Dealing with indirect illumination

15-463, 15-663, 15-862
Computational Photography
Fall 2022, Lecture 18

http://graphics.cs.cmu.edu/courses/15-463

Course announcements

- Homework assignment 6 has been posted.
  - Due on Monday, December 12th.
  - You can use all your remaining late days.
- Updated project logistics posted on Piazza.

Overview of today's lecture

- Direct and indirect illumination.
- Direct-indirect separation using high-frequency illumination.
- Back to structured light.
- Back to time-of-flight imaging.
- Direct-indirect separation using epipolar constraints.

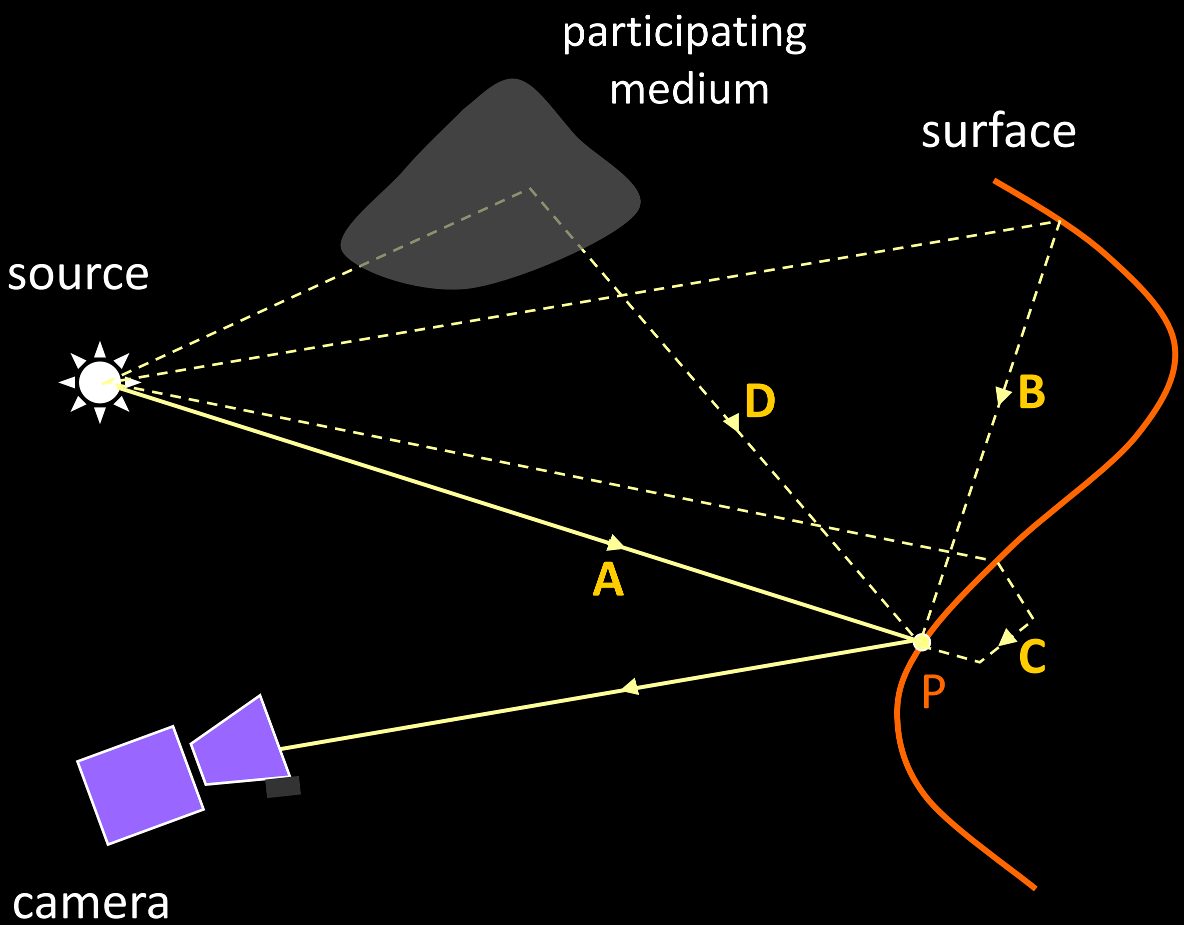
Slide credits

These slides were directly adapted from:

- Shree Nayar (Columbia).
- Matthew O’Toole (CMU).
- Supreeth Achar (Google, formerly CMU).
- Mohit Gupta (Wisconsin).

Direct and indirect illumination

Direct and Indirect Illumination



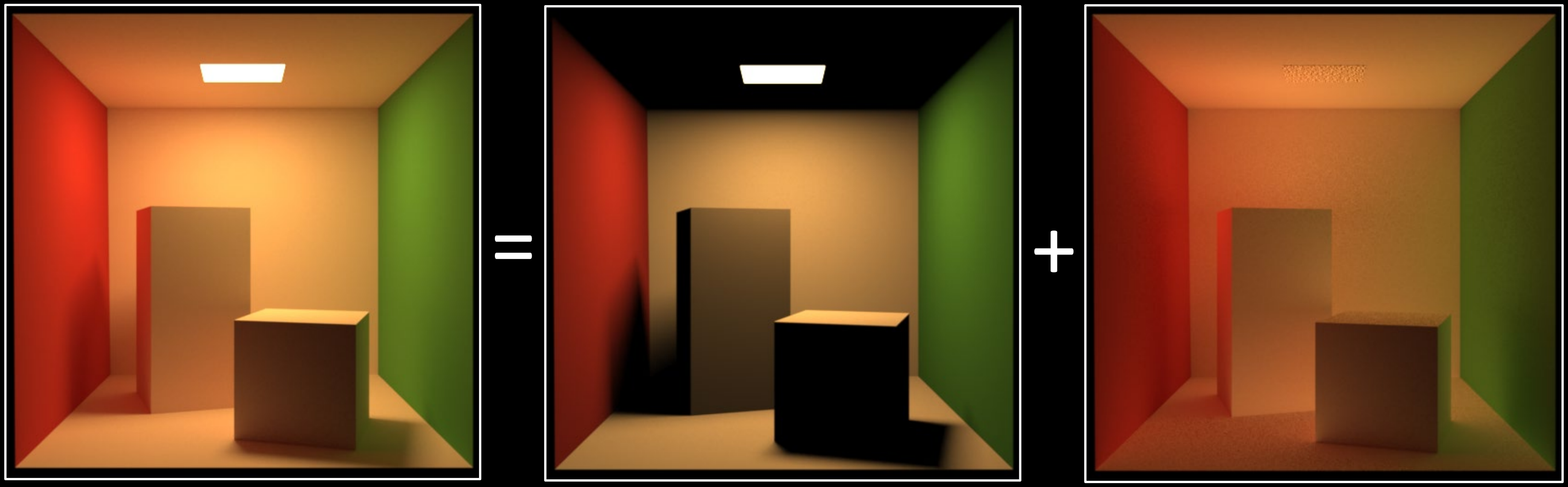
A : Direct

B : Interreflection

C : Subsurface

D : Volumetric

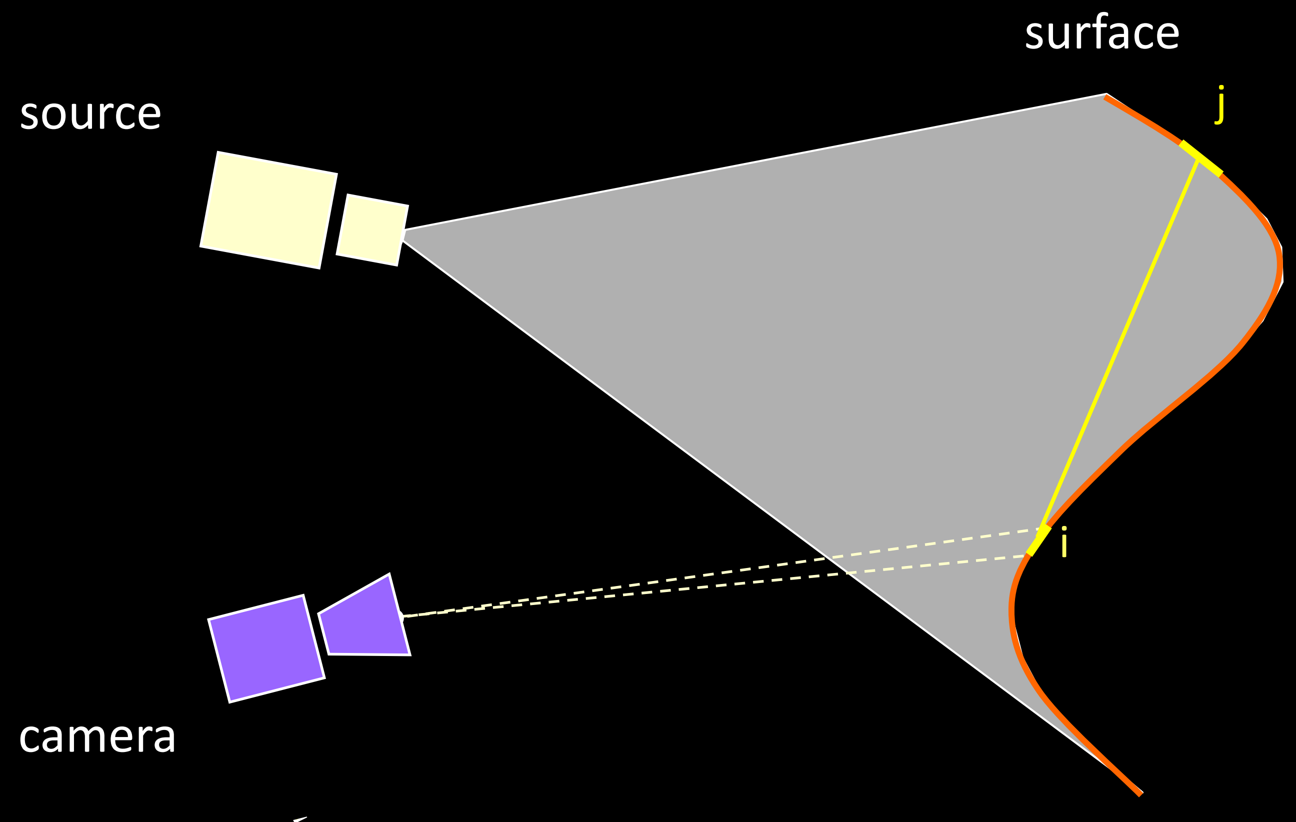
Easy to separate in a renderer



full image = direct + indirect

Direct-indirect separation using high-frequency illumination

Direct and indirect components: interreflections



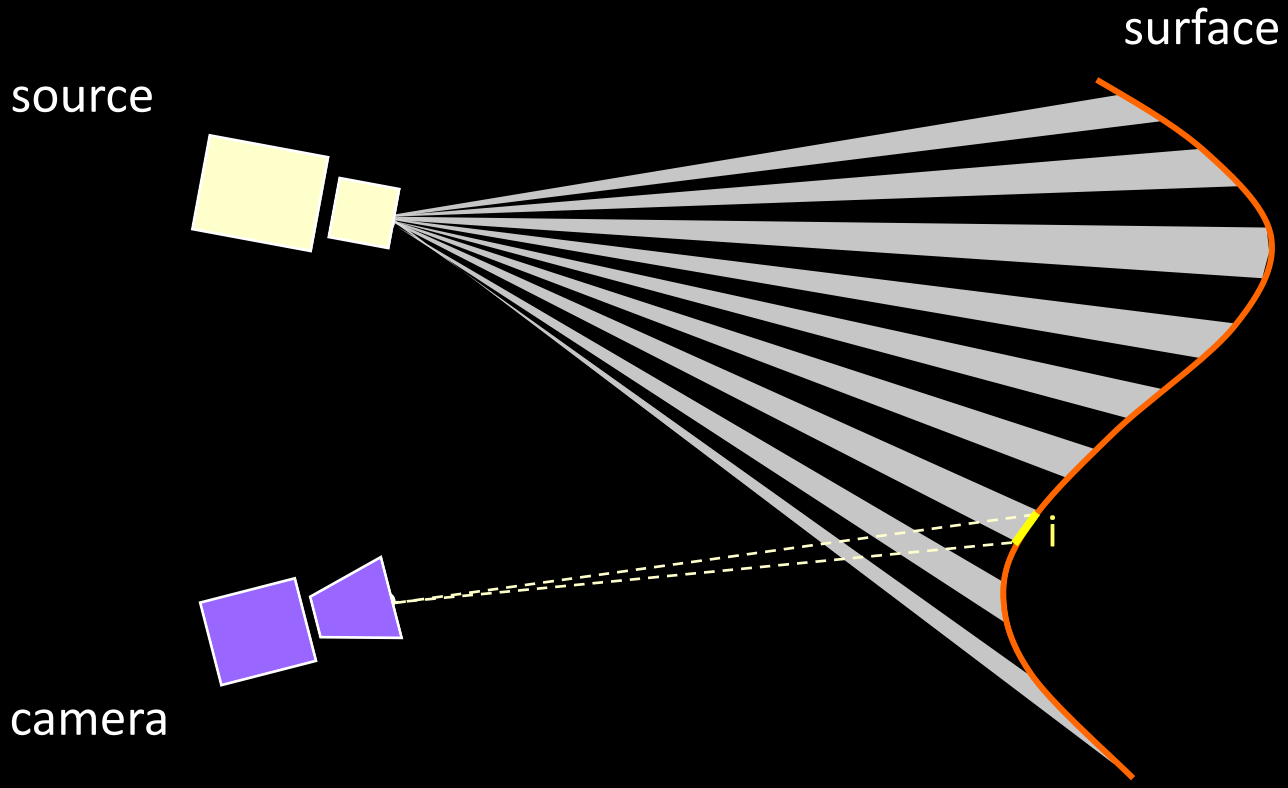
$$L[c,i] = L_d[c,i] + L_g[c,i]$$

radiance direct indirect

$$L_g[c,i] = \sum_P A[i,j]\, L[i,j]$$

BRDF and geometry

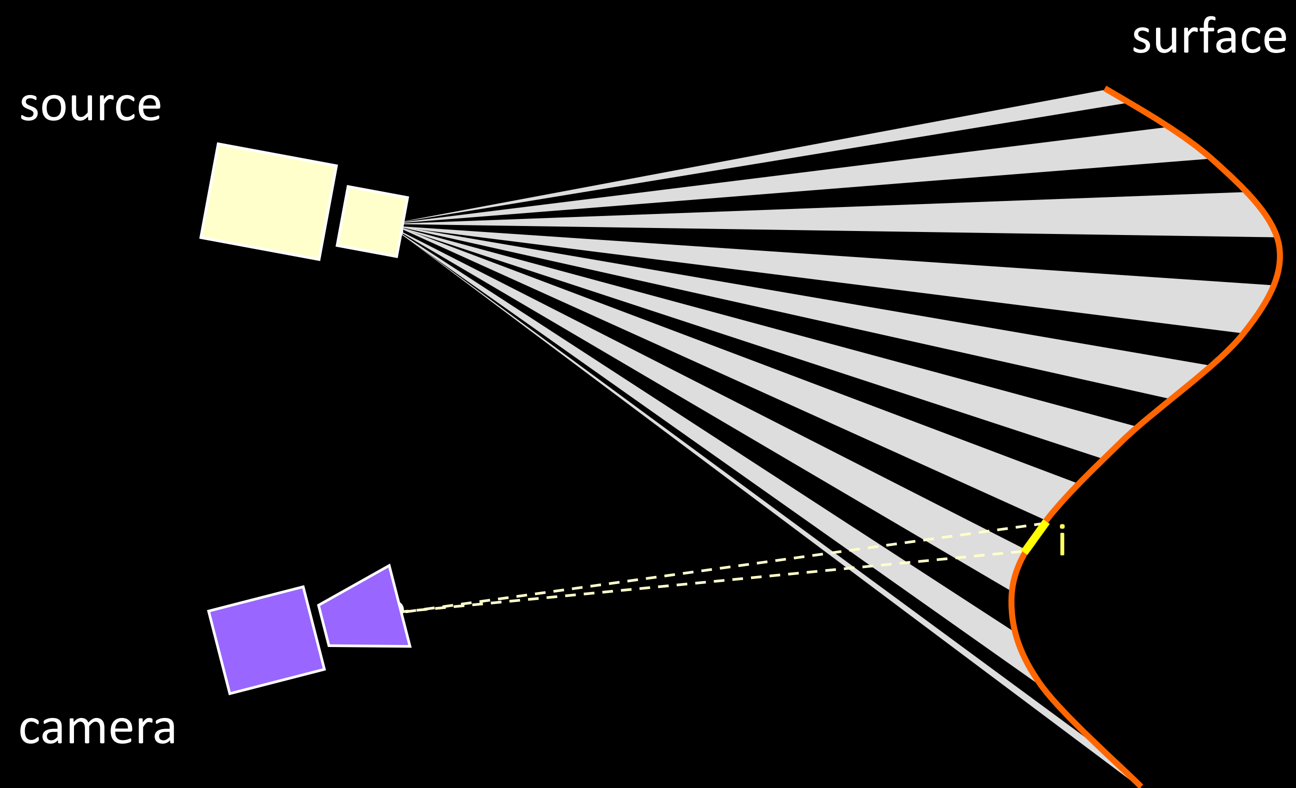
High Frequency Illumination Pattern



$$L^{+}[c,i] = L_d[c,i] + \alpha\, L_g[c,i]$$

fraction of activated source elements

High Frequency Illumination Pattern



$$L^{+}[c,i] = L_d[c,i] + \alpha L_g[c,i]$$

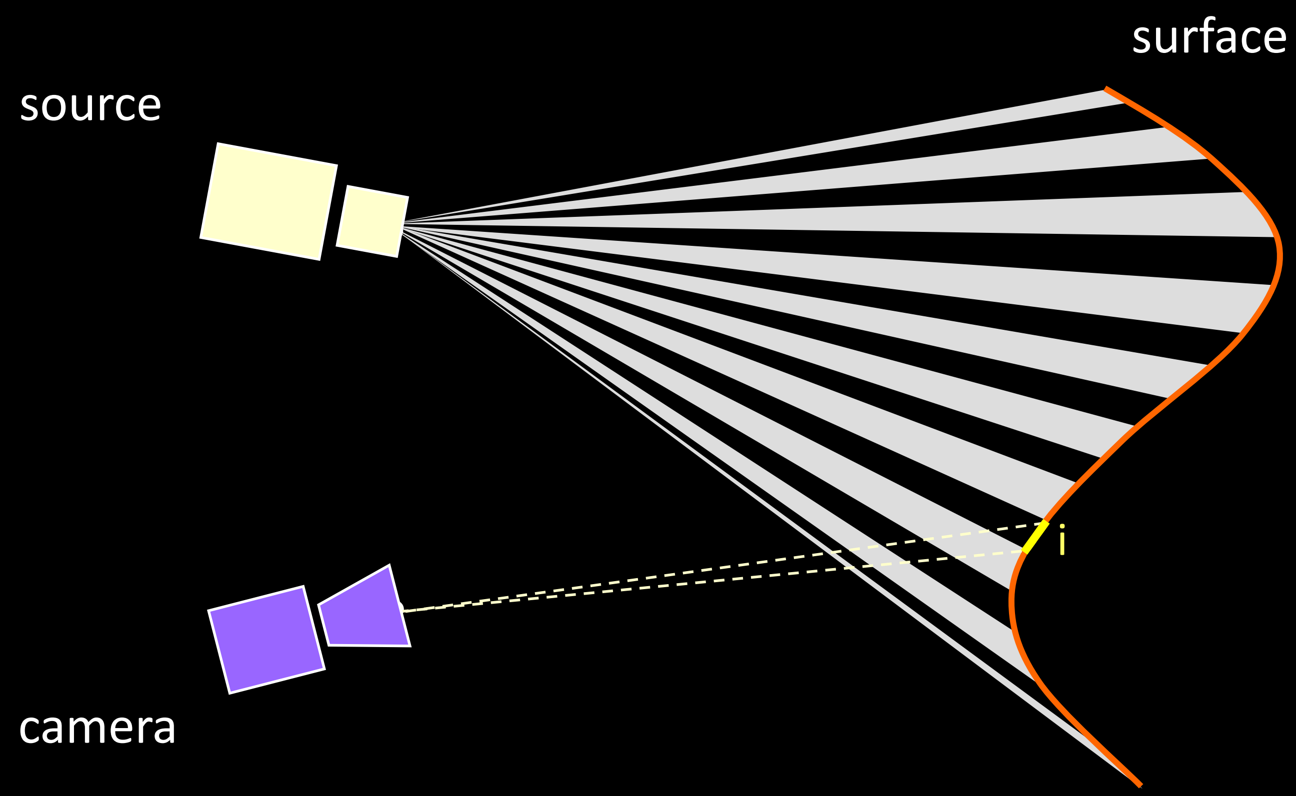
$$L^{-}[c,i] = (1-\alpha) L_g[c,i]$$

fraction of activated source elements

Important insight:

- Indirect illumination is approximately invariant to high-frequency lighting.
- You can think of indirect illumination effects as a low-pass filter.

High Frequency Illumination Pattern



$$L^{+}[c,i] = L_d[c,i] + \alpha L_g[c,i]$$

$$L^{-}[c,i] = (1-\alpha) L_g[c,i]$$

What does approximate invariance mean in this case?

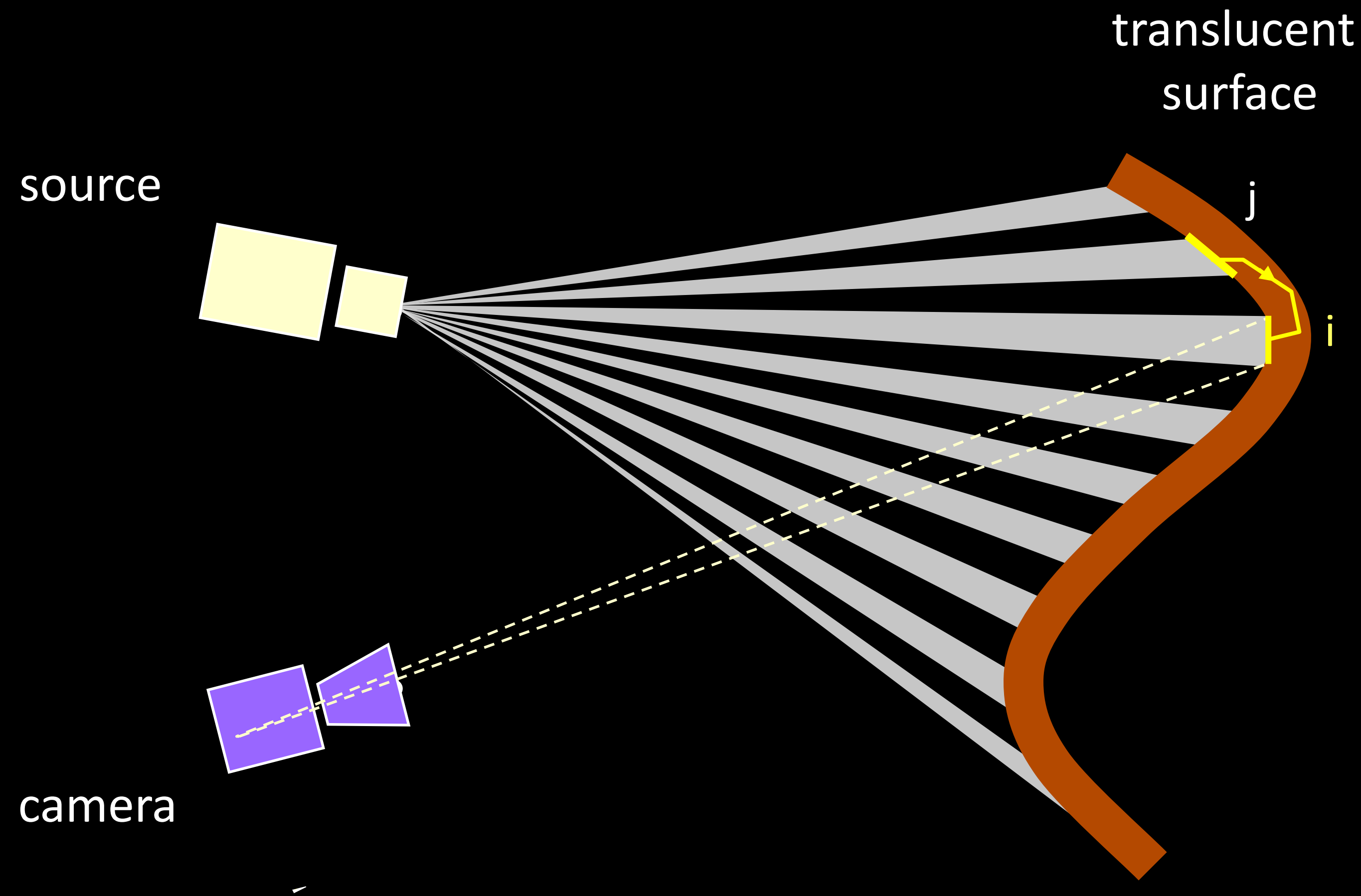
Separation from Two Images

$$\alpha = \frac{1}{2}: \quad \boxed{L_d = L_{\max} - L_{\min} \;,\; L_g = 2L_{\min}}$$

direct

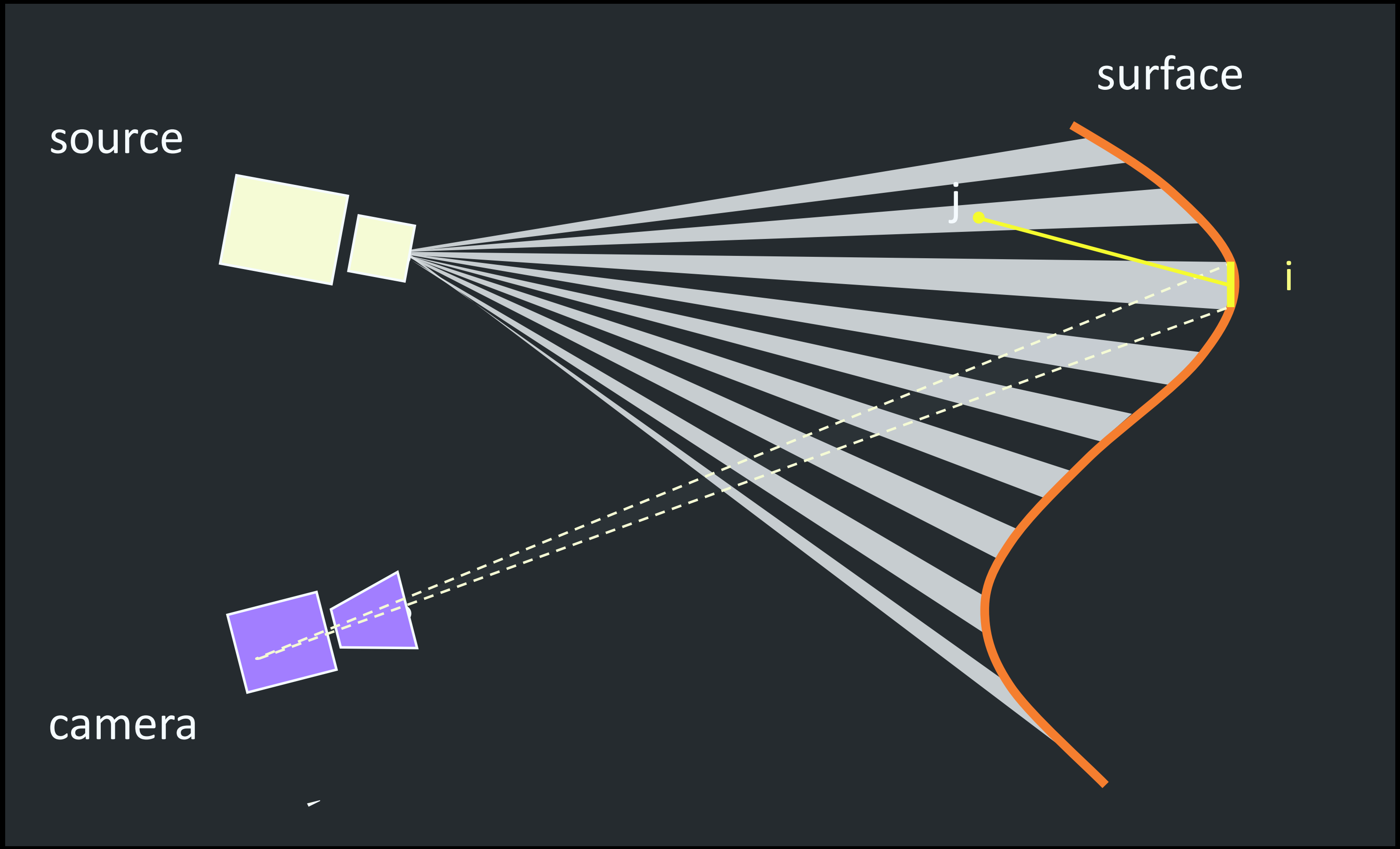
indirect

Other Indirect Effects: Subsurface Scattering



Other Indirect Effects: Volumetric Scattering

participating medium



Diffuse Interreflections

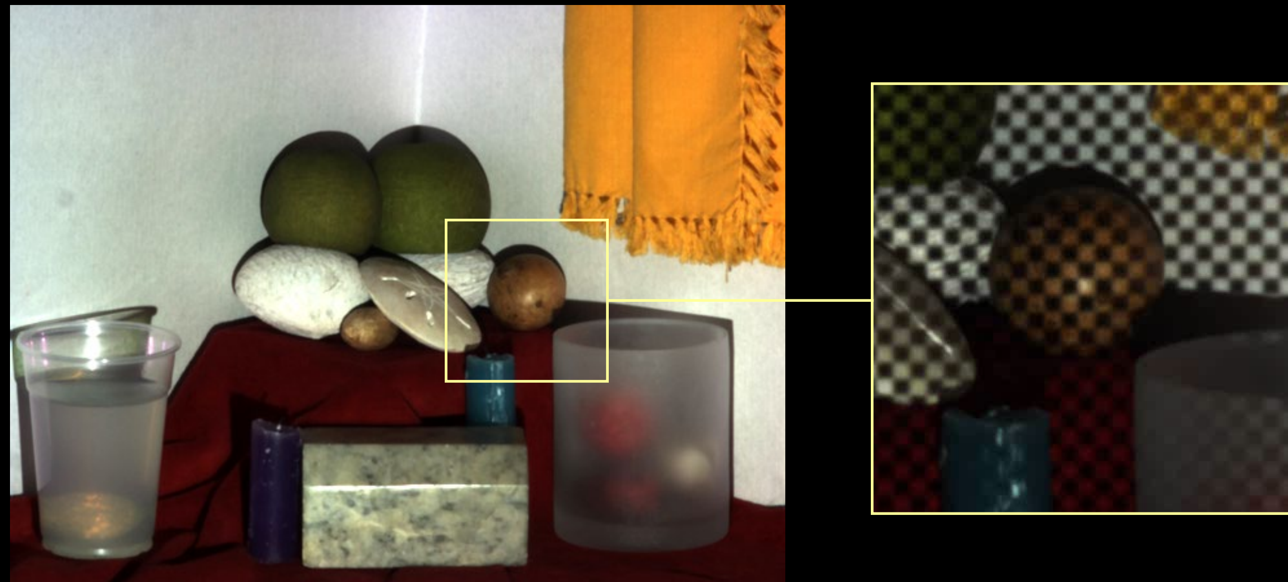
Specular Interreflections

Diffusion

Volumetric Scattering

Subsurface Scattering

Scene



Direct

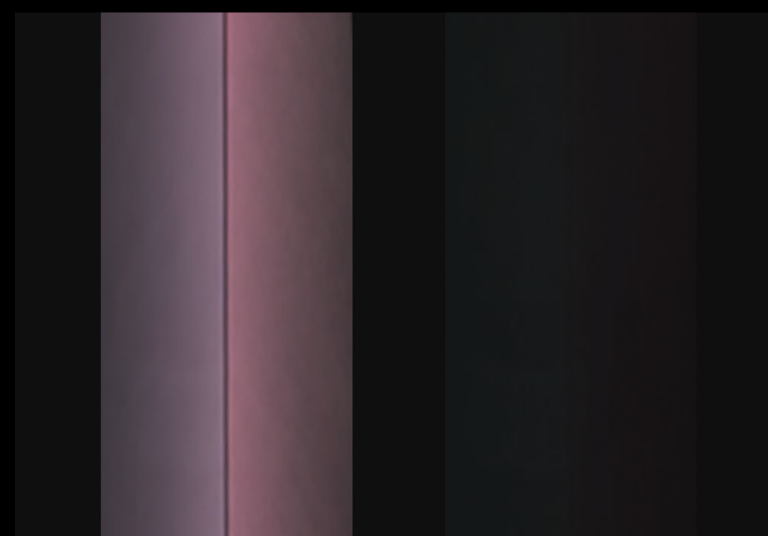
Indirect

V-Grooves: Diffuse Interreflections

concave convex

Psychophysics:
Gilchrist 79, Bloj et al. 04

Direct



Indirect

Real World Examples:

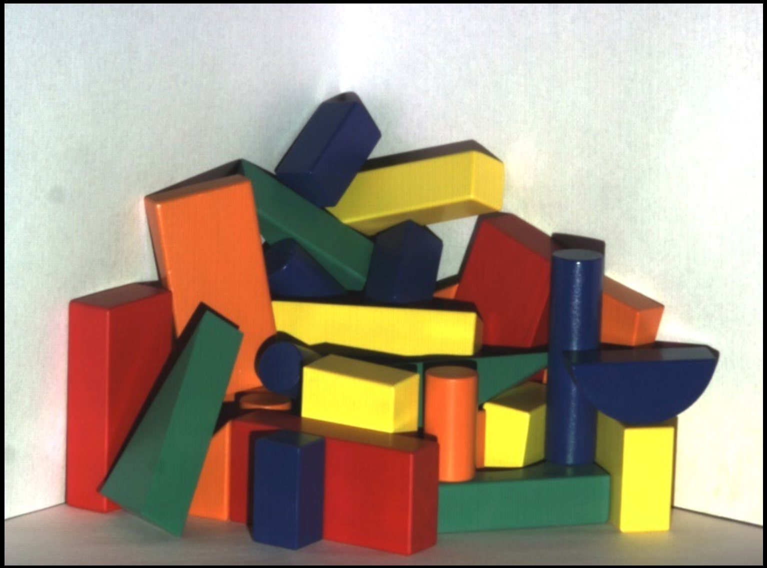
Can You Guess the Images?

