Multi-View 3D Reconstruction of Highly-Specular Objects

Master Thesis

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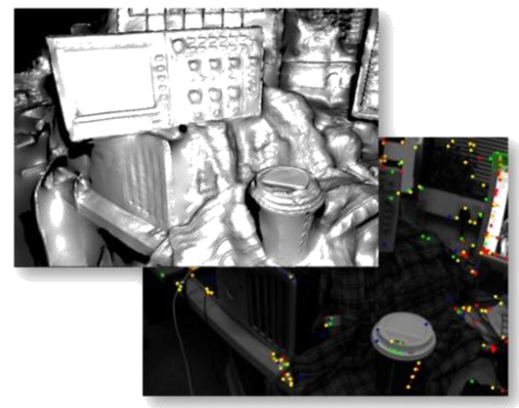
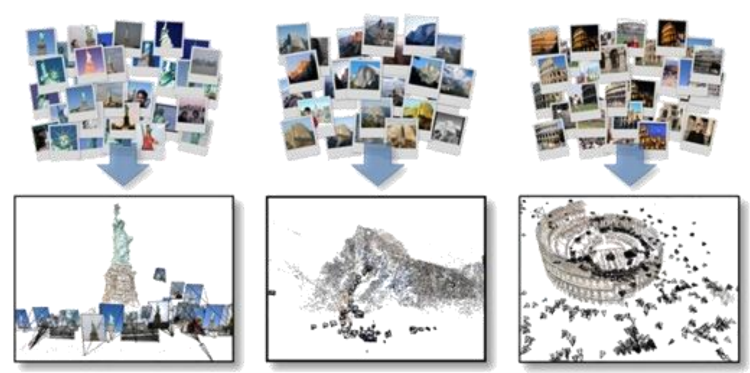
Motivation

- **Goal:** faithful reconstruction of full 3D shape of an object
- **Current techniques:**





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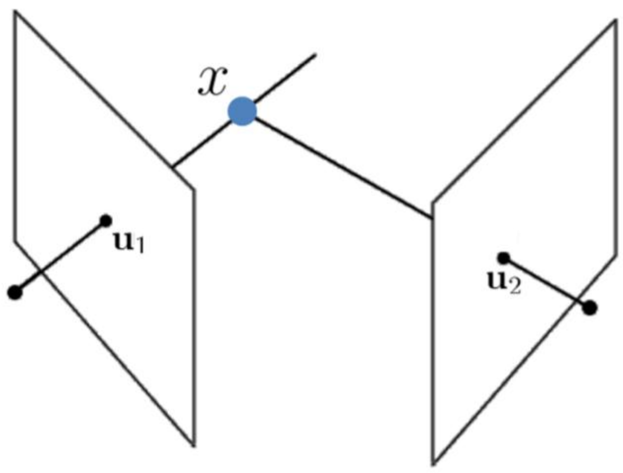
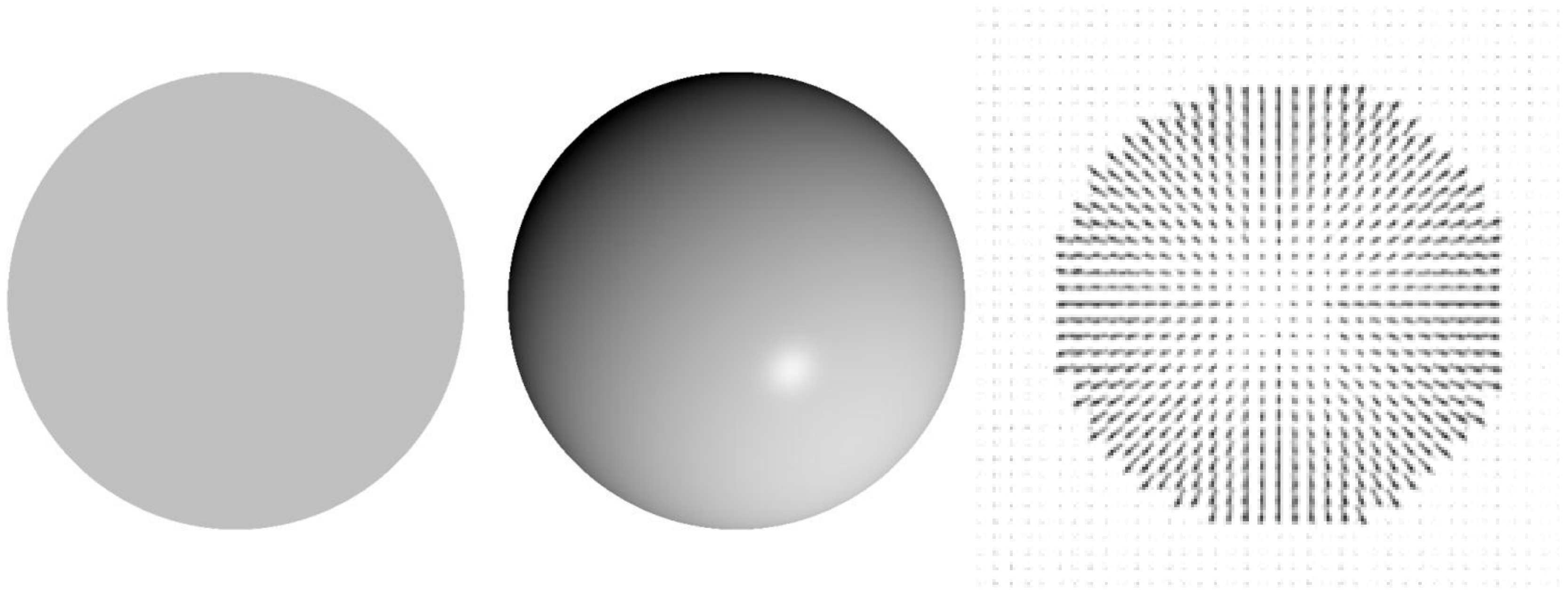
Motivation

- **Challenge:** objects exhibiting a complex reflectance behavior
- **Focus:** on opaque+specular materials



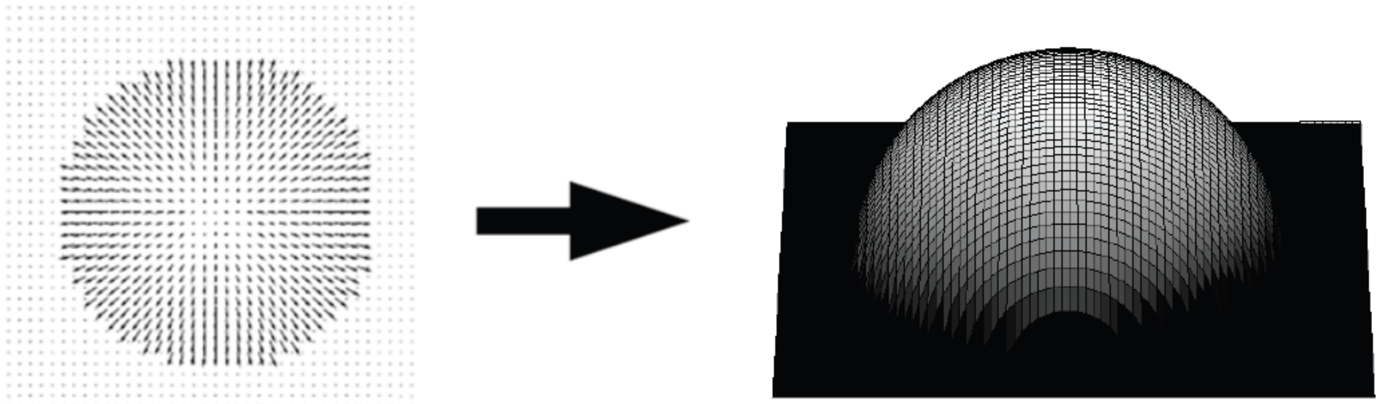
Introduction

- **Observation:** shading is a powerful visual cue
- Provides surface orientation information



Introduction

- Many techniques for surface normal field estimation using shading cues from single view



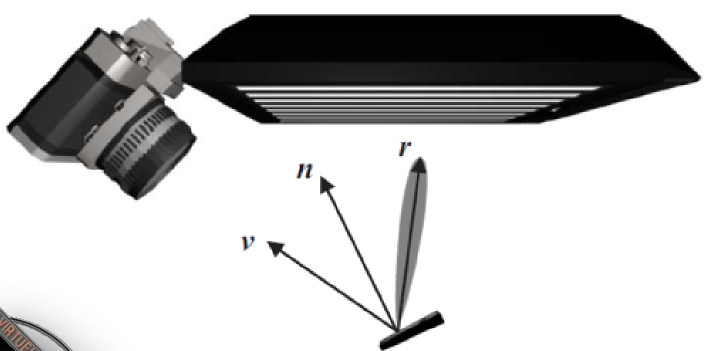
- How can information from several viewpoints be combined?
- Could 3D reconstruction of specular objects be addressed this way?

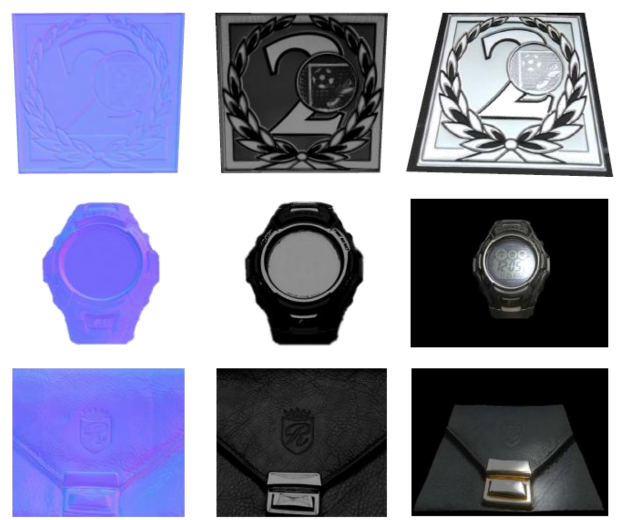
Image credits: N. Funk and Y.-H. Yang. Using a Raster Display Device for Photometric Stereo.

