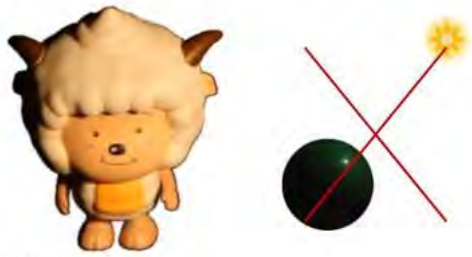
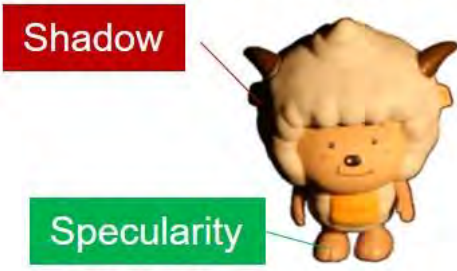


General-1: Uncalibrated



[CVPR 10]

General-2: Robust



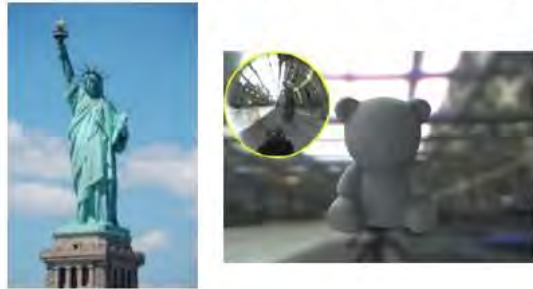
[ACCV 10]

General-3: General material



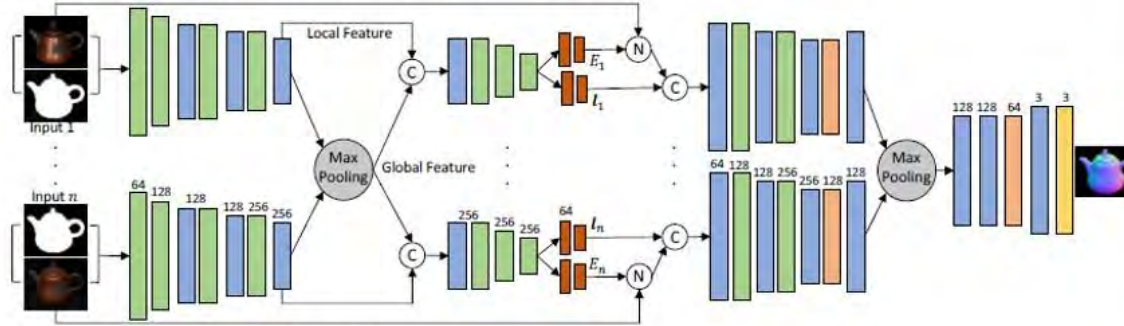
[CVPR 12, ECCV 12, TPAMI 14, ICCV 17, TIP 19, TPAMI19]

General-4: General lighting



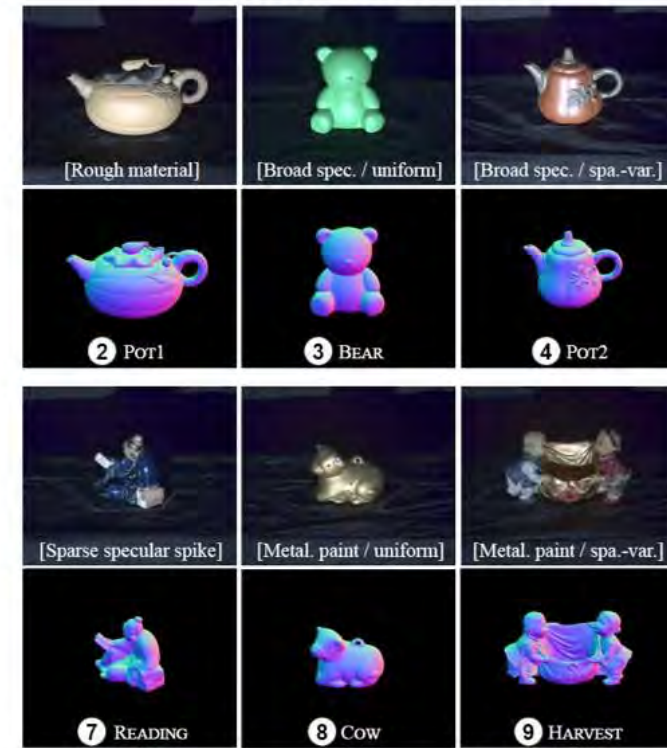
[3DV 14, CVPR 18]

General-5: Uncalibrated + general material



[CVPR 19, ICCV 19]

Benchmark dataset



[CVPR 16, TPAMI19]

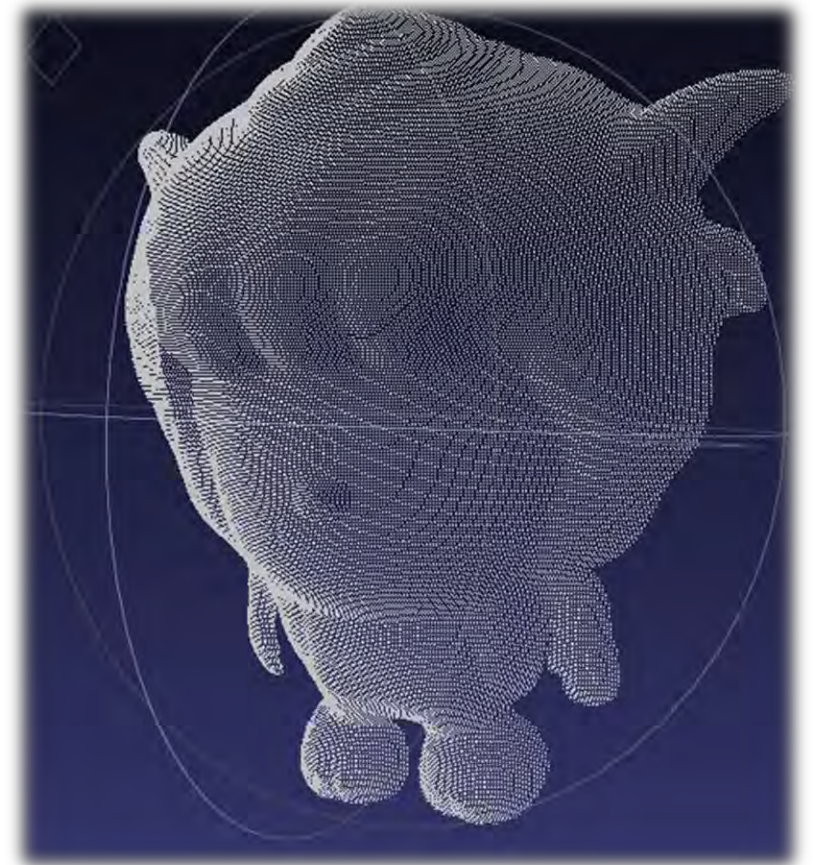
# Data-driven Photometric 3D Modeling for Complex Reflectances

Boxin Shi (Peking University)

<http://ci.idm.pku.edu.cn> | [shiboxin@pku.edu.cn](mailto:shiboxin@pku.edu.cn)

# Photometric Stereo Basics

# 3D imaging



# 3D modeling methods



Laser range scanning  
Bayon Digital Archive Project  
Ikeuchi lab., UTokyo



# 3D modeling methods



Multiview stereo

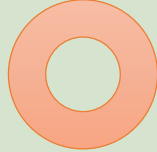





Reconstruction  
[Furukawa 10]



Ground truth

# Geometric vs. photometric approaches

	Geometric approach	Photometric approach
Gross shape		
Detailed shape		



# Shape from image intensity



149	127	168	210	222	232	239	233	200	152	145	144	134	88
147	113	184	252	255	254	248	239	232	220	188	150	178	115
113	145	248	254	251	245	235	226	215	203	188	173	190	104
130	239	255	250	245	236	224	212	197	181	170	150	144	86
188	255	248	243	236	225	212	197	177	163	150	136	124	70
213	250	241	234	226	214	197	179	162	148	135	122	114	57
222	240	233	224	211	195	178	164	149	134	121	110	104	57
216	231	223	213	197	181	165	149	134	120	107	98	94	52
206	219	209	195	180	165	150	135	121	107	95	86	82	53
201	199	187	175	162	149	134	121	108	95	84	75	73	62
182	163	164	155	143	131	118	105	92	81	72	59	85	71
111	160	150	129	121	110	98	86	75	65	52	67	120	71
186	211	187	129	94	81	71	60	50	41	68	116	123	67
192	199	195	180	126	85	79	72	61	76	130	137	136	96
213	214	212	209	204	200	199	200	200	204	208	209	209	206

How can machine understand the shape from image intensities ?

# Photometric 3D modeling

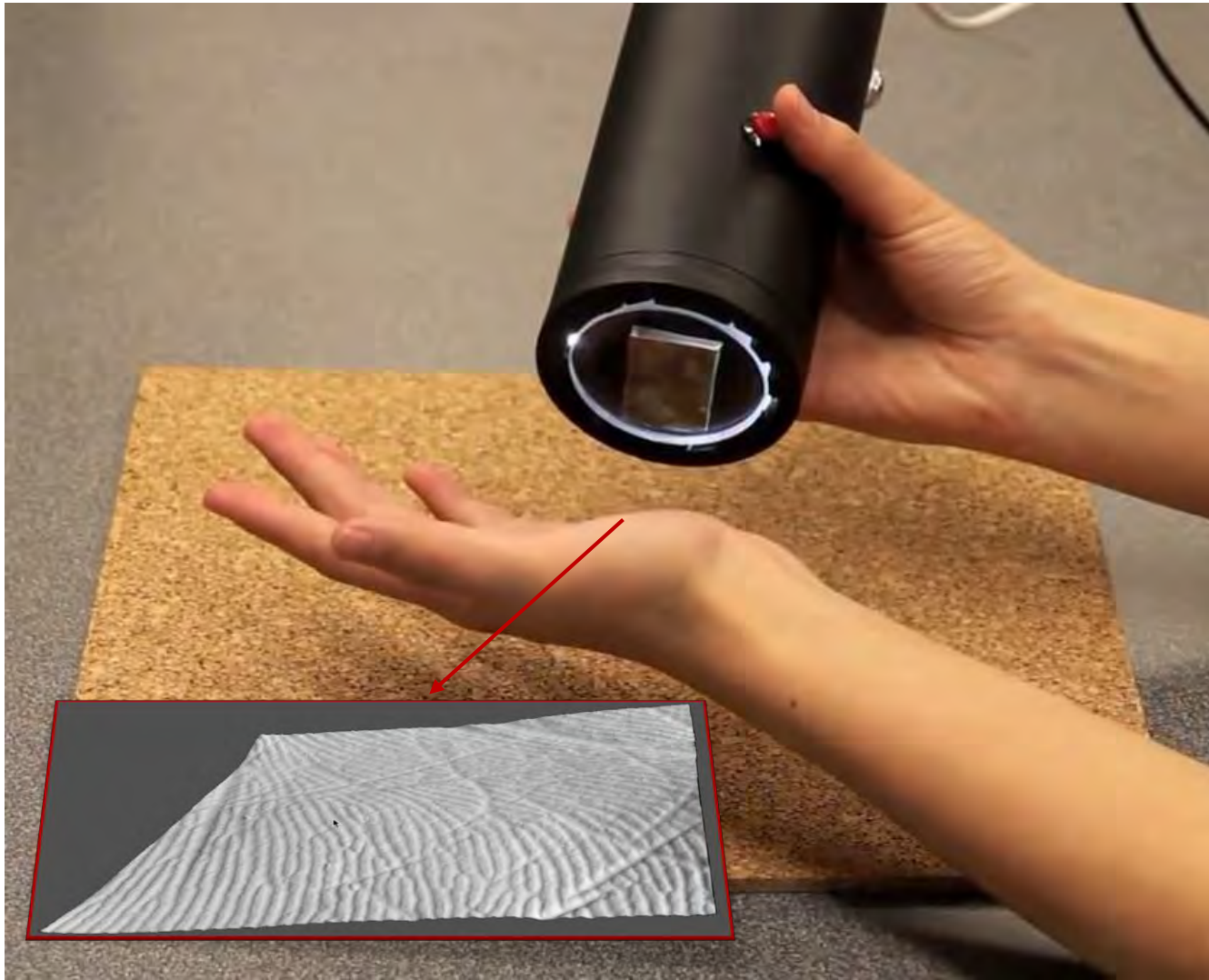
3D Scanning the President of the United States  
P. Debevec et al., USC, 2014





# Photometric 3D modeling

GelSight Microstructure 3D Scanner  
E. Adelson et al., MIT, 2011

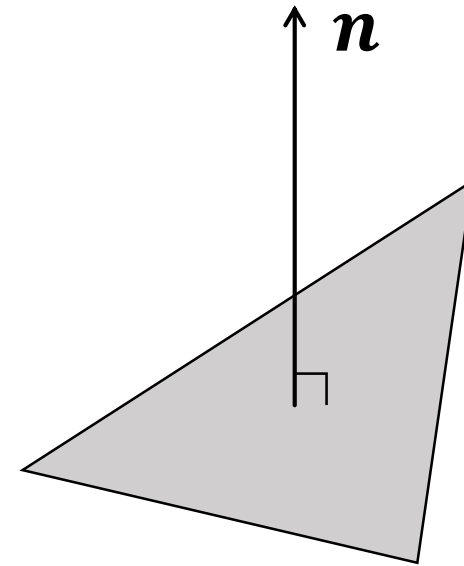


# Preparation 1: Surface normal

A surface normal  $\mathbf{n}$  to a surface is a vector that is **perpendicular** to the tangent plane to that surface.

$$\mathbf{n} \in \mathcal{S}^2 \subset \mathbb{R}^3, \|\mathbf{n}\|_2 = 1$$

$$\mathbf{n} = \begin{bmatrix} n_x \\ n_y \\ n_z \end{bmatrix}$$

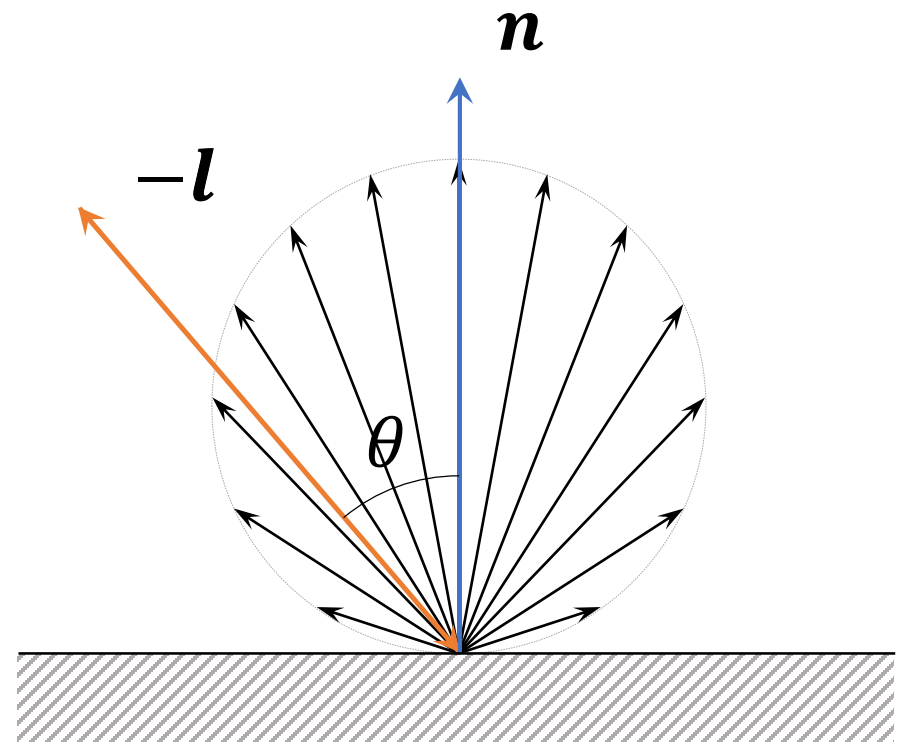


# Preparation 2: Lambertian reflectance

- Amount of reflected light proportional to  $\mathbf{l}^T \mathbf{n}$  ( $= \cos\theta$ )
- Apparent brightness does not depend on the viewing angle.

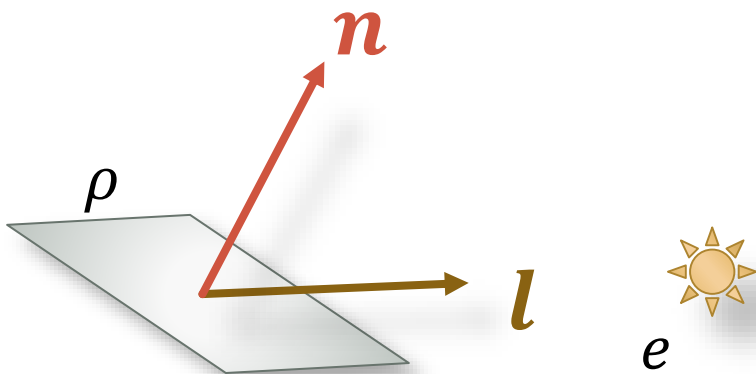
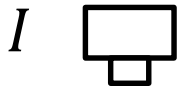
$$\mathbf{l} \in \mathcal{S}^2 \subset \mathbb{R}^3, \|\mathbf{l}\|_2 = 1$$

$$\mathbf{l} = \begin{bmatrix} l_x \\ l_y \\ l_z \end{bmatrix}$$



# Lambertian image formation model

$$I \propto e \rho \mathbf{l}^T \mathbf{n} = e \rho [l_x \quad l_y \quad l_z] \begin{bmatrix} n_x \\ n_y \\ n_z \end{bmatrix}$$



$I \in \mathbb{R}_+$ : Measured intensity for a pixel  
 $e \in \mathbb{R}_+$ : Light source intensity (or radiant intensity)  
 $\rho \in \mathbb{R}_+$ : Lambertian diffuse reflectance (or albedo)  
 $\mathbf{l}$ : 3-D unit light source vector  
 $\mathbf{n}$ : 3-D unit surface normal vector

# Simplified Lambertian image formation model

$$I \propto e\rho l^T \mathbf{n} = e\rho [l_x \quad l_y \quad l_z] \begin{bmatrix} n_x \\ n_y \\ n_z \end{bmatrix}$$



$$I = \rho l^T \mathbf{n}$$

# Photometric stereo

[Woodham 80]

Assuming  $\rho = 1$

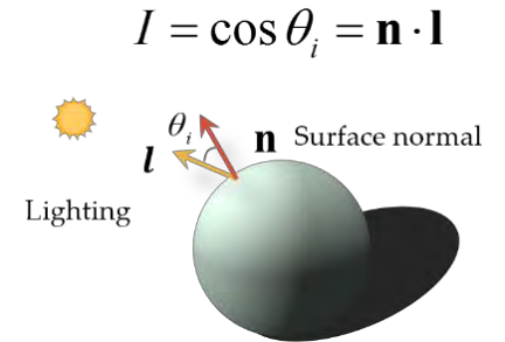


  $j$ -th image under  
 $j$ -th lightings  $l_j$ ,  
In total  $f$  images

For a pixel with  
normal direction  $\mathbf{n}$



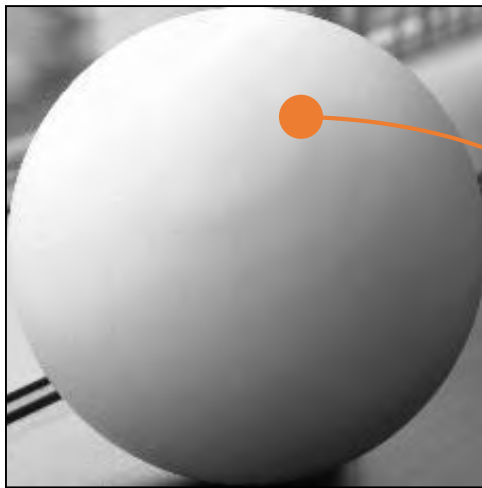
$$\begin{cases} I_1 = \mathbf{n} \cdot \mathbf{l}_1 \\ I_2 = \mathbf{n} \cdot \mathbf{l}_2 \\ \dots \\ I_f = \mathbf{n} \cdot \mathbf{l}_f \end{cases}$$



$$[I_1, I_2, \dots, I_f] = [n_x, n_y, n_z] \begin{bmatrix} l_{1x} & l_{2x} & \dots & l_{fx} \\ l_{1y} & l_{2y} & \dots & l_{fy} \\ l_{1z} & l_{2z} & \dots & l_{fz} \end{bmatrix}$$

# Photometric stereo

Matrix form  $I = NL$



$p$

$I$

$f$

$\left[ \begin{array}{c} \\ \\ \\ \end{array} \right]$

$=$

$p$

$\left[ \begin{array}{c} \\ \\ \\ \end{array} \right]$

$N$

$f$

$L$

$\left[ \begin{array}{c} \\ \\ \\ \end{array} \right]$

$\left[ \begin{array}{c} \\ \\ \\ \end{array} \right]$

$3$

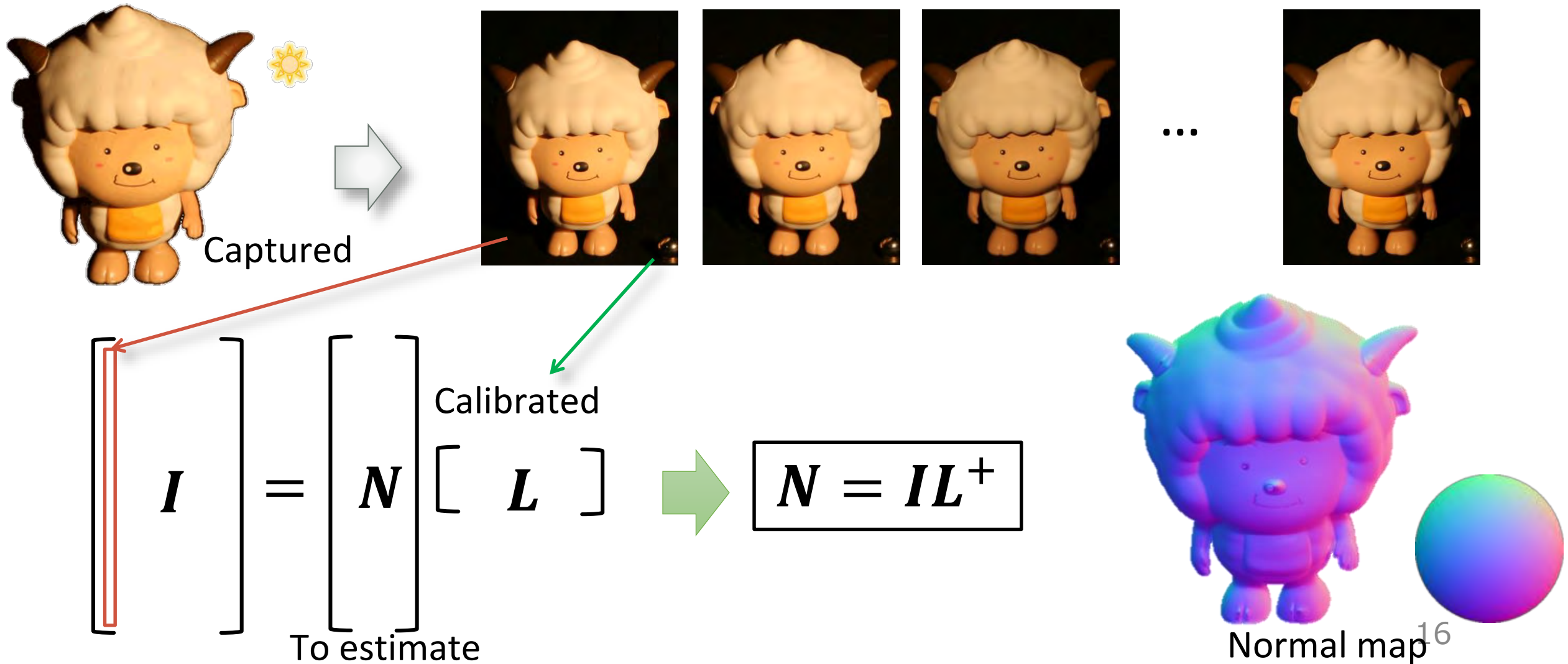
$p$ : Number of pixels  
 $f$ : Number of images



Least squares solution :

$$N = IL^+$$

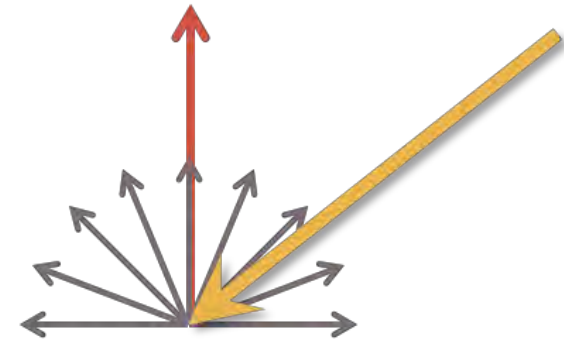
# Photometric stereo: An example



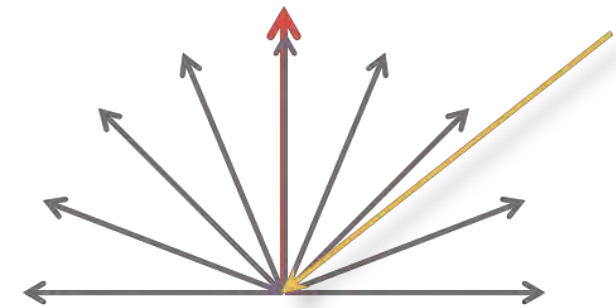


# Diffuse albedo

- We have ignored diffuse albedo so far
  - $I = NL$
- Normalizing the surface normal  $\mathbf{n}$  to 1, we obtain diffuse albedo (magnitude of  $\mathbf{n}$ )
  - $\rho = |\mathbf{n}|$
- Diffuse albedo is a relative value



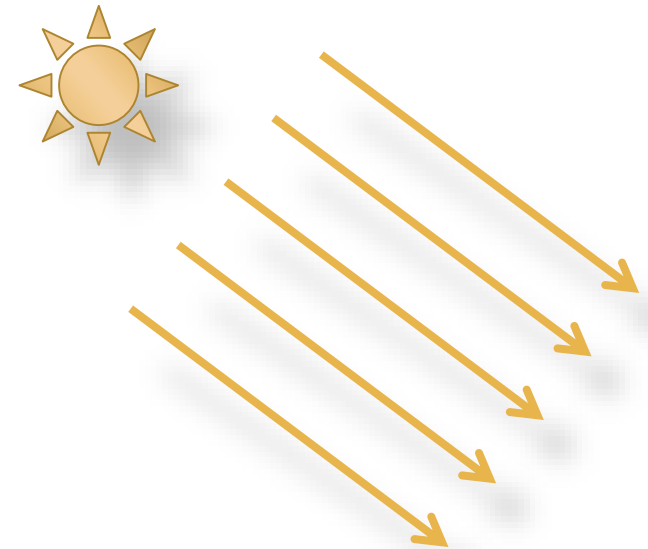
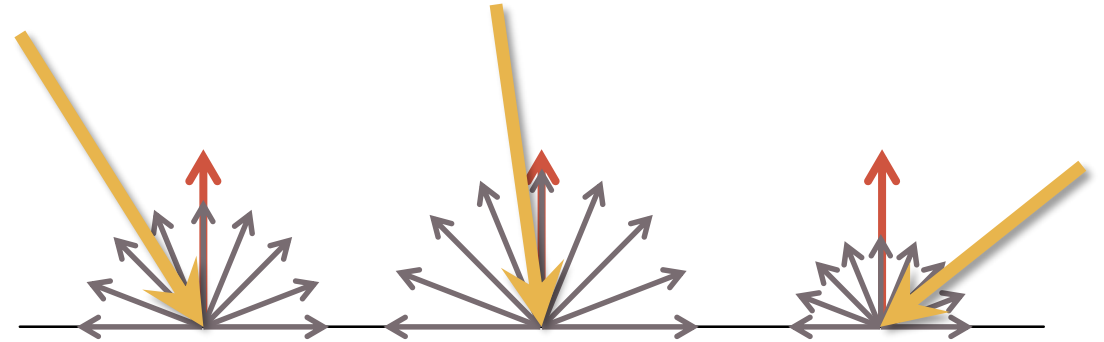
Low reflectance  
High light-source intensity



High reflectance  
Low light-source intensity

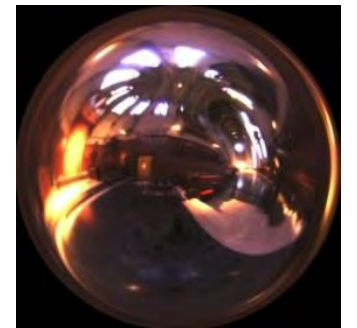
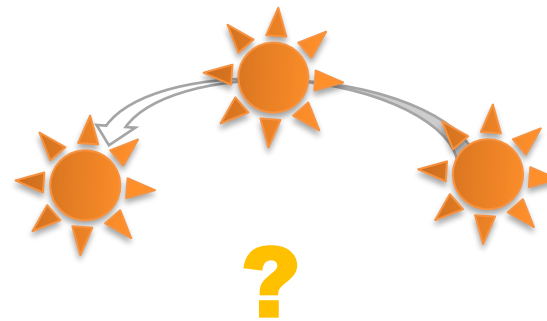
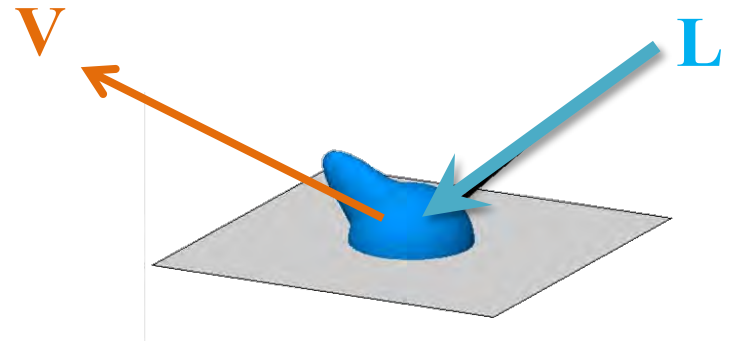
# So far, limited to...