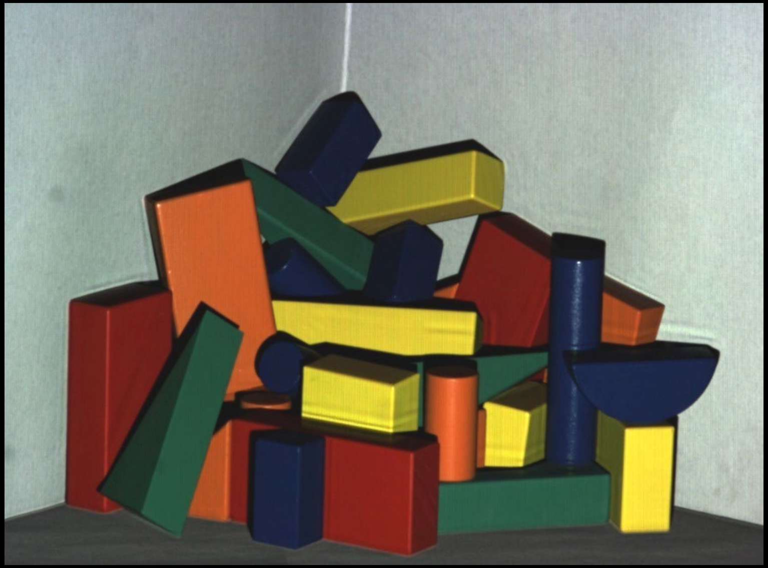
Eggs: Diffuse Interreflections

Direct

Indirect

Wooden Blocks: Specular Interreflections

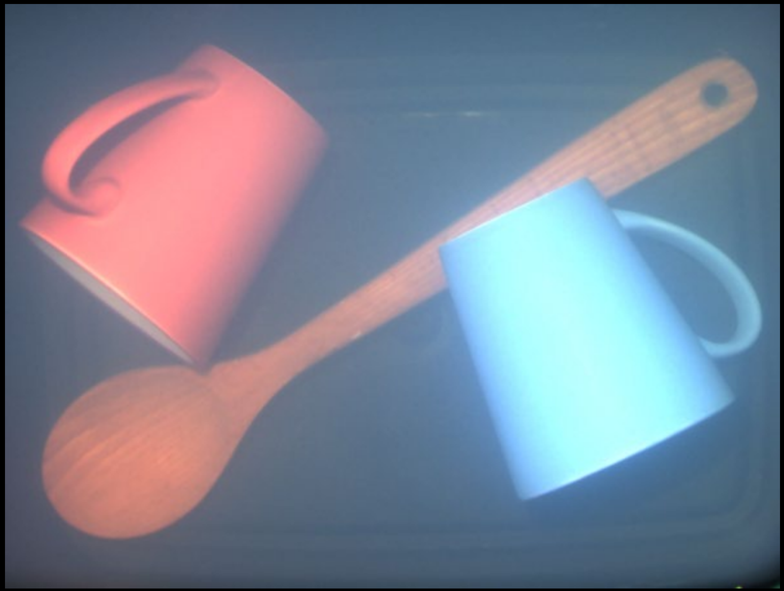




Direct

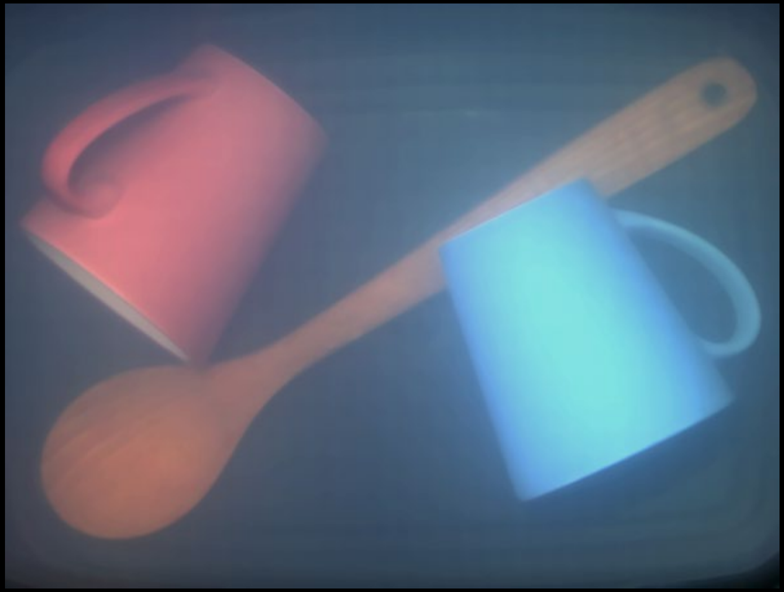
Indirect

Kitchen Sink: Volumetric Scattering



Volumetric Scattering:
Chandrasekar 50, Ishimaru 78

Direct



Indirect

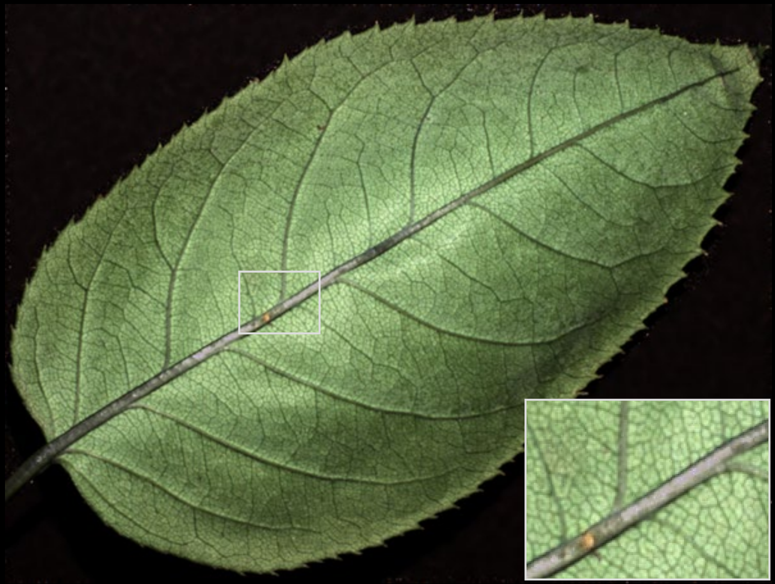
Peppers: Subsurface Scattering

Direct

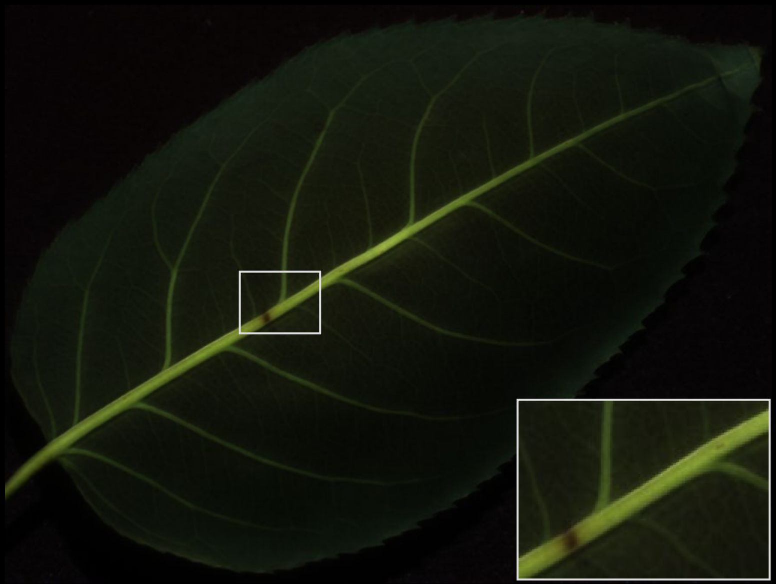
Indirect

Tea Rose Leaf

Leaf Anatomy: Purves et al. 03

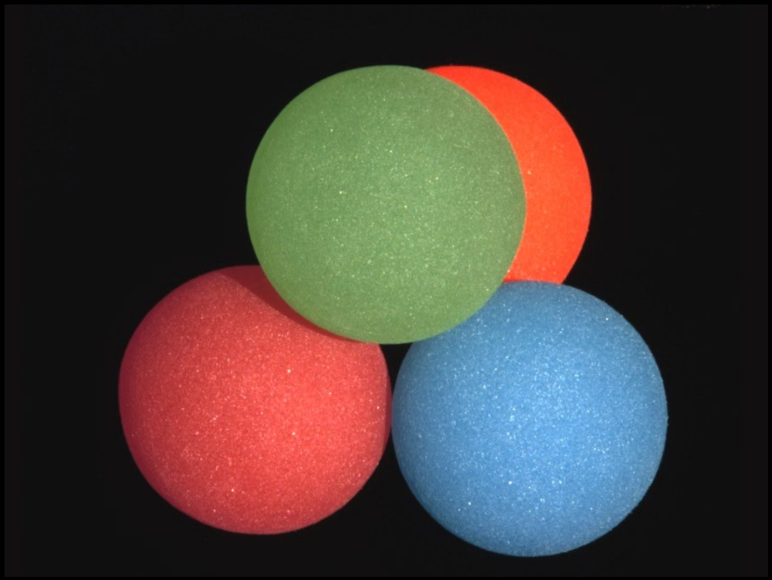


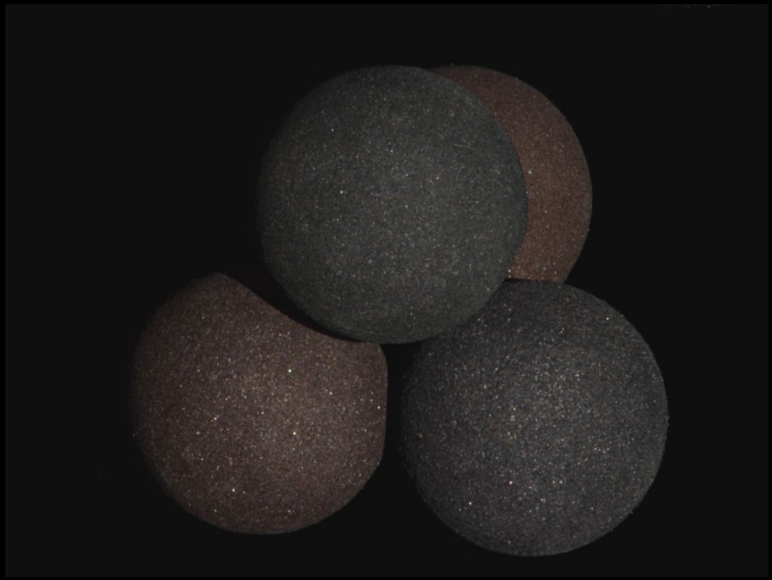
Direct



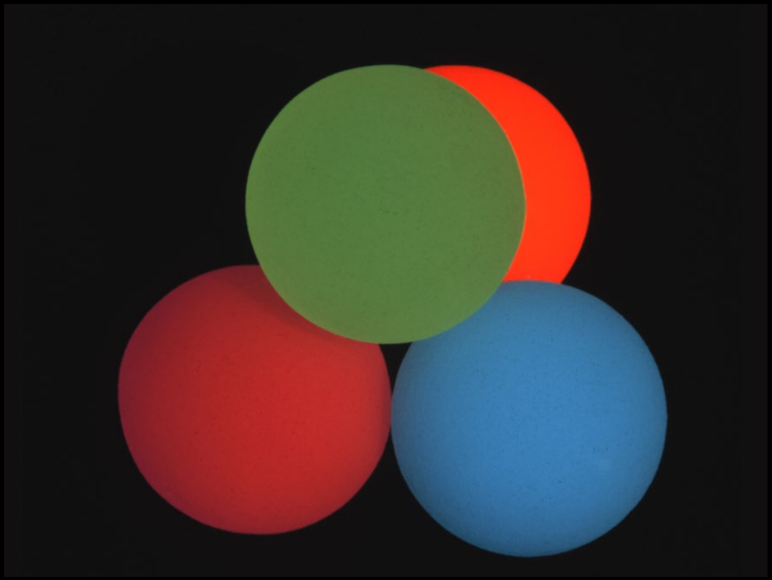
Indirect

Translucent Rubber Balls





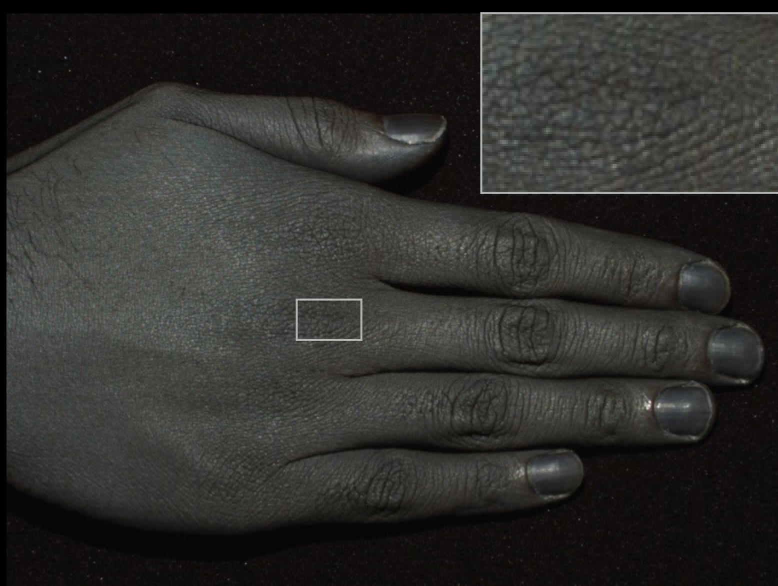
Direct



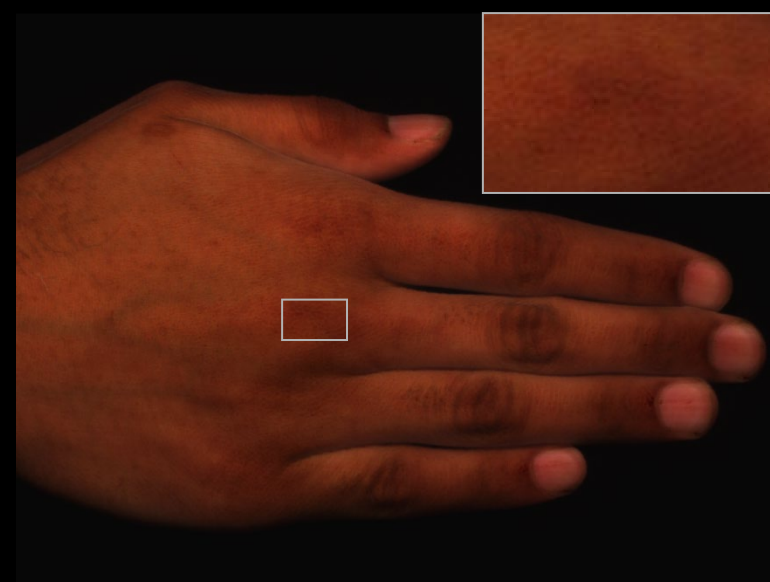
Indirect

Hand

Skin: Hanrahan and Krueger 93, Uchida 96, Haro 01, Jensen et al. 01, Igarashi et al. 05, Weyrich et al. 05



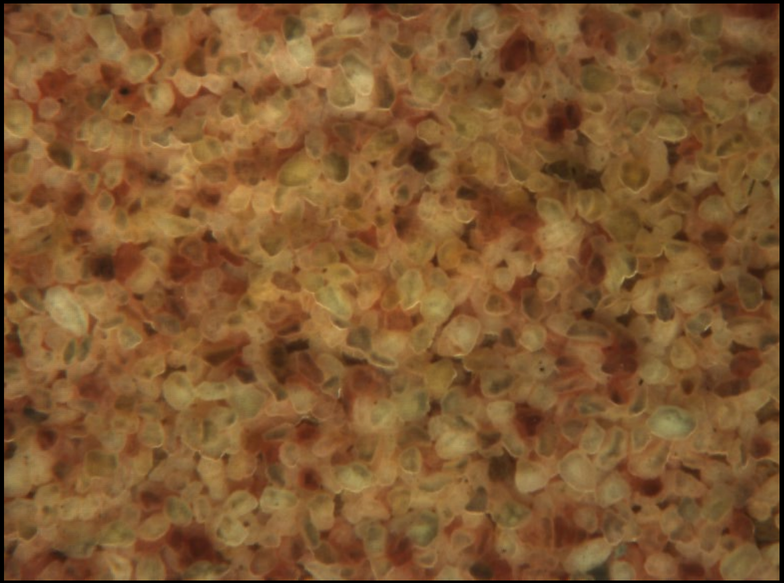
Direct



Indirect

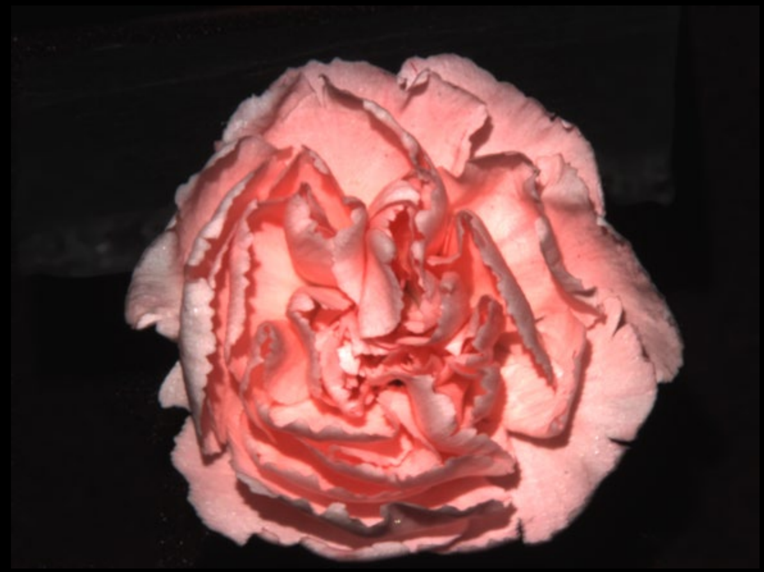
Pebbles: 3D Texture

Direct

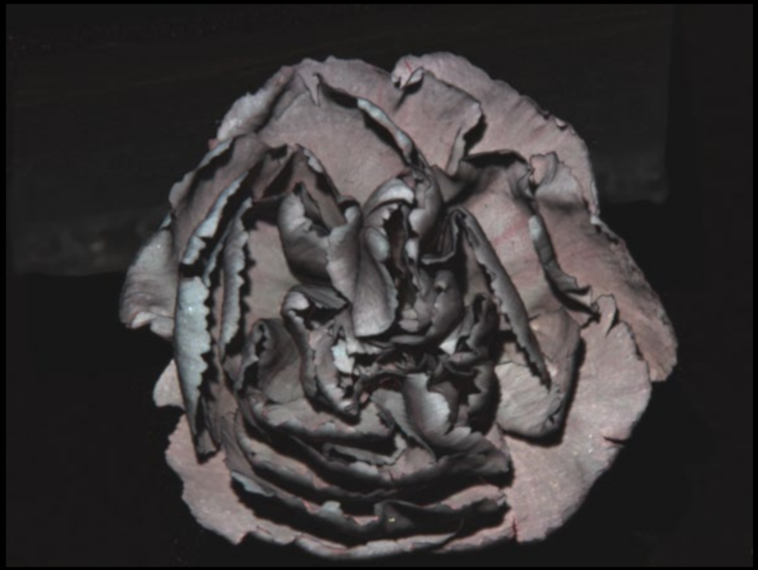


Indirect

Pink Carnation



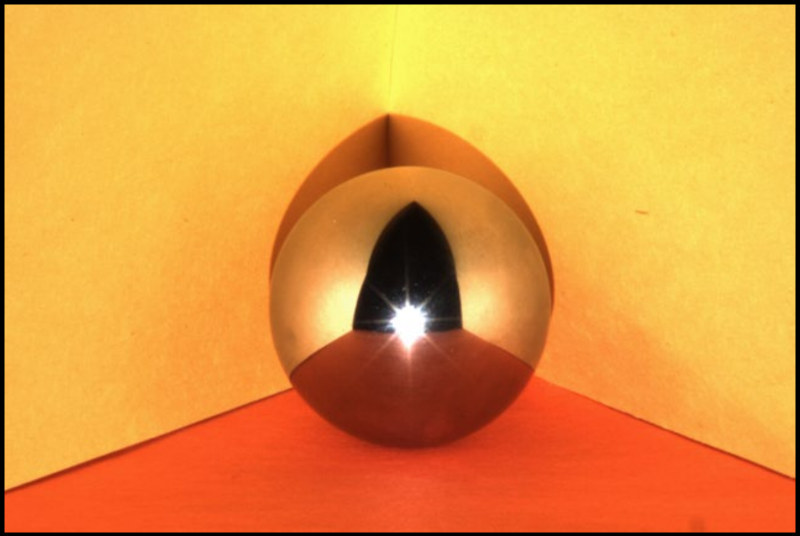
Spectral Bleeding: Funt et al. 91

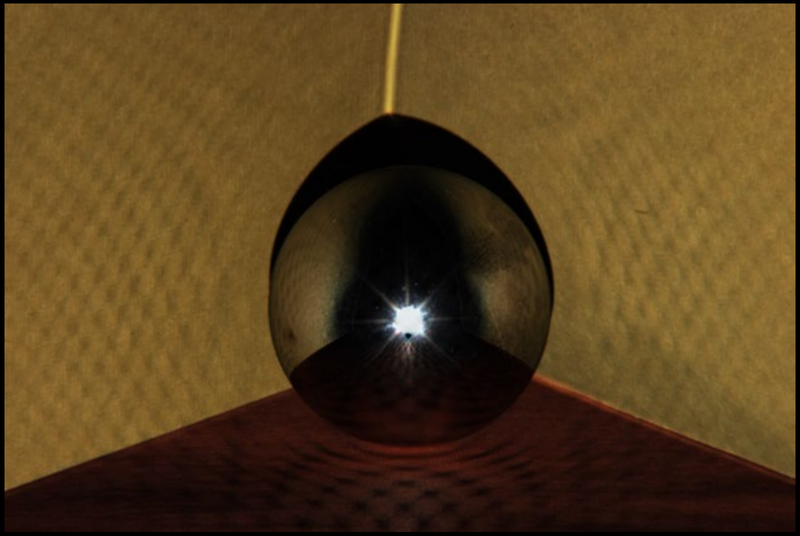


Direct

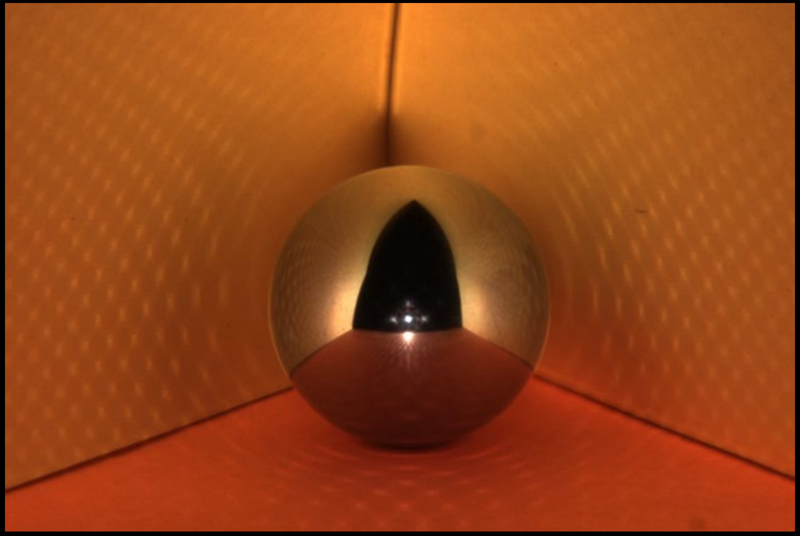
Indirect

Mirror Ball: Failure Case





Direct



Indirect

Building Corner

Stick

Shadow

3D from Shadows:
Bouguet and Perona 99

$$L_d = L_{\max} - L_{\min} \,, \quad L_g = L_{\min}$$

direct — indirect

Building Corner

Direct

Indirect

Photometric Stereo using Direct Images

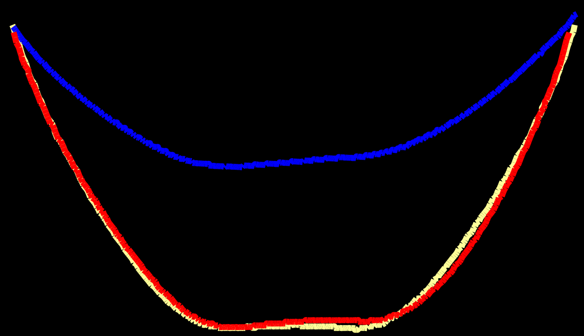
Source 1 Source 2 Source 3

Bowl

Indirect

Direct

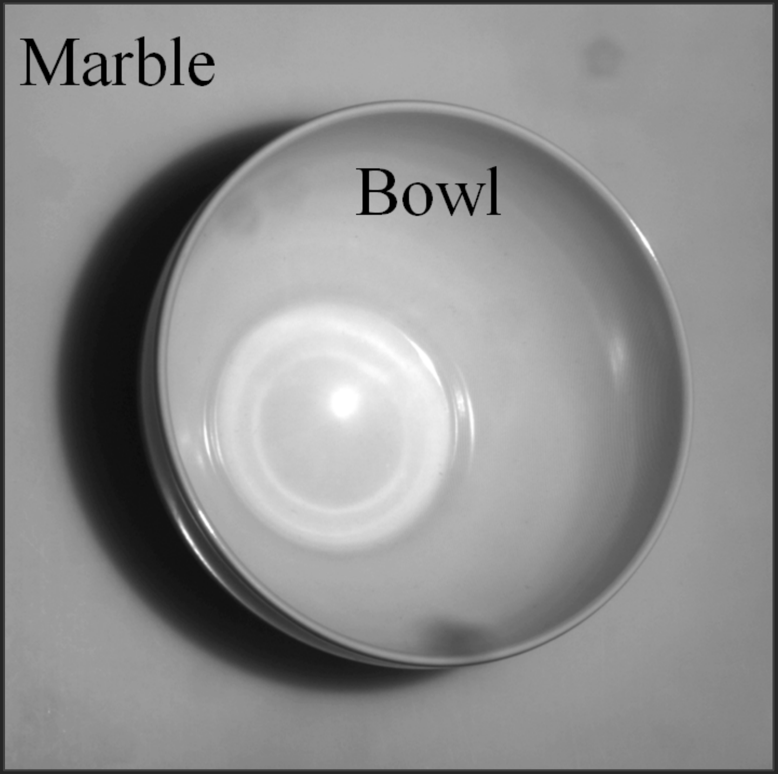
Shape



Application to structured light

Why is indirect illumination a problem?

Bowl on a Marble Slab

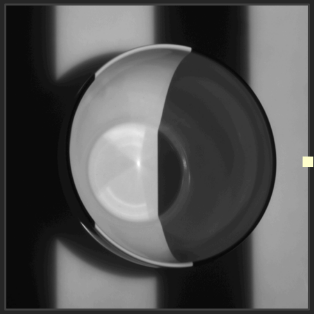


Captured images under conventional Gray codes

Lowest Frequency Illumination

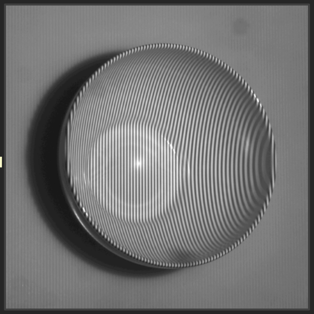
Highest Frequency Illumination

Pattern 1



Pattern 4

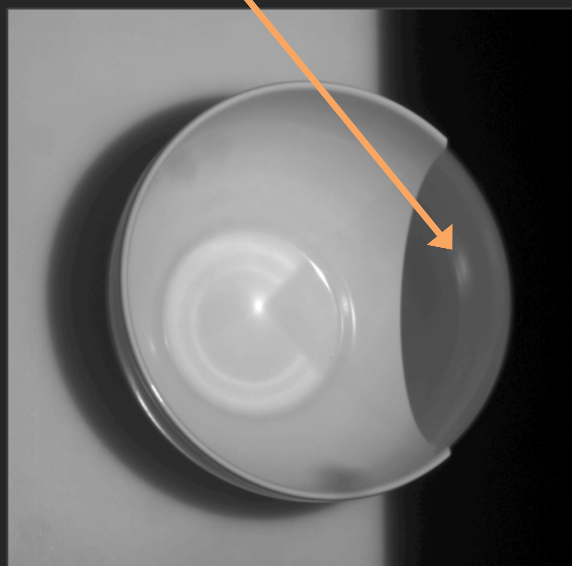
Pattern 7



Pattern 10

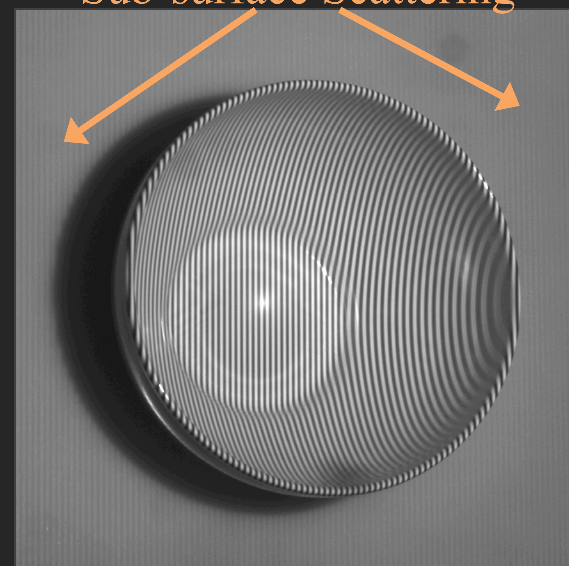
Issues due to indirect illumination effects

Strong Inter-reflections



Low-frequency pattern

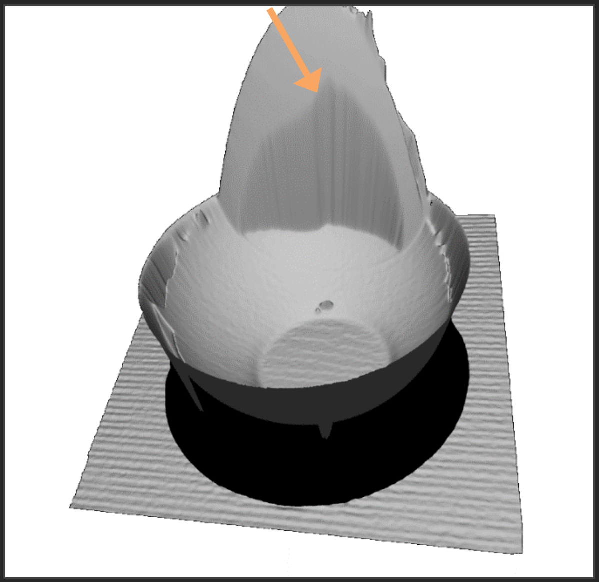
Blurring due to
Sub-surface Scattering



High-frequency pattern

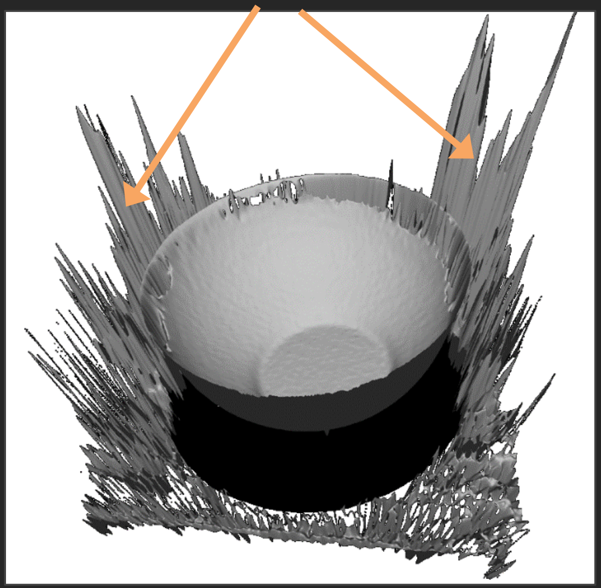
3D Visualizations: State of the Art

Errors due to interreflections



Conventional Gray
(11 images)

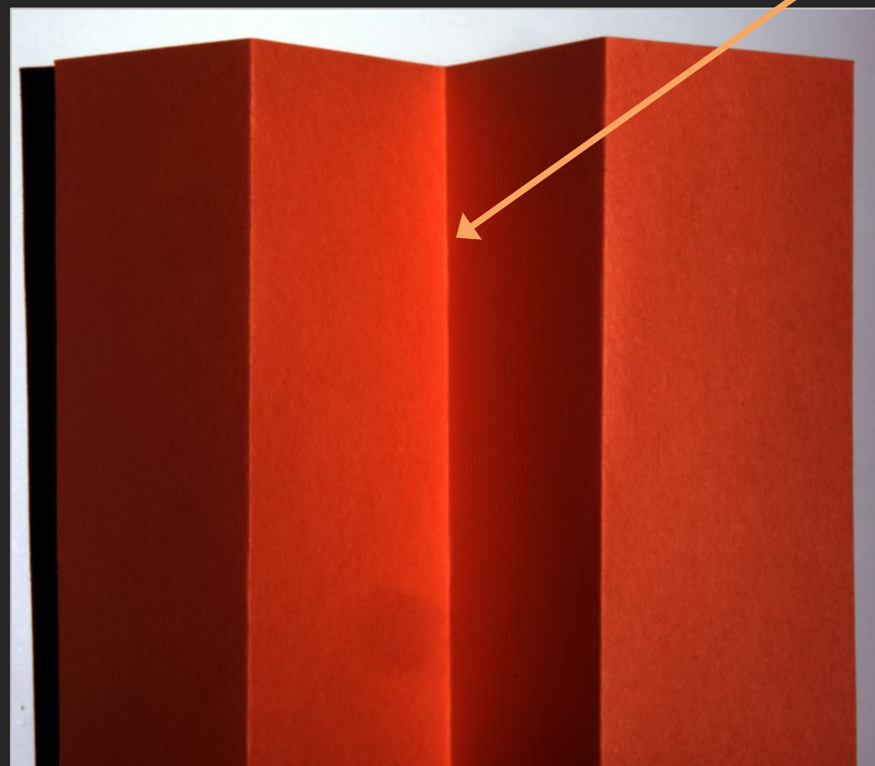
Errors due to sub-surface scattering



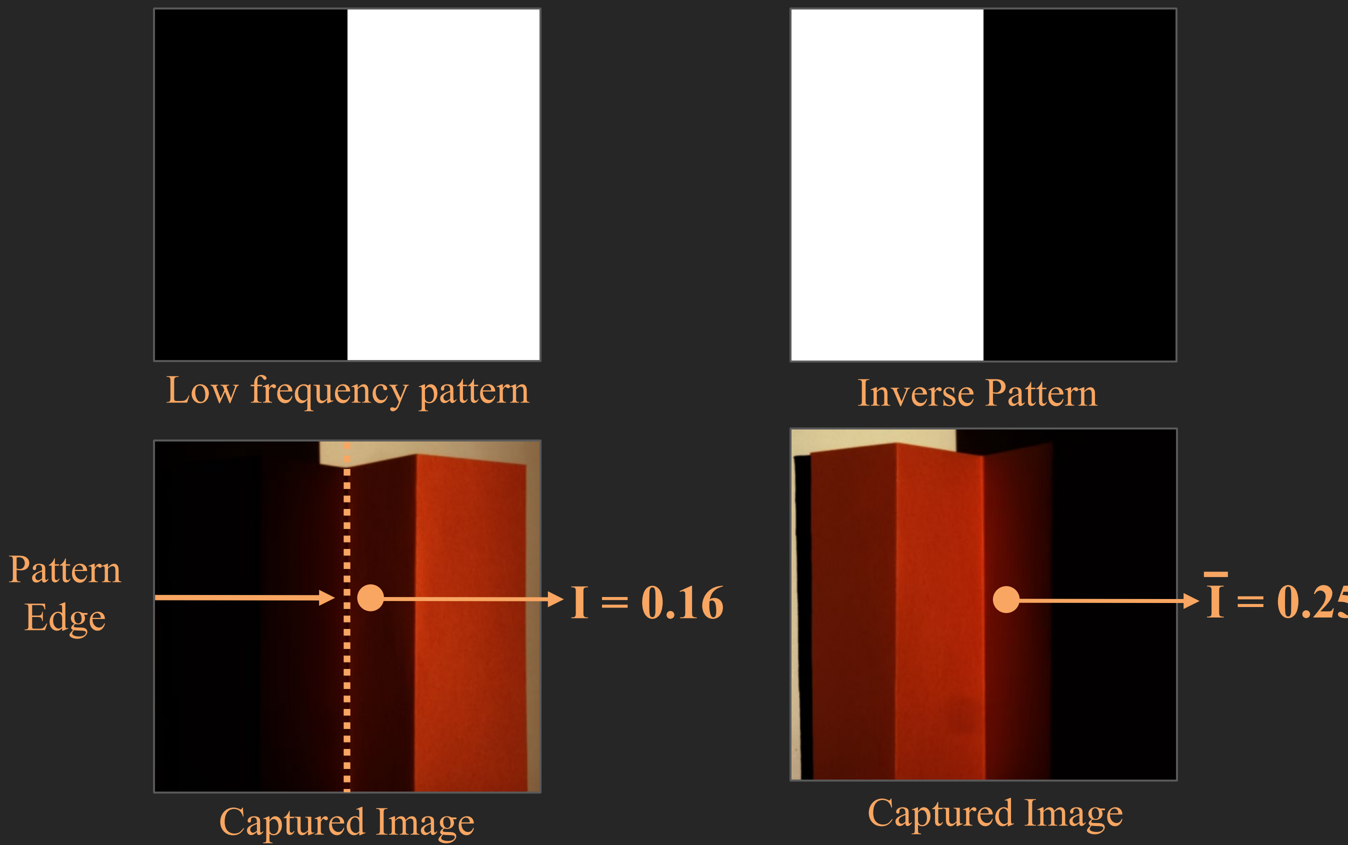
Modulated Phase-Shifting
(162 images)

