

Ninio, J. and Stevens, K. A. (2000) Variations on the Hermann grid: an extinction illusion. *Perception*, 29, 1209-1217.

Variations on the Hermann grid: an extinction illusion

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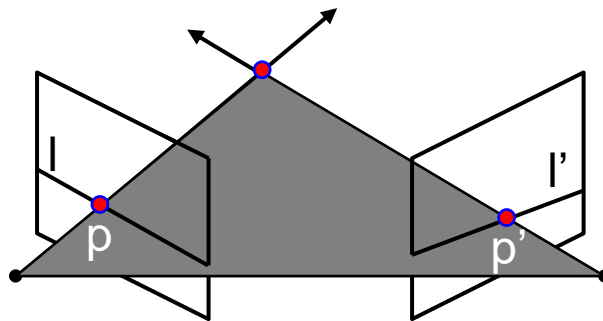
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Abstract. When the white disks in a scintillating grid are reduced in size, and outlined in black, they tend to disappear. One sees only a few of them at a time, in clusters which move erratically on the page. Where they are not seen, the grey alleys seem to be continuous, generating grey crossings that are not actually present. Some black sparkling can be seen at those crossings where no disk is seen. The illusion also works in reverse contrast.

The Hermann grid (Brewster 1844; Hermann 1870) is a robust illusion. It is classically presented as a two-dimensional array of black squares, separated by rectilinear alleys. It is thought to be caused by processes of local brightness computation in arrays of

Fundamental matrix

Let p be a point in left image, p' in right image



Epipolar relation

- p maps to epipolar line l'
- p' maps to epipolar line l

Epipolar mapping described by a 3x3 matrix F

$$p' F p = 0$$

Fundamental matrix

This matrix F is called

- the “Essential Matrix”
 - when image intrinsic parameters are known
- the “Fundamental Matrix”
 - more generally (uncalibrated case)

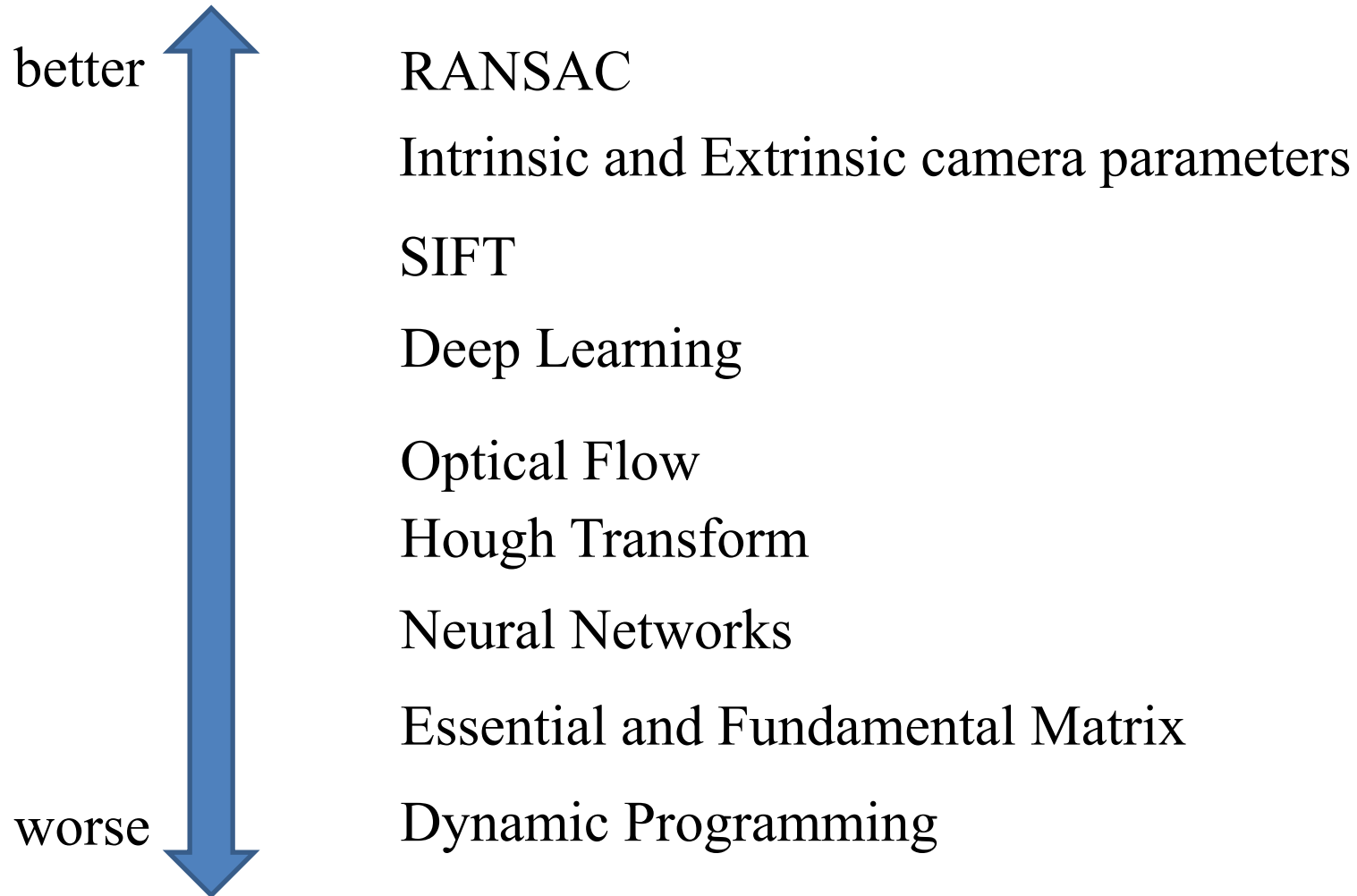
Can solve for F from point correspondences

- Each (p, p') pair gives one linear equation in entries of F

$$p' F p = 0$$

- F has 9 entries, but really only 7 or 8 degrees of freedom.
- With 8 points it is simple to solve for F , but it is also possible with 7. See [Marc Pollefev's notes](#) for a nice tutorial

