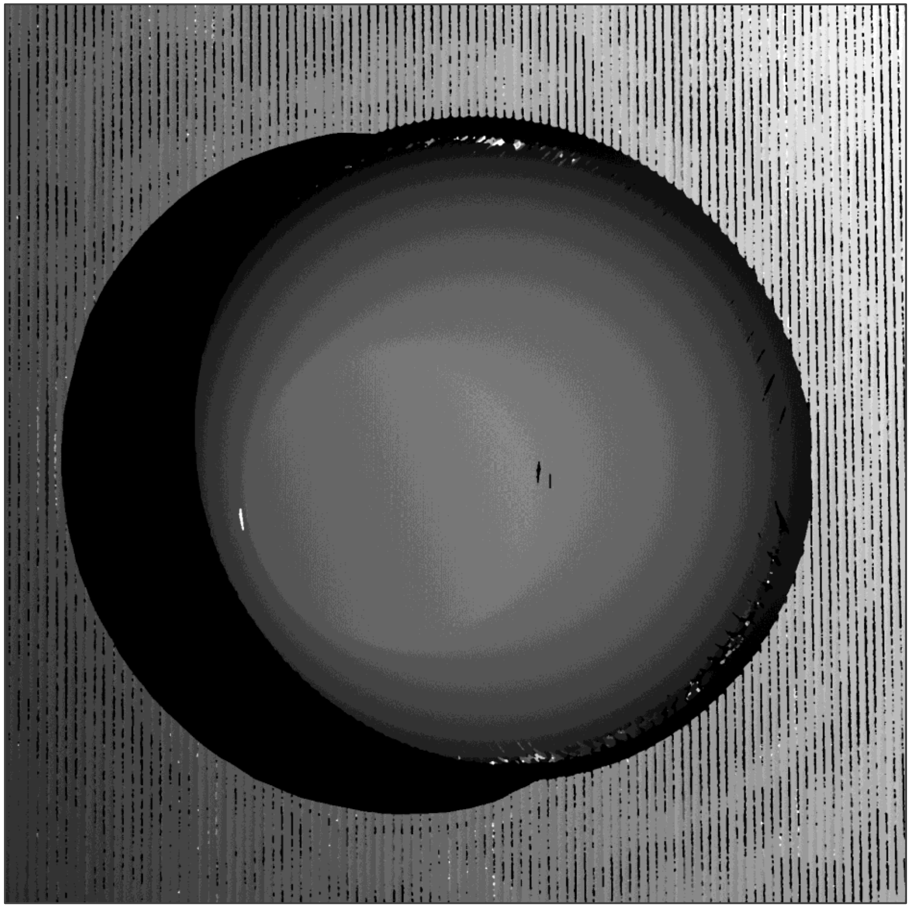
Structured light



15-463, 15-663, 15-862
Computational Photography
Fall 2017, Lecture 27

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

Course announcements

- Homework 5 has been graded.
  - Mean: 129.
  - Median: 150.

- Any questions about homework 6?

- Extra office hours this Wednesday, 3-5pm.

- Make sure to take the faculty course evaluation and the end-of-semester class survey.

Overview of today's lecture

- Stereo and triangulation.
- Structured light.
- Binary coding.
- Using shadows.
- The 3D scanning pipeline.
- Dealing with global illumination.

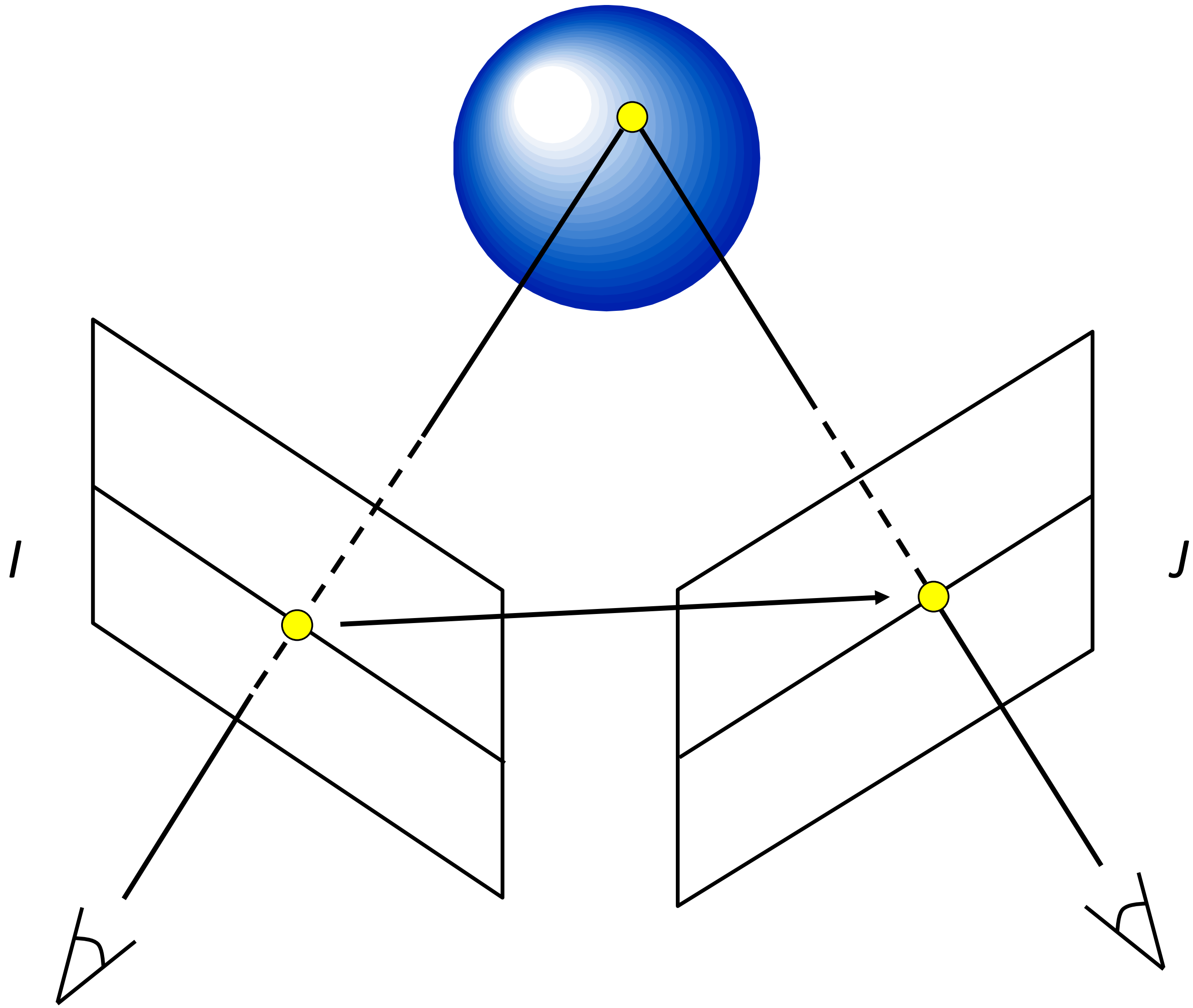
Slide credits

Most of these slides were directly adapted from:

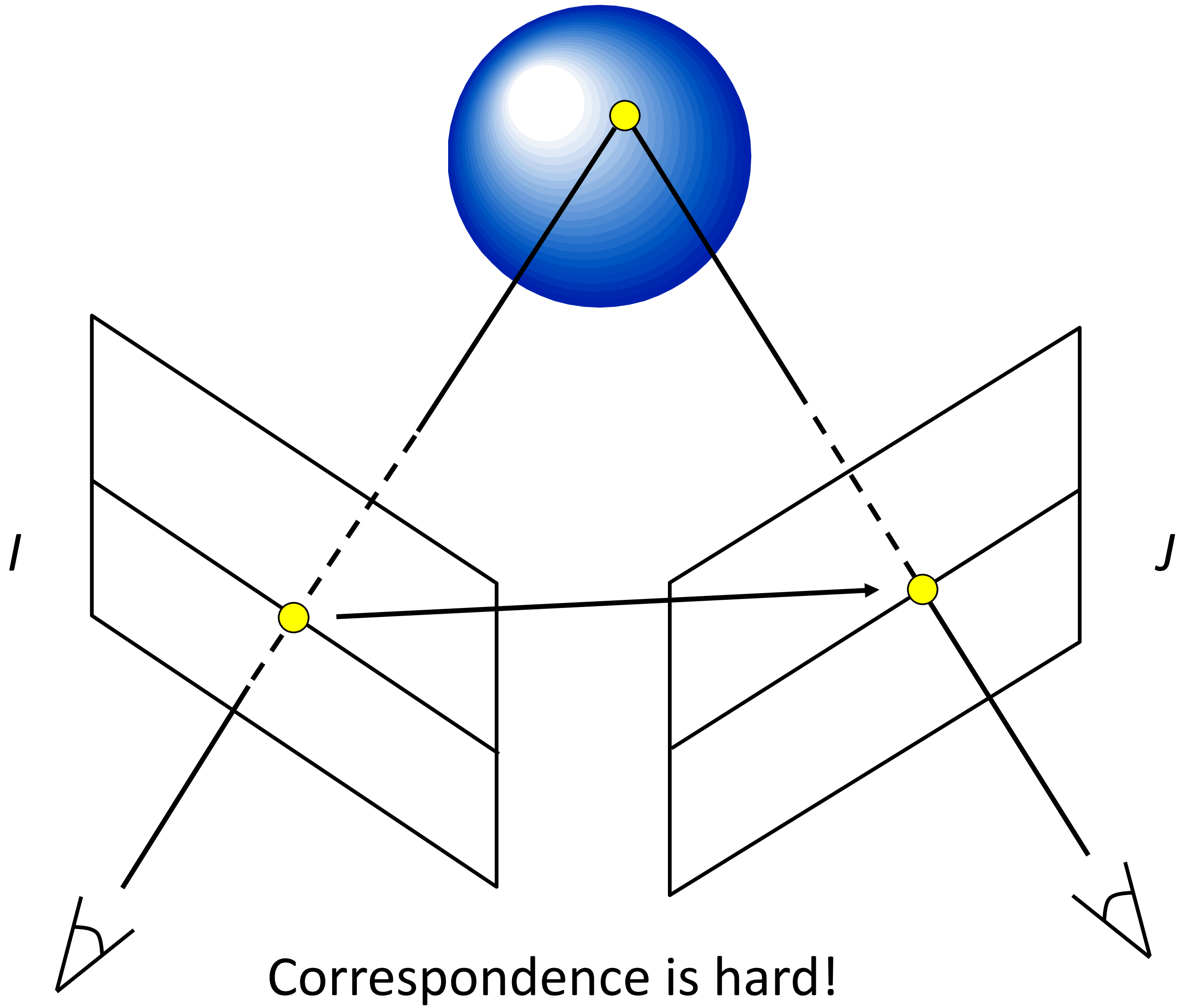
- Srinivasa Narasimhan (CMU).
- Mohit Gupta (Wisconsin).

Stereo and triangulation

Stereo Triangulation



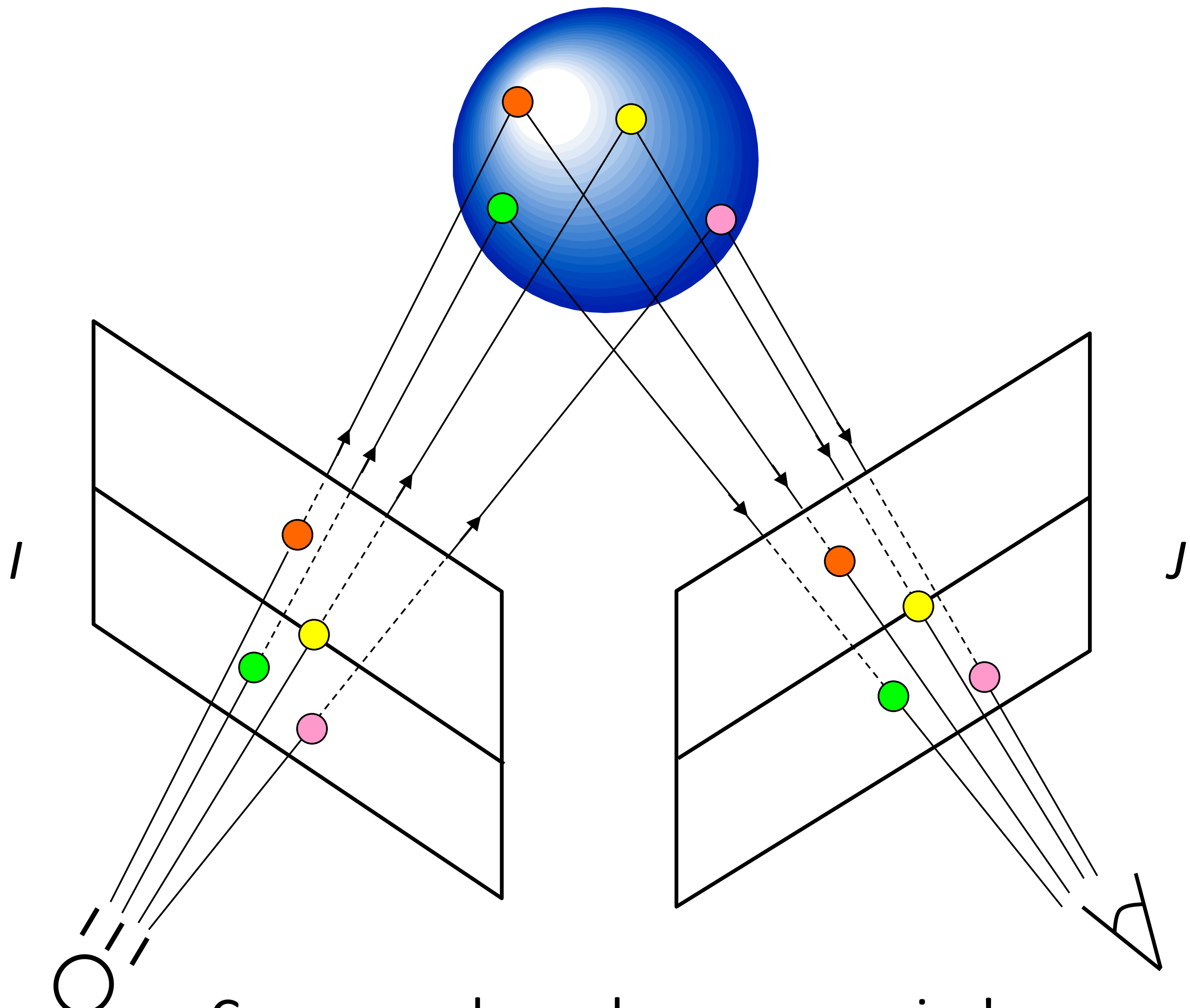
Stereo Triangulation



Correspondence is hard!

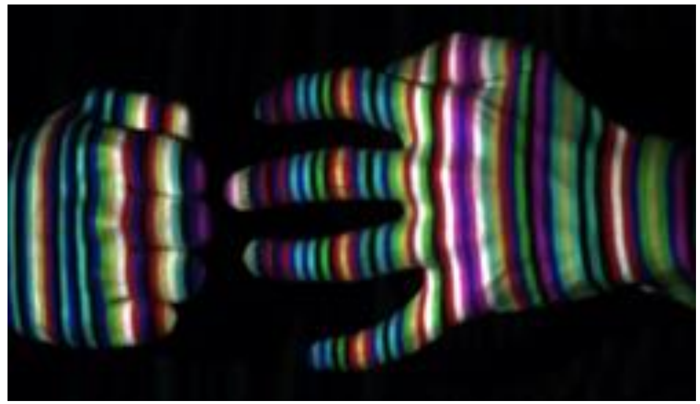
Structured light

Structured Light Triangulation



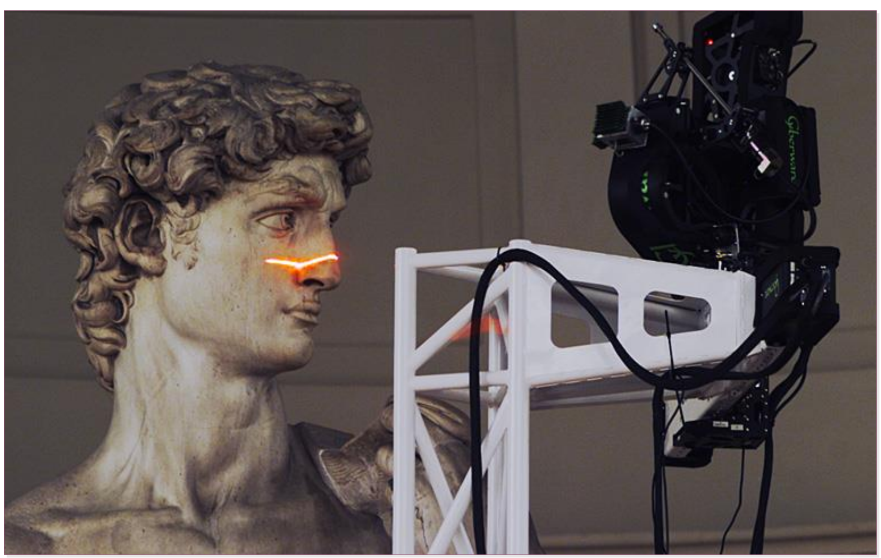
Correspondence becomes easier!

Structured Light

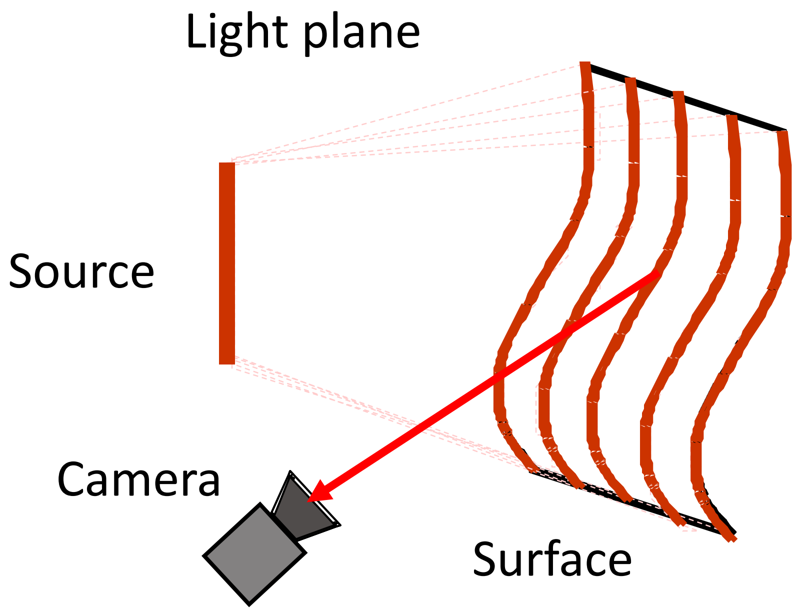




- Any spatio-temporal pattern of light projected on a surface (or volume).
- Cleverly illuminate the scene to extract scene properties (eg., 3D).
- Avoids problems of 3D estimation in scenes with complex texture/BRDFs.
- Very popular in vision and successful in industrial applications (parts assembly, inspection, etc).

3D Scanning using structured light

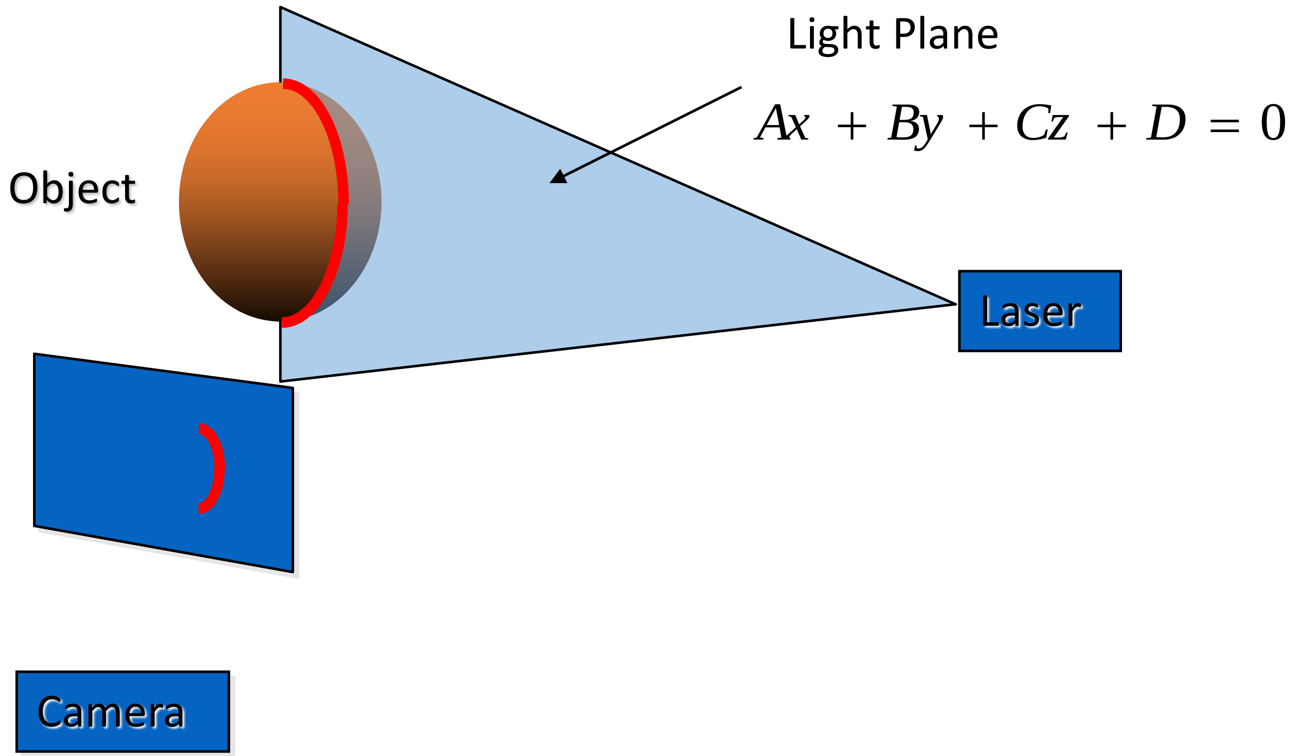


Light Stripe Scanning – Single Stripe



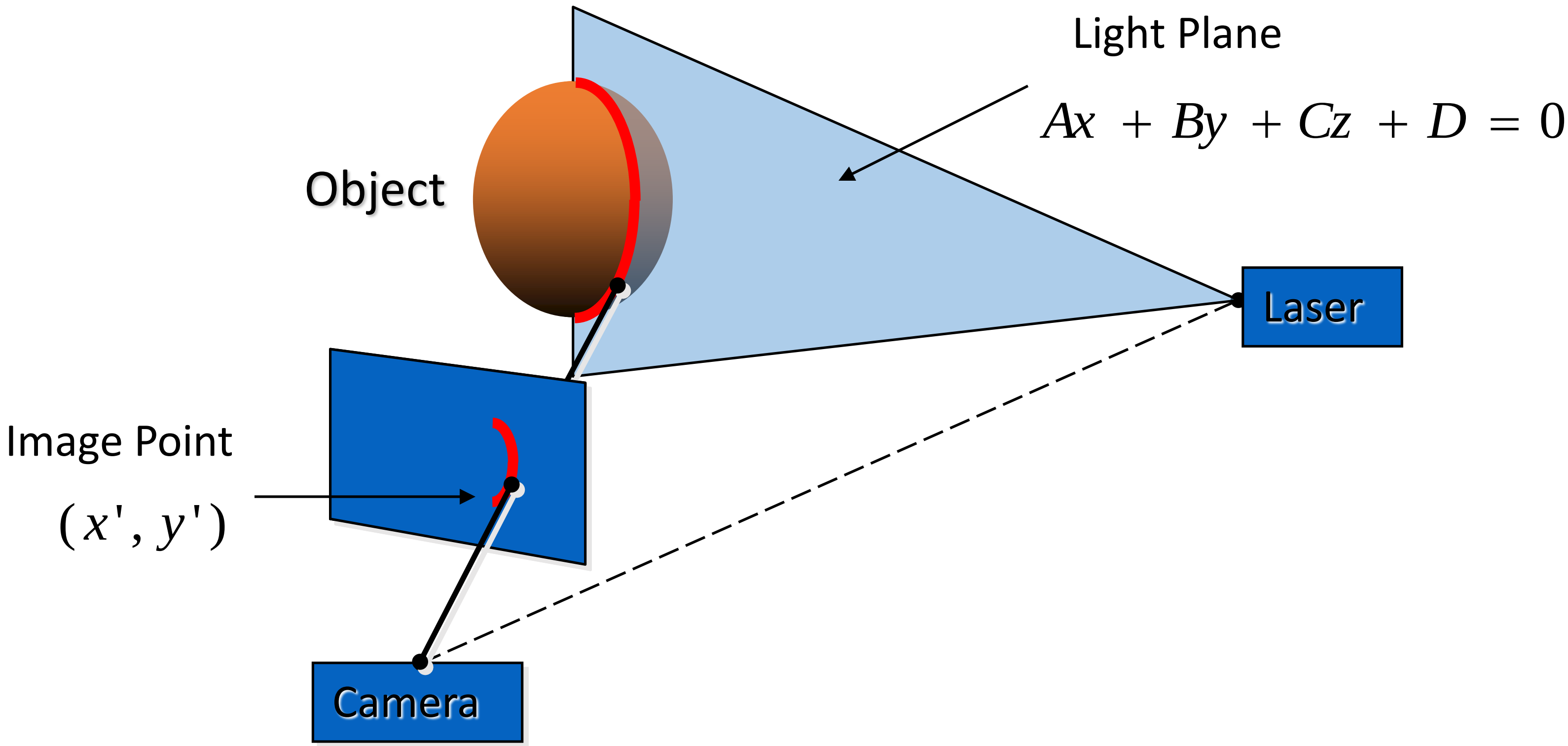
- Optical triangulation
  - Project a single stripe of laser light
  - Scan it across the surface of the object
  - This is a very precise version of structured light scanning
  - Good for high resolution 3D, but needs many images and takes time

Triangulation



- Project laser stripe onto object

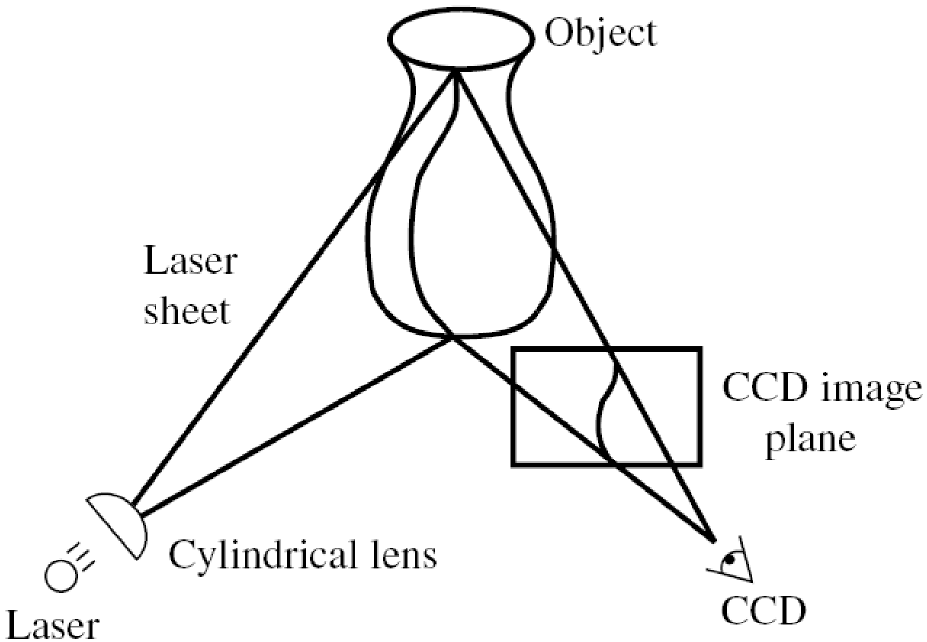
Triangulation



- Depth from ray-plane triangulation:
  - Intersect camera ray with light plane

$$x = x'z/f \qquad y = y'z/f \qquad z = \frac{-Df}{Ax' + By' + Cf}$$

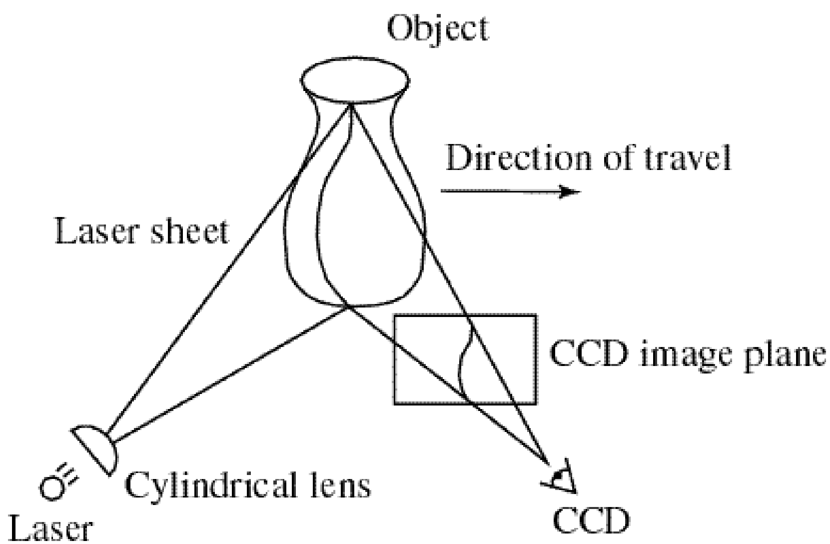
Example: Laser scanner

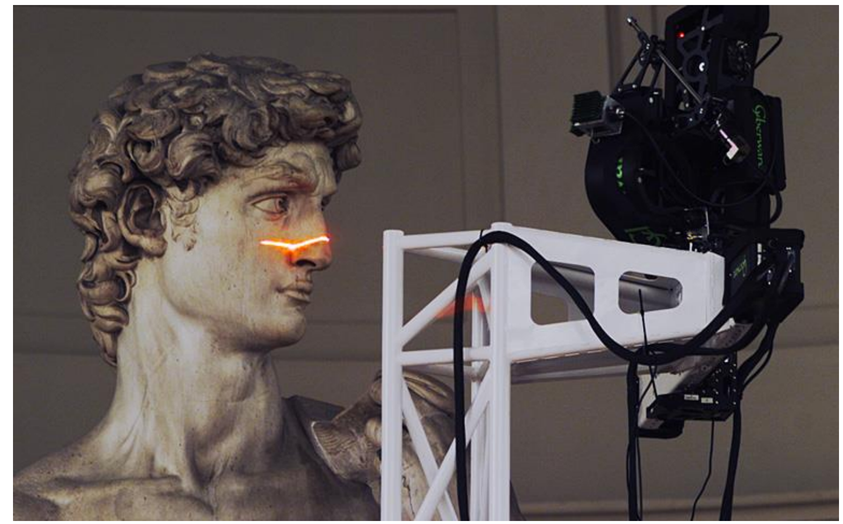


Cyberware® face and head scanner

+ very accurate < 0.01 mm
− more than 10sec per scan

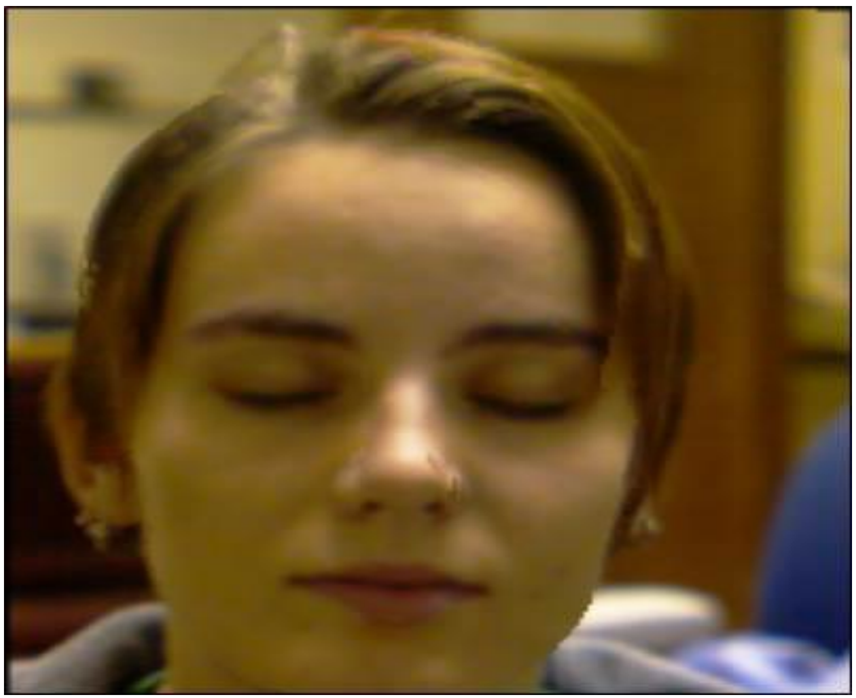
Example: Laser scanner





Digital Michelangelo Project
http://graphics.stanford.edu/projects/mich/

Portable 3D laser scanner (this one by Minolta)



Binary coding

Faster Acquisition?