- Lambertian reflectance
- Known, distant lighting



# Generalization of photometric stereo

- ~~Lambertian reflectance~~  
Outliers beyond Lambertian  
General BRDF
- ~~Known, distant lighting~~  
Unknown distant lighting  
Unknown general lighting



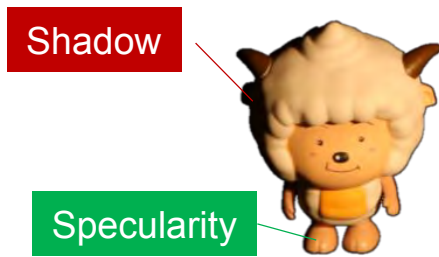
# Generalization of photometric stereo

General-1: Uncalibrated



[CVPR 10]

General-2: Robust



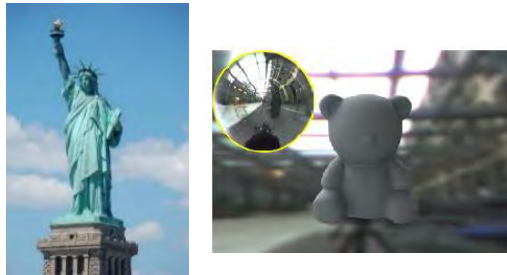
[ACCV 10]

General-3: General material



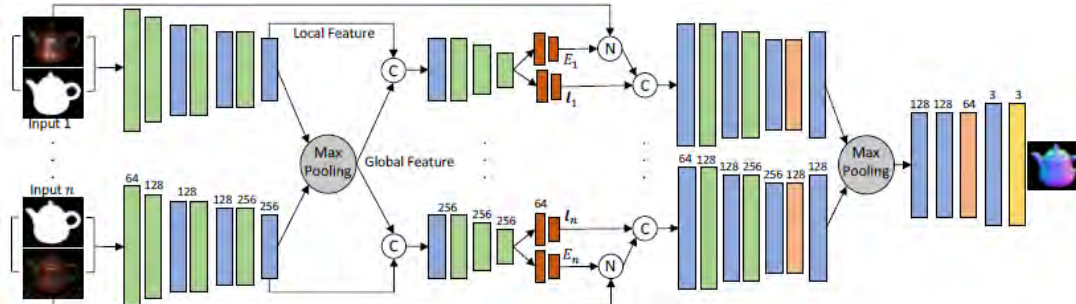
[CVPR 12, ECCV 12, TPAMI 14, ICCV 17, TIP 19, TPAMI19]

General-4: General lighting



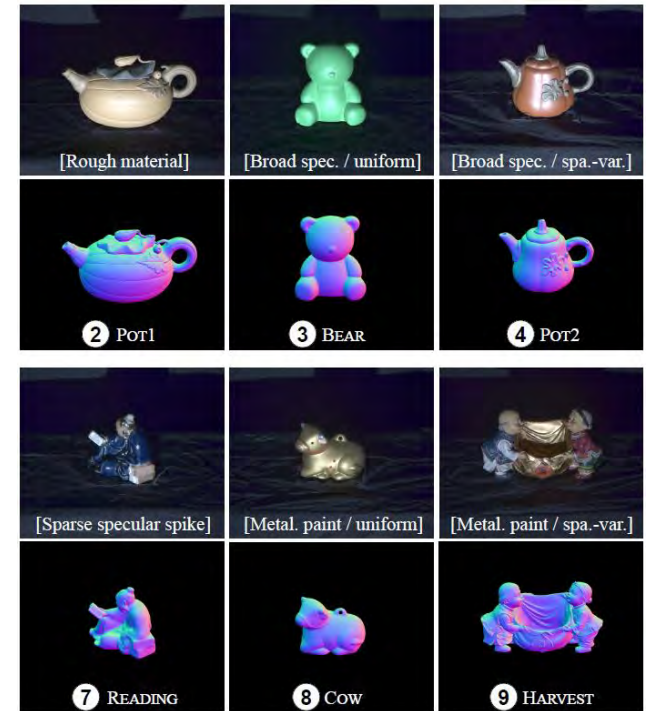
[3DV 14, CVPR 18]

General-5: Uncalibrated + general material



[CVPR 19, ICCV 19]

Benchmark dataset

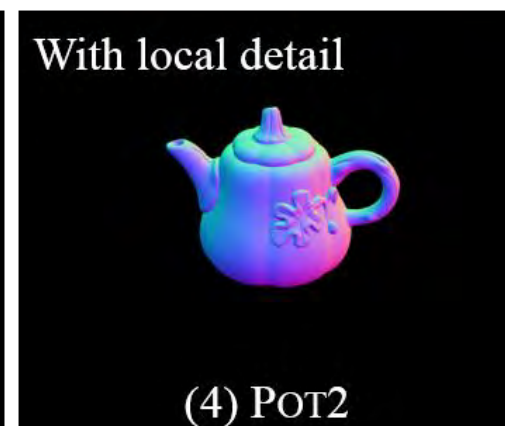
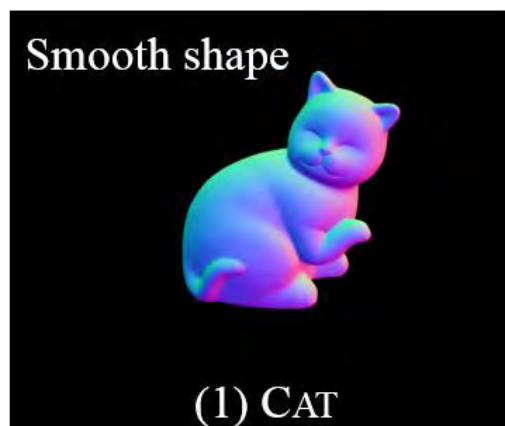
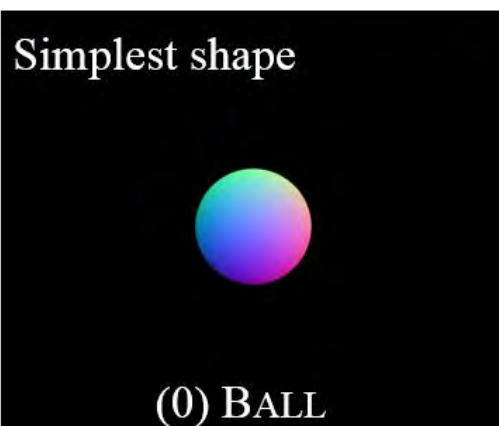


[CVPR 16, TPAMI19]

# Benchmark Datasets and Evaluation

# “DiLiGenT” photometric stereo datasets

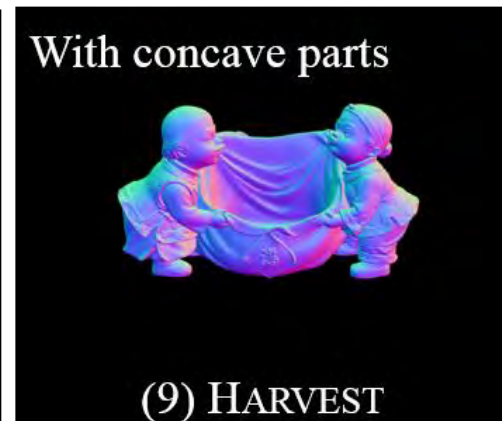
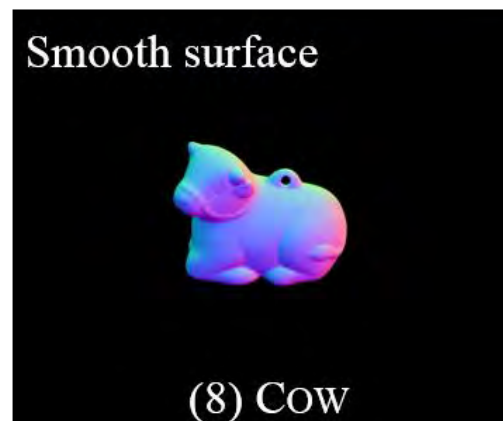
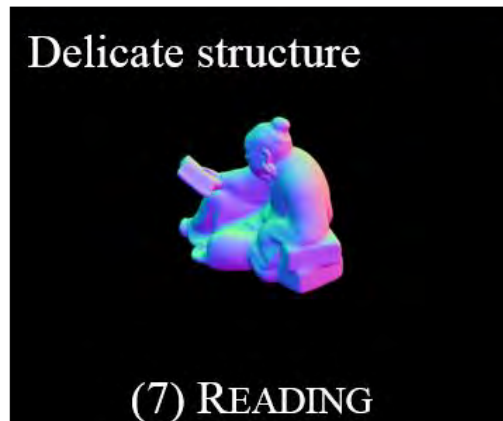
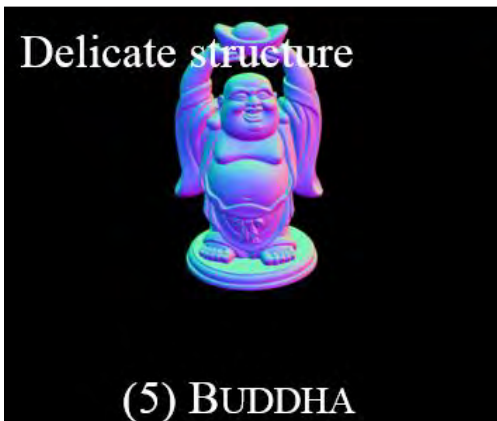
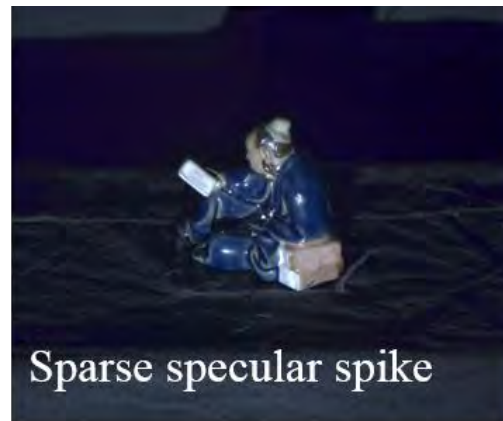
[Shi 16, 19] <https://sites.google.com/site/photometricstereodata>



Directional Lighting, General reflectance, with ground “Truth” shape 22

# “DiLiGenT” photometric stereo datasets

[Shi 16, 19] <https://sites.google.com/site/photometricstereodata>



Directional Lighting, General reflectance, with ground “Truth” shape 23

# Data capture

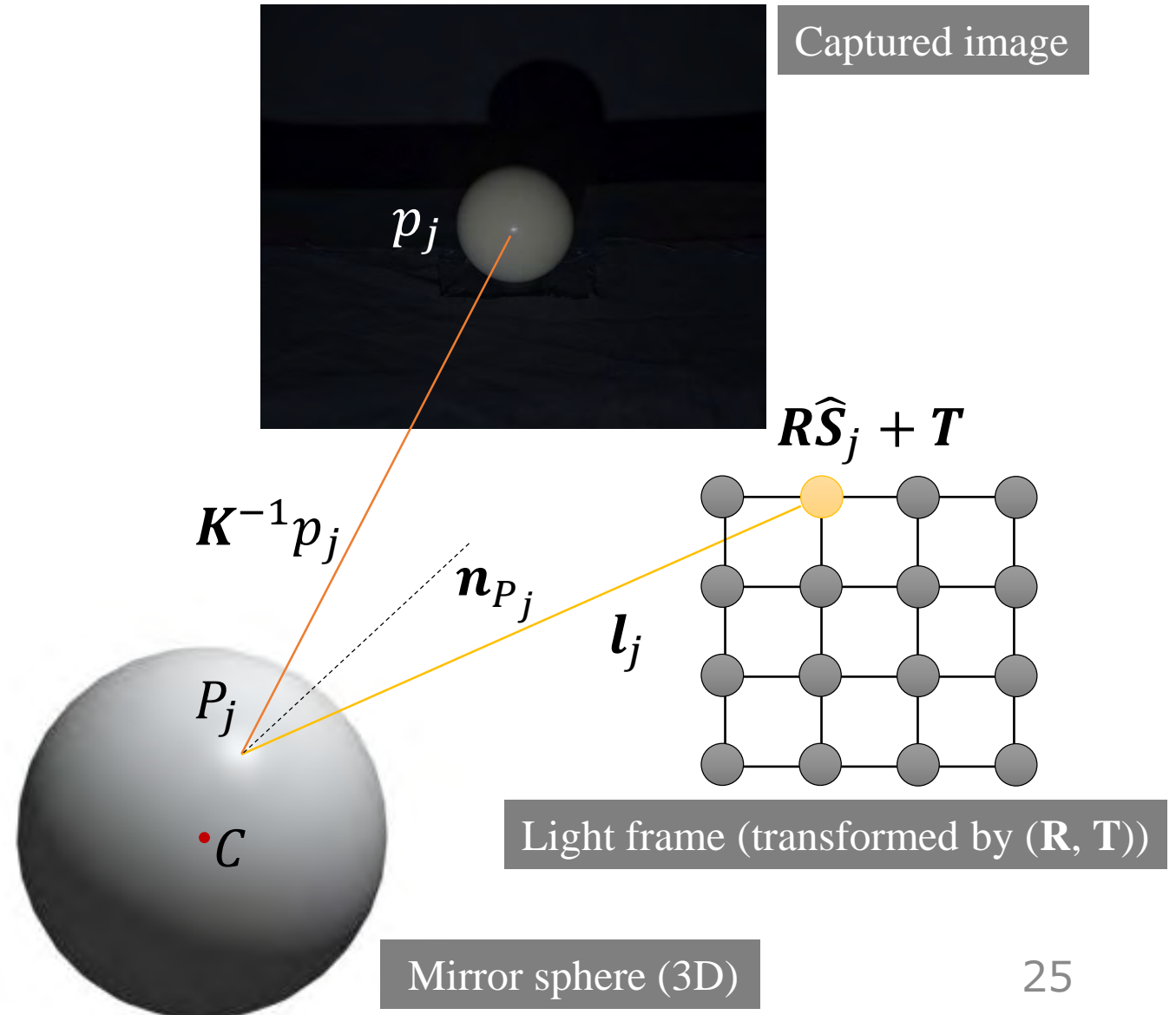
- Point Grey Grasshopper + 50mm lens
- Resolution: 2448 x 2048
- Object size: 20cm
- Object to camera distance: 1.5m
- 96 white LED in an 8 x 12 grid





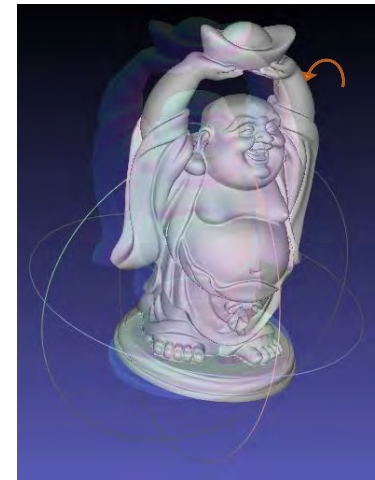
# Lighting calibration

- Intensity
  - Macbeth white balance board
- Direction
  - From 3D positions of LED bulbs for higher accuracy



# “Ground truth” shapes

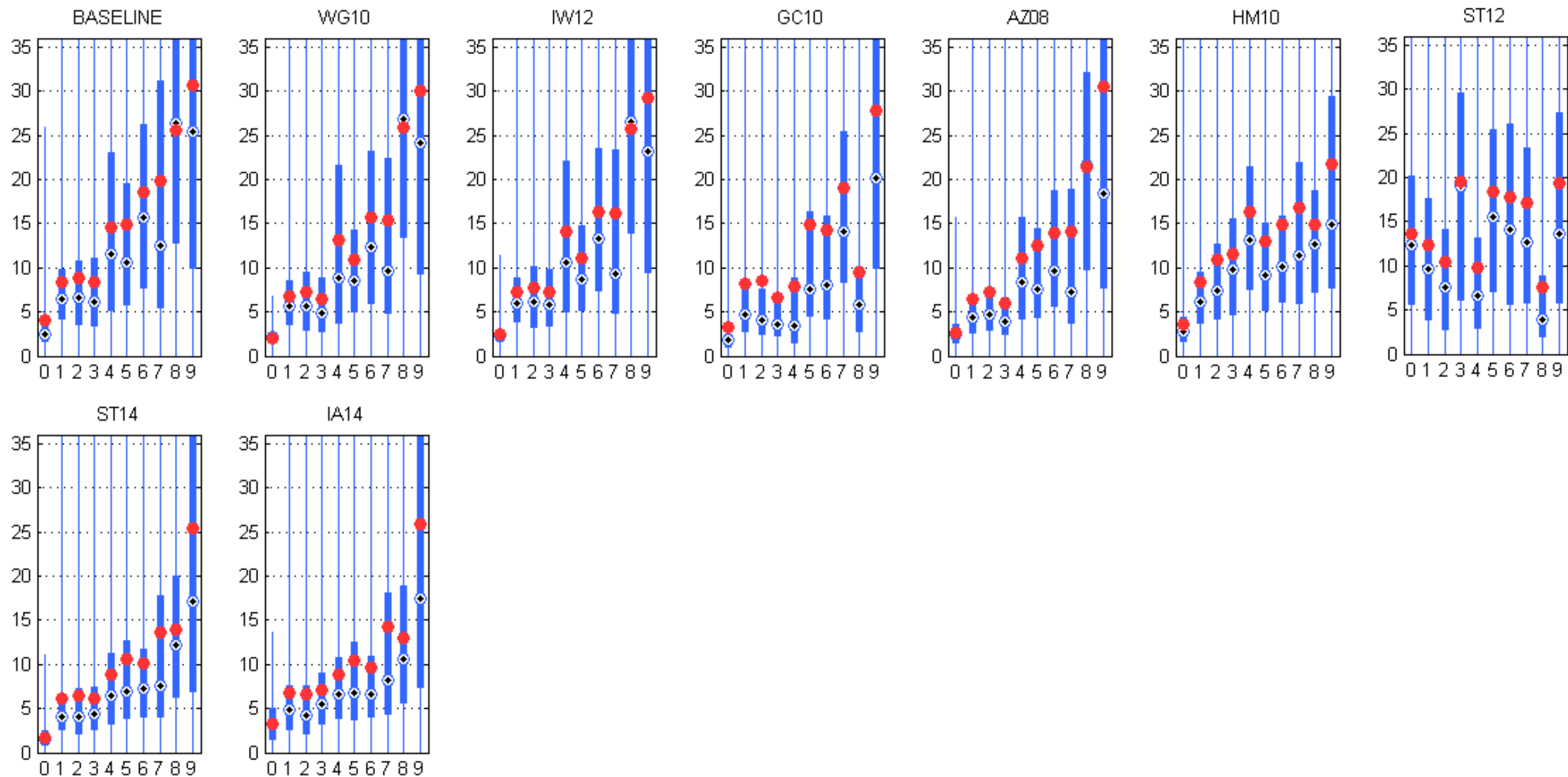
- 3D shape
  - Scanner: Rexcan CS+ (res. 0.01mm)
  - Registration: EzScan 7
  - Hole filling: Autodesk Meshmixer 2.8
- Shape-image registration
  - Mutual information method [Corsini 09]
  - Meshlab + manual adjustment
- Evaluation criteria
  - Statistics of angular error (degree)
    - Mean, median, min, max, 1<sup>st</sup> quartile, 3<sup>rd</sup> quartile



# Evaluation for non-Lambertian methods

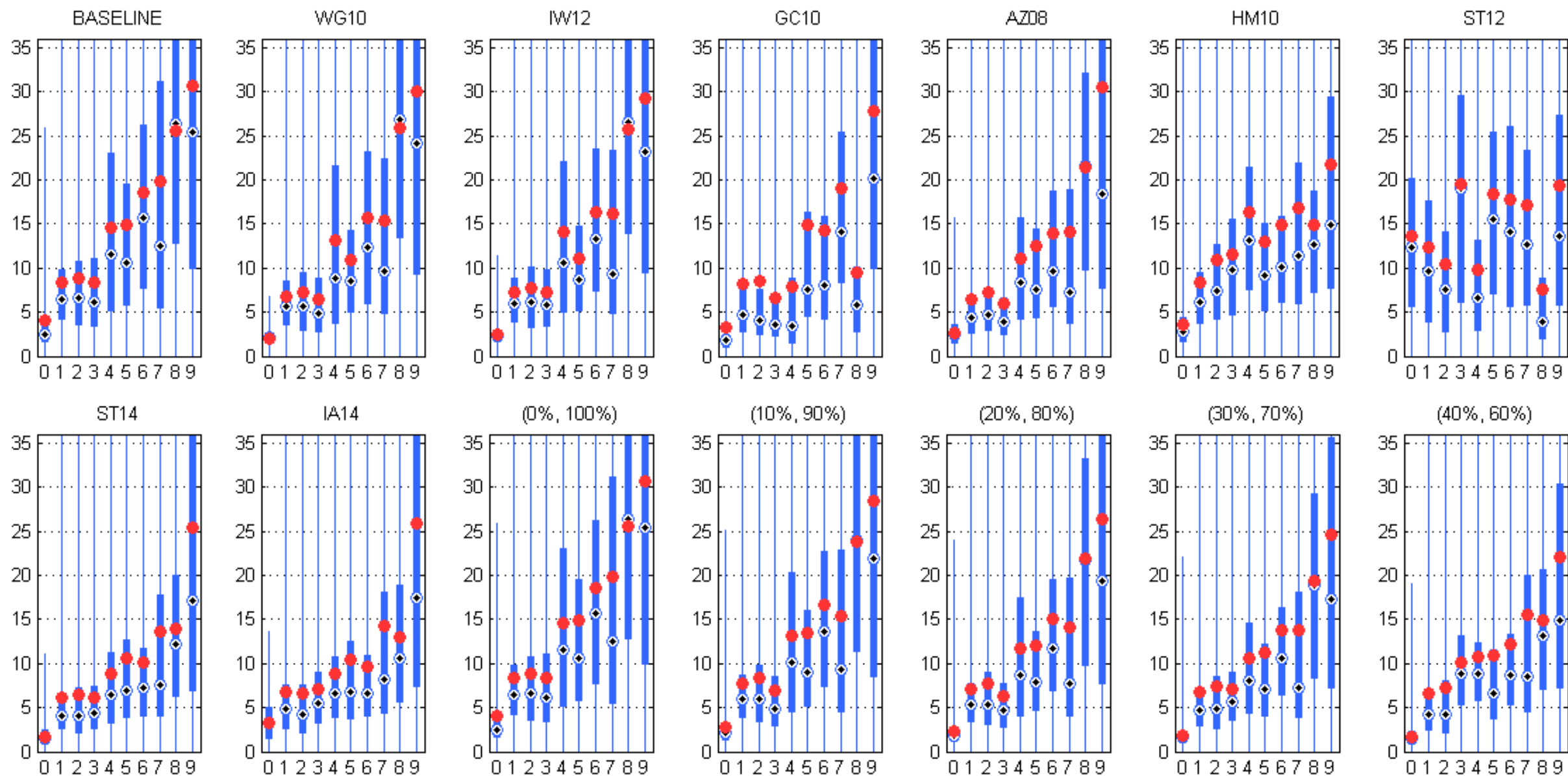
Solve  $\mathbf{N}$  from  $\mathbf{I} = \max\{\boldsymbol{\rho}(\mathbf{n}, \mathbf{l}) \circ (\mathbf{N}^\top \mathbf{L}), 0\}$  by using different assumptions and constraints on  $\boldsymbol{\rho}(\mathbf{n}, \mathbf{l})$   
 Notations:  $\mathbf{h} = (\mathbf{l} + \mathbf{v})/\|\mathbf{l} + \mathbf{v}\|$ ,  $\theta_h = \langle \mathbf{n}, \mathbf{h} \rangle = \arccos(\mathbf{n}^\top \mathbf{h})$ ,  $\theta_d = \langle \mathbf{l}, \mathbf{h} \rangle = \arccos(\mathbf{l}^\top \mathbf{h})$

