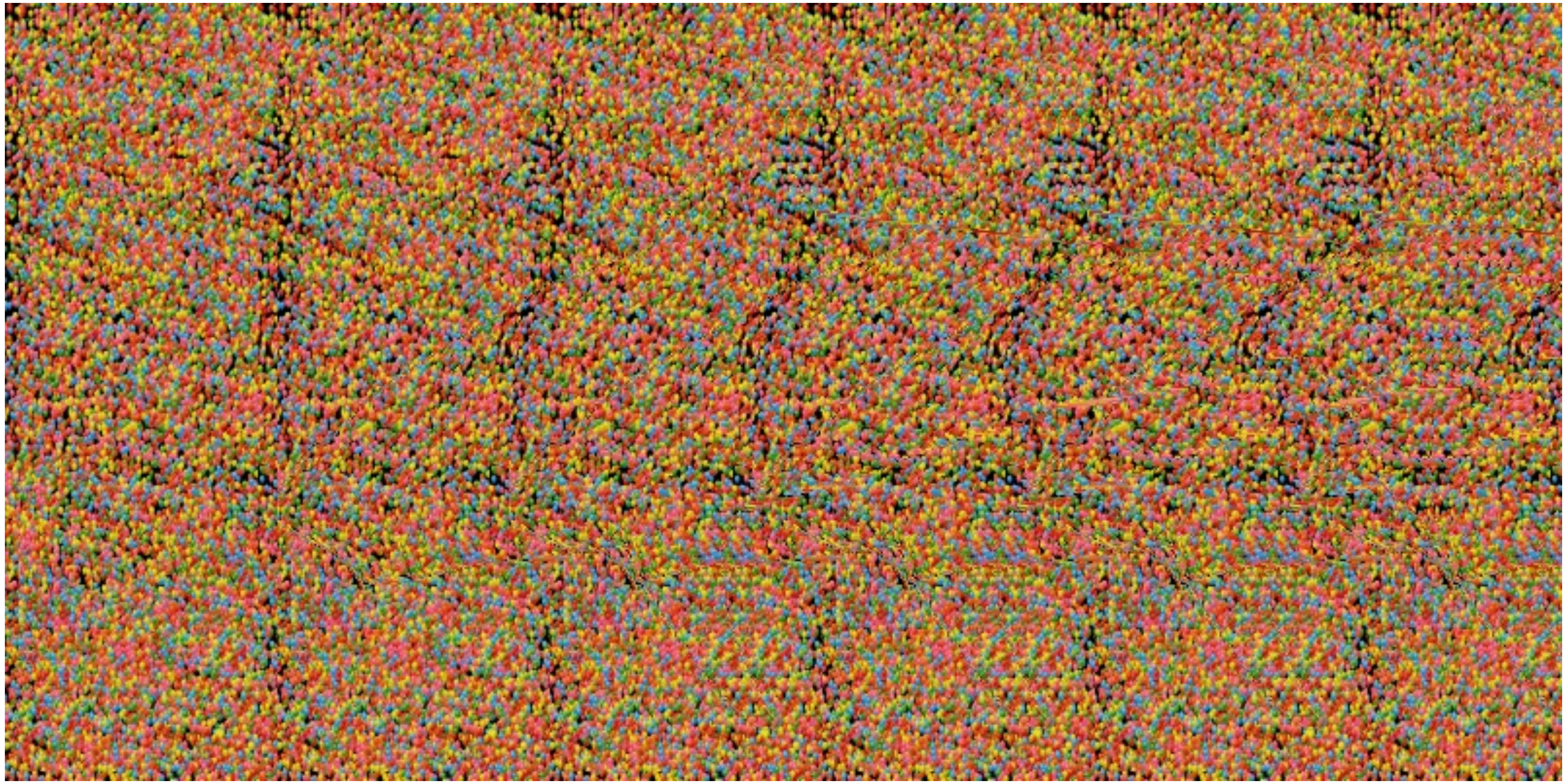
CS5670: Computer Vision

Binocular Stereo

What is this?



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

Announcements

- Project 3 due this Friday, March 17 at 8pm (code), Monday, March 20 at 8pm (artifact)

- Project 4 (Stereo) to be released on Tuesday, March 21, due Friday, April 31, by 8pm
  - To be done in groups of two

From last time: 3D modeling from a photograph

video by Antonio Criminisi

3D modeling from a photograph

Flagellation. Piero della Francesca. c1453.

Related problem: camera calibration

- Goal: estimate the camera parameters
  - Version 1: solve for 3x4 projection matrix

$$\mathbf{x} = \begin{bmatrix} wx \\ wy \\ w \end{bmatrix} = \begin{bmatrix} * & * & * & * \\ * & * & * & * \\ * & * & * & * \end{bmatrix} \begin{bmatrix} X \\ Y \\ Z \\ 1 \end{bmatrix} = \mathbf{\Pi X}$$

  - Version 2: solve for camera parameters separately
    - intrinsics (focal length, principal point, pixel size)
    - extrinsics (rotation angles, translation)
    - radial distortion

Vanishing points and projection matrix

$$\mathbf{\Pi} = \begin{array}{cccc} \begin{bmatrix} \boxed{\begin{matrix} * \\ * \\ * \end{matrix}} & \boxed{\begin{matrix} * \\ * \\ * \end{matrix}} & \boxed{\begin{matrix} * \\ * \\ * \end{matrix}} & \boxed{\begin{matrix} * \\ * \\ * \end{matrix}} \end{bmatrix} \\ \boldsymbol{\pi}_1 \quad \boldsymbol{\pi}_2 \quad \boldsymbol{\pi}_3 \quad \boldsymbol{\pi}_4 \end{array} = \begin{bmatrix} \boldsymbol{\pi}_1 & \boldsymbol{\pi}_2 & \boldsymbol{\pi}_3 & \boldsymbol{\pi}_4 \end{bmatrix}$$

- $\boldsymbol{\pi}_1 = \mathbf{\Pi}\begin{bmatrix}1 & 0 & 0 & 0\end{bmatrix}^T$ = $\mathbf{v}_X$ (X vanishing point)
- similarly, $\boldsymbol{\pi}_2 = \mathbf{v}_Y, \ \boldsymbol{\pi}_3 = \mathbf{v}_Z$
- $\boldsymbol{\pi}_4 = \mathbf{\Pi}\begin{bmatrix}0 & 0 & 0 & 1\end{bmatrix}^T = \text{projection of world origin}$

$$\mathbf{\Pi} = \begin{bmatrix} \mathbf{v}_X & \mathbf{v}_Y & \mathbf{v}_Z & \mathbf{o} \end{bmatrix}$$

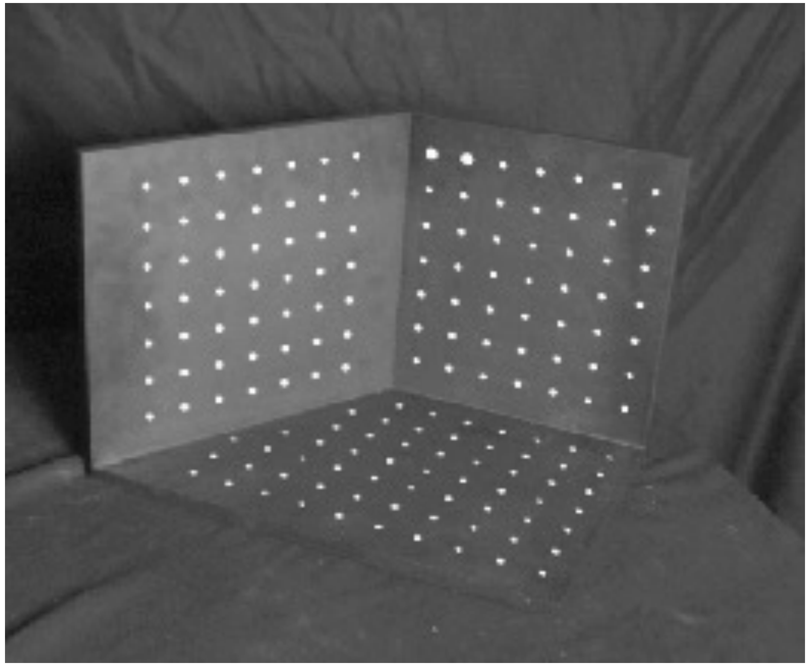
Not So Fast! We only know **v**'s up to a scale factor

$$\mathbf{\Pi} = \begin{bmatrix} a\mathbf{v}_X & b\mathbf{v}_Y & c\mathbf{v}_Z & \mathbf{o} \end{bmatrix}$$