V-Groove Scene

Inter-reflections

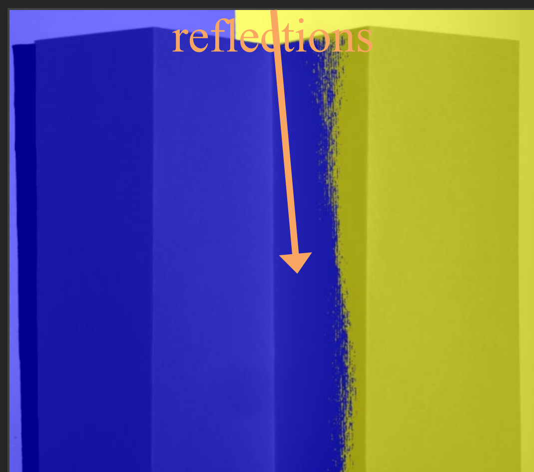


Conventional Gray codes

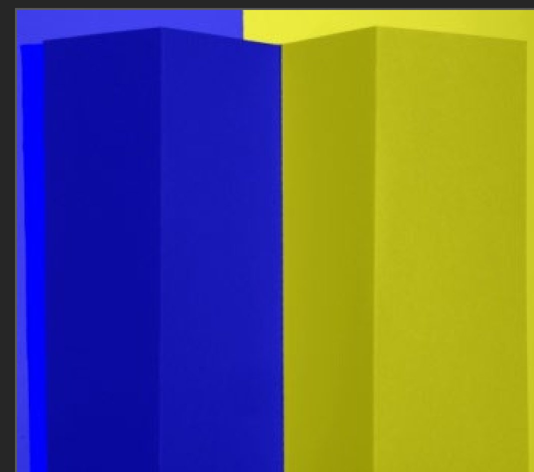


Binarization error

Errors due to inter-reflections



Incorrect Binarization

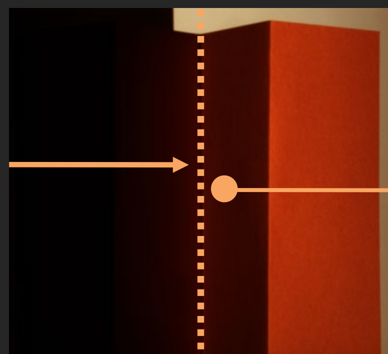


Ground-truth Binarization

One (illuminated) Zero (not-illuminated)

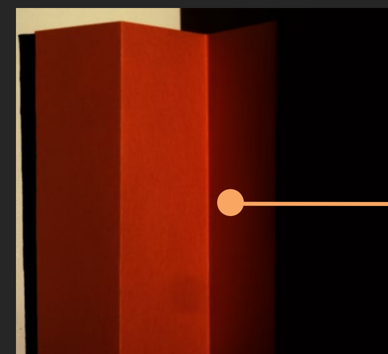
Low-frequency patterns

Pattern Edge



$I = 0.16$

Captured Image



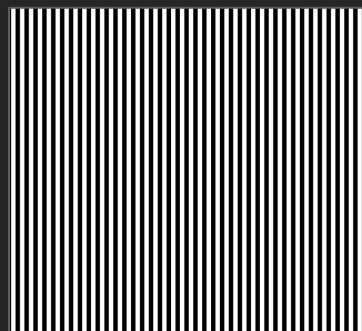
$\bar{I} = 0.25$

Captured Image

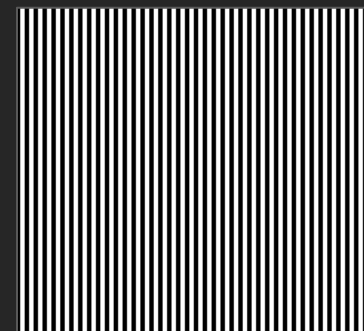
$$I = \text{Direct} + \alpha \,.\, \text{Indirect} \qquad \bar{I} = (1 - \alpha)\,.\, \text{Indirect}$$

$$\alpha \sim= 0, \ \text{Direct} < \text{Indirect} \quad => \quad I < \bar{I}$$

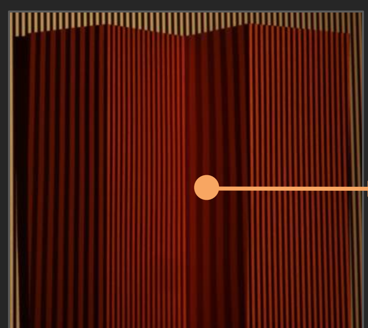
High-frequency patterns



Pattern

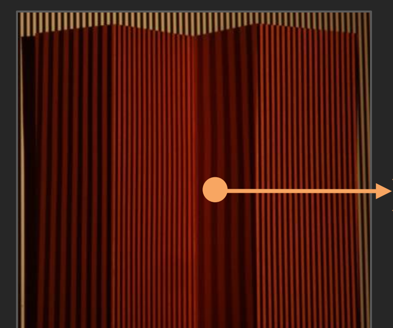


Inverse Pattern



$I = 0.25$

Captured Image

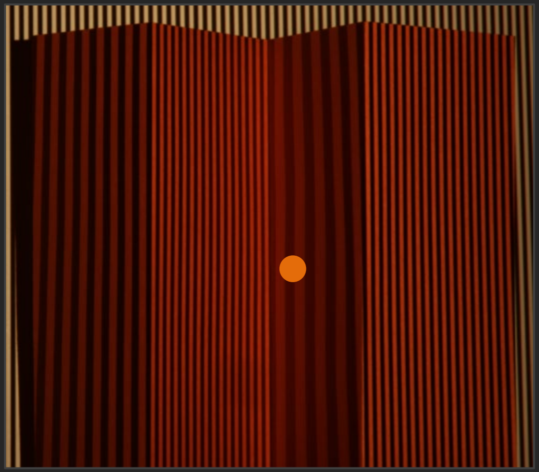


$\bar{I} = 0.16$

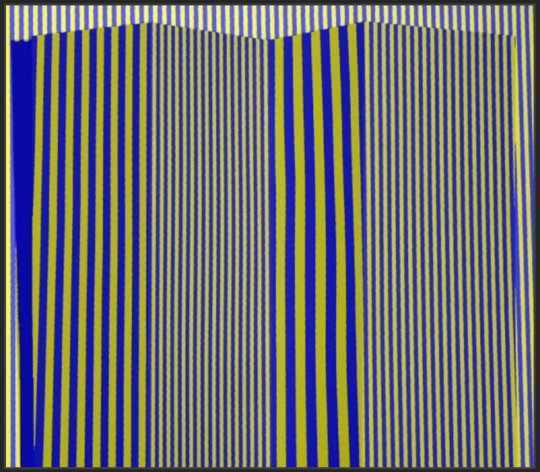
Captured Image

$$I = \text{Direct} + \mathbf{0.5}\ \text{Indirect} > \bar{I} = 0.5\ \text{Indirect}$$

High-frequency Patterns are Decoded Correctly



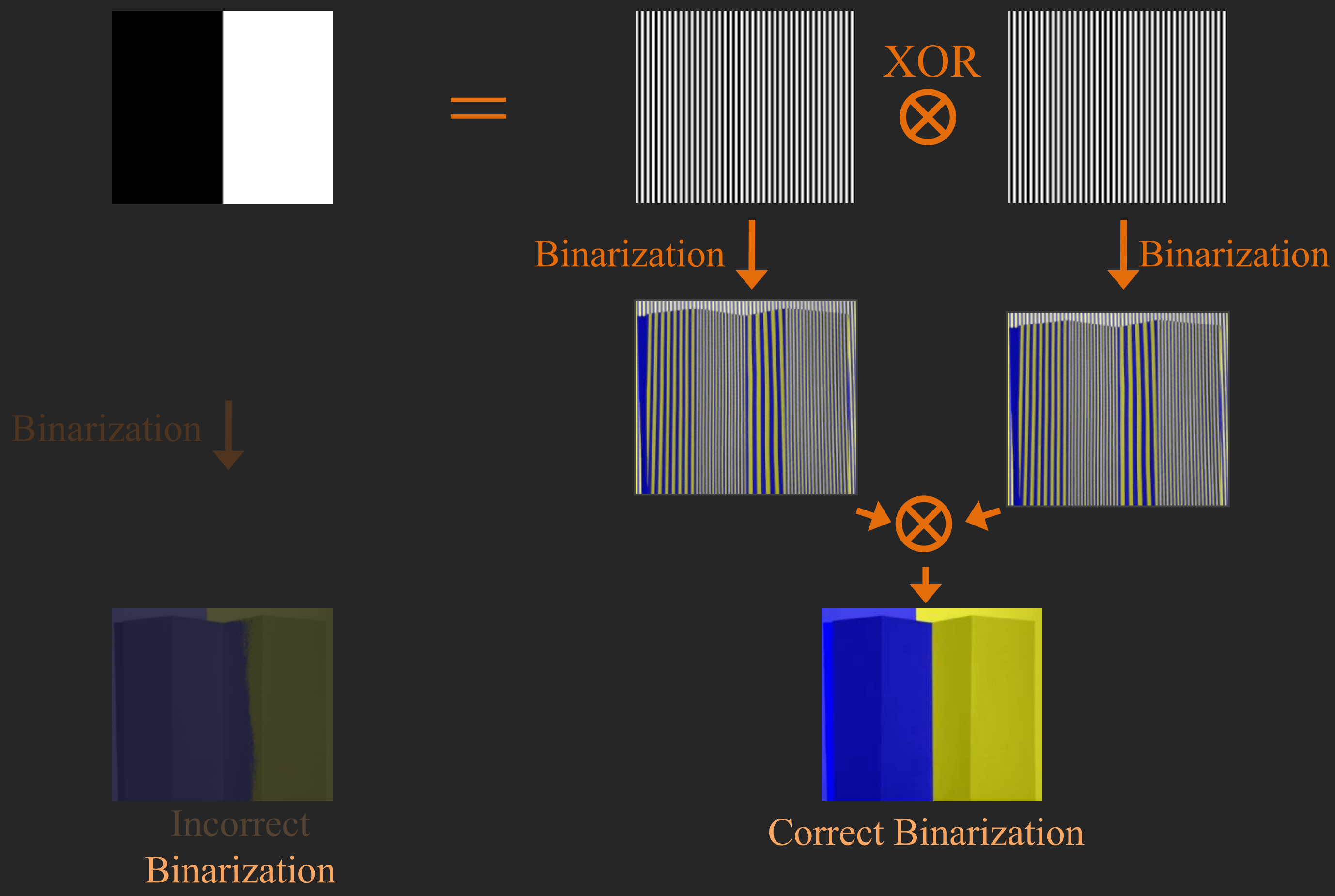
Captured Image



Binary Decoding

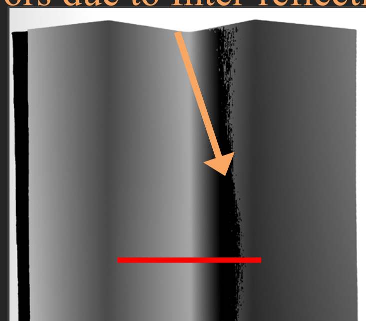
Logical Coding and Decoding

Logical Coding and Decoding

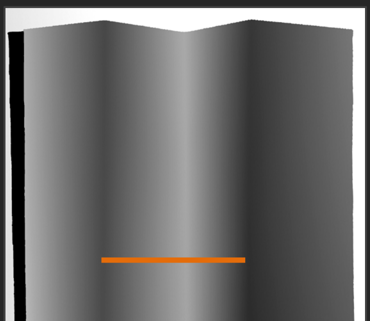


Depth Map Comparison

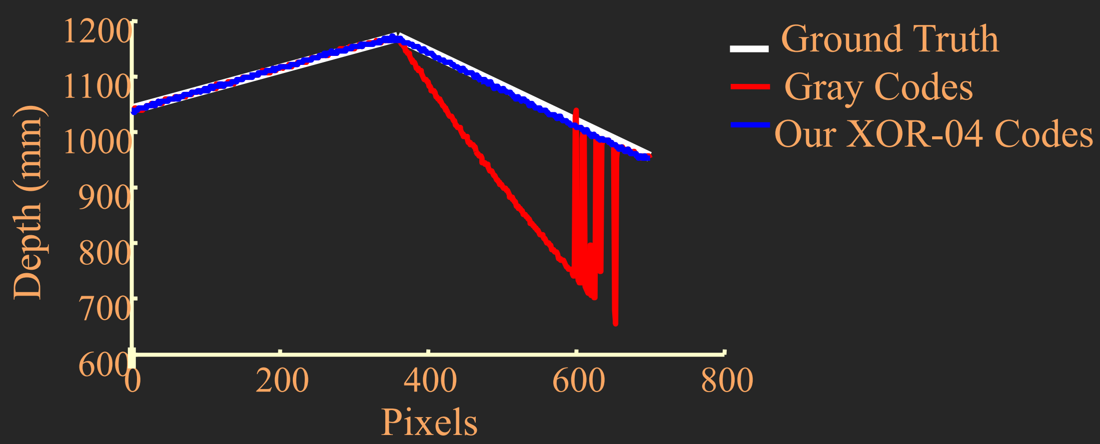
Errors due to Inter-reflections



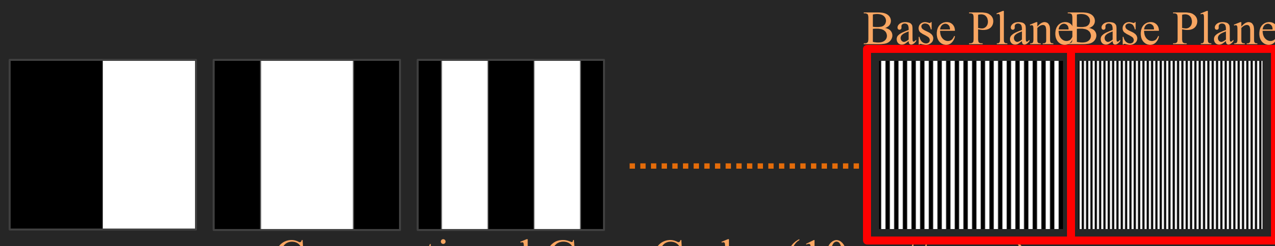
Conventional Gray Codes (11 images)



Our XOR-04 Codes (11 images)



Making the Logical XOR Codes

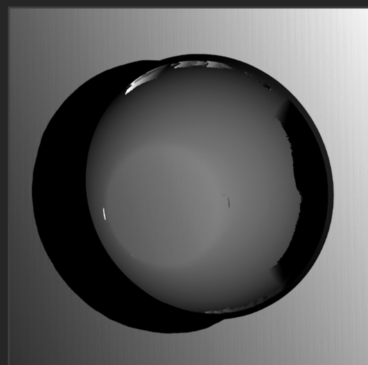


Conventional Gray Codes (10 patterns)

XOR of Last Pattern with Patterns 1-9 → *XOR-02 Codes (10 patterns)*

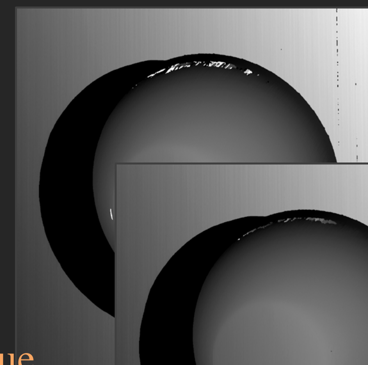
XOR of Second-last Pattern with Patterns 1-8 → *XOR-04* Codes (10 patterns)

Ensemble of Codes for General Scenes

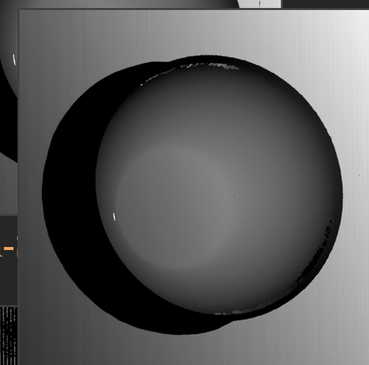


Conventional Gray (10 images)

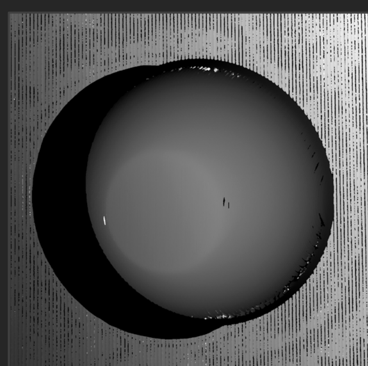
Return the consistent value



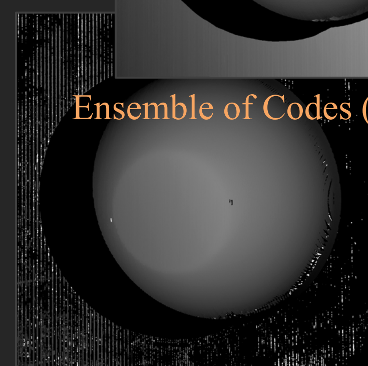
Max min-



Ensemble of Codes (41 images)

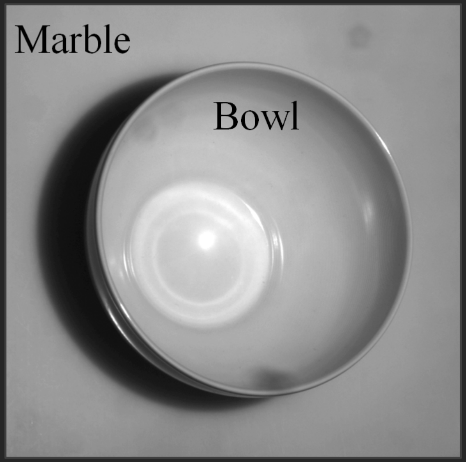


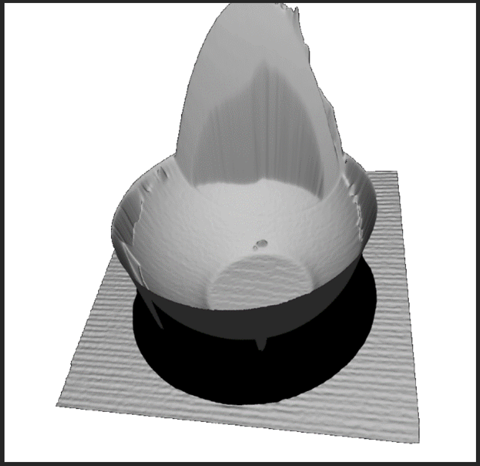
XOR-04 (10 images)



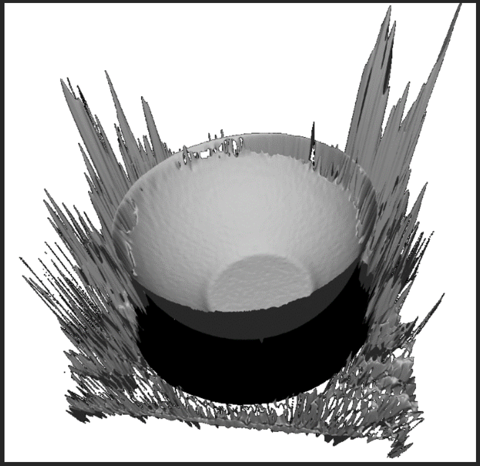
XOR-02 (10 images)

Shape Comparison

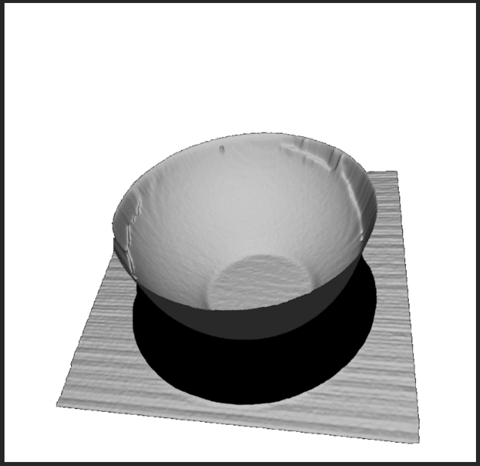




Conventional Gray
(11 images)



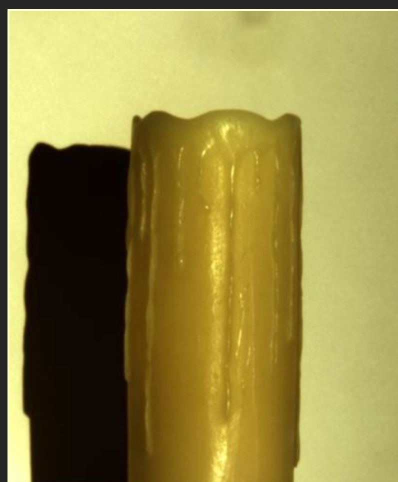
Modulated Phase-Shifting
(162 images)



Our Technique
(41 images)

Translucent Wax Candle

Errors due to strong sub-surface scattering



Scene

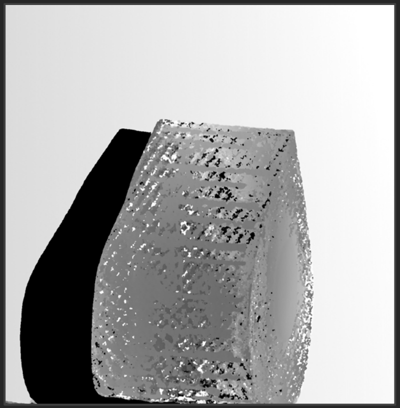
Modulated Phase-Shifting (162 images)

Our Ensemble Codes (41 images)

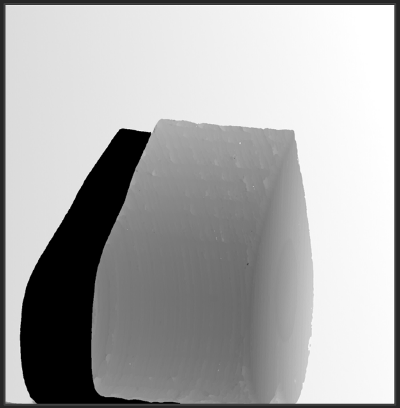
Translucent Wax Object

Errors due to strong sub-surface scattering

Scene



Modulated Phase-Shifting (162 images)



Our Ensemble Codes (41 images)

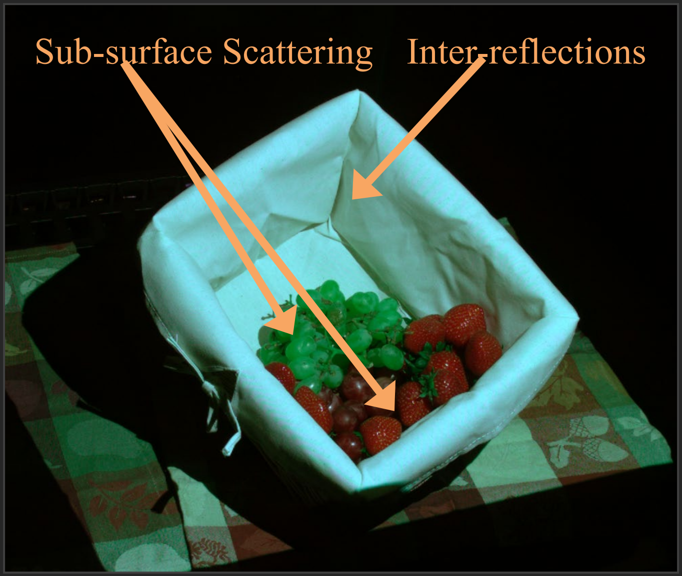
Depth-Map Comparison

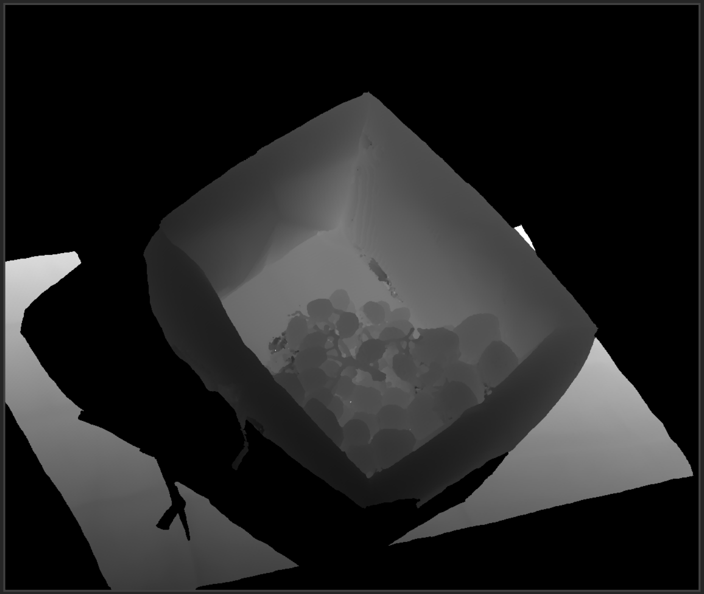
Regular Gray Codes (11 images)

Our Ensemble Codes (41 images)

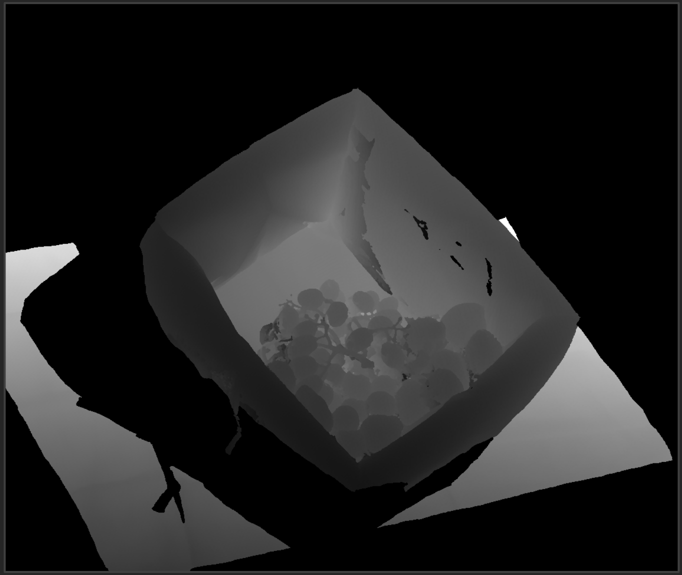
Fruit Basket: Multiple Effects

Depth-maps with previous state of the art

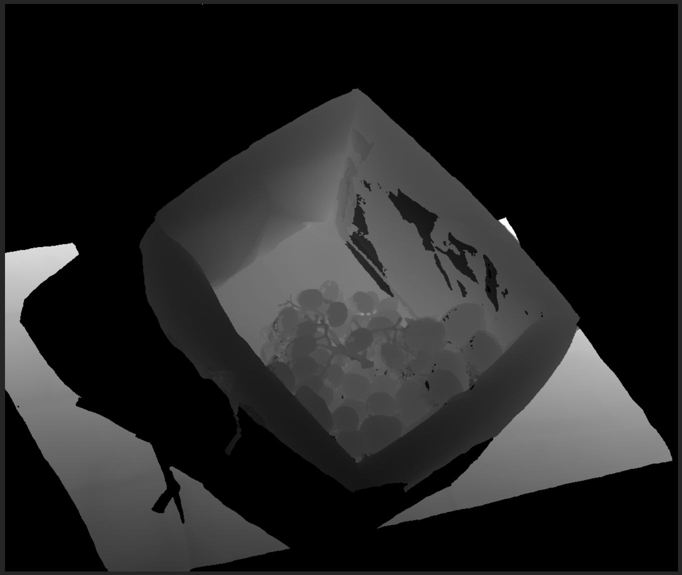




Our Ensemble Codes (41 images)

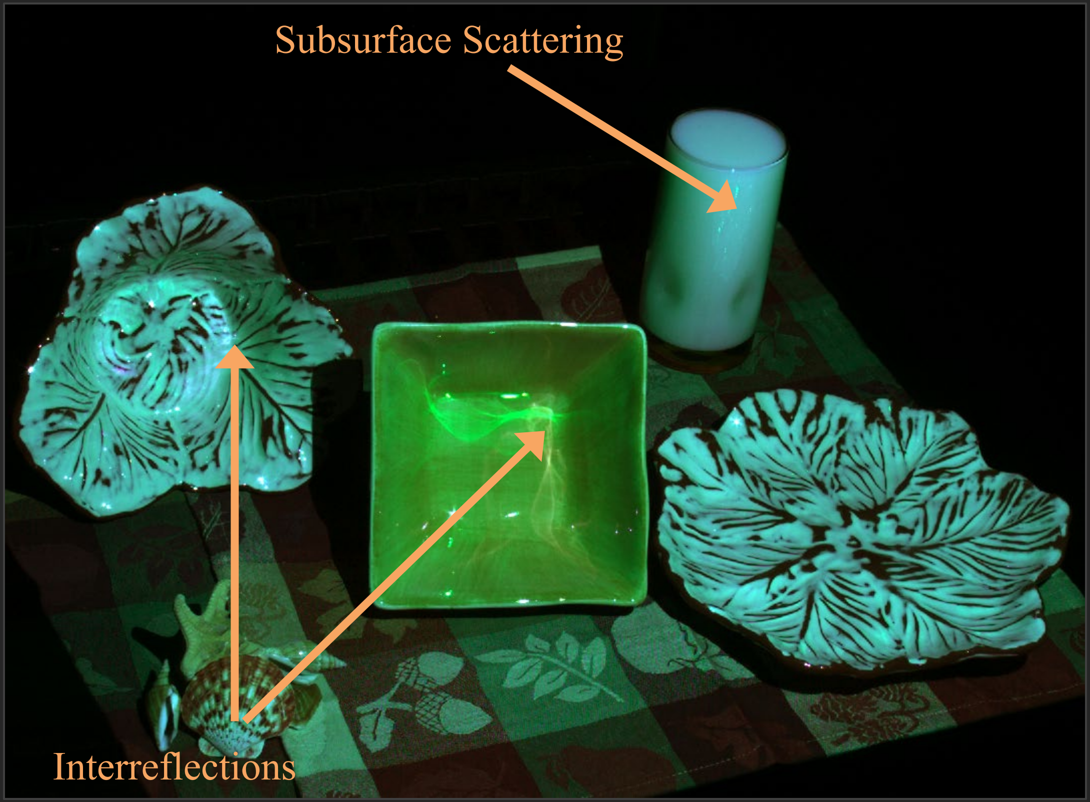


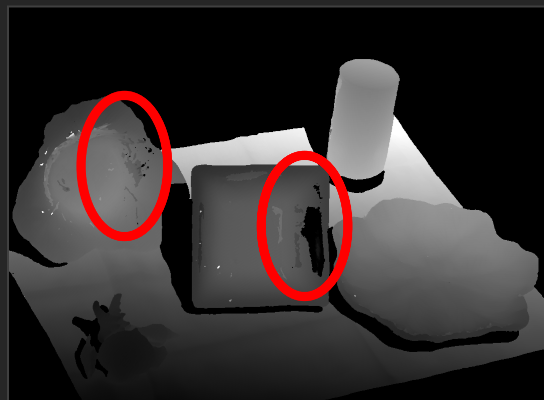
Regular Gray (11 images)



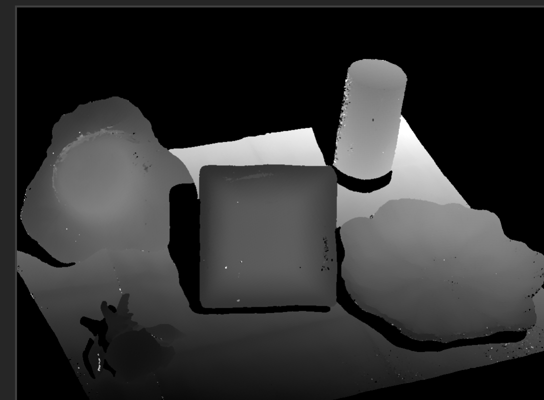
Phase-Shifting (18 images)