Faster Acquisition?

- Project multiple stripes simultaneously
- Correspondence problem: which stripe is which?

- Common types of patterns:
  - Binary coded light striping
  - Gray/color coded light striping

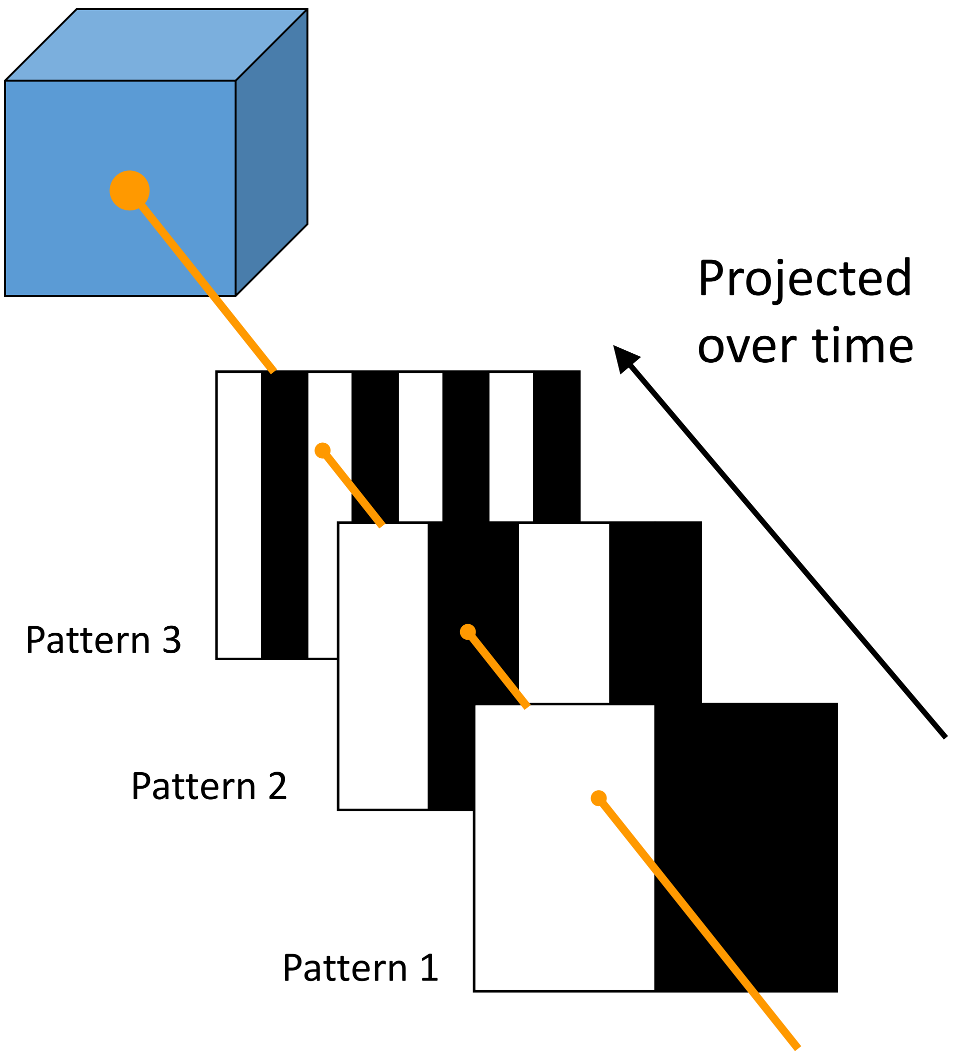
Binary Coding

Faster:

$2^n - 1$ stripes in n images.

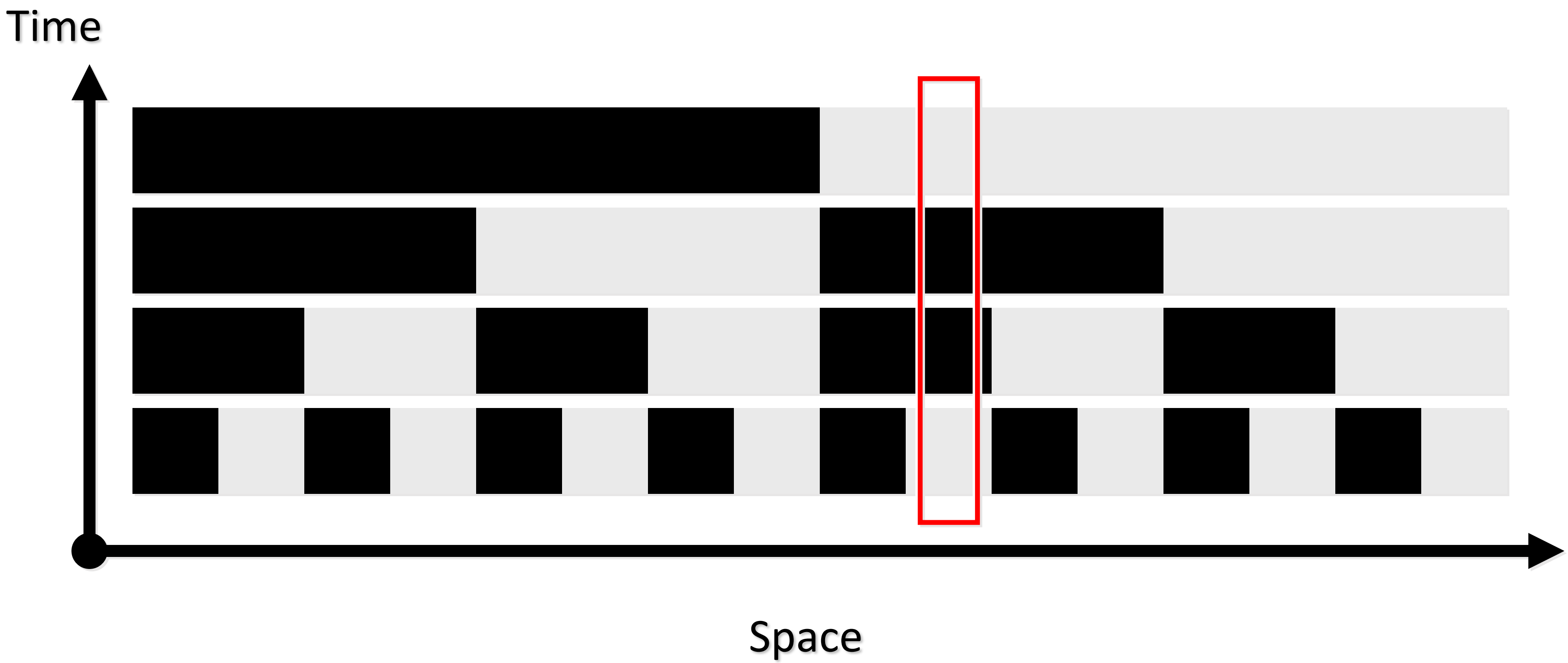
Example:

3 binary-encoded patterns which allows the measuring surface to be divided in 8 sub-regions

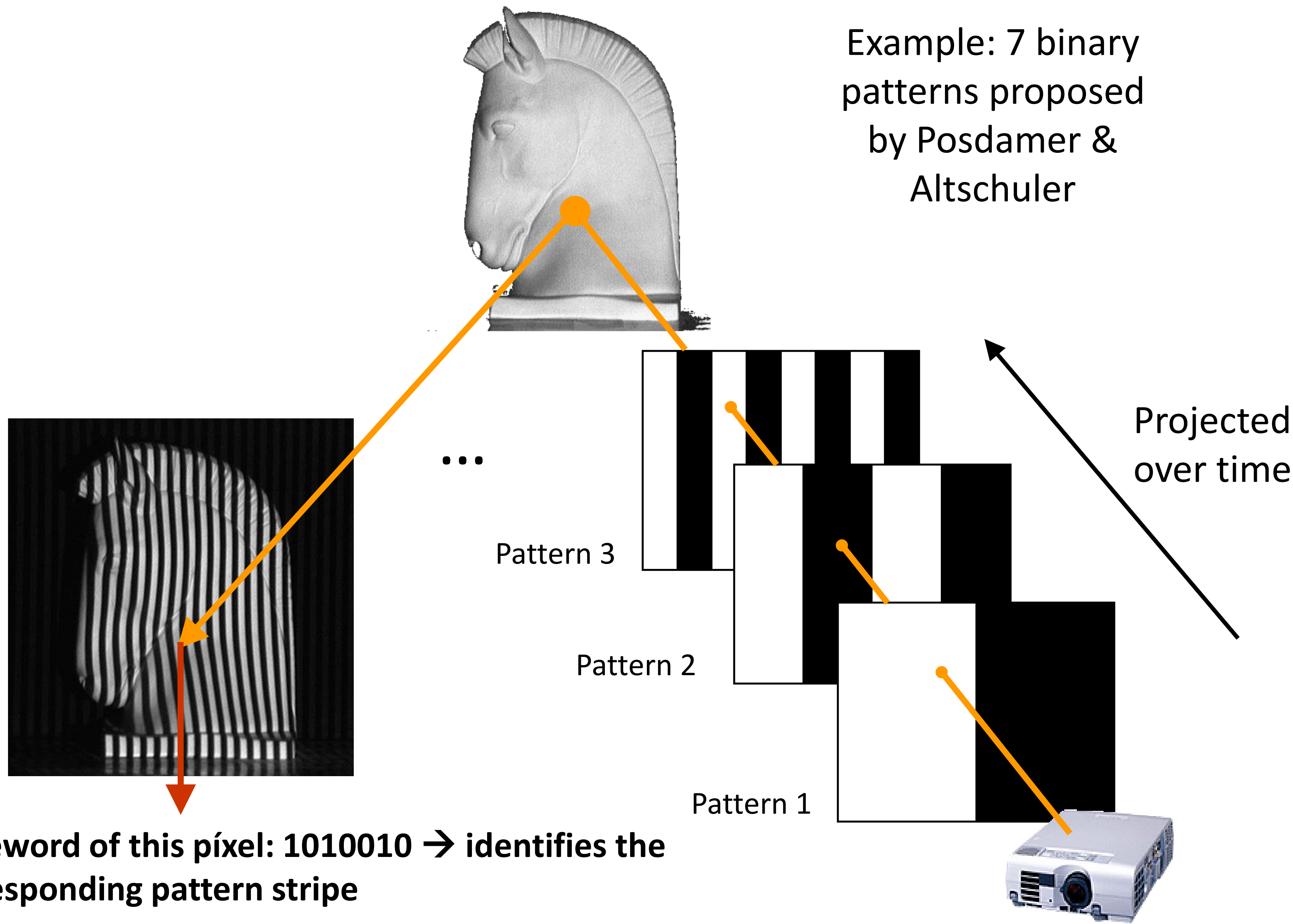


Binary Coding

- Assign each stripe a unique illumination code over time [Posdamer 82]

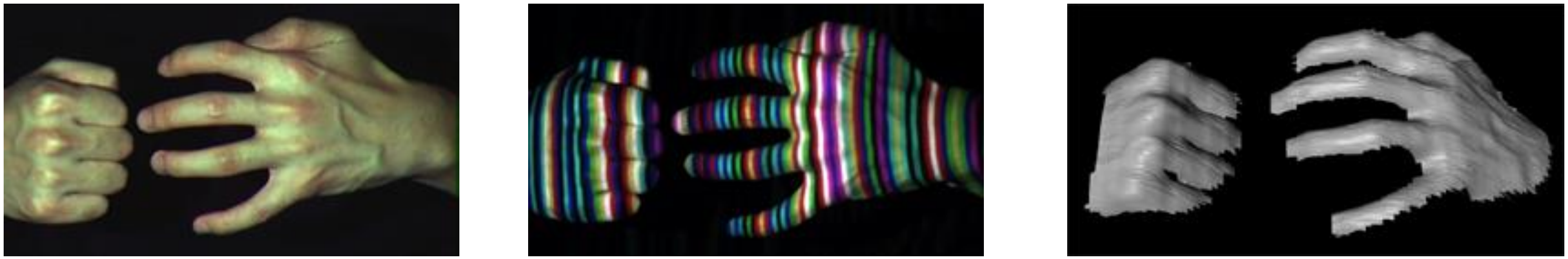


Binary Coding

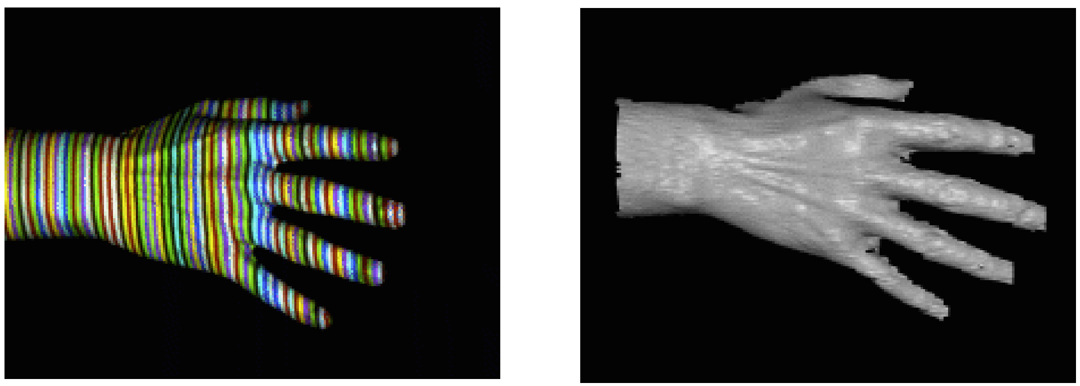


Codeword of this píxel: 1010010 → identifies the corresponding pattern stripe

More complex patterns



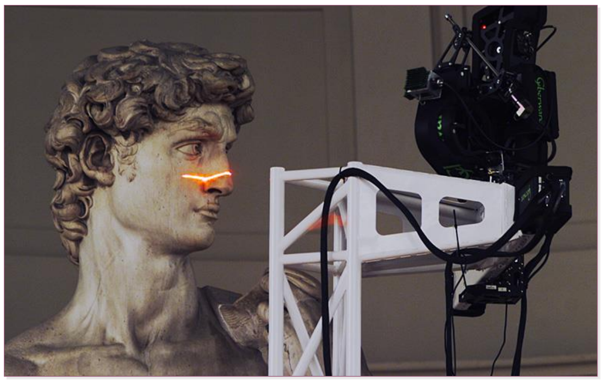
Works despite complex appearances



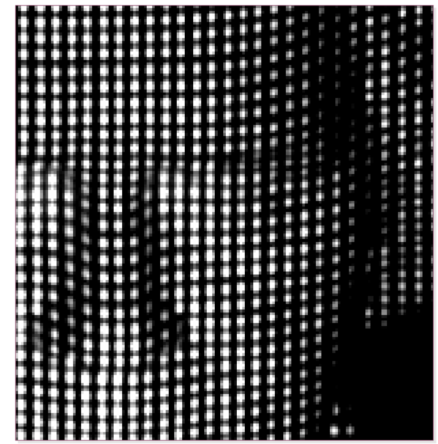
Works in real-time and on dynamic scenes

- Need very few images (one or two).
- But needs a more complex correspondence algorithm