- Can fully specify by providing 3 reference points with known coordinates

Calibration using a reference object

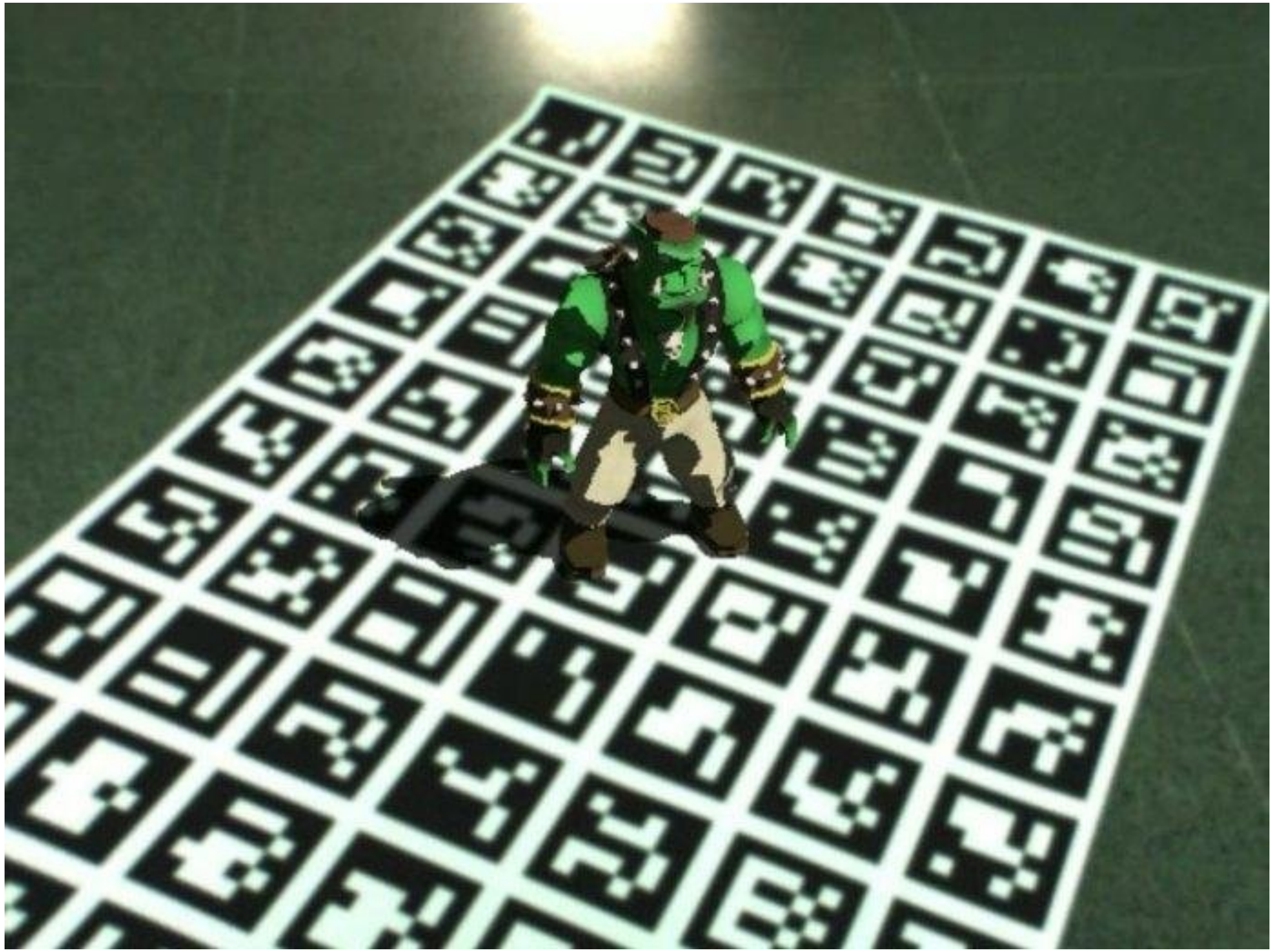
- Place a known object in the scene
  - – identify correspondence between image and scene
  - – compute mapping from scene to image



Issues

- must know geometry very accurately
- must know 3D -> 2D correspondence

AR codes

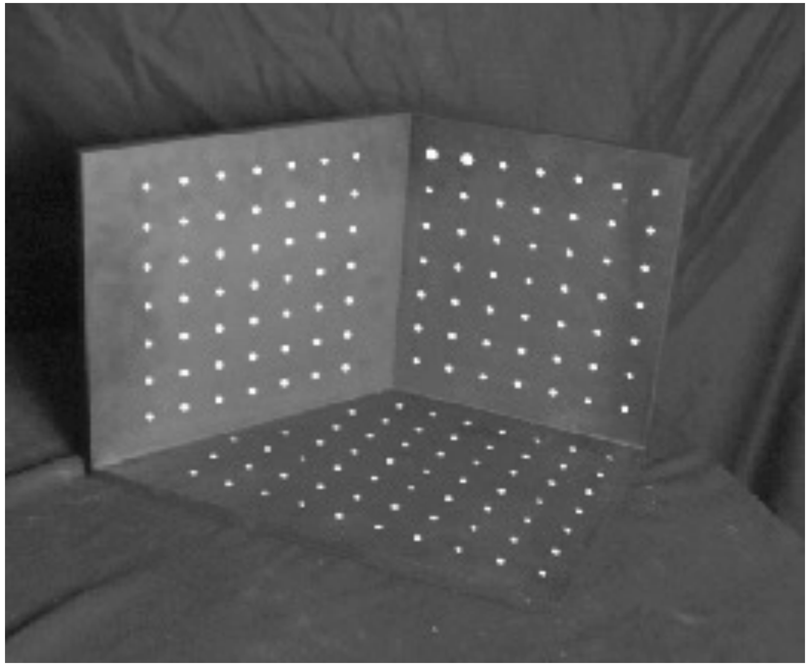


ArUco

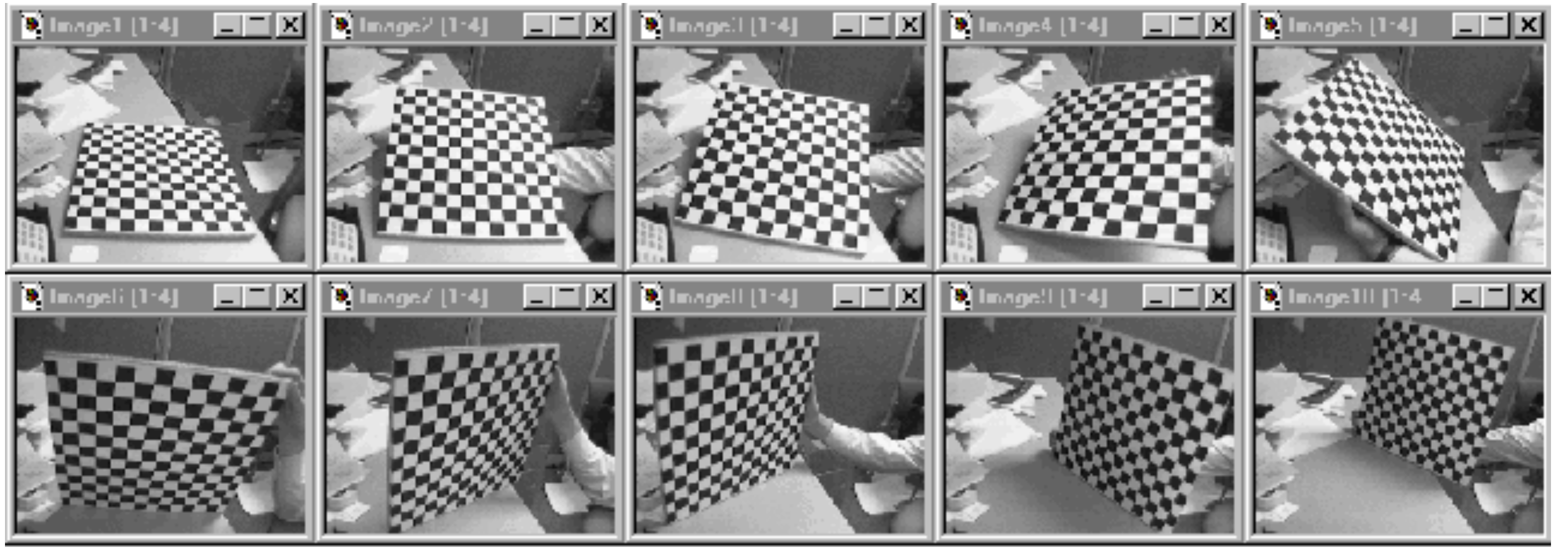
Estimating the projection matrix

- Place a known object in the scene
  - identify correspondence between image and scene
  - compute mapping from scene to image

$$\begin{bmatrix} u_i \\ v_i \\ 1 \end{bmatrix} \cong \begin{bmatrix} m_{00} & m_{01} & m_{02} & m_{03} \\ m_{10} & m_{11} & m_{12} & m_{13} \\ m_{20} & m_{21} & m_{22} & m_{23} \end{bmatrix} \begin{bmatrix} X_i \\ Y_i \\ Z_i \\ 1 \end{bmatrix}$$



Alternative: multi-plane calibration



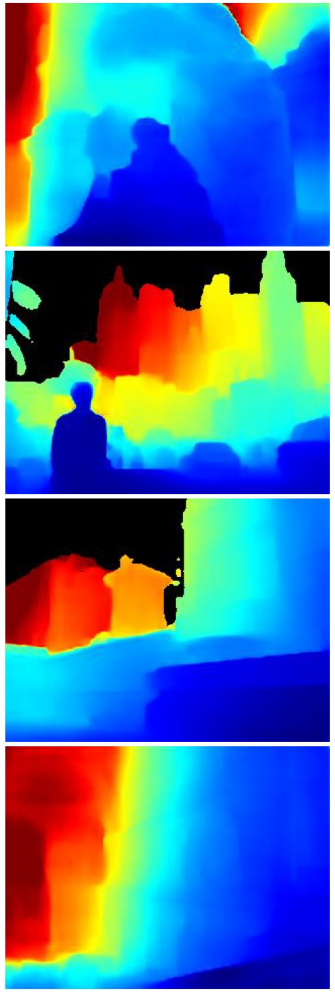
Images courtesy Jean-Yves Bouguet

Advantage

- Only requires a plane
- Don't have to know positions/orientations
- Good code available online! (including in OpenCV)
  - Matlab version by Jean-Yves Bouget: http://www.vision.caltech.edu/bouguetj/calib_doc/index.html
  - Amy Tabb's camera calibration software: https://github.com/amy-tabb/basic-camera-calibration

