Photometric Stereo With Non-Parametric and Spatially-Varying Reflectance

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Overview

Goal
- Simultaneously recover shape and reflectance from images acquired at a single viewpoint

Contribution
- Capture of complex reflectance:
  - Non-parametric reflectance model
  - Allow complex spatial variation

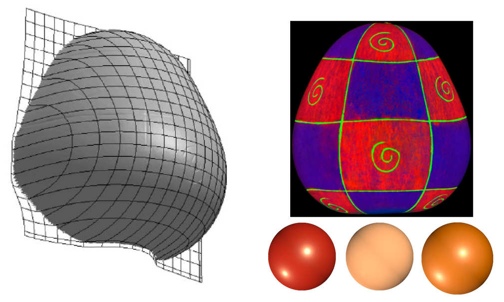
Approach
- Exploit symmetries of isotropic BRDFs
- Utilize linear BRDF basis for spatial variation

Result
- Highly accurate shape and reflectance for a broad class of surfaces
- Photo-realistic "appearance" capture

Input Images

1 of 102 input images acquired from a single viewpoint with known illumination.

Shape + Complex Reflectance

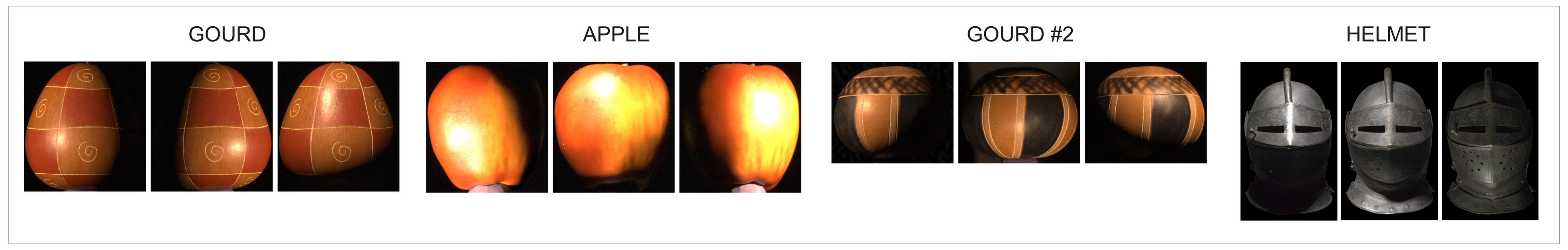


Recovered shape, material weight map, and basis BRDFs.

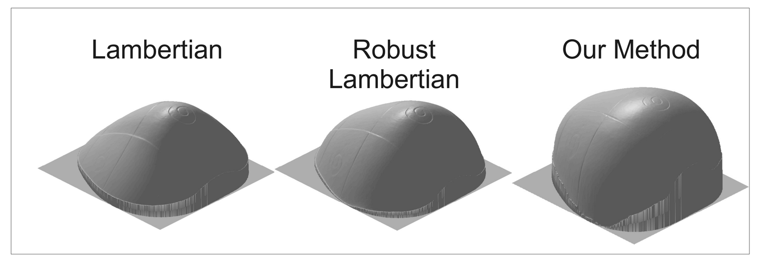
Novel View Synthesis

Rendering using recovered shape and reflectance with novel viewpoint / illumination.