BASELINE	$\boldsymbol{\rho}(\mathbf{n}, \mathbf{l}) \approx \mathbf{D}$ , where each row of $\mathbf{D}$ is a constant representing the albedo of a Lambertian surface
WG10	$\boldsymbol{\rho}(\mathbf{n}, \mathbf{l}) \approx \mathbf{D} + \mathbf{E}$ , where $\mathbf{E}$ is sparse and $\text{rank}(\mathbf{I})$ is minimized
IW12	$\boldsymbol{\rho}(\mathbf{n}, \mathbf{l}) \approx \mathbf{D} + \mathbf{E}$ , where $\mathbf{E}$ is sparse and $\text{rank}(\mathbf{I}) = 3$
GC10	$\boldsymbol{\rho}(\mathbf{n}, \mathbf{l}) \approx \sum_i \mathbf{w}_i \circ \rho_i(d_i, s_i, \alpha_i)$ , where $\rho_i(d_i, s_i, \alpha_i) = \frac{d_i}{\pi} + \frac{s_i}{4\pi\alpha_i^2\sqrt{(\mathbf{n}^\top \mathbf{l})(\mathbf{n}^\top \mathbf{v})}} \exp\left(\frac{(\mathbf{l} - \mathbf{l}/\mathbf{n}^\top \mathbf{h})}{\alpha_i^2}\right)$
AZ08	$\boldsymbol{\rho}(\mathbf{n}, \mathbf{l})$ is isotropic and depends only on $(\theta_h, \theta_d)$
ST12	$\boldsymbol{\rho}(\mathbf{n}, \mathbf{l})$ is isotropic, depends only on $\theta_h$ , and is monotonic about $\mathbf{n}^\top \mathbf{h}$
HM10	$\boldsymbol{\rho}(\mathbf{n}, \mathbf{l})$ is isotropic, monotonic about $\mathbf{n}^\top \mathbf{l}$ , and $\boldsymbol{\rho}(\mathbf{n}, \mathbf{l}) = 0$ for $\mathbf{n}^\top \mathbf{l} \leq 0$
ST14	The low-frequency part of $\boldsymbol{\rho}(\mathbf{n}, \mathbf{l})$ is a bi-polynomial $A(\cos(\theta_h))B(\cos(\theta_d))$ , where $A$ and $B$ are polynomials
IA14	$\boldsymbol{\rho}(\mathbf{n}, \mathbf{l}) \approx \sum_i \rho_i(\mathbf{n}^\top \alpha_i)$ , where $\alpha_i = (p_i \mathbf{l} + q_i \mathbf{v})/\ p_i \mathbf{l} + q_i \mathbf{v}\ $ , $p_i, q_i$ are nonnegative unknown values



# Evaluation for non-Lambertian methods

- Sort each intensity profile in ascending order
- Only use the data ranked between  $(T_{low}, T_{high})$



# Evaluation for uncalibrated methods

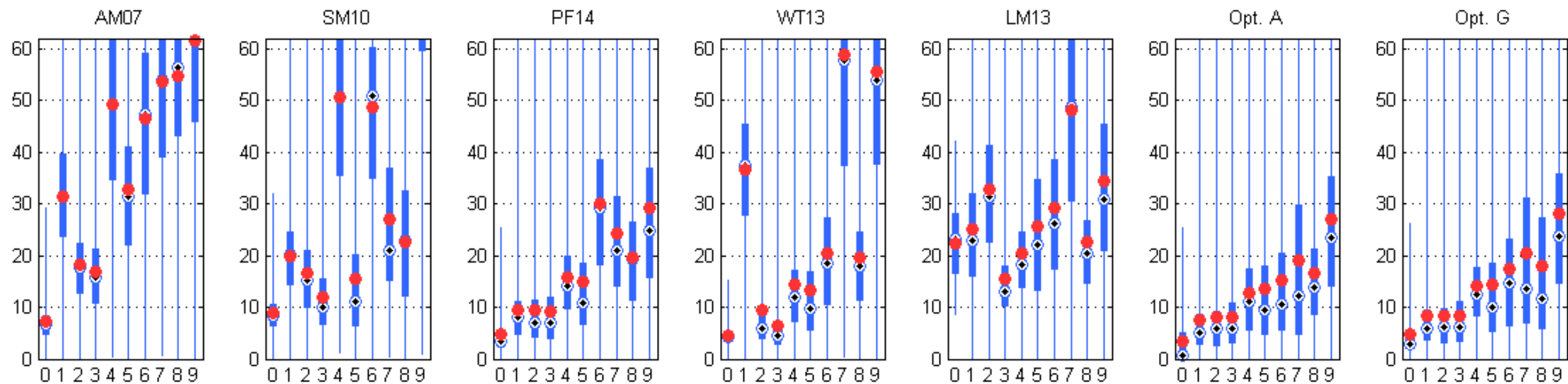
Solve  $\mathbf{N}$  from  $\mathbf{I} = \max\{\rho(\mathbf{n}, \mathbf{l}) \circ (\mathbf{N}^\top \mathbf{L}), 0\}$  when  $\mathbf{L}$  is unknown

For Lambertian objects,  $\mathbf{I} = \max\{\mathbf{D} \circ (\mathbf{N}^\top \mathbf{L}), 0\} = \mathbf{S}^\top \mathbf{L} = \tilde{\mathbf{S}}^\top \mathbf{A}^\top \mathbf{A}^{-1} \tilde{\mathbf{L}} = \hat{\mathbf{S}}^\top \mathbf{G}^\top \mathbf{G}^{-1} \hat{\mathbf{L}}$

AM07	$\mathbf{D}$ has only a few different albedos, <i>i.e.</i> , the rows of $\mathbf{S}$ have only a few different lengths
SM10	Several surface points have equal albedo, <i>i.e.</i> , several rows of $\mathbf{S}$ having equal length are identified
PF14	Several points with locally maximum intensity on a Lambertian surface, <i>i.e.</i> , points with $\mathbf{n} = \mathbf{l}$ are identified
WT13	$\rho(\mathbf{n}, \mathbf{l}) \approx \mathbf{D} + \rho_s(\theta_h, \theta_d)$ , <i>i.e.</i> , the specular reflection depends only on $\{\theta_h, \theta_d\}$

---

<b>Opt. A</b>	Fitting an optimal linear transform after factorization (pseudo-normal with $3 \times 3$ ambiguity)
<b>Opt. G</b>	Fitting an optimal GBR transform after applying integrability constraint (pseudo-normal up to GBR)





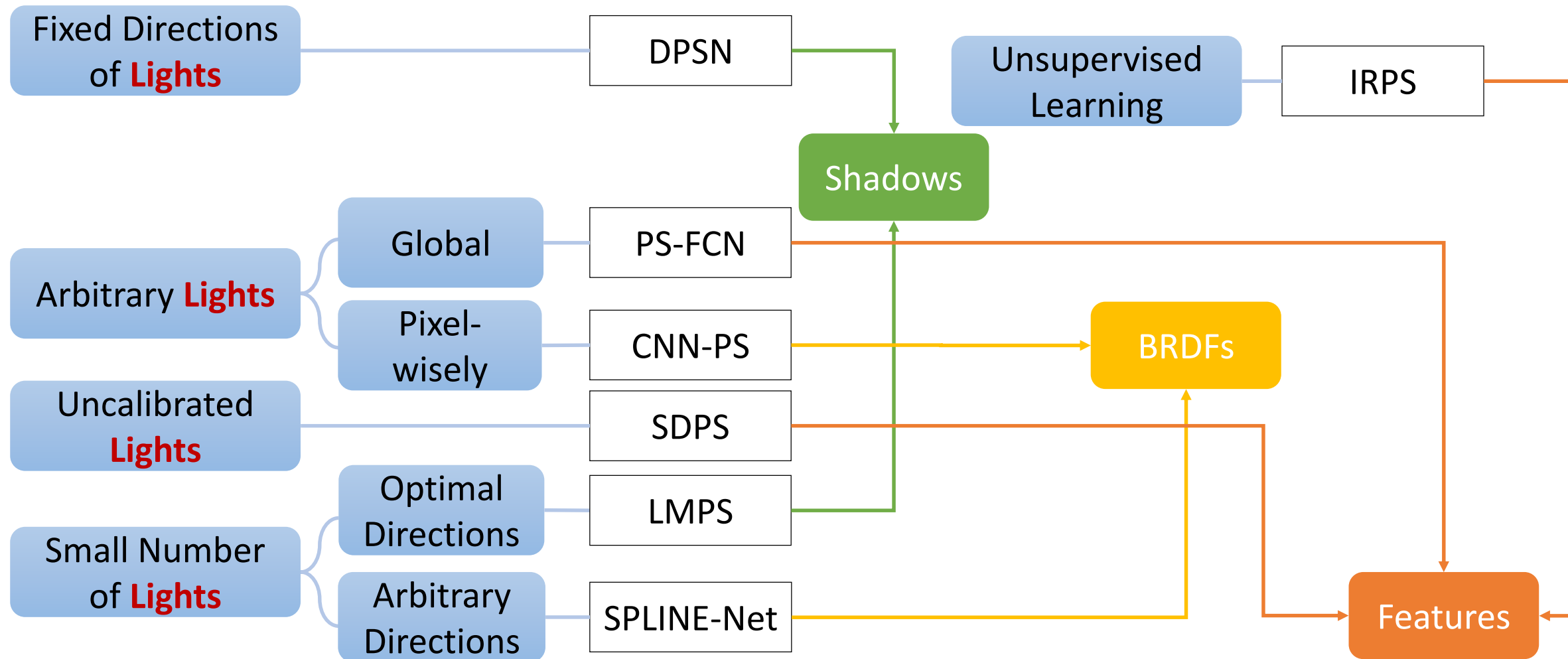
			BALL	CAT	POT1	BEAR	POT2	BUDDHA	GOBLET	READING	COW	HARVEST	Average
Main dataset	Non-Lambertian	BASELINE	4.10	8.41	8.89	8.39	14.65	14.92	18.50	19.80	25.60	30.62	15.39
		WG10	2.06	6.73	7.18	6.50	13.12	10.91	15.70	15.39	25.89	30.01	13.35
		IW14	2.54	7.21	7.74	7.32	14.09	11.11	16.25	16.17	25.70	29.26	13.74
		GC10	3.21	8.22	8.53	6.62	7.90	14.85	14.22	19.07	9.55	27.84	12.00
		AZ08	2.71	6.53	7.23	5.96	11.03	12.54	13.93	14.17	21.48	30.50	12.61
		HM10	3.55	8.40	10.85	11.48	16.37	13.05	14.89	16.82	14.95	21.79	13.22
		ST12	13.58	12.34	10.37	19.44	9.84	18.37	17.80	17.17	7.62	19.30	14.58
		ST14	1.74	6.12	6.51	6.12	8.78	10.60	10.09	13.63	13.93	25.44	10.30
		IA14	3.34	6.74	6.64	7.11	8.77	10.47	9.71	14.19	13.05	25.95	10.60
	Uncalibrated	AM07	7.27	31.45	18.37	16.81	49.16	32.81	46.54	53.65	54.72	61.70	37.25
		SM10	8.90	19.84	16.68	11.98	50.68	15.54	48.79	26.93	22.73	73.86	29.59
		PF14	4.77	9.54	9.51	9.07	15.90	14.92	29.93	24.18	19.53	29.21	16.66
		WT13	4.39	36.55	9.39	6.42	14.52	13.19	20.57	58.96	19.75	55.51	23.92
		Opt. A	3.37	7.50	8.06	8.13	12.80	13.64	15.12	18.94	16.72	27.14	13.14
		Opt. G	4.72	8.27	8.49	8.32	14.24	14.29	17.30	20.36	17.98	28.05	14.20
LM13		22.43	25.01	32.82	15.44	20.57	25.76	29.16	48.16	22.53	34.45	27.63	

# Photometric Stereo Meets Deep Learning

# Photometric stereo + Deep learning

- [ICCV 17 Workshop]
  - Deep Photometric Stereo Network (DPSN)
- [ICML 18]
  - Neural Inverse Rendering for General Reflectance Photometric Stereo (IRPS)
- [ECCV 18]
  - PS-FCN: A Flexible Learning Framework for Photometric Stereo
- [ECCV 18]
  - CNN-PS: CNN-based Photometric Stereo for General Non-Convex Surfaces
- [CVPR 19]
  - Self-calibrating Deep Photometric Stereo Networks (SDPS)
- [CVPR 19]
  - Learning to Minify Photometric Stereo (LMPS)
- [ICCV 19]
  - SPLINE-Net: Sparse Photometric Stereo through Lighting Interpolation and Normal Estimation Networks

# Photometric stereo + Deep learning



# [ICCV 17 Workshop]

## Deep Photometric Stereo Network

### Deep Photometric Stereo Network

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#### Abstract

*This paper presents a photometric stereo method based on deep learning. One of the major difficulties in photometric stereo is designing an appropriate reflectance model that is both capable of representing real-world reflectances and computationally tractable in terms of deriving surface normal. Unlike previous photometric stereo methods that rely on a simplified parametric image formation model, such as the Lambert's model, the proposed method*

it is known difficult to directly work with general non-parametric BRDFs in the context of photometric stereo. To ease the problem, there have been studies to use parametric representations to approximate BRDFs. However, so far, known parametric models have been only accurate for a limited class of materials, and the solution methods suffer from unstable optimization, which prohibits obtaining accurate estimates. Thus, it is needed to develop a photometric stereo method that is both computationally tractable and capable of handling diverse BRDFs.

# Research background

## Photometric Stereo

$f$  : reflectance model  
 $m$  : measurement vector  
 $L$  : light source direction  
 $n$  : normal vector

Measurements

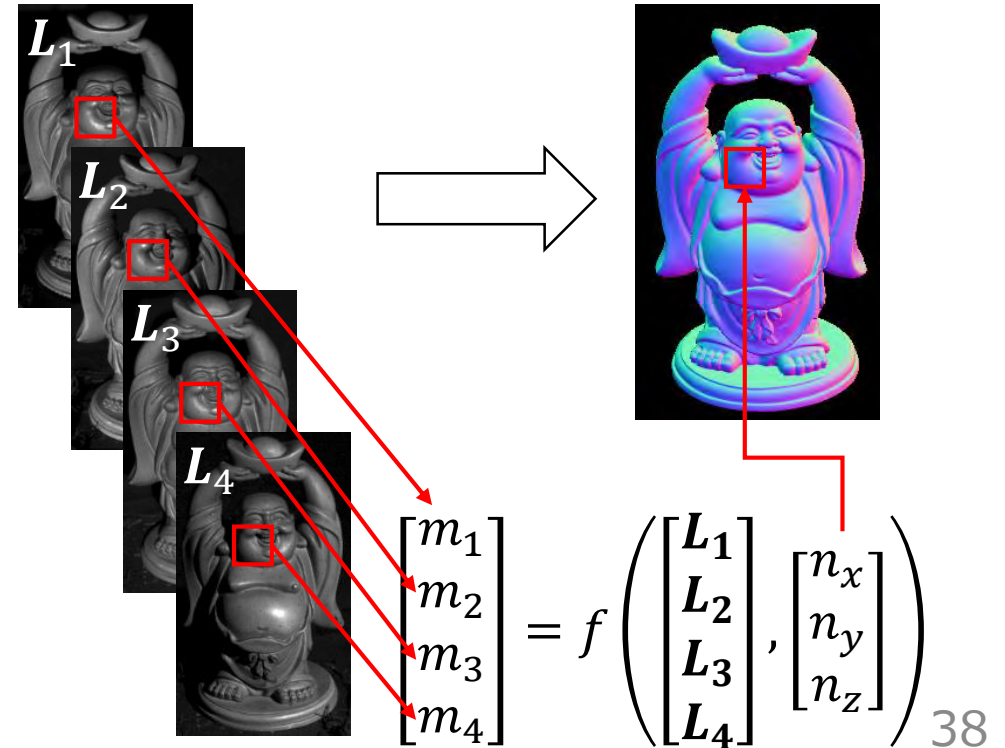


Normal map



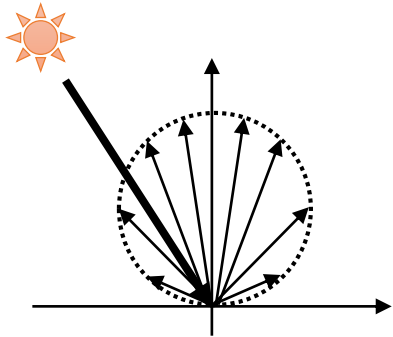
## Image formation

$$m = f(L, n)$$



# Motivations

## Parametric reflectance model



Lambertian model  
(Ideal diffuse reflection)

only accurate for a limited class of materials



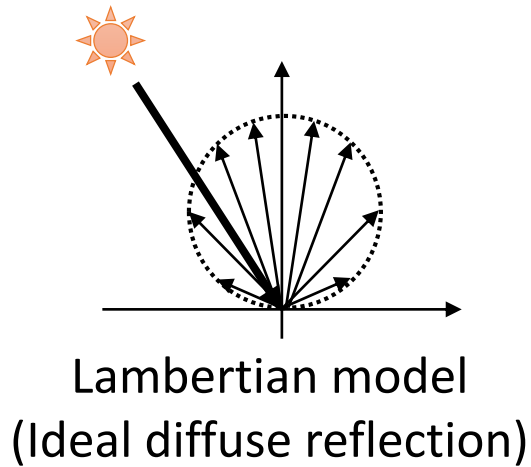
Metal



rough surface

# Motivations

## Parametric reflectance model



only accurate for a limited class of materials

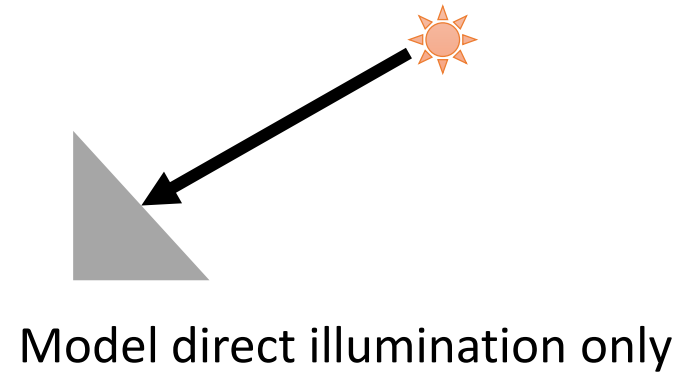


Metal

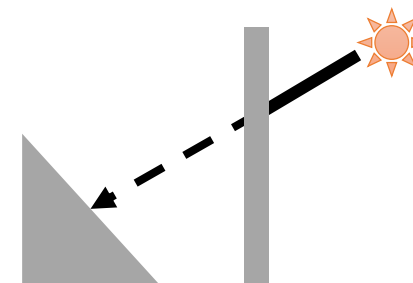


rough surface

## Local illumination model



Global illumination effects cannot be modeled



Cast shadow



# Motivations

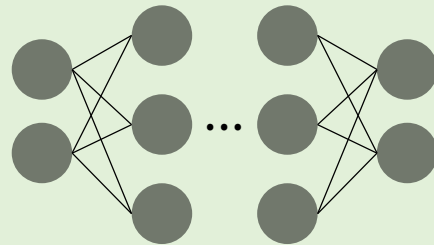
Para

- Model the mapping from measurements to surface normal directly using Deep Neural Network (DNN)
- DNN can express more flexible reflection phenomenon compared to existing models designed based on physical phenomenon

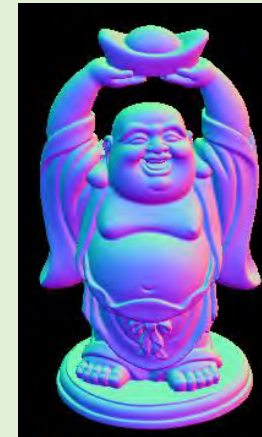
Measurements



Deep Neural Network



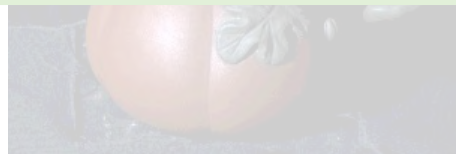
Normal map



only acc



Metal



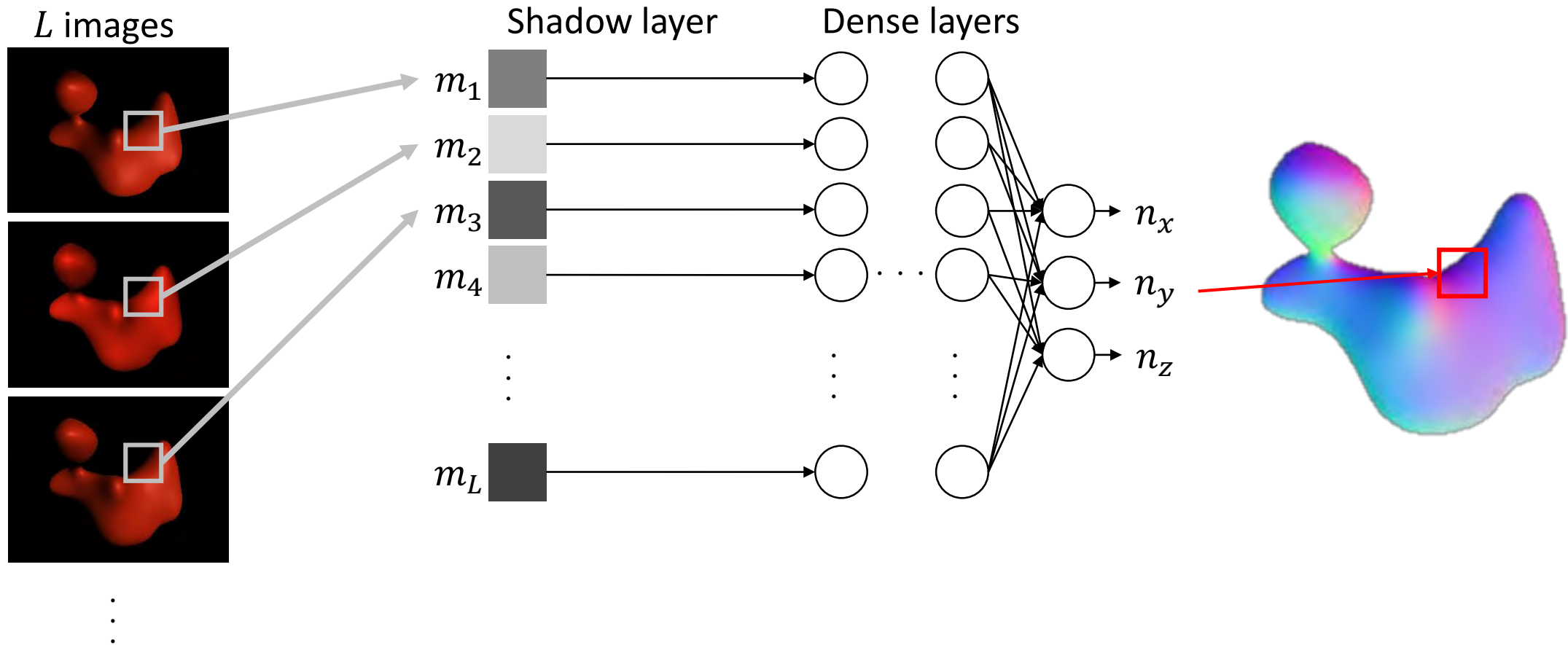
rough surface

Global illumination effects cannot be modeled

# Proposed method

## Reflectance model with Deep Neural Network

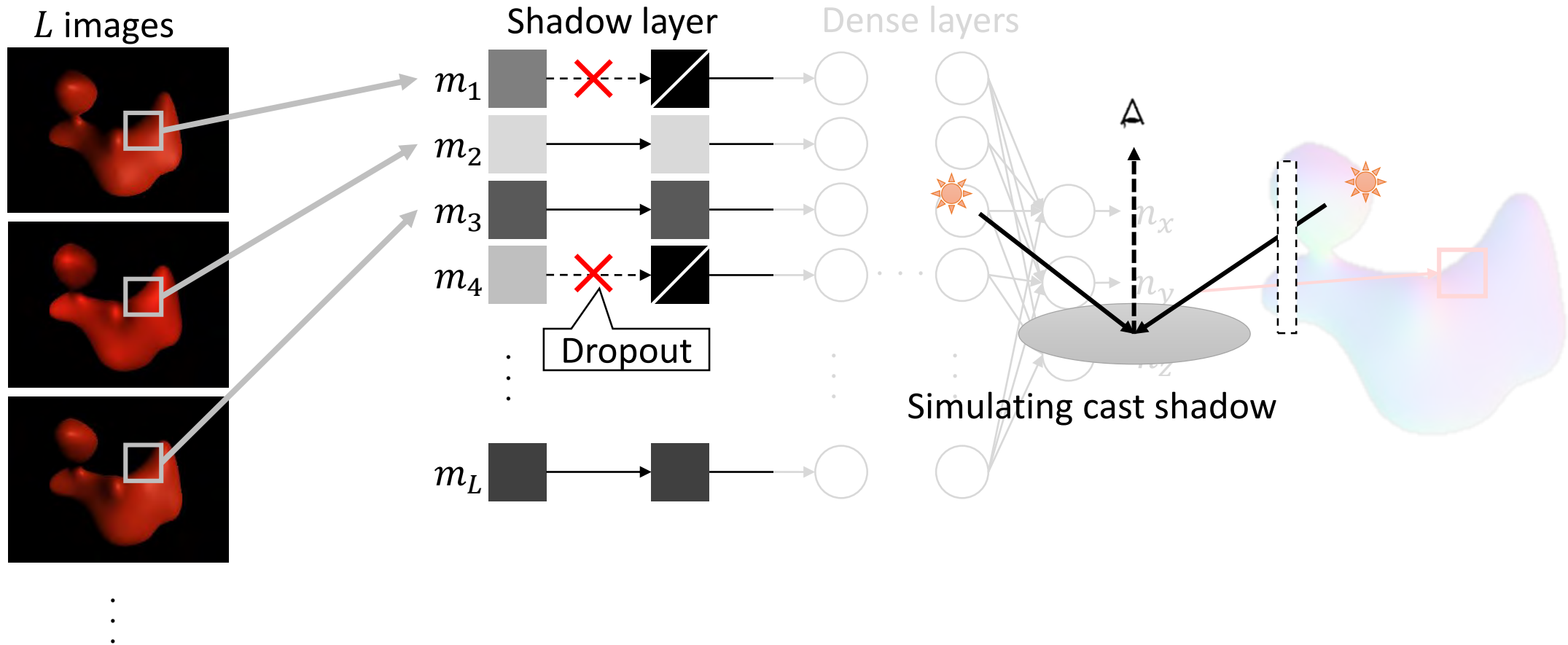
- mappings from measurement ( $\mathbf{m} = [m_1, m_2, \dots, m_L]^T$ ) to surface normal ( $\mathbf{n} = [n_x, n_y, n_z]^T$ )



