

*CVPR2013*

# Photometric Ambient Occlusion

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Cornell University

# Motivation

## A collage of 30 images of famous world landmarks and historical sites. The images are arranged in a grid-like fashion, with some overlapping. The landmarks include: the Sphinx, Statue of Liberty, Colosseum, Eiffel Tower, Taj Mahal, Leaning Tower of Pisa, Great Wall of China, and many others. The images are in various colors and sizes, creating a vibrant and diverse visual representation of world heritage.

## A collage of 40 images of famous world landmarks and historical sites. The images are arranged in a grid-like fashion, with some overlapping. The landmarks include: the Sphinx, Statue of Liberty, Colosseum, Eiffel Tower, Taj Mahal, Leaning Tower of Pisa, Great Wall of China, and many others. The images are in various colors and sizes, creating a vibrant and diverse visual representation of world heritage.

# Motivation



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✓ Geometry

# Motivation



✓ Geometry  
? Albedo

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- ✓ Geometry
- ? Albedo
- ? Illumination

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- ✓ Geometry
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**Albedo**  
**Illumination**  
**Local Visibility**

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## Bag of Observations

Varying and  
unknown illumination



**Albedo**  
**Illumination**  
**Local Visibility**

# Key Insight



## Bag of Observations

Varying and  
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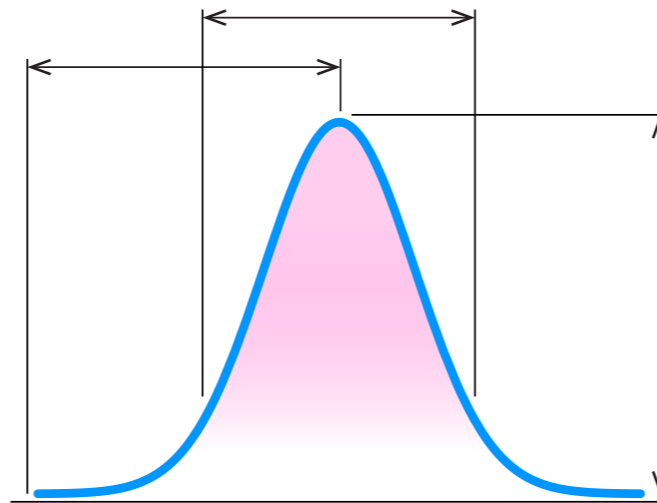
**Albedo**  
**Illumination**  
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**Pixel Statistics**

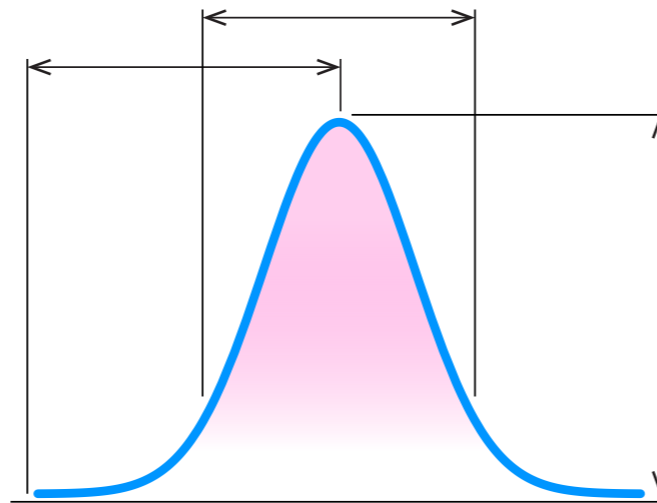
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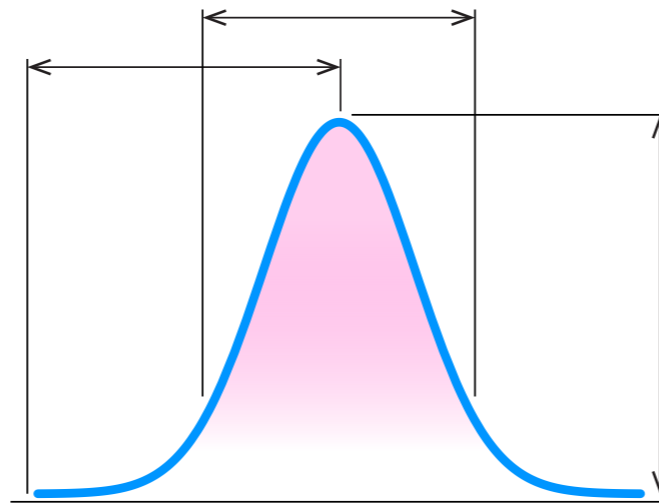
**Albedo  
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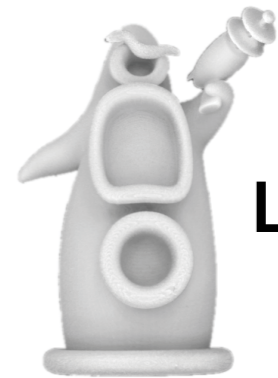


**Pixel Statistics**

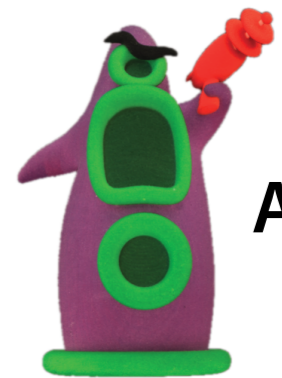


**Albedo  
Illumination  
Local Visibility**

# Key Insight



**Local Visibility**

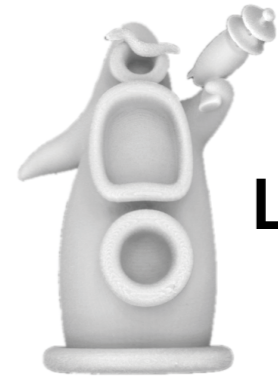


**Albedo**

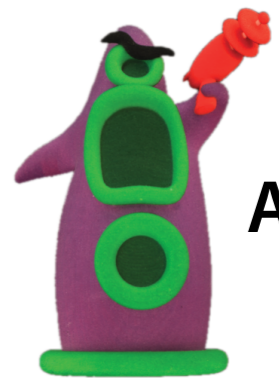


**Illumination**

# Overview



**Local Visibility**

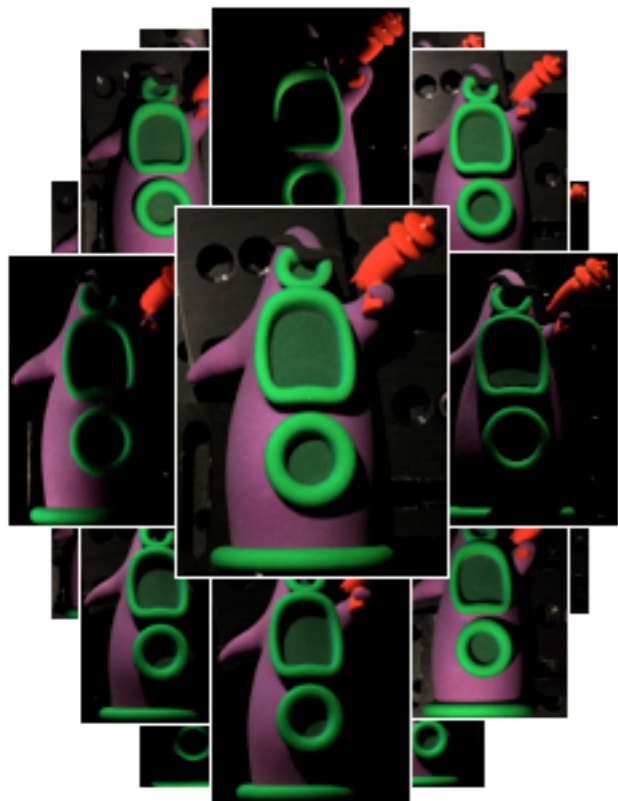


**Albedo**



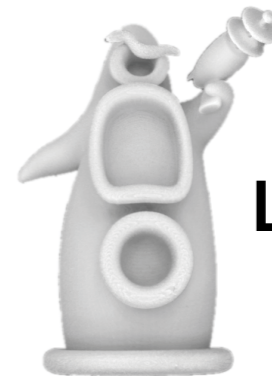
**Illumination**

# Overview

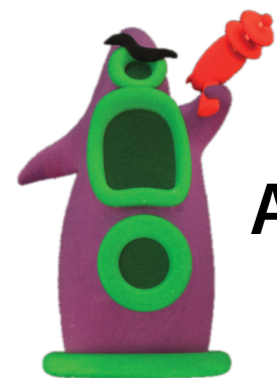


**Image Stack**

Varying and  
unknown illumination



**Local Visibility**

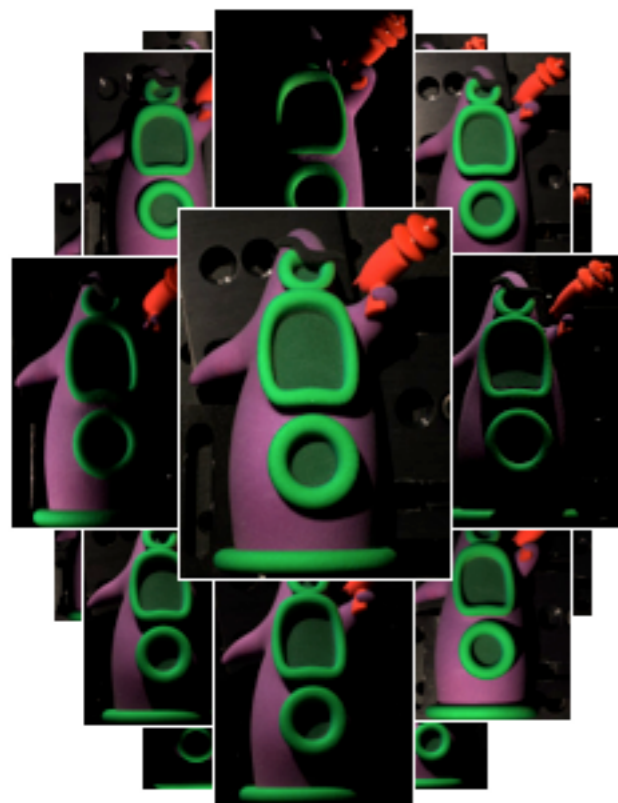


**Albedo**

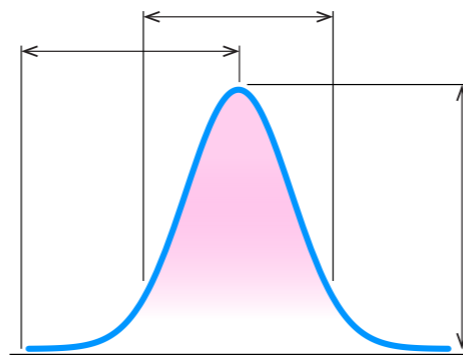


**Illumination**

# Overview



**Image Stack**  
Varying and  
unknown illumination



**Pixel Statistics**



**Local Visibility**

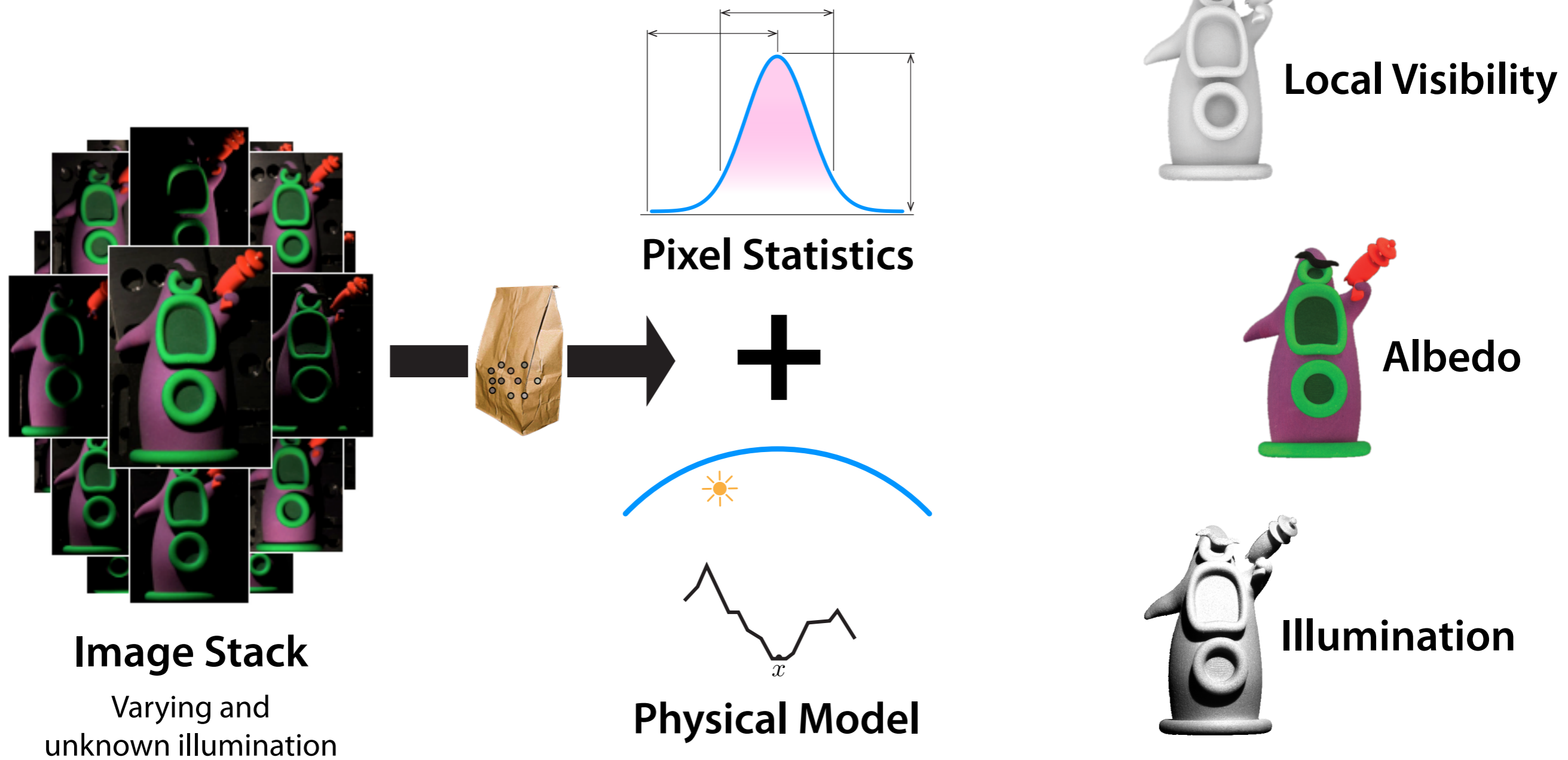


**Albedo**

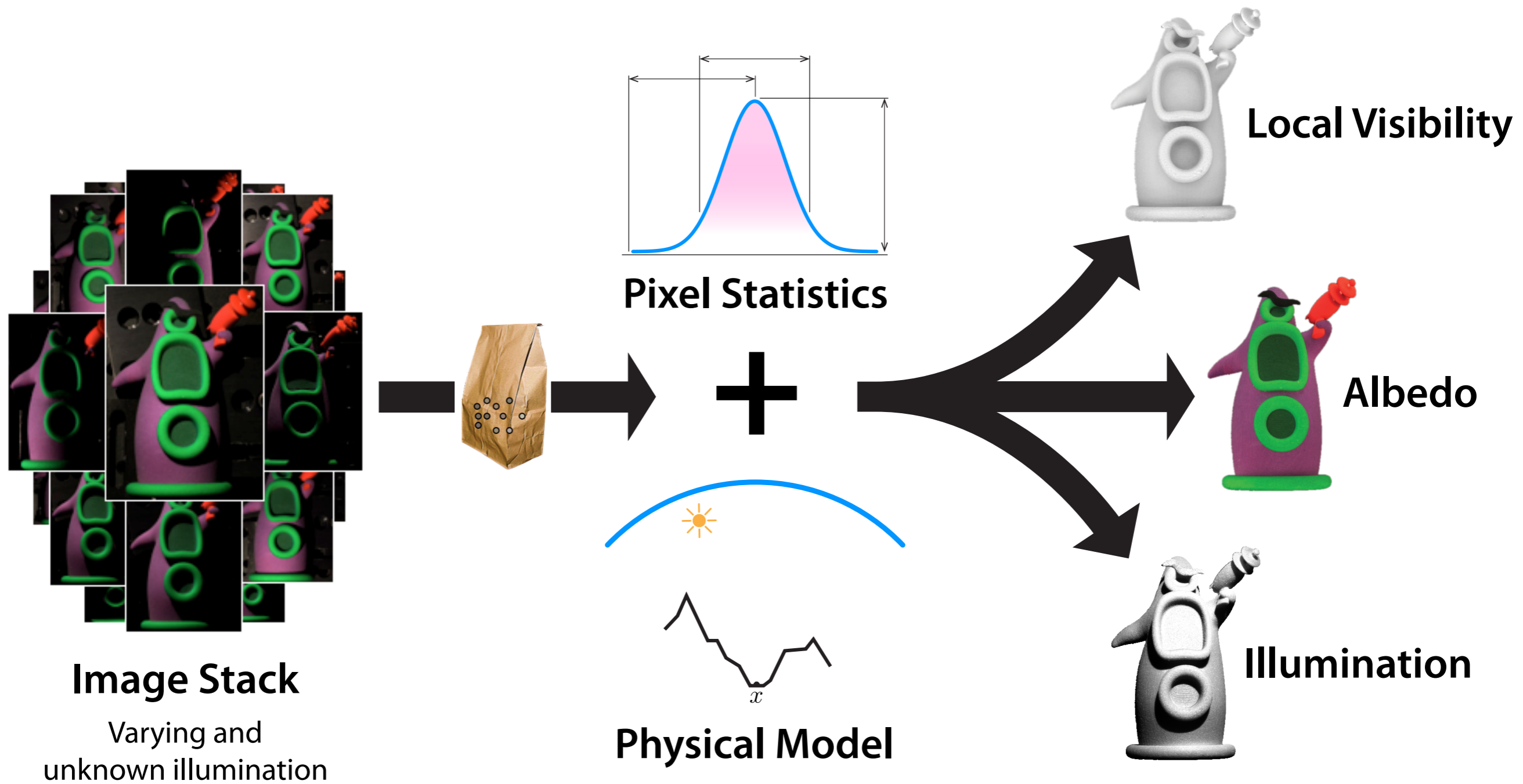


**Illumination**

# Overview



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- New intrinsic image decomposition

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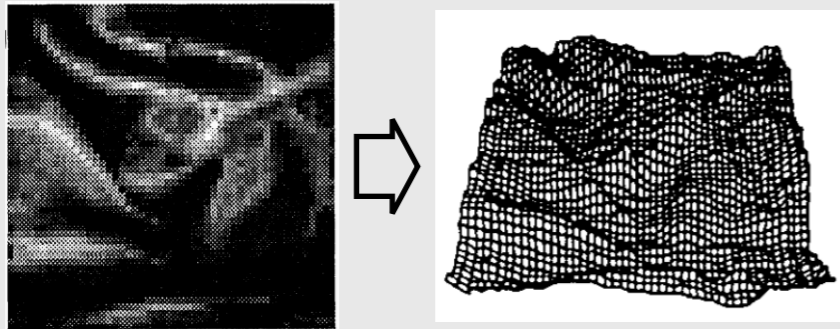
# Contributions

- New intrinsic image decomposition
  - Albedo + Lighting + **Local Visibility**
- First image space local visibility algorithm
  - Simple statistical approach
  - No geometry needed
  - Per-pixel: no smoothness prior

# Related Work

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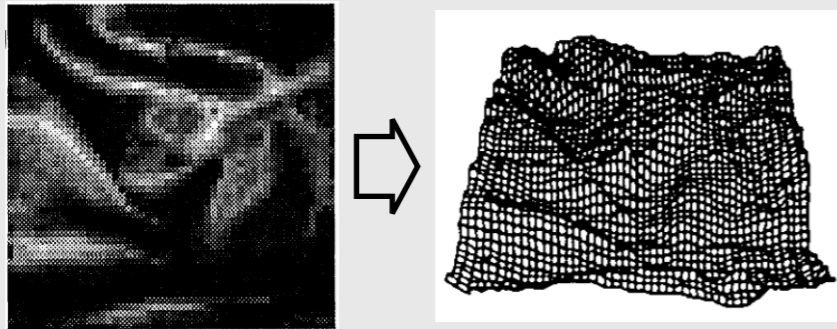
## Shape from Local Visibility



[Langer & Zucker, JOSA1994]

# Related Work

## Shape from Local Visibility

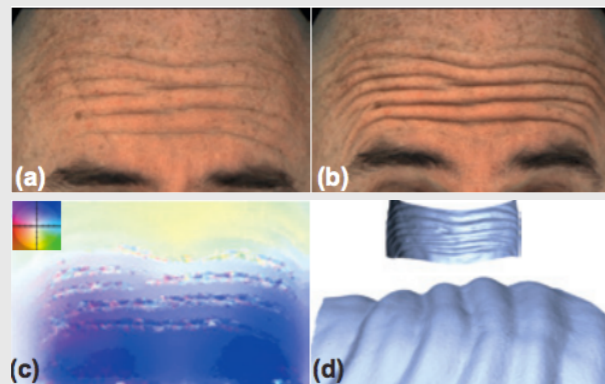


[Langer & Zucker, JOSA1994]

## Local Visibility in CV



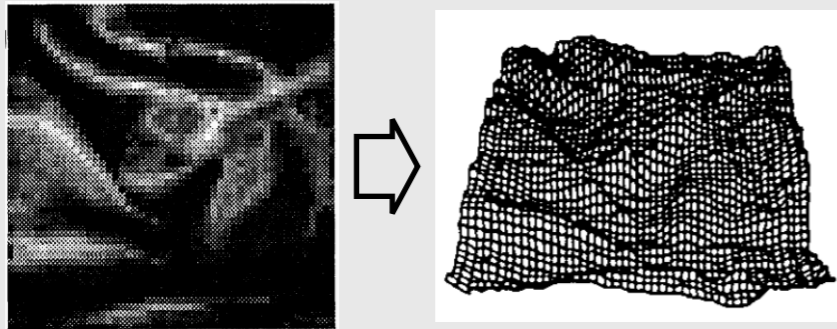
[Laffont et al., TOG 2012]



[Beeler et al., ECCV 2012]

# Related Work

## Shape from Local Visibility

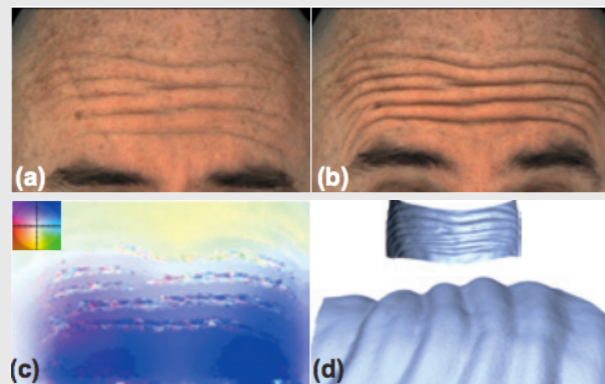


[Langer & Zucker, JOSA1994]

## Local Visibility in CV

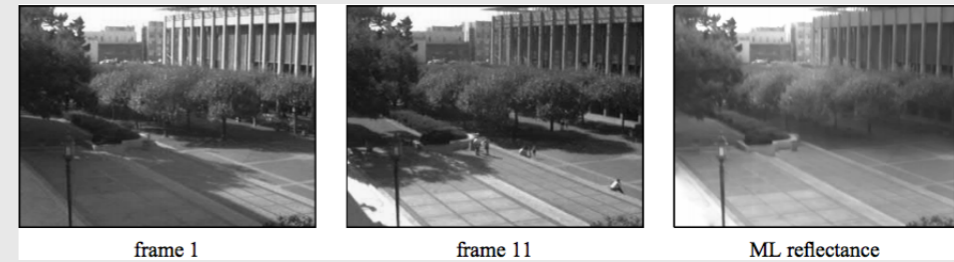


[Laffont et al., TOG 2012]

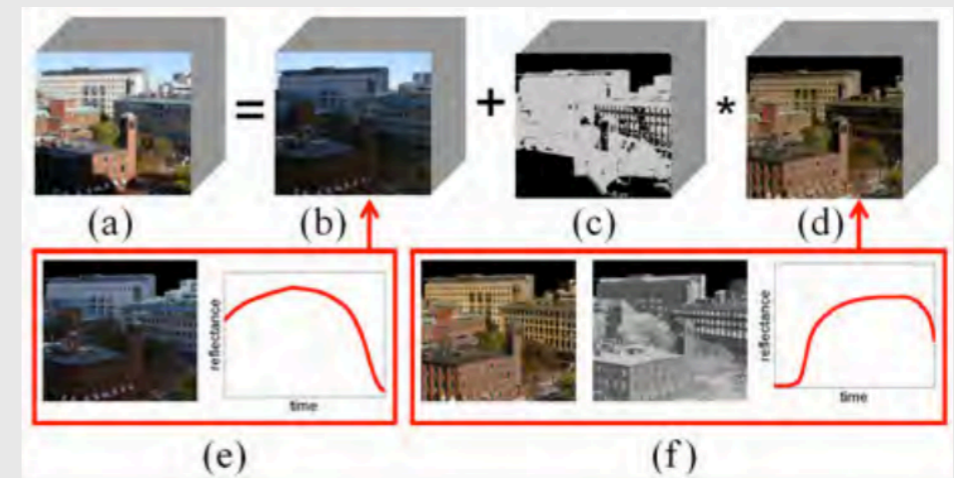


[Beeler et al., ECCV 2012]

## Statistical Image Properties



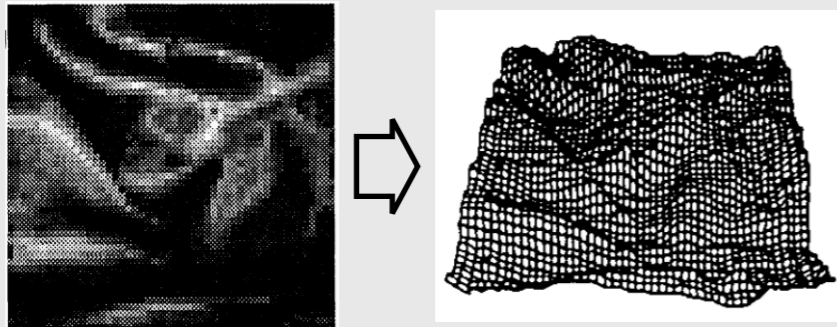
[Yair Weiss, ICCV2001]



[Sunkavalli et al., TOG2007]

# Related Work

## Shape from Local Visibility

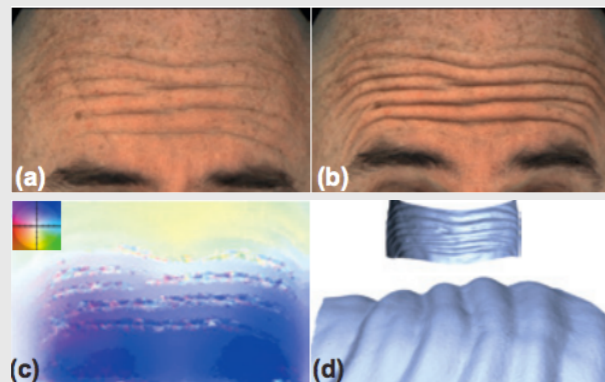


[Langer & Zucker, JOSA1994]

## Local Visibility in CV

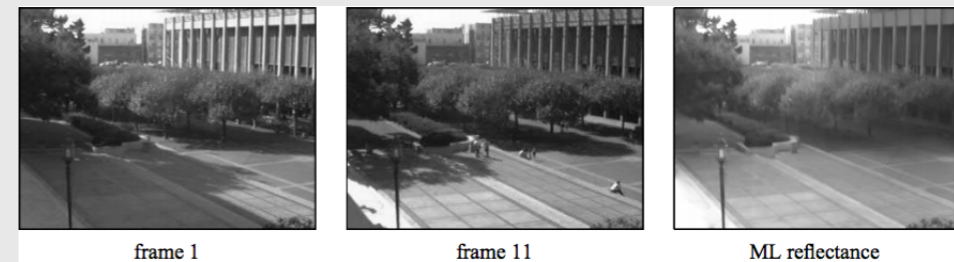


[Laffont et al., TOG 2012]

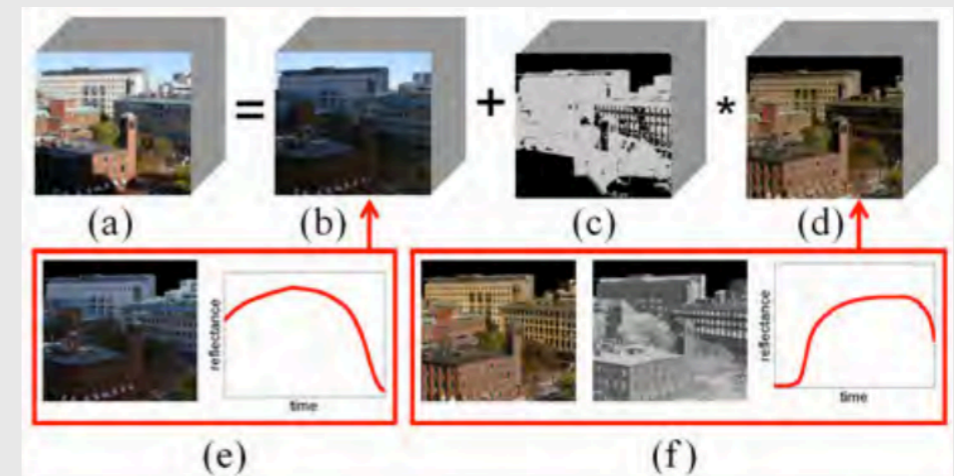


[Beeler et al., ECCV 2012]

## Statistical Image Properties

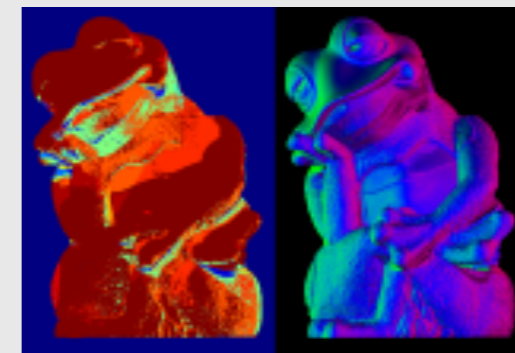


[Yair Weiss, ICCV2001]



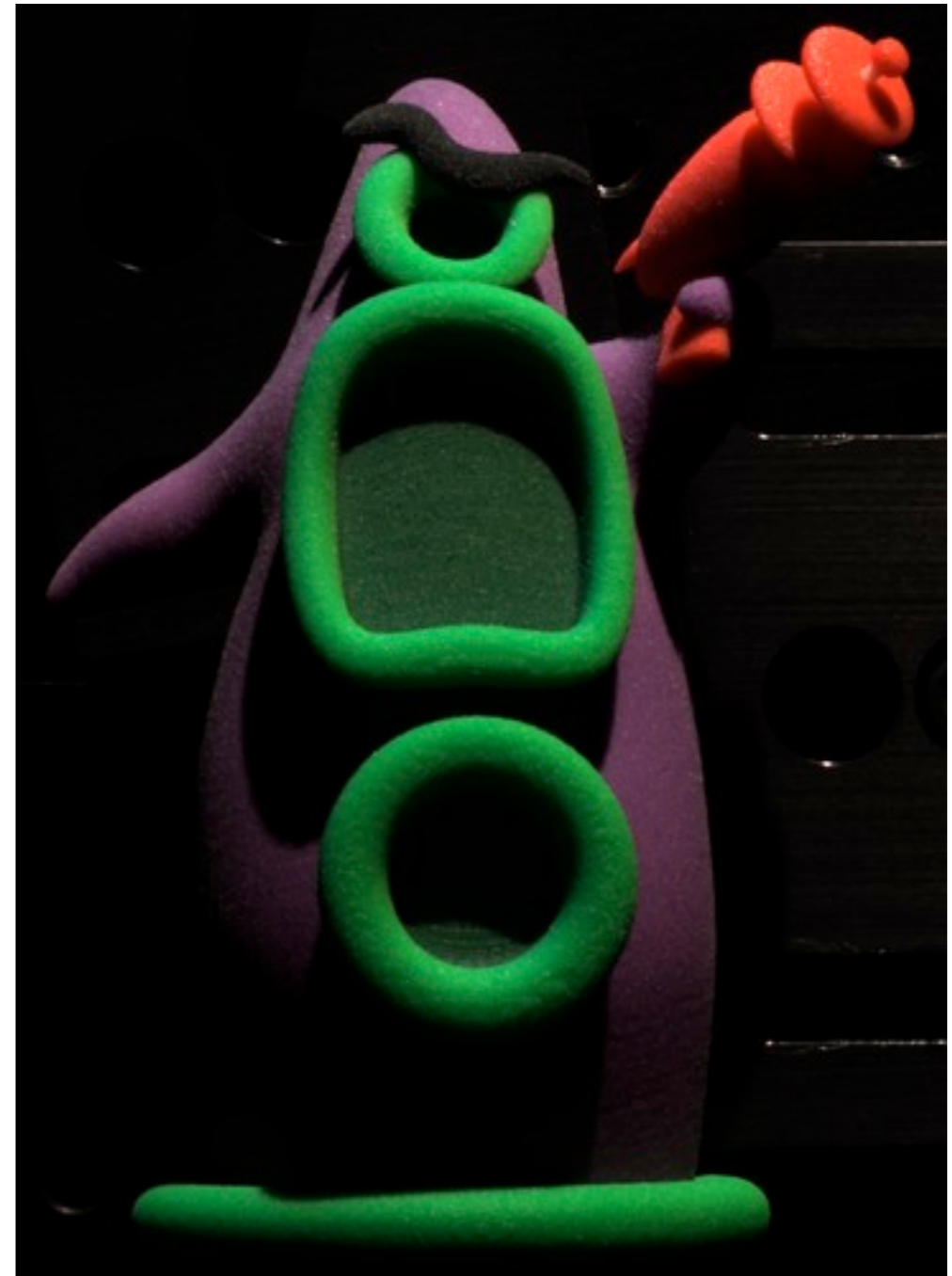
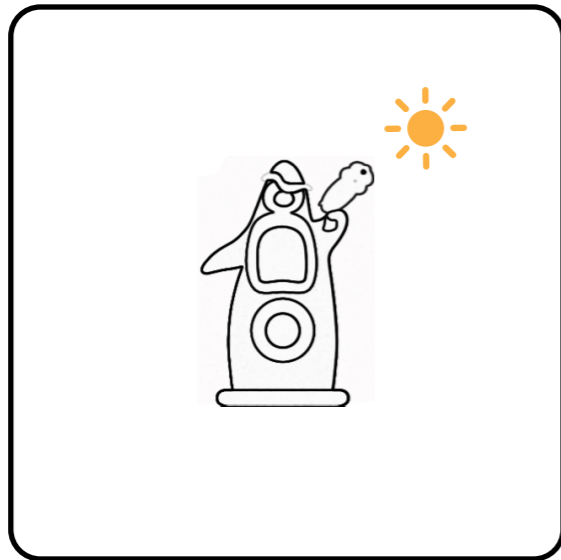
[Sunkavalli et al., TOG2007]

