Computational Optical Imaging - Optique Numerique

-- Active Light 3D--

Autumn 2015

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Overview

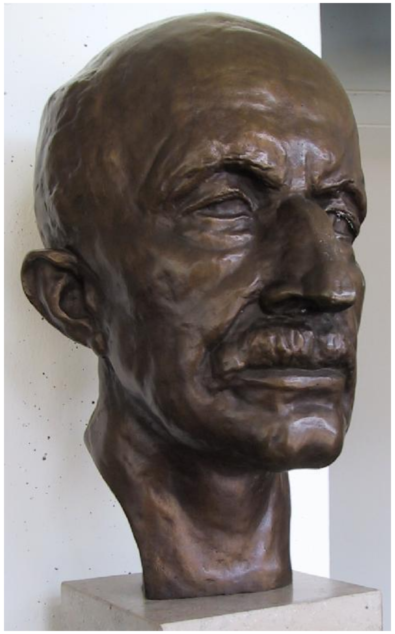
- 3D scanning techniques
  - Laser triangulation
  - Structured light
  - Photometric stereo
- Time-of-Flight
- Transient Imaging

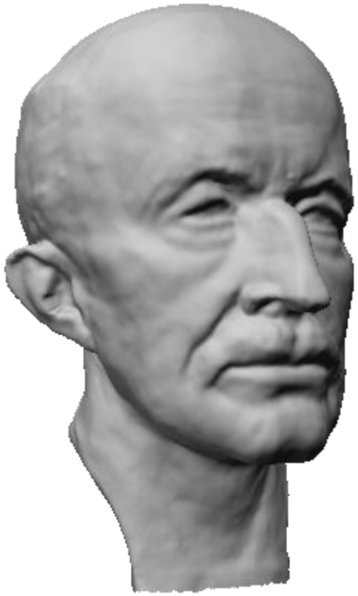
Active Light - 3D Scanning

Laser Scanning

Range scanning

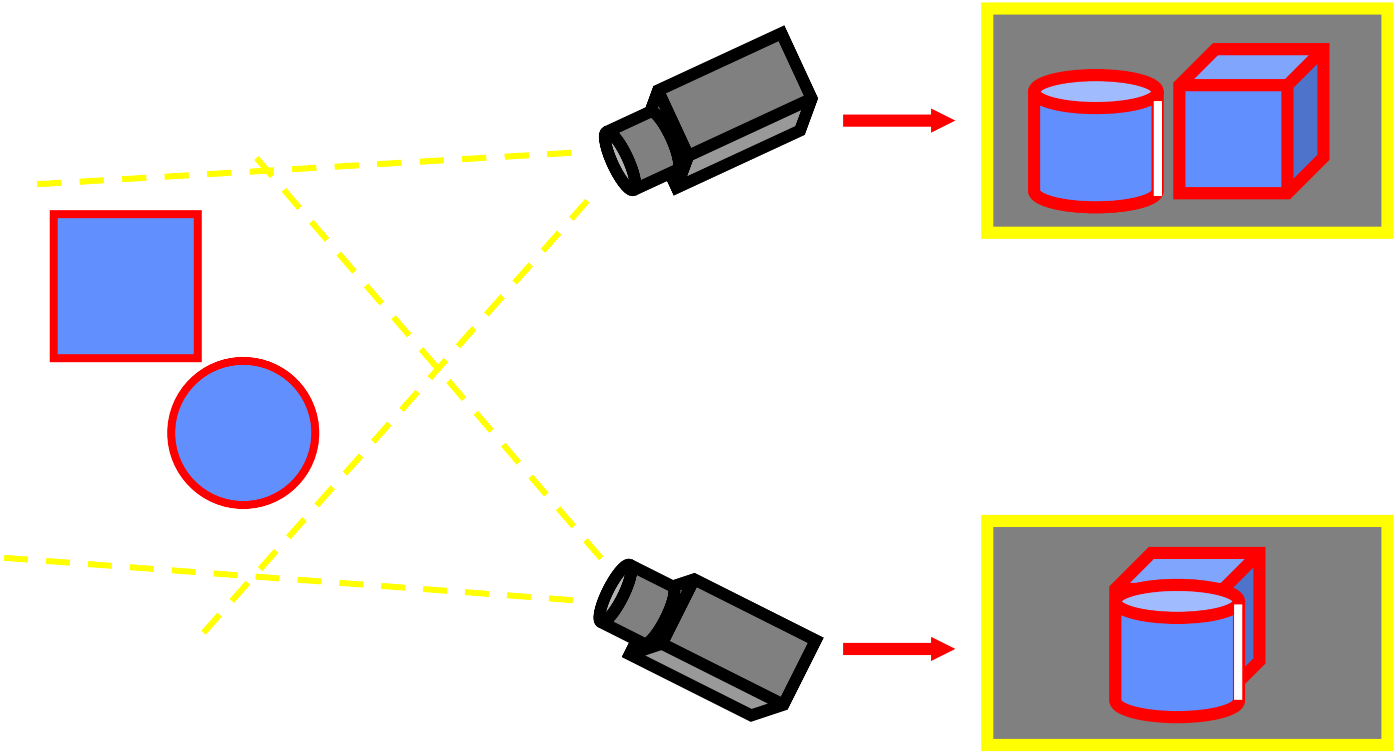
- Generate range from stereo information
  - Scales from desktop to whole body scanners





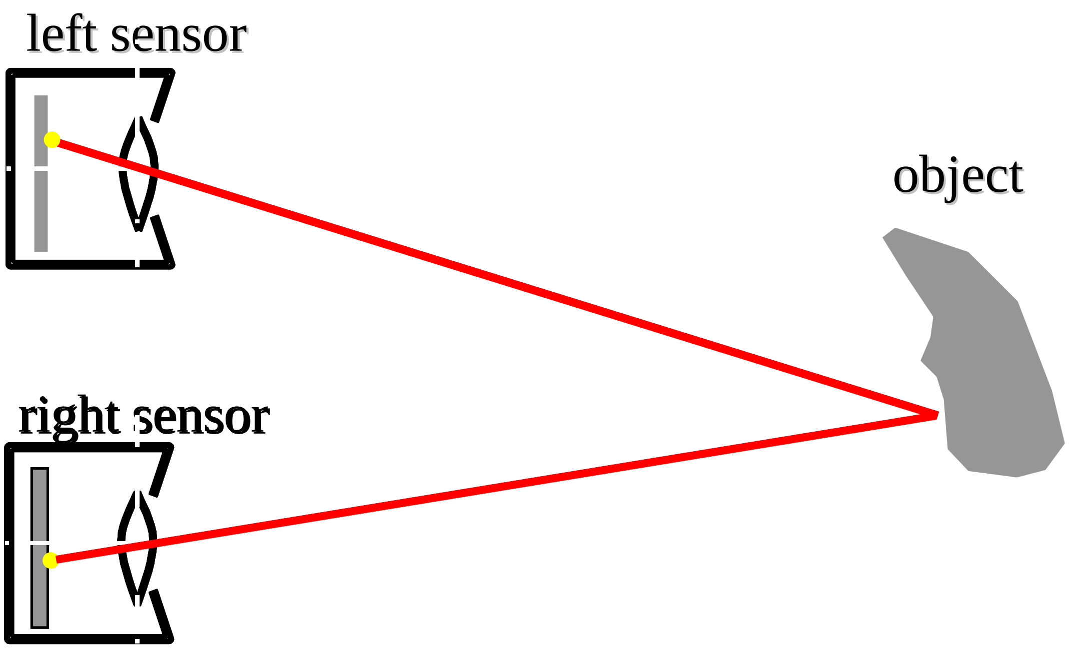
Range scanning systems

- Passive: n ≥ 2 cameras; match images



Optical Triangulation

- passive setup: match corresponding images



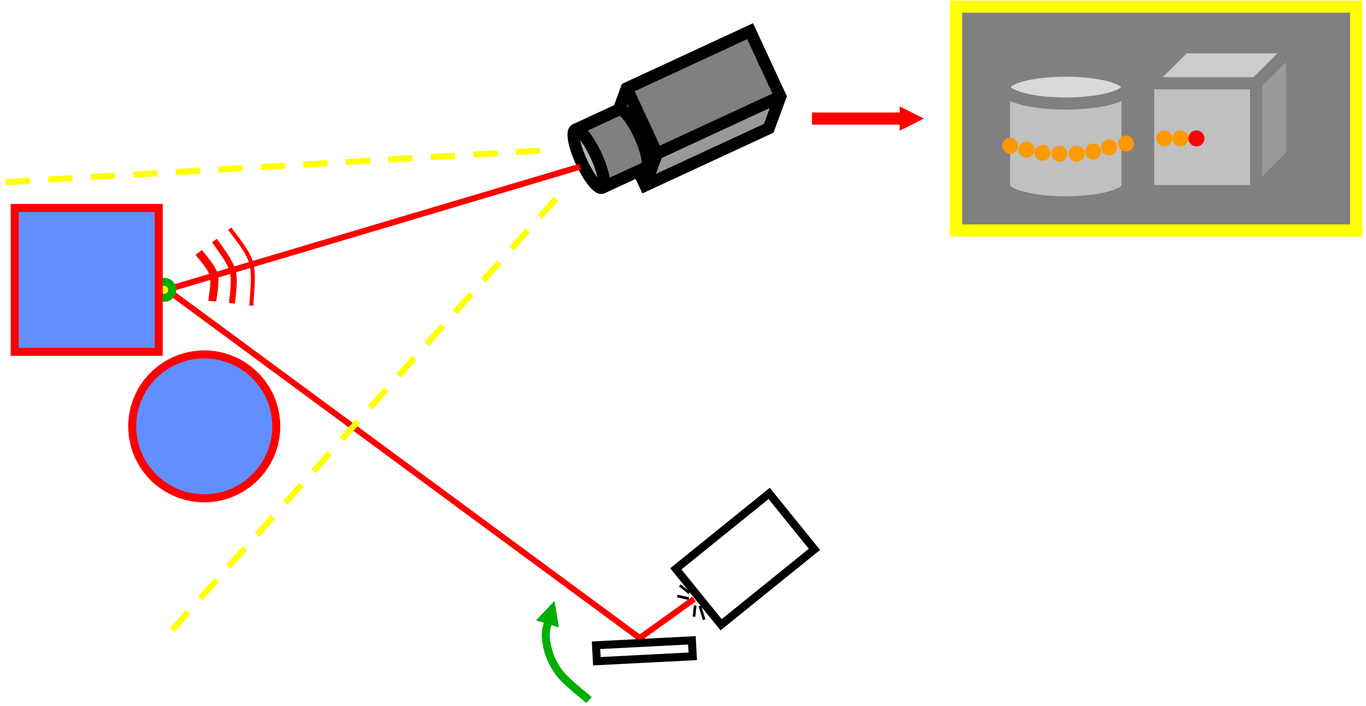
Active Techniques

- project some additional signal into the scene
  - requires signal source, and additional calibration
  - often more or less direct measurements
  - typically higher precision

- Examples:
  - range scanning
  - matting applications
  - measurement of reflection properties

Range scanning systems

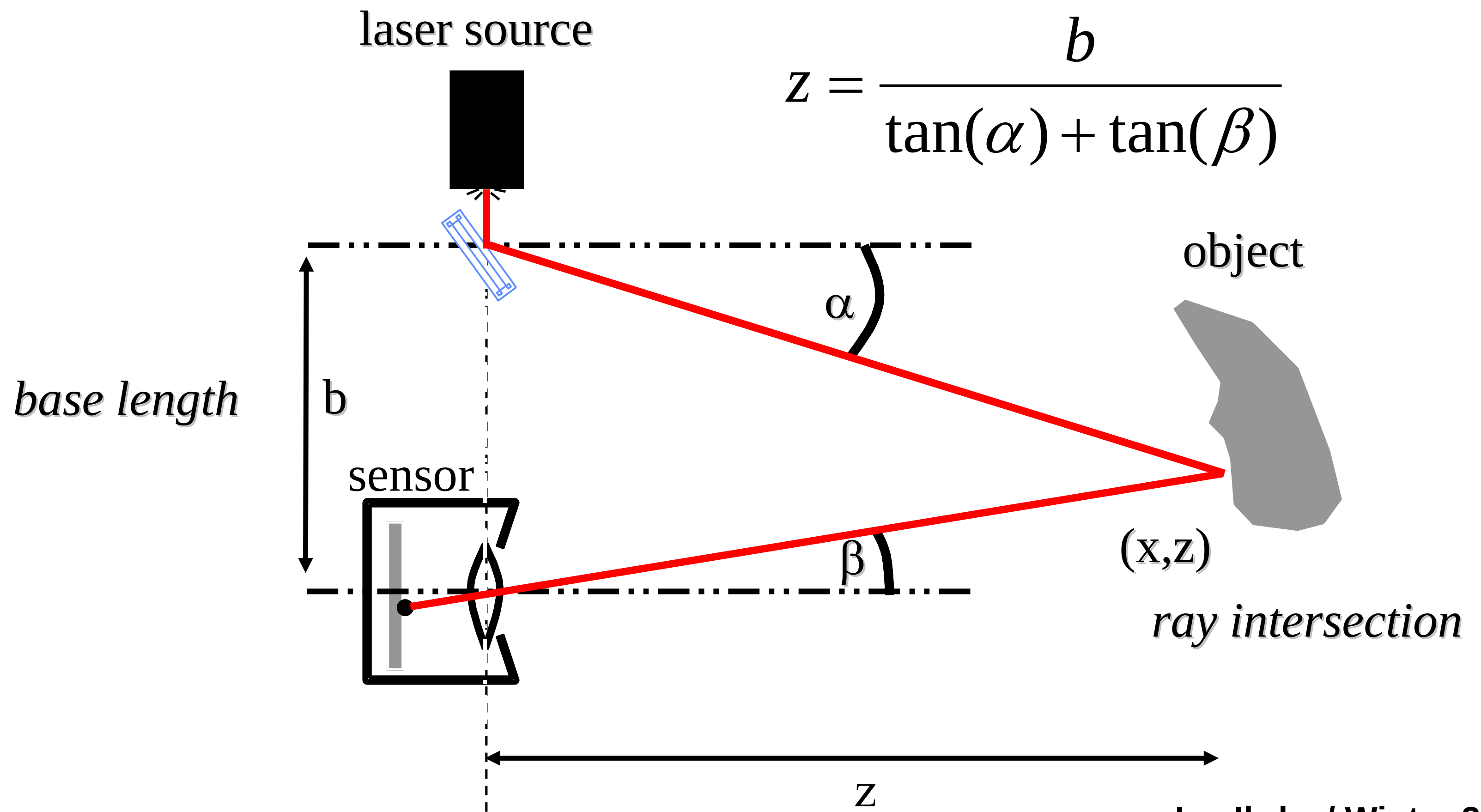
- Active: Laser light source
  - Sweep & track reflection (triangulation)