Single-image depth prediction using deep learning

Deep
learning



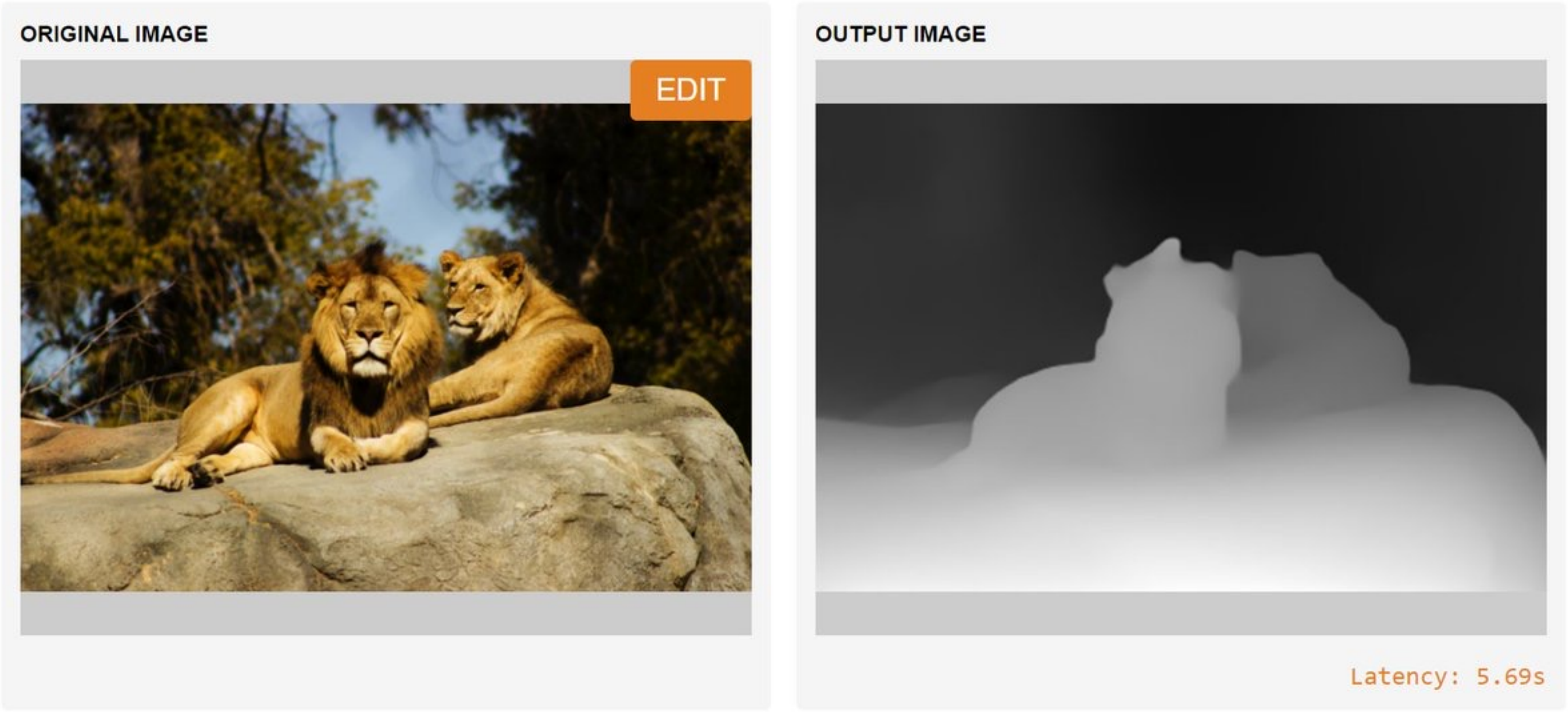
Image

Depth map

Li and Snavely. Megadepth: Learning single-view depth prediction from internet photos. CVPR 2018.

MiDaS depth prediction

Ranftl et al. *Towards Robust Monocular Depth Estimation: Mixing Datasets for Zero-shot Cross-dataset Transfer.*



https://gradio.app/g/AK391/MiDaS

https://github.com/intel-isl/MiDaS

Single-image depth prediction

Picture credit: Magritte, *The Treachery of Images*, and the Berkeley Computer Vision Group

Miangoleh*, Dille*, Mai, Paris, and Aksoy.
Boosting Monocular Depth Estimation Models to High-Resolution via Content-Adaptive Multi-Resolution Merging.
CVPR 2021

Deep geometry prediction

- More on this topic later!

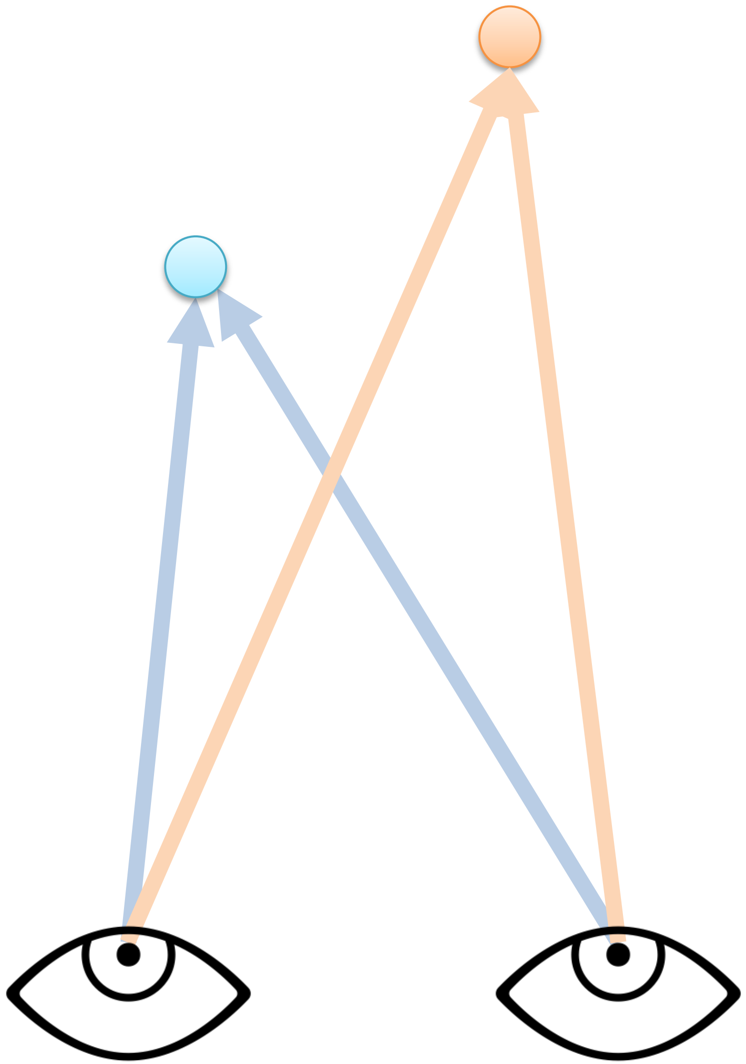
Questions?

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

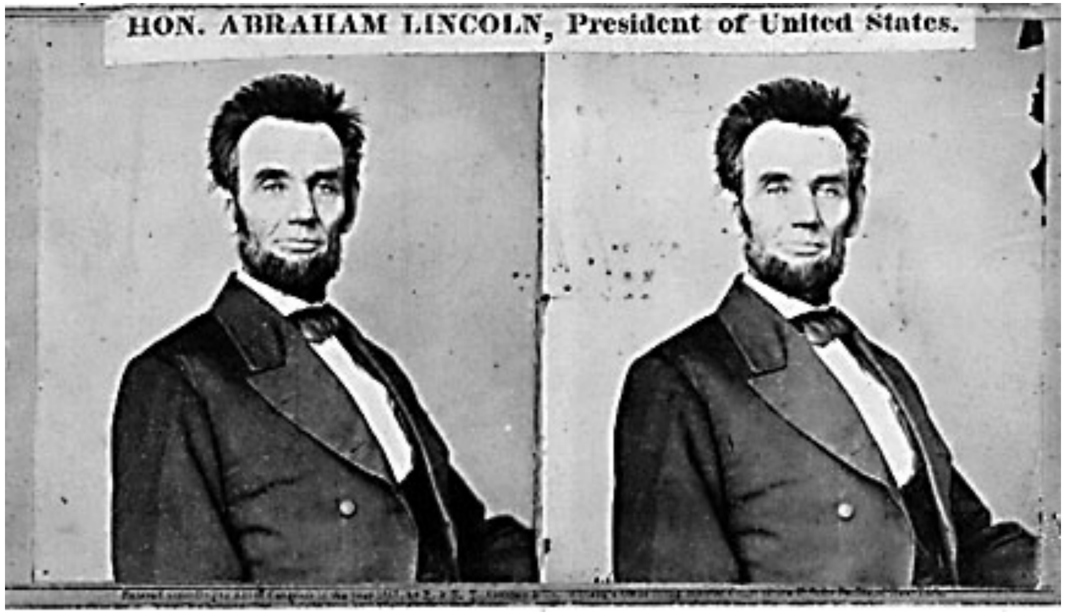
https://giphy.com/gifs/wigglegram-706pNfSKyaDug