# Proposed method

## Reflectance model with Deep Neural Network

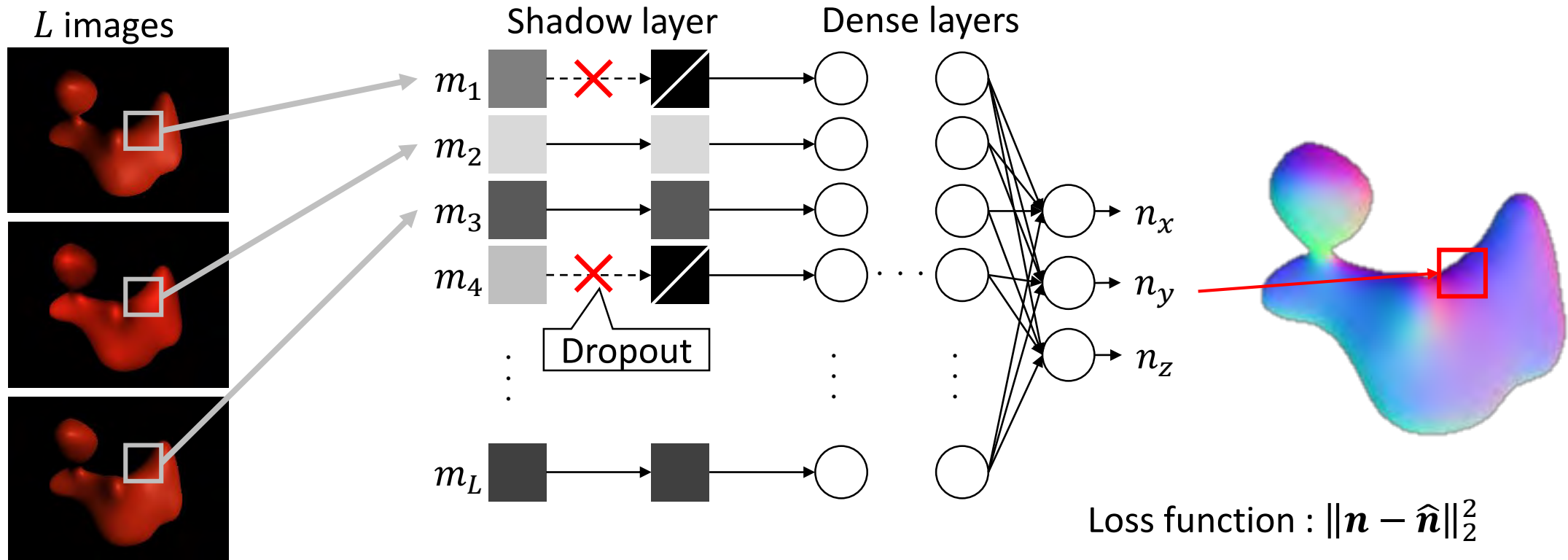
- mappings from measurement ( $\mathbf{m} = [m_1, m_2, \dots, m_L]^T$ ) to surface normal ( $\mathbf{n} = [n_x, n_y, n_z]^T$ )



# Proposed method

## Reflectance model with Deep Neural Network

- mappings from measurement ( $\mathbf{m} = [m_1, m_2, \dots, m_L]^T$ ) to surface normal ( $\mathbf{n} = [n_x, n_y, n_z]^T$ )



How to prepare training data

# Training data

## Rendering synthetic images

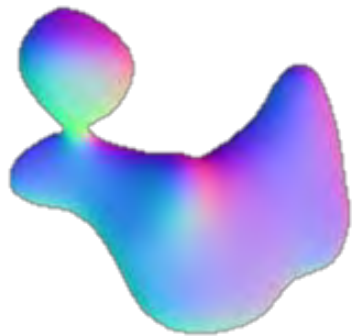
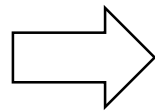
- Rendering with database (MERL BRDF database), which stores reflectance functions of 100 different real-world materials [Matusik 03]



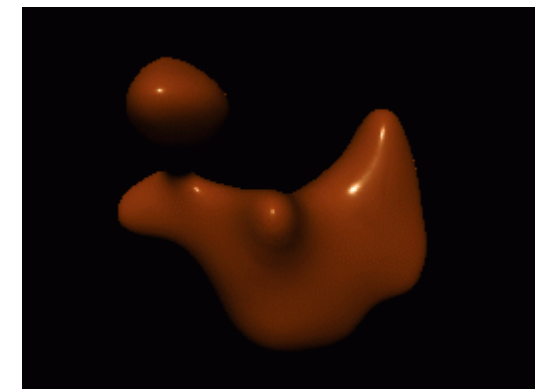
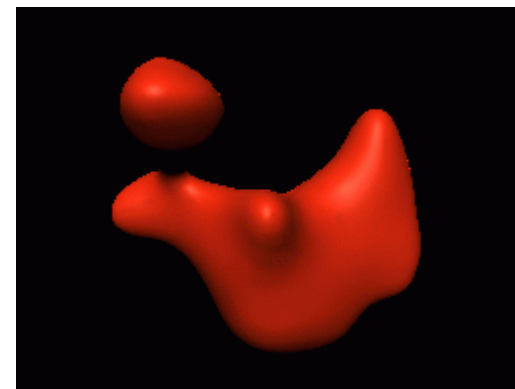
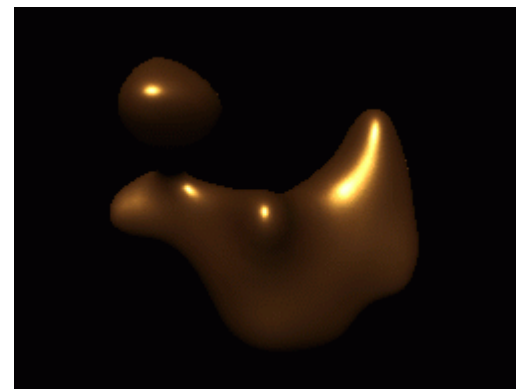
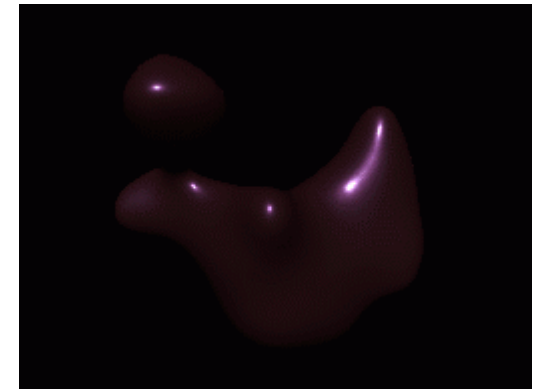
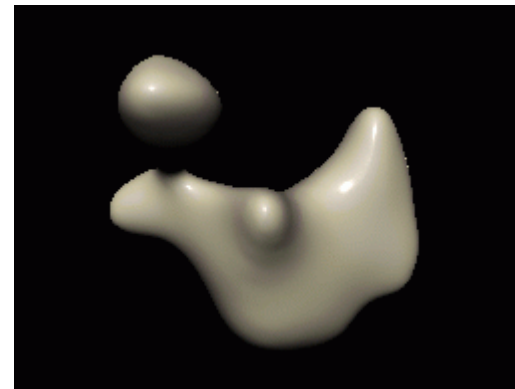
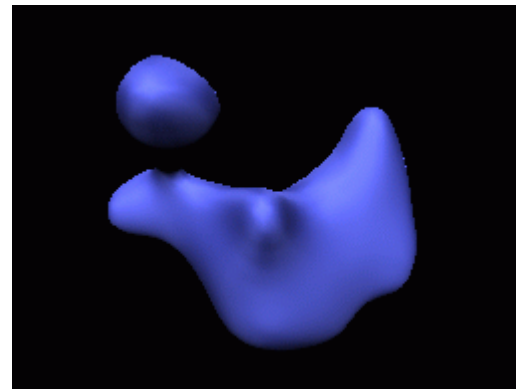
# Training data

## Rendering synthetic images

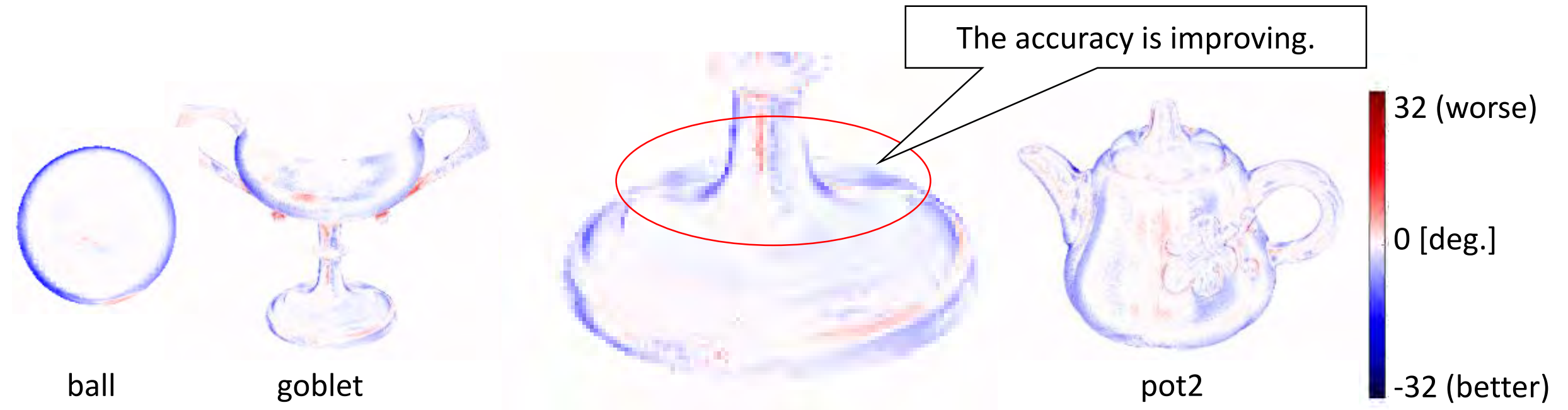
- Rendering with database (MERL BRDF database), which stores reflectance functions of 100 different real-world materials [Matusik 03]



Given normal map



# Effectiveness of the shadow layer



The difference map of error map between “Proposed” and “Proposed W/ SL”

Blue pixels : The estimation accuracy is improved by shadow layer

Red pixels : The estimation accuracy is NOT improved by shadow layer

# Benchmark results using “DiLiGenT”



	ball	cat	pot1	bear	buddha	cow	goblet	harvest	pot2	reading	AVG.
Proposed	3.44	7.21	7.90	7.20	13.30	8.49	12.35	<b>16.81</b>	8.80	17.47	10.30
Proposed W/ SL	2.02	6.54	7.05	6.31	12.68	8.01	11.28	16.86	<b>7.86</b>	15.51	<b>9.41</b>
ST14 (Shi+, PAMI, 2014)	<b>1.74</b>	<b>6.12</b>	<b>6.51</b>	6.12	10.60	13.93	10.09	25.44	8.78	<b>13.63</b>	10.30
IA14 (Ikehata+, CVPR, 2014)	3.34	6.74	6.64	7.11	<b>10.47</b>	13.05	<b>9.71</b>	25.95	8.77	14.19	10.60
WG10 (Wu+, ACCV, 2010)	2.06	6.73	7.18	6.50	10.91	25.89	15.70	30.01	13.12	15.39	13.35
AZ08 (Alldrin+, CVPR, 2008)	2.71	6.53	7.23	<b>5.96</b>	12.54	21.48	13.93	30.50	11.03	14.17	12.61
HM10 (Higo+, CVPR, 2010)	3.55	8.40	10.85	11.48	13.05	14.95	14.89	21.79	16.37	16.82	13.22
IW12 (Ikehata+, CVPR, 2012)	2.54	7.21	7.74	7.32	11.11	25.70	16.25	29.26	14.09	16.17	13.74
ST12 (Shi+, ECCV, 2012)	13.58	12.34	10.37	19.44	18.37	<b>7.62</b>	17.80	19.30	9.84	17.17	14.58
GC10 (Goldman+, PAMI, 2010)	3.21	8.22	8.53	6.62	14.85	9.55	14.22	27.84	7.90	19.07	12.00
BASELINE (L2)	4.10	8.41	8.89	8.39	14.92	25.60	18.50	30.62	14.65	19.80	15.39



[ICML 18]

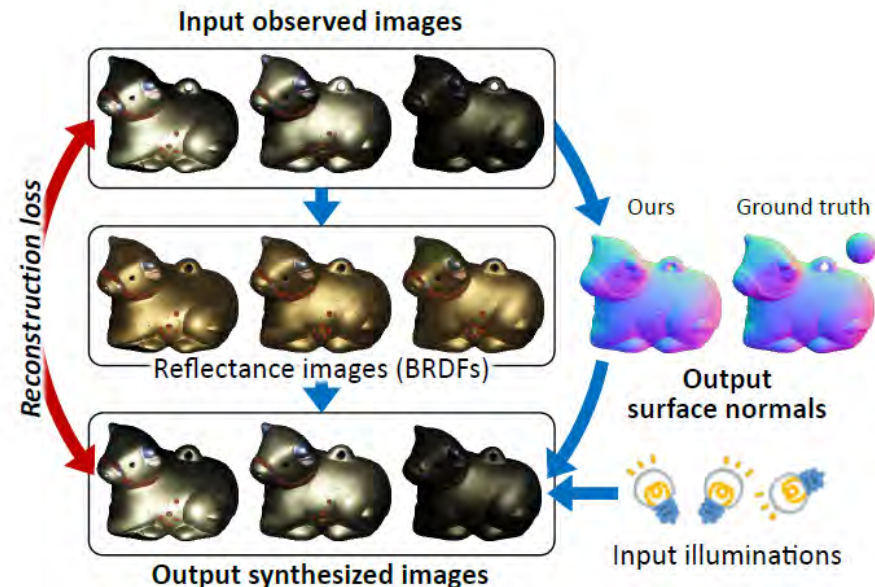
# Neural Inverse Rendering for General Reflectance Photometric Stereo

## Neural Inverse Rendering for General Reflectance Photometric Stereo

Tatsunori Tani<sup>1</sup> Takanori Maehara<sup>1</sup>

### Abstract

We present a novel convolutional neural network architecture for photometric stereo (Woodham, 1980), a problem of recovering 3D object surface normals from multiple images observed under varying illuminations. Despite its long history in computer vision, the problem still shows fundamental challenges for surfaces with unknown general reflectance properties (BRDFs). Leveraging deep neural networks to learn complicated reflectance models is promising, but studies in this direction are very limited due to difficulties in acquiring accurate ground truth for training and also

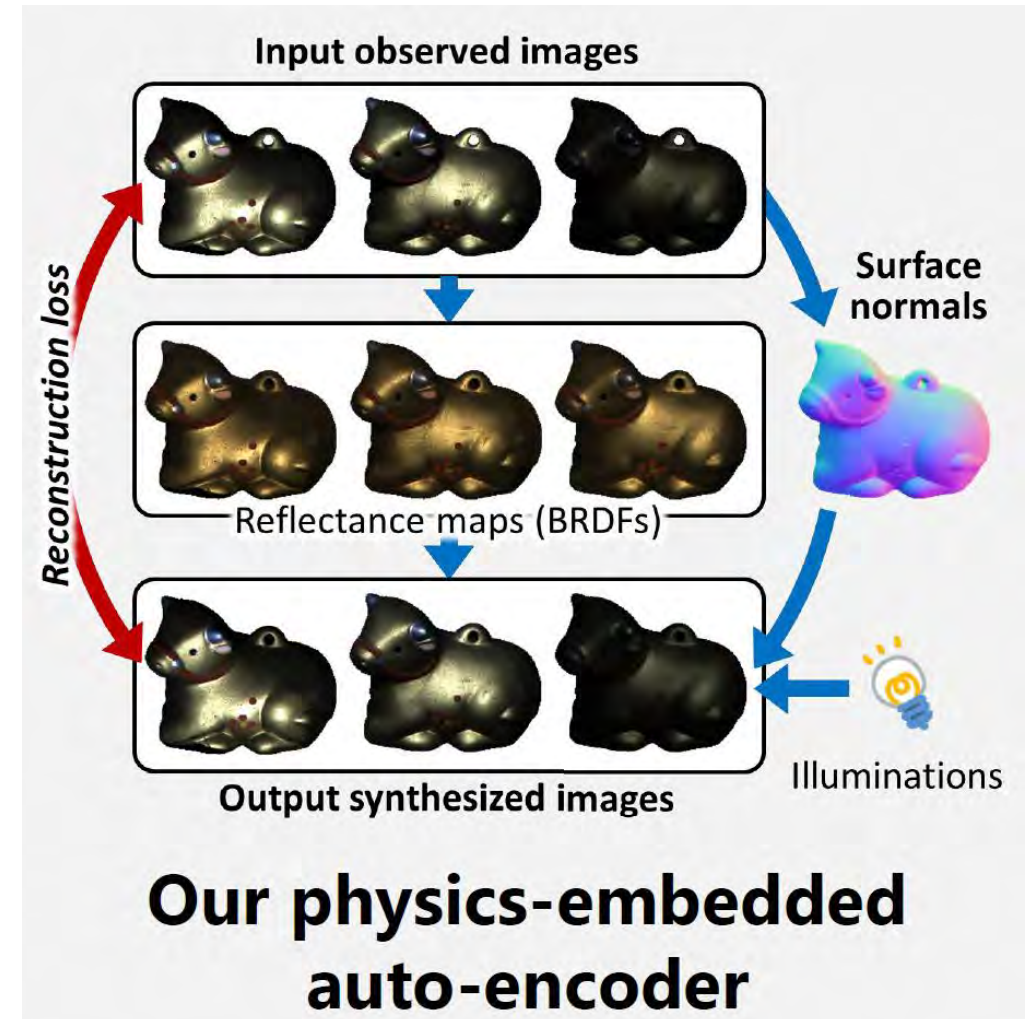
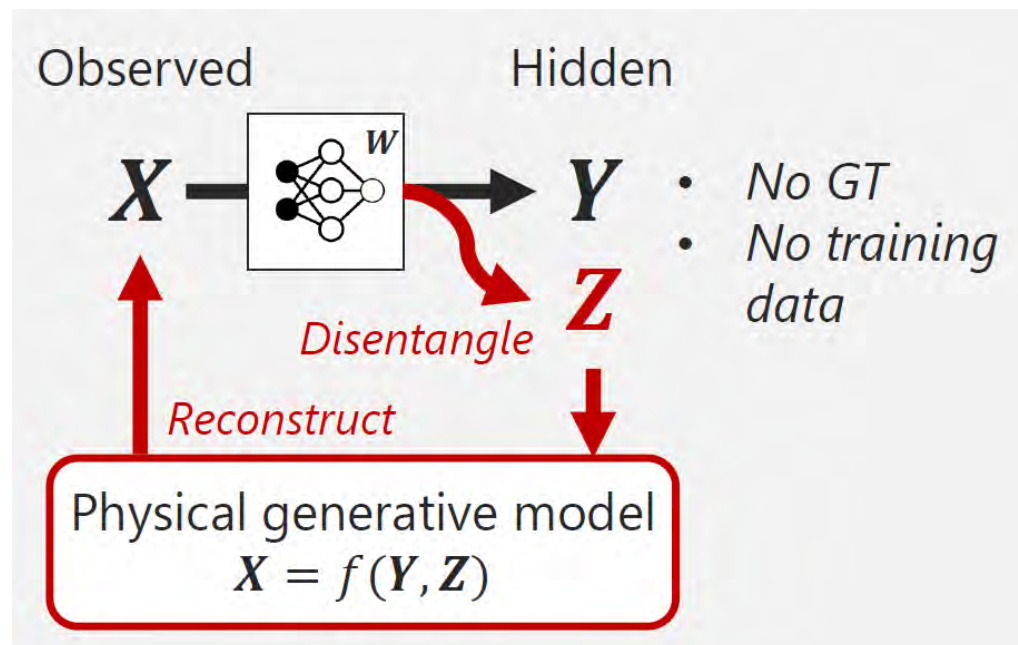


# Challenges

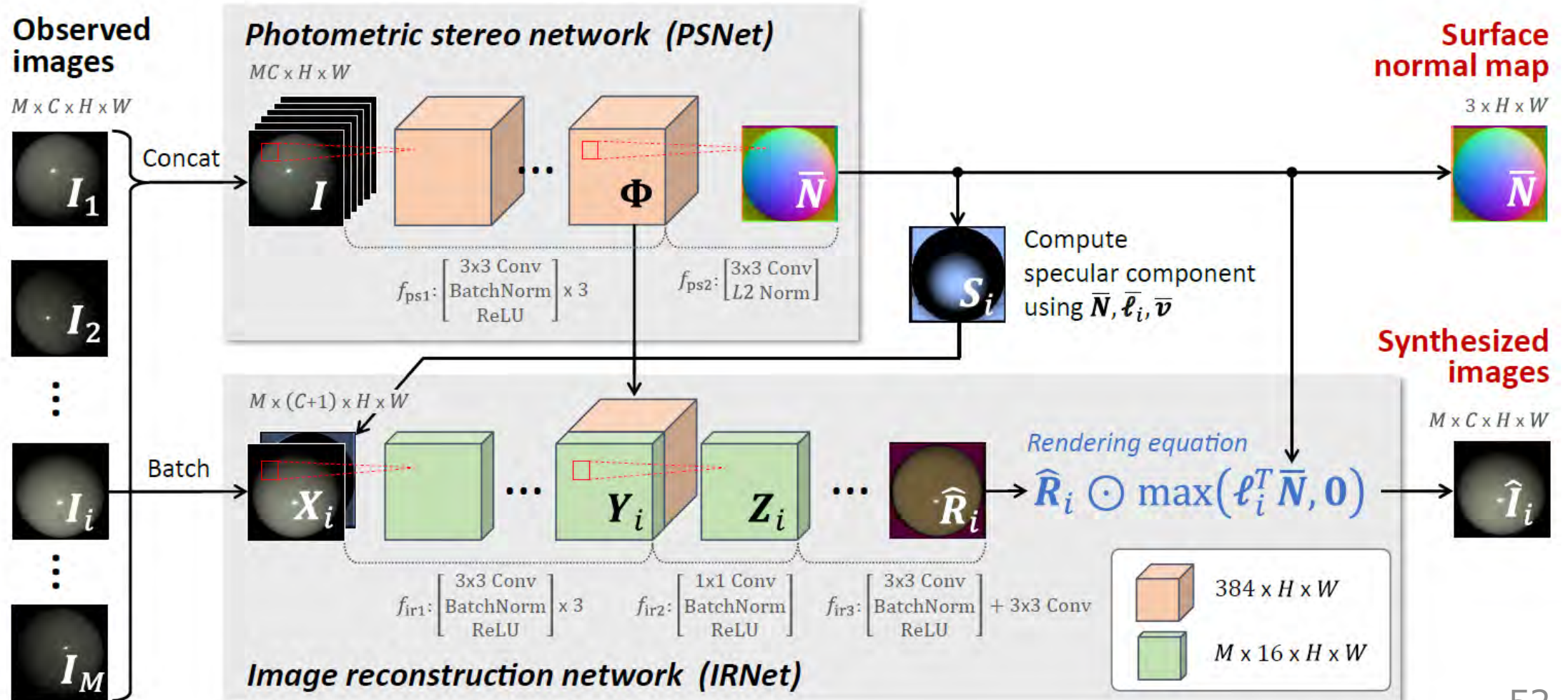
- **Complex unknown non-linearity:** Real objects have various reflectance properties (BRDFs) that are complex and unknown
- **Lack of training data:** Deeply learning for complex relations of surface normal and BRDFs is promising, but accurately measuring ground truth of surface normal and BRDFs is difficult
- **Permutation invariance:** Permuting input images should not change the resulting surface normals

# Key ideas

- Inverse rendering
- Reconstruction loss
- Unsupervised



# Network architecture



# Network architecture

Observed images

$M \times C \times H \times W$

Photometric stereo network (PSNet)

$M \times C \times H \times W$

Surface normal map

$3 \times H \times W$

## Loss function

*Image reconstruction loss*

$$L = \frac{1}{M} \sum_{i=1}^M \|\hat{I}_i - I_i\|_1$$

Minimize intensity differences btw synthesized  $\hat{I}_i$  and observed  $I_i$  images.

*Least squares (LS) prior*

$$\lambda_t \|\bar{N} - \bar{N}'\|_2^2$$

Constrain the output normals  $\bar{N}$  to be close to prior normals  $\bar{N}'$  obtained by the LS method.



$f_{ir1}: \begin{bmatrix} 3 \times 3 \text{ Conv} \\ \text{BatchNorm} \\ \text{ReLU} \end{bmatrix} \times 3$

$f_{ir2}: \begin{bmatrix} 1 \times 1 \text{ Conv} \\ \text{BatchNorm} \\ \text{ReLU} \end{bmatrix}$

$f_{ir3}: \begin{bmatrix} 3 \times 3 \text{ Conv} \\ \text{BatchNorm} \\ \text{ReLU} \end{bmatrix} + 3 \times 3 \text{ Conv}$

Image reconstruction network (IRNet)



$384 \times H \times W$



$M \times 16 \times H \times W$

# Benchmark results using “DiLiGenT”



	BALL	CAT	POT1	BEAR	POT2	BUDDHA	GOBLET	READING	COW	HARVEST	AVG.
<b>Proposed</b>	<b>1.47</b>	<b>5.44</b>	<b>6.09</b>	<b>5.79</b>	<b>7.76</b>	<b>10.36</b>	11.47	<b>11.03</b>	<b>6.32</b>	22.59	<b>8.83</b>
Santo et al. (2017)	2.02	6.54	7.05	6.31	7.86	12.68	11.28	15.51	8.01	<b>16.86</b>	9.41
Shi et al. (2014)	1.74	6.12	6.51	6.12	8.78	10.60	10.09	13.63	13.93	25.44	10.30
Ikehata & Aizawa (2014)	3.34	6.74	6.64	7.11	8.77	10.47	<b>9.71</b>	14.19	13.05	25.95	10.60
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Shi et al. (2012)	13.58	12.34	10.37	19.44	9.84	18.37	17.80	17.17	7.62	19.30	14.58
Baseline (least squares)	4.10	8.41	8.89	8.39	14.65	14.92	18.50	19.80	25.60	30.62	15.39

[ECCV 18]

# PS-FCN: A Flexible Learning Framework for Photometric Stereo

## PS-FCN: A Flexible Learning Framework for Photometric Stereo

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**Abstract.** This paper addresses the problem of photometric stereo for non-Lambertian surfaces. Existing approaches often adopt simplified reflectance models to make the problem more tractable, but this greatly

# Overview of PS-FCN

Given an arbitrary number of images and their associated light directions as input, PS-FCN estimates a normal map of the object in a fast feed-forward pass.