Background

- Mesostructure from Specularity (Chen et al., CVPR '06)

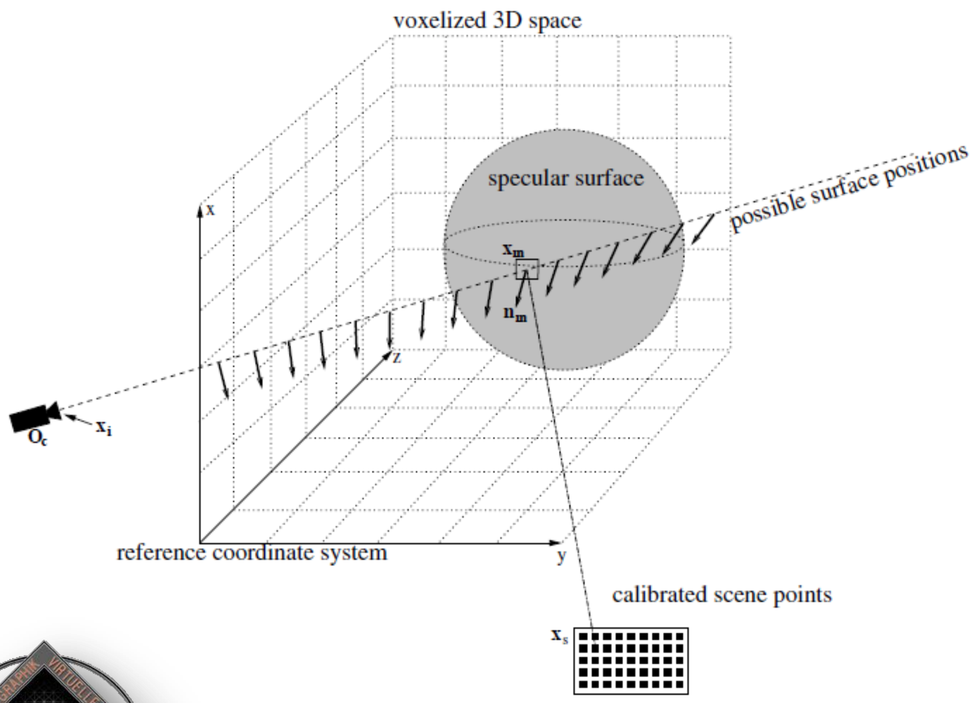
- Gloss and Normal Map Acquisition of Mesostructures Using Gray Codes (Francken et al., ISVC '09)





Background

- Specularity-Consistency based methods
  - Voxel Carving for Specular Surfaces (Bonfort et al., ICCV '03)
  - Dense 3D Reconstruction from Specularity Consistency (Nehab et al., CVPR '08)



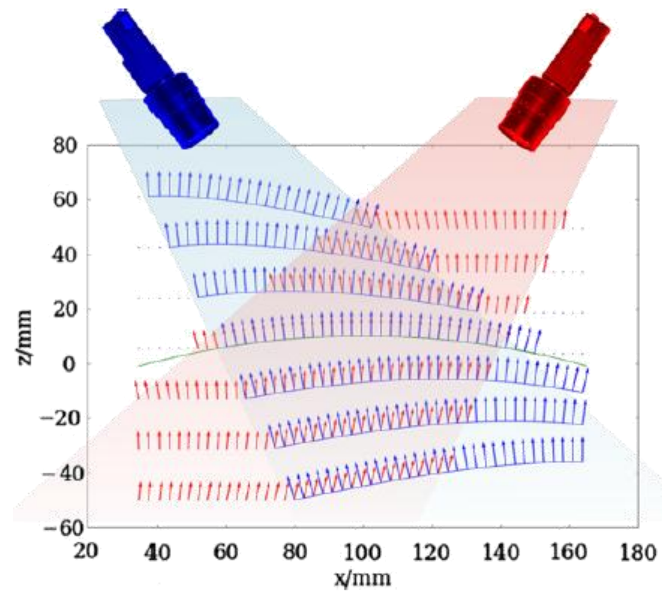
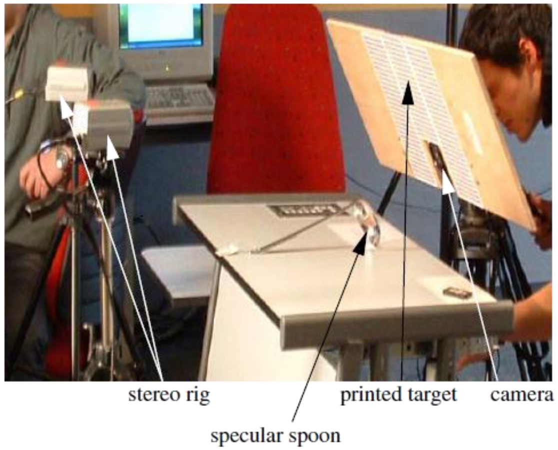
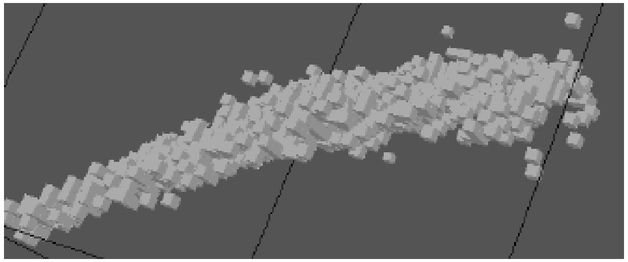


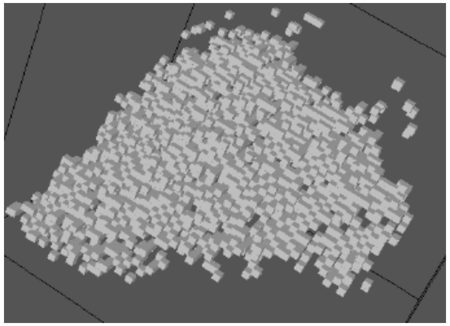
Image credits: T. Bonfort and P. Sturm. Voxel carving for specular surfaces *(left)*, J. Balzer and S.Werling. Principles of Shape from Specular Reflection *(right)*

Background

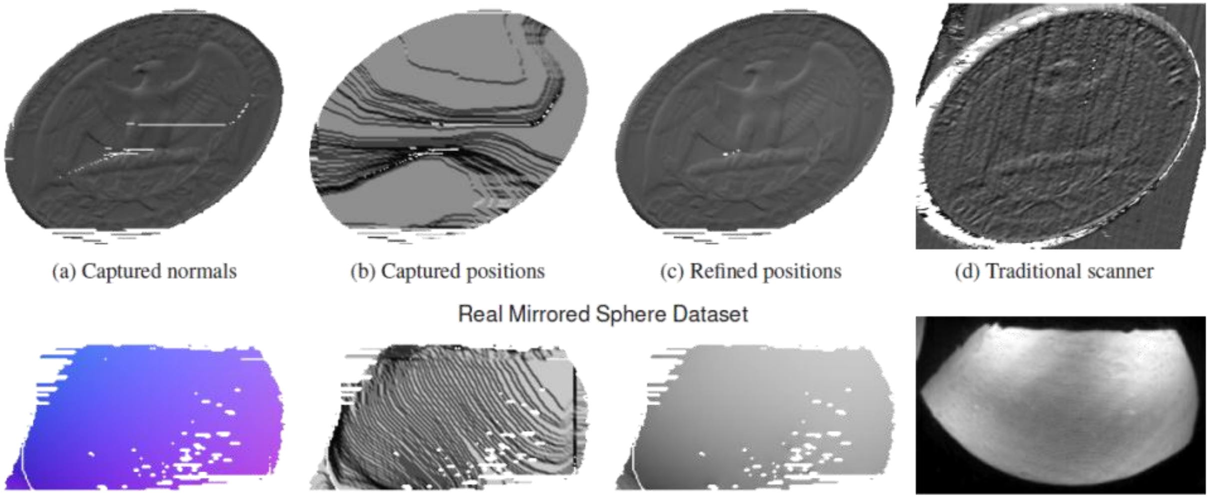
- Results







Real Quarter Dataset



(a) Captured normals (b) Captured positions (c) Refined positions (d) Traditional scanner

Real Mirrored Sphere Dataset

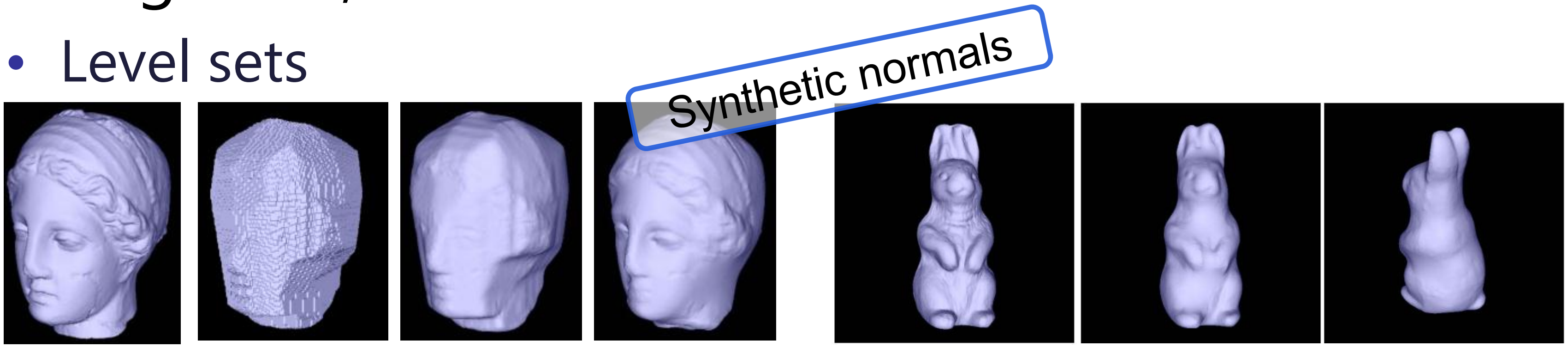
(e) Captured normals (f) Captured positions (g) Refined positions (h) Photograph

Our Approach

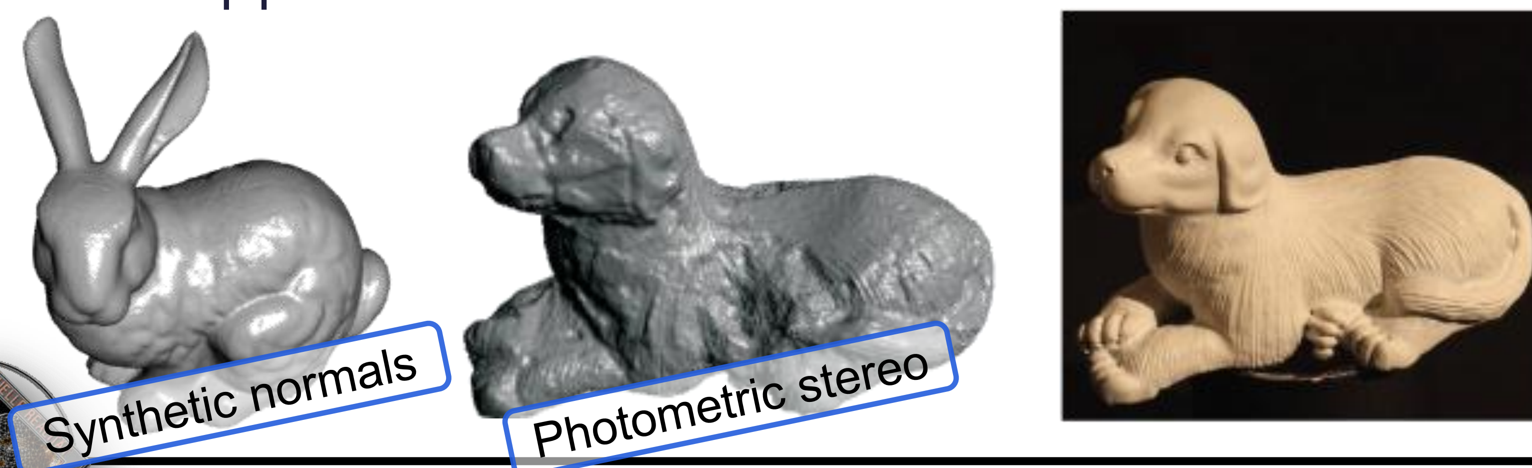
- Estimate multi-view normal fields using structured environment
- Multi-view normal field integration problem
  - Need very robust algorithm!