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



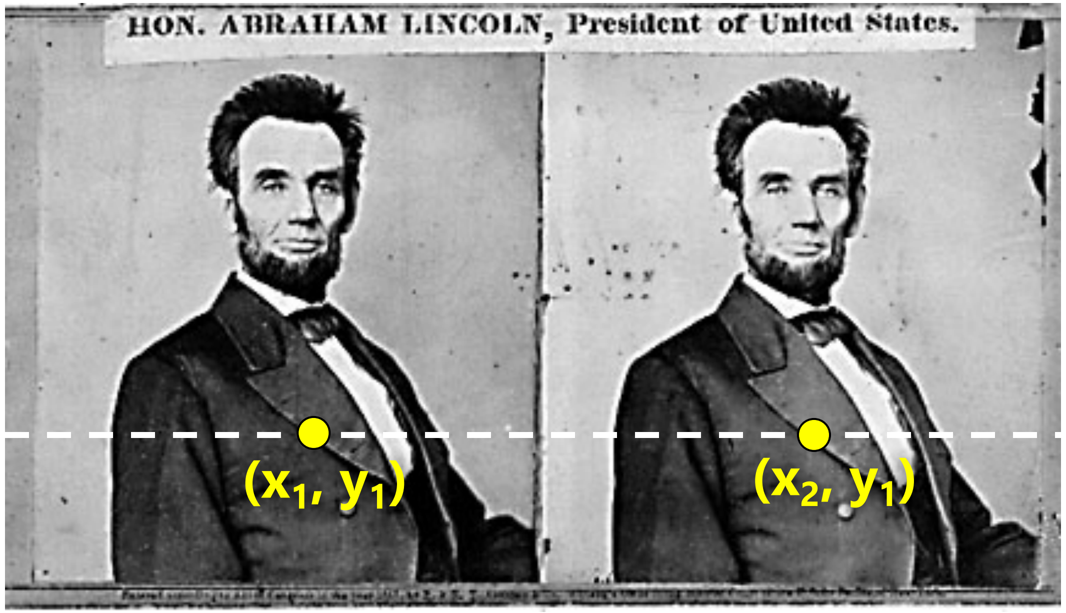
Stereo



- 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

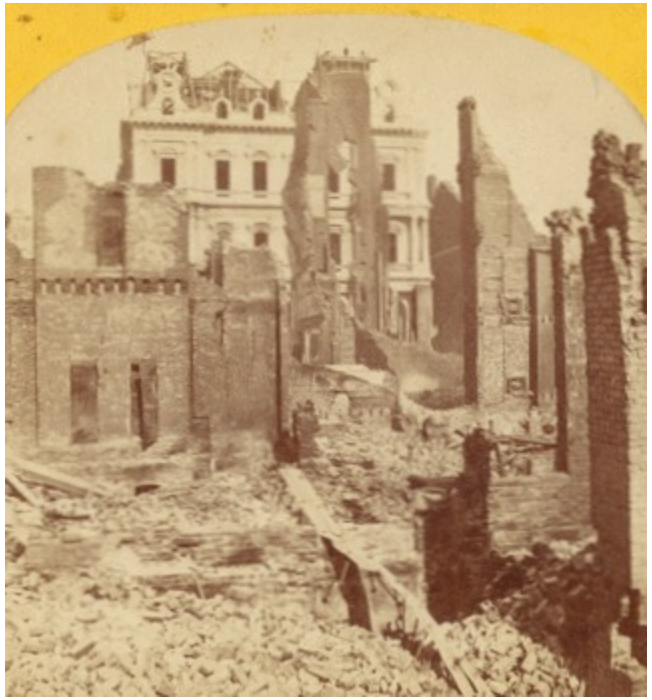
epipolar
lines



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



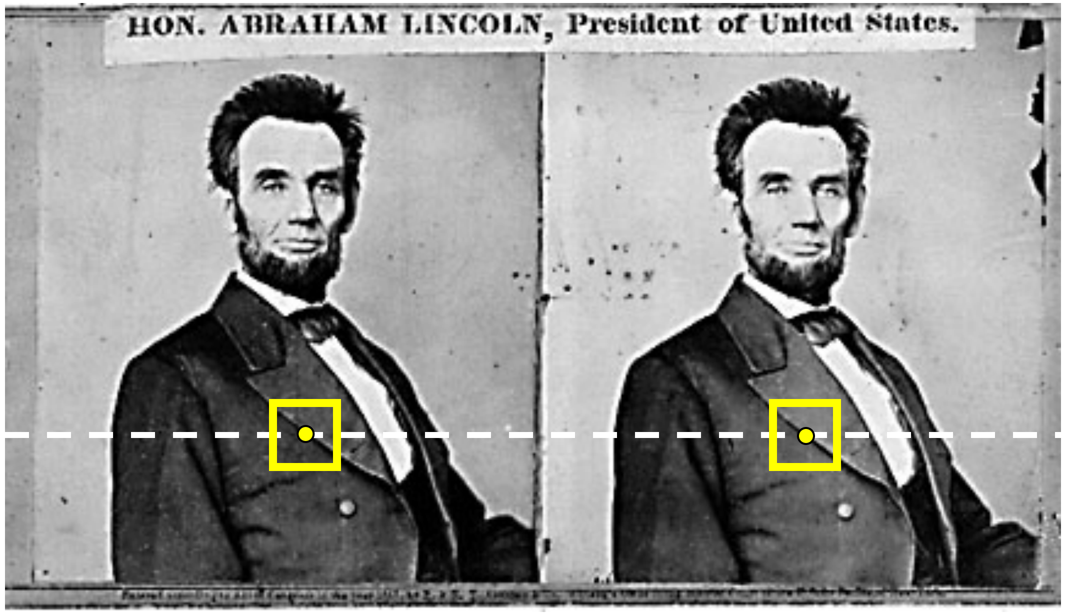
http://stereo.nypl.org/view/41729

(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



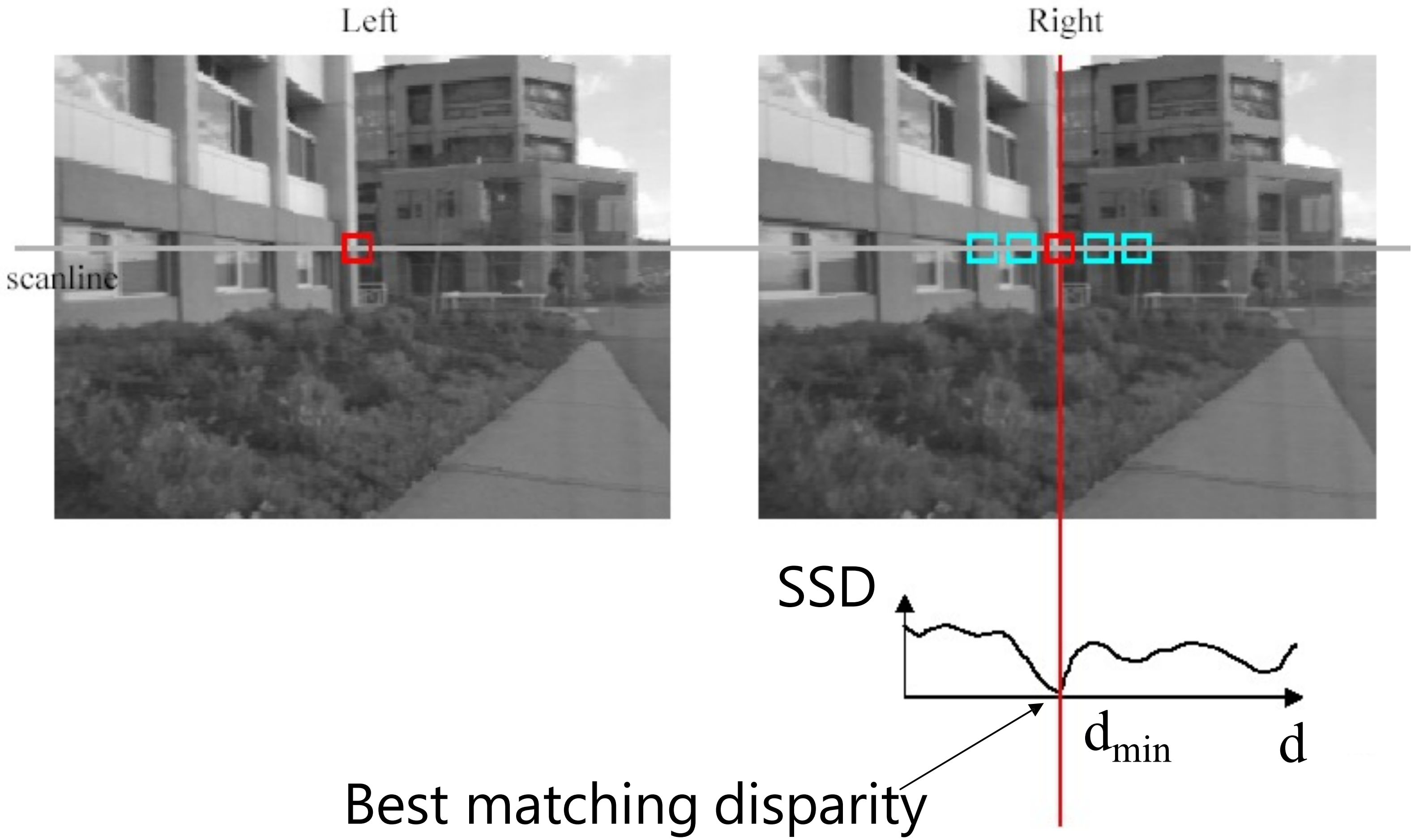
For each epipolar line

For each pixel in the left image

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

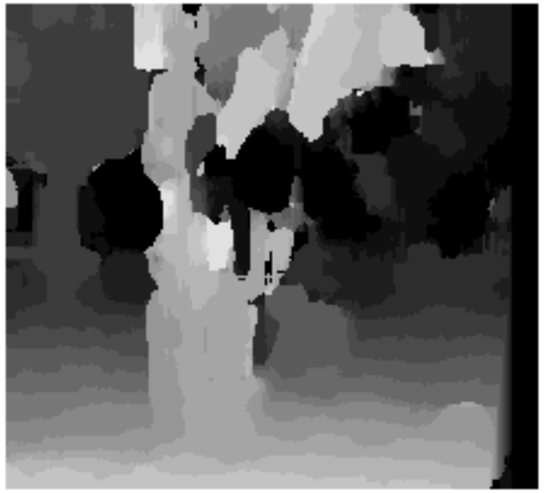
Improvement: match ***windows***

Stereo matching based on SSD



Window size

W = 3



W = 20

Effect of window size

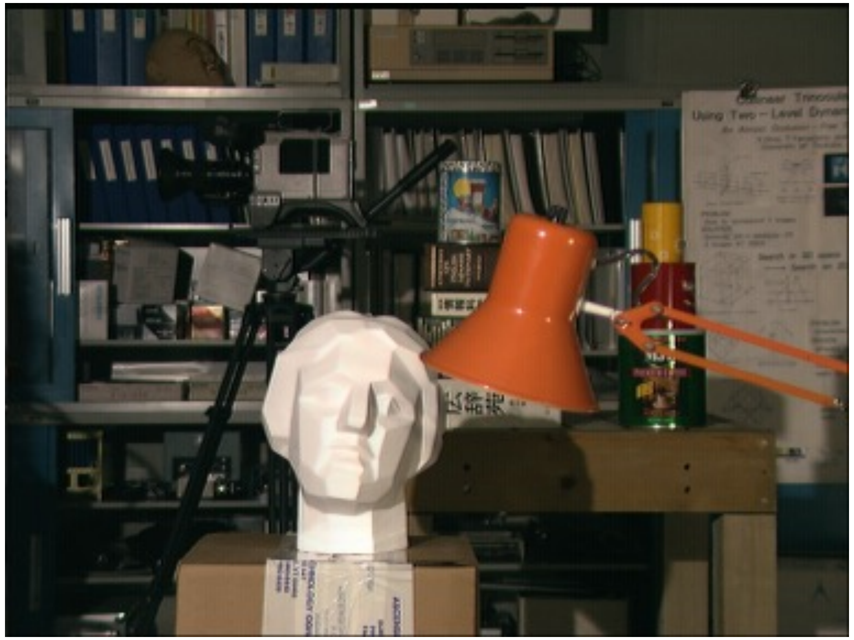
- Smaller window
  - + more detail
  - - more noise
- Larger window
  - + less noise
  - - less detail

Better results with *adaptive window*

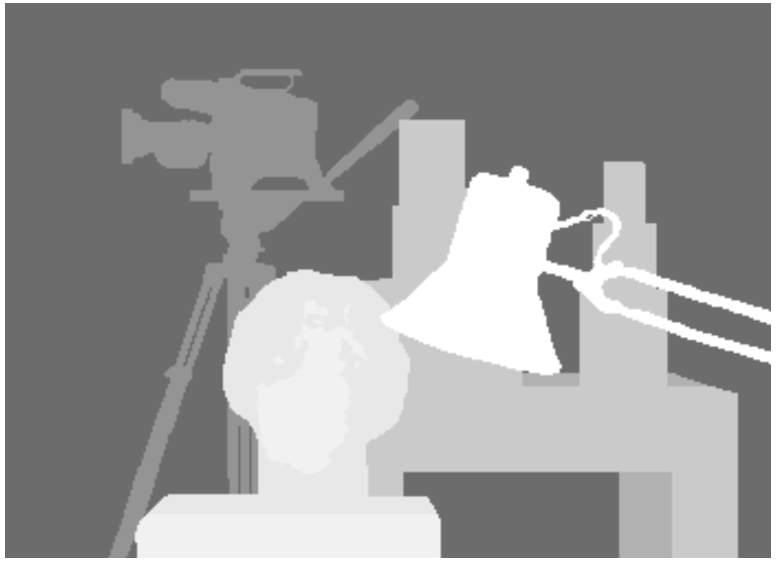
- T. Kanade and M. Okutomi, *A Stereo Matching Algorithm with an Adaptive Window: Theory and Experiment*, ICRA 1991.
- D. Scharstein and R. Szeliski. Stereo matching with nonlinear diffusion. IJCV, July 1998