## Photometric Stereo

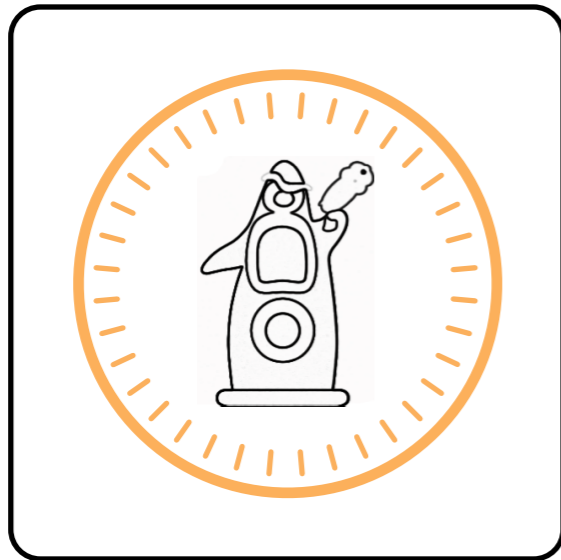


[Sunkavalli et al., ECCV2010]

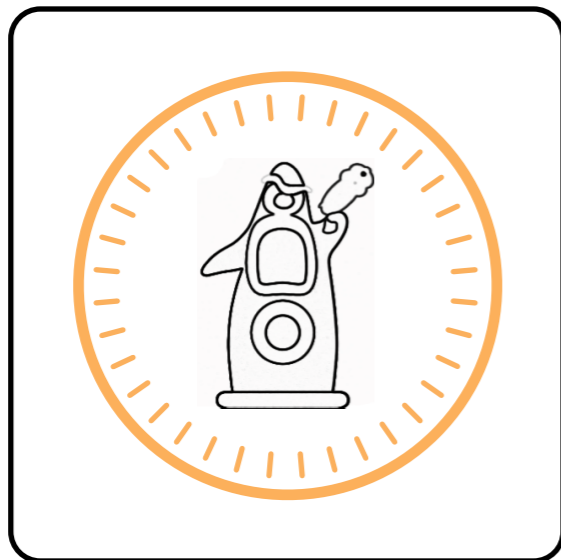
# Local Visibility



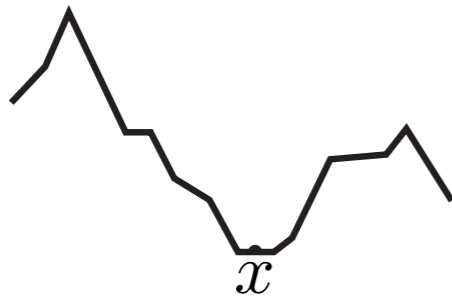
# Local Visibility



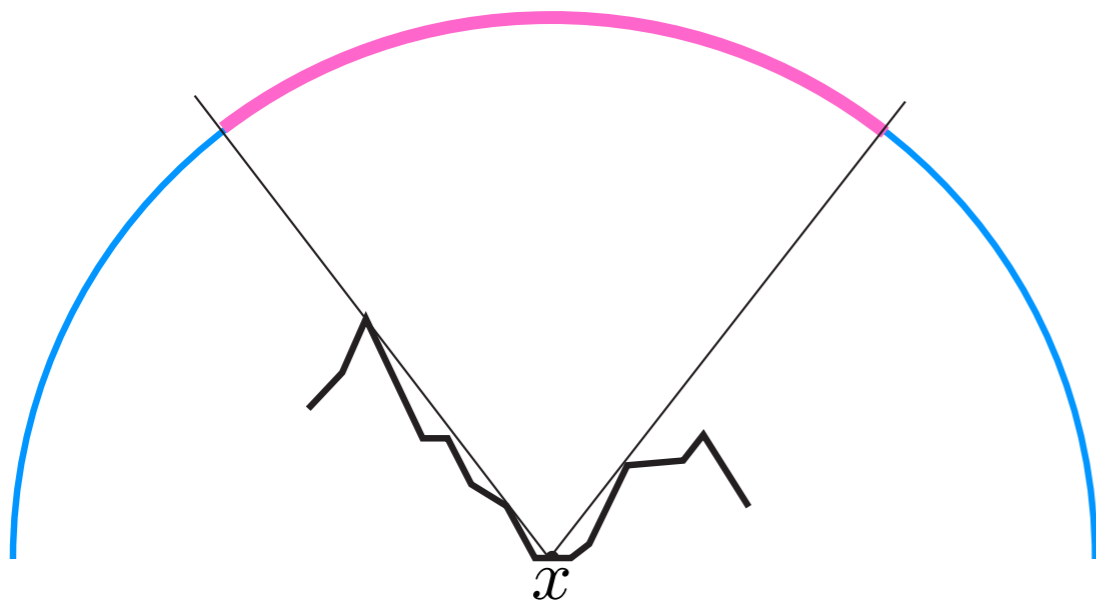
# Local Visibility



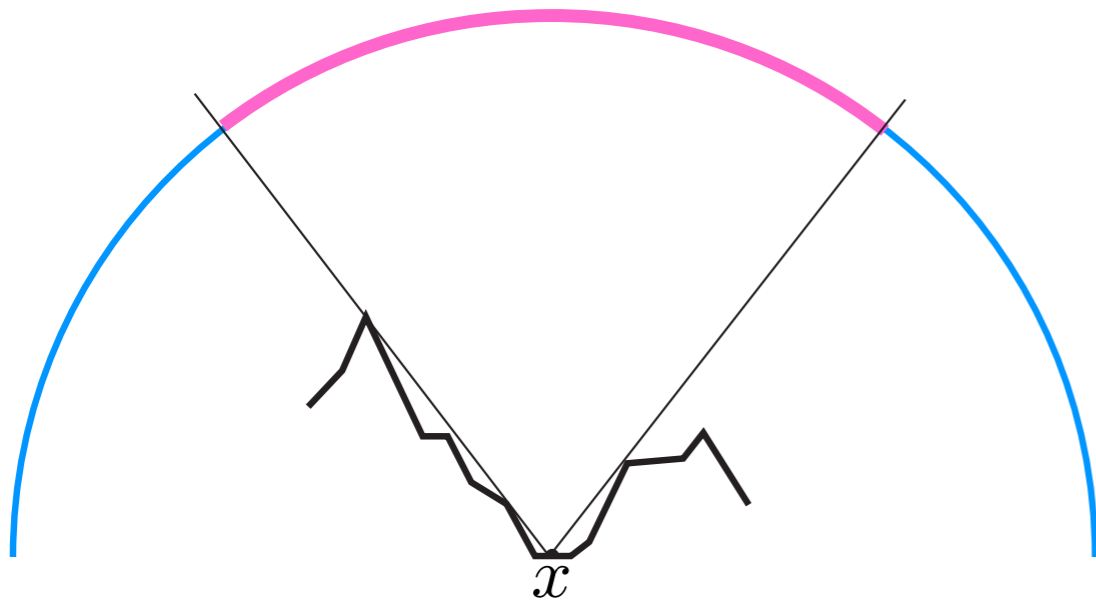
# Ambient Occlusion



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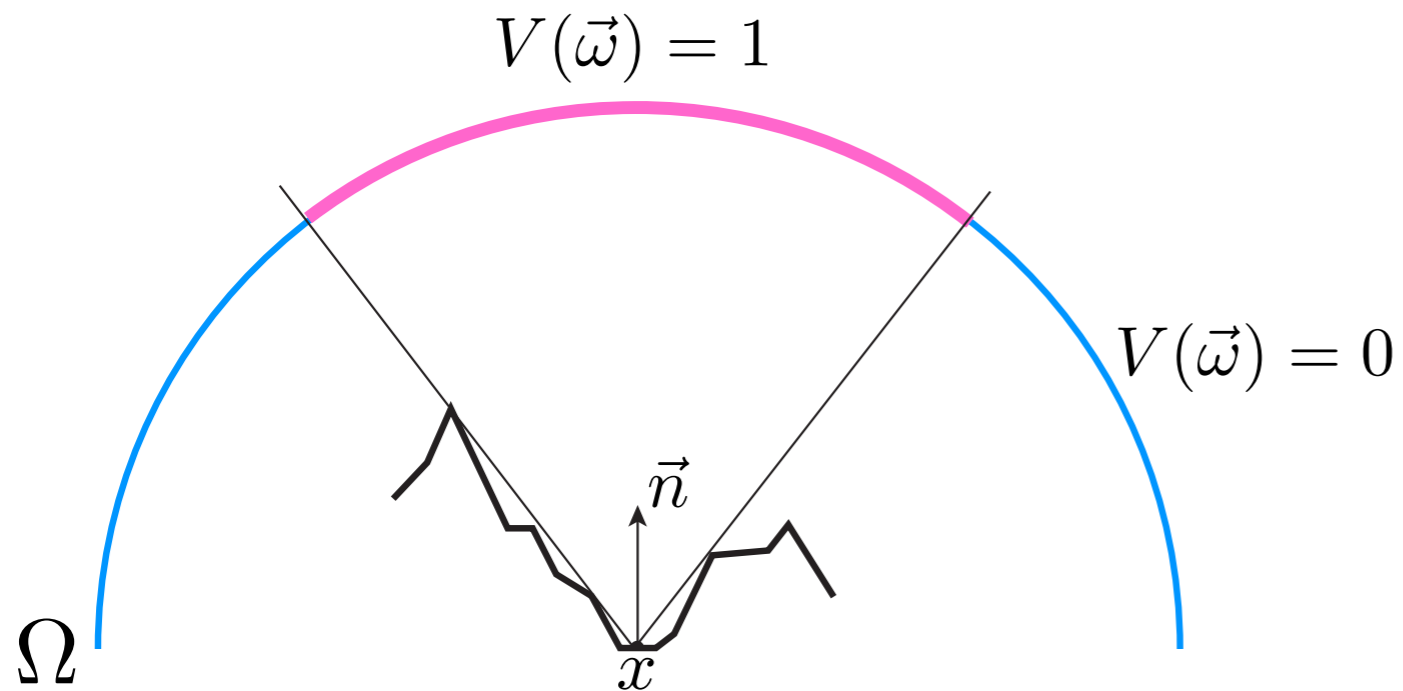


# Ambient Occlusion



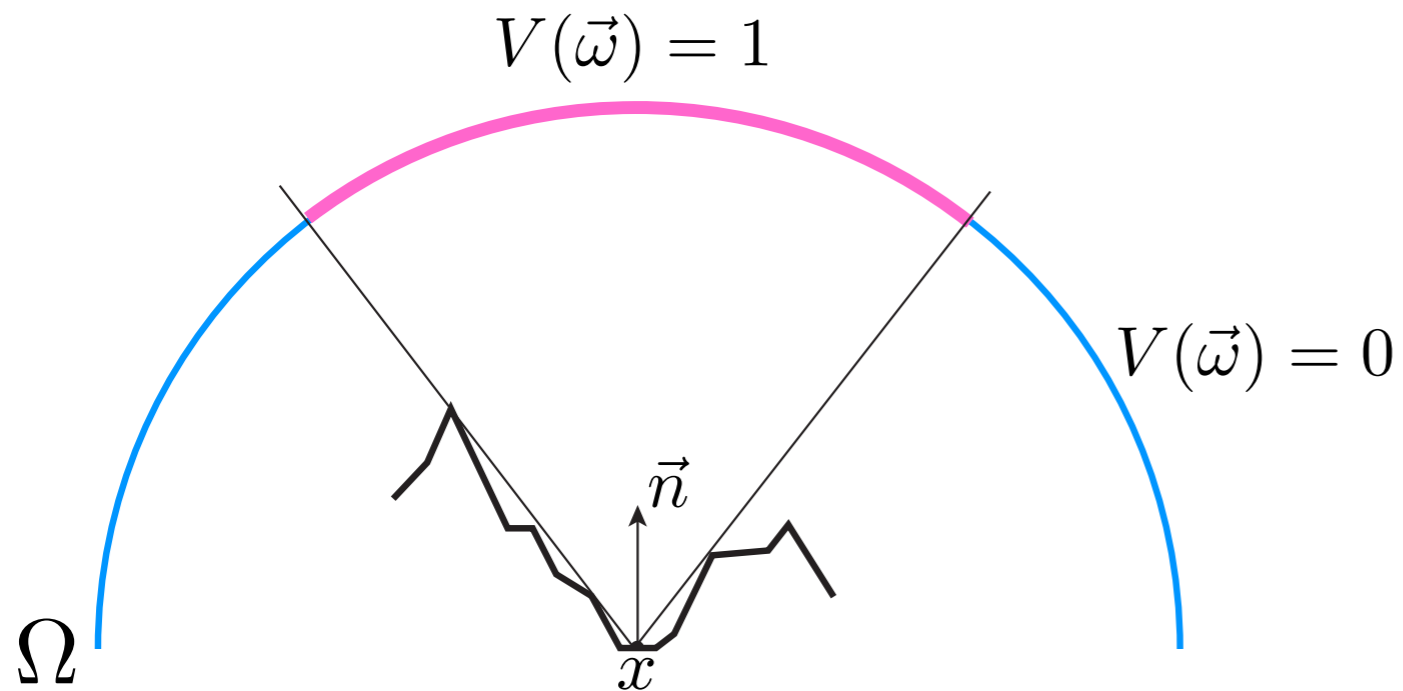
$$AO = \frac{1}{\pi} \int_{\Omega} V(\vec{\omega}) \langle \vec{n}, \vec{\omega} \rangle d\omega$$

# Ambient Occlusion

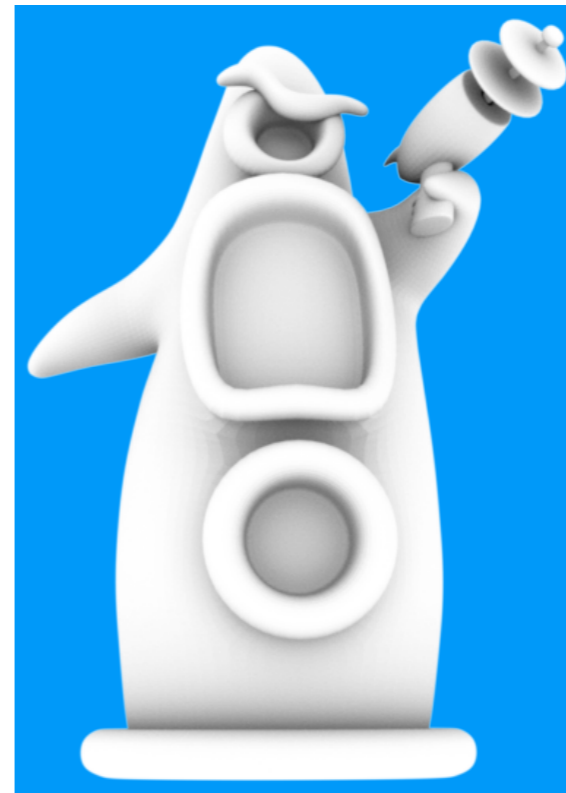


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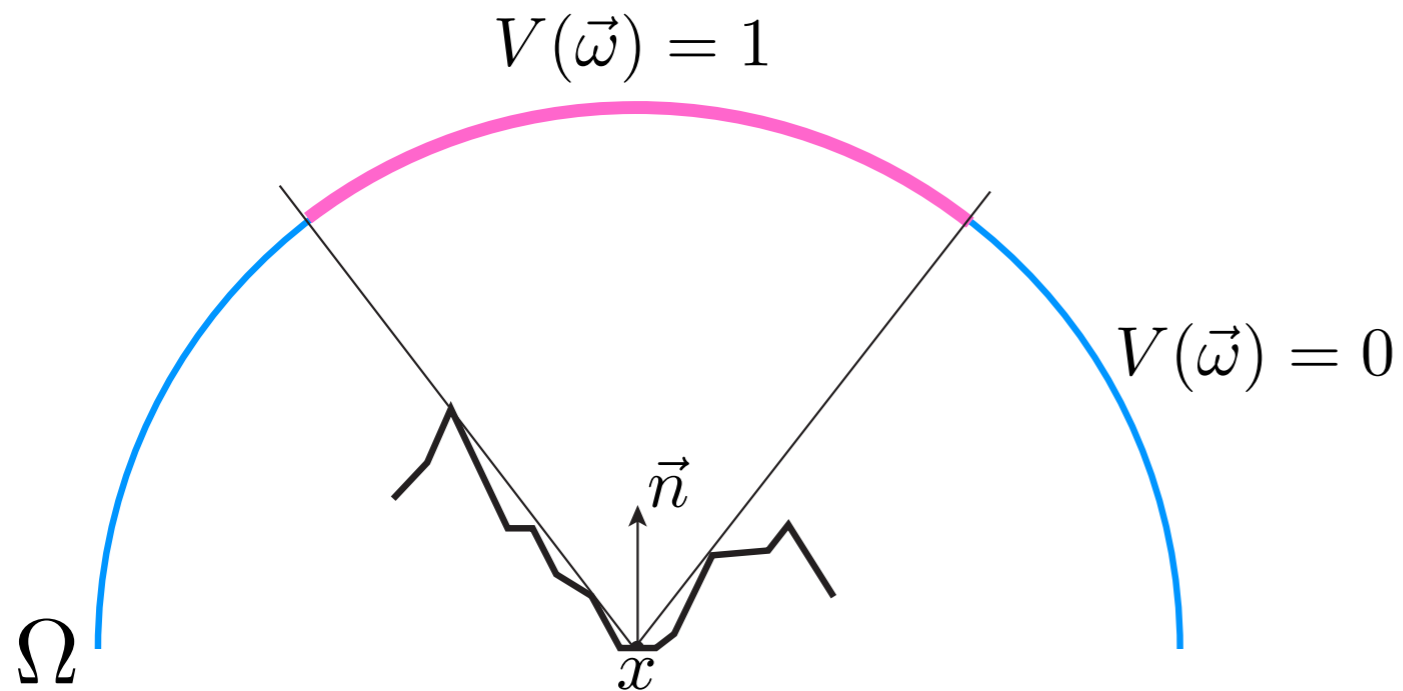


$$AO = \frac{1}{\pi} \int_{\Omega} V(\vec{\omega}) \langle \vec{n}, \vec{\omega} \rangle d\omega$$

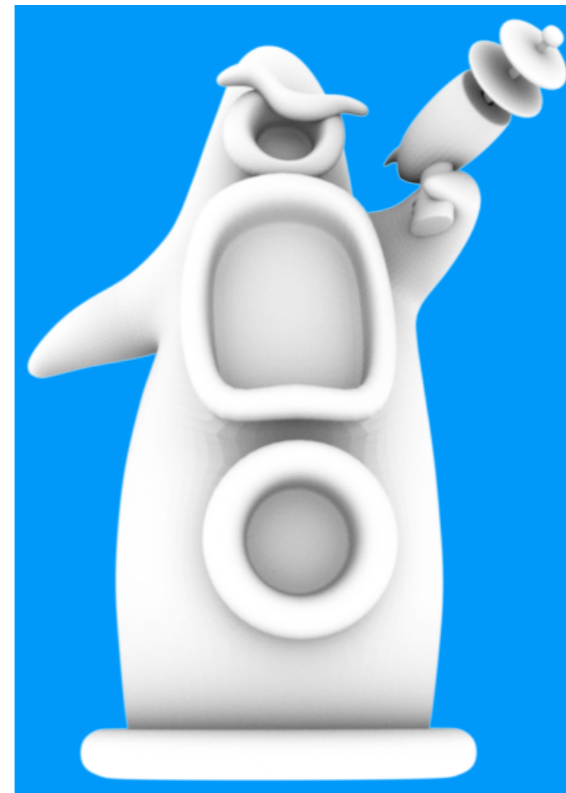


Ambient Occlusion  
(simulated)

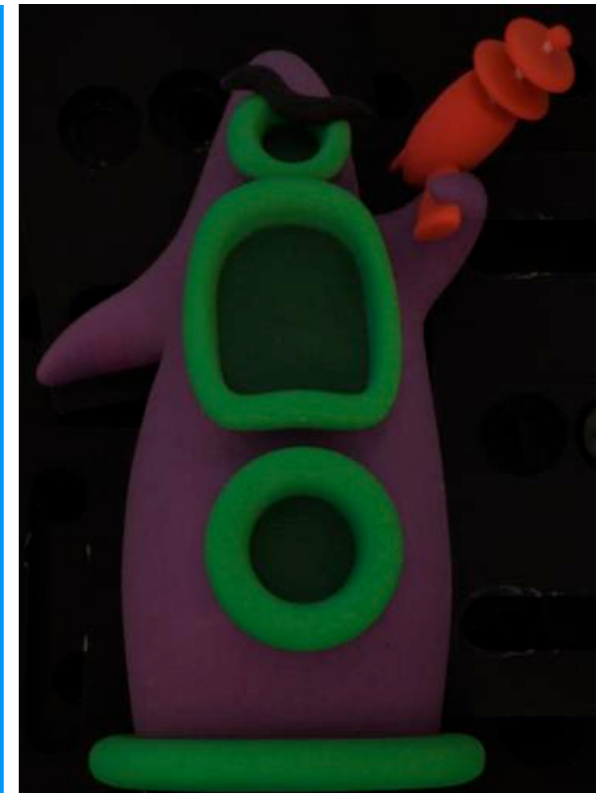
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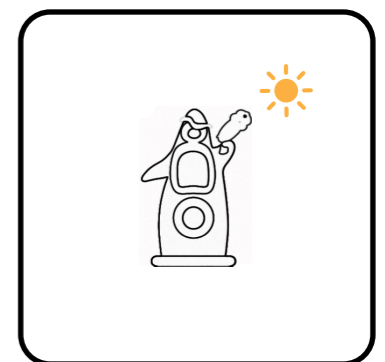
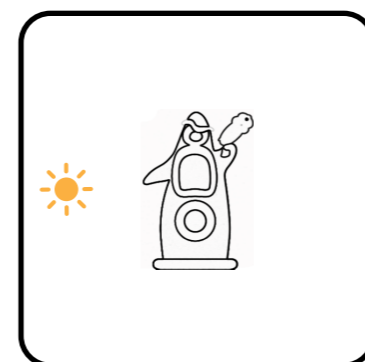
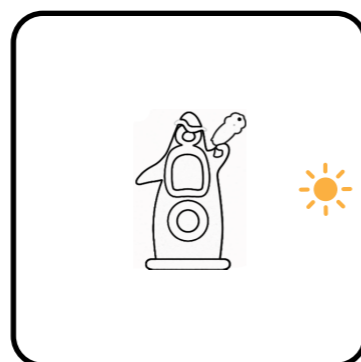
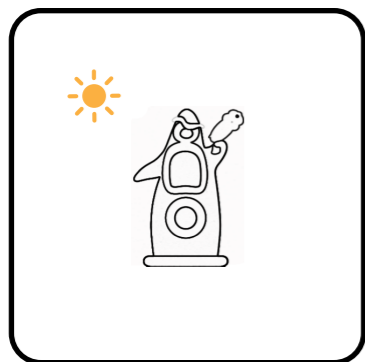
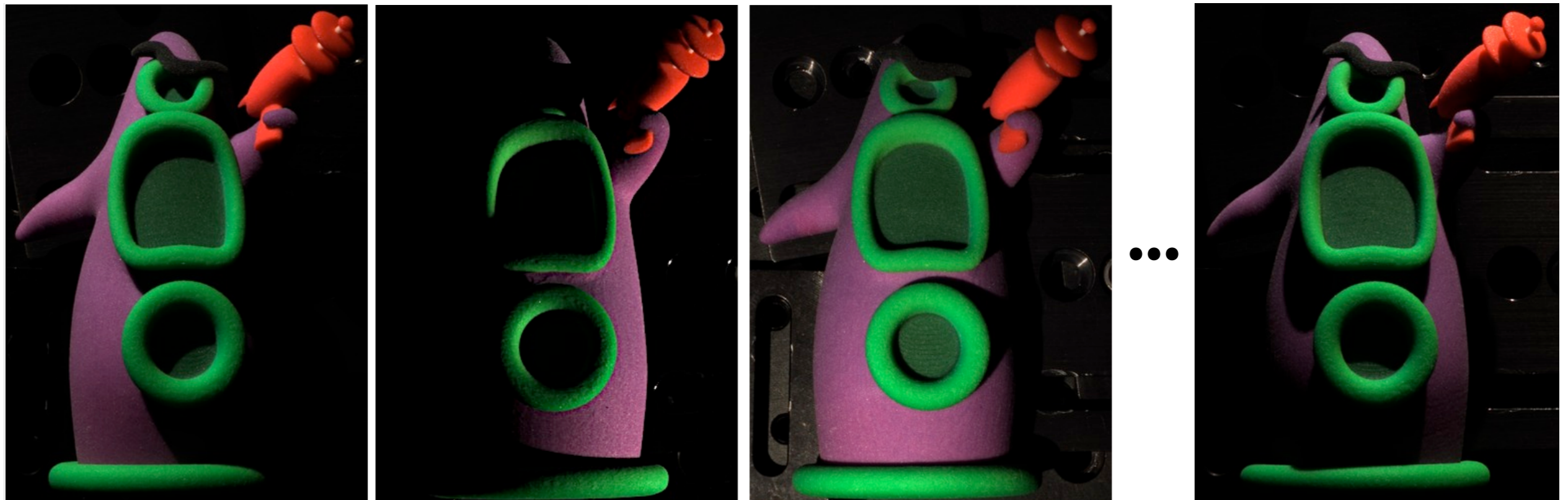
Ambient Occlusion  
(simulated)



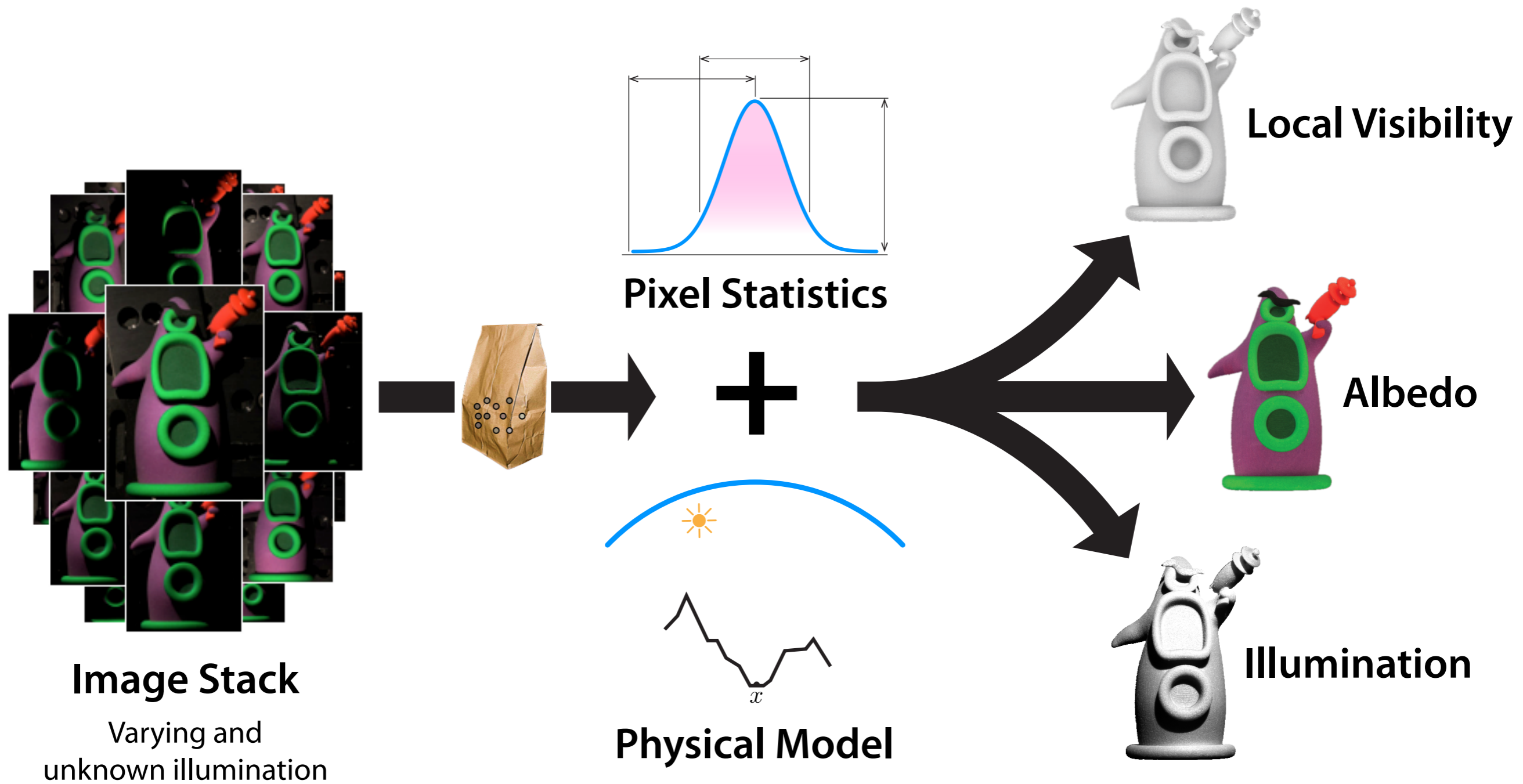
Scene under  
uniform lighting

# Input

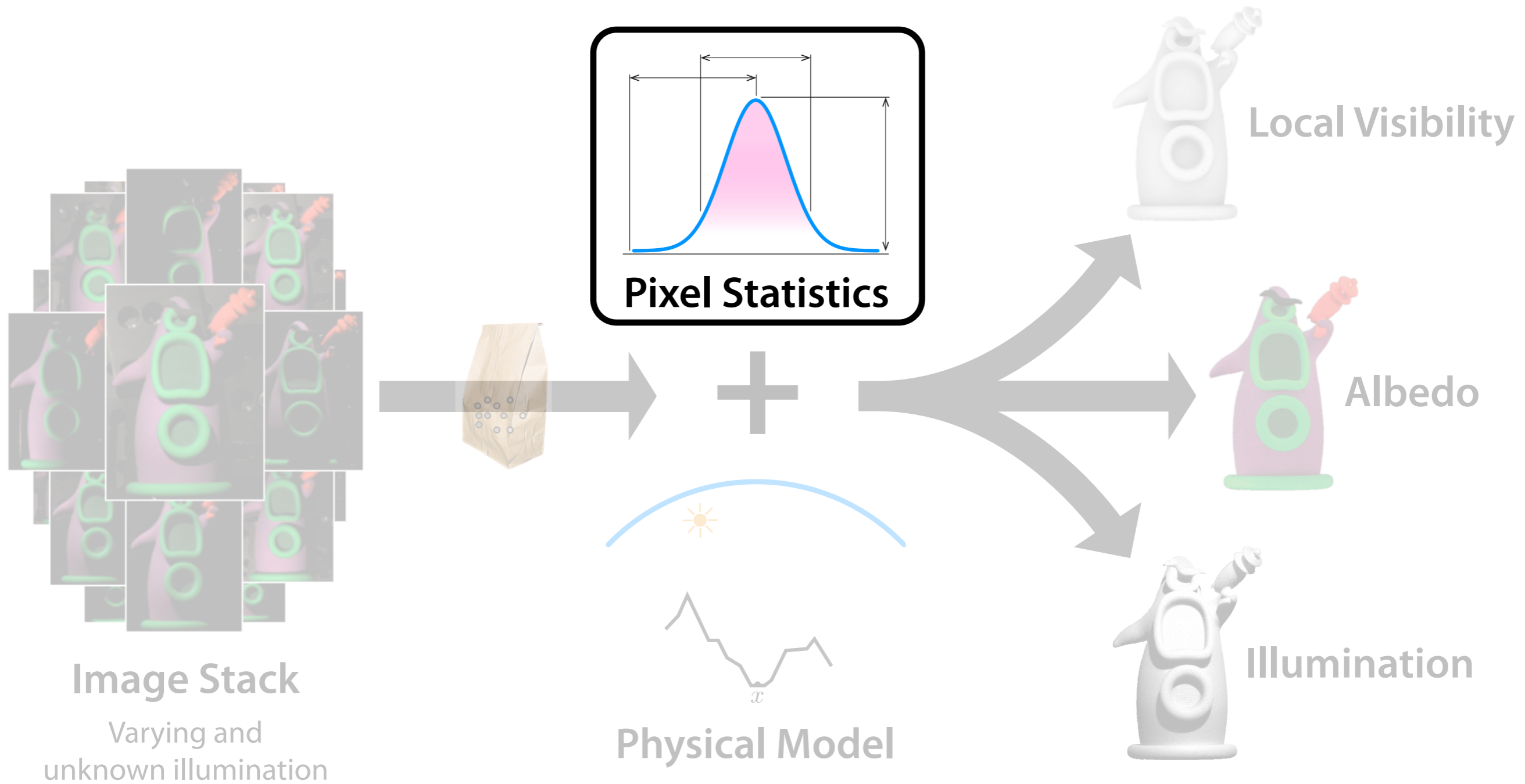
- Collection of images with varying but unknown illumination



