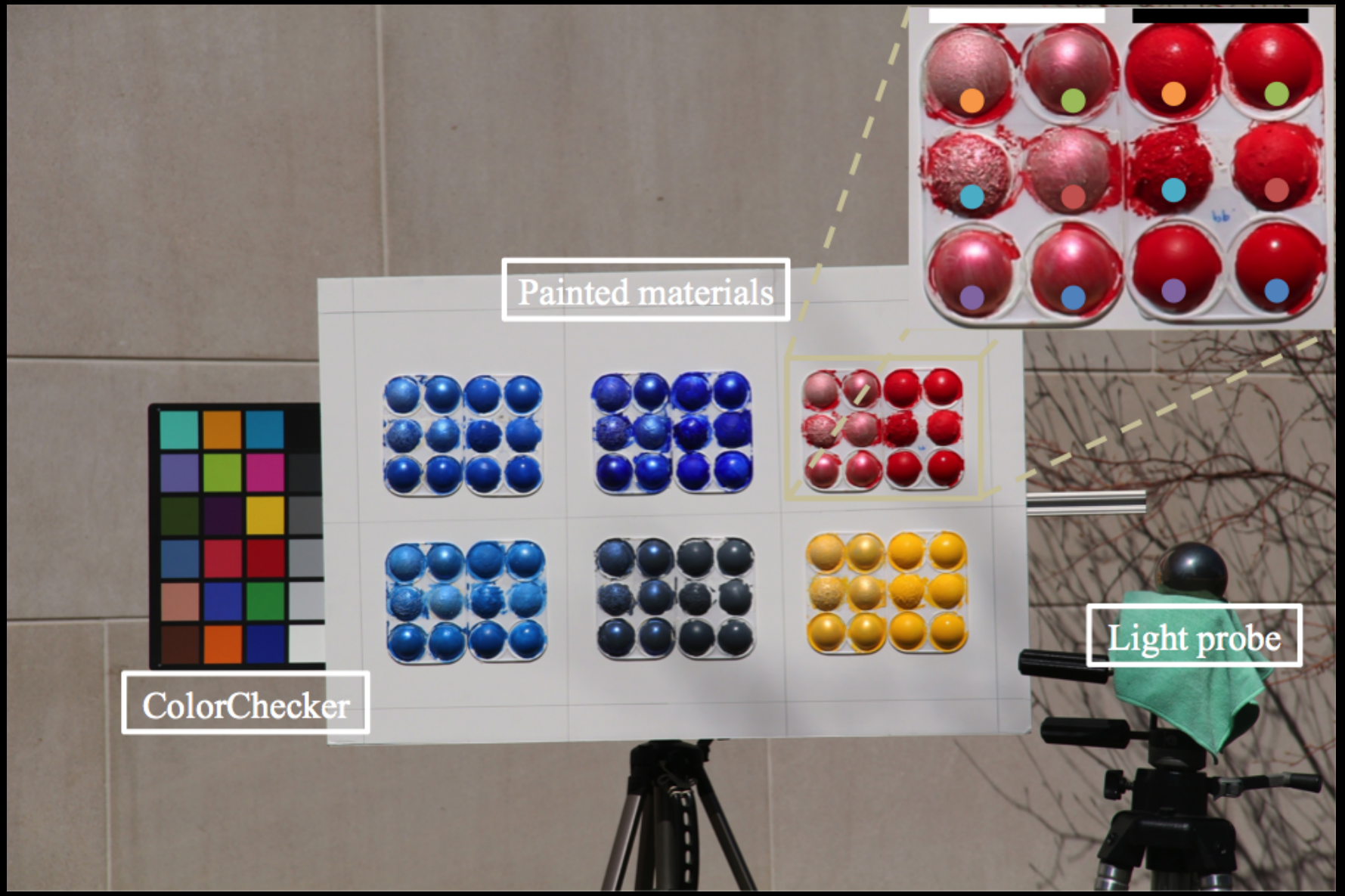
Material Transfer



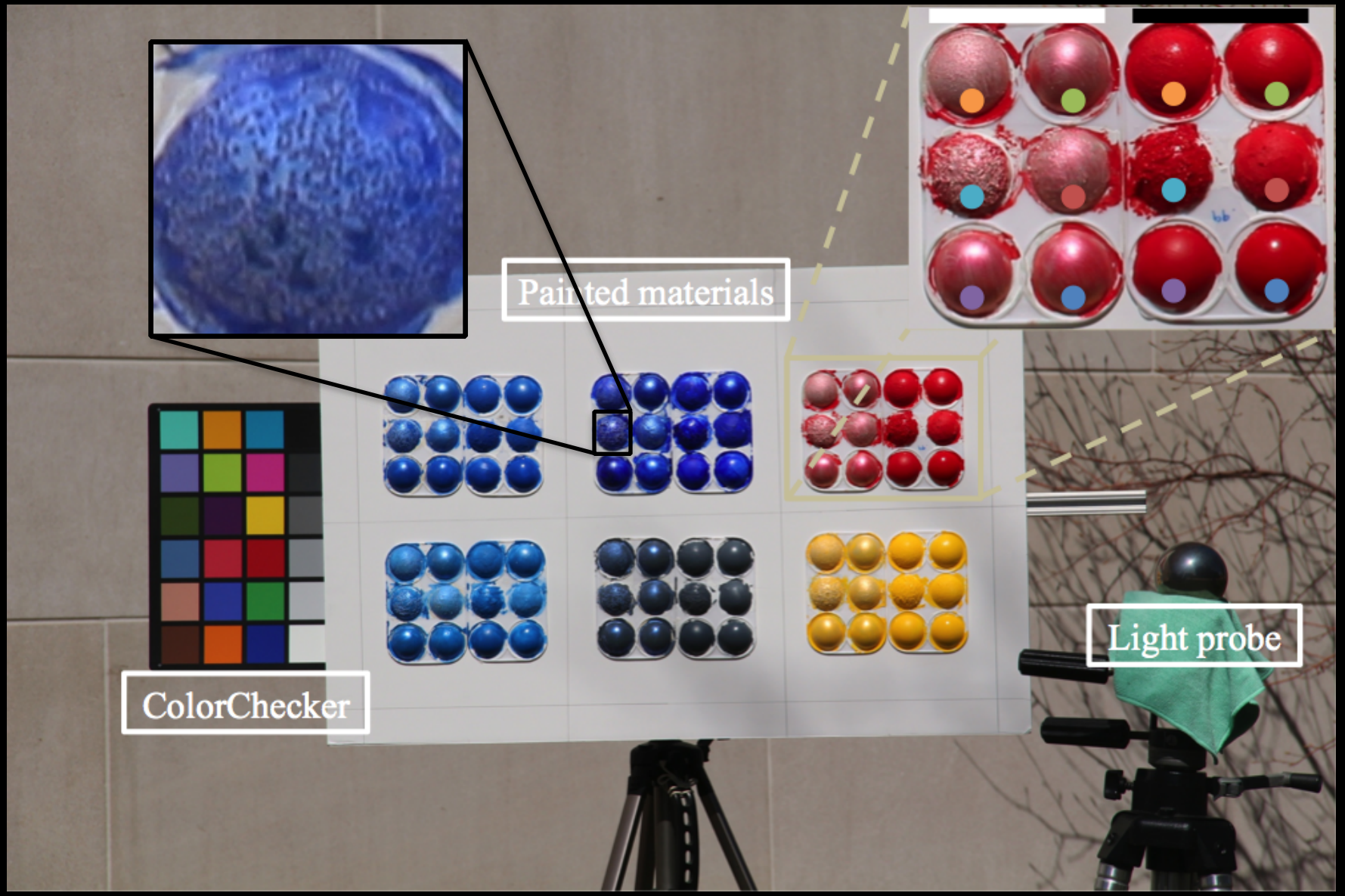
Material Transfer



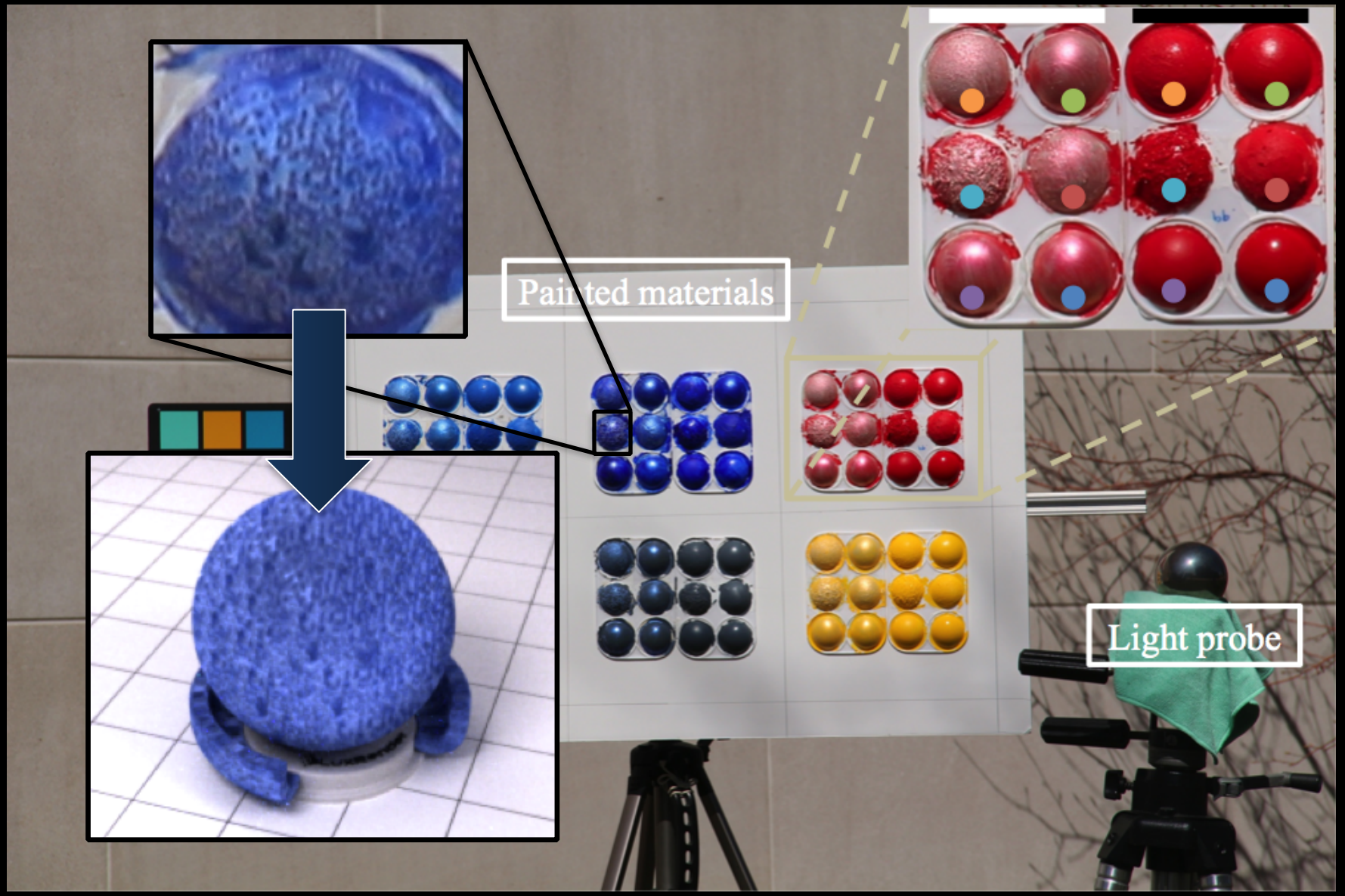
Material Classification



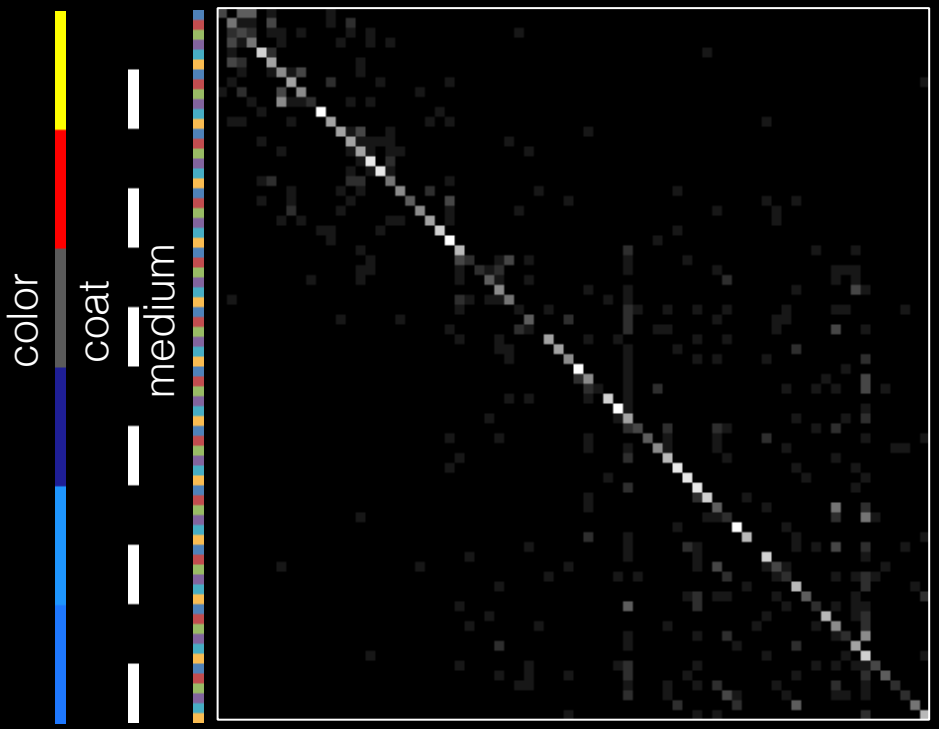
Material Classification