The scale of algorithm / concept name quality



Today's lecture

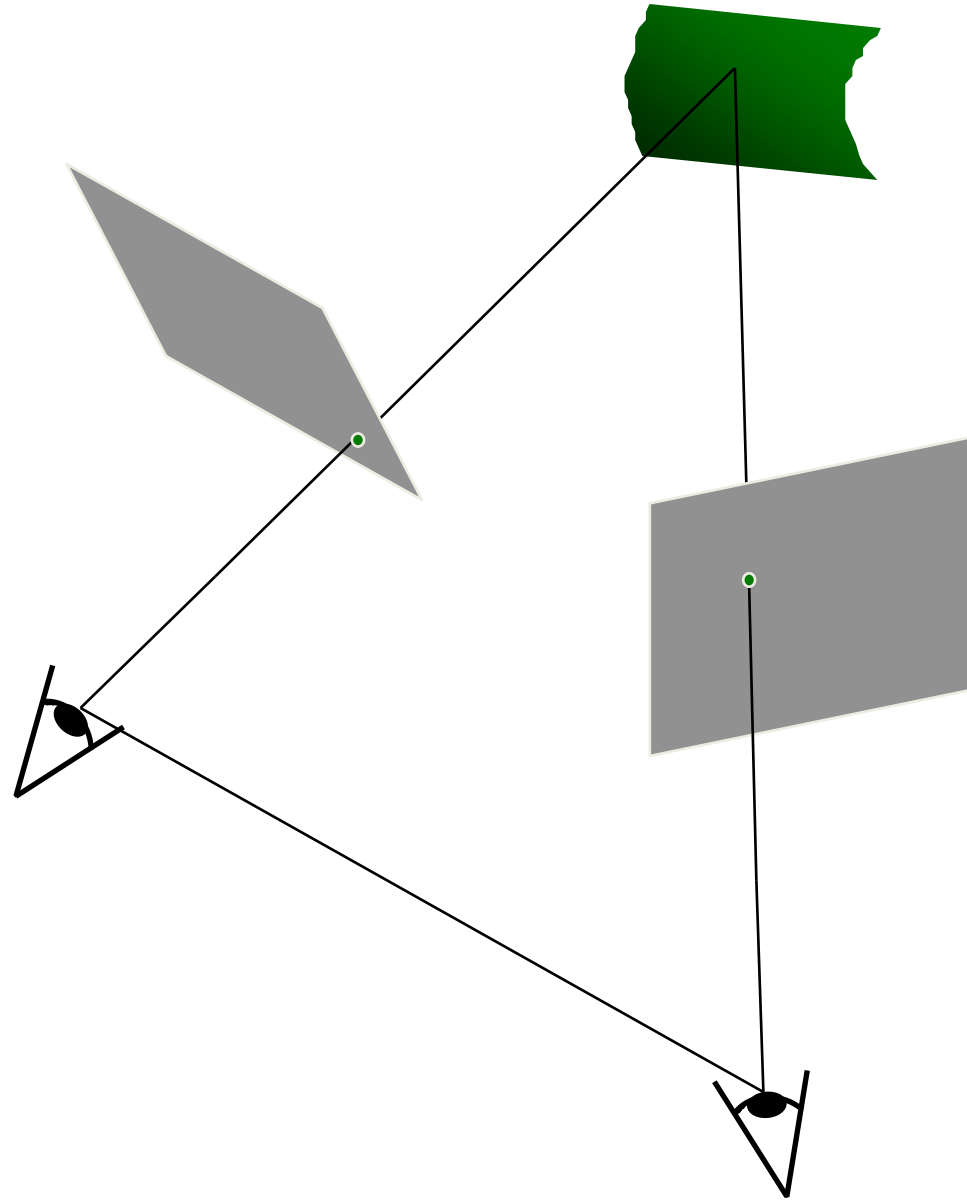
- Stereo Matching (Sparse correspondence to Dense Correspondence)

- Next lecture: Optical Flow (Dense motion estimation)

Stereo Matching

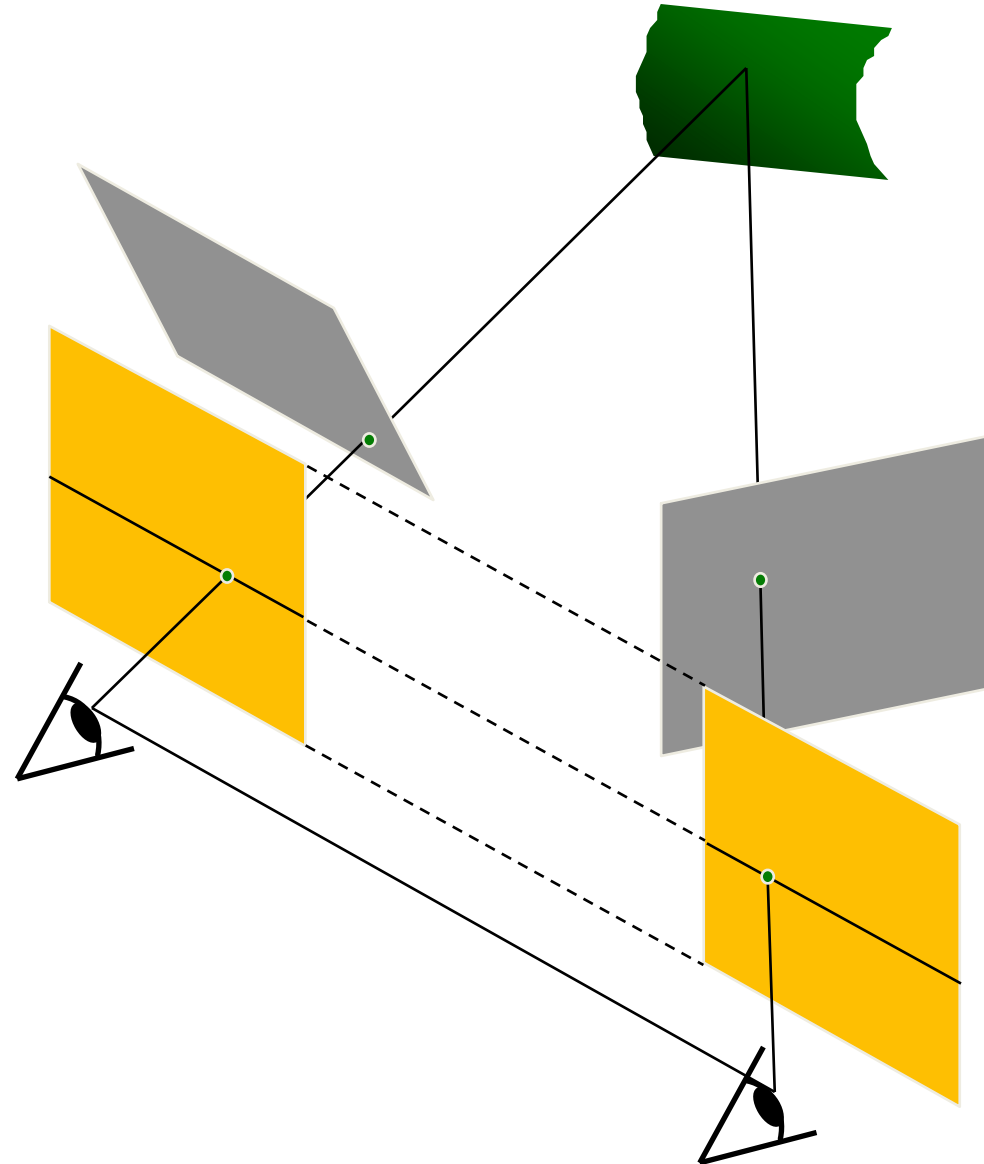


Stereo image rectification

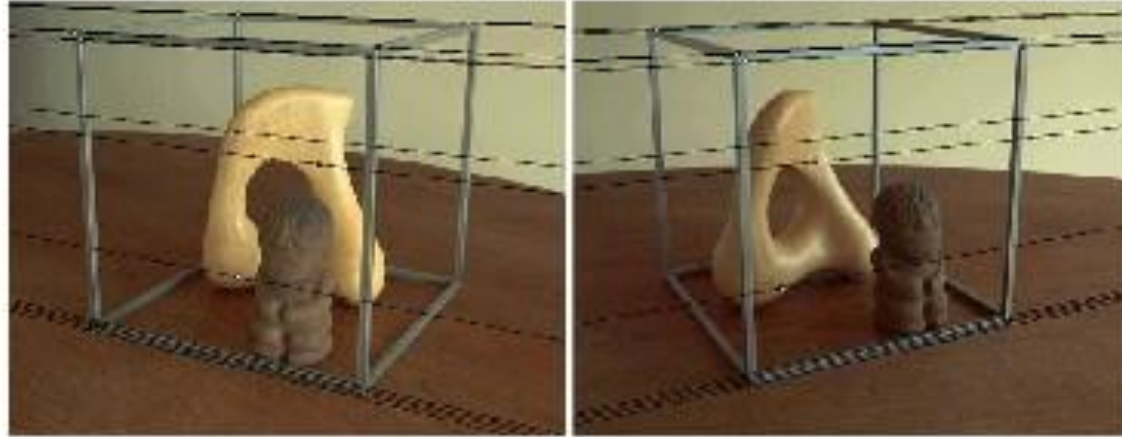


Stereo image rectification

- Reproject image planes onto a common plane parallel to the line between camera centers
- Pixel motion is horizontal after this transformation
- Two homographies (3x3 transform), one for each input image reprojection
- C. Loop and Z. Zhang. [Computing Rectifying Homographies for Stereo Vision](#). IEEE Conf. Computer Vision and Pattern Recognition, 1999.