Continuum of Triangulation Methods



Multi-stripe
Multi-frame



Single-stripe

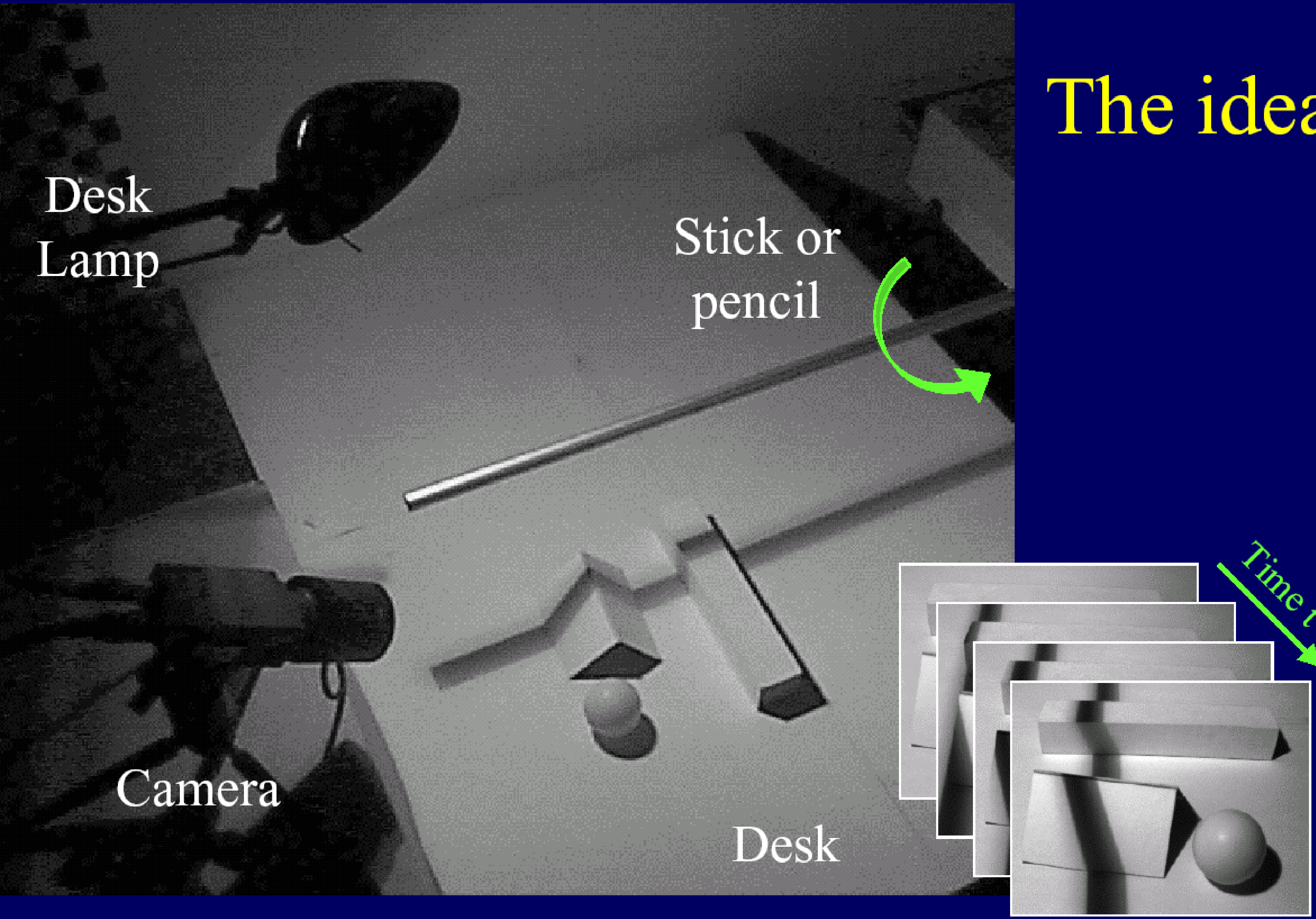
Single-frame

Slow, robust

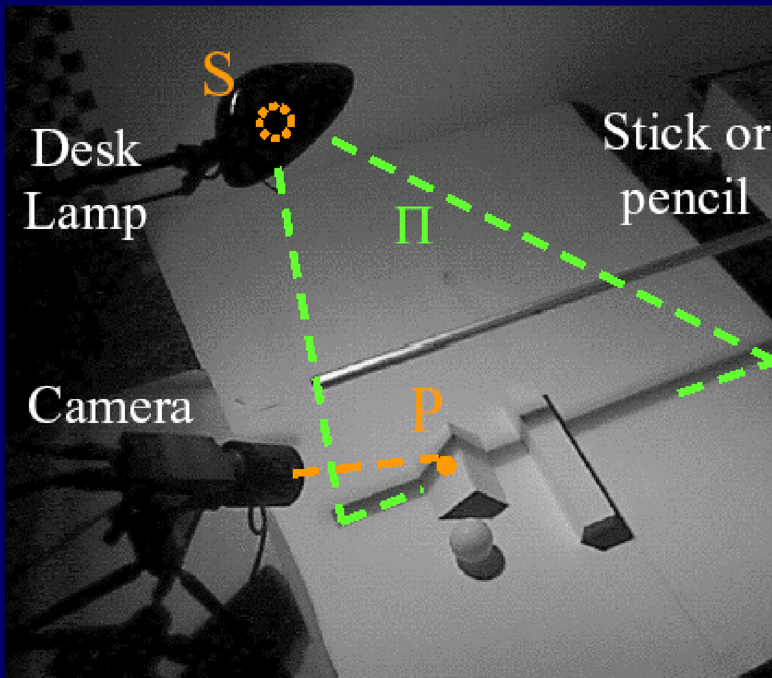
Fast, fragile

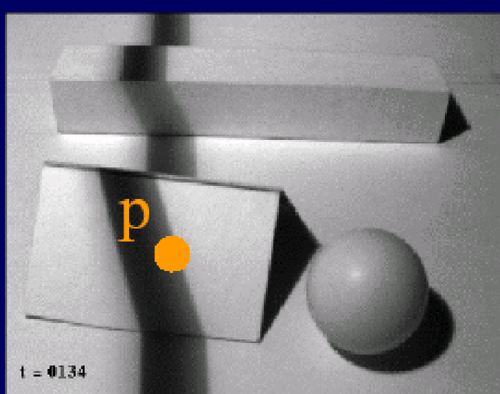
Using shadows

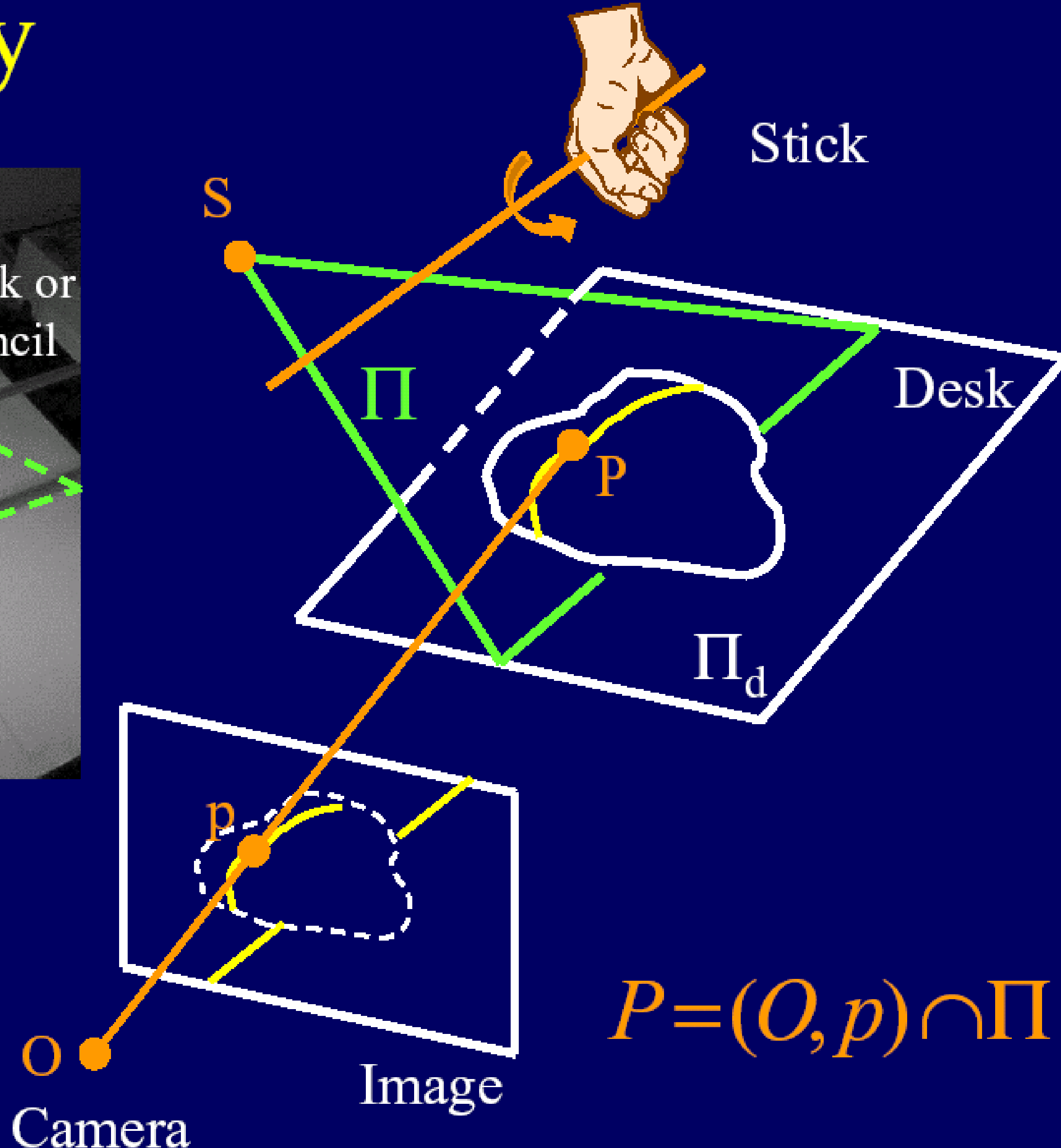
The idea



The geometry

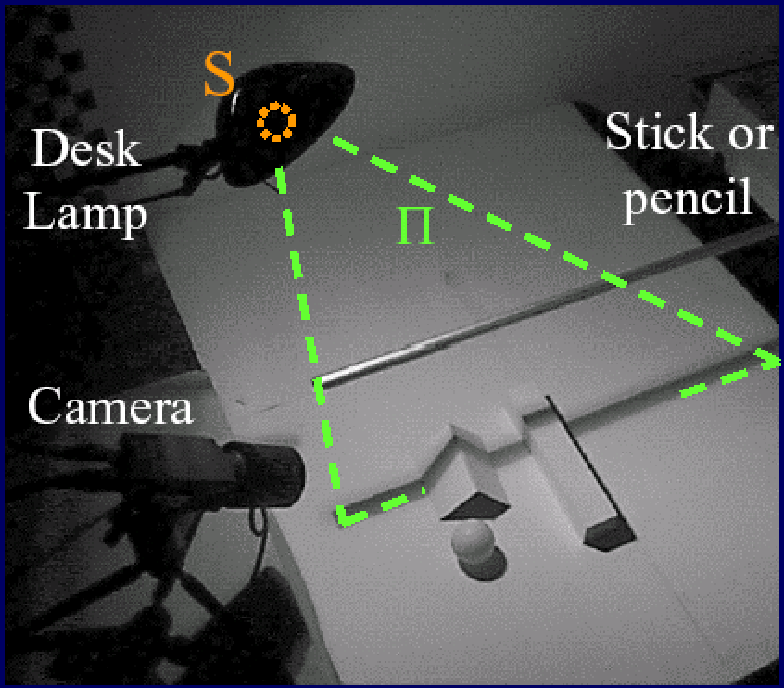


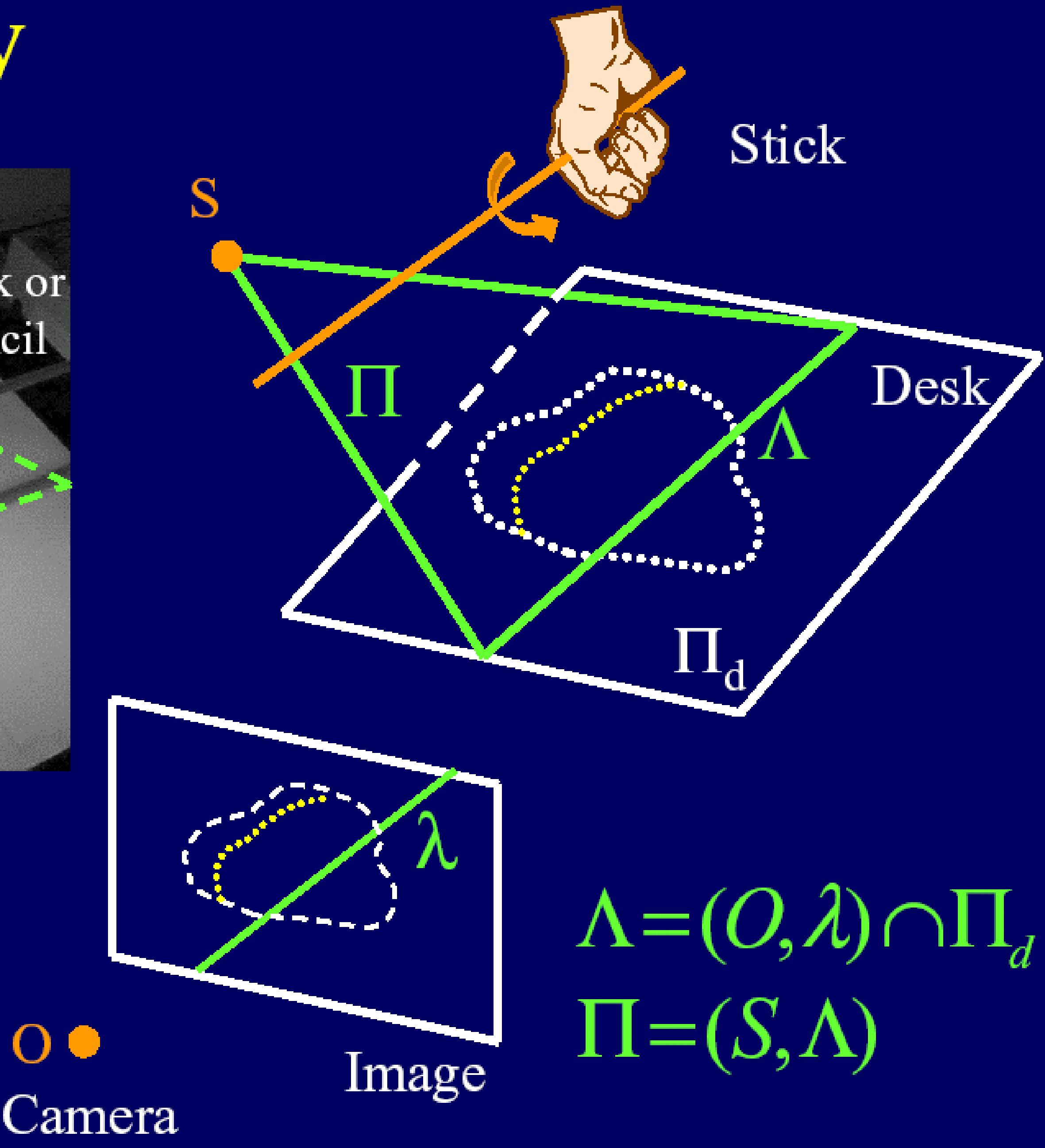


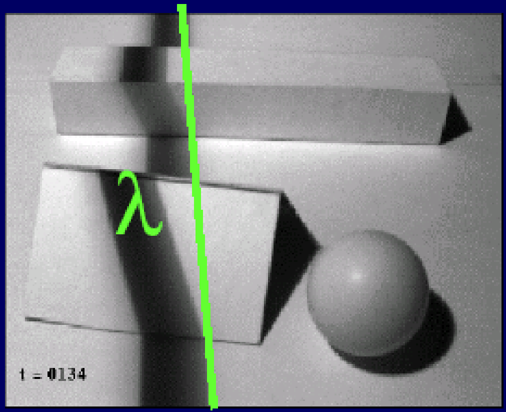


$$P = (O, p) \cap \Pi$$

The geometry



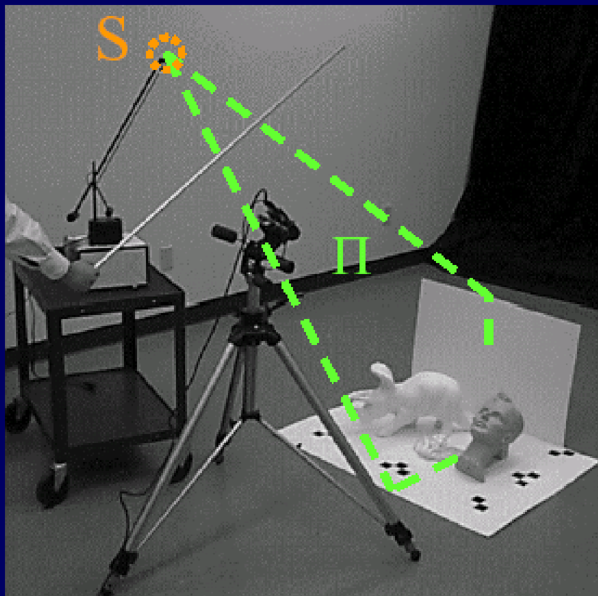


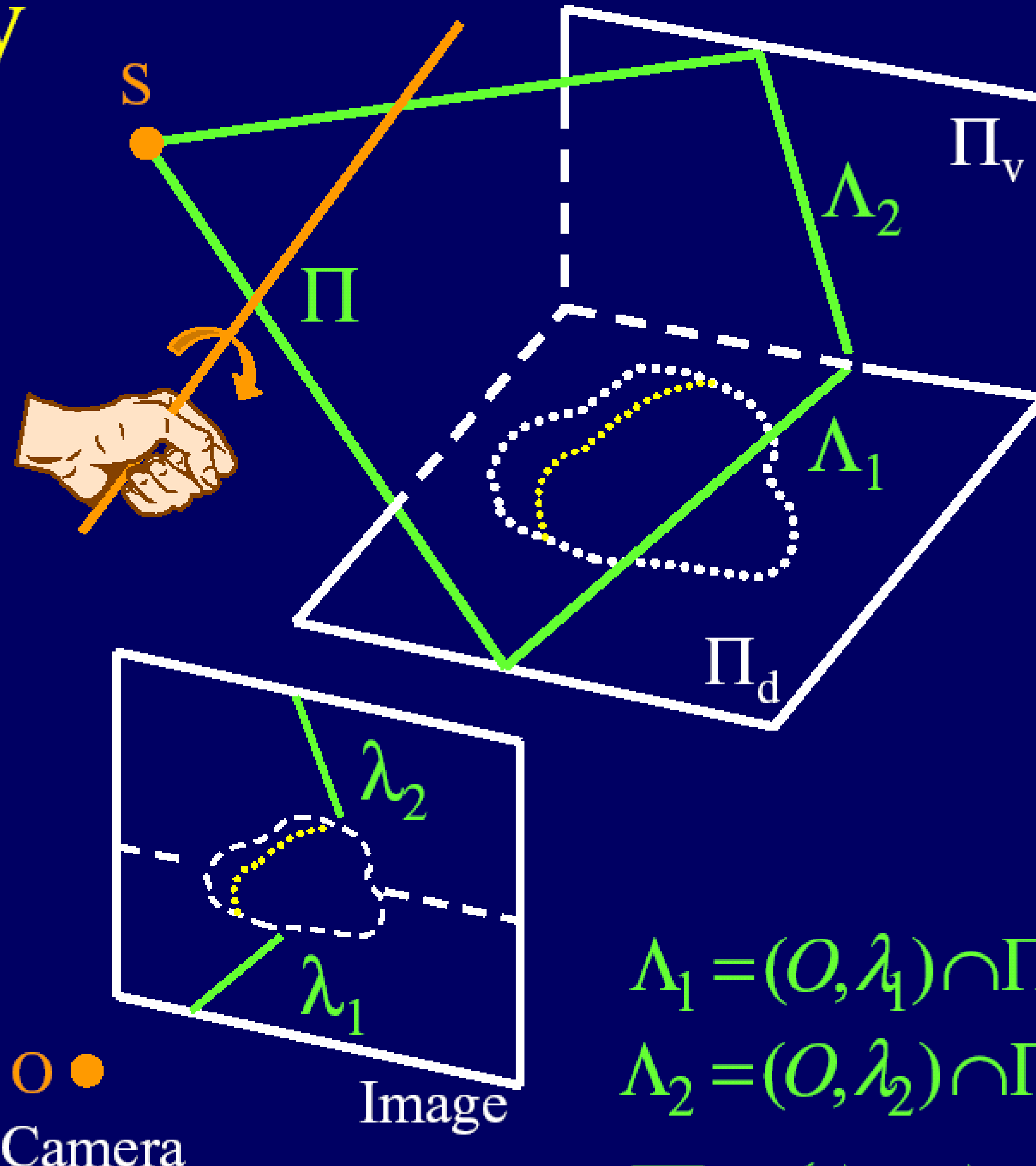


$$\Lambda = (O, \lambda) \cap \Pi_d$$

$$\Pi = (S, \Lambda)$$

The geometry





$$\Lambda_1 = (O, \lambda_1) \cap \Pi_d$$

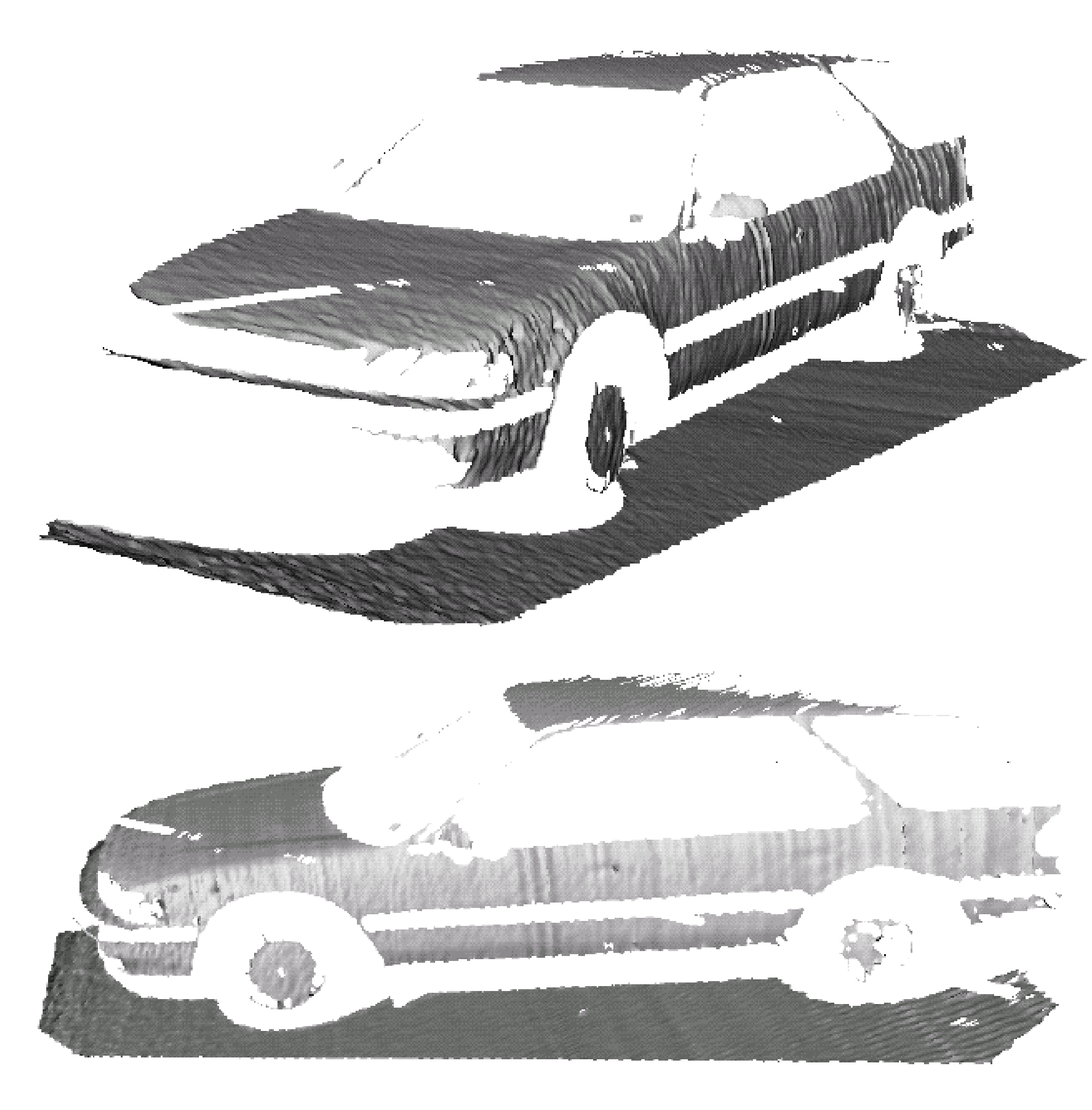
$$\Lambda_2 = (O, \lambda_2) \cap \Pi_v$$

$$\Pi = (\Lambda_1, \Lambda_2)$$

Angel experiment

Accuracy: 0.1mm over 10cm ➡ ~ 0.1% error

Scanning with the sun



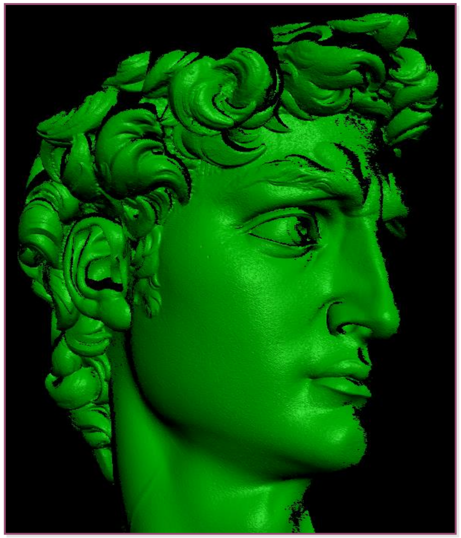
Accuracy: 1cm over 2m

~ 0.5% error

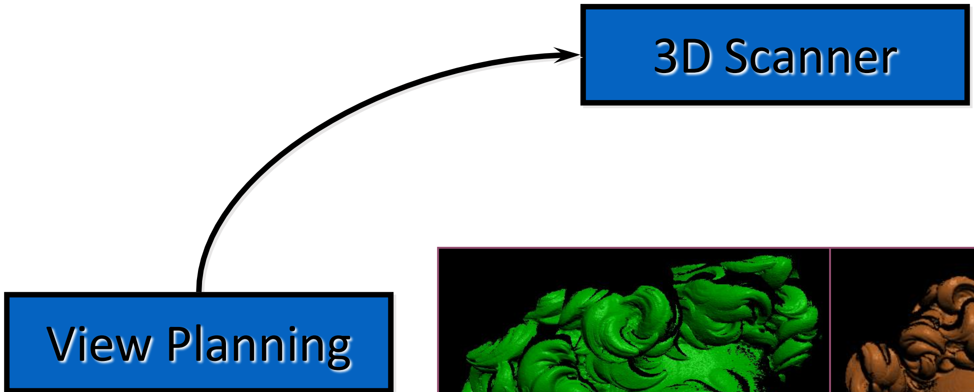
The 3D scanning pipeline

3D Model Acquisition Pipeline

3D Scanner



3D Model Acquisition Pipeline

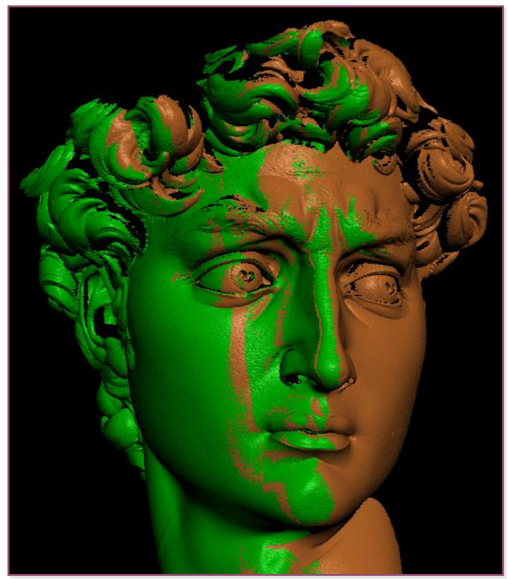


3D Model Acquisition Pipeline

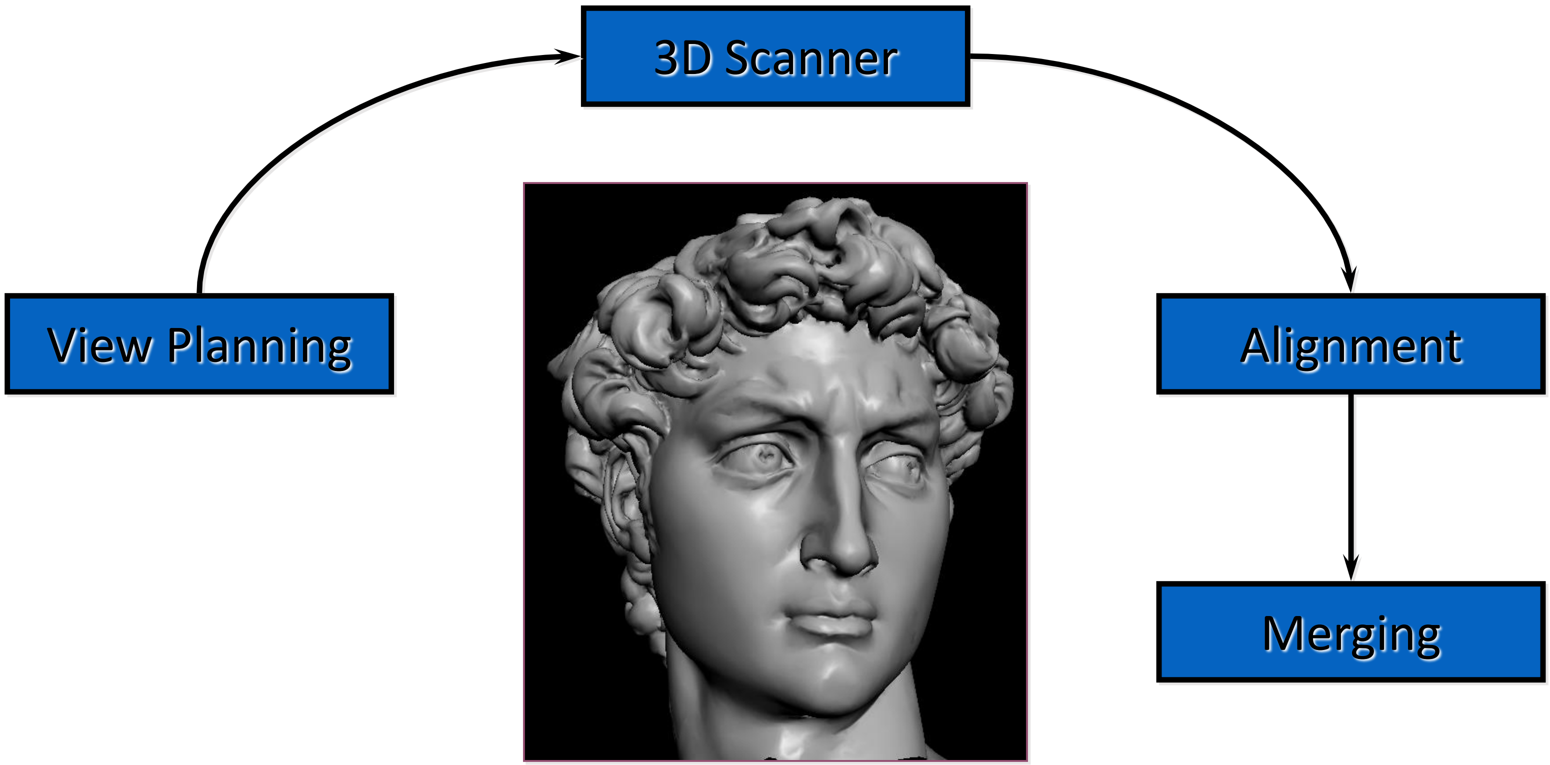
3D Scanner

View Planning

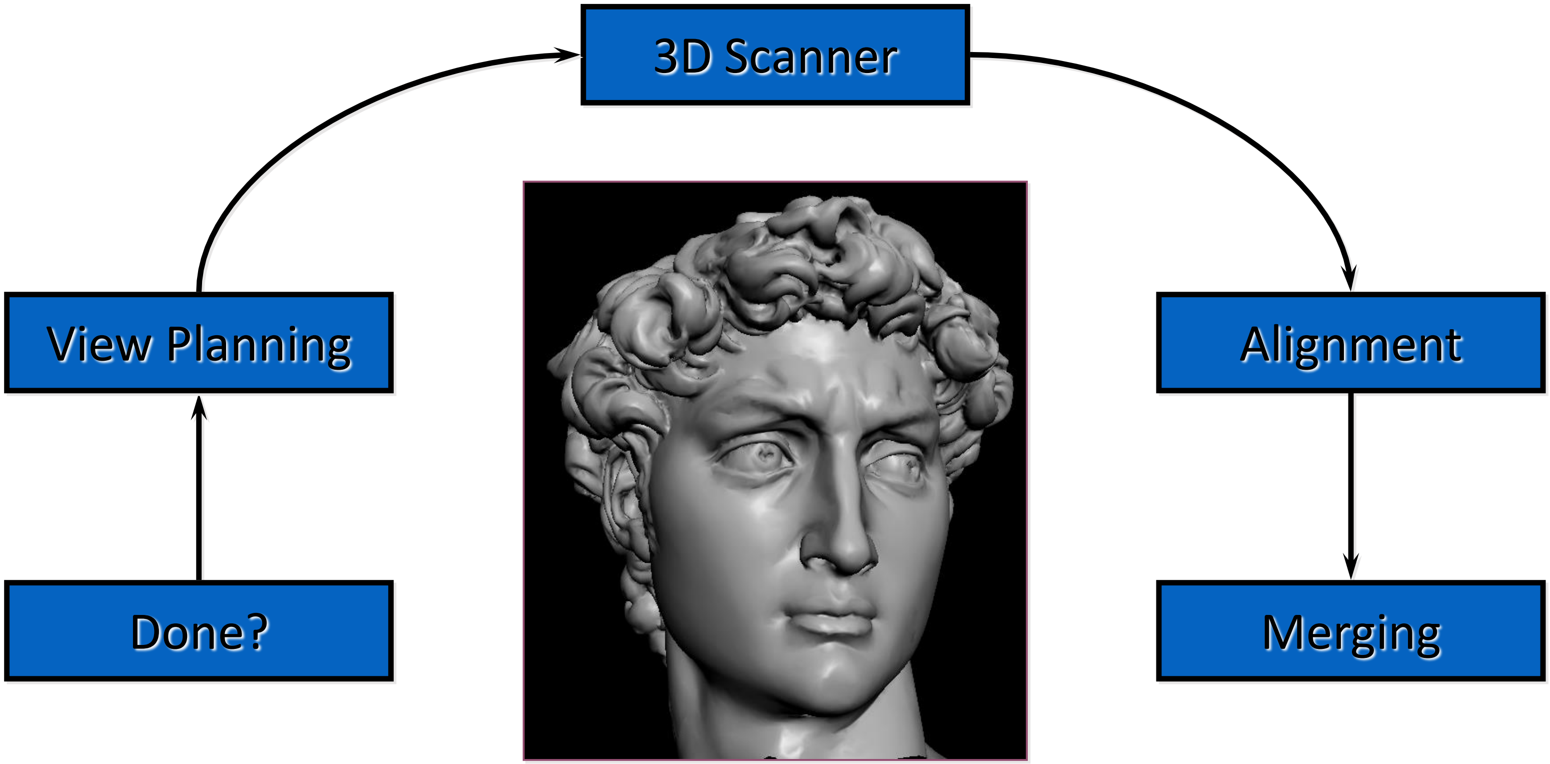
Alignment



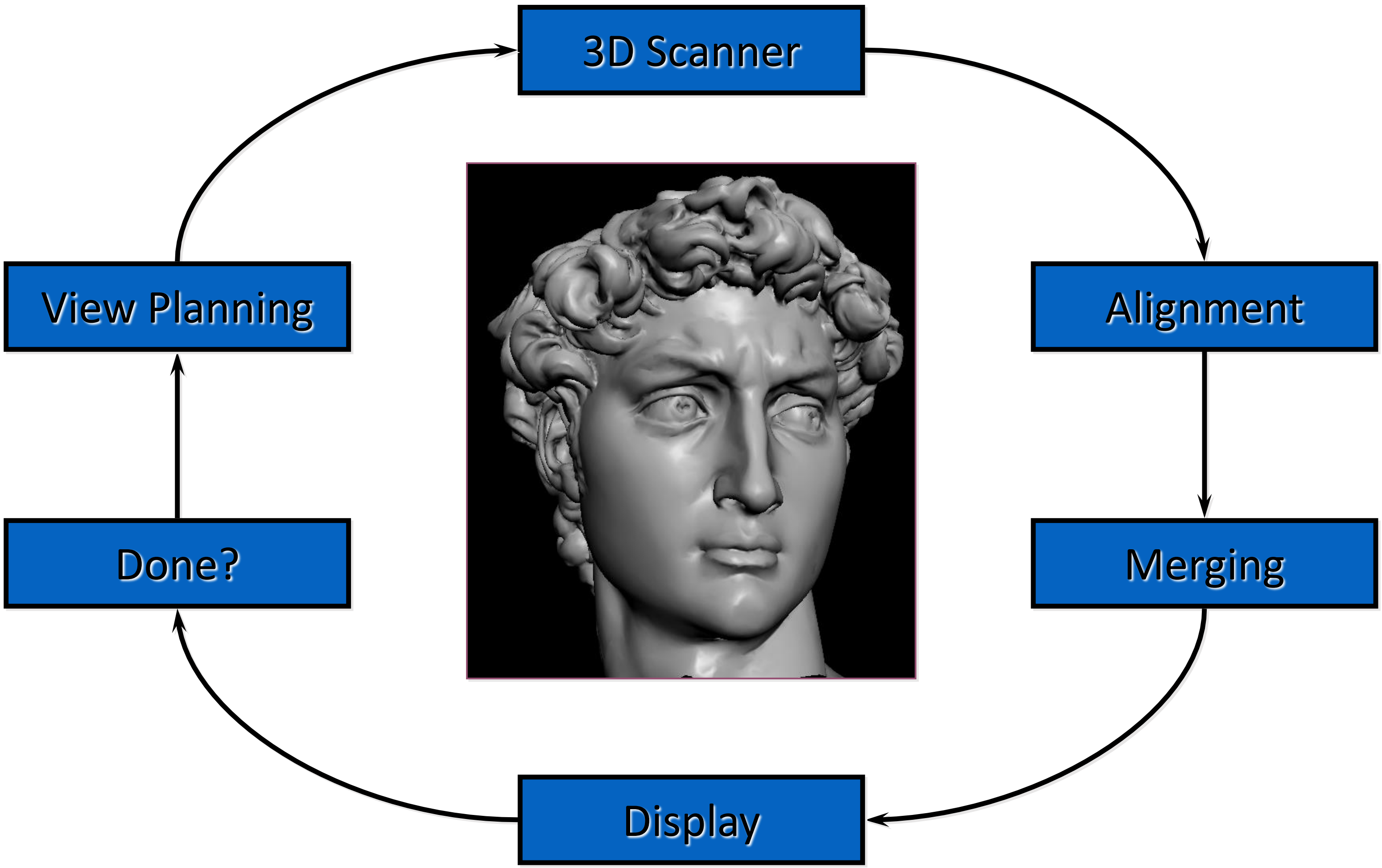
3D Model Acquisition Pipeline



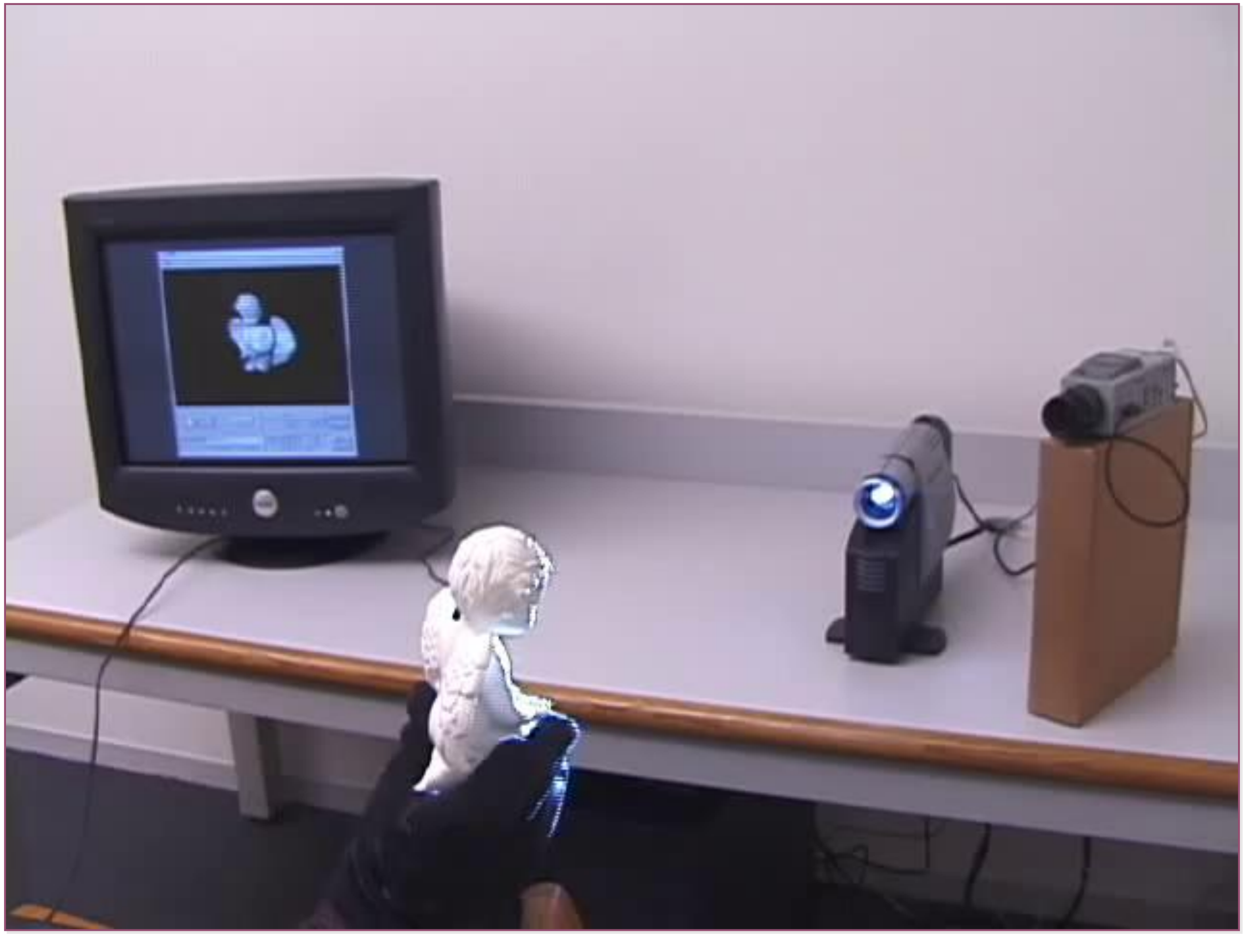
3D Model Acquisition Pipeline



3D Model Acquisition Pipeline

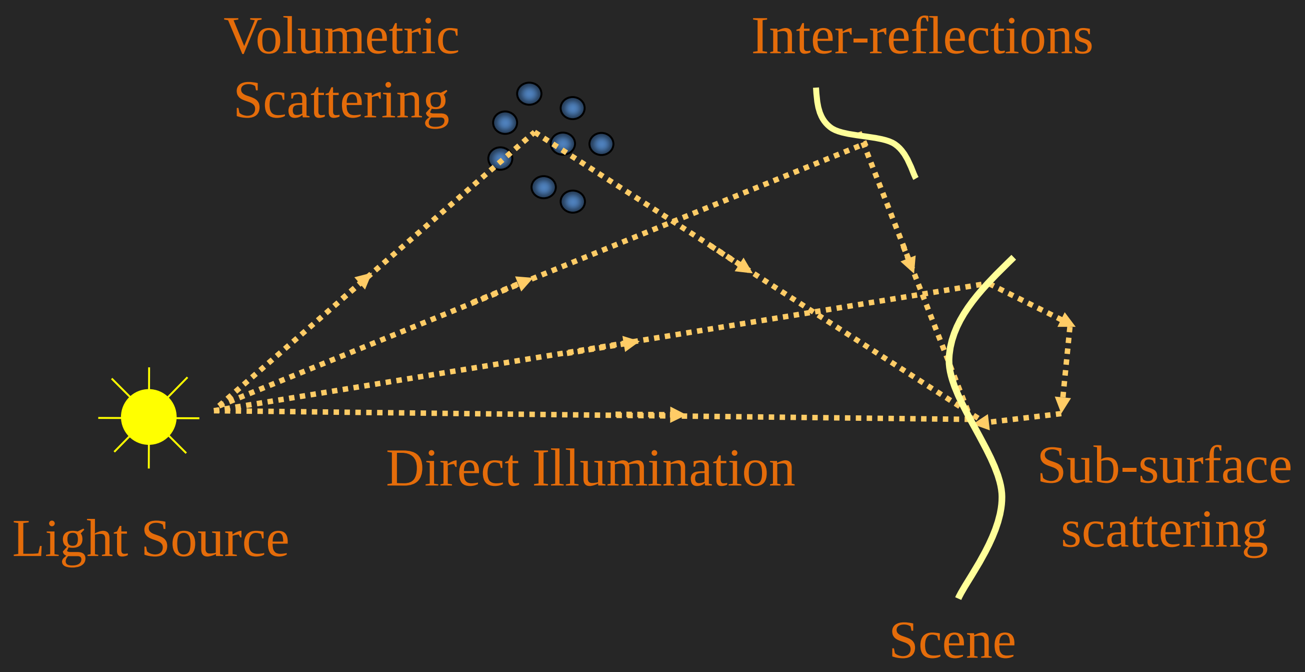


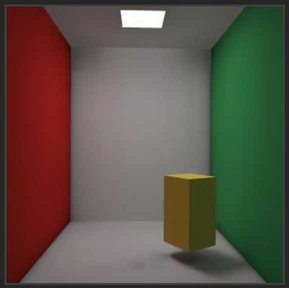
Real-Time 3D Model Acquisition



Dealing with global illumination

Light Transport





Slide adapted from Nayar et al

Why has global light transport been ignored?