Multi-View Normal Field Integration

- Chang et al., CVPR'07
  - Level sets



- Master thesis of Z. Dai
  - MRF approach



Overview

I. Multi-View Normal Field Integration

II. Multi-View Shape-from-Specularity

III. Evaluation

IV. Conclusion and Future Work

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Problem Statement

- **Given:**
  - κ_C calibrated cameras C_i
  - Projection matrices $P_i = K_i [R_i | t_i]$
  - Normal fields $\mathcal{N}_i$

$$i = 1 \ldots \kappa_C$$

- **Goal:**
  - Reconstruction of surface ∂S

- **Problem:**
  - Inferring coordinates of all surface point given normal fields estimates

Challenges

- Noise
- Outliers
- Systematic errors
- Holes
- Initial guess (visual hull) in practice difficult to compute
- Implementation concerns
  - Fine-detail reconstruction

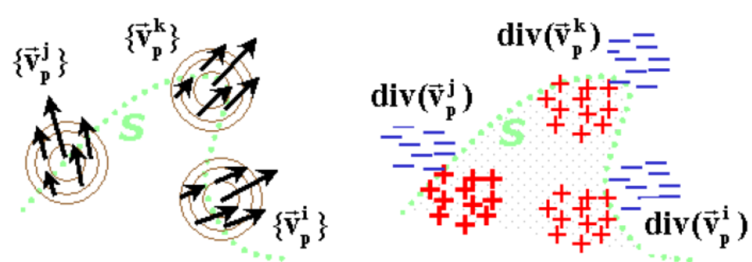
Variational Approach

- Solve variational problem:

$$E\left(\partial S\right)=\lambda_1\underbrace{\int_{\partial S} dA}_{E_1}-\lambda_2\underbrace{\int_{\partial S}\langle c\mathbf{N},\mathbf{n}\rangle\ dA}_{E_2},$$

  - **N**(**x**) … vector field, reconstructed from normal fields
  - c(**x**) … surface consistency

- Solving minimal surface problems
  - Active contour
  - Level sets
  - Graph cuts
  - **Convex relaxation**



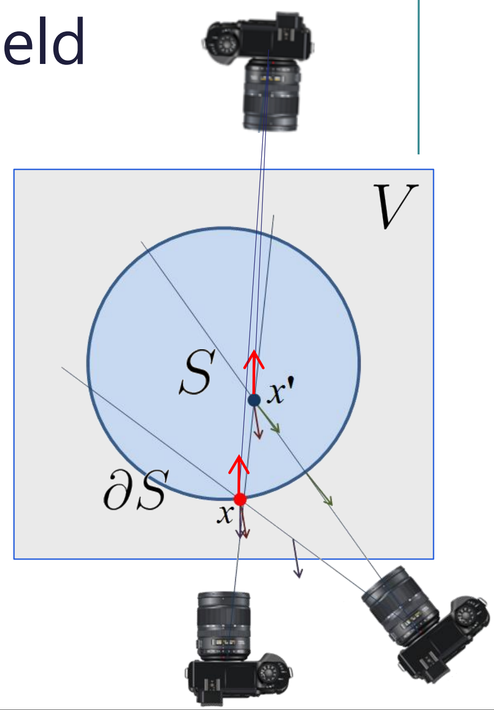
(a) Flux (b) Divergence

Image credits: V. Lempitsky and Y. Boykov: Global Optimization for Shape Fitting

Vector Field Computation: Idea

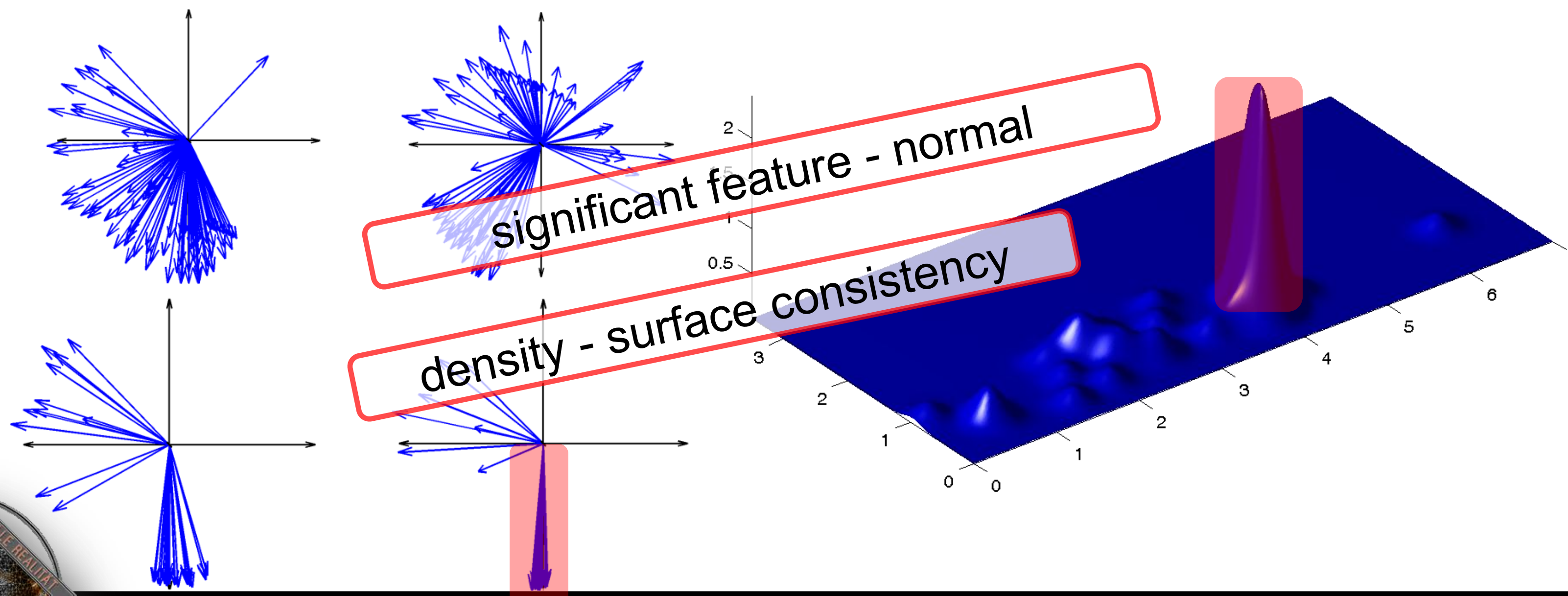
- Core of our approach
- Key questions:
  - Surface consistency measure
    $c(\mathbf{x}) : \mathbf{x} \mapsto \mathbb{R}$
  - Value of vector field
    $\mathbf{N}(\mathbf{x}) : \mathbf{x} \mapsto \mathbb{S}^2$

$$\mathbf{x} \in V \subset \mathbb{R}^3$$



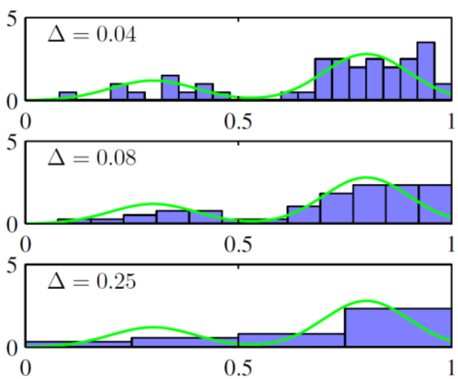
Vector Field Computation

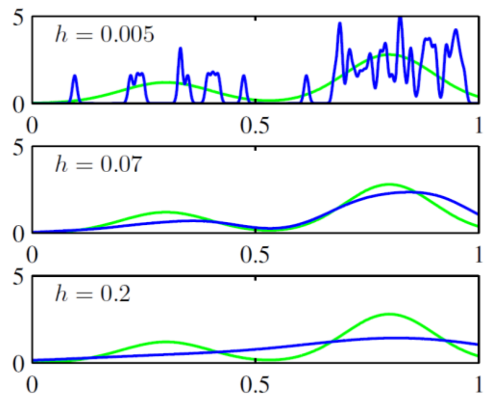
- Back-project normal fields into volume V
- Map back-projected normals to feature space
- Density estimation to find the patterns - normal
  - Based on discrete, back-projected normal samples
  - Non-parametric method essential