Rectification example



The correspondence problem

- Epipolar geometry constrains our search, but we still have a difficult correspondence problem.

Fundamental Matrix + Sparse correspondence

Photo Tourism

Exploring photo collections in 3D

Noah Snavely Steven M. Seitz Richard Szeliski
University of Washington *Microsoft Research*

SIGGRAPH 2006

Fundamental Matrix + Dense correspondence

The Visual Turing Test for Scene Reconstruction Supplementary Video

Qi Shan⁺ Riley Adams⁺ Brian Curless⁺
Yasutaka Furukawa^{*} Steve Seitz⁺⁺

⁺University of Washington ^{*}Google

3DV 2013

SIFT + Fundamental Matrix + RANSAC

Despite their scale invariance and robustness to appearance changes, SIFT features are *local* and do not contain any global information about the image or about the location of other features in the image. Thus feature matching based on SIFT features is still prone to errors. However, since we assume that we are dealing with rigid scenes, there are strong geometric constraints on the locations of the matching features and these constraints can be used to clean up the matches. In particular, when a rigid scene is imaged by two pinhole cameras, there exists a 3×3 matrix F , the *Fundamental matrix*, such that corresponding points x_{ij} and x_{ik} (represented in homogeneous coordinates) in two images j and k satisfy¹⁰:

$$x_{ij}^\top F x_{ij} = 0. \quad (3)$$

A common way to impose this constraint is to use a greedy randomized algorithm to generate suitably chosen random estimates of F and choose the one that has the largest support among the matches, i.e., the one for which the most matches satisfy (3). This algorithm is called Random Sample Consensus (RANSAC)⁶ and is used in many computer vision problems.

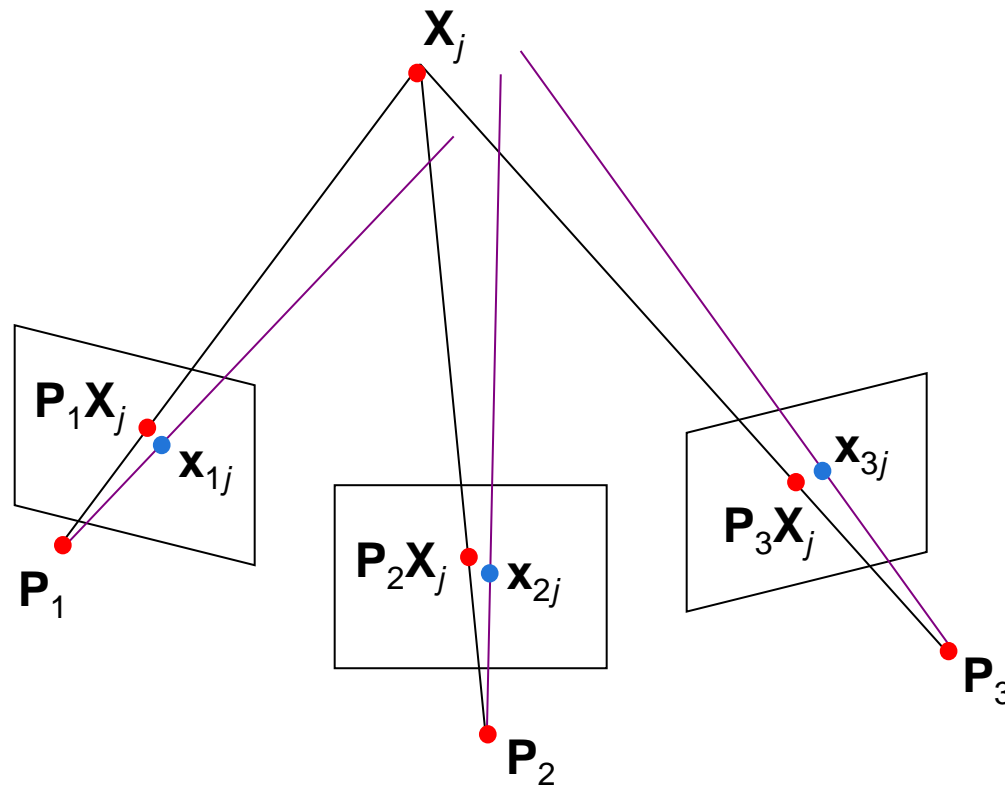
Building Rome in a Day

By Sameer Agarwal, Yasutaka Furukawa, Noah Snavely, Ian Simon, Brian Curless, Steven M. Seitz, Richard Szeliski
Communications of the ACM, Vol. 54 No. 10, Pages 105-112

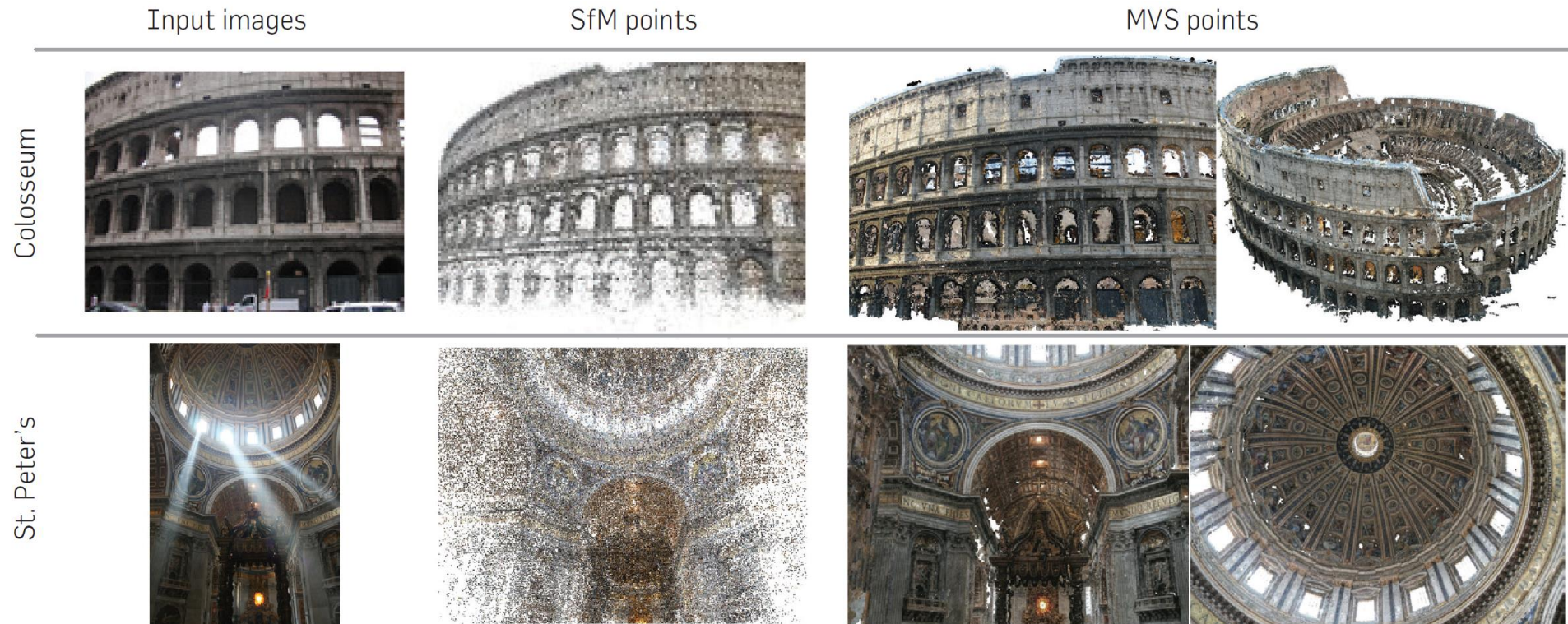
Bundle adjustment

- Non-linear method for refining structure and motion
- Minimizing reprojection error

