Structured-Light Based Acquisition (Part 1)

CS635
Daniel G. Aliaga
Department of Computer Science
Purdue University

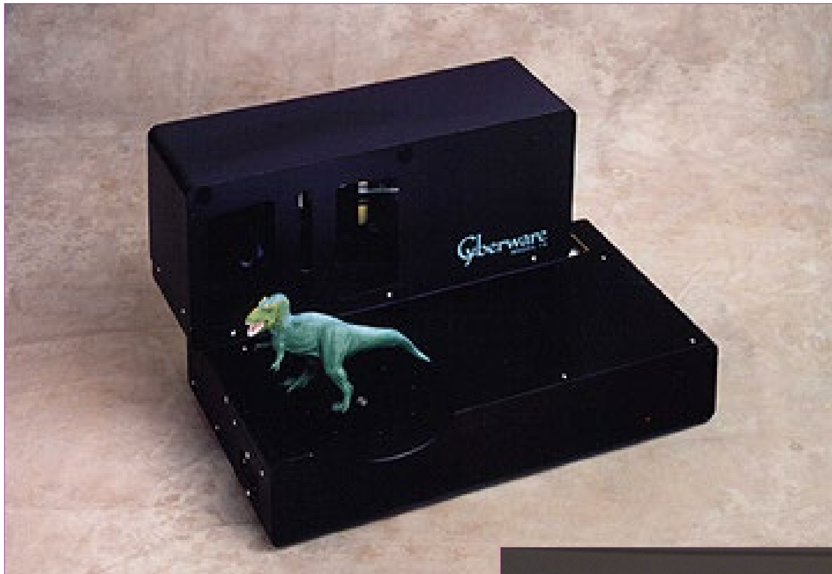
Passive vs. Active Acquisition

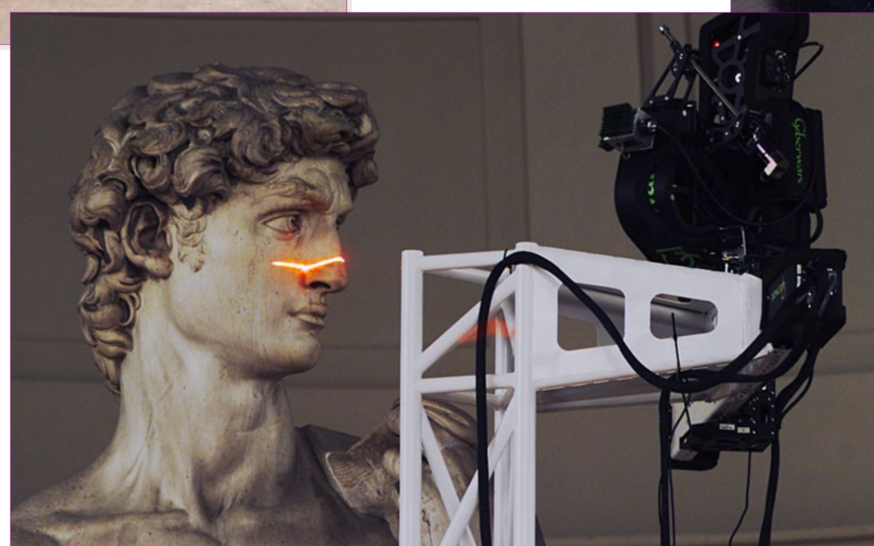
- Passive
  - \+ Just take pictures
  - \+ Does not intrude in the environment (=passive)
  - – Some surfaces cannot be acquired
  - – Robustness is problematic
- Active
  - \+ Emit “light” into the scene so as to force the generation of robust correspondence
  - – Environment is intruded (=active)

Active Acquisition

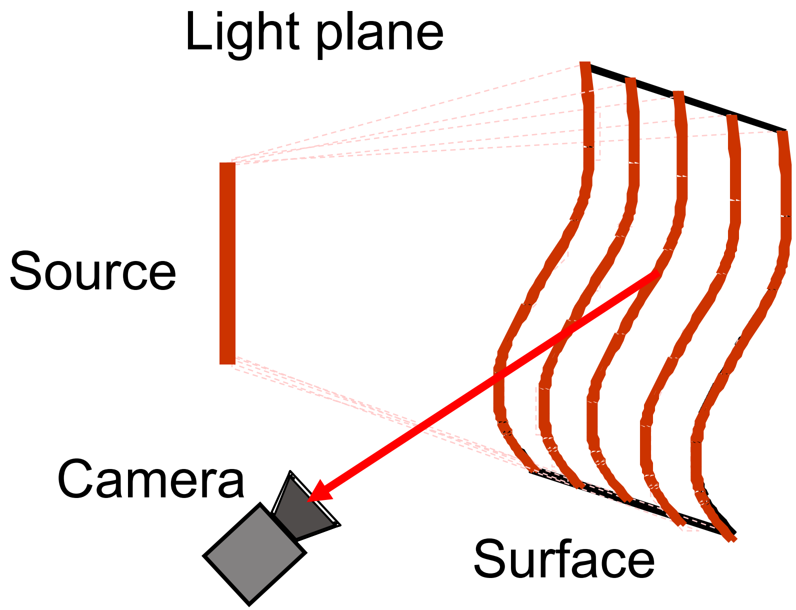
- Some options:
  - Laser scanning
  - “Structured Light”

Laser Scanning



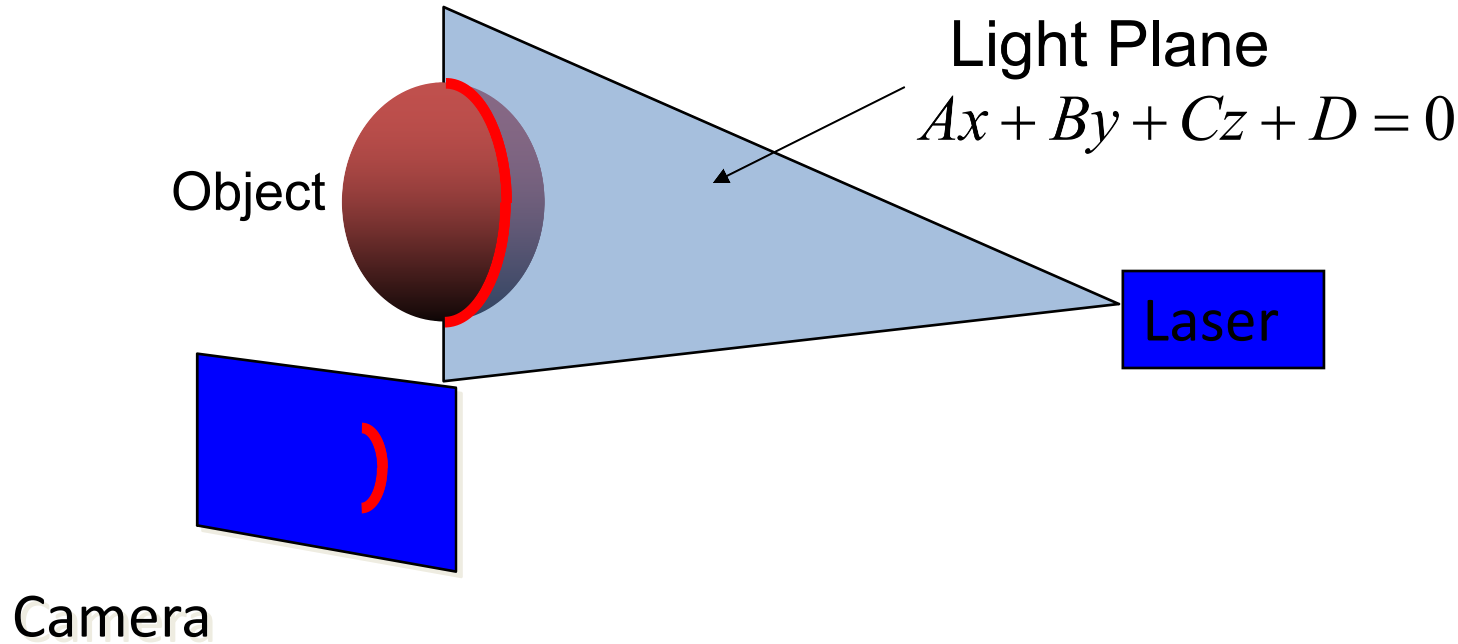


Light Stripe Scanning (Single Stripe)



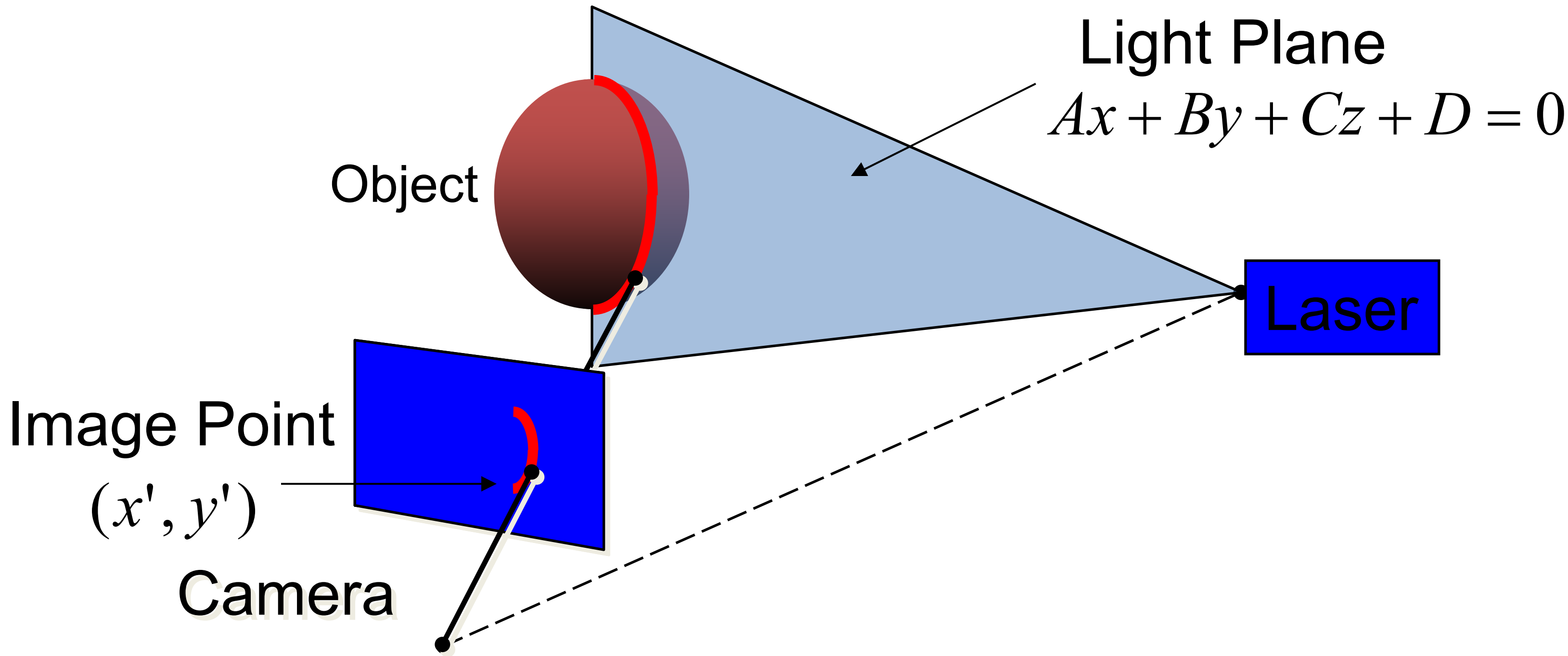
- Optical triangulation
  - Project a single stripe of laser light
  - Scan it across the surface of the object
  - This is a very precise version of structured light scanning
  - Good for high resolution 3D, but needs many images and takes time

