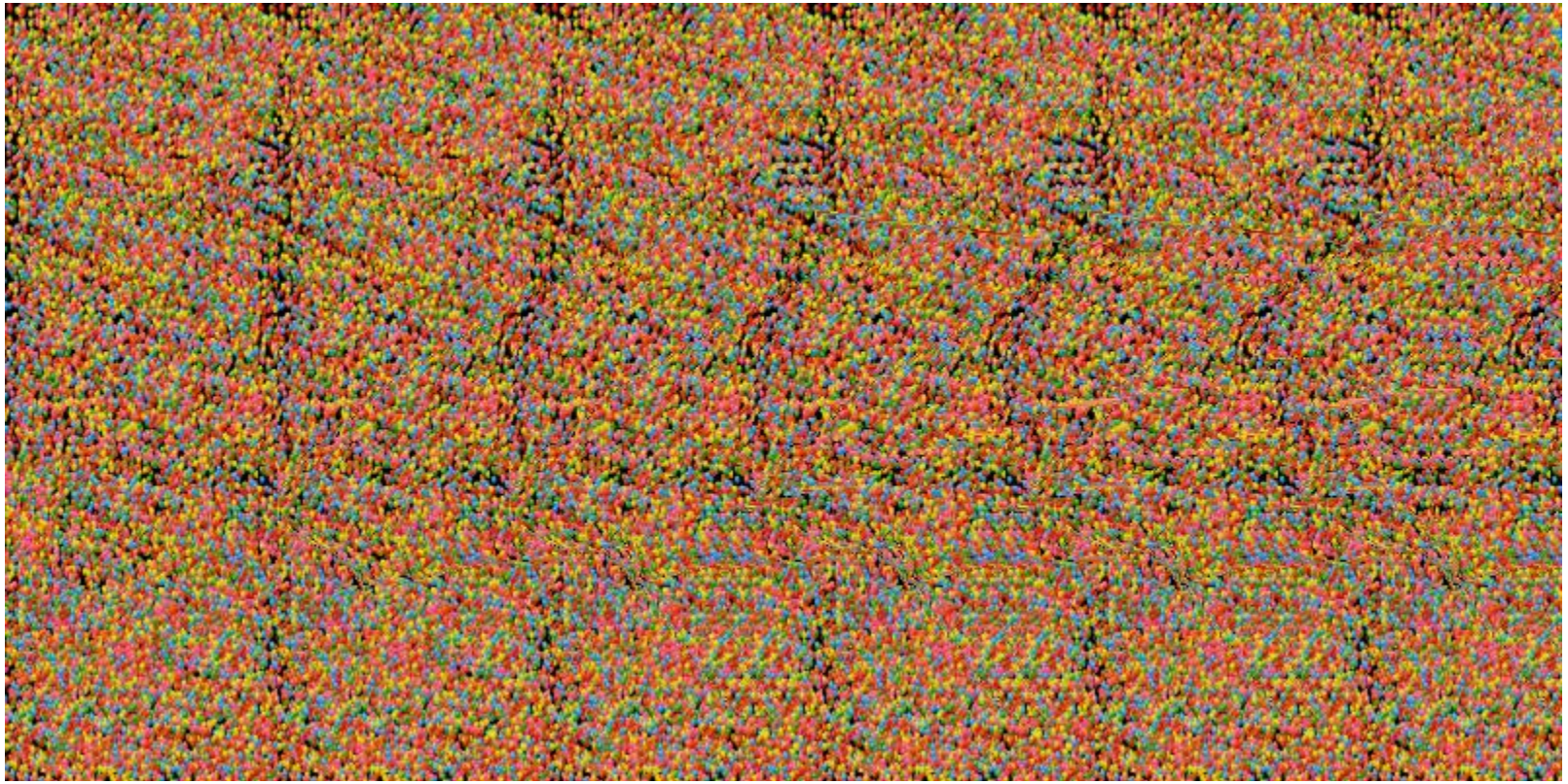
CS5670: Computer Vision

Binocular Stereo

What is this?



Single image stereogram,
https://en.wikipedia.org/wiki/Autostereogram

Announcements

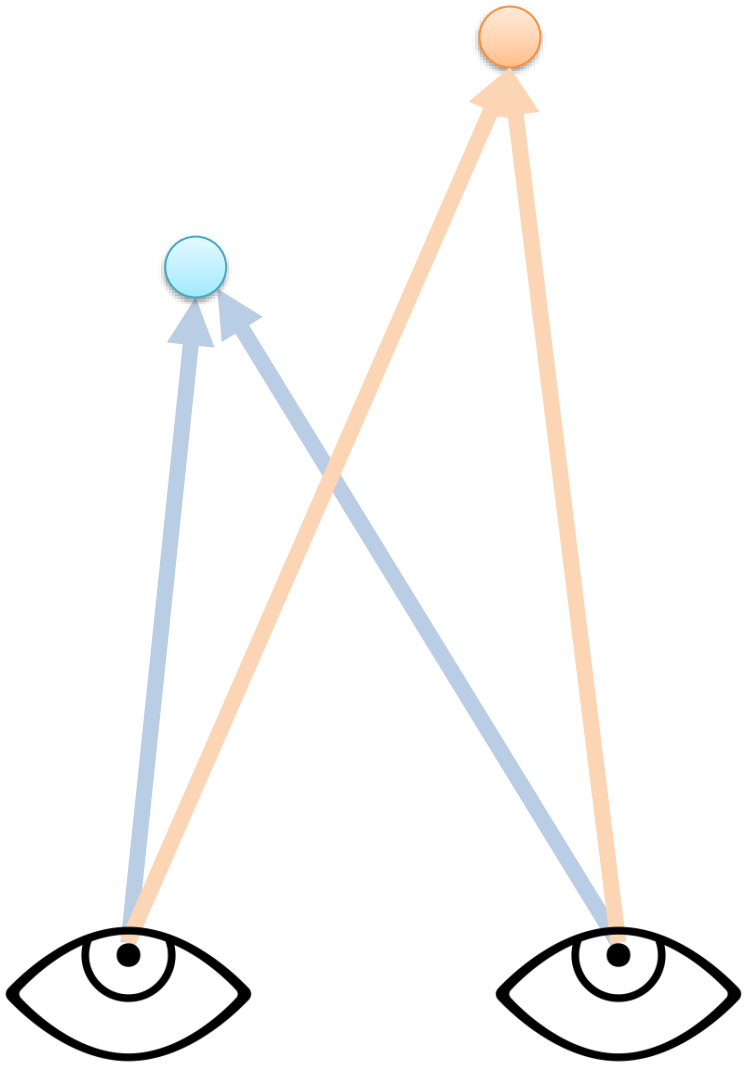
- Project 3
  - Code due this Friday, April 2, by 7pm to Github Classrooms
  - Artifact due Monday, April 5, by 7pm
- New quiz policy
  - Quizzes every Wednesday, ending 7 minutes after the start of class
  - Lowest 2 quiz grades will be dropped
- Project 4 will be out soon (stay tuned)
- Midterm grades will be released shortly