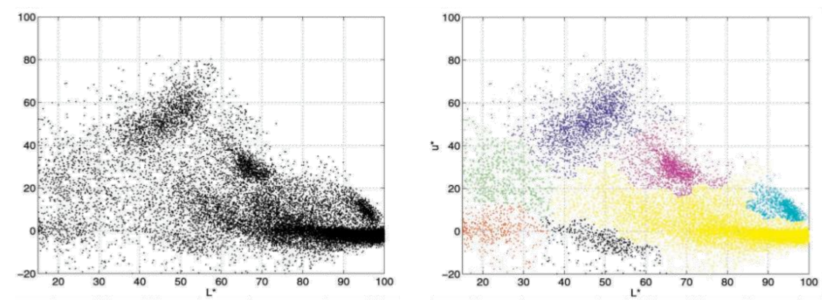


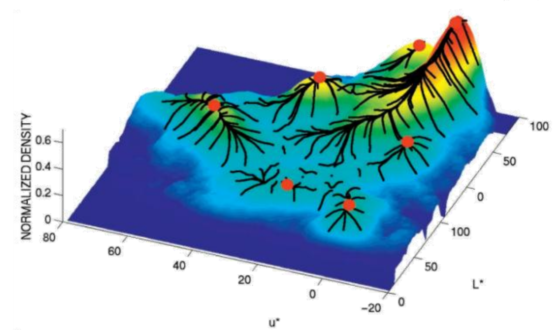
Feature Space Analysis

- Histogram method
- Kernel density estimation
- **Mean-Shift clustering**









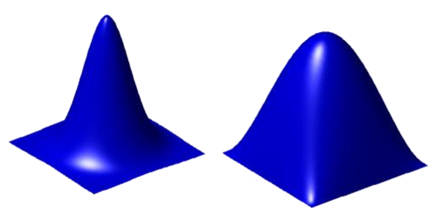
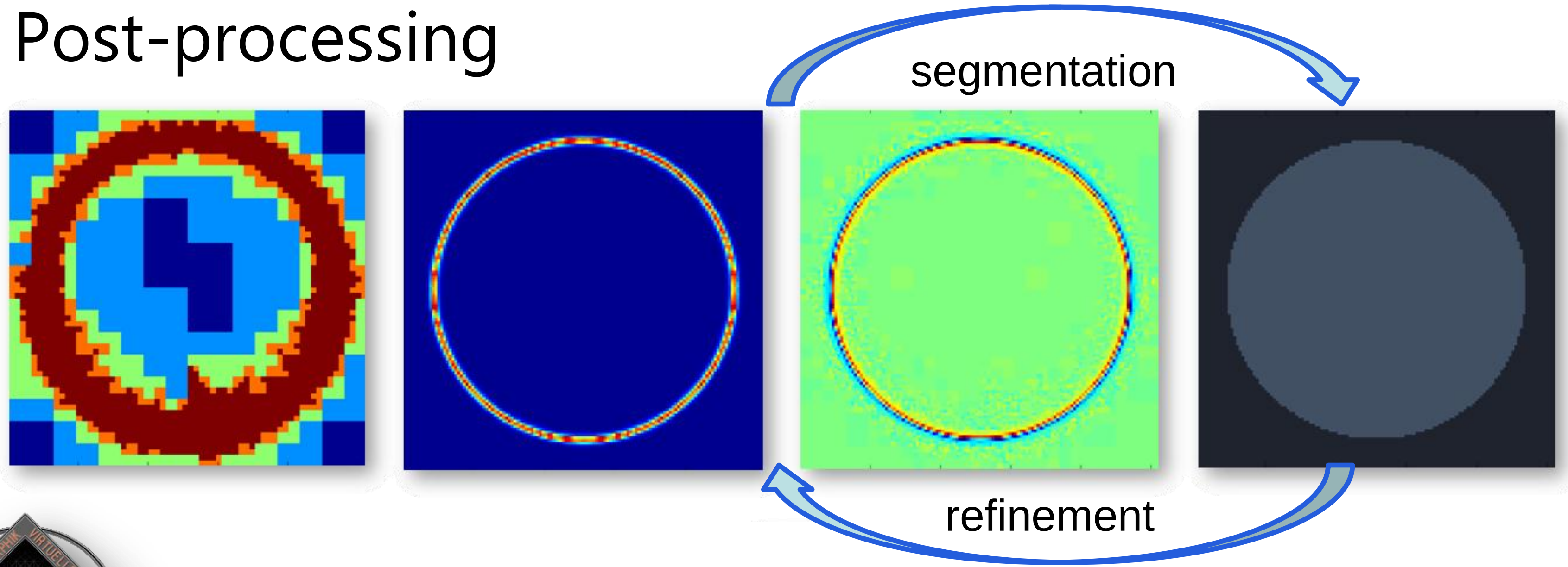


Image credits: Christopher M. Bishop. Pattern Recognition and Machine Learning (Information Science and Statistics) *(left)*, D. Comaniciu and P. Meer. Mean shift: A robust approach toward feature space analysis *(right)*,

Implementation

- Octree-based discretization of bounding volume V
- Initial refinement strategy
- Continuous Max-Flow based volume segmentation
- Iterative scheme
- Post-processing



I. Multi-View Normal Field Integration

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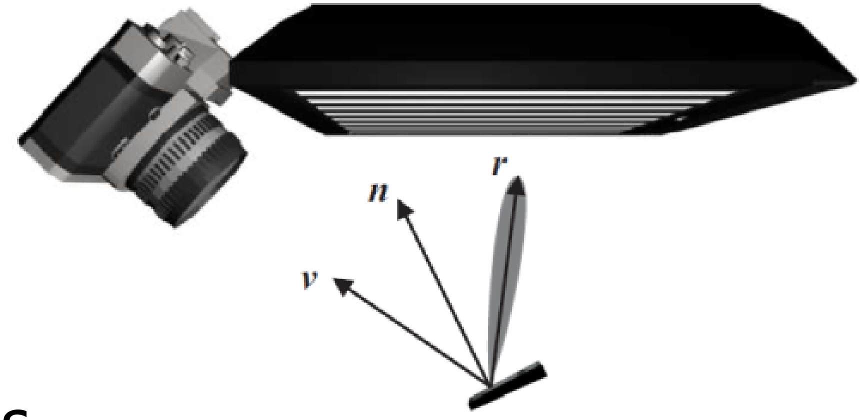
Multi-View Shape-from-Specularity

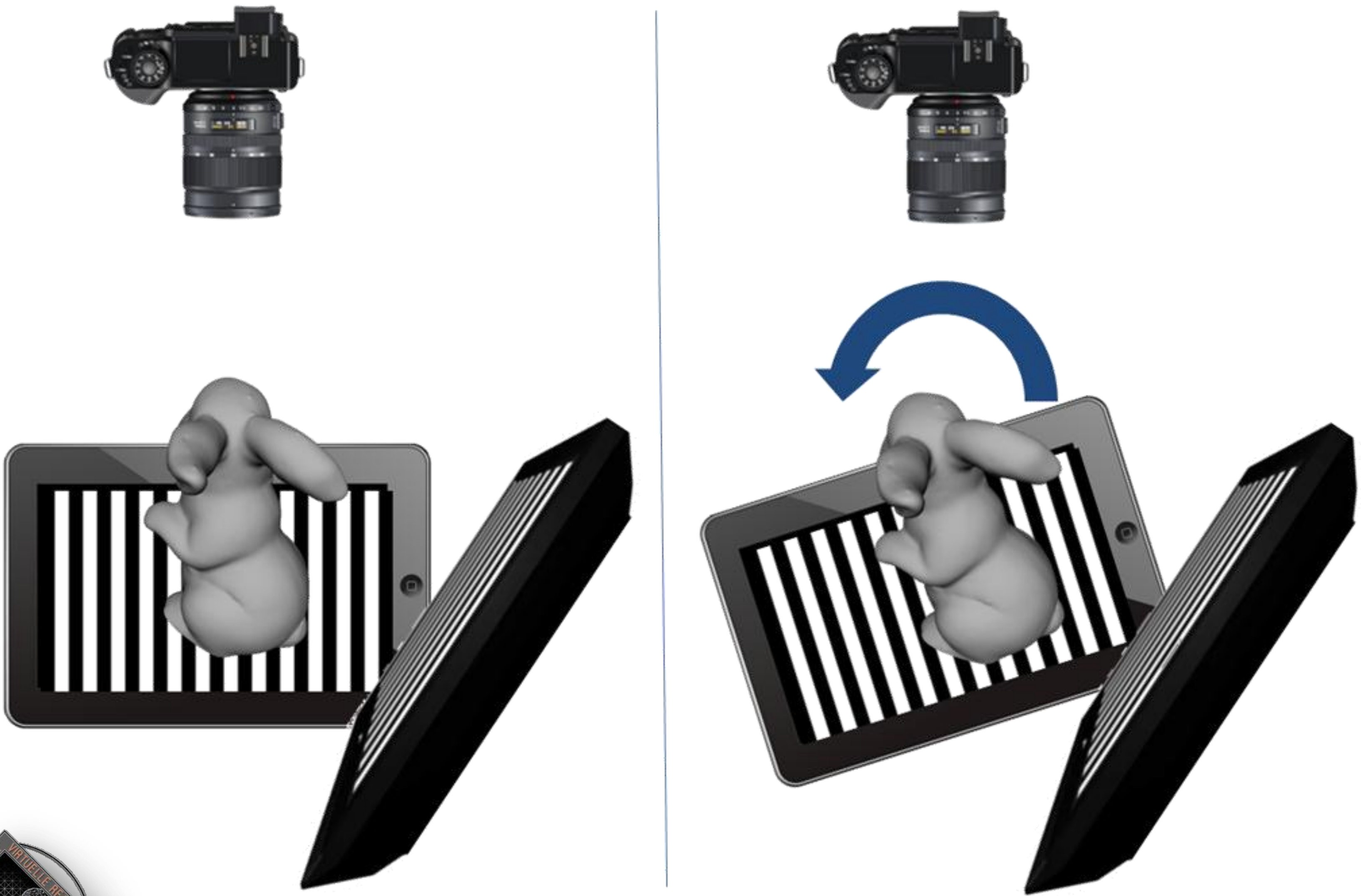
- How to compute normal fields of specular objects?



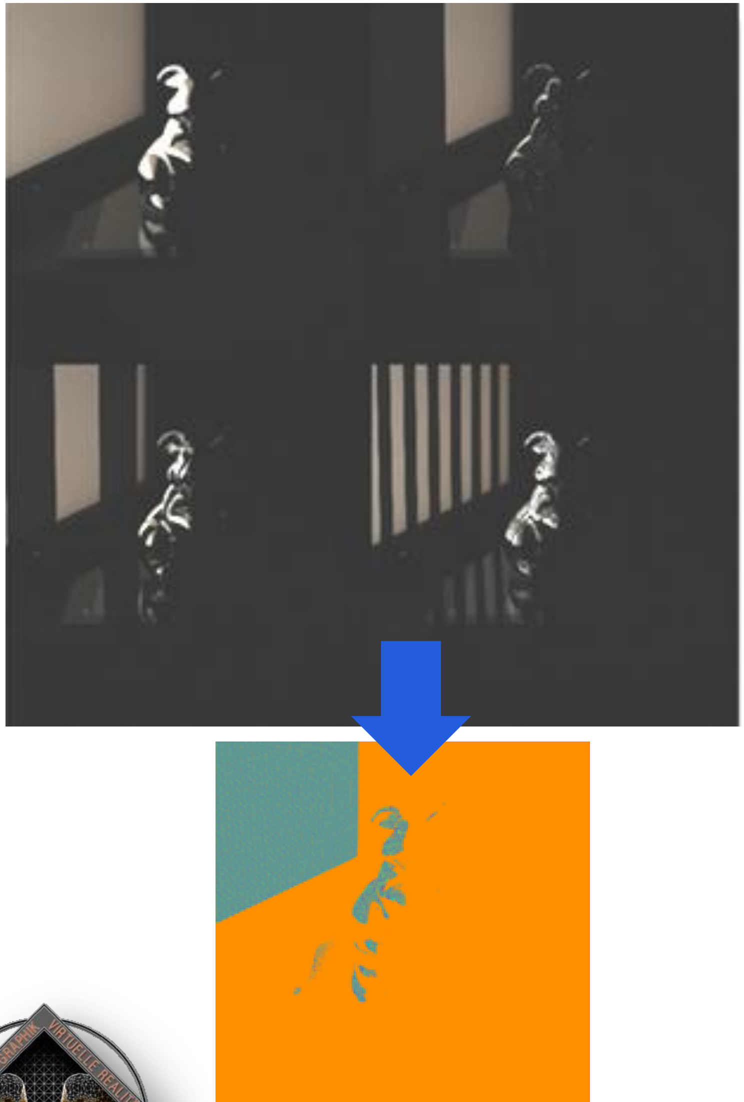
- Challenges
  - How to lit object fully?
  - Distant light assumption violation
  - How to reliably decode patterns?
  - Screen calibration