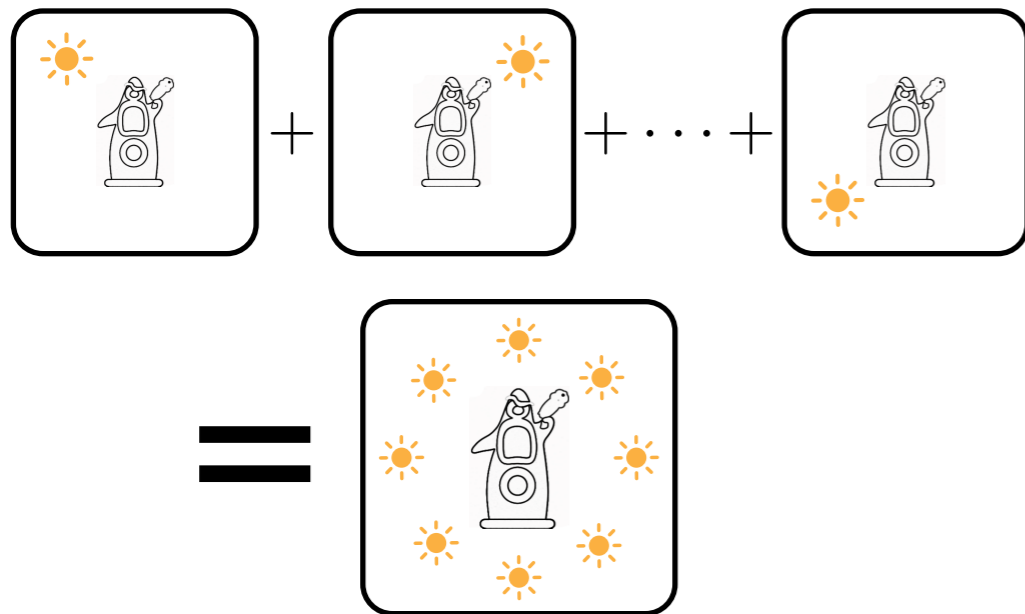
# Overview



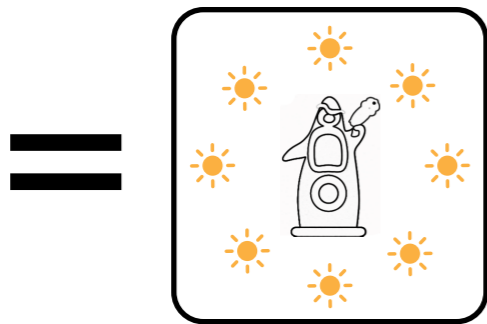
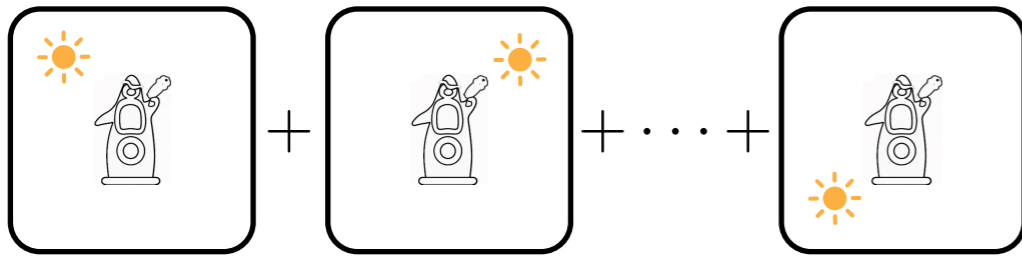
# Overview



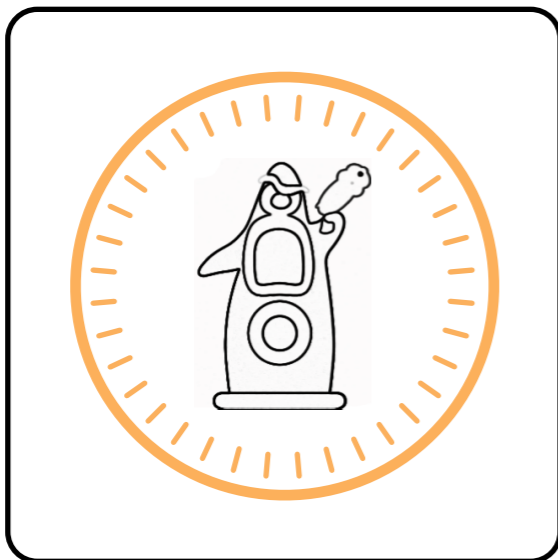
# Average Image



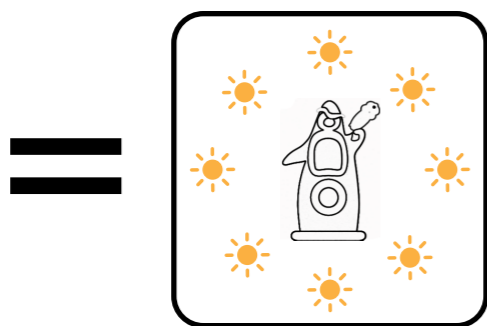
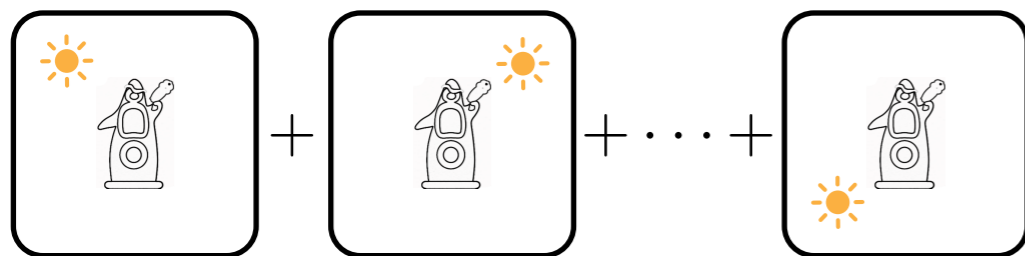
# Average Image



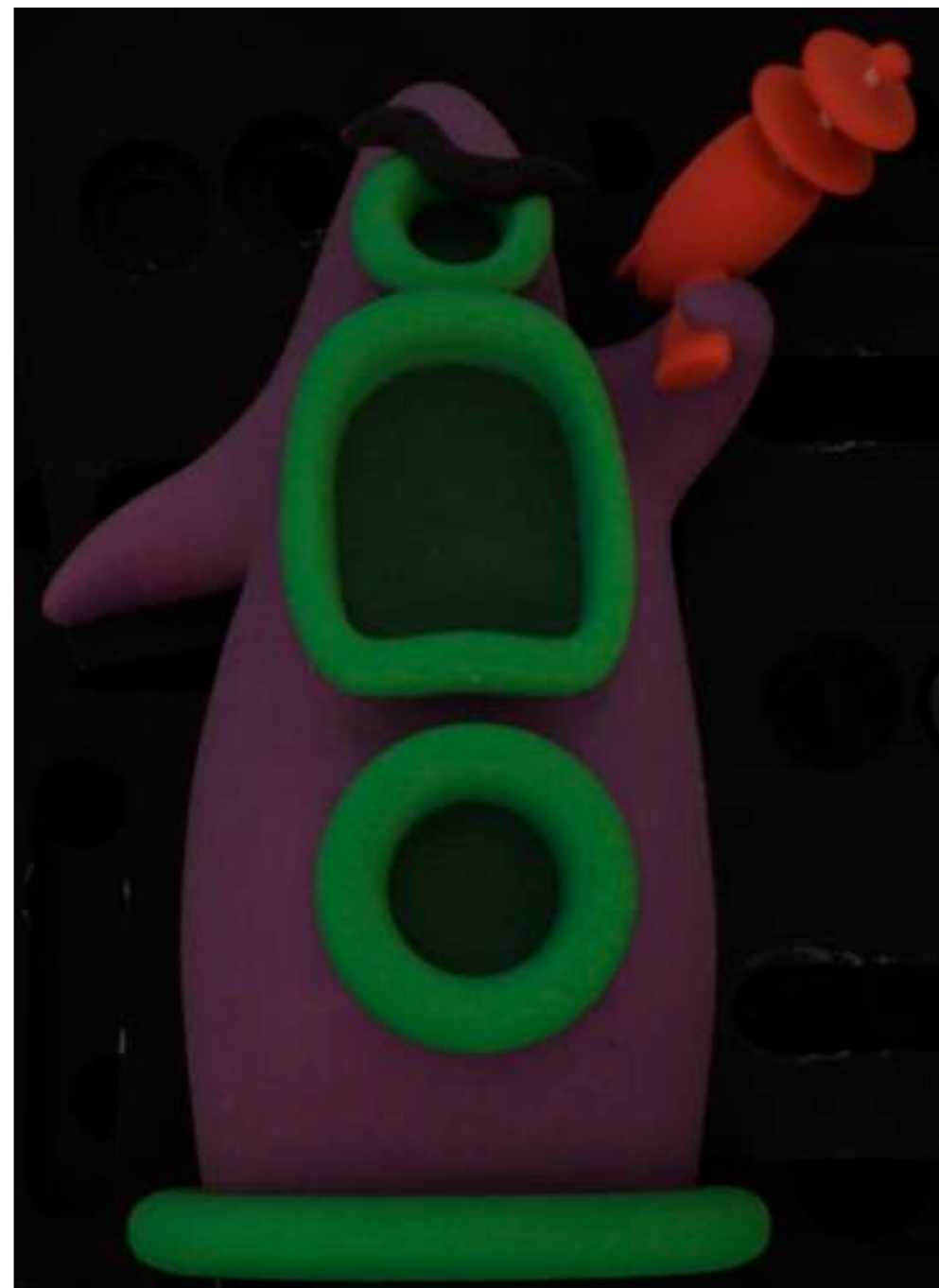
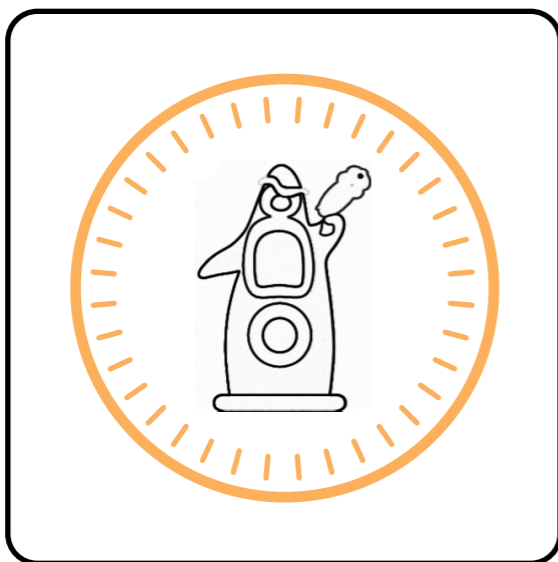
≈



# Average Image



$\approx$

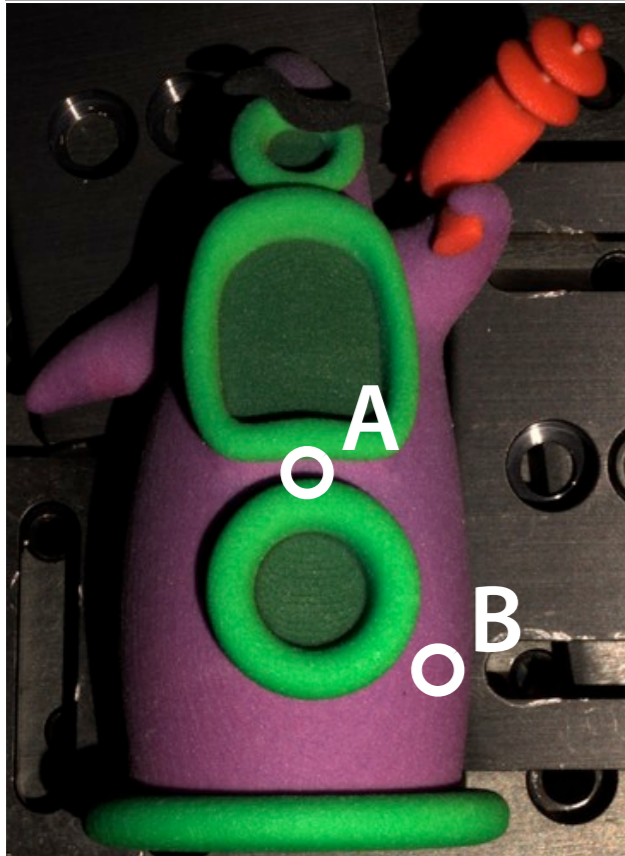


$\mathcal{E}[I]$

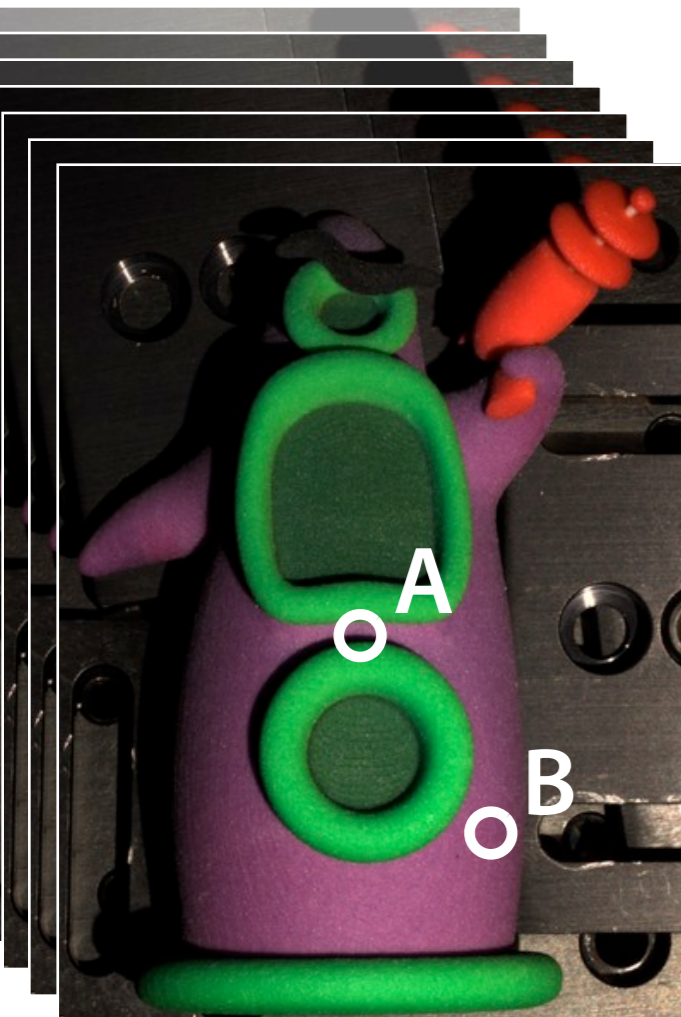
# Pixel Intensity Distribution



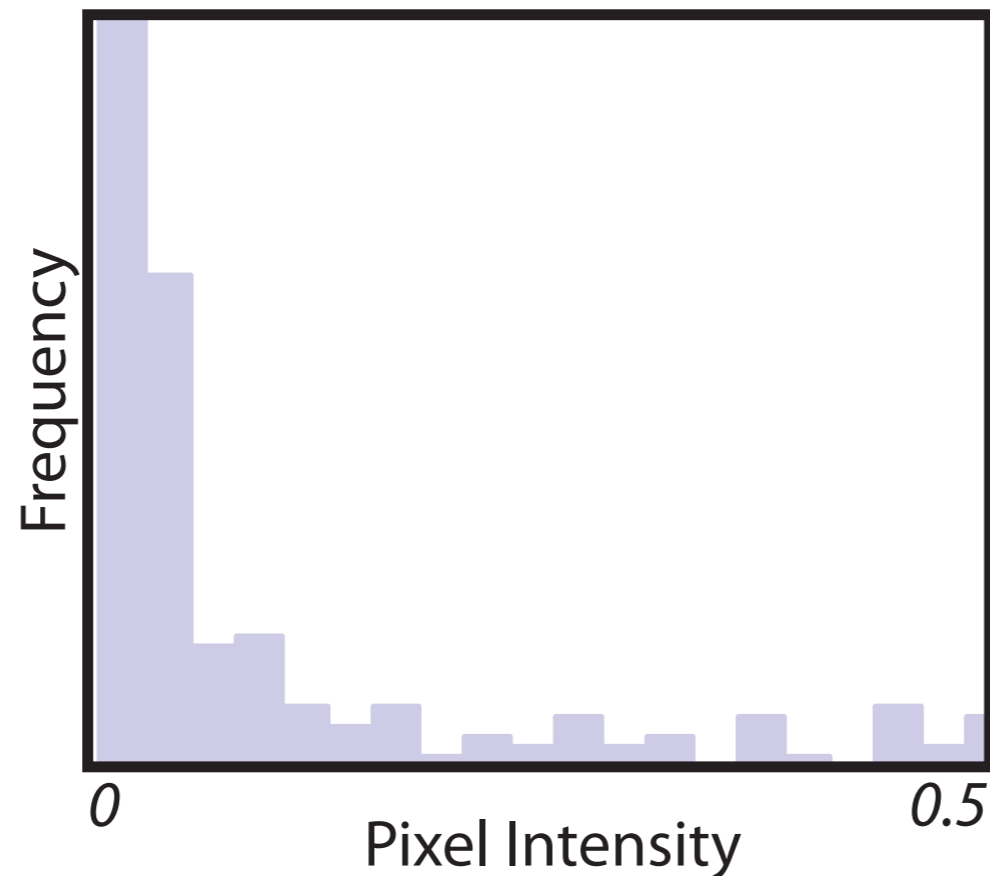
# Pixel Intensity Distribution



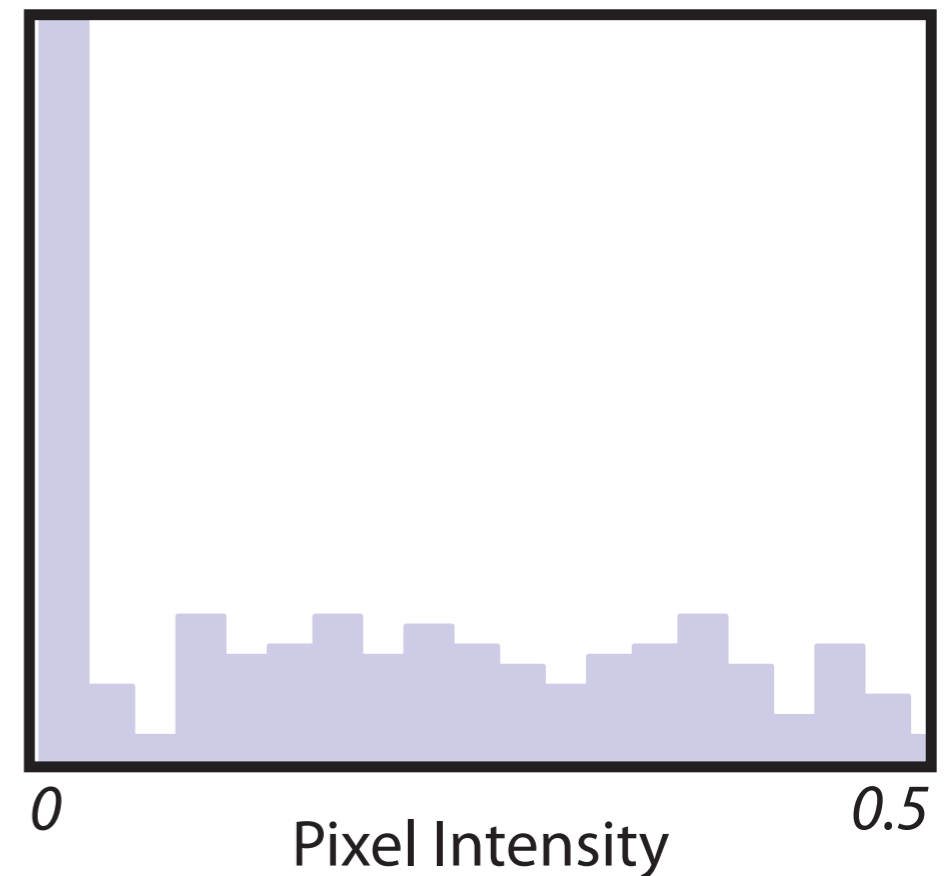
# Pixel Intensity Distribution



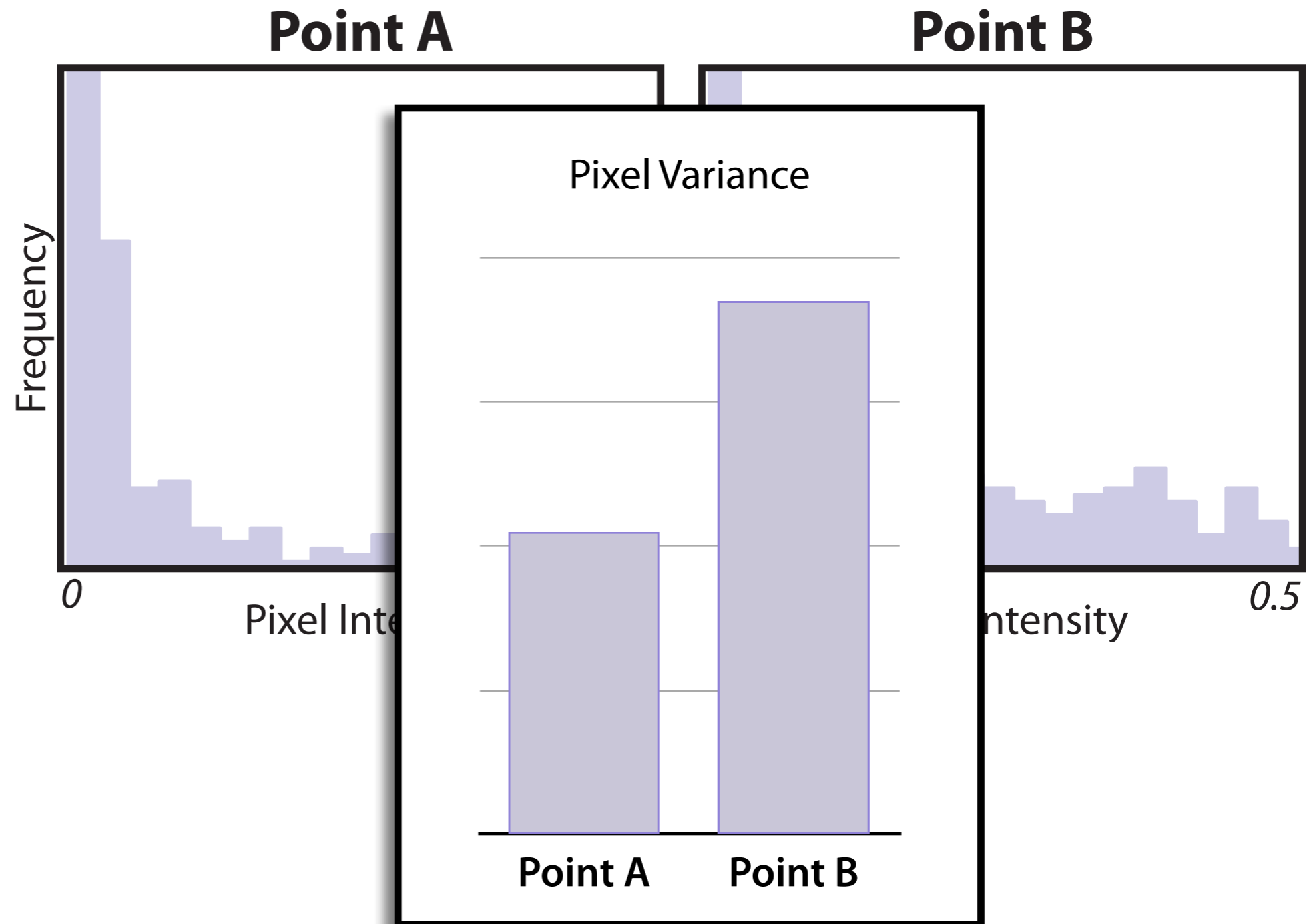
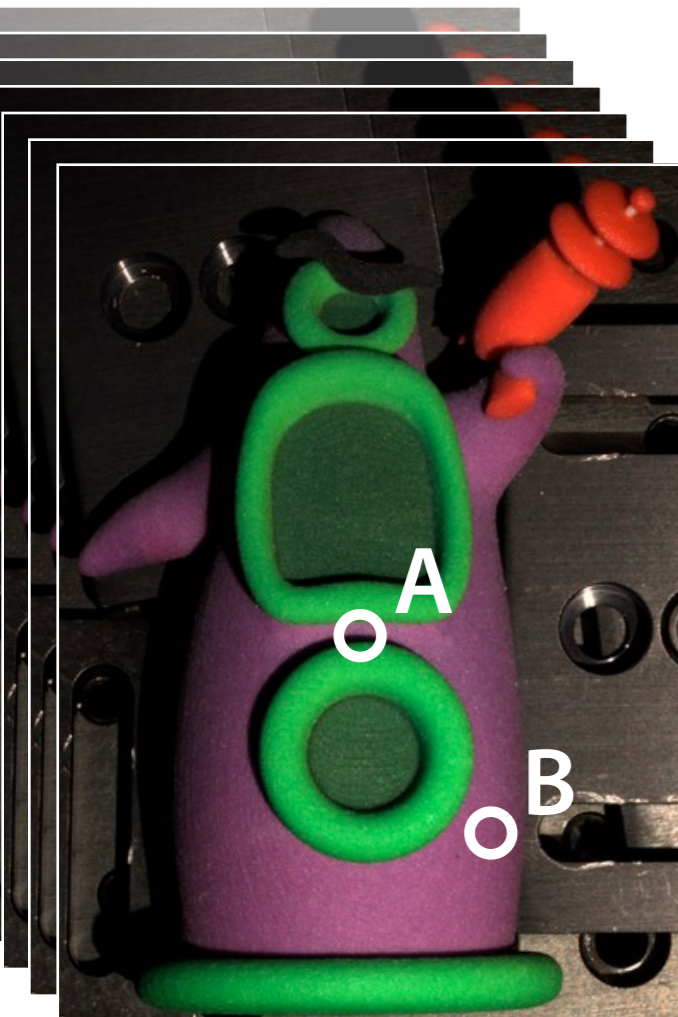
**Point A**



**Point B**



# Pixel Intensity Distribution



# Image Formation Model

# Image Formation Model

Image



$$I(x)$$

# Image Formation Model

Image

Albedo



=



$$I(x) = \rho(x)$$

*Diffuse Albedo*

# Image Formation Model

Image



=

Albedo



×

Illumination



$$I(x) = \rho(x) \times L(x)$$

*Diffuse Albedo*

*Light + Geometry*

# Image Formation Model

Image

Albedo

Illumination



$$I(x) = \rho(x) \times L(x)$$

*Diffuse Albedo* *Light + Geometry*

- Assumptions:
  - Single bounce of light
  - Scene is Lambertian

# Pixel Statistics

# Pixel Statistics

- Pixel Variance

$$\text{Var}[I]$$

# Pixel Statistics

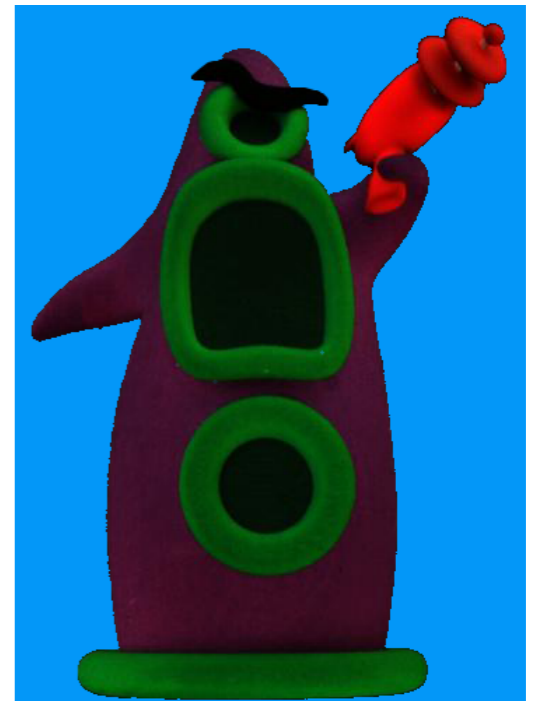
- Pixel Variance

$$\text{Var}[I] = \mathcal{E}[I^2] - \mathcal{E}[I]^2$$

# Pixel Statistics

- Pixel Variance

$$\begin{aligned}\text{Var}[I] &= \mathcal{E}[I^2] - \mathcal{E}[I]^2 \\ &= \rho^2(\mathcal{E}[L^2] - \mathcal{E}[L]^2)\end{aligned}$$



$\text{Var}[I]$

# Pixel Statistics

- Pixel Variance

$$\begin{aligned}\text{Var}[I] &= \mathcal{E}[I^2] - \mathcal{E}[I]^2 \\ &= \rho^2(\mathcal{E}[L^2] - \mathcal{E}[L]^2)\end{aligned}$$

- The statistic  $\kappa$

$\kappa$



$\text{Var}[I]$

# Pixel Statistics

- Pixel Variance

$$\begin{aligned}\text{Var}[I] &= \mathcal{E}[I^2] - \mathcal{E}[I]^2 \\ &= \rho^2(\mathcal{E}[L^2] - \mathcal{E}[L]^2)\end{aligned}$$



$\text{Var}[I]$

- The statistic  $\kappa$

$$\kappa = \frac{\mathcal{E}[I]^2}{\mathcal{E}[I^2]}$$

# Pixel Statistics

- Pixel Variance

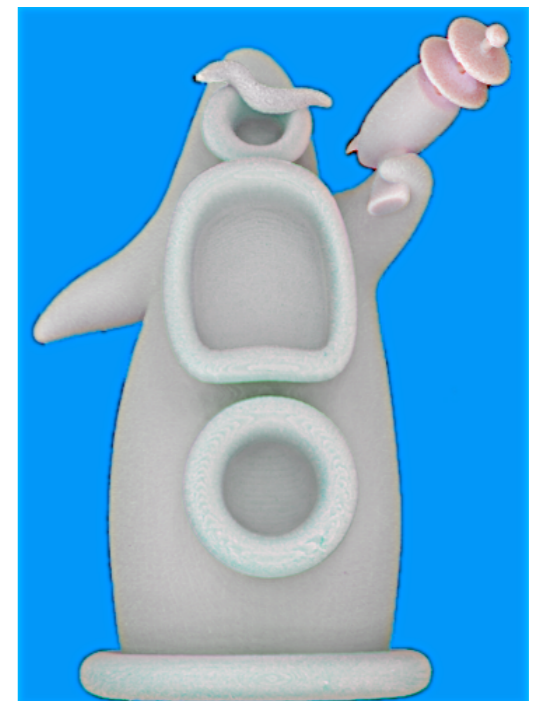
$$\begin{aligned}\text{Var}[I] &= \mathcal{E}[I^2] - \mathcal{E}[I]^2 \\ &= \cancel{\rho^2}(\mathcal{E}[L^2] - \mathcal{E}[L]^2)\end{aligned}$$