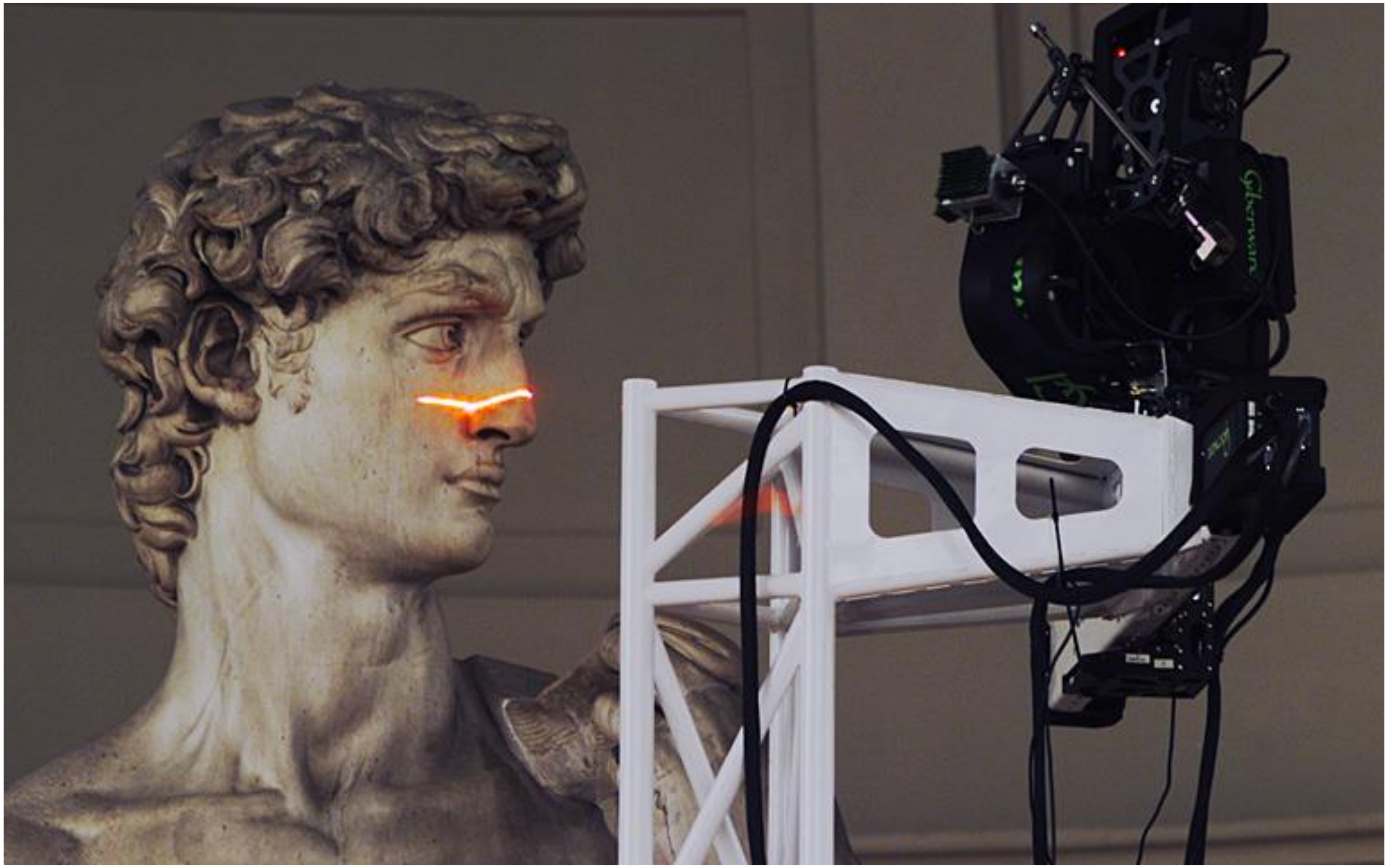
  - Project a line instead of a single point

Optical triangulation

- active setup: track light spot

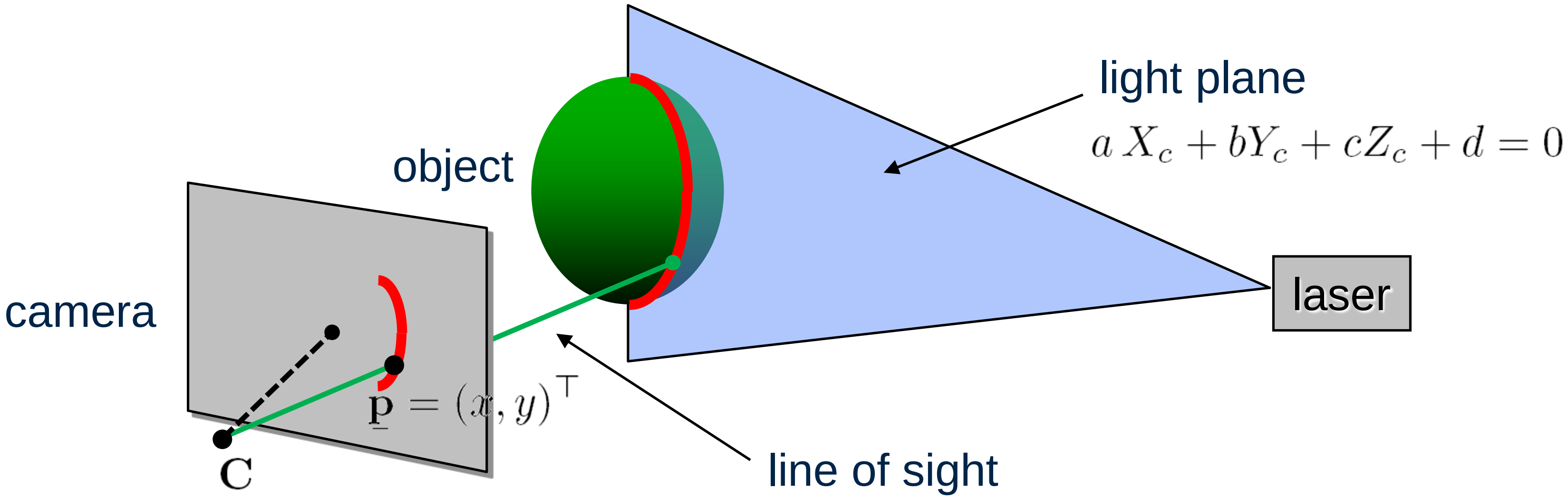


Laser triangulation



Source: The Digital Michelangelo Project, Stanford University

Laser triangulation



- Depth from ray-plane triangulation:
  - Intersect line of sight with light plane (canonical camera)

$$x = f\,\frac{X_c}{Z_c} \qquad y = f\,\frac{Y_c}{Z_c} \qquad \hat{Z}_c = \frac{-d}{a\,\frac{x}{f} + b\,\frac{y}{f} + c}$$

Laser triangulation

- Advantages
  - simple approach
  - works quite reliable
  - accuracy proportional to working volume (typical is ~1000:1)
    - scales down to small working volume (e.g. 5 cm. working volume, 50 μm. accuracy)
- Disadvantages
  - long scanning time (no real-time capture of moving objects)
  - does not scale up (baseline too large…)
  - two-lines-of-sight problem (shadowing from either camera or laser)
    - triangulation angle: lower accuracy if too small, shadowing if too big (useful range: 15°-30°)
    - needs stable reliable calibration with good mechanics, thus often expensive to buy

Digital Michelangelo Project,1997-2000

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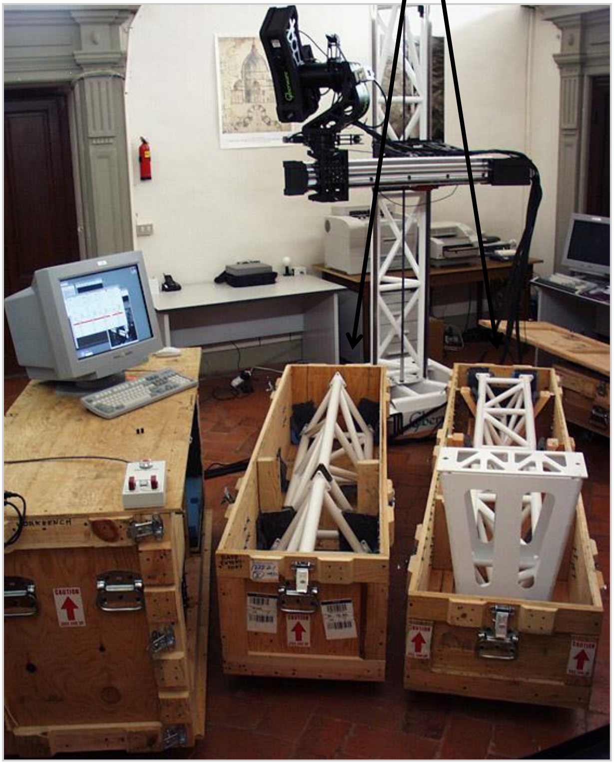
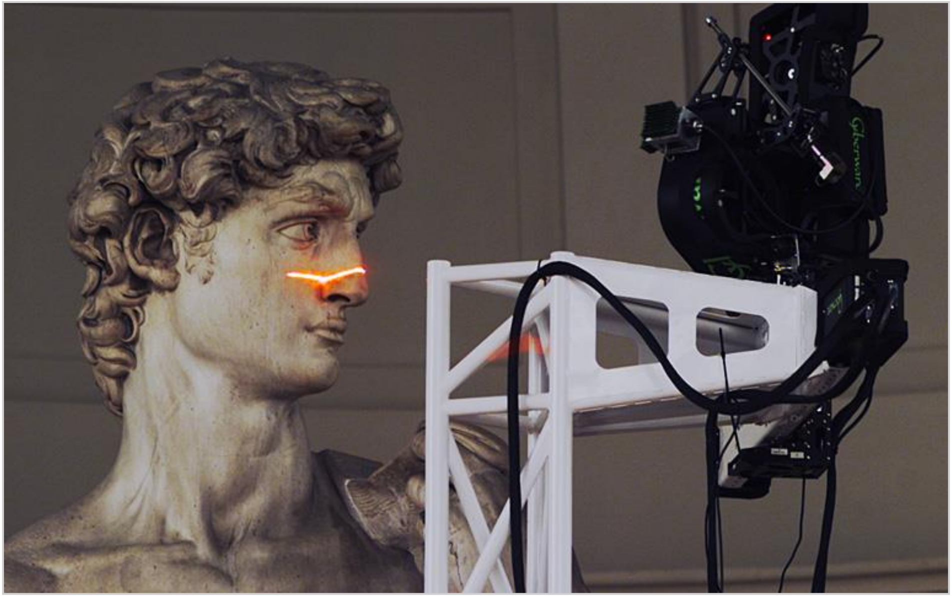
4 motorized axes

extensions
for tall statues



cyberware scanner (laser triangulation)

Digital Michelangelo Project, 1997-2000



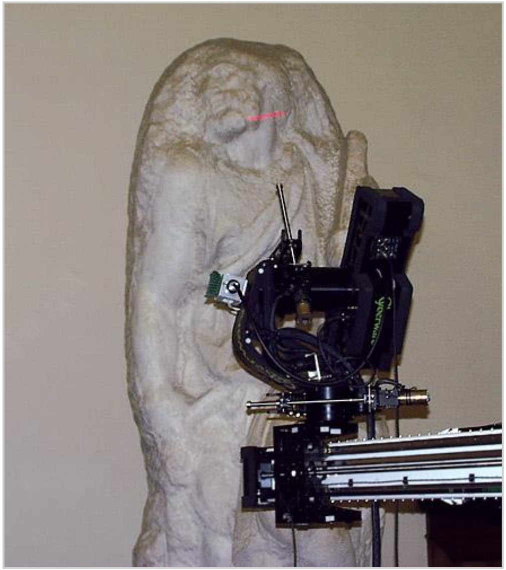
height of gantry: 7.5 meters

weight of gantry: 800 kilograms

Source: The Digital Michelangelo Project, Stanford University

Digital Michelangelo Project, 1997-2000

working in the museum



scanning geometry

scanning color

Source: The Digital Michelangelo Project, Stanford University

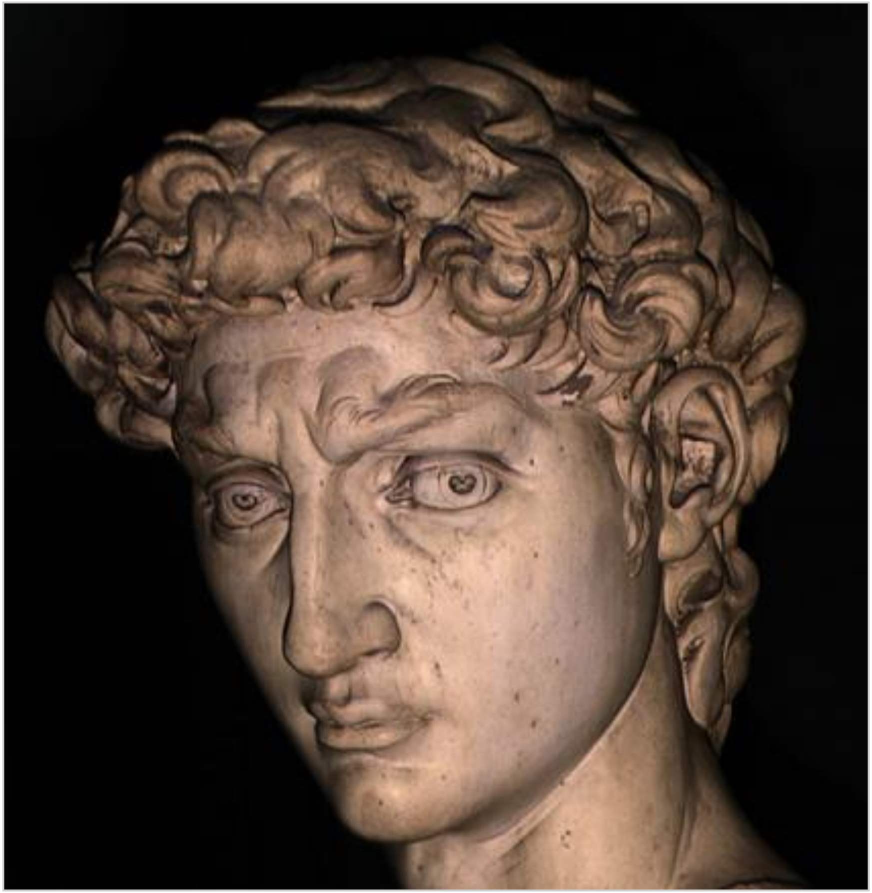
Digital Michelangelo Project, 1997-2000

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

Source: The Digital Michelangelo Project, Stanford University

Digital Michelangelo Project, 1997-2000

photograph



1.0 mm computer model

Source: The Digital Michelangelo Project, Stanford University

Digital Michelangelo Project, 1997-2000

St. Matthew

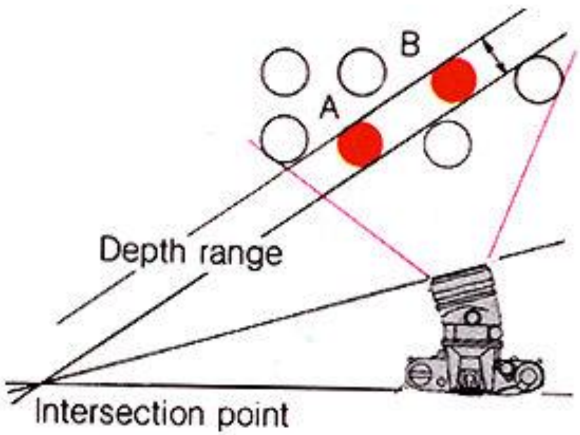
David

Forma Urbis Romae

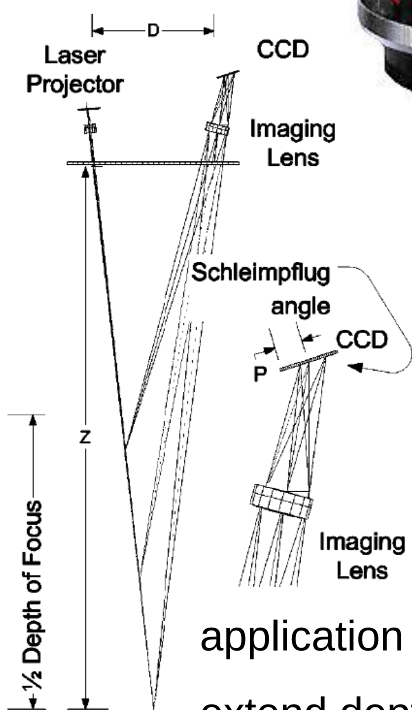
Source: The Digital Michelangelo Project, Stanford University