$$E(\mathbf{P}, \mathbf{X}) = \sum_{i=1}^m \sum_{j=1}^n D(\mathbf{x}_{ij}, \mathbf{P}_i \mathbf{X}_j)^2$$



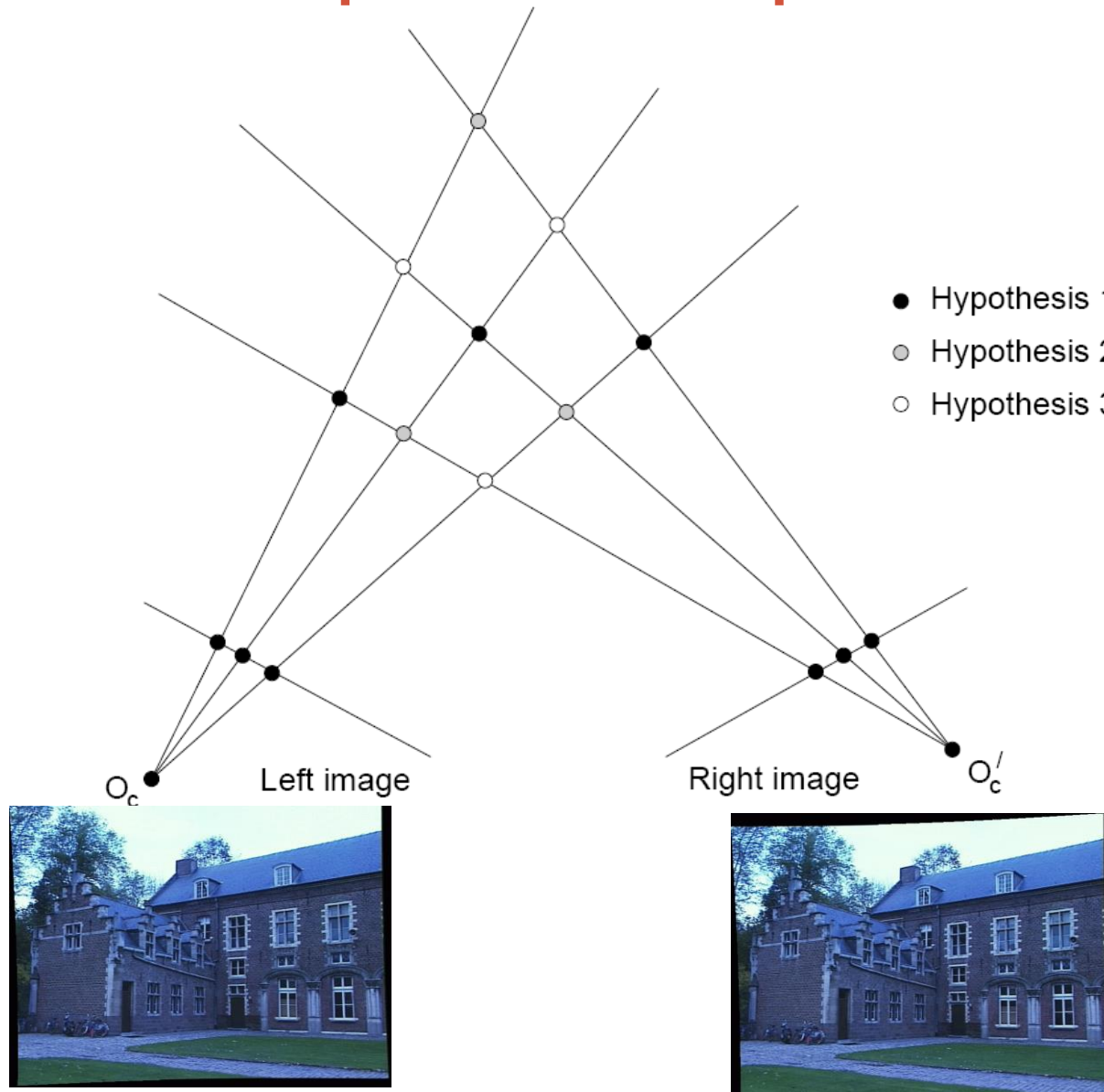
Sparse to Dense Correspondence



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Correspondence problem



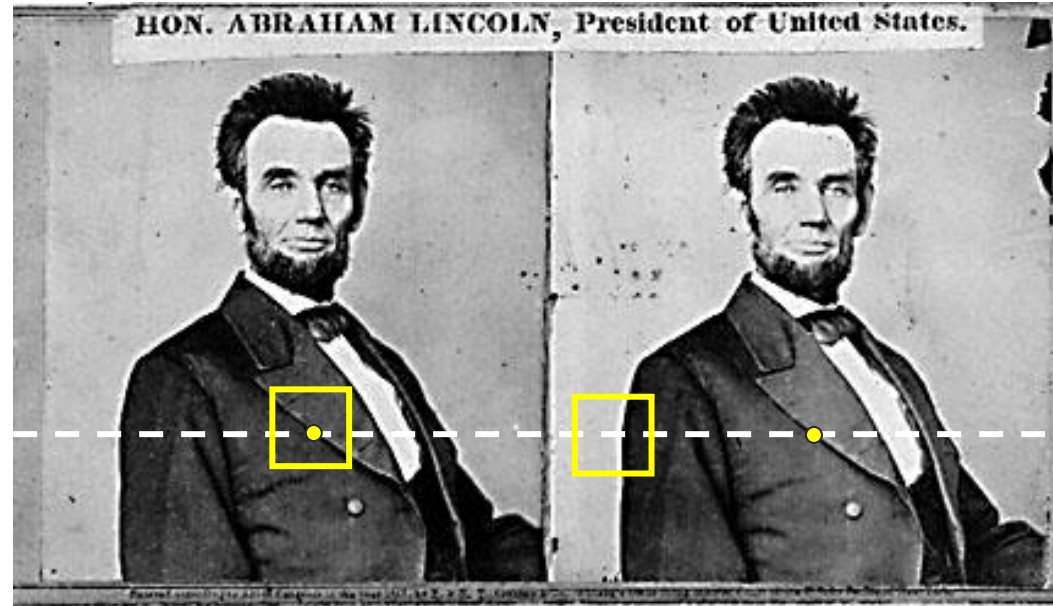
Multiple match hypotheses satisfy epipolar constraint, but which is correct?