Stripe Triangulation



- Project laser stripe onto object

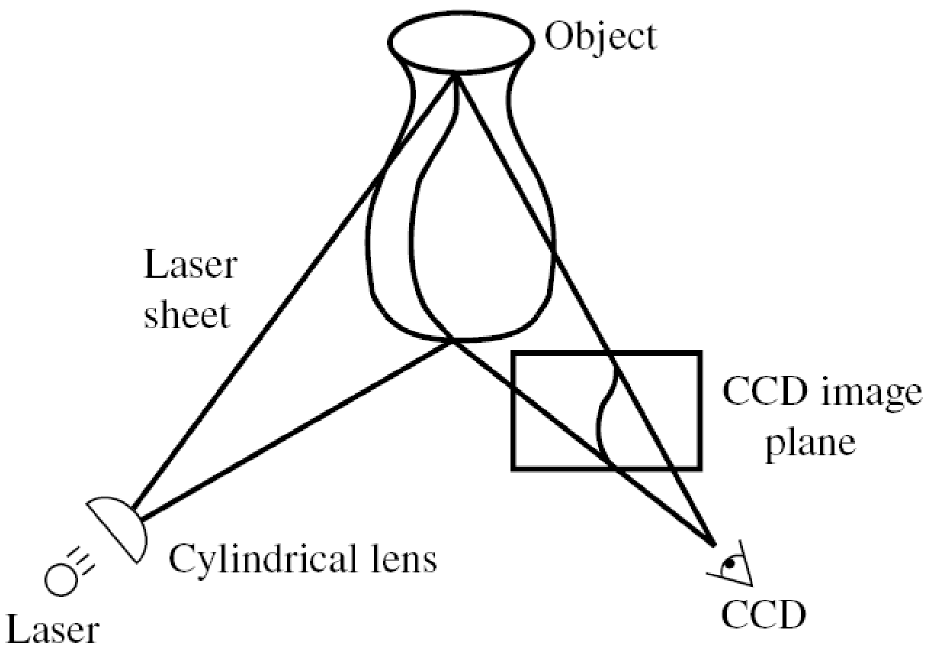
Stripe Triangulation



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

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

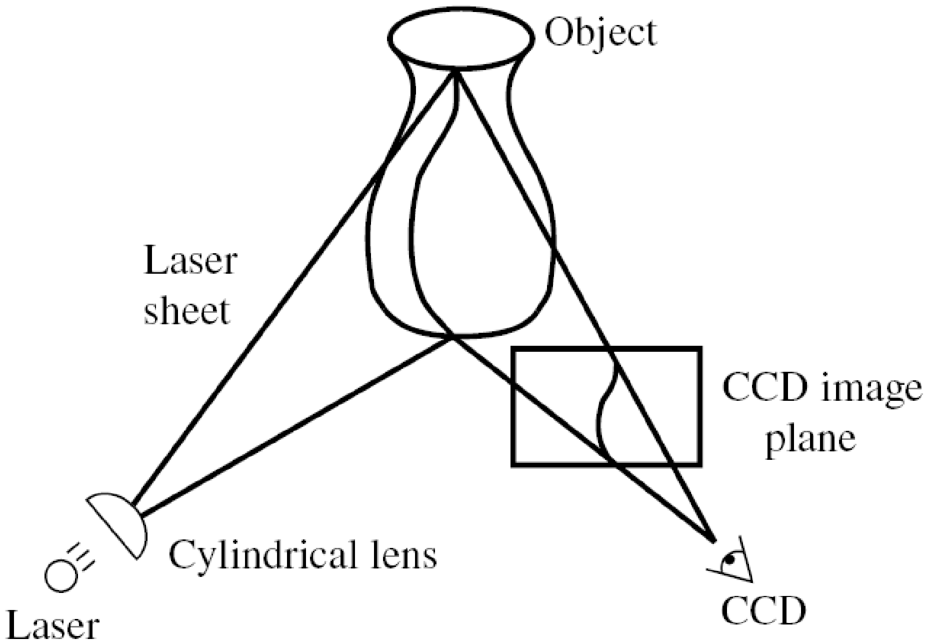
Example: Laser scanner

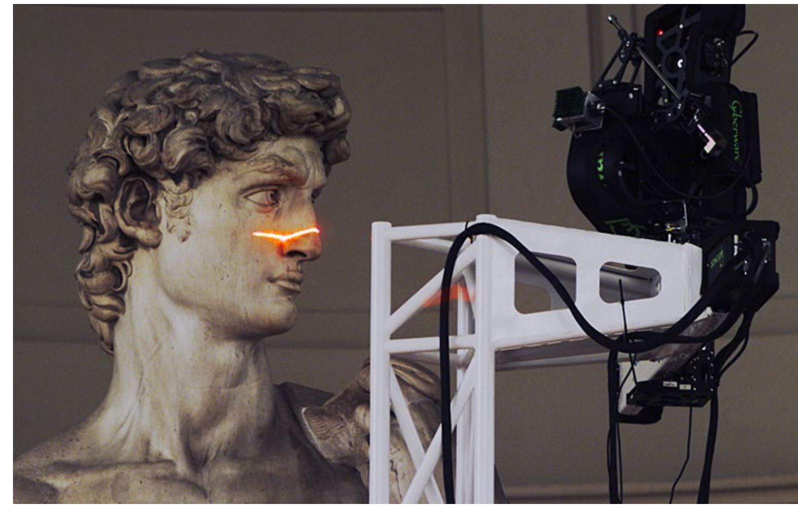


- \+ very accurate < 0.01 mm
- − more than 10sec per scan

Cyberware® face and head scanner

Example: Laser scanner

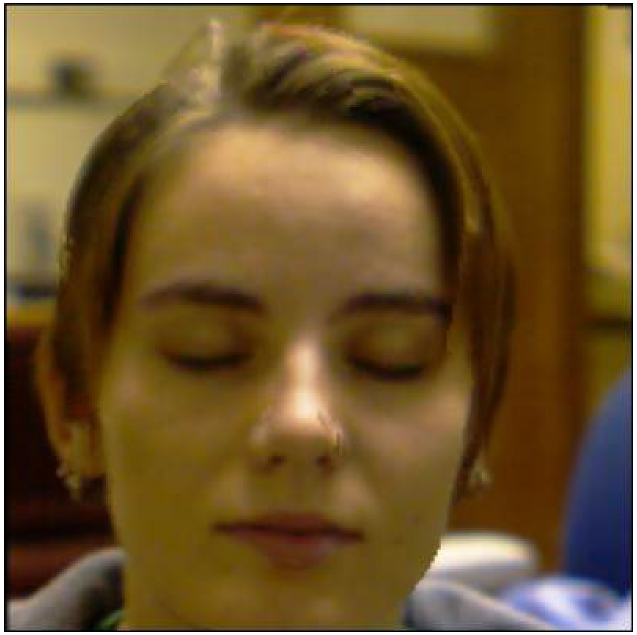




Digital Michelangelo Project

http://graphics.stanford.edu/projects/mich/

Example: Laser scanner



Portable scanner by Minolta

Digital Projector Structured Light

- Goal: generate correspondences so as to enable a robust 3D reconstruction

Digital Projector Structured Light

- Method:
  - Use the projector as a “pattern” generator
  - Have the camera see the “pattern” and generate 1 or more corresponded points

Digital Projector Structured Light

- What are possible patterns?
  - Spatial patterns
  - Temporal patterns
  - Color patterns
  - And combinations of the above

Digital Projector Structured Light

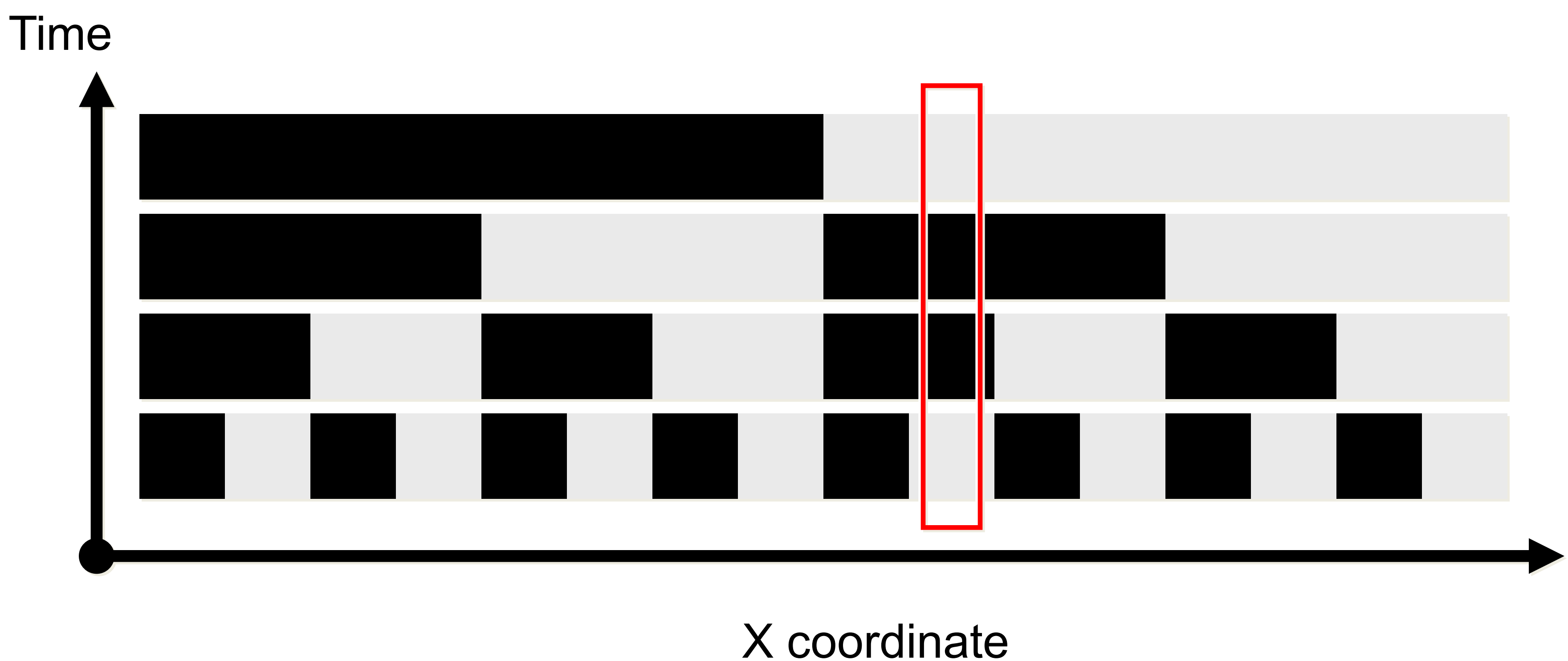
			Scene applicability: Static	Scene applicability: Moving	Pixel depth: Binary	Pixel depth: Grey levels	Pixel depth: Colour	Coding strategy: Periodical	Coding strategy: Absolute
Time-multiplexing	Binary codes	Posdamer et al.	√		√				√
		Inokuchi et al.	√		√				√
		Minou et al.	√		√				√
		Trobina	√		√				√
		Valkenburg and McIvor	√		√				√
		Skocaj and Leonardis	√		√				√
		Rocchini et al.	√				√		√
	n-ary codes	Caspi et al.	√				√		√
		Horn and Kiryati	√			√			√
	Gray code + Phase shifting	Bergmann	√			√			√
		Sansoni et al.	√		√				√
		Wiora	√			√			√
		Gühring	√		√				√
	Hybrid methods	Kosuke Sato	√		√	√			√
		Hall-Holt and Rusinkiewicz		√	√				√
Spatial Neighborhood	Non-formal codification	Maruyama and Abe		√	√			√	
		Durdle et al.		√		√		√	
		Ito and Ishii		√		√			√
		Boyer and Kak		√			√		√
		Chen et al.		√			√		√
	De Bruijn sequences	Hügli and Maître		√			√		√
		Monks et al.		√			√		√
		Vuylsteke and Oosterlinck		√	√				√
		Salvi et al.		√			√		√
		Lavoie et al.		√			√		√
		Zhang et al.	√	√			√		√
	M-arrays	Morita et al.	√		√				√
		Petriu et al.		√	√				√
		Kiyasu et al.		√	√				√
		Spoelder et al.		√	√				√
		Griffin and Yee		√	√		√		√
		Davies and Nixon		√			√		√
		Morano et al.	√		√		√		√
Direct coding	Grey levels	Carrihill and Hummel	√			√			√
		Chazan and Kiryati	√			√			√
		Hung		√		√		√	
	Colour	Tajima and Iwakawa	√				√		√
		Smutny and Pajdla	√				√		√
		Geng		√			√		√
		Wust and Capson		√			√	√	
		Tatsuo Sato	√				√	√	