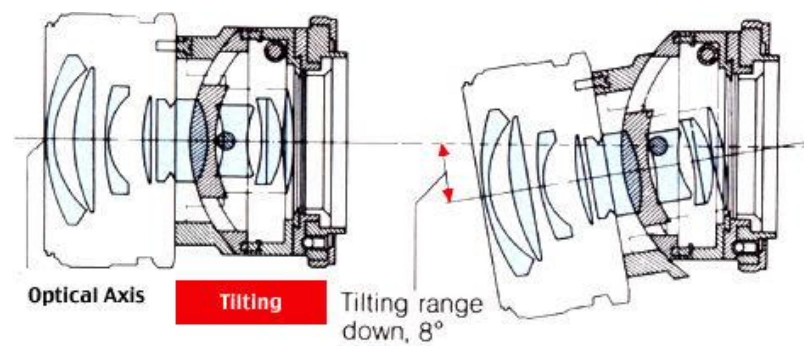
Range Scanners – Optical Considerations

- Laser Range Scanners – focal plane selection
- Scheimpflug principle
- tilt-shift lenses



focal plane





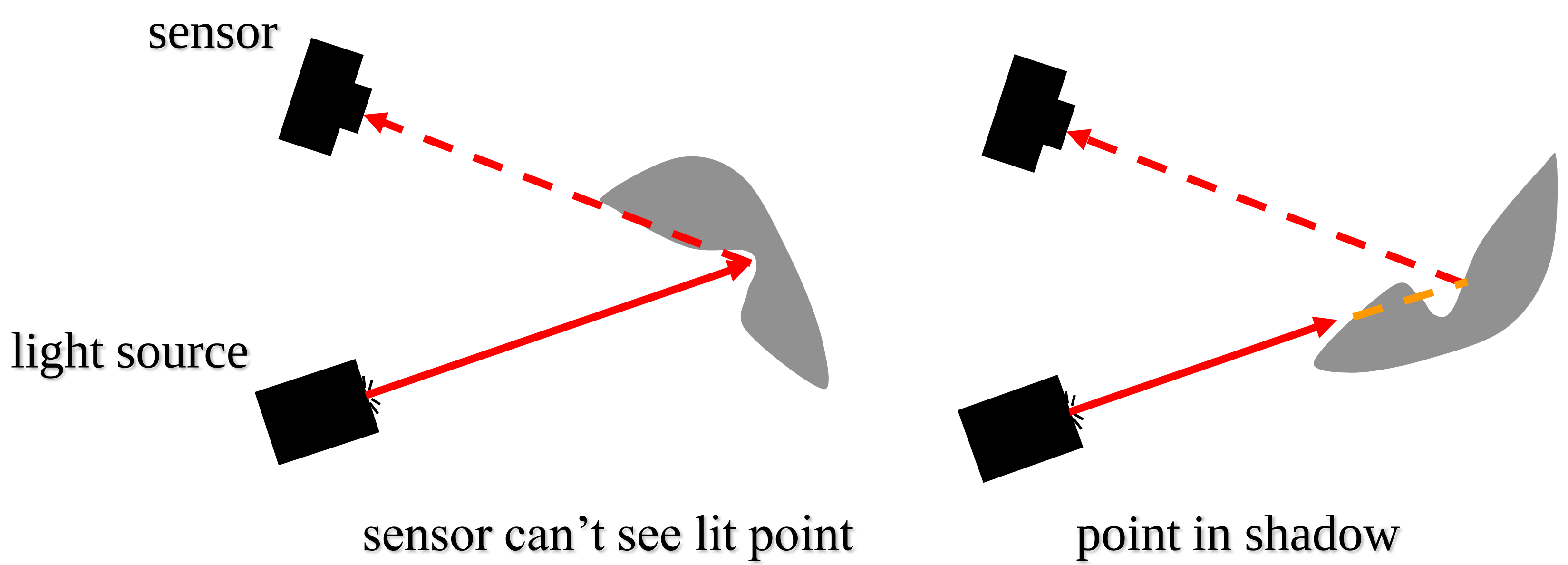
Scheimpflug principle

application in range scanning

extend depth of field

Tilt-Shift Lens Photographic Examples

Range Scanning Problems - Shadowing



- longer baseline:
- more shadowing

shorter baseline:
less precision

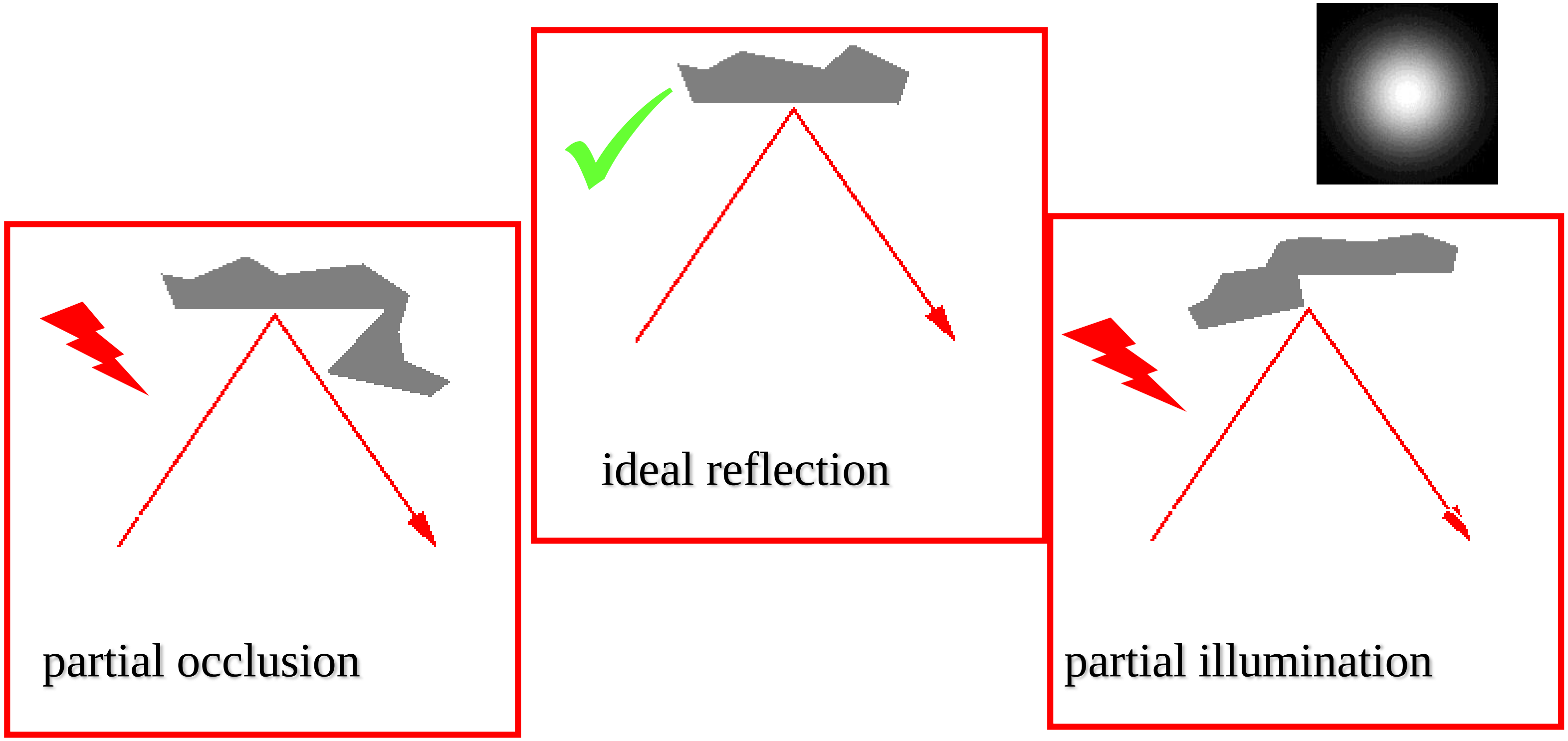
Range Scanning Problems – Acquired Range Image

- a single range image

  is acquired for each view
- Artifacts:
  - ribbed
  - lots of holes
    - due to surface properties
    - due to occlusion
- Solution:
  - Merging of multiple scans -> (ICP, Gaël Guennebaud)

Range Scanning Problems
- Beam location error

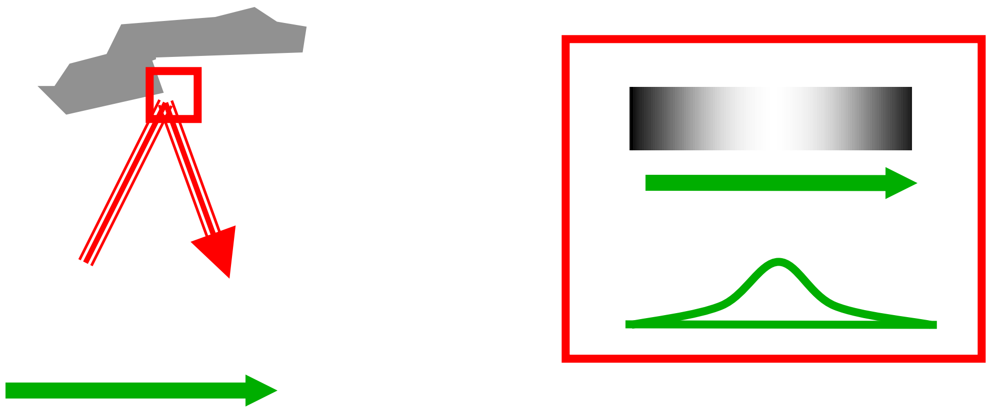
- Assumption: Reflection has Gaussian shape



- Corrupt due to occlusion or texture → Biased depth estimate

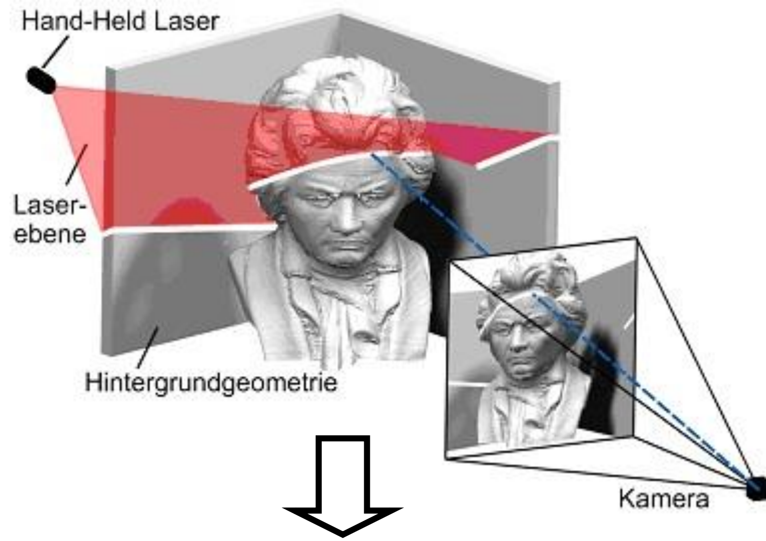
Beam location error

- Possible solution: Spacetime analysis [Curless, Levoy 95]
  - Estimate *when* beam centered on spot



DIY Range Scanners

- Laser Range Scanning – Cheapo Version [Winkelbach06]
- hand-held line laser
- known background geometry
- need two planes that are not co-planar
- known camera calibration
- compute laser plane from lines
  on the background planes
- triangulate by ray-plane intersection



Active Light - 3D Scanning

Structured Light

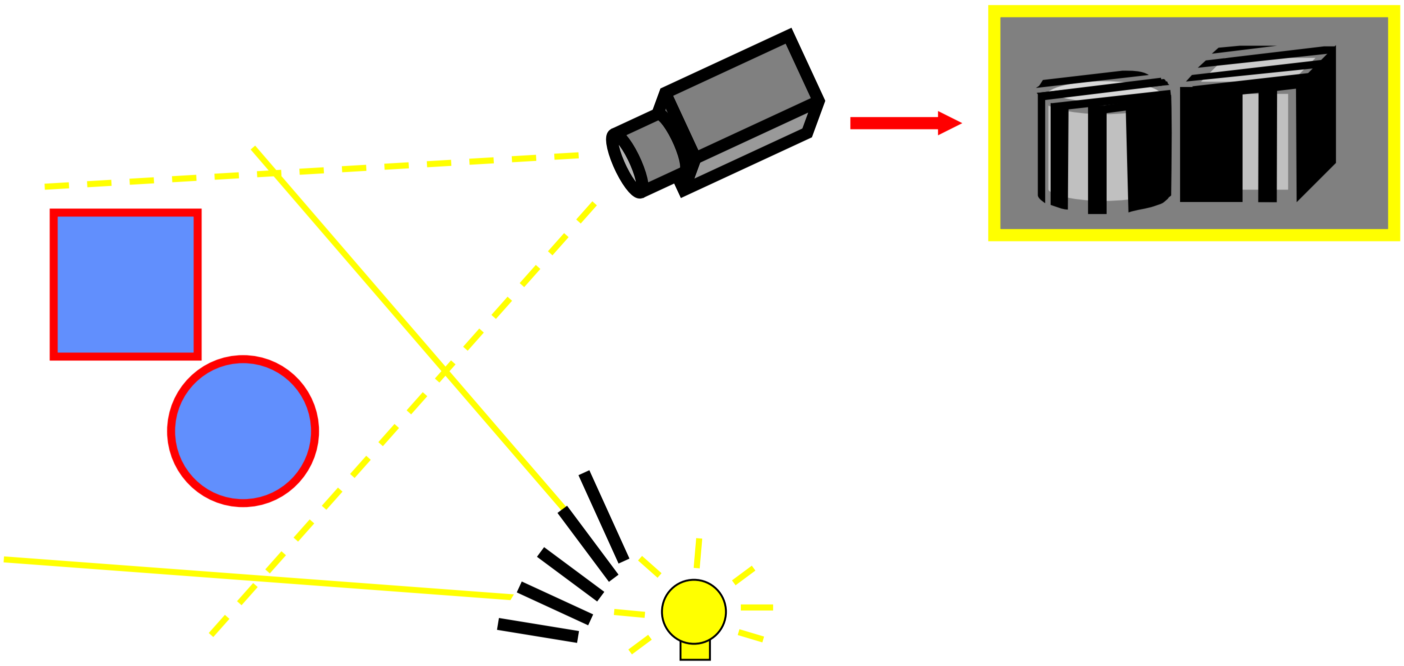
Structured Light

- Idea: increase speed by projecting multiple stripes
- But which stripe is which?

