SIGGRAPH ASIA 2018 TOKYO

Practical SVBRDF Acquisition of 3D Objects with Unstructured Flash Photography

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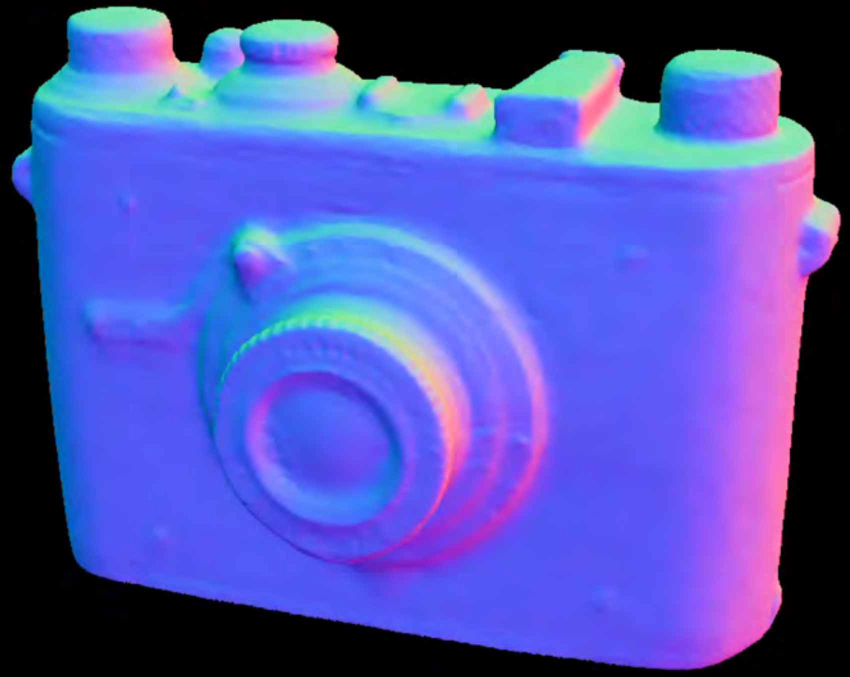
[†] KAIST [§] Universidad de Zaragoza, I3A

Input & Output

Unstructured flash photographs



3D geometry

Input & Output

Unstructured flash photographs

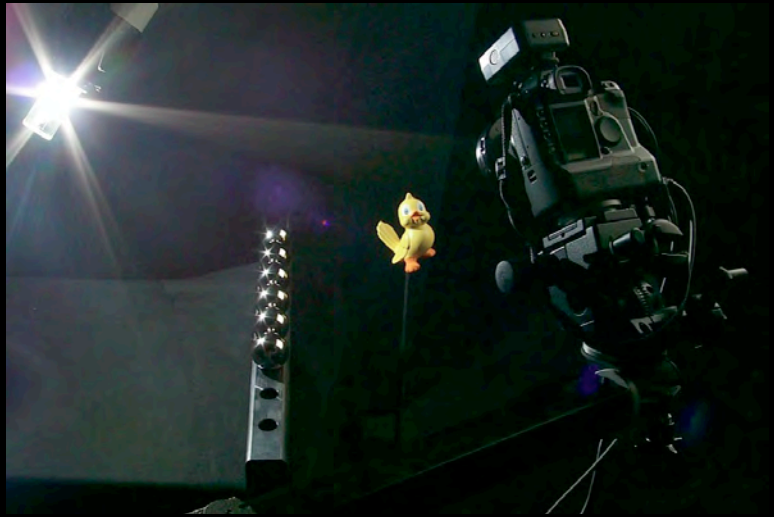
Spatially-varying BRDF

Input & Output

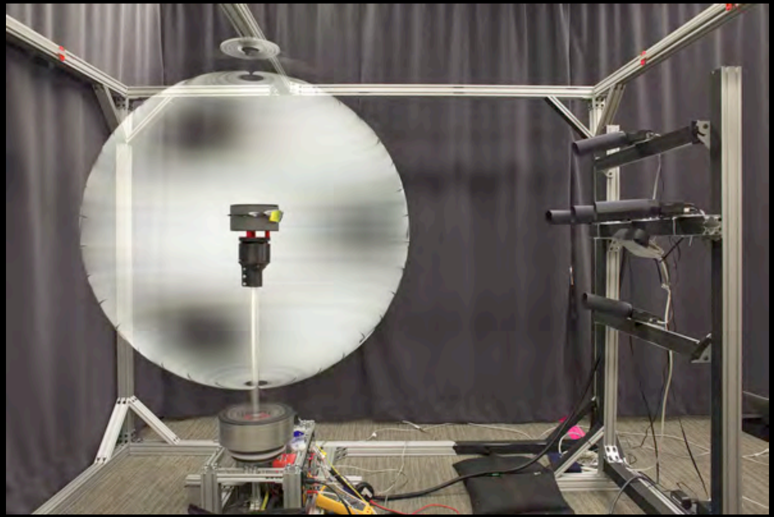
Unstructured flash photographs

Reproduction in a virtual environment

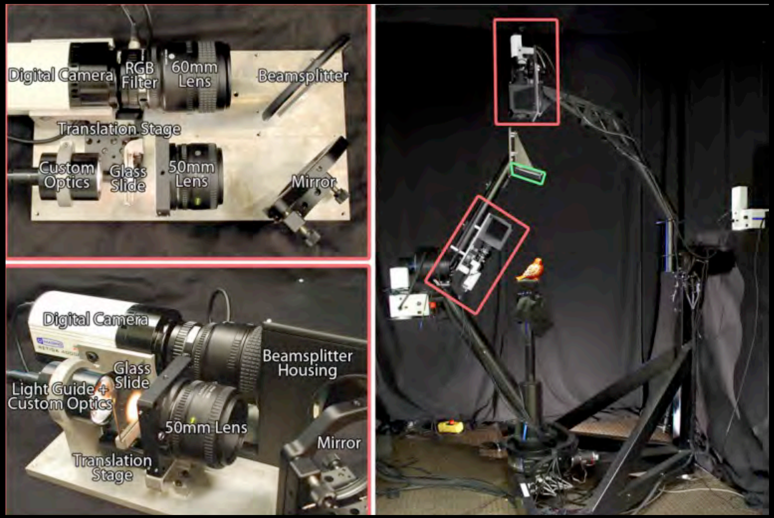
Previous Work



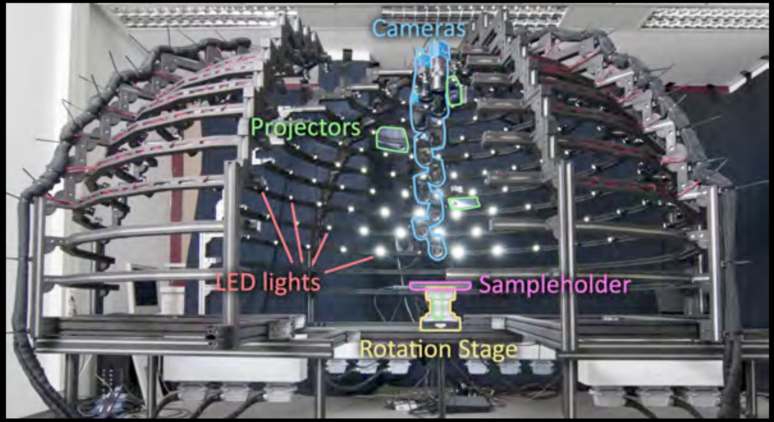
[Lensch et al., 2003]



[Tunwattanapong et al., 2013]

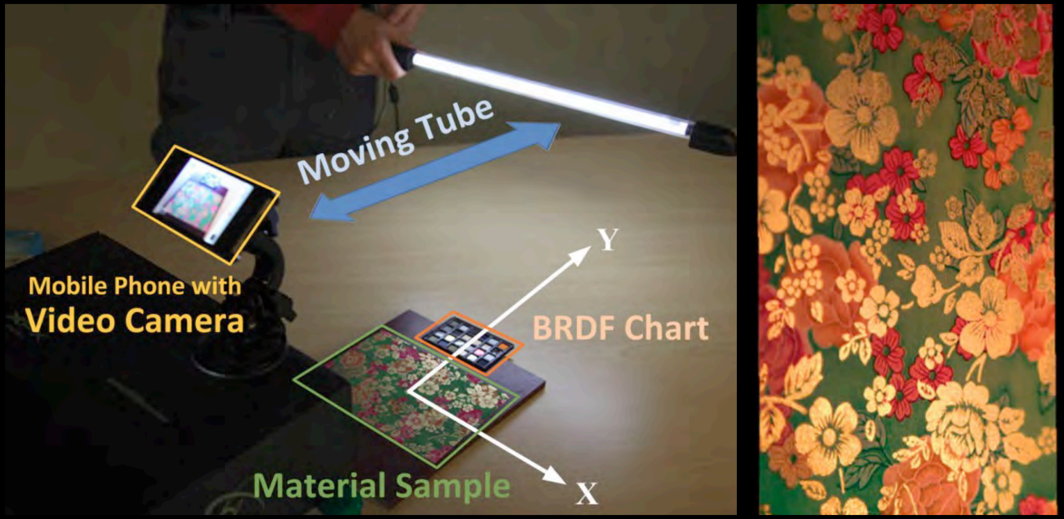


[Holroyd et al., 2010]

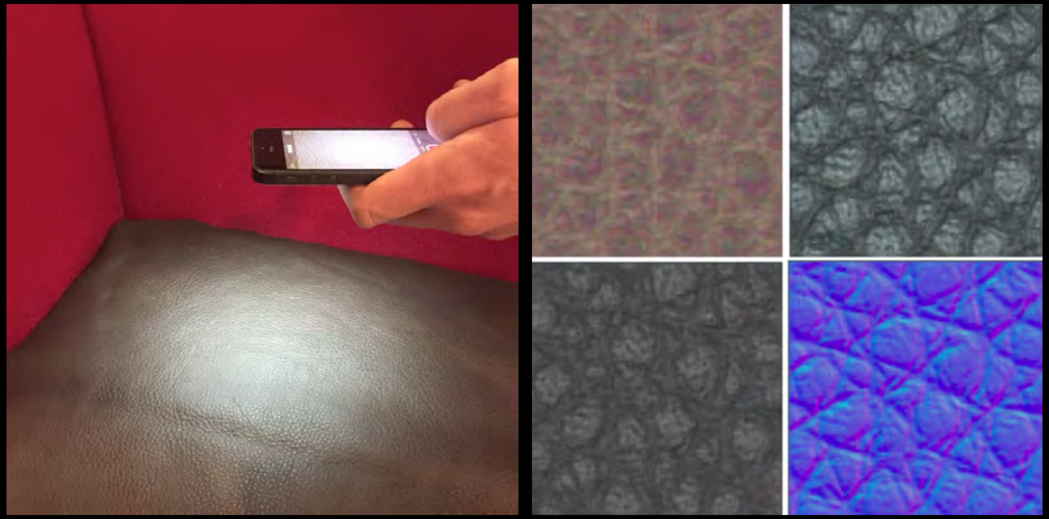


[Schwartz et al., 2013]

Previous Work



[Ren et al., 2011]