$\text{Var}[I]$

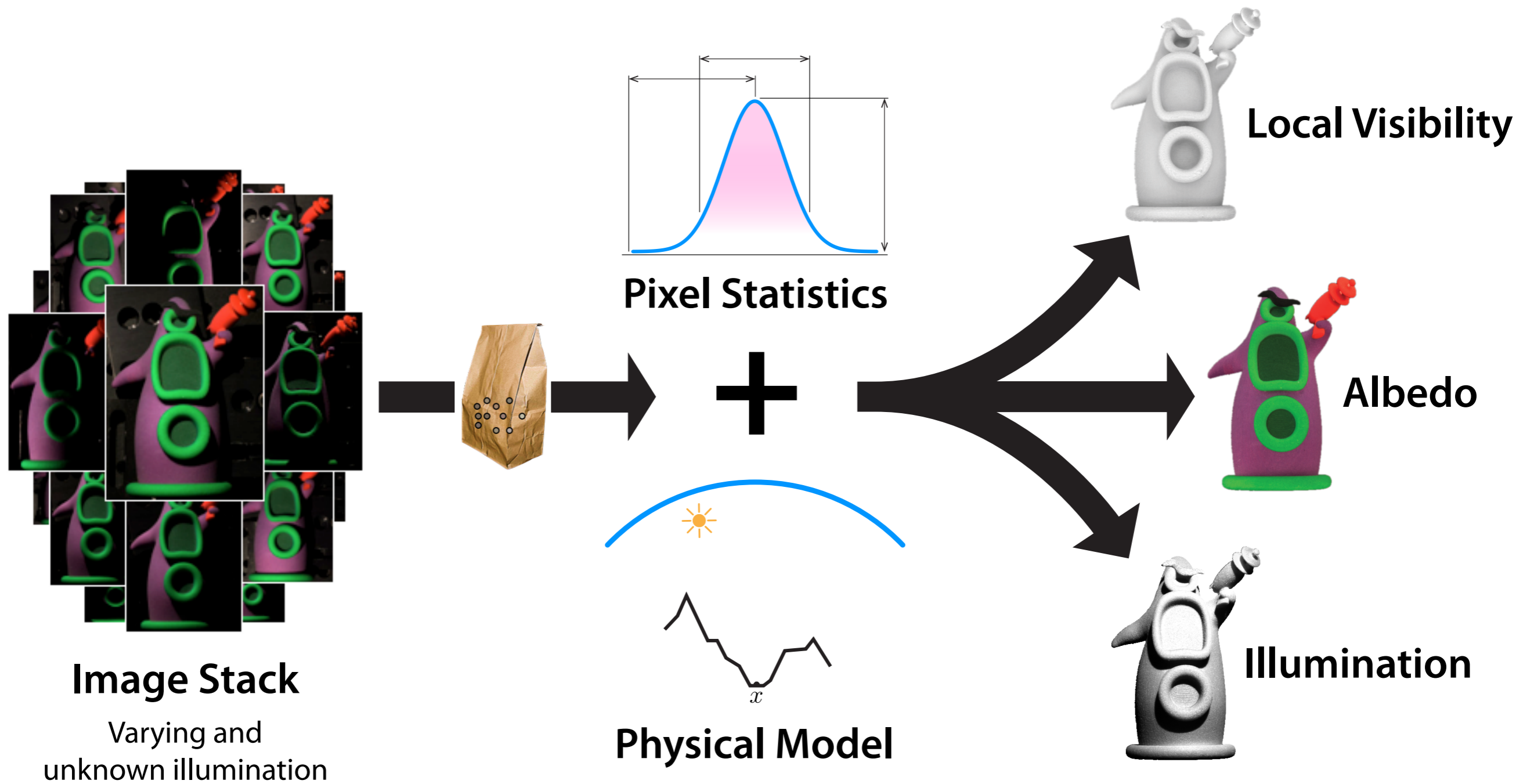
- The statistic  $\kappa$

$$\kappa = \frac{\mathcal{E}[I]^2}{\mathcal{E}[I^2]} = \frac{\cancel{\rho^2} \mathcal{E}[L]^2}{\cancel{\rho^2} \mathcal{E}[L^2]}$$

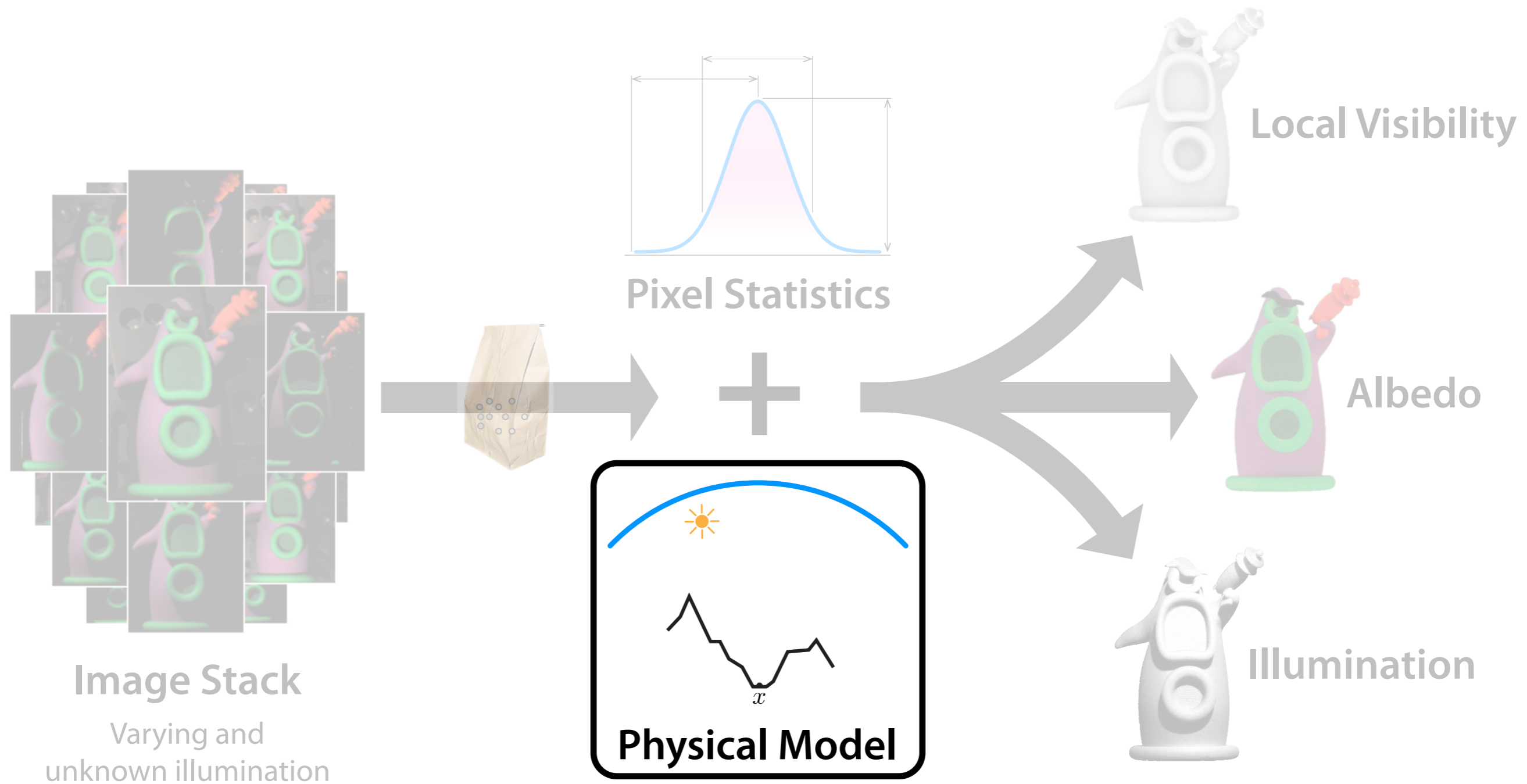


$\kappa$

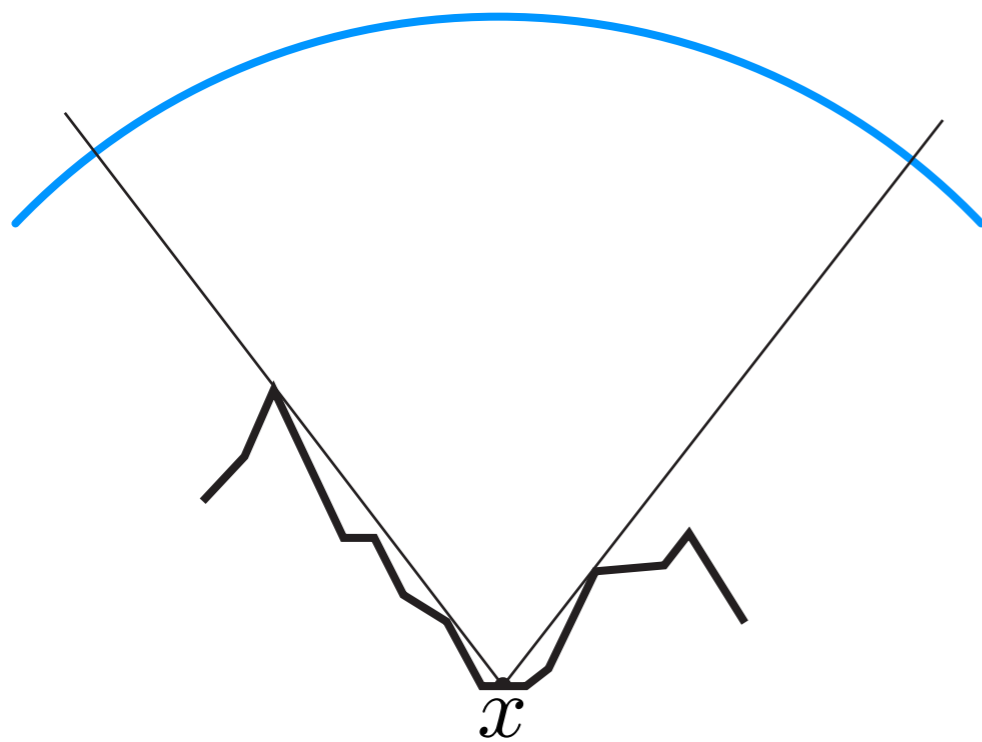
# Overview



# Overview



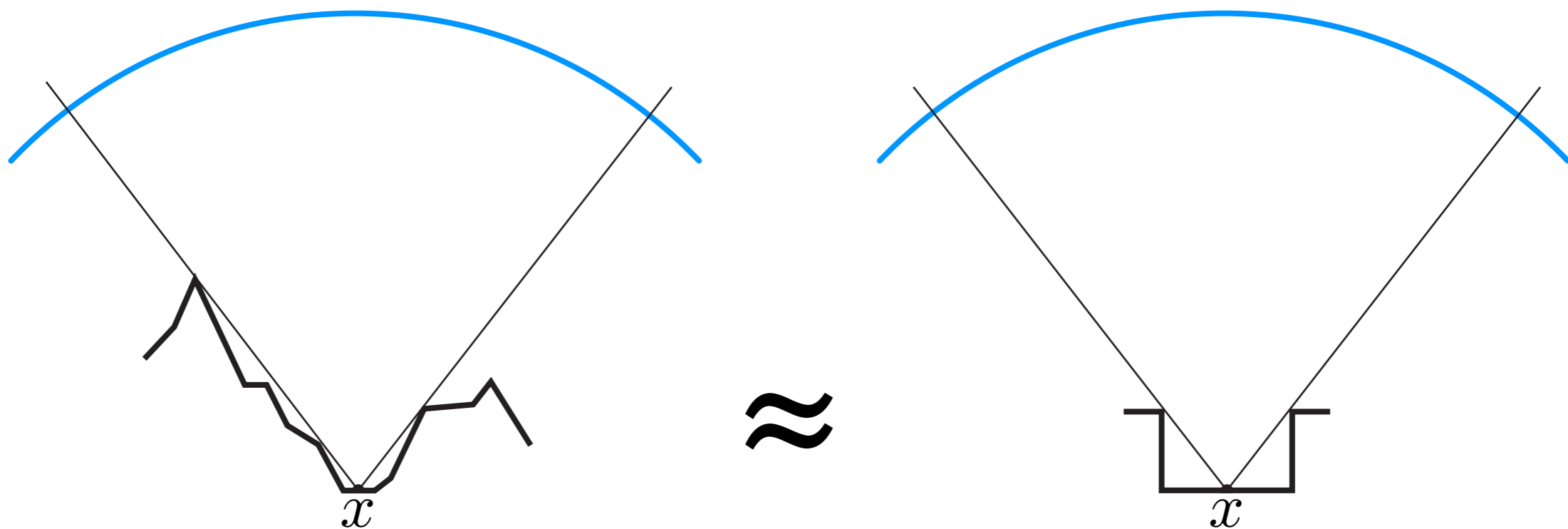
# Local Geometry



Geometry around  
a point  $x$  can be arbitrarily  
complex

# Local Geometry

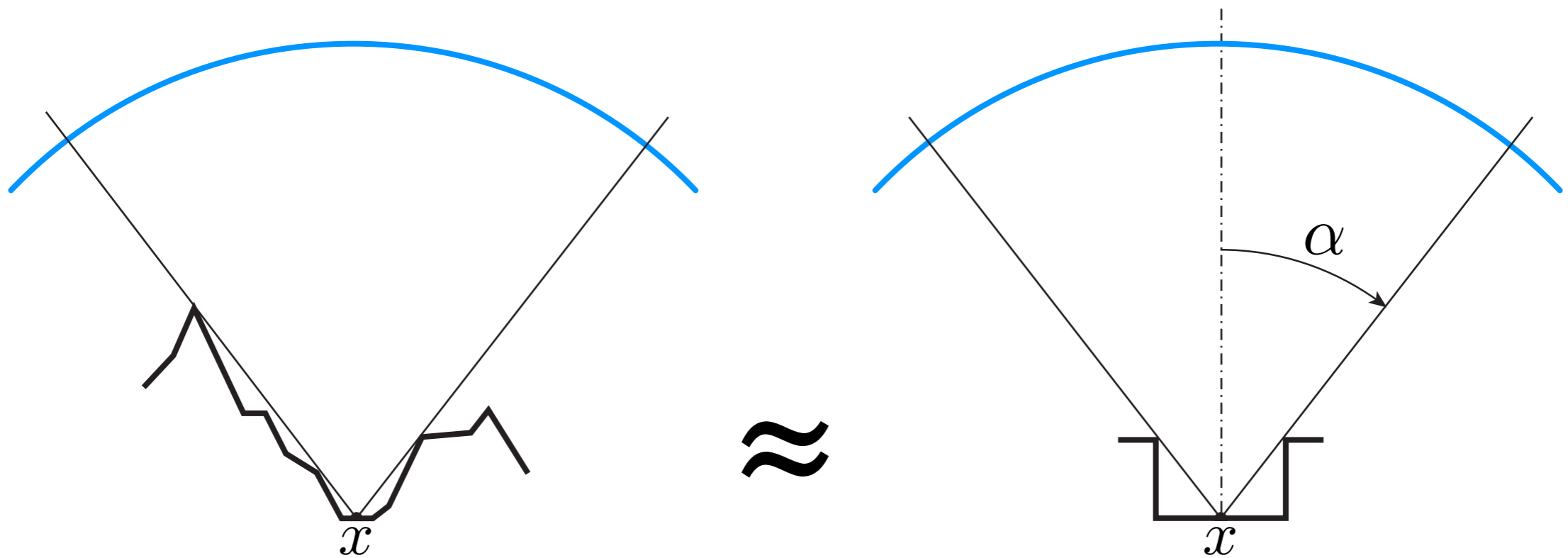
## Cylindrical crevice approximation



Geometry around  
a point  $x$  can be arbitrarily  
complex

# Local Geometry

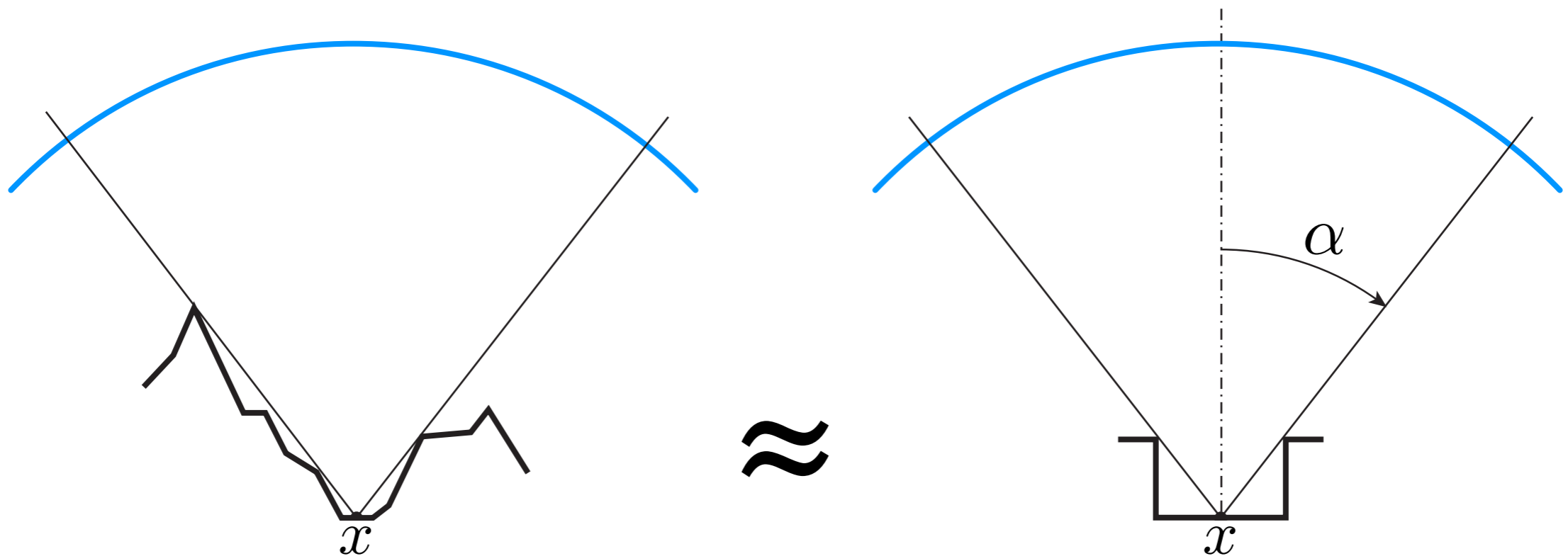
## Cylindrical crevice approximation



Geometry around  
a point  $x$  can be arbitrarily  
complex

# Local Geometry

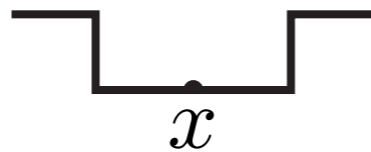
## Cylindrical crevice approximation



Geometry around  
a point  $x$  can be arbitrarily  
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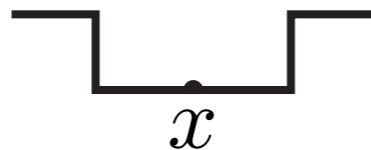
$$AO = \sin(\alpha)^2$$

# Lighting



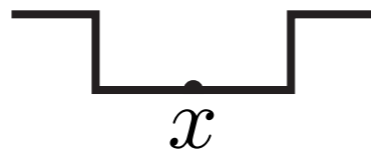
# Lighting

- $l_d$ : direct term with unit intensity



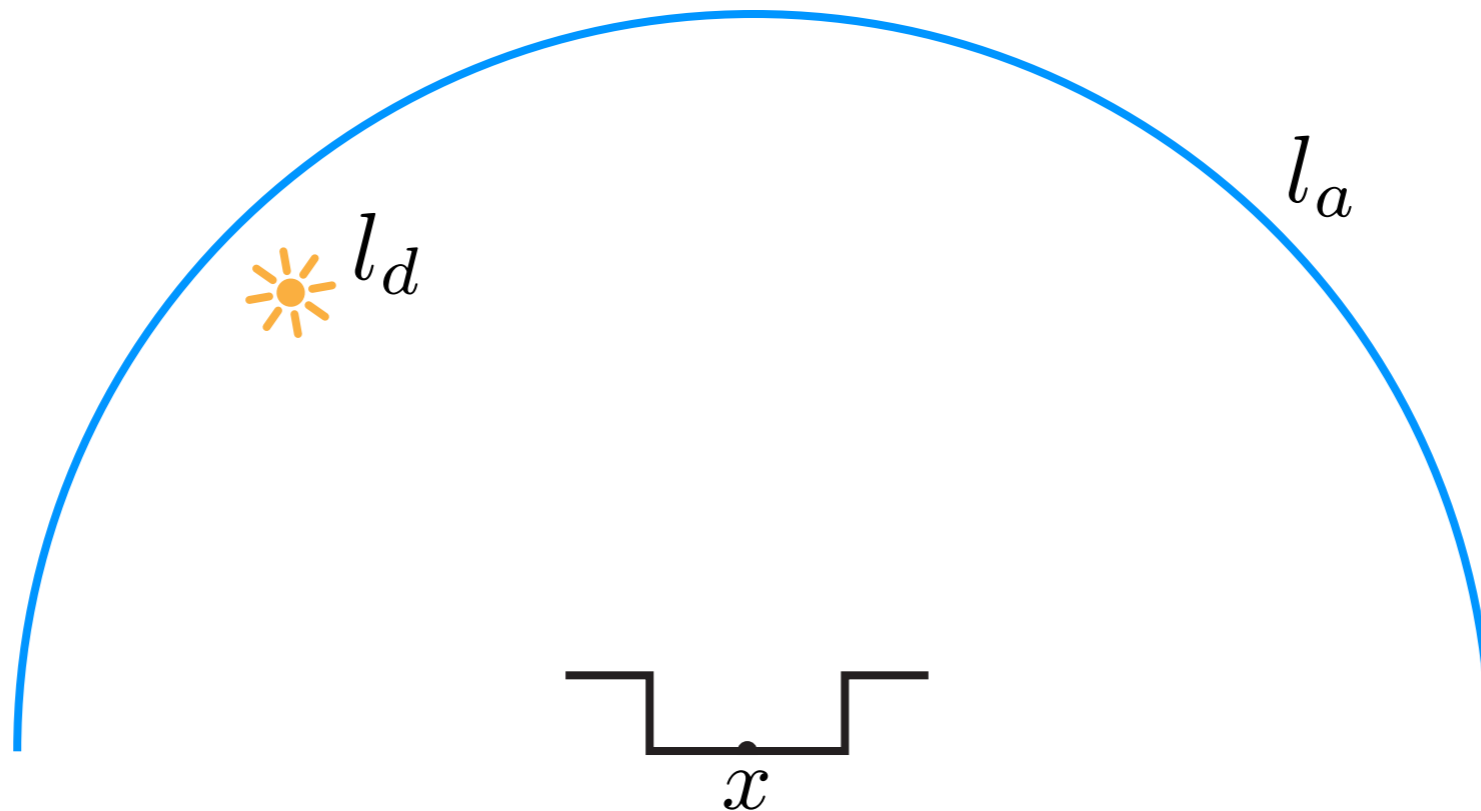
# Lighting

- $l_d$ : direct term with unit intensity
  - Covers entire hemisphere uniformly at random

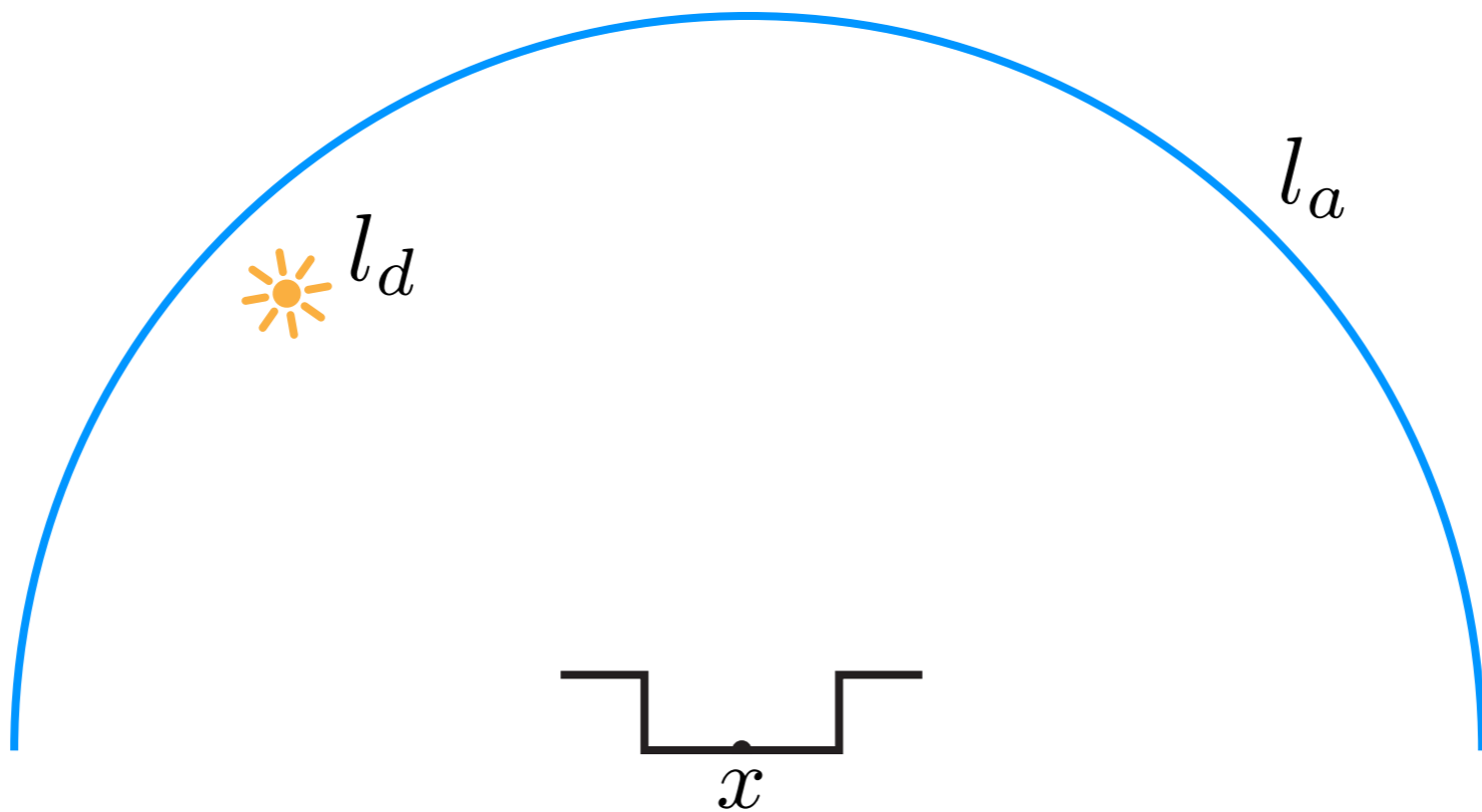


# Lighting

- $l_d$ : direct term with unit intensity
  - Covers entire hemisphere uniformly at random
- $l_a$ : ambient illumination

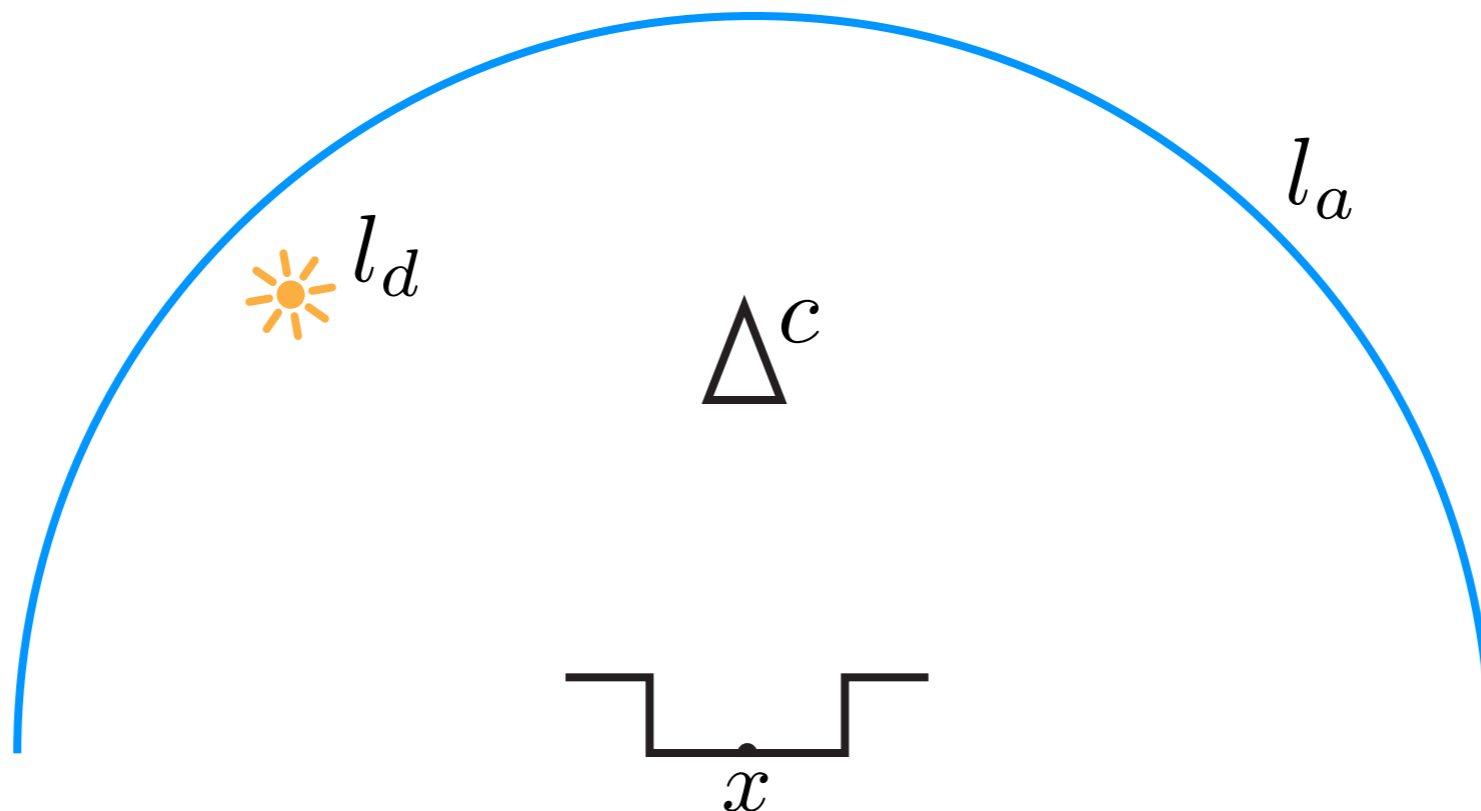


# Image Intensity



# Image Intensity

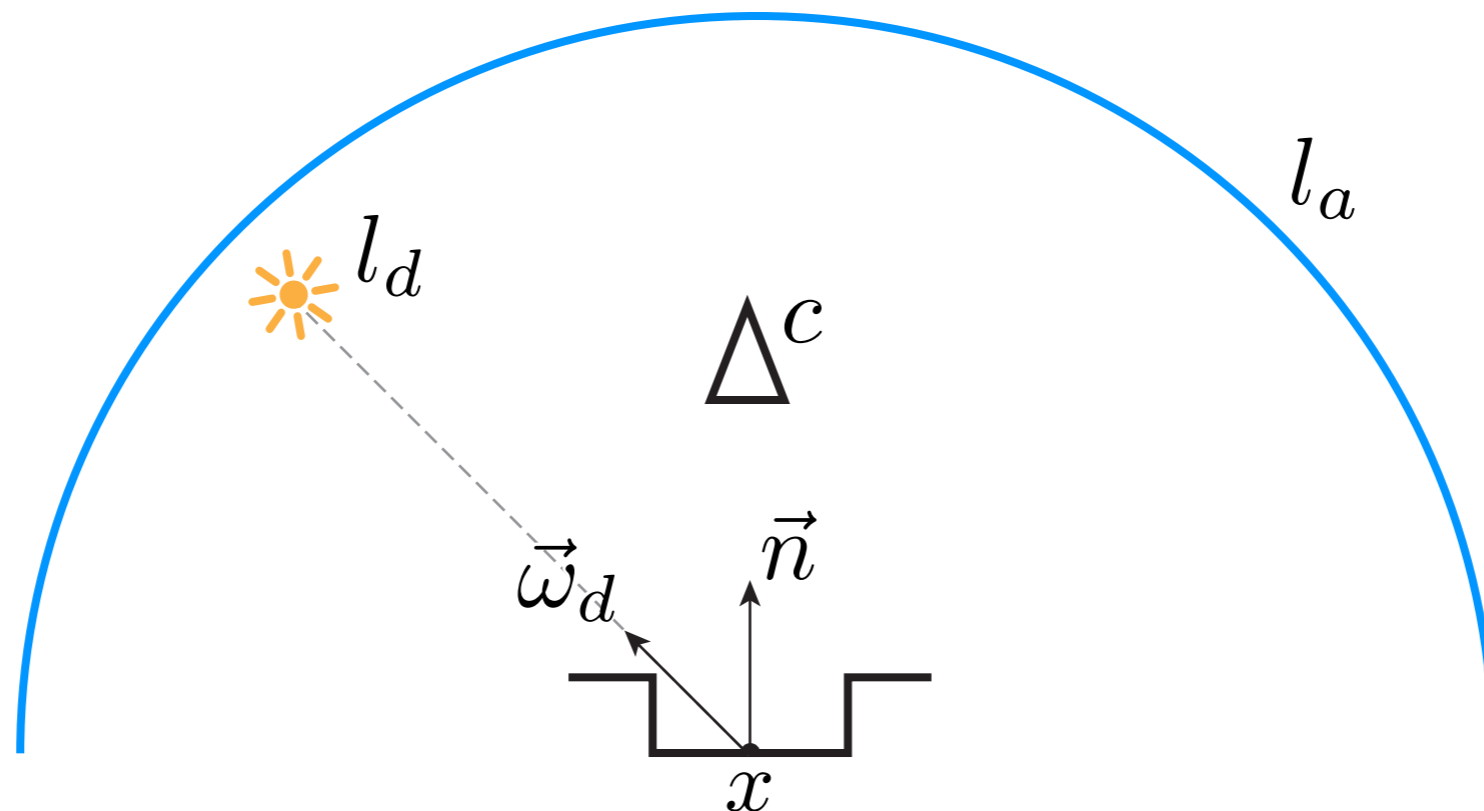
- $c$ : camera observes point from above