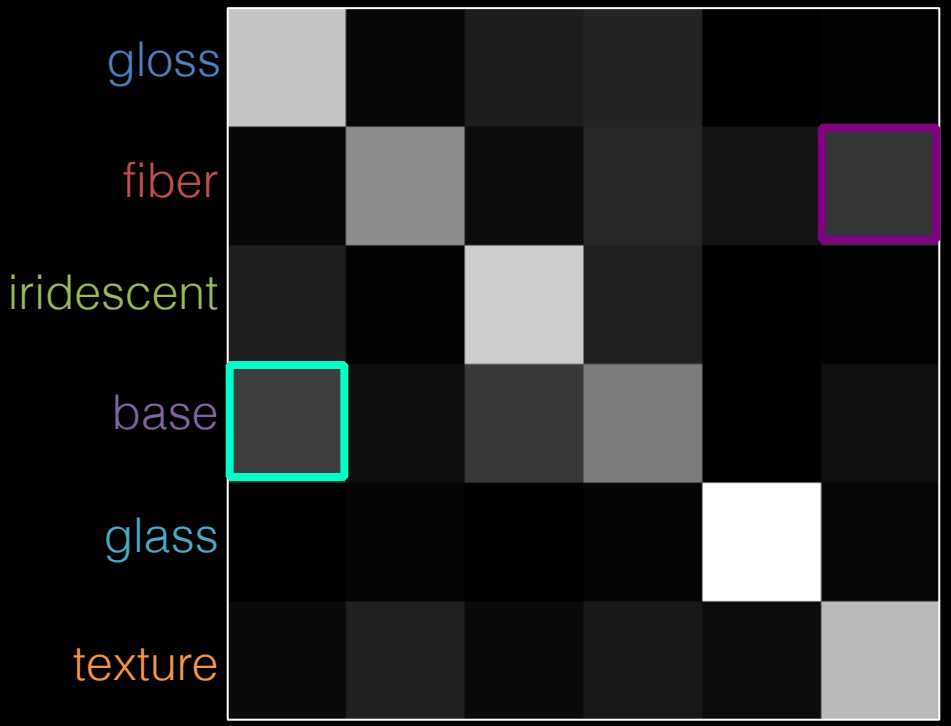


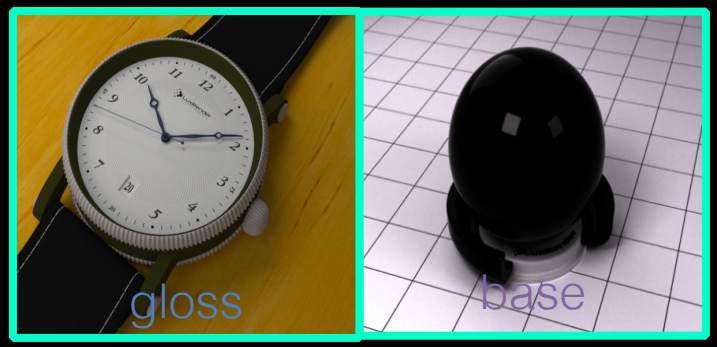
Material Classification

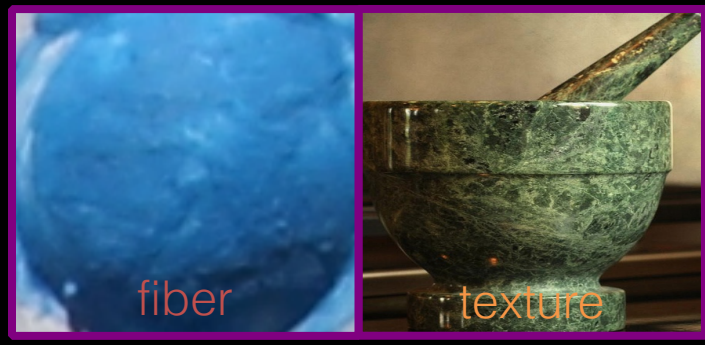


Material Classification

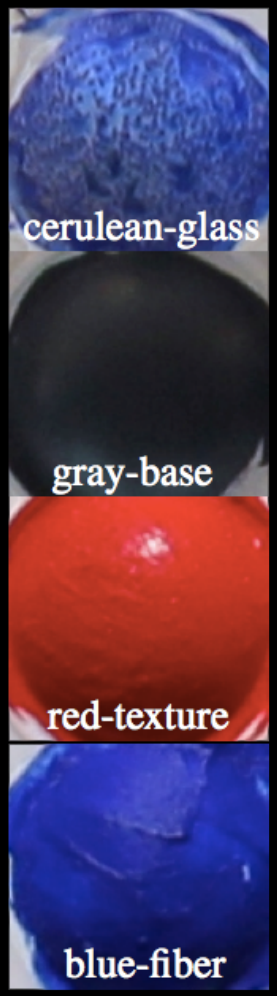


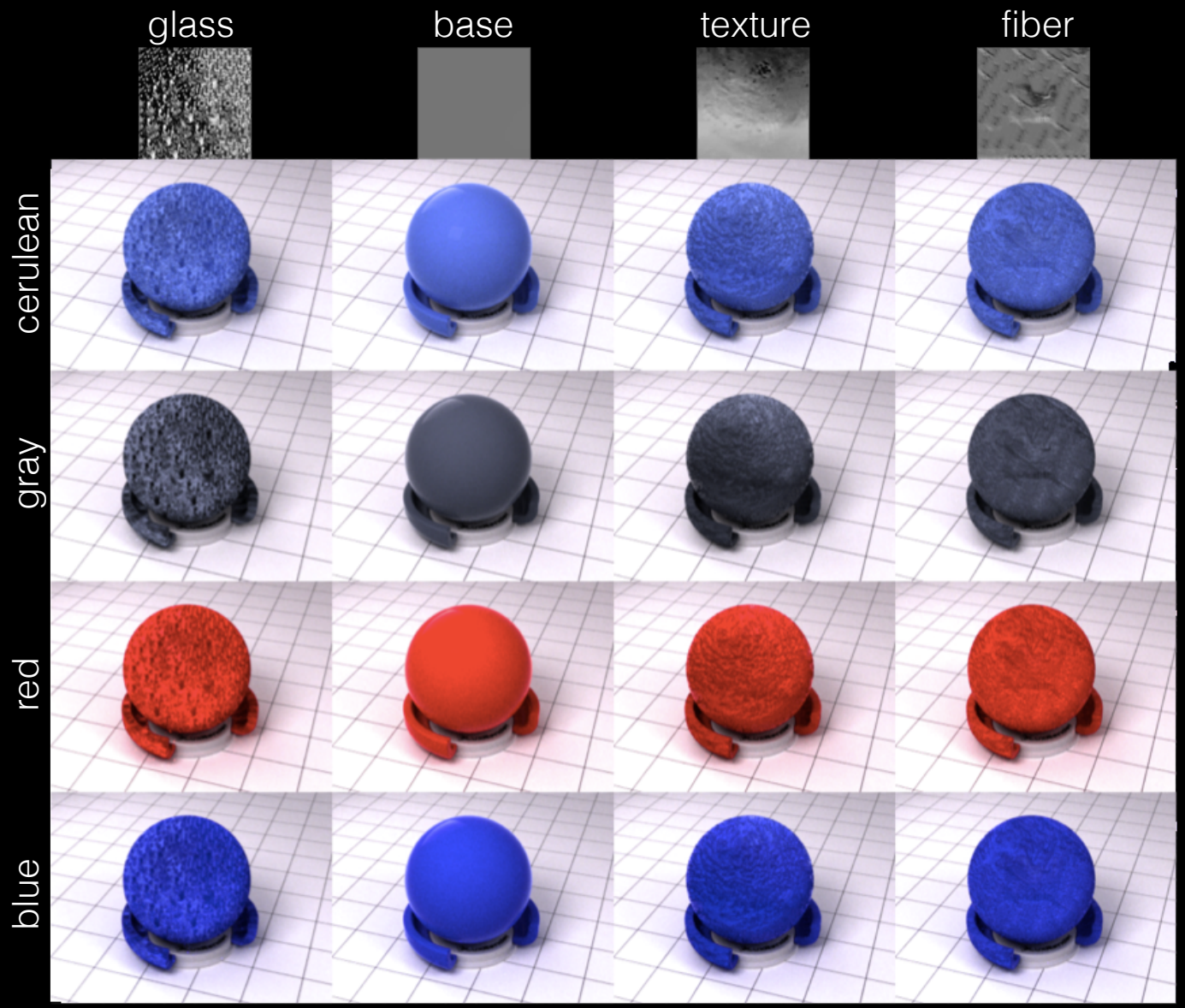






