Structured Light Methods for Depth Recovery

Introduction to Computational Photography:

EECS 395/495

Northwestern University

Structured Light Methods

Finding depth using projected light patterns.

Topics:

(1) Active Stereo

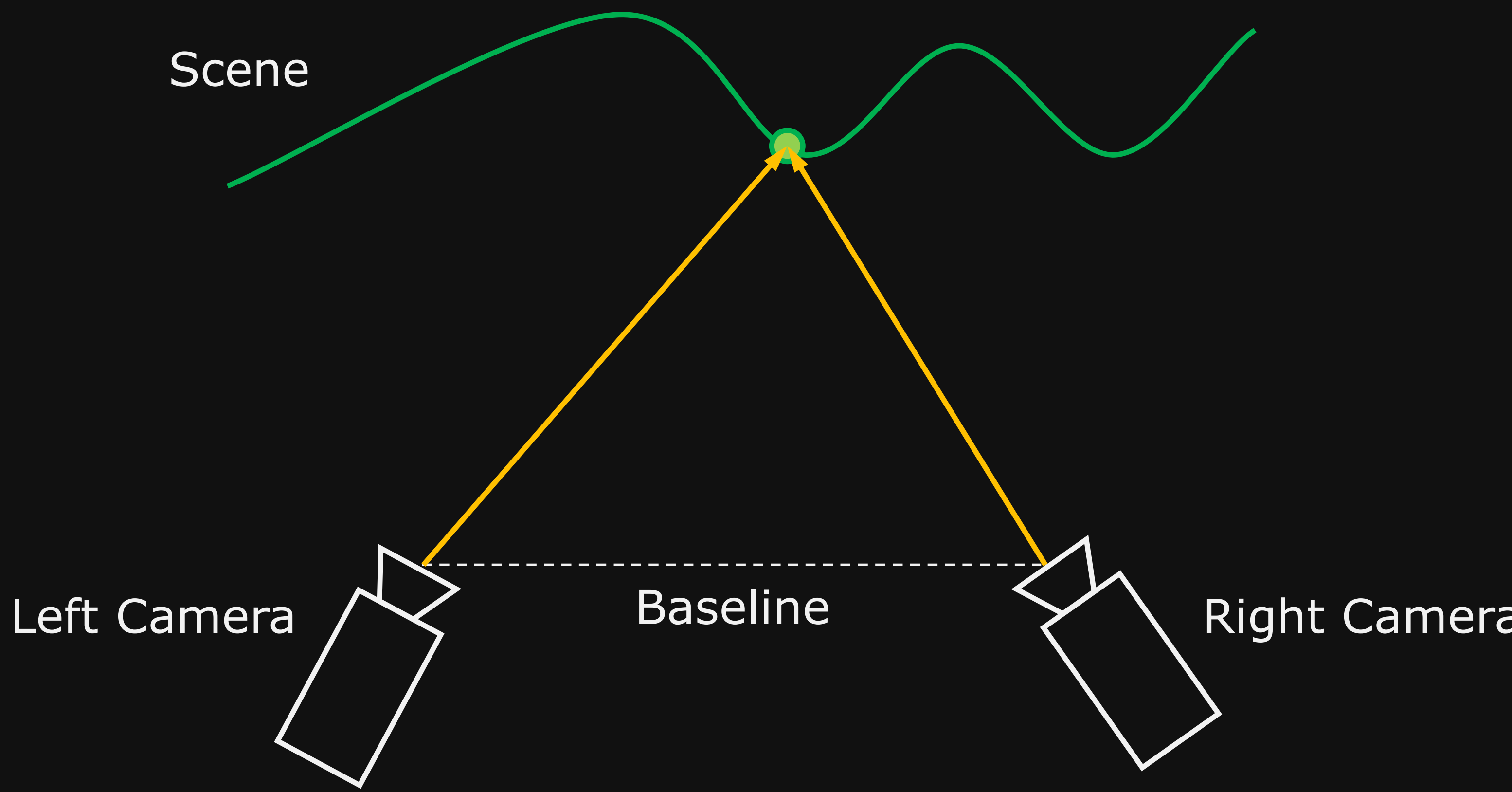
(2) Structured Light Range Finding

(3) Binary and k-ary Structured Light Methods

(4) Intensity Ratio Method

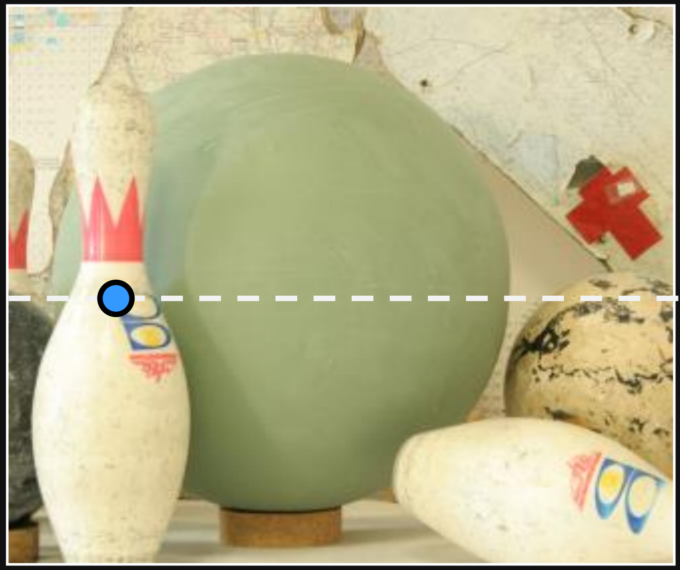
(5) Phase Shift Method

Binocular Stereo



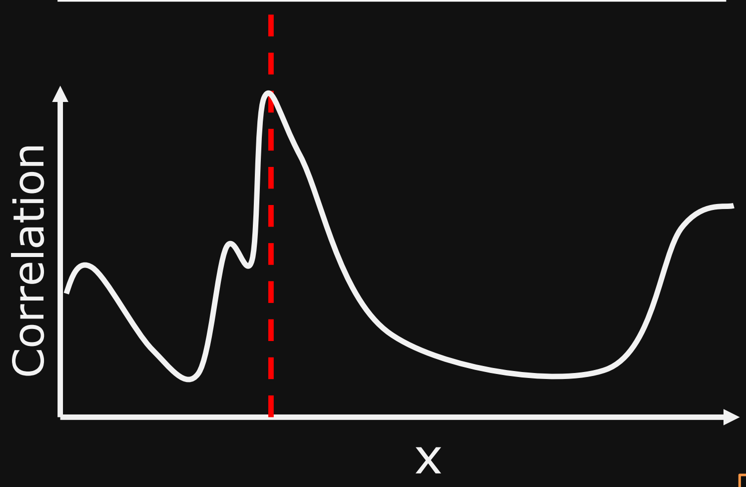
Stereo Pair Correspondence

Left Image



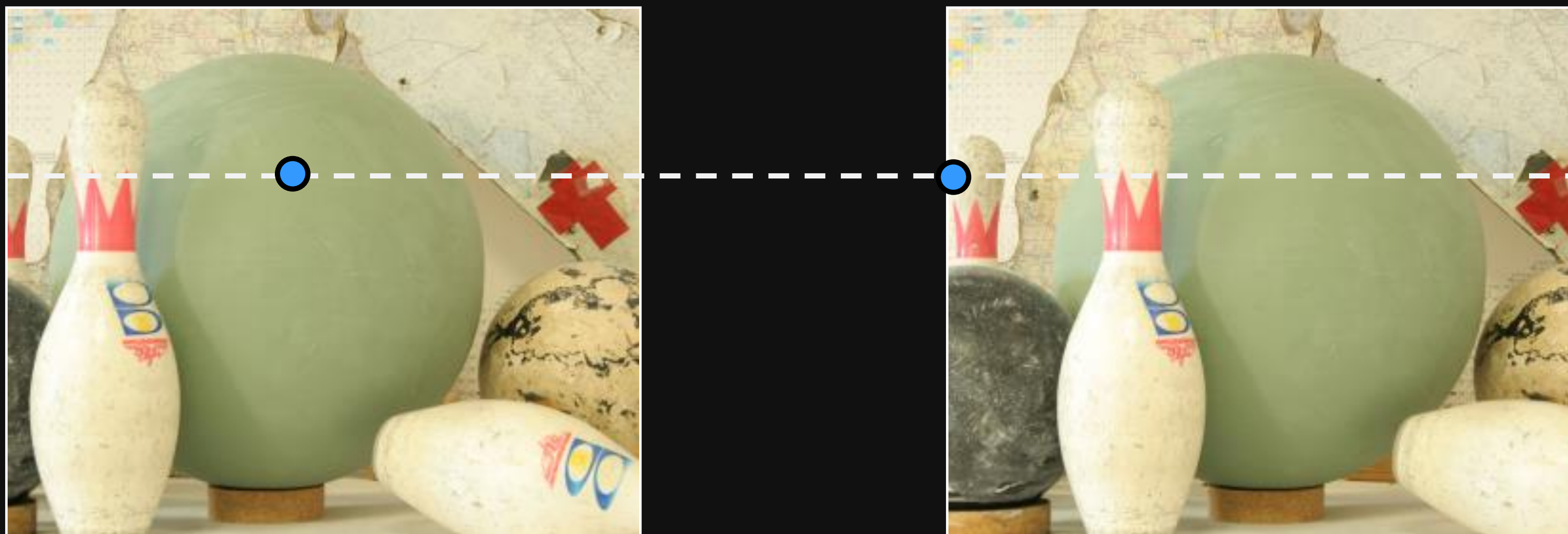
Right Image

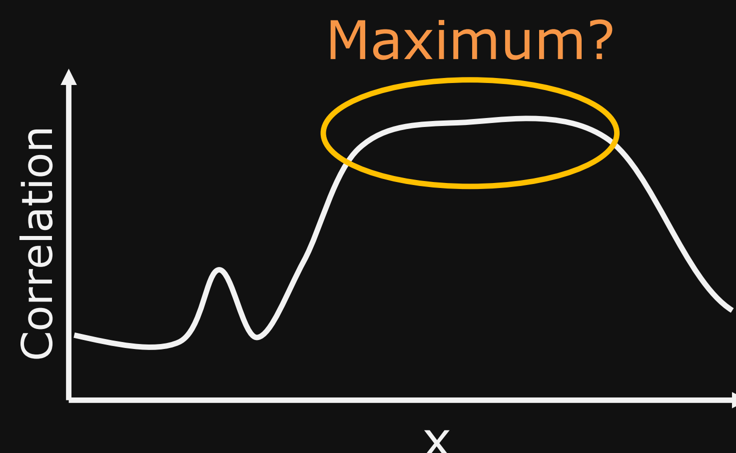
- Epipolar Constraint
- Window Based Matching (SAD/SSD/NCC)