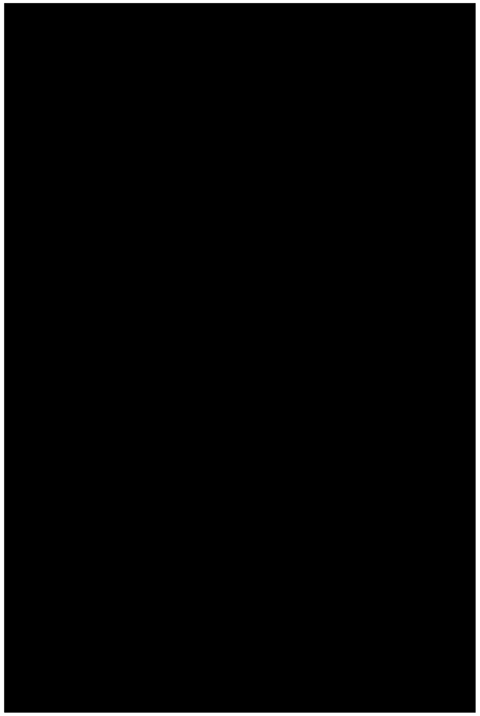
- Answer: Coded stripe patterns
  - Binary code
  - Gray code
  - Color code

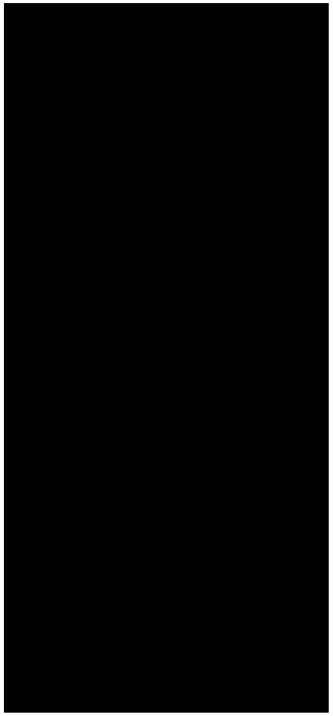
Range scanning systems

- Active: Structured light source
  - Analyze image of stripe pattern



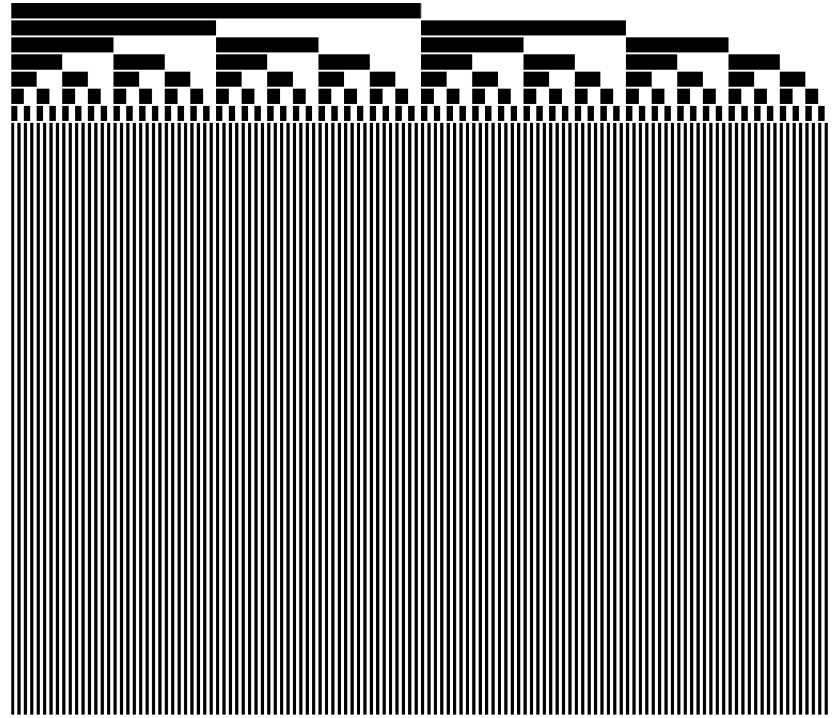
Structured Lighting: Swept-Planes Revisited





- Swept-plane scanning recovers 3D depth using ray-plane intersection
- Use a data projector to replace manually-swept laser/shadow planes
- How to assign correspondene from projector planes to camera pixels?
- Solution: Project a spatially- and temporally-encoded image sequence
- **What is the optimal image sequence to project?**

Structured Lighting: Binary Codes

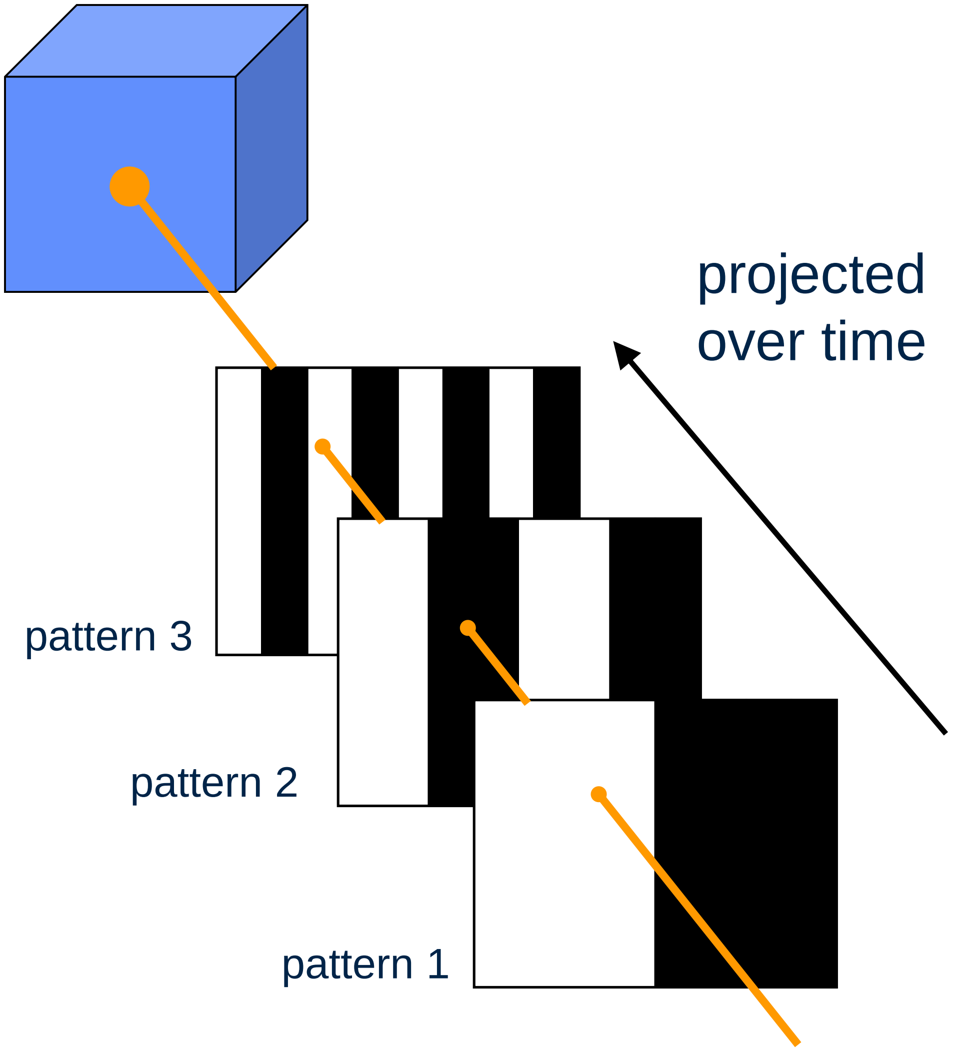


Binary Image Sequence [Posdamer and Altschuler 1982]

- Each image is a bit-plane of the binary code for projector row/column
- Minimum of 10 images to encode 1024 columns or 768 rows
- In practice, 20 images are used to encode 1024 columns or 768 rows
- Projector and camera(s) must be synchronized