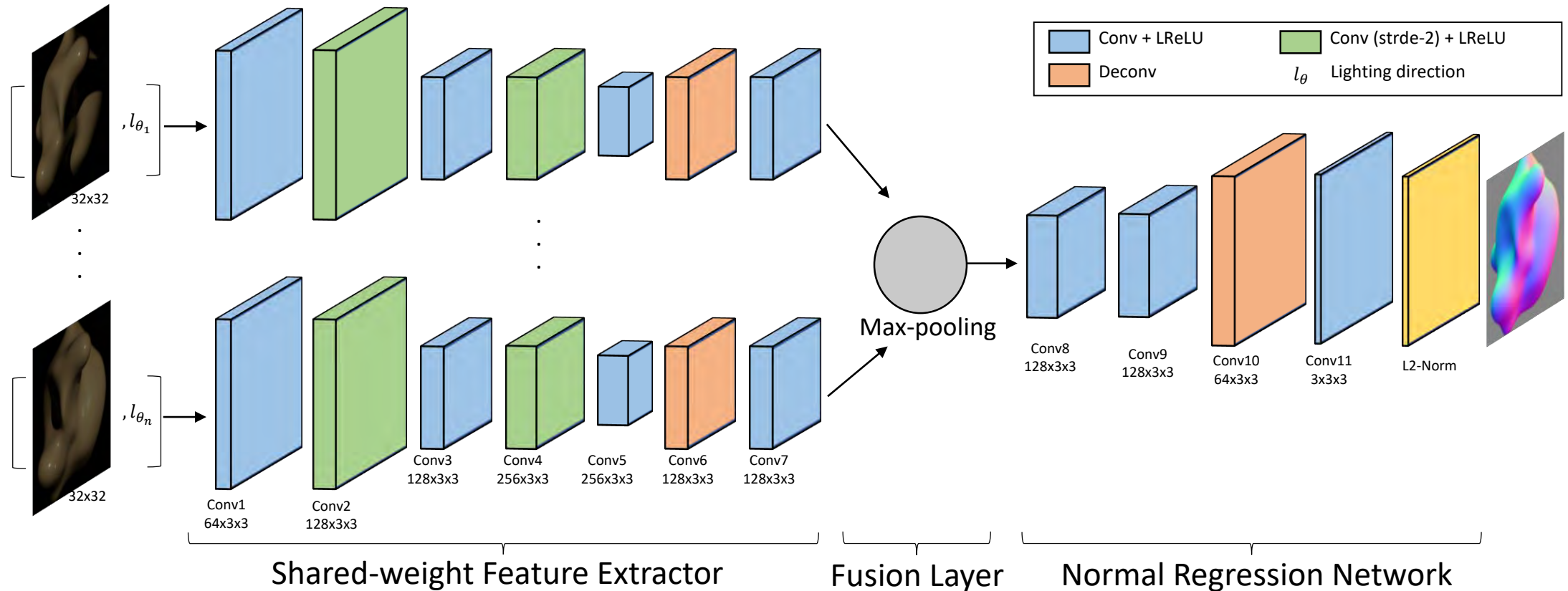


## Advantages:

- Does not depend on a pre-defined set of light directions
- Can handle input images in an order-agnostic manner



# Network architecture

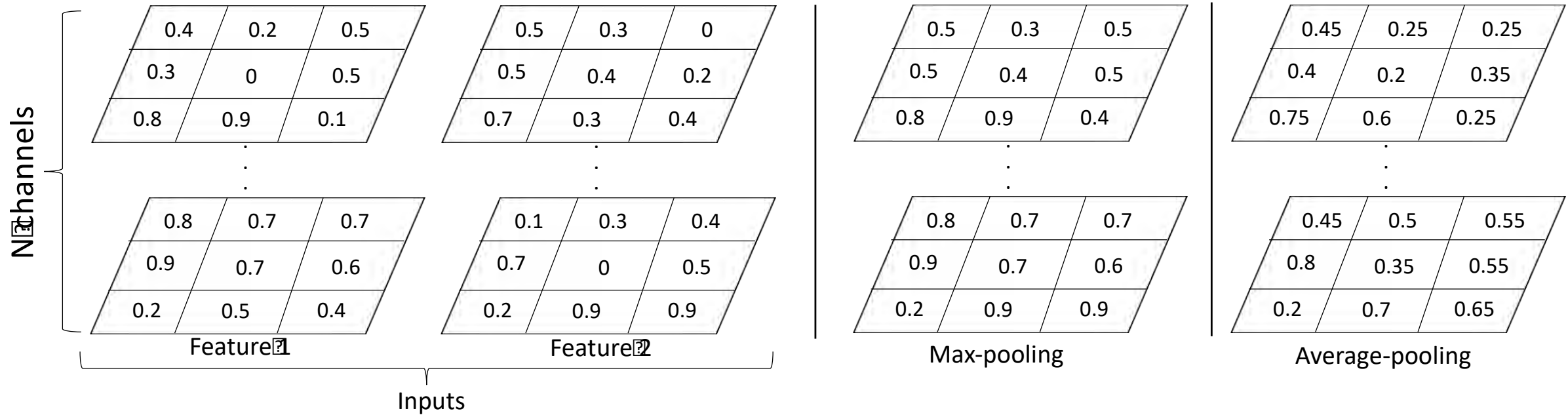


PS-FCN consists of three components:

- A Shared-weight Feature Extractor
- A Fusion Layer
- A Normal Regression Network

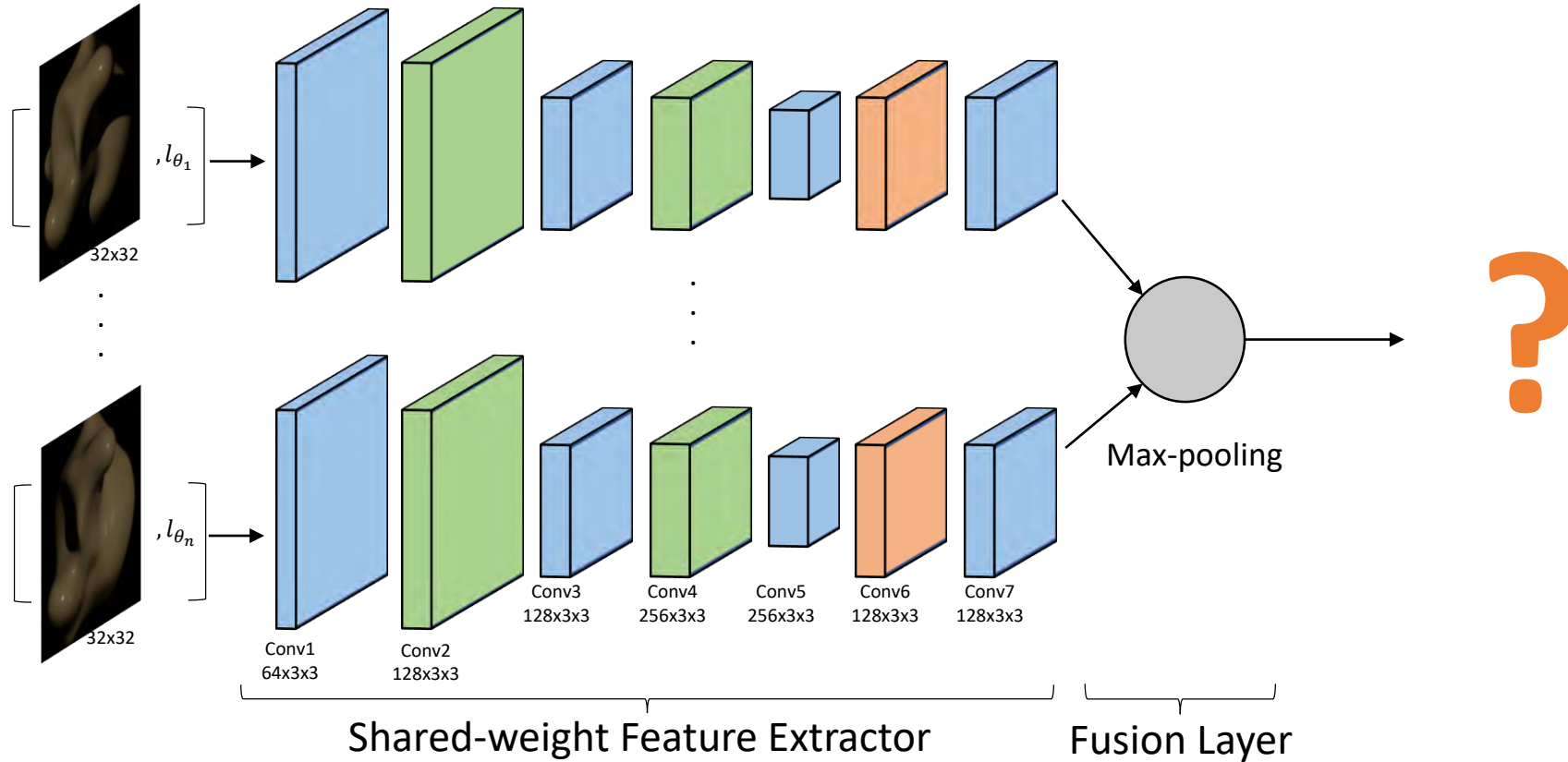
Loss function:

$$L_{normal} = \frac{1}{HW} \sum_{i,j} (1 - N_{ij} \cdot \tilde{N}_{ij})$$



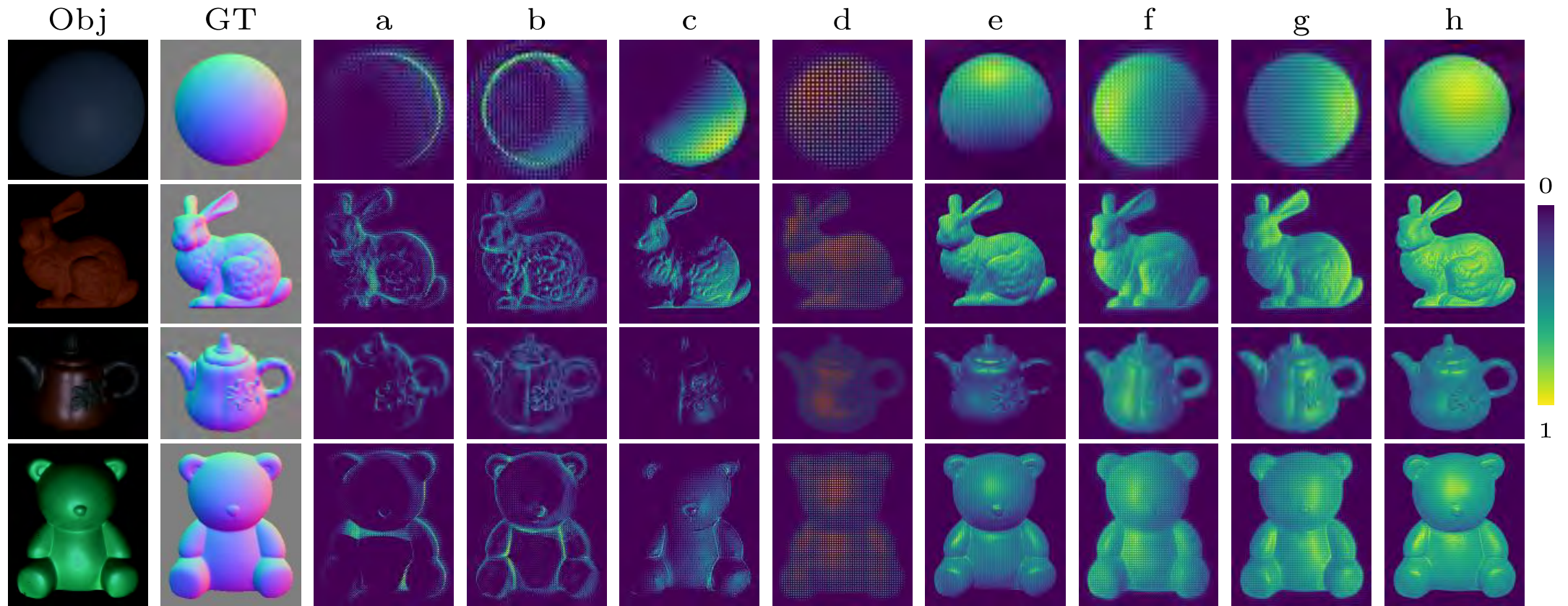
Max-pooling is well-suited for this task:

# Feature visualization



What is encoded in the fused feature?

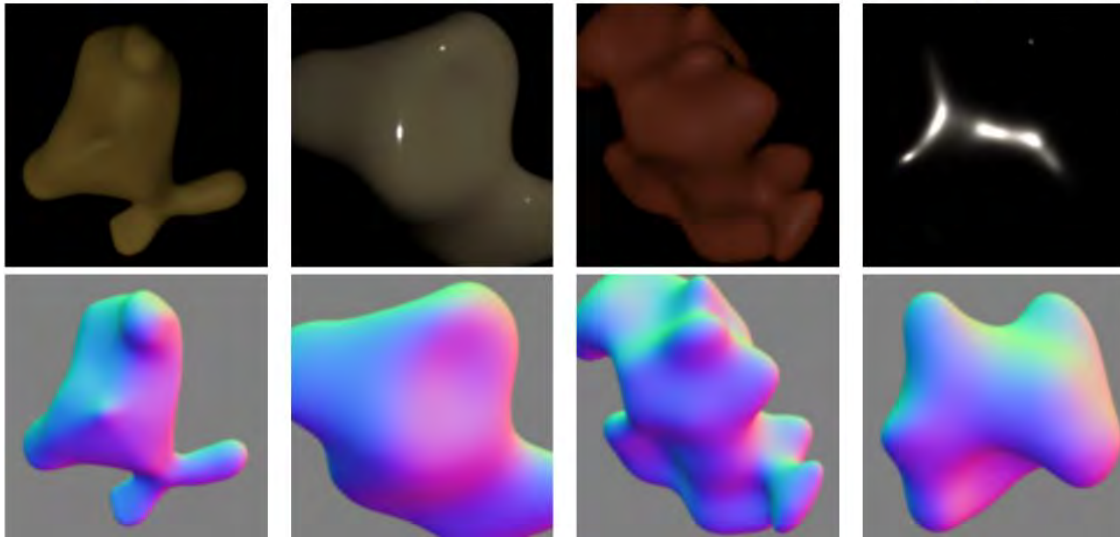
# Visualization for the fused features



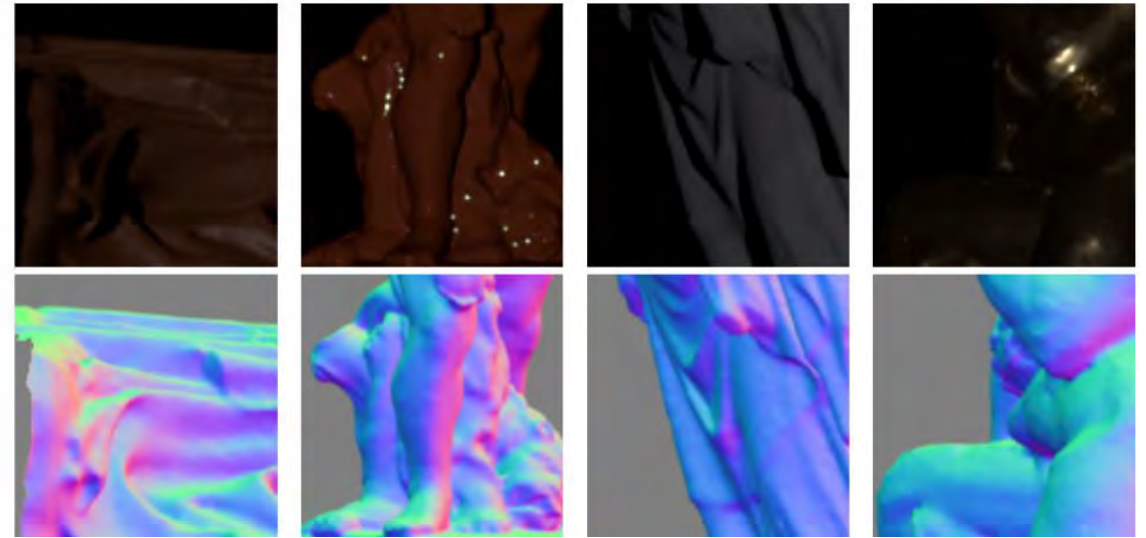
- Different regions with similar normal directions are fired in different channels
- Each channel can be interpreted as the probability of the normal belonging to a certain direction

# Two synthetic training datasets

Bloppy shape (26K samples).



Sculpture shape (59K samples).



- 100 BRDFs from MERL dataset [Matusik 03]
- Rendered with the physically based raytracer Mitsuba
- Trained only on the synthetic data, PS-FCN generalizes well on real data

# Benchmark results using “DiLiGenT”



Method	ball	cat	pot1	bear	pot2	buddha	goblet	reading	cow	harvest	Avg.
L2	4.10	8.41	8.89	8.39	14.65	14.92	18.50	19.80	25.60	30.62	15.39
AZ08	2.71	6.53	7.23	<b>5.96</b>	11.03	12.54	13.93	14.17	21.48	30.50	12.61
WG10	2.06	6.73	7.18	6.50	13.12	10.91	15.70	15.39	25.89	30.01	13.35
IA14	3.34	6.74	6.64	7.11	8.77	10.47	9.71	14.19	13.05	25.95	10.60
ST14	<b>1.74</b>	<b>6.12</b>	<b>6.51</b>	6.12	8.78	10.60	10.09	13.63	13.93	25.44	10.30
DPSN	2.02	6.54	7.05	6.31	7.86	12.68	11.28	15.51	8.01	16.86	9.41
PS-FCN (16)	3.31	7.64	8.14	7.47	8.22	8.76	9.81	14.09	8.78	17.48	9.37
PS-FCN (96)	2.82	6.16	7.13	7.55	<b>7.25</b>	<b>7.91</b>	<b>8.60</b>	<b>13.33</b>	<b>7.33</b>	<b>15.85</b>	<b>8.39</b>

[ECCV 18]

# CNN-PS: CNN-based Photometric Stereo for General Non-Convex Surfaces

## CNN-PS: CNN-based Photometric Stereo for General Non-Convex Surfaces

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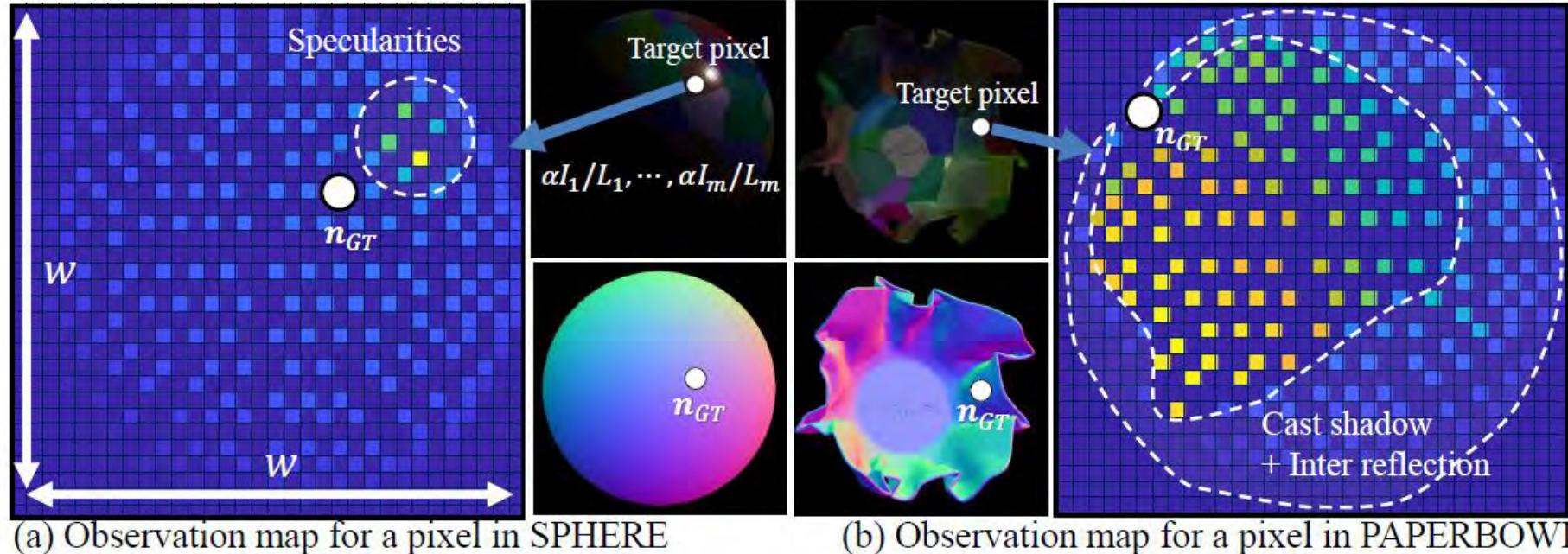
**Abstract.** Most conventional photometric stereo algorithms inversely solve a BRDF-based image formation model. However, the actual imaging process is often far more complex due to the global light transport on

# Observation map (per-pixel)

- Find an easy-to-learn representation

Definition of an observation map ( $\alpha$  is normalizing factor,  $L$  is light intensity)

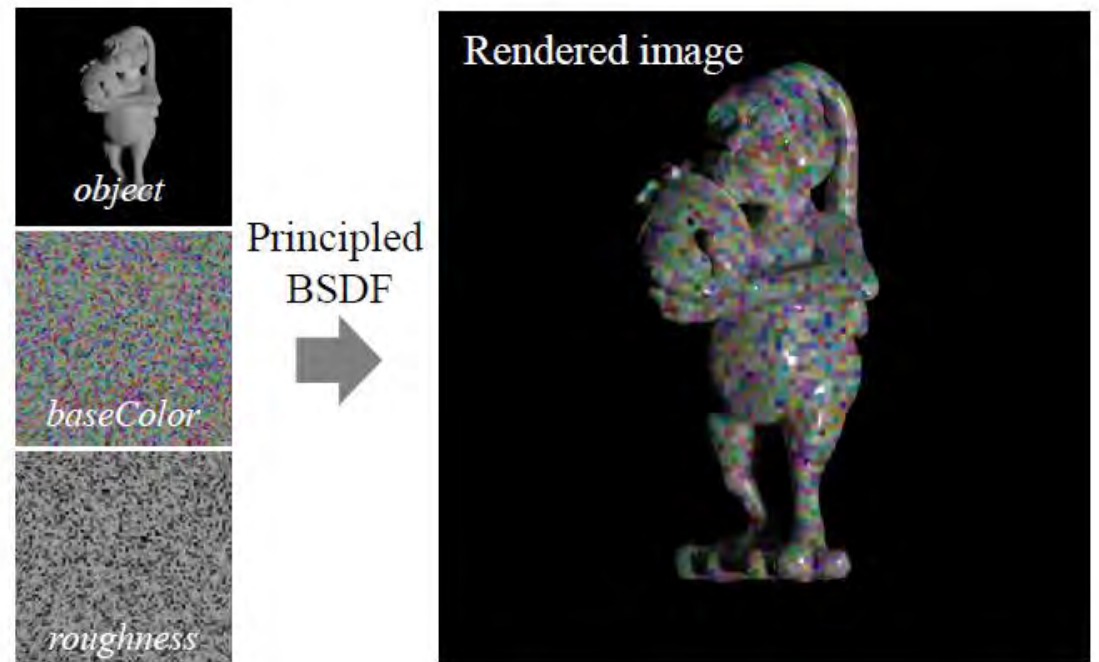
$$O_{\text{int}(w(l_x+1)/2), \text{int}(w(l_y+1)/2)} = \alpha I_j / L_j \quad \forall j \in 1, \dots, m,$$





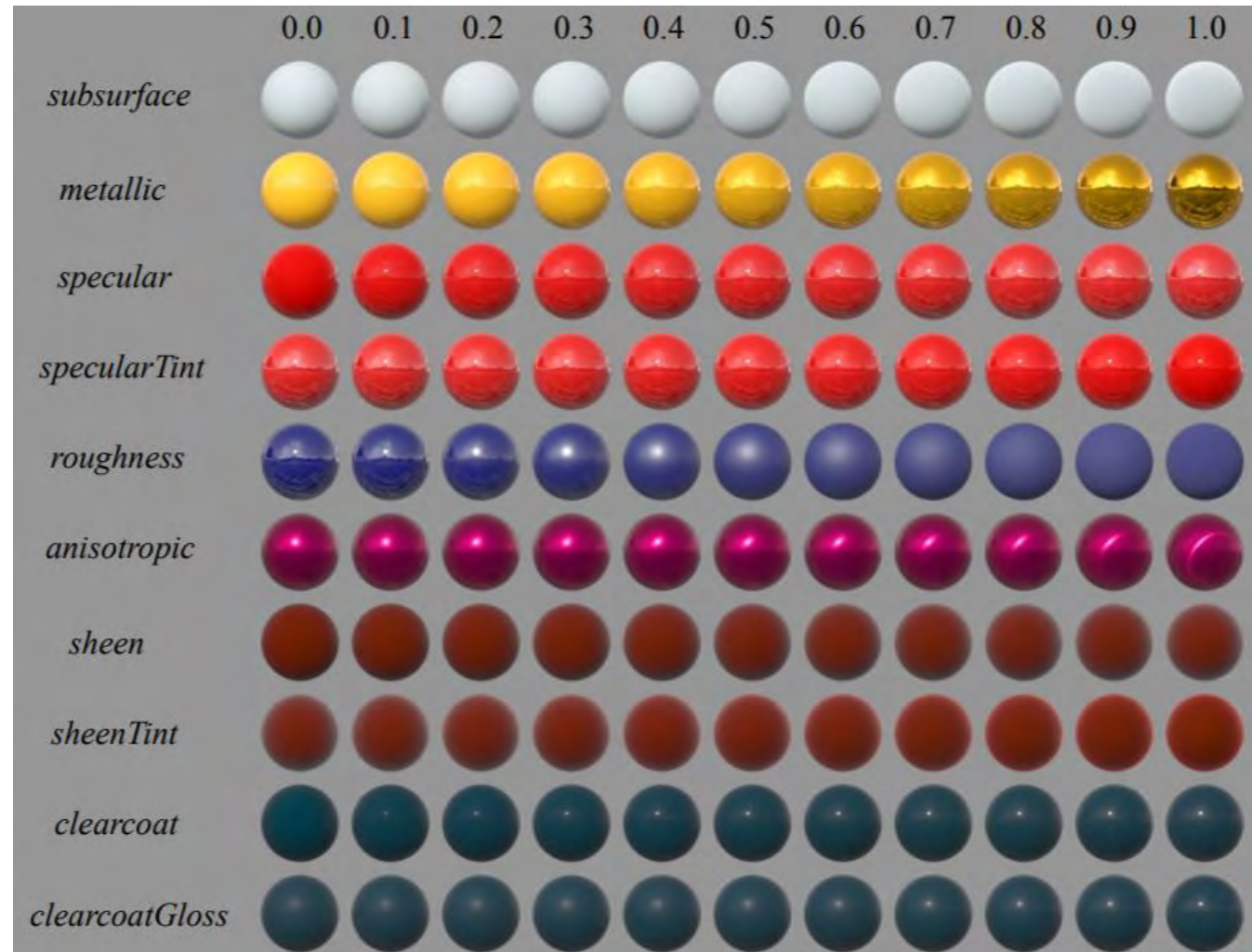
# Training dataset

- Cycles renderer in Blender
- A set of 3-D model, BSDF parameter maps (Disney's Principled BSDF model), and lighting configuration
- Generate observation map pixelwisely