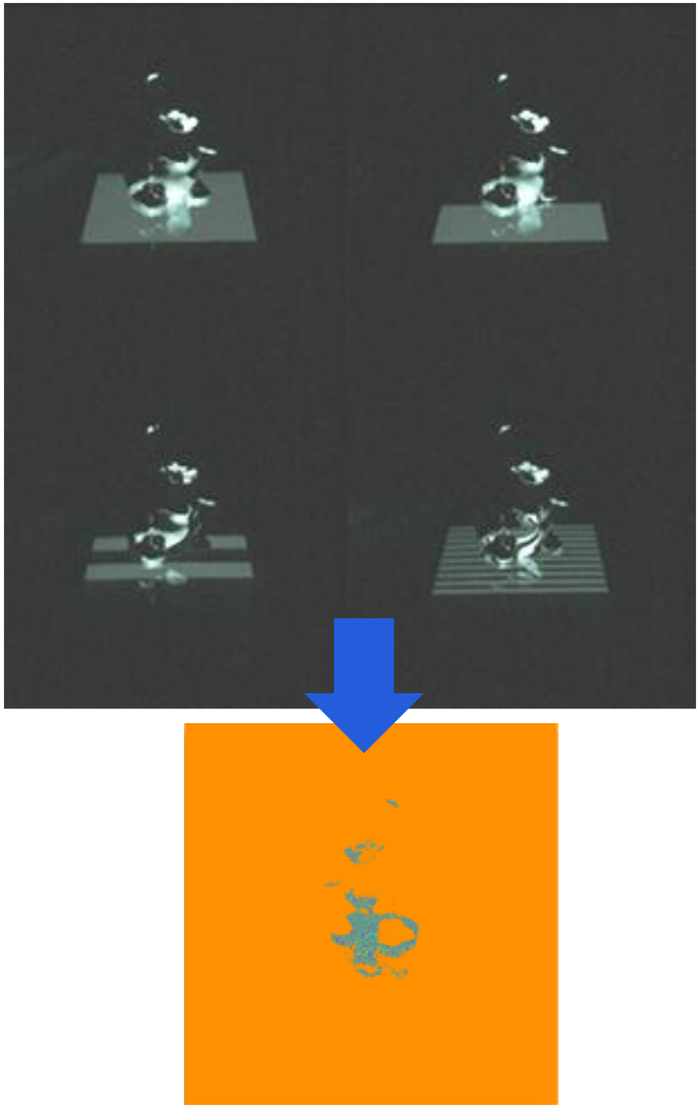
Image credits: Y. Francken, T. Cuypers, T. Mertens, and P. Bekaert: Gloss and normal map acquisition of mesostructures using gray codes.

Proposed Setup



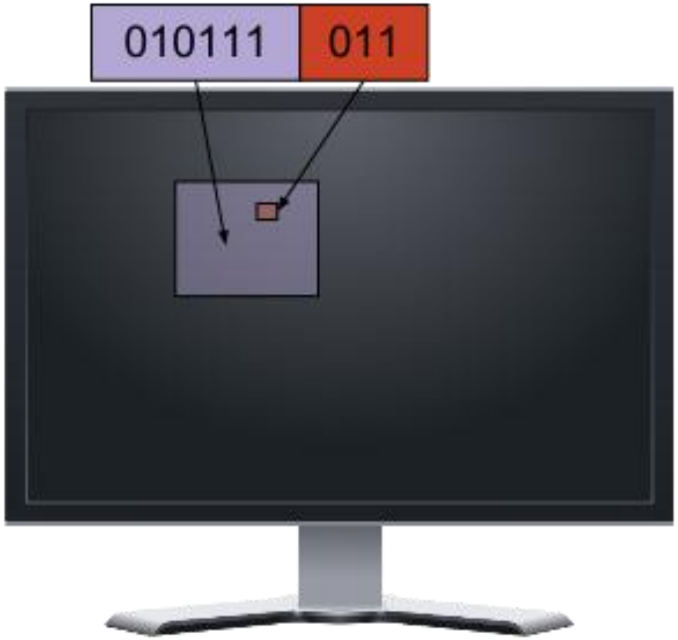
Capturing the Data





Computing Light Maps

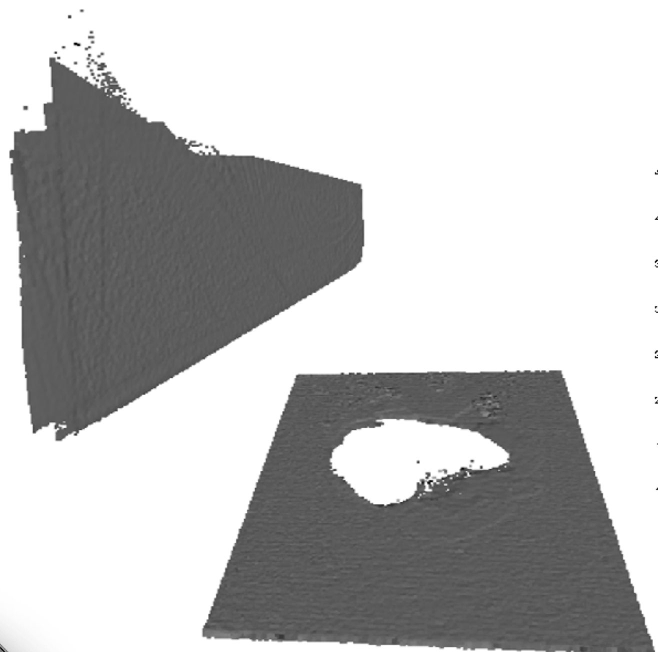
- Fuzzy decoding

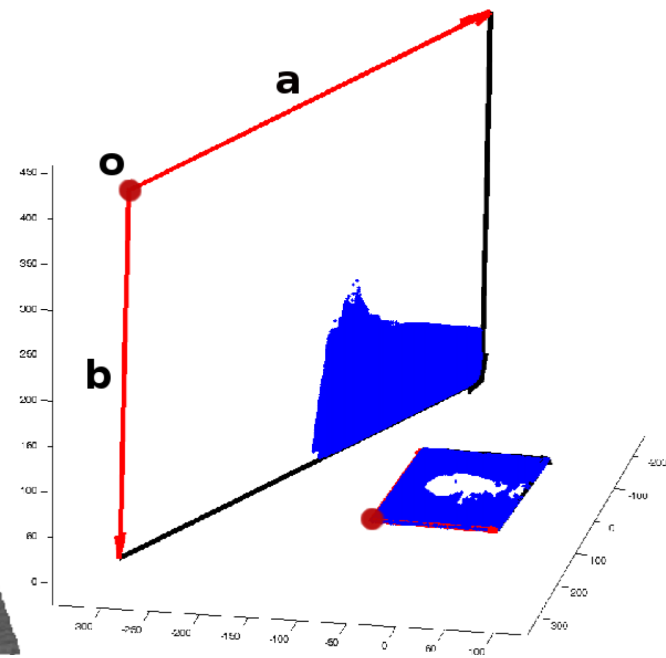


Screen Calibration

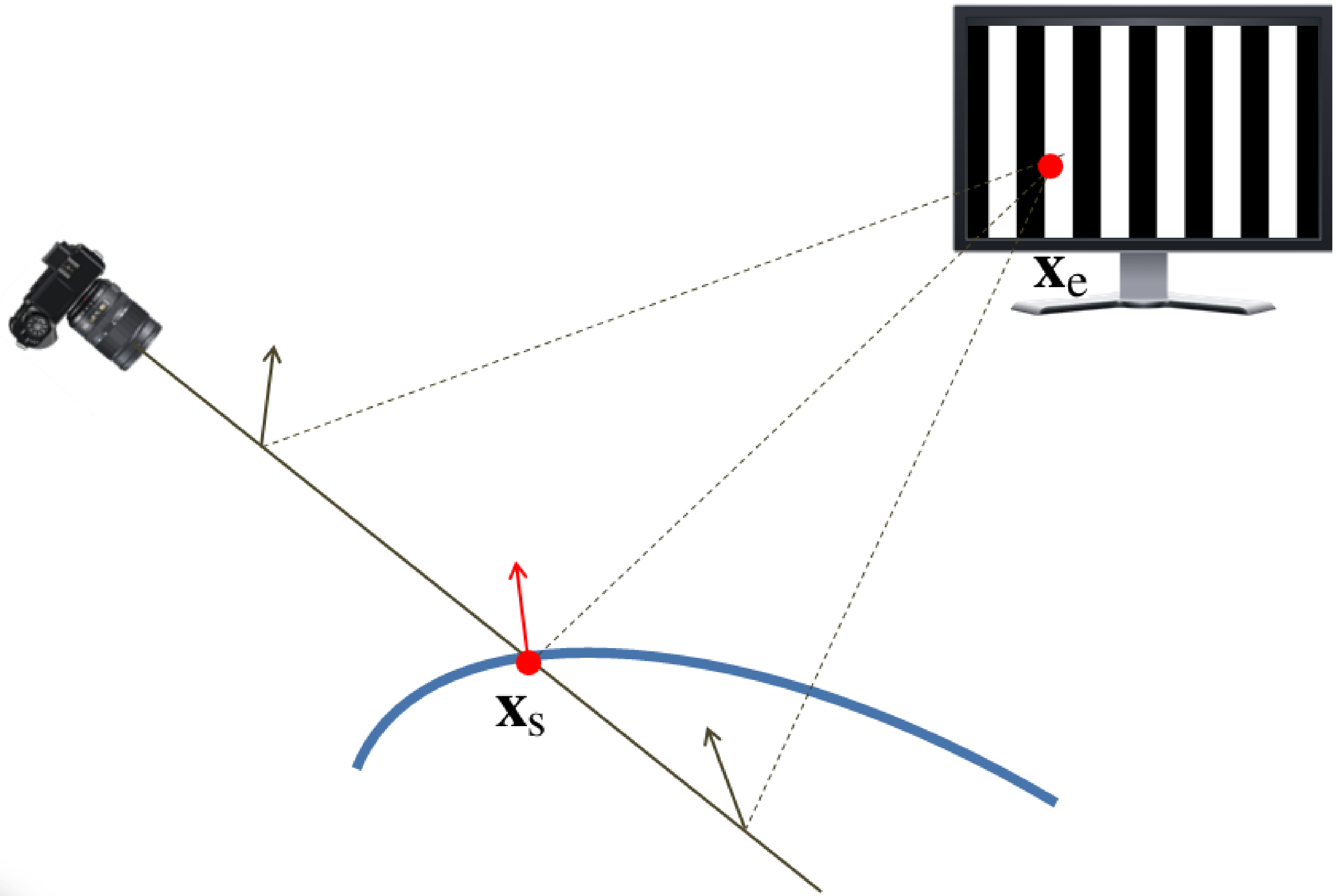
- Structured pattern based triangulation

$$Q = \sum_{m=1}^{M} \left(\mathbf{p}_m - (\mathbf{o} + q_{x,m}\mathbf{a} + q_{y,m}\mathbf{b})\right)^2$$