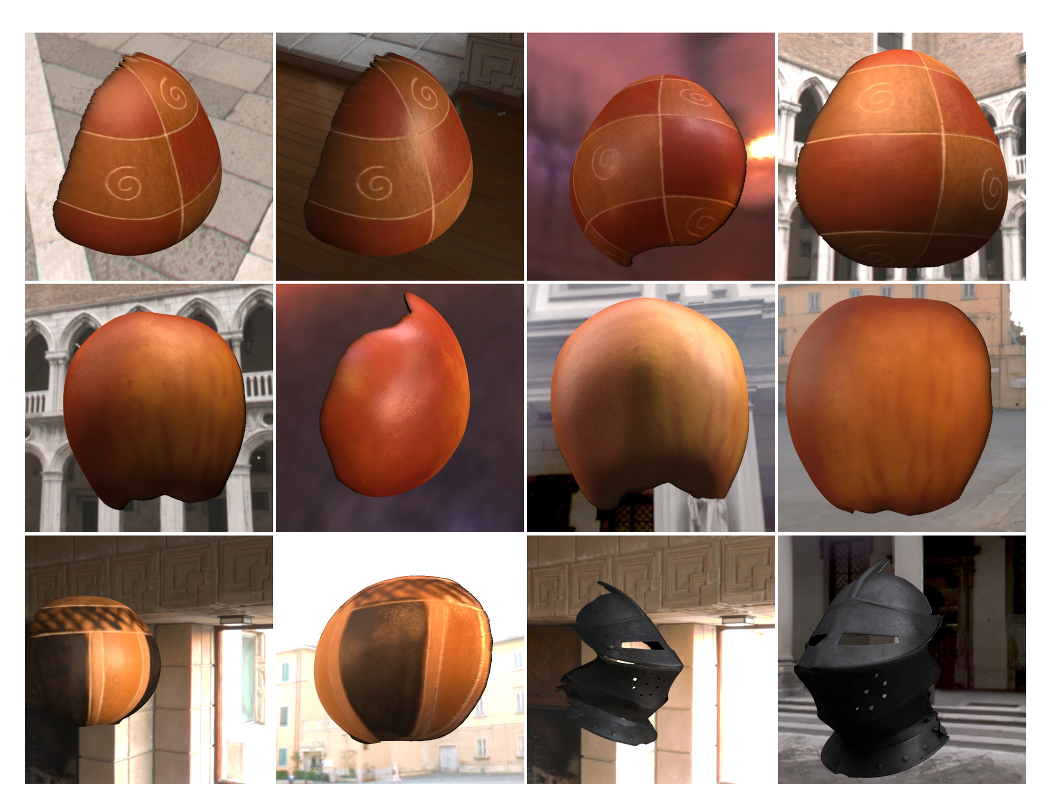
Results



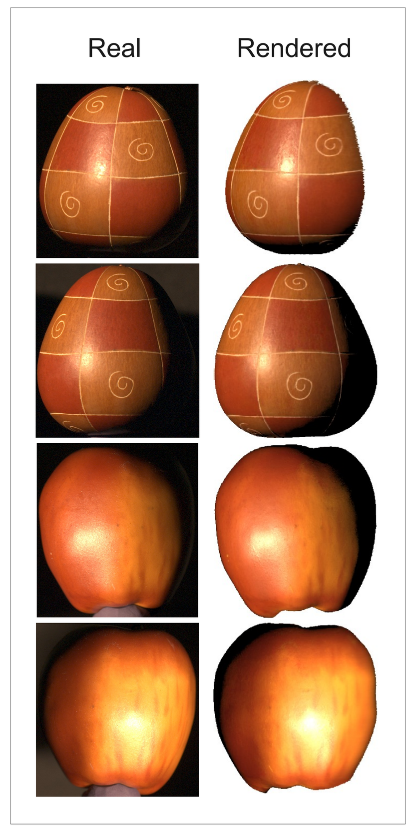
Example input images, ~100 per dataset. Images acquired from a single viewpoint with known illumination.



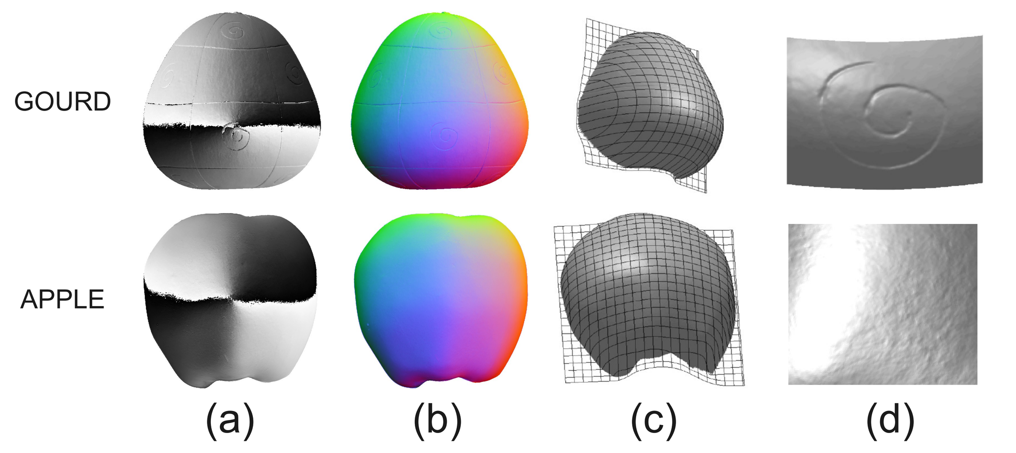
Comparison of GOURD shape recovered by our method to best fit using Lamberitan reflectance model.