Stereo results

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

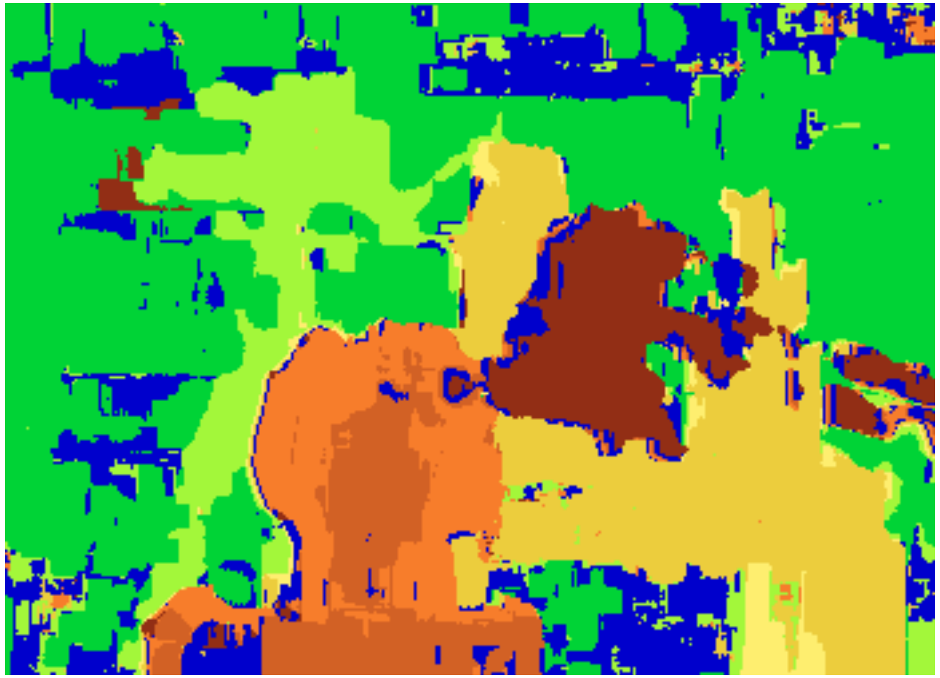


Scene



Ground truth

Results with window search



Window-based matching
(best window size)

Ground truth

Better methods exist...

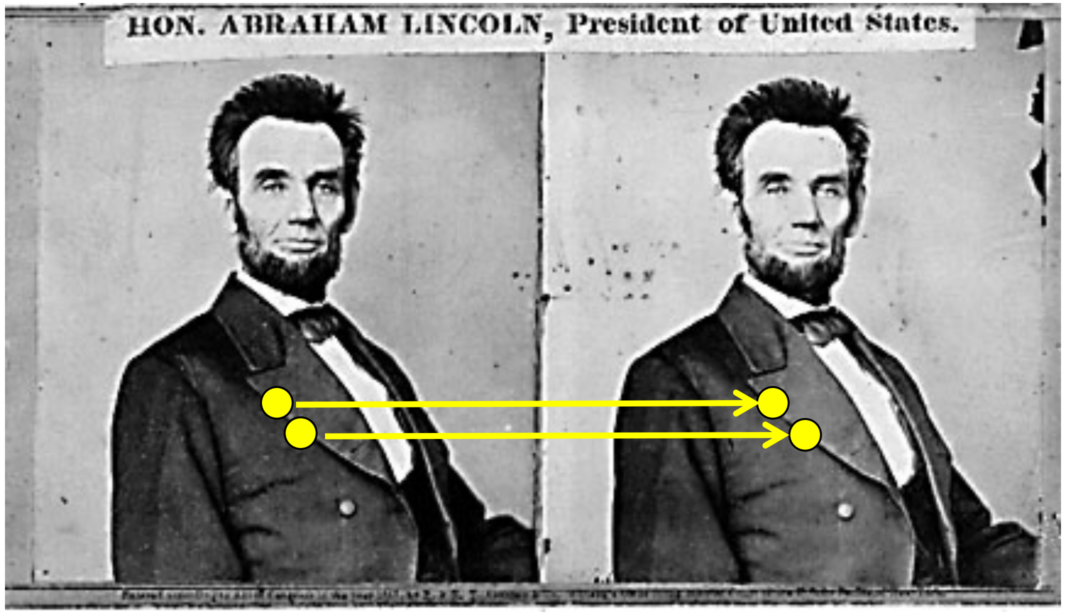
Graph cuts-based method

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

Ground truth

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

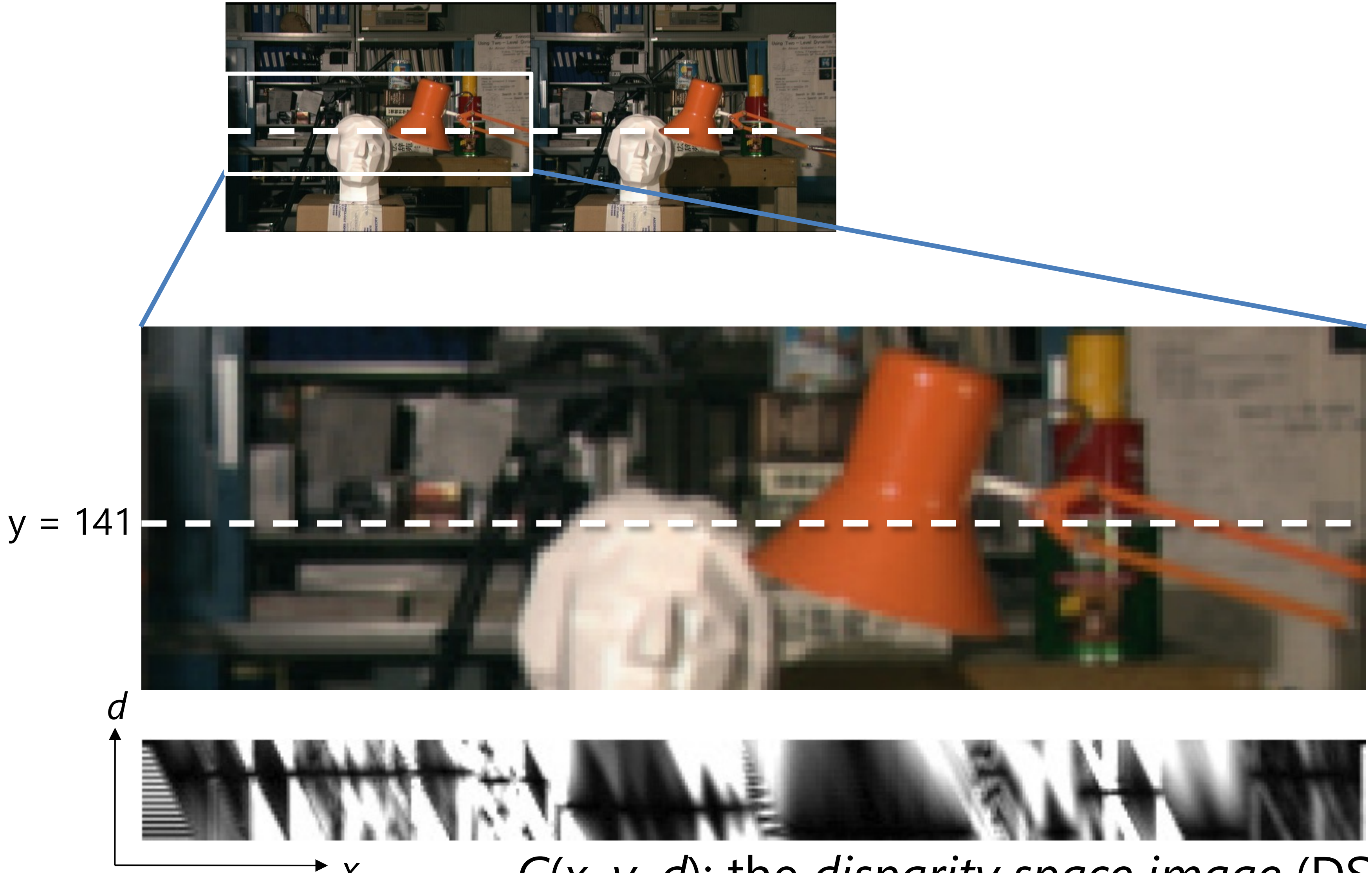
- Find disparity map *d* that minimizes an *energy function* $E(d)$

- 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



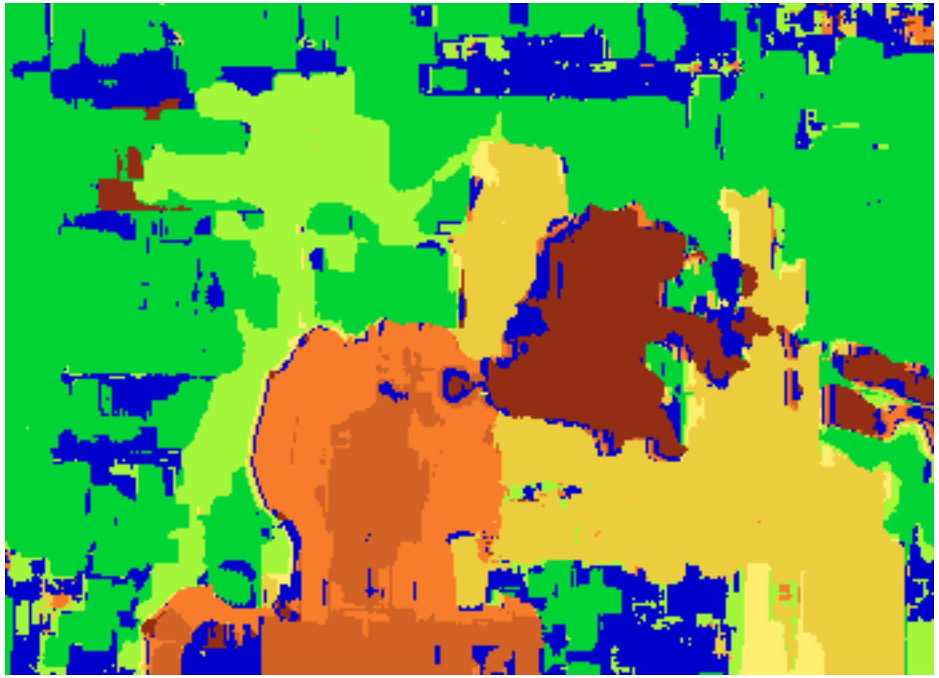
$C(x, y, d)$; the *disparity space image* (DSI)

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

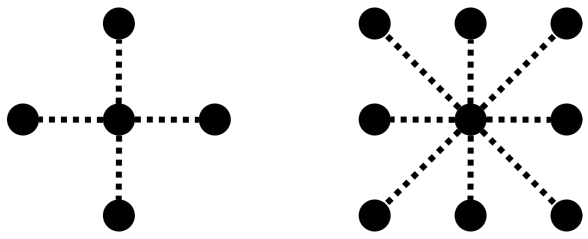
Stereo as energy minimization

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

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

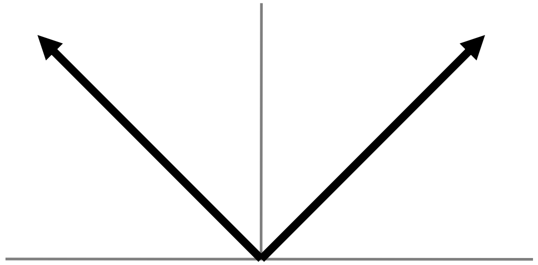
Smoothness cost

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

How do we choose *V*?