“Mark Twain at Pool Table", no date, UCR Museum of Photography

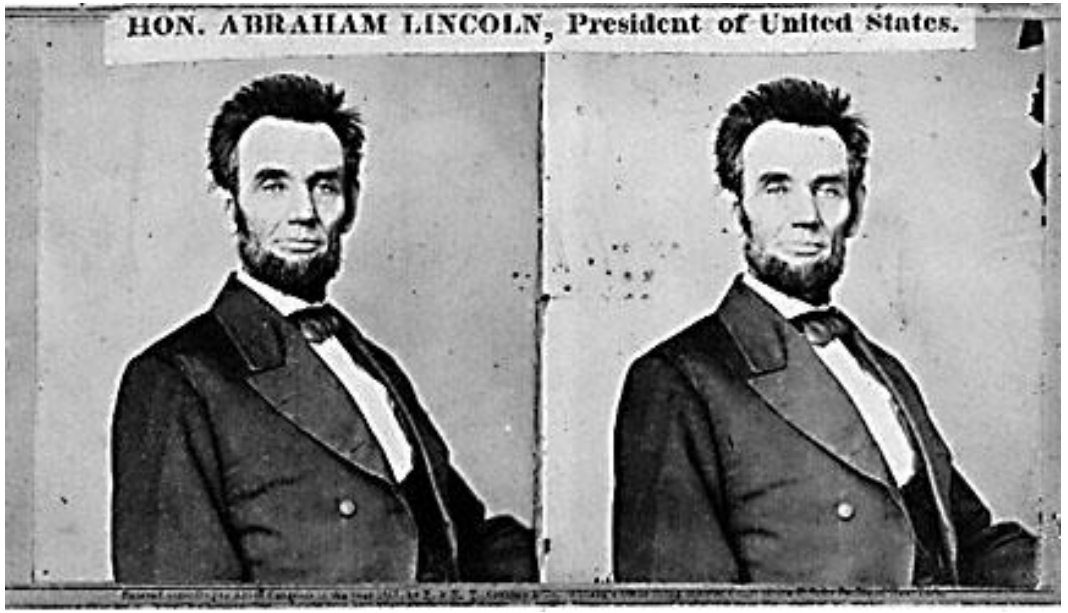
https://giphy.com/gifs/wigglegram-706pNfSKyaDug

Stereo Vision as Localizing Points in 3D

- An object point will project to some point in our image
- That image point corresponds to a ray in the world
- Two rays intersect at a single point, so if we want to localize points in 3D we need 2 eyes

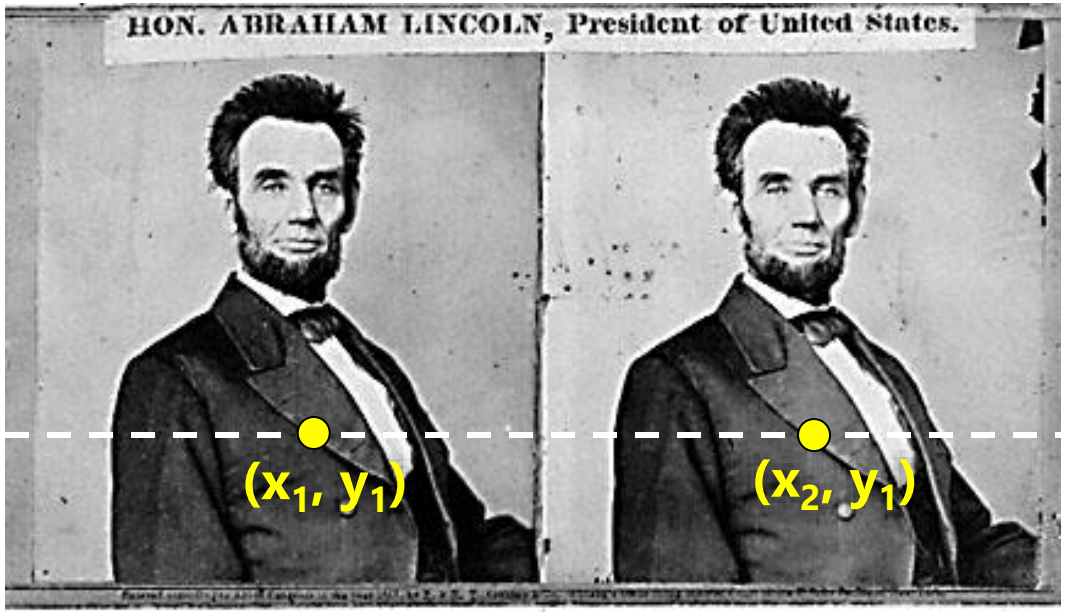


Stereo



- Given two images from different viewpoints
  - How can we compute the depth of each point in the image?
  - Based on *how much each pixel moves* between the two images

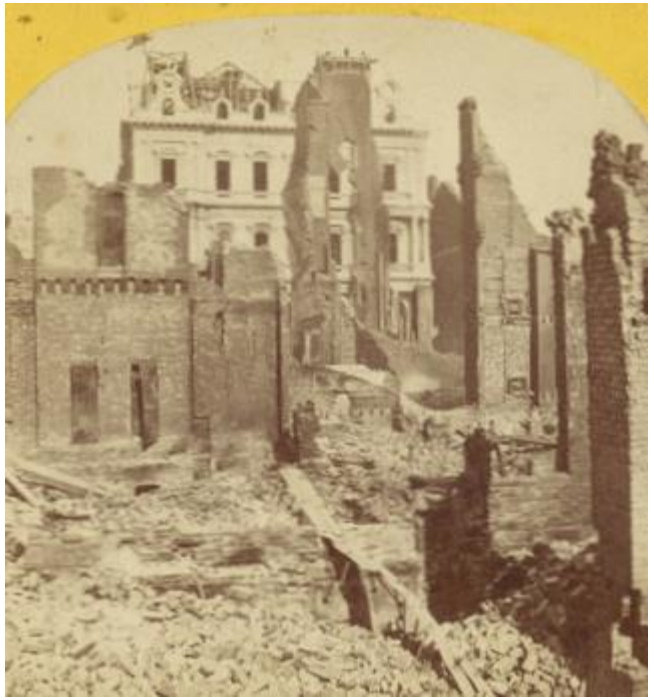
Epipolar geometry



Two images captured by a purely horizontal translating camera
(*rectified* stereo pair)

$x_2 - x_1$ = the *disparity* of pixel (x_1, y_1)

Disparity = inverse depth



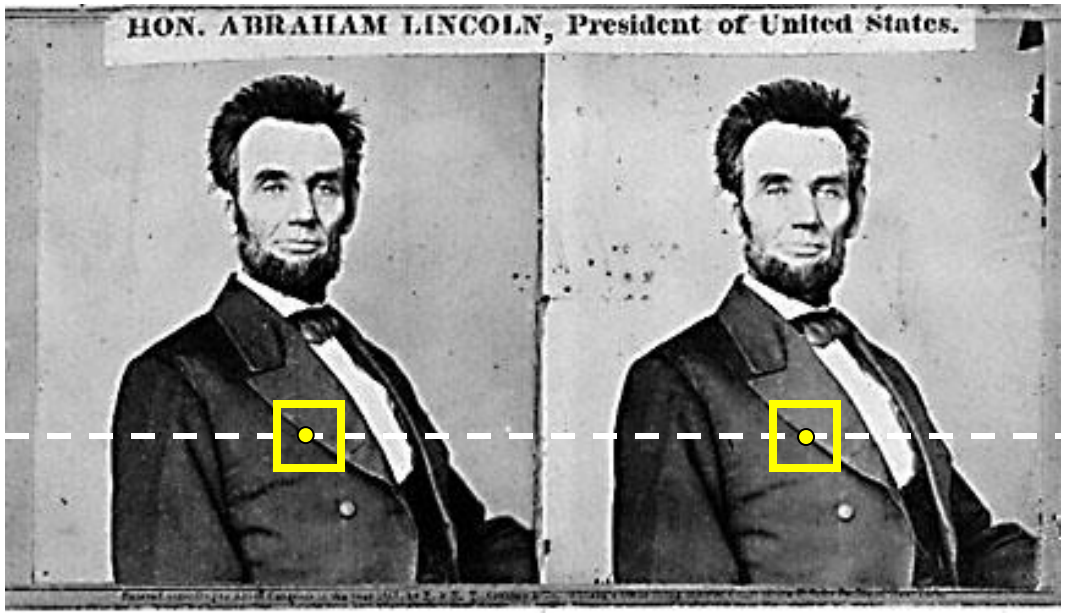
http://stereo.nypl.org/view/41729

(Or, hold a finger in front of your face and wink each eye in succession.)