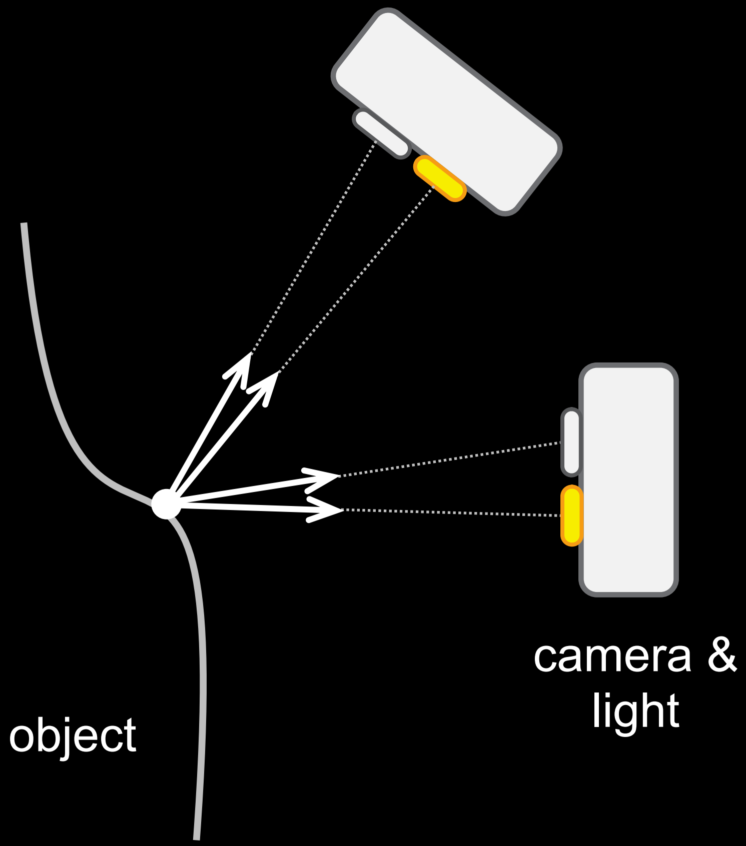
[Aittala et al., 2015]

[Riviere et al., 2015]

[Hui et al., 2017]

Challenges

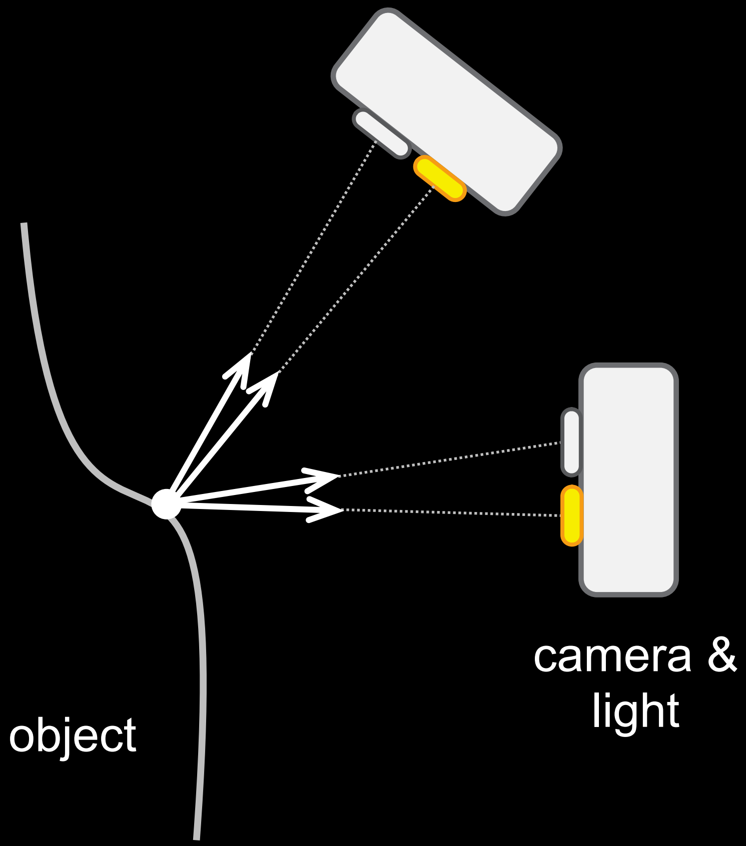
- Limited sampling angles for BRDF acquisition



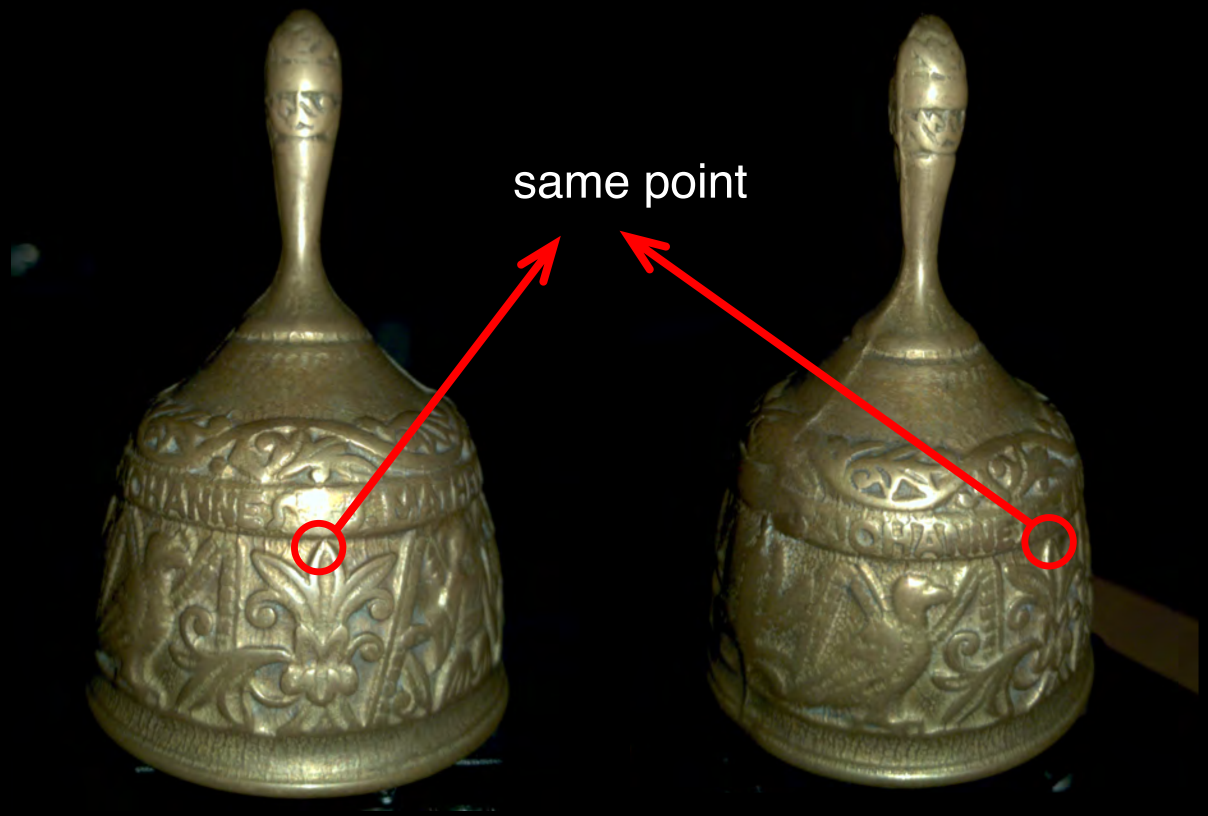
How can we reconstruct a full BRDF from retro-reflected observations?

Challenges

- Simultaneous acquisition of SVBRDF and 3D geometry

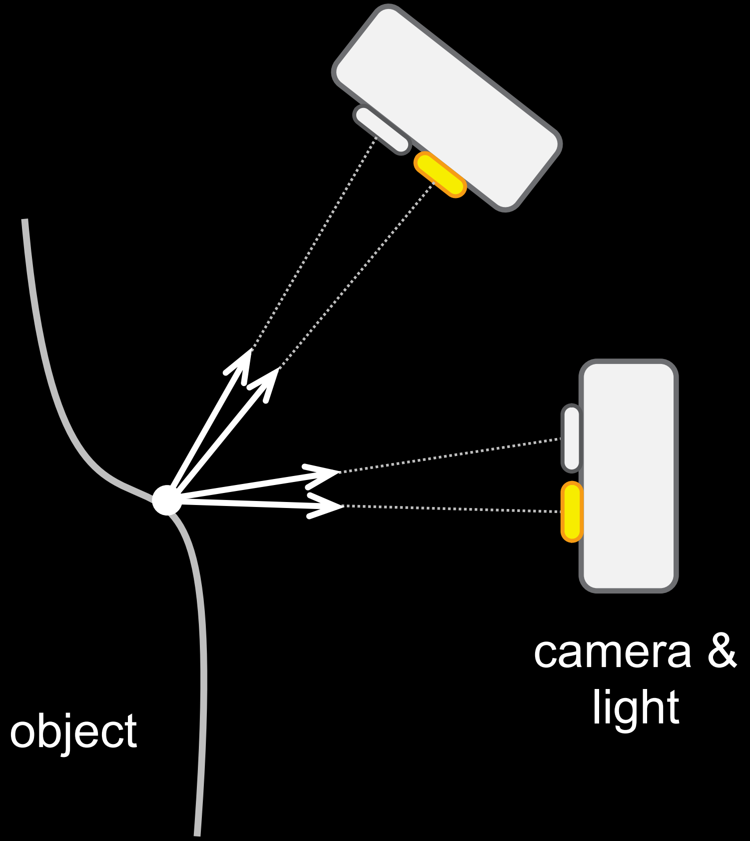


How can we ensure 3D-2D correspondence?