Stereo Pair Correspondence

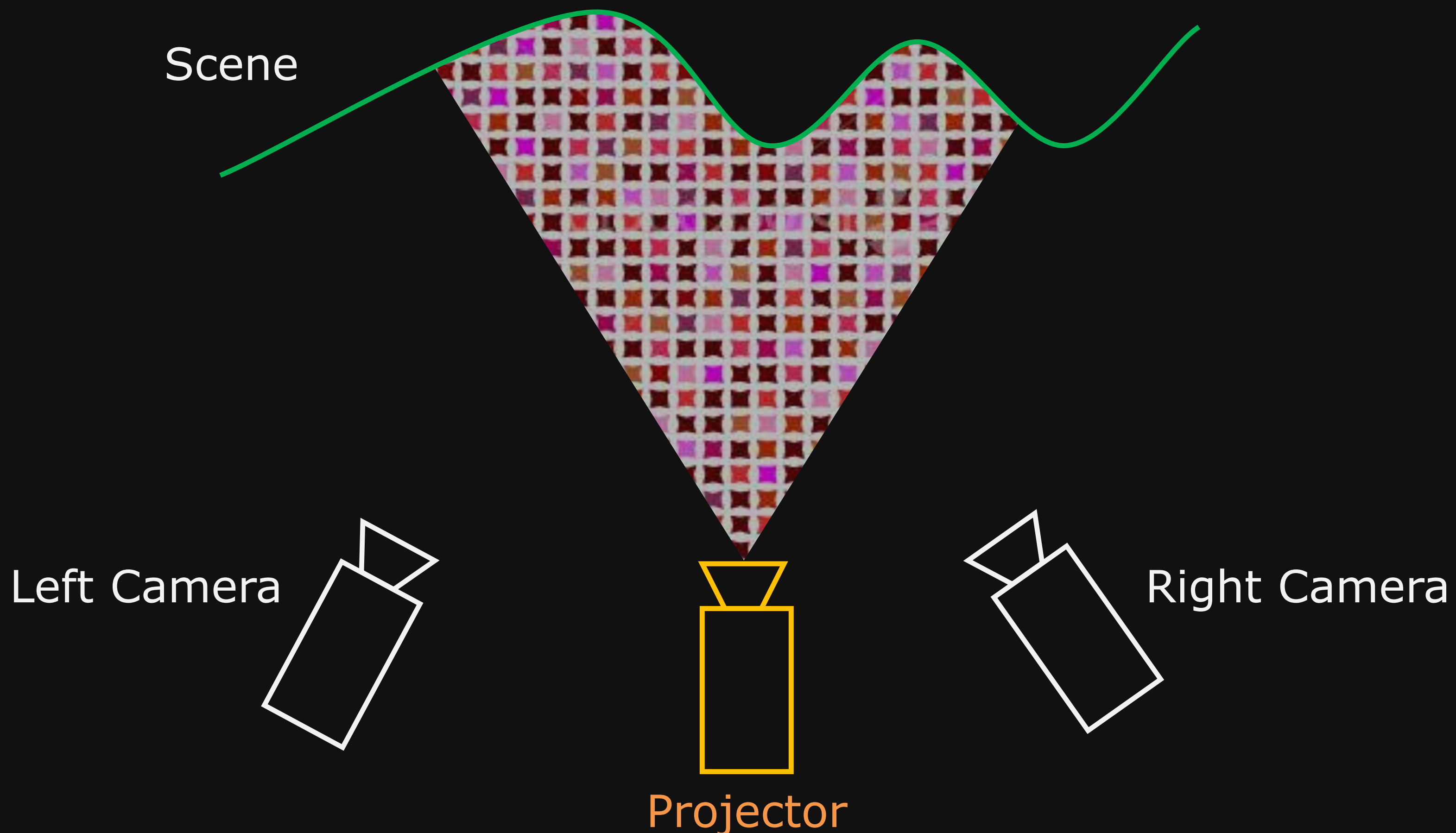
Left Image Right Image



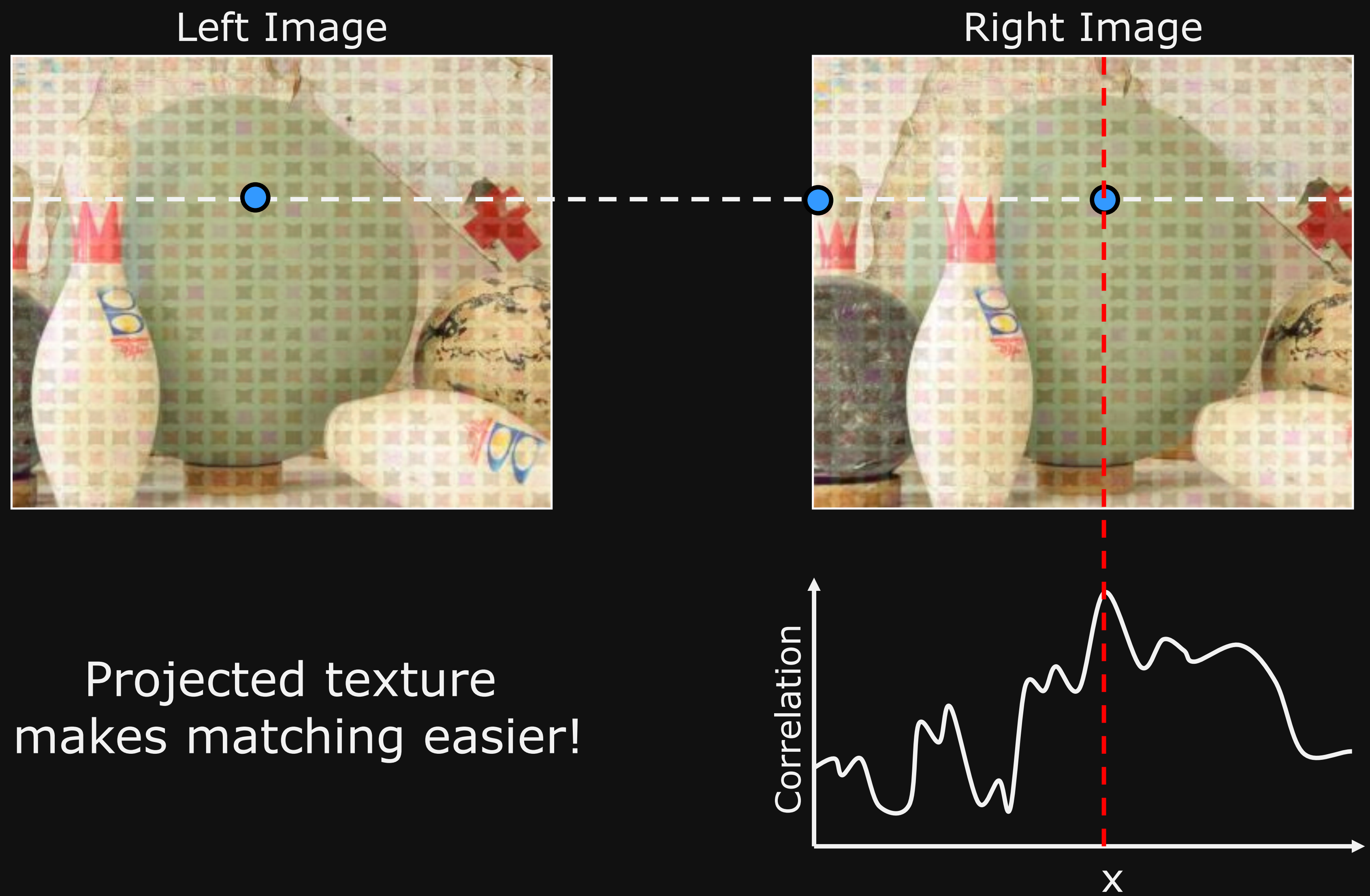


Ambiguous!