Lets focus on binary striped patterns…

Binary Pattern Structured Light

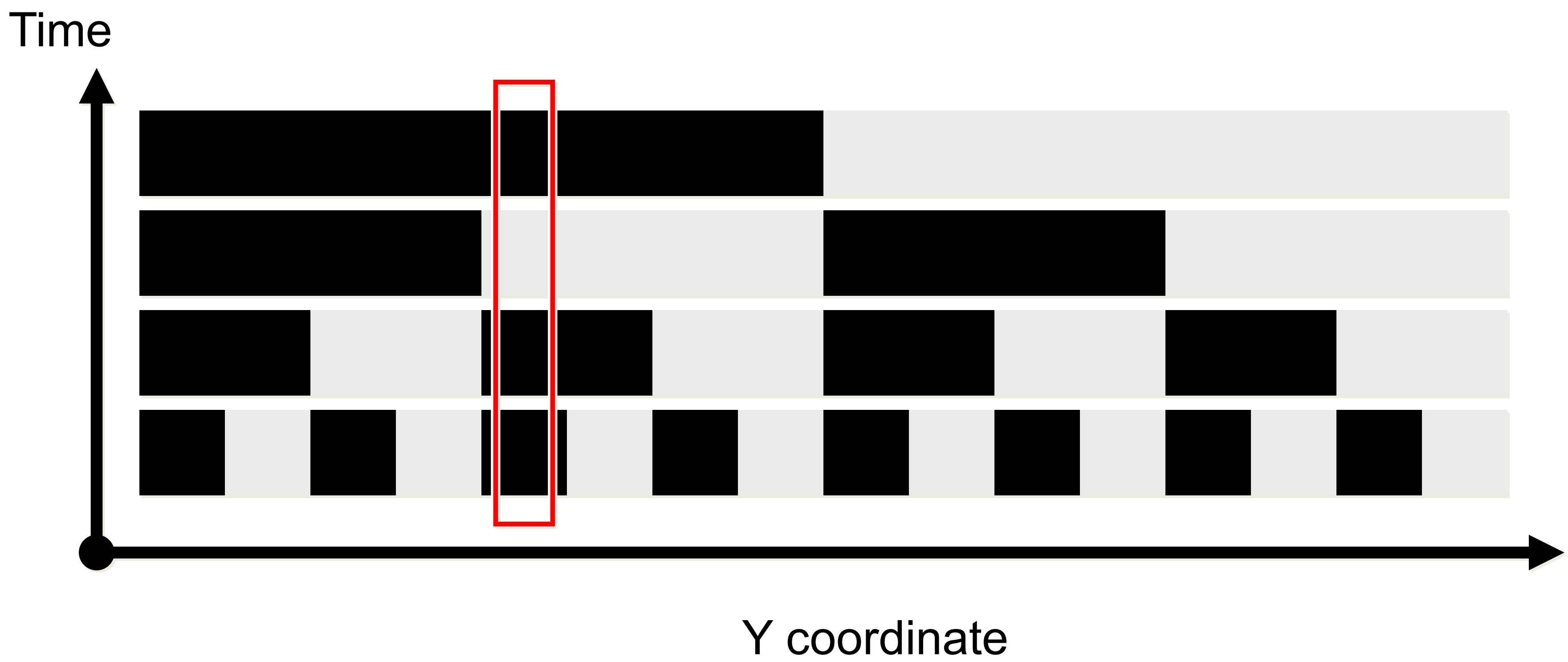
Binary Coding

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



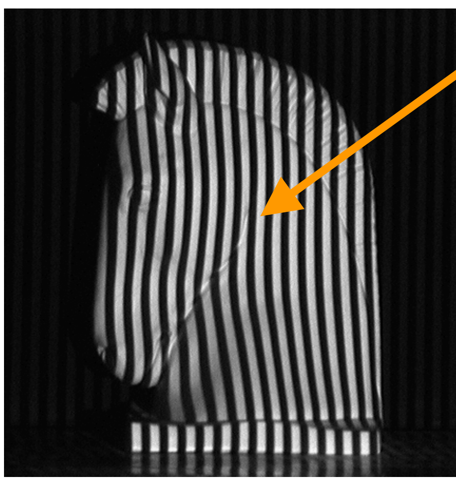
Binary Coding

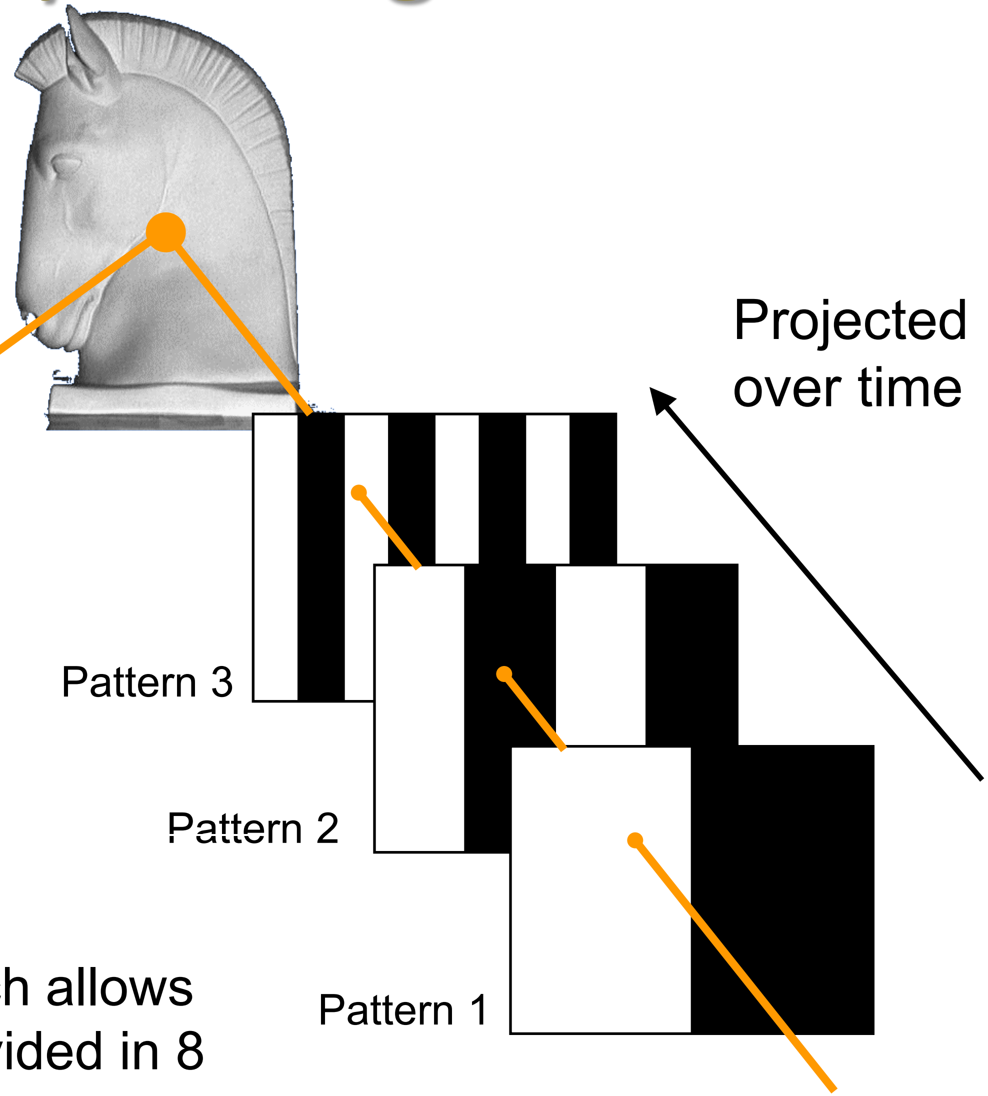
- Assign each pixel a unique illumination code over time [Posdamer 82]



Binary Coding

$2^n - 1$ stripes in n images





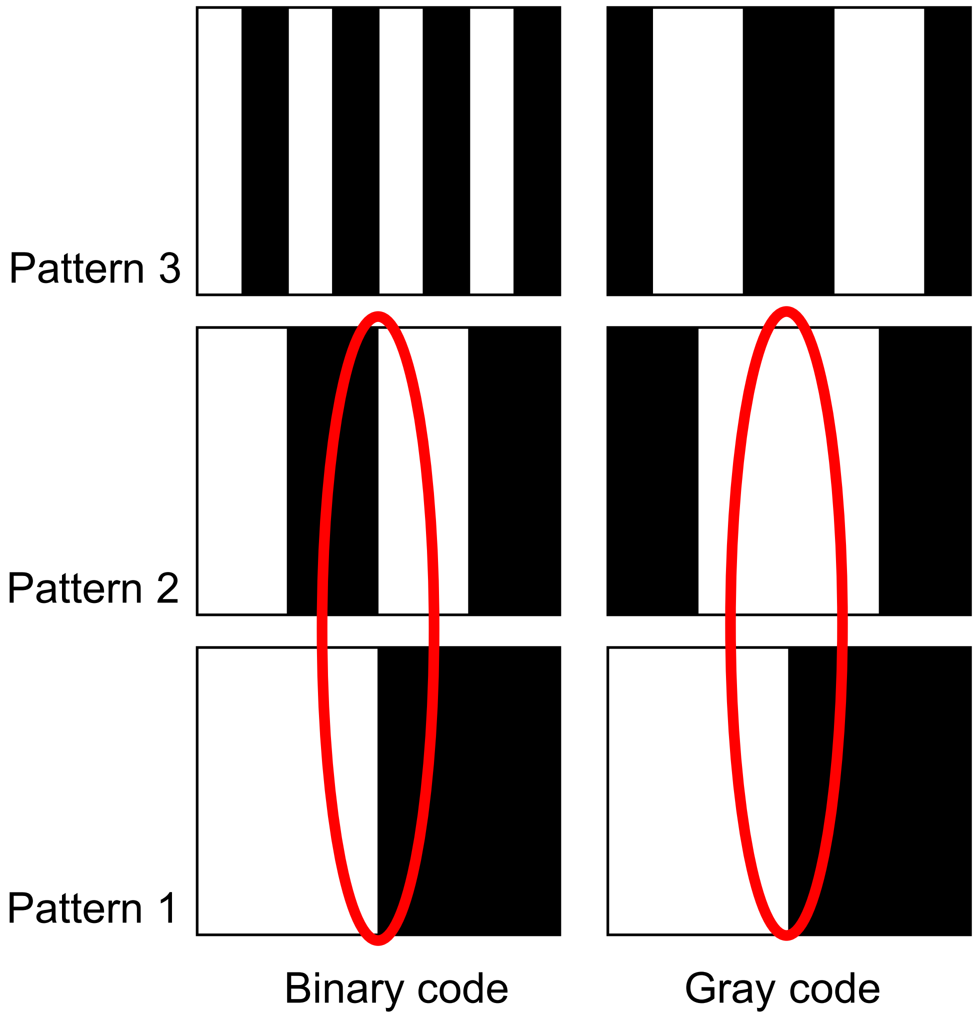
Example:

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

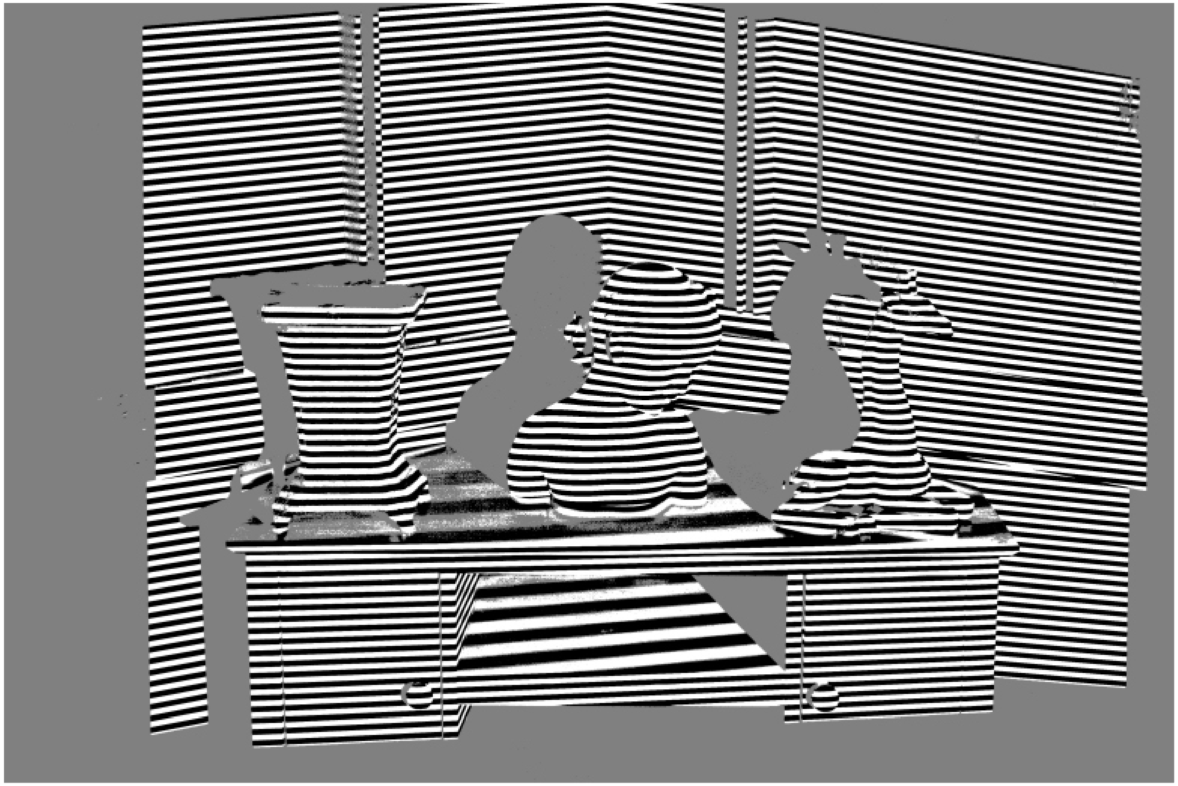
Binary vs Gray Codes

Decimal	Binary	Gray Code
0	0000	0000
1	0001	0001
2	0010	0011
3	0011	0010
4	0100	0110
5	0101	0111
6	0110	0101
7	0111	0100
8	1000	1100
9	1001	1101
10	1010	1111