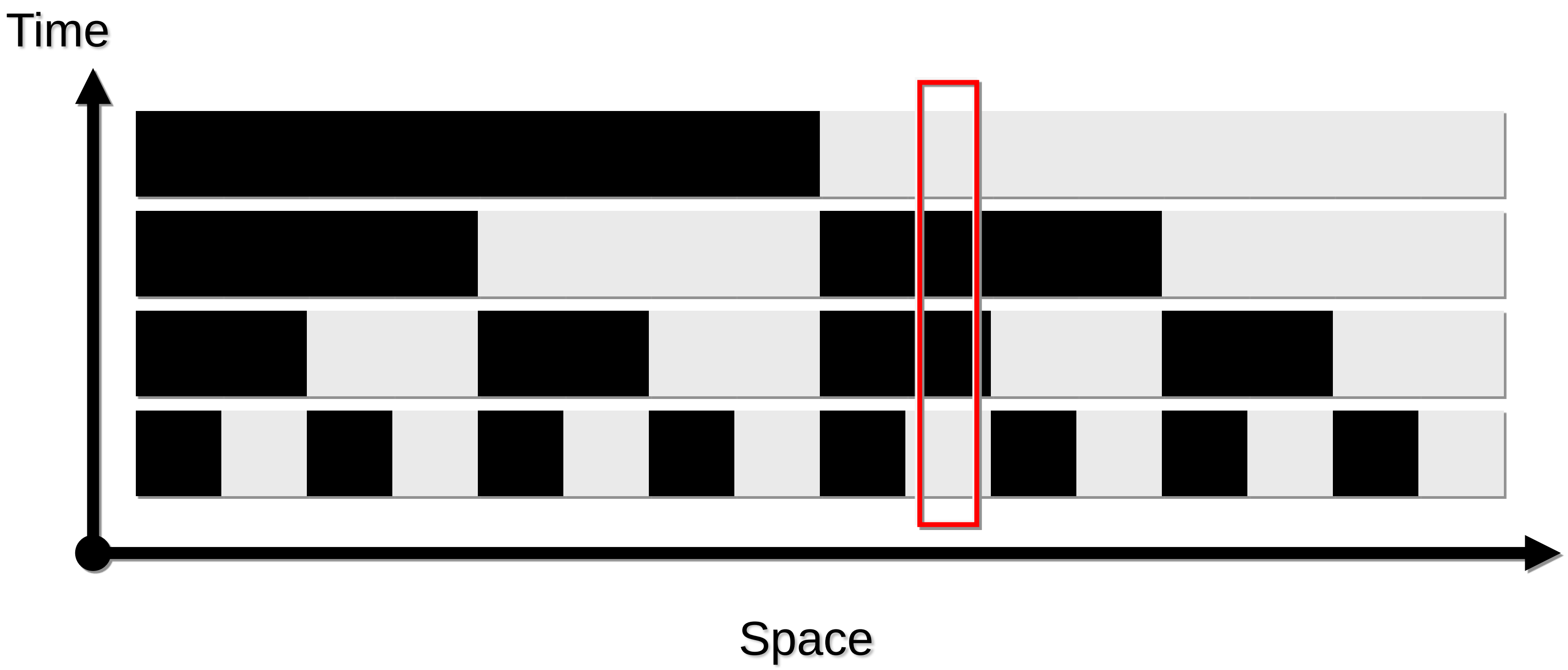
Structured Light - Binary Coding

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

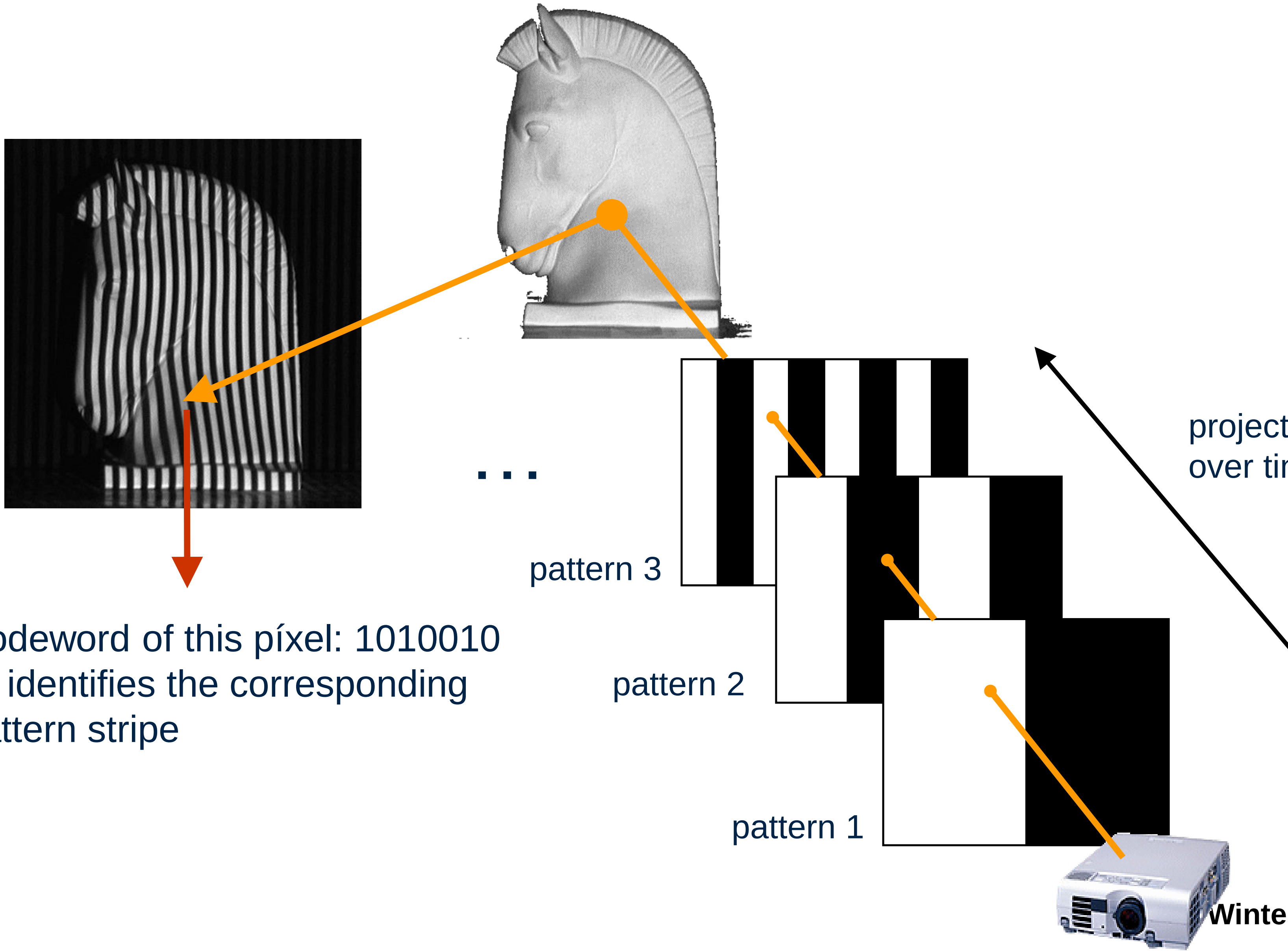


Structured Light - Binary Coding

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

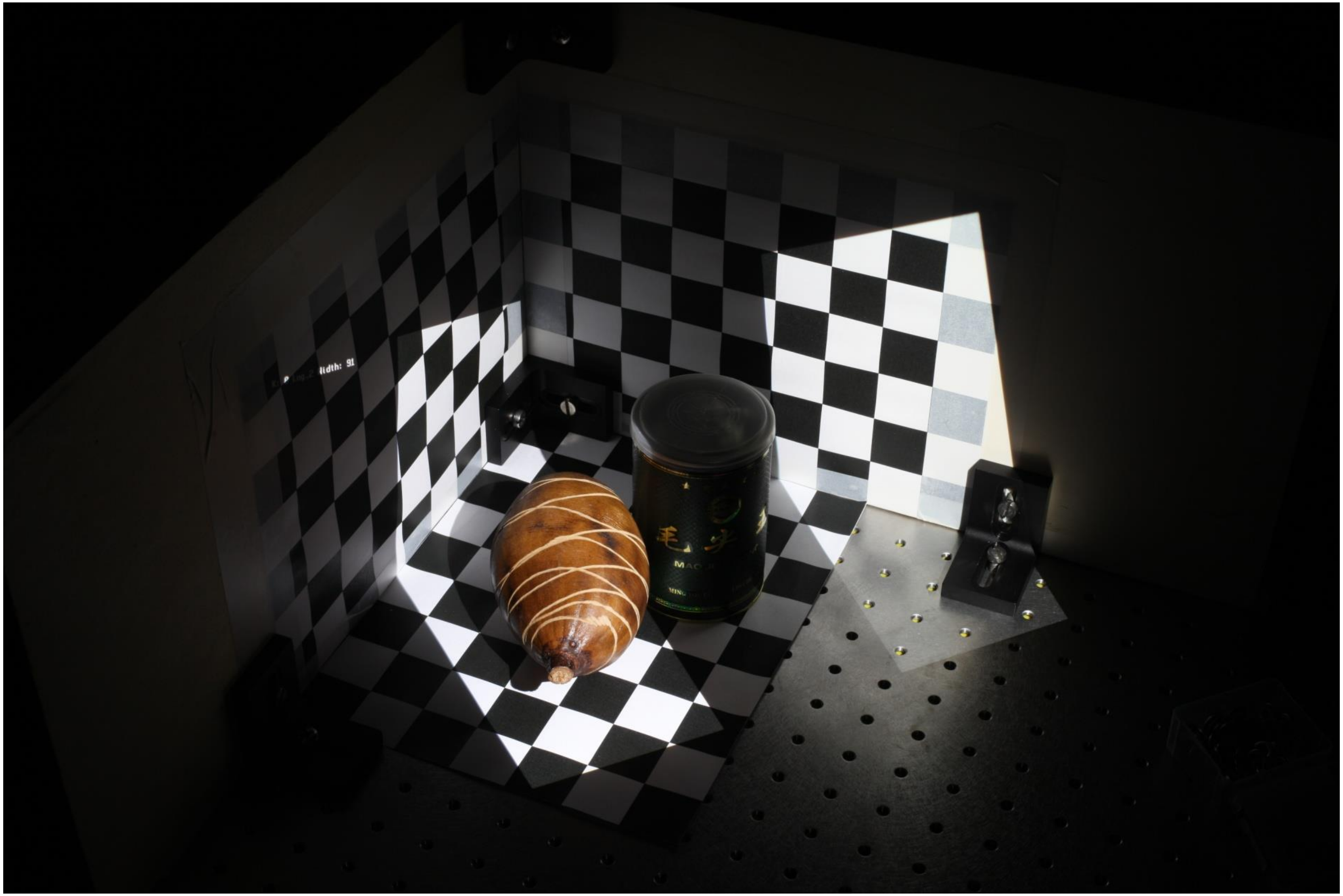


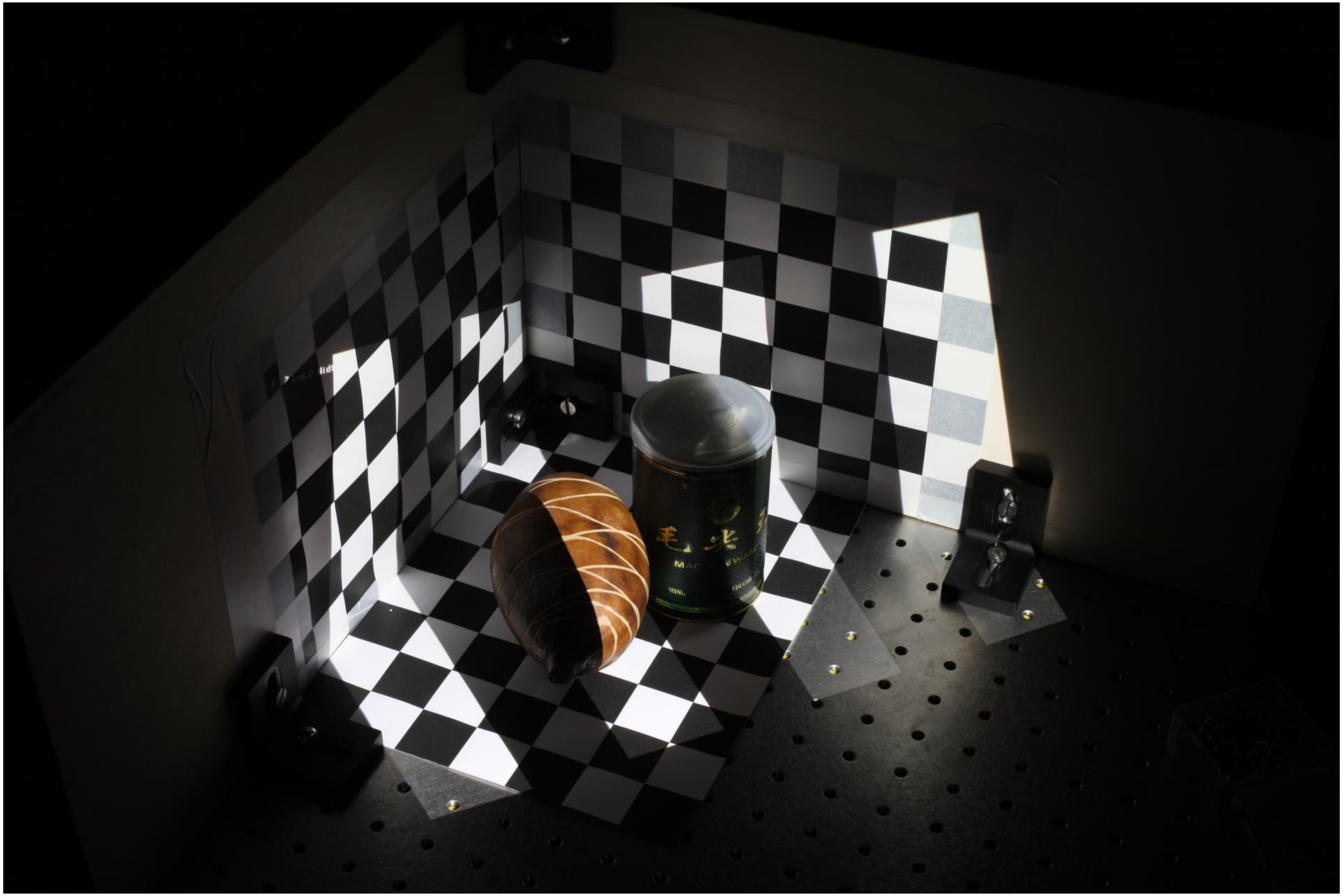
Structured Light - Binary Coding

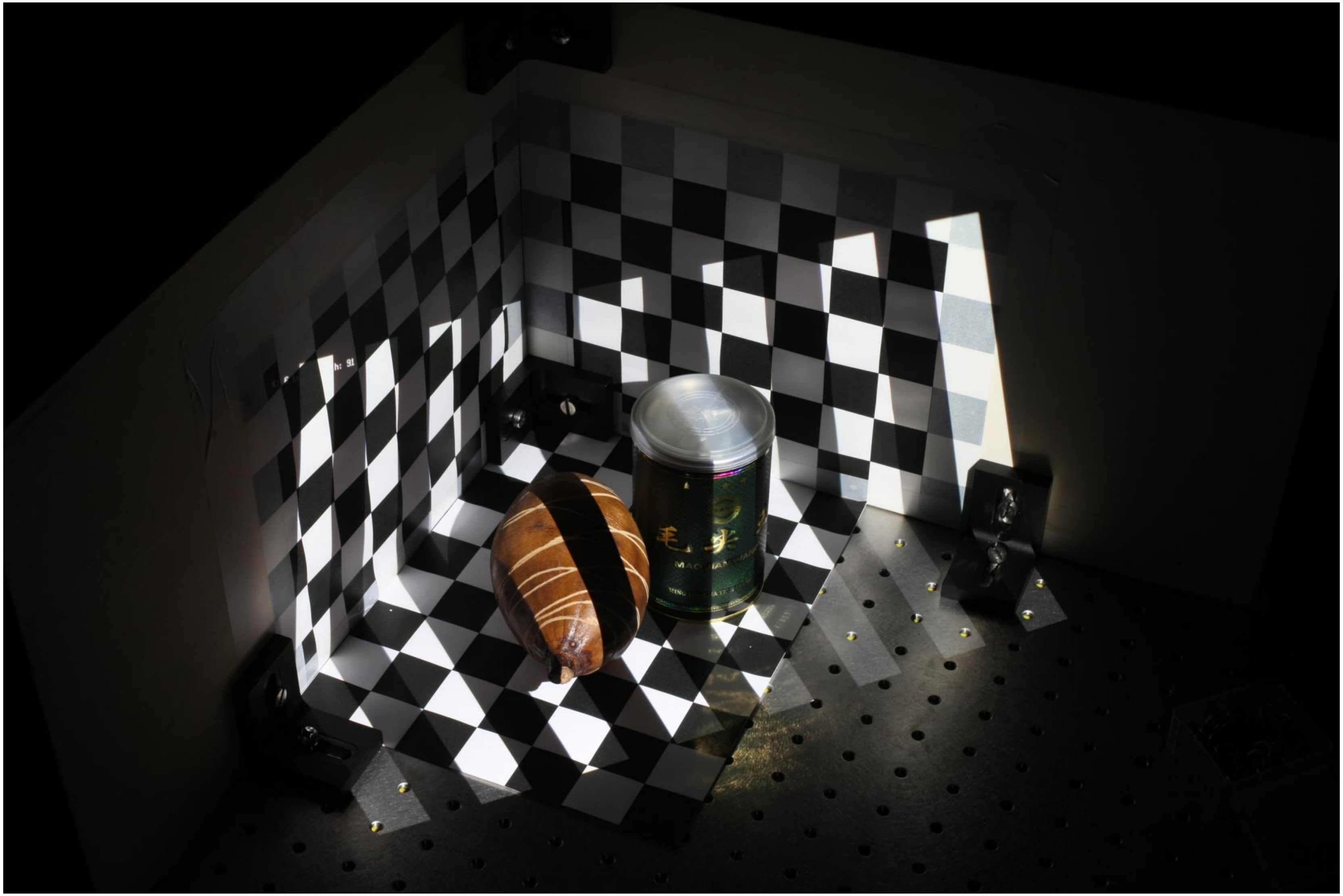


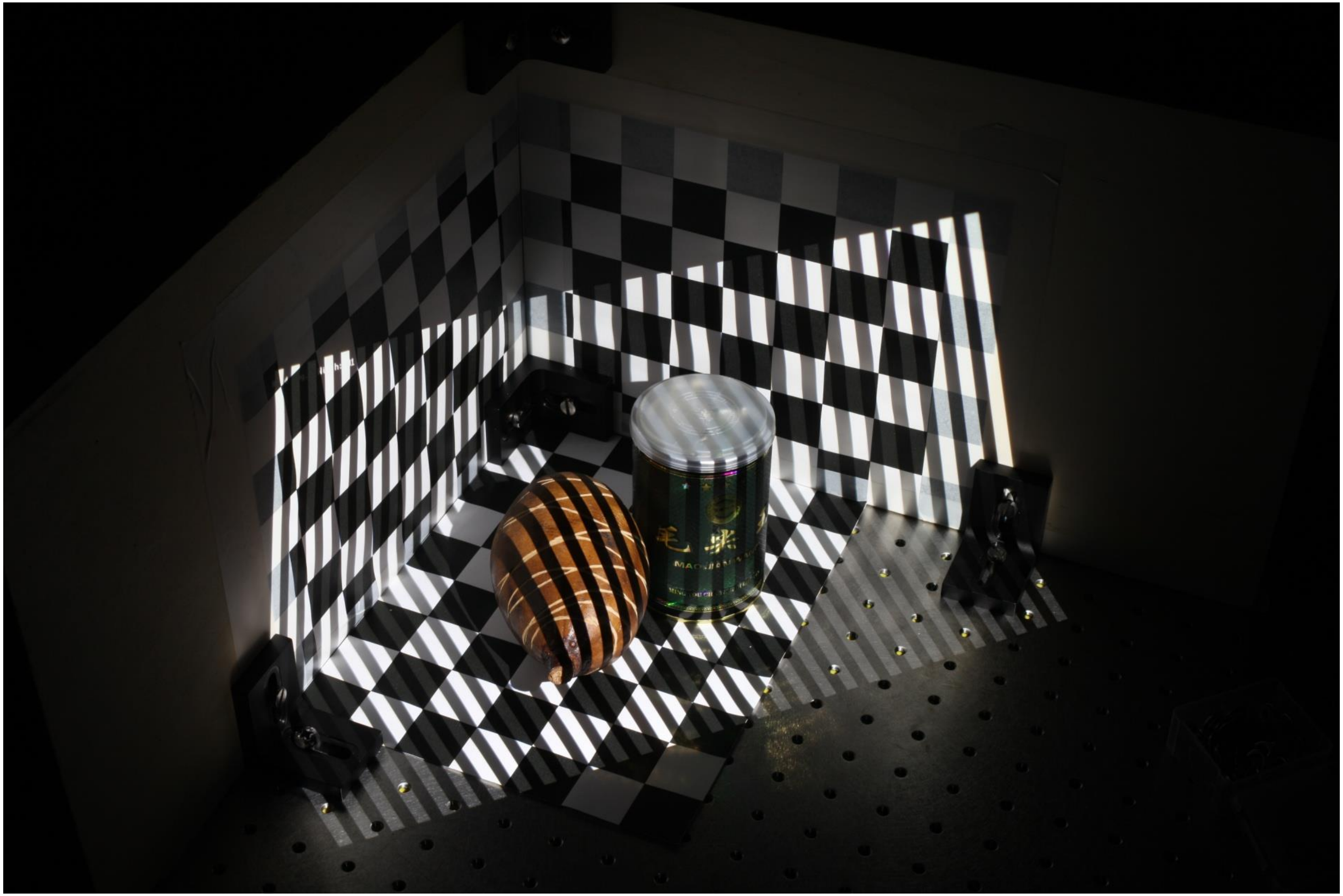
Codeword of this píxel: 1010010
→ identifies the corresponding pattern stripe