Your basic stereo matching algorithm

- **Match Pixels in Conjugate Epipolar Lines**
  - Assume brightness constancy
  - This is a challenging problem
  - Hundreds of approaches
    - A good survey and evaluation: http://www.middlebury.edu/stereo/

Your basic stereo matching algorithm



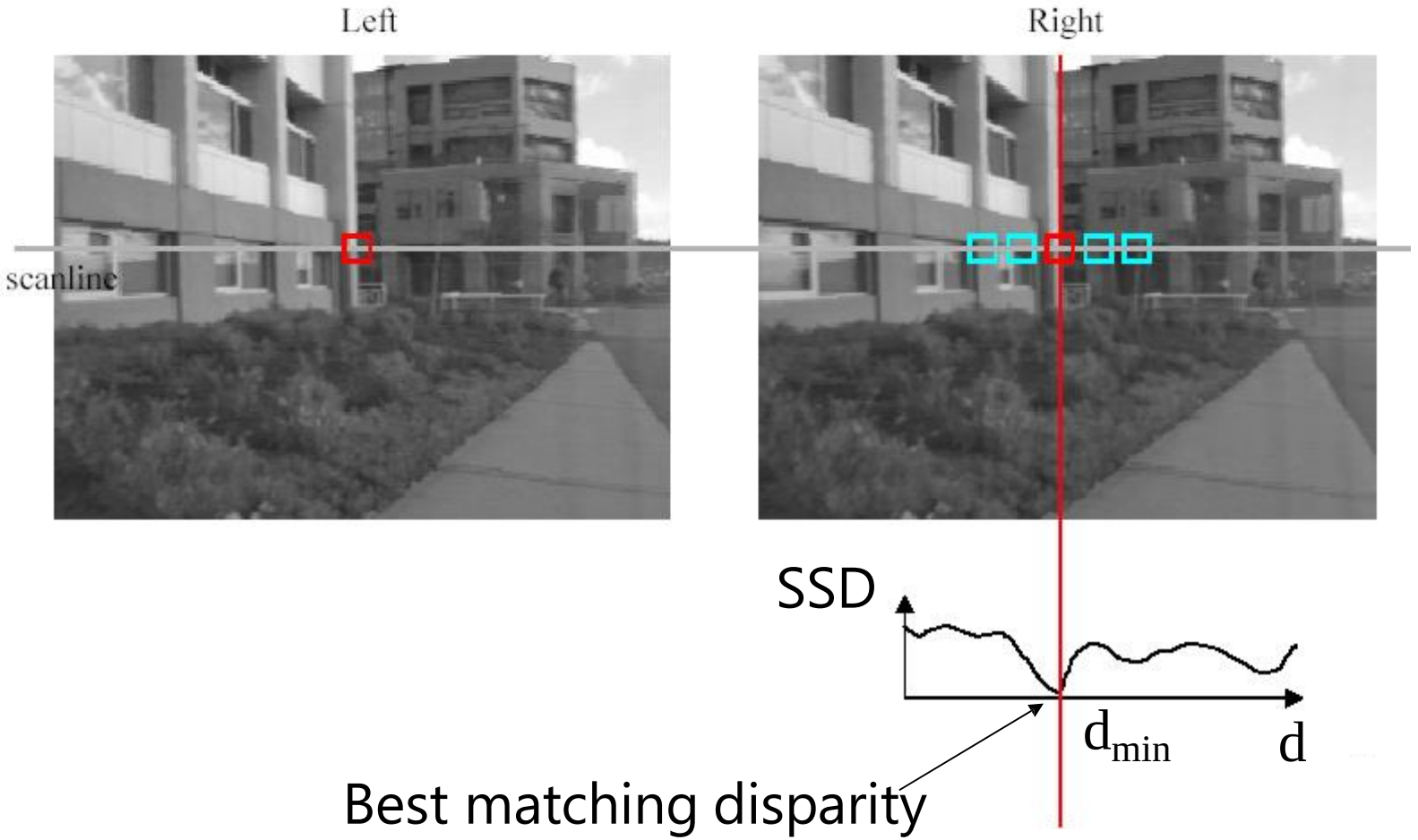
For each epipolar line

For each pixel in the left image

- compare with every pixel on same epipolar line in right image
- pick pixel with minimum match cost

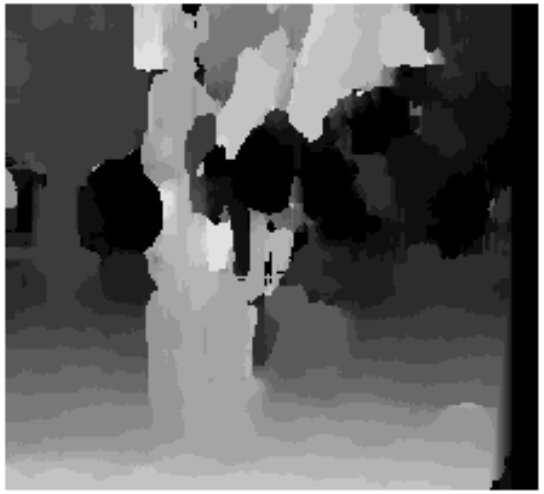
Improvement: match ***windows***

Stereo matching based on SSD



Window size

W = 3



W = 20

Effect of window size

- Smaller window
  - \+ more detail
  - \- more noise
- Larger window
  - \+ less noise
  - \- less detail

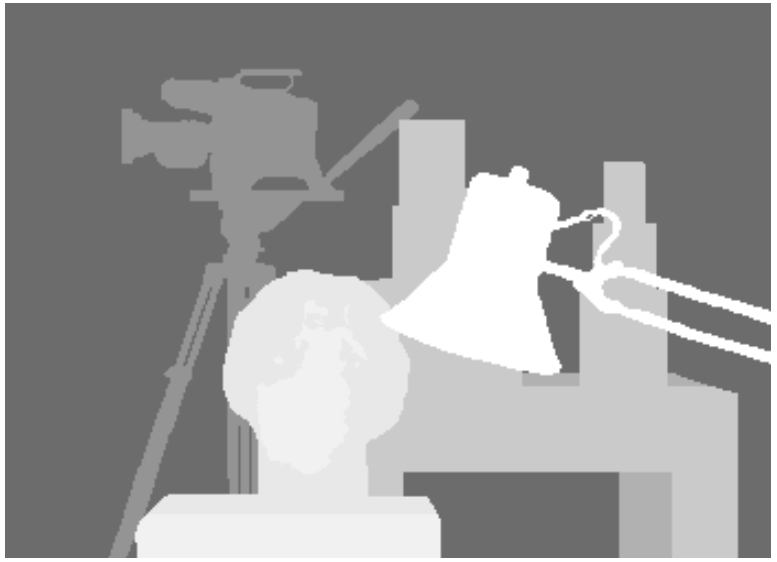
Better results with *adaptive window*

- T. Kanade and M. Okutomi, *A Stereo Matching Algorithm with an Adaptive Window: Theory and Experiment*, ICRA 1991.
- D. Scharstein and R. Szeliski. Stereo matching with nonlinear diffusion. IJCV, July 1998