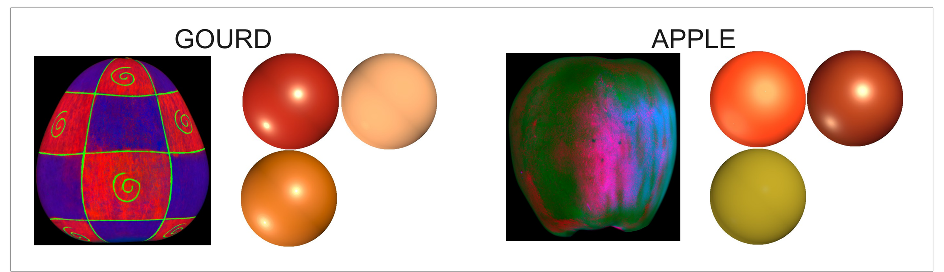
Rendered images using recovered shape and reflectance from novel viewpoints under complex illumination.



Comparison of real and synthetic images from novel views.



Recovered shape. (a) Azimuth component of normal map. (b) Normal map (rgb encoded). (c) Surface height map, (d) Close up of surface, showing recovered mesostructure.



Recovered material weight maps (rgb encoded) and basis BRDFs.

Constraints

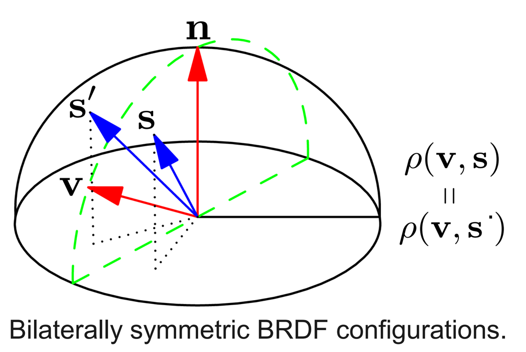
Isotropic BRDF

$\rho(\theta_i, \phi_i, \theta_o, \phi_o) \simeq \rho_{\text{isotropic}}(\theta_i, \theta_o, \|\phi_i - \phi_o\|)$

- BRDF invarient to rotation and reflection about the surface tangent plane
- Restricts surface normals to 1 d.o.f., see [1]

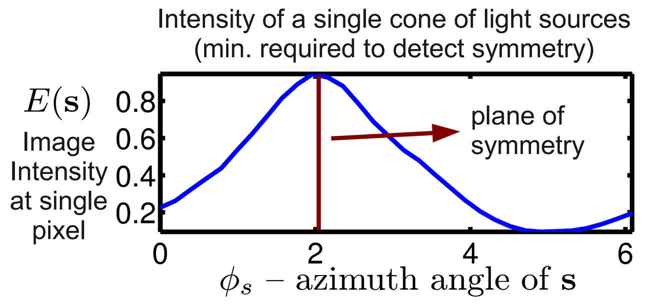
Consider local coordinate system at a single surface point with normal n, viewing direction v, and light source direction s

Identical BRDF / image intensity when s reflected about the plane spanned by n and v

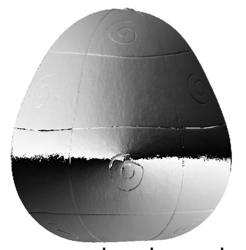


Bilaterally symmetric BRDF configurations.

Pixel intensity is a symmetric function of s



Detection of symmetry plane yields azimuthal component of surface normal (computed independently per pixel)



Phase map showing azimuthal components of a normal map

BRDF basis

- We model the BRDF at each surface point as a weighted sum of basis BRDFs,

$$\rho(x, y; \mathbf{v}, \mathbf{s}) = \sum_{i=1}^{k} w_i(x, y)\rho_i(\mathbf{v}, \mathbf{s})$$

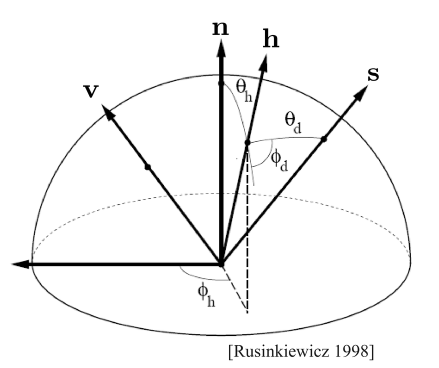
BRDF at a single pixel — per-pixel material weights — i[th] basis BRDF

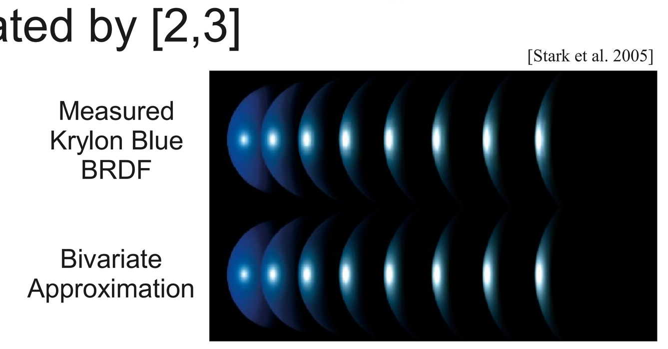
- Restricts spatial variation of the BRDF