Figure from Gee & Cipolla 1999

Correspondence problem

- Beyond the hard constraint of epipolar geometry, there are “soft” constraints to help identify corresponding points
 - Similarity
 - Uniqueness
 - Ordering
 - Disparity gradient
- To find matches in the image pair, we will assume
 - Most scene points visible from both views
 - Image regions for the matches are similar in appearance

Dense correspondence search

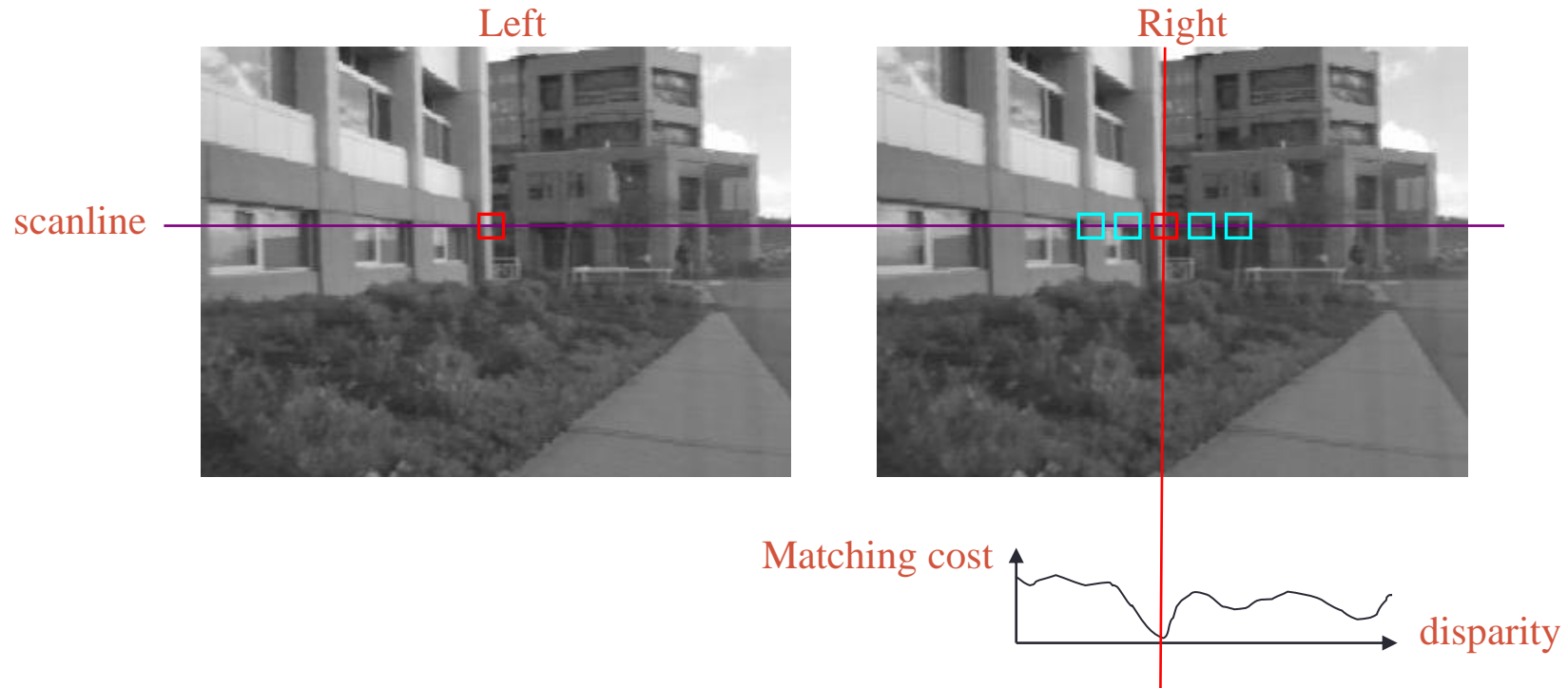


For each epipolar line

For each pixel / window in the left image

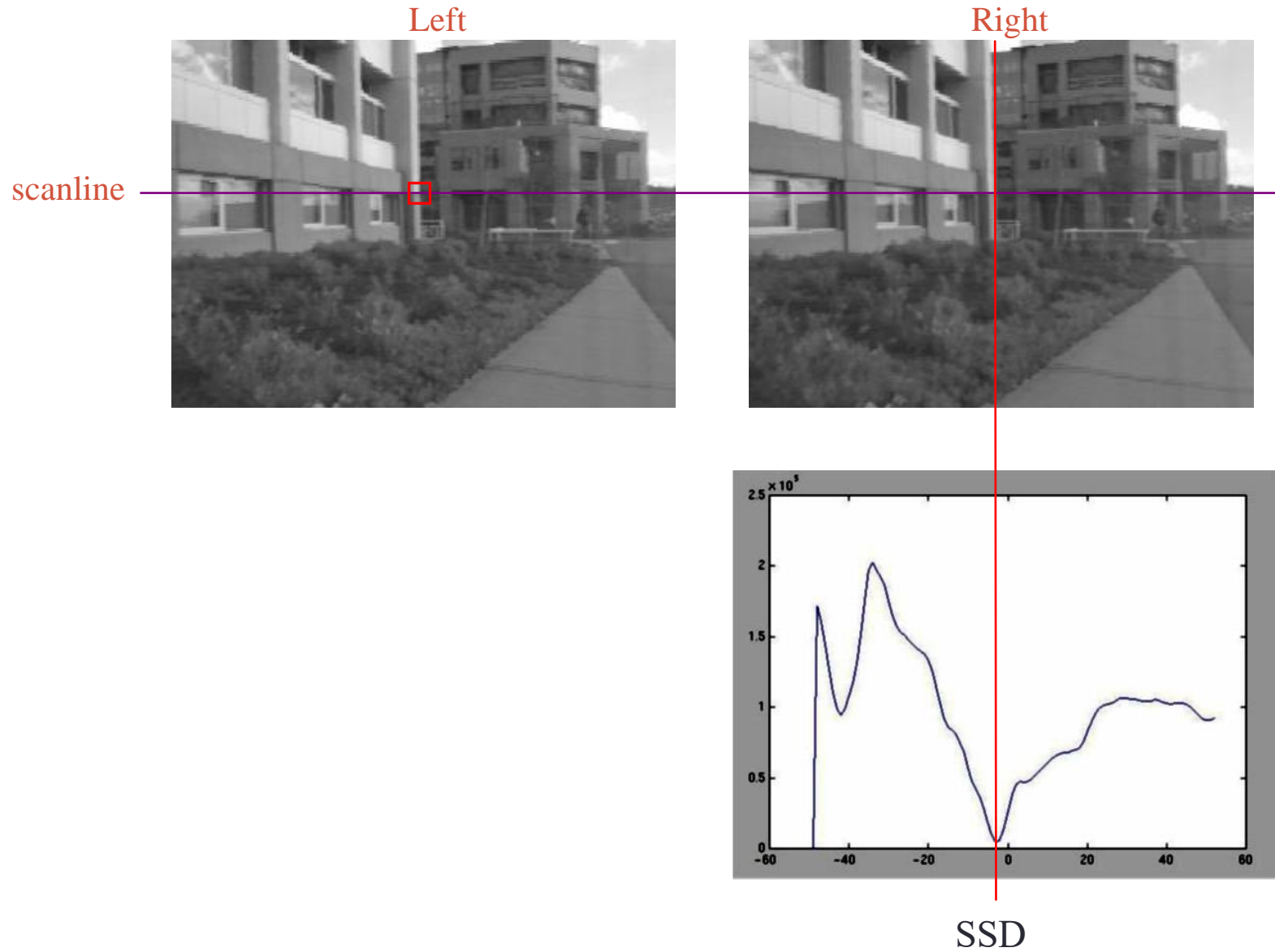
- compare with every pixel / window on same epipolar line in right image
- pick position with minimum match cost (e.g., SSD, normalized correlation)