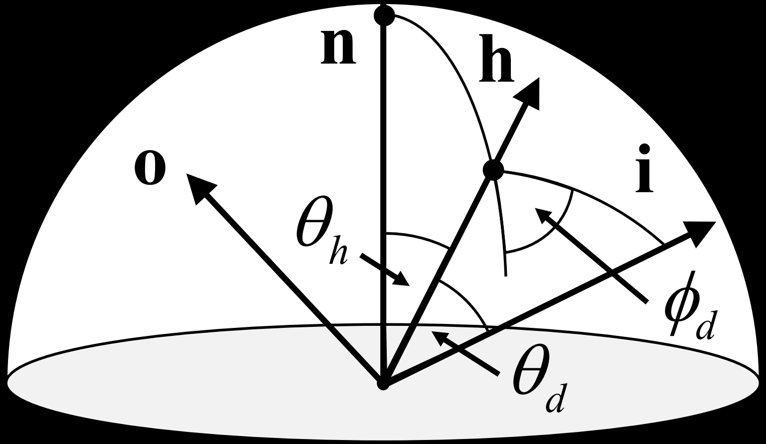


BRDF Acquisition from Flash Photography

- Parameter space for isotropic BRDFs

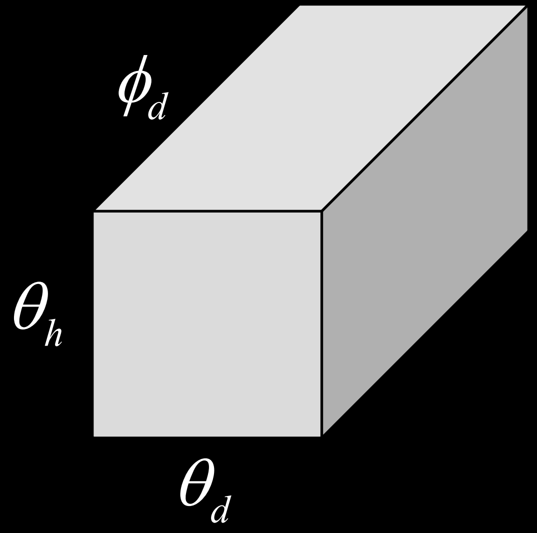


$$f(\mathbf{i},\mathbf{o}) = f(\theta_h, \theta_d, \phi_d)$$



[Rusinkiewicz 98]

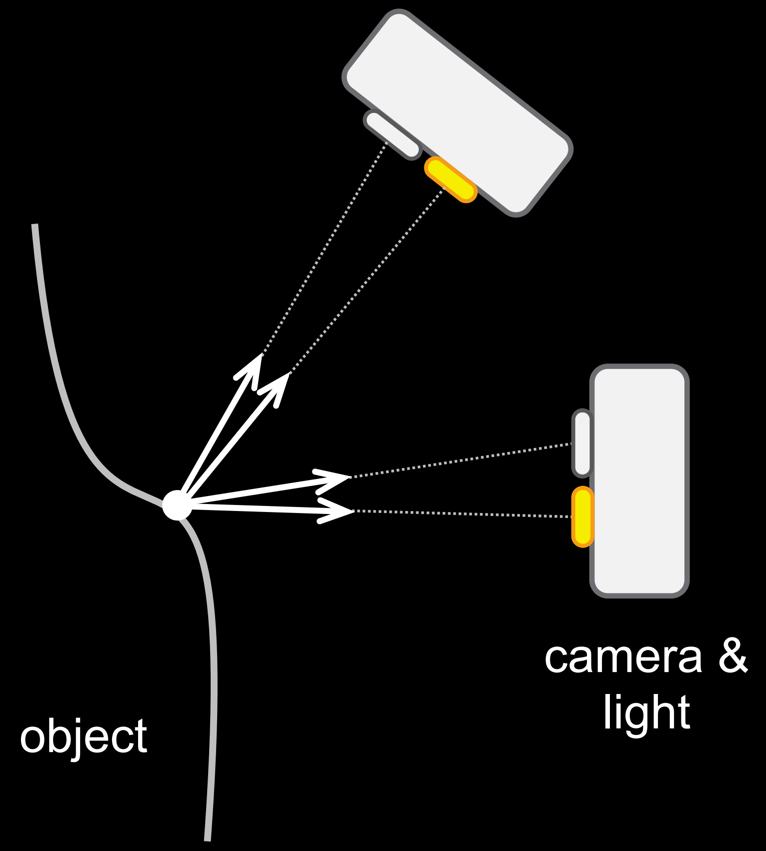
a 3D BRDF data

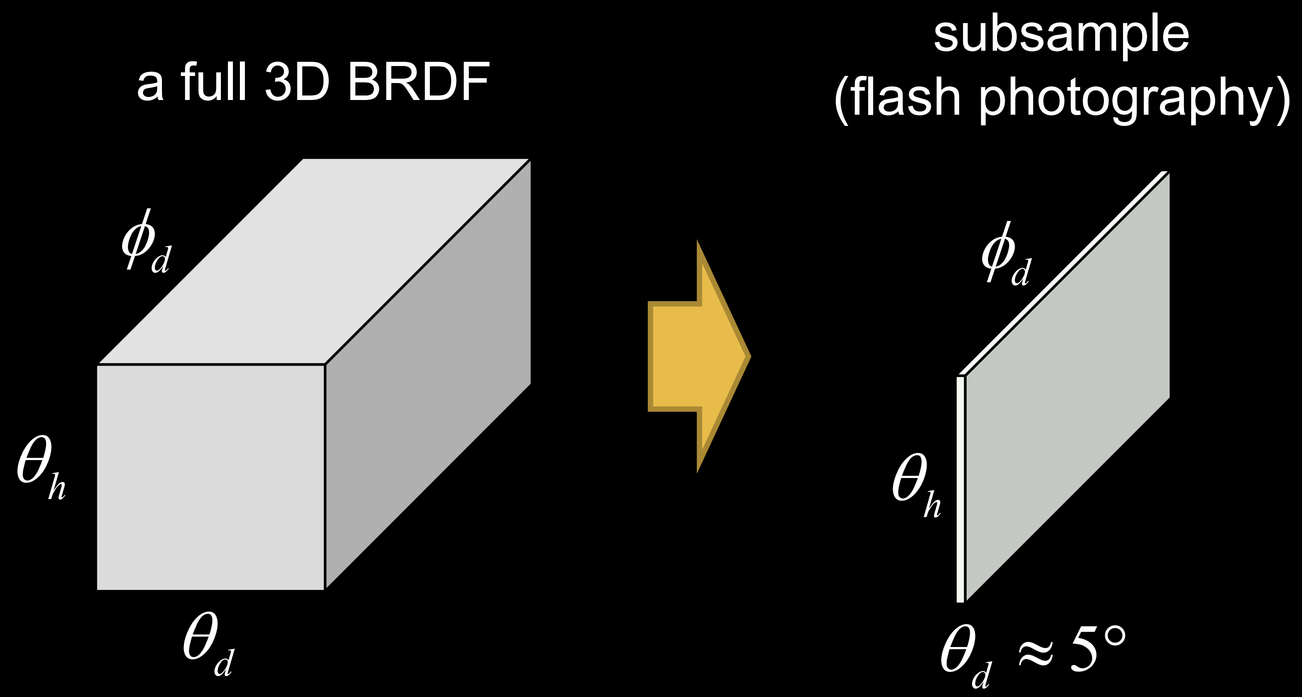


[Matusik 02]

BRDF Acquisition from Flash Photography

- Limited BRDF sampling angle in flash photography

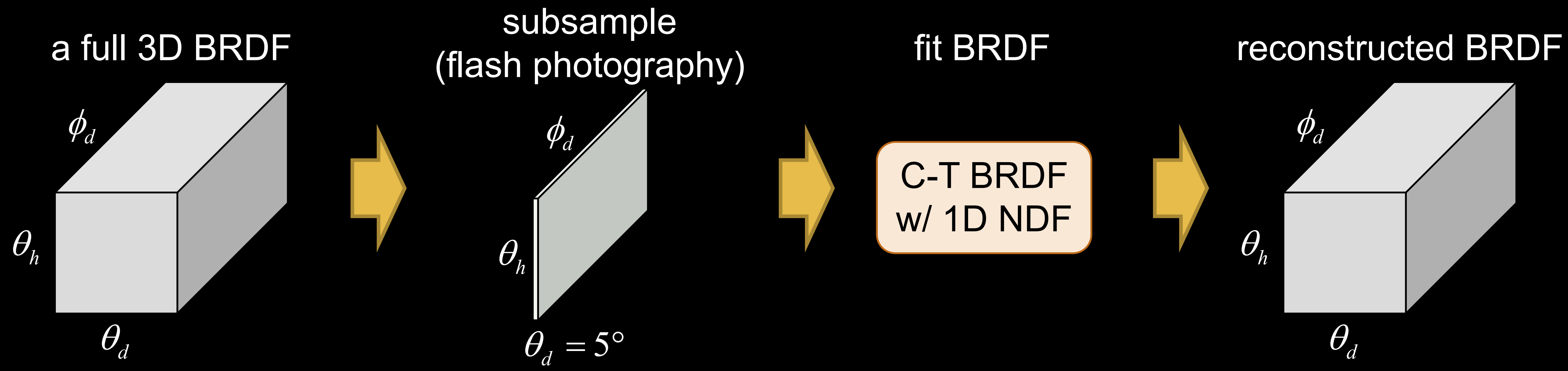




BRDF Model Validation

- Cook-Torrance BRDF with 1D data-driven NDF

$$f(\mathbf{i},\mathbf{o}) = \frac{\rho_d}{\pi} + \rho_s \frac{D(\mathbf{h})G(\mathbf{n},\mathbf{i},\mathbf{o})F(\mathbf{h},\mathbf{i})}{4(\mathbf{n}\cdot\mathbf{i})(\mathbf{n}\cdot\mathbf{o})}$$

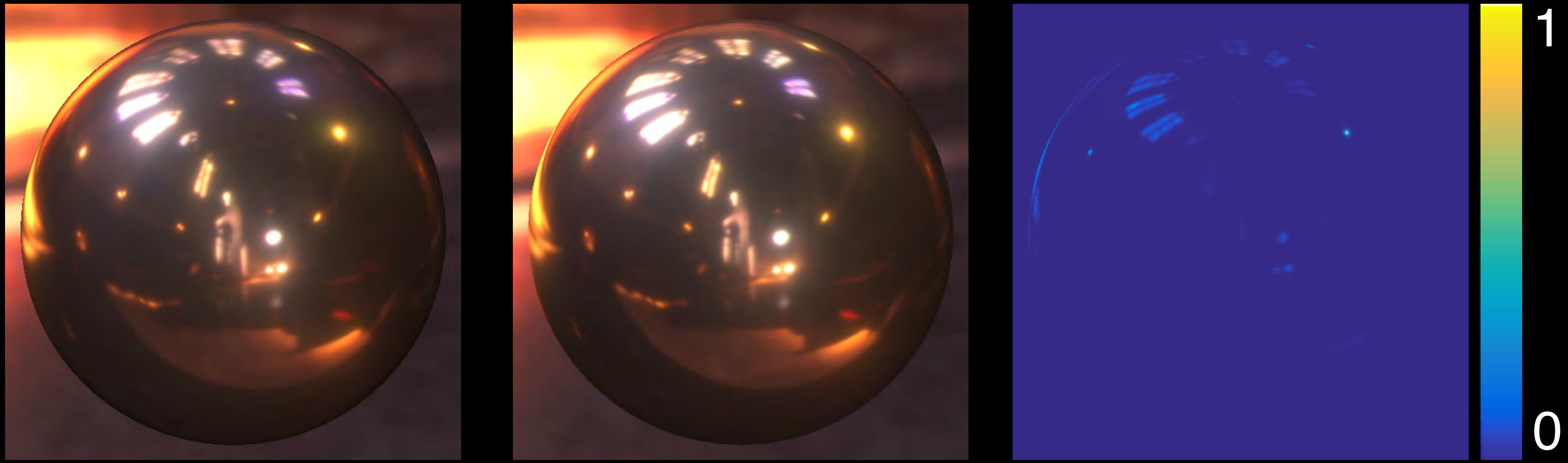


[MERL BRDF dataset]