Inter-reflections

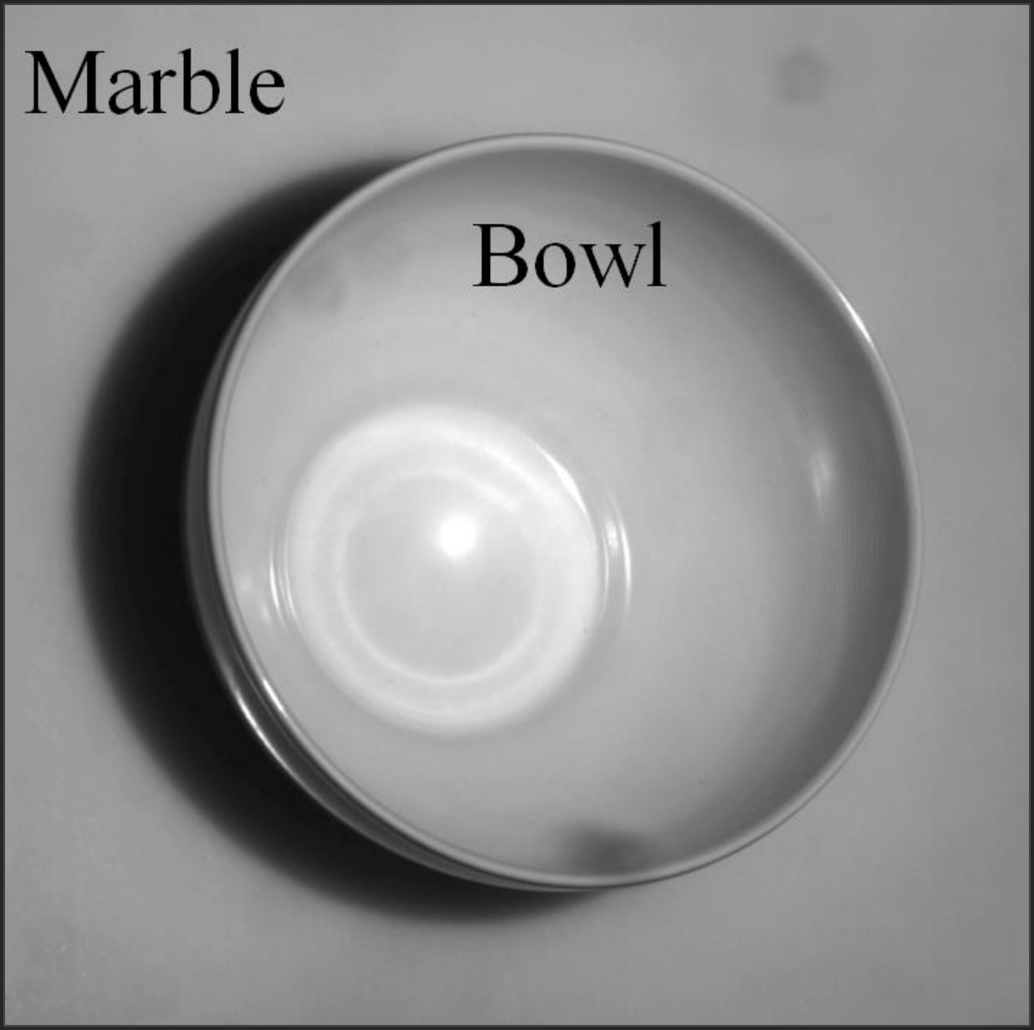
$$L(x) = L_o(x) + \int_a^b \underbrace{\rho(x)}_{\text{Albedo}} \underbrace{K(x,y)}_{\text{Form-factor}} L(y)\, dy$$

Scattering

$$(\hat{s}.\nabla) L(\mathrm{r},\hat{s}) = -\underbrace{\mu_t}_{\text{Absorption coefficient}} L(\mathrm{r},\hat{s}) + \underbrace{\mu_s}_{\text{Scattering coefficient}} \oint_{4\pi} \underbrace{\theta(\hat{s},\hat{s}')}_{\text{Phase Function}} L(\mathrm{r},\hat{s}')\, d\omega'$$

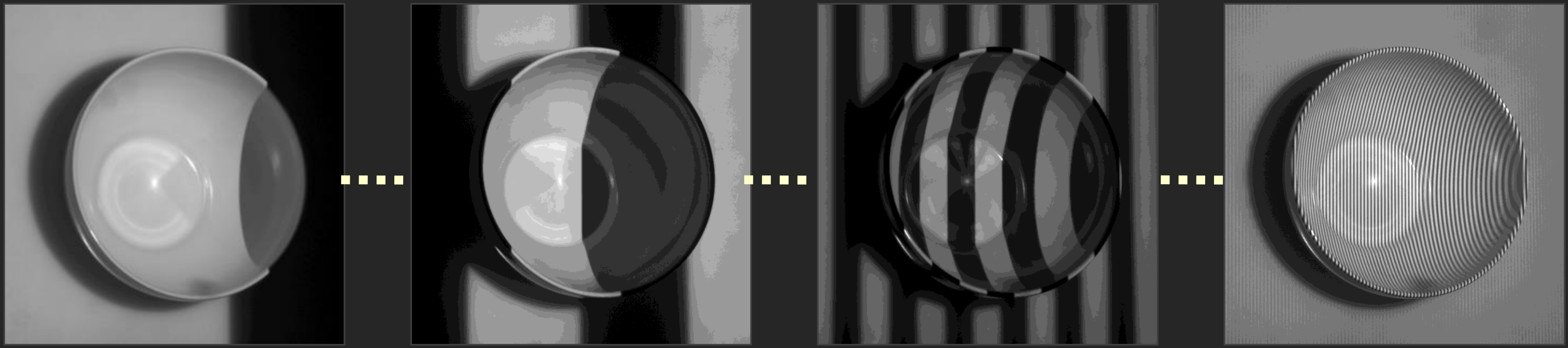
$$\boxed{\text{Analytical models of light transport are complex}}$$

Bowl on a Marble Slab



Captured images under conventional Gray codes

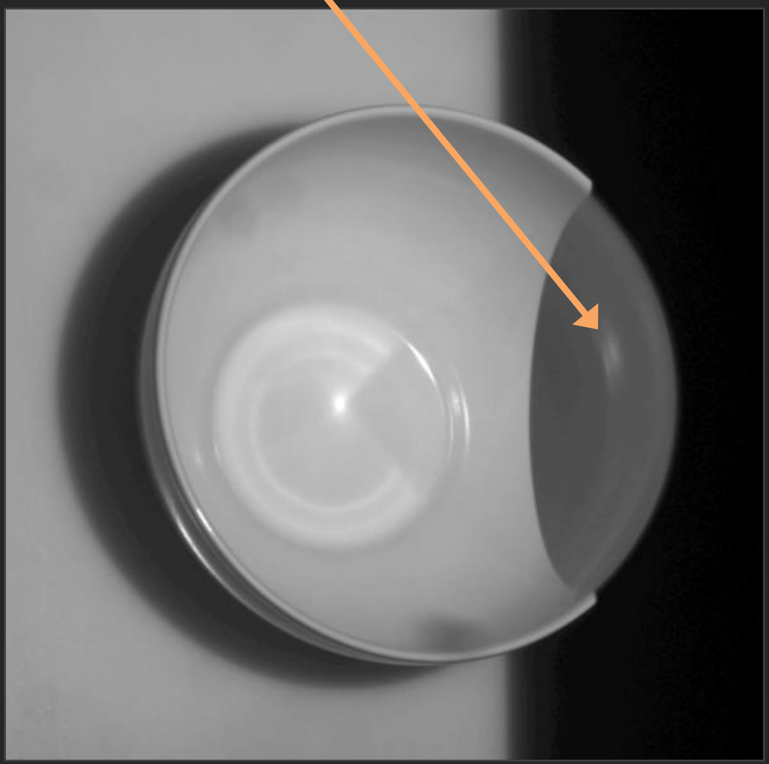
Lowest Frequency Illumination → Highest Frequency Illumination



Pattern 1 Pattern 4 Pattern 7 Pattern 10

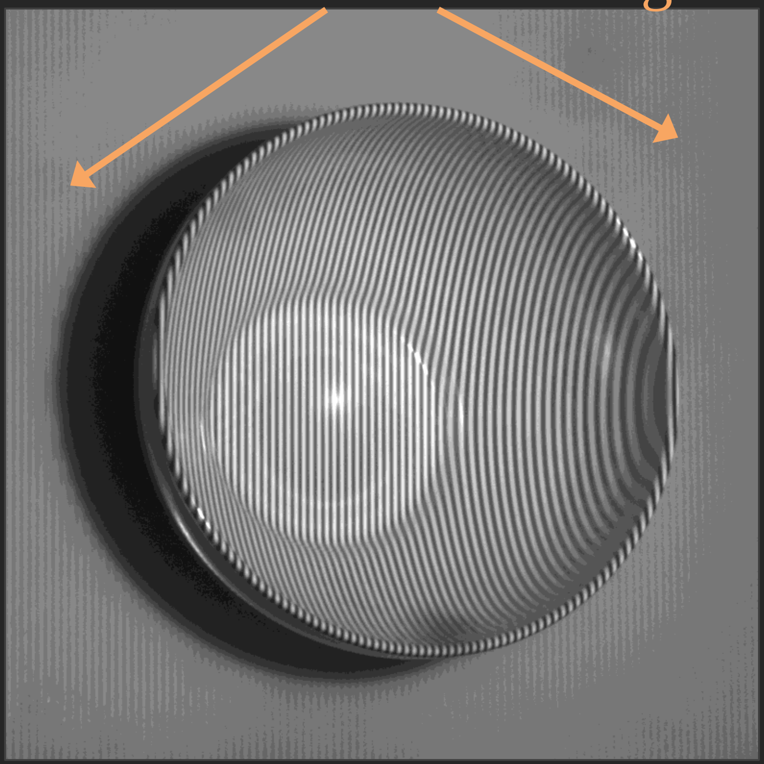
Issues due to global illumination effects

Strong Inter-reflections



Low-frequency pattern

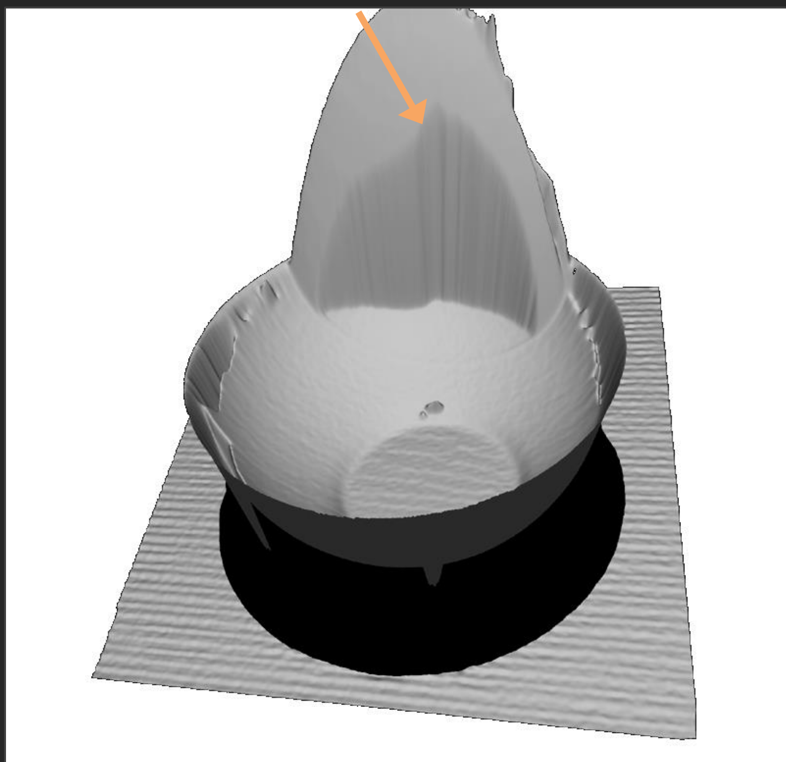
Blurring due to
Sub-surface Scattering



High-frequency pattern

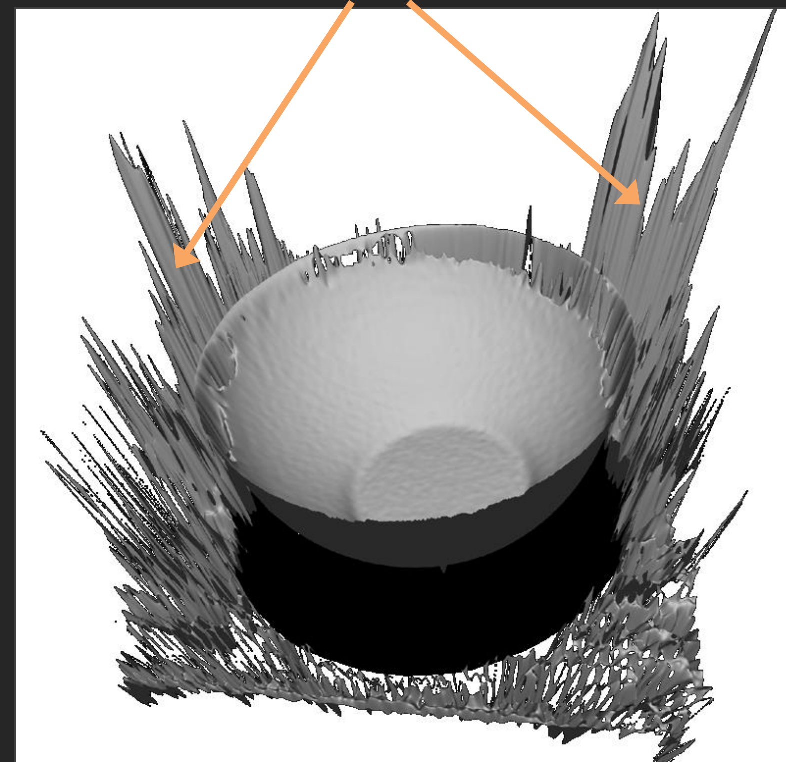
3D Visualizations: State of the Art

Errors due to
interreflections



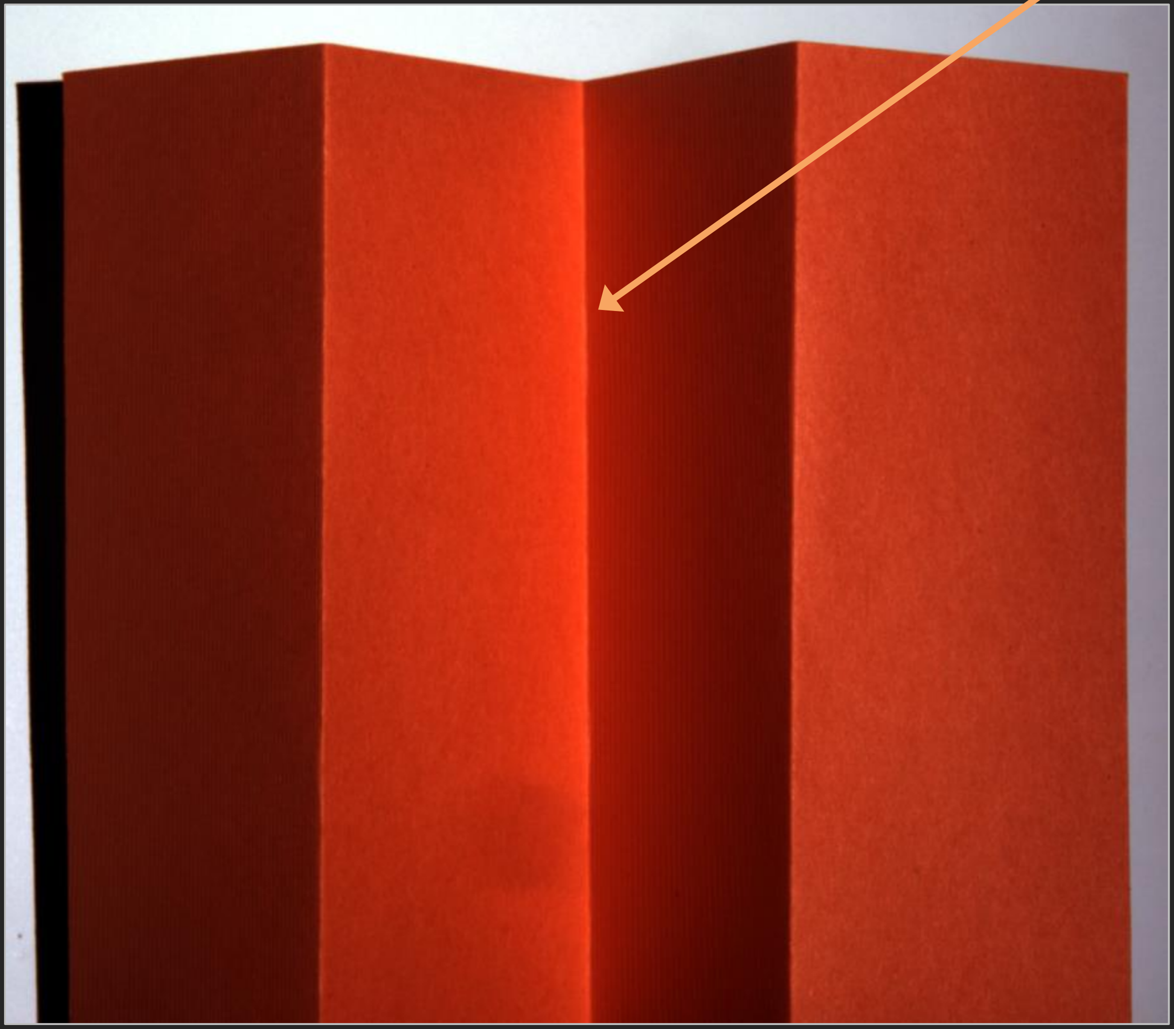
Conventional Gray
(11 images)

Errors due to
sub-surface scattering

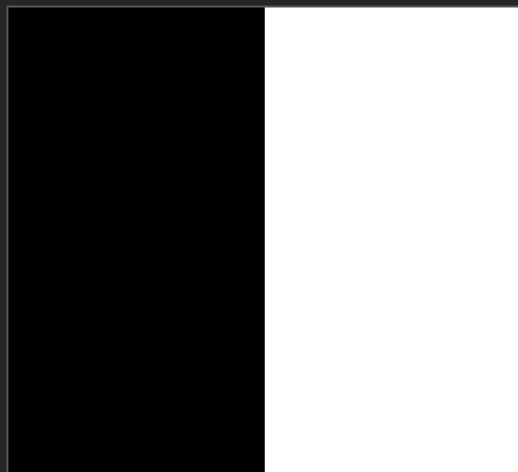


Modulated Phase-Shifting
(162 images)

V-Groove Scene



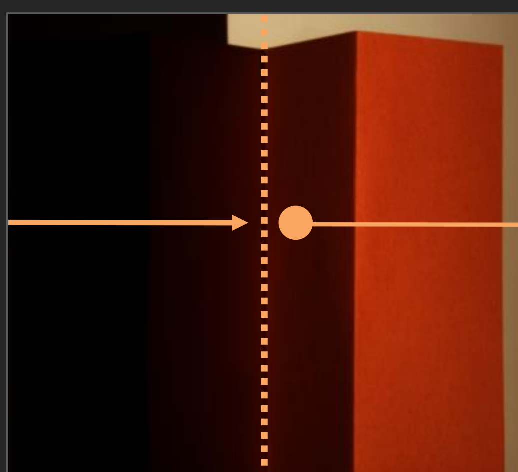
Conventional Gray codes



Low frequency pattern

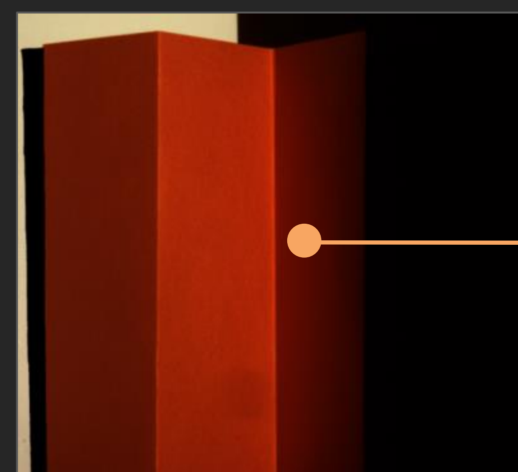
Inverse Pattern

Pattern
Edge



$I = 0.16$

Captured Image

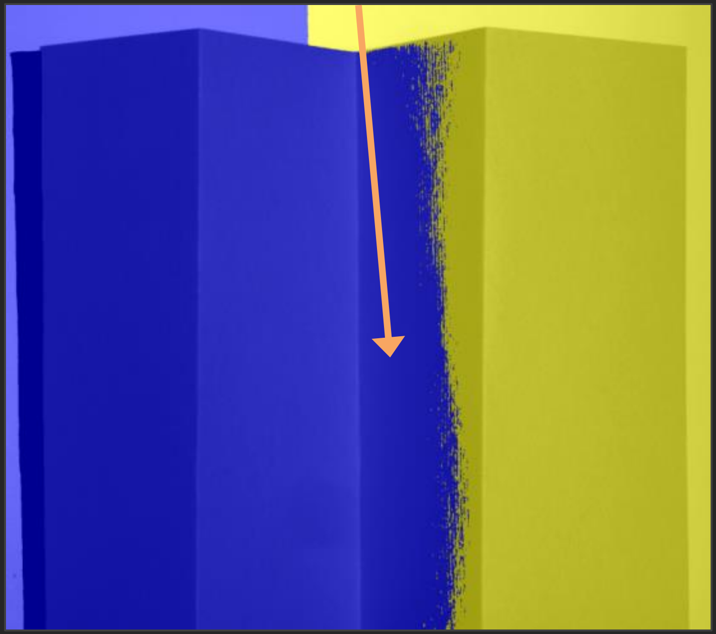


$\bar{I} = 0.25$

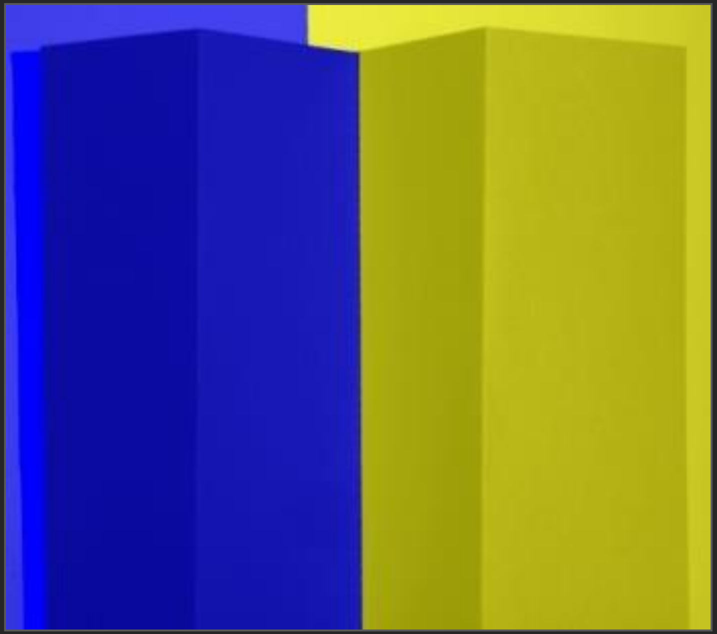
Captured Image

Binarization error

Errors due to inter-reflections



Incorrect Binarization

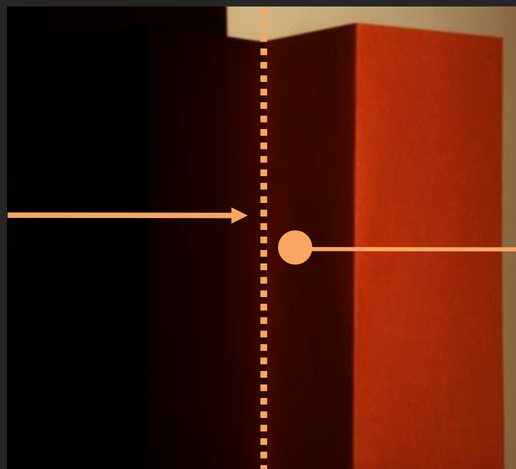


Ground-truth Binarization

One (illuminated) Zero (not-illuminated)

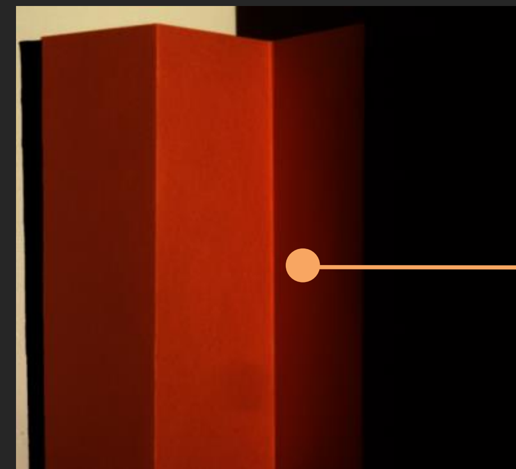
Why is the Decoding Incorrect for Low-frequencies?