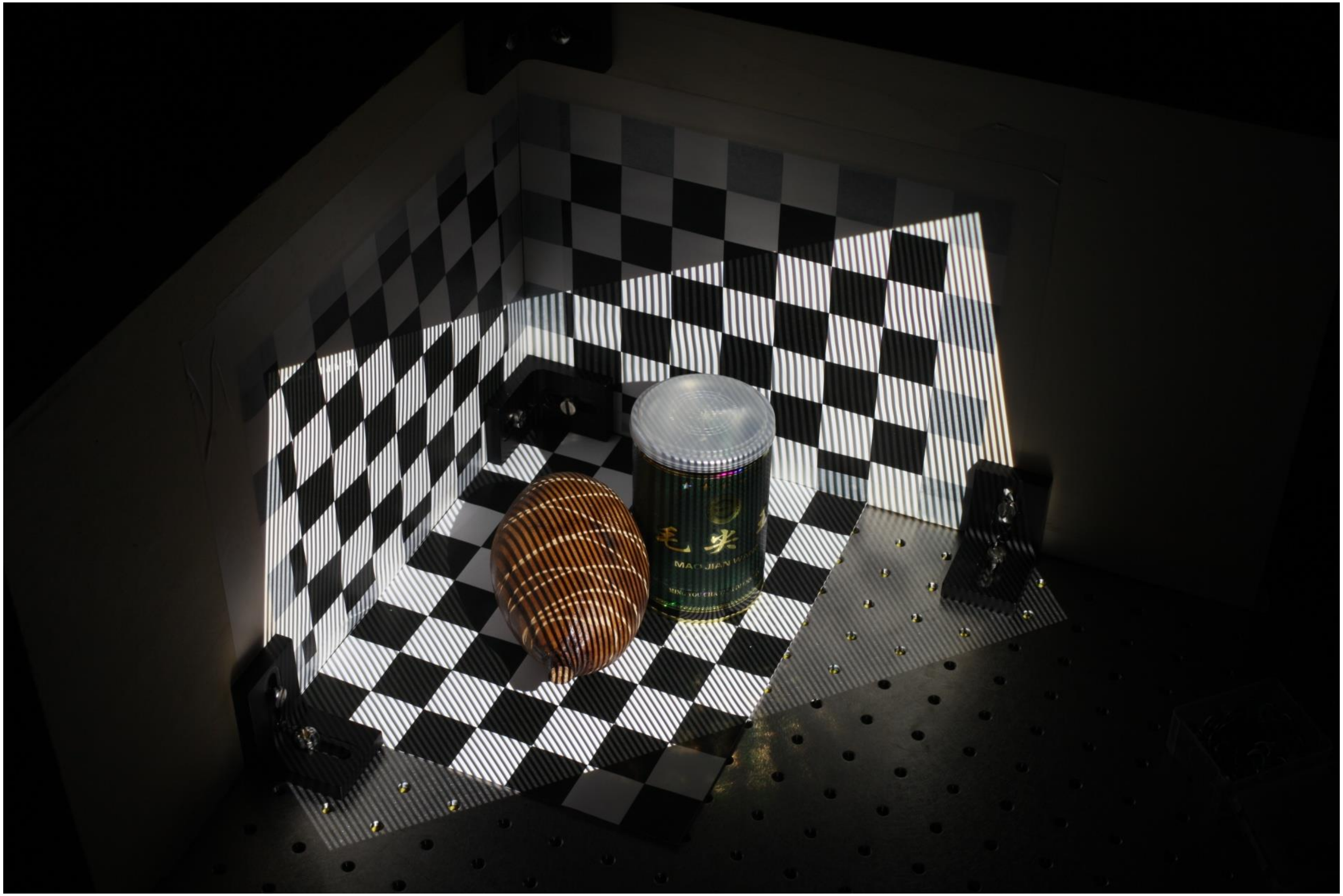
Our Example Scene

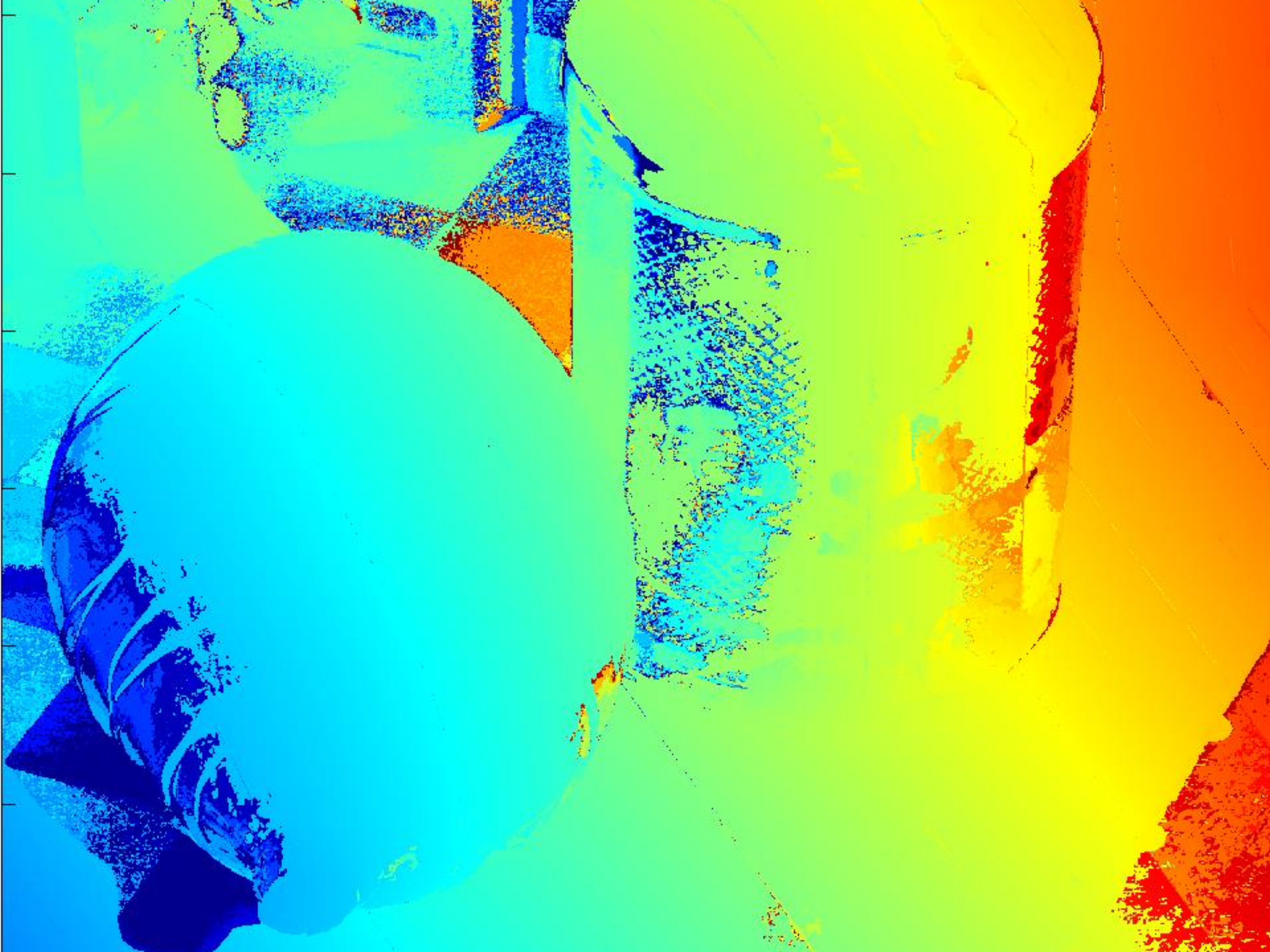




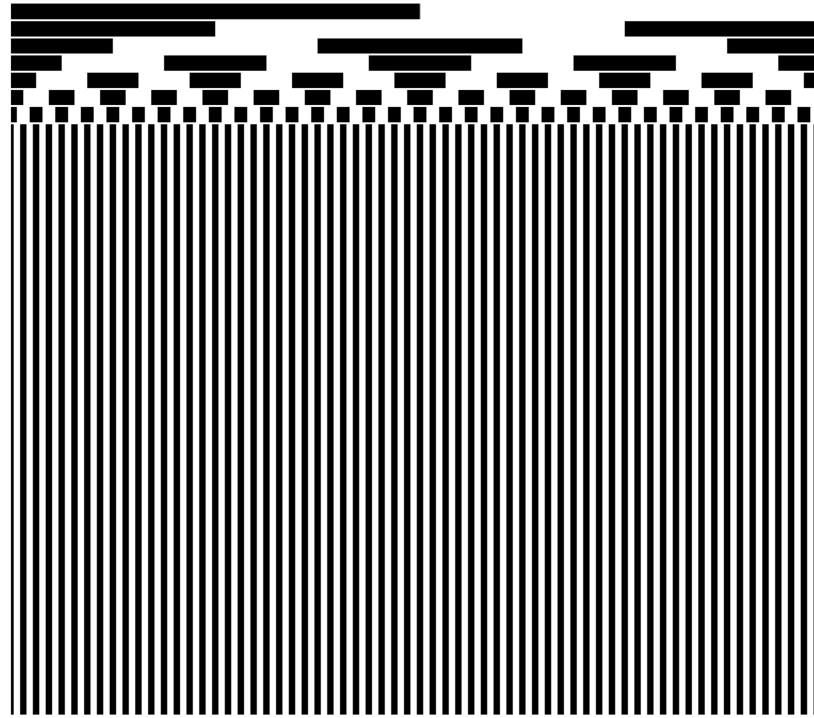





MAOJIAN



Structured Lighting: Gray Codes



Gray Code Image Sequence [Inokuchi 1984]

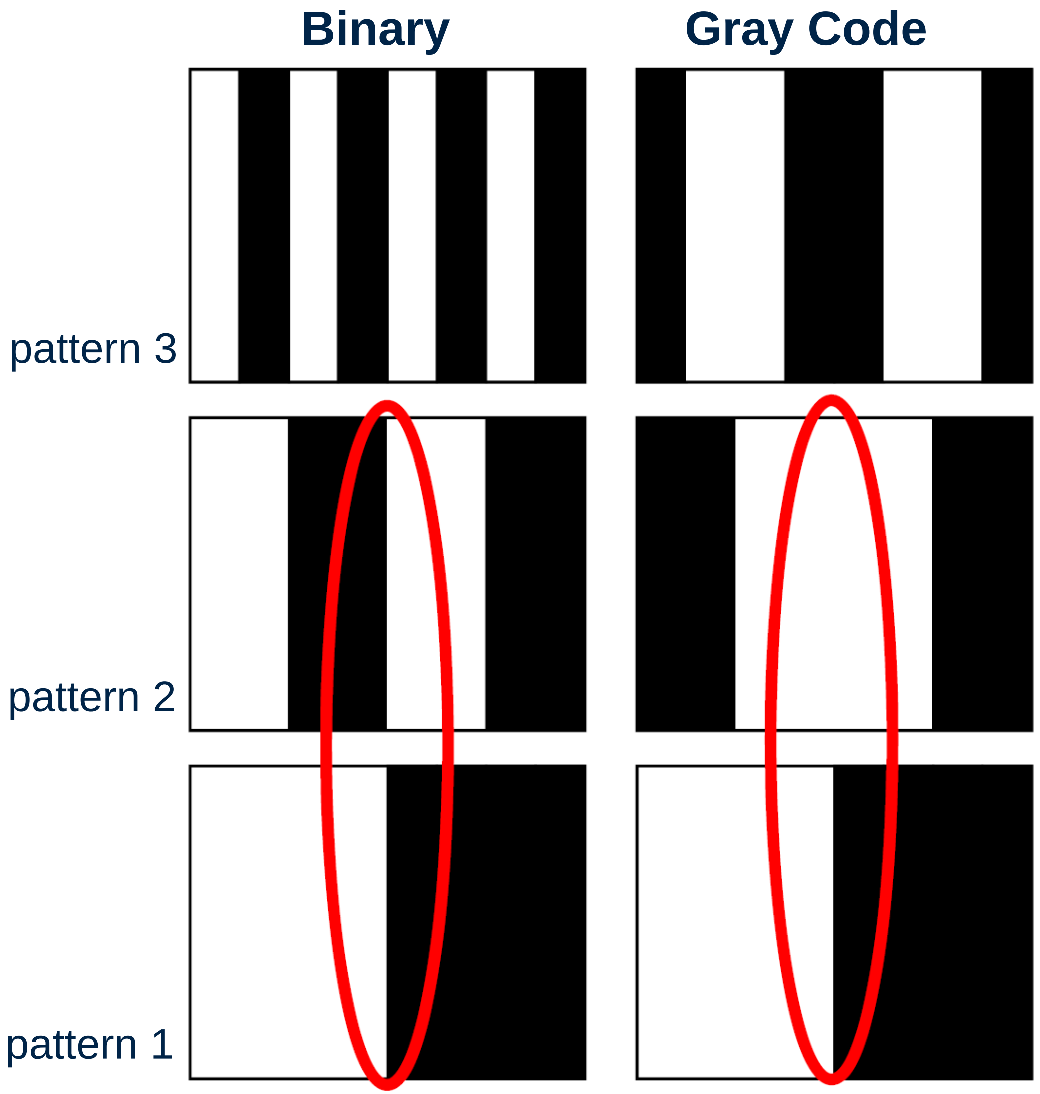
- Each image is a bit-plane of the Gray code for each projector row/column
- Requires same number of images as a binary image sequence, but has better performance in practice

```
Bin2Gray(B,G)
G ← B
for i ← n-1 downto 0
    G[i] ← B[i+1] xor B[i]
```