# Image Intensity

- $c$ : camera observes point from above

$$I = \rho \left[ l_d \langle \vec{n}, \vec{\omega}_d \rangle + \pi l_a \sin(\alpha)^2 \right]$$



# Analytical $\kappa$

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$$\kappa = \frac{\mathcal{E}[I]^2}{\mathcal{E}[I^2]}$$

$$\kappa(\alpha, l_a, l_d) = \frac{3}{4} \frac{(2\pi l_a + l_d)^2 \sin^4(\alpha)}{(3\pi l_a(\pi l_a + l_d) \sin^4(\alpha) - l_d^2 \cos^3(\alpha) + l_d^2)}$$

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Substitute  $f = \frac{l_a}{l_d}$

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Substitute  $f = \frac{l_a}{l_d}$

$$\kappa(\alpha, f) = \frac{3}{4} \frac{(2\pi f + 1)^2 \sin^4 \alpha}{1 - \cos^3 \alpha + 3\pi f(\pi f + 1) \sin^4 \alpha}$$

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$f = \frac{\text{ambient}}{\text{direct}}$	$\kappa = \frac{\mathcal{E}[I]^2}{\mathcal{E}[I^2]}$
--	--

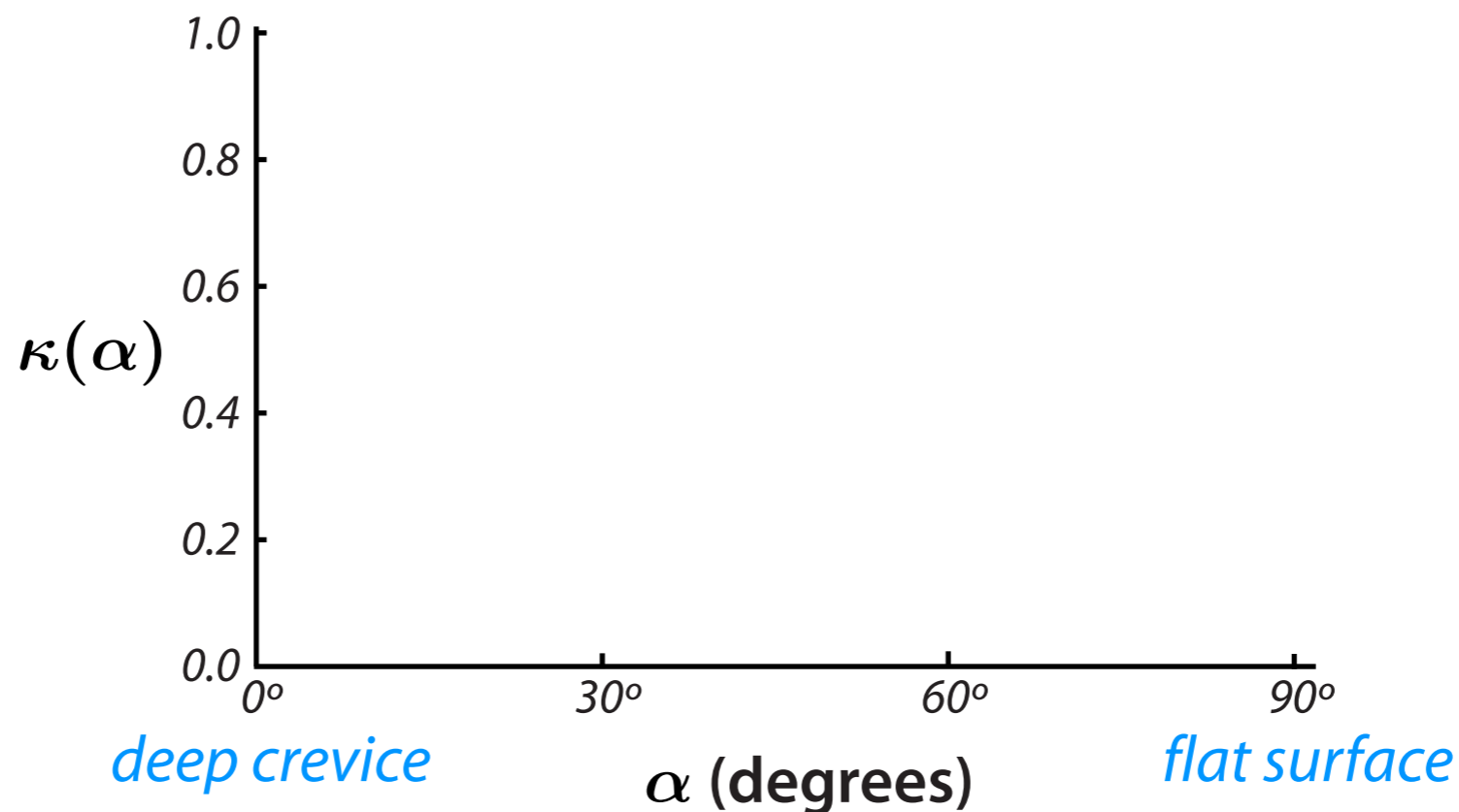
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# Analytical $\kappa$

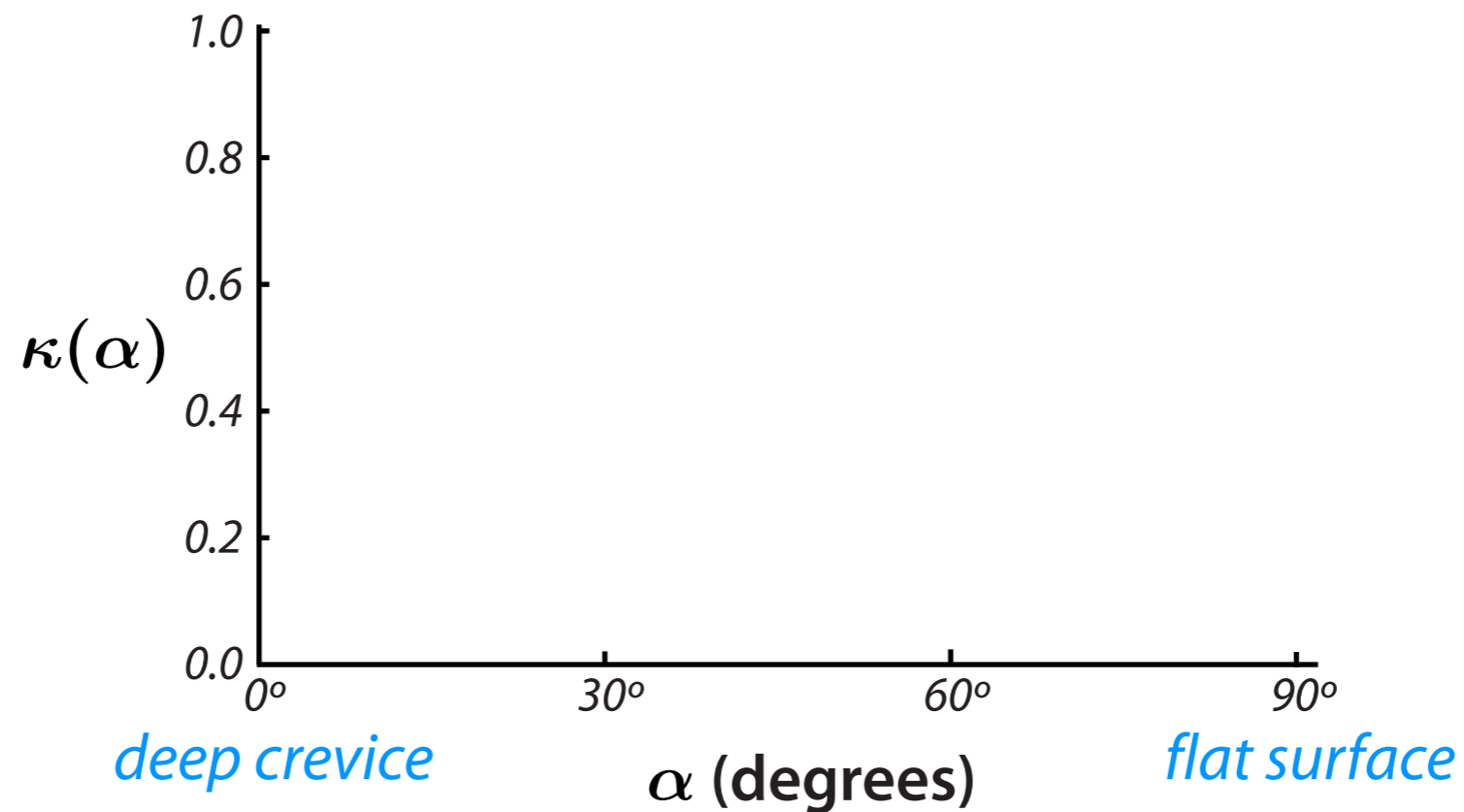
$$\kappa(\alpha, f) = \frac{3}{4} \frac{(2\pi f + 1)^2 \sin^4 \alpha}{1 - \cos^3 \alpha + 3\pi f(\pi f + 1) \sin^4 \alpha}$$



$$f = \frac{\text{ambient}}{\text{direct}} \quad \kappa = \frac{\mathcal{E}[I]^2}{\mathcal{E}[I^2]}$$

# Analytical $\kappa$

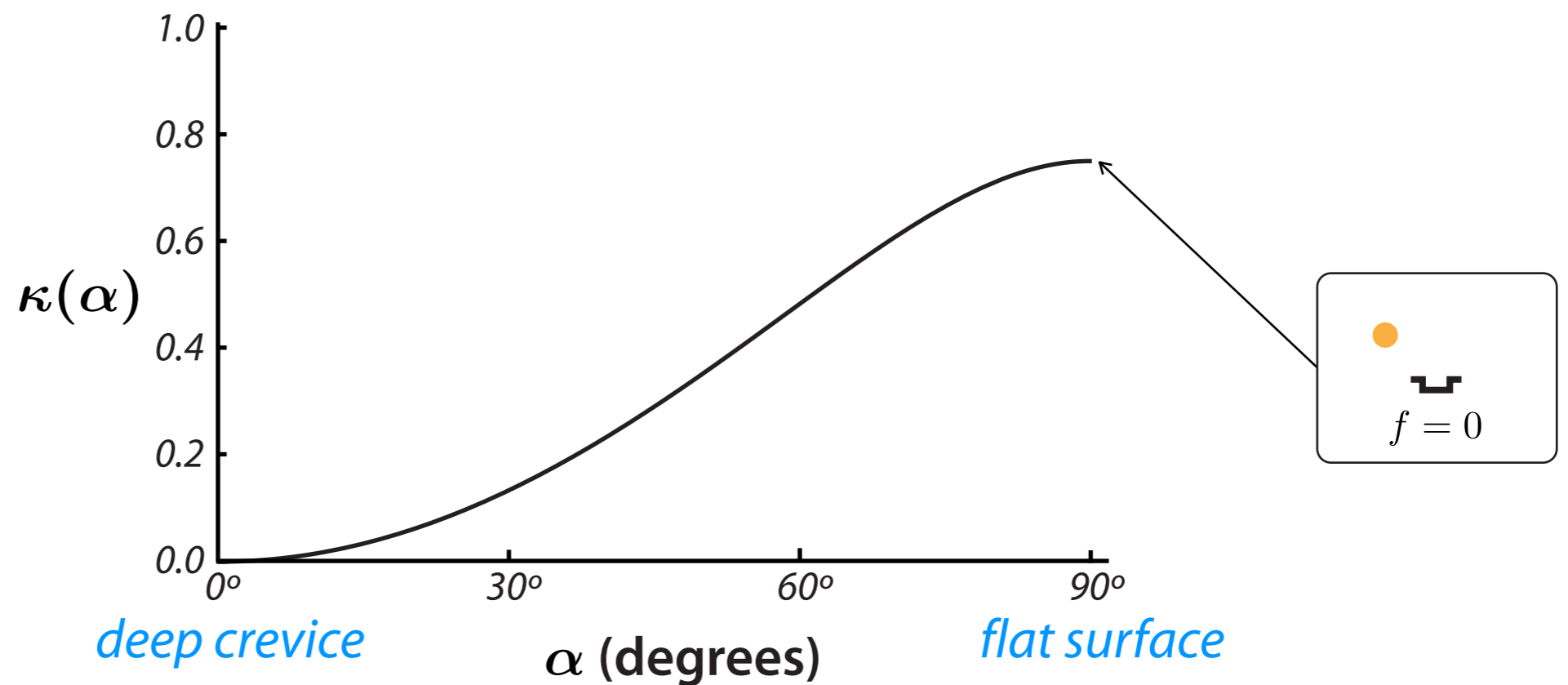
$$\kappa(\alpha, 0) = \frac{3}{4} \frac{\sin^4(\alpha)}{(1 - \cos^3(\alpha))}$$



$$f = \frac{\text{ambient}}{\text{direct}} \quad \kappa = \frac{\mathcal{E}[I]^2}{\mathcal{E}[I^2]}$$

# Analytical $\kappa$

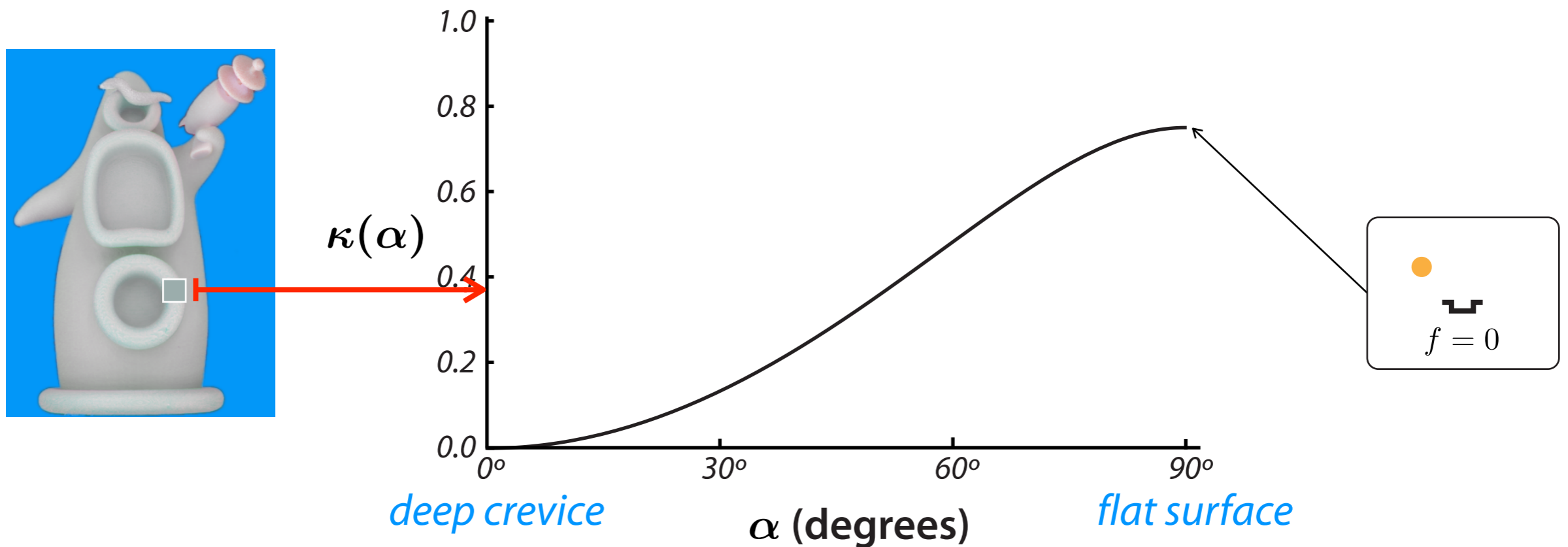
$$\kappa(\alpha, 0) = \frac{3}{4} \frac{\sin^4(\alpha)}{(1 - \cos^3(\alpha))}$$



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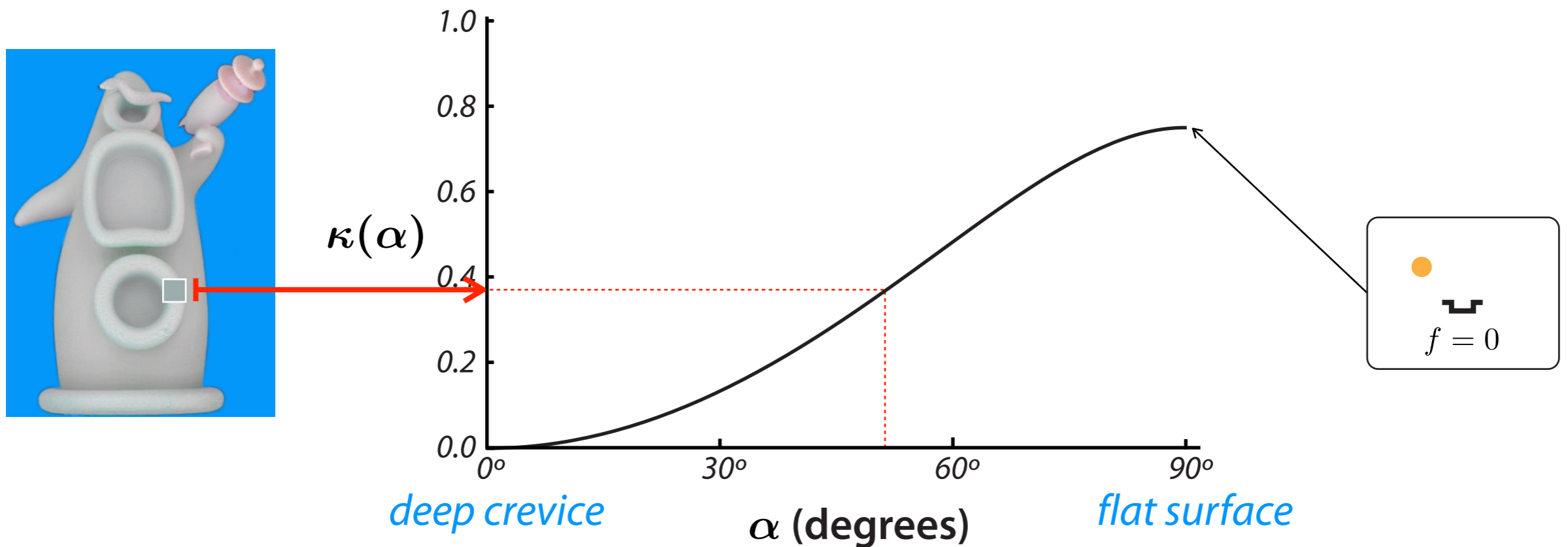
$$\kappa(\alpha, 0) = \frac{3}{4} \frac{\sin^4(\alpha)}{(1 - \cos^3(\alpha))}$$



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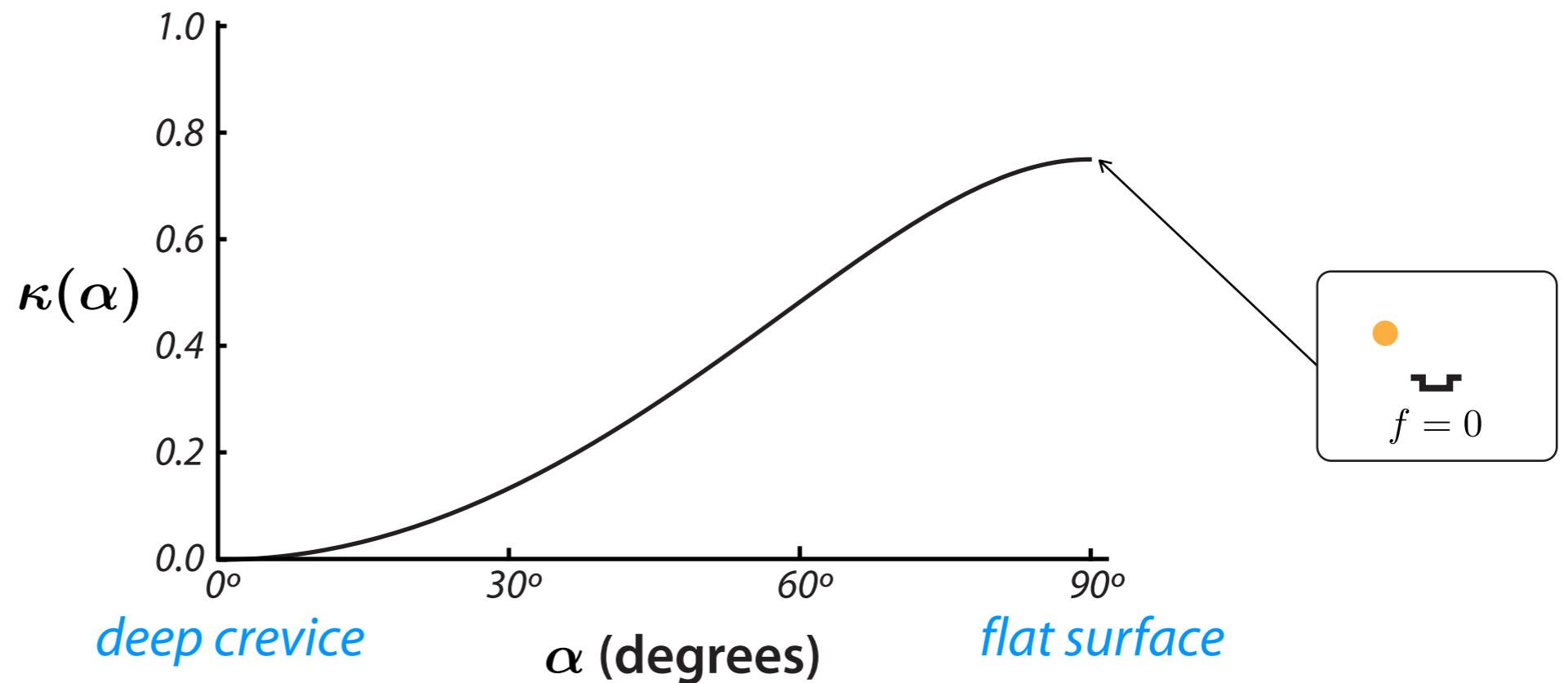
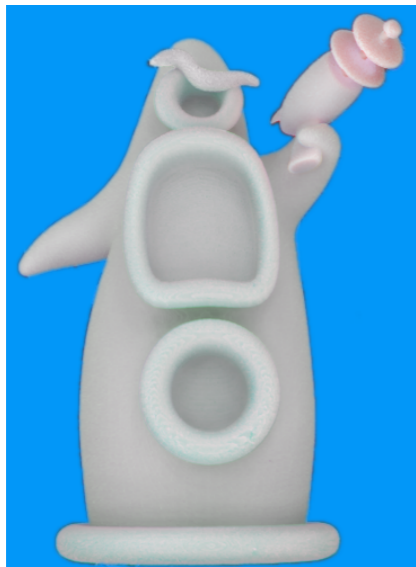
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$$f = \frac{\text{ambient}}{\text{direct}} \quad \kappa = \frac{\mathcal{E}[I]^2}{\mathcal{E}[I^2]}$$

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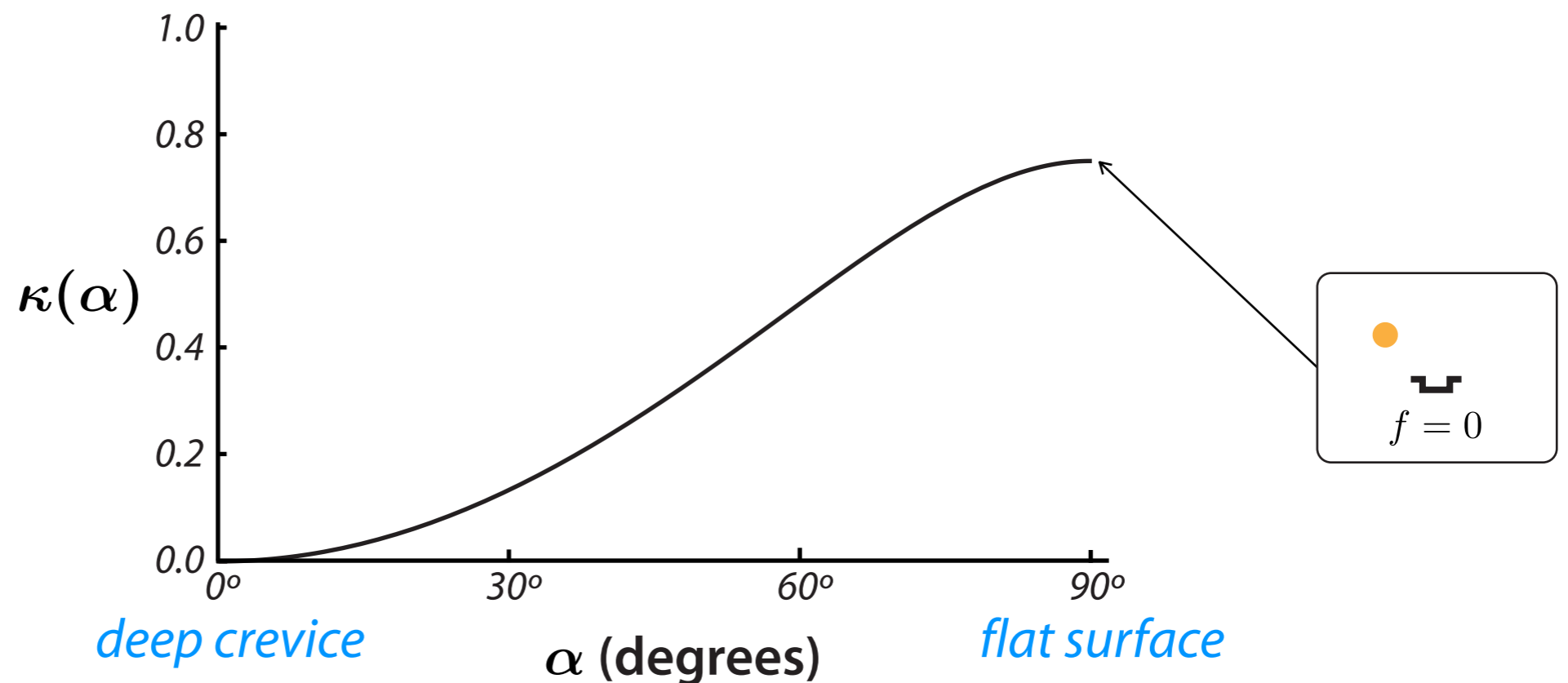
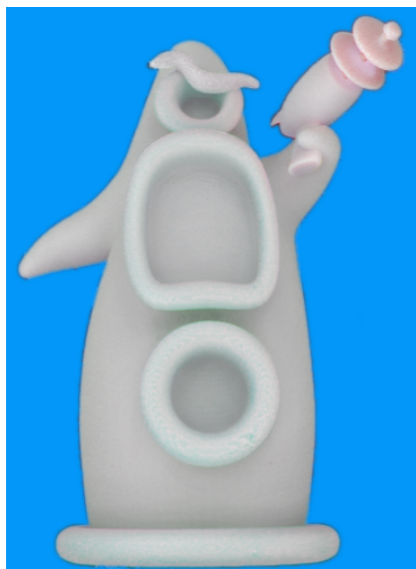
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$$f = \frac{\text{ambient}}{\text{direct}} \quad \kappa = \frac{\mathcal{E}[I]^2}{\mathcal{E}[I^2]}$$

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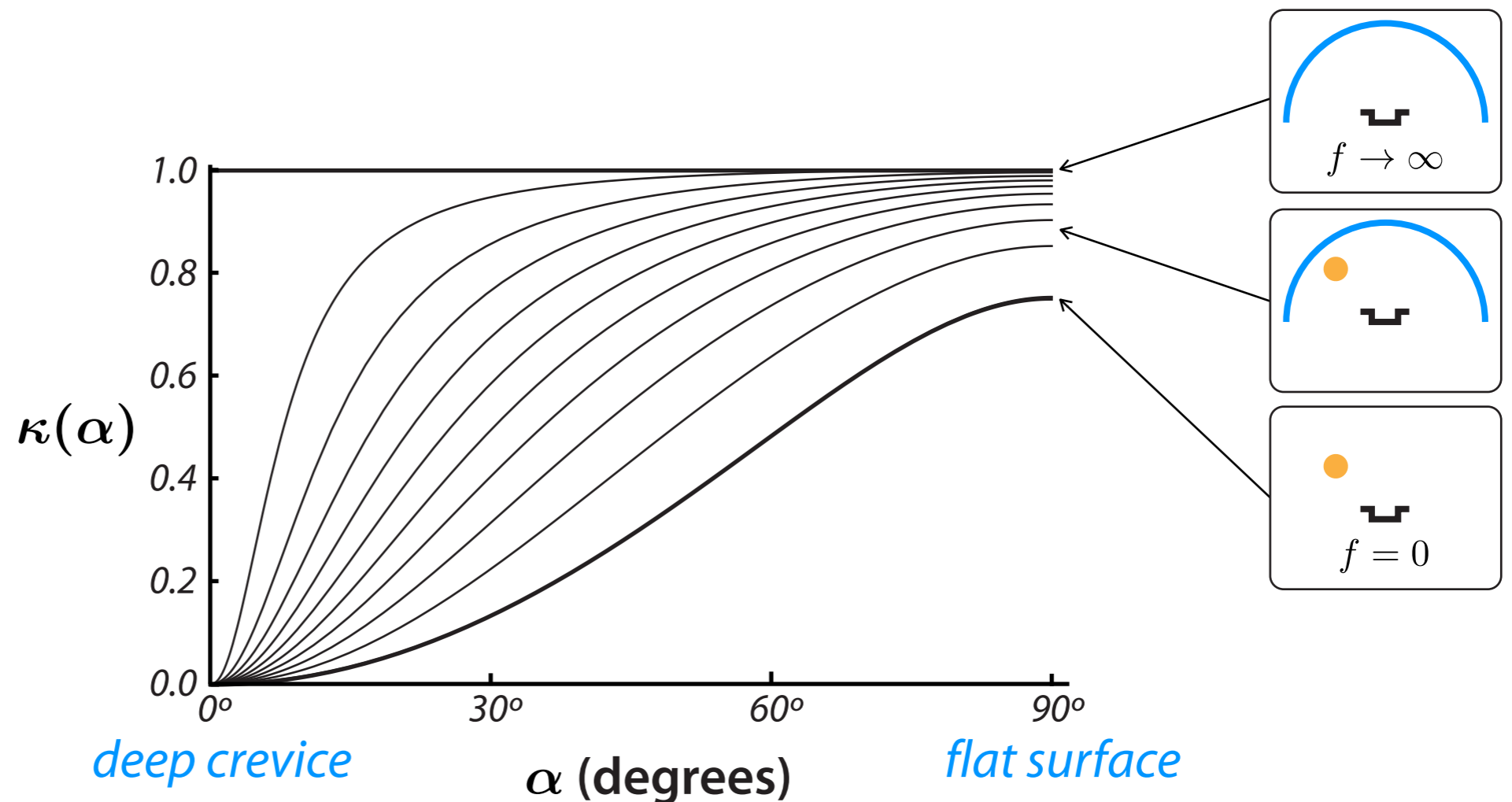
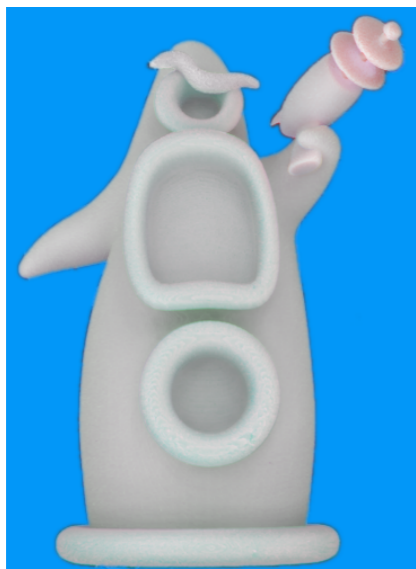
$$\kappa(\alpha, f) = \frac{3}{4} \frac{(2\pi f + 1)^2 \sin^4 \alpha}{1 - \cos^3 \alpha + 3\pi f(\pi f + 1) \sin^4 \alpha}$$