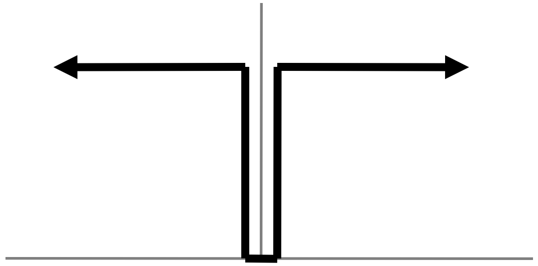
$$V(d_p, d_q) = |d_p - d_q|$$

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

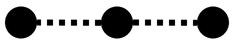
$$E(d) = E_d(d) + \lambda E_s(d)$$

- 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

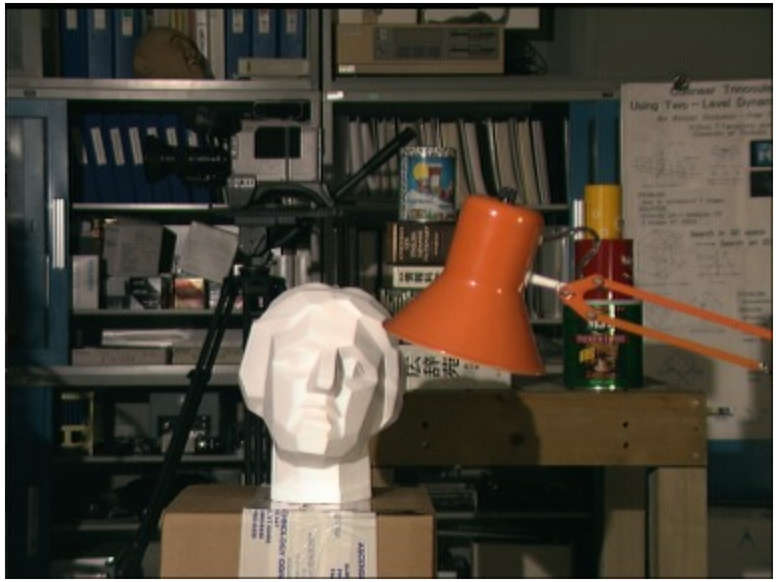
$$E(d) = E_d(d) + \lambda E_s(d)$$

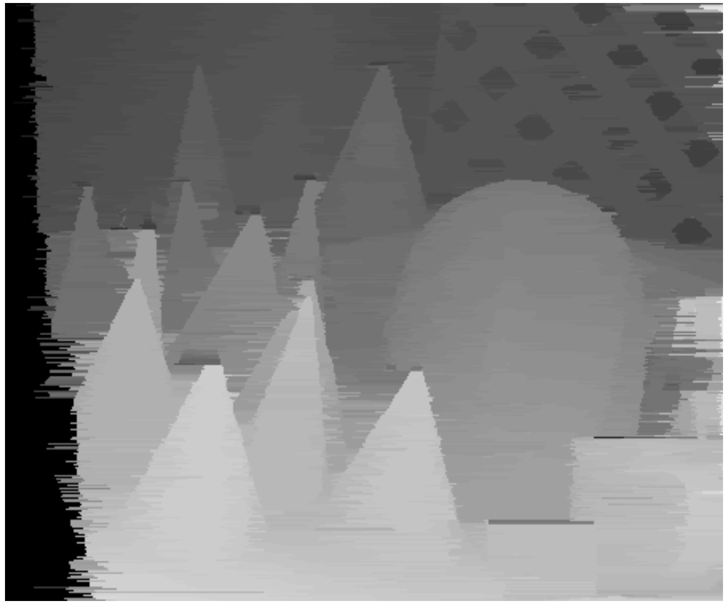
- Can minimize this independently per scanline using dynamic programming (DP) 

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

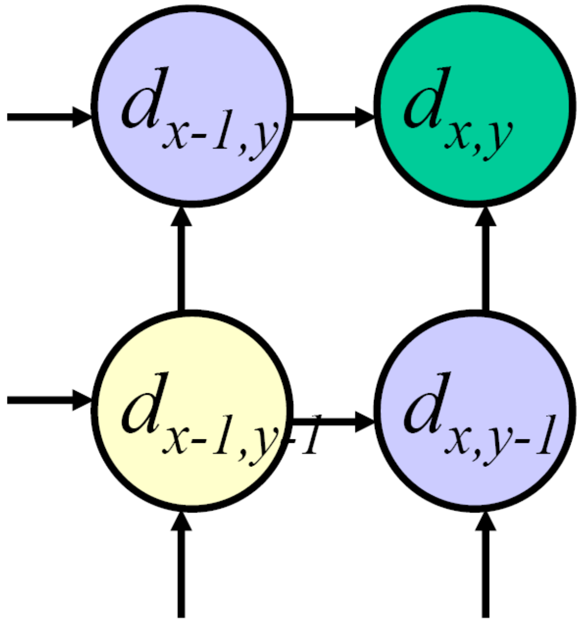
Dynamic Programming





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

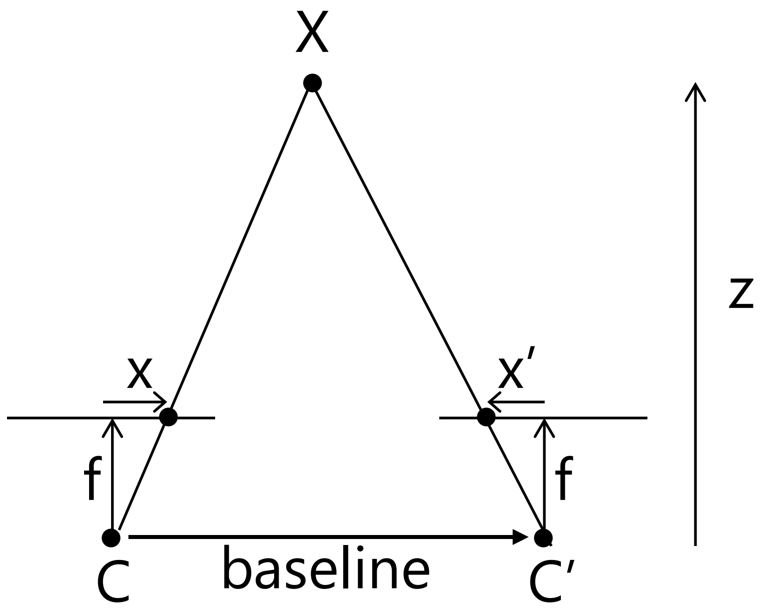
Stereo as a minimization problem

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

- 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



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

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**

Variants of stereo

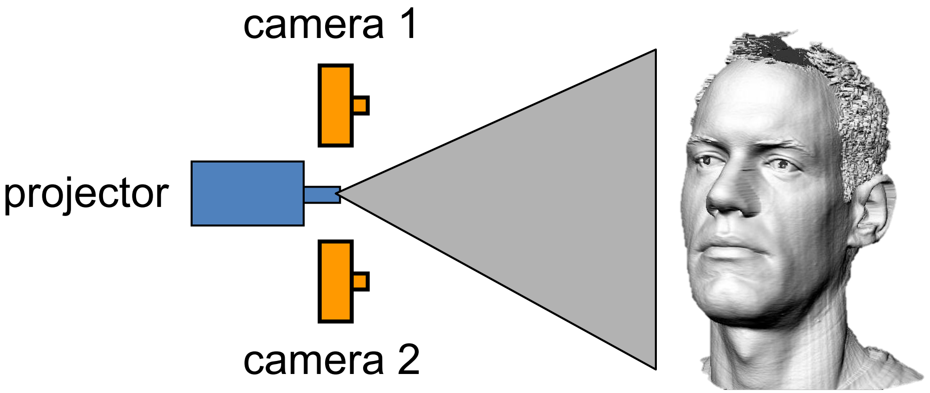
Real-time stereo

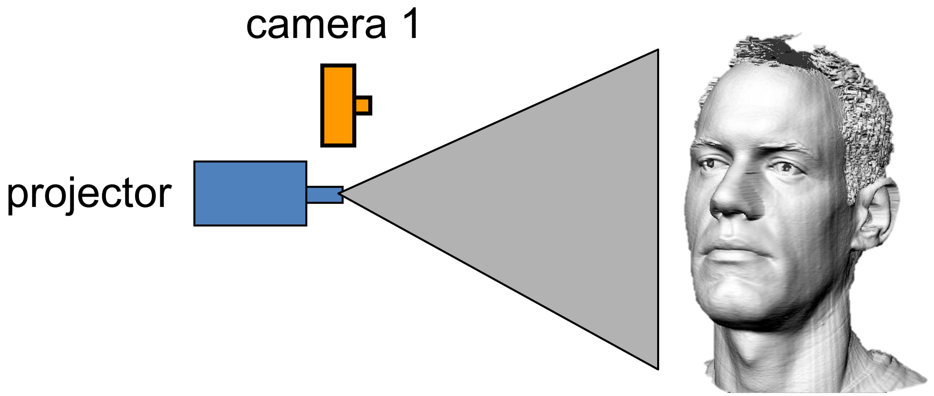
Nomad robot searches for meteorites in Antartica