Correspondence search with similarity constraint

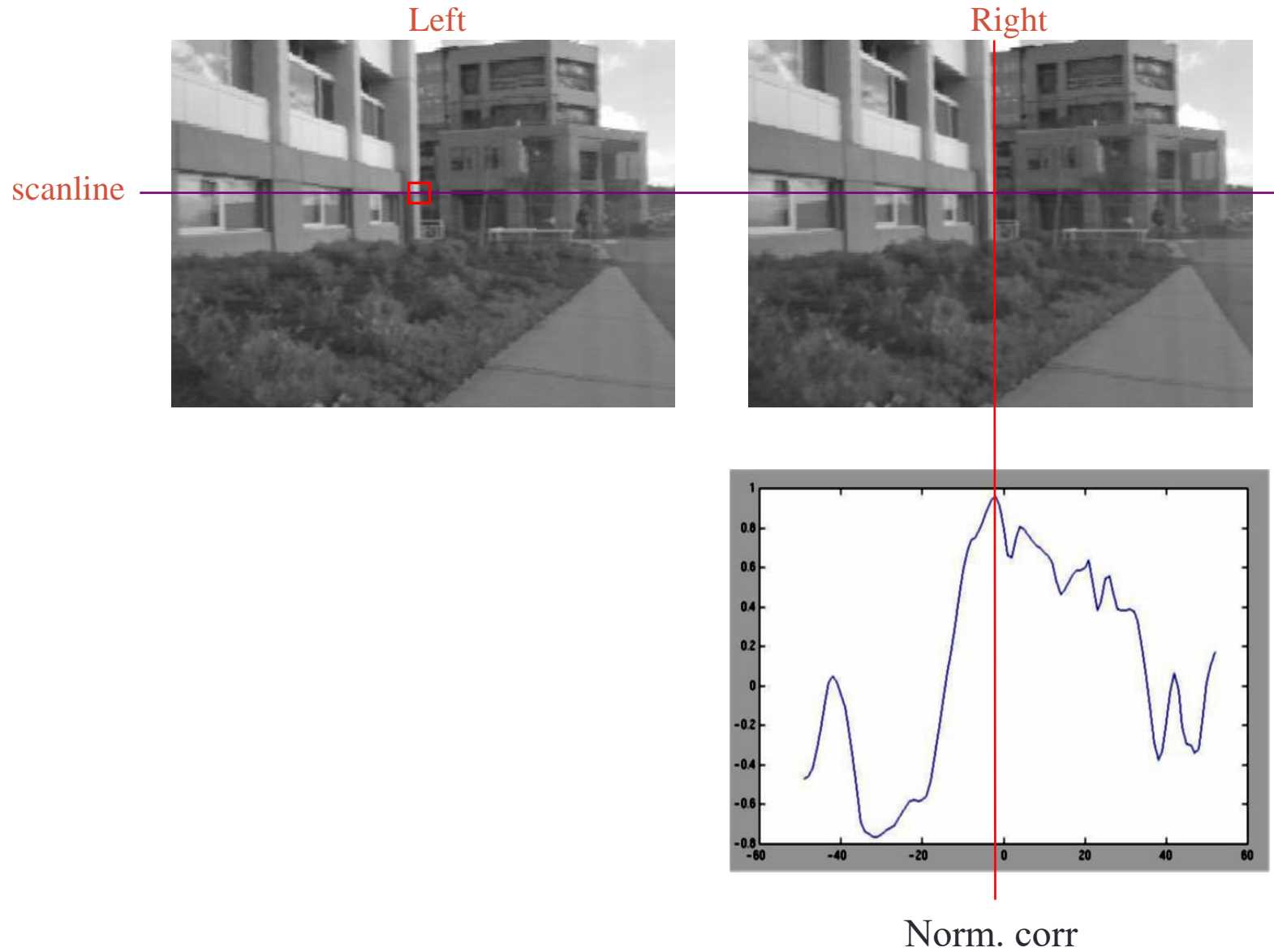


- Slide a window along the right scanline and compare contents of that window with the reference window in the left image
- Matching cost: SSD or normalized correlation

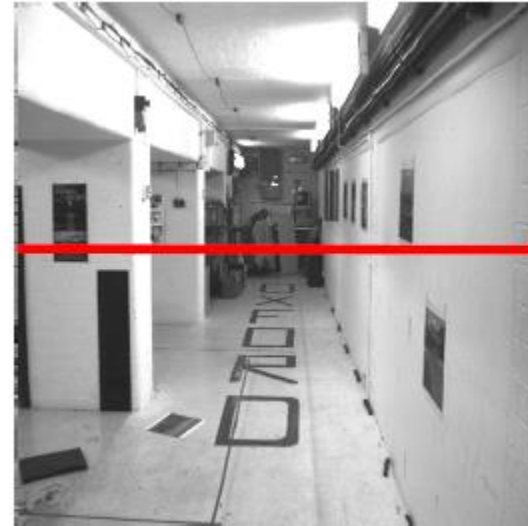
Correspondence search with similarity constraint



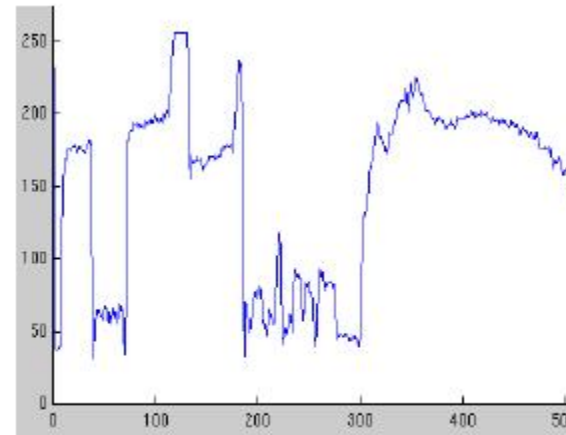
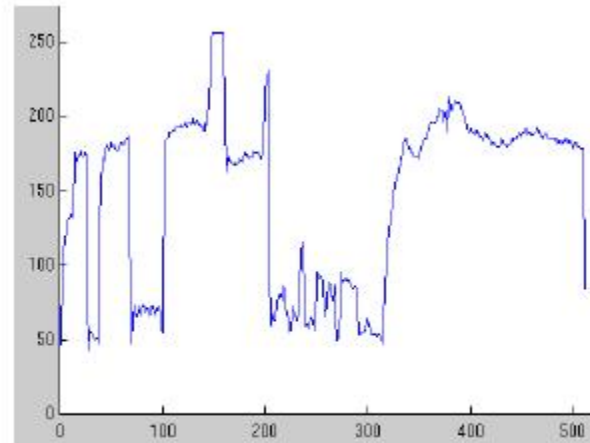
Correspondence search with similarity constraint