Binocular Stereo… and a Projector

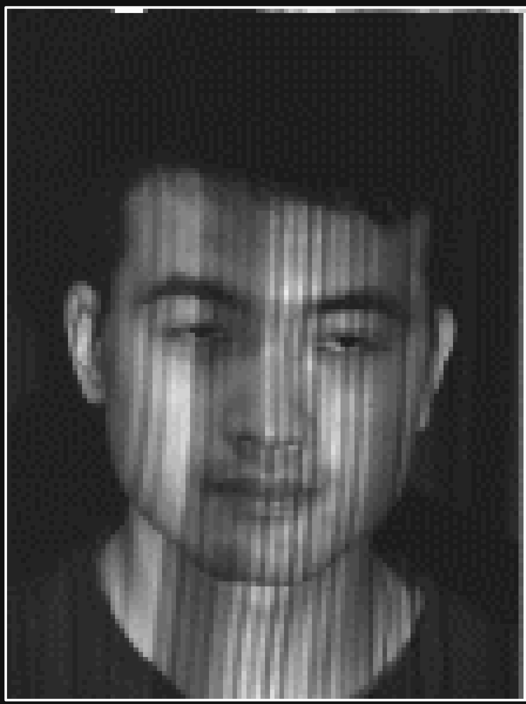
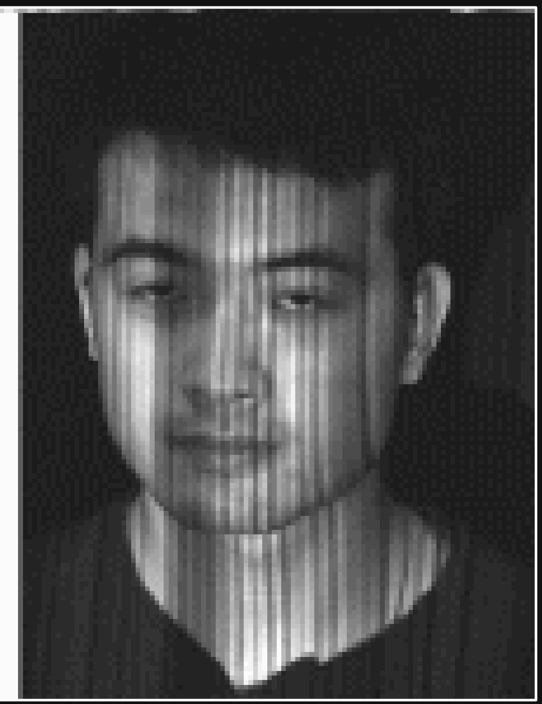
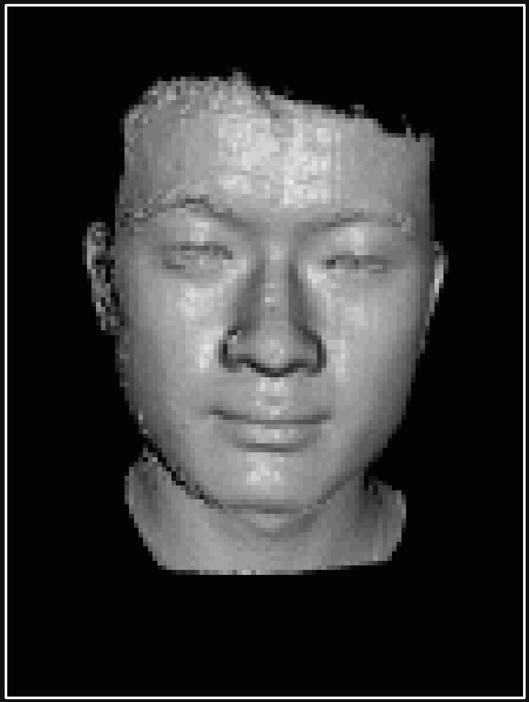


Active Stereo



Projected texture
makes matching easier!

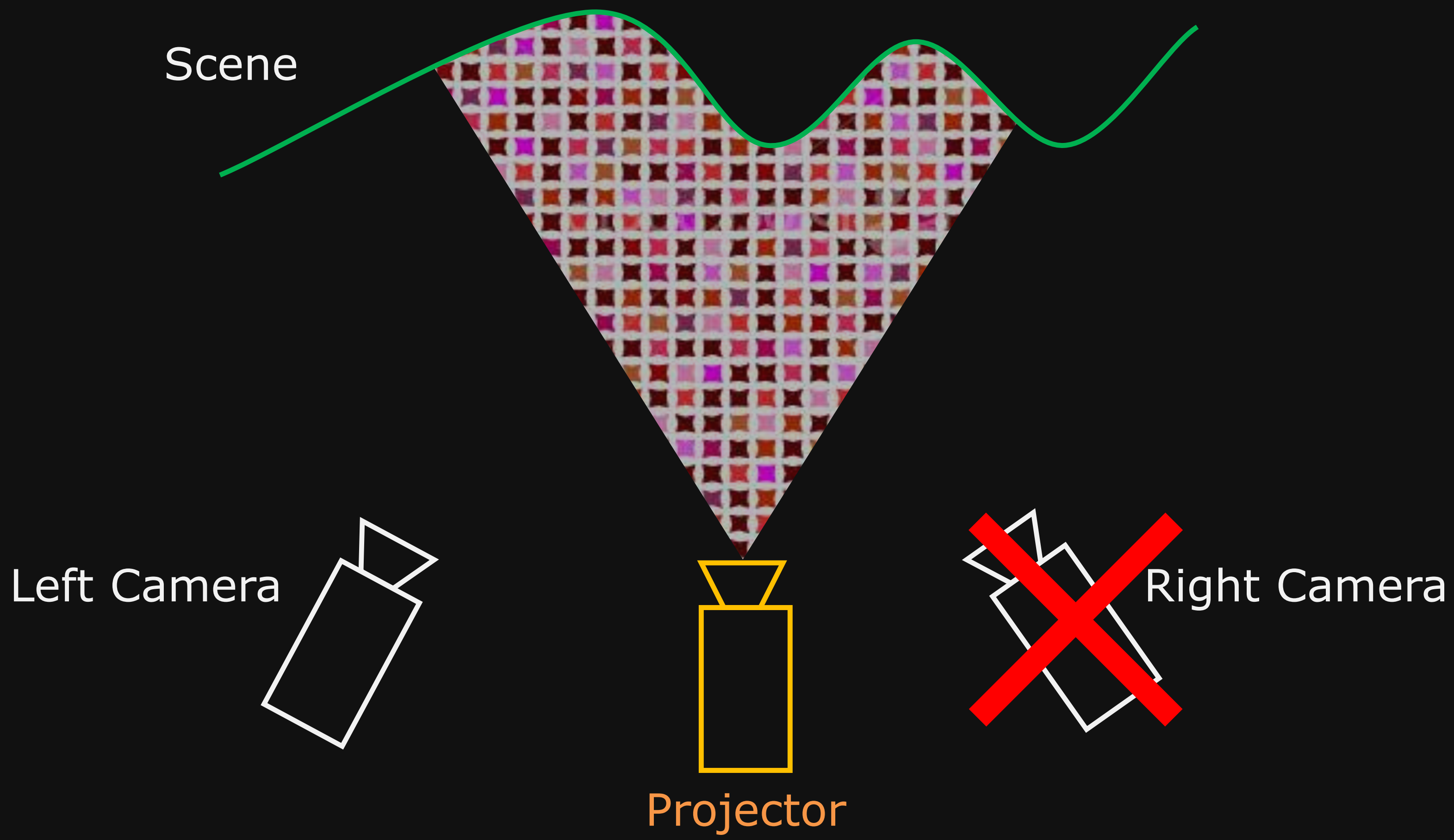
Active Stereo Results

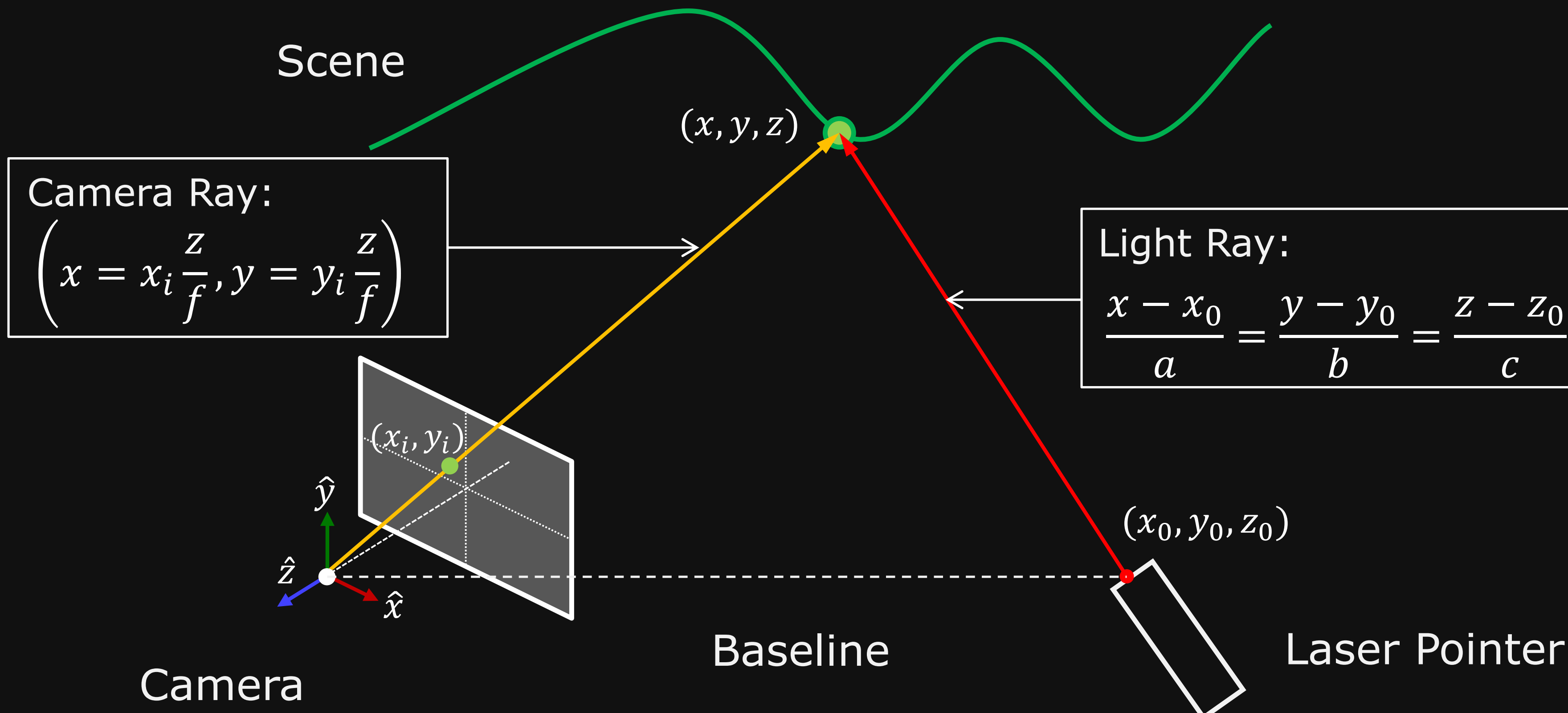
Left Image Right Image 3D Structure

Structured Light Range Finding

Remove one of the cameras ...