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

Active stereo with structured light

Li Zhang's one-shot stereo



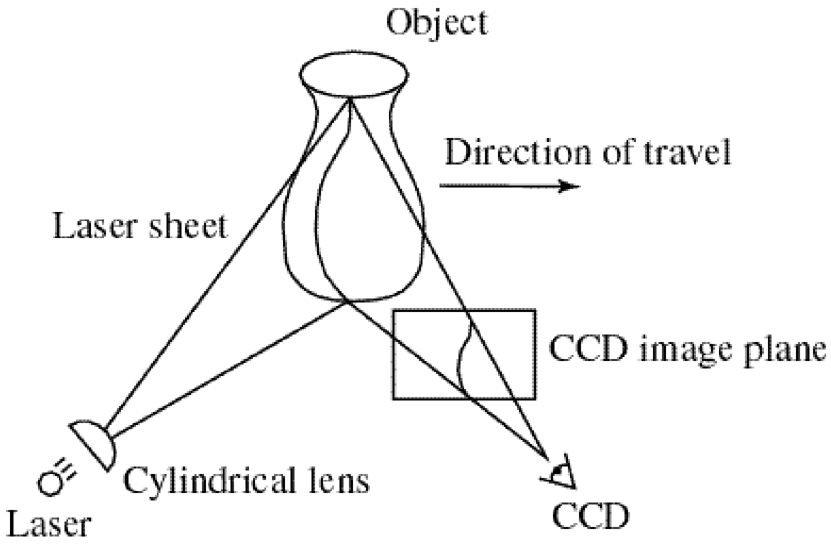


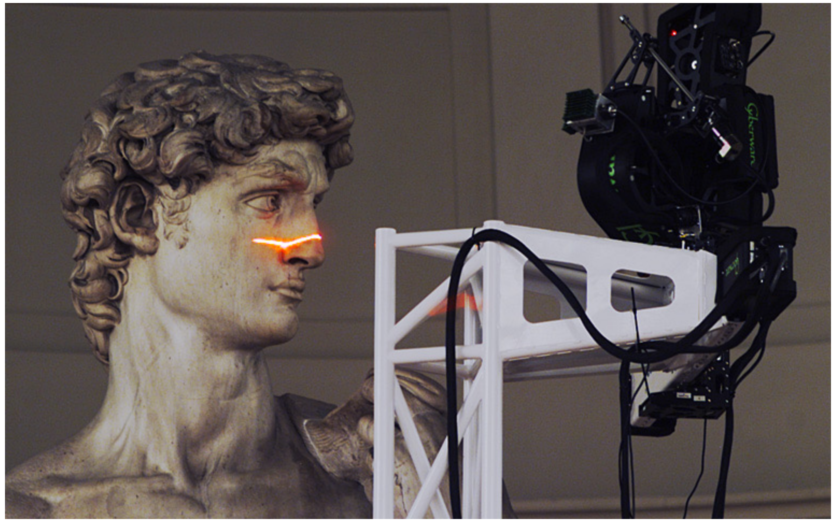
- Project "structured" light patterns onto the object
  - simplifies the correspondence problem
  - basis for active depth sensors, such as Kinect and iPhone X (using IR)

Active stereo with structured light

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

Laser scanning





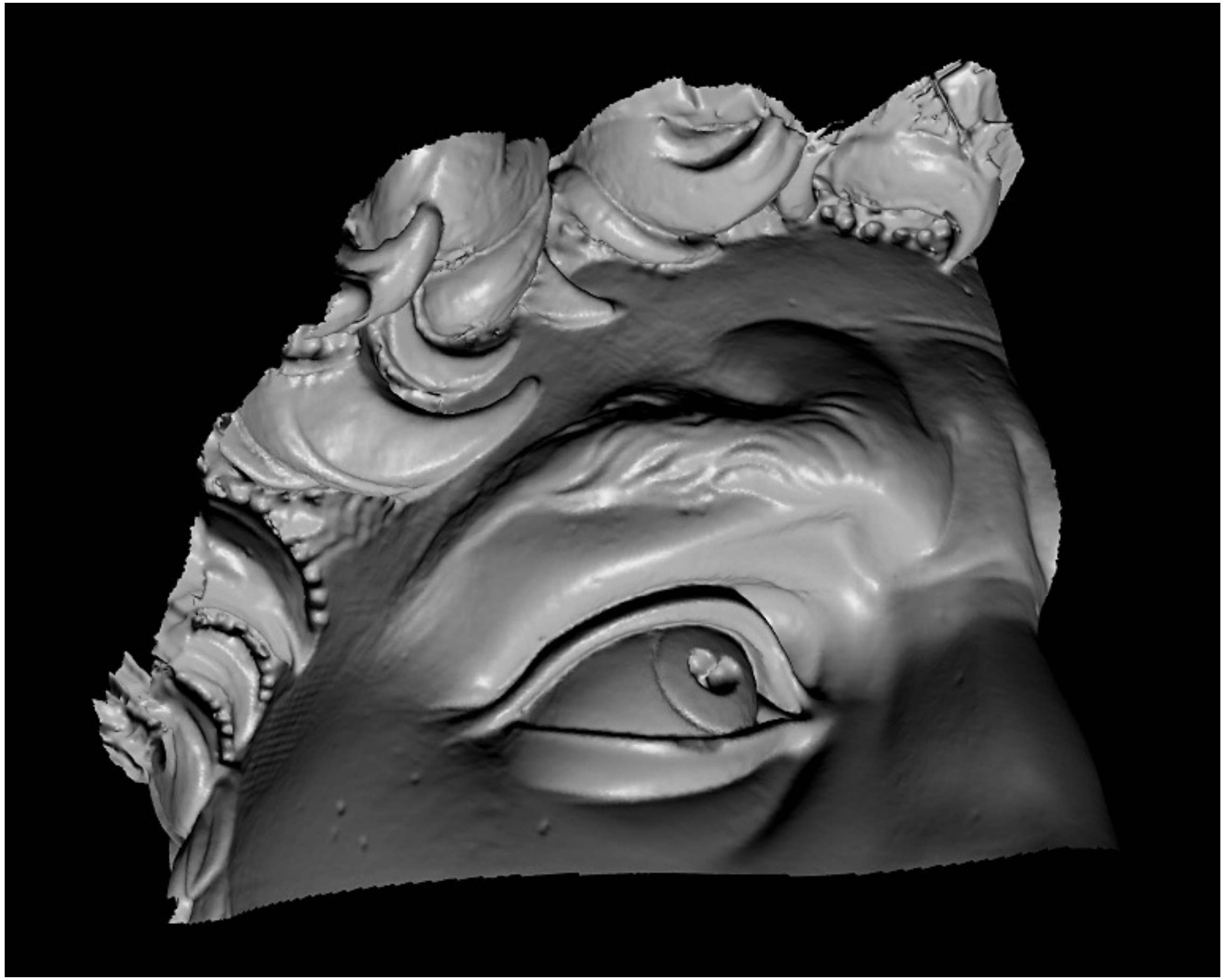
Digital Michelangelo Project
http://graphics.stanford.edu/projects/mich/

- 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

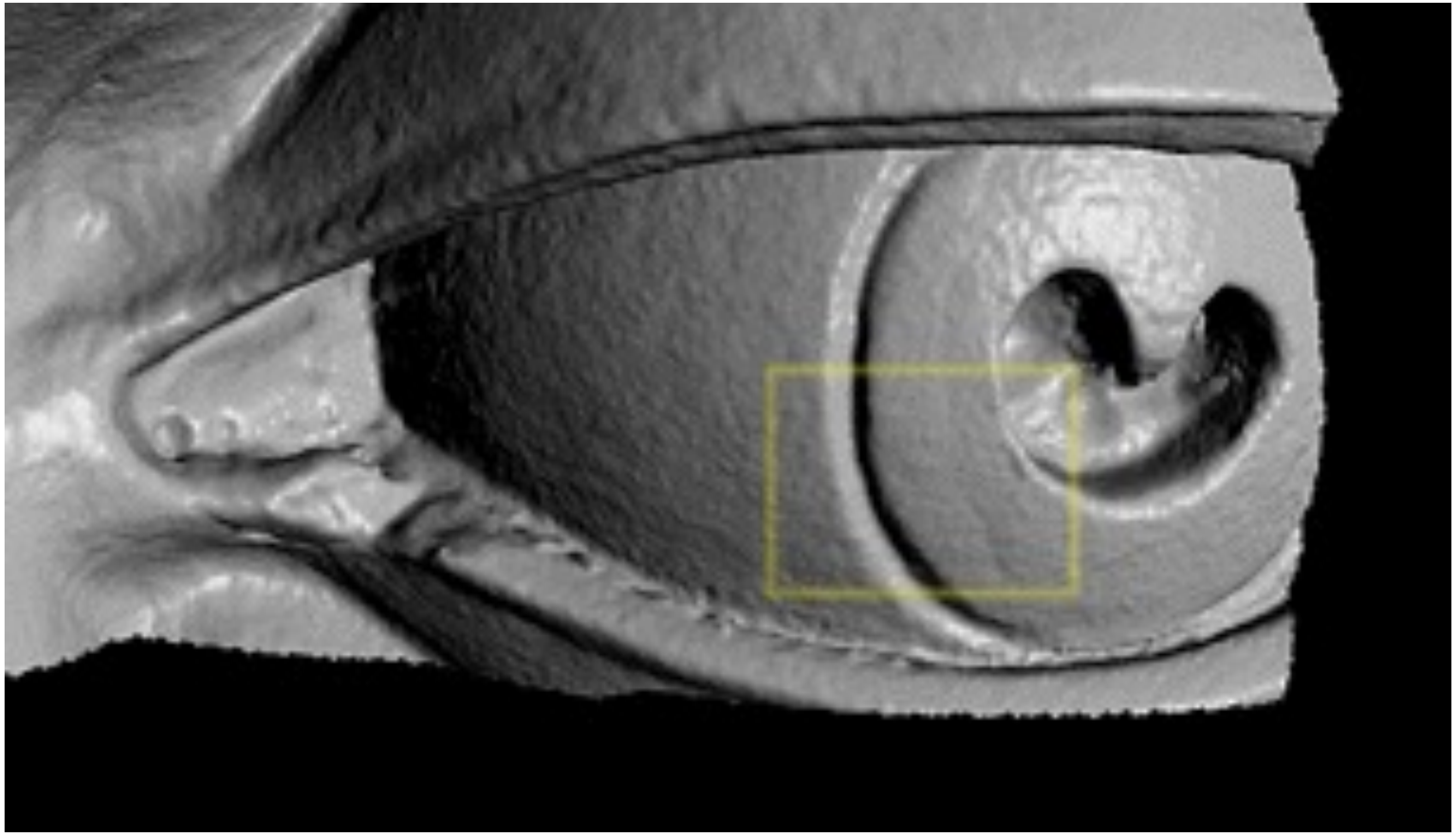
The Digital Michelangelo Project, Levoy et al.