Correspondence problem

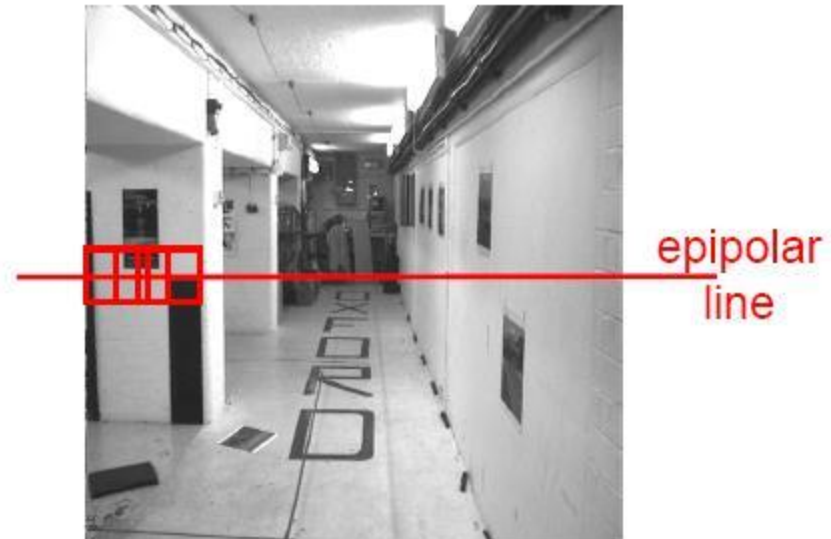


Intensity profiles



- Clear correspondence between intensities, but also noise and ambiguity

Correspondence problem



Neighborhoods of corresponding points are similar in intensity patterns.

Correlation-based window matching



left image band (x)

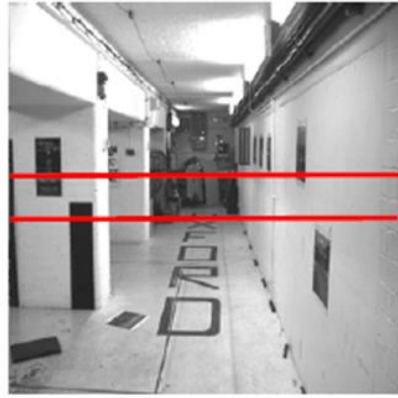
Correlation-based window matching



left image band (x)

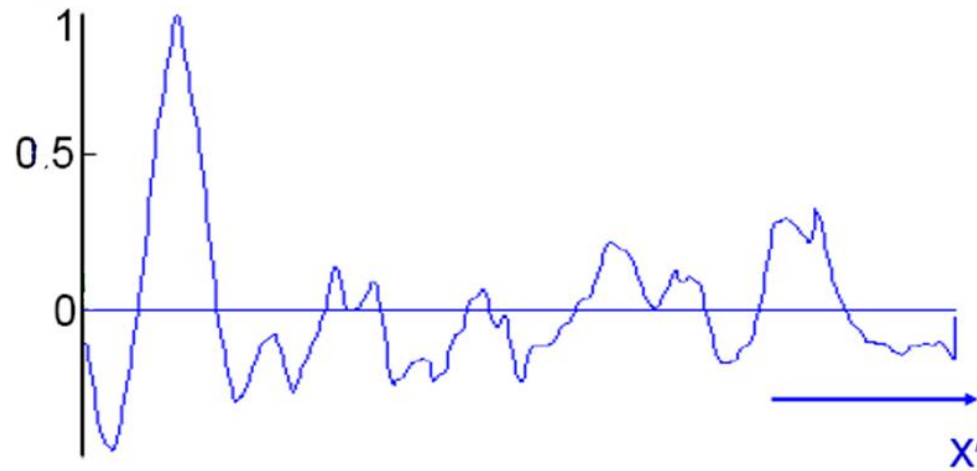
right image band (x')

Correlation-based window matching



left image band (x)

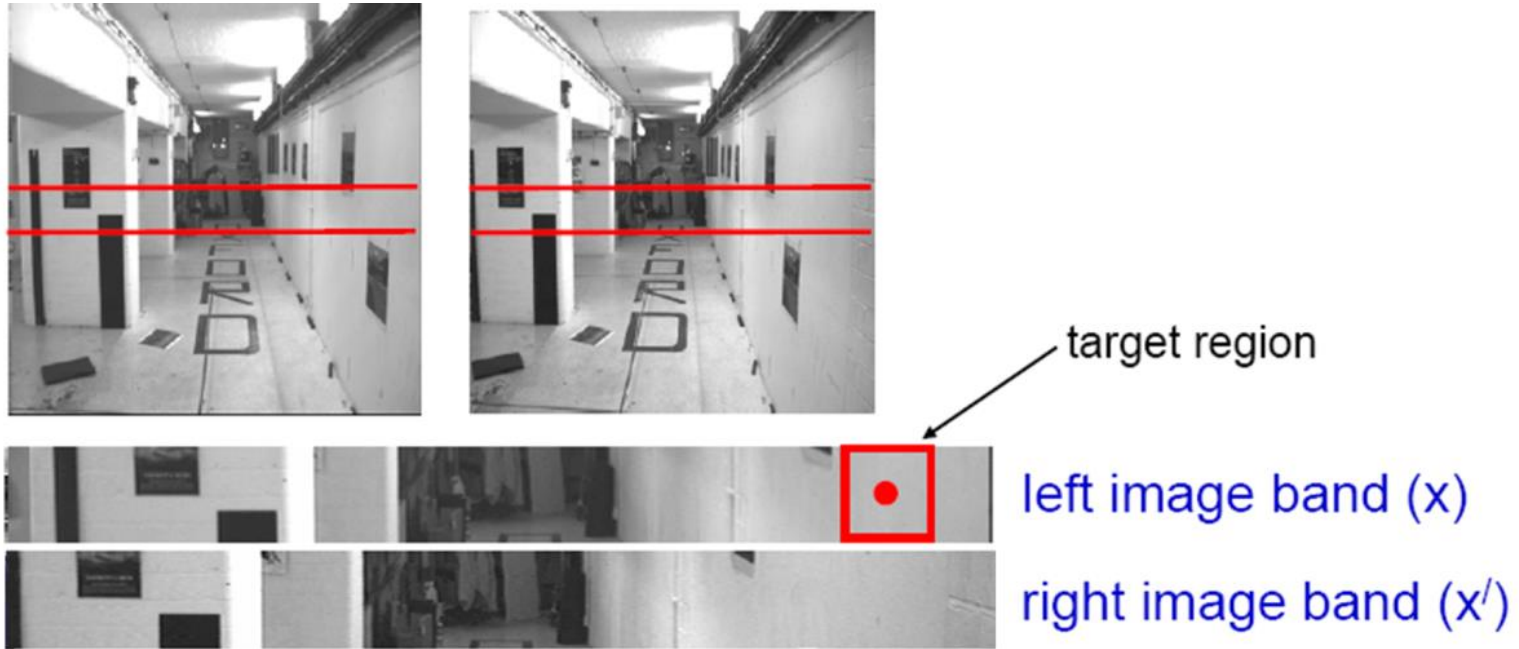
right image band (x')