Bowls and Milk: Multiple Effects

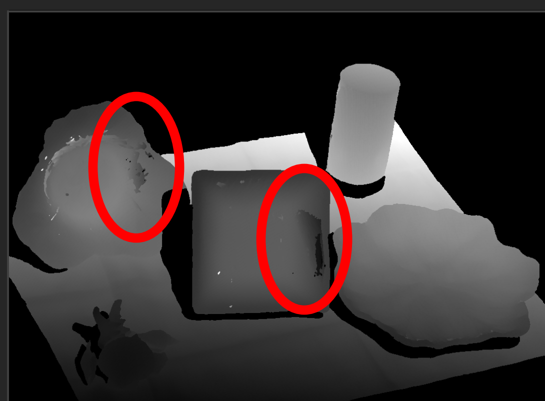




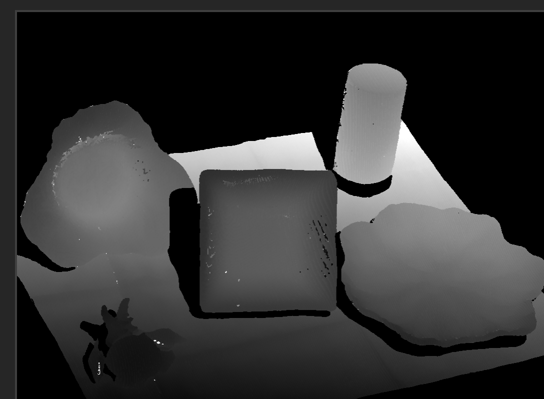
Phase-Shifting (18 images)



Modulated Phase-Shifting (162 images)



Regular Gray Codes (11 images)



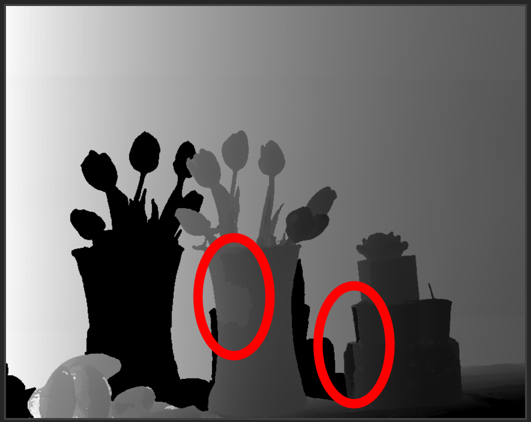
Our XOR Codes (11 images)

Flower-Vase

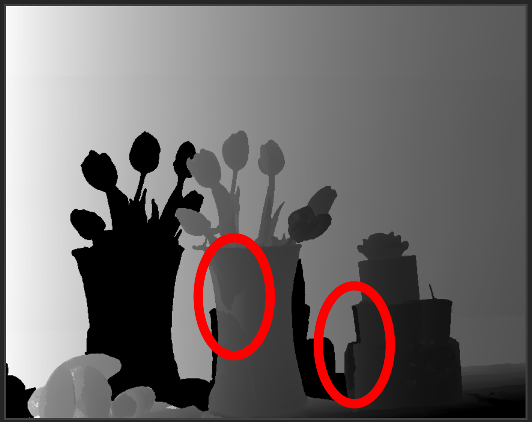
Diffusion

Sub-surface Scattering

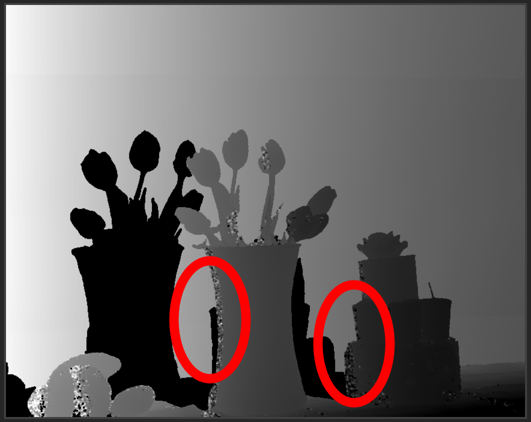
Comparison



Phase-Shifting (18 images)



Regular Gray Code (11 images)

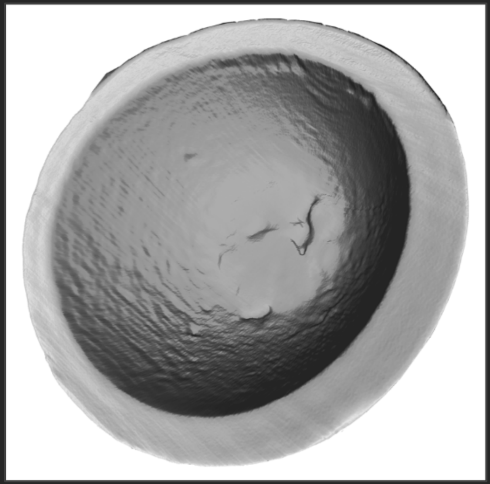


Modulated Phase-Shifting (162 images)

Our Ensemble Codes (41 images)

Multiple Indirect Illumination Effects

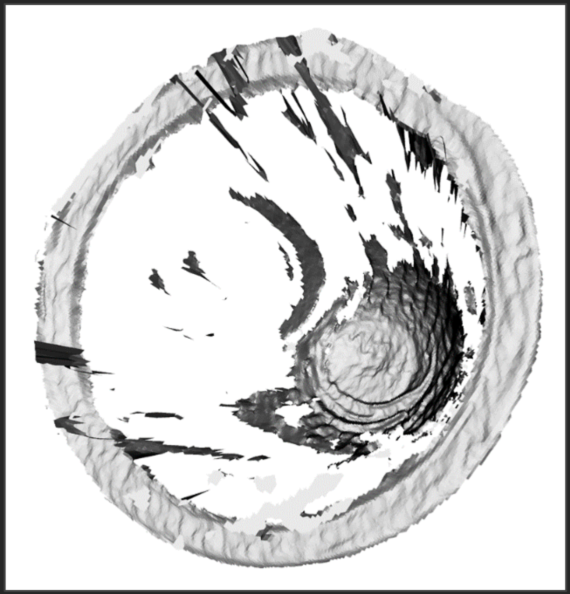
Wax Bowl



Shape Using Ensemble Codes

Multiple Indirect Illumination Effects

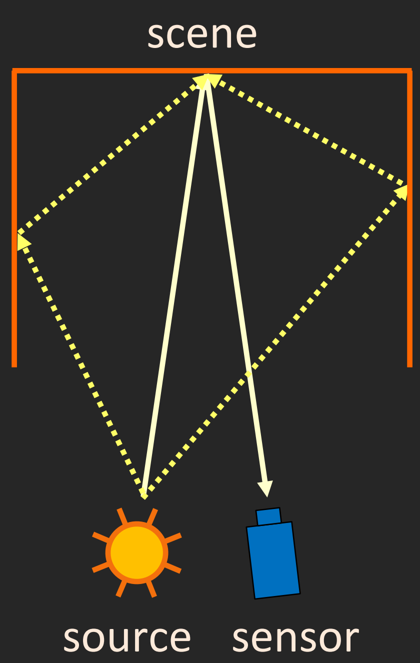
Deep Wax Container

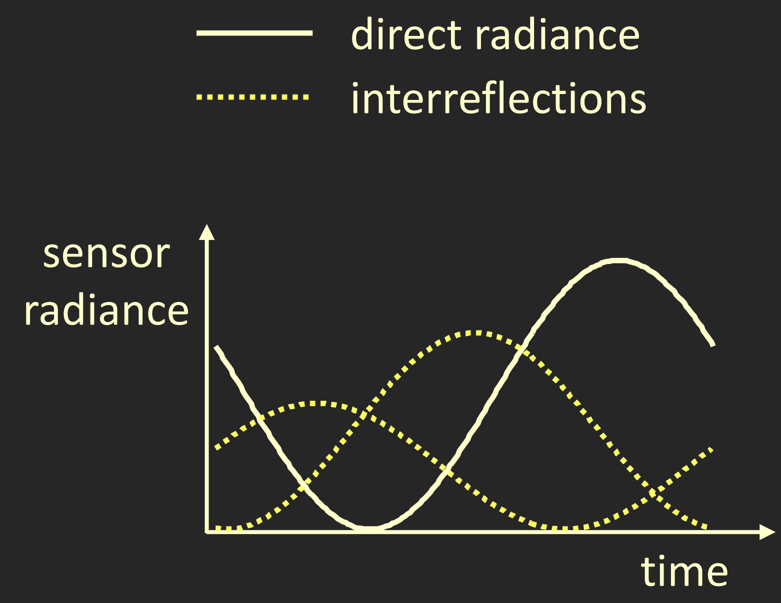


Shape Using Ensemble Codes

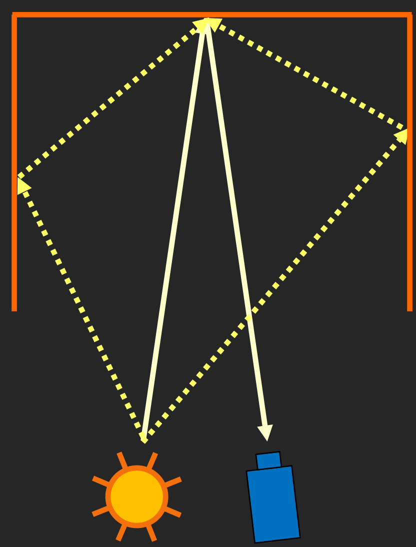
Application to time-of-flight imaging

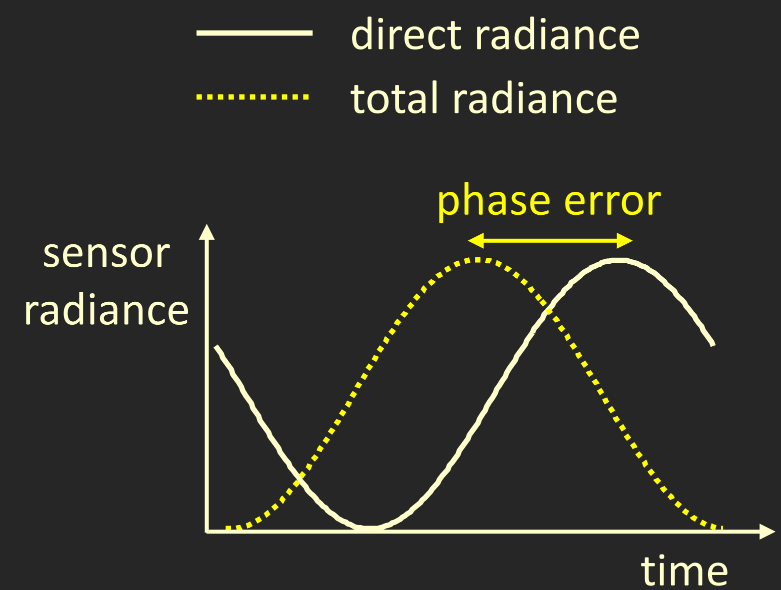
Interreflections and ToF Imaging





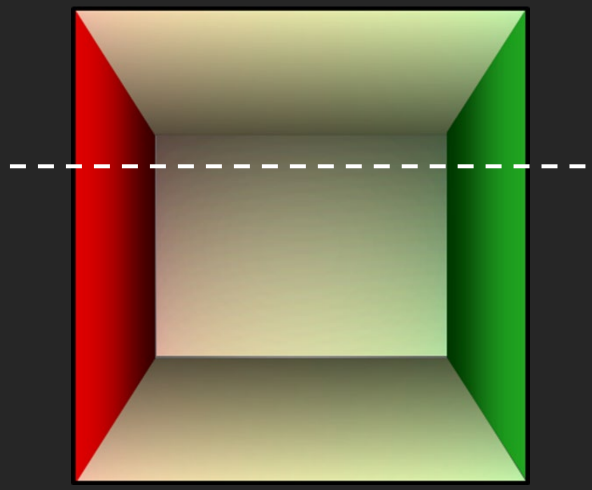
Interreflections and ToF Imaging



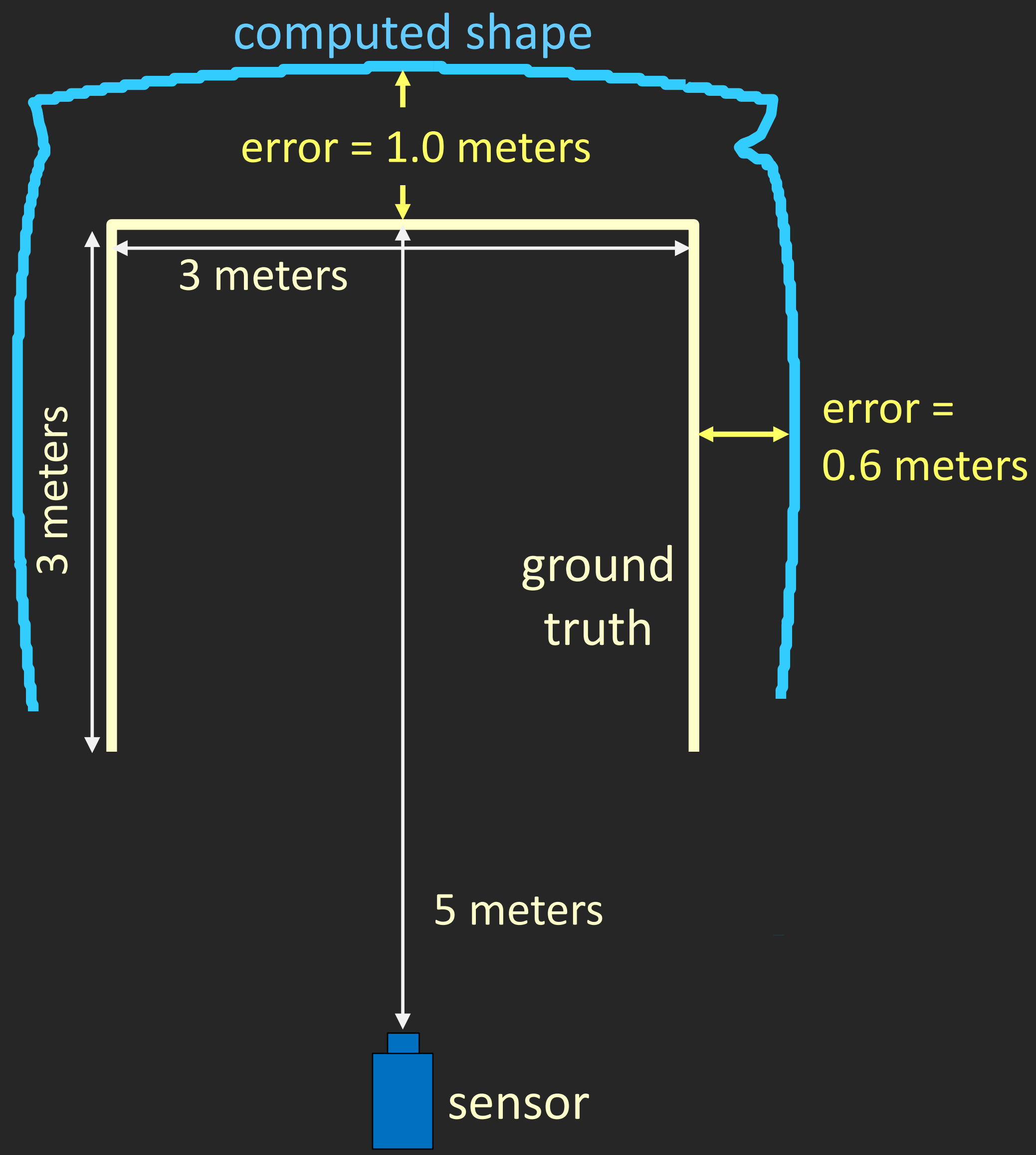


Interreflections Produce Incorrect Phase

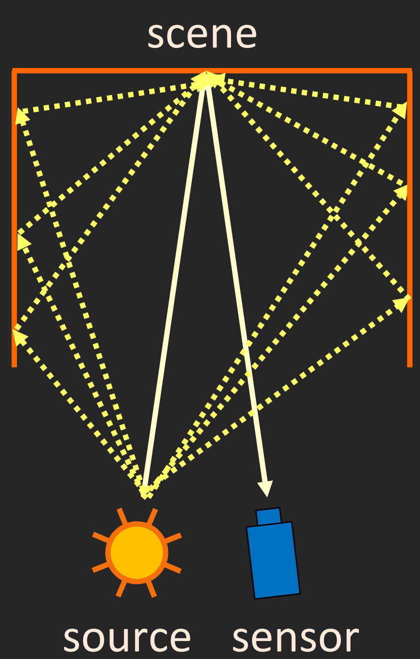
Errors in Shape Recovery

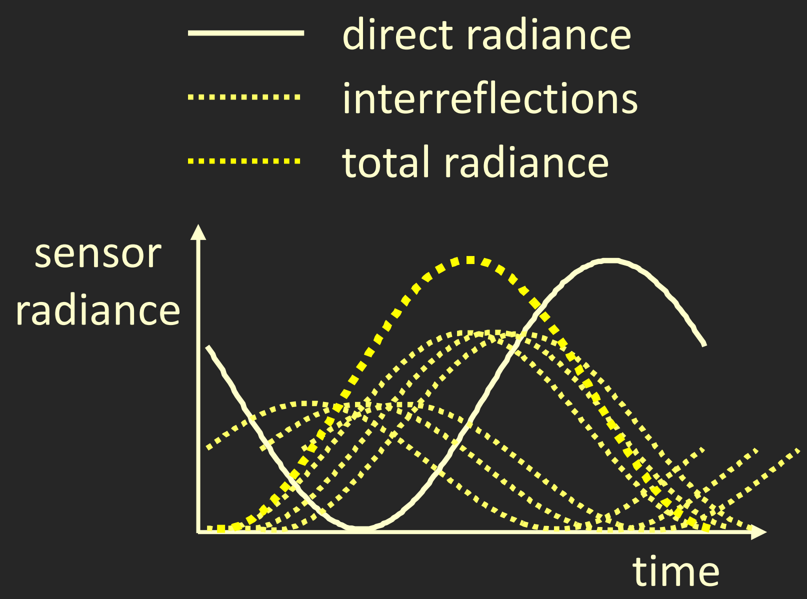


camera view



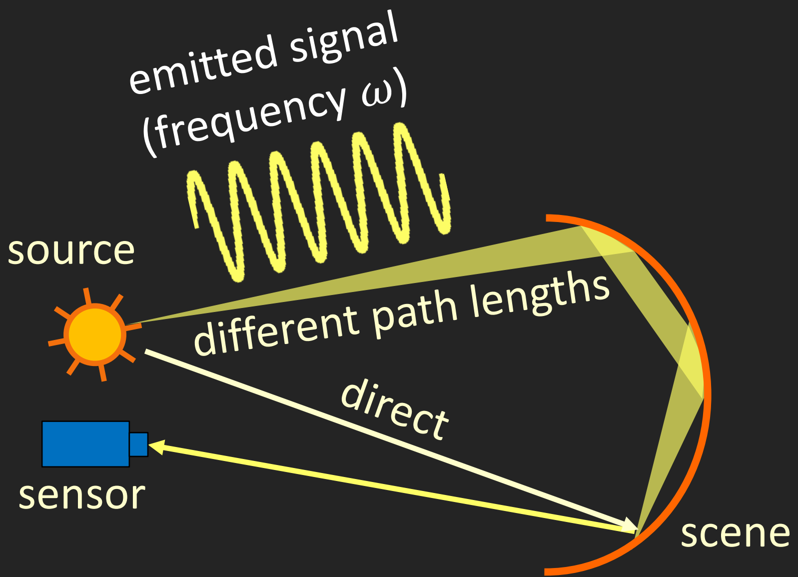
Multipath Interference: Existing Work

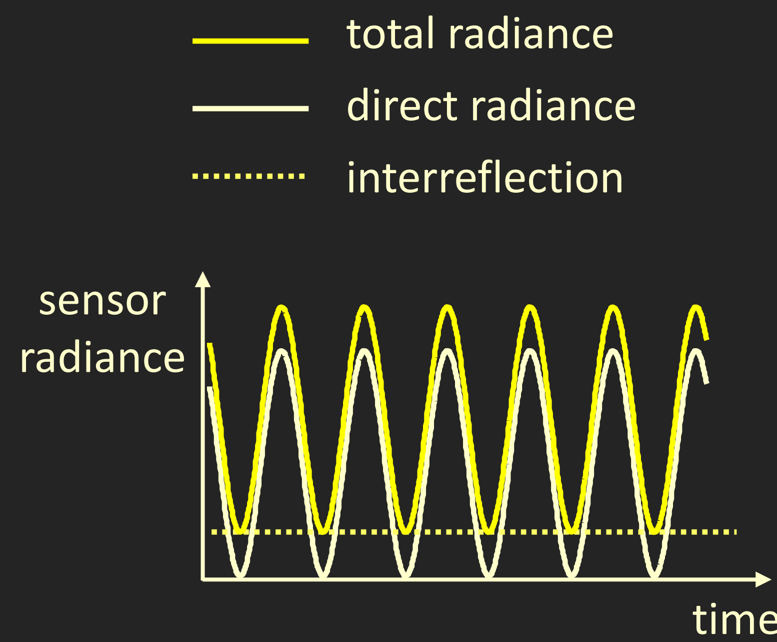




How To Separate Different Components?

Interreflections vs. Modulation Frequency



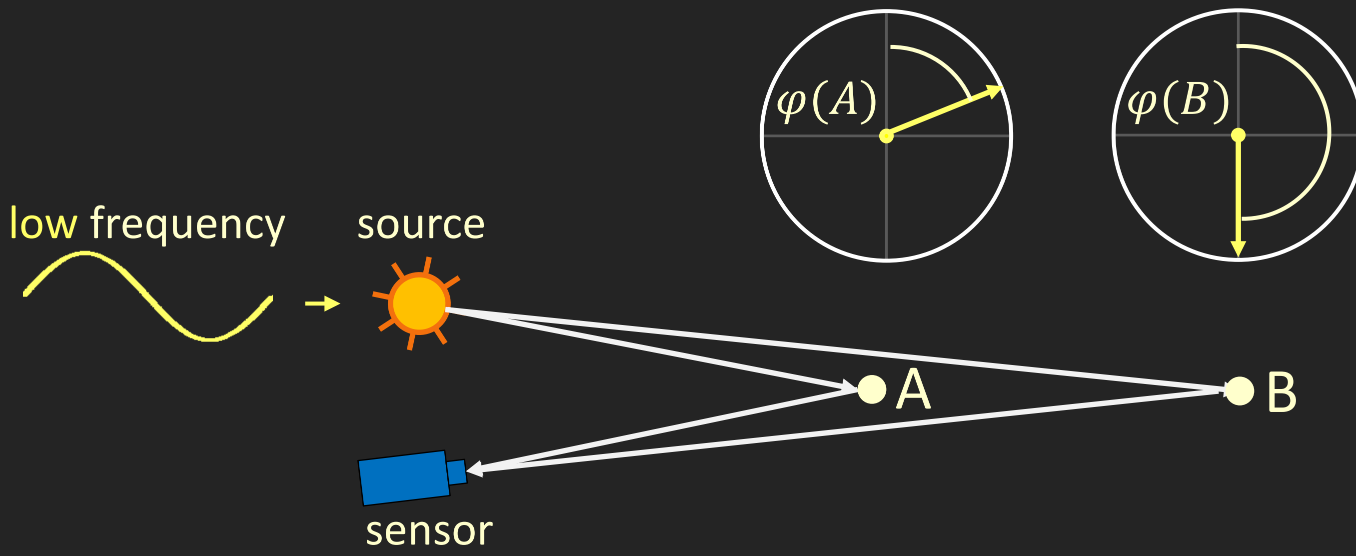


For High Temporal Frequency

Interreflection Component Constant

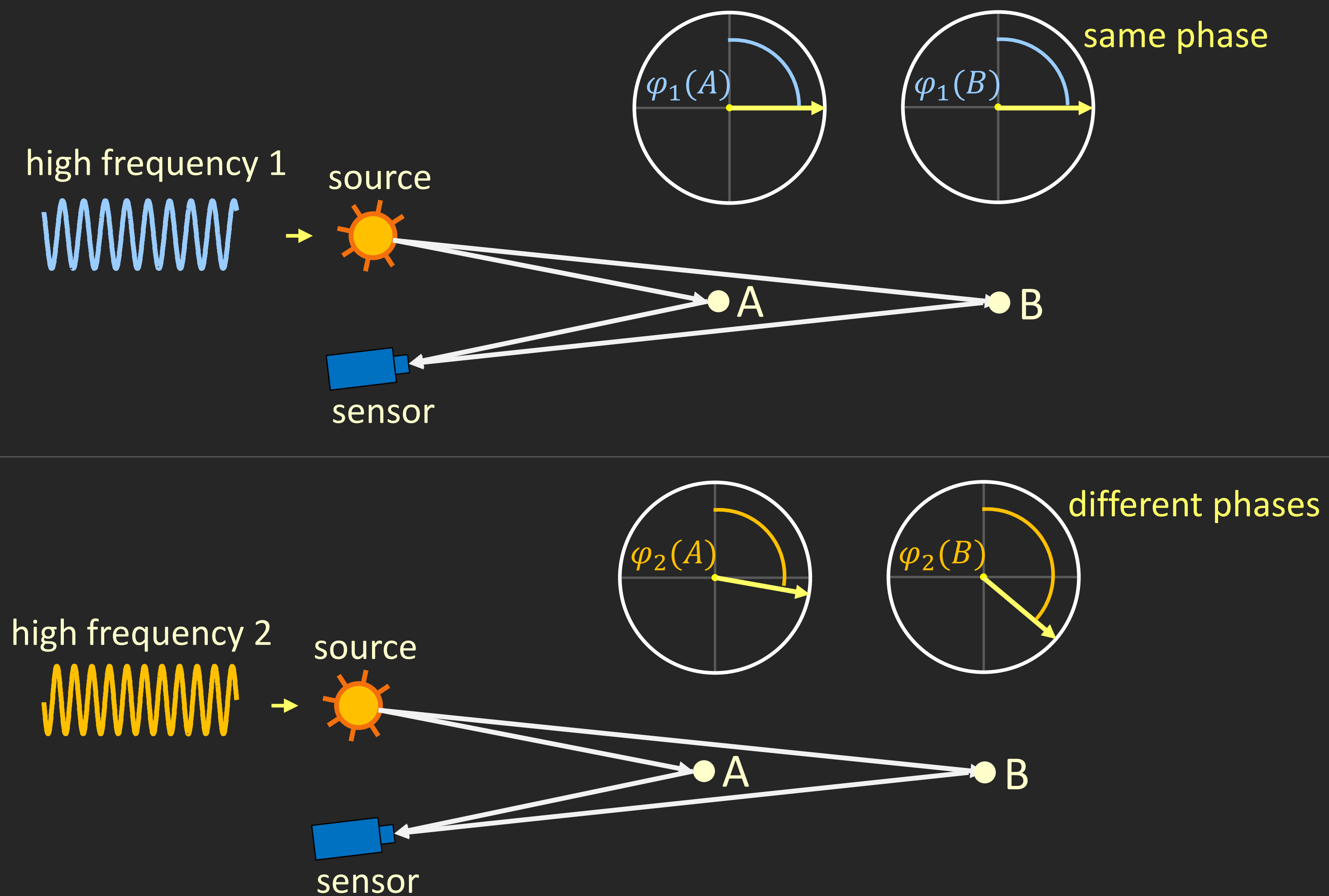
Interreflections Do Not Affect Phase

Phase Ambiguity



Unambiguous Depth Range: $R_{unambiguous} = \frac{1}{2\omega}$

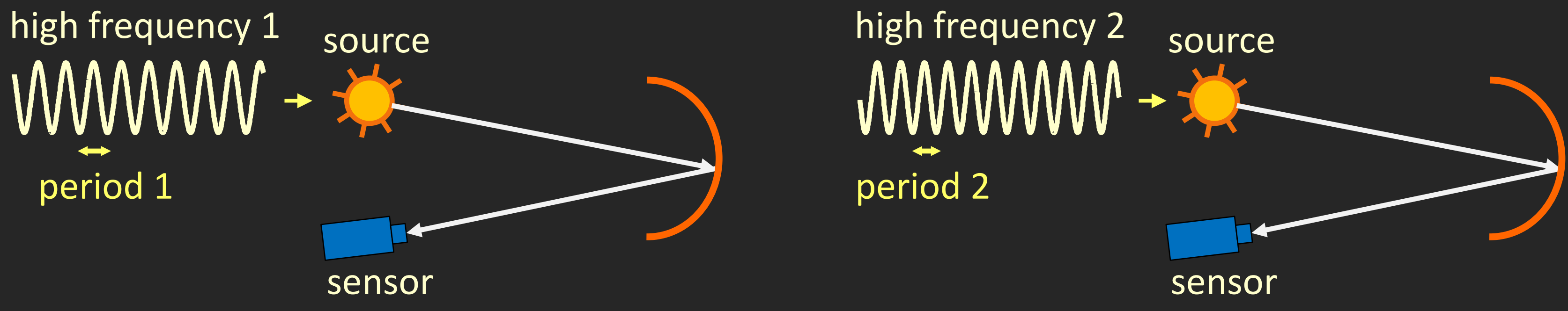
Disambiguating Phase



Compute Phases at Two High Frequencies

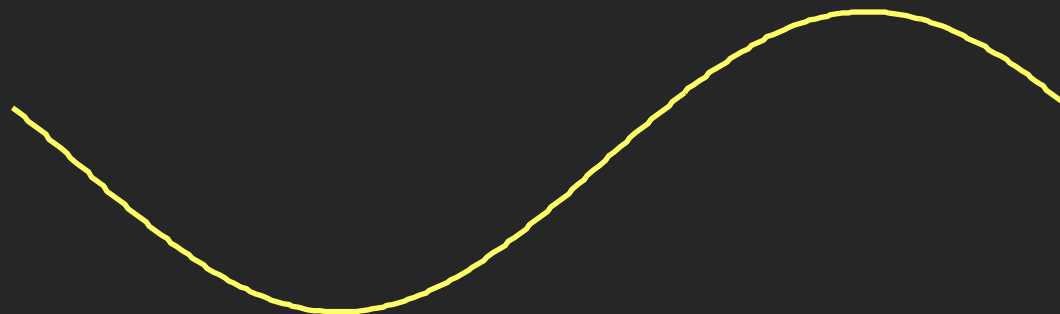
[Jongenelen *et al.* 2010, 2011]

Micro Time-of-Flight Imaging



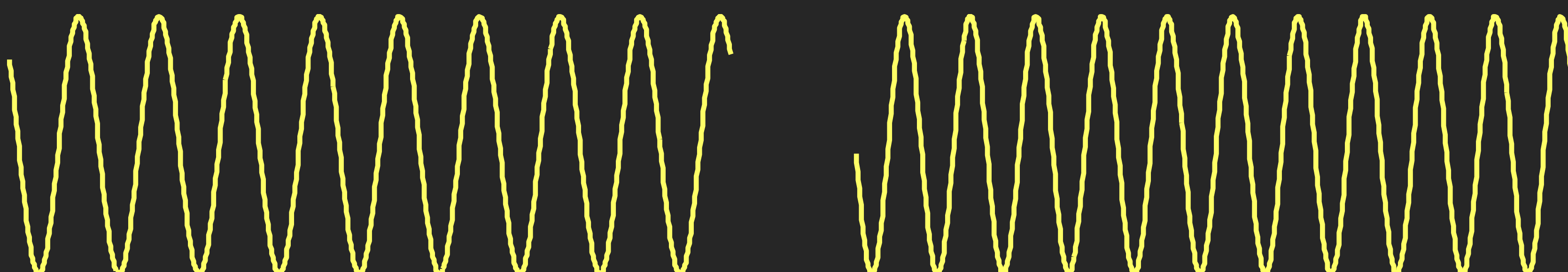
Modulation Signals With Micro (Small) Periods

Conventional vs. Micro ToF Imaging



Conventional ToF Shifting: One Low Frequency

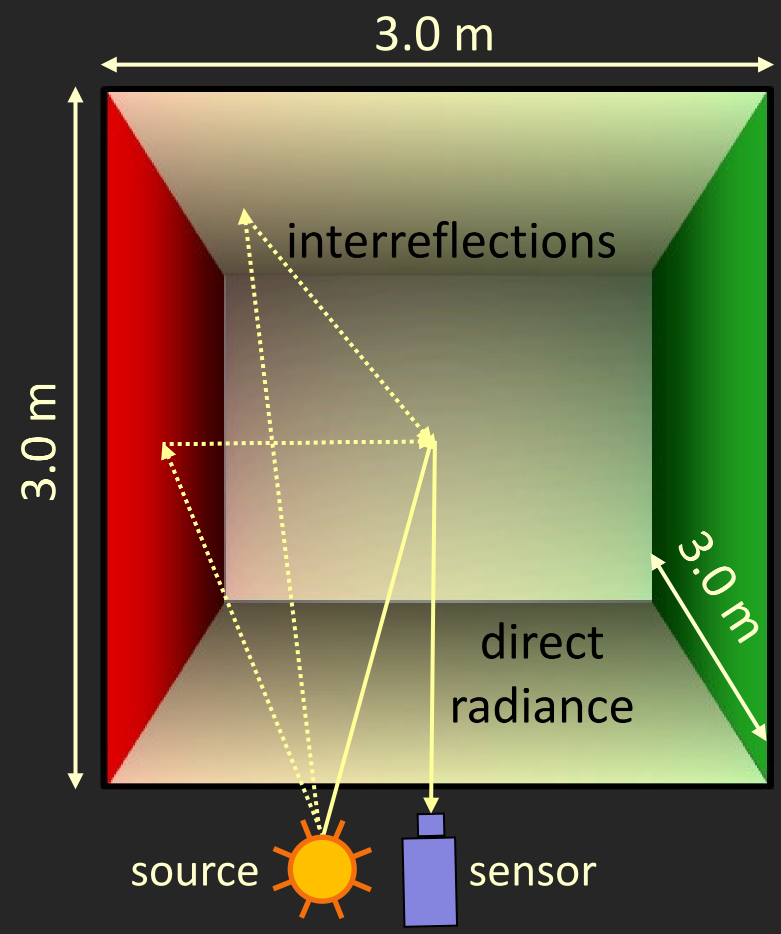
Three Measurements



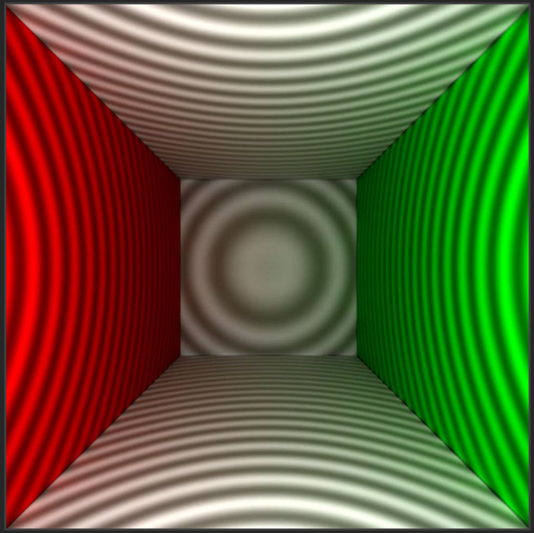
Micro ToF Shifting: Two High Frequencies

Four Measurements

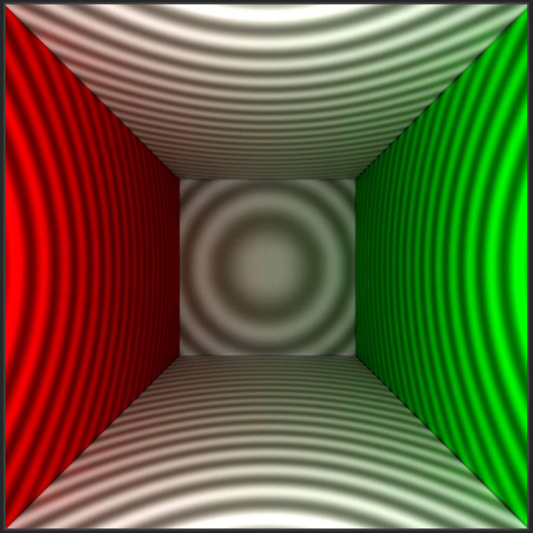
Simulations: Cornell Box



Cornell Box: Input Images



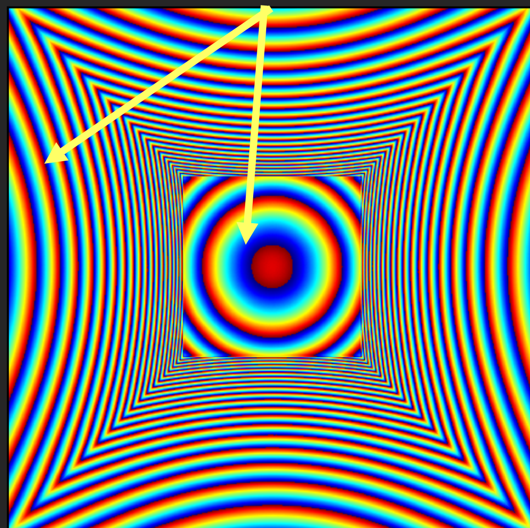
957 MHz.