Laser scanned models



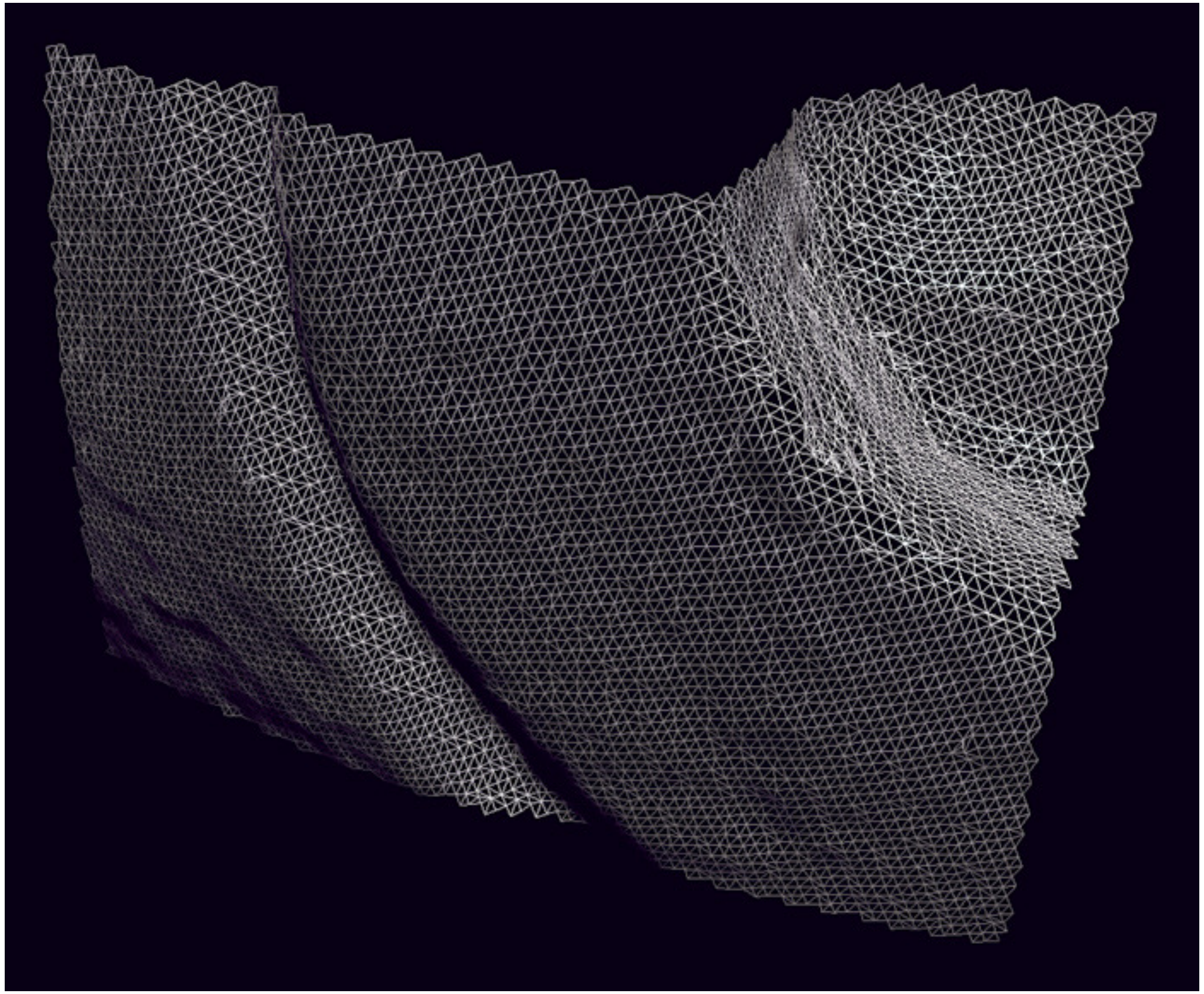
The Digital Michelangelo Project, Levoy et al.

Laser scanned models



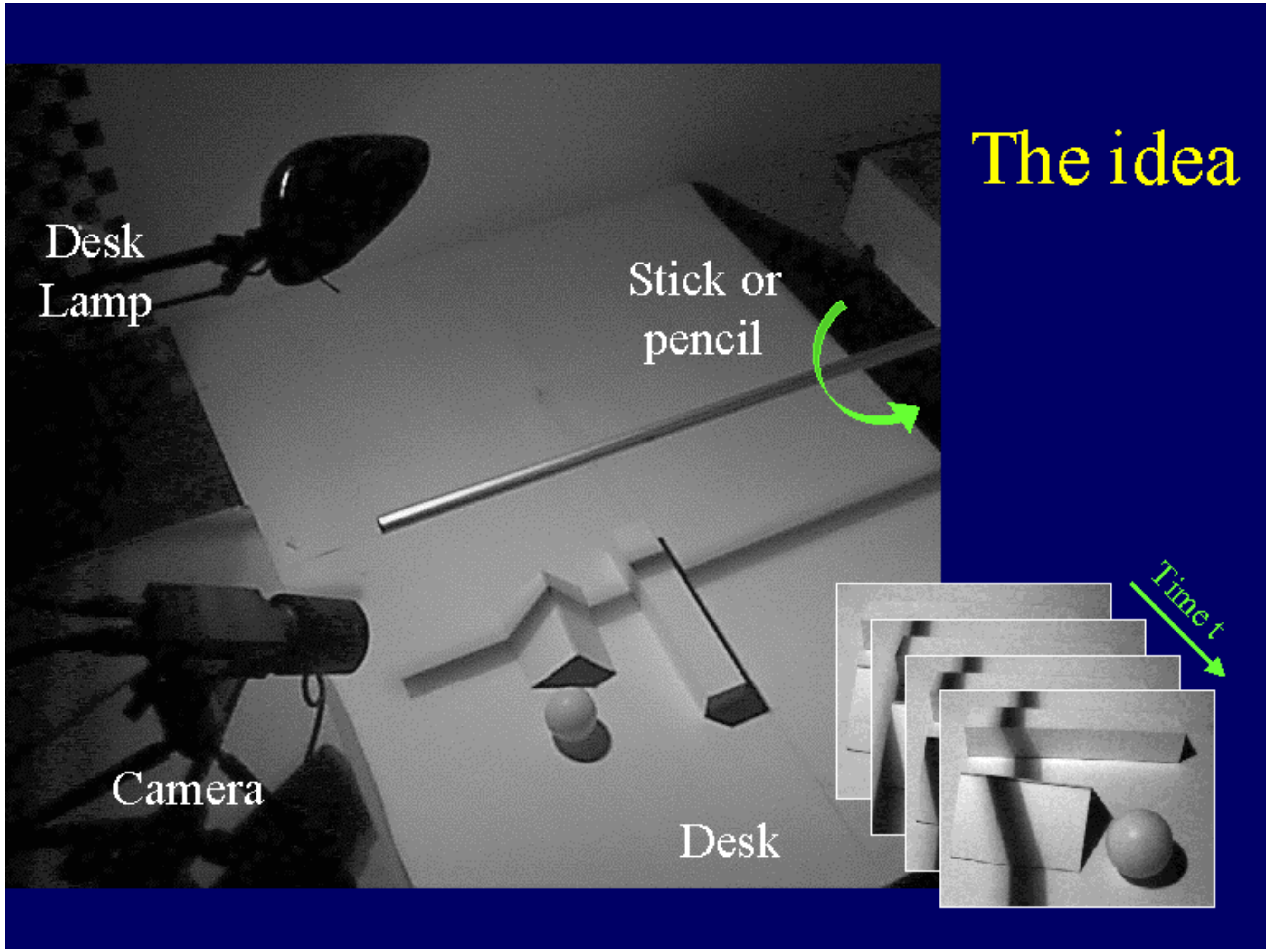
The Digital Michelangelo Project, Levoy et al.

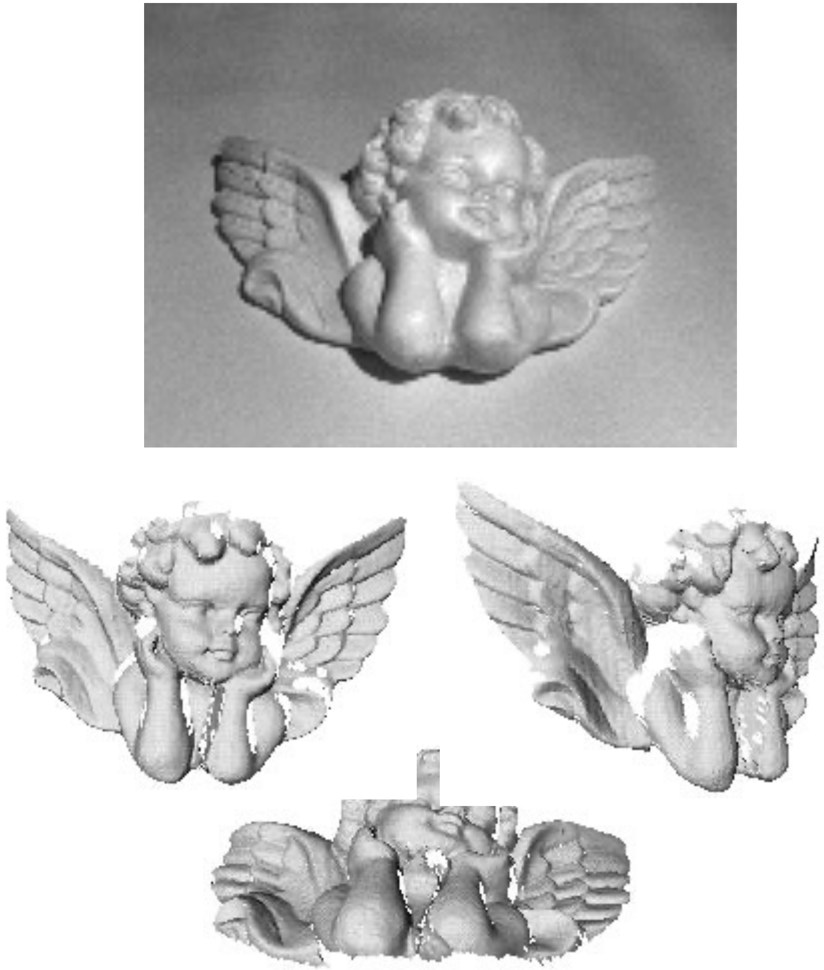
Laser scanned models



The Digital Michelangelo Project, Levoy et al.

3D Photography on your Desk





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

Questions?