Point Based Range Finding



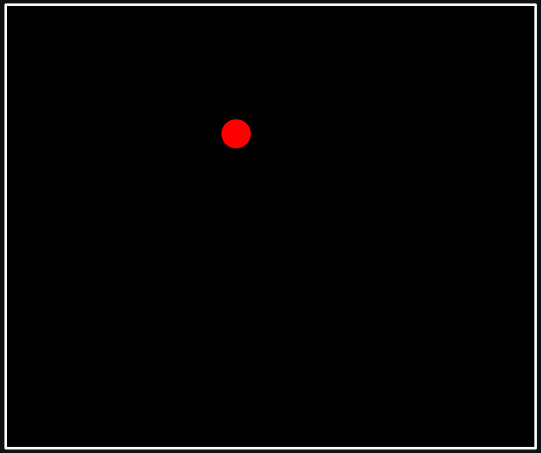
Scene Point (x, y, z)= Camera Ray ∩ Light Ray

$$\boxed{z = \frac{f(cx_0 - az_0)}{(cx_i - af)}}$$

Detecting the Illuminated Point


Background Image (I_B)


Captured Image with Pointer (I_P)


Difference Image ($I_P - I_B$)


Use Infrared Camera with Infrared Pointer

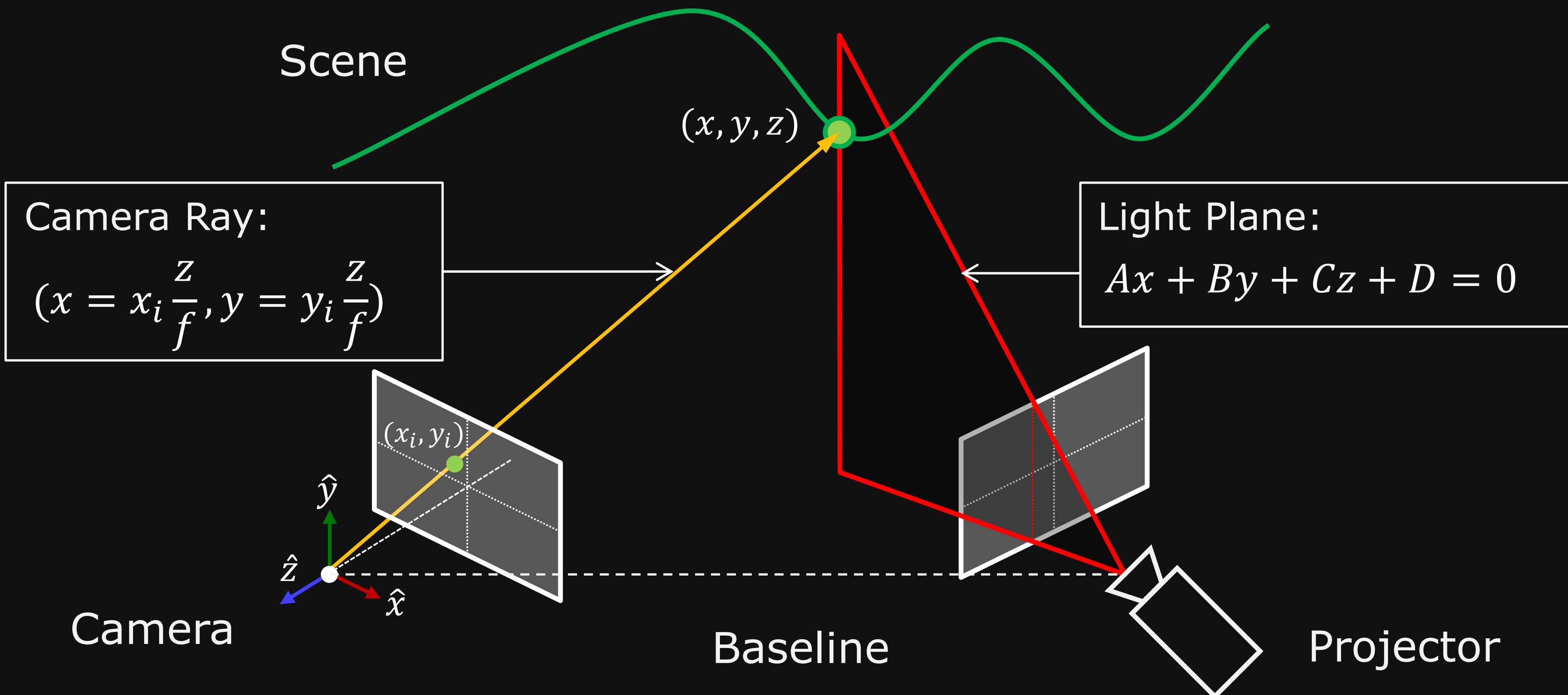
How Many Images?

One image per pixel!

For 640x480 image: >300,000 images!

At 30fps: ~3 hours!

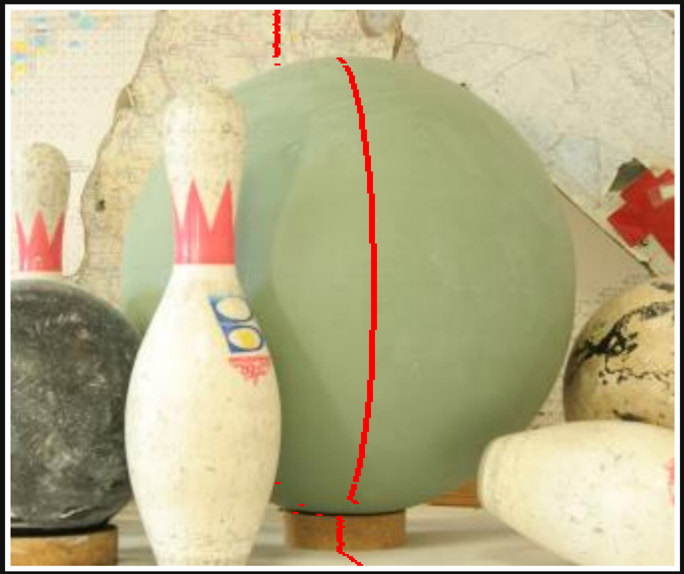
Line Stripe Range Finding



Scene Point (x, y, z)= Camera Ray ∩ Light Plane

$$\boxed{z = \frac{-Df}{Ax_i + By_i + Cf}}$$

How Many Images?



What camera sees

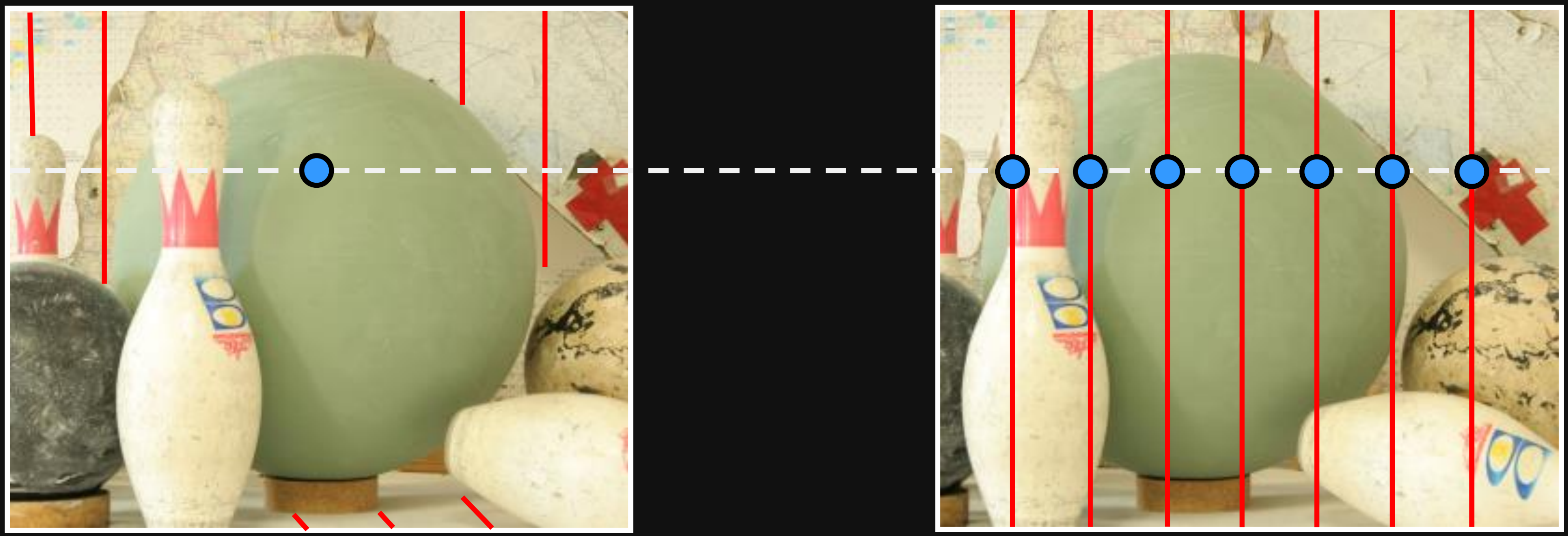
What projector “sees”

One image per column

For 640x480 image: still 640 images!

At 30fps: ~21s

Can we do Multiple Stripes at Once?



What camera sees

What projector “sees”

Ambiguous!