Binary vs Gray Codes



Standard Pixel Classification

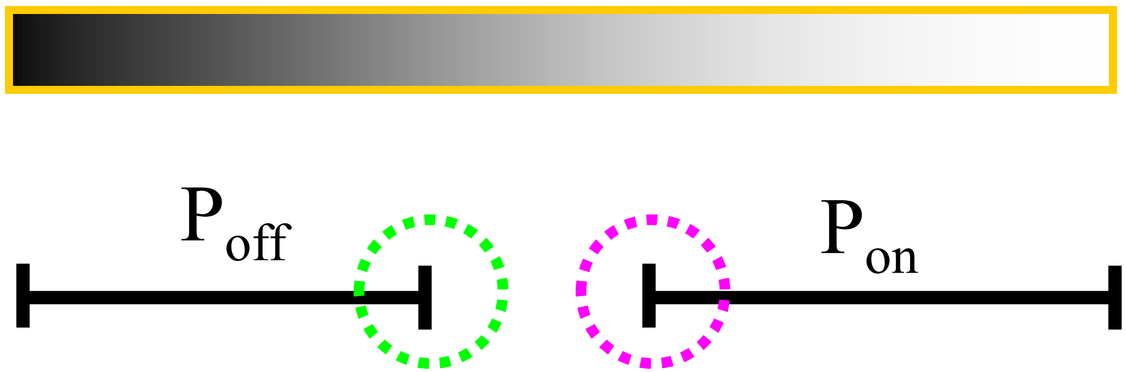


ON(1) OFF(0) Uncertain

Pixel Classification Challenges

Standard Pixel Classification

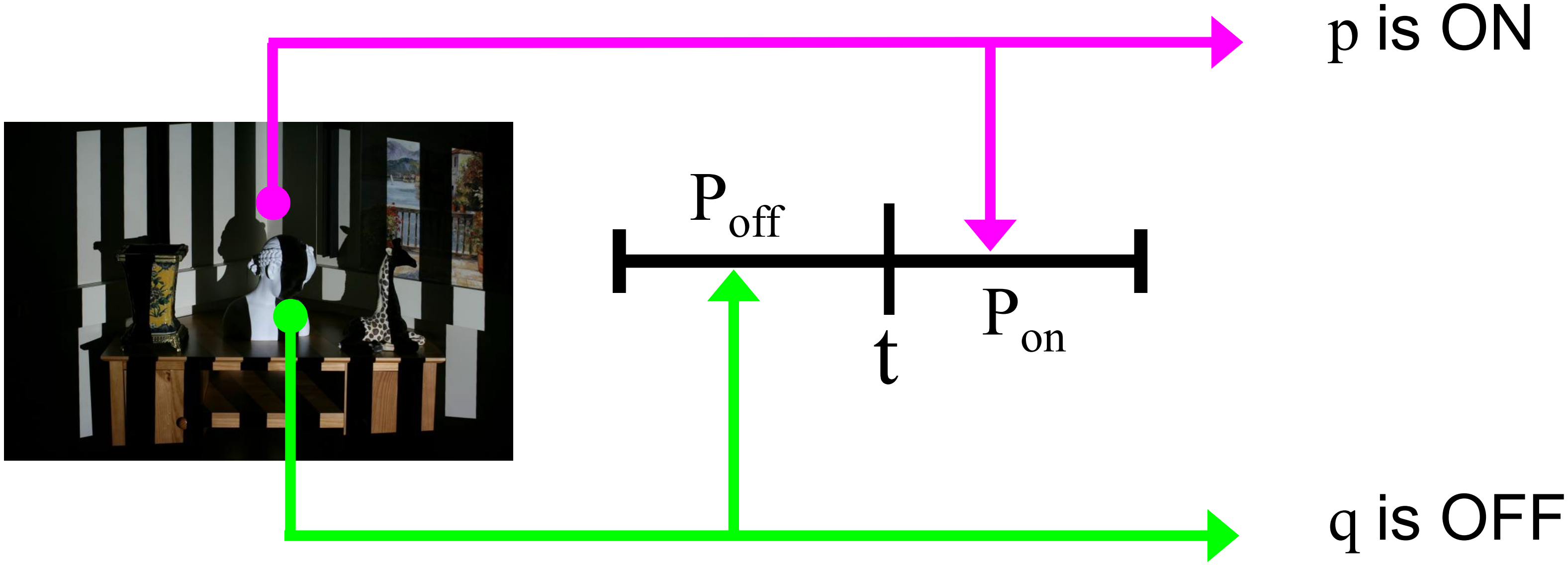
- Interval



- Common methods
  - Simple threshold
  - Albedo threshold
  - Dual pattern

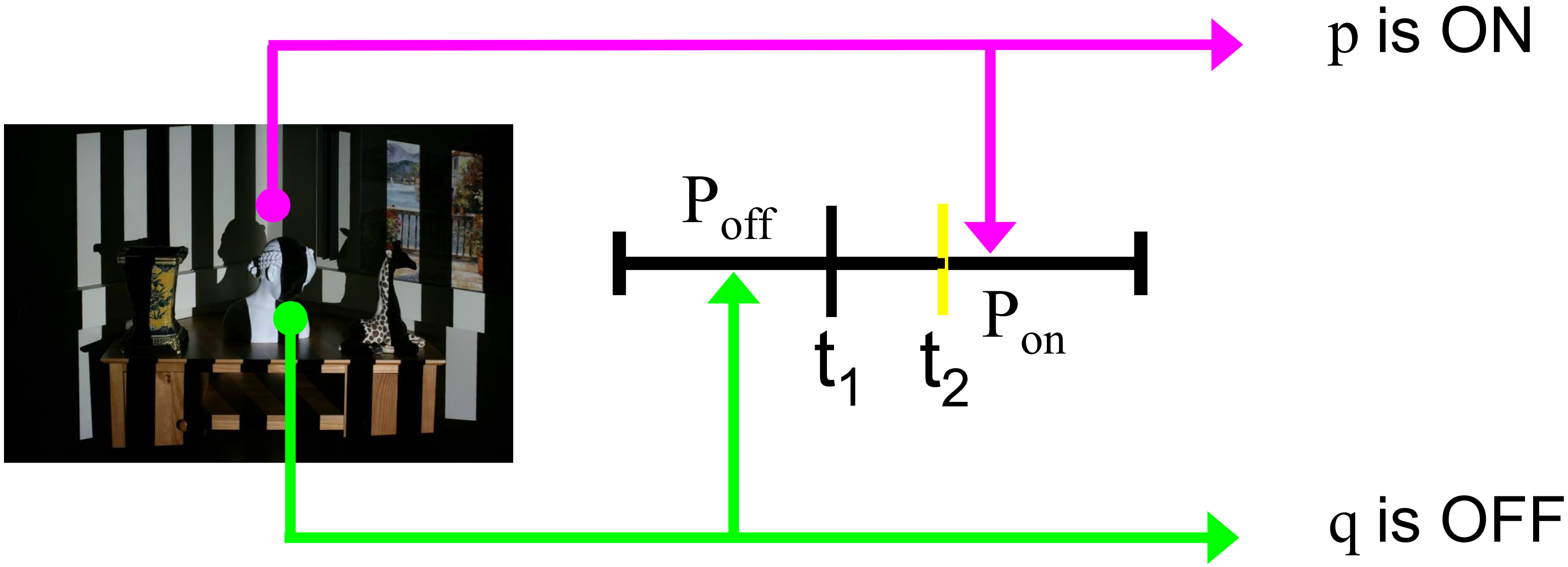
1. Simple Threshold

User specifies one threshold t for all pixels



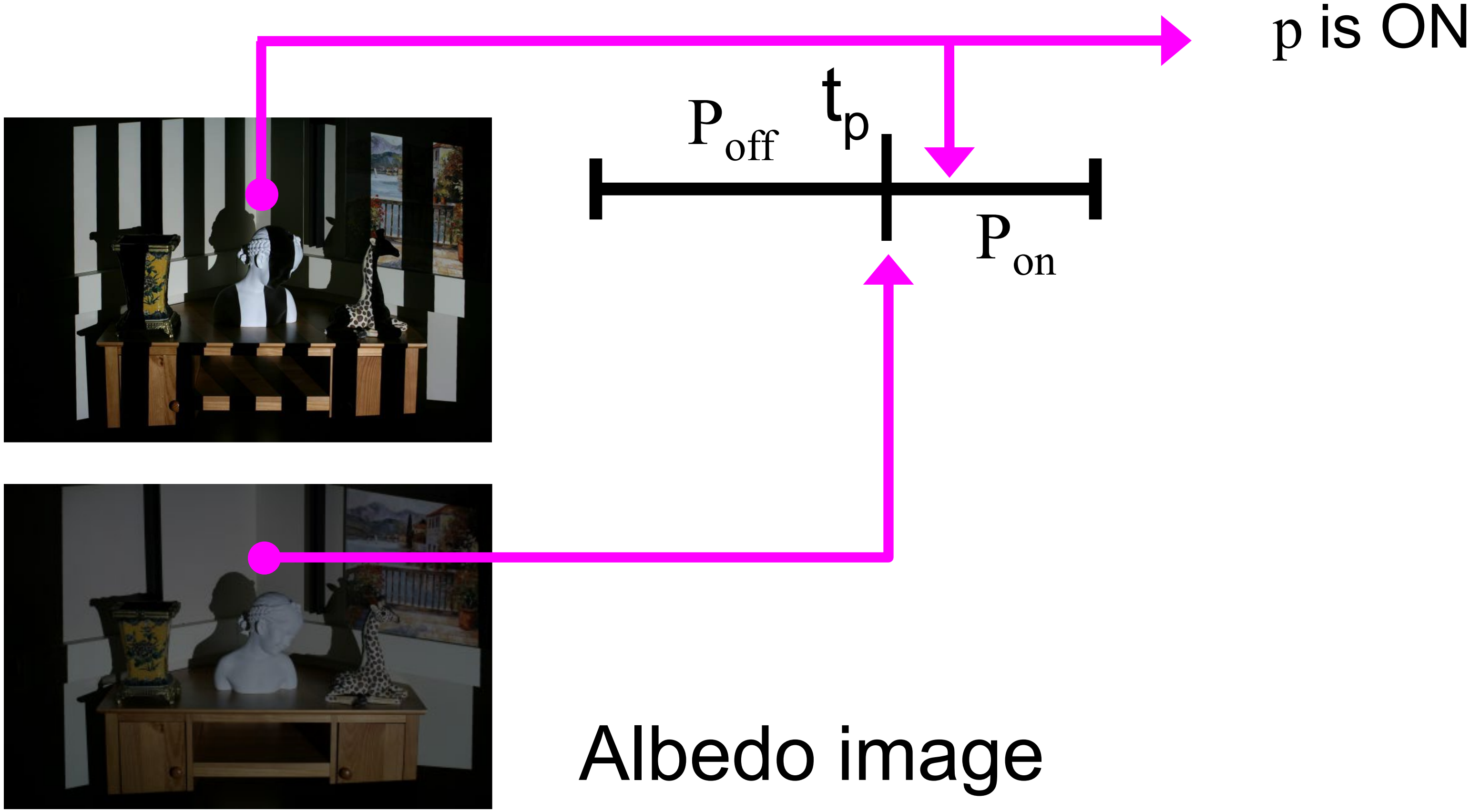
1. Simple Threshold

User specifies two thresholds t_1, t_2



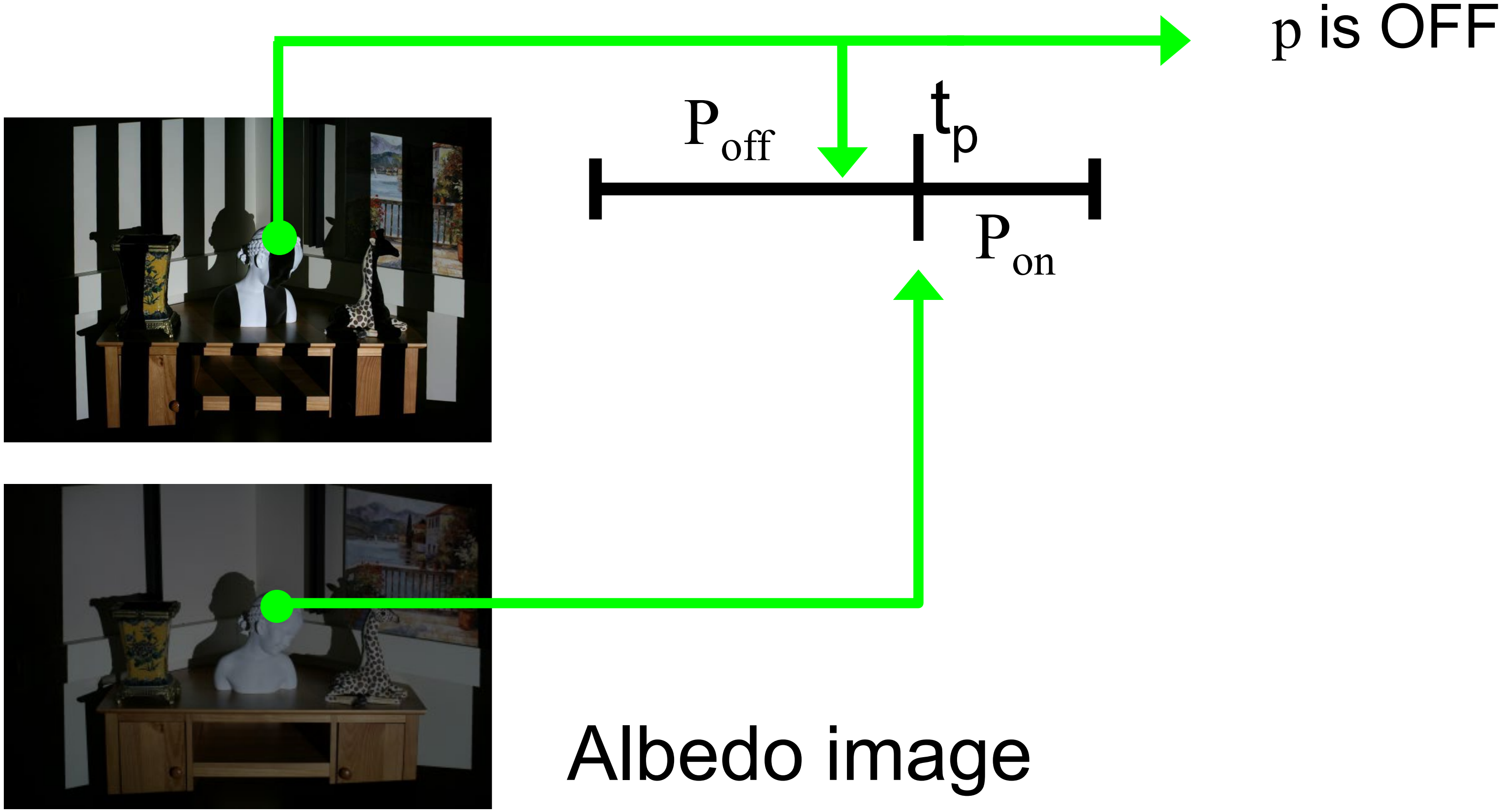
2. Albedo Threshold

Compute the albedo t_p for each pixel



2. Albedo Threshold

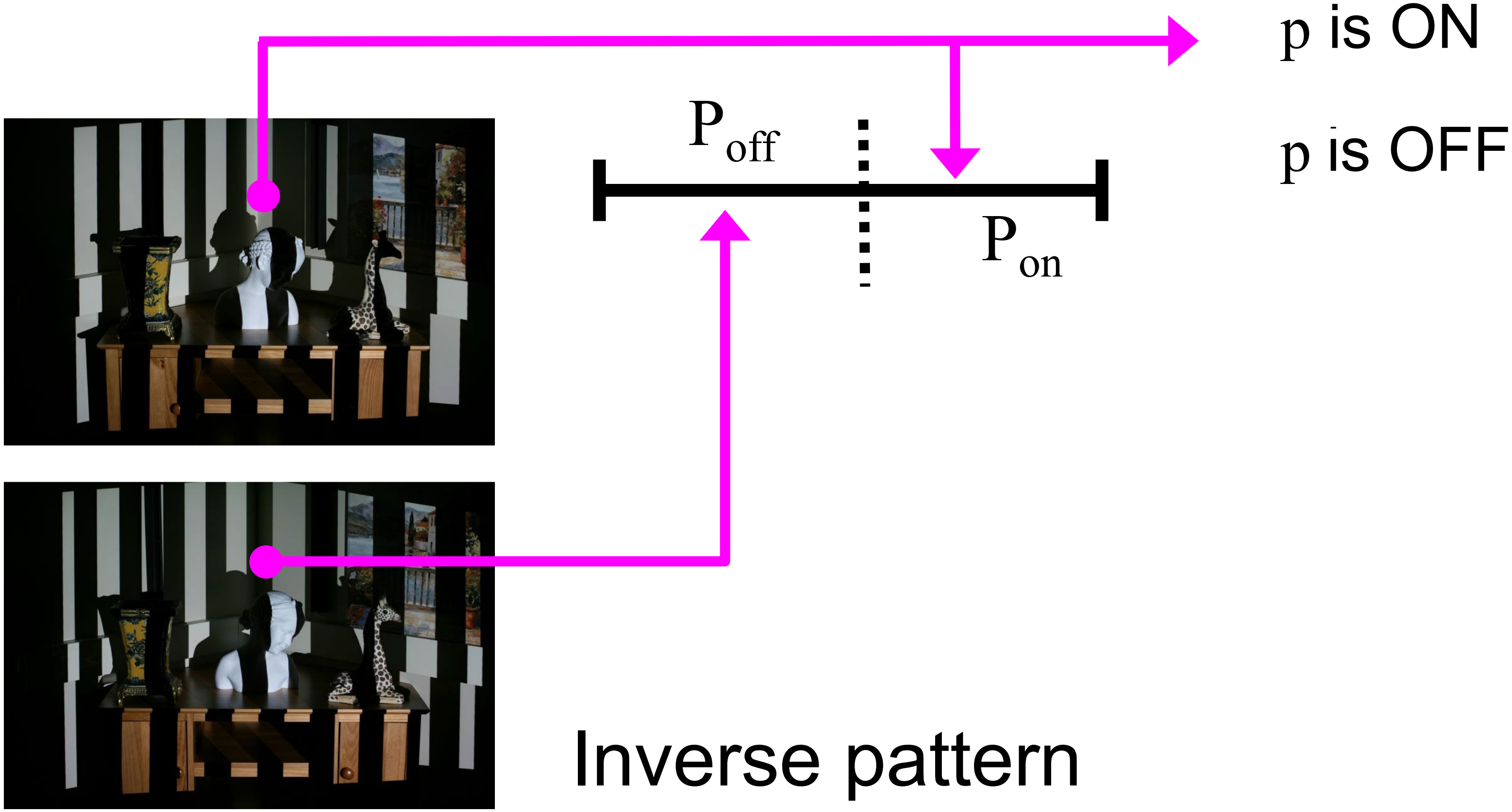
Compute the albedo t_p for each pixel



Albedo image

3. Dual Pattern: Pattern and Inverse

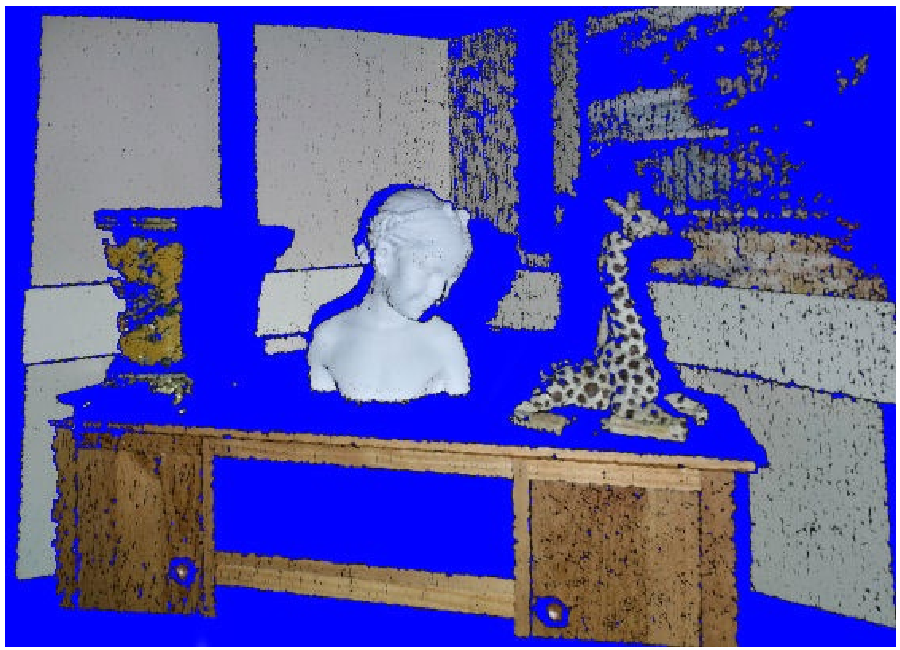
Without explicitly computing t_p



Limitations of Standard Methods

- All three methods assume the two intervals do not overlap
  - This is incorrect when there is strong indirect (global) light
- Haven’t actually established the correct bounds