Pattern Edge



$I = 0.16$

Captured Image



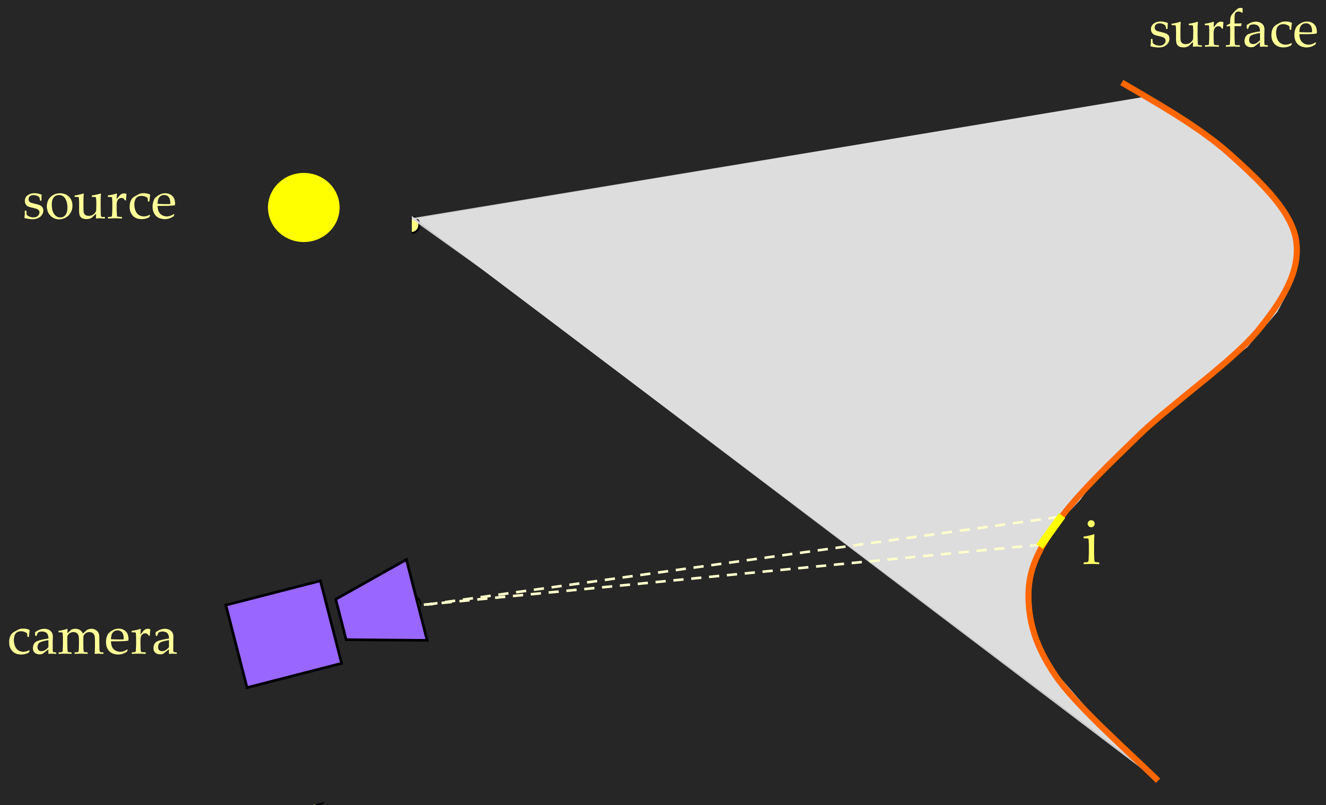
$\bar{I} = 0.25$

Captured Image

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

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

Point Light Source Illuminating the Scene

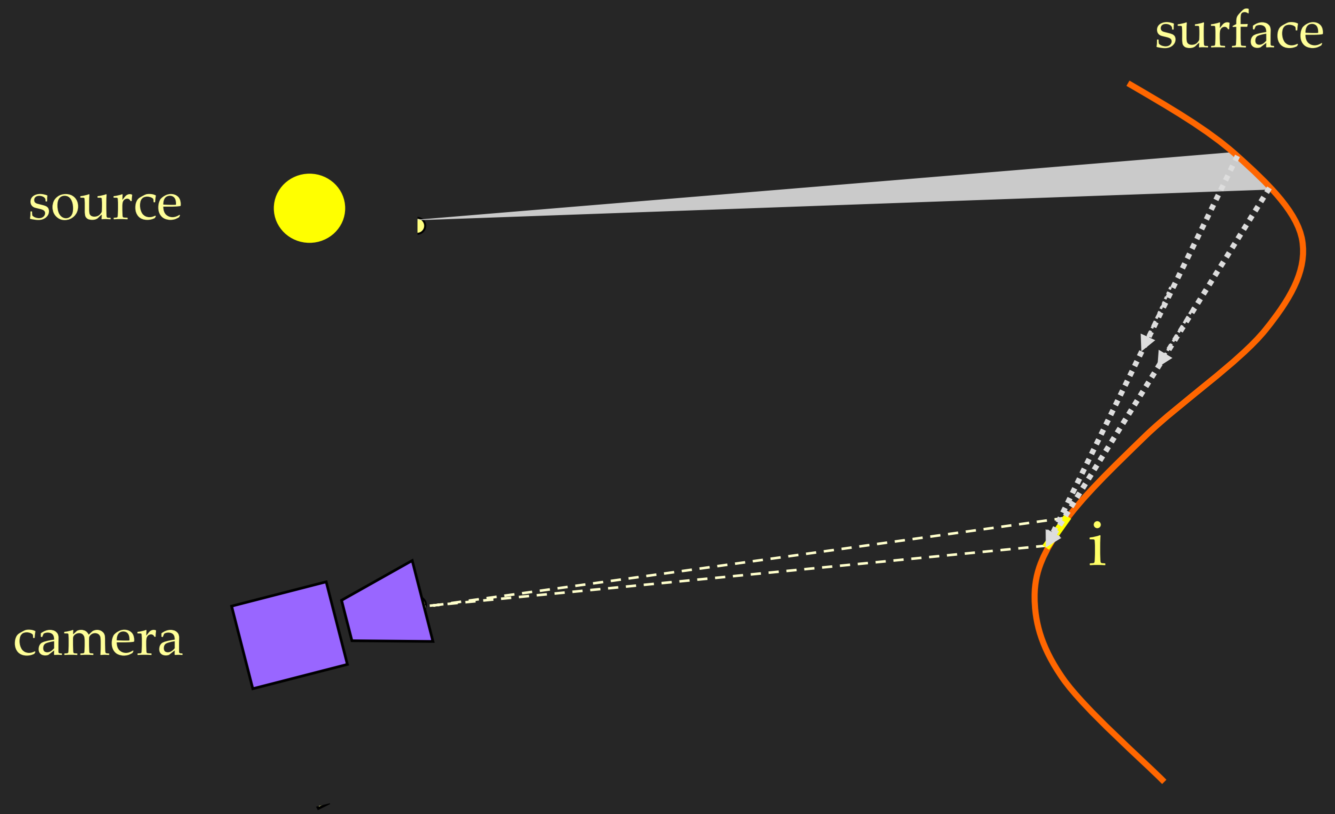


$$L[i] = L_d[i] + L_g[i]$$

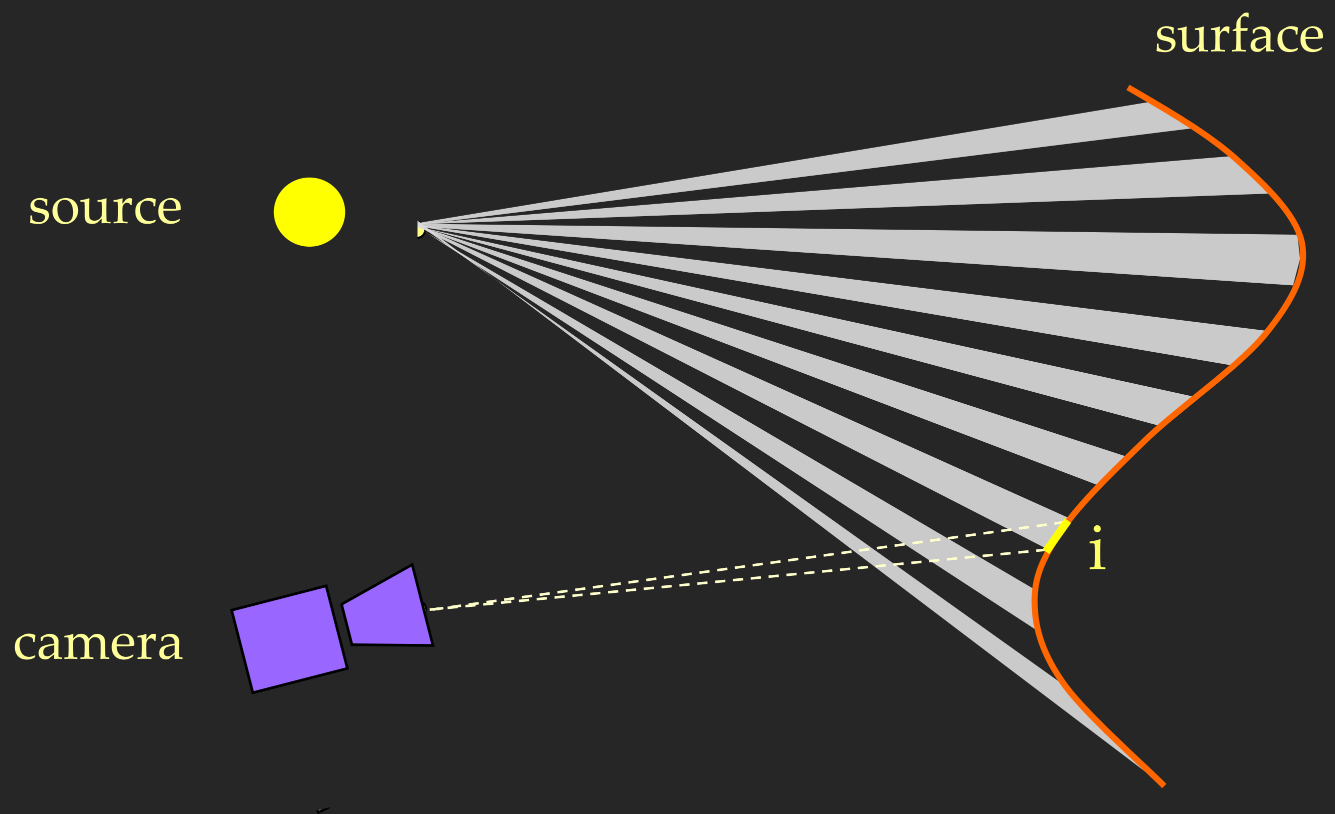
Direct Component

Global Component

Global Illumination is Locally Constant

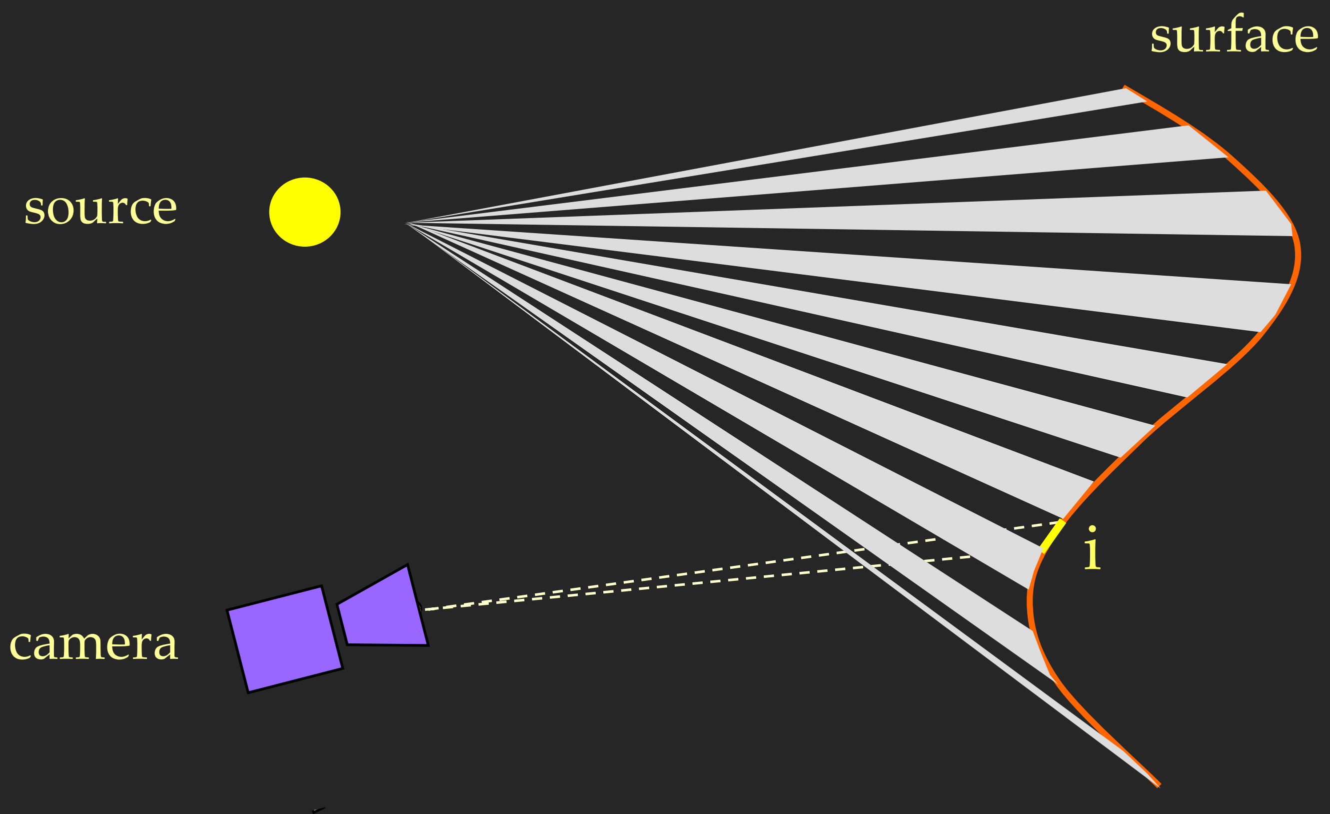


Under High-Frequency Illumination…



$$L_+[i] = L_d[i] + 0.5\, L_g[i]$$

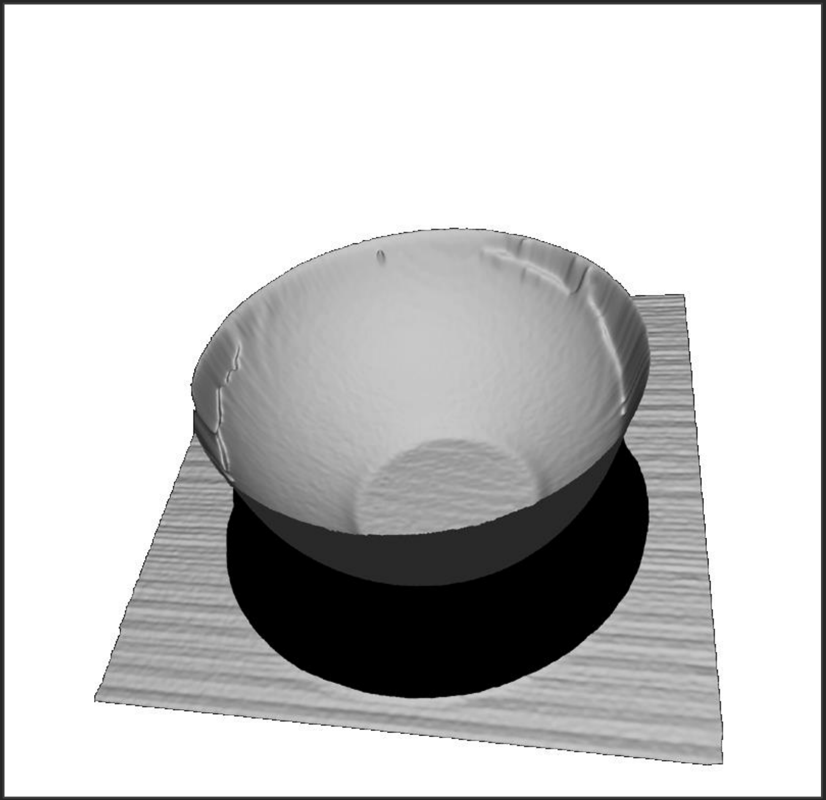
…Global Illumination Contribution is Constant



$$L_+[i] = L_d[i] + 0.5\, L_g[i]$$

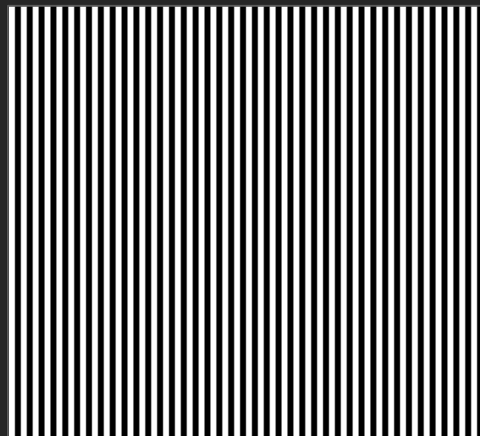
$$L_-[i] = 0.5\, L_g[i]$$

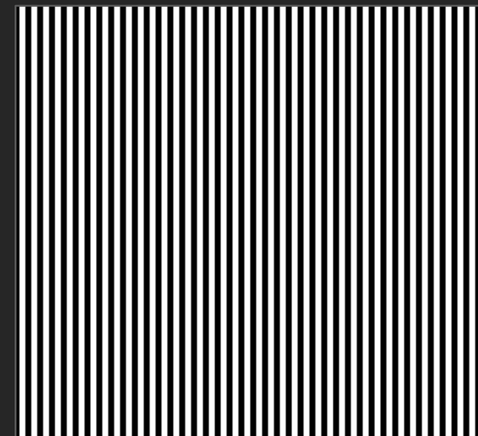
3D Visualizations: Our Result

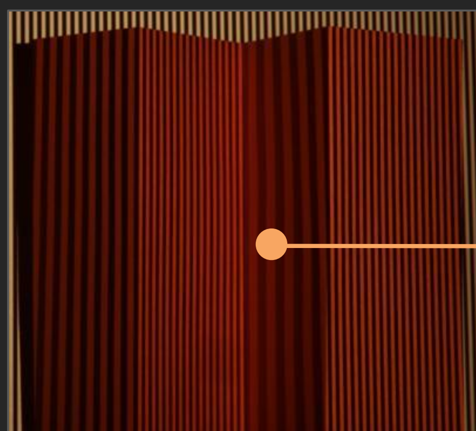


Our Technique
(41 images)

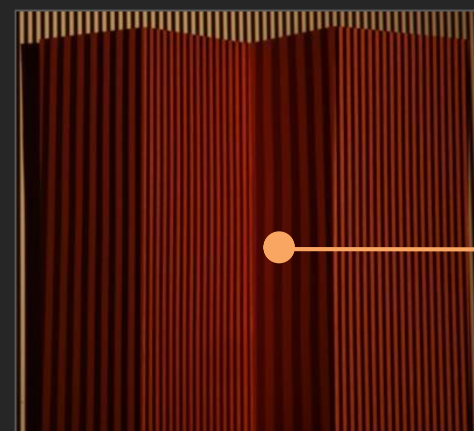
Binarization for high-frequency pattern


Pattern


Inverse Pattern


Captured Image

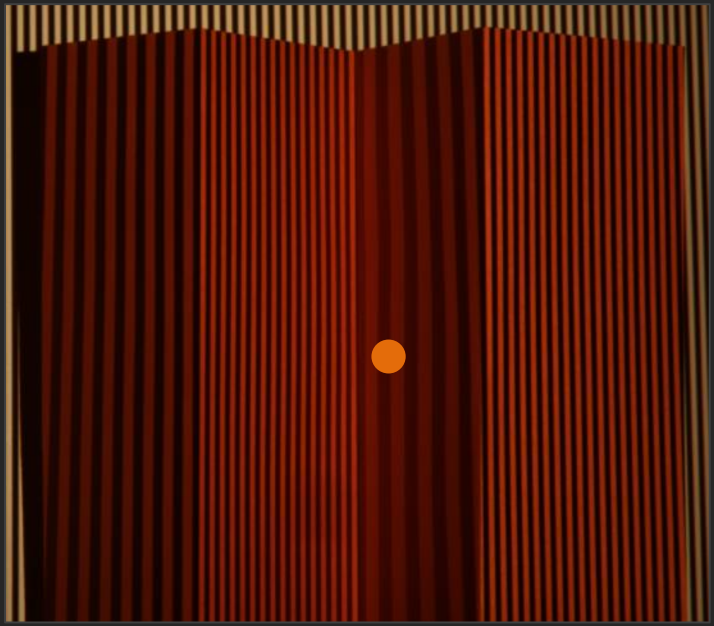
$I = 0.25$


Captured Image

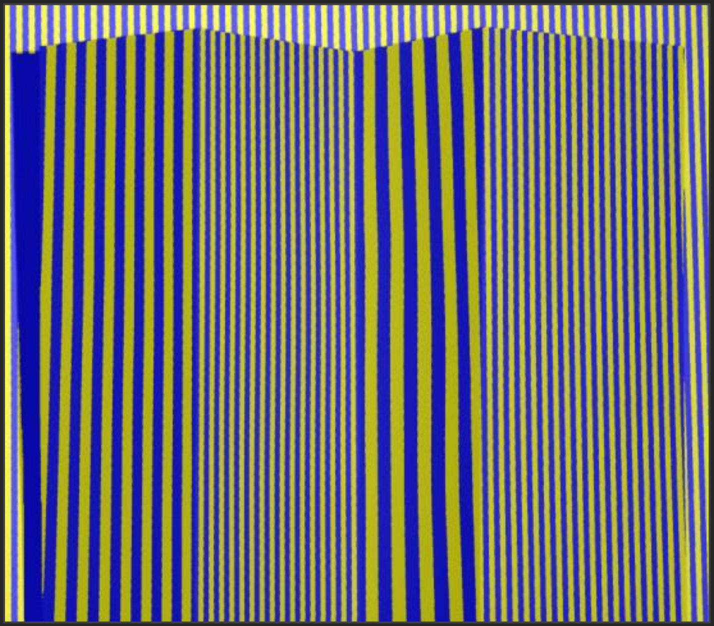
$\bar{I} = 0.16$

I = Direct + **0.5** Global $>$ $\bar{I}$ = 0.5 Global

High-frequency Patterns are Decoded Correctly



Captured Image

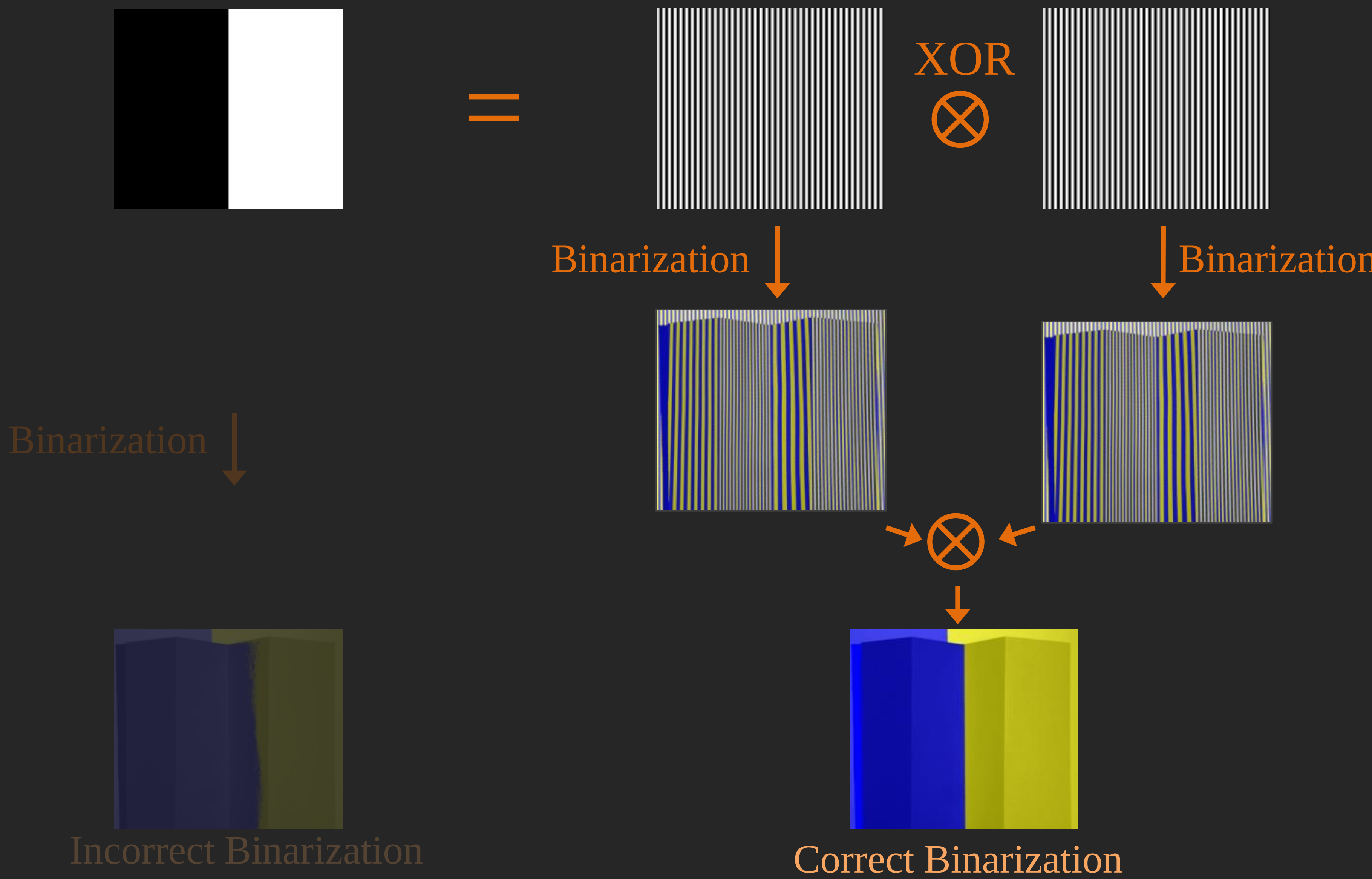


Binary Decoding

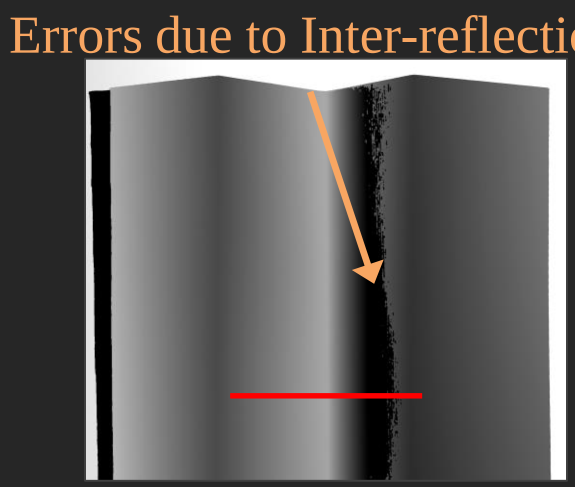
Preventing errors due to long-range effects

Logical Coding and Decoding

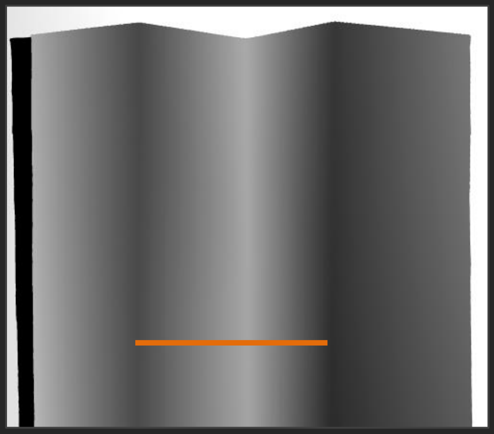
Logical Coding and Decoding



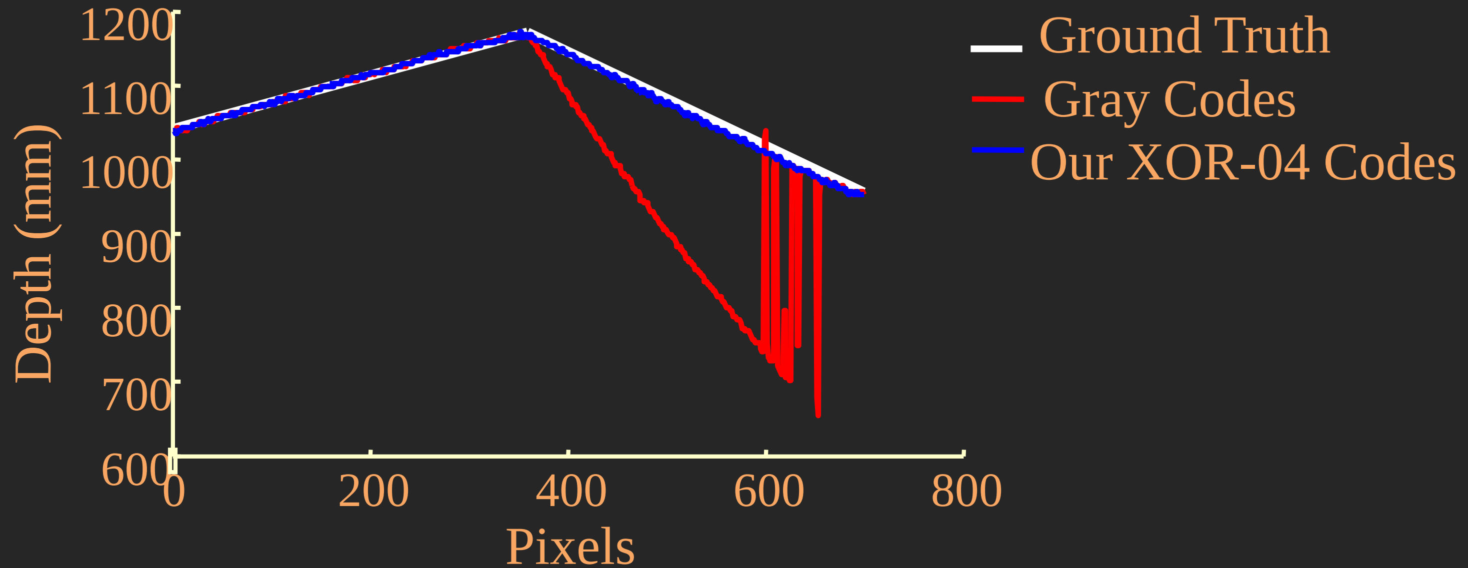
Depth Map Comparison



Conventional Gray Codes (11 images)

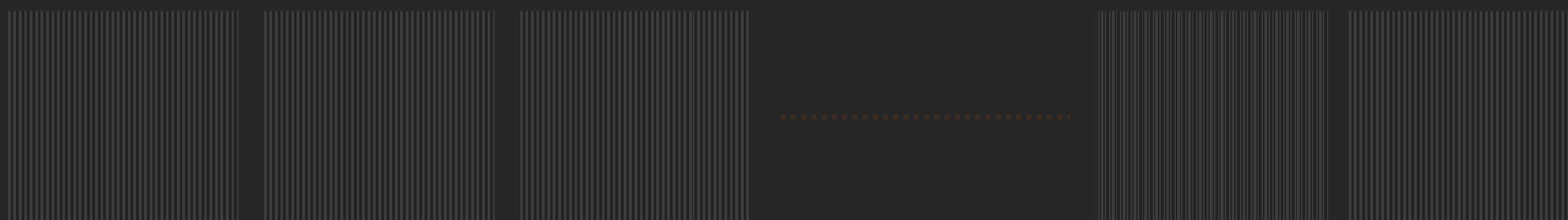


Our XOR-04 Codes (11 images)



Making the Logical XOR Codes

Conventional Gray Codes (10 patterns)

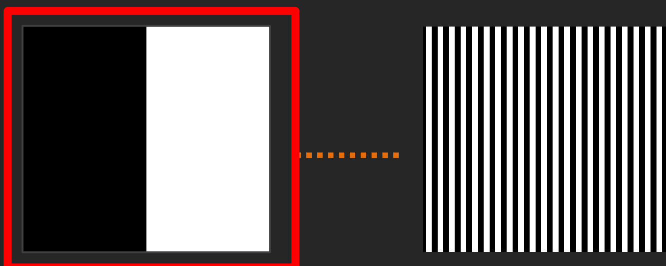


XOR of Last Pattern with Patterns 1-9 → XOR-02 Codes (10 patterns)