Stereo results

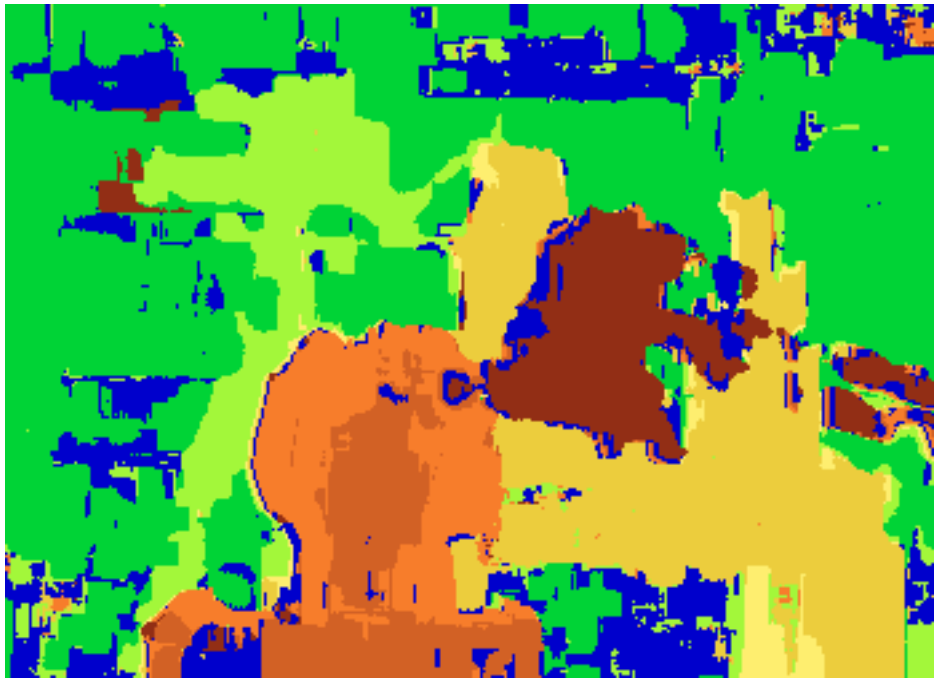
- Data from University of Tsukuba
- Similar results on other images without ground truth

Scene



Ground truth

Results with window search



Window-based matching
(best window size)

Ground truth

Better methods exist…

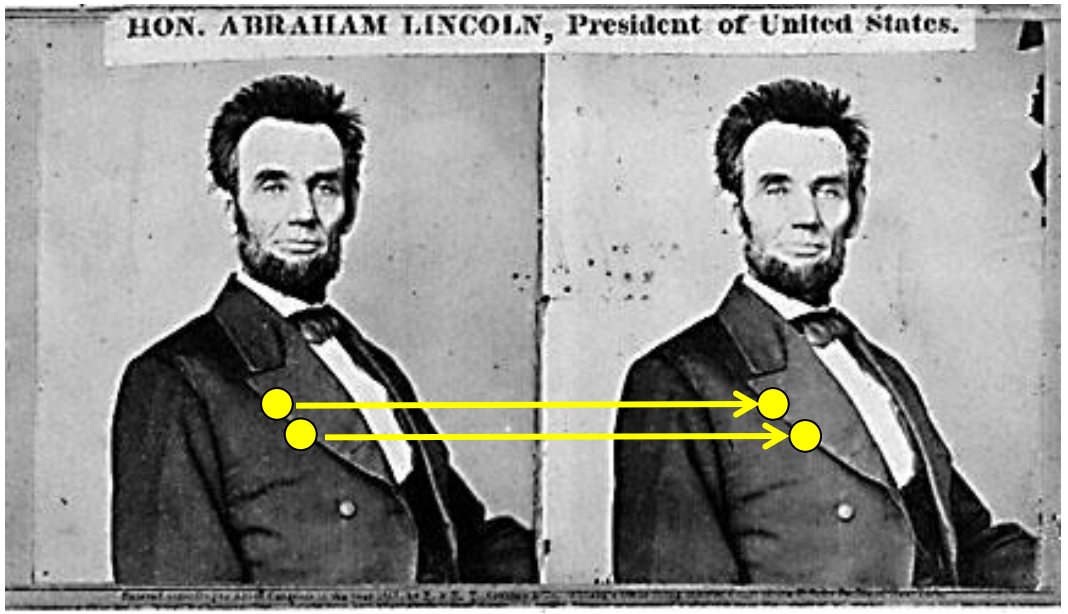
Graph cuts-based method

Ground truth

Boykov et al., Fast Approximate Energy Minimization via Graph Cuts, International Conference on Computer Vision 1999.

For the latest and greatest: http://www.middlebury.edu/stereo/

Stereo as energy minimization



- What defines a good stereo correspondence?
  1. Match quality
     - Want each pixel to find a good match in the other image
  2. Smoothness
     - If two pixels are adjacent, they should (usually) move about the same amount

Stereo as energy minimization

- Find disparity map *d* that minimizes an *energy function* $E(d)$

- Simple pixel / window matching

$$E(d) = \sum_{(x,y) \in I} C(x, y, d(x, y))$$

$C(x, y, d(x, y))$ = SSD distance between windows $I(x, y)$ and $J(x + d(x,y), y)$

Stereo as energy minimization

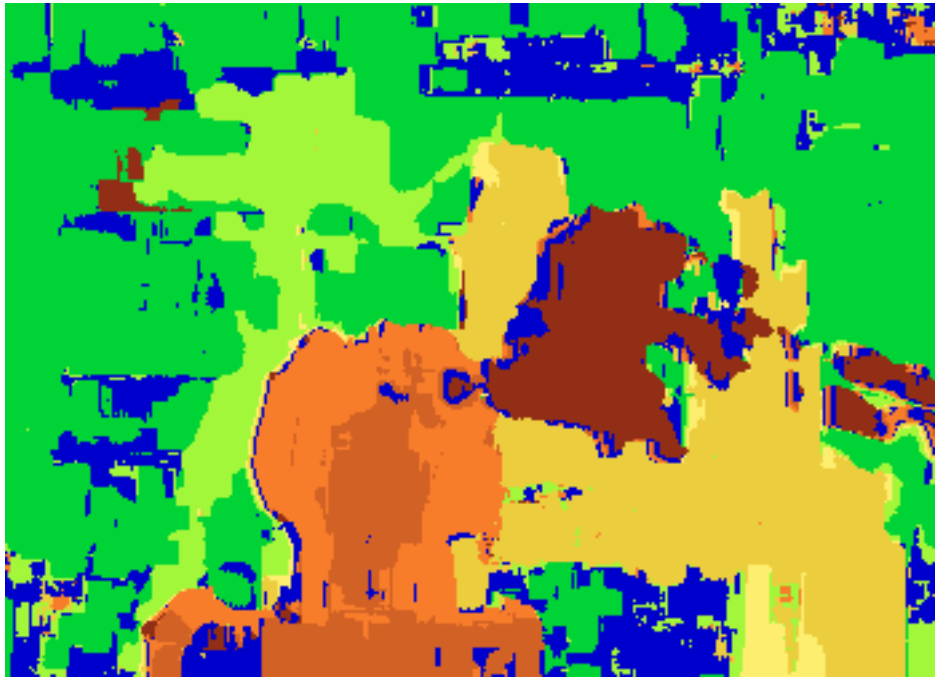
$C(x, y, d)$; the *disparity space image* (DSI)

Stereo as energy minimization

Simple pixel / window matching: choose the minimum of each column in the DSI independently:

$$d(x, y) = \arg\min_{d'} C(x, y, d')$$

Greedy selection of best match



Stereo as energy minimization

- Better objective function

$$E(d) = \underbrace{E_d(d)}_{\text{match cost}} + \lambda \underbrace{E_s(d)}_{\text{smoothness cost}}$$