BRDF Model Validation

- Cook-Torrance BRDF with 1D data-driven NDF

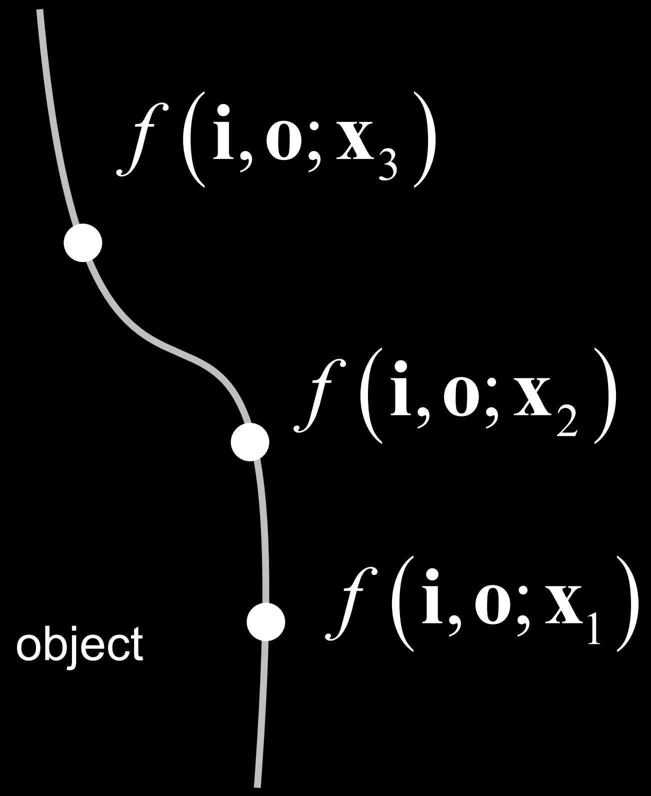
$$f\left(\mathbf{i},\mathbf{o}\right)=\frac{\rho_d}{\pi}+\rho_s\frac{D(\mathbf{h})G(\mathbf{n},\mathbf{i},\mathbf{o})F(\mathbf{h},\mathbf{i})}{4\left(\mathbf{n}\cdot\mathbf{i}\right)\left(\mathbf{n}\cdot\mathbf{o}\right)}$$



reference reconstructed difference

SVBRDF Representation

- Basis BRDFs and spatial blending weights



$$f(\mathbf{i},\mathbf{o};\mathbf{x}) = \sum_{b=1}^{B} \omega_b f_b(\mathbf{i},\mathbf{o})$$

$f(\mathbf{i},\mathbf{o};\mathbf{x})$: SVBRDF

$f_b(\mathbf{i},\mathbf{o})$: basis BRDF

ω : blending weight

B : # of basis BRDFs

Problem Definition

- Objective function using photometric consistency

photographs

rendering

$$\underset{\mathbf{X},\mathbf{N},\mathbf{W},\mathbf{F}_\mathbf{b}}{\text{minimize}} \left\| \text{photographs} - \text{rendering} \right\|^2$$

$\mathbf{X}$: 3D vertices

$\mathbf{N}$: surface normals

$\mathbf{W}$: blending weights

$\mathbf{F}_\mathbf{b}$: basis BRDFs

Problem Definition

- Objective function using photometric consistency

$$\underset{\mathbf{X},\mathbf{N},\mathbf{W},\mathbf{F_b}}{\text{minimize}} \sum_{p=1}^{P}\sum_{k=1}^{K}\left(L(\mathbf{o};\mathbf{x}) - f(\mathbf{i},\mathbf{o};\mathbf{x})L(-\mathbf{i};\mathbf{x})(\mathbf{n}\cdot\mathbf{i})\right)^2$$

for all images &
for all 3D vertices

captured radiance

reconstructed radiance

$\mathbf{X}$: 3D vertices

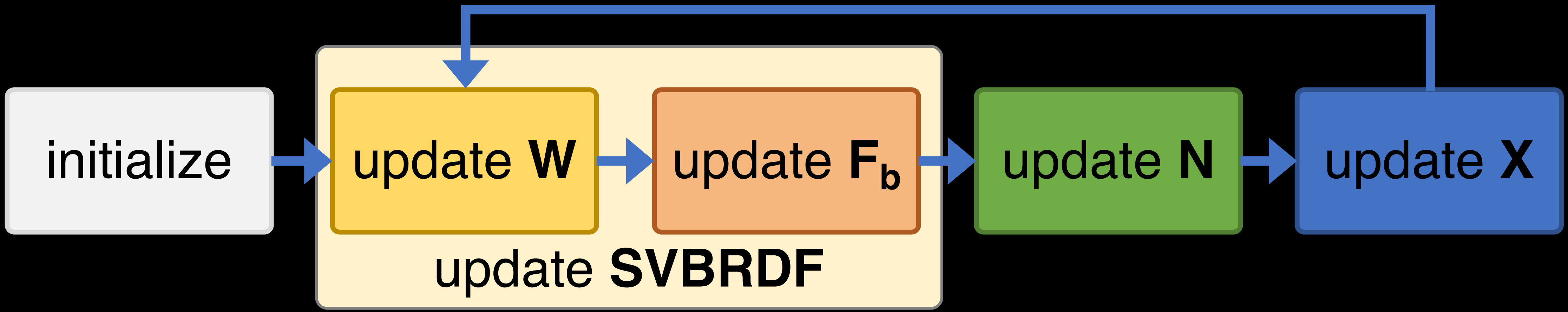
$\mathbf{N}$: surface normals

$\mathbf{W}$: blending weights

$\mathbf{F_b}$: basis BRDFs

Overview

- Iterative & alternating optimization of $\{\mathbf{X}, \mathbf{N}, \mathbf{W}, \mathbf{F_b}\}$



$\mathbf{X}$: 3D vertices
$\mathbf{N}$: surface normals
$\mathbf{W}$: blending weights
$\mathbf{F_b}$: basis BRDFs

Data Capture

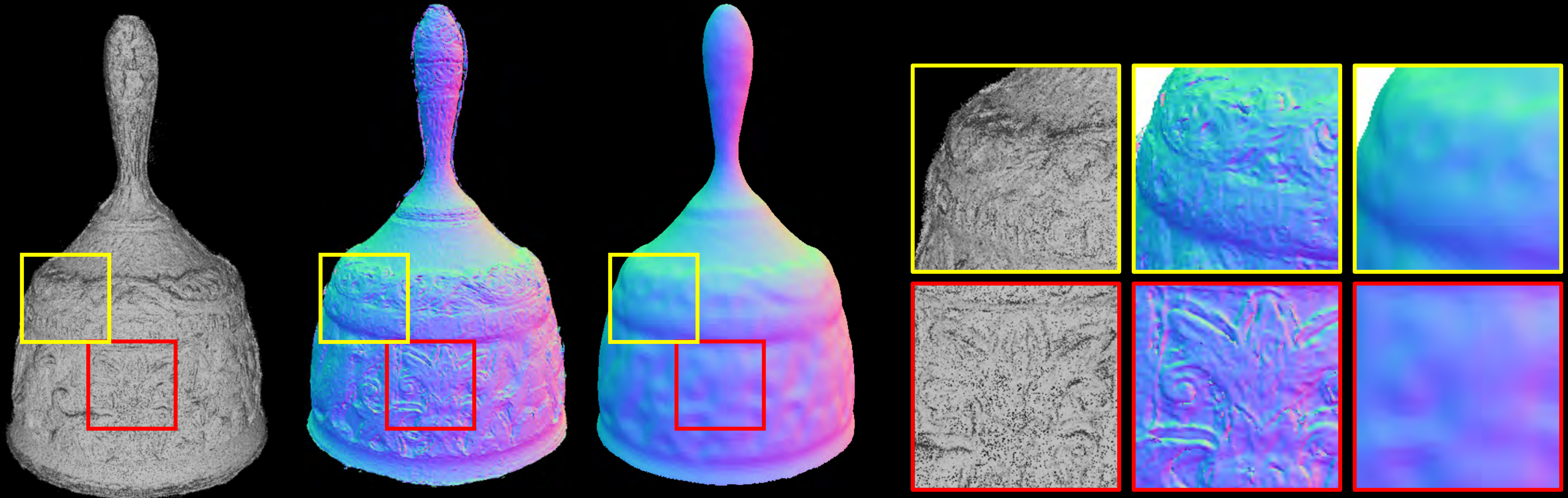
- Any camera with a flash will work
- We test two types of cameras
  - Mobile phone with built-in LED
  - DSLR with built-in flash
- 100 - 200 images (still/video)

example images

Initialization

- Initial geometry from image-based 3D modeling

  COLMAP [Schönberger 2016]: SfM ➔ MVS ➔ meshing

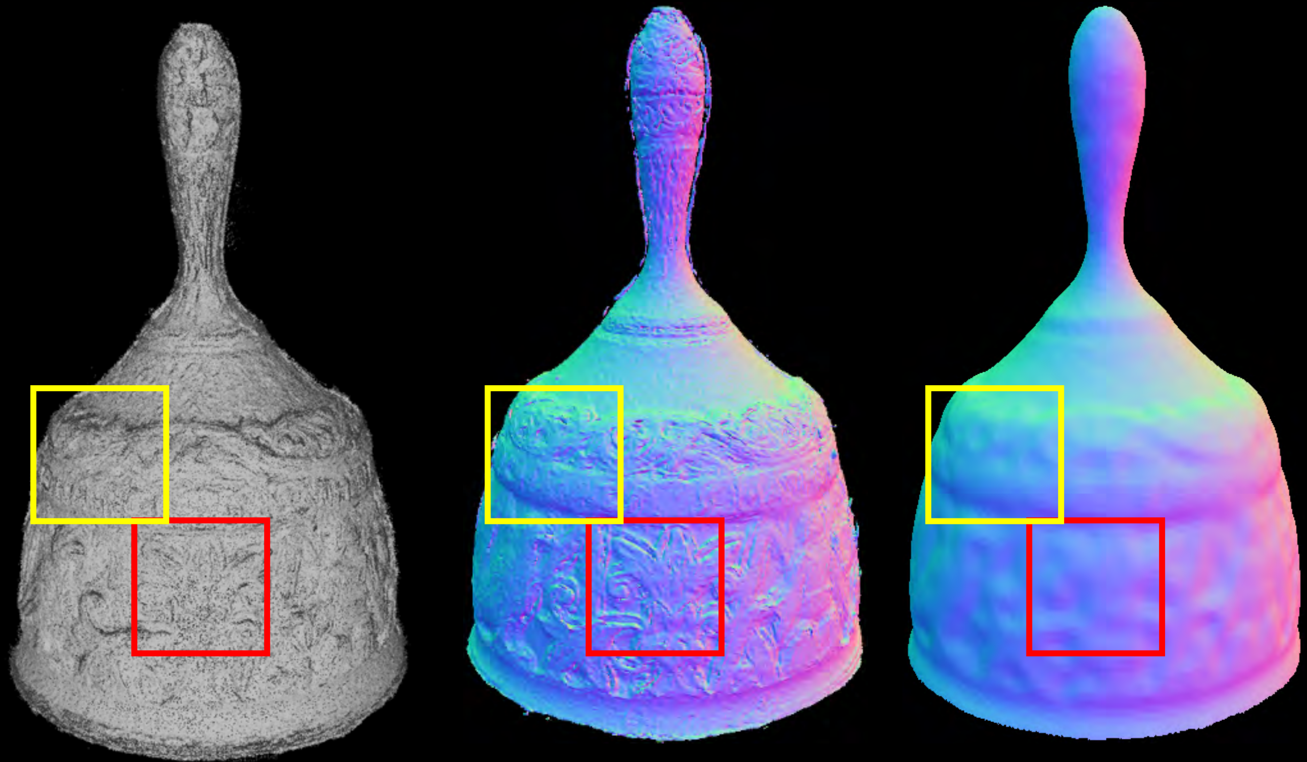


point cloud | high-res mesh | low-res mesh (our initial geo.) | point cloud | high-res mesh | low-res mesh