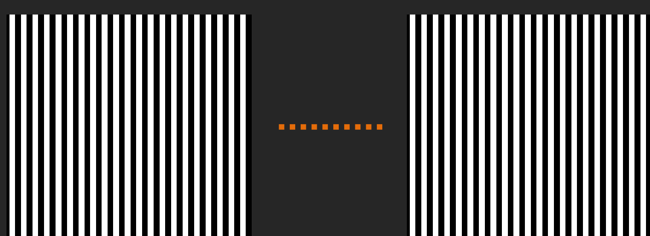
XOR of Second-last Pattern with Patterns 1-8 → XOR-04 Codes (10 patterns)

Inter-reflections vs. Sub-surface scattering

Long-Range Inter-reflections

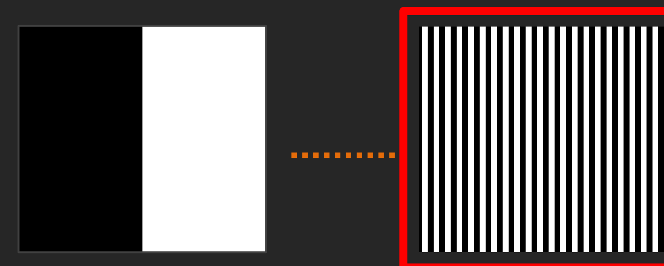


Conventional Gray Codes

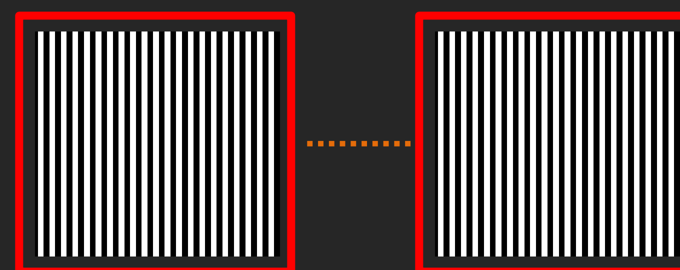


XOR Codes

Short-Range Sub-surface Scattering



Conventional Gray Codes



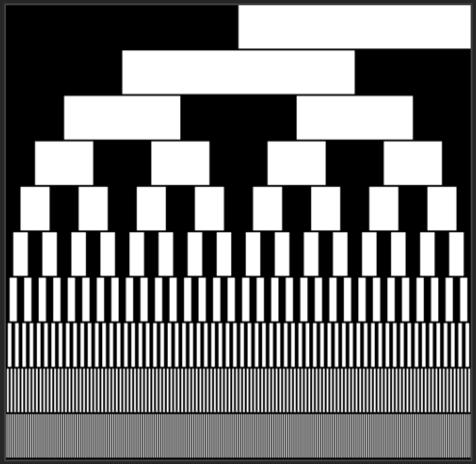
XOR Codes

Gray Codes with Low Spatial Frequencies

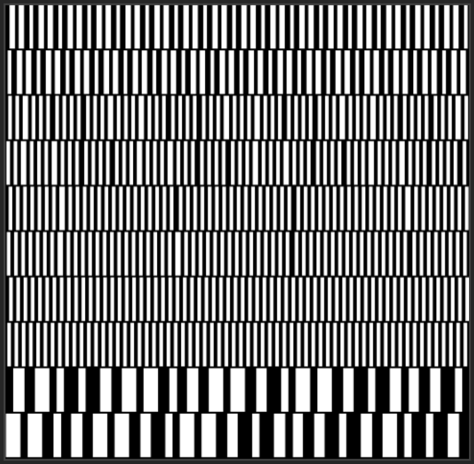
Max min-stripe-width Gray Codes

Conventional Gray Codes

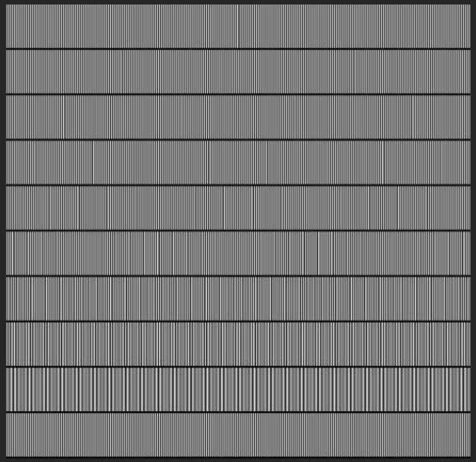
Ensemble of Codes for General Scenes



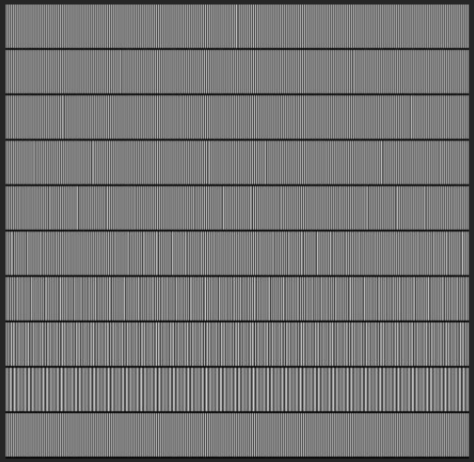
Conventional Gray (10 images)



Max min-SW Gray (10 images)

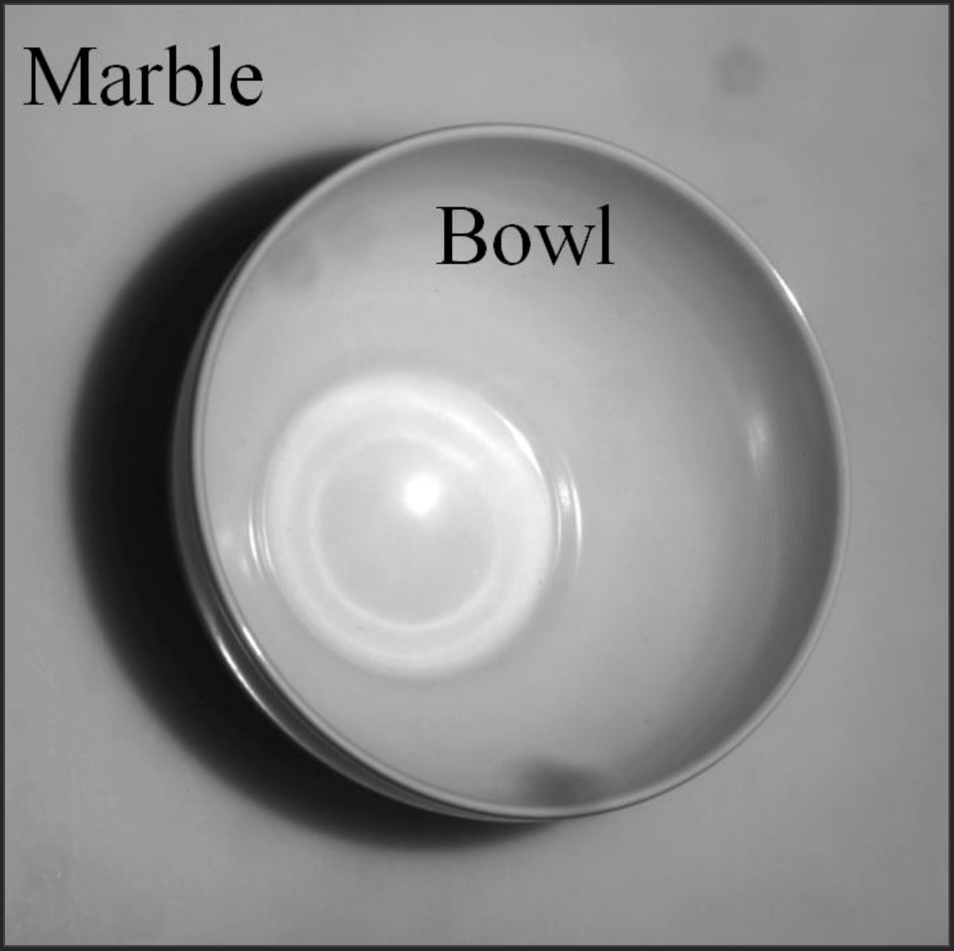


XOR-04 (10 images)

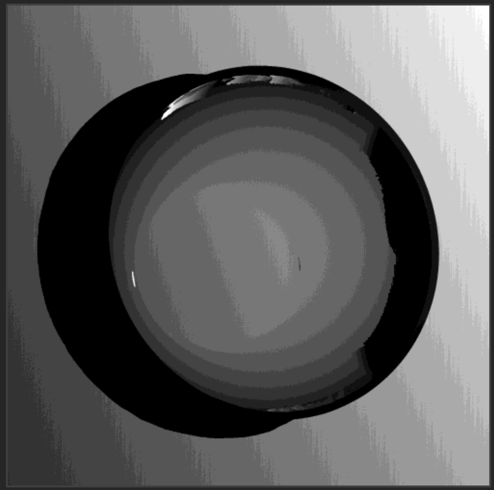


XOR-02 (10 images)

Reconstructing General Scenes

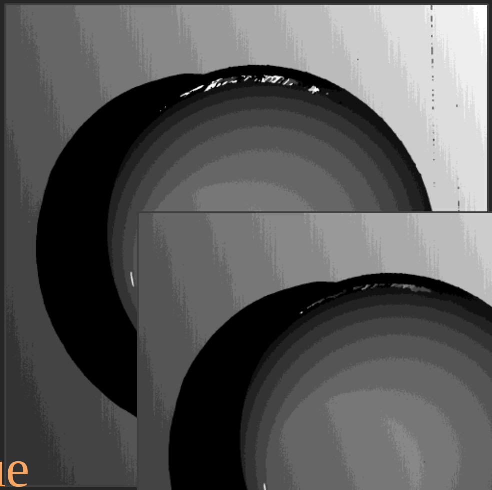


Ensemble of Codes for General Scenes

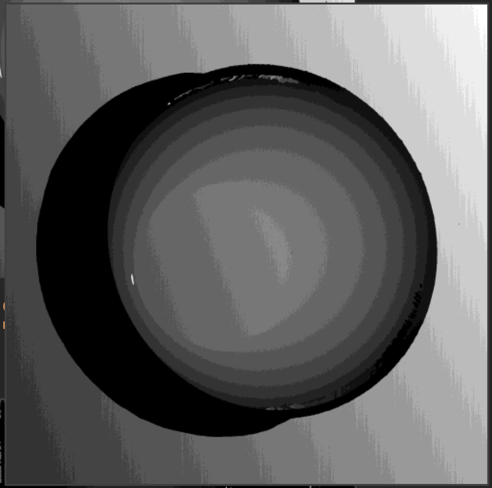


Conventional Gray (10 images)

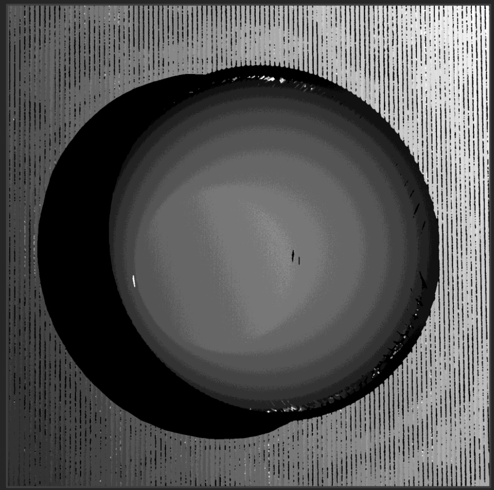
Return the
consistent value



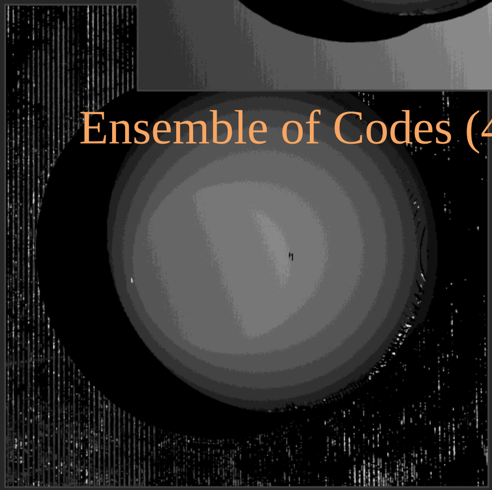
Max min-



Ensemble of Codes (41 images)

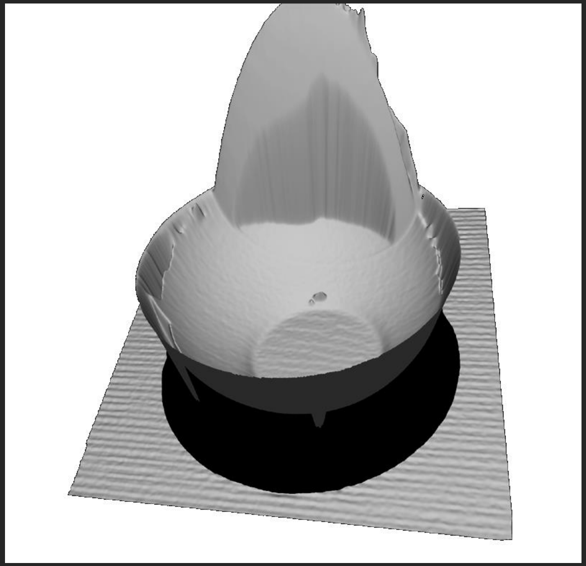


XOR-04 (10 images)

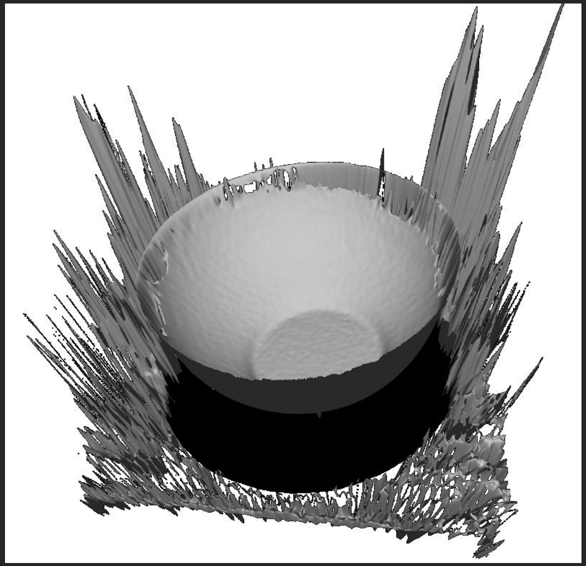


XOR-02 (10 images)

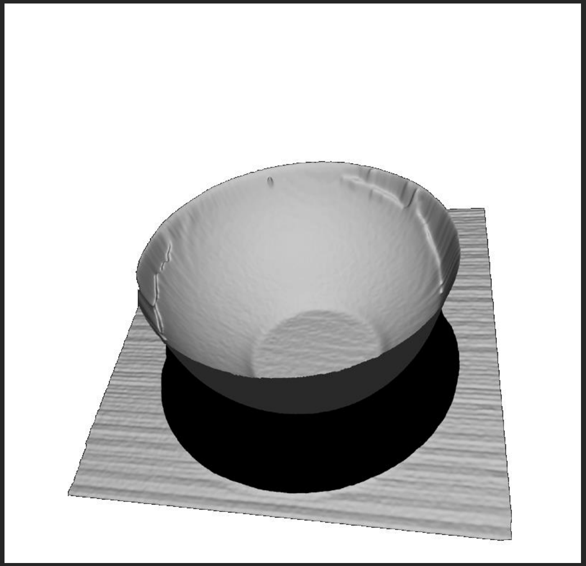
Shape Comparison



Conventional Gray
(11 images)

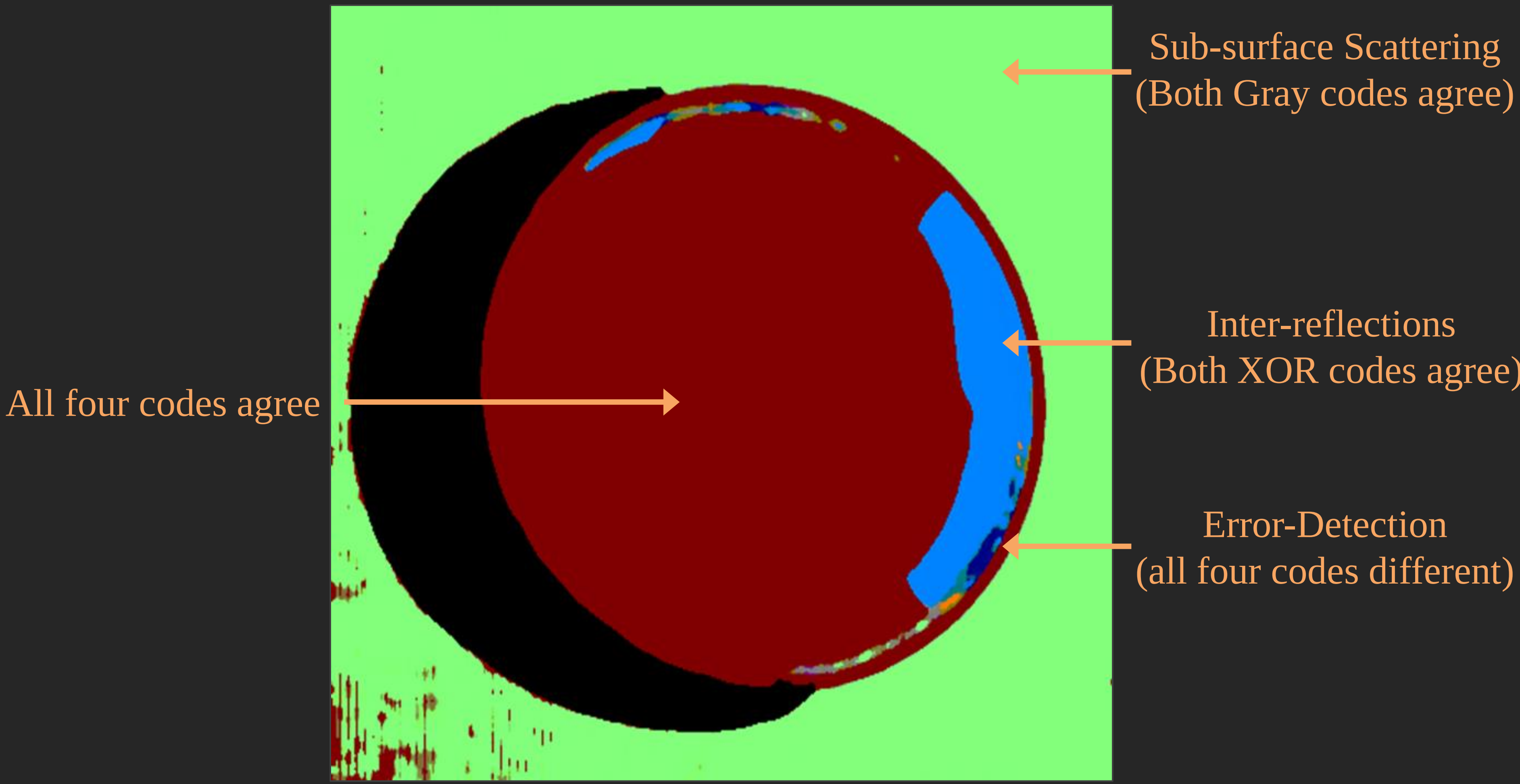


Modulated Phase-Shifting
(162 images)

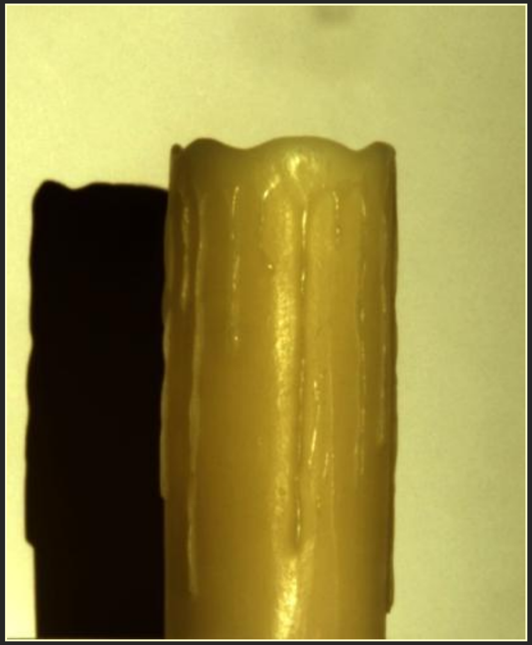


Our Technique
(41 images)

Qualitative Light Transport Analysis

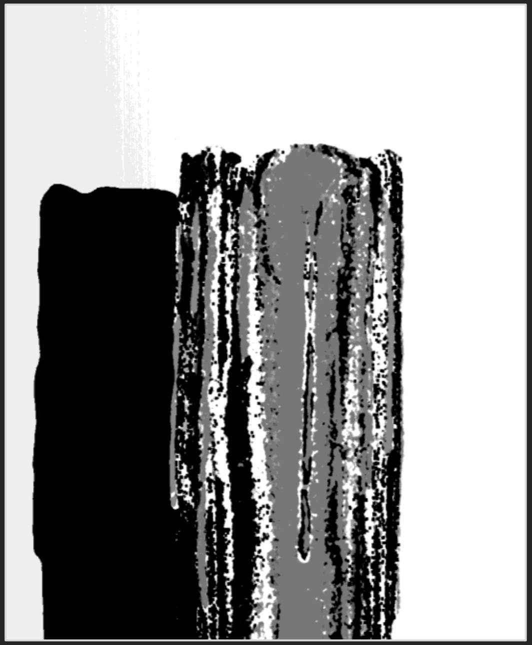


Translucent Wax Candle

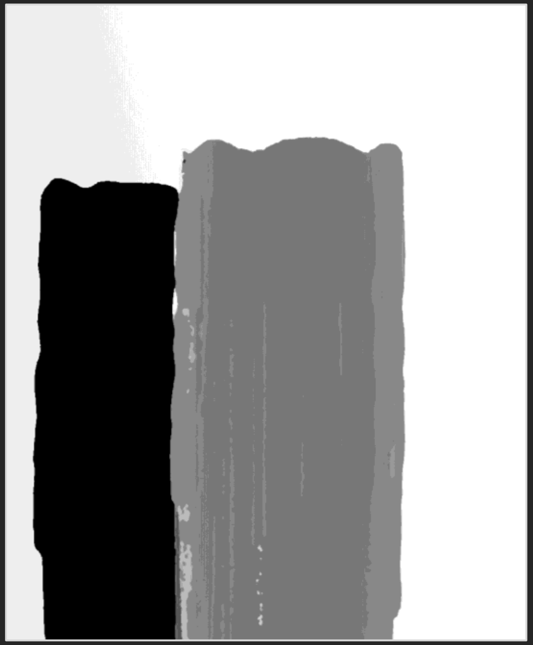


Scene

Errors due to strong sub-surface scattering



Modulated Phase-Shifting (162 images)

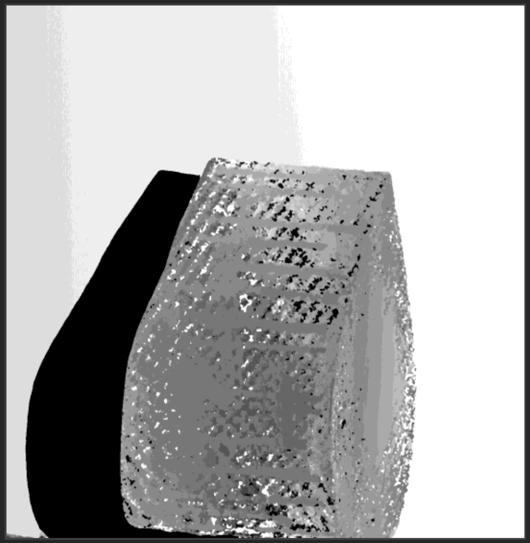


Our Ensemble Codes (41 images)

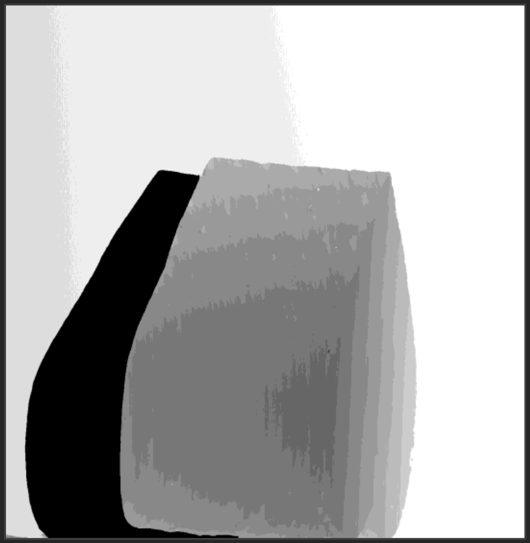
Translucent Wax Object

Errors due to strong
sub-surface scattering

Scene



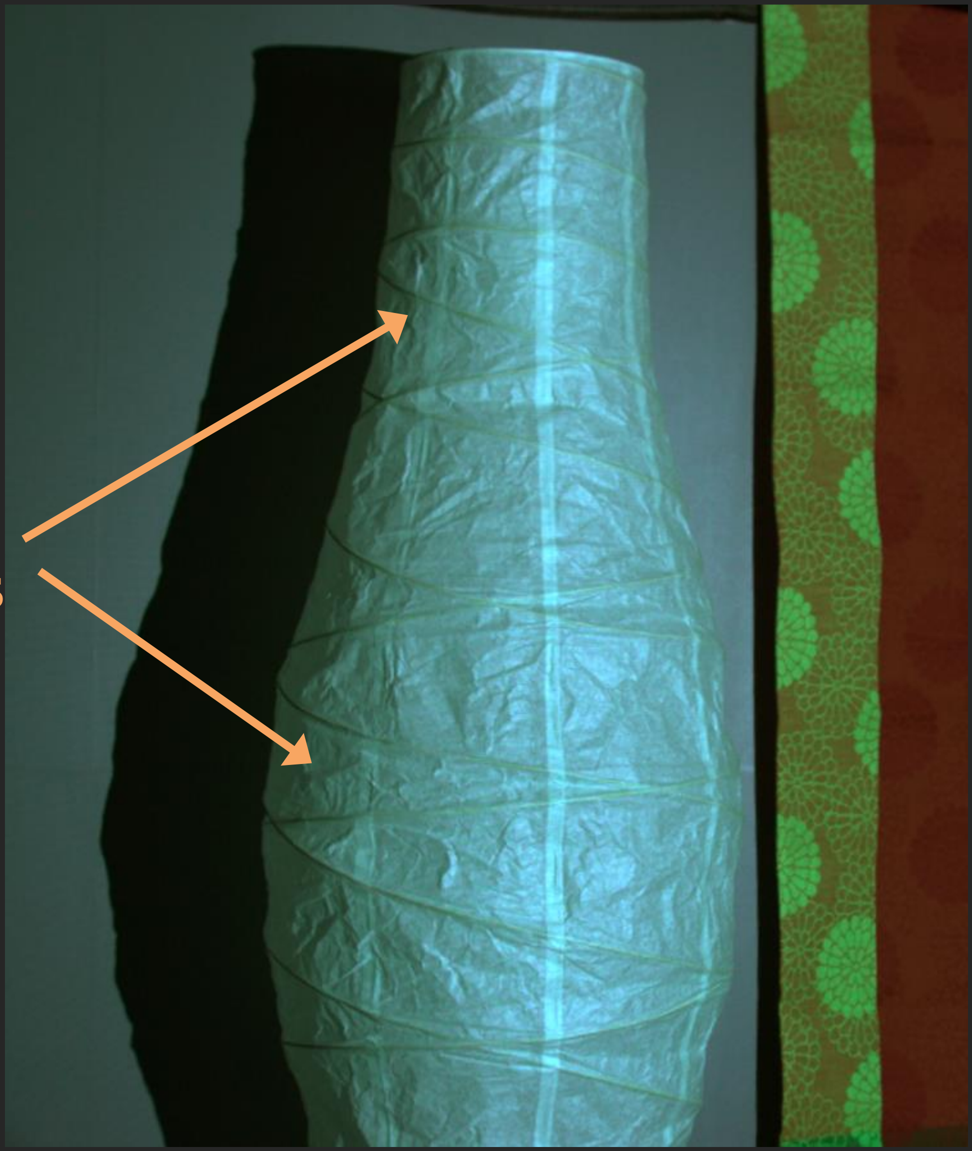
Modulated Phase-
Shifting (162 images)



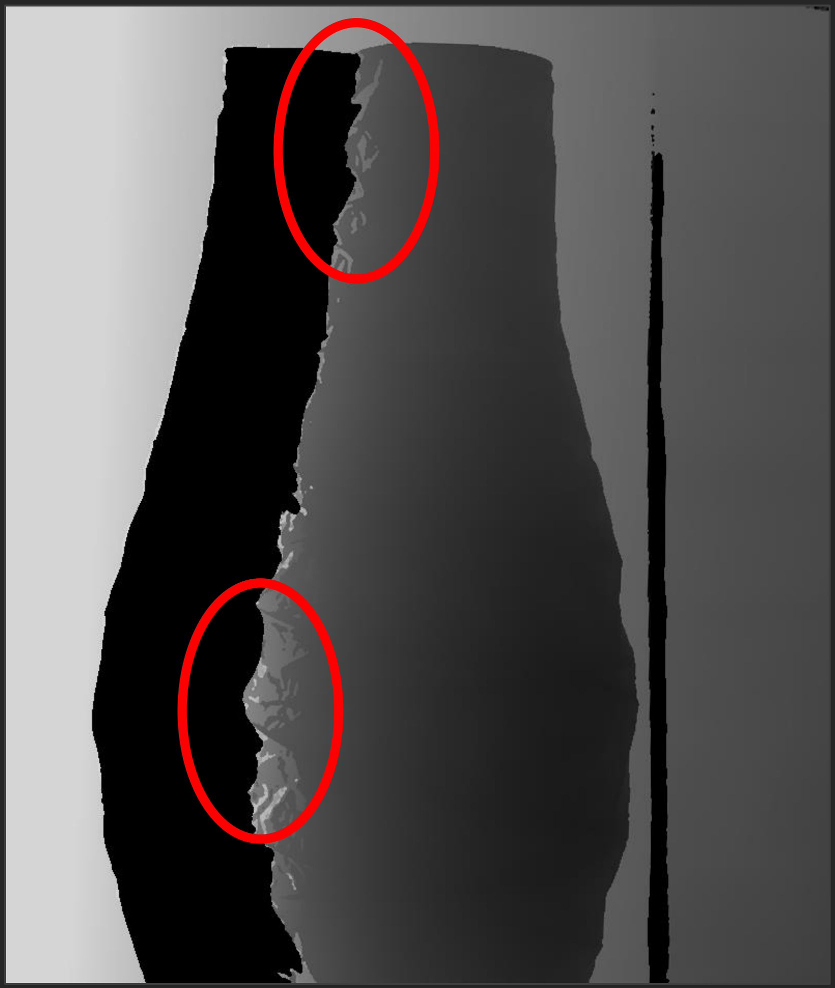
Our Ensemble Codes
(41 images)