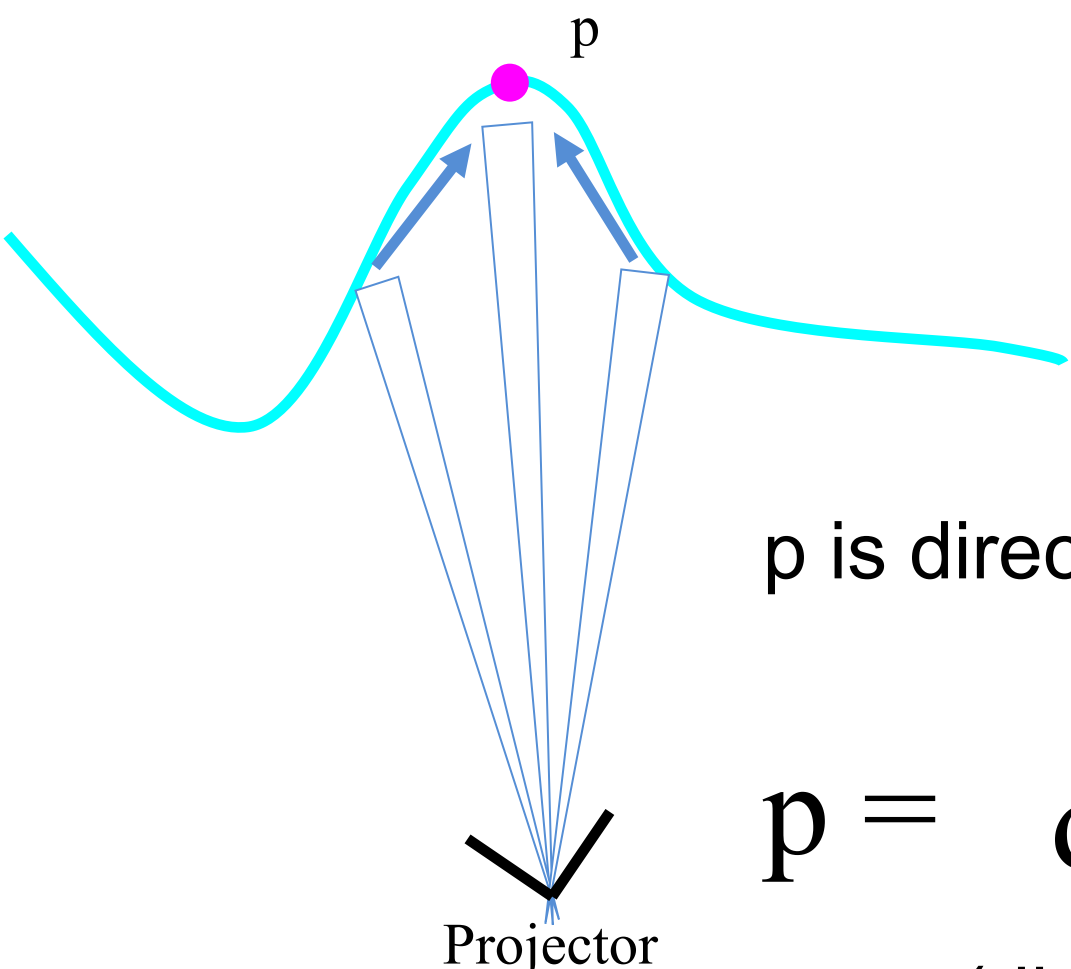
Example Comparison



Using light-separated pixel classification

Using standard pixel classification

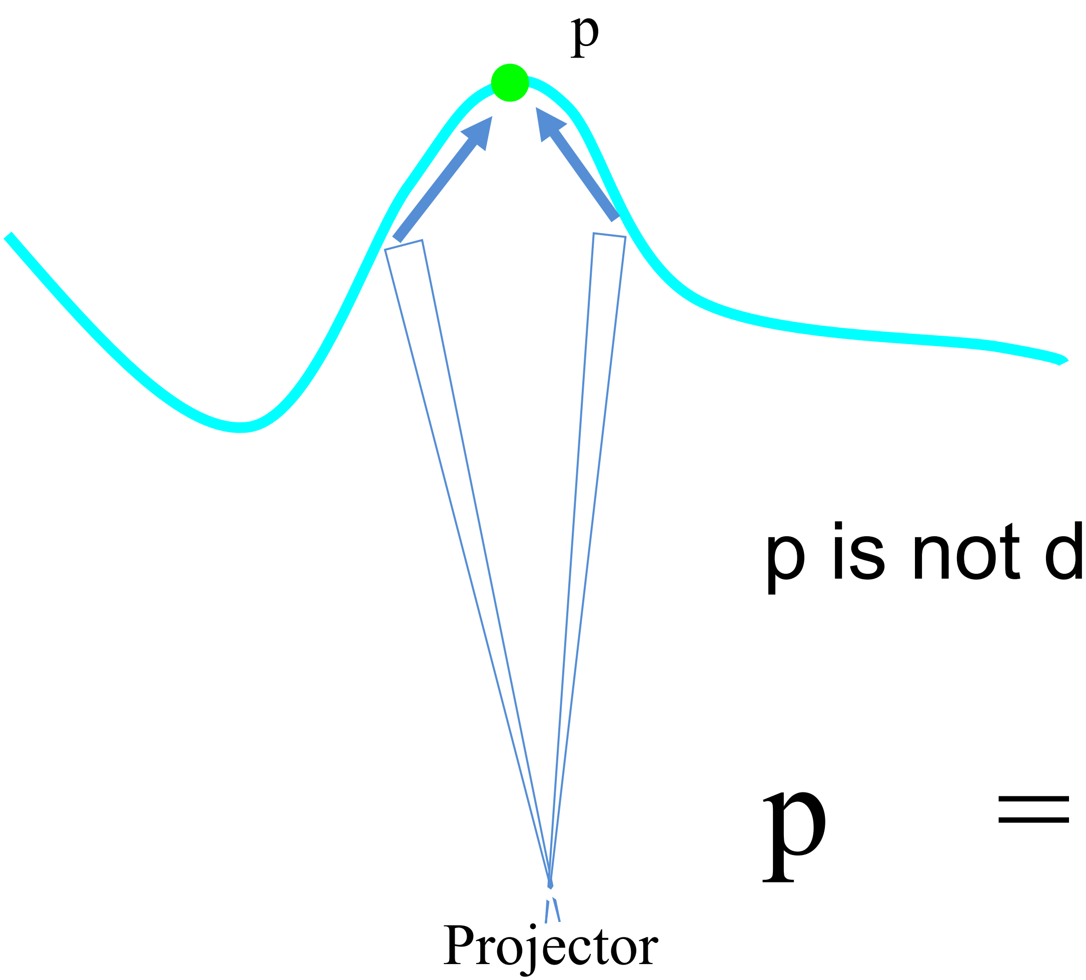
Pixel Intensity (p is ON)



p is directly illuminated

$$p = \underbrace{d}_{\text{(direct)}} + \underbrace{i_{on}}_{\text{(indirect)}}$$

Pixel Intensity (*p* is OFF)



p is not directly illuminated

$$p = i_{off}$$

(indirect)

Pixel Intensity

$$p = \begin{cases} d + i_{on} & \text{If } p \text{ is ON} \\ i_{off} & \text{If } p \text{ is OFF} \end{cases}$$

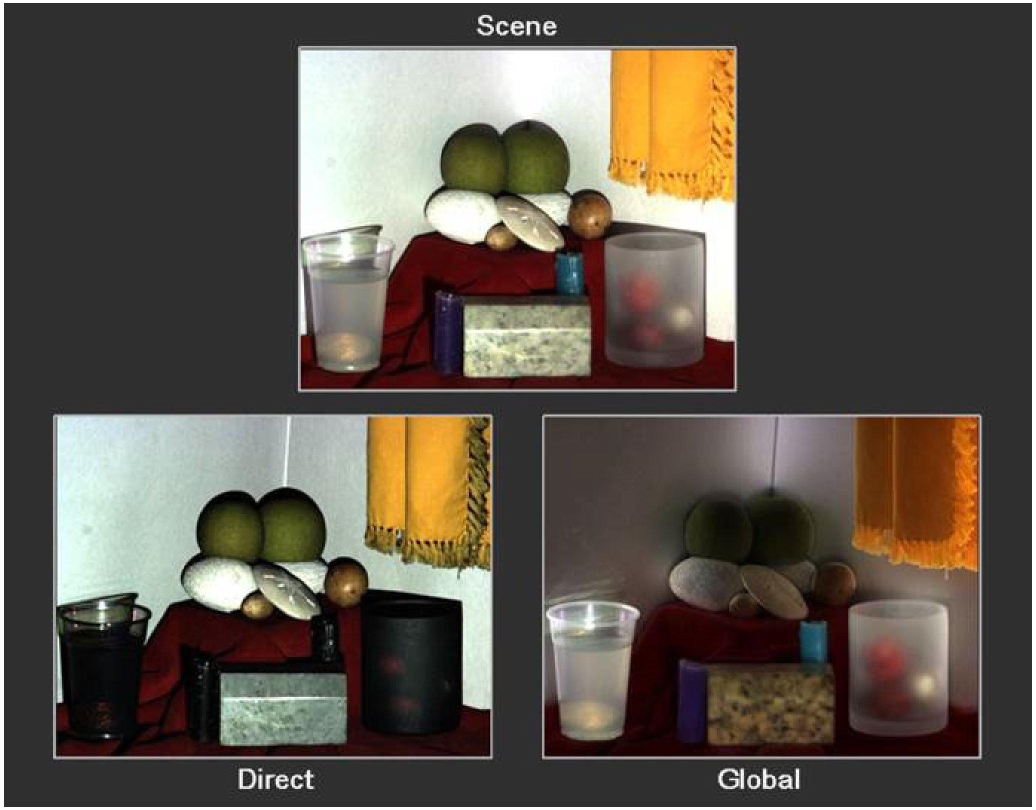
- Chicken and egg problem is
  - Need to know d, i_{on}, i_{off} to classify a pixel.
  - ~~Need to classify a pixel to know~~ $\cancel{d, i_{on}, i_{off}}$

ALL white pattern

(all projector pixels on)

Direct and Indirect Separation

- Direct and indirect (global) components of each pixel can be separated easily (Nayar et al. SIGGRAPH'06).

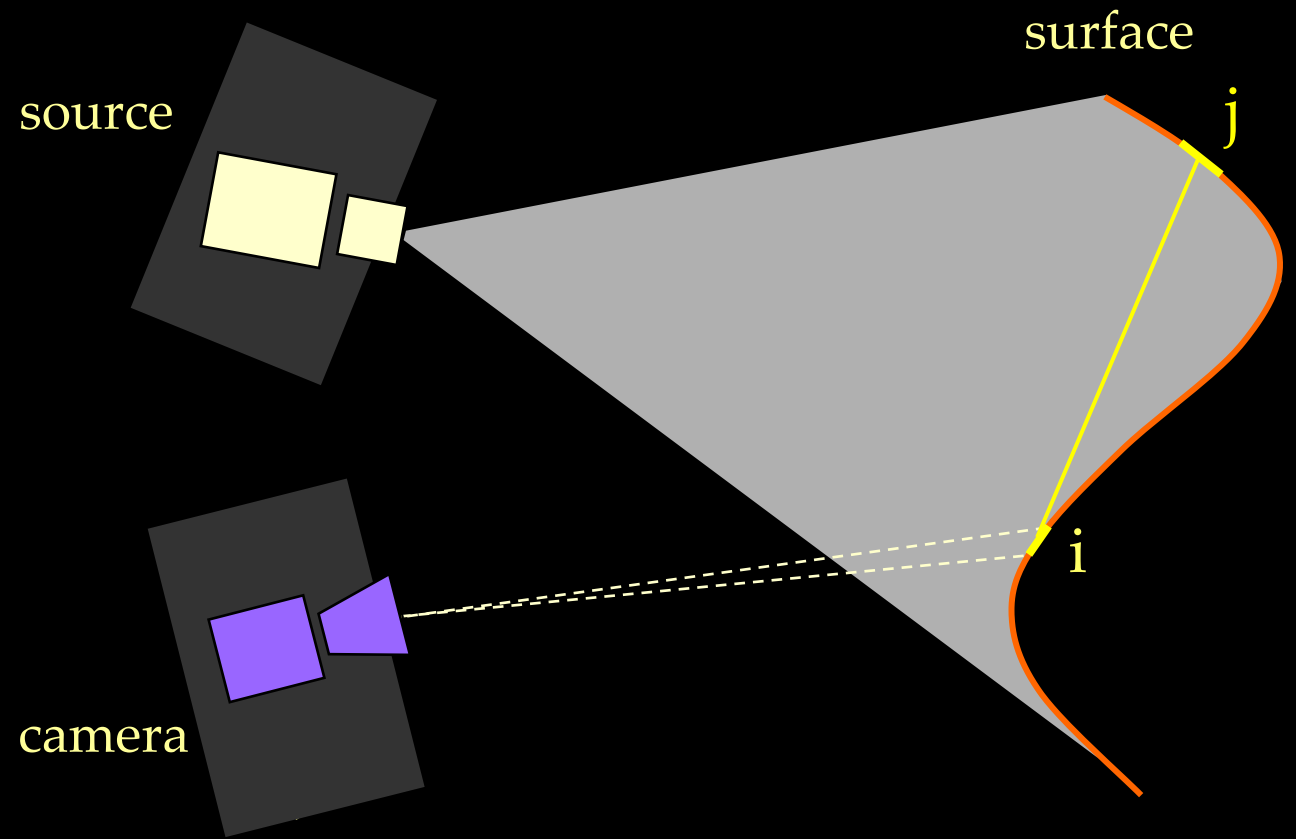


Direct and Indirect Separation

- Direct and indirect (global) components of each pixel can be separated easily (Nayar et al. SIGGRAPH'06).