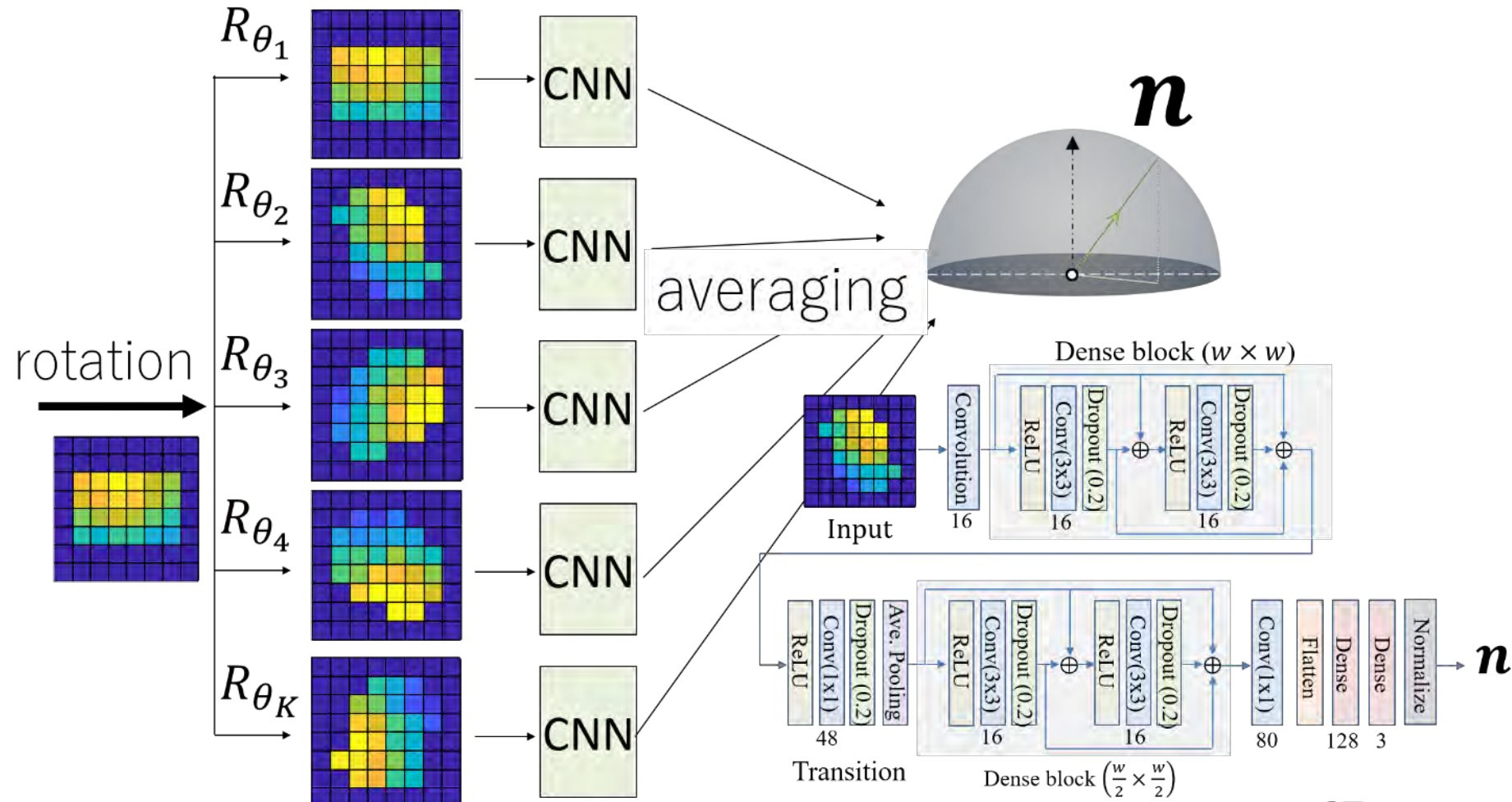
# Disney's principled BSDFs model

- Intuitive rather than physical parameters should be used
- As few parameters as possible
- Parameters should be zero to one over their plausible range
- Parameters should be allowed to be pushed beyond their plausible range where it makes sense
- All combinations of parameters should be as robust and plausible as possible



# Normal prediction

Observation map

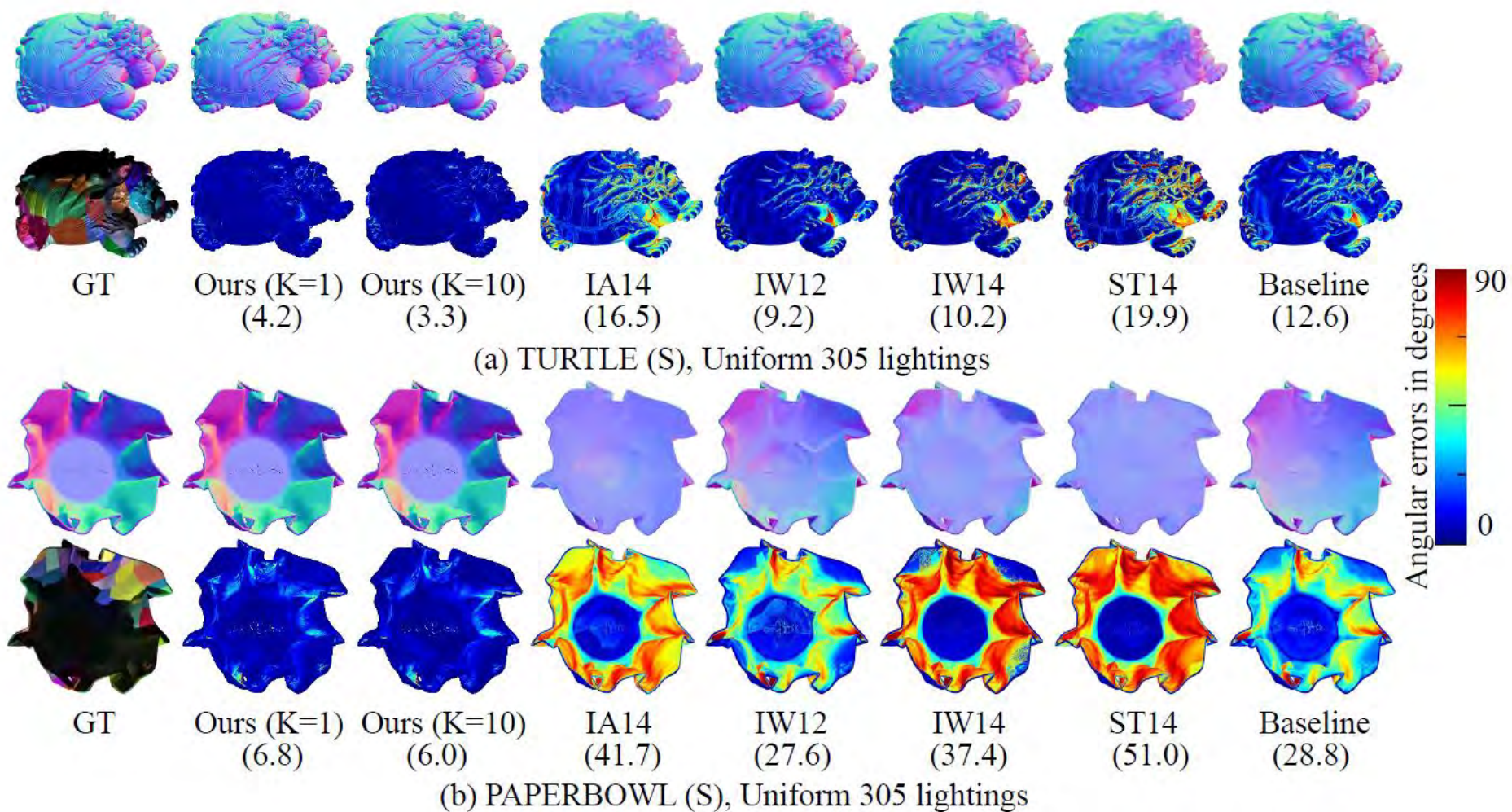


# Benchmark results using “DiLiGenT”



	BALL	BEAR	BUDDHA	CAT	COW	GOBLET	HARVEST	POT1	POT2	READING	AVE. ERR	RANK
OURS (K=10)	2.2	4.1 *	7.9	4.6	8.0	7.3	14.0	5.4	6.0	12.6	7.2	1
OURS (K=1)	2.7	4.5 *	8.6	5.0	8.2	7.1	14.2	5.9	6.3	13.0	7.6	2
HS17 [20]	1.3	5.6	8.5	4.9	8.2	7.6	15.8	5.2	6.4	12.1	7.6	2
TM18 [21]	1.5	5.8	10.4	5.4	6.3	11.5	22.6	6.1	7.8	11.0	8.8	4
IW14 [7]	2.0	4.8	8.4	5.4	13.3	8.7	18.9	6.9	10.2	12.0	9.0	5
SS17 [20]	2.0	6.3	12.7	6.5	8.0	11.3	16.9	7.1	7.9	15.5	9.4	6
ST14 [18]	1.7	6.1	10.6	6.1	13.9	10.1	25.4	6.5	8.8	13.6	10.3	7
SH17 [25]	2.2	5.3	9.3	5.6	16.8	10.5	24.6	7.3	8.4	13.0	10.3	7
IA14 [17]	3.3	7.1	10.5	6.7	13.1	9.7	26.0	6.6	8.8	14.2	10.6	9
GC10 [14]	3.2	6.6	14.9	8.2	9.6	14.2	27.8	8.5	7.9	19.1	12.0	10
BASELINE [12]	4.1	8.4	14.9	8.4	25.6	18.5	30.6	8.9	14.7	19.8	15.4	-

# Results: CyclePS test dataset



[CVPR 19]

# Self-calibrating Deep Photometric Stereo Networks

## Self-calibrating Deep Photometric Stereo Networks

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### Abstract

*This paper proposes an uncalibrated photometric stereo method for non-Lambertian scenes based on deep learning. Unlike previous approaches that heavily rely on assumptions of specific reflectances and light source distributions, our method is able to determine both shape and light directions of a scene with unknown arbitrary reflectances observed under unknown varying light directions. To achieve this goal, we propose a two-stage deep learning architecture, called SDPS-Net, which can effectively take advantage of intermediate supervision, resulting in reduced learning difficulty compared to a single-stage model. Experiments on both synthetic and real datasets show that our proposed approach significantly outperforms previous uncalibrated photometric stereo methods.*

31, 15, 5]. Instead of explicitly modeling complex surface reflectances, they directly learn the mapping from reflectance observations to surface normal given light directions. Although they have obtained promising results in a calibrated setting, they cannot handle the more challenging problem of *uncalibrated* photometric stereo, where light directions are unknown. One simple strategy to handle uncalibrated photometric stereo with deep learning is to directly learn the mapping from images to surface normal without taking the light directions as input. However, as reported in [5], the performance of such a model lags far behind those which take both images and light directions as input.

In this paper, we propose a two-stage model named Self-calibrating Deep Photometric Stereo Networks (SDPS-Net) to tackle this problem. The first stage of SDPS-Net, denoted as *Lighting Calibration Network* (LCNet), takes an

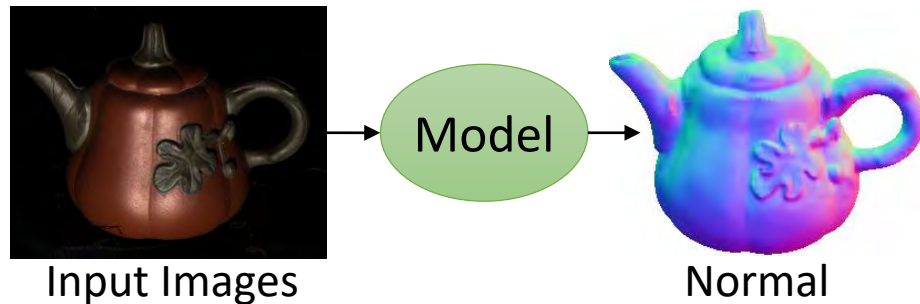
# Motivation

- Recent learning based methods for PS often assume known light directions
  - DPSN
  - IRPS
  - CNN-PS
  - PS-FCN
- The performance of the existing learning based method for UPS is far from satisfactory
  - PS-FCN + uncalibrated setting

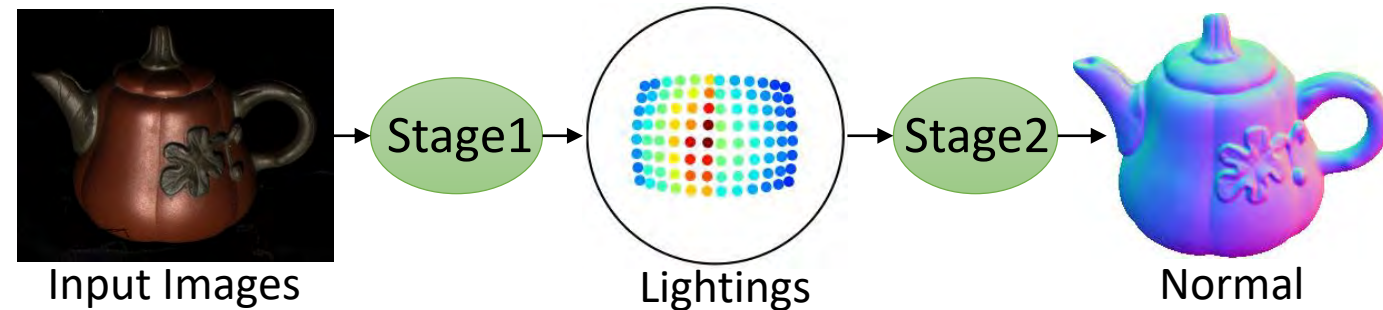


# Main idea of SDPS-Net

Single-stage method:



Two-stage method:

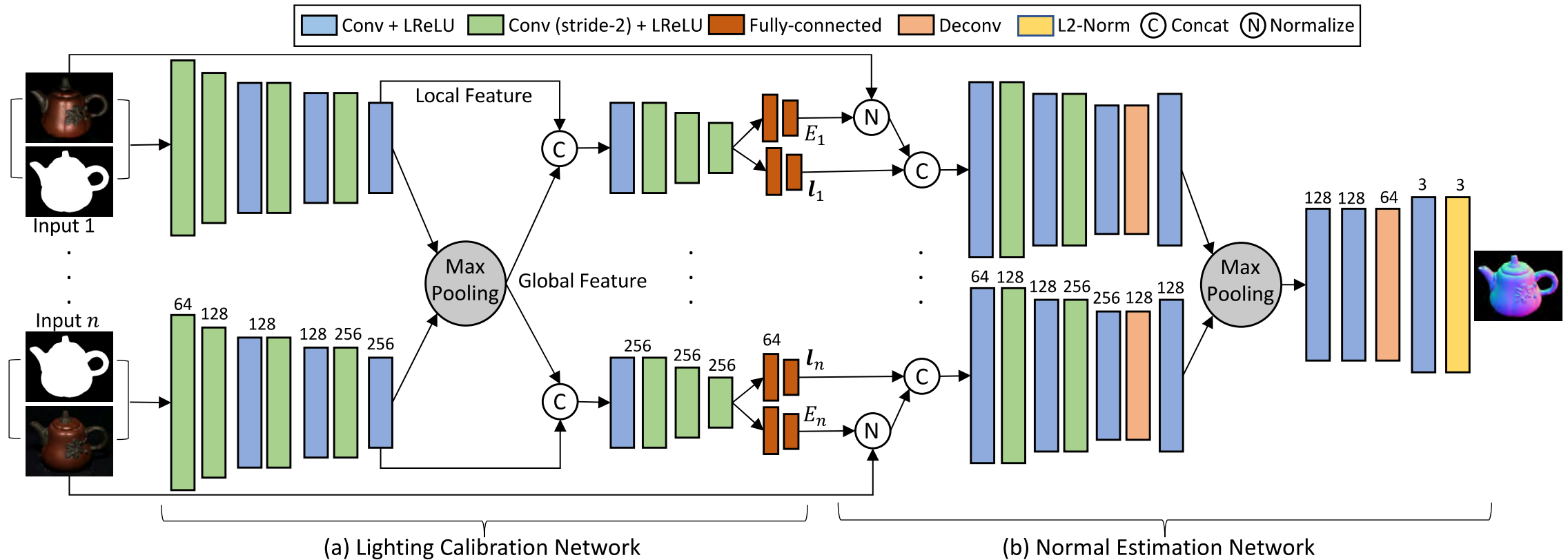


Advantages of the proposed two-stage method:

- Directional lightings are much easier to estimate than surface normals
- Take advantage of the intermediate supervision (more interpretable)
- The estimated lightings can be utilized by existing calibrated methods



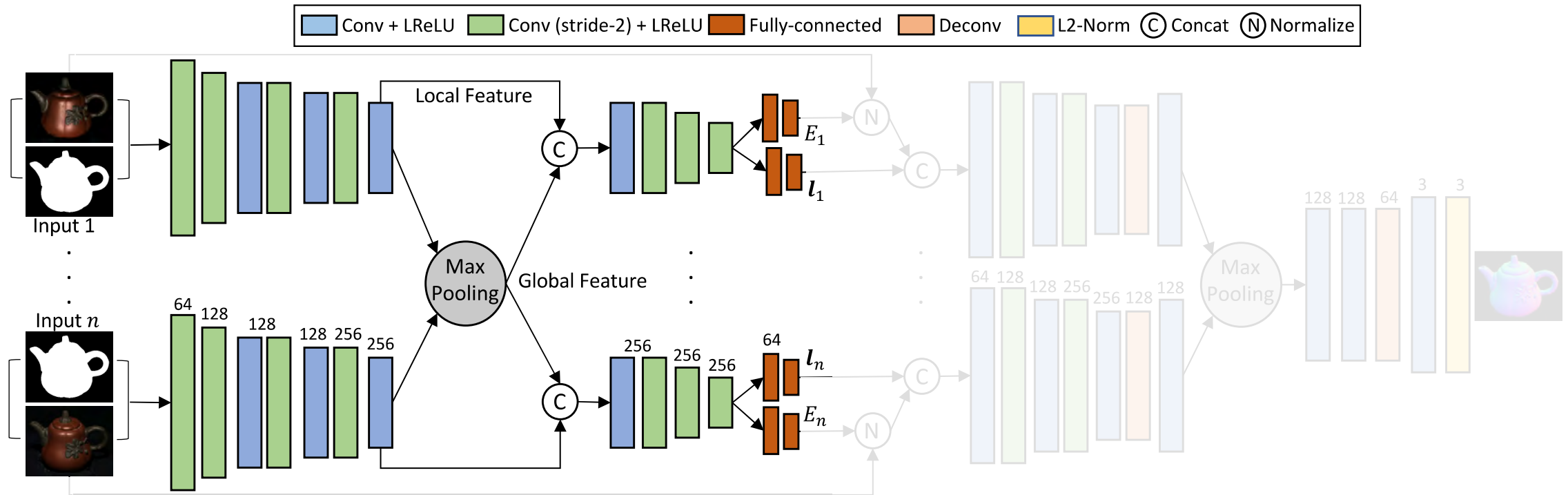
# The proposed two-stage framework



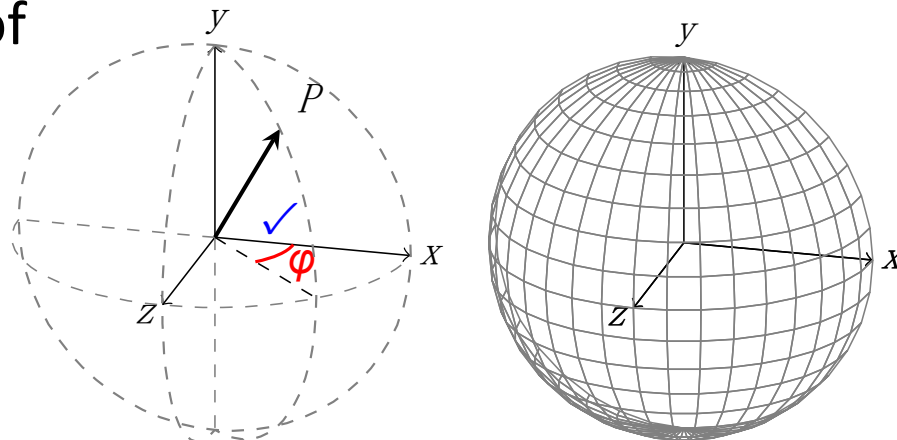
SDPS-Net consists of two stages:

- Stage 1: Lighting Calibration Network (LCNet) for lighting estimation
- Stage 2: Normal Estimation Network (NENet) for normal estimation

# Stage 1: Lighting calibration network



Discretization of lighting space:

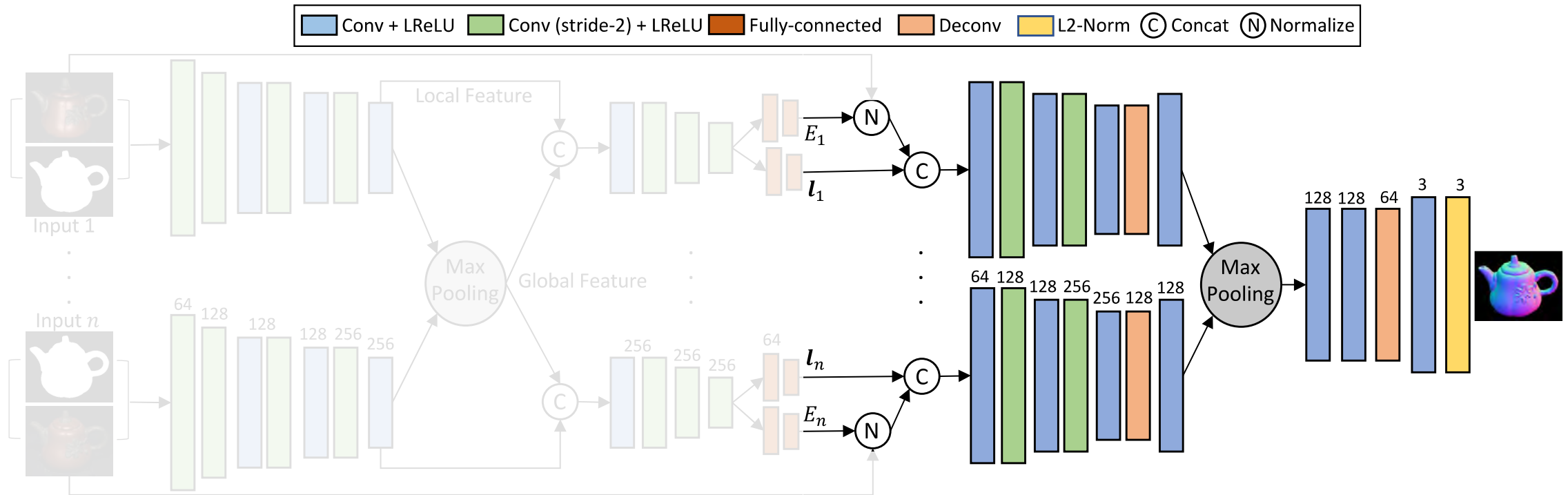


Loss function:

$$\mathcal{L}_{\text{Light}} = \lambda_{l_a} \mathcal{L}_{l_a} + \lambda_{l_e} \mathcal{L}_{l_e} + \lambda_e \mathcal{L}_e$$

- $\mathcal{L}_{l_a}$ : azimuth classification loss
- $\mathcal{L}_{l_e}$ : elevation classification loss
- $\mathcal{L}_e$ : light intensity classification loss

# Stage 2: Normal estimation network



Loss function:

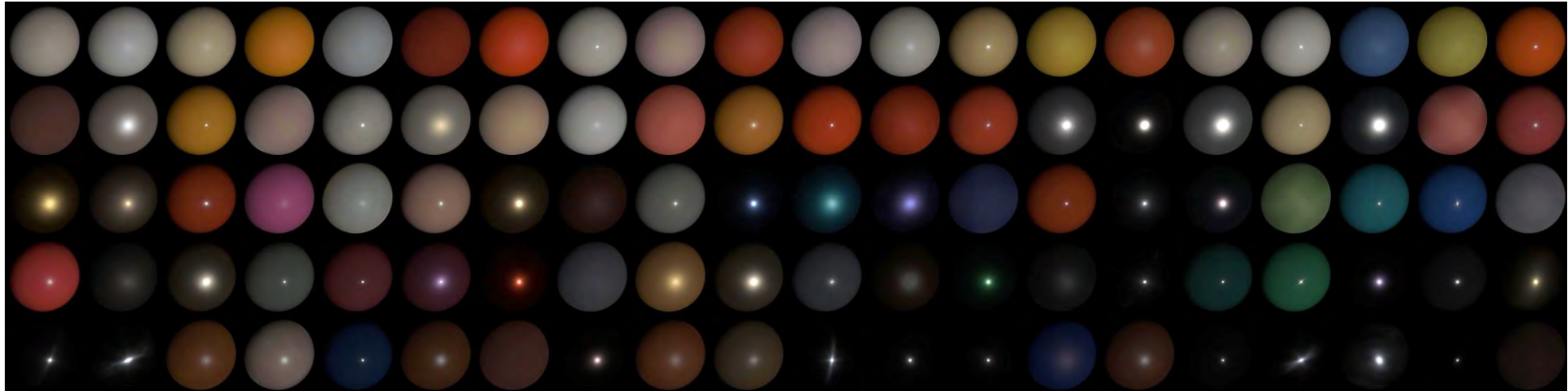
$$\mathcal{L}_{\text{Normal}} = \frac{1}{hw} \sum_i^{hw} (1 - \mathbf{n}_i^\top \tilde{\mathbf{n}}_i)$$

- Cosine similarity loss

- Our framework can handle an arbitrary number of images in an order agnostic manner.