Initialization

- Initial geometry from image-based 3D modeling

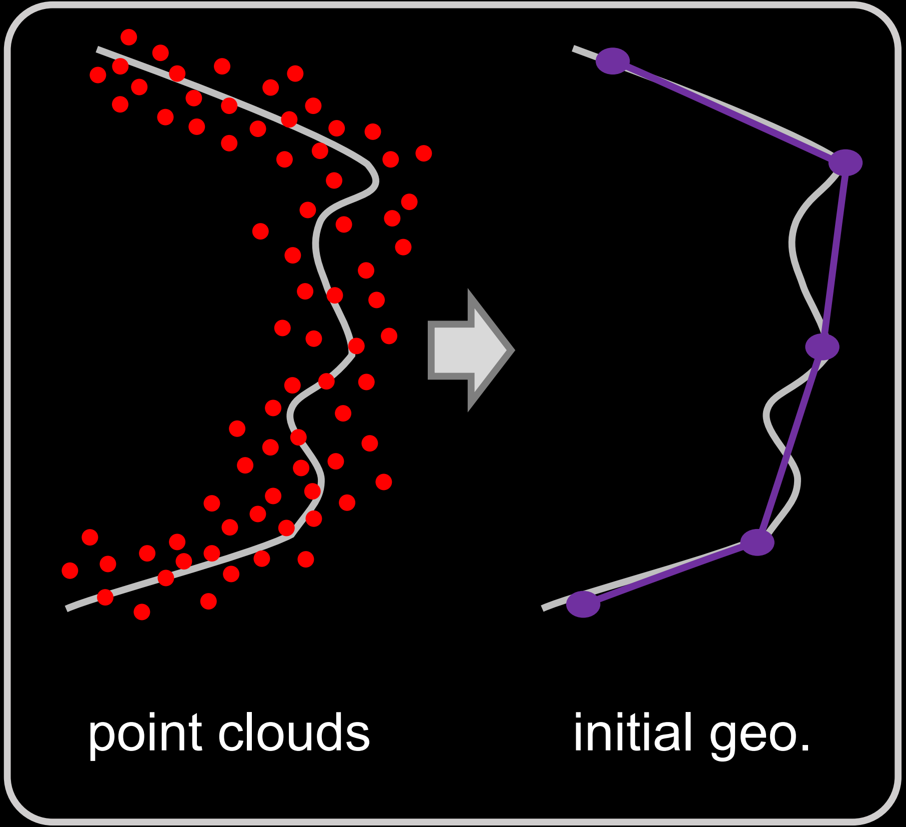
  COLMAP [Schönberger 2016]: SfM ➔ MVS ➔ meshing



point cloud

high-res mesh

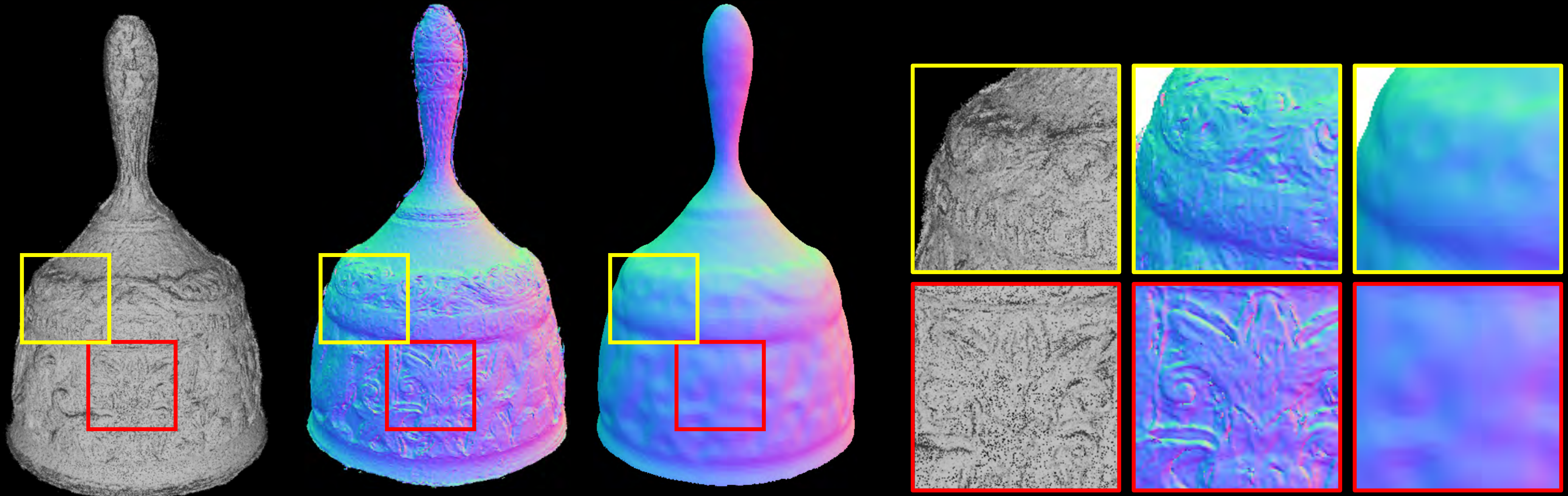
low-res mesh
(our initial geo.)



Initialization

- Initial geometry from image-based 3D modeling

  COLMAP [Schönberger 2016]: SfM ➔ MVS ➔ meshing



point cloud | high-res mesh | low-res mesh (our initial geo.) | point cloud | high-res mesh | low-res mesh

Initialization

- Initial geometry from image-based 3D modeling

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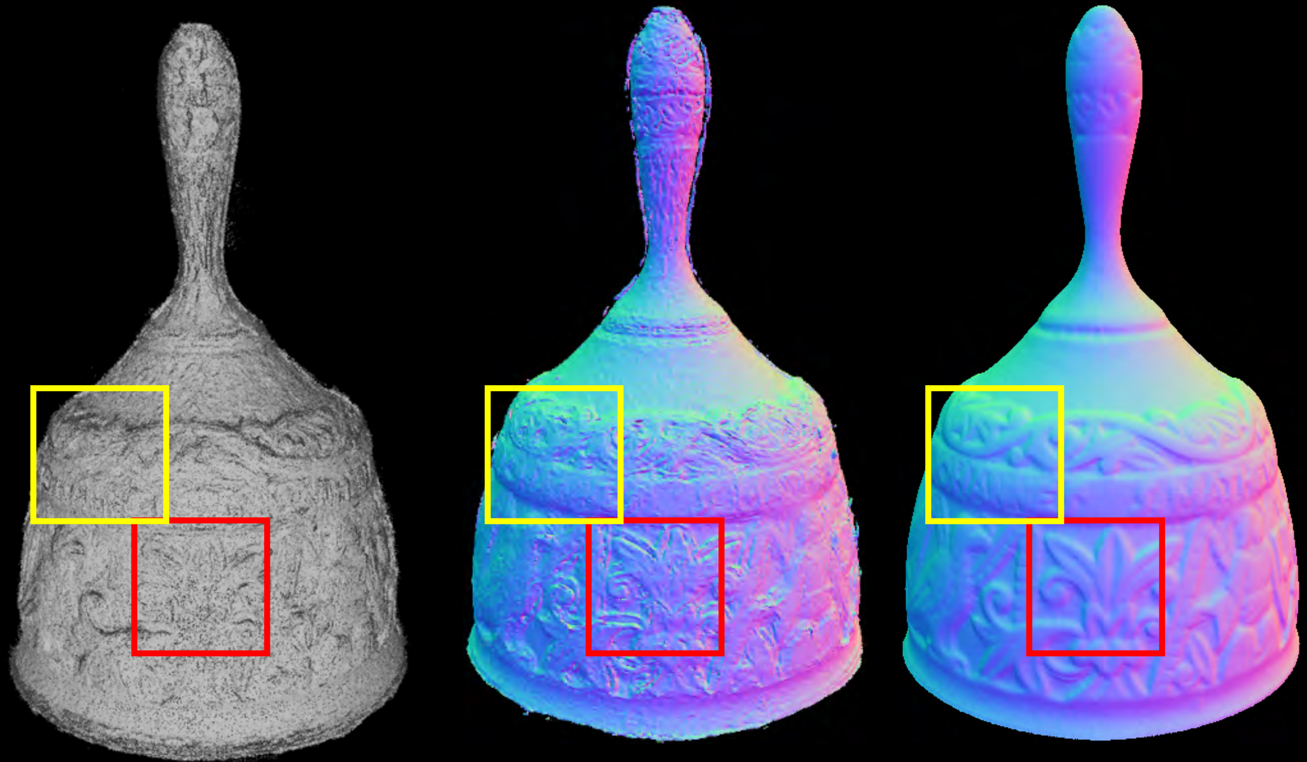
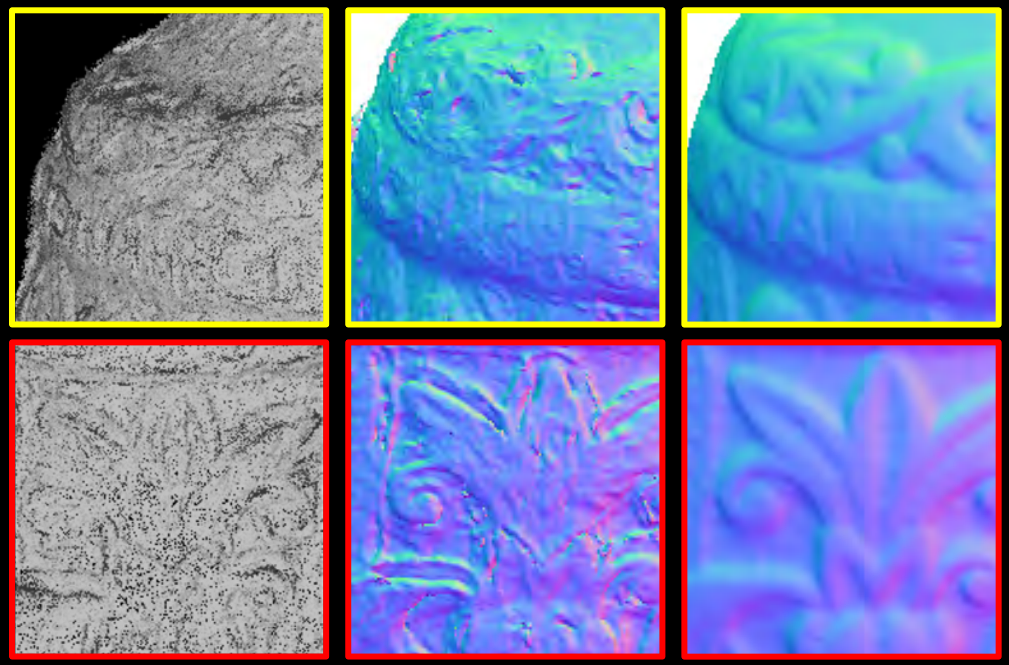
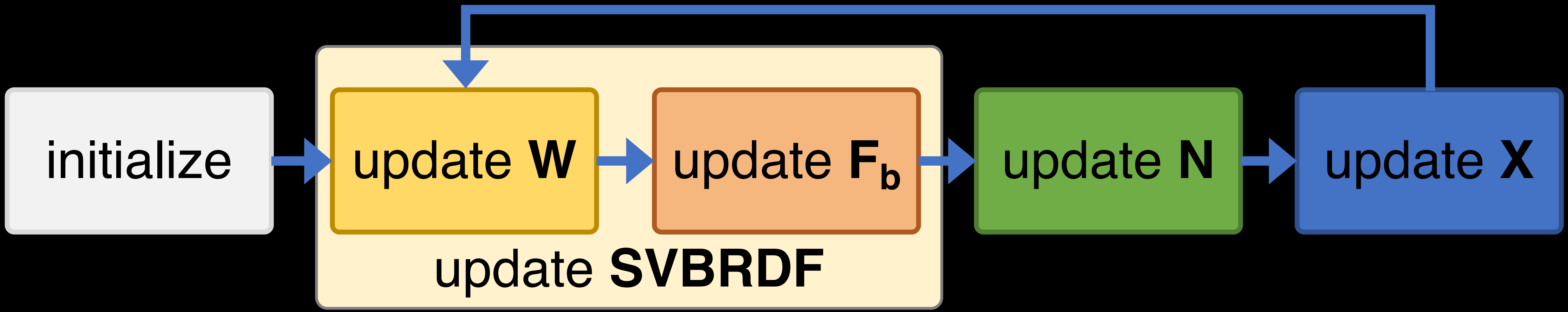