Want each pixel to find a good match in the other image

Adjacent pixels should (usually) move about the same amount

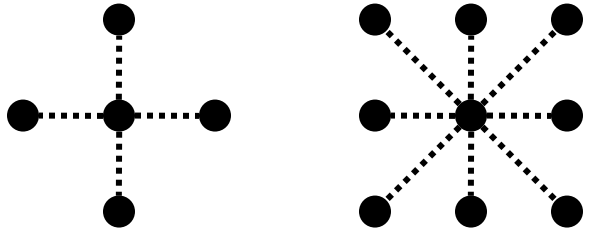
Stereo as energy minimization

$$E(d) = E_d(d) + \lambda E_s(d)$$

match cost: $$E_d(d) = \sum_{(x,y)\in I} C(x, y, d(x, y))$$

smoothness cost: $$E_s(d) = \sum_{(p,q)\in\mathcal{E}} V(d_p, d_q)$$

$\mathcal{E}$: set of neighboring pixels



4-connected neighborhood

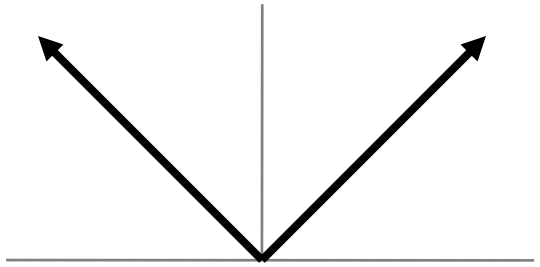
8-connected neighborhood

Smoothness cost $E_s(d) = \sum_{(p,q)\in\mathcal{E}} V(d_p, d_q)$

How do we choose *V*?

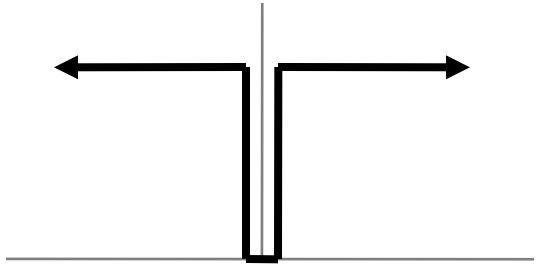
$$V(d_p, d_q) = |d_p - d_q|$$

L_1 distance



$$V(d_p, d_q) = \begin{cases} 0 & \text{if } d_p = d_q \\ 1 & \text{if } d_p \neq d_q \end{cases}$$

"Potts model"



Smoothness cost

$$E(d) = E_d(d) + \lambda E_s(d)$$

- If λ = infinity, then we only consider smoothness
- Optimal solution is a surface of constant depth/disparity
  - *Fronto-parallel* surface

- In practice, want to balance data term with smoothness term

Dynamic programming

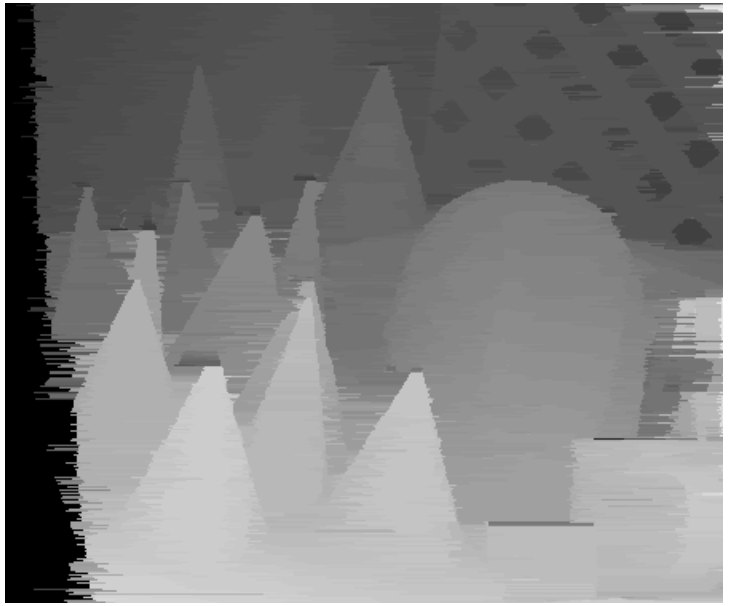
$$E(d) = E_d(d) + \lambda E_s(d)$$

- Can minimize this independently per scanline using dynamic programming (DP)

Dynamic programming

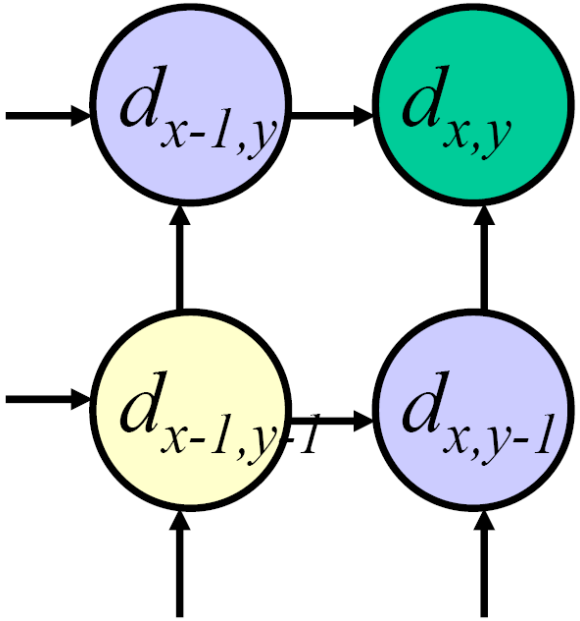
- Finds “smooth”, low-cost path through DPI from left to right
- Visiting a node incurs its data cost, switching disparities from one column to the next also incurs a (smoothness) cost

Dynamic Programming



Dynamic programming

- Can we apply this trick in 2D as well?



- No: the shortest path trick only works to find a 1D path

Slide credit: D. Huttenlocher

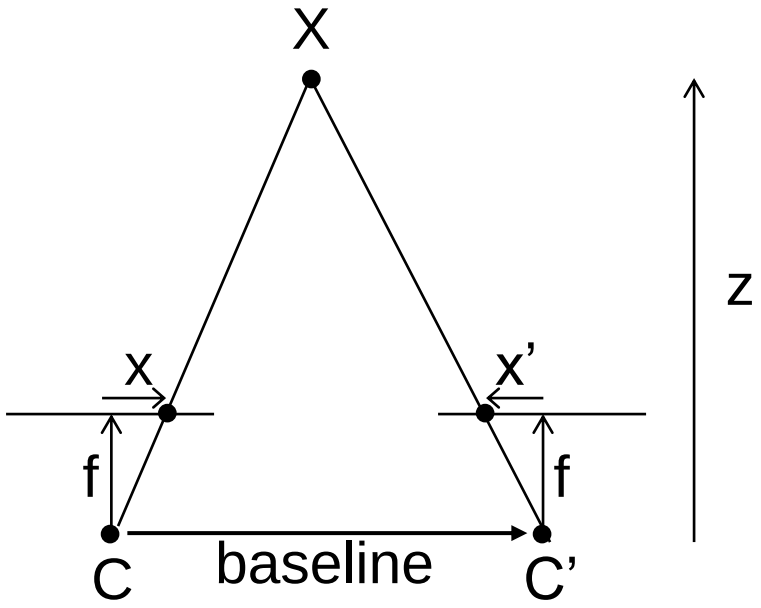
Stereo as a minimization problem

$$E(d) = E_d(d) + \lambda E_s(d)$$

- The 2D problem has many local minima
  - Gradient descent doesn't work well
- And a large search space
  - *n* x *m* image w/ *k* disparities has k^{nm} possible solutions
  - Finding the global minimum is NP-hard in general
- Good approximations exist (e.g., graph cuts algorithms)

Questions?