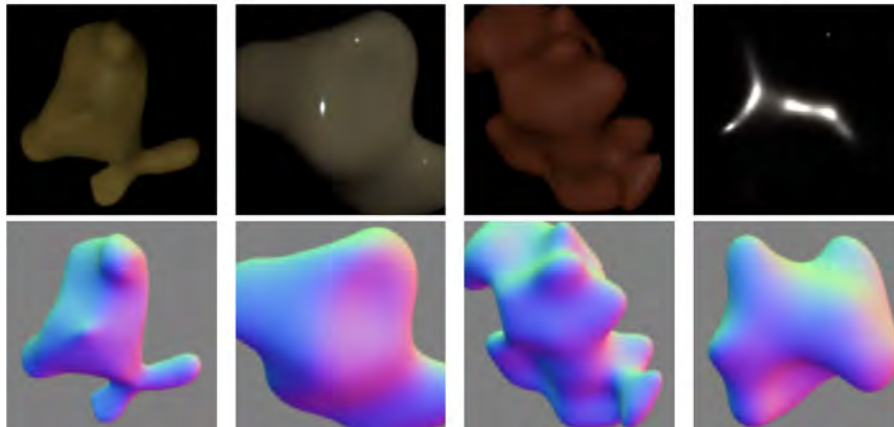
# Synthetic training dataset [Chen 18]

- 100 measured BRDFs from MERL dataset

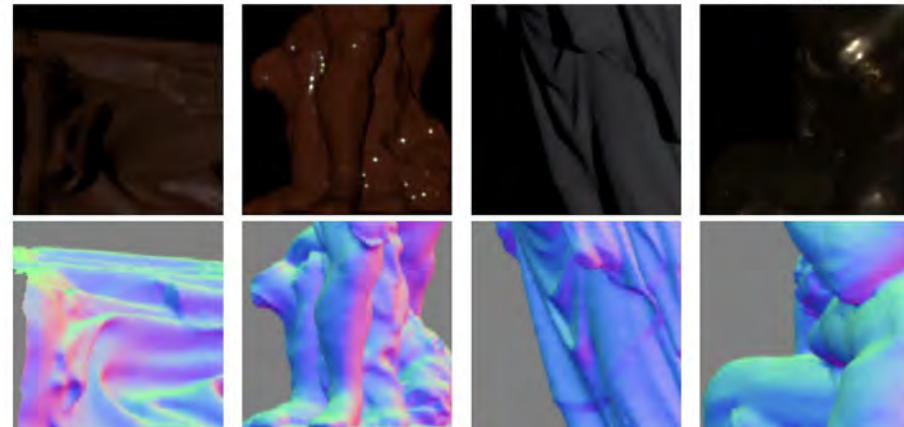


- Cast-shadow and inter-reflection are considered using Mitsuba.

Bloppy shape (26K samples).



Sculpture shape (59K samples).



# Benchmark results using “DiLiGenT”



Method	BALL	CAT	POT1	BEAR	POT2	BUDD.	GOBL.	READ.	COW	HARV.	Avg.
AM07	7.3	31.5	18.4	16.8	49.2	32.8	46.5	53.7	54.7	61.7	37.3
SM10	8.9	19.8	16.7	12.0	50.7	15.5	48.8	26.9	22.7	73.9	29.6
WT13	4.4	36.6	9.4	<b>6.4</b>	14.5	13.2	20.6	59.0	19.8	55.5	23.9
LM13	22.4	25.0	32.8	15.4	20.6	25.8	29.2	48.2	22.5	34.5	27.6
PF14	4.8	9.5	9.5	9.1	15.9	14.9	29.9	24.2	19.5	29.2	16.7
LC18	9.3	12.6	12.4	10.9	15.7	19.0	18.3	22.3	15.0	28.0	16.3
UPS-FCN	6.6	14.7	14.0	11.2	14.2	15.9	20.7	23.3	11.9	27.8	16.0
LCNet + L2	4.9	11.1	9.7	9.4	14.7	14.9	18.3	20.1	25.1	29.2	15.7
SDPS-Net	<b>2.8</b>	<b>8.1</b>	<b>8.1</b>	6.9	<b>7.5</b>	<b>9.00</b>	<b>11.9</b>	<b>14.9</b>	<b>8.5</b>	<b>17.4</b>	<b>9.5</b>

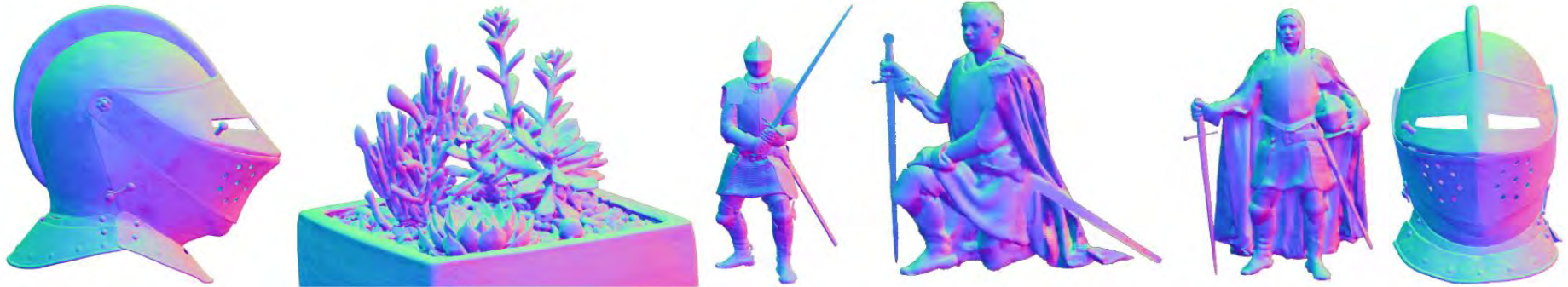
- Our method achieves state-of-the-art results (value the lower the better)
- The proposed LCNet can be integrated with the previous calibrated methods

# Qualitative results on light stage data gallery

Object



Ours



UPS-FCN



# [CVPR 19]

## Learning to Minify Photometric Stereo

### Learning to Minify Photometric Stereo

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#### Abstract

*Photometric stereo estimates the surface normal given a set of images acquired under different illumination conditions. To deal with diverse factors involved in the image formation process, recent photometric stereo methods demand a large number of images as input. We propose a method that can dramatically decrease the demands on the number of images by learning the most informative ones under different illumination conditions. To this end, we use a deep learning framework to automatically learn the critical illumination conditions required at input. Furthermore, we present an occlusion layer that can synthesize cast shad-*

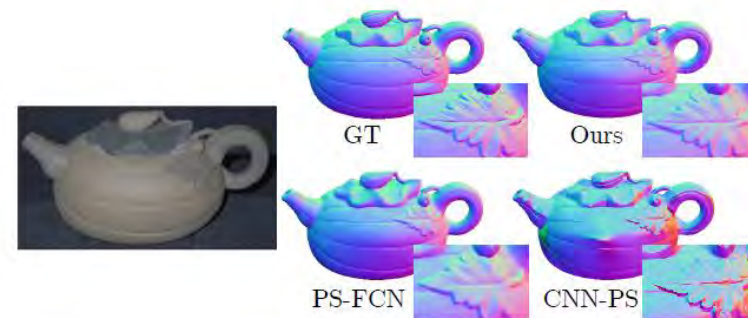
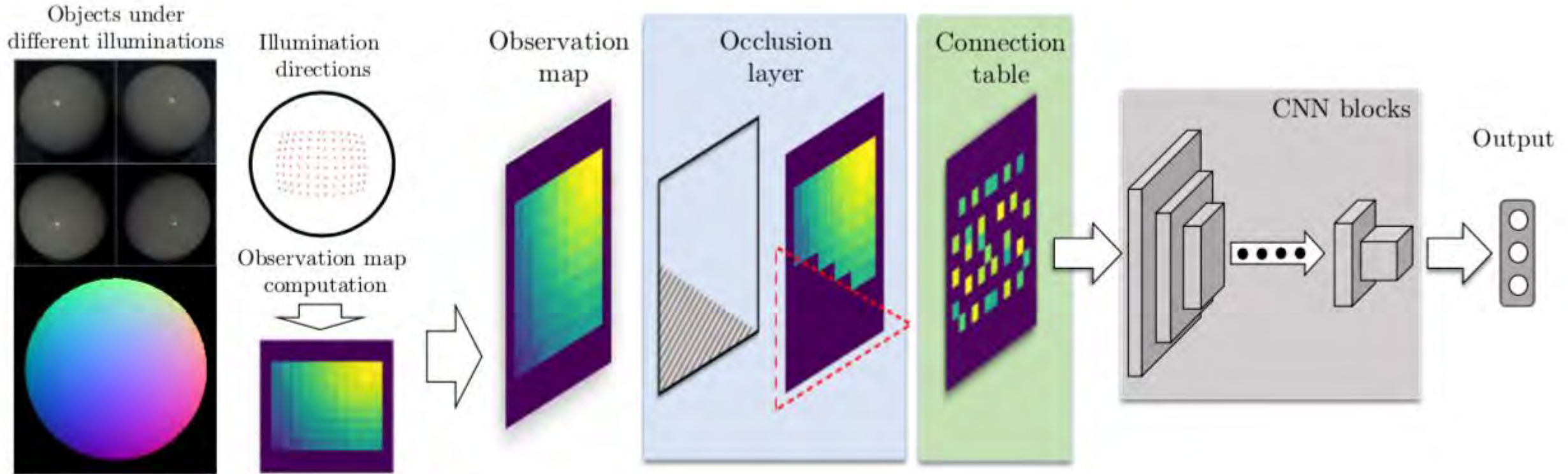


Figure 1. Performance with only 8 inputs for our method, PS-FCN [3] and CNN-PS [8] on the “pot1” from DiLiGenT [17]. Note we outperform the alternatives.

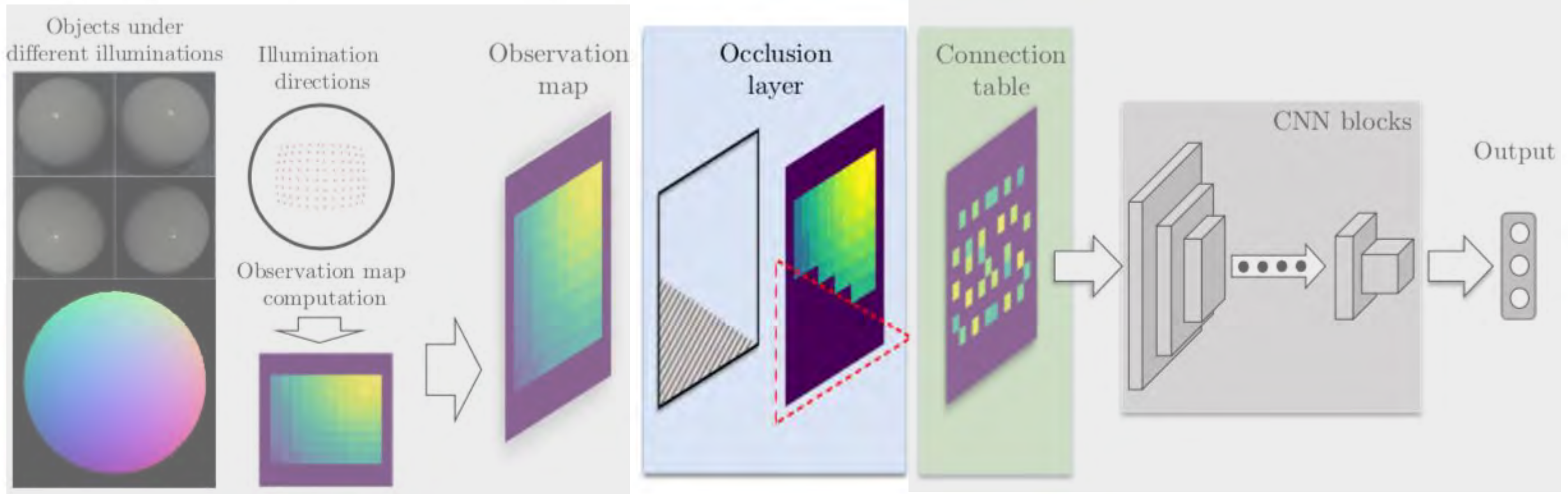
ages so as to minify the photometric stereo input. We ap-

# Main idea



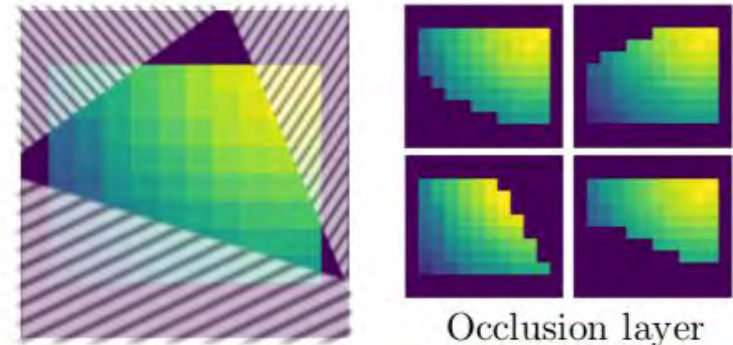


# Main idea

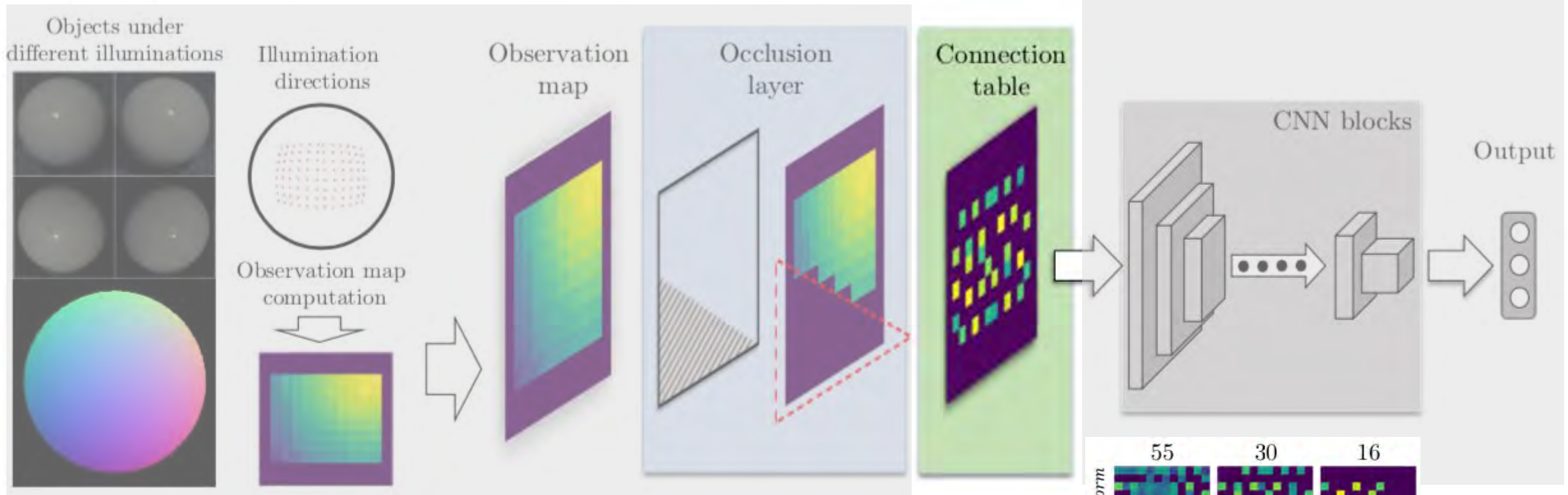


## Occlusion layer

- Cast-shadows are consistent patterns with a relatively sharp and straight boundary
- Randomly select two sides of the map, and randomly picks a point on each side



# Main idea



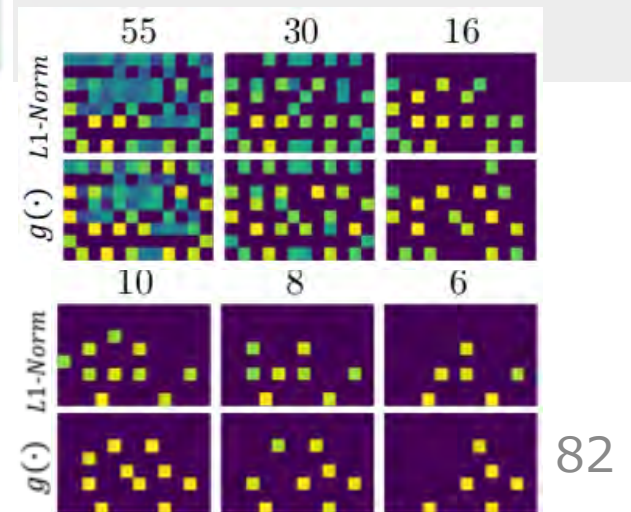
## Sparse connection table

- Select the most relevant illuminant directions at input
- Fixed after training

## Loss functions

$$\mathcal{L} = \|\mathbf{n} - \mathbf{n}'\|_2^2 + \lambda g(\mathbf{C})$$

$$g(\mathbf{C}) = \sum_{i,j} \left( 2C_{i,j} - \frac{C_{i,j}^2}{2\alpha} \right)$$



# Effectiveness of occlusion layer

- Compared with random zeroing in DPSN



# Benchmark results using “DiLiGenT”

\*10 selected lights

Light-Config	Proposed	PS-FCN	CNN-PS	IW12	LS
Random (10 trials)	<b>10.02</b>	10.51	14.34	16.37	17.31
Selected by Proposed method		11.35	13.02	15.83	17.12
Optimal [Drbohlav 05]		8.73	13.35	15.50	16.57

[ICCV 19]

# SPLINE-Net: Sparse Photometric Stereo through Lighting Interpolation and Normal Estimation Networks

## SPLINE-Net: Sparse Photometric Stereo through Lighting Interpolation and Normal Estimation Networks

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### Abstract

*This paper solves the Sparse Photometric stereo through Lighting Interpolation and Normal Estimation using a generative Network (SPLINE-Net). SPLINE-Net contains a lighting interpolation network to generate dense lighting observations given a sparse set of lights as inputs followed by a normal estimation network to estimate surface normals. Both networks are jointly constrained by the proposed symmetric and asymmetric loss functions to enforce isotropic constrain and perform outlier rejection of global illumination effects. SPLINE-Net is verified to outperform existing methods for photometric stereo of general BRDFs by using only ten images of different lights instead of using nearly one hundred images.*

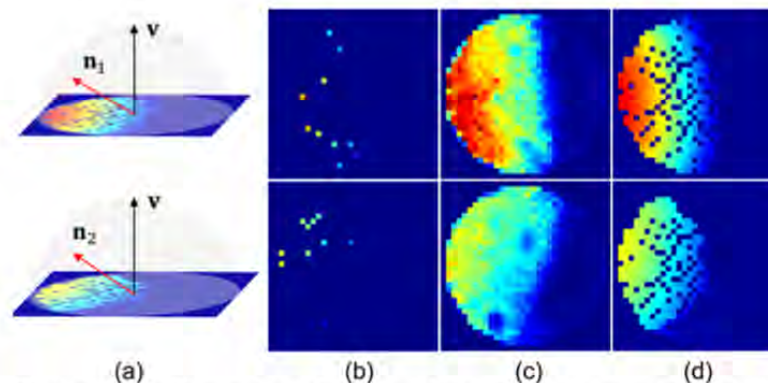


Figure 1. An illustration of observation maps corresponding to two surface normals (a brief introduction of observation maps can be found in Section 3.2 and [18]). (a) Two surface normals and their observation maps with dense lights, (b) sparse observation maps with 10 order-agnostic lights, (c) dense observation maps generated by our SPLINE-Net given sparse observation maps in (b) as

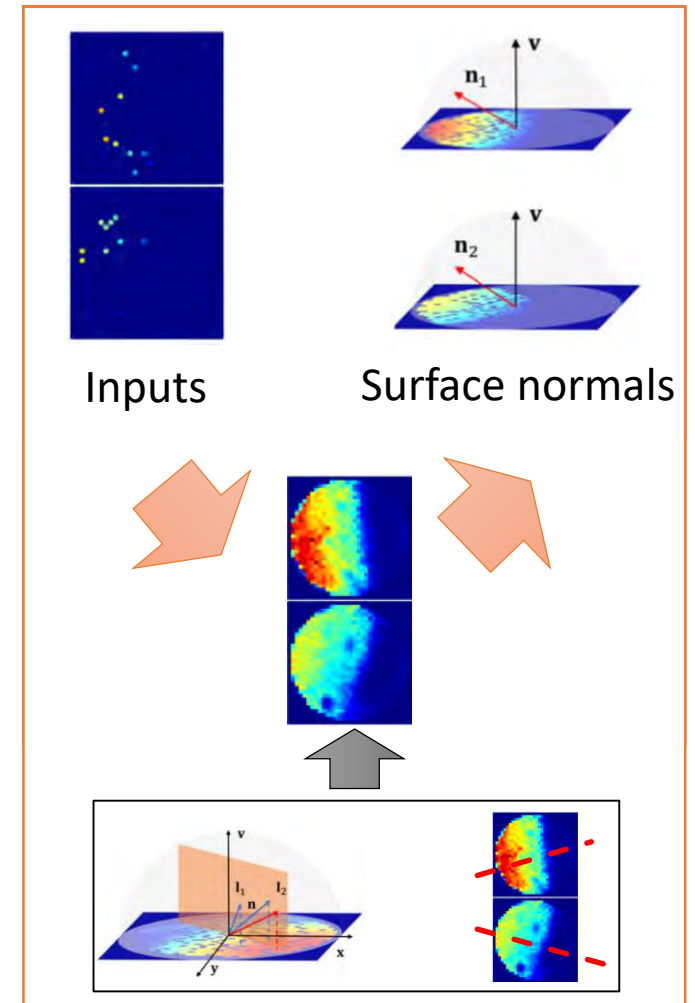
# Key idea

- Sparse photometric stereo
  - Fixed number of inputs with **arbitrary** lightings
- Basic idea
  - Spatial continuity: dense interpolation
  - Isotropy of BRDFs: physics constraint

**Random** positions of valid pixels in observation maps

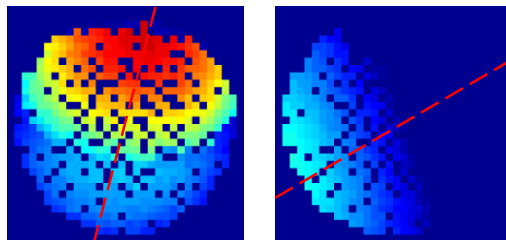
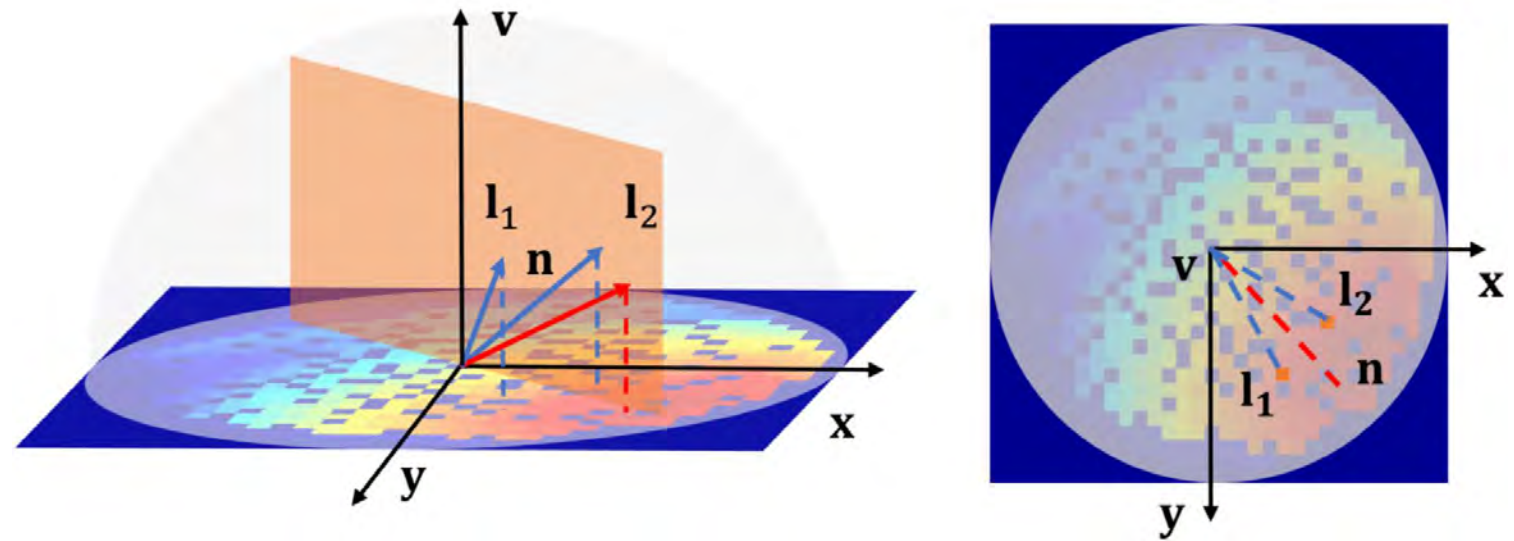
Lighting interpolation **guides** normal estimation

**Symmetric** pattern in observation maps



# Isotropic BRDFs in observation maps

- $\rho(\mathbf{n}^T \mathbf{l}, \mathbf{n}^T \mathbf{v}, \mathbf{v}^T \mathbf{l})$



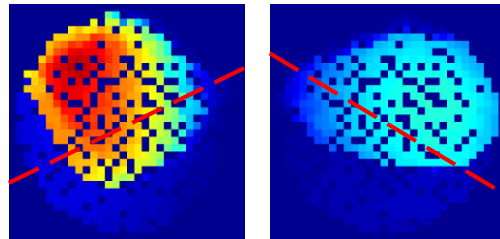
Loss functions of symmetric

$$\mathcal{L}_s = \mathcal{L}_s(\mathbf{D}, \mathbf{n}) = |\mathbf{D} - r(\mathbf{D}, \mathbf{n})|_1$$

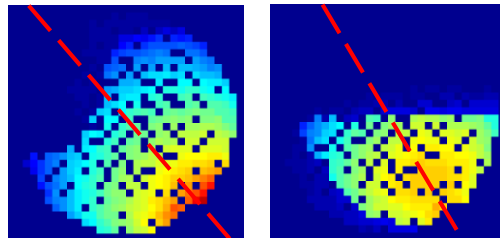
$r(\cdot)$  is a mirror function

# Global illumination effects in observation maps

- Inter-reflections



- Cast shadows



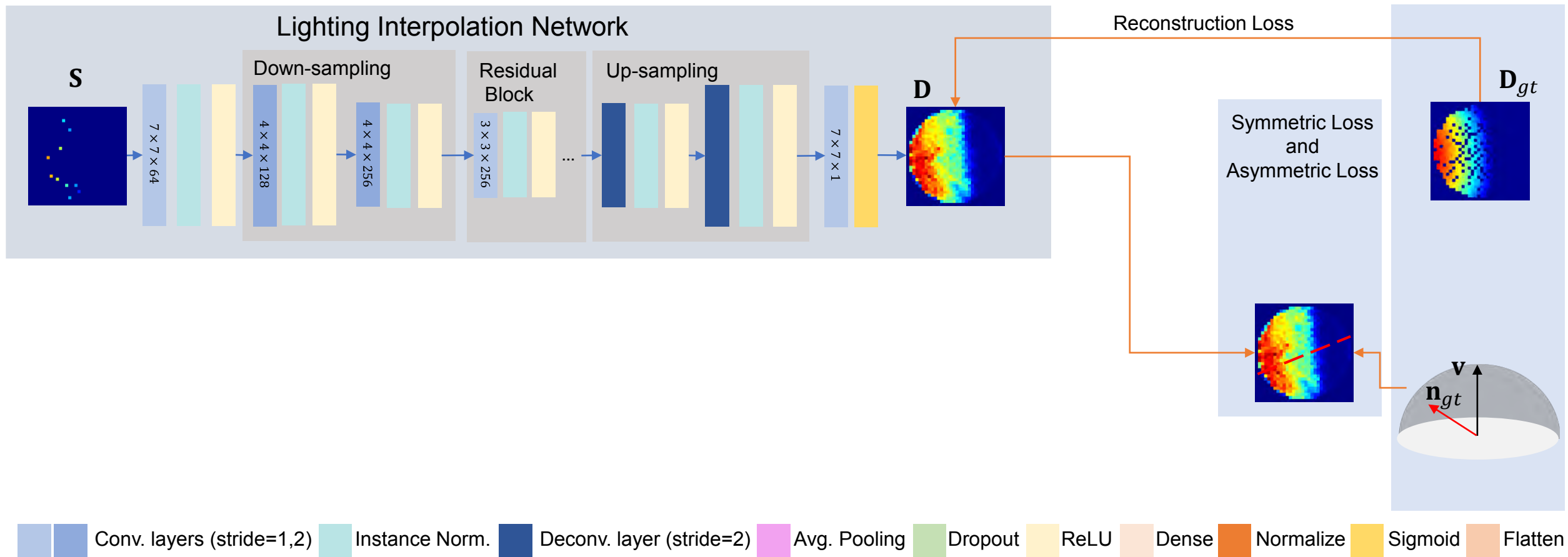
Loss functions of asymmetric

$$\mathcal{L}_a = \mathcal{L}_a(\mathbf{D}, \mathbf{n}) = \left| \|\mathbf{D} - r(\mathbf{D}), \mathbf{n}\|_1 - \eta \right|_1 + \lambda_c \left| \|p(\mathbf{D}) - r(p(\mathbf{D}), \mathbf{n})\|_1 - \eta \right|_1$$