Binary Coded Structured Light

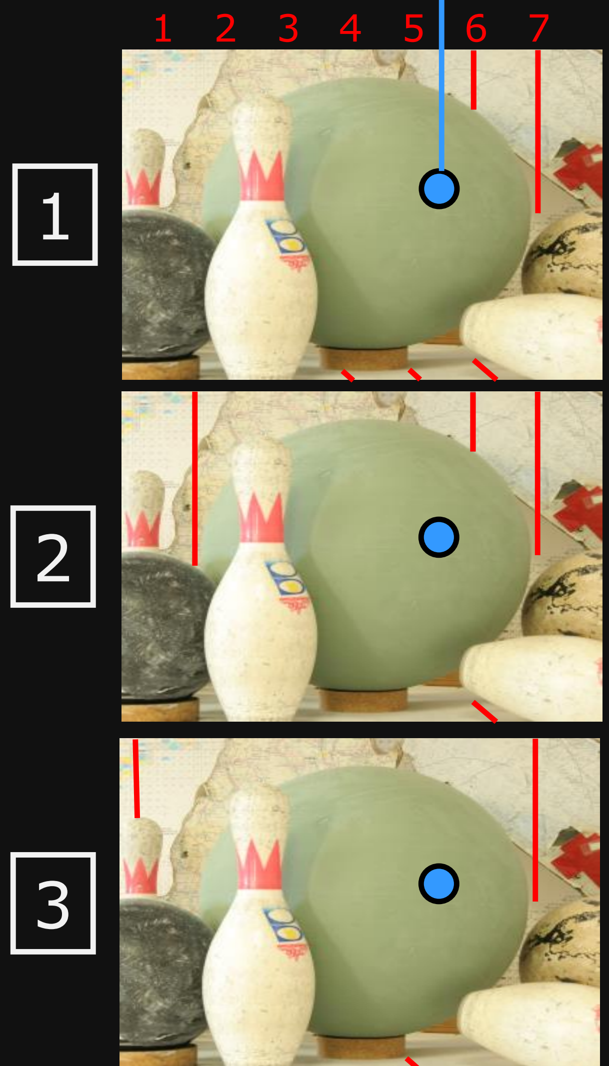


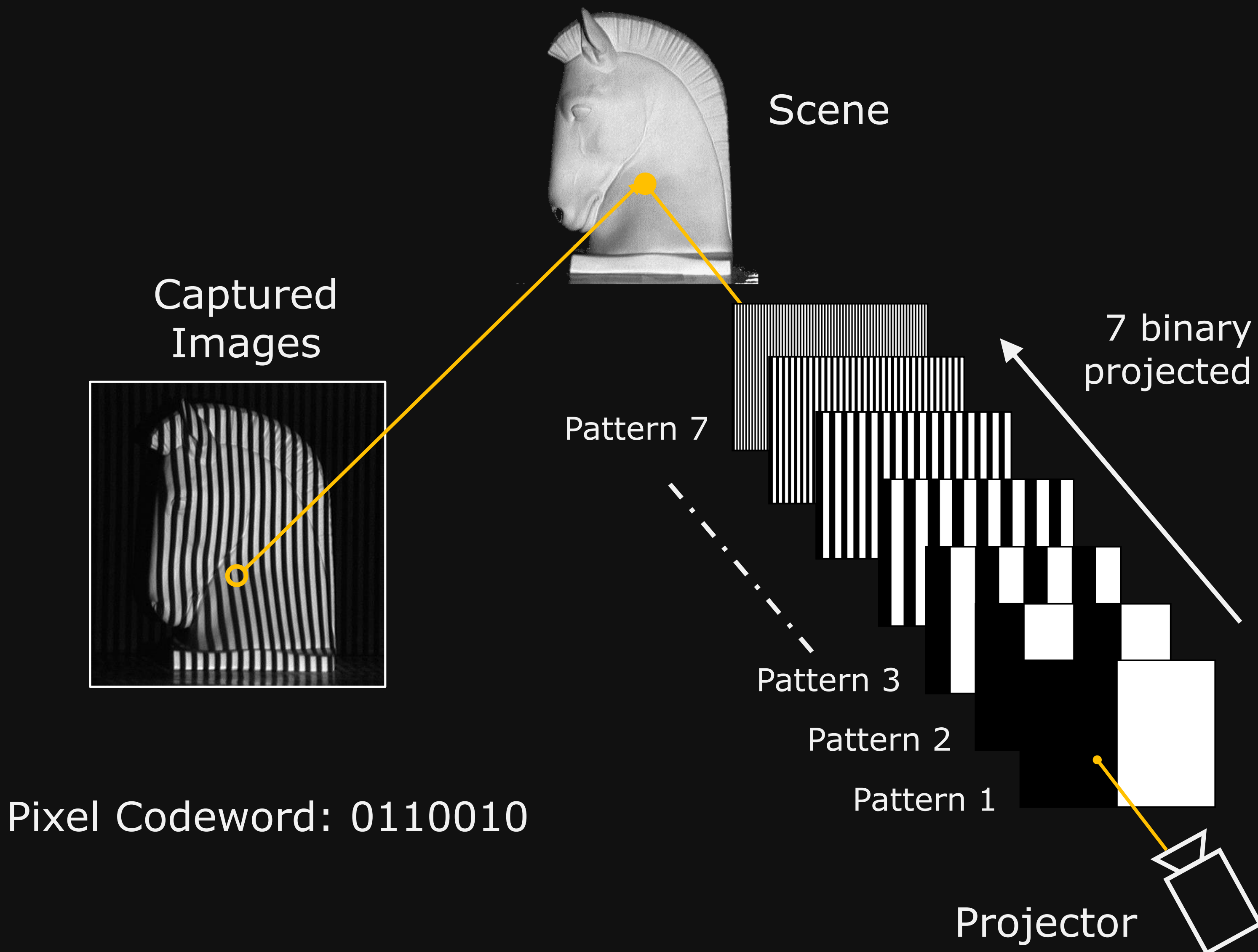
Image							
	Projection Pattern						
1 Bit 1	0	0	0	1	1	1	1
2 Bit 2	0	1	1	0	0	1	1
3 Bit 3	1	0	1	0	1	0	1
(In Binary)	(001)	(010)	(011)	(100)	(101)	(110)	(111)
Stripe Numbers	1	2	3	4	5	6	7

7 stripes in 3 images!

In general, we can do
$2^n - 1$ stripes in n Images

[Posdamer 1981]

Binary Coded Structured Light: Example



Binary Coded Structured Light: Example

Scene

Captured Images

3D Reconstruction

Errors due to Light Bleeding

Image	Projection Pattern						
1	0	0	0	1	1	1	1
2	0	1	1	0	0	1	1
3	1	0	1	0	1	0	1
(in binary)	(001)	(010)	(011)	(100)	(101)	(110)	(111)
Stripe Number	1	2	3	4	5	6	7

We could have as many as 10 errors!

Gray Coding to Reduce Errors

Image	Projection Pattern						
1	0	0	0	1	1	1	1
2	0	1	1	1	1	0	0
3	1	1	0	0	1	1	0
(in binary)	(001)	(010)	(011)	(100)	(101)	(110)	(111)
Stripe Number	1	2	3	4	5	6	7
	(001)	**(011)**	**(010)**	**(110)**	**(111)**	**(101)**	**(100)**

Gray Code: Binary numeral system where successive values differ by only one bit.

Reduced to a maximum of 6 errors!

[Inokuchi 1984]

Extending Binary to k-ary Methods

Coding	Base	Values
Binary	2	0, 1 (Off, On)
Tertiary	3	0, 1, 2 (R, G, B), (Off, ½On, On)
k-ary	k	0, 1, 2,… k-1

Color Coding with R, G, B (Tertiary)

1

2

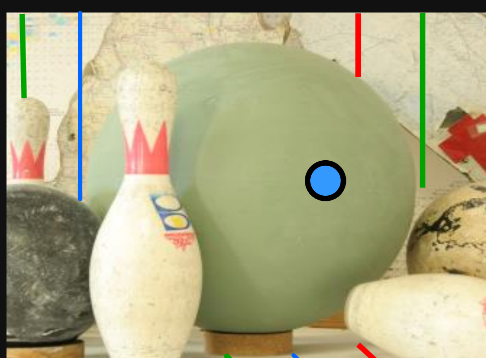


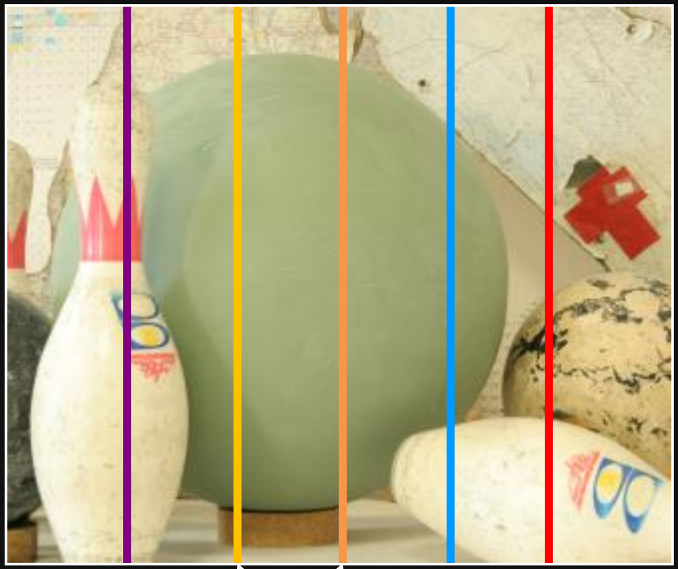
Image	Projection Pattern						
1	R	R	G	G	G	B	B
2	G	B	R	G	B	R	G
(In Base 3)	(01)	(02)	(10)	(11)	(12)	(20)	(21)
Stripe Numbers	1	2	3	4	5	6	7

7 stripes in 2 images!