930 MHz.

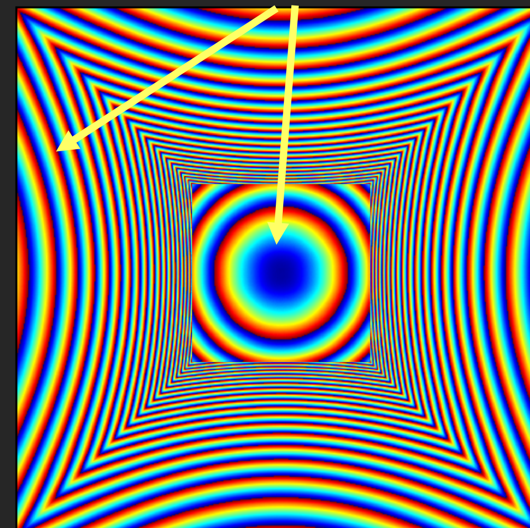
Cornell Box: Phase Maps

ambiguities



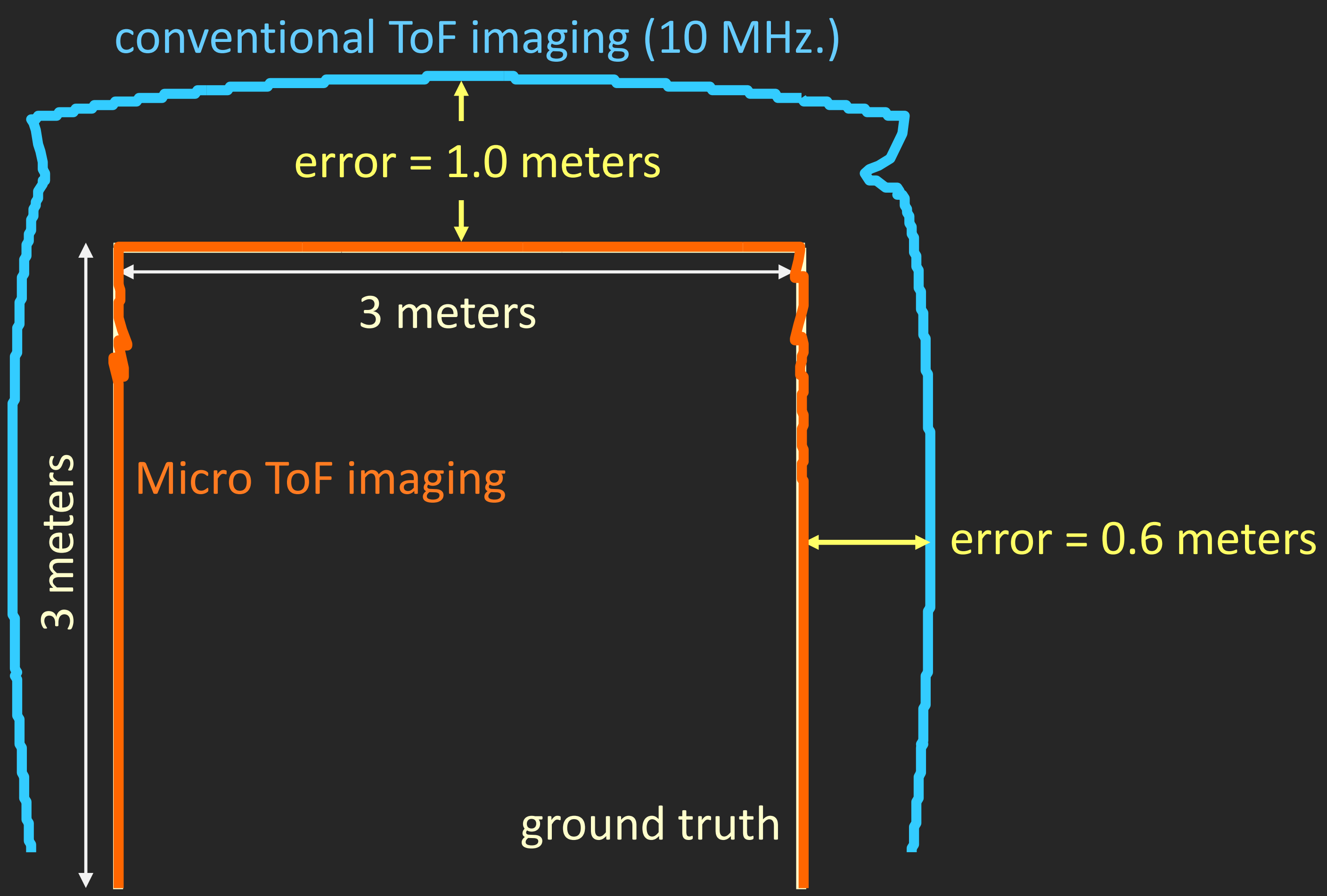
957 MHz.

ambiguities

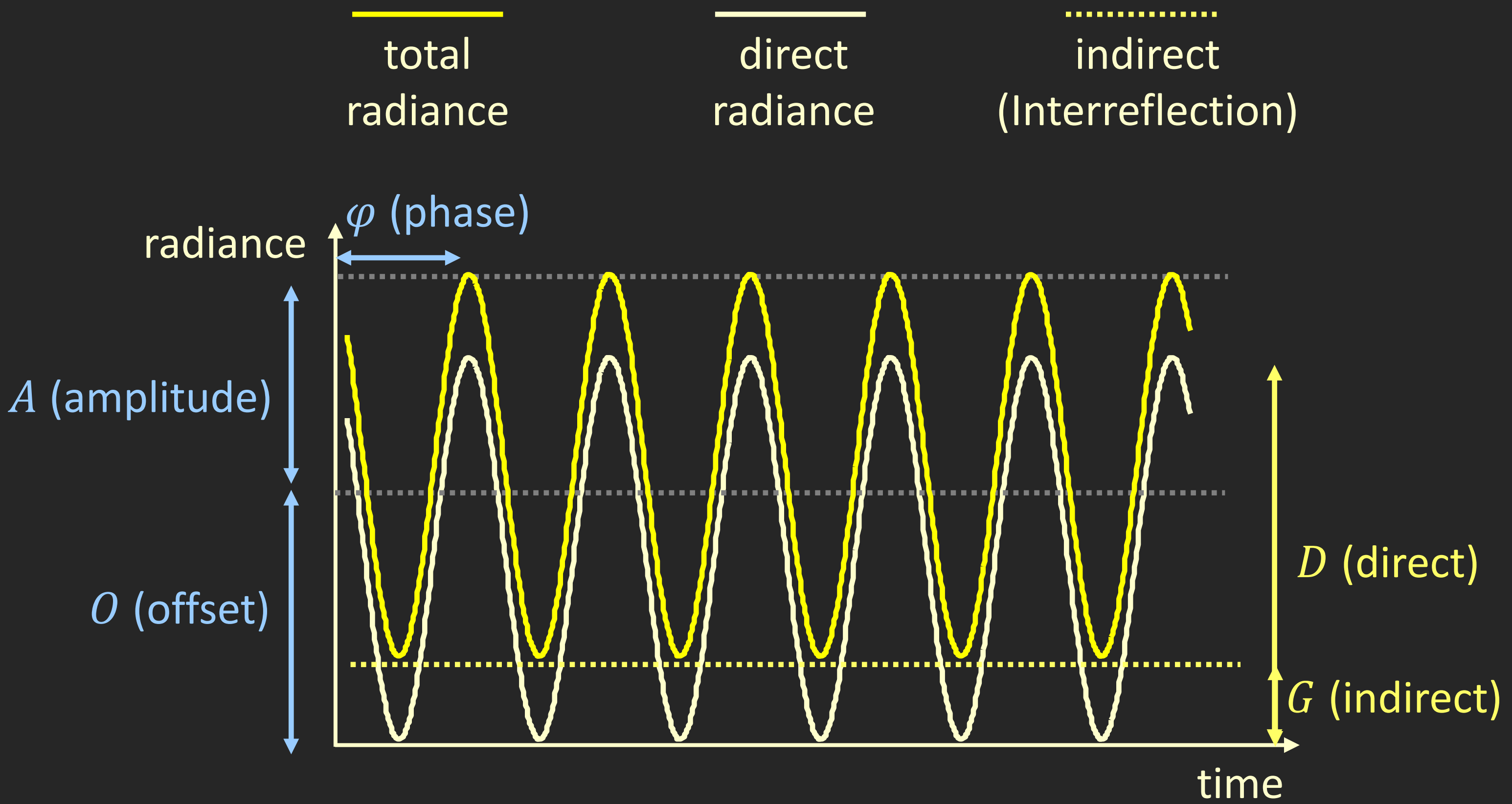


930 MHz.

Cornell Box: Shape Comparison



Direct-Indirect Separation

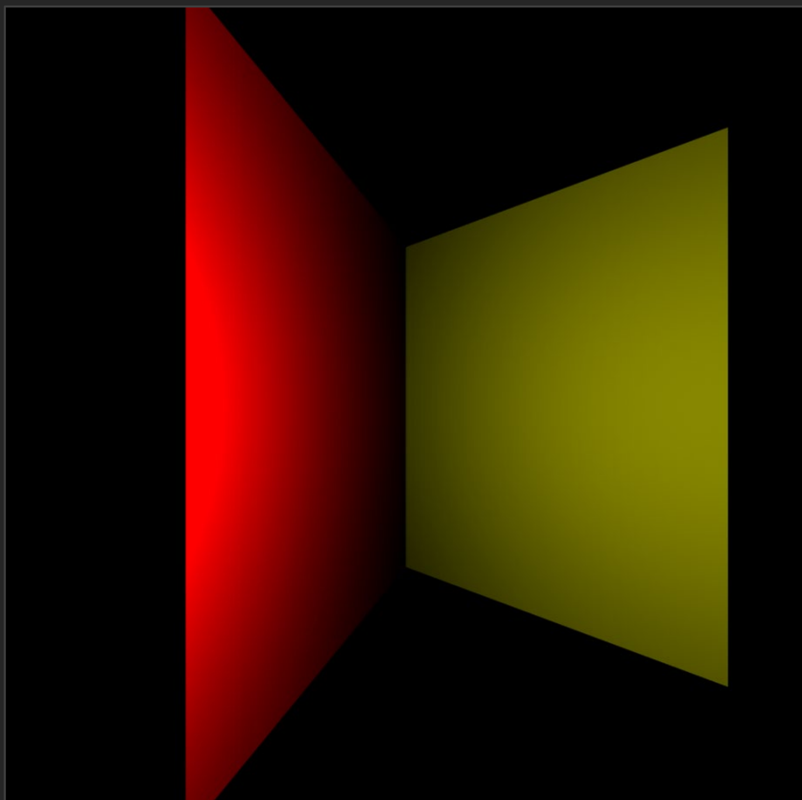


$$D = 2A \quad G = O - A$$

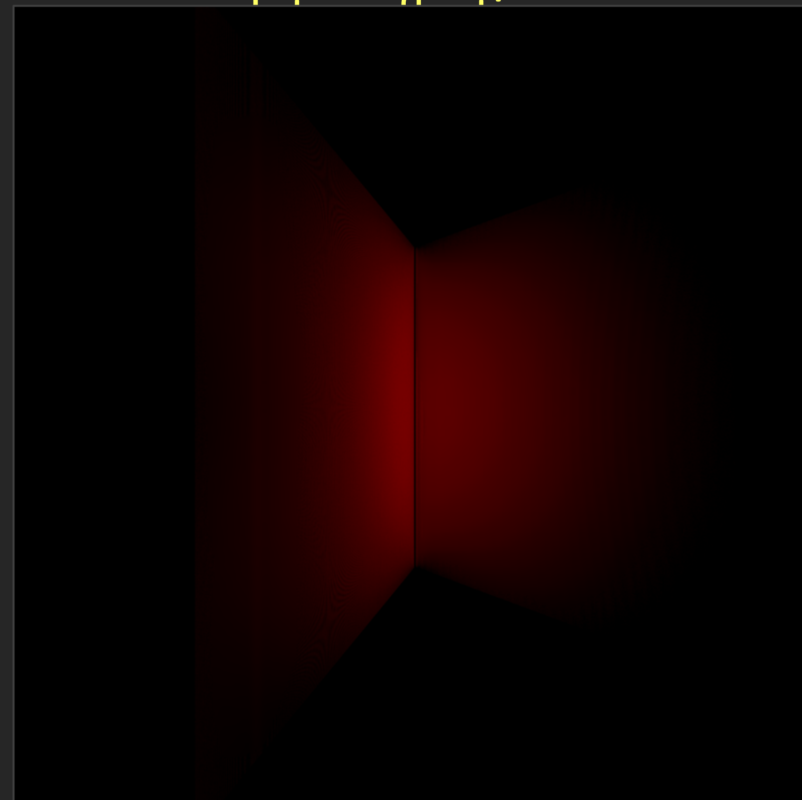
Direct-Indirect Separation Using Three Measurements

Direct-Indirect Separation

Color Bleeding due to

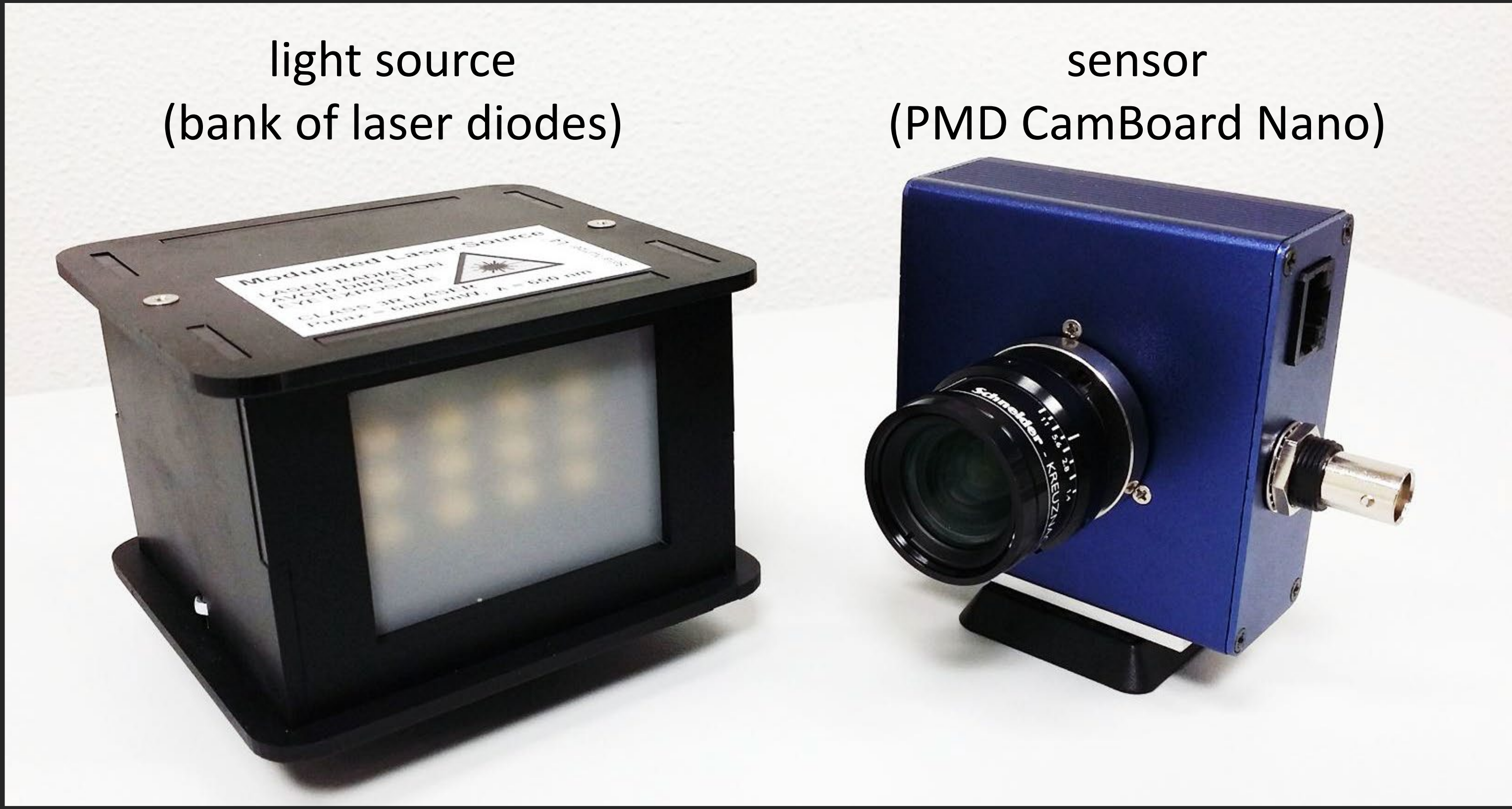


Direct Component
Direct Component



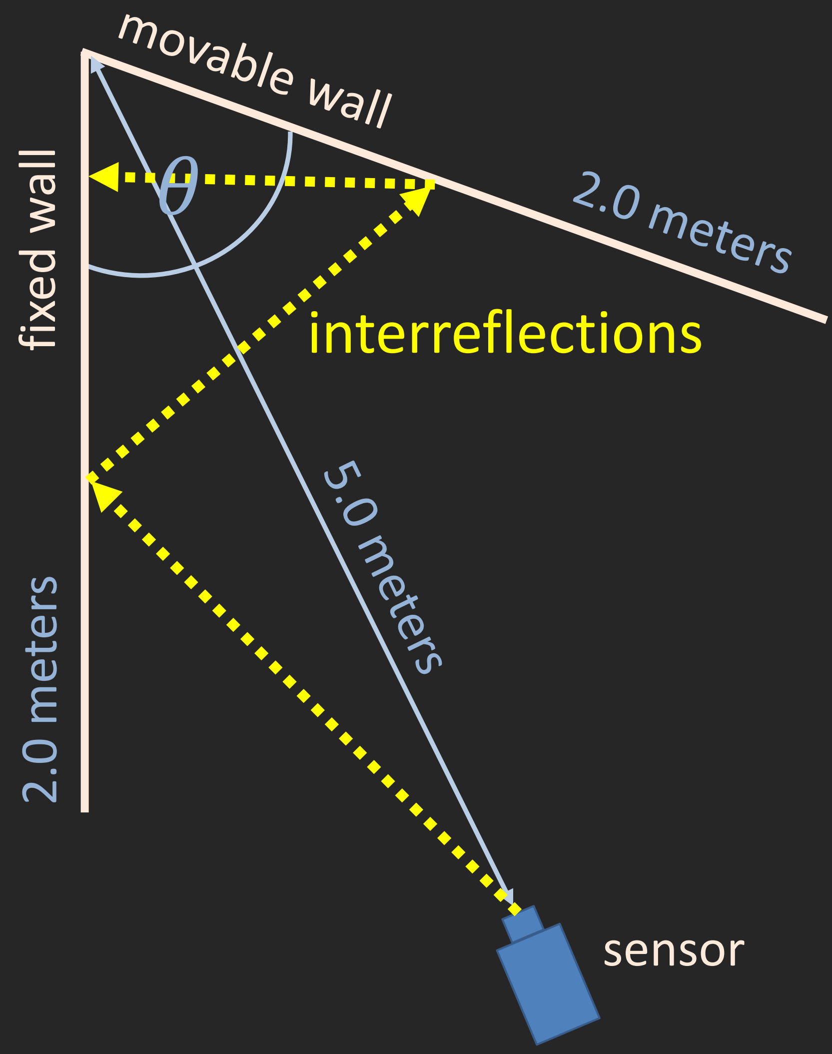
Indirect Component (x2)
Indirect Component (x2)

Experimental Setup

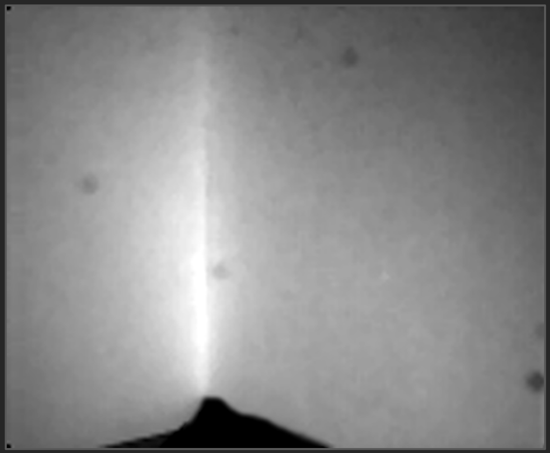


Maximum System Modulation Frequency = 125 MHz.