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# Analytical $\kappa$

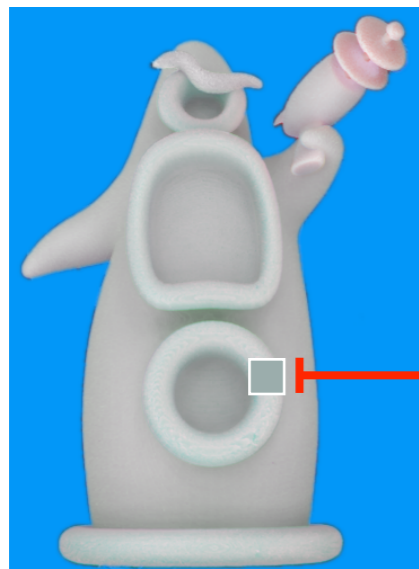
$$\kappa(\alpha, f) = \frac{3}{4} \frac{(2\pi f + 1)^2 \sin^4 \alpha}{1 - \cos^3 \alpha + 3\pi f(\pi f + 1) \sin^4 \alpha}$$



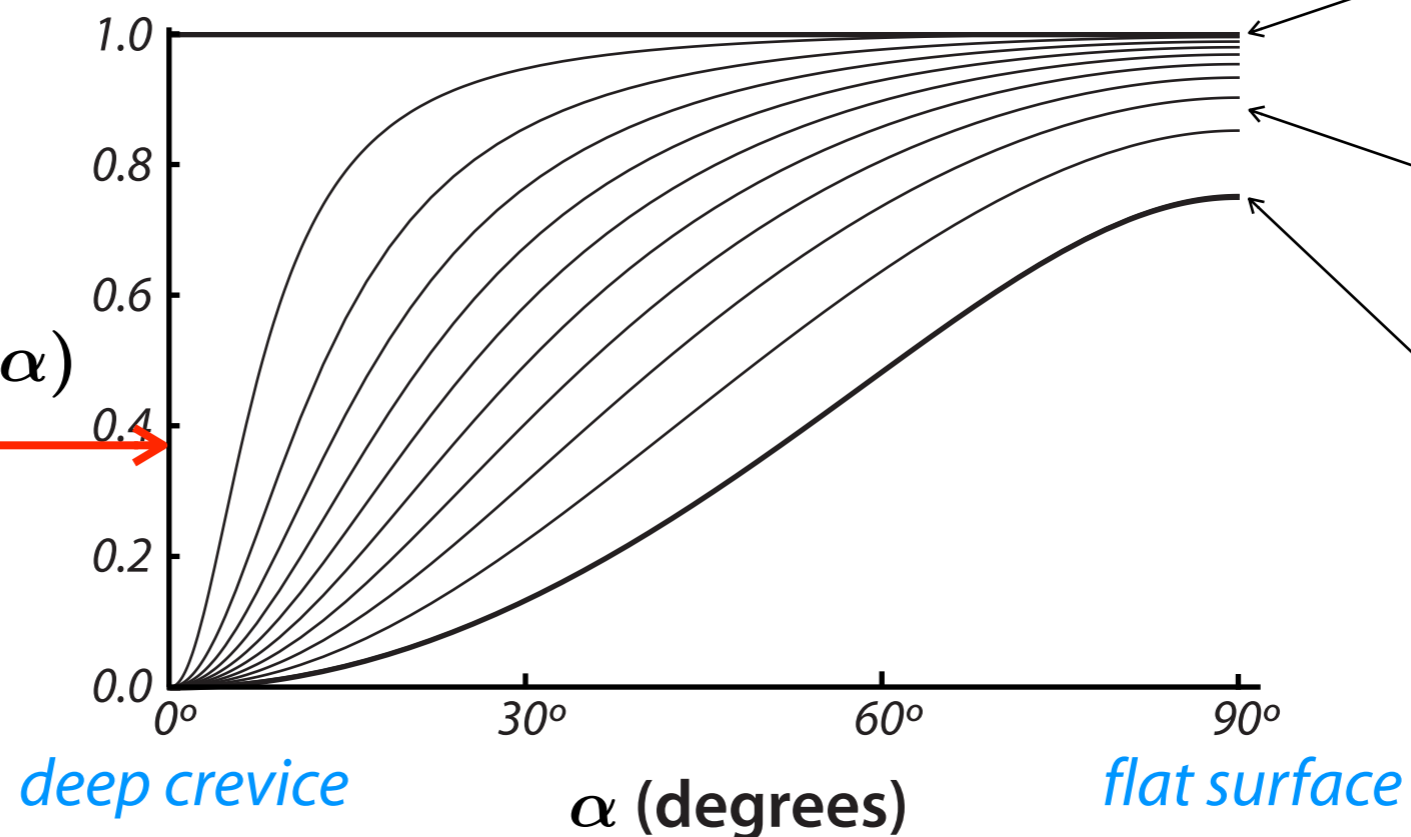
$$f = \frac{\text{ambient}}{\text{direct}} \quad \kappa = \frac{\mathcal{E}[I]^2}{\mathcal{E}[I^2]}$$

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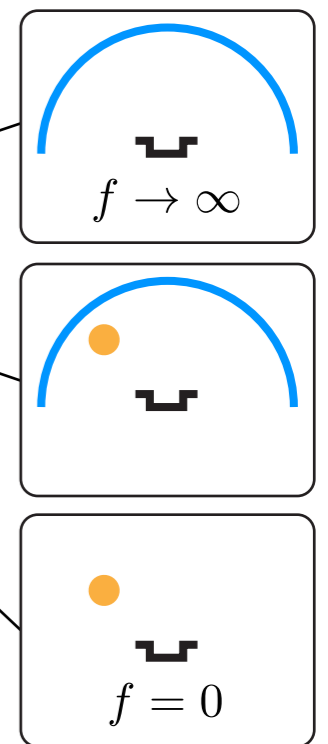
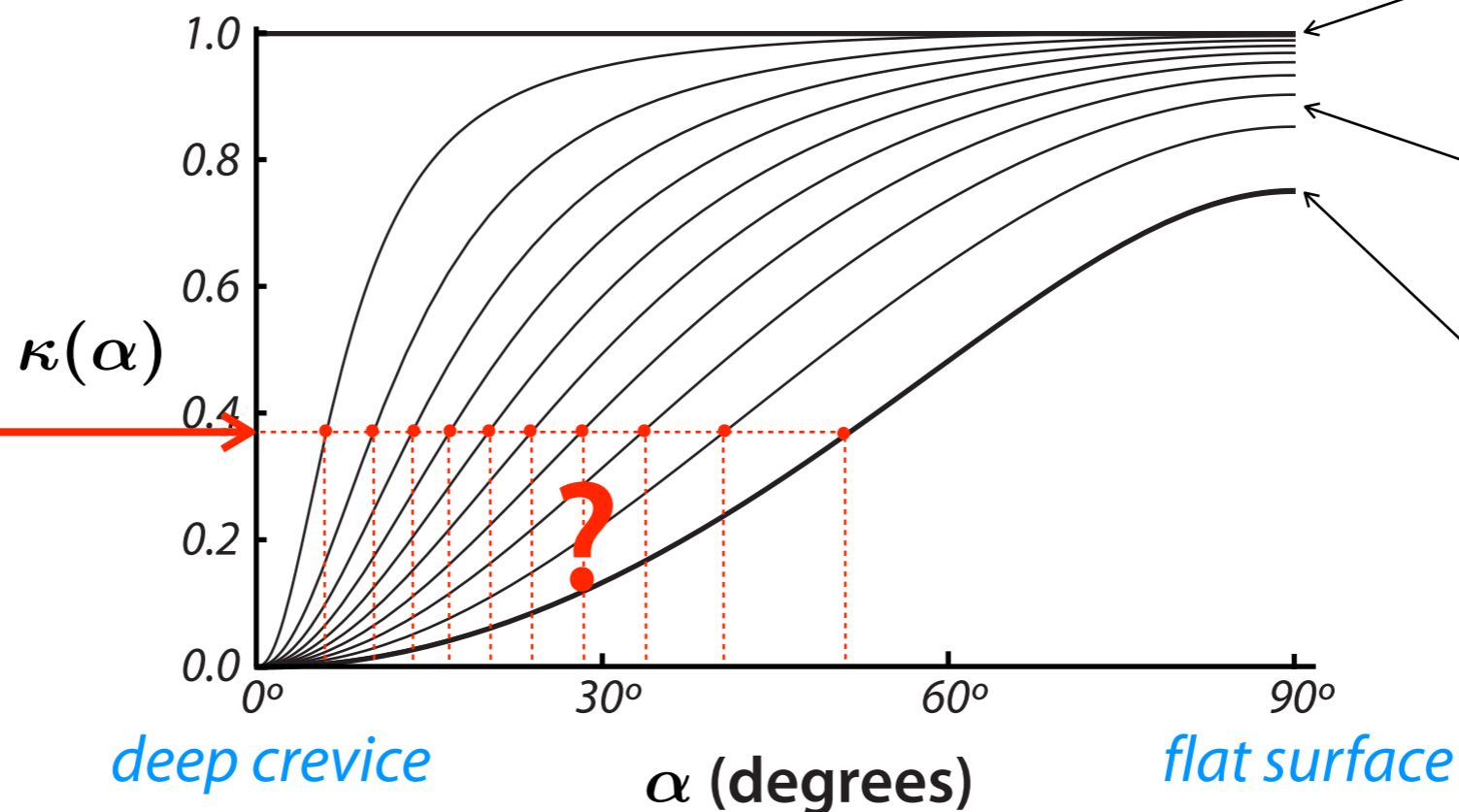
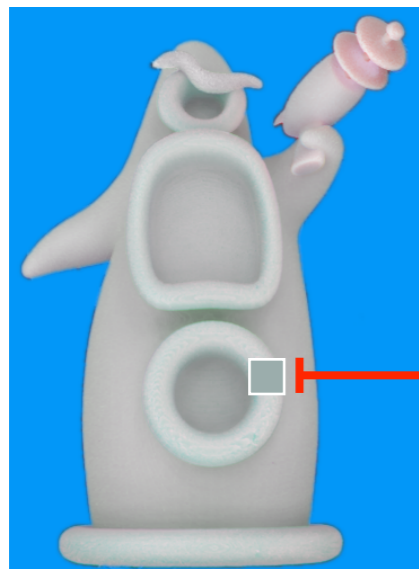
$\kappa(\alpha)$



$$f = \frac{\text{ambient}}{\text{direct}} \quad \kappa = \frac{\mathcal{E}[I]^2}{\mathcal{E}[I^2]}$$

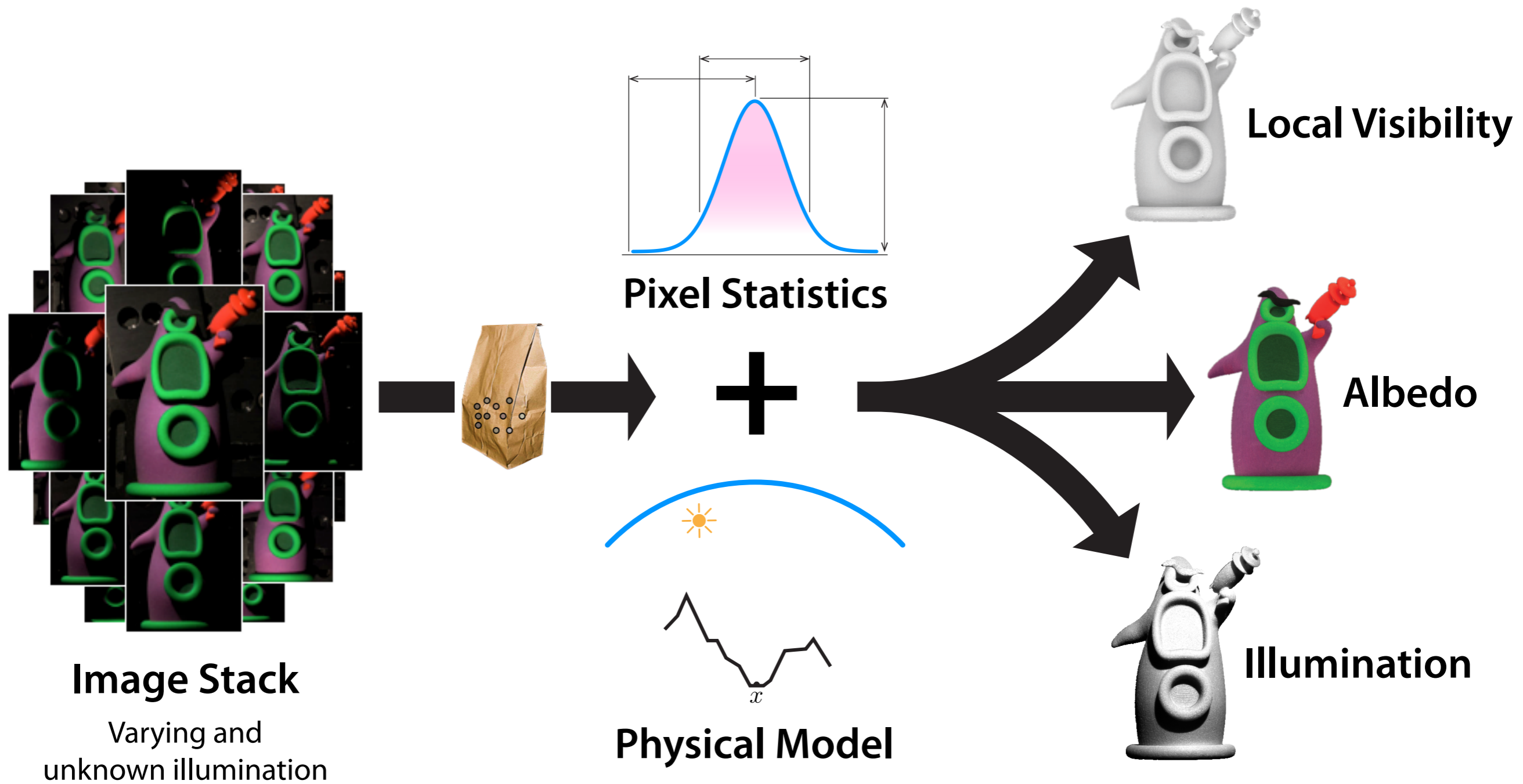
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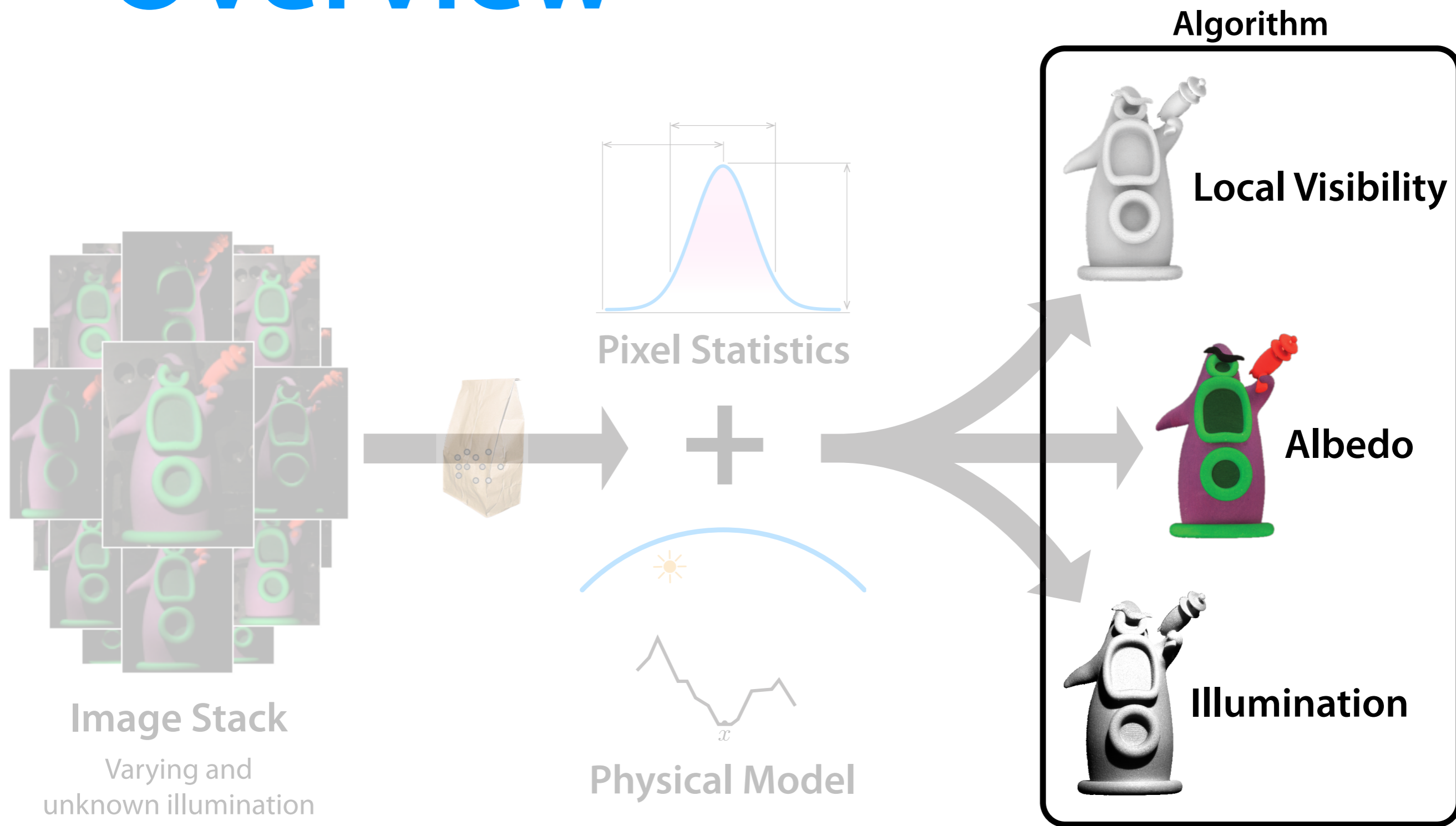


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# Overview



# Overview



# Estimating AO



# Estimating AO



# Estimating AO

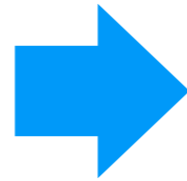


# Estimating AO

$$\mathcal{E}[I]$$

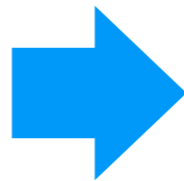


$$\mathcal{E}[I^2]$$

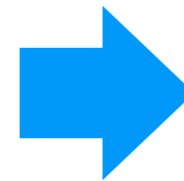


# Estimating AO

$$\mathcal{E}[I]$$



$$\mathcal{E}[I^2]$$



$$\kappa_{obs}$$

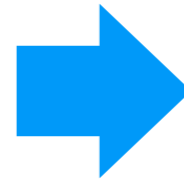


# Estimating AO

$$\mathcal{E}[I]$$



$$\mathcal{E}[I^2]$$



$$\kappa_{obs}$$



# Estimating AO

$\kappa_{obs}$



Input



Pixel Statistics



# Estimating AO

$\kappa_{obs}$



Input



Pixel Statistics



# Estimating AO

$\kappa_{obs}$



Assume  $f = 0$

Input

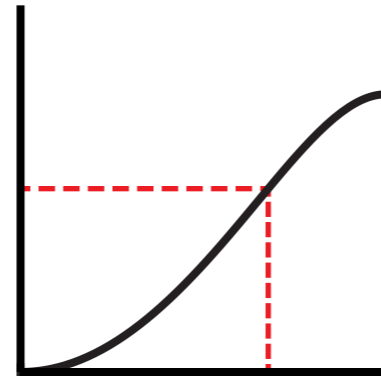


Pixel Statistics



# Estimating AO

$\kappa_{obs}$



Assume  $f = 0$

Input

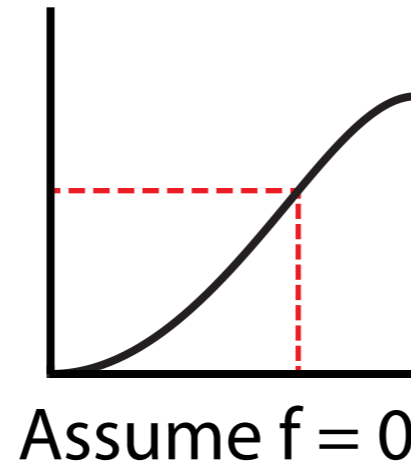


Pixel Statistics



# Estimating AO

$\kappa_{obs}$



$\alpha_0$



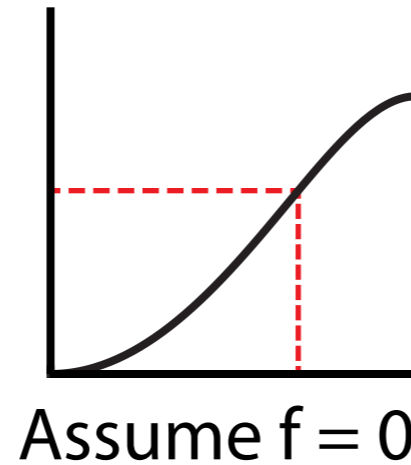
Input

Pixel Statistics



# Estimating AO

$\kappa_{obs}$



$\alpha_0$



Input

Pixel Statistics



# Estimating AO

$\alpha_0$



$f = 0$

Input



Pixel Statistics



# Estimating AO

$\alpha_0$



$f = 0$

Input



Pixel Statistics



# Estimating AO

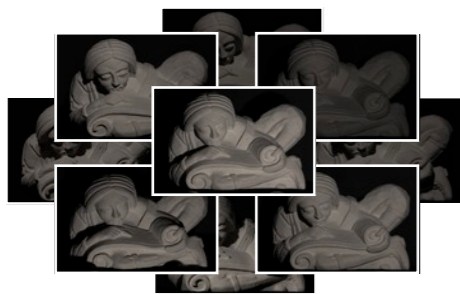
$\alpha_0$



$f = 0$

$$\min_{\alpha, f} \sum \|\kappa_{obs} - \kappa(\alpha, f)\|$$

Input



Pixel Statistics



# Estimating AO

$\alpha_0$



$f = 0$

$$\min_{\alpha, f} \sum \|\kappa_{obs} - \kappa(\alpha, f)\|$$

$\alpha_1$



Input



Pixel Statistics



# Estimating AO

$\alpha_0$



$f = 0$

$$\min_{\alpha, f} \sum \|\kappa_{obs} - \kappa(\alpha, f)\|$$

$\alpha_1$



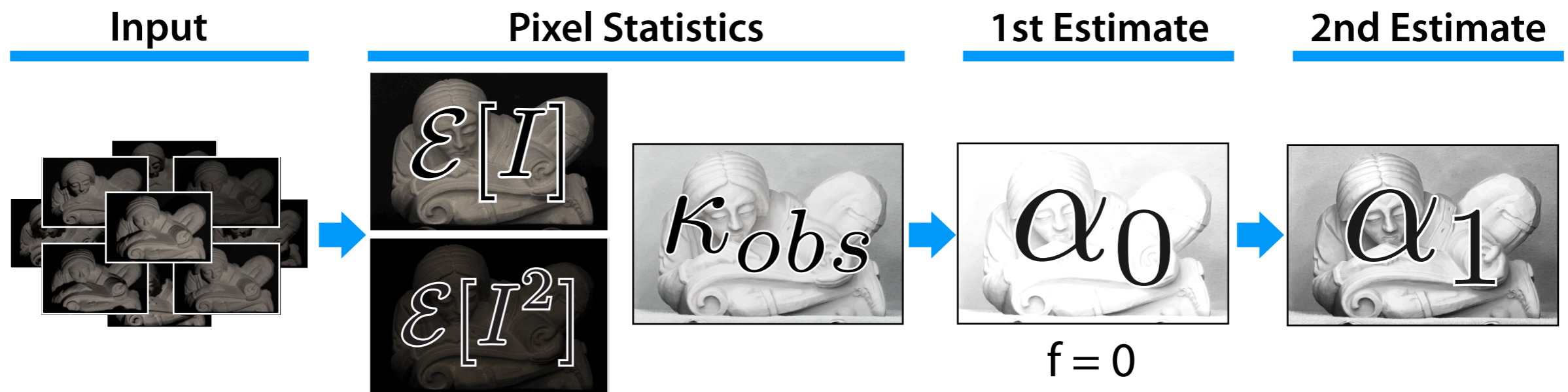
Input



Pixel Statistics



# Estimating AO



# Albedo & Illumination

- AO = shading under uniform lighting



$$\mathcal{E}[I] \approx I_a$$

# Albedo & Illumination

- AO = shading under uniform lighting



$$\mathcal{E}[I] \approx I_a$$


÷



$$AO$$


# Albedo & Illumination

- AO = shading under uniform lighting


$$\mathcal{E}[I] \approx I_a \quad \div \quad AO \quad = \quad \rho$$

# Albedo & Illumination

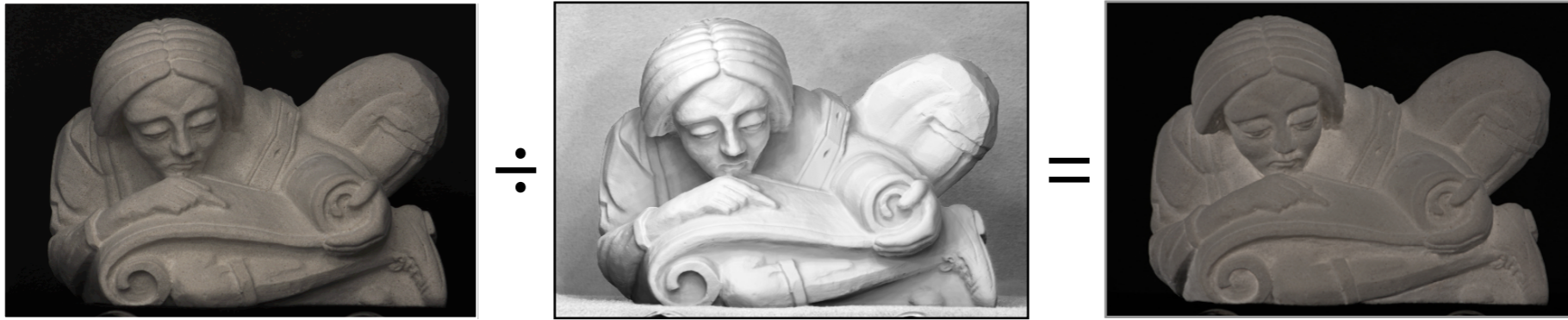
- AO = shading under uniform lighting


$$\mathcal{E}[I] \approx I_a \div AO = \rho$$

- Illumination: follows from intrinsic image equation

# Albedo & Illumination

- AO = shading under uniform lighting



The diagram illustrates the relationship between an intrinsic image, albedo, and the expected image under uniform lighting. It consists of three grayscale images of a classical sculpture, separated by a division symbol ( $\div$ ) and an equals sign ( $=$ ). The first image on the left shows the sculpture with strong directional lighting, creating deep shadows and bright highlights. The middle image shows the same sculpture under uniform, ambient lighting, where the shading is more even. The third image on the right shows the result of dividing the first image by the second, which is the albedo map, where the surface properties are isolated from the lighting effects.


$$\mathcal{E}[I] \approx I_a \quad \div \quad AO = \rho$$

- Illumination: follows from intrinsic image equation



# Albedo & Illumination

- AO = shading under uniform lighting

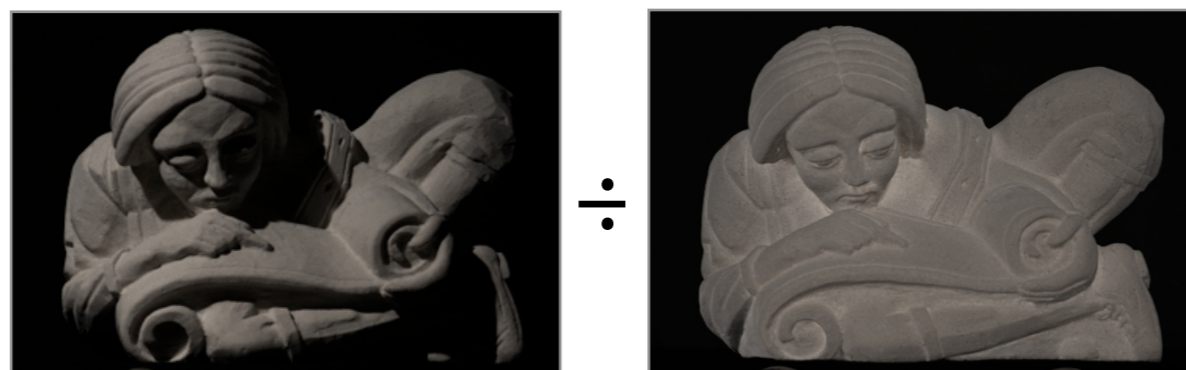


The diagram illustrates the calculation of albedo ( $\rho$ ) from an expected image ( $\mathcal{E}[I] \approx I_a$ ) and an ambient occlusion (AO) map. The equation is represented as:

$$\mathcal{E}[I] \approx I_a \div AO = \rho$$

Below the images, the labels  $\mathcal{E}[I] \approx I_a$ ,  $AO$ , and  $\rho$  are positioned under their respective images.

- Illumination: follows from intrinsic image equation




The diagram illustrates the calculation of illumination ( $I$ ) from an observed image ( $I$ ) and an albedo map ( $\rho$ ). The equation is represented as:

$$I \div \rho = I$$


Below the images, the labels  $I$  and  $\rho$  are positioned under their respective images.