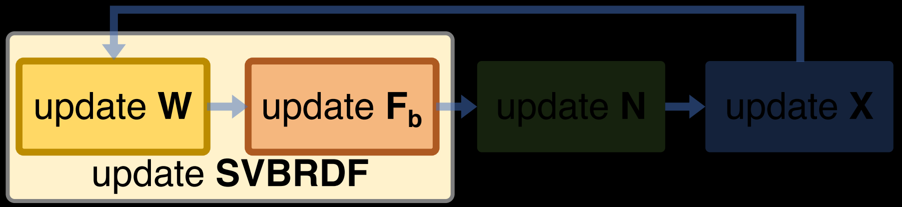
Overview

- Iterative & alternating optimization of $\{\mathbf{X}, \mathbf{N}, \mathbf{W}, \mathbf{F_b}\}$



$\mathbf{X}$: 3D vertices
$\mathbf{N}$: surface normals
$\mathbf{W}$: blending weights
$\mathbf{F_b}$: basis BRDFs

Update SVBRDF



- Re-formulate the equation w.r.t. the reflectance

$$\underset{\mathbf{X},\mathbf{N},\mathbf{W},\mathbf{F}_b}{\text{minimize}} \sum_{p=1}^{P}\sum_{k=1}^{K}\Big(L(\mathbf{o};\mathbf{x}) - f(\mathbf{i},\mathbf{o};\mathbf{x})L(-\mathbf{i};\mathbf{x})(\mathbf{n}\cdot\mathbf{i})\Big)^2$$

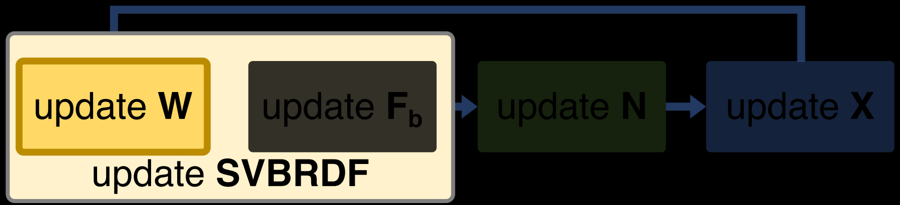
$$\underset{\mathbf{W},\mathbf{F}_b}{\text{minimize}} \sum_{p=1}^{P}\sum_{k=1}^{K} v_{p,k}\left(f'_{p,k} - \mathbf{\Phi}_{p,k}\sum_{b=1}^{B}\omega_{p,b}\mathbf{f}_b\right)^2$$

captured reflectance — reconstructed reflectance

W: blending weights

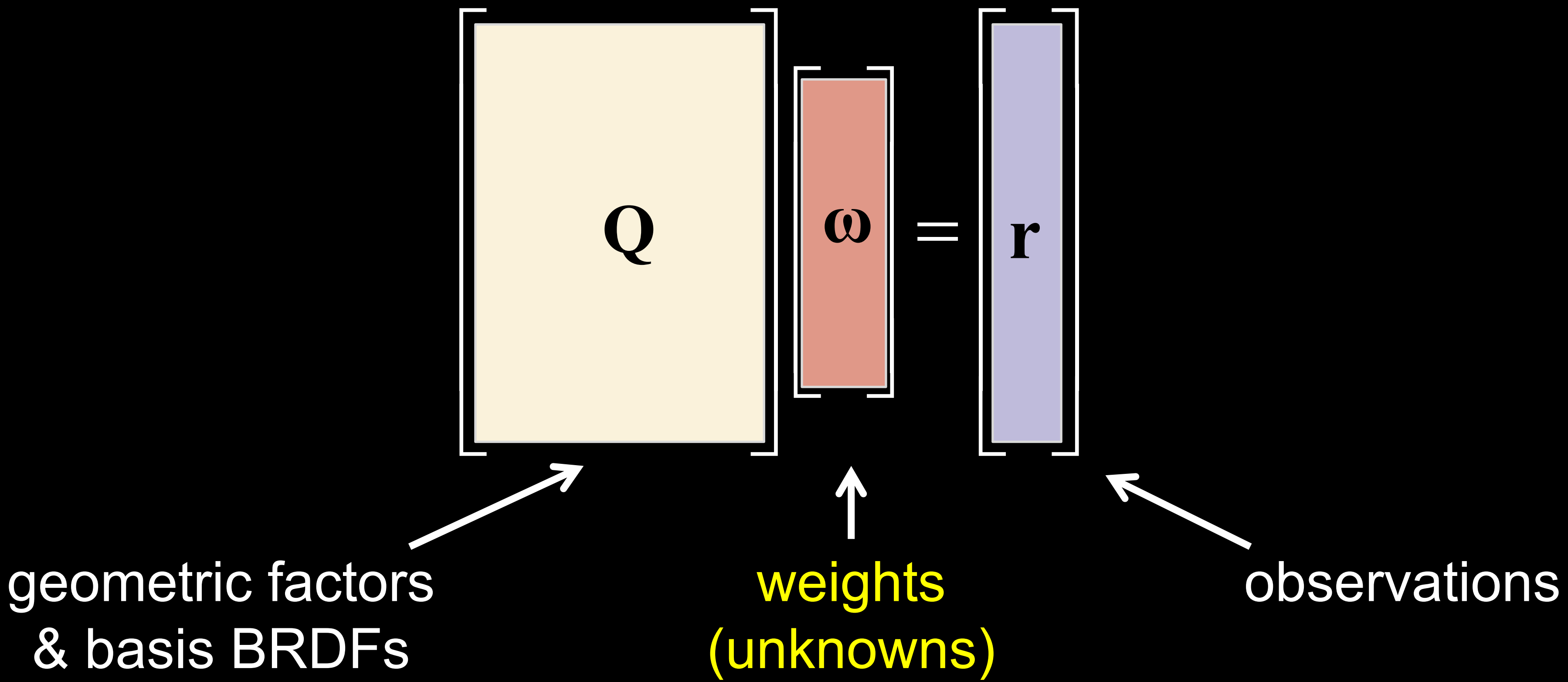
$\mathbf{F}_b$: basis BRDFs

Update SVBRDF: Blending Weights

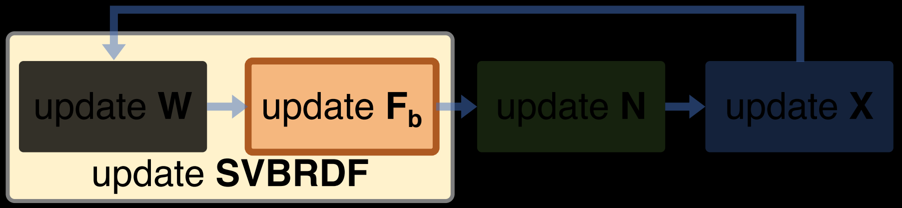


- Per-vertex optimization

$$\underset{\boldsymbol{\omega}}{\text{minimize}} \frac{1}{2}\left\|\mathbf{Q}\boldsymbol{\omega}-\mathbf{r}\right\|^2 \quad \text{s.t.} \quad \omega_b > 0, \quad \sum_{b=1}^{B} \omega_{p,b} = 1$$



Update SVBRDF: Basis BRDFs



- Optimize for all observations (NOT per-vertex)
- Hold $\mathbf{W}$ fixed and solve for $\mathbf{F_b}$
- Sparse quadratic programming

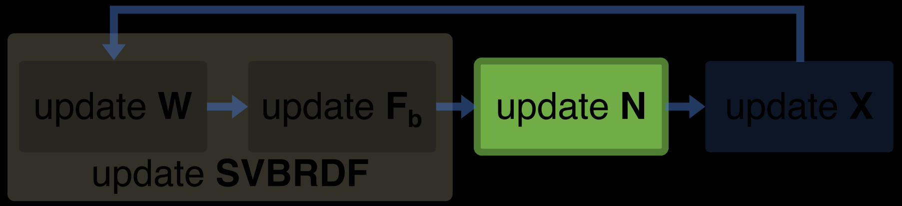
$$\underset{\mathbf{F_b}}{\text{minimize}} \sum_{p=1}^{P} \sum_{k=1}^{K} v_{p,k} \left(f'_{p,k} - \mathbf{\Phi}_{p,k} \sum_{b=1}^{B} \omega_{p,b} \mathbf{f}_b \right)^2$$

observation

estimated weights

basis BRDFs (unknowns)

Update Normals



- Per-vertex optimization

$$\underset{\mathbf{n}}{\text{minimize}} \sum_{k=1}^{K} \left(L(\mathbf{o};\mathbf{x}) - f(\mathbf{i},\mathbf{o};\mathbf{x},\mathbf{n}) L(-\mathbf{i};\mathbf{x}) (\mathbf{n} \cdot \mathbf{i}) \right)^2$$

K: # of images

normal for BRDF

normal for irradiance

- Non-linear optimization ➔ hard to solve!