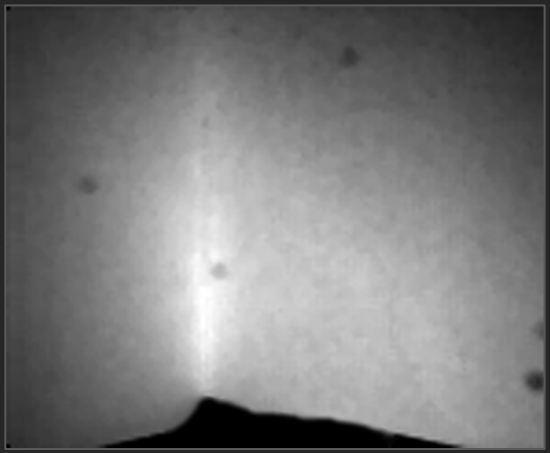
Experiments: V-Groove



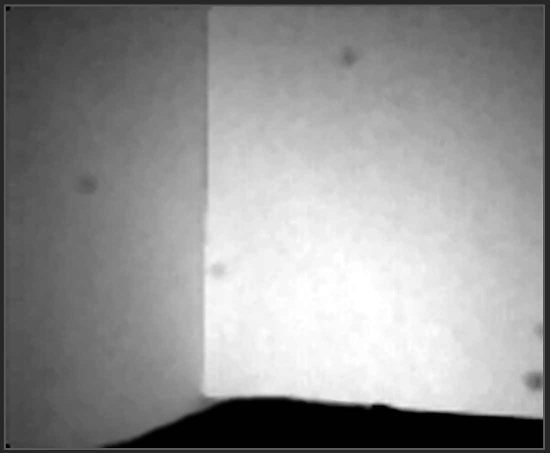
Scene Images Captured By PMD Sensor



apex angle = 45°



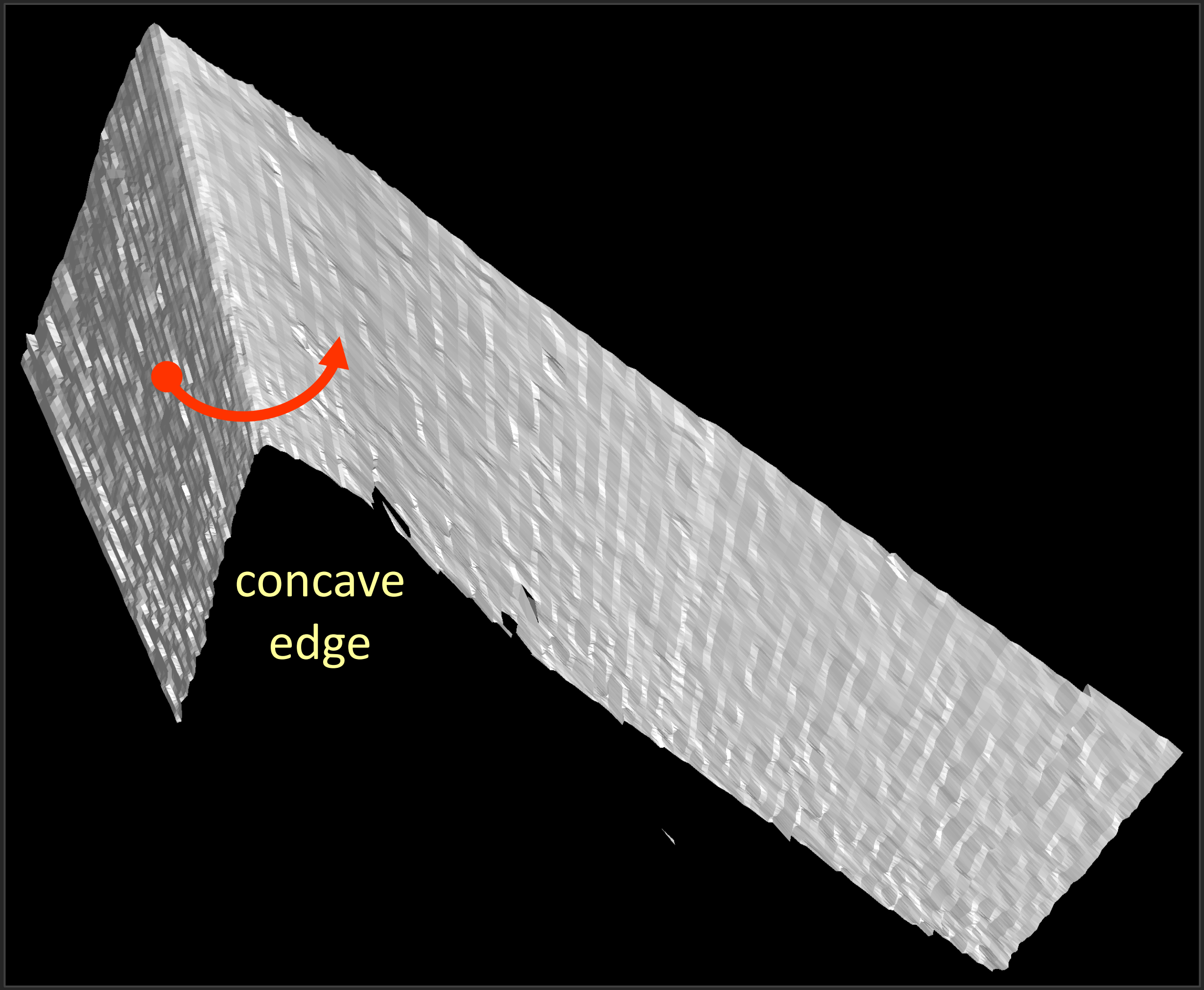
apex angle = 60°



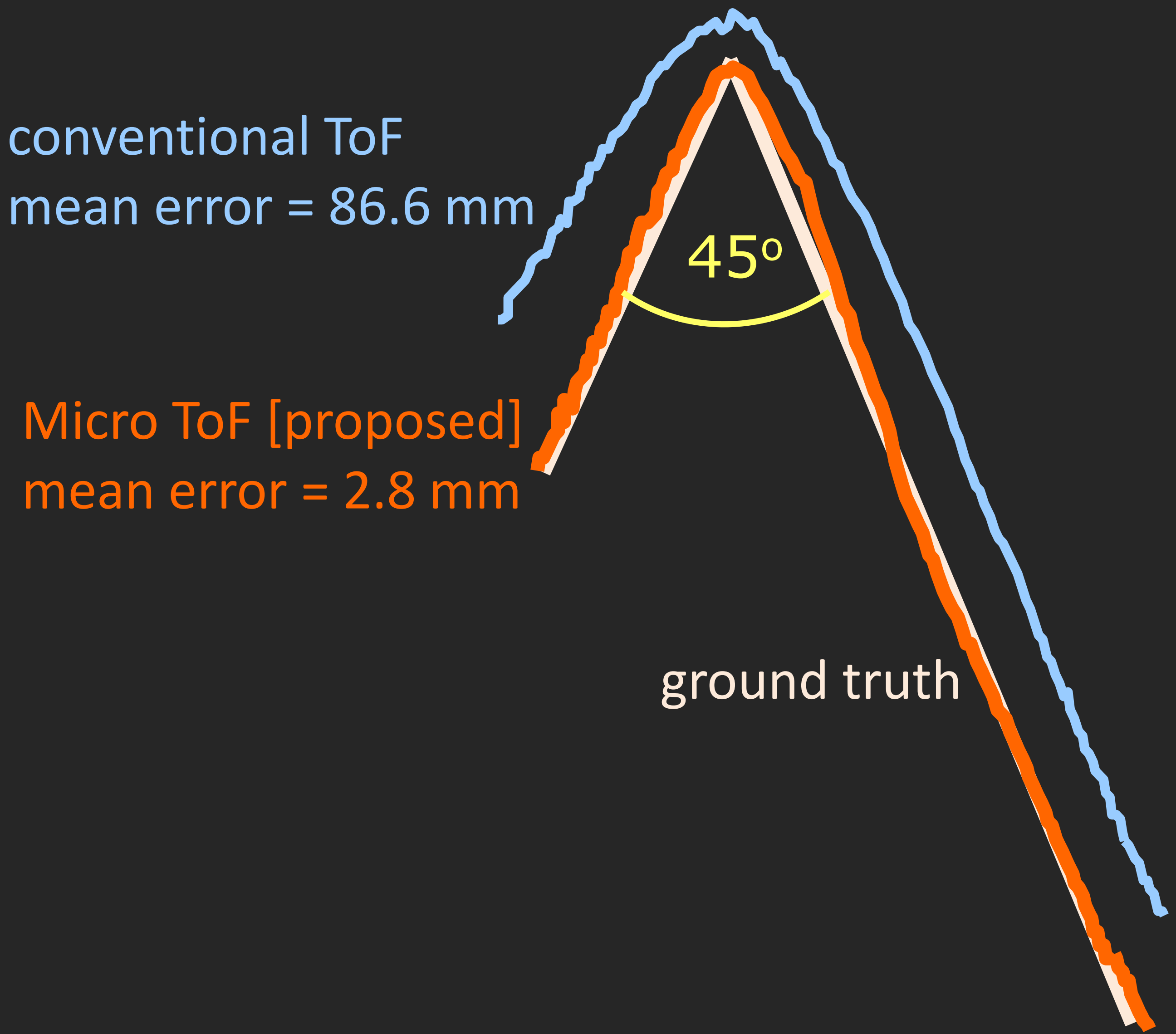
apex angle = 90°

image resolution = 120 x 165

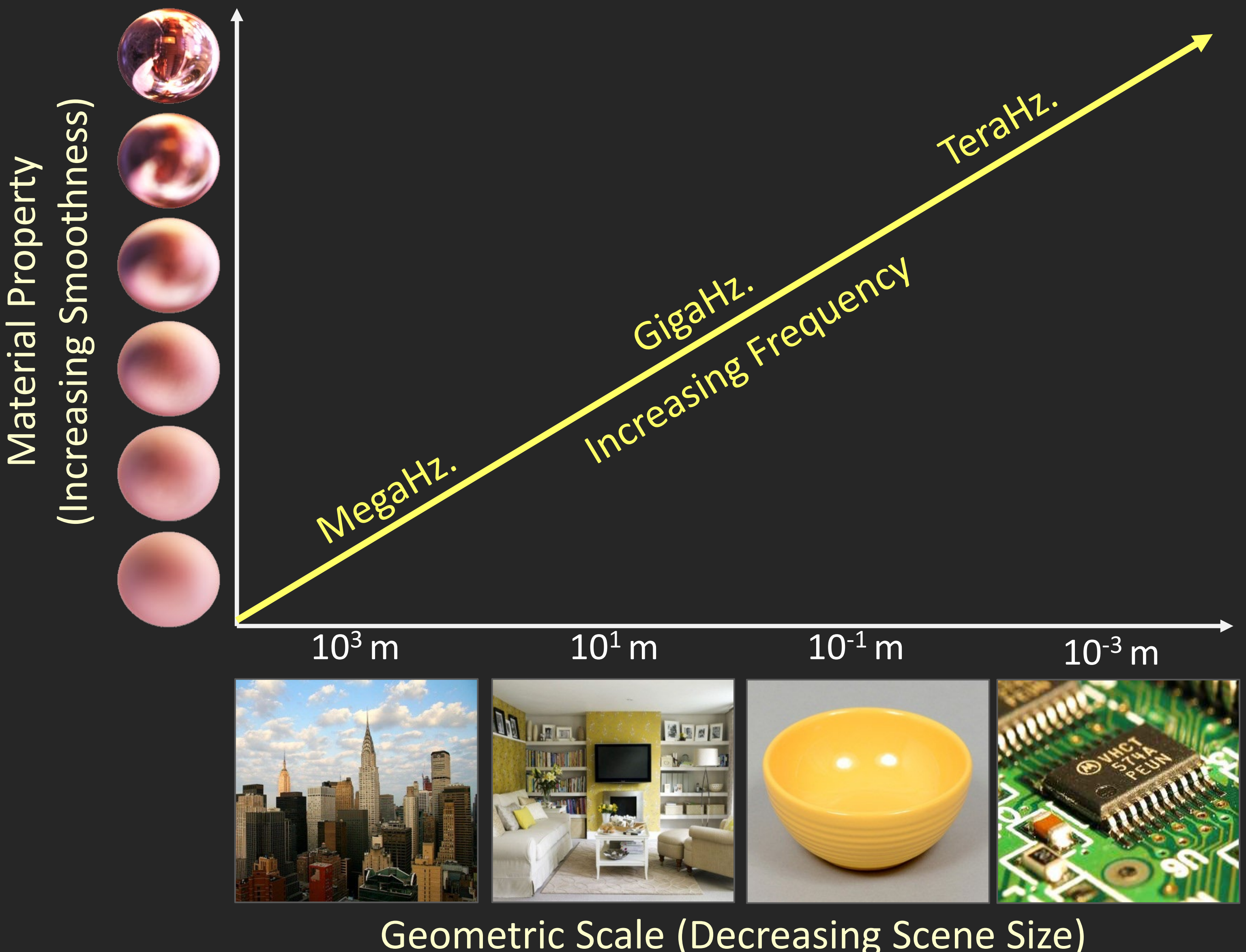
Reconstructed Shape using Micro ToF



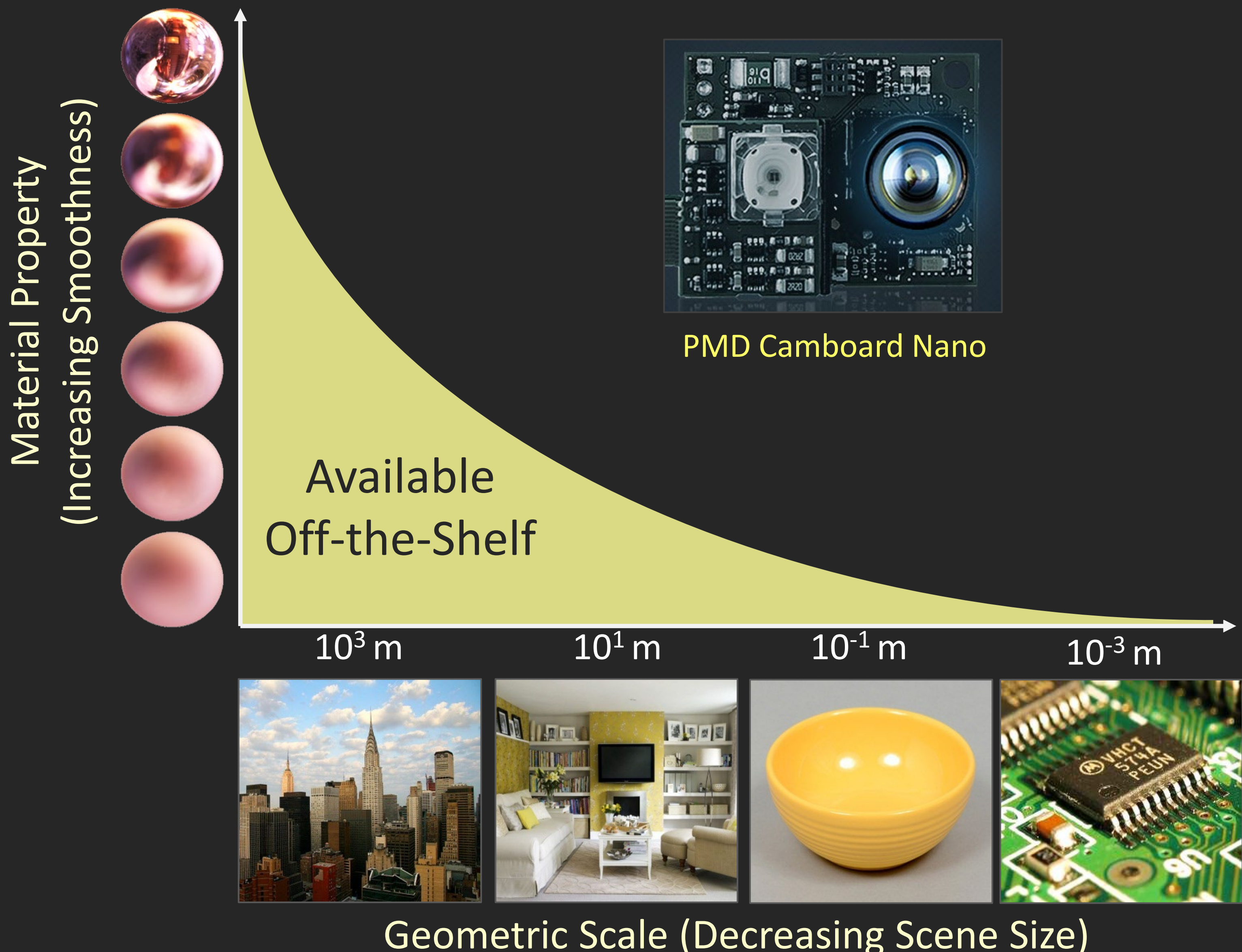
Shape Comparisons



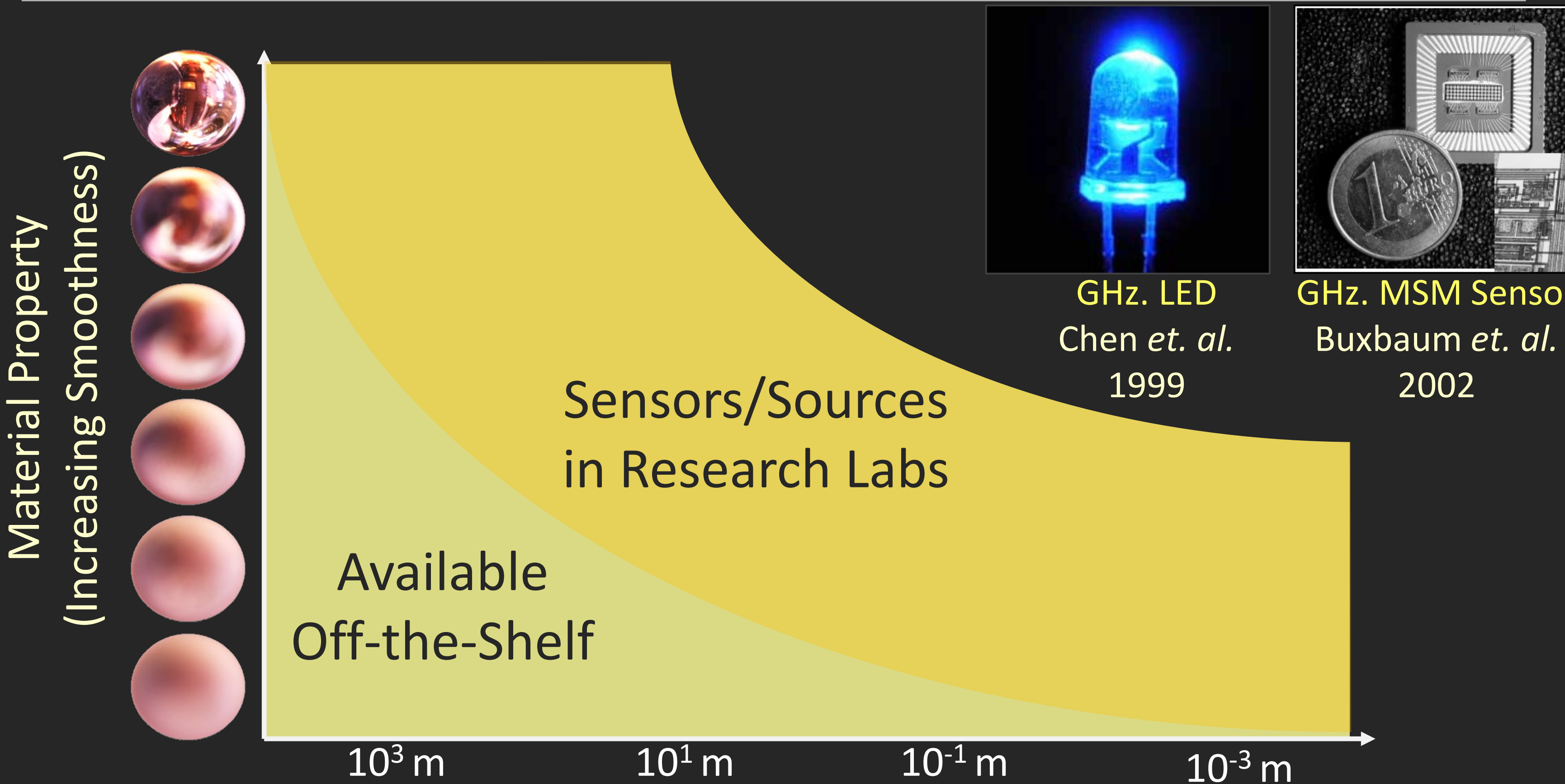
How High Should The Frequency Be?



Technology (Devices) Required



Technology (Devices) Required

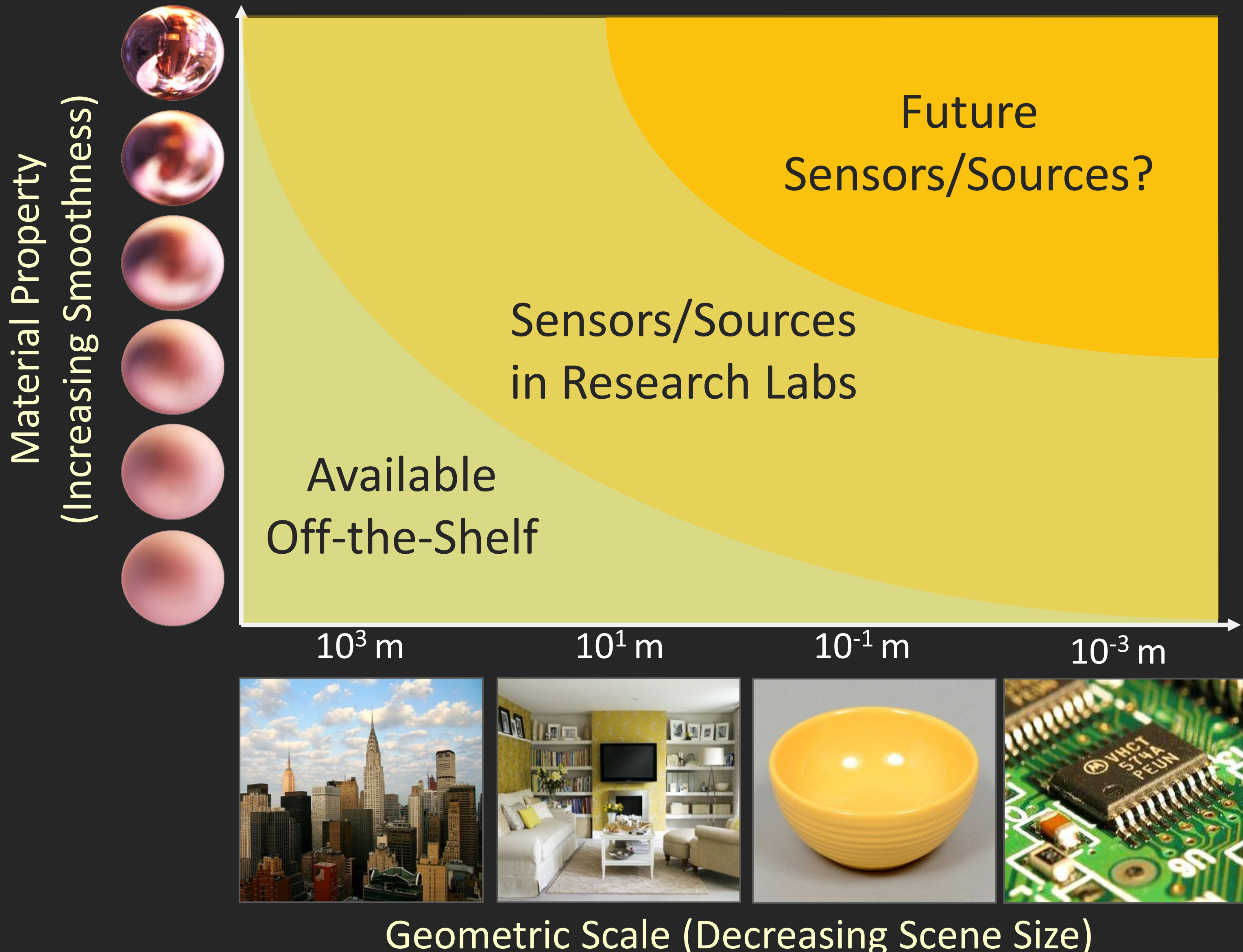


GHz. LED
Chen *et. al.*
1999

GHz. MSM Sensor
Buxbaum *et. al.*
2002

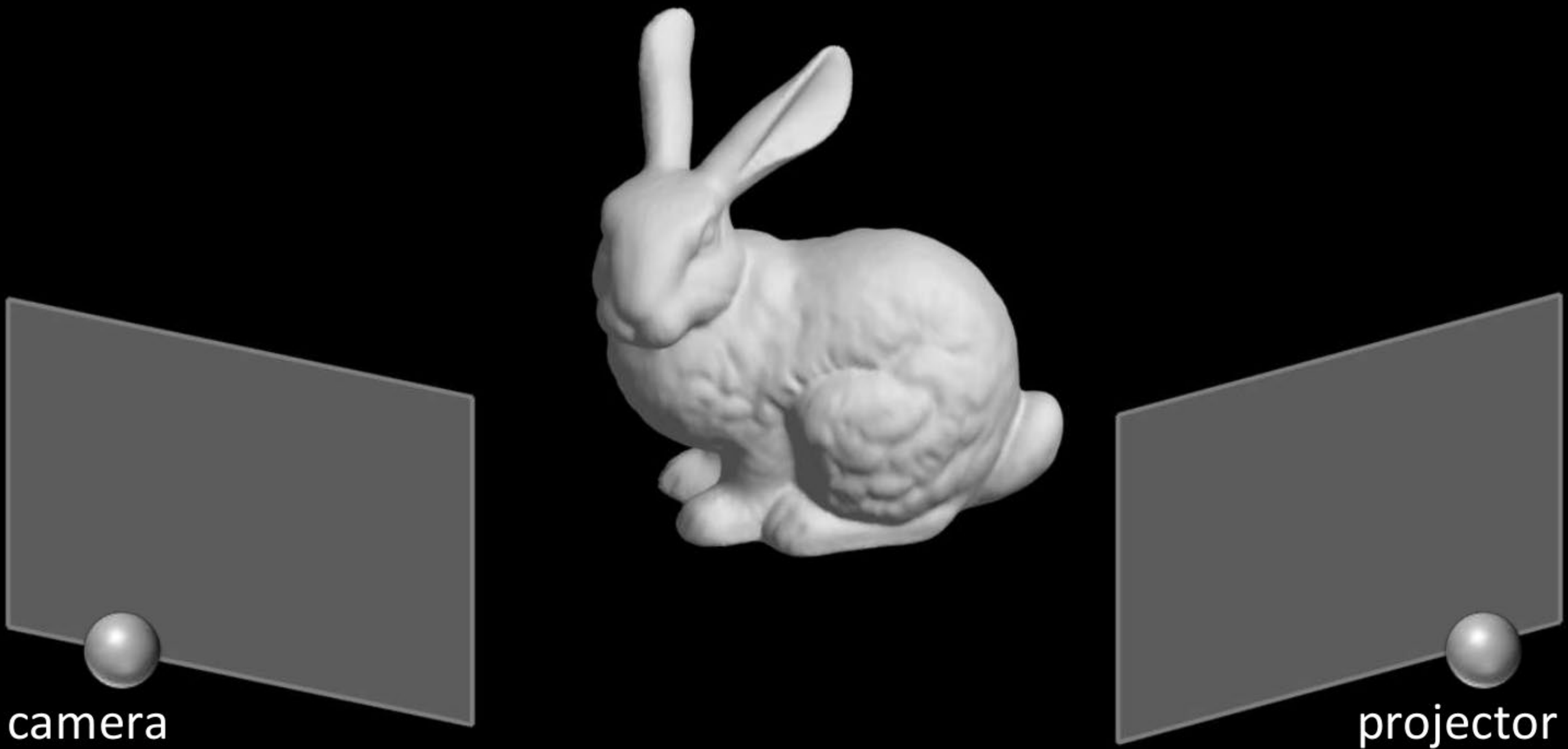
Geometric Scale (Decreasing Scene Size)