# Albedo & Illumination

- AO = shading under uniform lighting


$$\mathcal{E}[I] \approx I_a \quad \div \quad AO = \rho$$

- Illumination: follows from intrinsic image equation

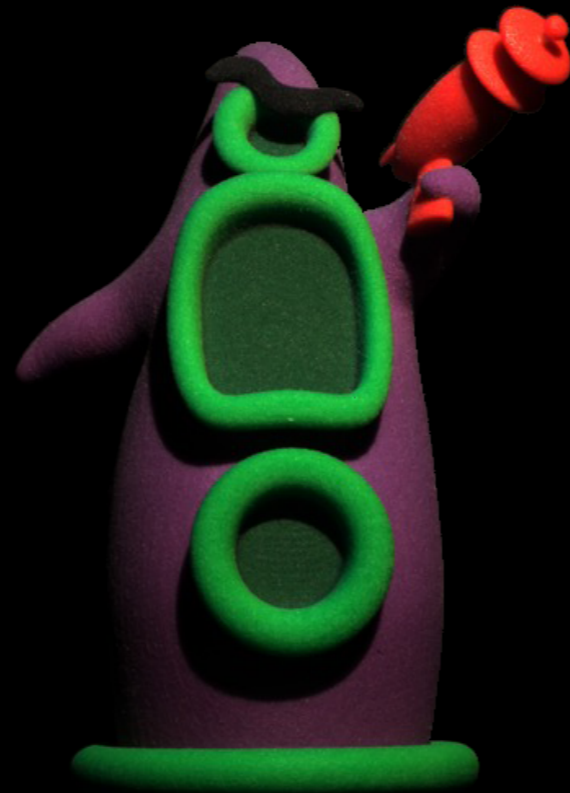

$$I \quad \div \quad \rho = L$$

# Results



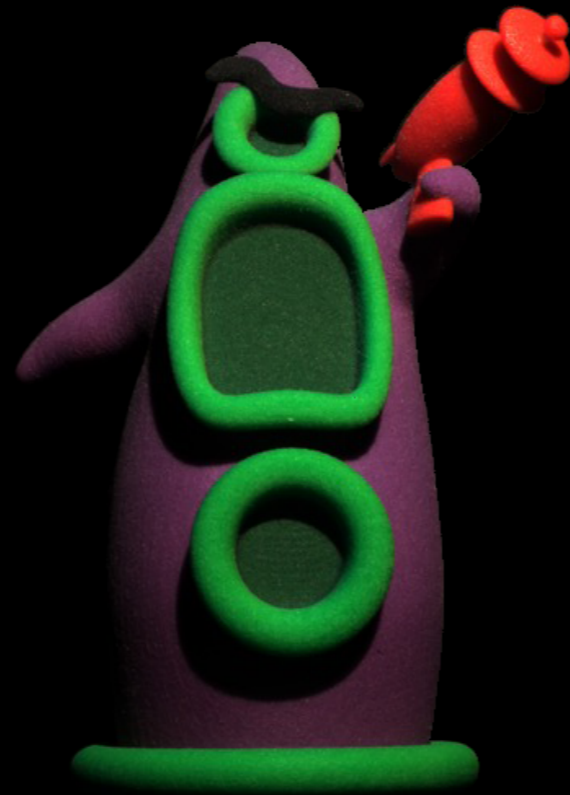
Sample Image

Dataset: TENTACLE



Background masked  
to reduce clutter

Sample Image



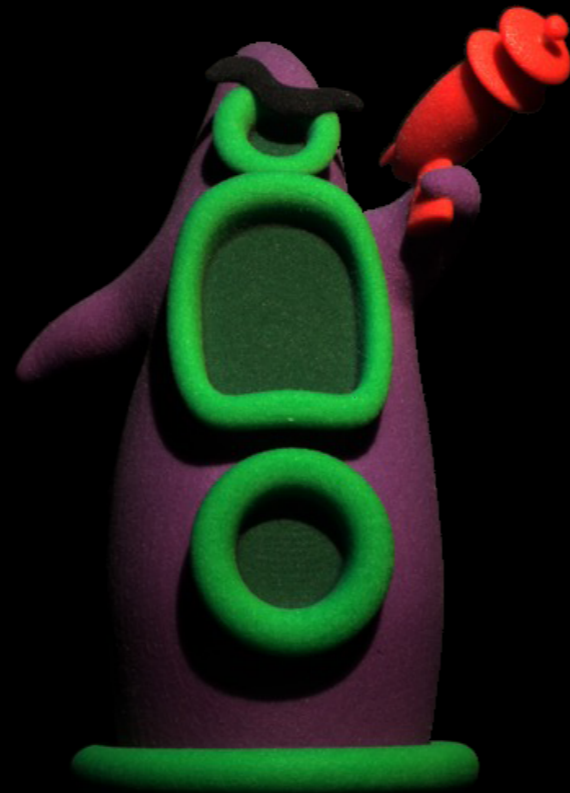
Ambient Occlusion



Dataset: TENTACLE

Background masked  
to reduce clutter

Sample Image

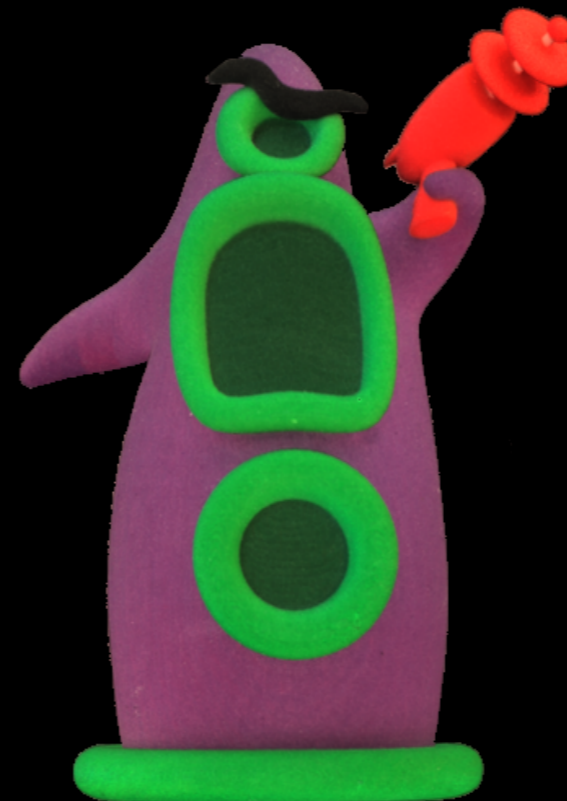


Ambient Occlusion



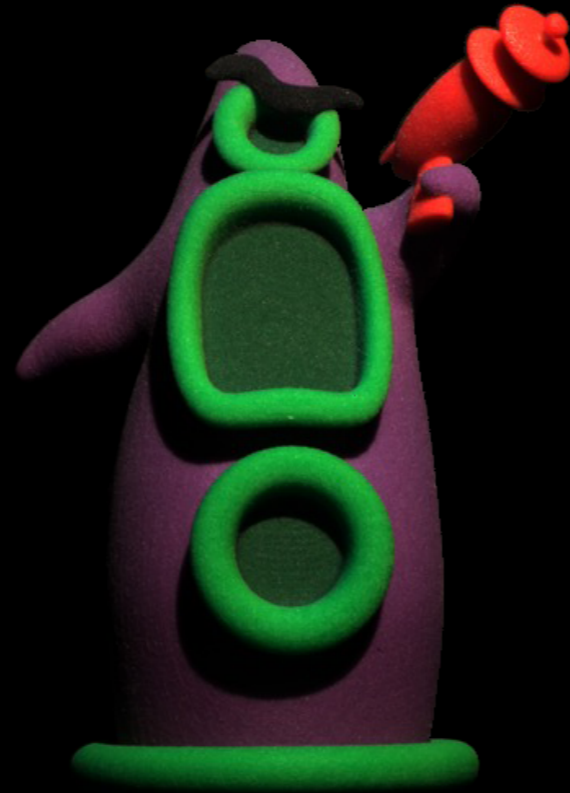
Dataset: TENTACLE

Background masked  
to reduce clutter



Albedo

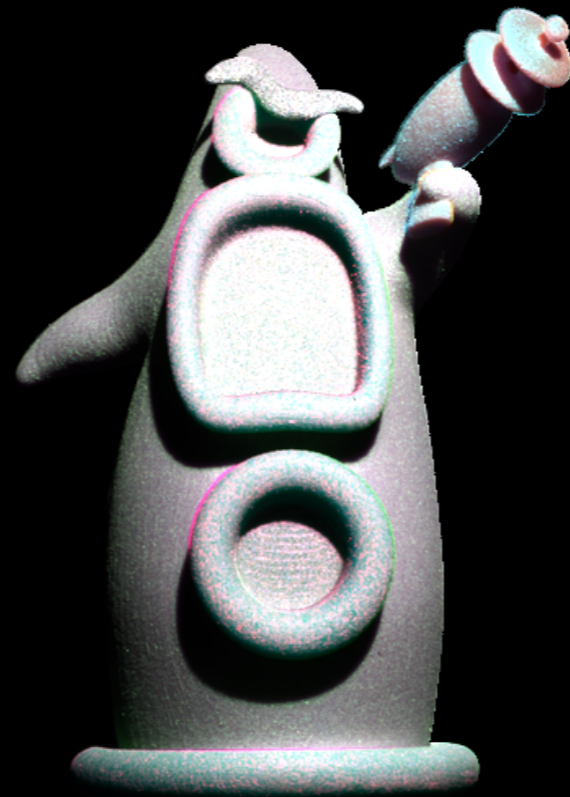
Sample Image



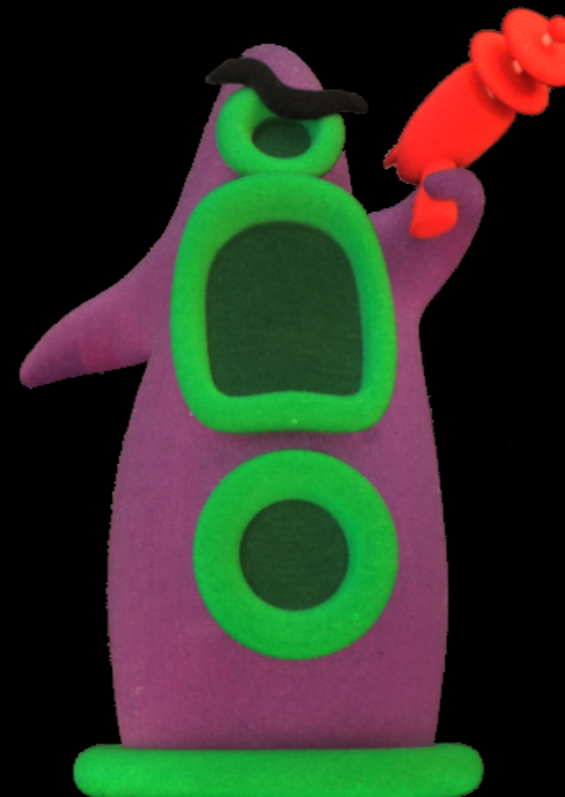
Ambient Occlusion



Dataset: TENTACLE



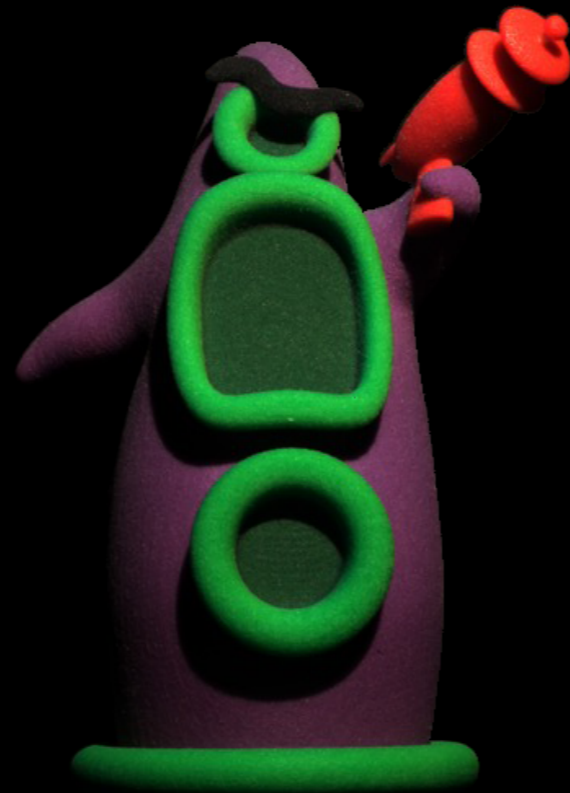
Illumination



Albedo

Background masked  
to reduce clutter

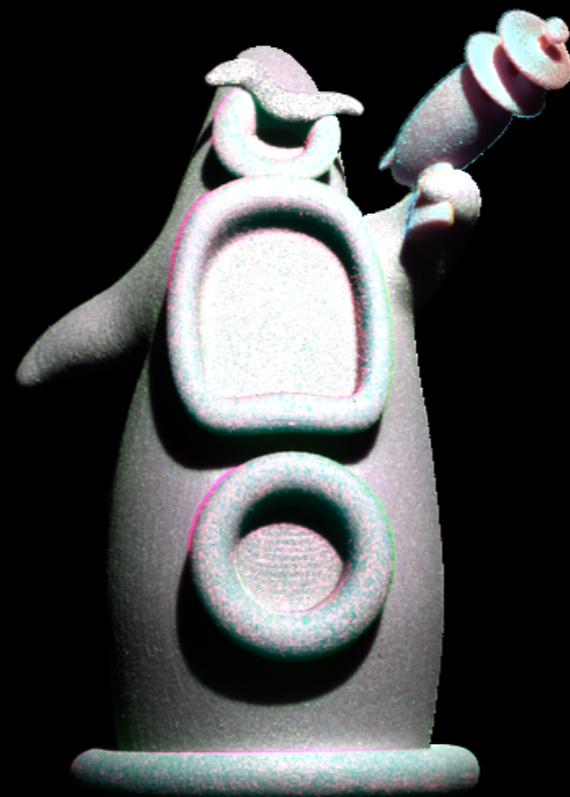
Sample Image



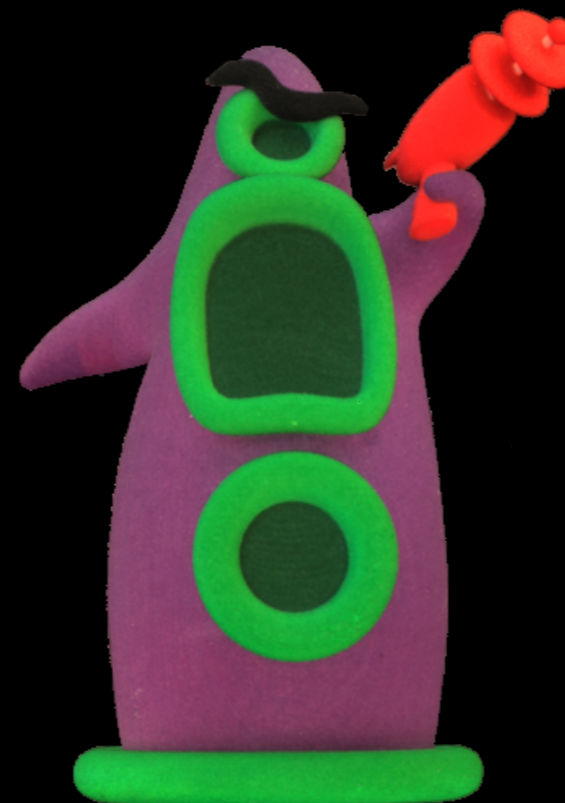
Ambient Occlusion



Dataset: TENTACLE



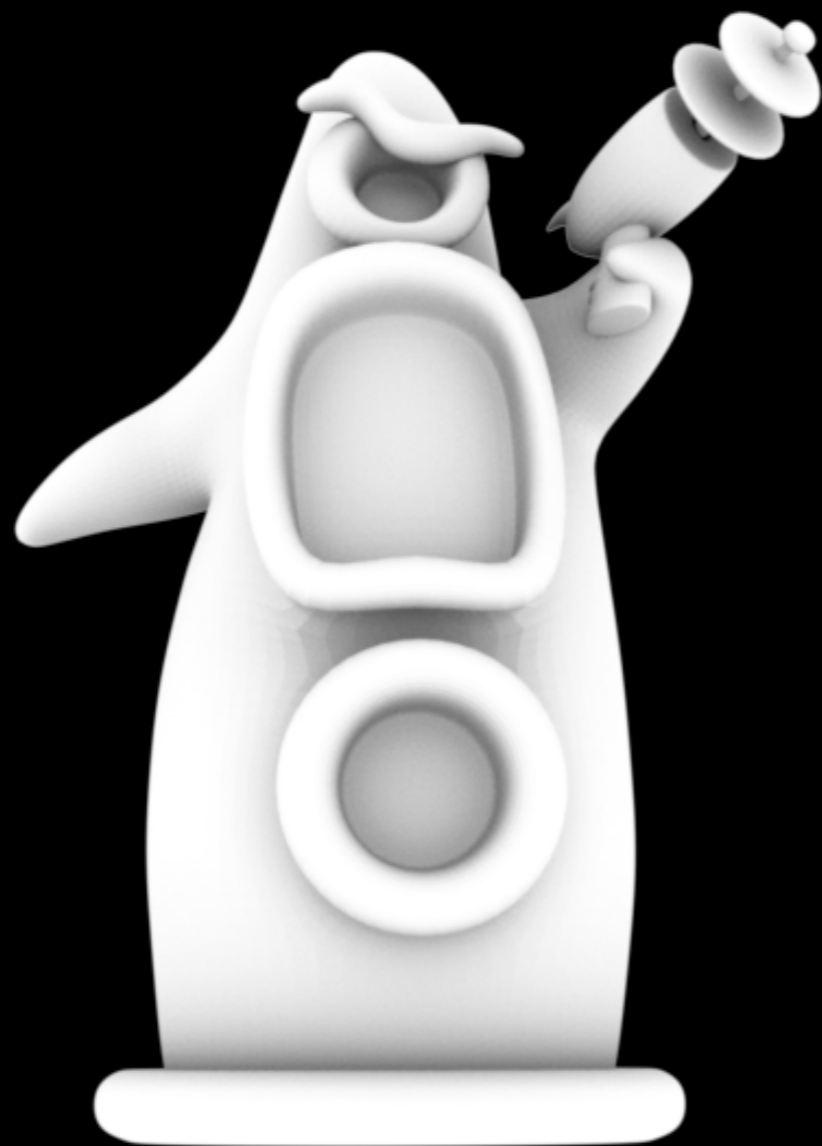
Illumination



Albedo

Background masked  
to reduce clutter

# Ambient Occlusion



Ground Truth



Ours

Background masked  
to reduce clutter



Sample Image



Sample Image



Ambient Occlusion



Sample Image



Ambient Occlusion



Albedo

Sample Image



Ambient Occlusion



Illumination



Albedo

Sample Image



Ambient Occlusion



Illumination



Albedo

Sample Image



Ambient Occlusion



Illumination



Albedo

Sample Image



Ambient Occlusion



Illumination

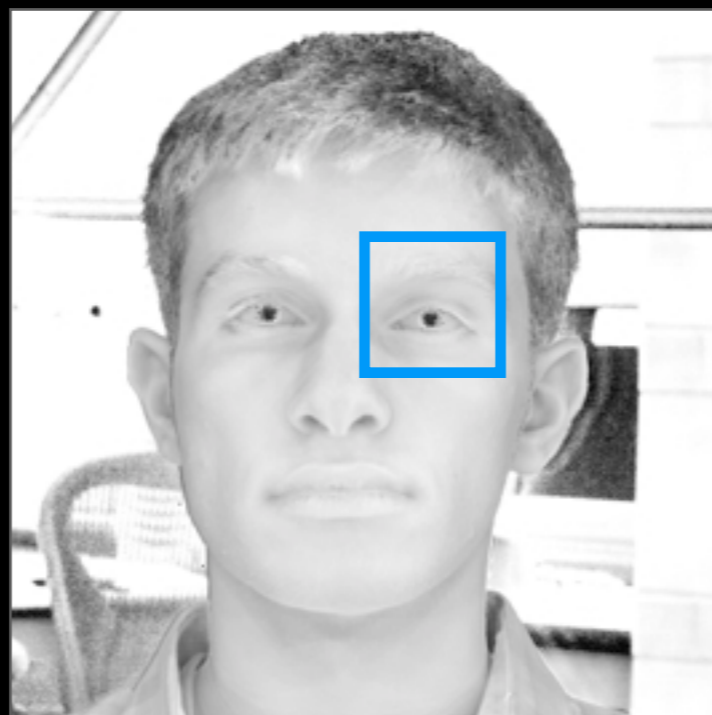


Albedo

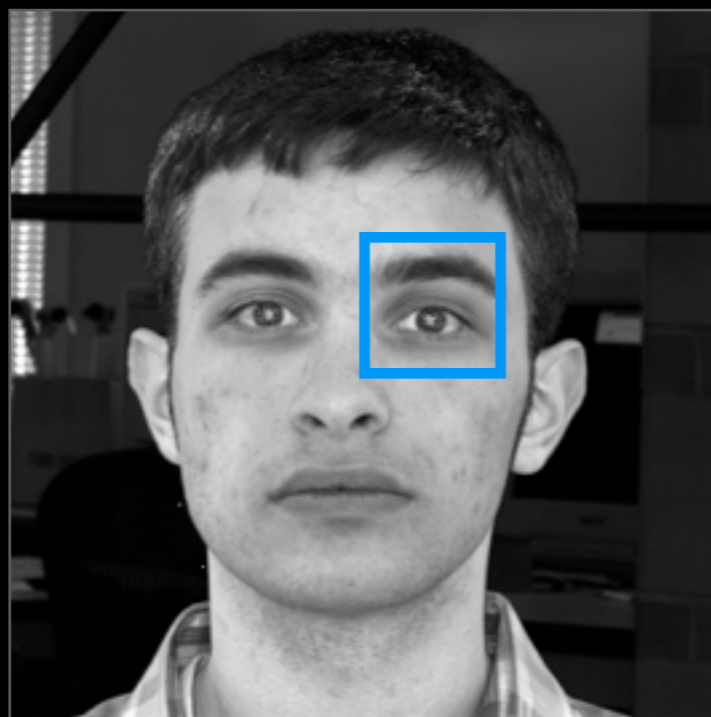
Sample Image



Ambient Occlusion



Illumination

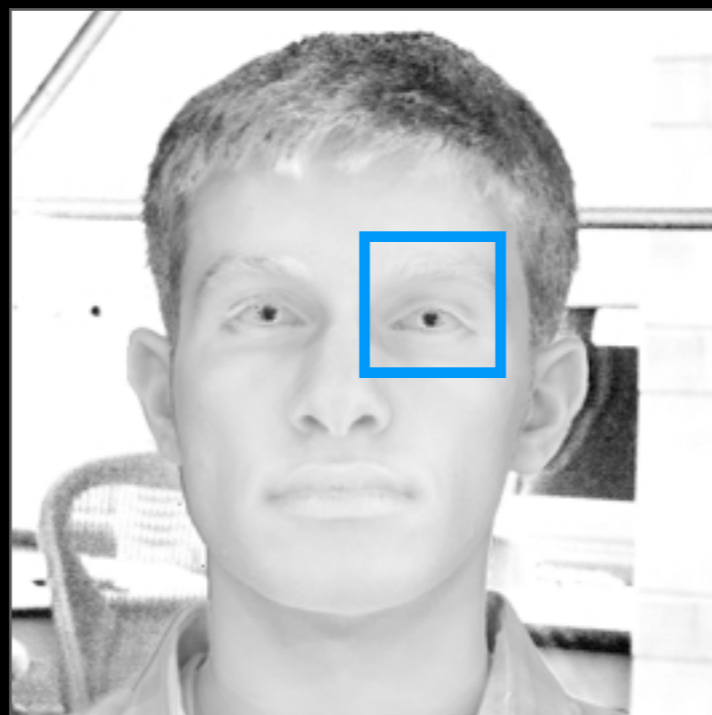


Albedo

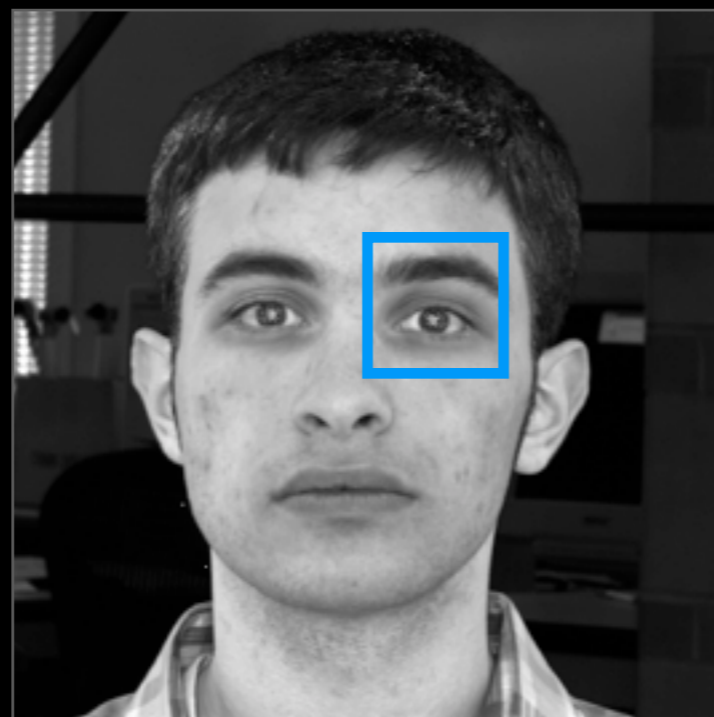
Sample Image



Ambient Occlusion



Illumination

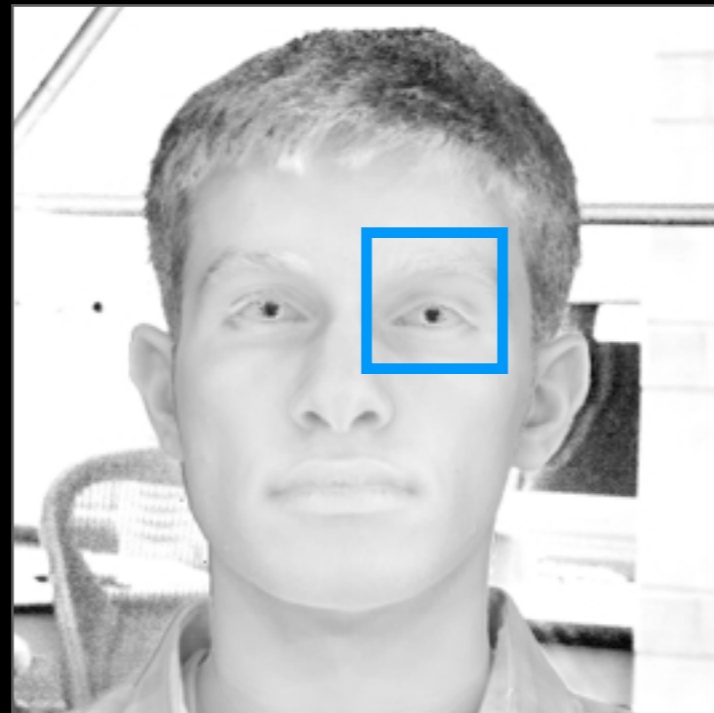


Albedo

Sample Image



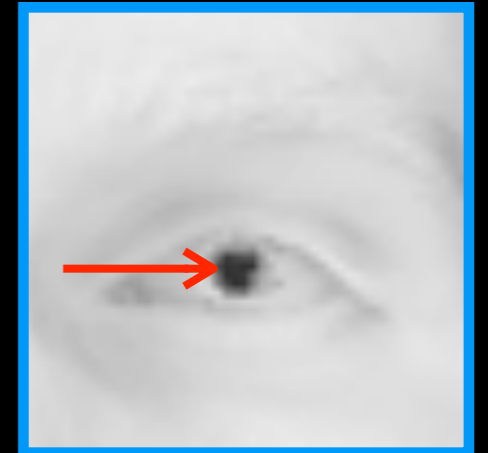
Ambient Occlusion



Albedo



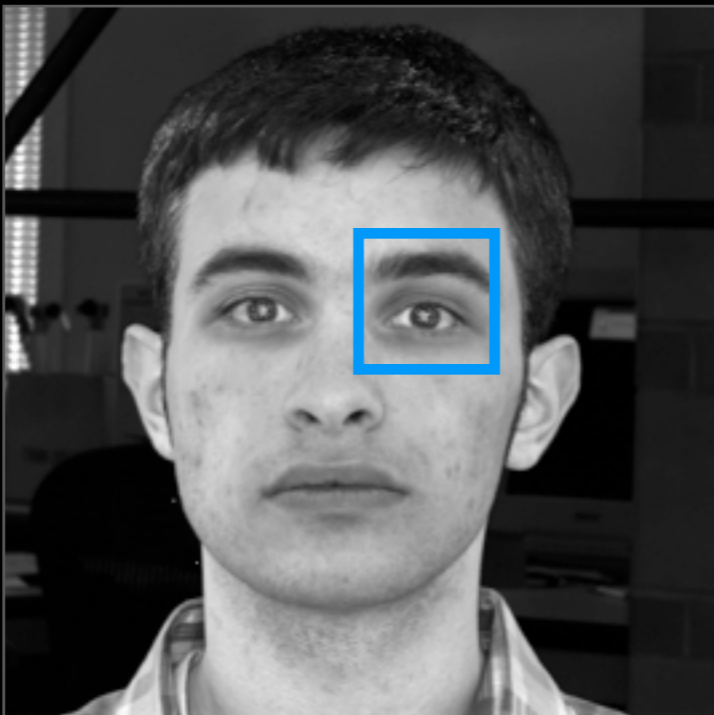
AO



Illumination



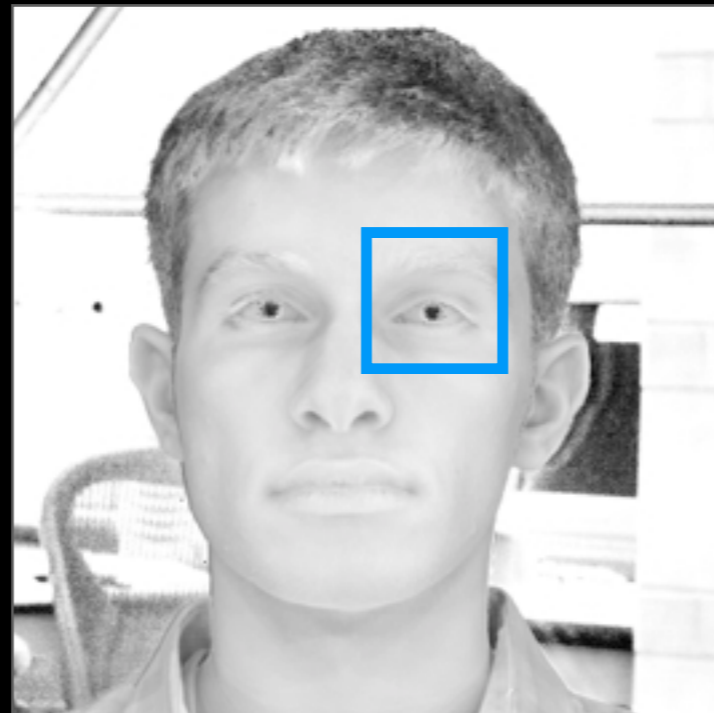
Albedo



Sample Image



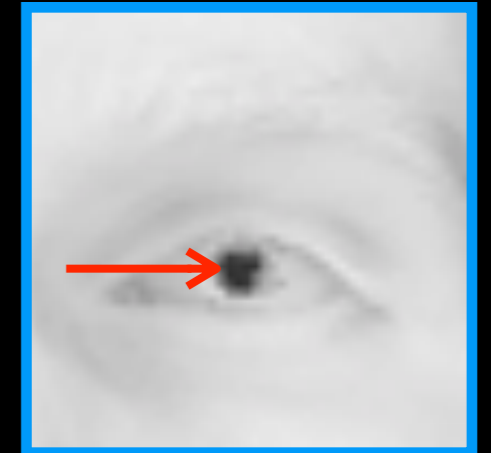
Ambient Occlusion



Albedo



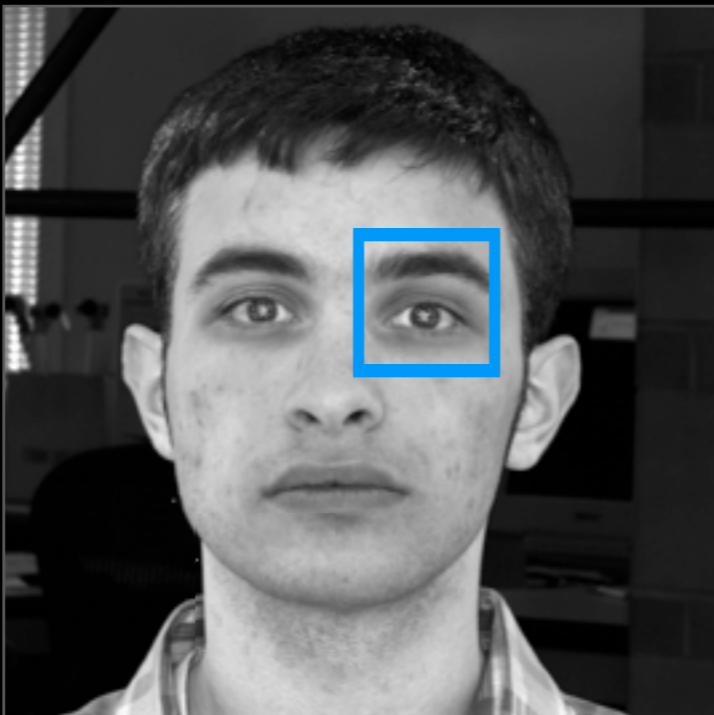
AO



Illumination



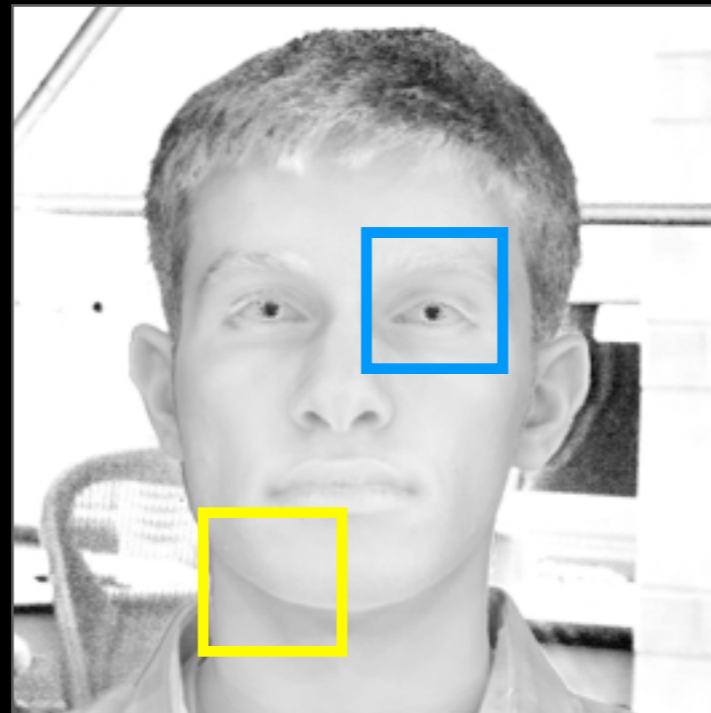
Albedo



Sample Image



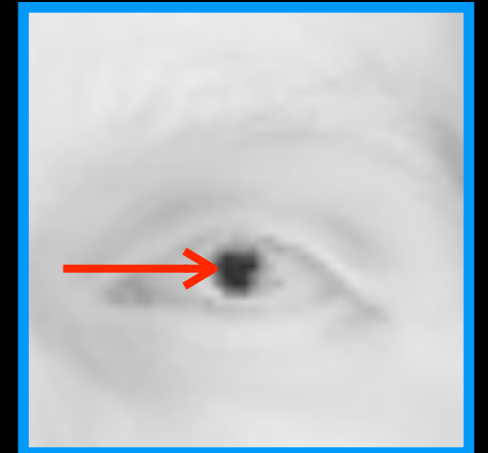