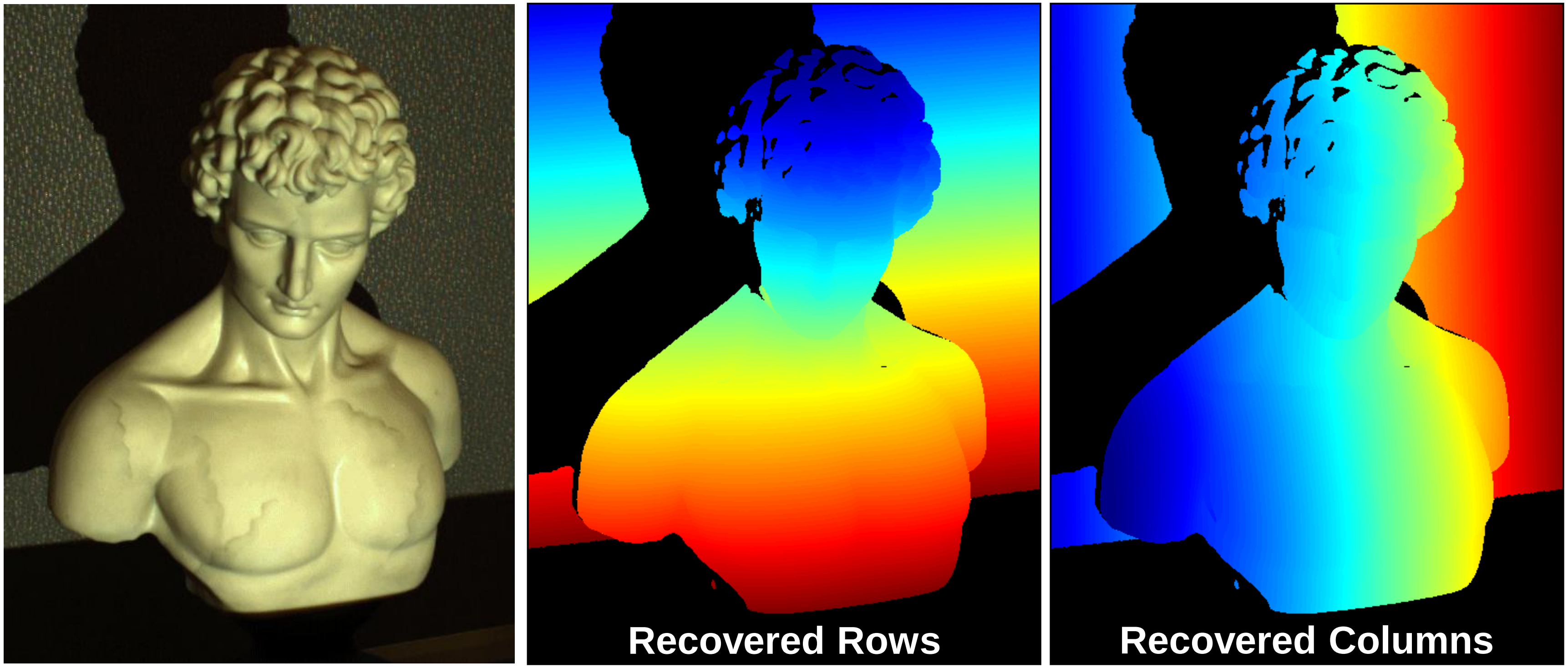
Binary vs Gray Codes

Decimal	Binary	Gray Code
00	0000	0000
01	0001	0001
02	0010	0011
03	0011	0010
04	0100	0110
05	0101	0111
06	0110	0101
07	0111	0100
08	1000	1100
09	1001	1101
10	1010	1111

Binary vs Gray Codes



Gray Codes: Decoding Performance



3D Reconstruction using Structured Light [Inokuchi 1984]

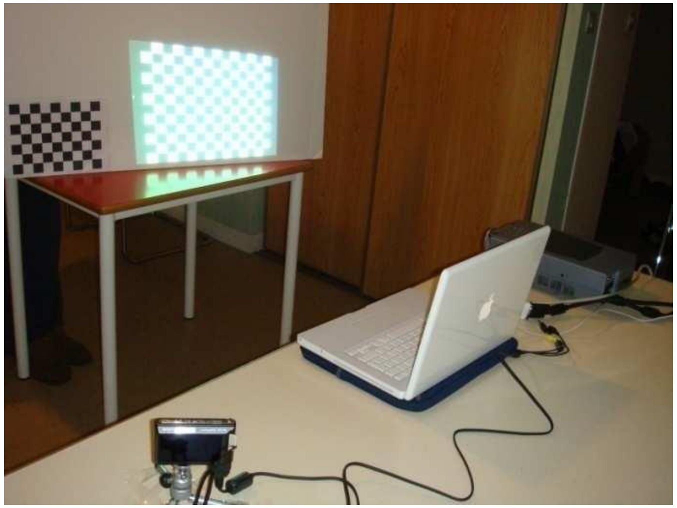
- Implemented using a total of 42 images
  (2 to measure dynamic range, 20 to encode rows, 20 to encode columns)
- Individual bits assigned by detecting if bit-plane (or its inverse) is brighter
- Decoding algorithm: Gray code → binary code → integer row/column index

Calibration of a Projector-Camera System

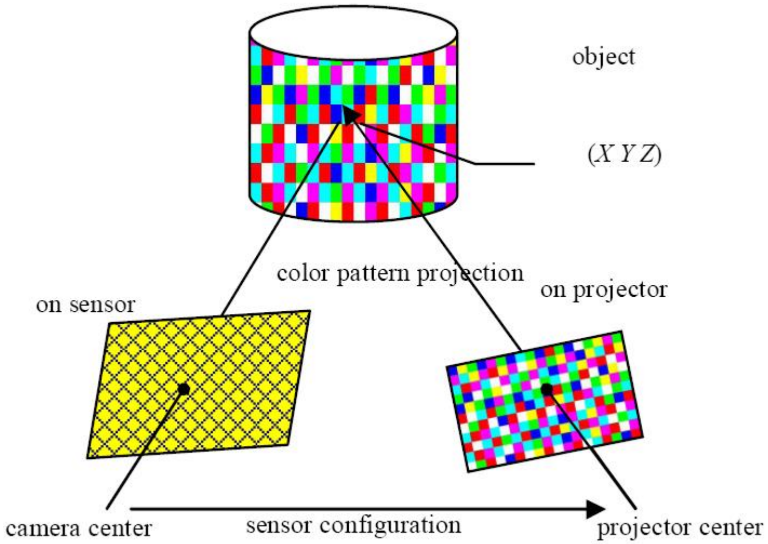
- Camera calibration (matlab and OpenCV)
  http://www.vision.caltech.edu/bouguetj/calib_doc/
- Extention for projector calibration (matlab)
  http://code.google.com/p/procamcalib/
- Idea: Consider the projector as an inverse camera, which maps 2D image points into 3D rays, thus making the calibration of a projector the same as that of a camera

Calibration of a Projector-Camera System

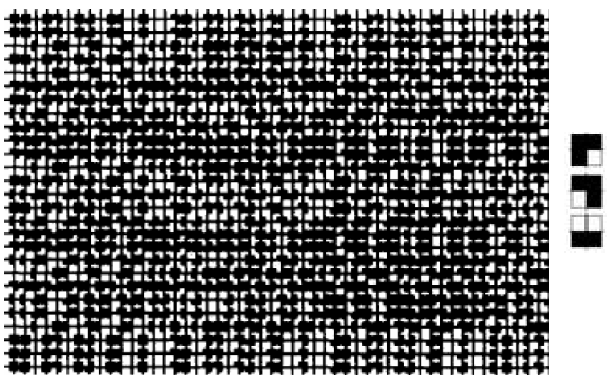
- Calibrate the camera using [Zhang 2000]
- Recover calibration plane in camera coordinate system
- Project a checkerboard on the calibration board and detect corners
- Apply ray-plane intersection to recover 3D position for each projected corner
- Calibrate the projector using the correspondences between the 2D points of the projector image and the recovered 3D position of projected points (Zhang's method).



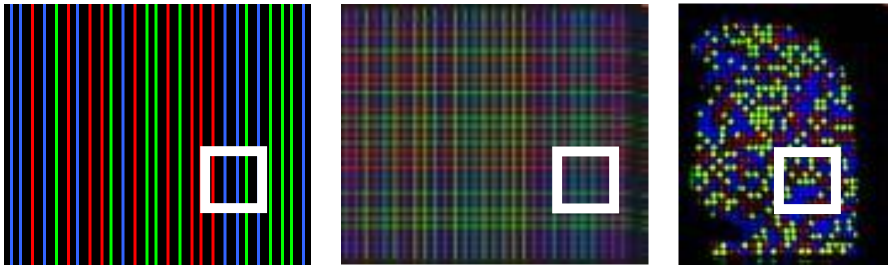
Dynamic Scanning



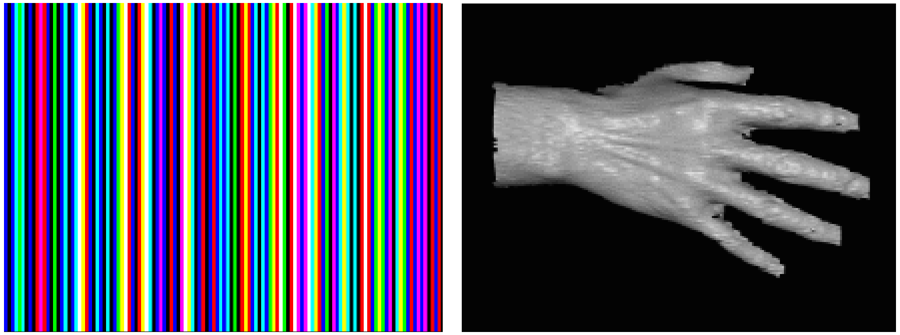
Spatial encoding strategies [Chen et al. 2007]



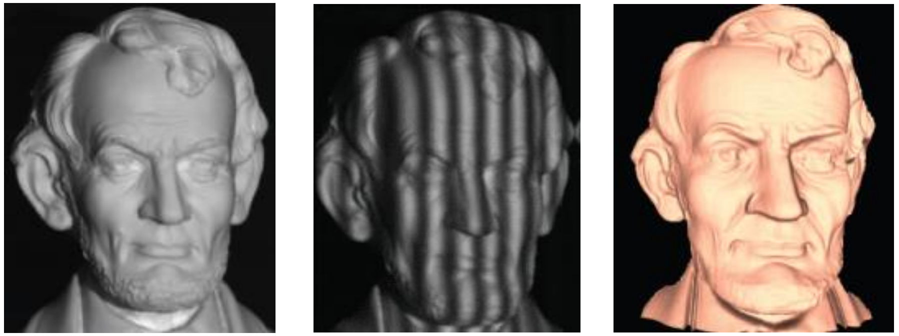
Pseudorandom and M-arrays [Griffin 1992]



“Single-shot” patterns (N-arrays, grids, random, etc.)



De Bruijn sequences [Zhang et al. 2002]



Phase-shifting [Zhang et al. 2004]

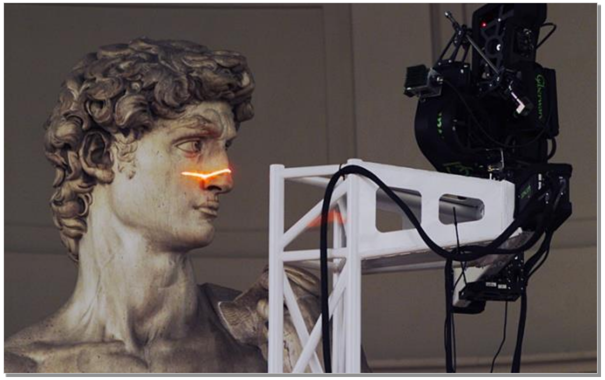
J. Salvi, J. Pagès, and J. Batlle. Pattern Codification Strategies in Structured Light Systems

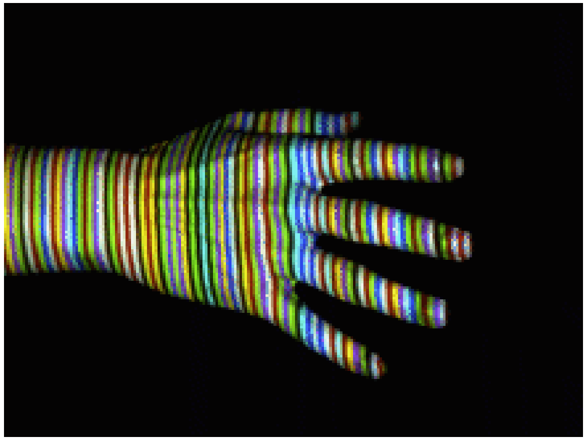
Popular example: Kinect I

[Andres Reza]

[Matthew Fisher]

Continuum of Triangulation Methods





Multi-stripe
Multi-frame

Single-stripe

Single-frame

Slow, robust

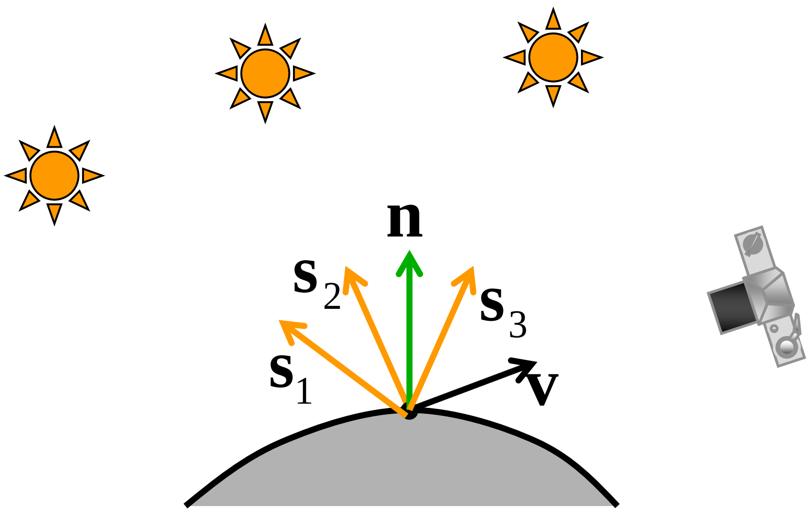
Fast, fragile

Active Light – Photometric Stereo

The Basics and Some Hints
Towards More Complex Issues

Photometric Stereo

- Idea: One camera, multiple (known) light sources



Lambertian reflection

$$
\begin{aligned}
I_1 &= \rho\, \mathbf{n}^\top \mathbf{s}_1 \\
I_2 &= \rho\, \mathbf{n}^\top \mathbf{s}_2 \\
I_3 &= \rho\, \mathbf{n}^\top \mathbf{s}_3
\end{aligned}
$$

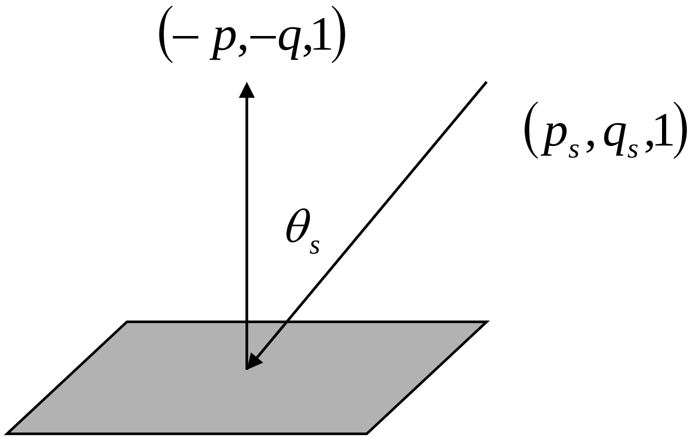
in matrix form

$$
\begin{pmatrix} I_1 \\ I_2 \\ I_3 \end{pmatrix} = \rho \begin{bmatrix} \mathbf{s}_1^\top \\ \mathbf{s}_2^\top \\ \mathbf{s}_3^\top \end{bmatrix} \mathbf{n}
$$

$$
\mathbf{n} = \begin{bmatrix} \mathbf{s}_1^\top \\ \mathbf{s}_2^\top \\ \mathbf{s}_3^\top \end{bmatrix}^{-1} \frac{1}{\rho} \begin{pmatrix} I_1 \\ I_2 \\ I_3 \end{pmatrix}
$$