https://cave.cs.columbia.edu/gallery/separation/RWO

Direct and Global Components: Interreflections



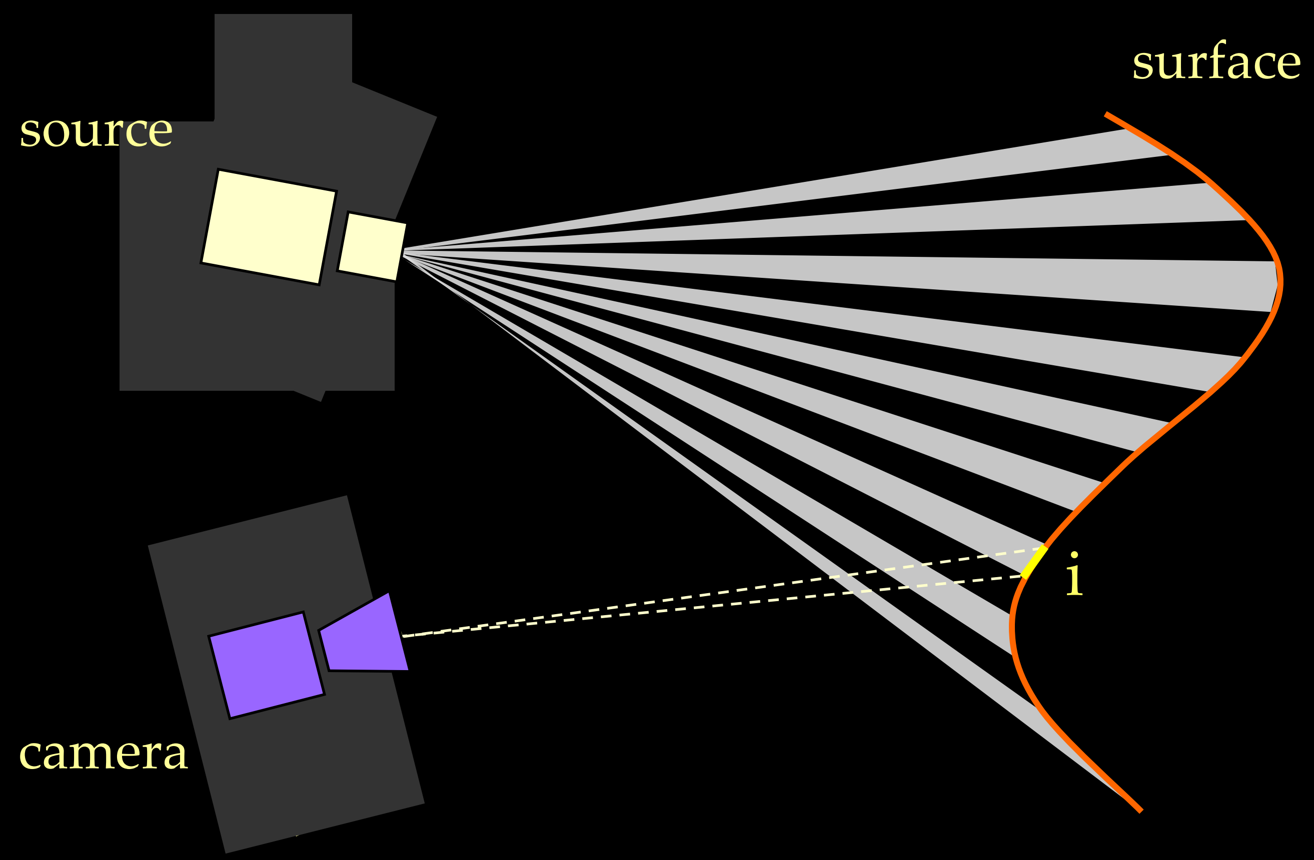
$$L[c,i] = L_d[c,i] + L_g[c,i]$$

radiance direct global

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

BRDF and geometry

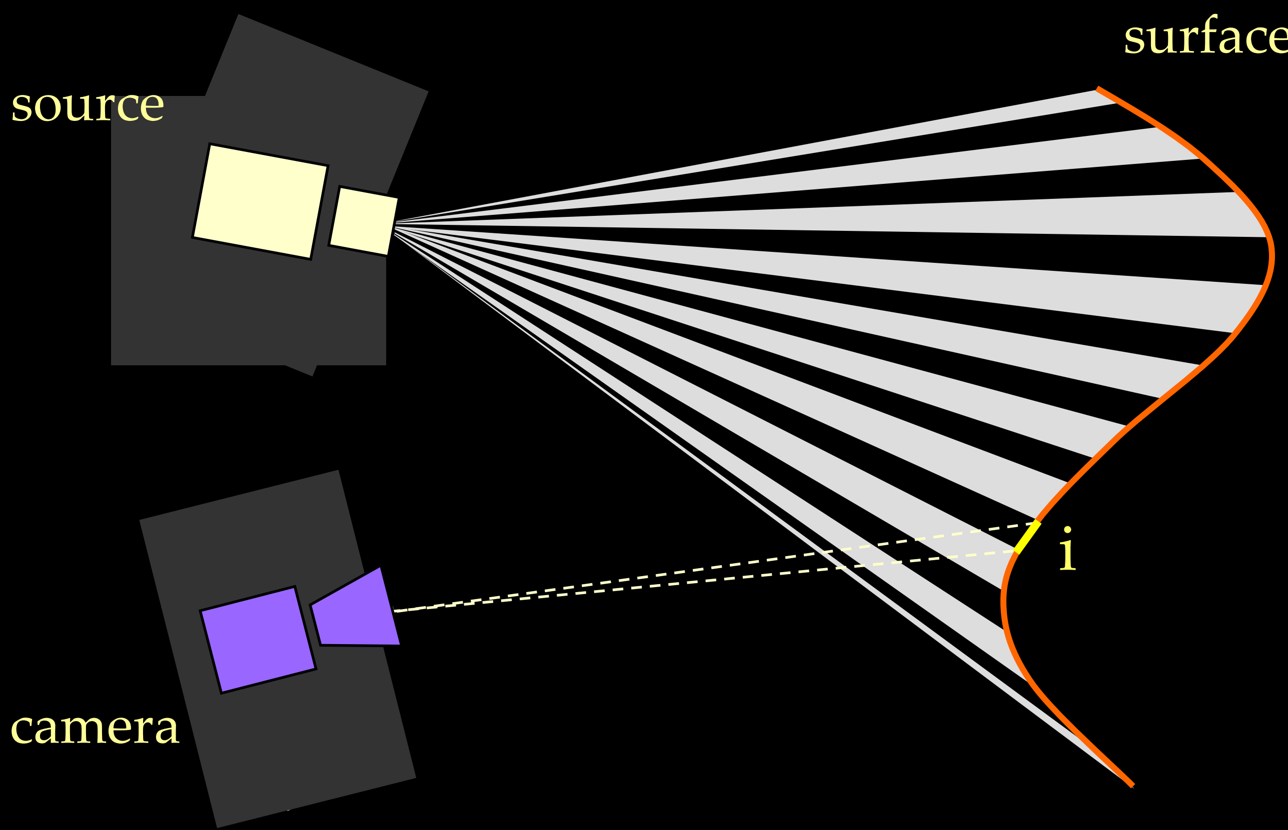
High Frequency Illumination Pattern



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

fraction of activated source elements

High Frequency Illumination Pattern



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

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

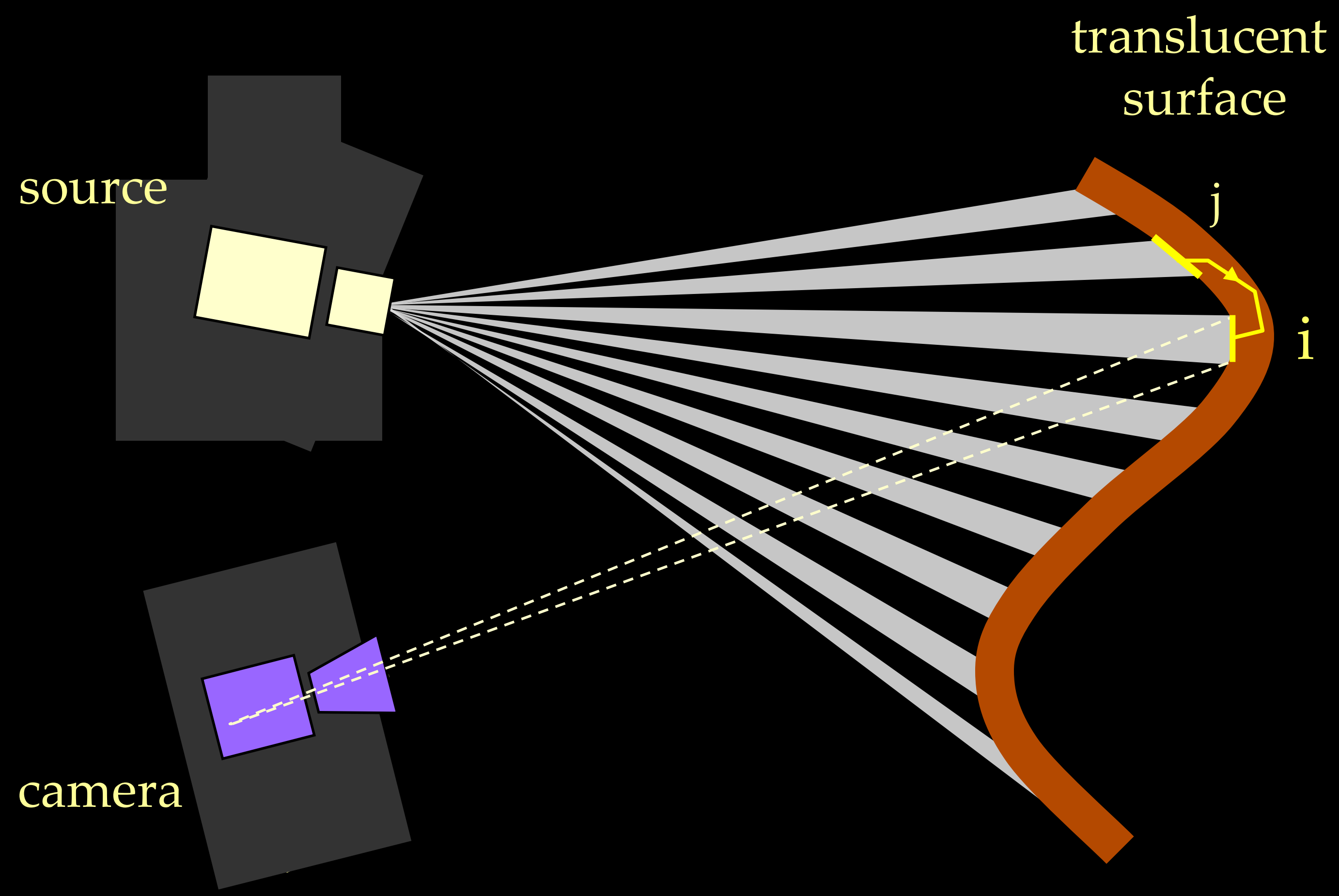
fraction of activated source elements

Separation from Two Images

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

direct global

Other Global Effects: Subsurface Scattering



Direct and Indirect Separation

- Direct and indirect (global) components of each pixel under ALL white pattern can be separated easily (Nayar et al. SIGGRAPH'06).

$$p \quad = \quad d_{total} \quad + \quad i_{total}$$

Direct and Indirect Separation

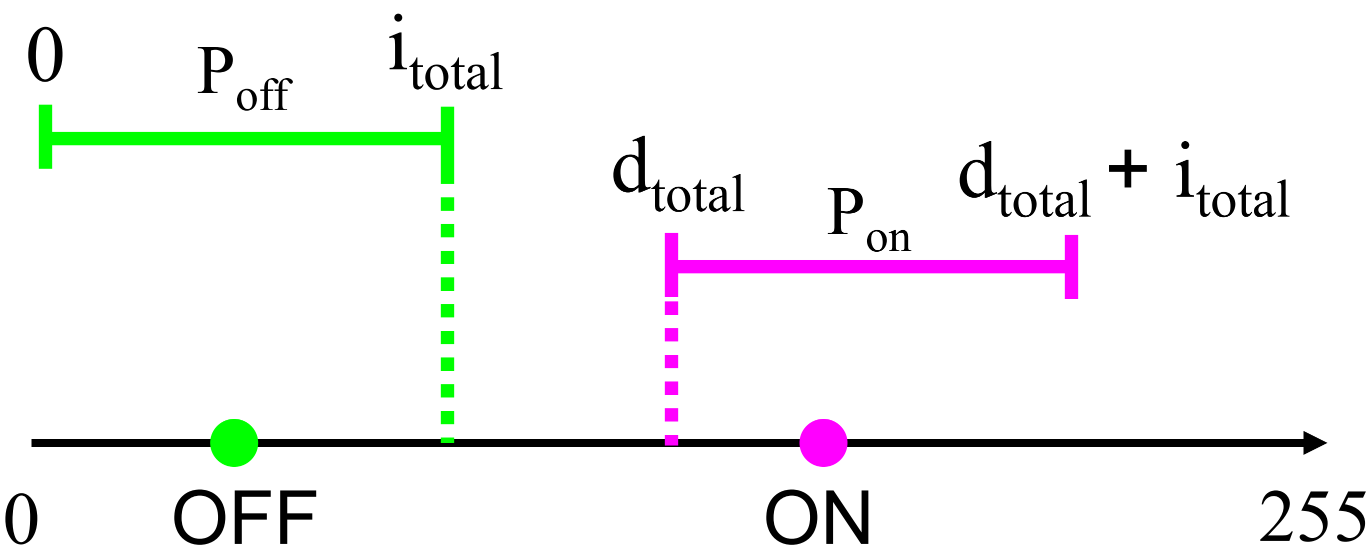
- Project high frequency binary pattern and its inverse to separate light components.