In general, with k colors/intensities,
$k^n - 1$ stripes in n Images

[Caspi 1998]

The More Colors, The Less Distinguishable

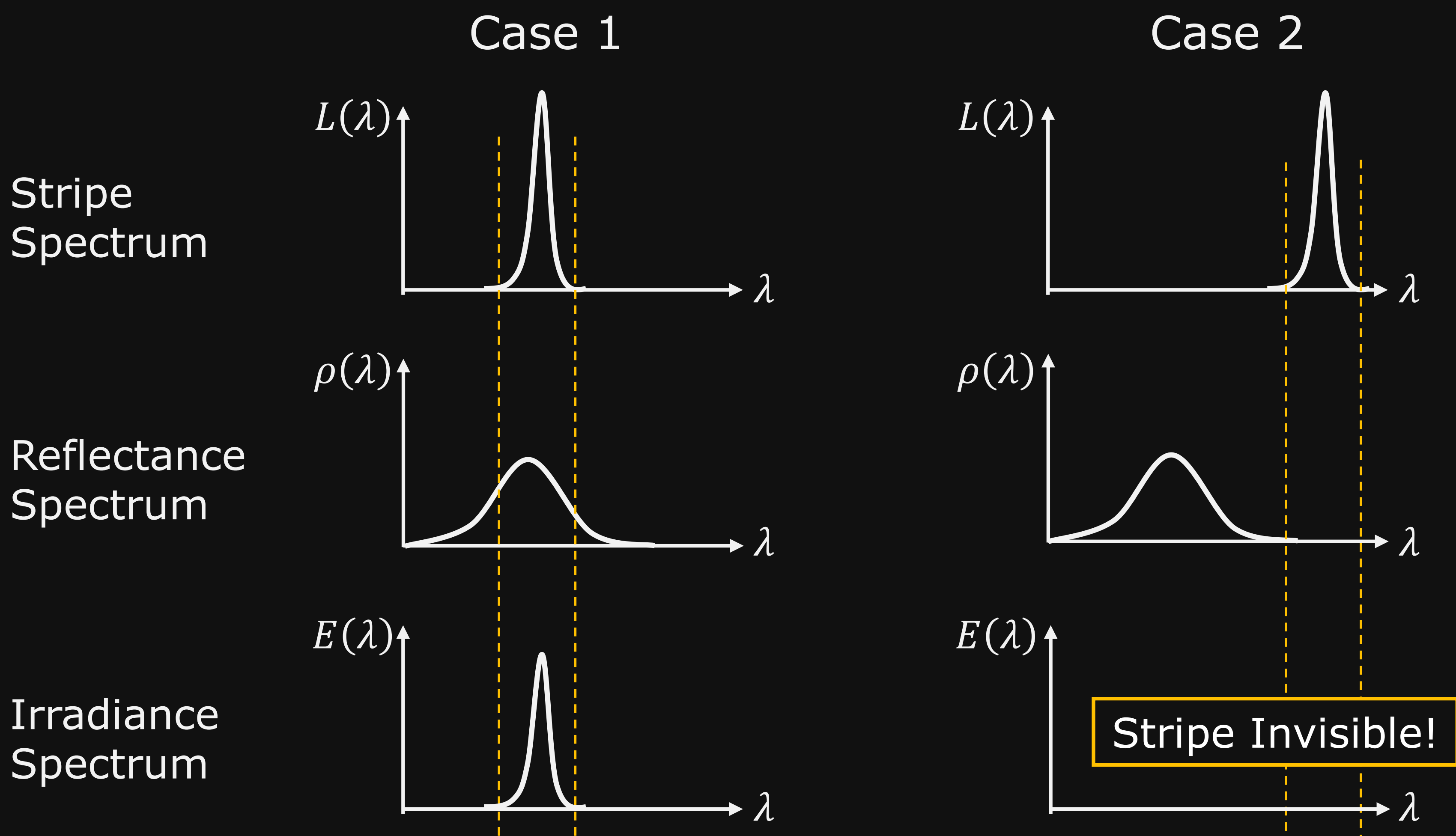


Similar colors

More precise equipment needed to measure accurately.

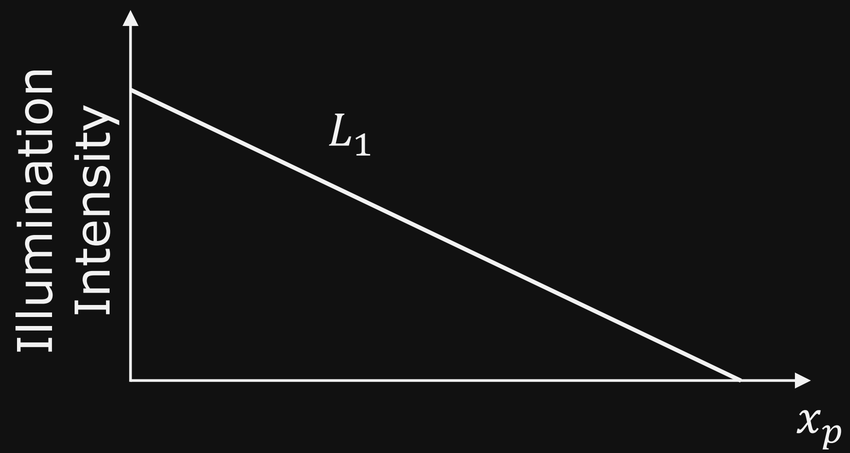
Effect of Surface Reflectance

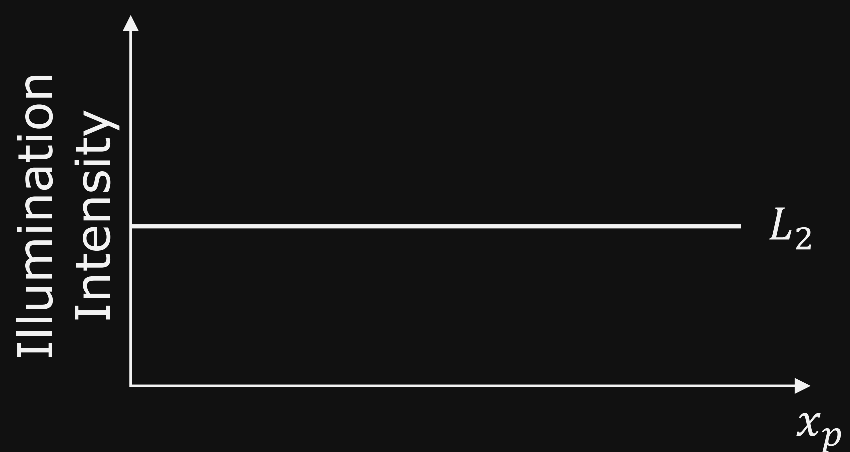
Image Irradiance: $E(\lambda) = L(\lambda)\rho(\lambda)$



Intensity Ratio Method

Projection Pattern





Captured Image

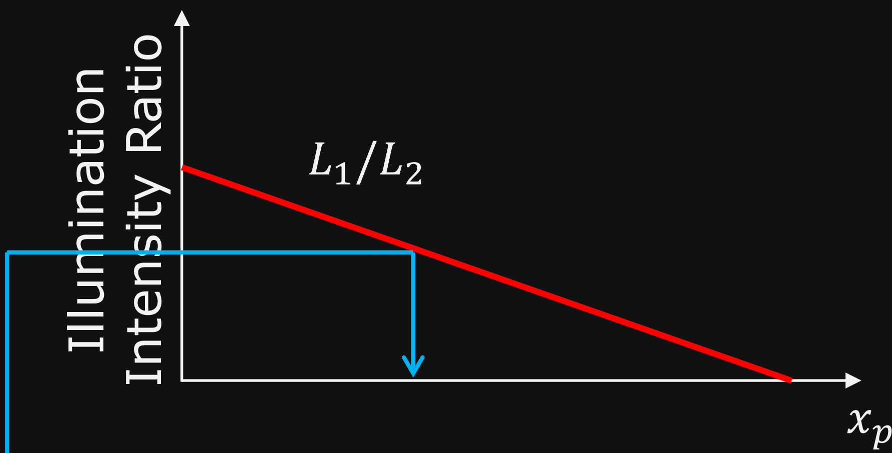
$E_1 = \rho \cdot L_1$

$E_2 = \rho \cdot L_2$

[Carrihill 1985]