Technology (Devices) Required

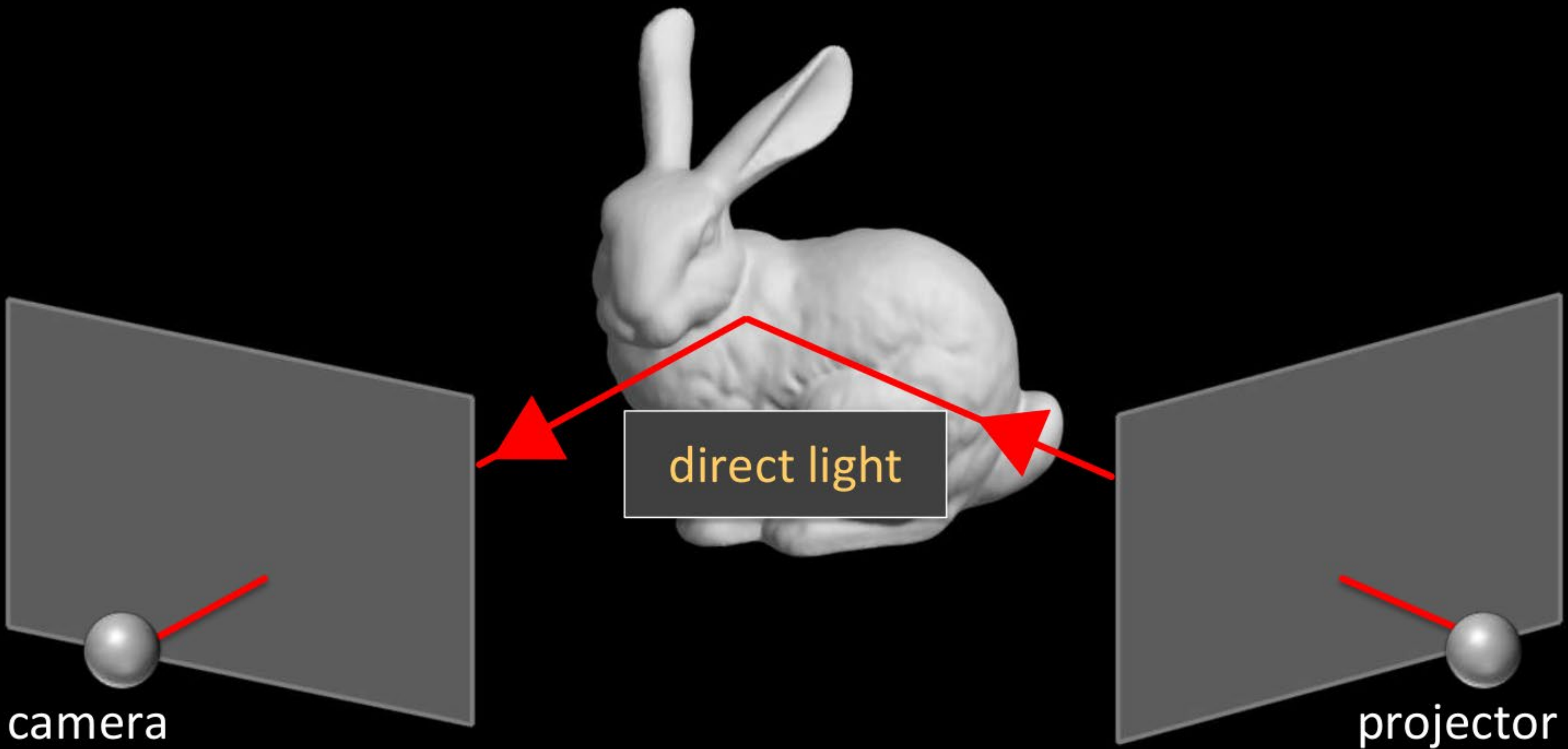


Direct-global separation using epipolar probing

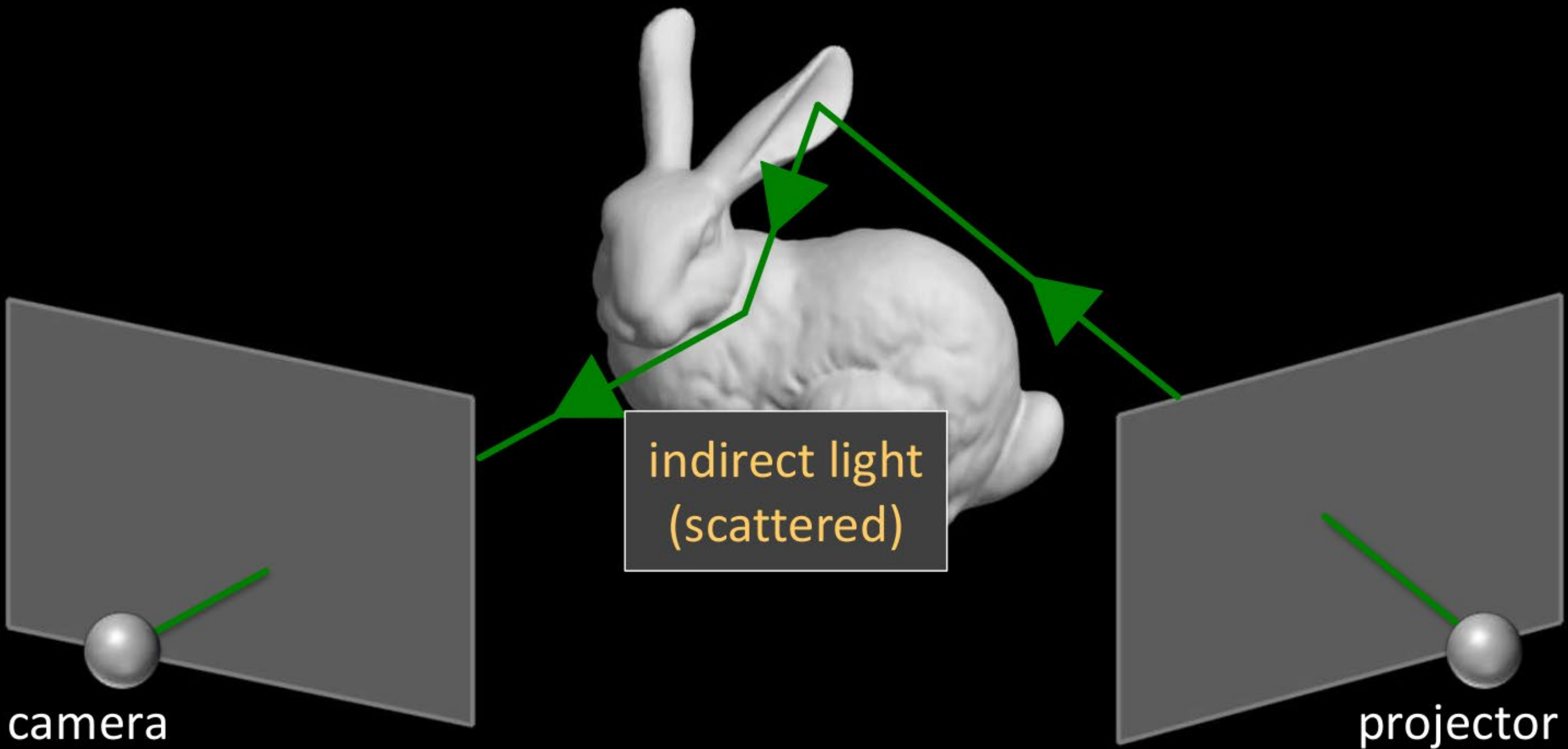
basic light paths



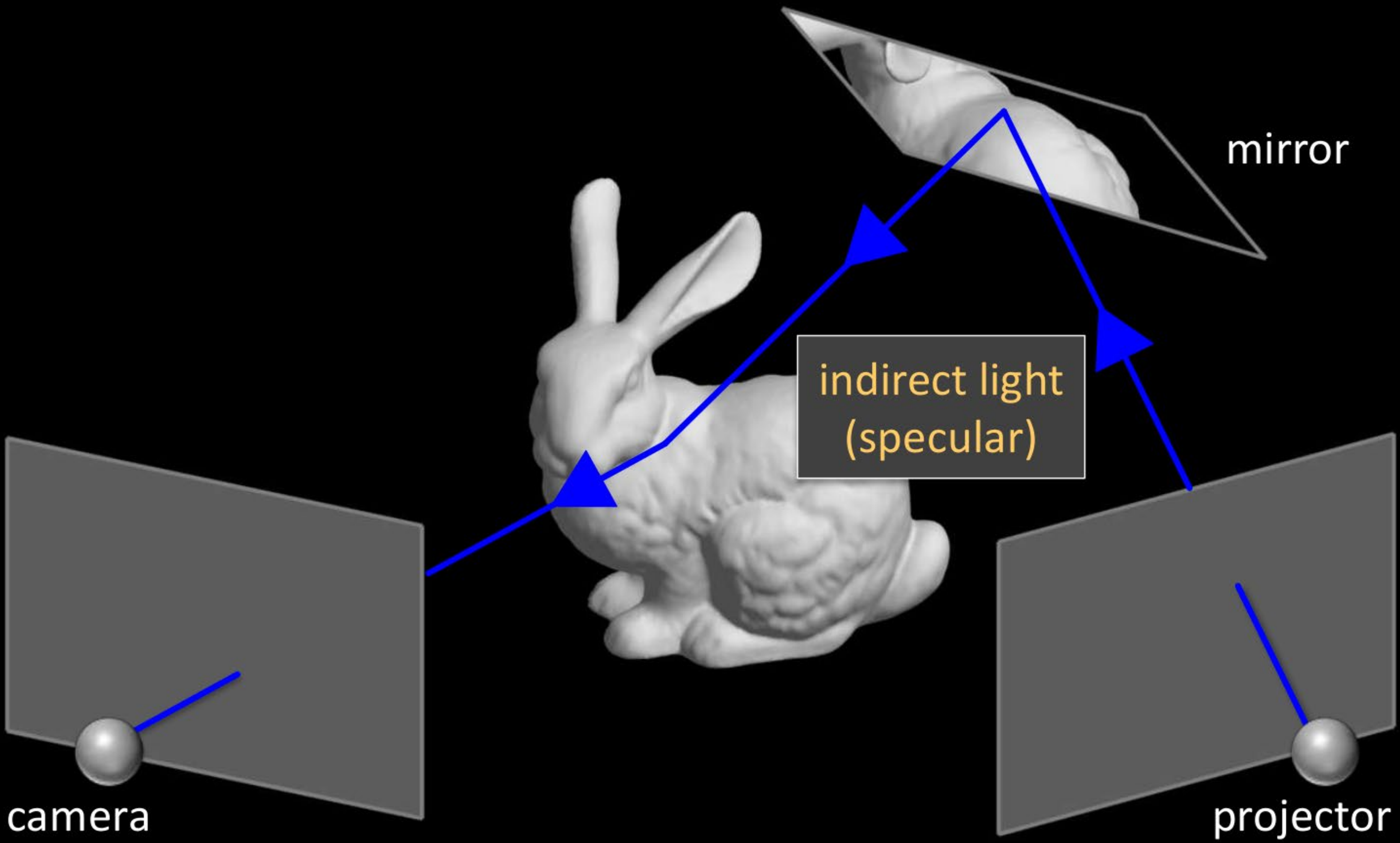
basic light paths



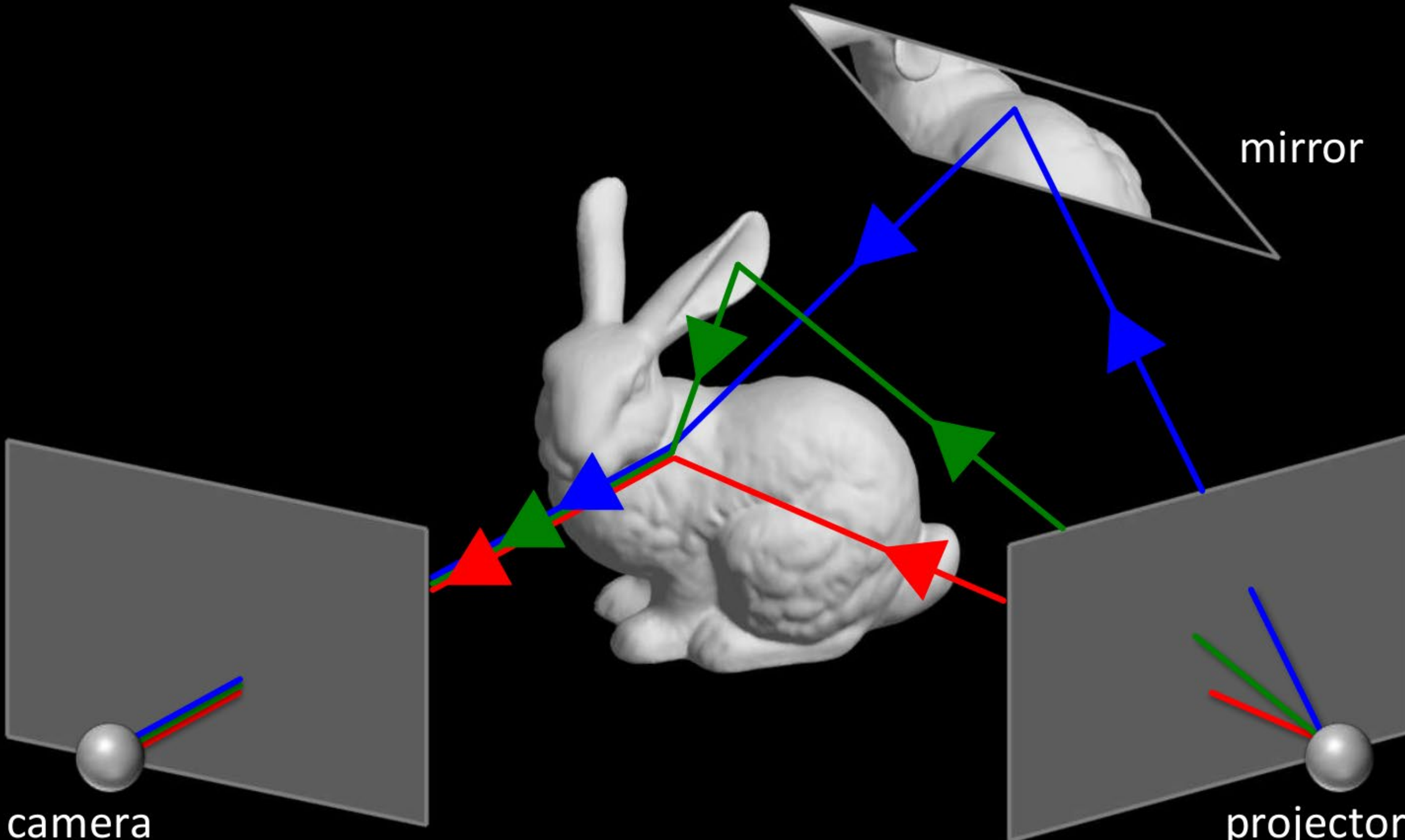
basic light paths



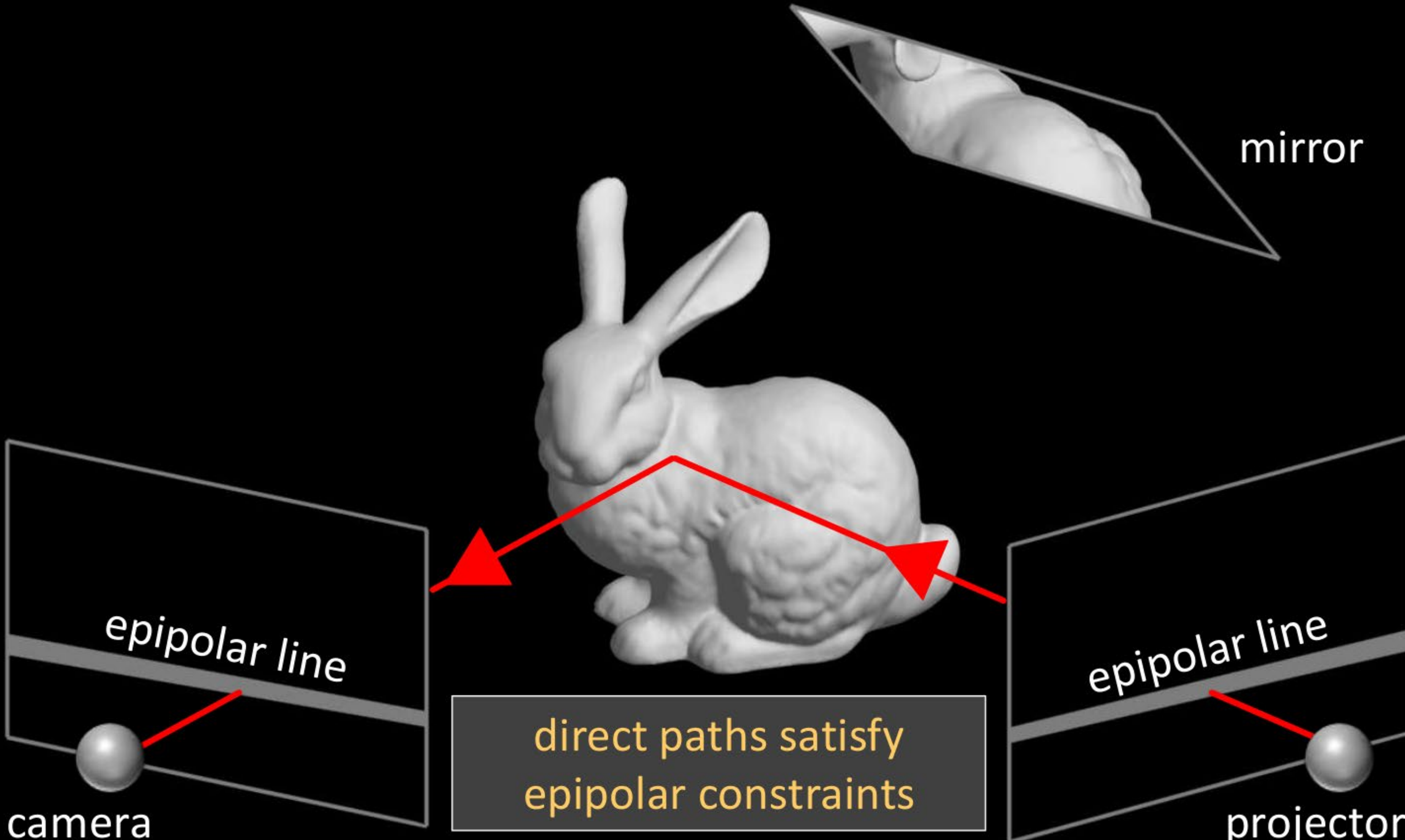
basic light paths



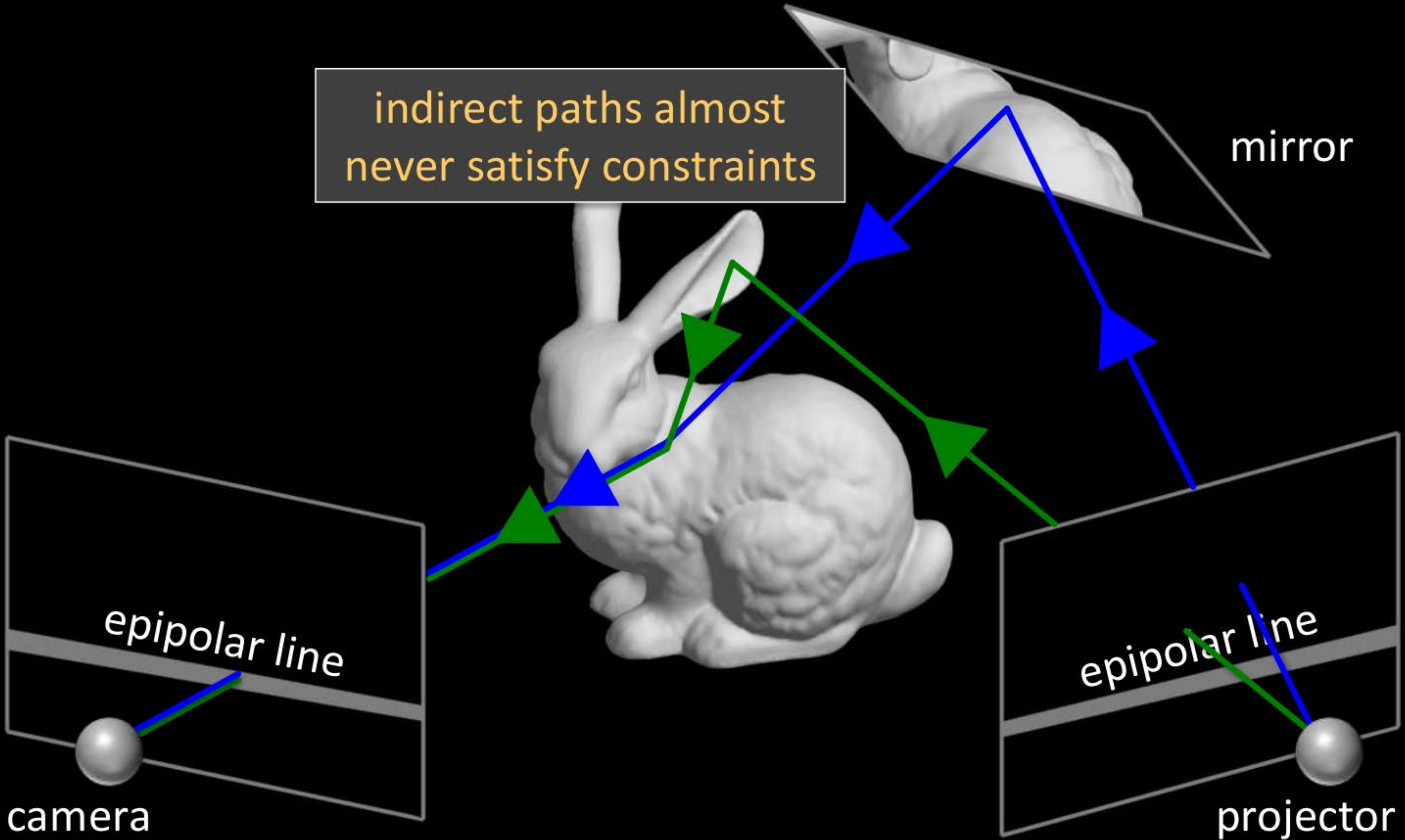
basic light paths



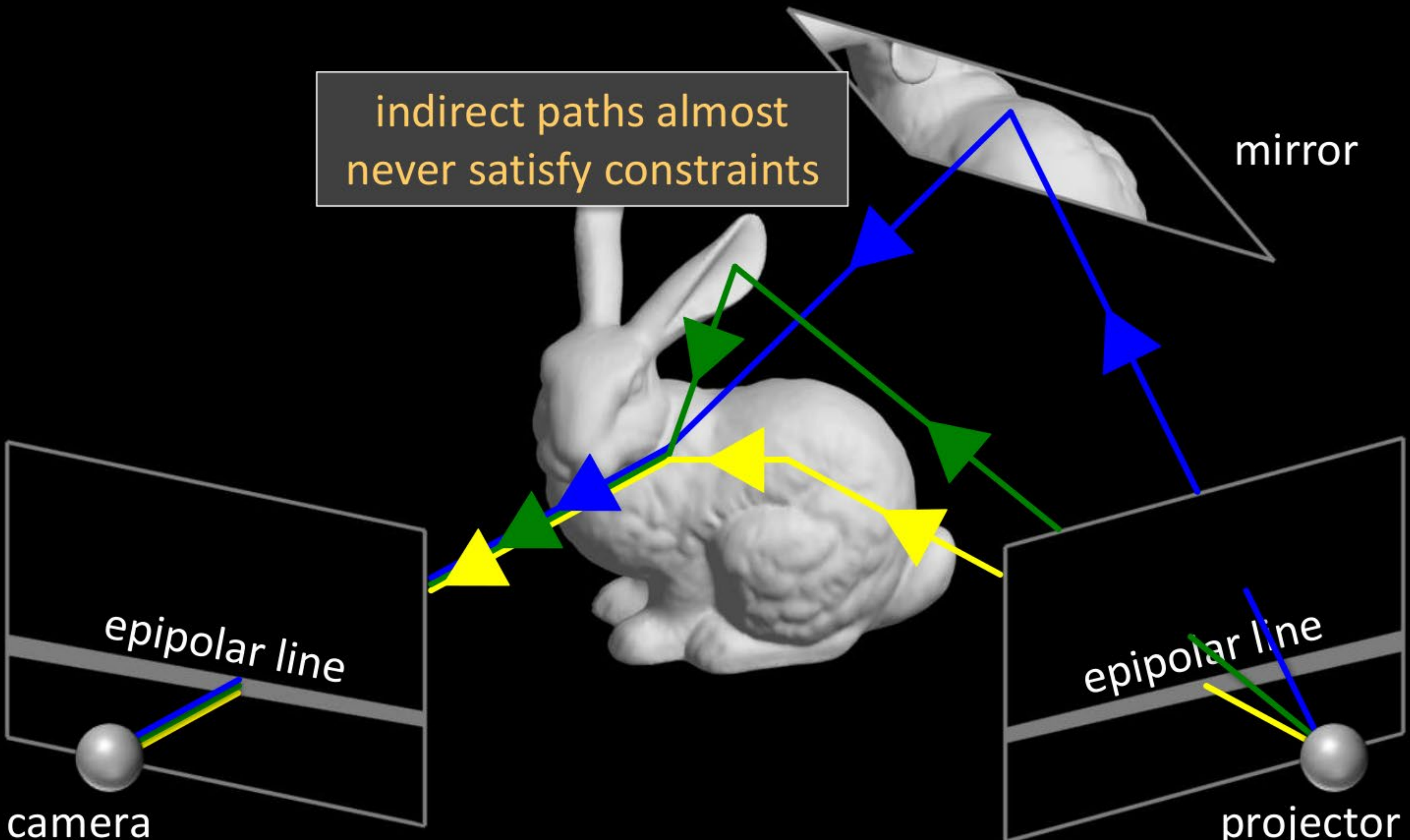
epipolar constraint & light transport



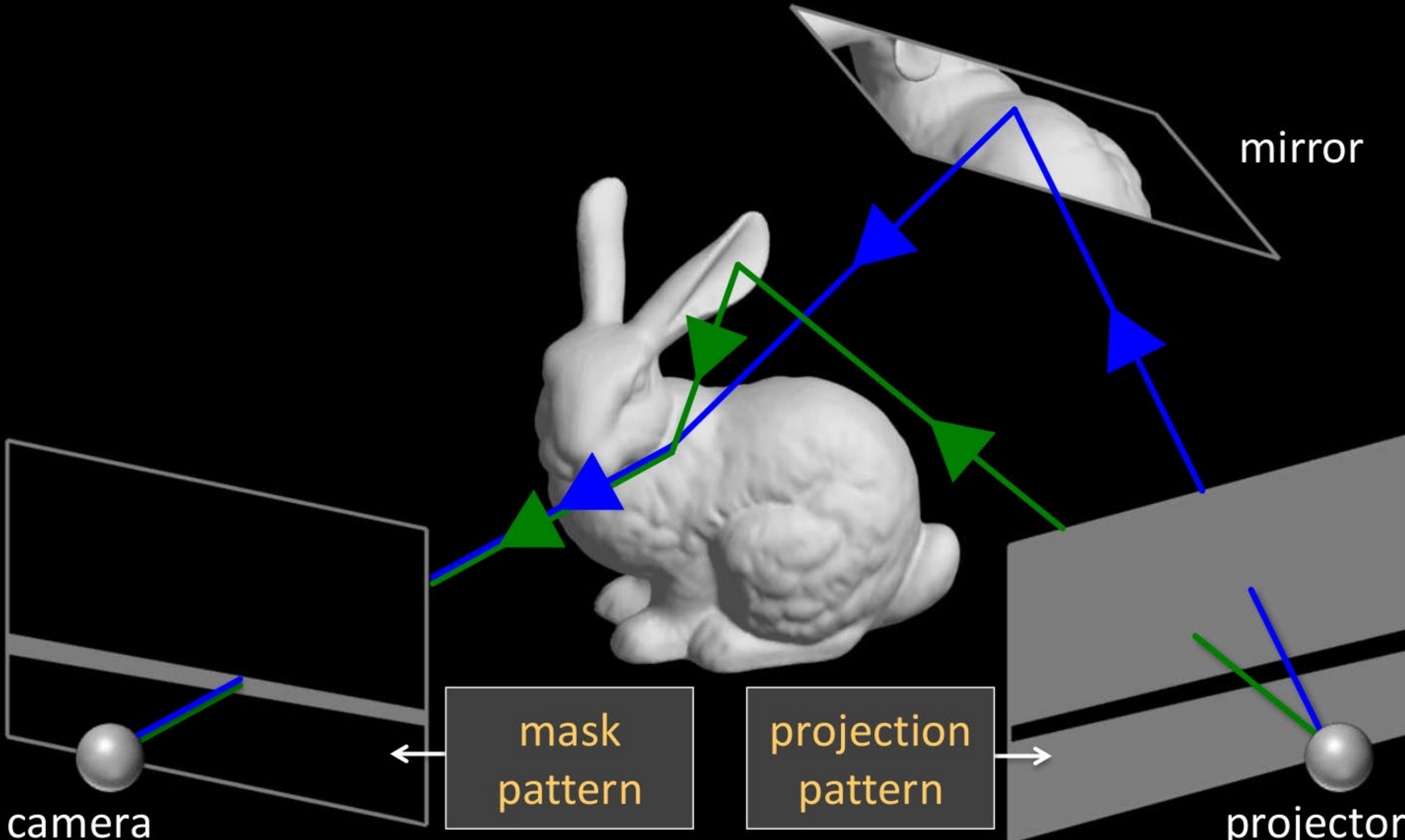
epipolar constraint & light transport



epipolar constraint & light transport

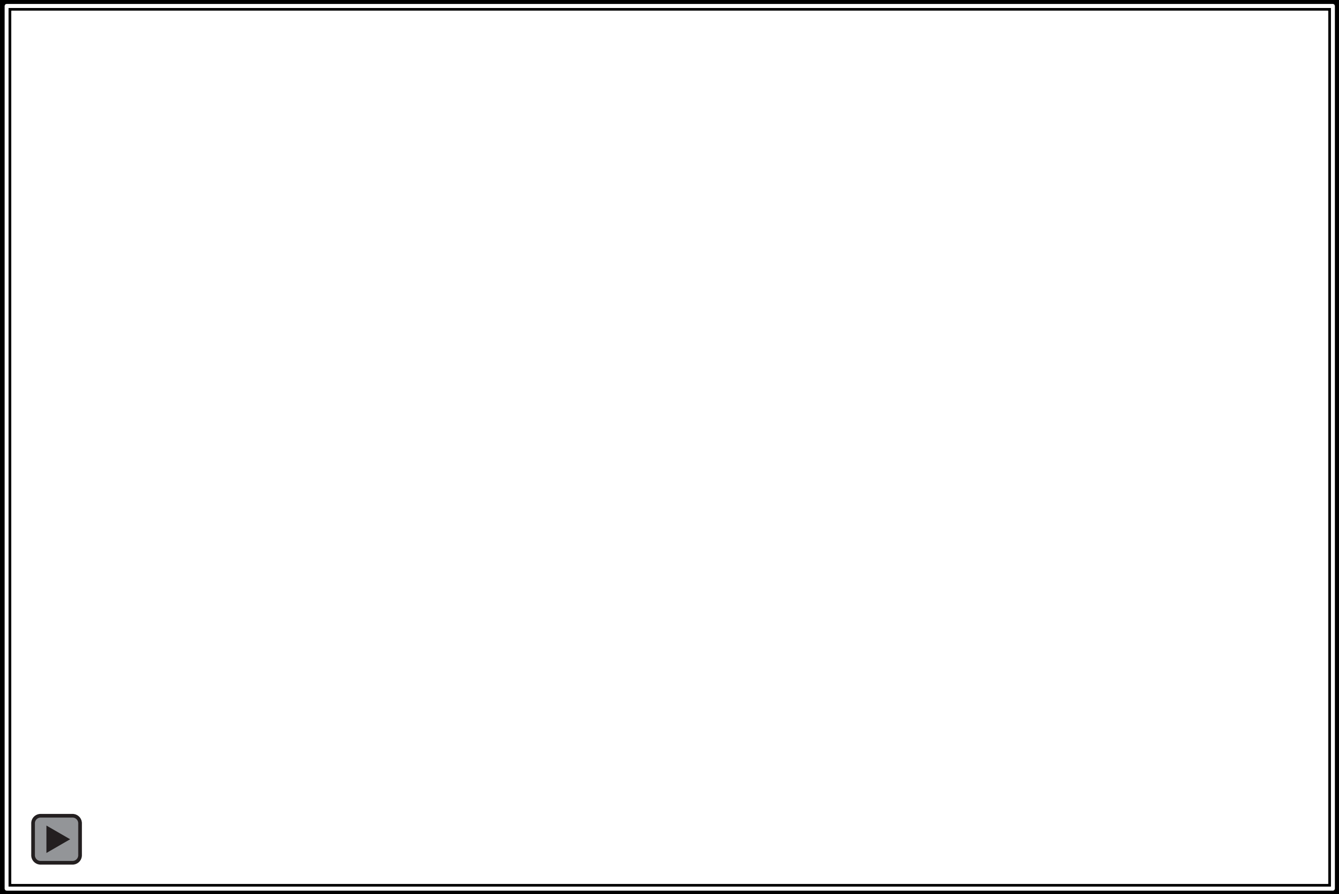


blocking epipolar paths with patterns & masks

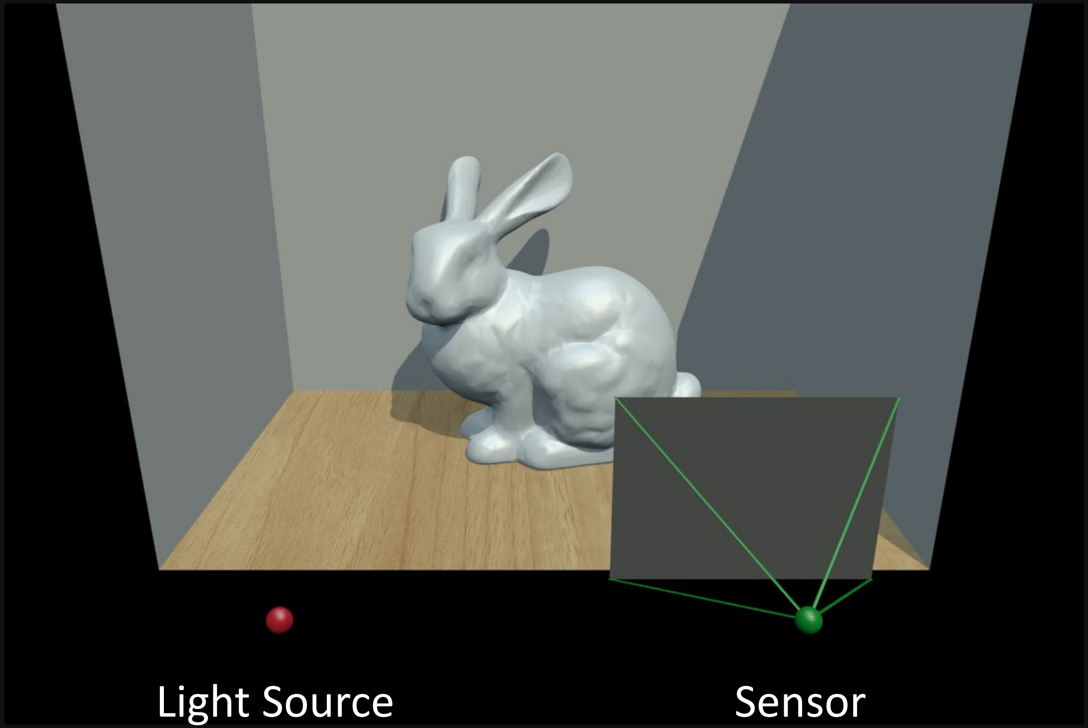


Energy-efficient epipolar imaging

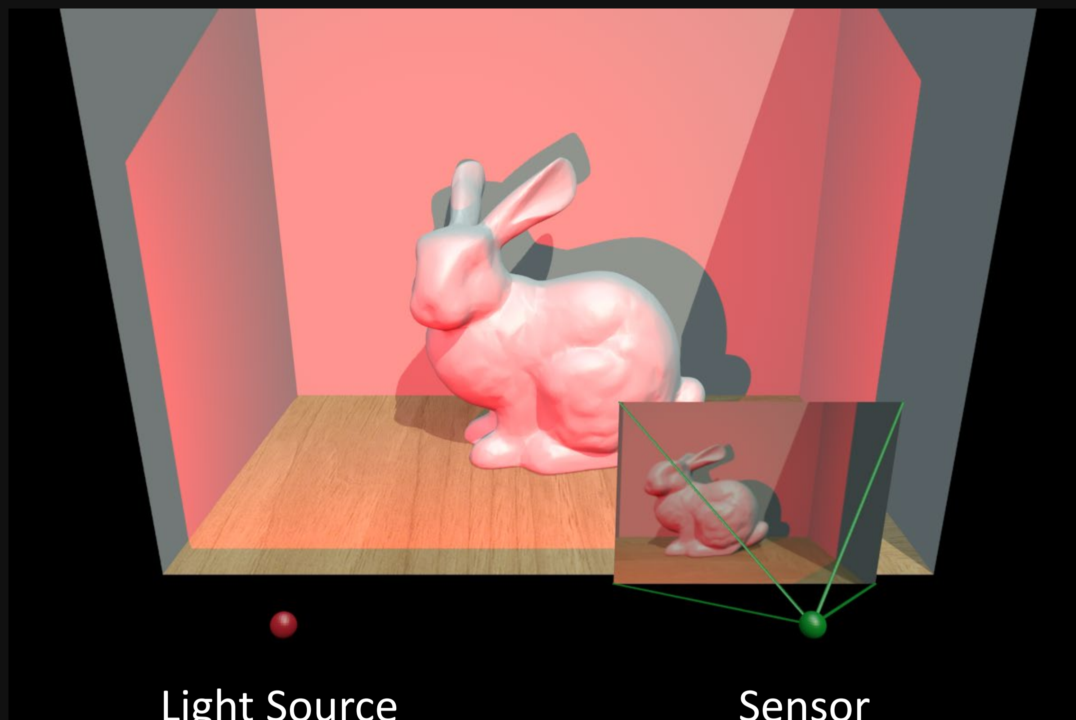
Energy-efficient transport parsing



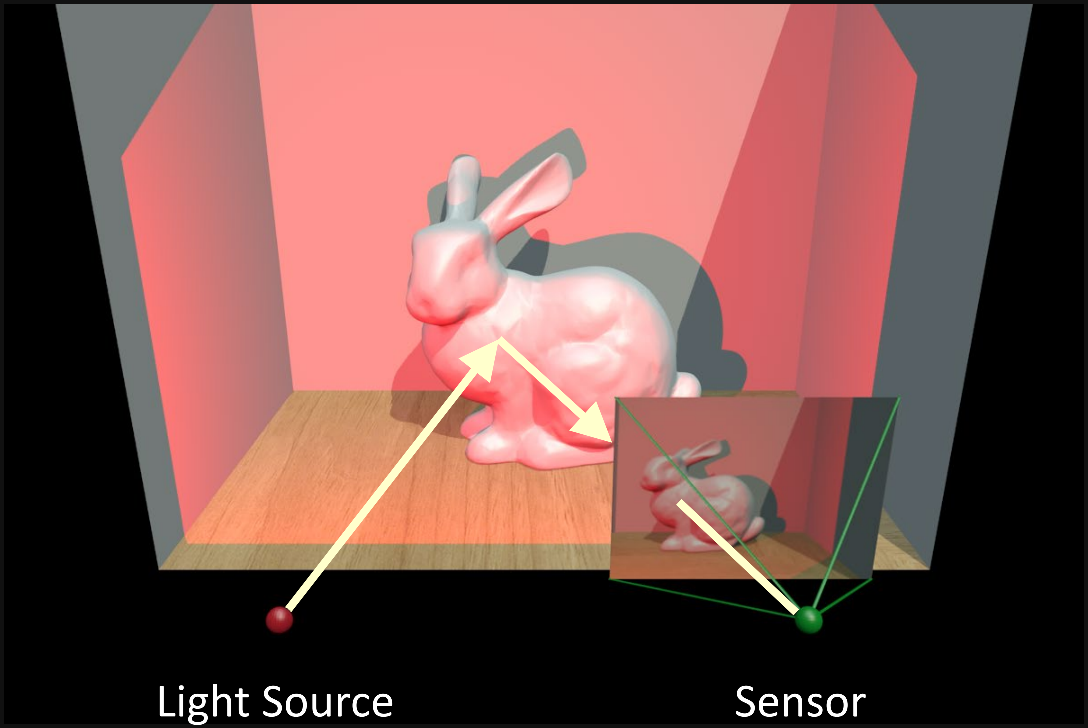
Regular Imaging



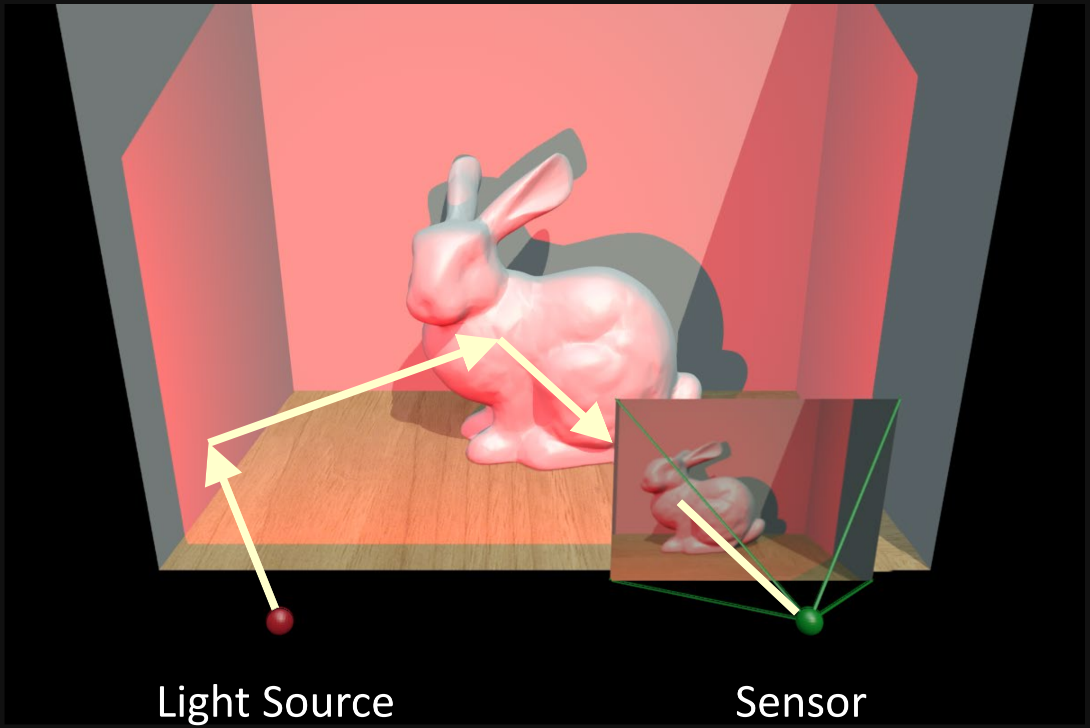
Regular Imaging



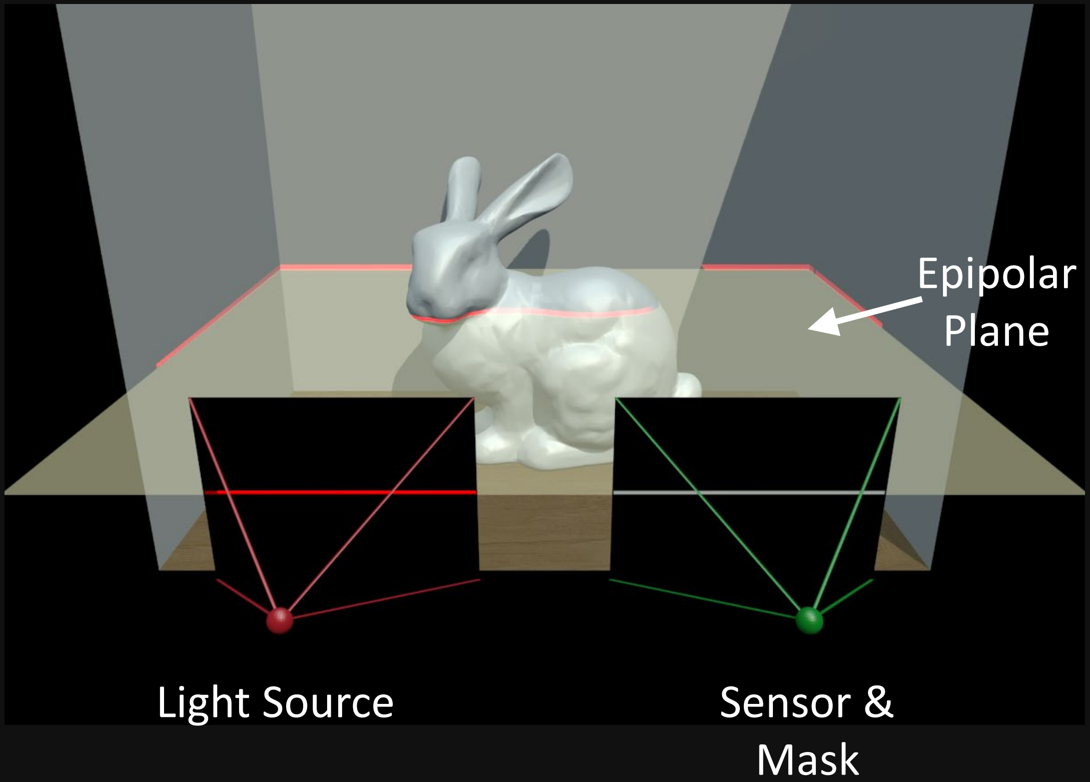
Regular Imaging



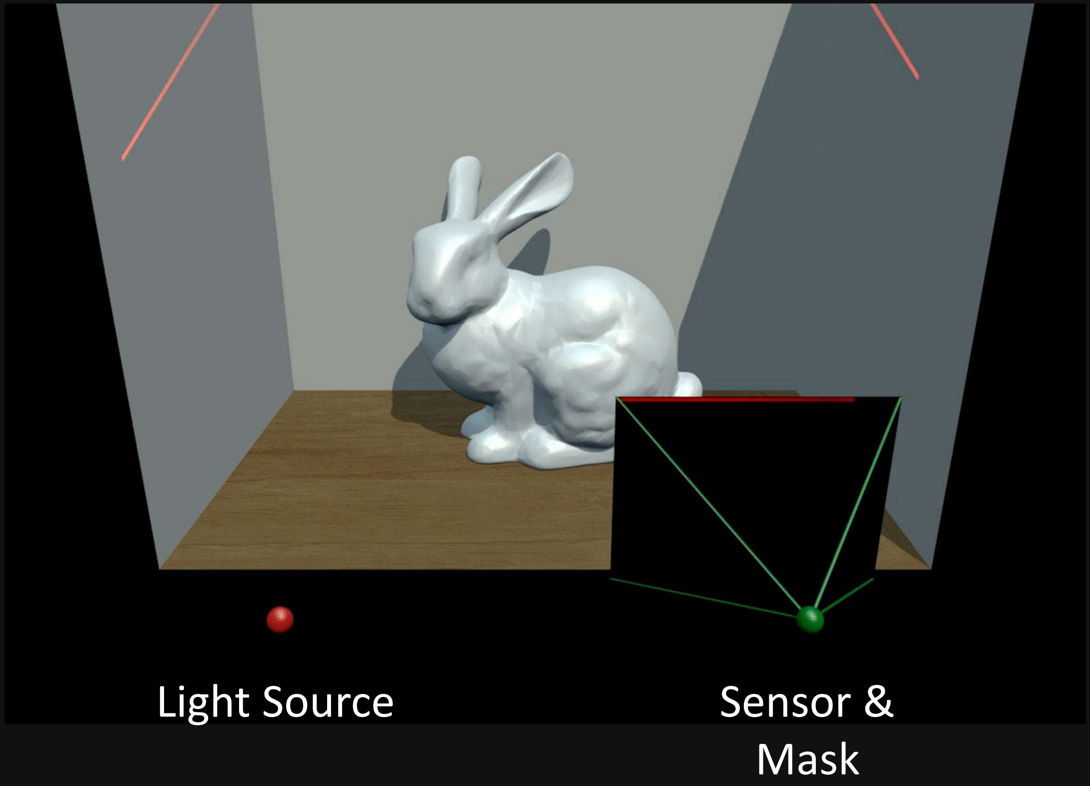
Regular Imaging



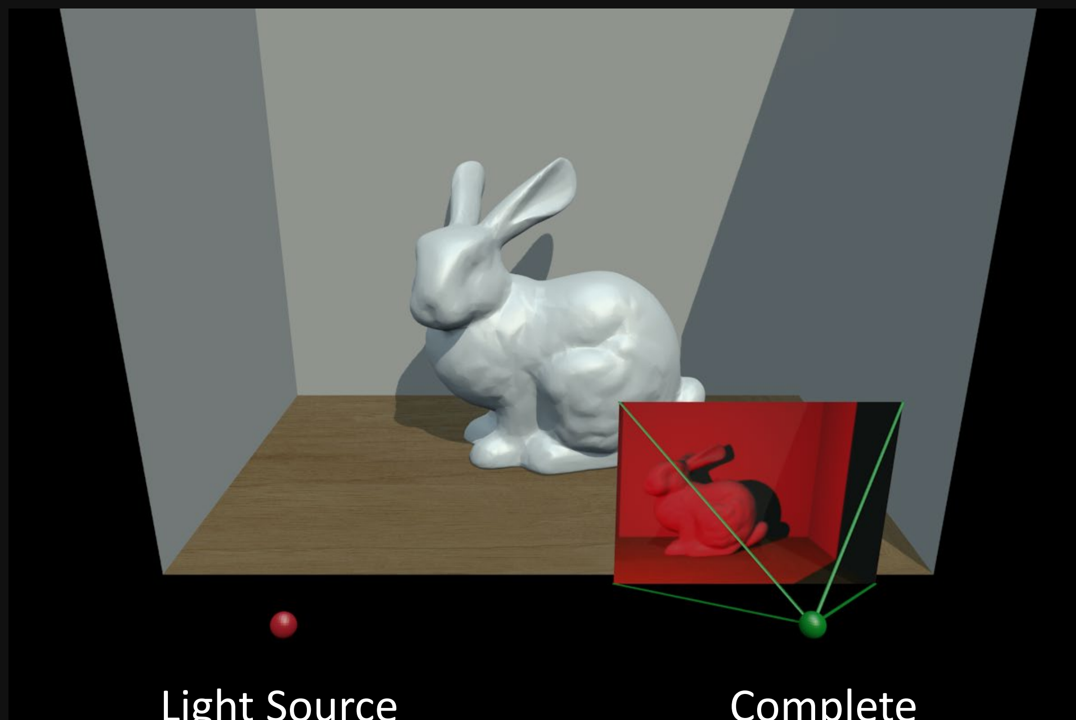
Epipolar Imaging



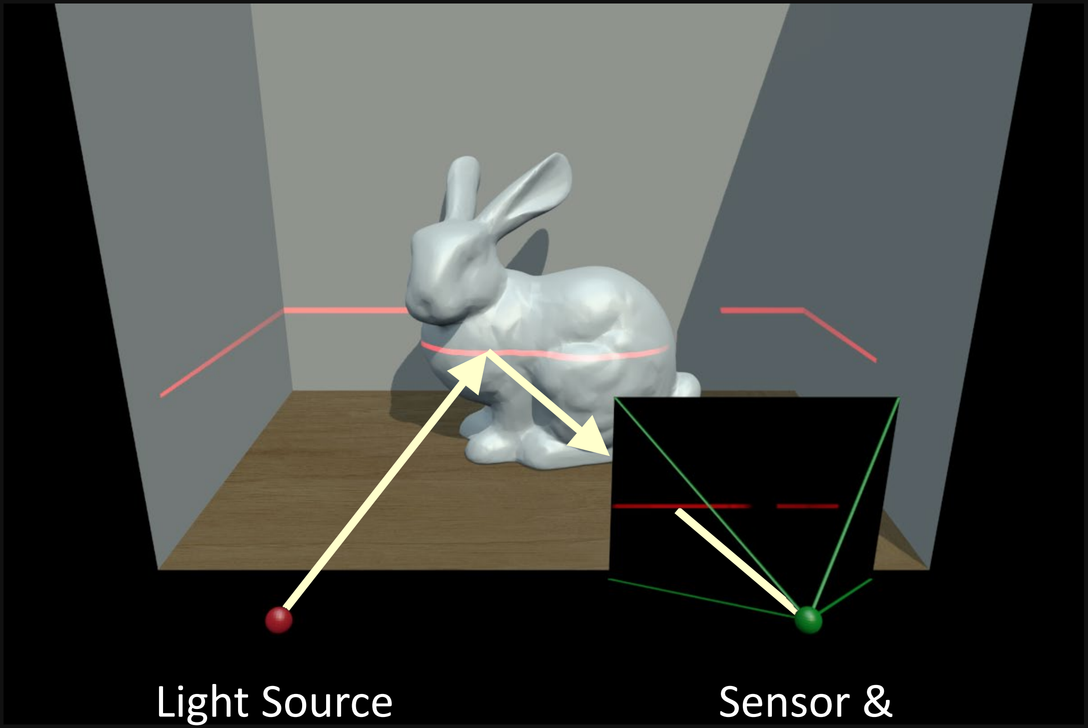
Epipolar Imaging



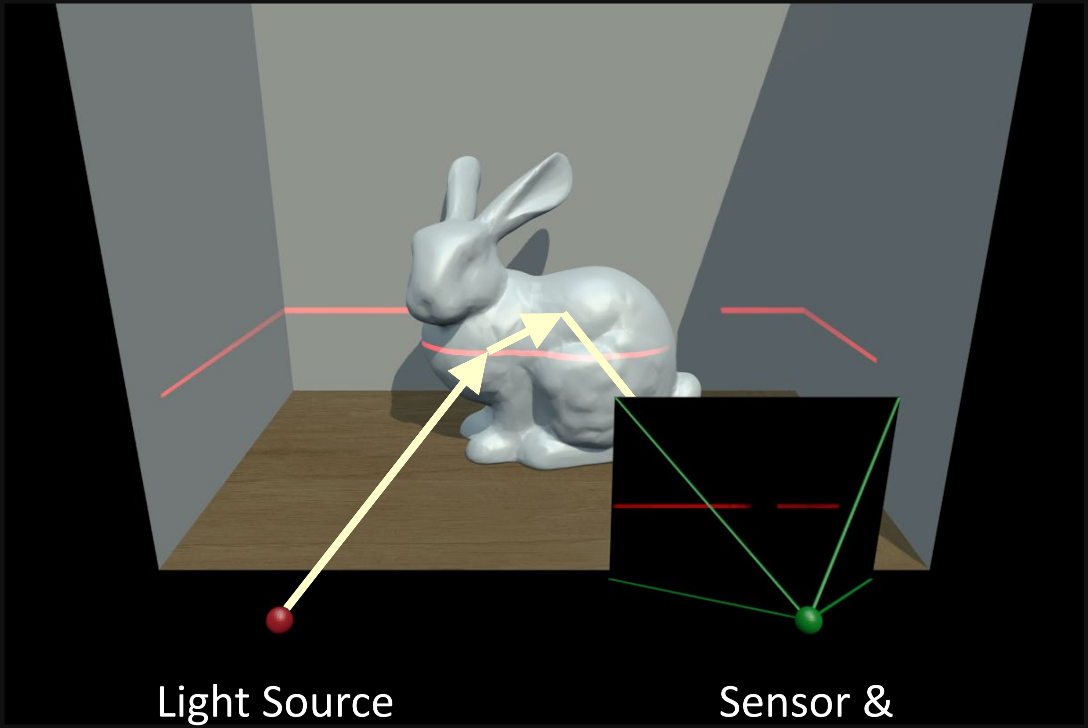
Epipolar Imaging



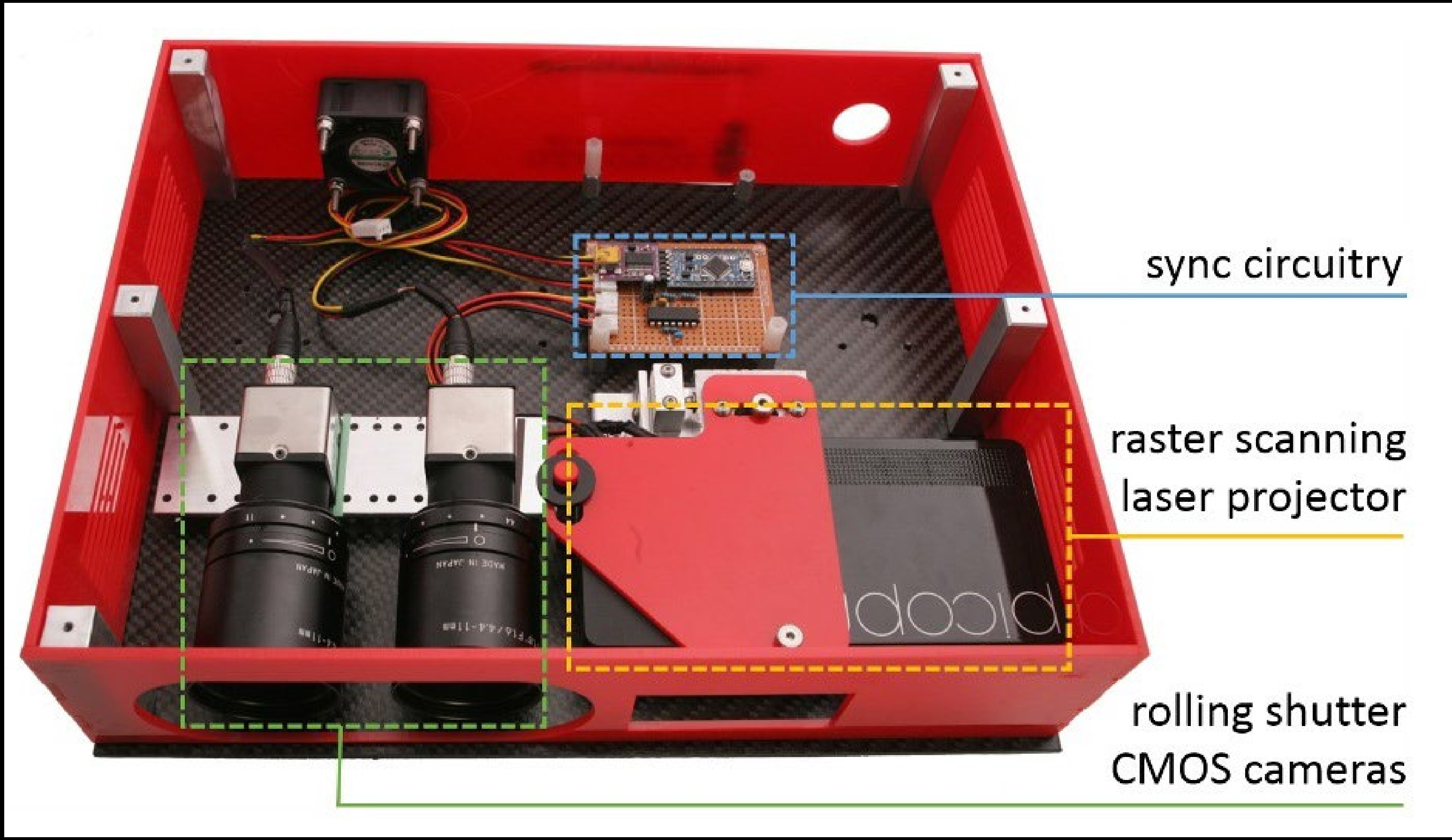
Epipolar Imaging



Epipolar Imaging



Energy-efficient transport parsing



all paths

planar (mostly direct)

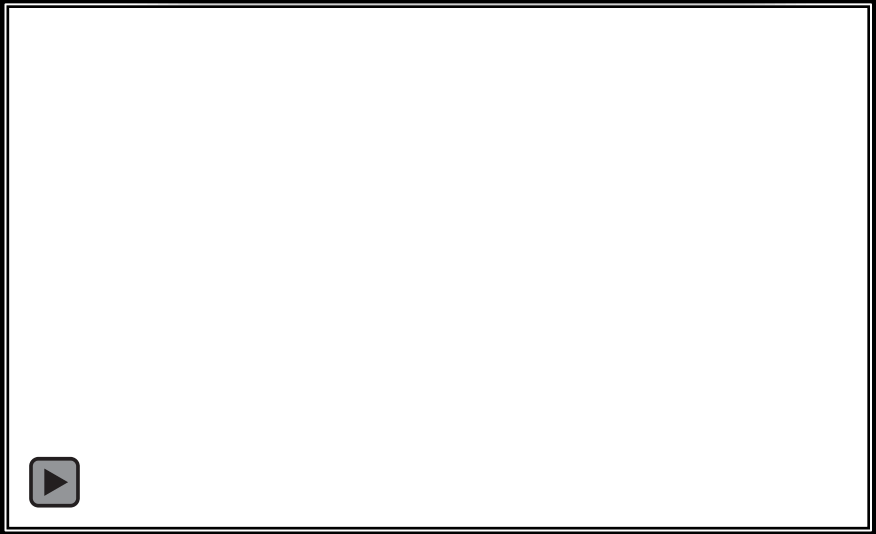
non-planar (always indirect)

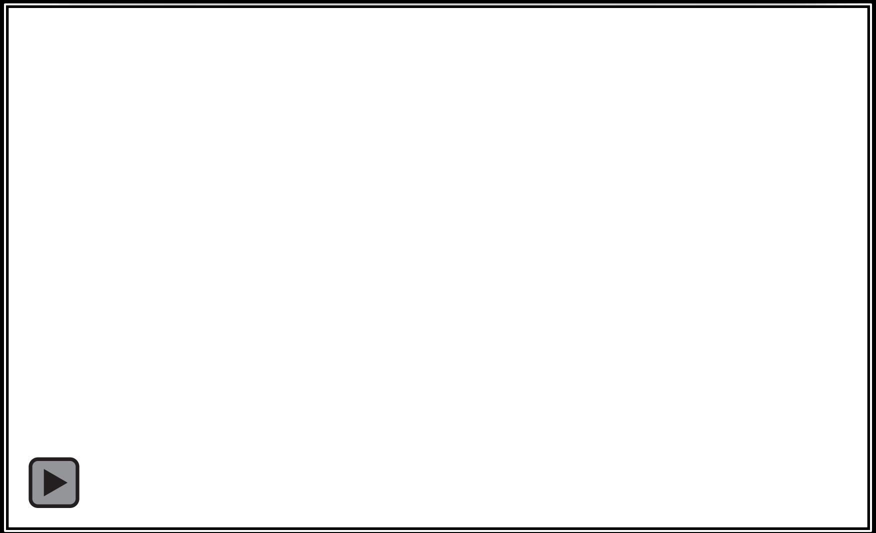
a great deal of indirect transport
occurs in many common LOS scenes

all paths

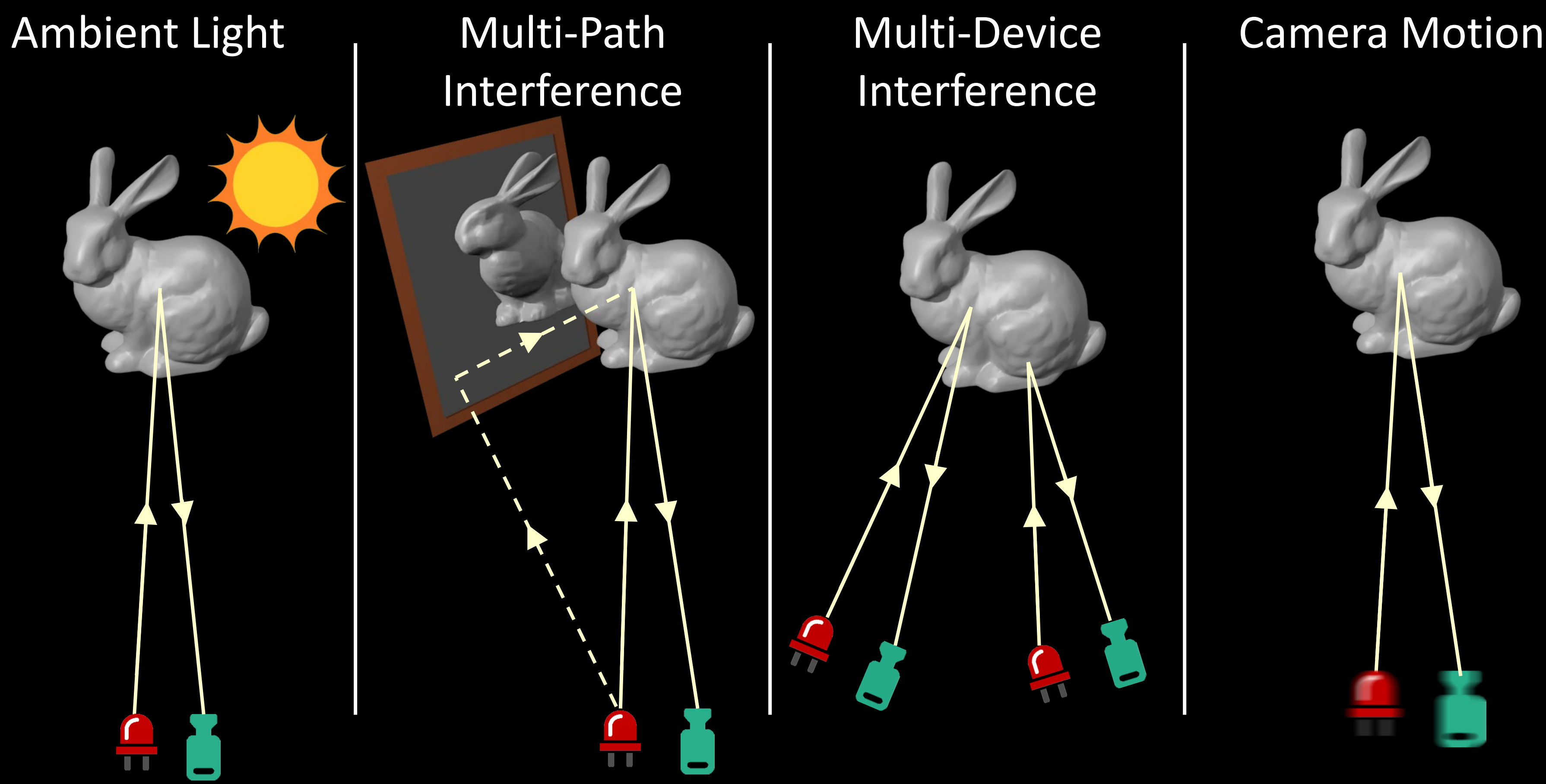
planar (mostly direct)

non-planar (always indirect)

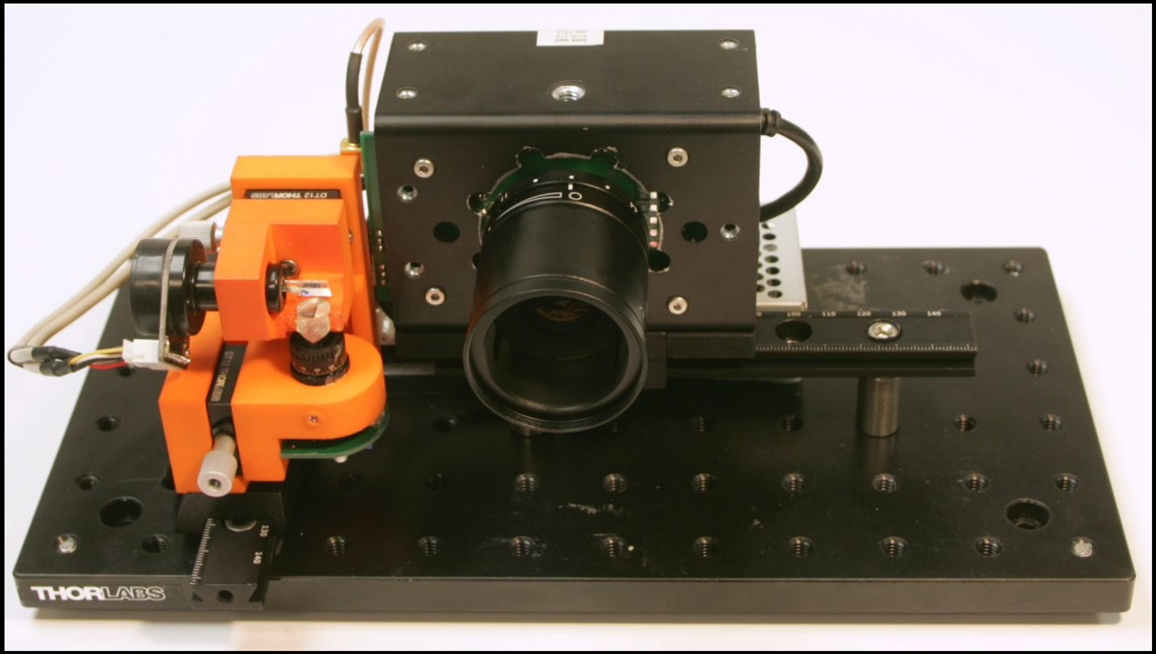




Benefits of Epipolar ToF Imaging

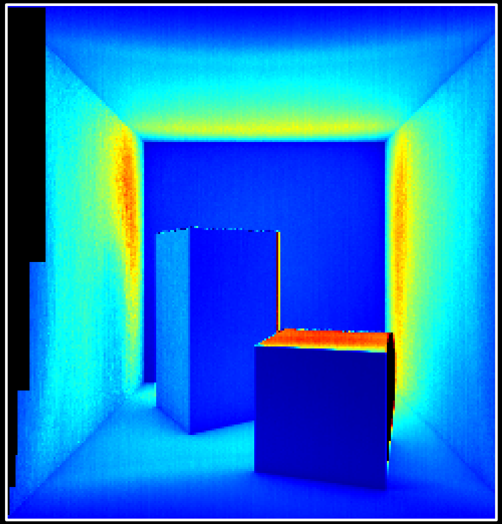


Epipolar ToF Prototype

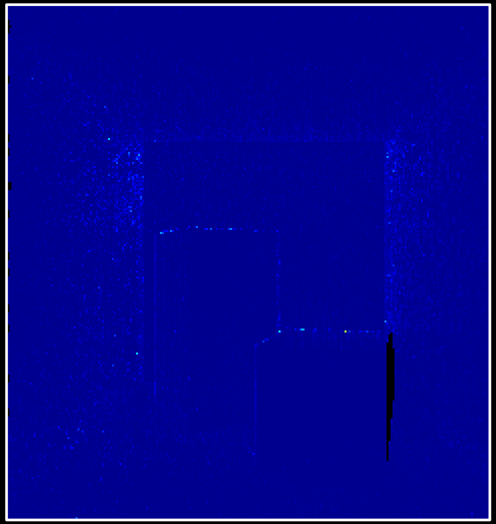


Epipolar ToF and Global Illumination

Depth Errors (in meters)



Regular ToF @ 30MHz



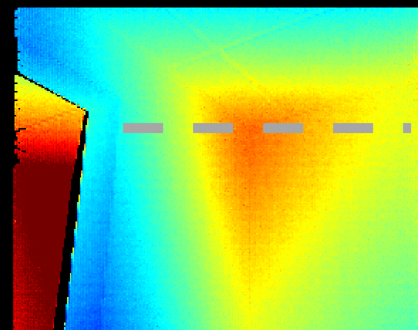
Epipolar ToF @ 30MHz

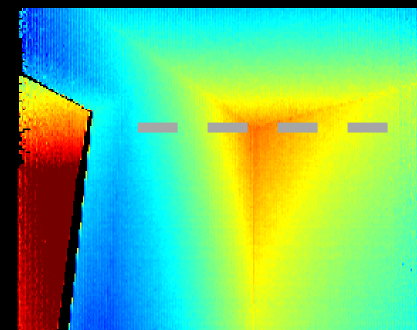
Epipolar ToF and Global Illumination

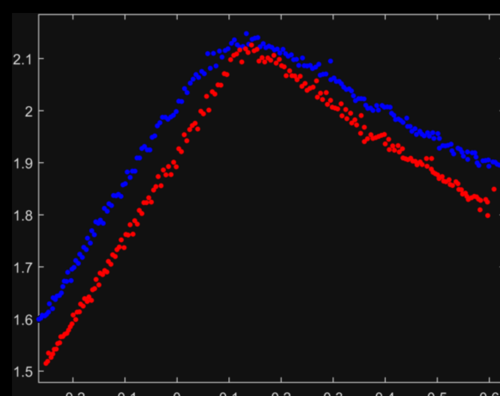
Regular ToF

Epipolar ToF

Corner of Room





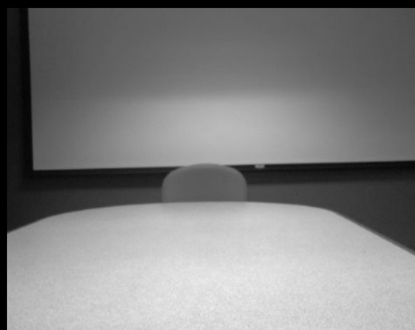


- Regular ToF
- Epipolar ToF

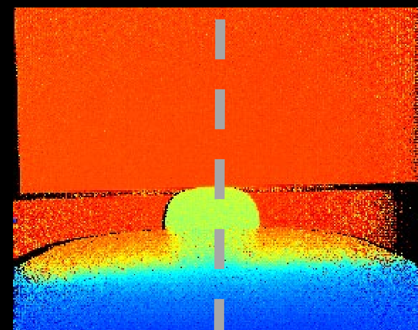
Epipolar ToF and Global Illumination

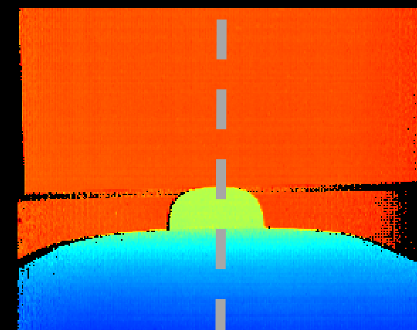
Regular ToF

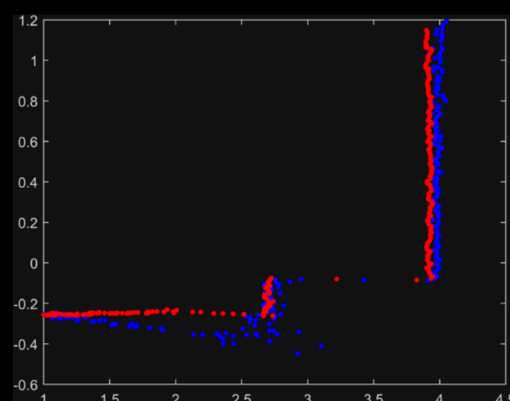
Epipolar ToF



Conference Room





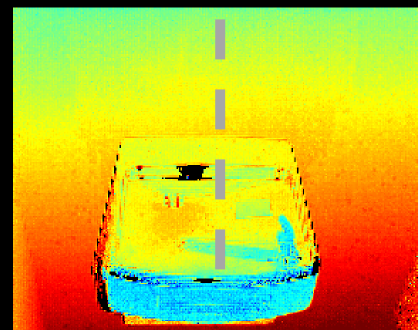


- Regular ToF
- Epipolar ToF

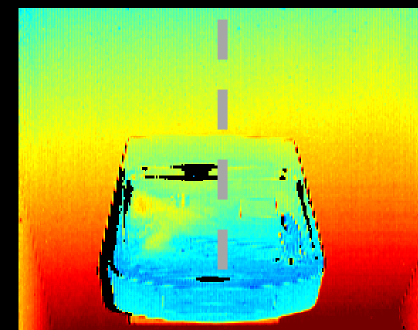
Epipolar ToF and Global Illumination

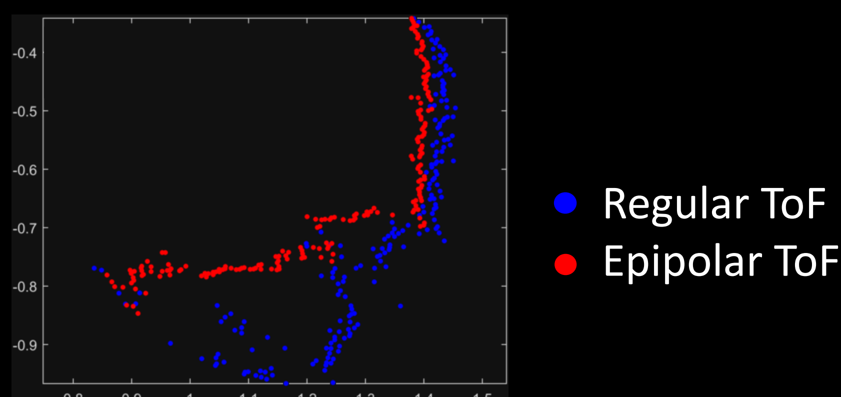
Water Fountain

Regular ToF