Normal-Depth Ambiguity



Reconstruction

- Input are light-maps and not normal fields
- Project labels to octree corners and compute normal hypotheses
- Reconstruct vector field and compute surface consistency
- Fit surface to vector field

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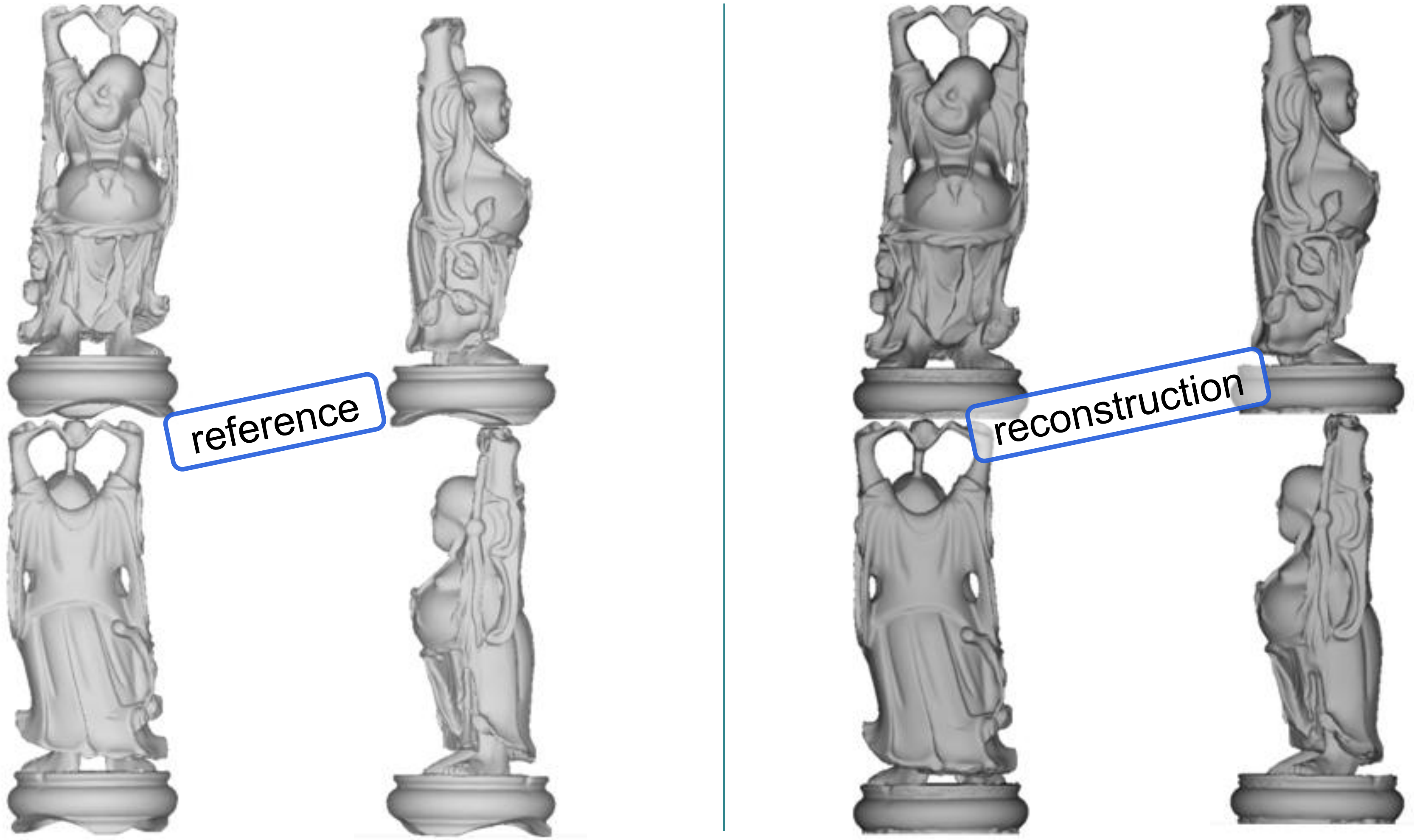
Synthetic Normal Fields



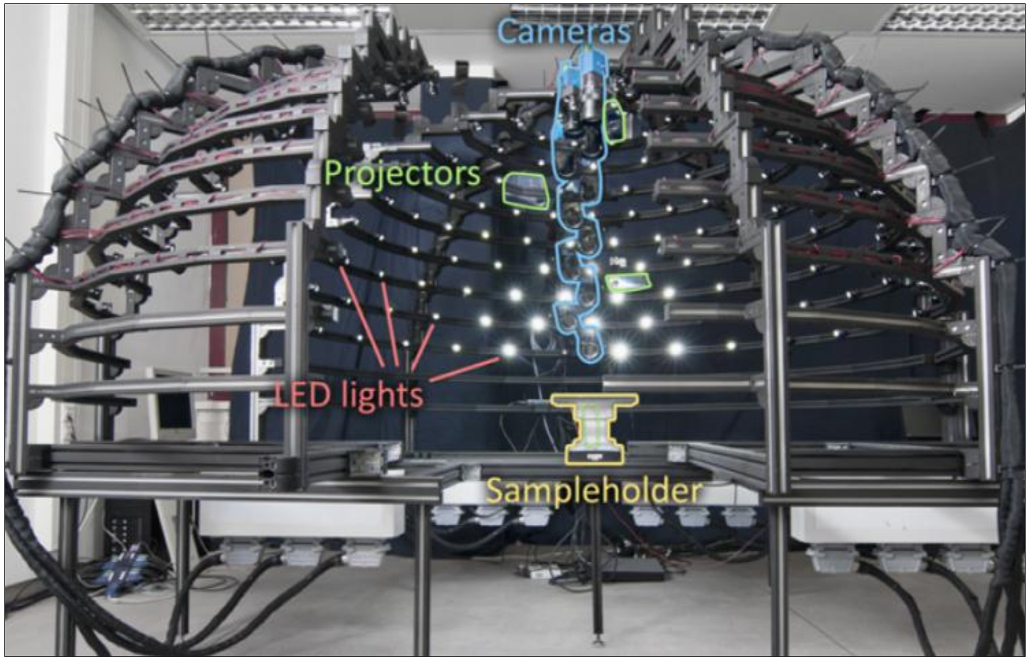
Happy Buddha, 75 cameras

Synthetic Normal Fields

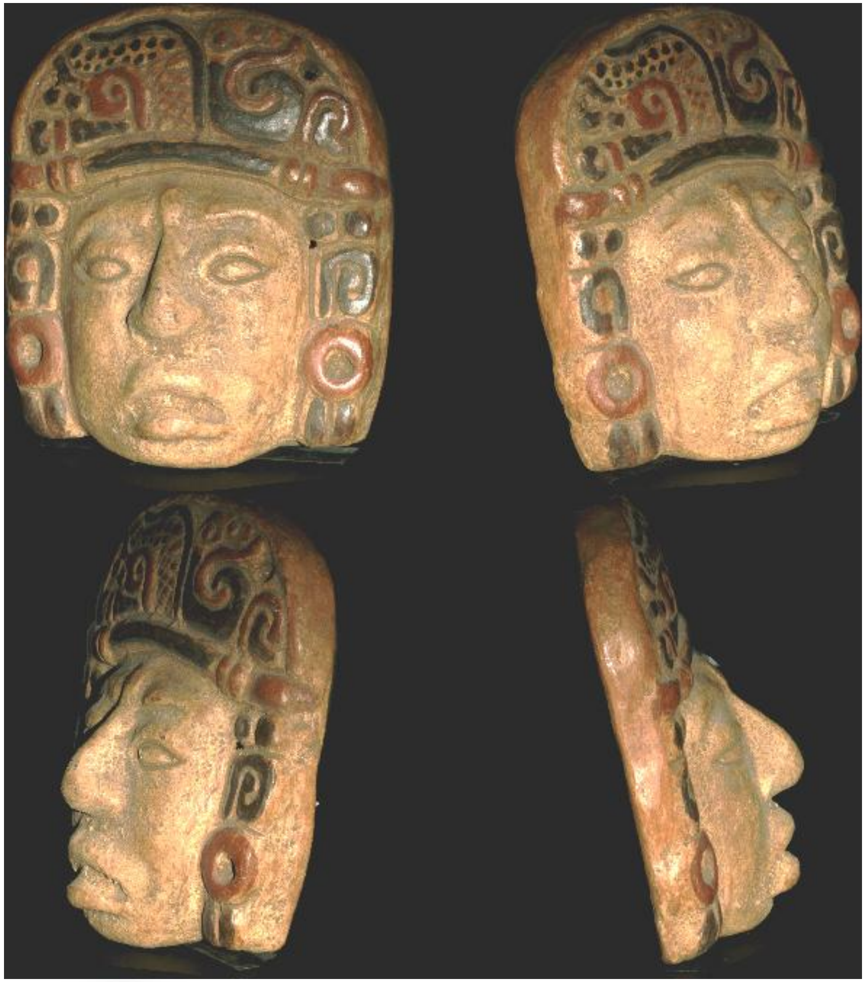
Happy Buddha, 10 *(left)* and 20 *(right)* cameras

Real Data: Photometric Stereo

- Classic least-squares photometric stereo
  - Simple thresholding prior to fitting
- 6 cameras, 12 rotations, 72 views
- 198 images for computation of single normal field