Update Normals

update W → update F_b → update N → update X

update SVBRDF

- Per-vertex optimization

$$\underset{\mathbf{n}}{\text{minimize}} \sum_{k=1}^{K} \left(L(\mathbf{o};\mathbf{x}) - f(\mathbf{i},\mathbf{o};\mathbf{x},\mathbf{n}) L(-\mathbf{i};\mathbf{x})(\tilde{\mathbf{n}} \cdot \mathbf{i}) \right)^2$$

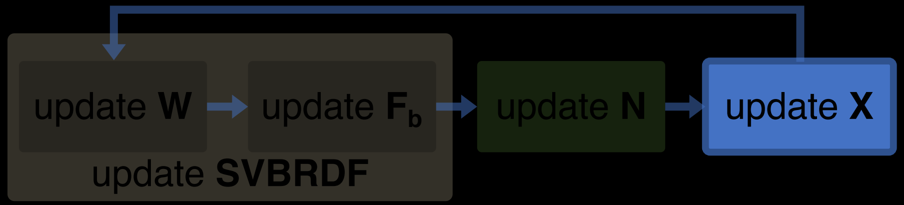
K: # of images

geometric normal ($\mathbf{n}$, known)

shading normal ($\tilde{\mathbf{n}}$, unknown)

- Linear regression ➔ easy to solve!

Update Geometry



- Screened Poisson surface reconstruction [Kazhdan 2015]

$$\underset{\chi}{\text{minimize}} \int \left\| \mathbf{V}(\mathbf{x}_p) - \nabla \chi(\mathbf{x}_p) \right\|^2 d\mathbf{x}_p + \alpha \sum_{\mathbf{x}_p \in \mathbf{X}} \chi^2(\mathbf{x}_p)$$

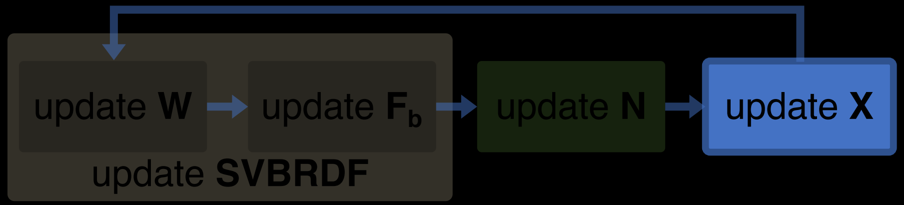
3D vector field from shading normals

gradient of new geometry

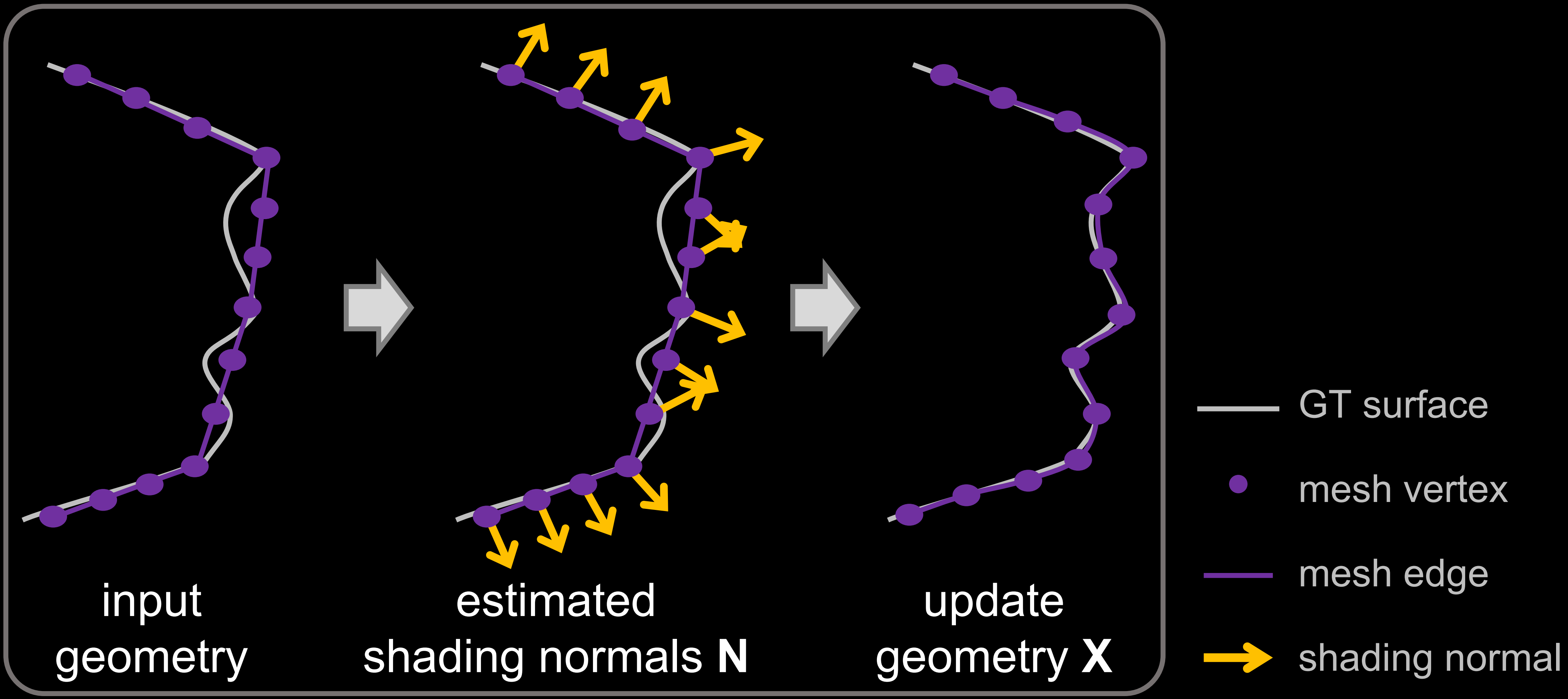
squared distance of current and new geometry

χ : new geometry (unknown)

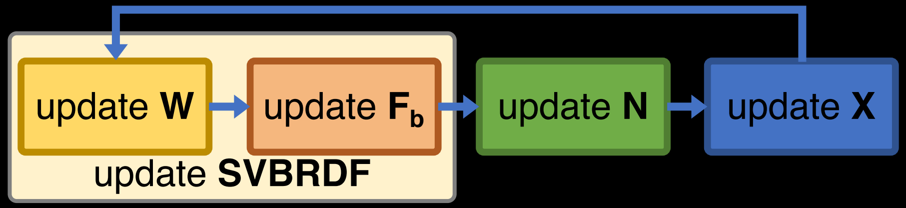
Update Geometry



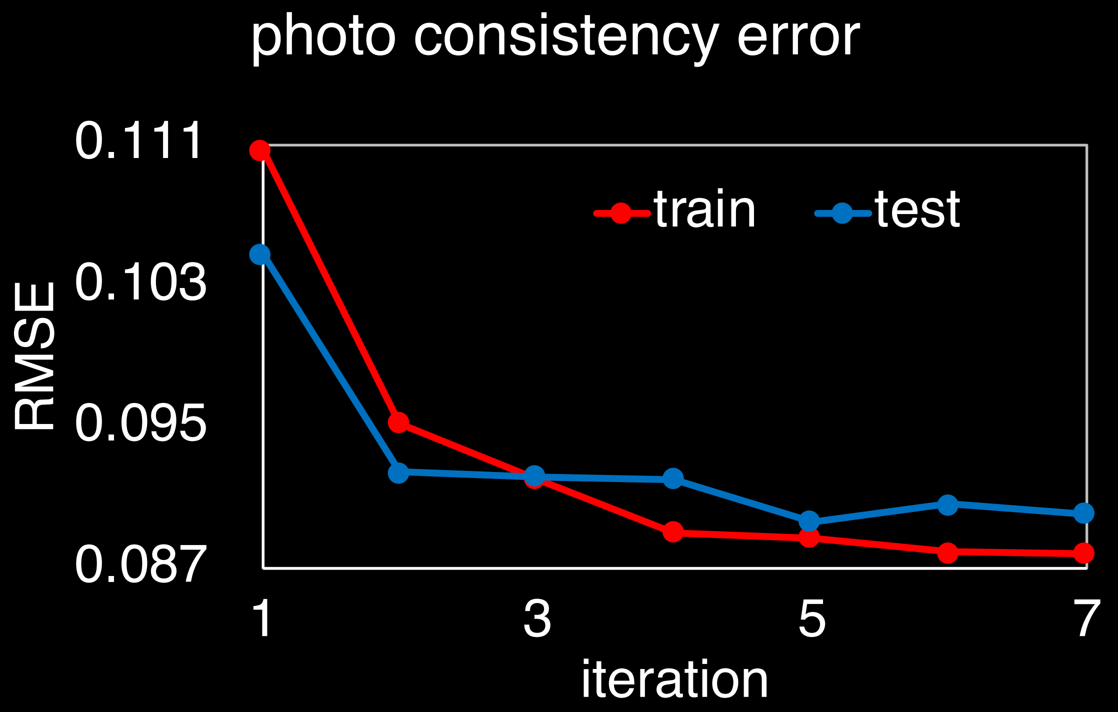
- Screened Poisson surface reconstruction [Kazhdan 2015]