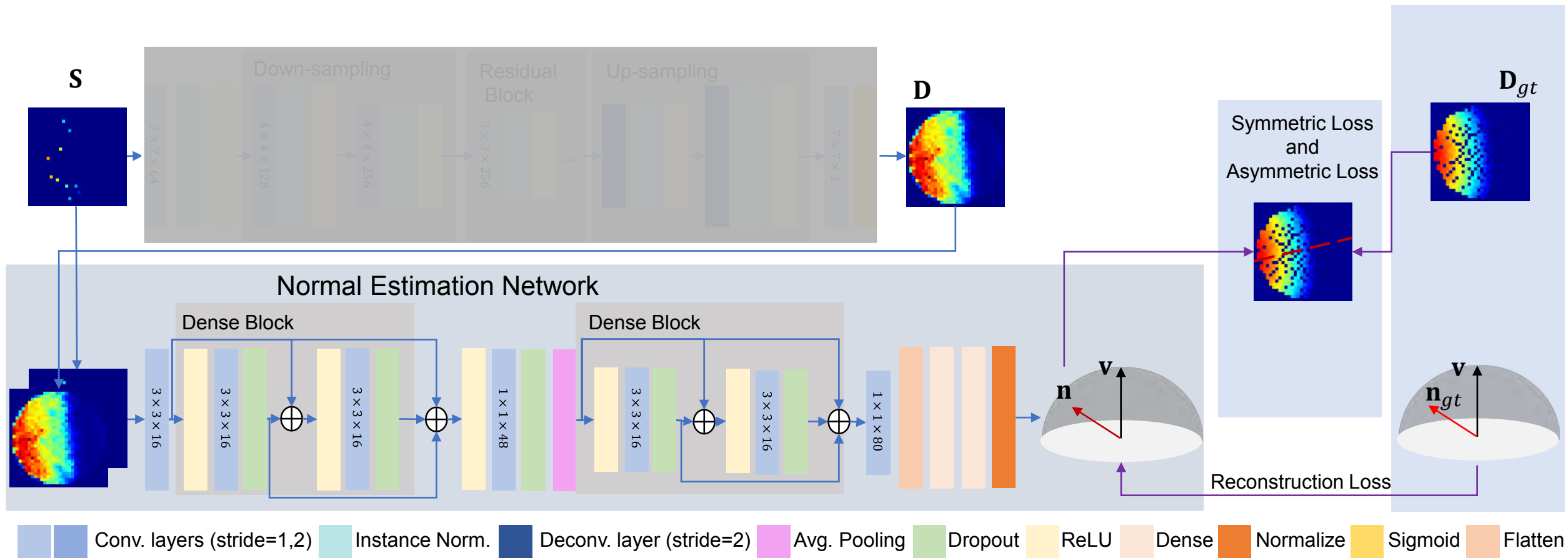
$p(\cdot)$  is a max pooling operation



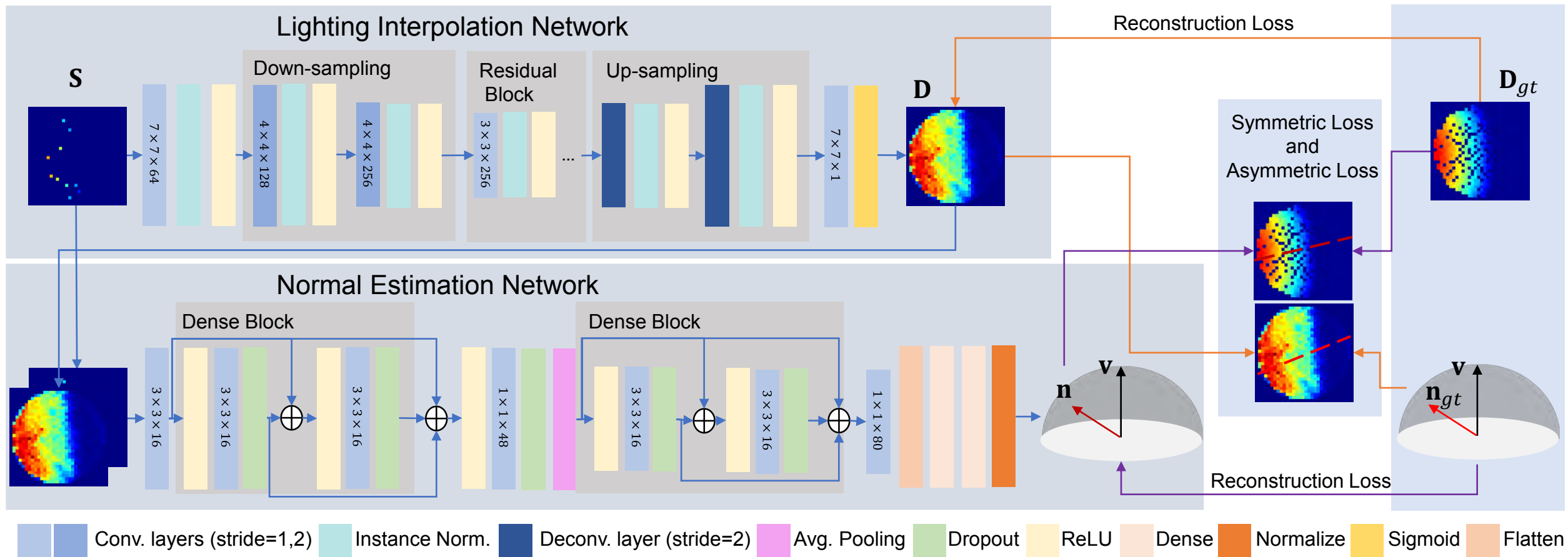
# Framework



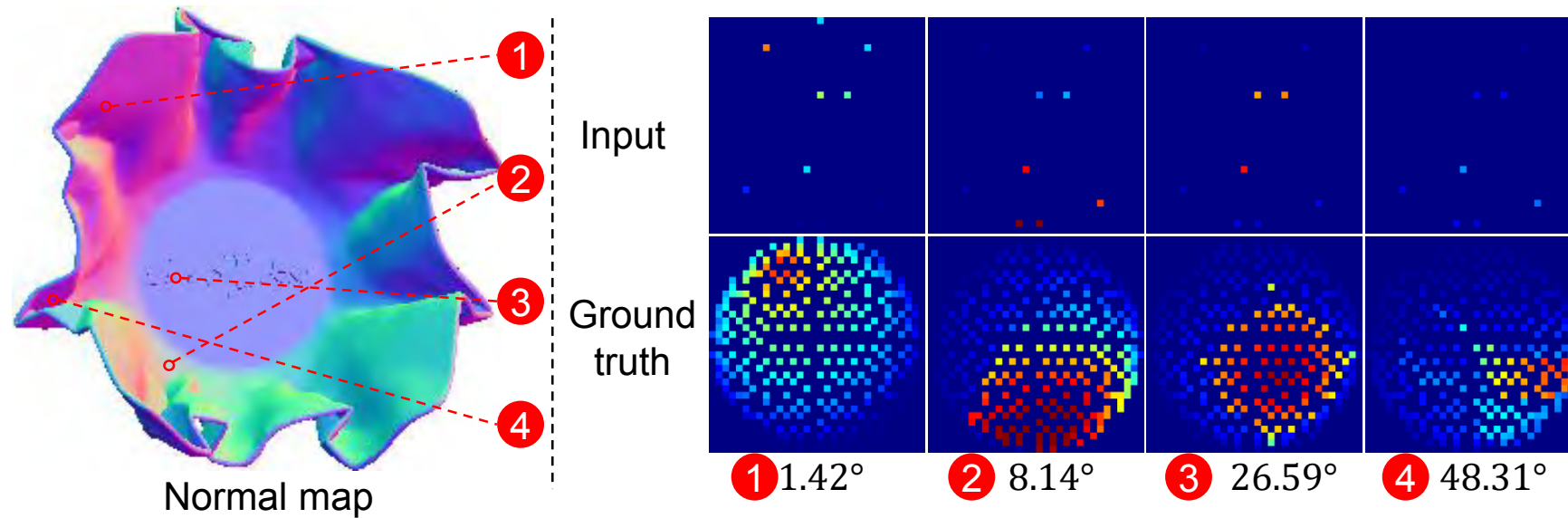
# Framework



# Framework

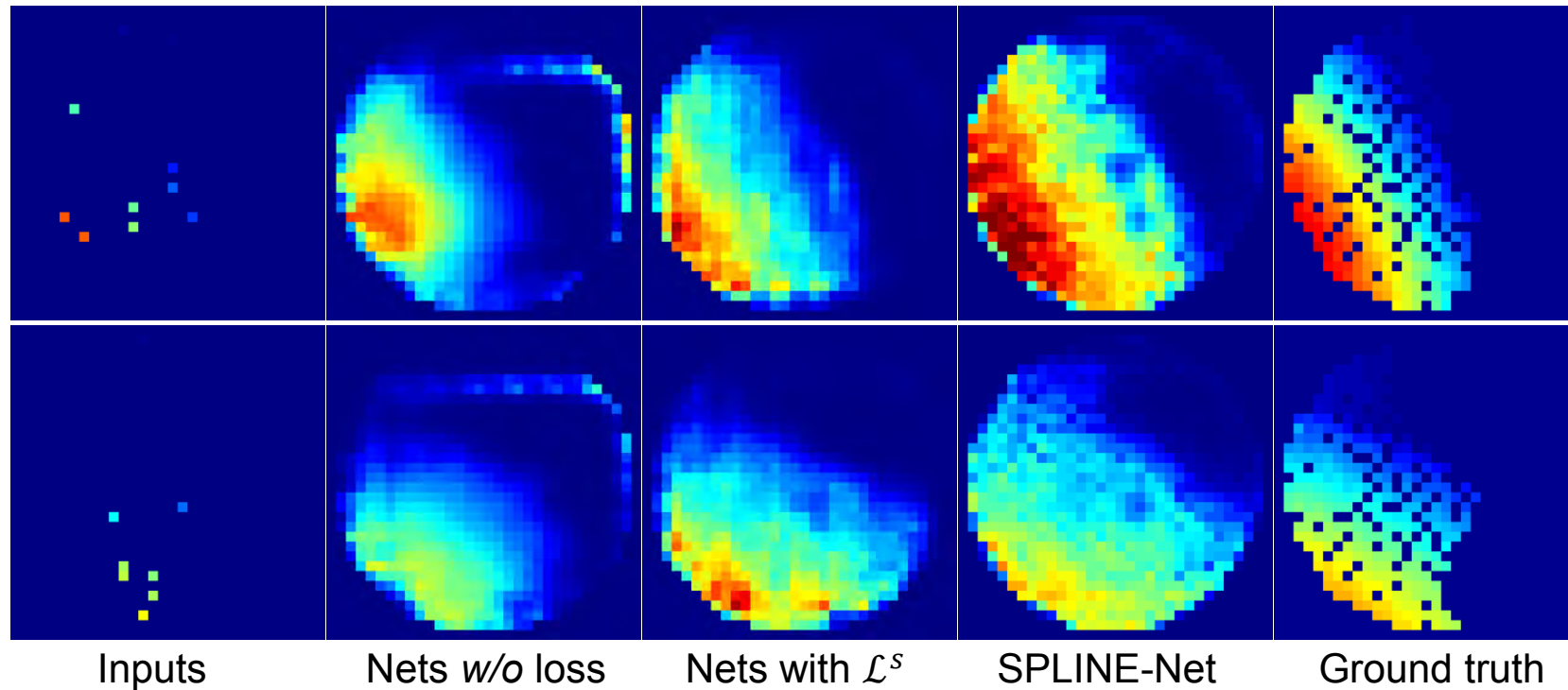


# Noise in sparse observation maps (inputs)



- More brighter pixels, less shadows
- More 'valid' pixels, more accurate results

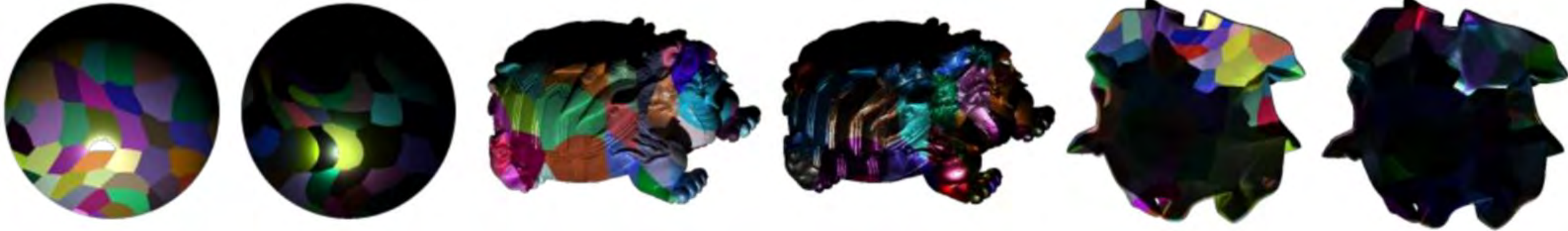
# Generated dense observation maps



- Symmetric loss and asymmetric loss help generate more accurate dense observation maps

# Benchmark results using Cycle-PS dataset

\*10 selected lights, 100 random trials



	PAPERBOWL		SPHERE		TURTLE		Avg.	PAPERBOWL		SPHERE		TURTLE		Avg.
	M	S	M	S	M	S		M	S	M	S	M	S	
LS	41.47	35.09	18.85	10.76	27.74	19.89	25.63	43.09	37.36	20.19	12.79	28.51	21.76	27.28
IW12	46.68	33.86	16.77	<b>2.23</b>	31.83	12.65	24.00	48.01	37.10	21.93	<b>3.19</b>	34.91	16.32	26.91
ST14	42.94	35.13	22.58	4.18	34.30	17.01	26.02	44.44	37.35	25.41	4.89	36.01	19.06	27.86
IA14	48.25	43.51	18.62	11.71	30.59	23.55	29.37	49.01	45.37	21.52	13.63	32.82	26.27	31.44
CNN-PS	37.14	23.40	17.44	6.99	22.86	10.74	19.76	38.45	26.90	18.25	9.04	23.91	14.36	21.82
SPLINE-Net	<b>29.87</b>	<b>18.65</b>	<b>6.59</b>	3.82	<b>15.07</b>	<b>7.85</b>	<b>13.64</b>	<b>33.99</b>	<b>23.15</b>	<b>9.21</b>	6.69	<b>17.35</b>	<b>12.01</b>	<b>17.07</b>

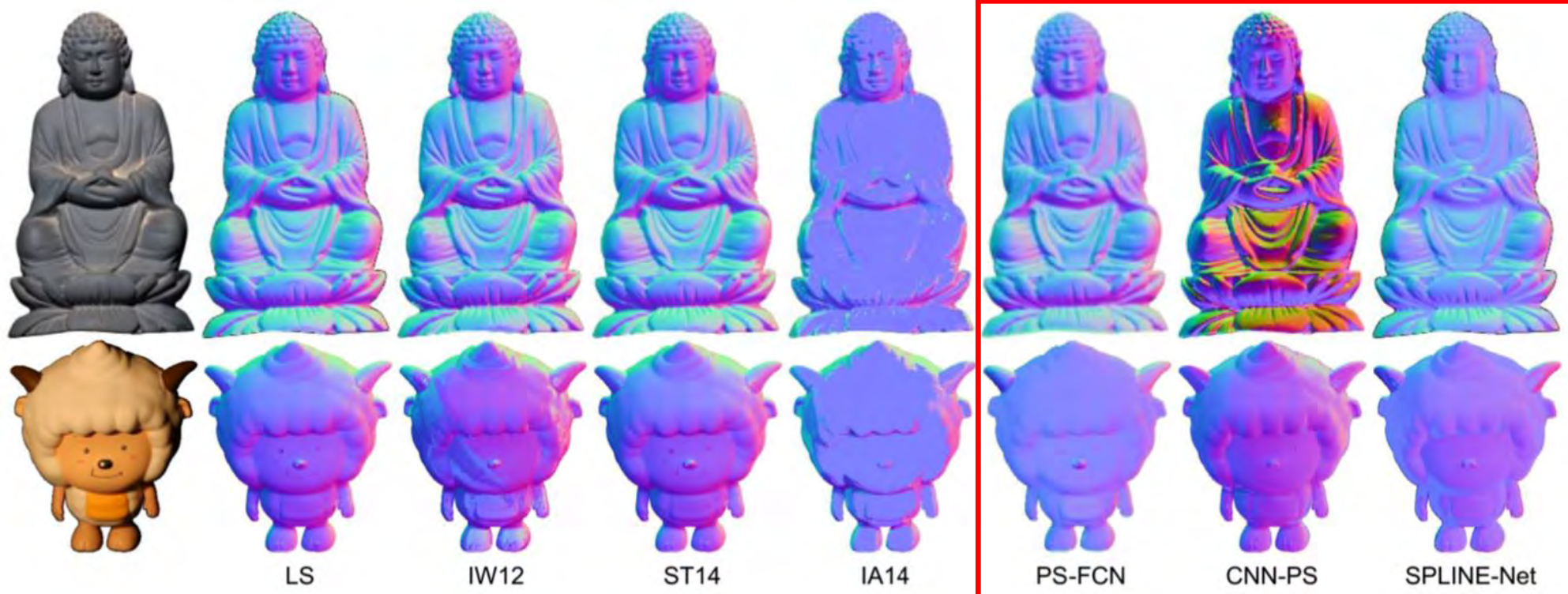
# Benchmark results using “DiLiGenT”

\*10 selected lights, 100 random trials



Methods	BALL	BEAR	BUDDHA	CAT	COW	GOBLET	HARVEST	POT1	POT2	READING	Avg.
LS	4.41	9.05	15.62	9.03	26.42	19.59	31.31	9.46	15.37	20.16	16.04
IW12	<b>3.33</b>	7.62	13.36	8.13	25.01	18.01	29.37	8.73	14.60	16.63	14.48
ST14	5.24	9.39	15.79	9.34	26.08	19.71	30.85	9.76	15.57	20.08	16.18
IA14	12.94	16.40	20.63	15.53	18.08	18.73	32.50	<b>6.28</b>	14.31	24.99	19.04
CNN-PS	17.86	13.08	19.25	15.67	19.28	21.56	21.52	16.95	18.52	21.30	18.50
Nets w/o loss	6.06	7.01	10.69	8.38	10.39	11.37	<b>19.02</b>	9.42	12.34	16.18	11.09
Nets with $\mathcal{L}^s$	5.04	<b>5.89</b>	10.11	7.79	9.38	10.84	19.03	8.91	<b>11.47</b>	<b>15.87</b>	10.43
SPLINE-Net	4.96	5.99	<b>10.07</b>	<b>7.52</b>	<b>8.80</b>	<b>10.43</b>	19.05	8.77	11.79	16.13	<b>10.35</b>

# Open problems for data-driven methods

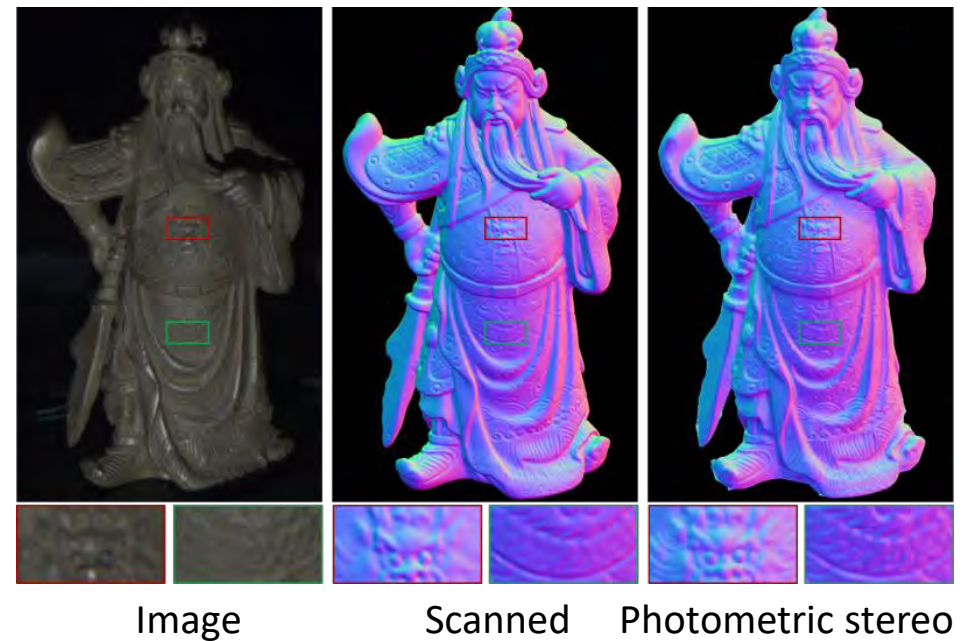


- When input light becomes sparse, data-driven methods does not outperform baseline (L2) for diffuse datasets



# Open problems for dataset

- “DiLiGenT” only provides the “ground truth” of scanned shape
  - How to measure the true surface normal precisely
- For more delicate structures, a scanned shape is too “blurred” to evaluate photometric stereo
  - Integrating scanned shapes and photometric stereo for very high quality 3D modeling



# Acknowledgement

- Many slides are adopted from my collaborators:



Yasuyuki Matsushita  
Osaka University



Qian Zheng  
Nanyang Technological University



Hiroaki Santo  
Osaka University



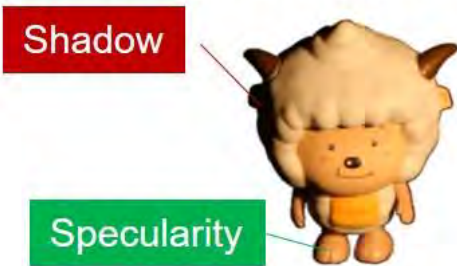
Guanying Chen  
University of Hong Kong

### General-1: Uncalibrated



[CVPR 10]

### General-2: Robust



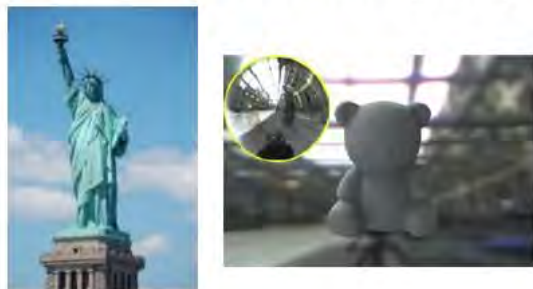
[ACCV 10]

### General-3: General material



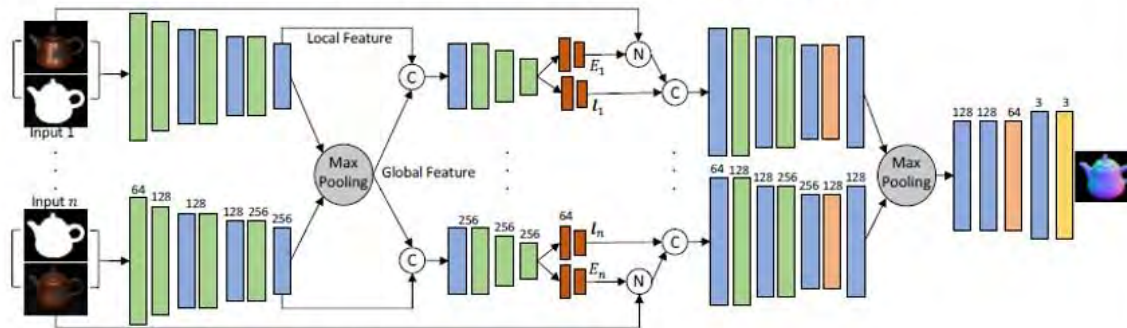
[CVPR 12, ECCV 12, TPAMI 14, ICCV 17, TIP 19, TPAMI19]

### General-4: General lighting



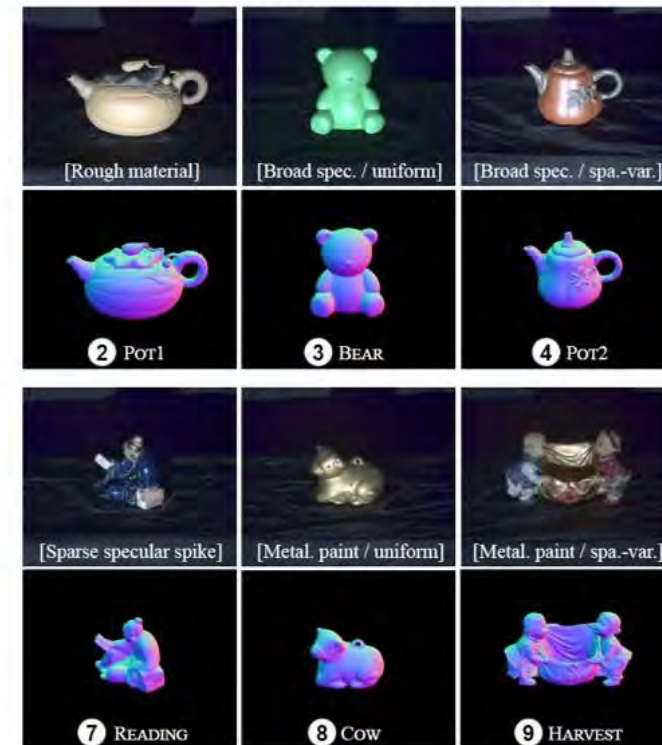
[3DV 14, CVPR 18]

### General-5: Uncalibrated + general material



[CVPR 19, ICCV 19]

### Benchmark dataset



[CVPR 16, TPAMI19]

# Thank You!

# Q&A

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