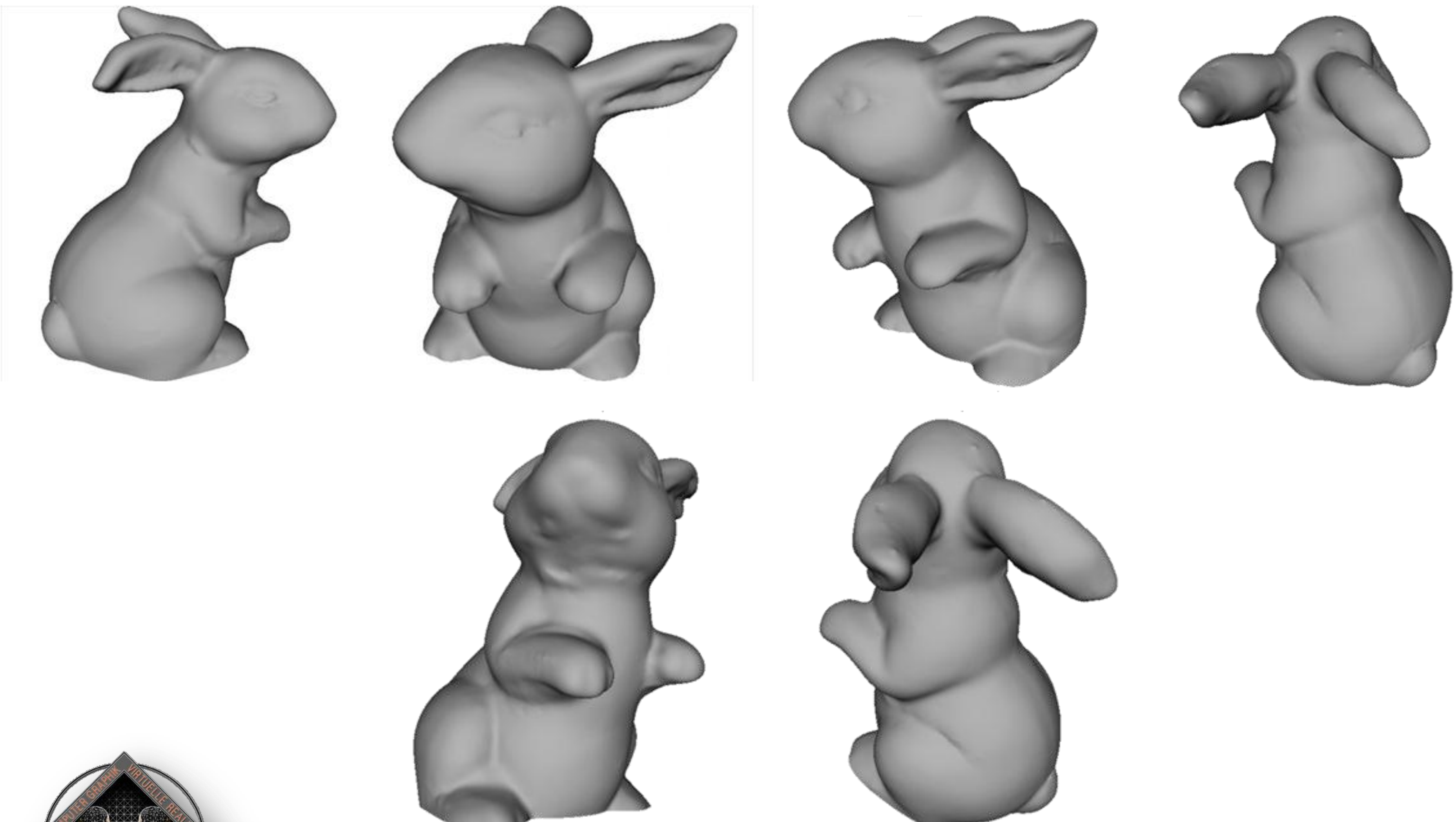
Real Data: Photometric Stereo



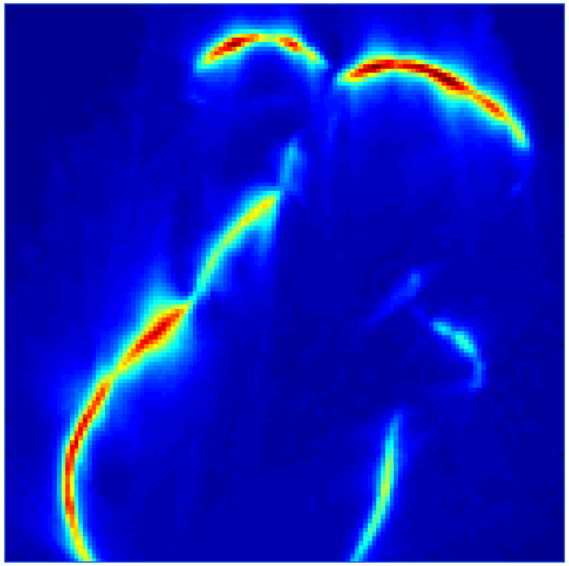
Real Data: Shape-from-Specularity

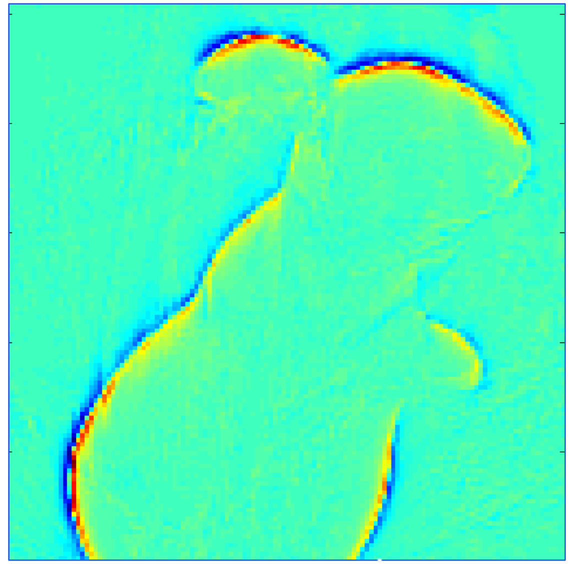
- 10 cameras, 24 rotations, 240 views, two sources of structured illumination
- Mirror bunny