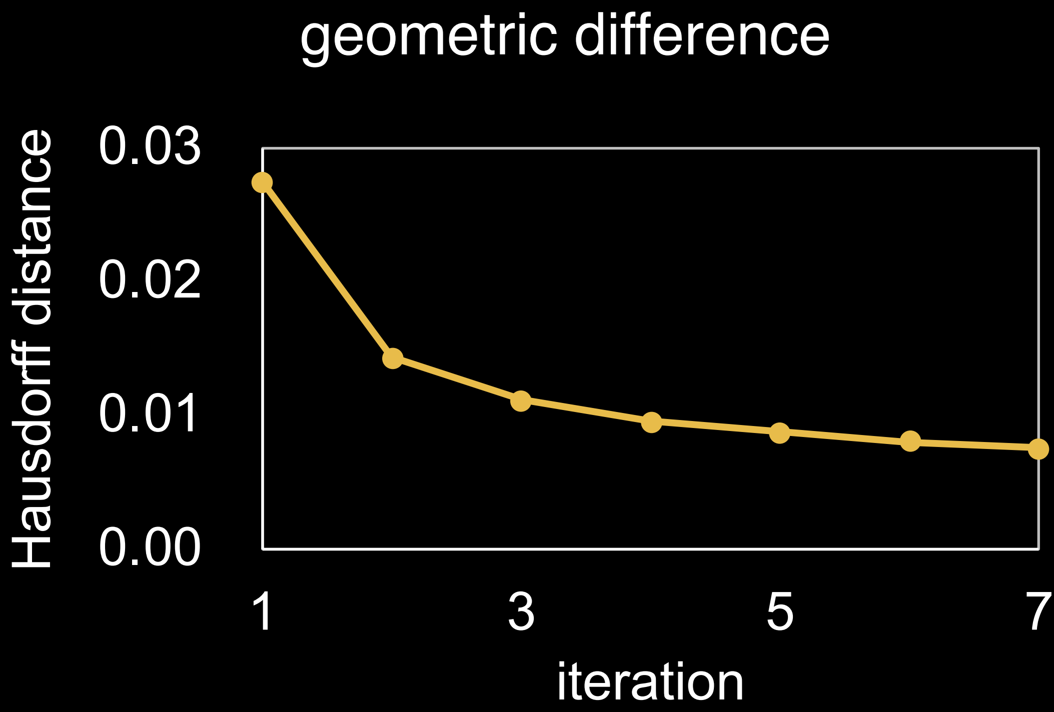


Iterative Optimization



- Iterate the whole process until RMSE of the test set starts to increase





Results

point-light rendering

geometry

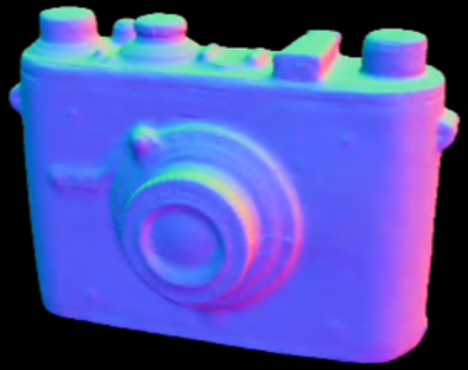
Results

point-light rendering

geometry

Results

point-light rendering

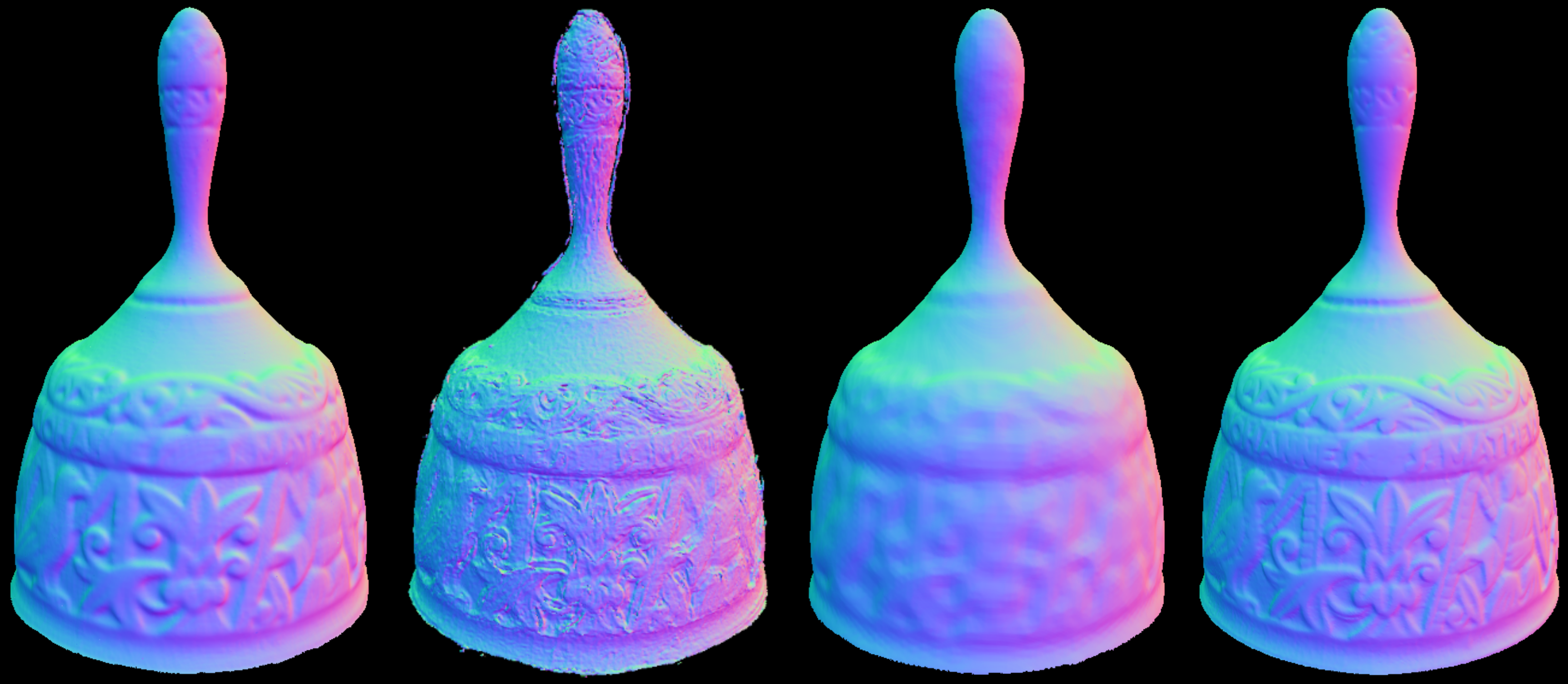


geometry

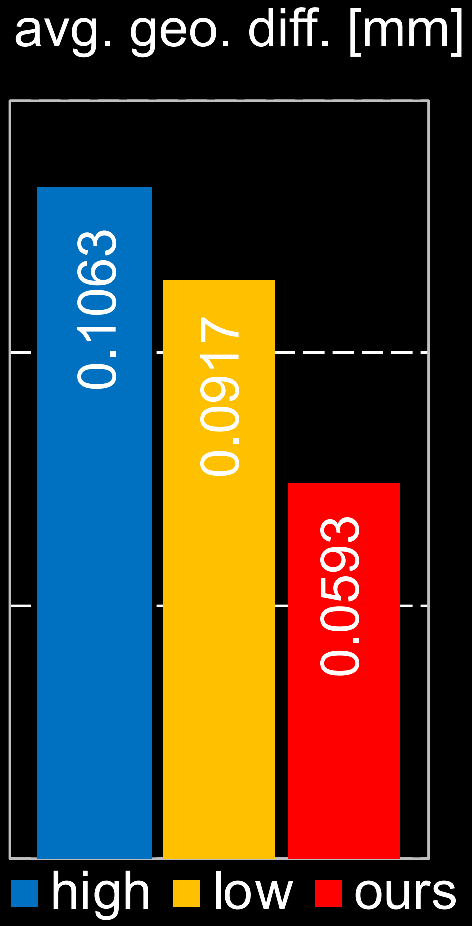
Comparison with Previous Work

reference (NextEngine) | Xia SIGA'16 (passive env. lighting) | Ours (active flashlight)

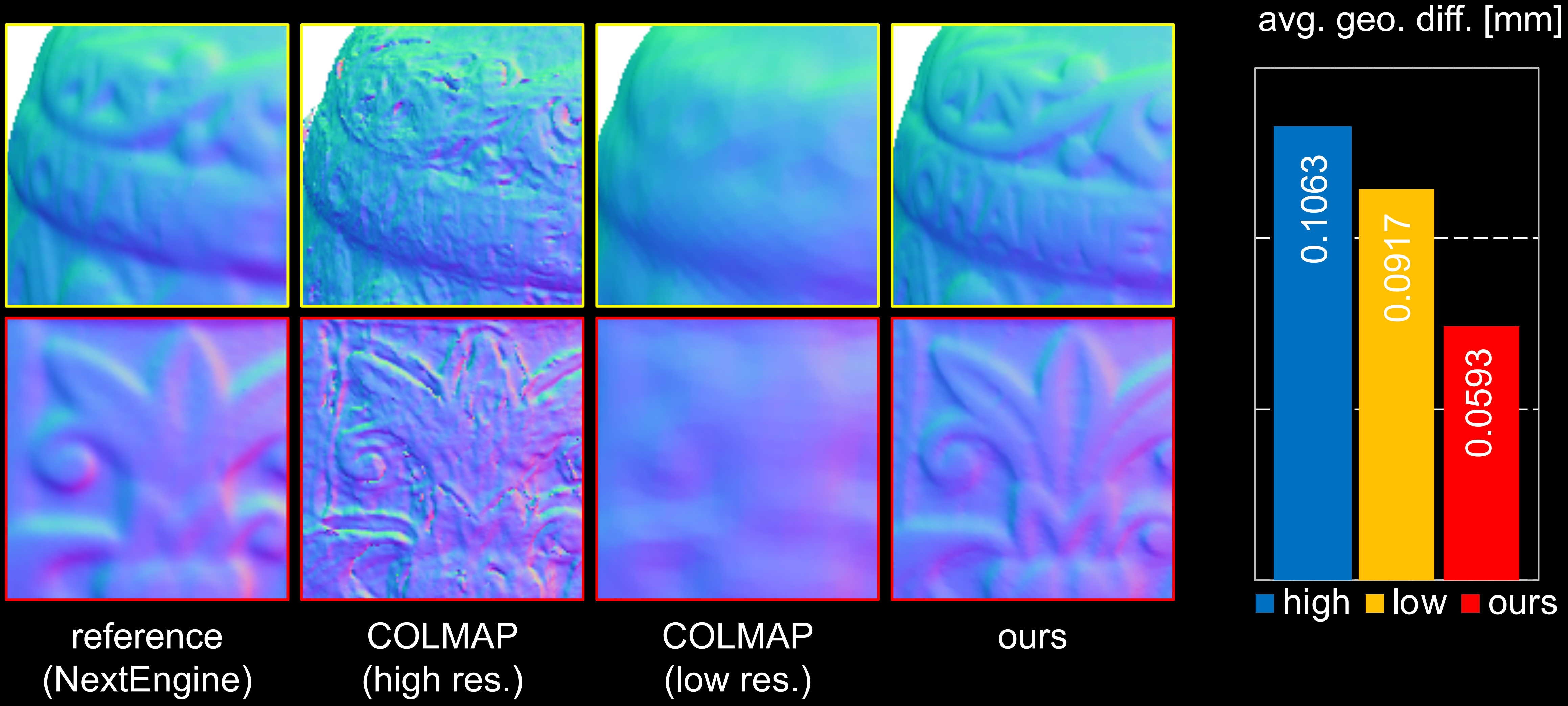
Evaluation: Geometry Refinement



reference (NextEngine) | COLMAP (high res.) | COLMAP (low res.) | ours



Evaluation: Geometry Refinement



Discussion: DLSR vs. Mobile Phone

- DLSRs
  - Higher sensor signal-to-noise ratio
  - Brighter flashlight intensity
  - Does not need a darkroom

experiment setup

flash in a darkroom

flash + indoor light

Discussion: DLSR vs. Mobile Phone

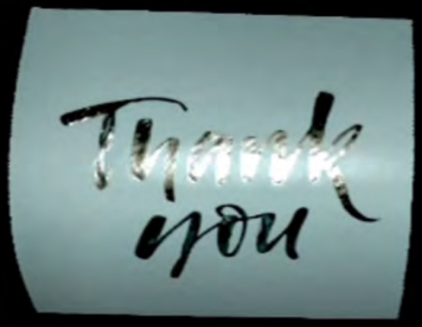
- Mobile phones
  - Better portability
  - Record a video with the LED light on

Limitation

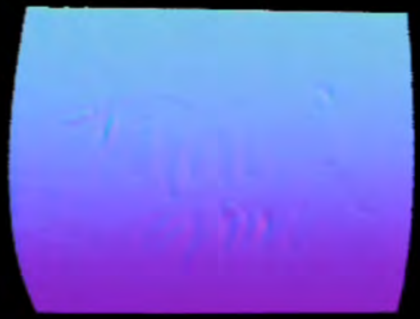
- Geometry
  - Complex geometries cannot be reconstructed accurately from image-based 3D modeling.
    - Pinecones, hair strands, etc.
- Material Appearance
  - Inter-reflections
  - Subsurface scattering
  - Transparency

Conclusion

- Capture images using commercial cameras with flash lights
- You will get high-quality 3D geometry & SVBRDF!



point-light rendering



geometry