Ikea Lamp

Diffusion +
Inter-reflections



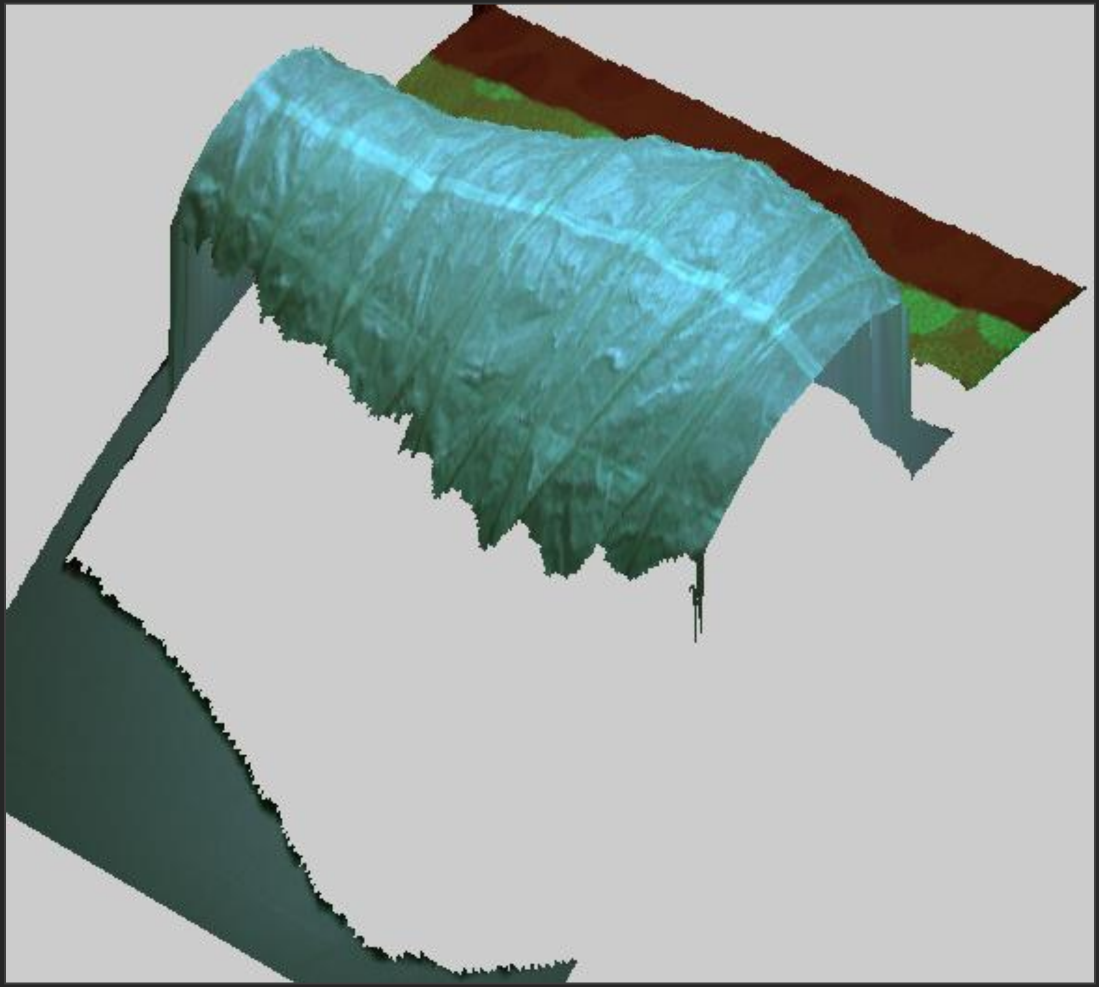
Depth-Map Comparison



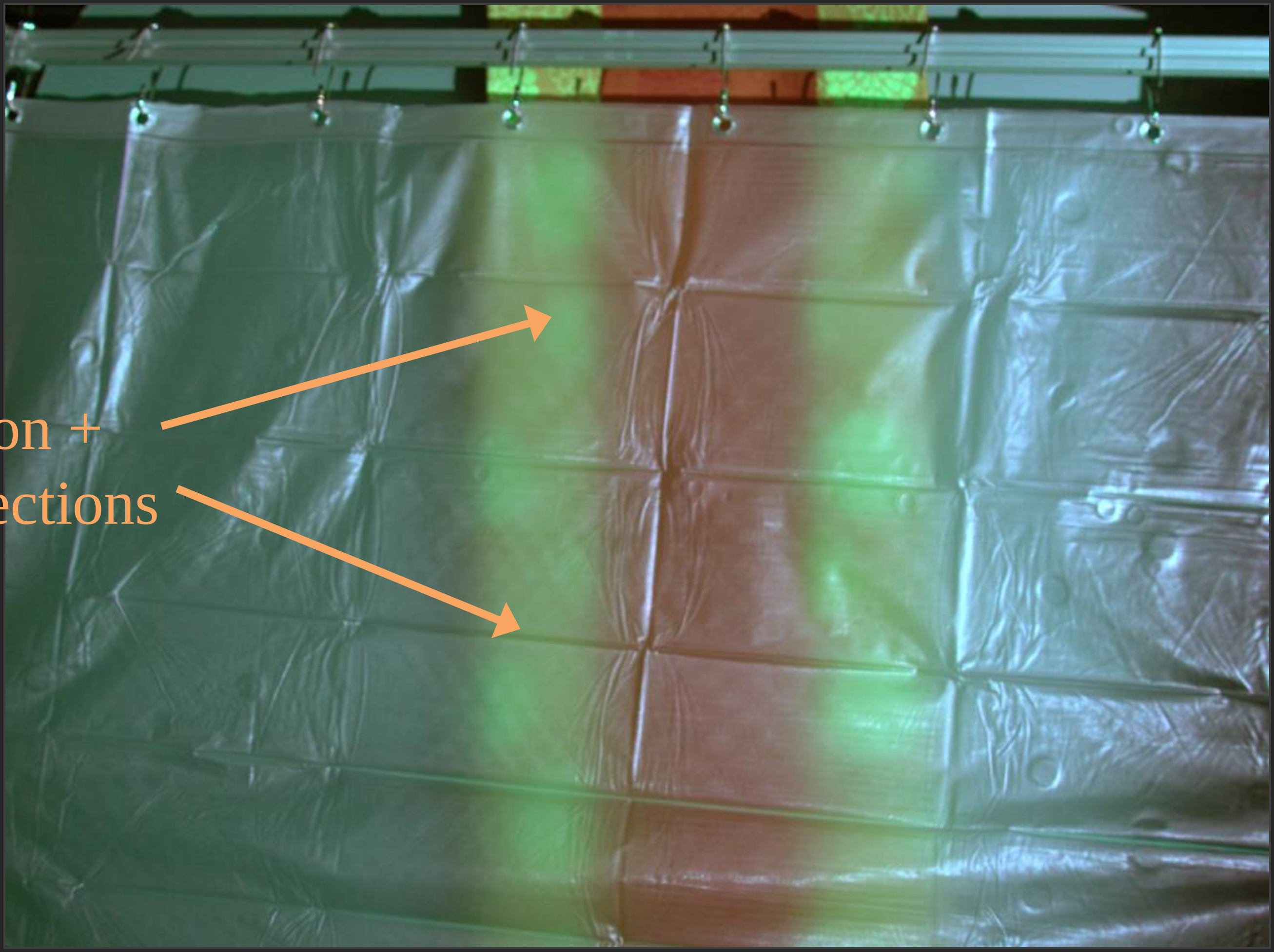
Regular Gray Codes (11 images)

Our Ensemble Codes (41 images)

3D Visualization using our ensemble codes



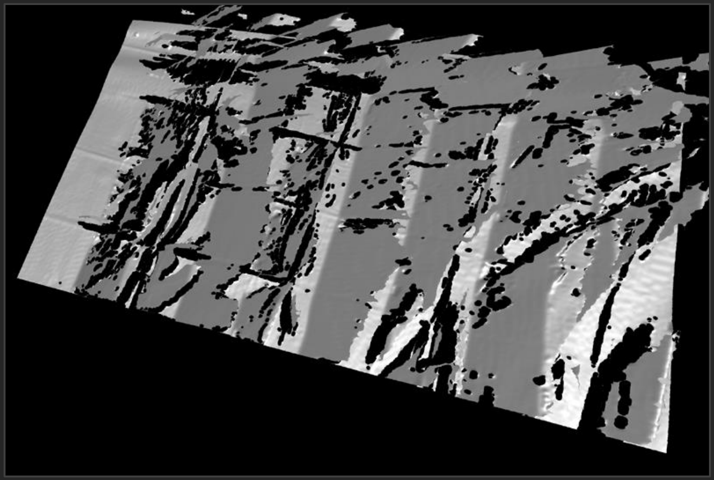
Shower Curtain



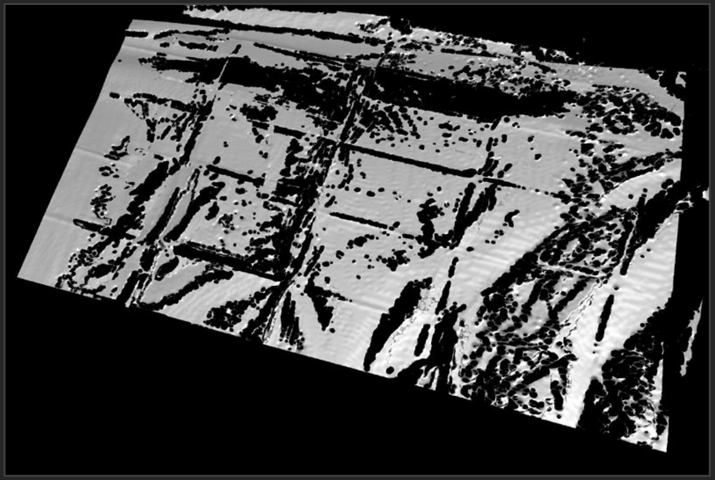
Diffusion + Inter-reflections

Goal is to reconstruct the shape of the shower-curtain. Shape of the curtain is planar because it was taped to the rod to avoid movement while capture.

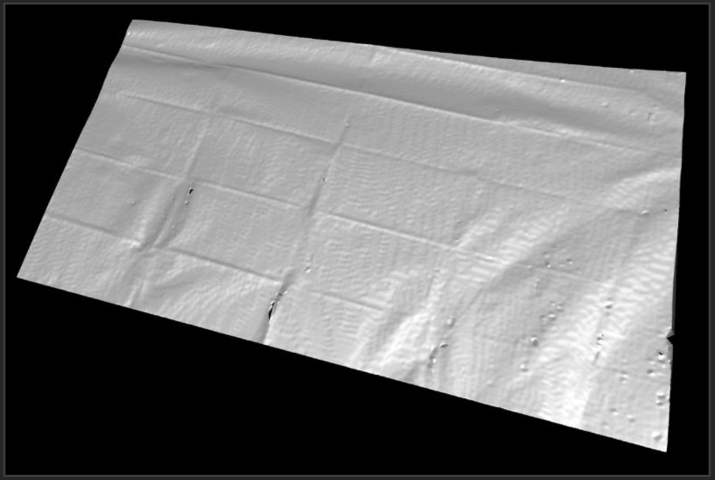
Shape Comparisons



Regular Gray Codes (11 images)

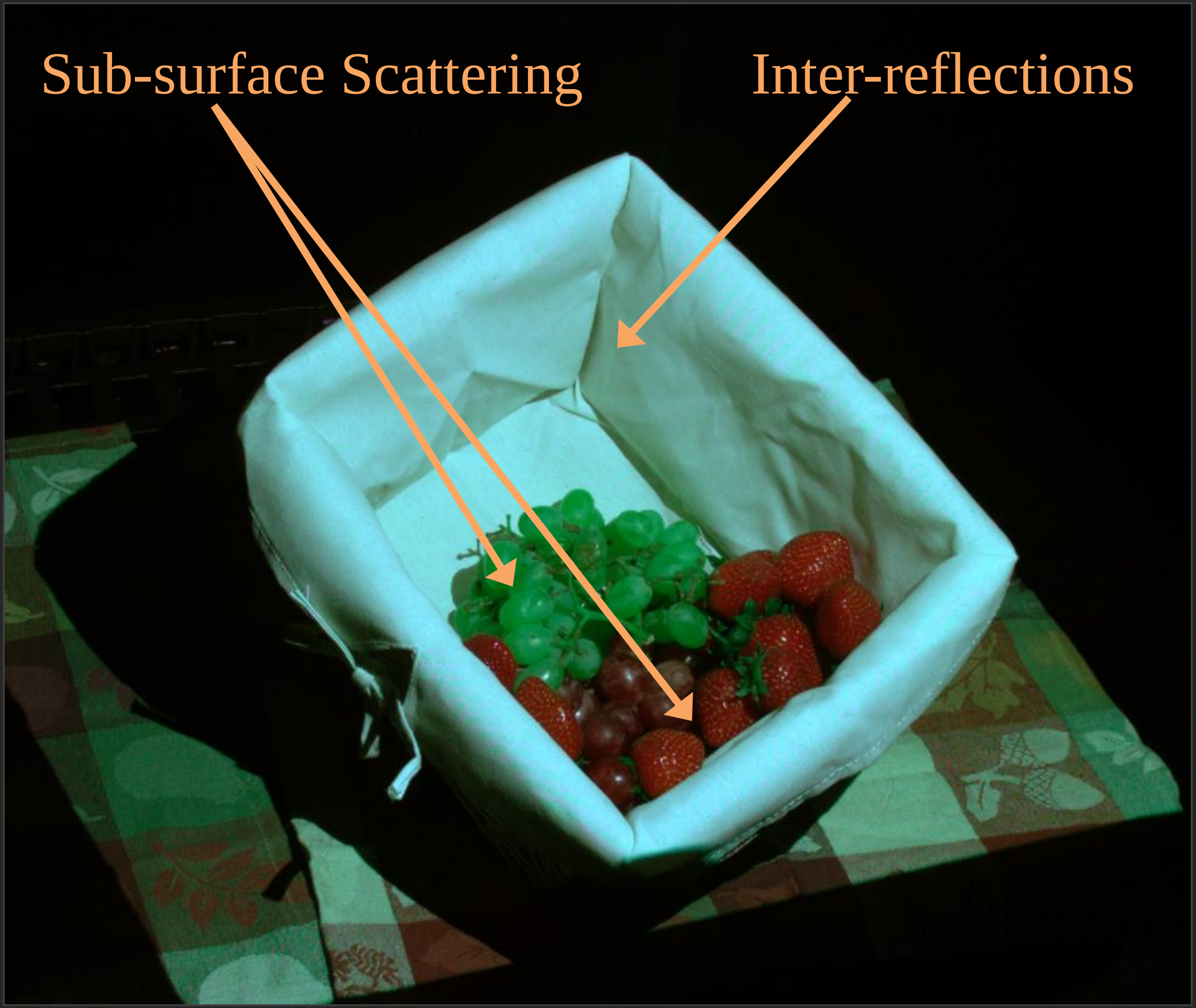


Phase-Shifting (18 images)

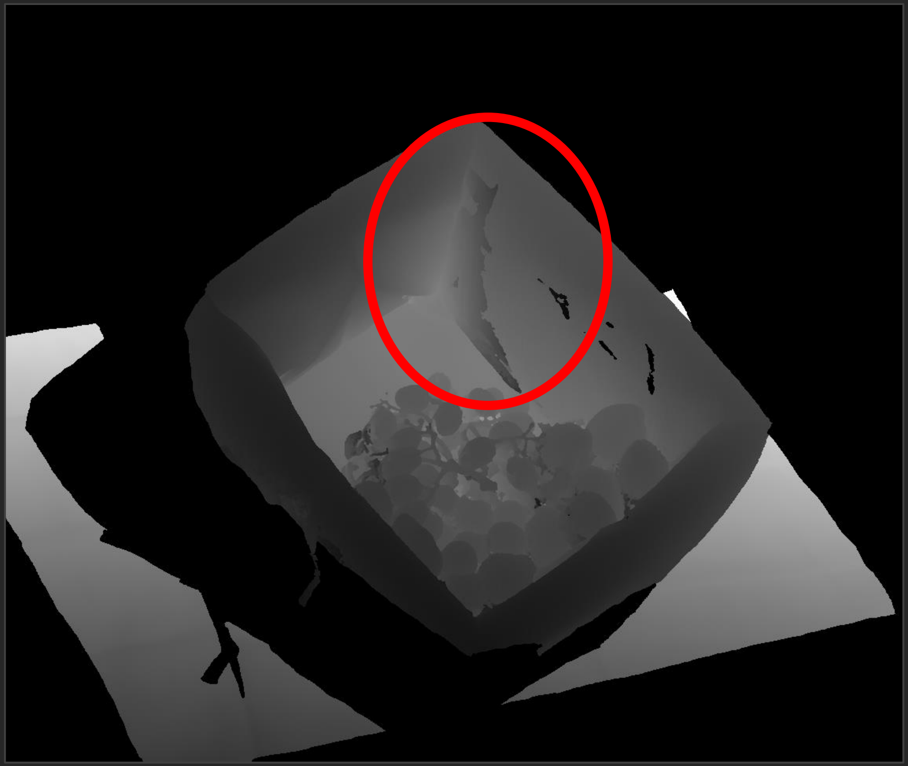


Our XOR Codes (11 images)

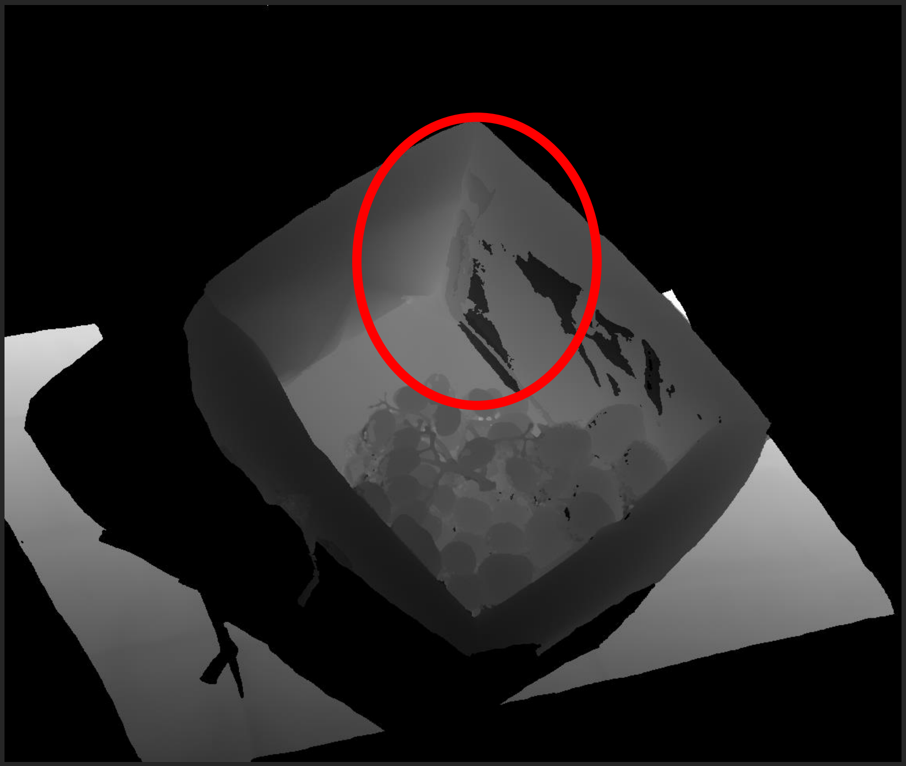
Fruit Basket: Multiple Effects



Depth-maps with previous state of the art

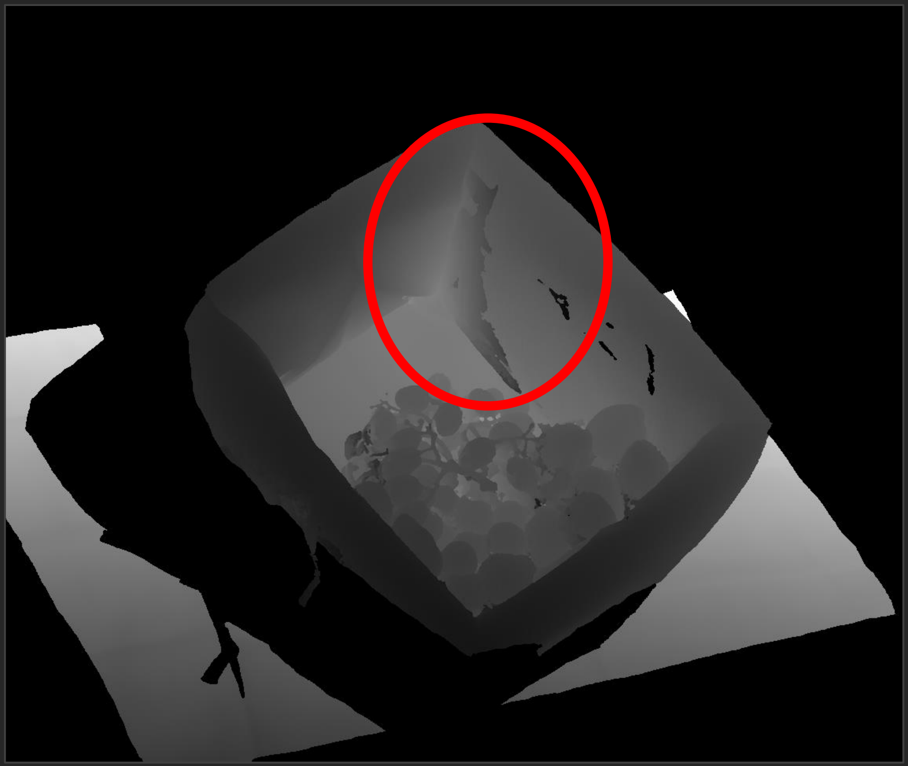


Regular Gray (11 images)

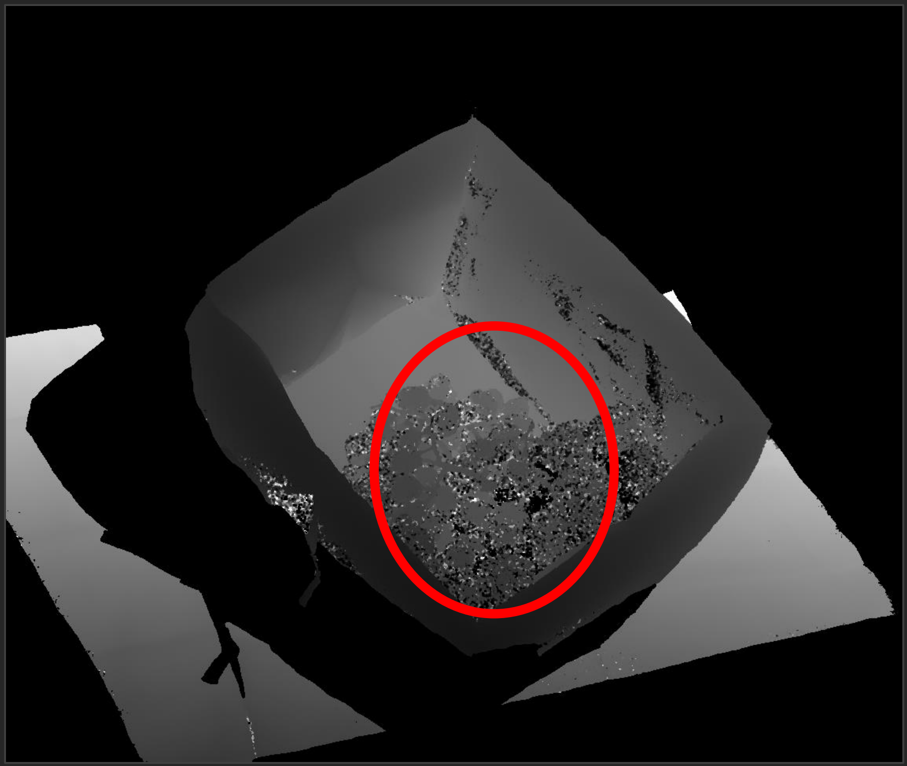


Phase-Shifting (18 images)

Depth-maps with previous state of the art

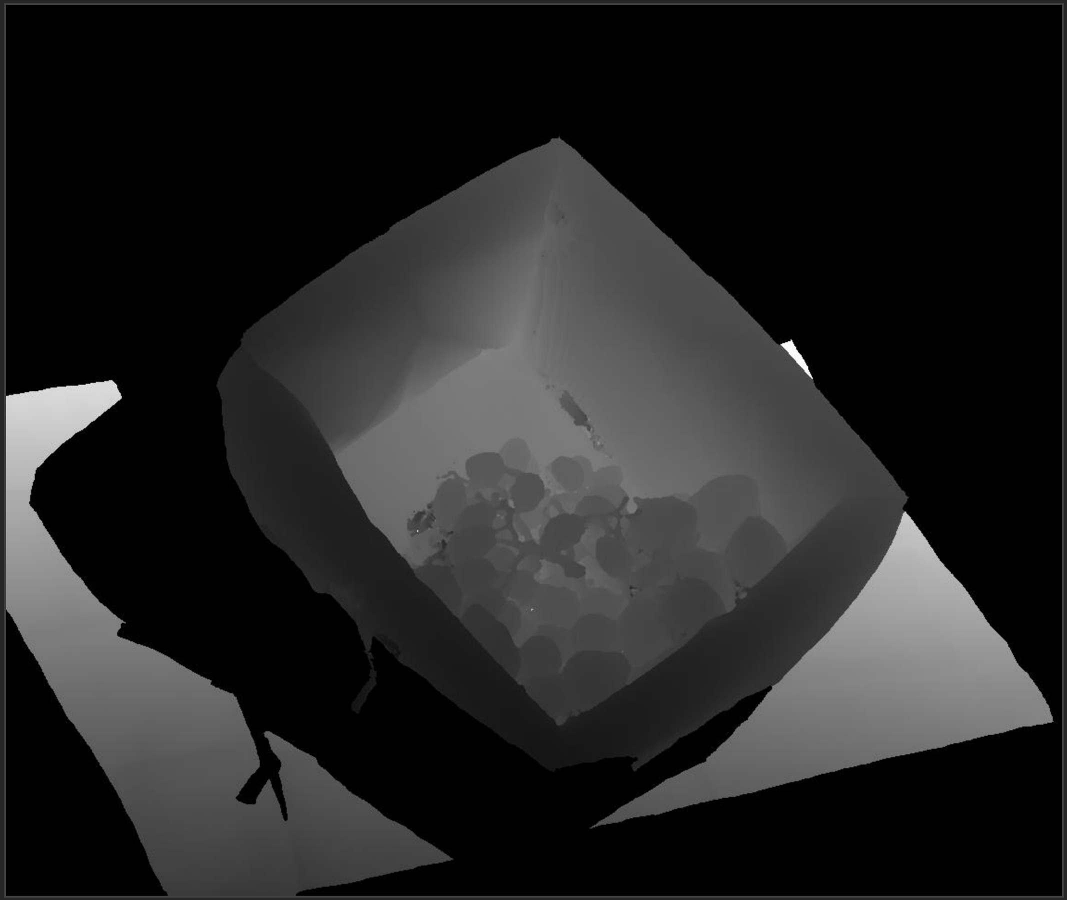


Regular Gray (11 images)



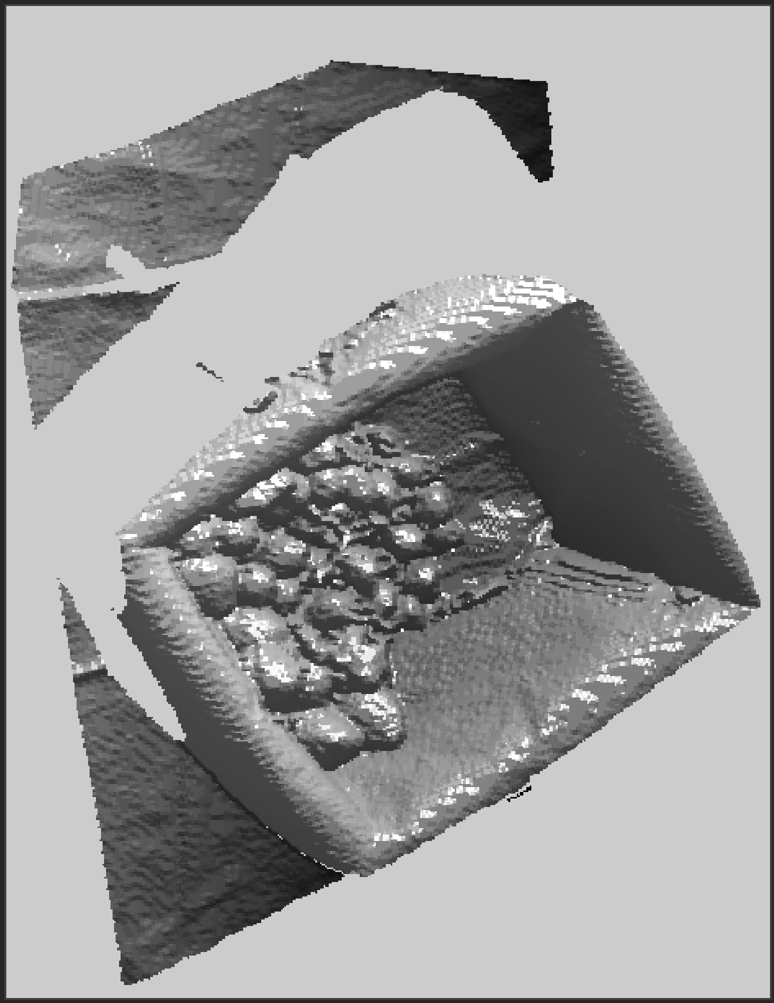
Modulated Phase-Shifting (162 images)