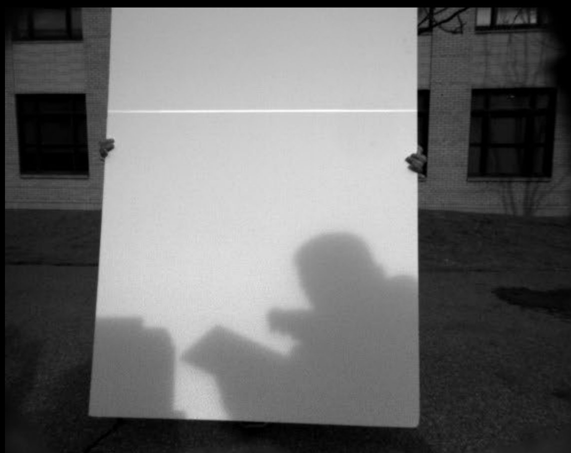
Epipolar ToF



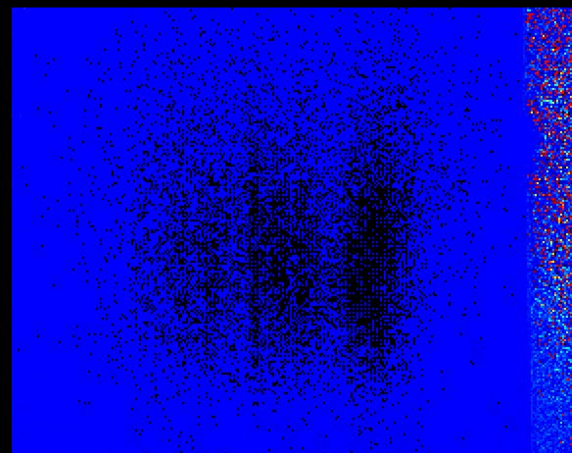


Outdoors (Cloudy – 10 kilolux)

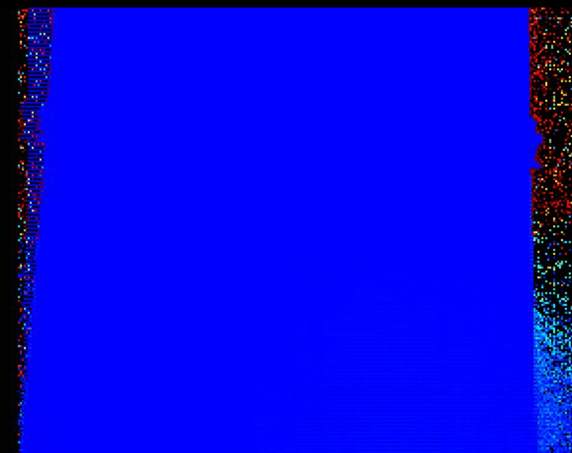
Scene



Regular ToF



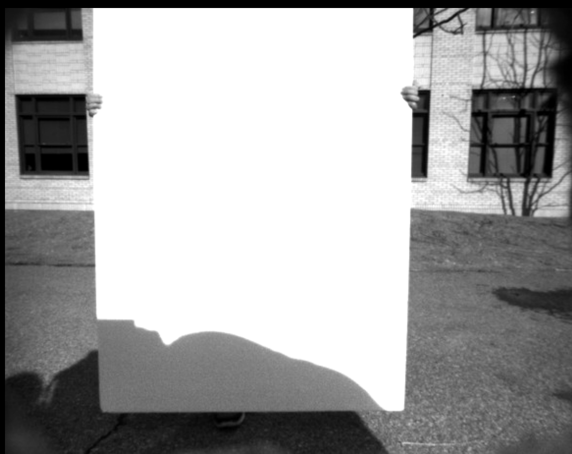
Epipolar ToF



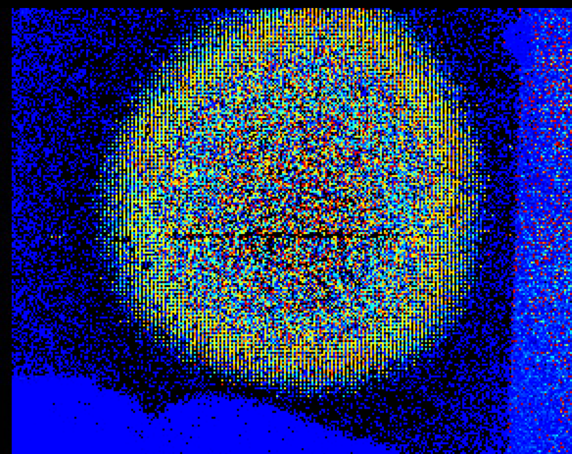
Depth (meters)

Outdoors (Sunny – 70 kilolux)

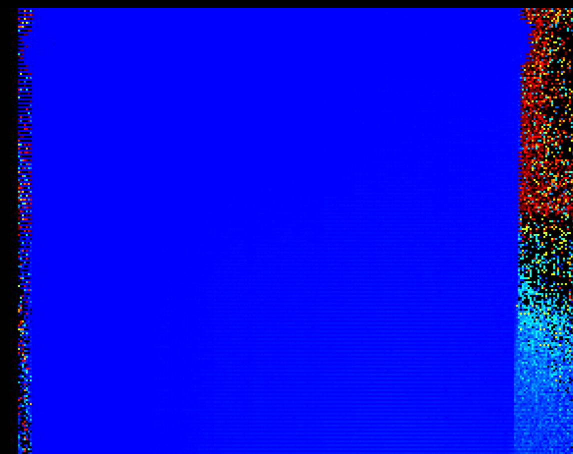
Scene

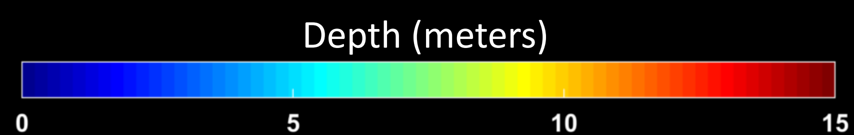


Regular ToF

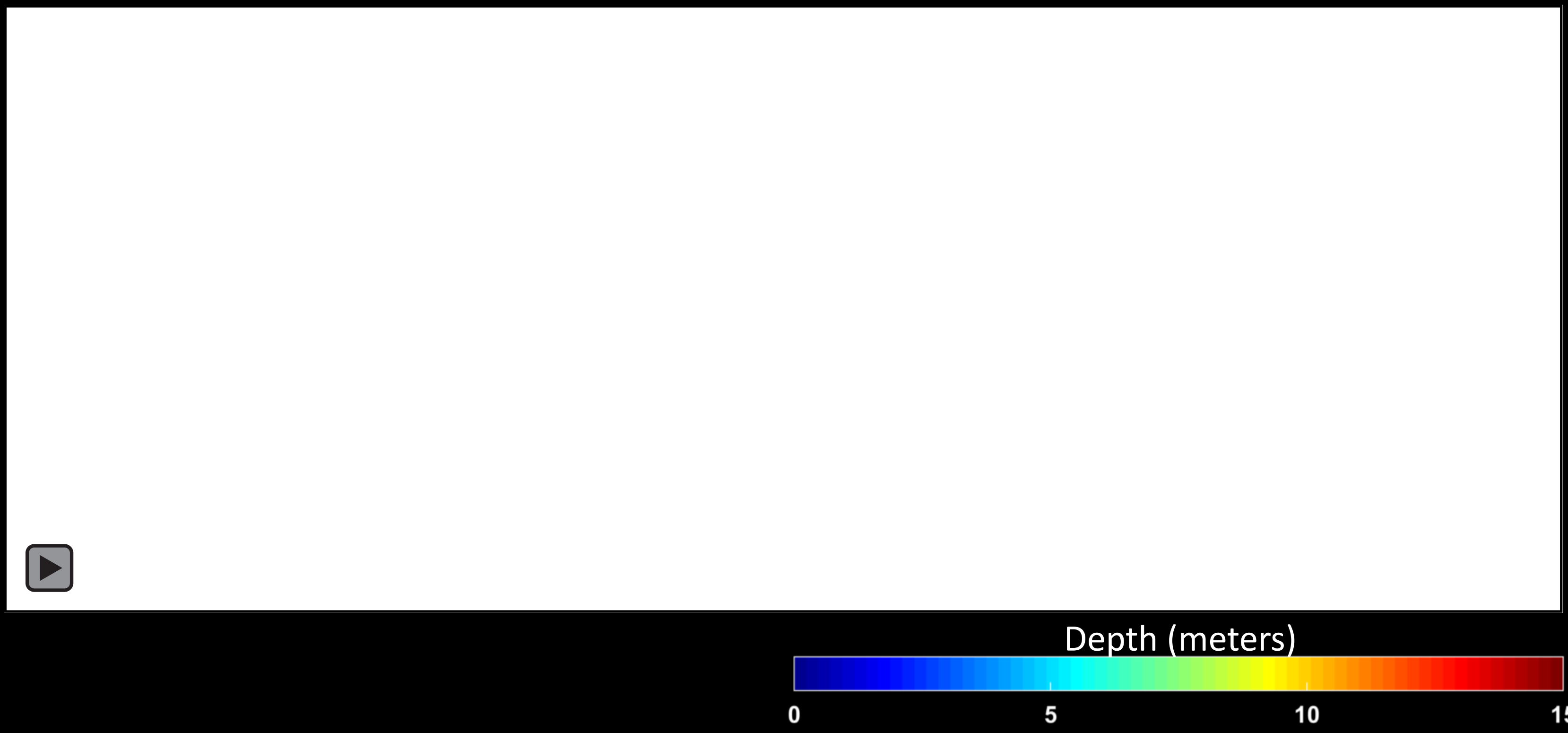


Epipolar ToF





Outdoors (Sunny – 70 kilolux)



References

Basic reading:

- Nayar et al., "Fast separation of direct and indirect components of a scene using high frequency illumination," SIGGRAPH 2004.
  The paper on separation of direct and indirect illumination using high-frequency illumination.
- Gupta et al., "A Practical Approach to 3D Scanning in the Presence of Interreflections, Subsurface Scattering and Defocus," IJCV 2013.
  The paper on using XOR codes to deal with indirect illumination in structured light 3D.
- Gupta et al., "Phasor imaging: A generalization of correlation-based time-of-flight imaging," TOG 2015.
  The paper on using high-frequency modulation to deal with interreflections and MPI in CW-ToF imaging.
- O'Toole et al., "Primal-dual coding to probe light transport," SIGGRAPH 2012.
- O'Toole et al., "3d shape and indirect appearance by structured light transport," CVPR 2014.
  These two papers introduce the concepts of light transport probing and epipolar probing, as well as explain how to use primal-dual coding to achieve them.
- O'Toole et al., "Homogeneous codes for energy-efficient illumination and imaging," SIGGRAPH 2015.
  This paper shows how to efficiently implement epipolar imaging with a simple projector and camera.
- Achar et al., "Epipolar time-of-flight imaging," SIGGRAPH 2017.
  This paper combines epipolar imaging and time-of-flight imaging.

Additional reading:

- Seitz et al., "A theory of inverse light transport," ICCV 2005.
  This early paper shows a way to *exactly* decompose light transport by number of bounces, under certain assumptions for the imaged scene.
- Chandraker et al., "On the duality of forward and inverse light transport," PAMI 2011.
- Reddy et al., "Frequency-space decomposition and acquisition of light transport under spatially varying illumination," ECCV 2012.
  These two papers have additional analysis about the relationship between direct and indirect illumination and illumination frequency.
- Durand et al., "A frequency analysis of light transport," SIGGRAPH 2005.
  This paper more formally discusses the notion of light transport frequency, and the frequency characteristics of different light transport effects (specular versus diffuse reflections, hard versus smooth shadows).