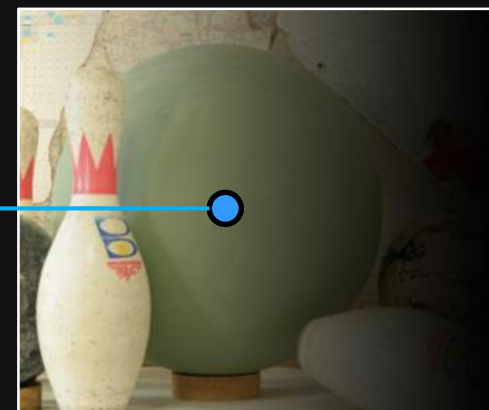
Camera-Projector Correspondence

Projection Pattern Ratio

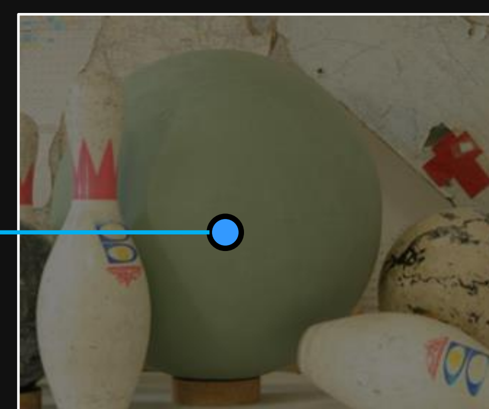


$$\frac{E_1}{E_2} = \frac{\rho L_1}{\rho L_2}$$

Captured Image



$E_1 = \rho \cdot L_1$



$E_2 = \rho \cdot L_2$

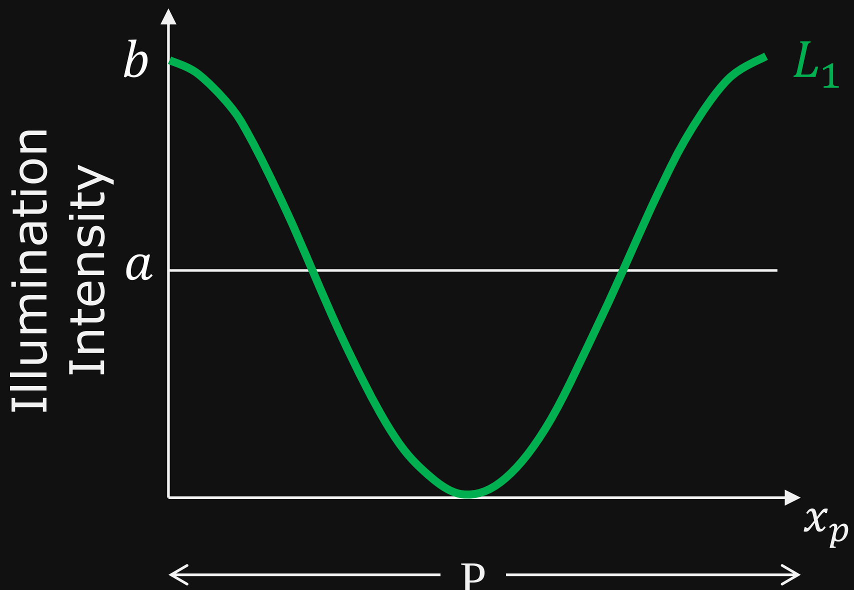
[Carrihill 1985]

Issues with Intensity Ratio Method

- Method sensitive to noise. Need to precisely measure each intensity level.
- What if you have more than 255 projector columns? Will need a high dynamic range projector.

Phase Shift Method: Sinusoidal Patterns

Projected Pattern



Captured Image

$$L_1(x_p) = a + b\cos\left(\frac{2\pi x_p}{P}\right)$$

$$I_1(x_c, y_c) = \rho a + \rho b\cos\left(\frac{2\pi x_p}{P}\right)$$

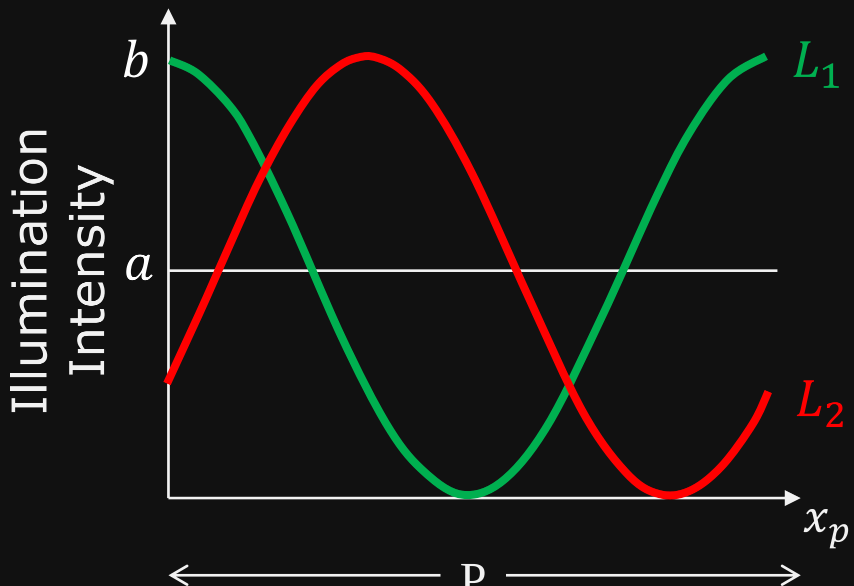
(ρ, x_p): Unknown

ρ: Scene Reflectance

[Wust 1991]

Phase Shift Method: Sinusoidal Patterns

Projected Pattern



Captured Image

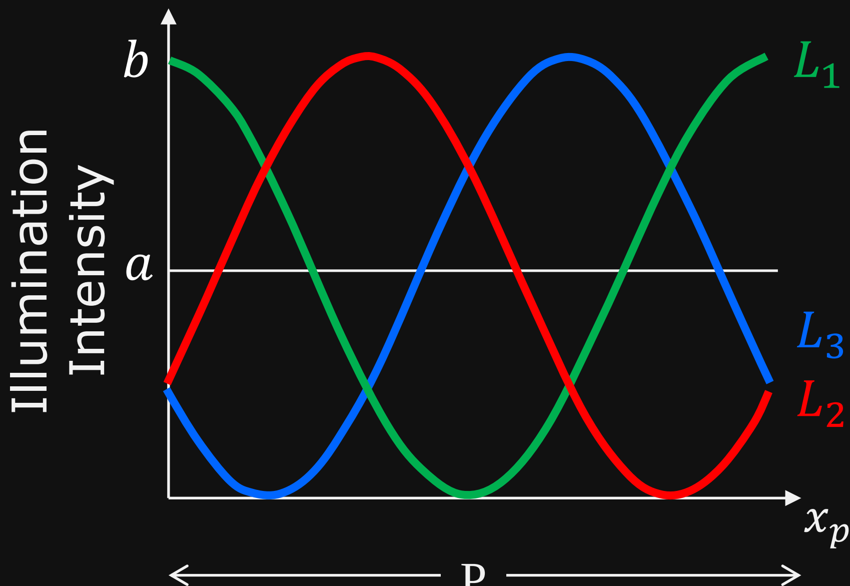
$$L_2(x_p) = a + b\cos\left(\frac{2\pi x_p}{P} - \frac{2\pi}{3}\right)$$

$$I_2(x_c, y_c) = \rho a + \rho b\cos\left(\frac{2\pi x_p}{P} - \frac{2\pi}{3}\right)$$

[Wust 1991]

Phase Shift Method: Sinusoidal Patterns

Projected Pattern



Captured Image

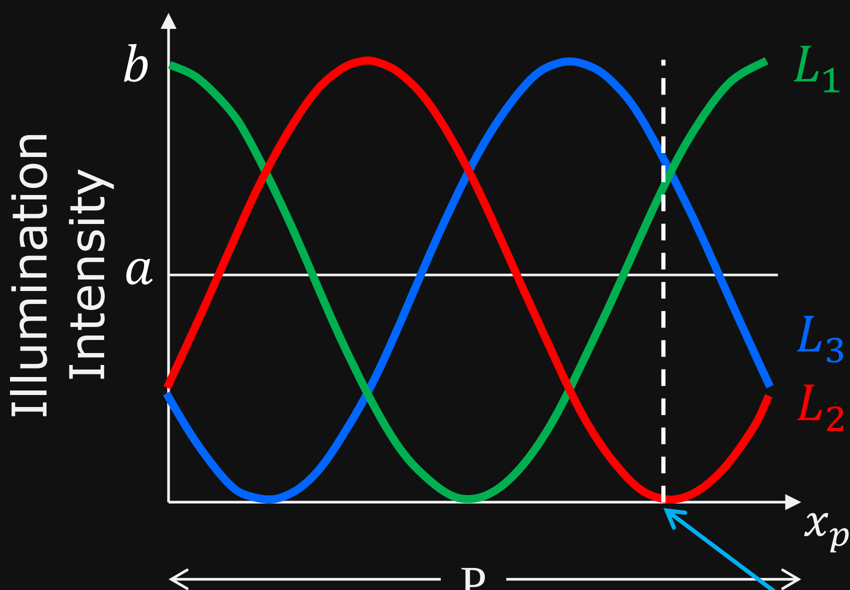
$$L_3(x_p) = a + b\cos\left(\frac{2\pi x_p}{P} + \frac{2\pi}{3}\right)$$

$$I_3(x_c, y_c) = \rho a + \rho b\cos\left(\frac{2\pi x_p}{P} + \frac{2\pi}{3}\right)$$

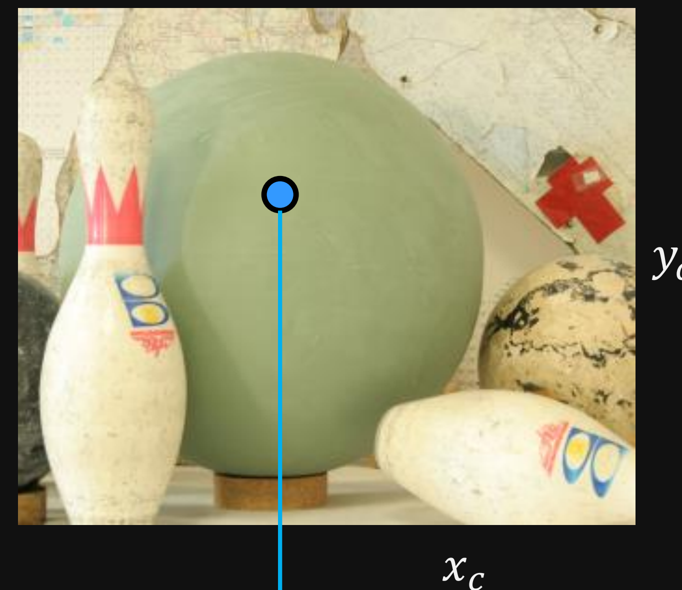
[Wust 1991]

Phase Shift Method: Correspondence

Projected Pattern



Captured Image



$$I_1(x_c, y_c) = \rho a + \rho b \cos\left(\frac{2\pi x_p}{P}\right)$$

$$I_2(x_c, y_c) = \rho a + \rho b \cos\left(\frac{2\pi x_p}{P} - \frac{2\pi}{3}\right)$$

$$I_3(x_c, y_c) = \rho a + \rho b \cos\left(\frac{2\pi x_p}{P} + \frac{2\pi}{3}\right)$$

$$\boxed{x_p = \frac{P}{2\pi} \tan^{-1}\left(\sqrt{3}\,\frac{I_2 - I_3}{2I_1 - I_2 - I_3}\right)}$$