Depth-maps with our Ensemble Codes



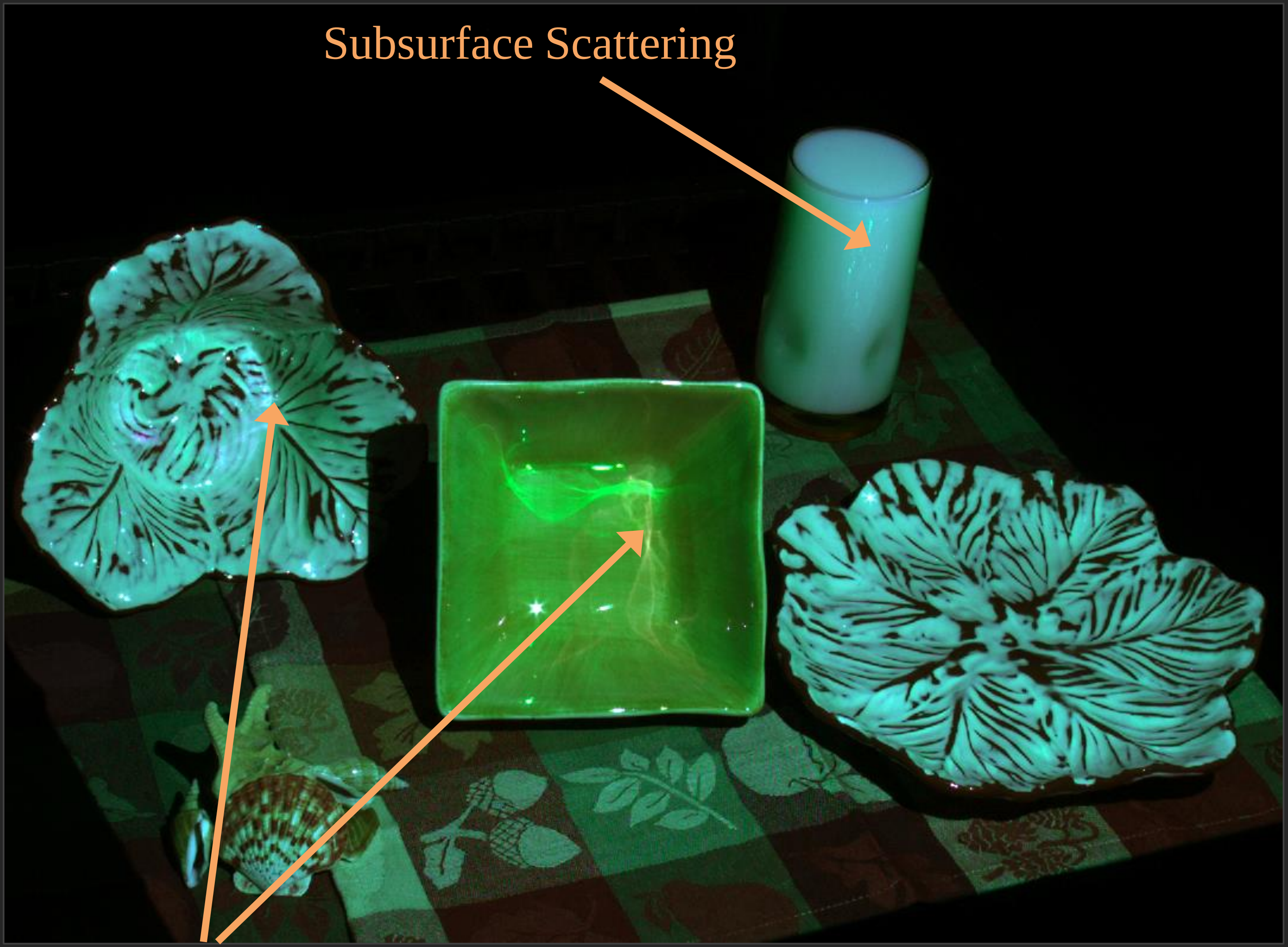
Our Ensemble Codes (41 images)

3D Visualizations with our ensemble codes

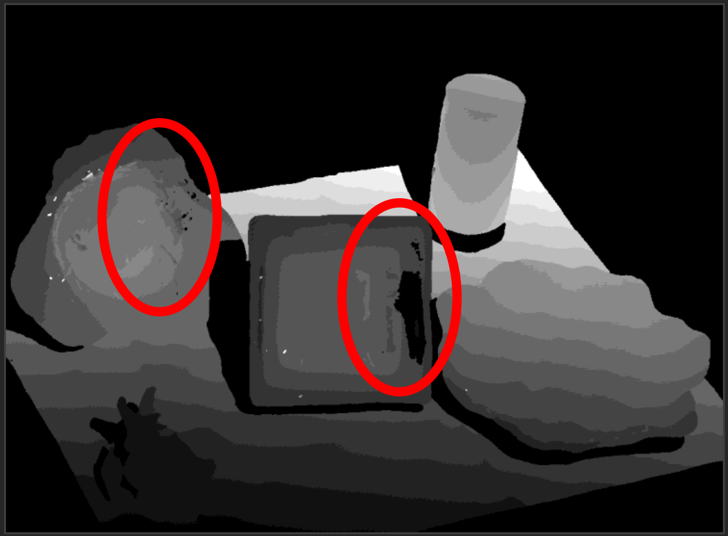


3D Visualization with our ensemble codes

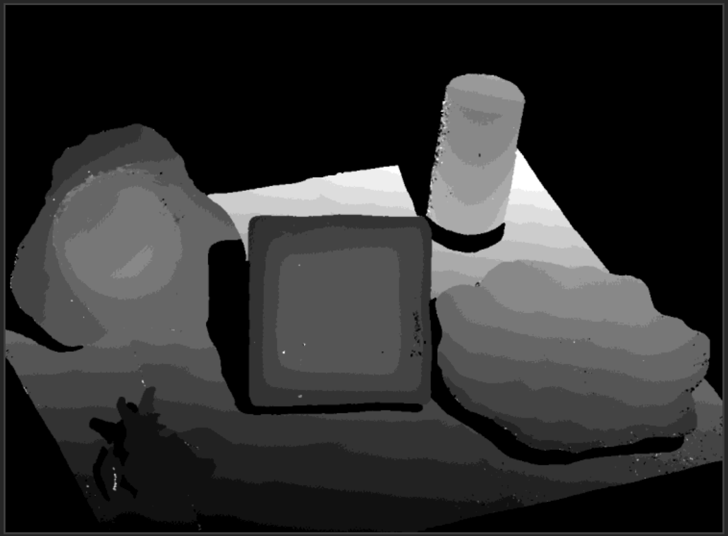
Bowls and Milk: Multiple Effects



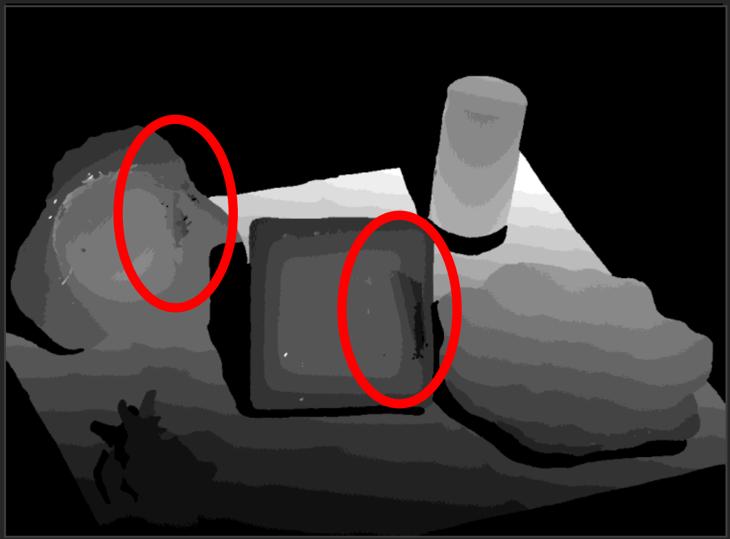
Interreflections



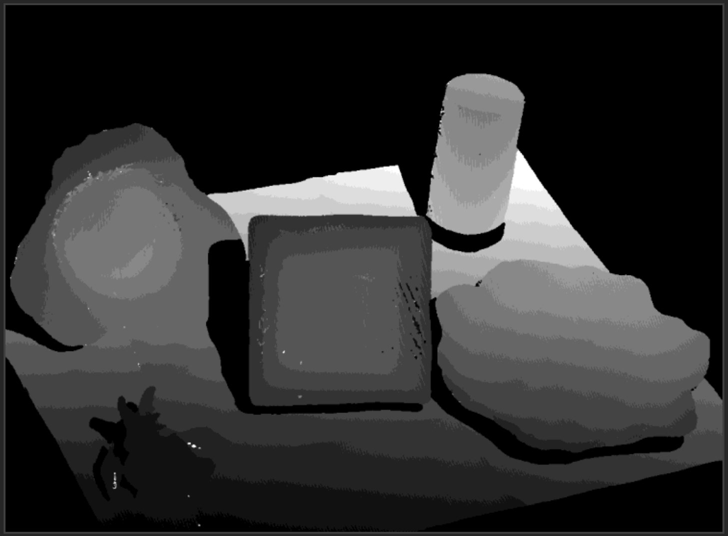
Phase-Shifting (18 images)



Modulated Phase-Shifting (162 images)

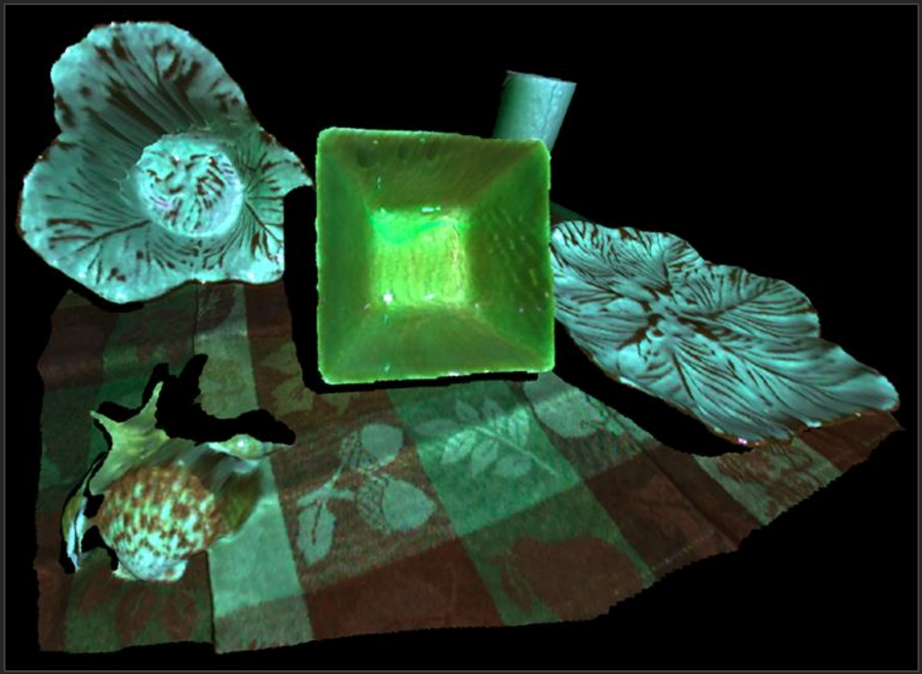


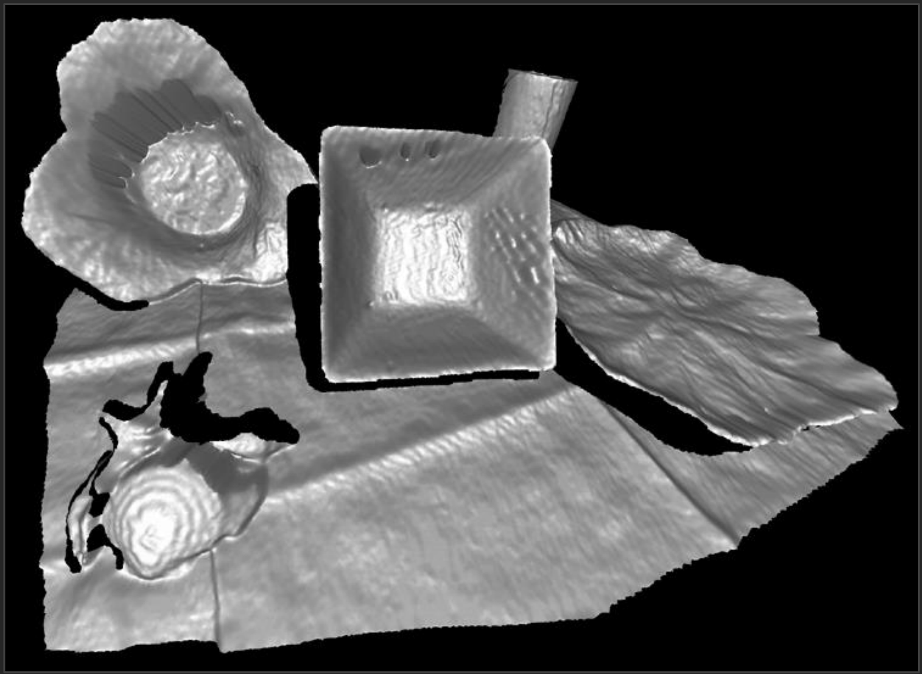
Regular Gray Codes (11 images)



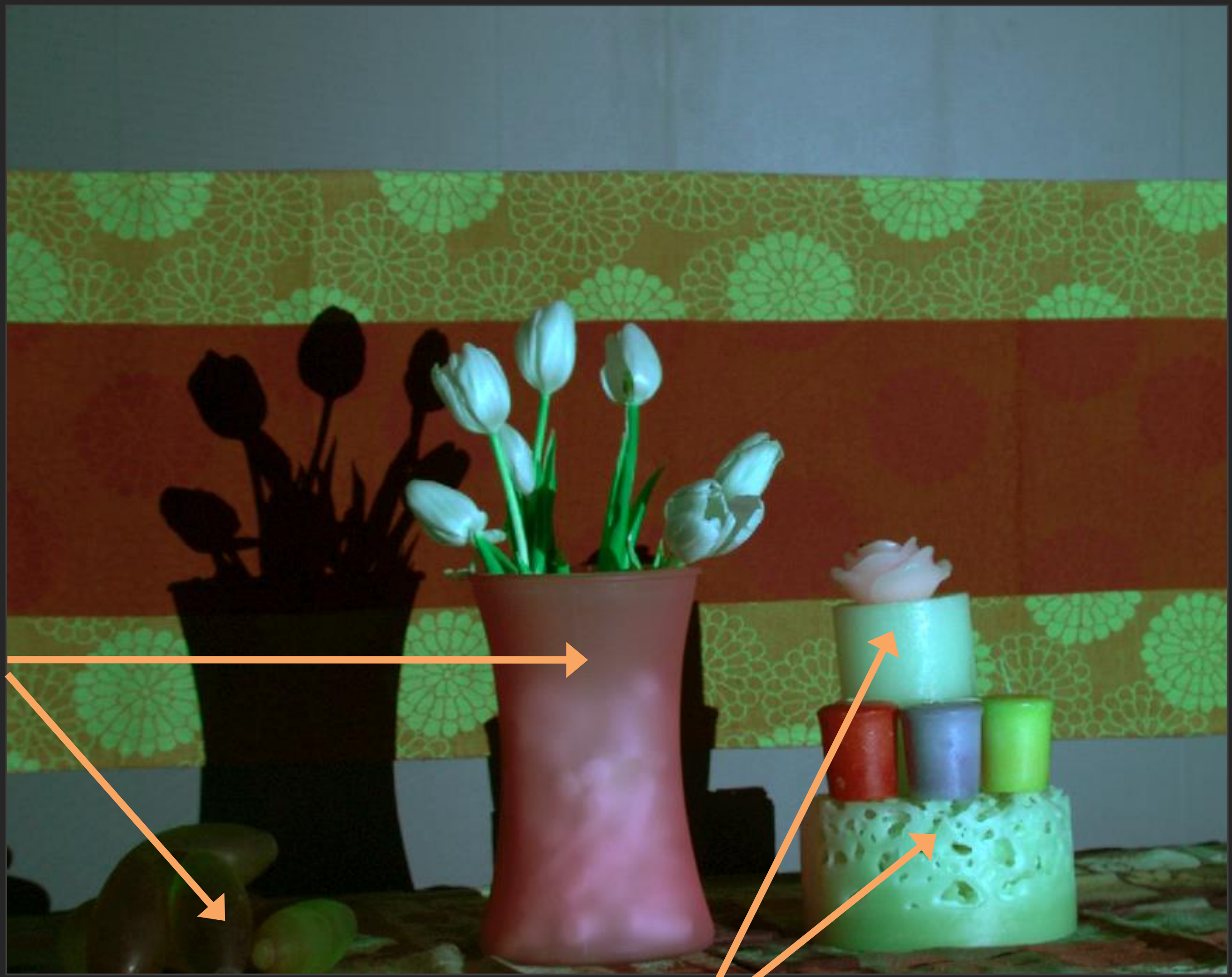
Our XOR Codes (11 images)

3D Visualizations with our ensemble codes





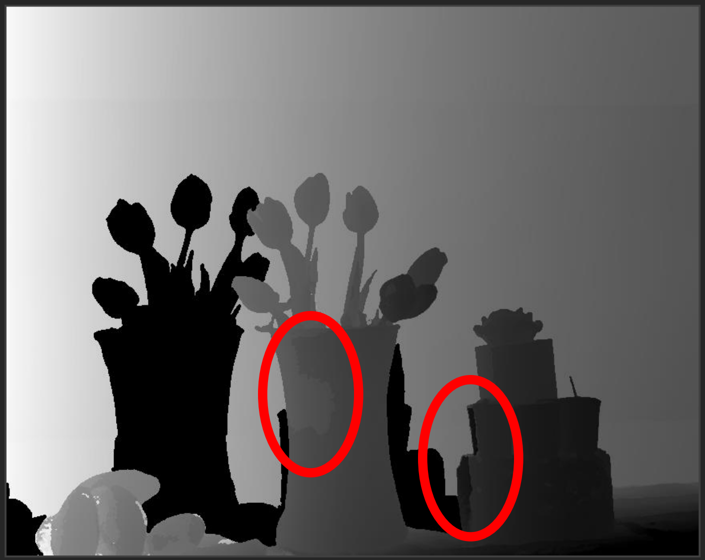
Flower-Vase



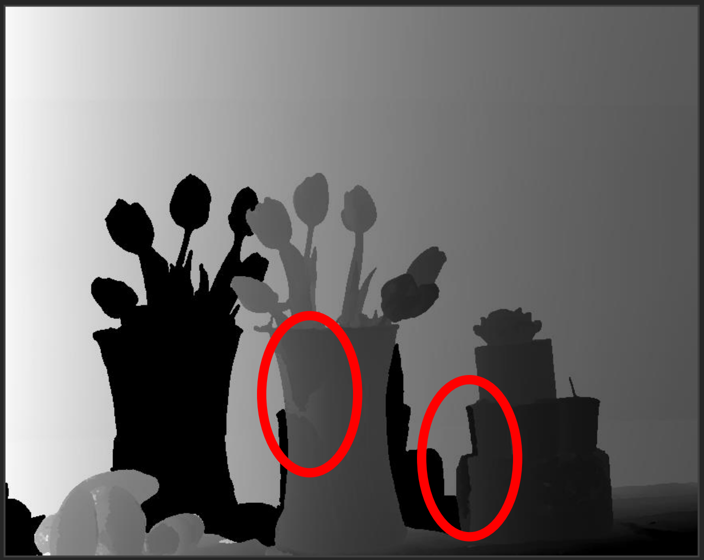
Diffusion

Sub-surface Scattering

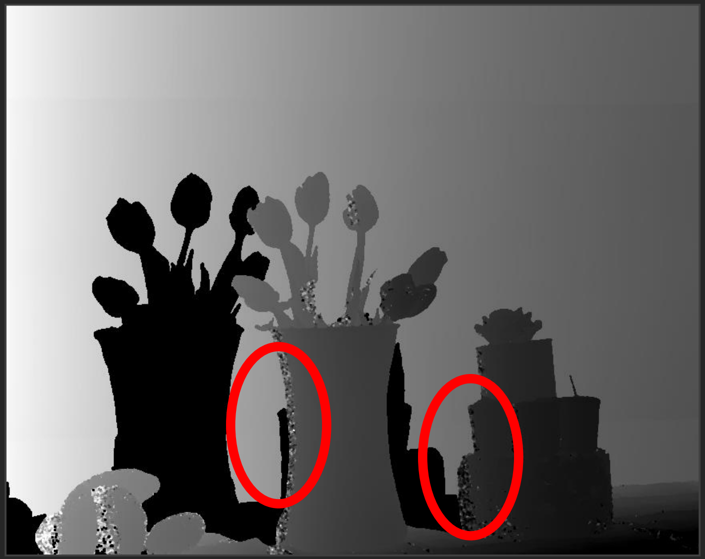
Comparison



Phase-Shifting (18 images)



Regular Gray Code (11 images)



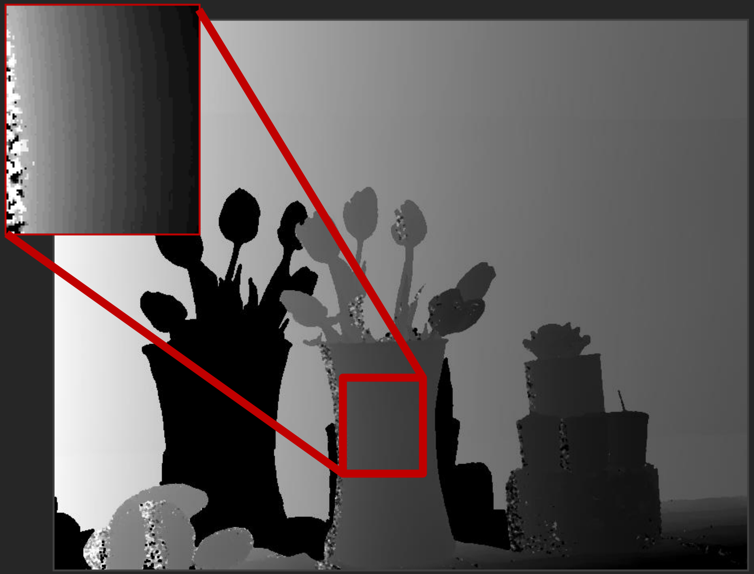
Modulated Phase-Shifting (162 images)

Our Ensemble Codes (41 images)

Comparison

Phase-Shifting (18 images)

Regular Gray Code (11 images)

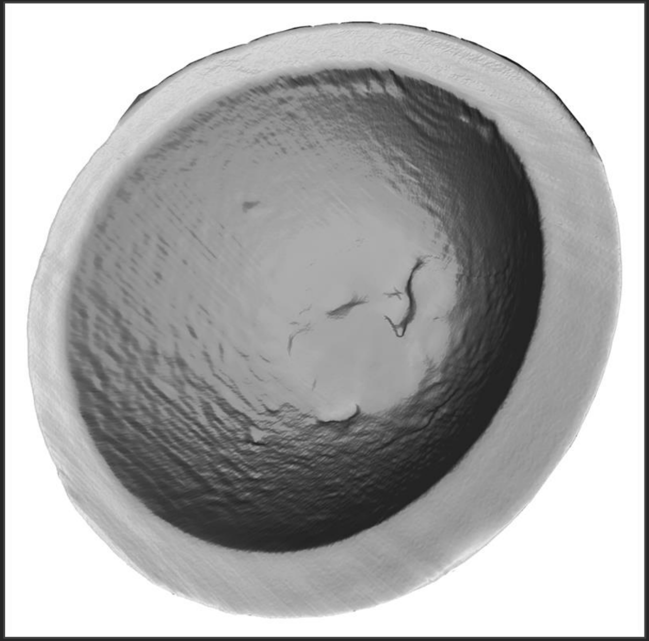


Modulated Phase-Shifting (162 images)

Our Ensemble Codes (41 images)

Multiple Global Illumination Effects

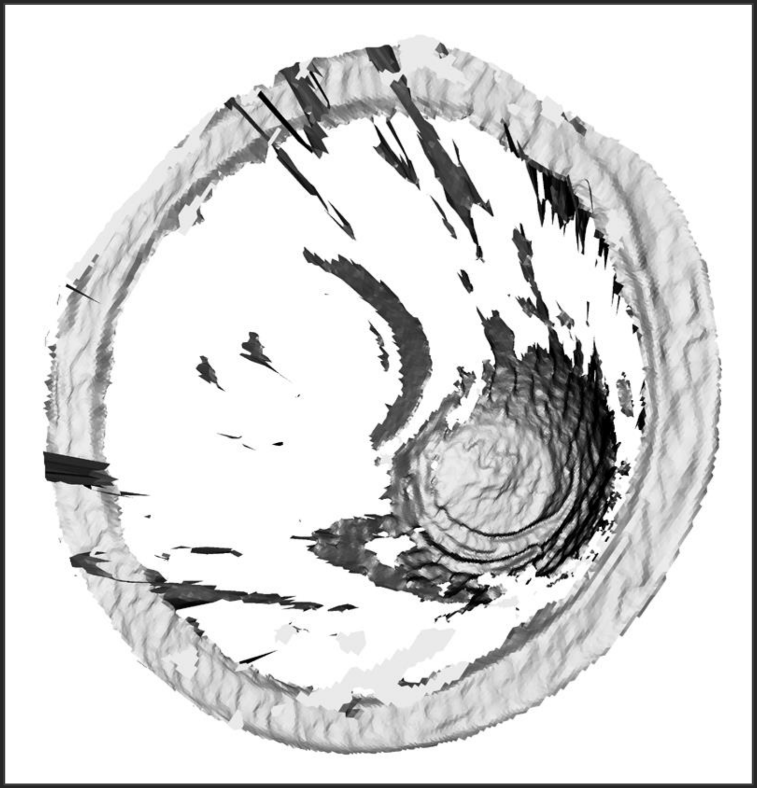
Wax Bowl



Shape Using Ensemble Codes

Multiple Global Illumination Effects

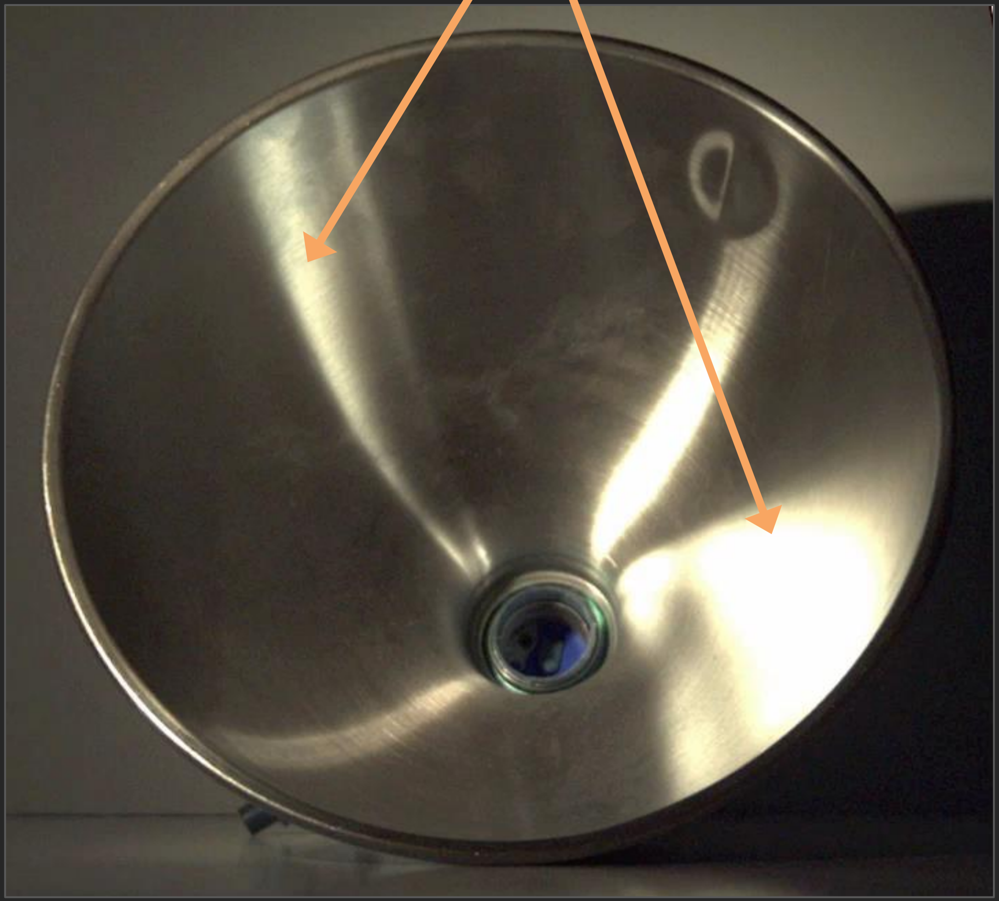
Deep Wax Container



Shape Using Ensemble Codes

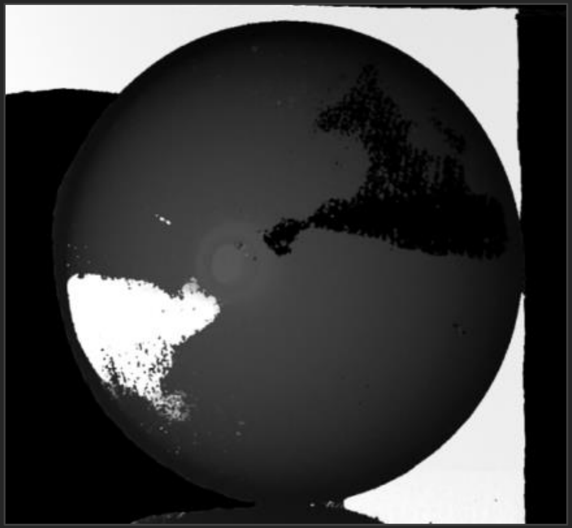
Lamp made of shiny brushed metal

Strong and high-frequency inter-reflections



Depth Map Comparison

Regular Gray (11 images)



Our Ensemble Codes (41 images)

References

Basic reading:

- Szeliski textbook, Sections 7.1, 11.1, 12.1.
- Lanman and Taubin, “Build Your Own 3D Scanner: Optical Triangulation for Beginners,” SIGGRAPH course 2009.

  this very comprehensive course has everything you need to know about 3D scanning using structured light, including details on how to build your own.
- Gupta et al., “A Practical Approach to 3D Scanning in the Presence of Interreflections, Subsurface Scattering and Defocus,” IJCV 2013.

  this paper has a very detailed treatment of problems to structured-light-based 3D scanning caused because of global illumination, and proposes the robust XOR patterns we discussed.

Additional reading:

- Gupta et al., “A Combined Theory of Defocused Illumination and Global Light Transport,” IJCV 2012.

  an earlier paper discussing global illumination and 3D scanning with structured light.
- O’Toole et al., “Homogeneous codes for energy-efficient illumination and imaging,” SIGGRAPH 2015.

  the epipolar imaging paper we covered in a previous class also includes a discussion of how epipolar imaging helps when performing stereo-based 3D scanning in the presence of global illumination.