Depth from disparity



$$disparity = x - x' = \frac{baseline * f}{z}$$

Real-time stereo

Nomad robot searches for meteorites in Antartica

- Used for robot navigation (and other tasks)
  - Several real-time stereo techniques have been developed (most based on simple discrete search)

Stereo reconstruction pipeline

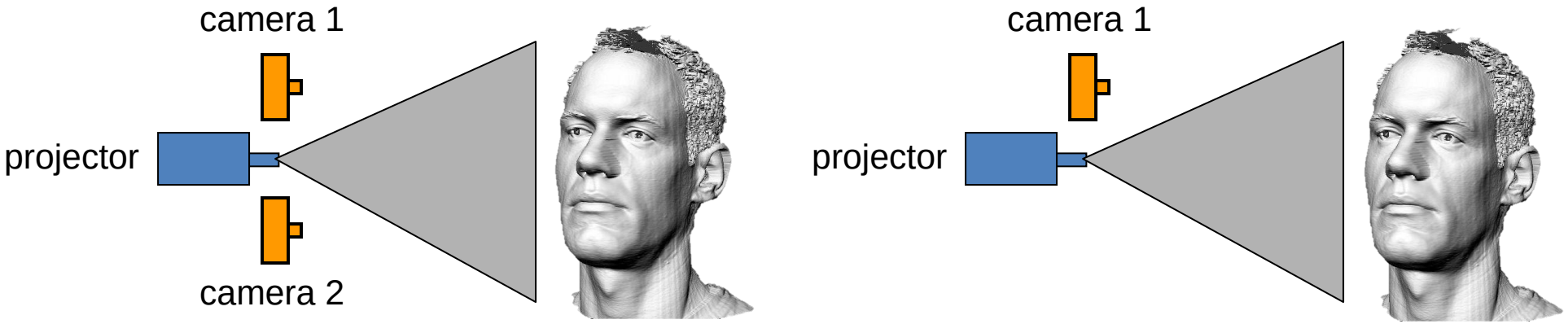
- Steps
  - Calibrate cameras
  - Rectify images
  - Compute disparity
  - Estimate depth

What will cause errors?

- Camera calibration errors
- Poor image resolution
- Occlusions
- Violations of brightness constancy (specular reflections)
- Large motions
- **Low-contrast image regions**

Active stereo with structured light

Li Zhang's one-shot stereo

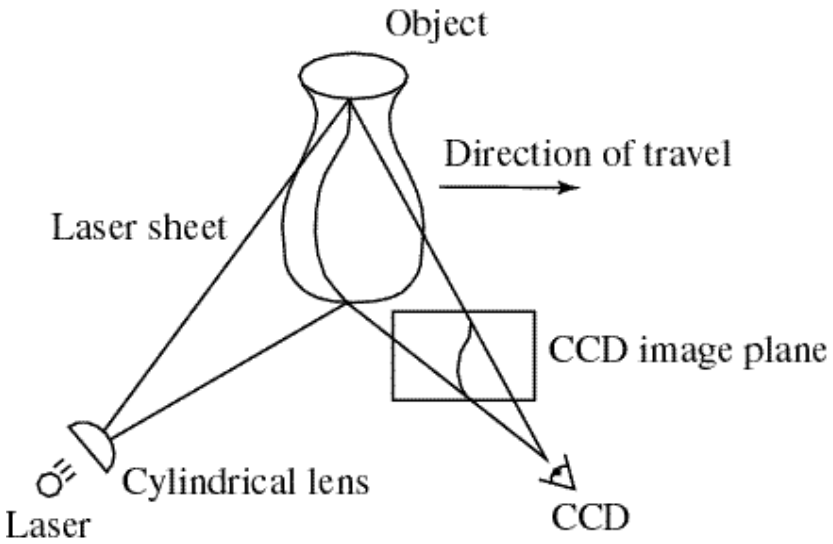


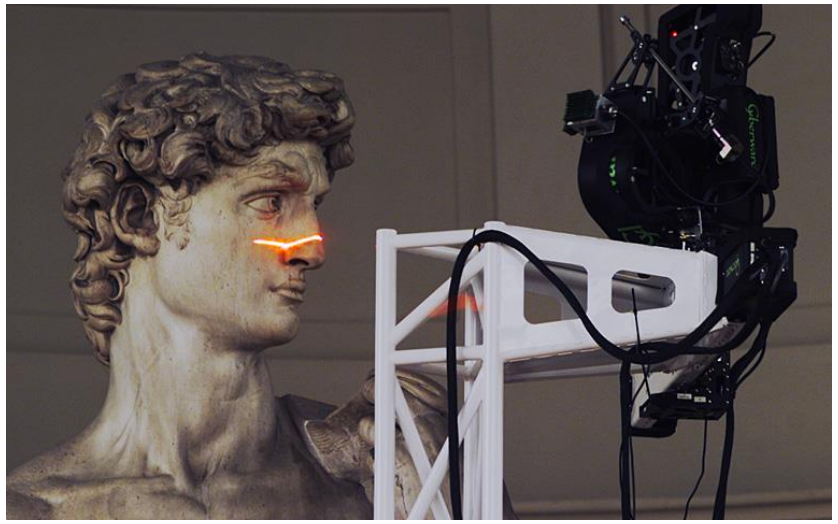
- Project "structured" light patterns onto the object
  - simplifies the correspondence problem
  - basis for active depth sensors, such as Kinect and iPhone X (using IR)

Active stereo with structured light

https://ios.gadgethacks.com/news/watch-iphone-xs-30k-ir-dots-scan-your-face-0180944/