- Structured light patterns include the separation patterns.
  - Thus, separation can be applied to previously captured data to obtain per pixel

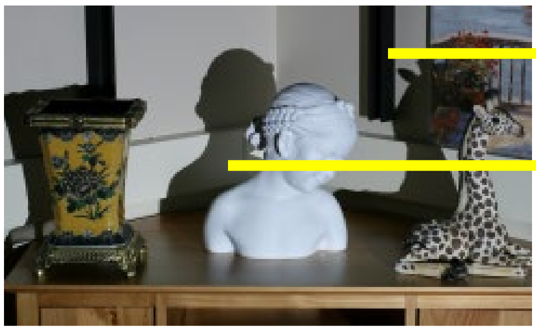
$$p = d_{total} + i_{total}$$

Pixel Classification Scenarios

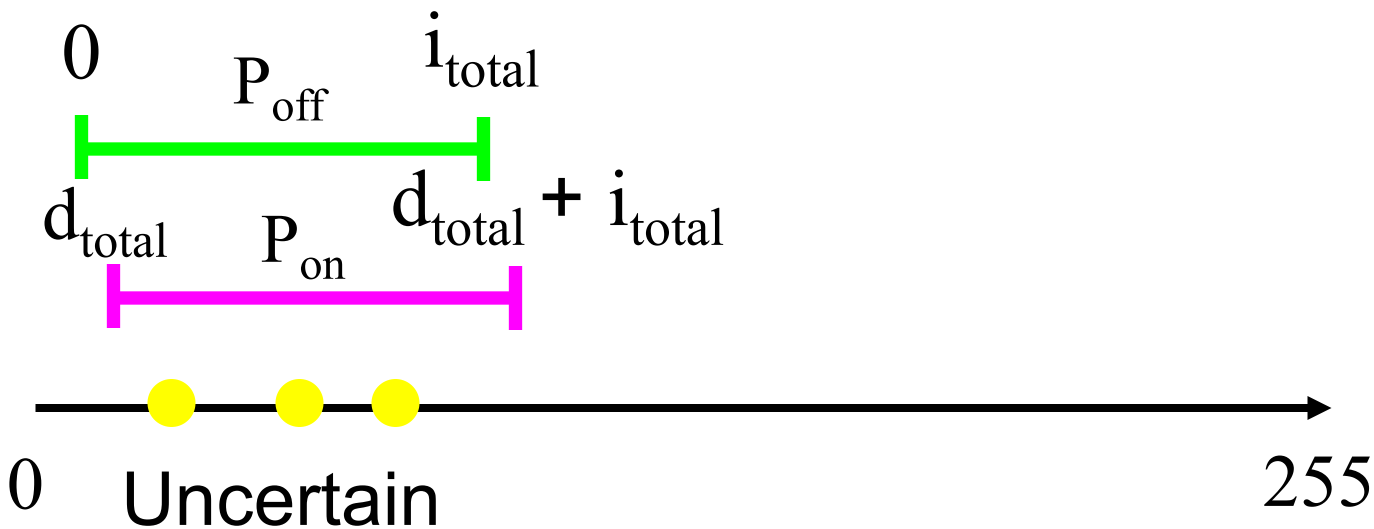
$d_{total} > i_{total}$



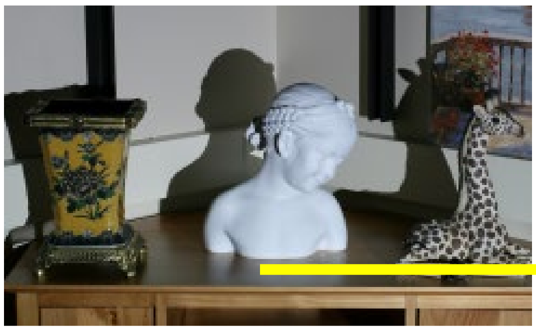
Pixel Classification Scenarios



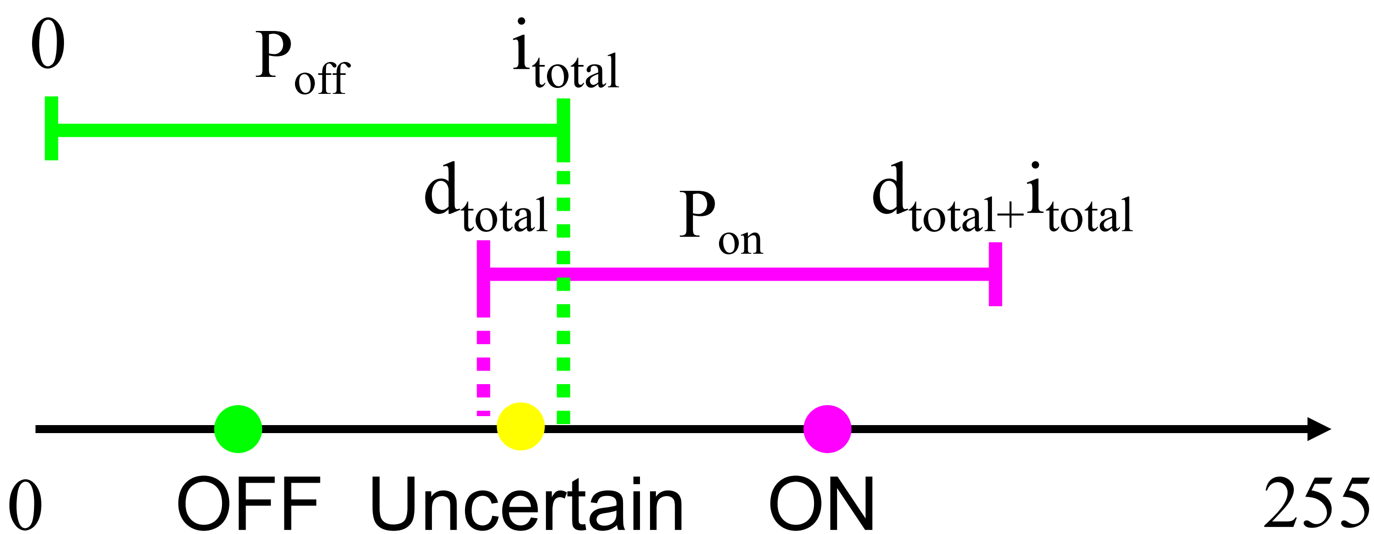
$d_{total} \approx 0$



Pixel Classification Scenarios



$$d_{total} \le i_{total}$$

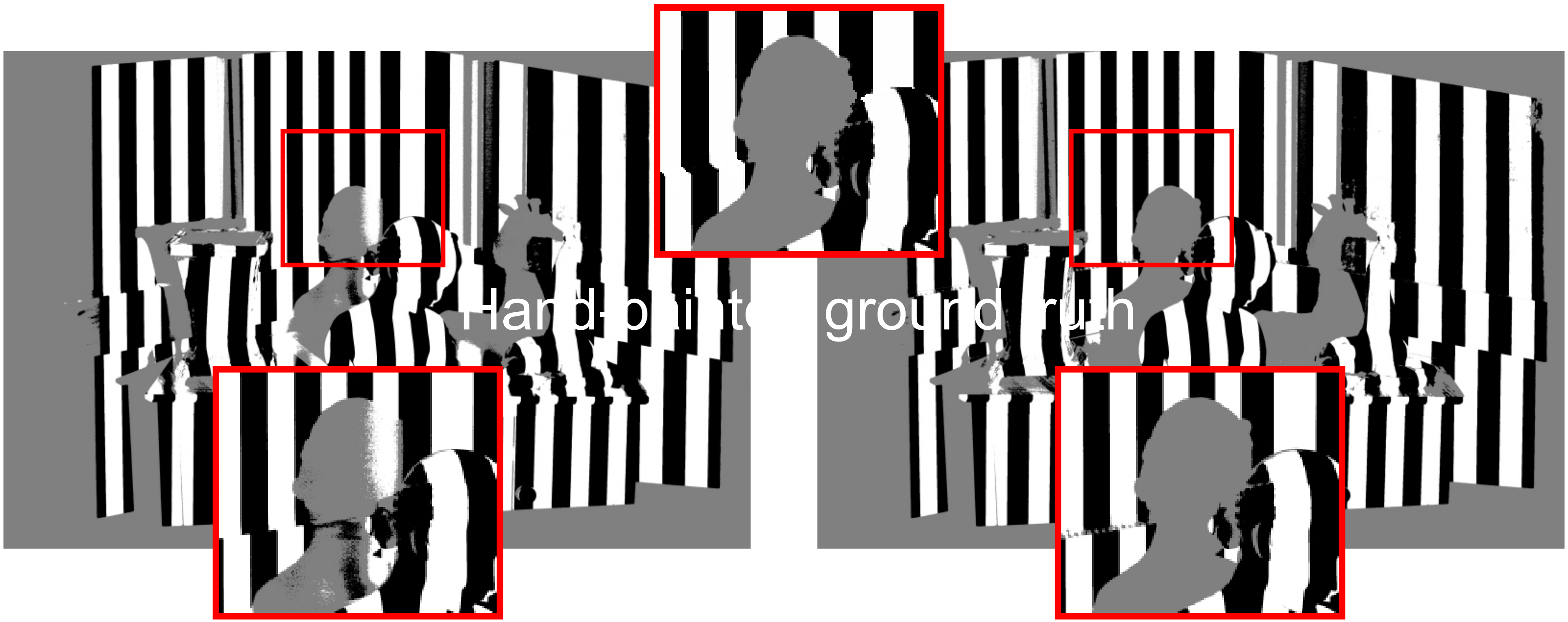


Single Pattern Classification Rules

- $\boldsymbol{d}_{\textbf{total}} < \boldsymbol{m}$ → pixel is *uncertain*
- $\boldsymbol{p} < \min(\boldsymbol{d}_{\boldsymbol{total}}, \boldsymbol{i}_{\boldsymbol{total}})$ → pixel is *off*
- $\boldsymbol{p} > \max(\boldsymbol{d}_{\boldsymbol{total}}, \boldsymbol{i}_{\boldsymbol{total}})$ → pixel is *on*
- otherwise → pixel is *uncertain*