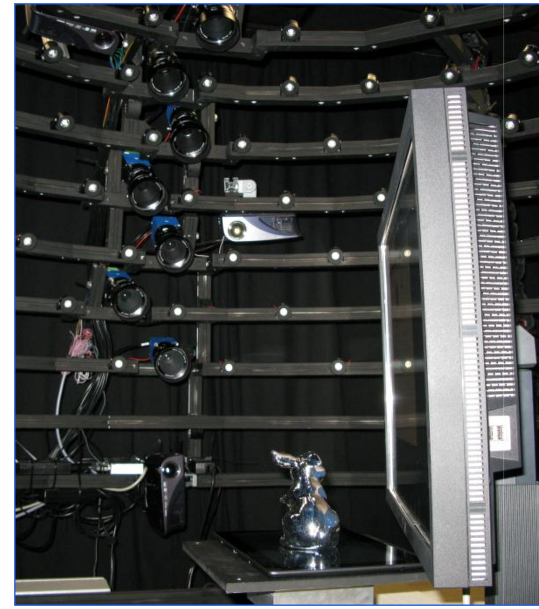
Real Data: Shape-from-Specularity

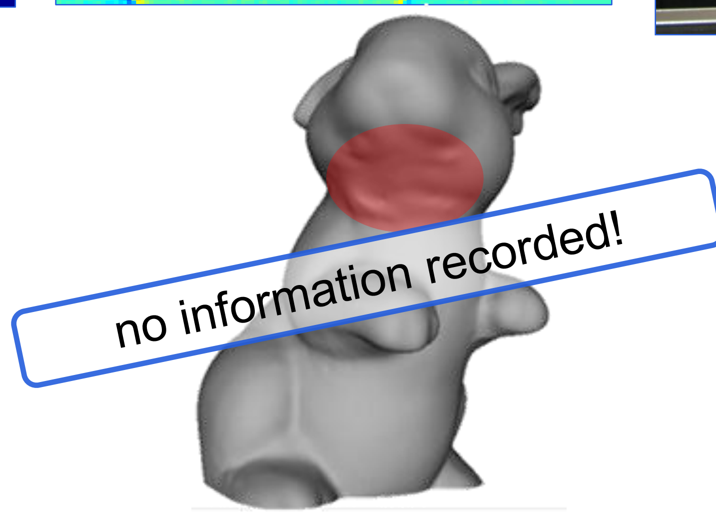


Real Data: Shape-from-Specularity

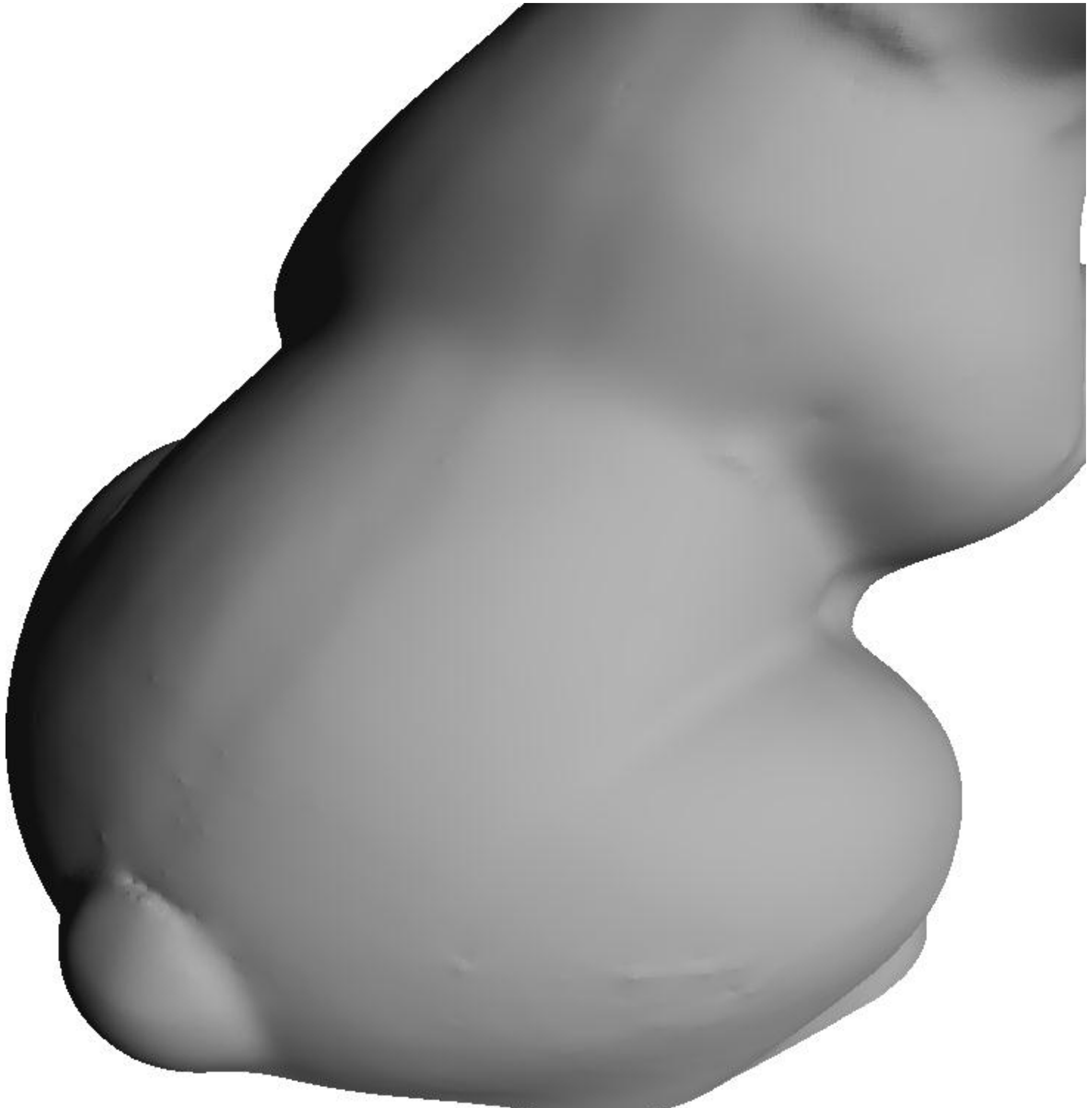








Real Data: Shape-from-Specularity



Conclusion

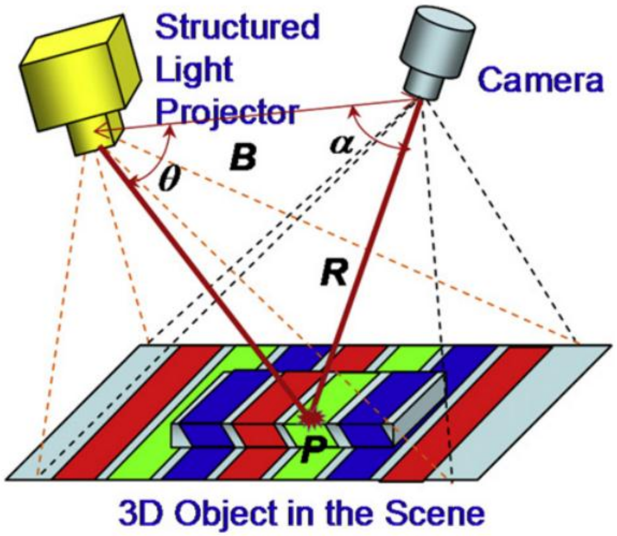
- New, robust multi-view normal field integration algorithm
  - No initial guess (visual hull) needed
  - First results, demonstrated on captured data
  - Efficient numerical techniques
- New dome-based method for reconstruction of highly specular objects
  - Display screens as sources of structured lighting
  - Normal computation and integration based approach
  - State-of-the-art results

Future Work

- Testing integration algorithm using more general normal estimation techniques
- Coding the light pattern using different coding strategies
- Weight normals coming from specular surfaces according to uncertainty of source of illumination
- Parallelization potential

Thank you for your attention!

Structured Light 3D Scanning



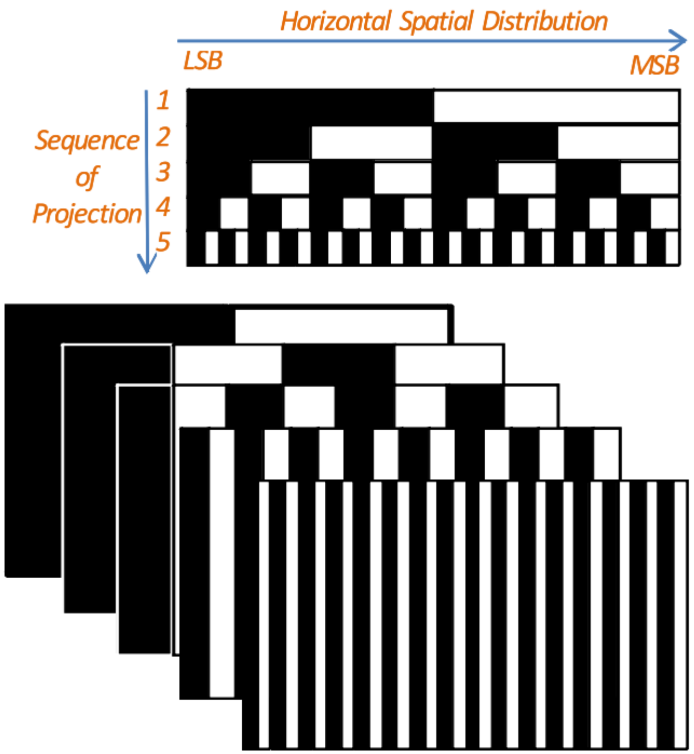
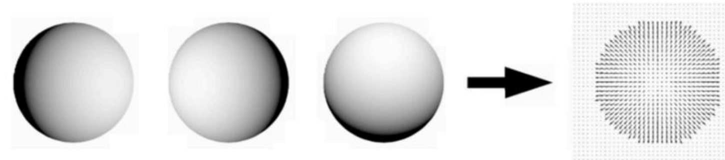


Image credits: J. Geng: Structured-Light 3D Surface Imaging: A Tutorial

Photometric Stereo

- Lambertian assumption:

$$\mathcal{I}(\mathbf{u}_\mathbf{x}) = k_\mathbf{x} \cdot (\mathbf{n}_\mathbf{x}^\top \cdot \mathbf{l})$$



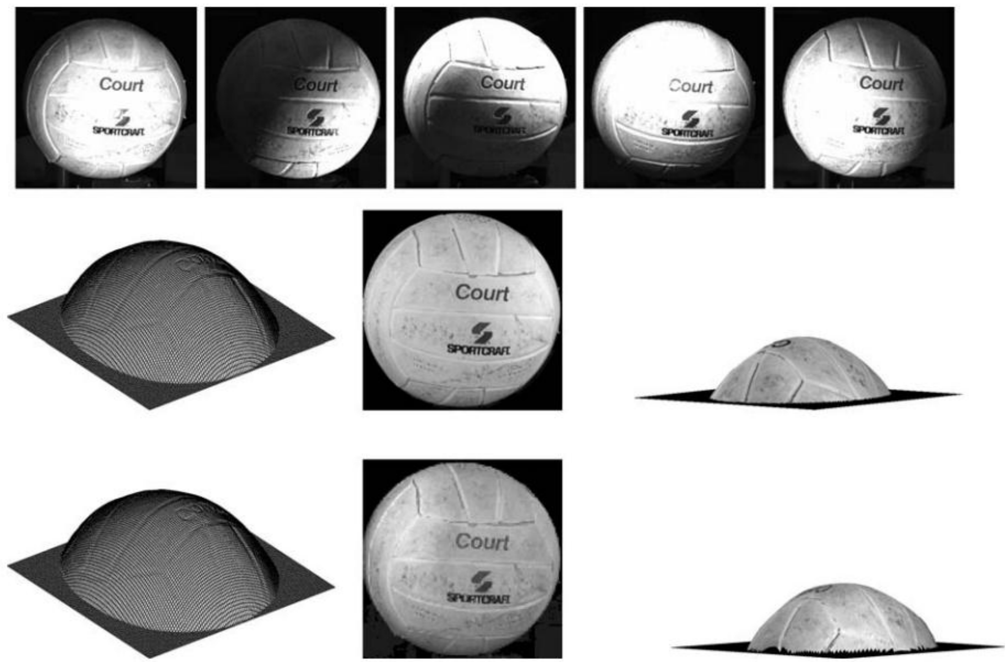


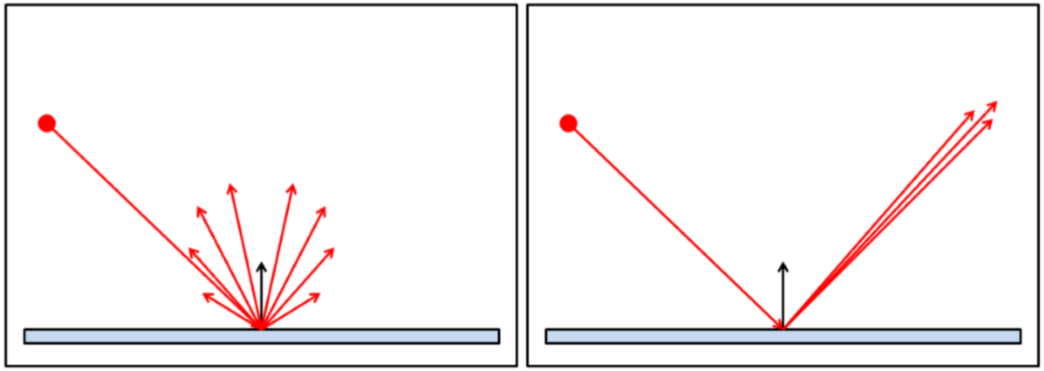
Image credits: R. Basri, D. Jacobs, I. Kemelmacher: Photometric Stereo with General, Unknown Lighting (*bottom image*)

Convex Relaxation

$$E(\gamma) = \lambda_1 \int_V \|\nabla \gamma\| \; dV - \lambda_2 \int_V (\nabla \cdot (c\mathbf{N}))\, \gamma \, dV$$

$$w.r.t \; \gamma : V \mapsto [0, 1]$$

Reflectance Models



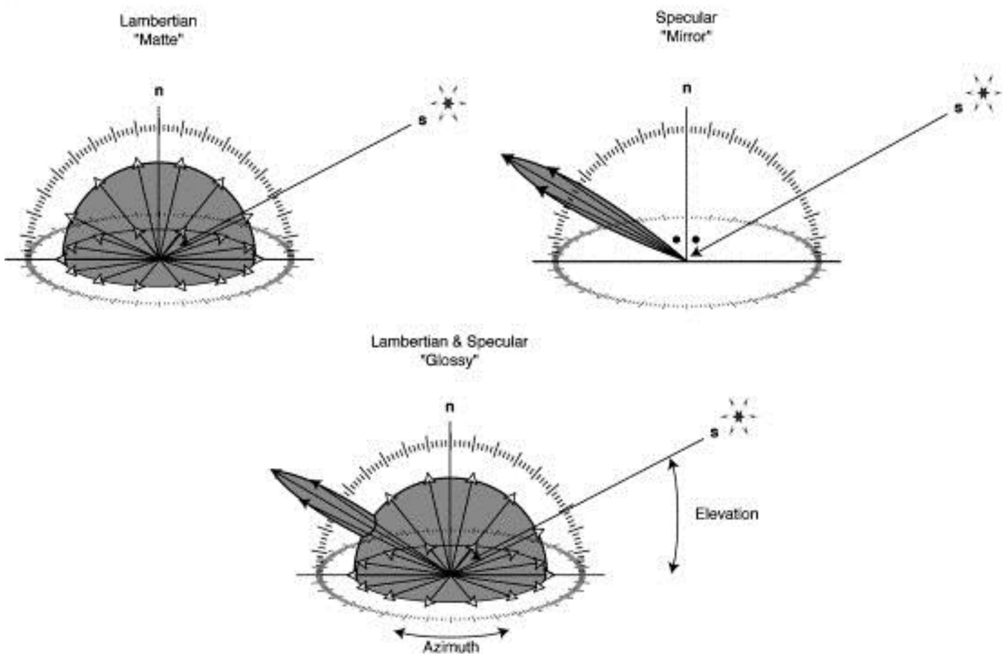


Image credits: H. T. Nefs, J. J. Koenderink, A. M.L. Kappers: Shape-from-Shading for Matte and Glossy Objects (*bottom*).