Laser scanning





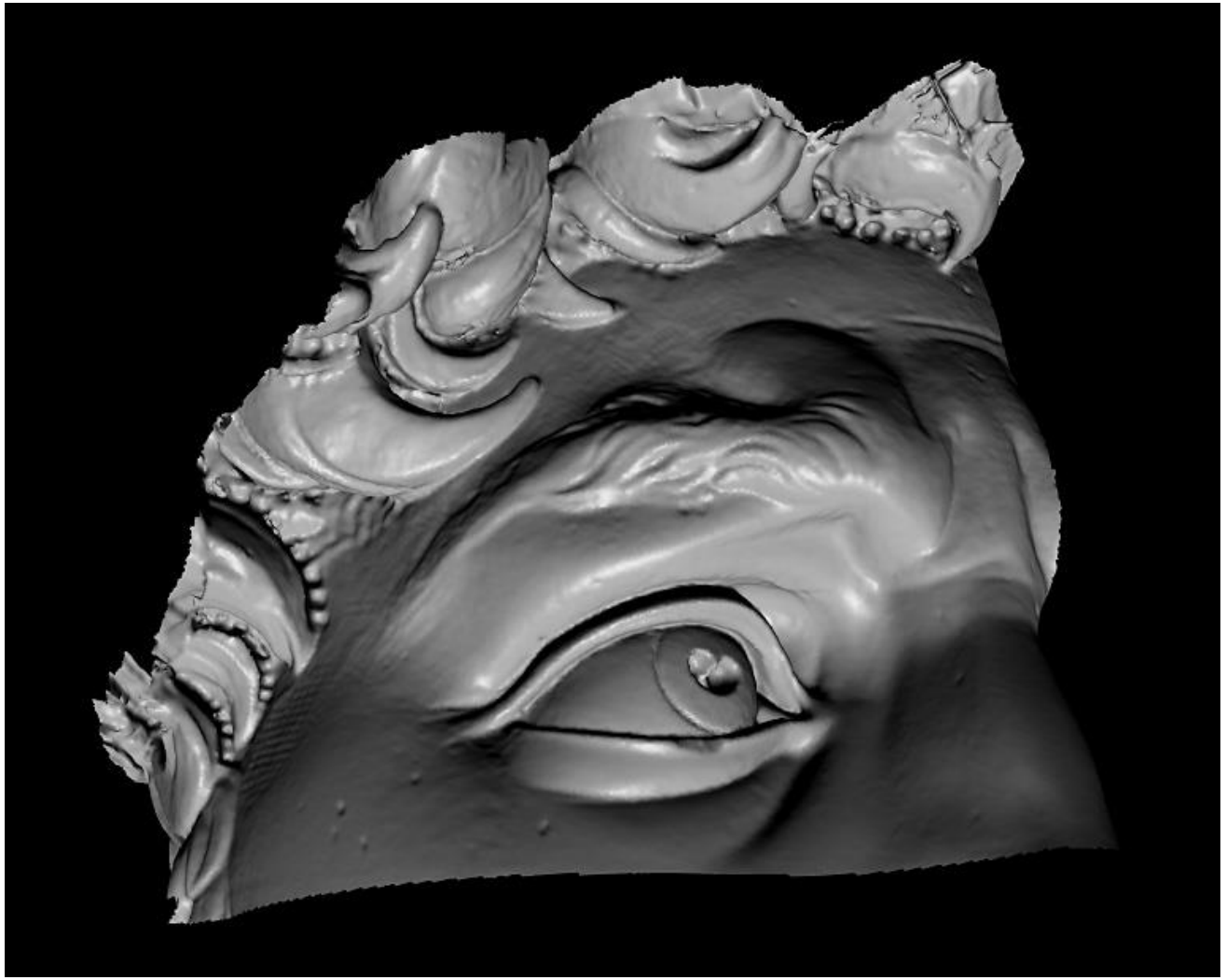
Digital Michelangelo Project
http://graphics.stanford.edu/projects/mich/

- 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

Laser scanned models

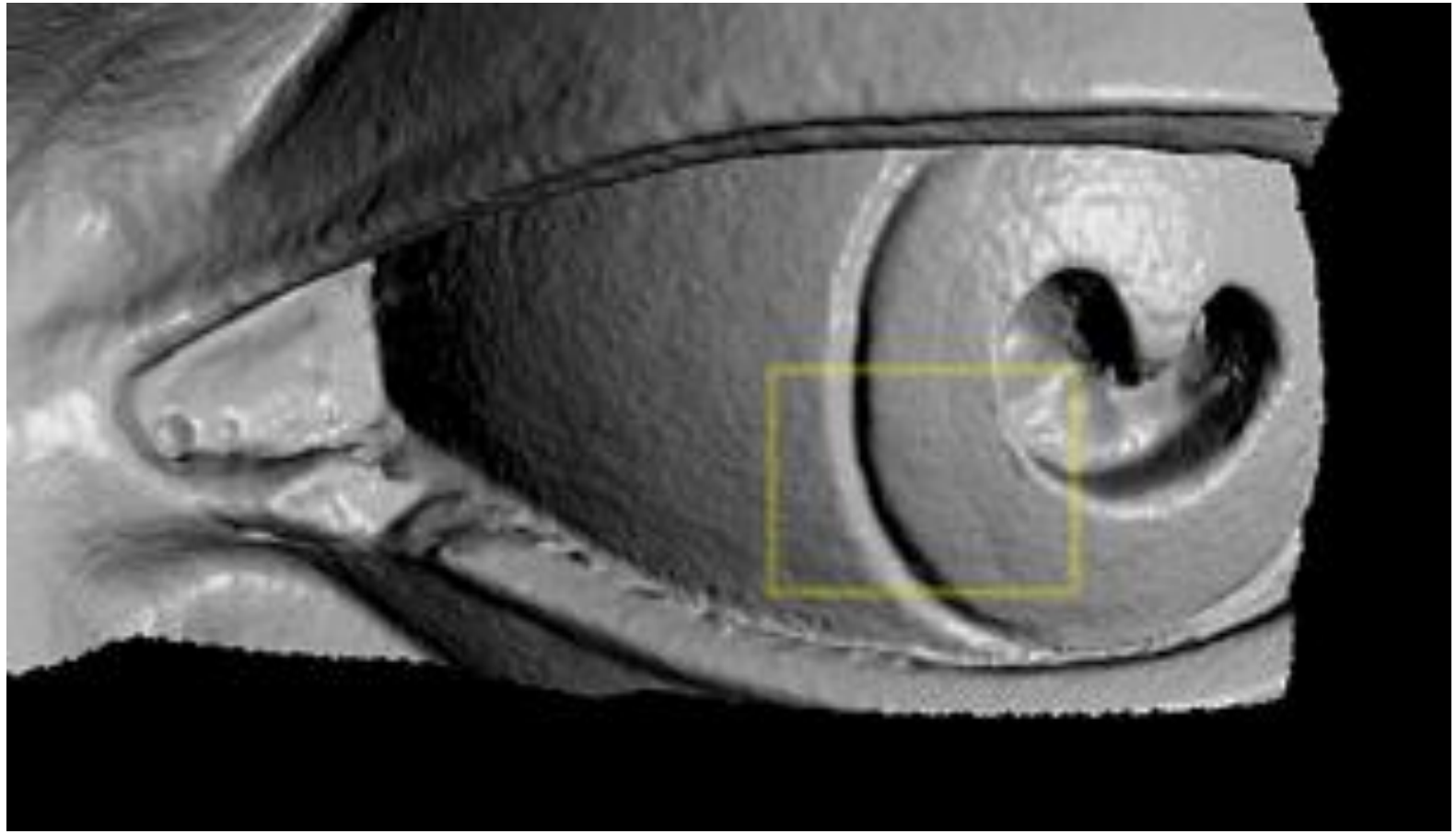
The Digital Michelangelo Project, Levoy et al.

Laser scanned models



The Digital Michelangelo Project, Levoy et al.