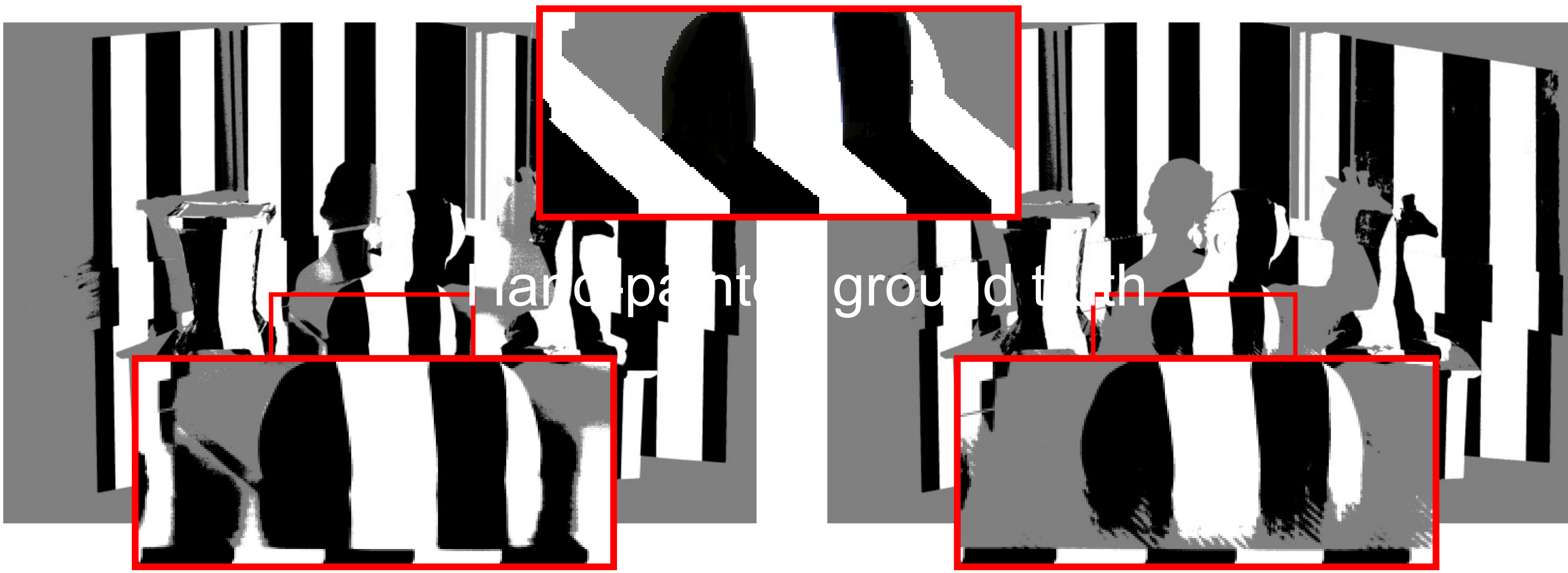
Classification Results

ON(1) OFF(0) Uncertain

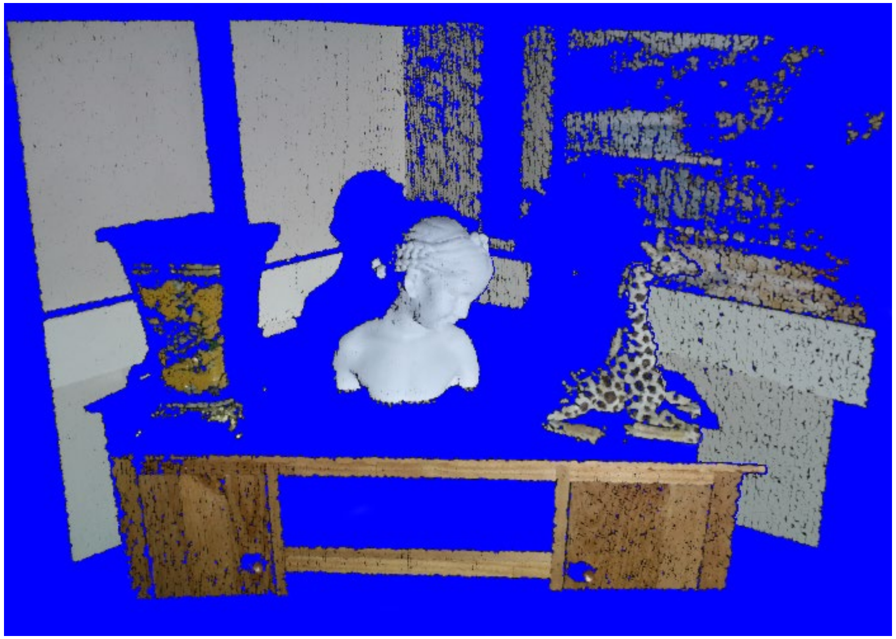


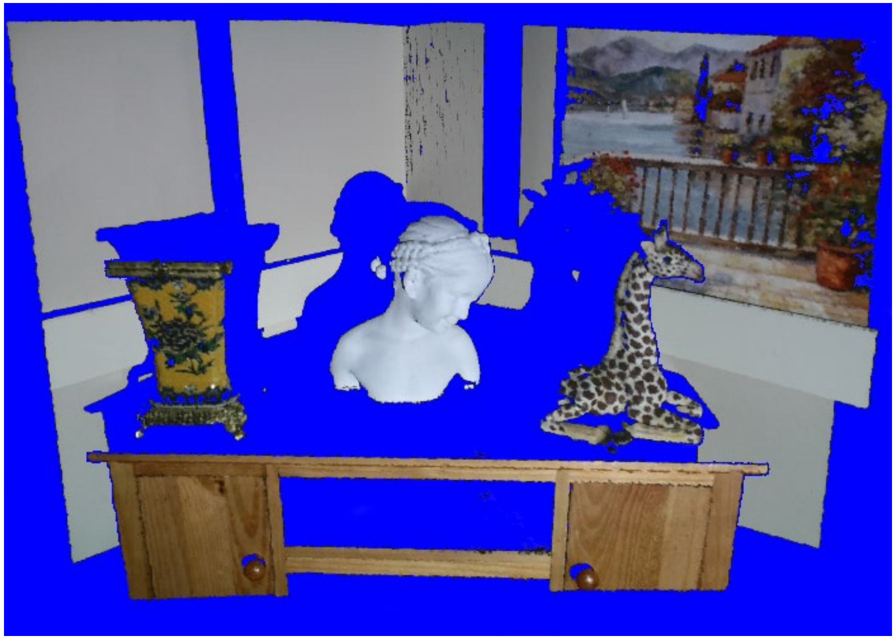
Classification Results

ON(1) OFF(0) Uncertain



Increased Reconstructed Points





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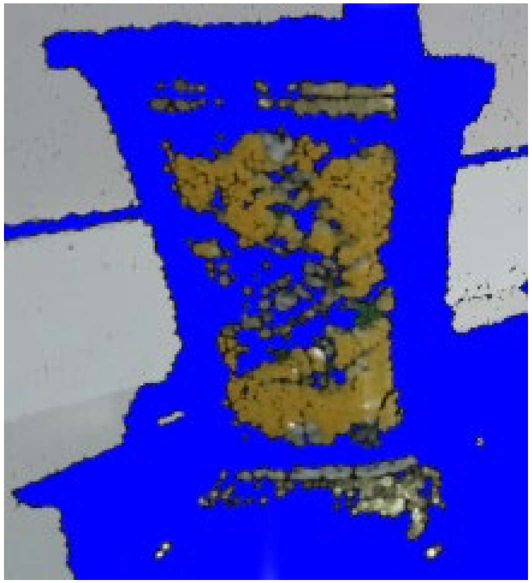
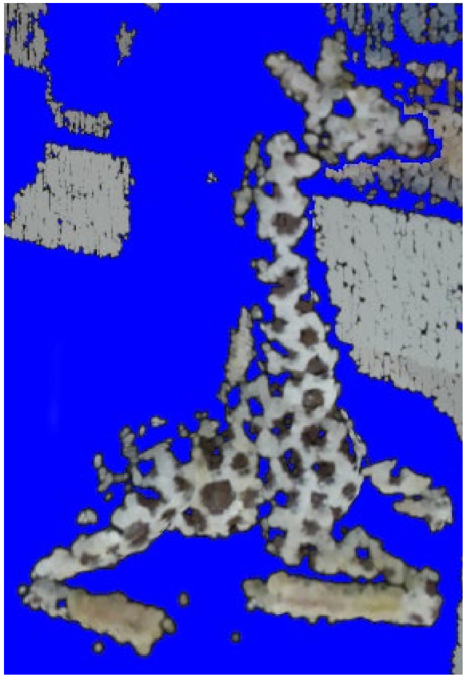


Increased Reconstructed Points



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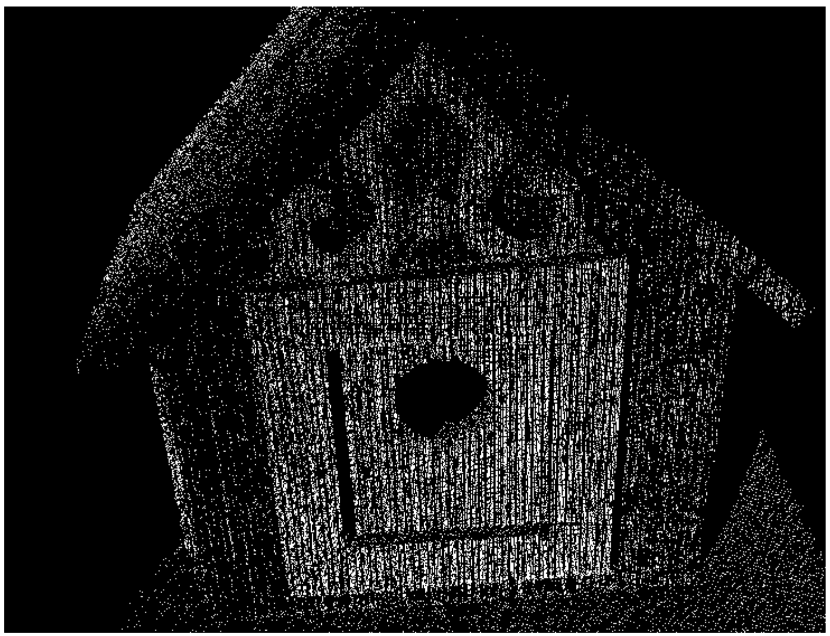
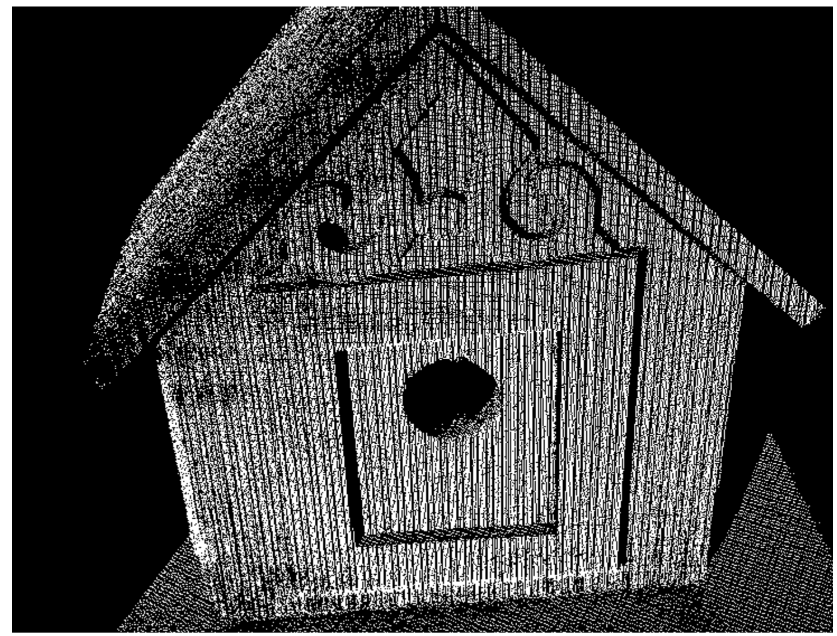
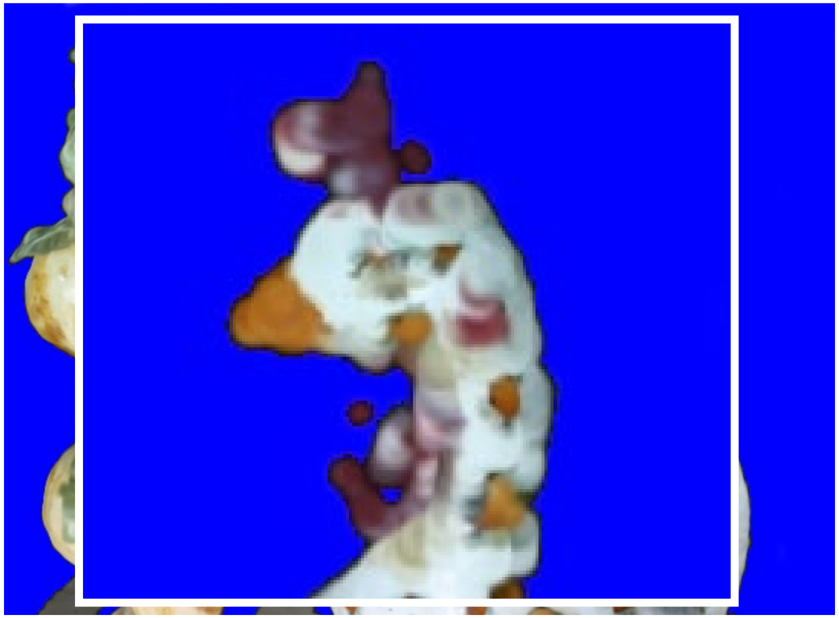




Increased Reconstructed Points



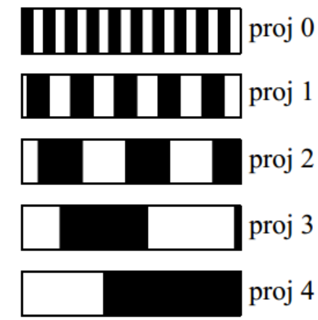
Another issue…

Another issue…

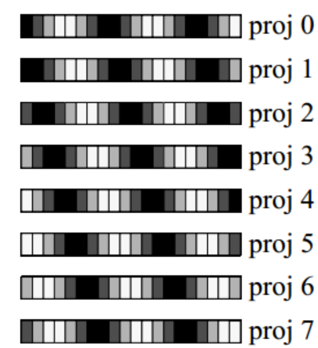
- Classify…
  - pixels at stripe boundaries?
  - pixels at strip middle?
  - all pixels?

Structured Light using Phase shifting

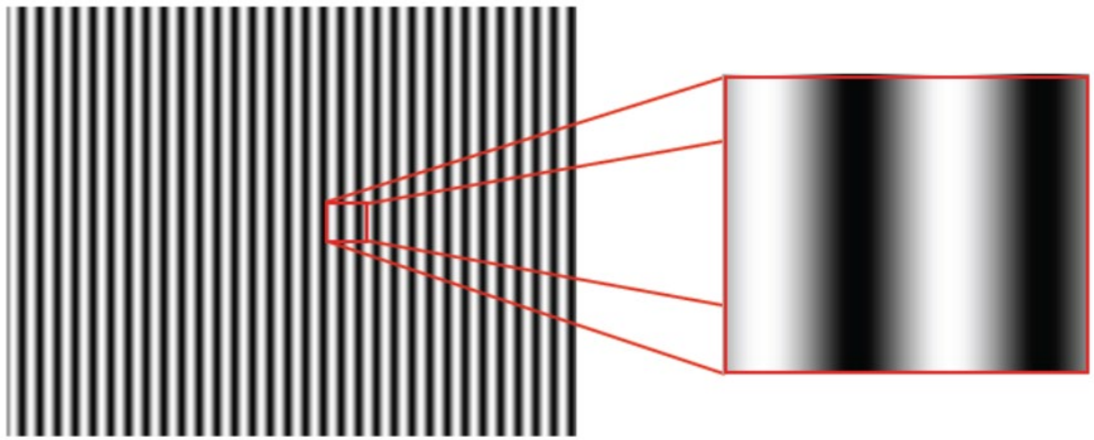
- Binary/gray code structured light
  - limited to (integer) projector resolution
  - has trouble with the LSB bits



- Alternative is **phase shifting**
  - Able to produce subpixel accuracies
  - Able to capture LSB bits more robustly



Phase Shifting



- Project 3 or more "phase shifted" sinusoidal patterns
- For example:

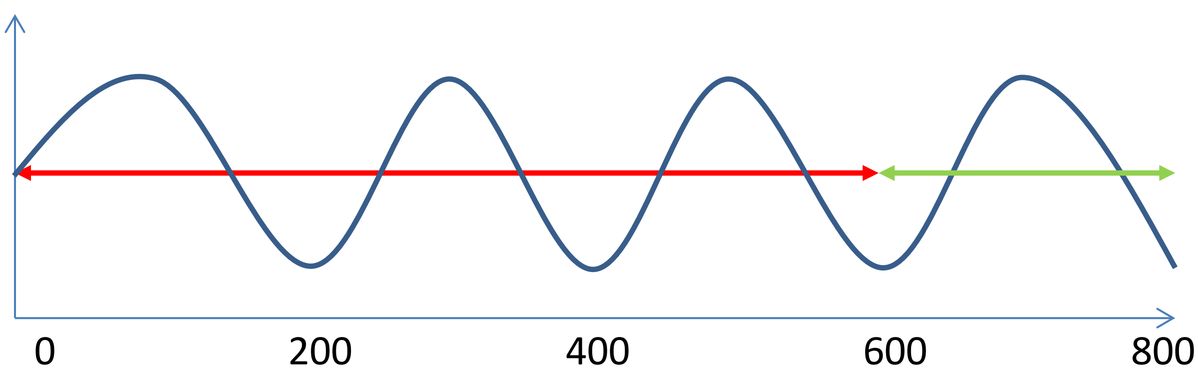
$$I_- = I_b + I_v \cos(\phi - \theta)$$
$$I_* = I_b + I_v \cos(\phi)$$
$$I_+ = I_b + I_v \cos(\phi + \theta)$$

- The variable ϕ is the phase of each column

Phase Shifting

- Since binary/gray code good for MSB (and phase shifting less reliably for large ranges), we define absolute and relative phase shifts:

$$\phi'(x,y) = \underbrace{2\pi k(x,y)}_{\text{(from binary codes)}} + \underbrace{\phi(x,y)}_{\text{(relative phase shift)}} \text{ where } k = [0, N-1]$$



Phase Shifting

$$I_- = I_b + I_v \cos(\phi - \theta)$$
$$I_* = I_b + I_v \cos(\phi)$$
$$I_+ = I_b + I_v \cos(\phi + \theta)$$

- How do you remove dependence on I_b, I_v?
- One option: use 3 images and compute

$$\frac{I_- - I_+}{2I_* - I_- - I_+}$$

Phase Shifting

$$\frac{I_- - I_+}{2I_* - I_- - I_+}$$

$$= \frac{2\sin(\phi)\sin(\theta)}{2\cos(\phi)(1-\cos(\theta))} = \frac{\tan(\phi)}{\tan(\frac{\theta}{2})}$$

thus

$$\phi(0,2\pi) = \arctan(\tan(\frac{\theta}{2})\frac{I_- - I_+}{2I_* - I_- - I_+})$$

Phase-shift projection

- Phase angle from brightness
  - Computed from the three images
  - Ambient light and projector power can be ignored
  - Result tells you location within one period…thus "micro-correspondence" and not "macro correspondence"
  - Empirically, good for last few bits:
    - E.g., to get 10 bits of correspondence, use gray code for 7 msb and phase shifting for 3 lsb
    - Total images: 2 x 7 x 2 + 3 x 2 = 34 instead of 2 x 10 x 2 = 40 (but also maybe more robust)