The Reflectance Map

Reflectance Map: image intensity of a pixel as a function of surface orientation of the corresponding scene point



$(-p,-q,1)$ Surface normal

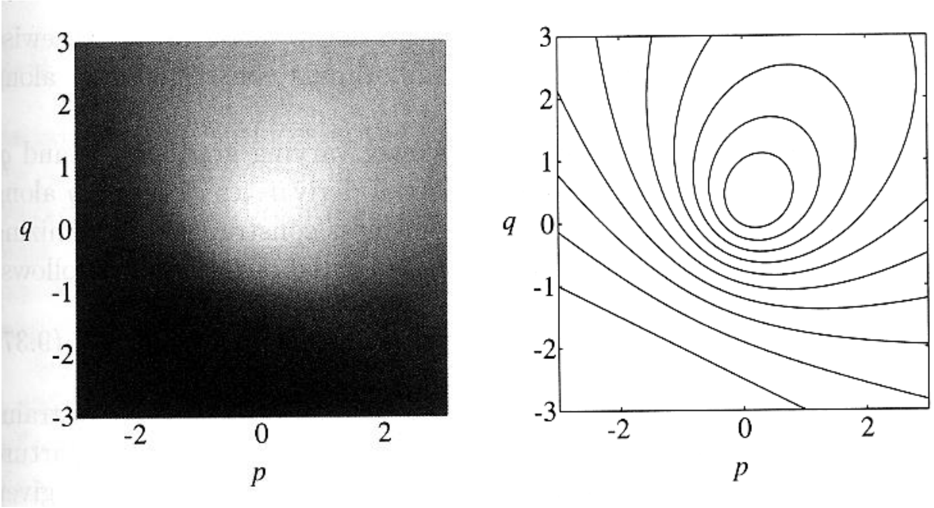
$(p_s,q_s,1)$ Light source direction

$$\cos\theta_s = \frac{(-p,-q,1)}{\sqrt{1+p^2+q^2}} \frac{(-p_s,-q_s,1)}{\sqrt{1+p_s^{\ 2}+q_s^{\ 2}}}$$

$$= \frac{1+p_s p+q_s q}{\sqrt{1+p^2+q^2}\sqrt{1+p_s^{\ 2}+q_s^{\ 2}}}$$

Angle between surface normal and direction to point light source

The Reflectance Map II



Reflectance map of Lambertian surface for $p_s = 0.2, q_s = 0.4$

$R(p,q)$: Reflectance for all surface orientations (p,q) for a given light source distribution and a given surface material

Lambertian surface $$R(p,q) \propto \cos\theta_s = \frac{1 + p_s p + q_s q}{\sqrt{1 + p^2 + q^2}\sqrt{1 + {p_s}^2 + {q_s}^2}}$$

Photometric Stereo

- Point light source: lines of constant reflectance in reflectance map defined by second-order polynomial

  $\Rightarrow$ For each image point (*x,y*), the possible surface orientation (*p,q*) is restricted to lie on the curve defined by the polynomial

  $\Rightarrow$ 3 different point sources give 3 second-order curves

Photometric Stereo II

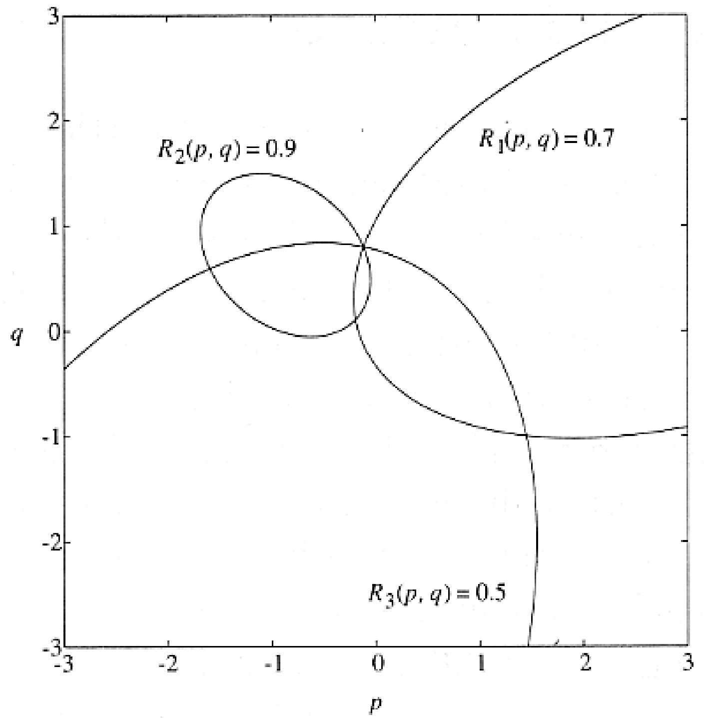
Light source from left

Light source from top

Light source from right

http://amba.charite.de/~ksch/spsm/beet.html

Photometric Stereo III



p,q: surface normal direction

For each pixel, the 3 measured intensities corresponding to the 3 different illumination directions lie on 3 different curves in the reflectance map that intersect in one point

Photometric Stereo IV

Image irradiance $\boxed{E(x,y) = \rho \cdot R(p,q)}$ ρ: surface albedo

Surface normal $$\hat{\mathbf{n}} = \frac{(-p,-q,1)}{\sqrt{1+p^2+q^2}}$$

Point light source direction $$\hat{\mathbf{s}}_i = \frac{(-p_i,-q_i,1)}{\sqrt{1+p_i^2+q_i^2}}$$

Lambertian reflection $$E_i = \rho\,\hat{\mathbf{s}}_i \cdot \hat{\mathbf{n}}_i$$

3 illumination directions/ substitution

$$\mathbf{E} = \begin{pmatrix} E_1 \\ E_2 \\ E_3 \end{pmatrix} \qquad \mathbf{S} = \begin{pmatrix} \hat{\mathbf{s}}_1 \\ \hat{\mathbf{s}}_2 \\ \hat{\mathbf{s}}_3 \end{pmatrix} = \begin{pmatrix} s_{1,x} & s_{1,y} & s_{1,z} \\ s_{2,x} & s_{2,y} & s_{2,z} \\ s_{3,x} & s_{3,y} & s_{3,z} \end{pmatrix}$$

$$\mathbf{E} = \rho\,\mathbf{S} \cdot \hat{\mathbf{n}}$$

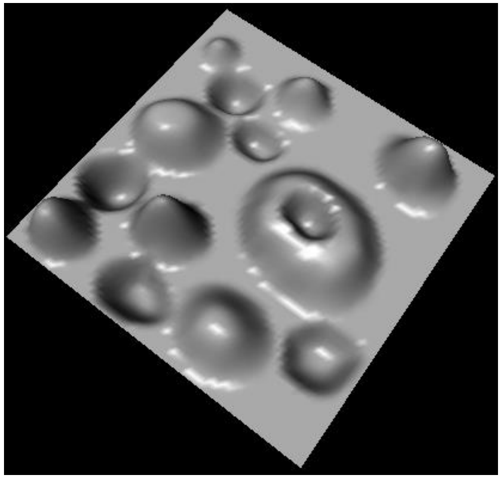
Linear set of 3 equations per pixel $$\boxed{\rho\,\hat{\mathbf{n}} = \mathbf{S}^{-1}\mathbf{E}}$$

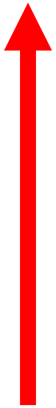
Photometric Stereo

- Advantages
  - A normal value for each pixel with very few images
  - Approach captures details, like pores, wrinkles, or spots
- Disadvantages
  - Normals must be integrated to get a 3D model
    (errors will accumulate)
  - Needs controlled lighting or robust estimation of light direction

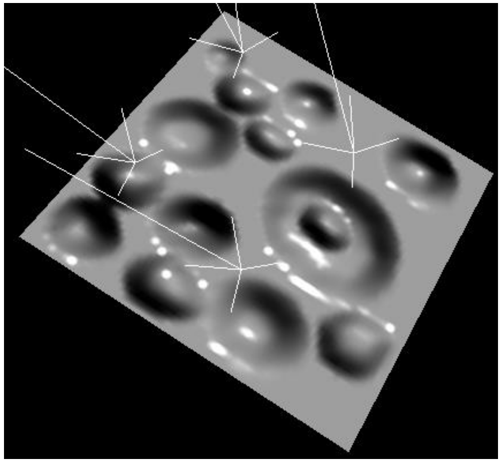
Photometric Stereo V

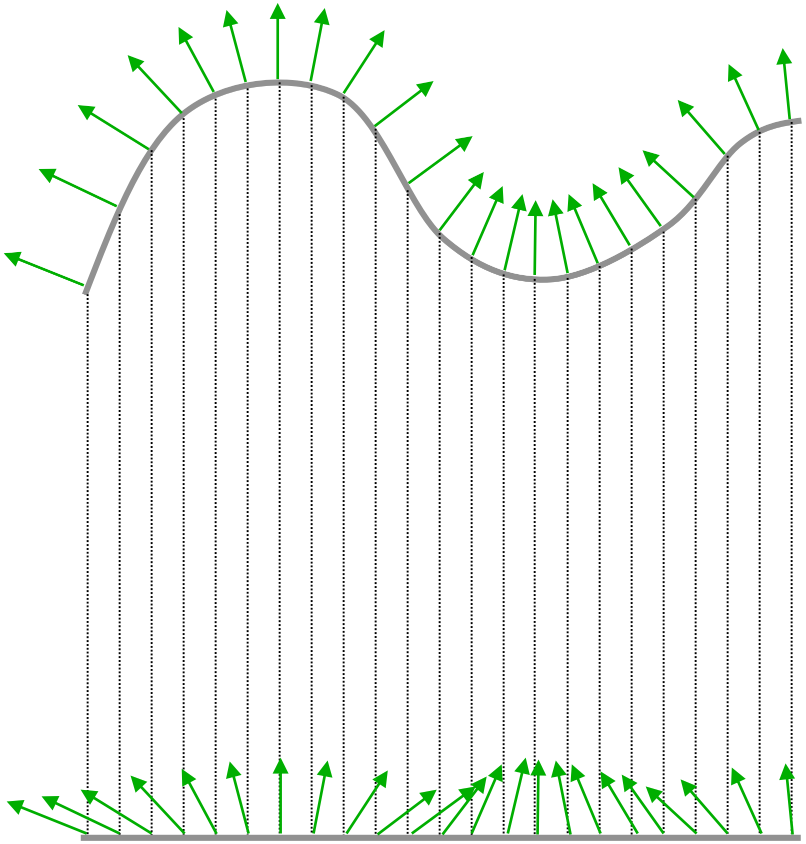
Real Geometry





Normal Map





Integrating the normals

- Normals of a height field surface: $z = f(x,y)$
  - Tangent space is spanned by $\begin{pmatrix} 1 \\ 0 \\ \frac{\partial f}{\partial x} \end{pmatrix} \begin{pmatrix} 0 \\ 1 \\ \frac{\partial f}{\partial y} \end{pmatrix}$

$$\Rightarrow \mathbf{n} = \begin{pmatrix} 1 \\ 0 \\ \frac{\partial f}{\partial x} \end{pmatrix} \times \begin{pmatrix} 0 \\ 1 \\ \frac{\partial f}{\partial y} \end{pmatrix} = \begin{pmatrix} -\frac{\partial f}{\partial x} \\ -\frac{\partial f}{\partial y} \\ 1 \end{pmatrix}$$

- Laplacian operator

discretize

$$\nabla \cdot \nabla f = \frac{\partial}{\partial x} \frac{\partial f}{\partial x} + \frac{\partial}{\partial y} \frac{\partial f}{\partial y} = \triangle \hat{f}$$

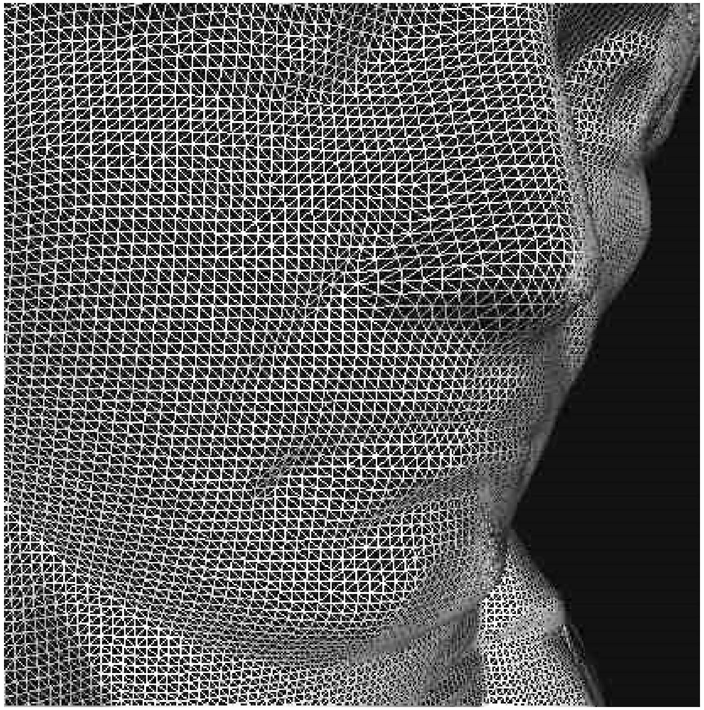
Integrating the normals

- Solve system

$$\frac{1}{h^2}\begin{pmatrix} -4 & 1 & 0 & \dots & 1 & \dots & 0 & 0 \\ 1 & -4 & 1 & 0 & \dots & 1 & \dots & 0 \\ 0 & 1 & -4 & 1 & \ddots & \ddots & \ddots & 0 \\ 0 & \ddots & \ddots & \ddots & \ddots & \ddots & \ddots & 0 \\ \end{pmatrix} \begin{pmatrix} \hat{f}_{1,1} \\ \hat{f}_{1,2} \\ \vdots \\ \hat{f}_{M,N} \end{pmatrix} = \begin{pmatrix} \nabla\cdot(\nabla f)_{1,1} \\ \nabla\cdot(\nabla f)_{1,2} \\ \vdots \\ \nabla\cdot(\nabla f)_{M,N} \end{pmatrix}$$

- Compute right-hand side numerically
- Include Boundary conditions: e.g. von Neumann = 0
  - Modify system above – it corresponds to $\hat{f} = 0$ on the boundary

Photometric Stereo VI



- Reconstruct normal directions
- Integrate normal directions to obtain depth map
- Triangulate depth map

Photometric Stereo Assumptions

- Assumptions:
  - Surface has Lambertian reflectance characteristics
  - Illumination directions are known
  - Illumination sources are distant from object
  - Secondary illumination is insignificant
  - There are no cast shadows
  - Distant camera (orthographic projection)
- Extensions
  - Non-local illumination or views
  - Non-Lambertian BRDF