Material Composition and Generation





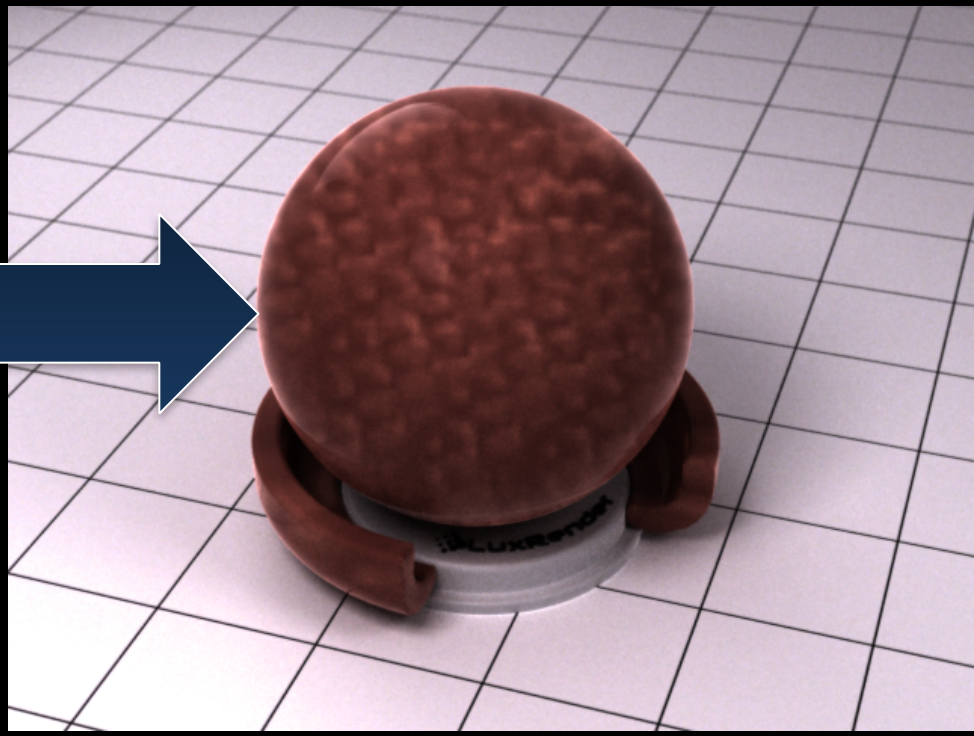
Limitations

- Material and lighting models
  - Desirable from inference standpoint
  - Better than standard diffuse models
  - Not a general material description

Rendered with BRDF + IBL

Rendered with our models

Failures



Failures

Input image

Rendered result

Mixture map

Conclusions

- Towards a material representation that is
  - Compositional
    - Material consists of several easily combined elements
    - Shape, medium, coat, etc
  - Practical
    - Can be recovered blindly from a single image
  - Transferable
    - Can be rendered onto other shapes in different lighting
  - Discriminative

- Still a lot left to do…

Thoughts for moving forward

- How should scenes be parameterized?
  - Must consider estimation cost
  - Application dependent
- Need some good datasets
- How to incorporate physical phenomena?
  - Global illumination, shadows, SSS
- Does 3D / perspective matter?
  - Which representations?