Ambient Occlusion



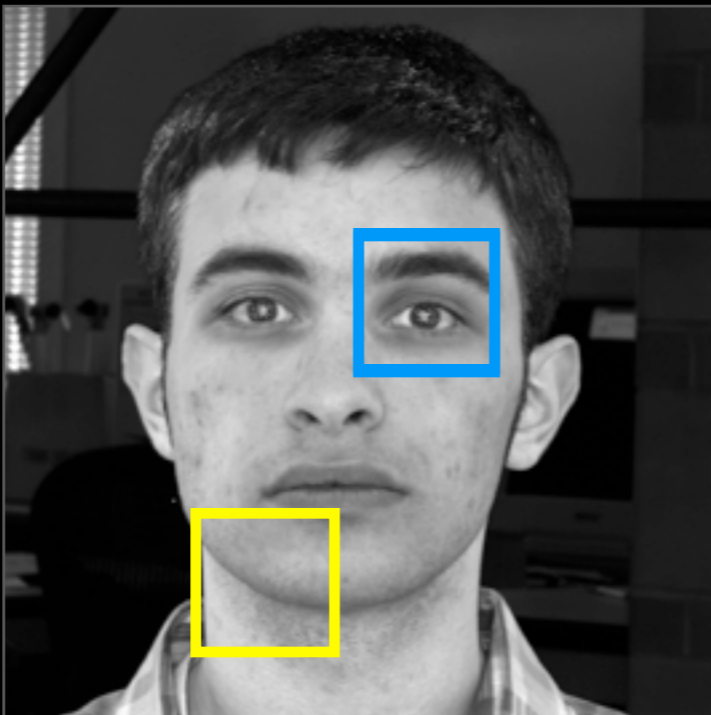
Albedo



AO



Illumination



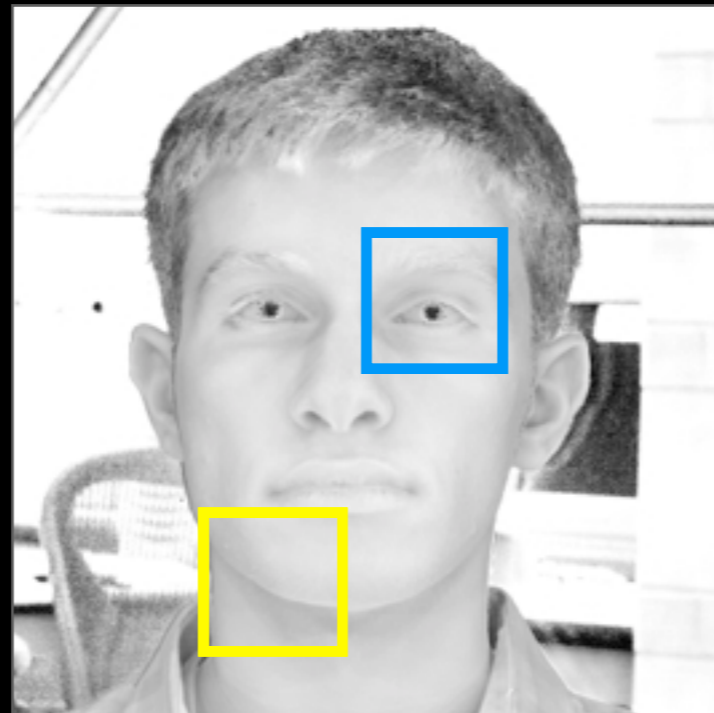
Albedo



Sample Image



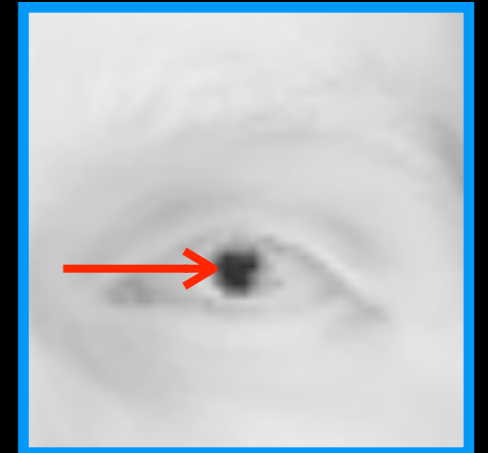
Ambient Occlusion



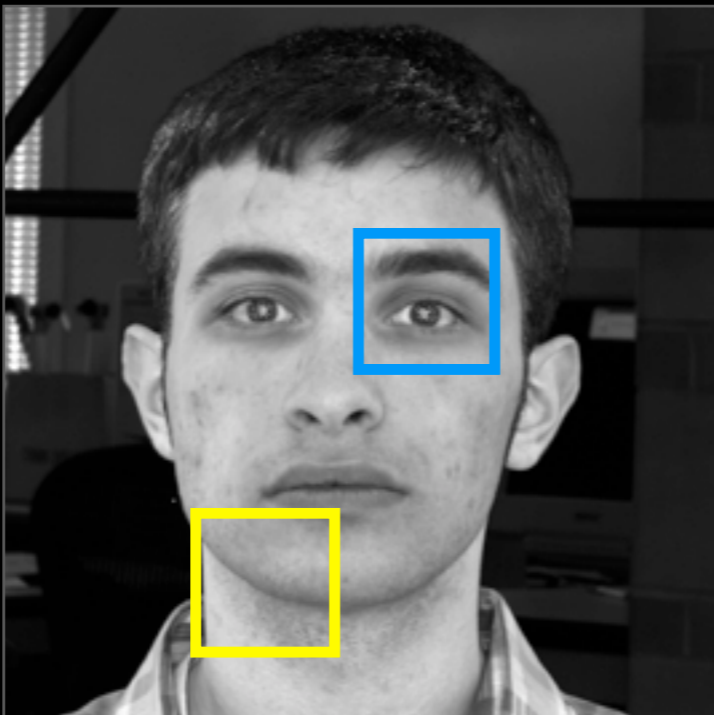
Albedo



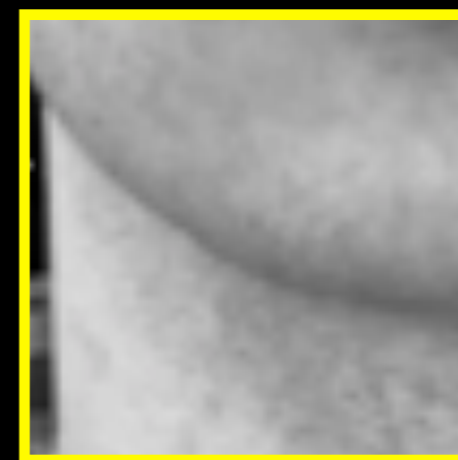
AO



Illumination



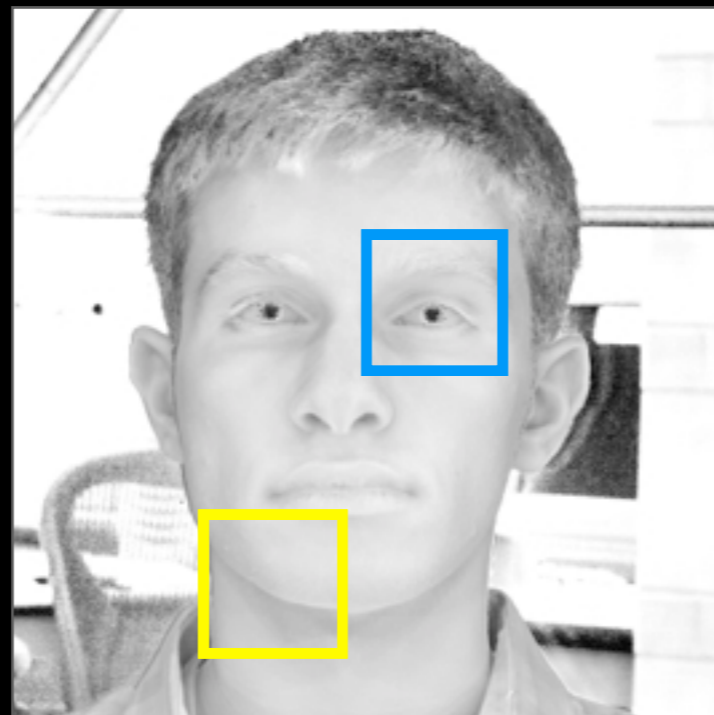
Albedo



Sample Image



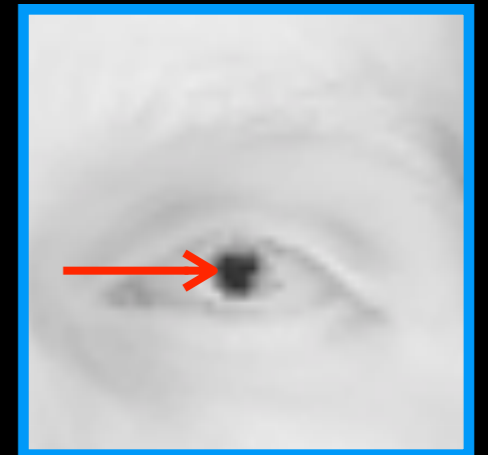
Ambient Occlusion



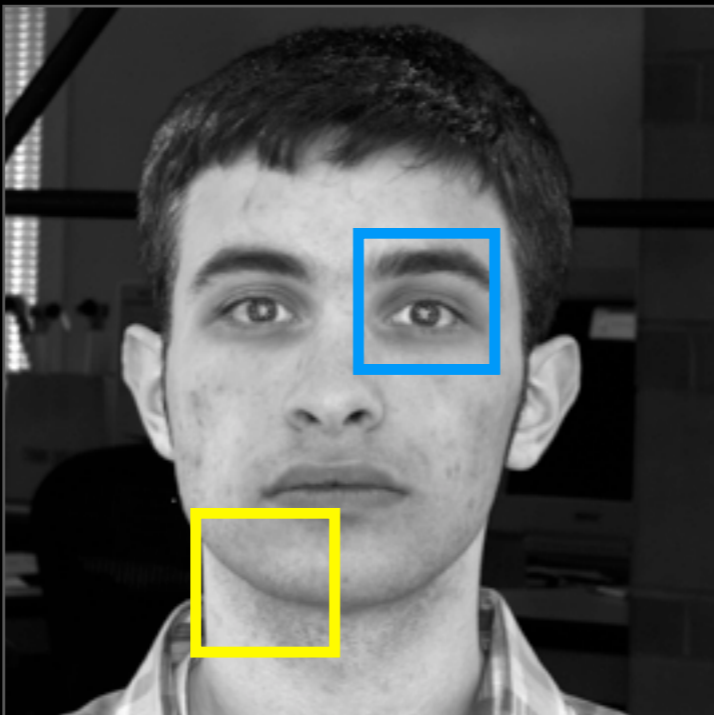
Albedo



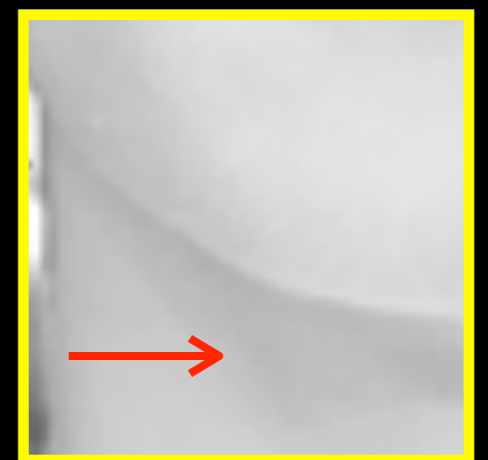
AO



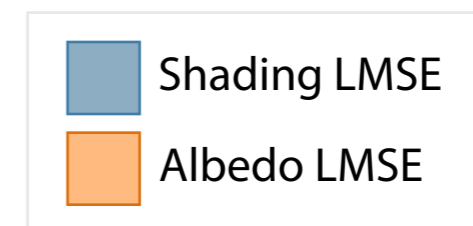
Illumination



Albedo



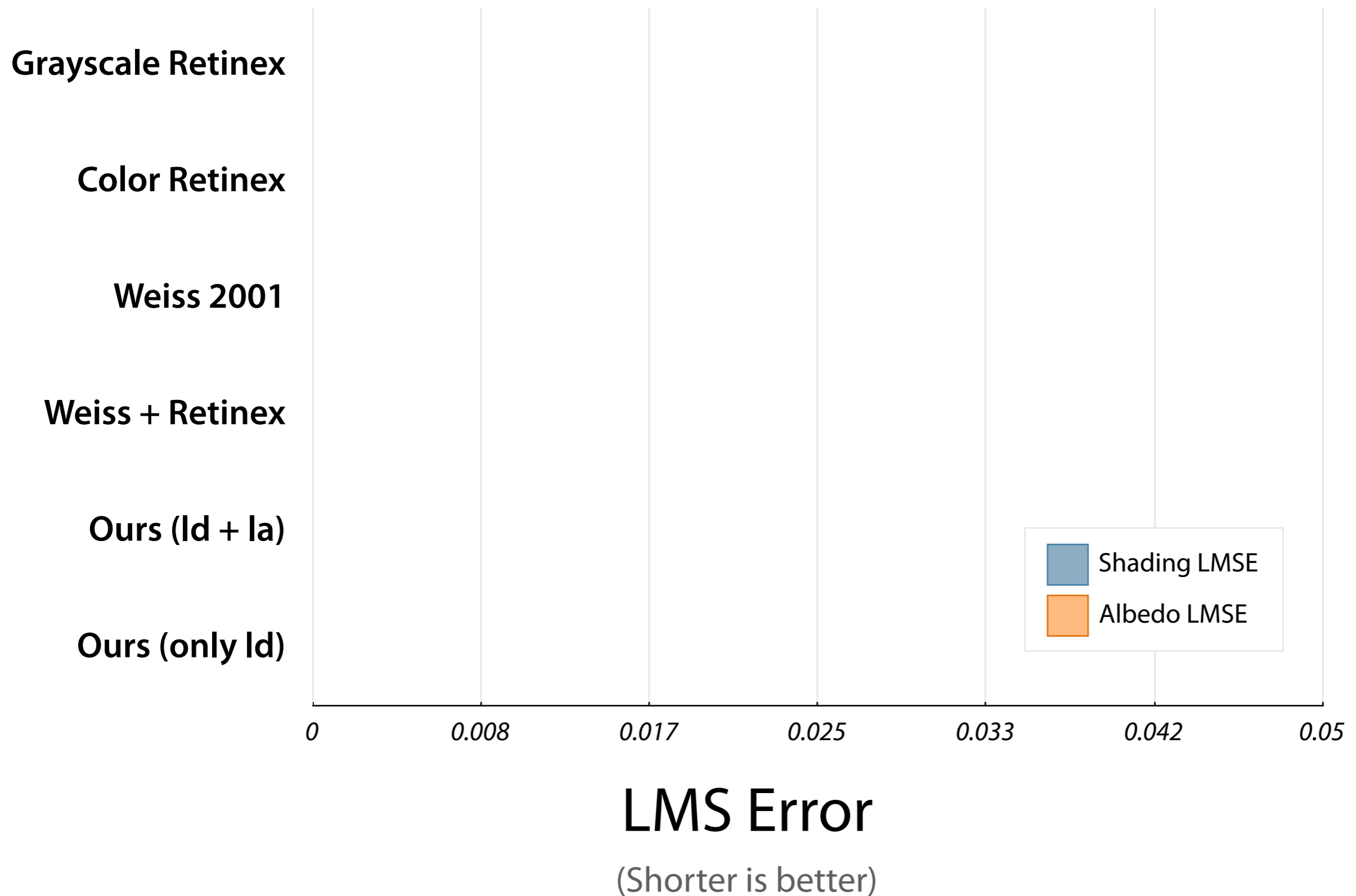
# MIT Intrinsic Image Benchmark



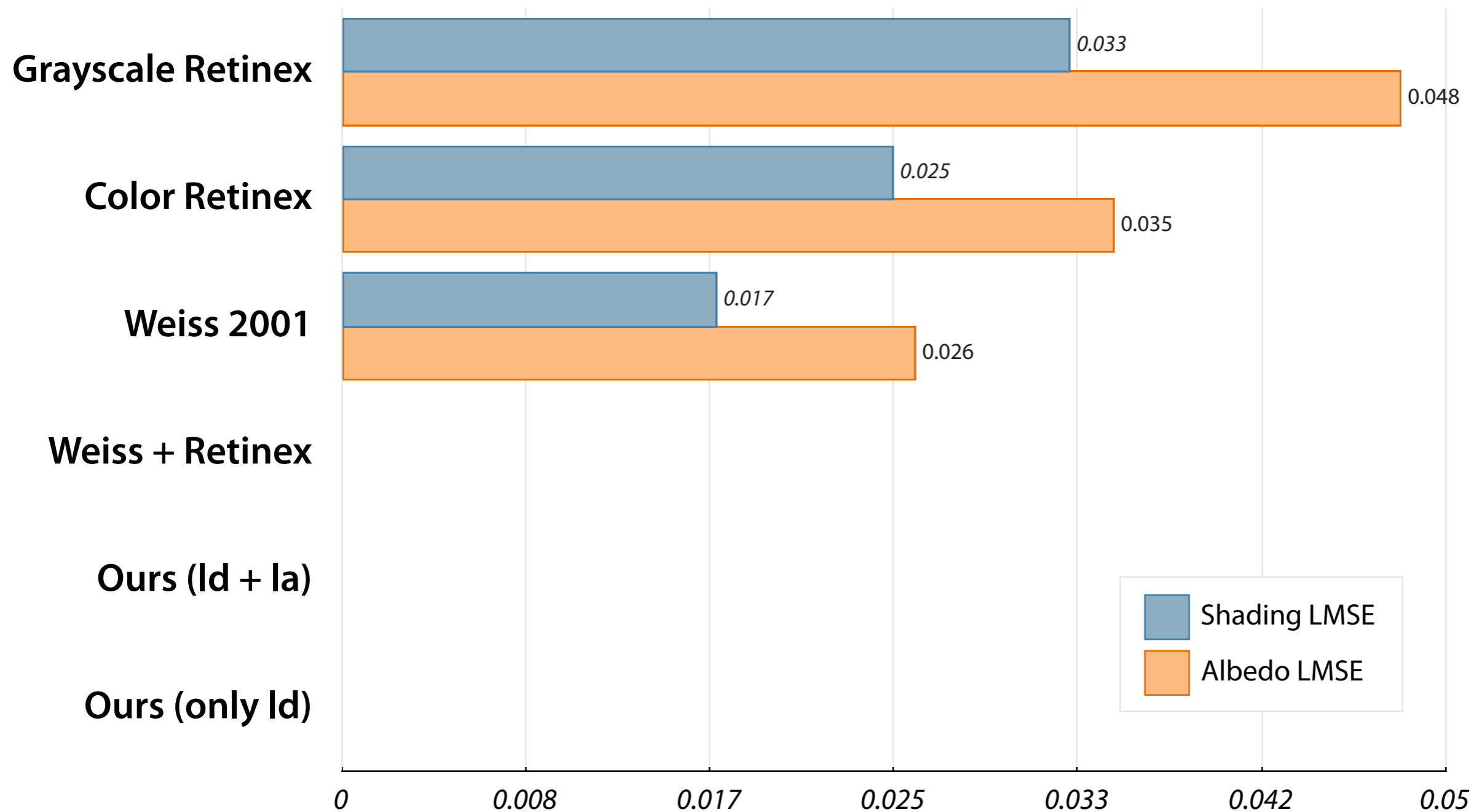
**LMS Error**

(Shorter is better)

# MIT Intrinsic Image Benchmark



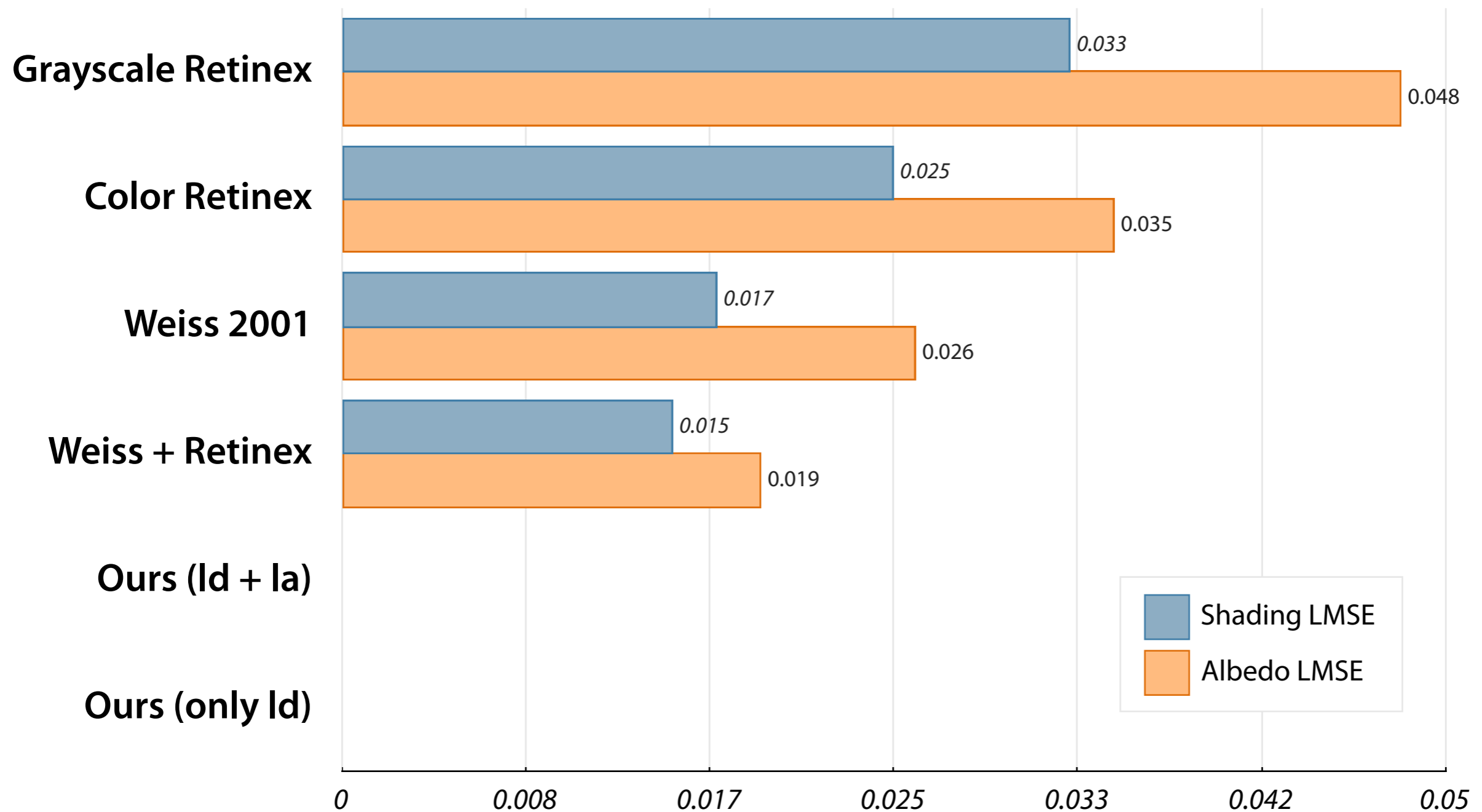
# MIT Intrinsic Image Benchmark



LMS Error

(Shorter is better)

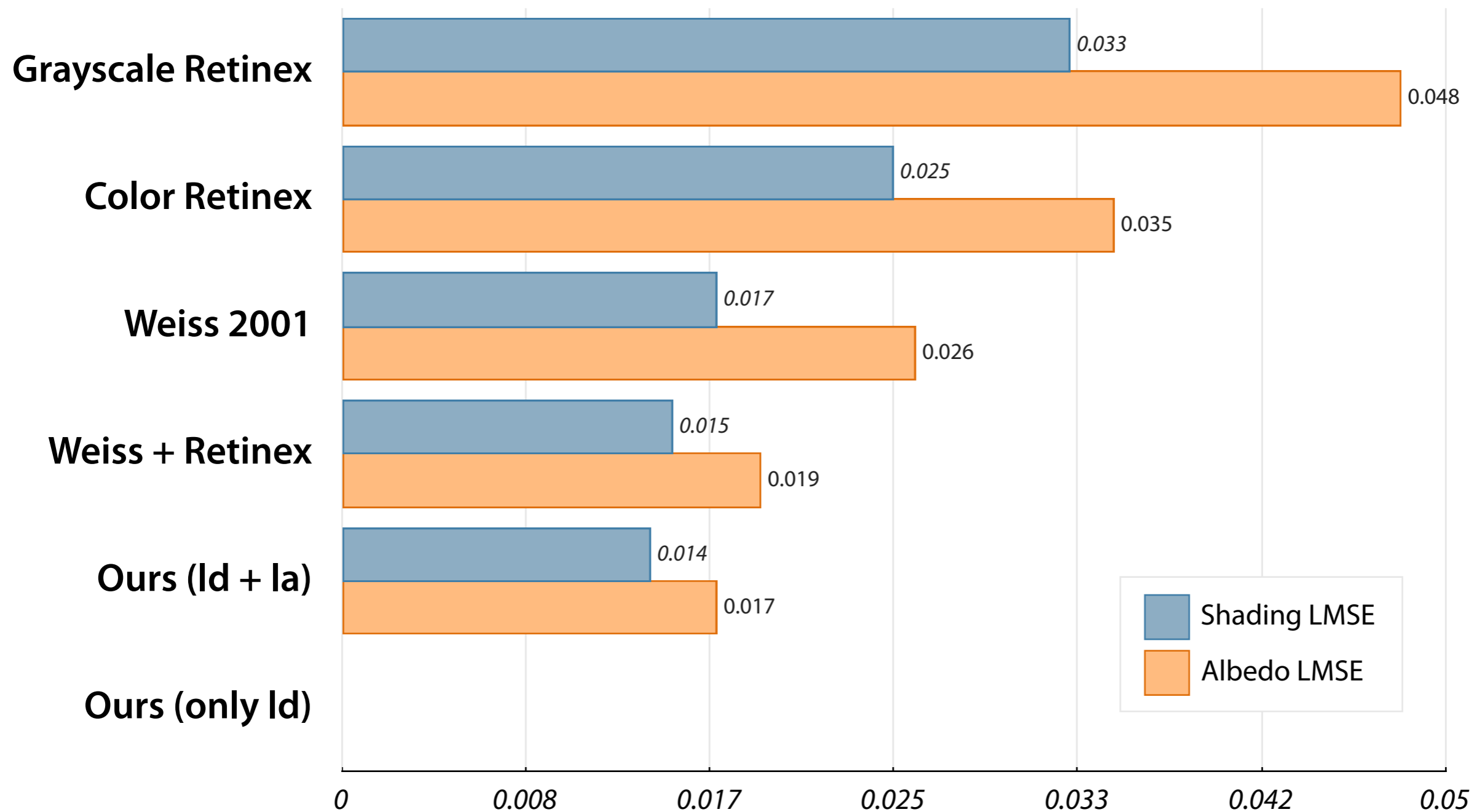
# MIT Intrinsic Image Benchmark



LMS Error

(Shorter is better)

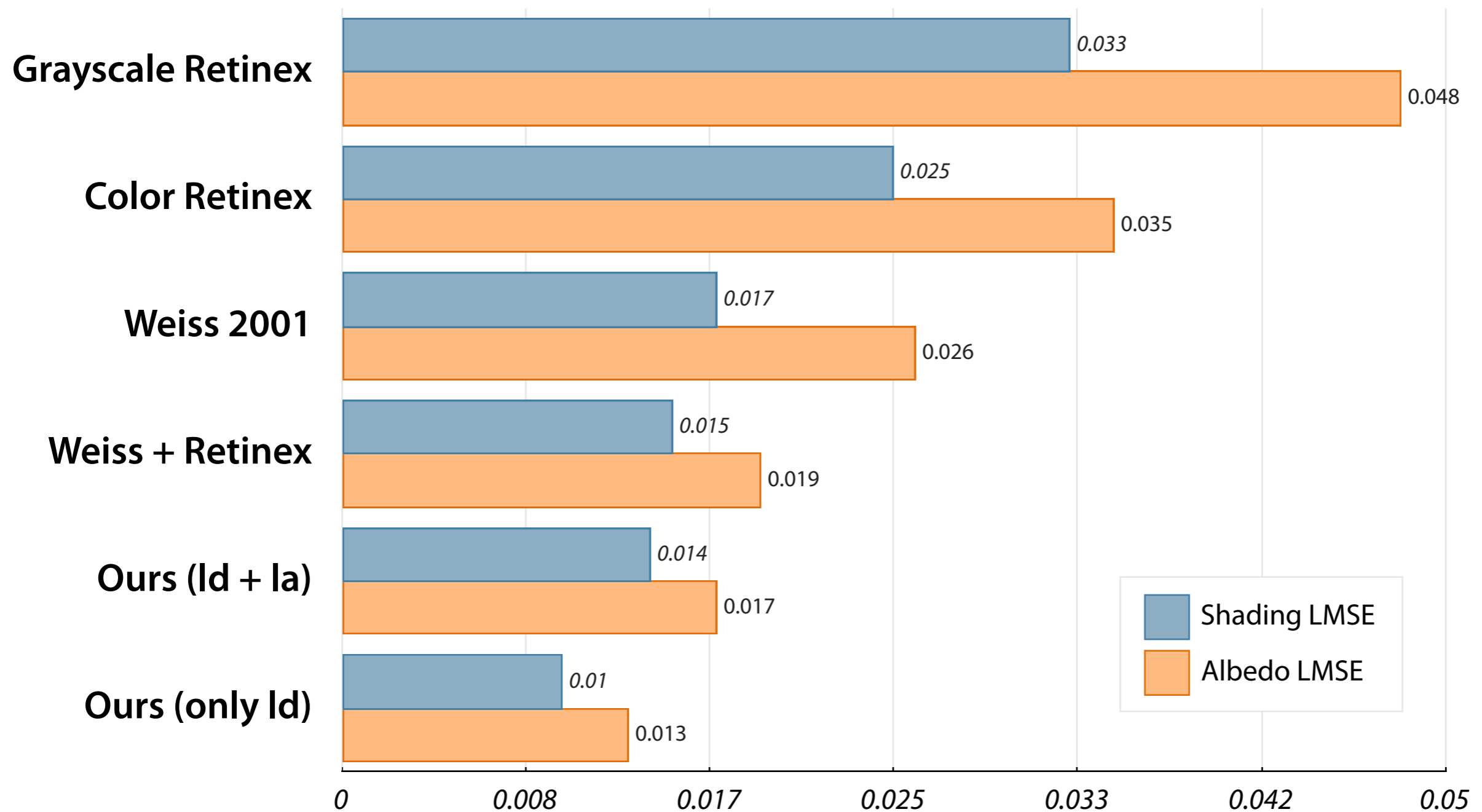
# MIT Intrinsic Image Benchmark



LMS Error

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# MIT Intrinsic Image Benchmark



LMS Error

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# Conclusions

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- Simple per-pixel algorithm
- No need for
  - Scene geometry
  - Light source position

# Future Work

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- Towards internet photo collections

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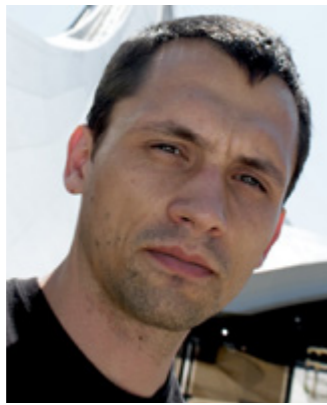
- Towards internet photo collections
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- Towards internet photo collections
  - More general light source distribution, model light source color shifts, camera response, ...
- Richer local geometry model, incorporate anisotropy
- Handle multiple bounces of light



**Daniel  
Hauagge**



**Scott  
Wehrwein**

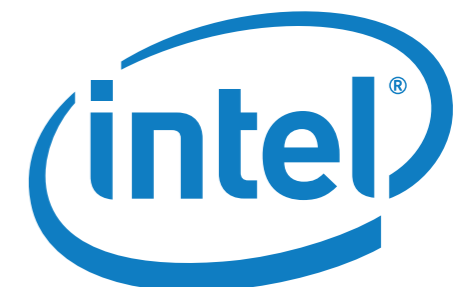
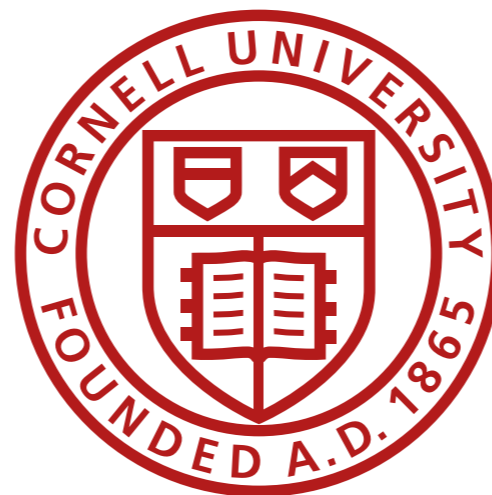


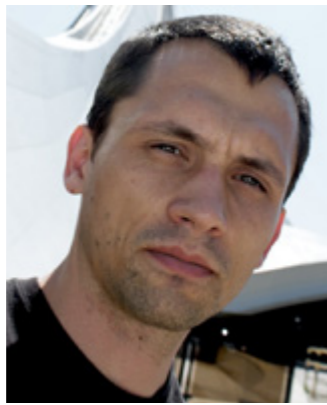
**Kavita  
Bala**



**Noah  
Snavely**

For code and data visit  
[\*www.cs.cornell.edu/projects/photoao\*](http://www.cs.cornell.edu/projects/photoao)





**Daniel  
Hauagge**



**Scott  
Wehrwein**



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