[Wust 1991]

Structured Light: Summary

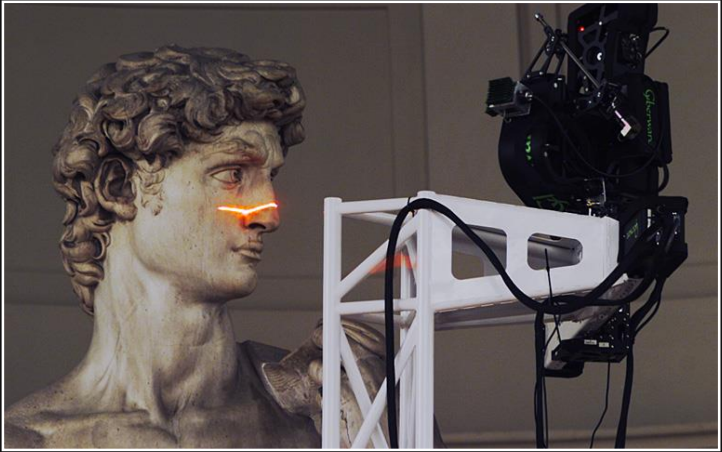
Method	Number of Images
Point based Structured Light	MN
Line based Structured Light	N
Binary Coded Structured Light	$\lceil \log_2(N+1) \rceil$
k-ary (Color) Coded Structured Light	$\lceil \log_k(N+1) \rceil$
Intensity Ratio Lighting	2
Phase-Shift Lighting	3

$[M, N]$: Camera Image Size

k : Number of colors/intensities

$\lceil x \rceil$: Smallest integer ≥ x

Example: Digital Michelangelo Project

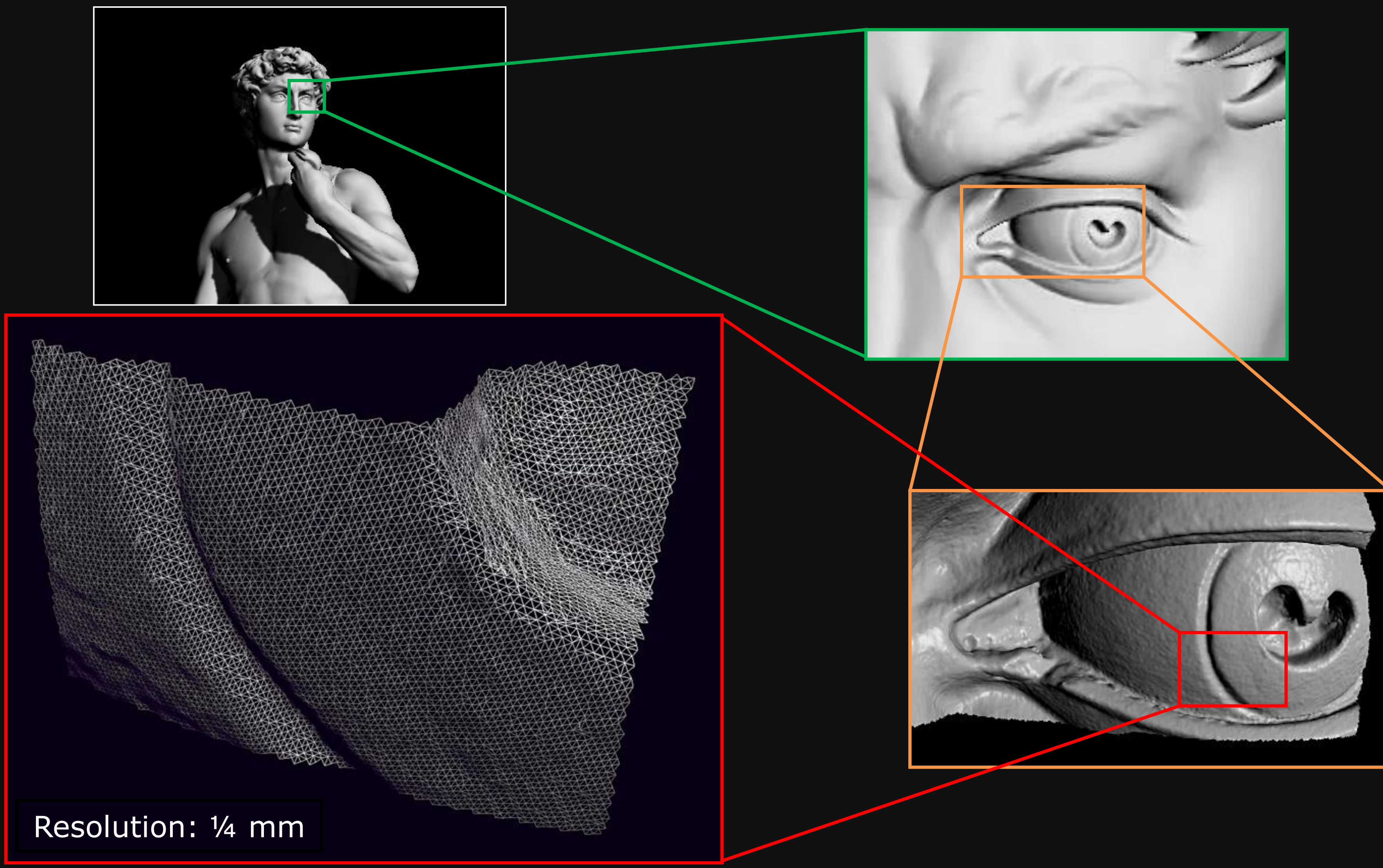


Michelangelo's David:

- 480 individually aimed scans
- 2 billion polygons
- 7,000 color images
- 32 gigabytes of data
- 30 nights of scanning
- 22 people

 [Levoy 2000]

Example: Digital Michelangelo Project



 [Levoy 2000]

Benefits of Structured Light Methods

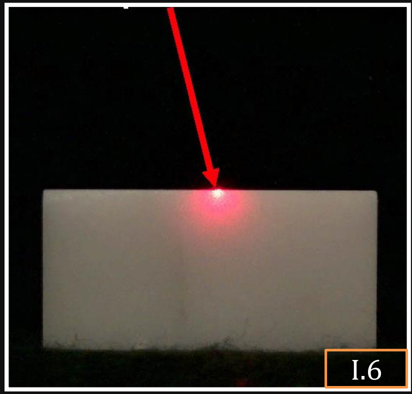
- Local, pixel-wise algorithm. No support region needed.
- Very precise depth estimates. Down to micrometers!
- Reasonably fast. Real-time systems exist.

Issues with Structured Light Methods

- Restricted to controlled environments.
- Camera-Projector calibration needs to be precise.
- Timing synchronization needs to be precise to avoid stripes “blurring” into each other.
- Dynamic range and signal-to-noise ratio must be high to distinguish different intensities.

Limits of Structured Light Methods

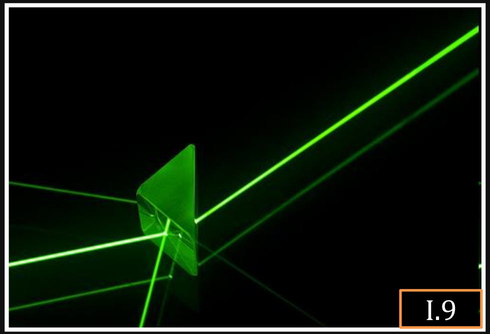
Optically uncooperative materials



Scattering surface
(marble)

Scattering environment
(underwater)

Specular surface
(mirror-like)



Transparent surface
(glass)

Fuzzy
(hair)

References

[Carrihill 1985] B. Carrihill and R. Hummel. *Experiments with the intensity ratio depth sensor.* Computer Vision, Graphics and Image Processing, vol.32, 1985, pp.337-358.

[Caspi 1998] D. Caspi, N. Kiryati, and J. Shamir. *Range imaging with adaptive color structured light*. IEEE Trans. on PAMI, 20(5), 1998, pp.470-480.

[Inokuchi 1984] S. Inokuchi, K. Sato and F. Matsuda. *Range imaging system for 3-D object recognition*. ICPR, 1984, pp.806-808.

[Levoy 2000] M. Levoy et al., *The Digital Michelangelo Project: 3D Scanning of Large Statues*. Siggraph, 2000.

[Posdamer 1981] J. L. Posdamer and M. D. Altschuler. *Surface measurement by space-encoded projected beam systems*. Computer Graphics and Image Processing, 18(1), pp.1-17. 1981.

[Salvi 2004] J. Salvi, J. Pages, and J. Batlle. *Pattern codification strategies in structured light systems.* Pattern Recognition, vol.37, no.4, 2004, pp.827-849.

[Wust 1991] C. Wust and D. W. Capson. *Surface profile measurement using color fringe projection*. Machine Vision and Applications, vol.4, 1991, pp.193-203.

Image Credits

I.1	http://vision.middlebury.edu/stereo/data/scenes2006/
I.2	http://grail.cs.washington.edu/projects/ststereo/
I.3	http://jordipages.webs.com/codedlight/examples/examples.html
I.4	http://jordipages.webs.com/codedlight/examples/examples.html
I.5	http://graphics.stanford.edu/projects/mich/
I.6	http://graphics.stanford.edu/papers/marble-assessment/laser-striking-marble.jpg
I.7	http://www.cs.columbia.edu/CAVE/projects/struc_light/
I.8	http://www.artisanti.com/ekmps/shops/artisanti/images/electro-plate-buddha-head-10876-p.jpg
I.9	http://www.flickr.com/photos/mattbell/1591769889/
I.10	http://www.flipwallpapers.com/wallpapers/the_curly_hair_girl-2560x1600.jpg