Laser scanned models



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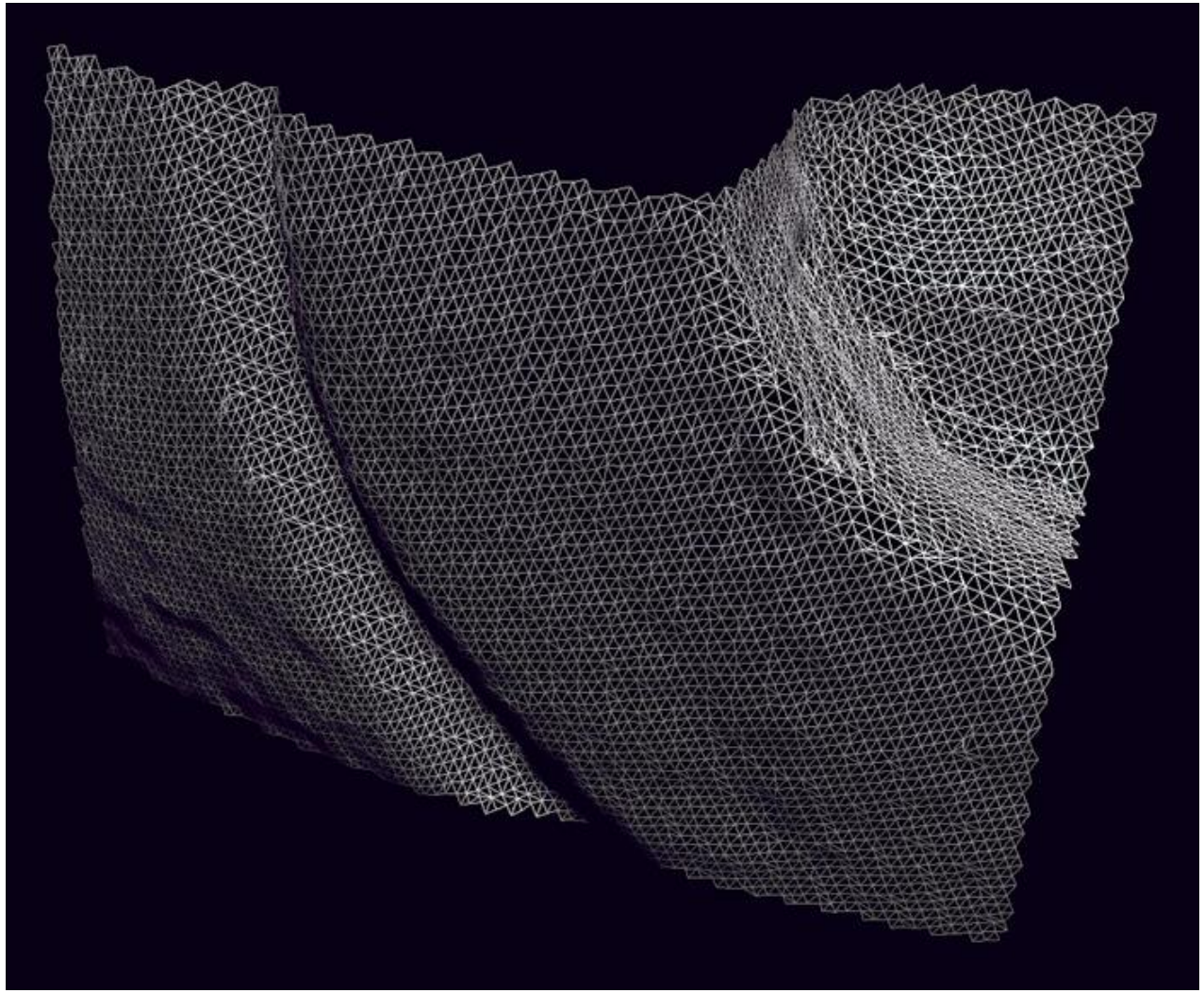
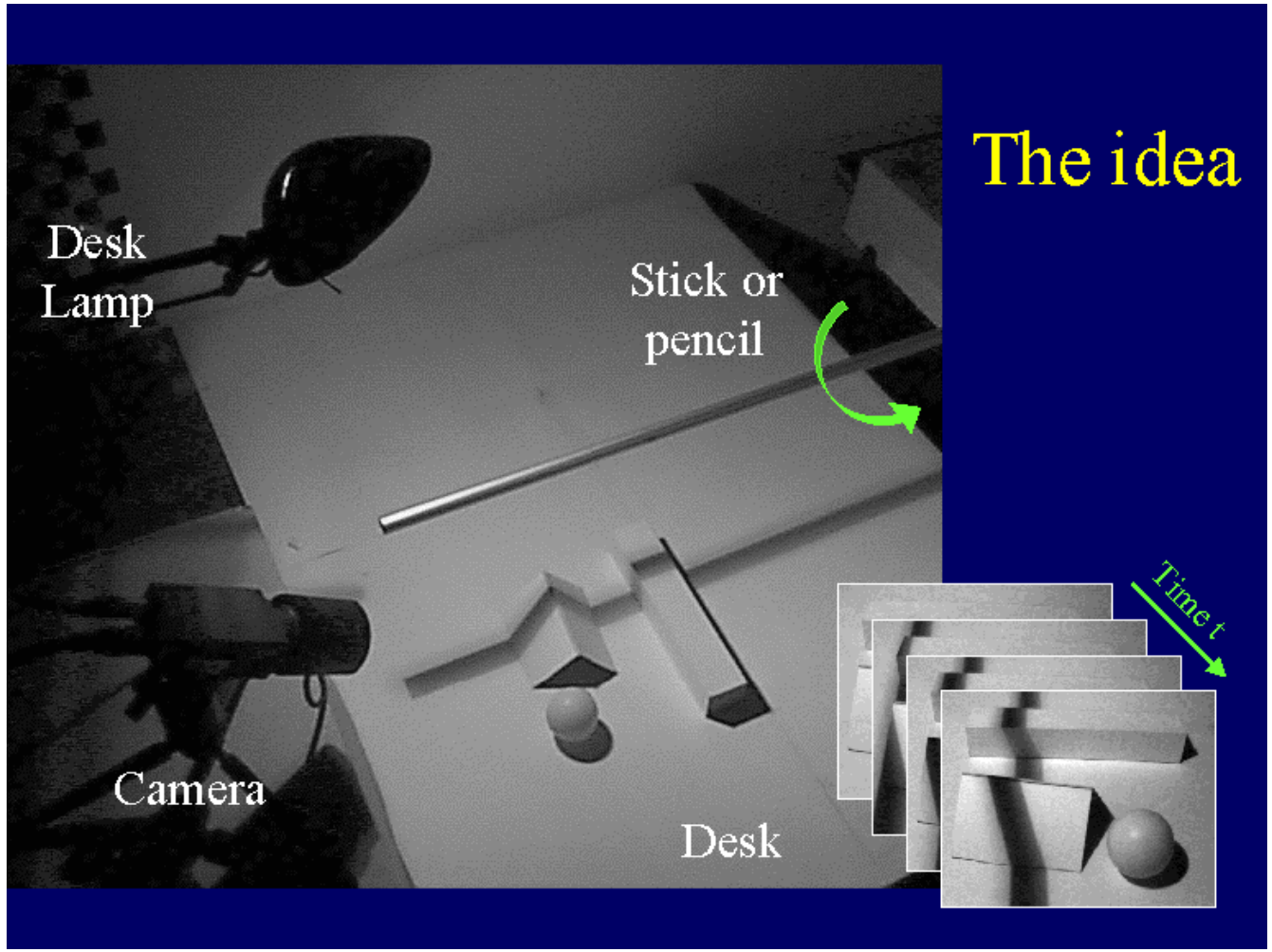
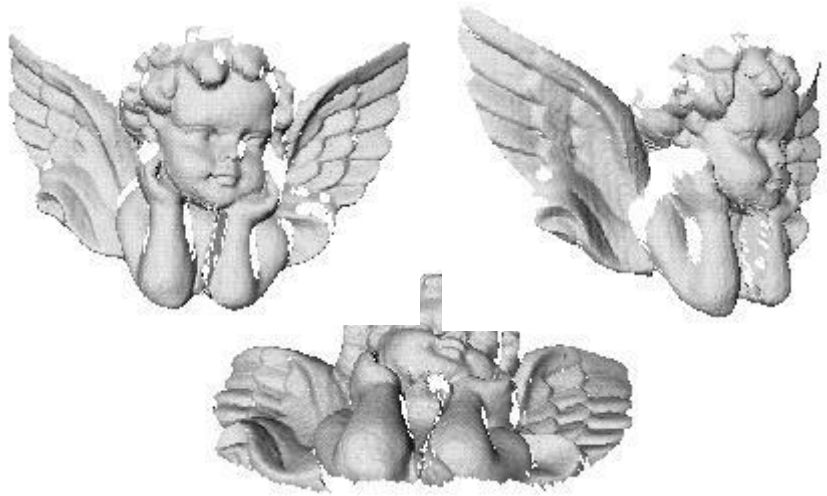


The Digital Michelangelo Project, Levoy et al.

3D Photography on your Desk





http://www.vision.caltech.edu/bouguetj/ICCV98/

Questions?