Bivariate BRDF

$\rho(\theta_i, \phi_i, \theta_o, \phi_o) \simeq \rho_{\text{bivariate}}(\theta_h, \theta_d)$

- Each basis BRDF is modeled as a bivariate function of the half angle θ_h and difference angle θ_d
- Parameterization motivated by [2,3]

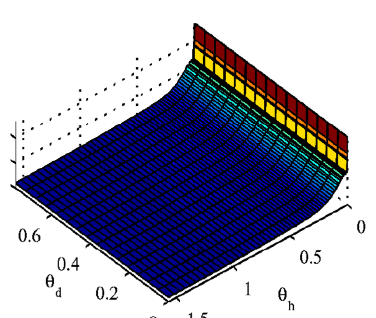




Bivariate approximation accurately captures complex reflection.

Discrete BRDF domain

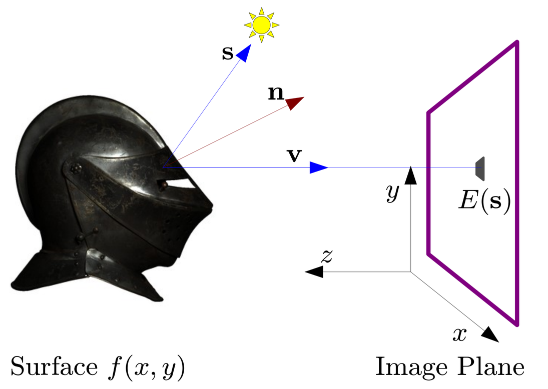
- 64 x 16 samples per BRDF (per color channel) used in our experiments
- Linear interpolation provides intermediate BRDF values



A single color channel of a basis BRDF.

Image Formation Model

Assumptions
- Fixed viewpoint
- Distant point sources
- Orthographic camera
- Ignore global illumination effects (e.g., cast shadows)



Surface Model
- Height map $f(x, y)$ / normal map $\mathbf{n} \propto \left(-\frac{\partial f}{\partial x}, -\frac{\partial f}{\partial y}, 1\right)^\top$

BRDF
- n pixels per image
- k basis BRDFs
- d sample values per basis BRDF

$\mathbf{B} \in \mathbb{R}^{d \times k}$ — basis BRDF matrix

$\mathbf{W} \in \mathbb{R}^{n \times k}$ — material weight matrix

$\mathbf{W}\mathbf{B}^\top \in \mathbb{R}^{n \times d}$ — per-pixel BRDFmatrix

Image Intensity

$$e_{ij} = \mathbf{w}_i^\top \mathbf{B}^\top \mathbf{\Phi}_{ij} \max\{0, \mathbf{n}_i^\top \mathbf{s}_j\}$$
$$= \mathbf{w}_i^\top \mathbf{B}^\top \widetilde{\mathbf{\Phi}}_{ij}$$

e_{ij}: pixel intensity; $\mathbf{w}_i$: material weights; $\mathbf{B}$: basis BRDF matrix; $\widetilde{\mathbf{\Phi}}_{ij}$: interpolation vector / shading term

- Linear w.r.t. material weights / BRDF values
- $\widetilde{\mathbf{\Phi}}$ depends non-linearly on $\mathbf{n}$

Objective & Optimization

Objective
- Find W, B, and n that minimizes L2 error between measurements and image formation model.

Additional Constraints
- Non-negative W, B
- Monotonic & smooth basis BRDFs
- Confidence weights

Alternating Minimization
1. Global min. over B
   - Constrained least squares
2. Global min. over W and n
   - Exhaustive search over domain of n (1 d.o.f. from isotropy)

- Motivated by [4]

References

[1] N. Alldrin and D. Kriegman. Toward reconstructing surfaces with arbitrary isotropic reflectance : A stratified photometric stereo approach. ICCV, 2007.
[2] S. Rusinkiewicz. A new change of variables for efficient BRDF representation. In Eurographics Rendering Workshop, 1998.
[3] M. Stark, J. Arvo, and B. Smits. Barycentric parameterizations for isotropic BRDFs. IEEE Transactions on Visualization and Computer Graphics, 2005.
[4] J. Lawrence et al. Inverse shade trees for non-parametric material representation and editing. SIGGRAPH, 2006.