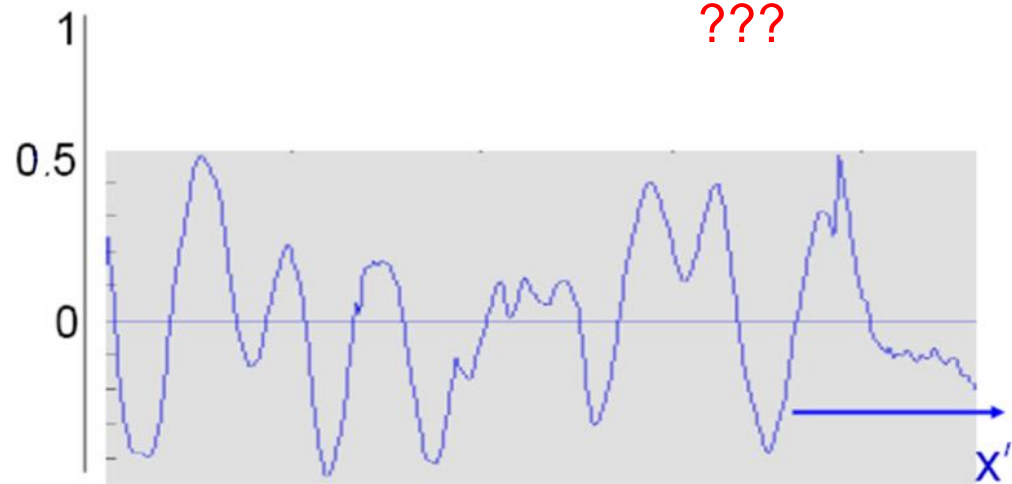
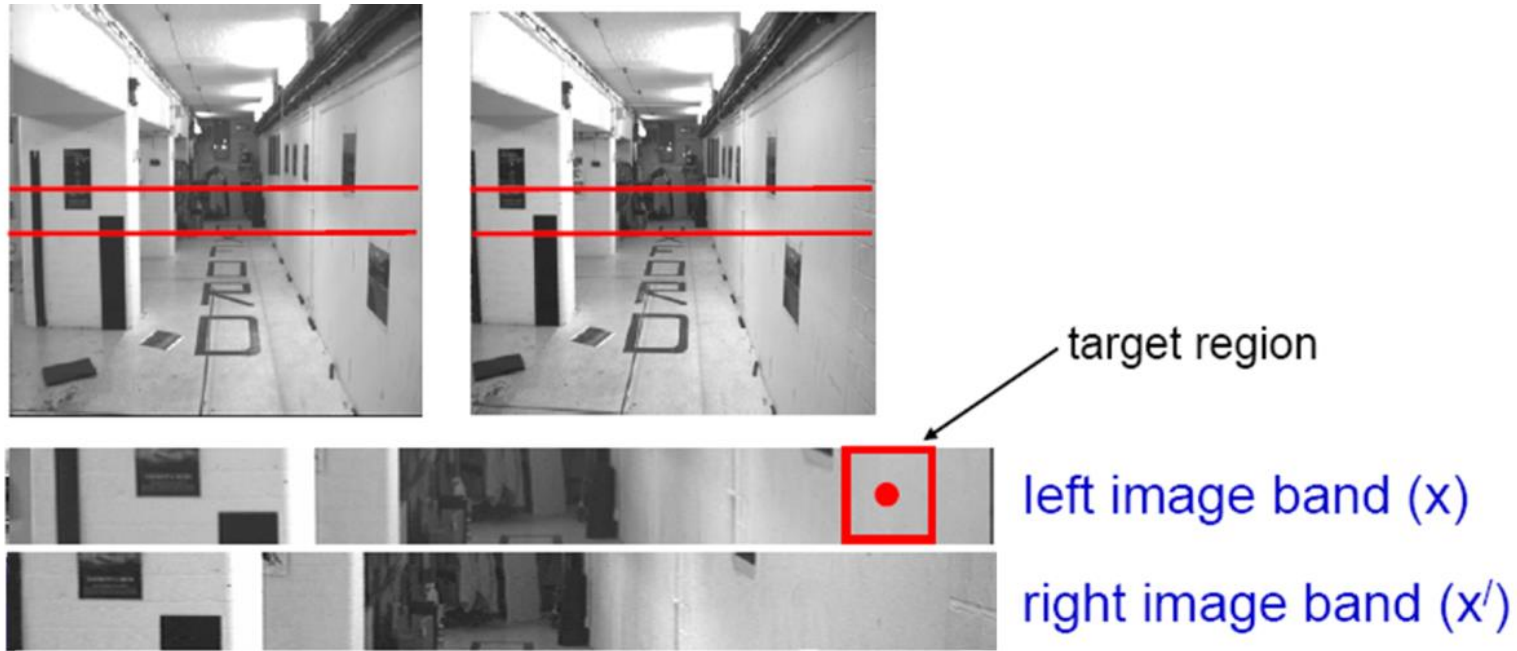
↑
cross
correlation

→ x'
disparity = $x' - x$

Correlation-based window matching



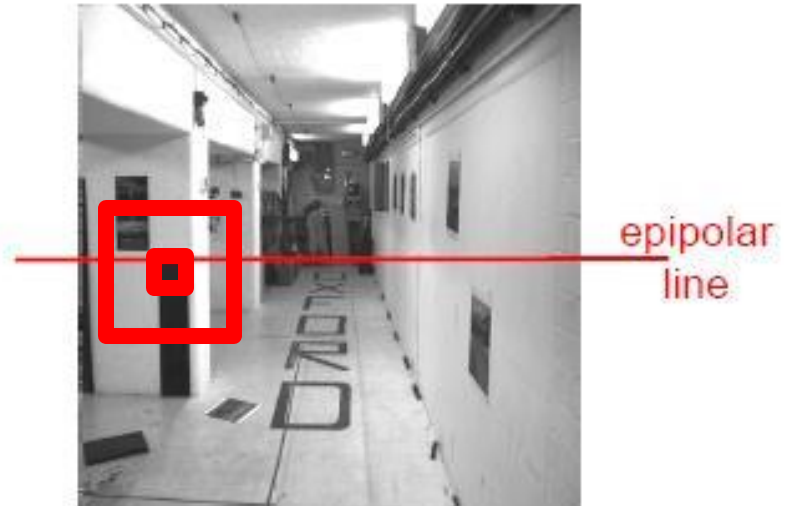
Correlation-based window matching



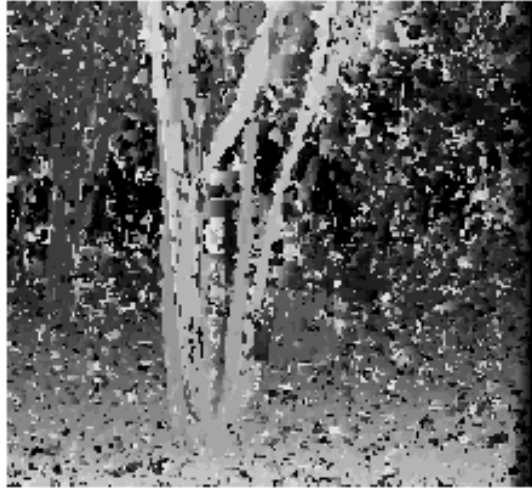
cross
correlation

Textureless regions are
non-distinct; high
ambiguity for matches.

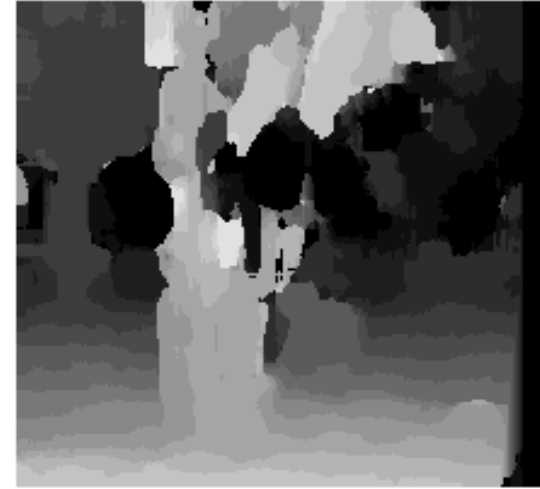
Effect of window size



Effect of window size

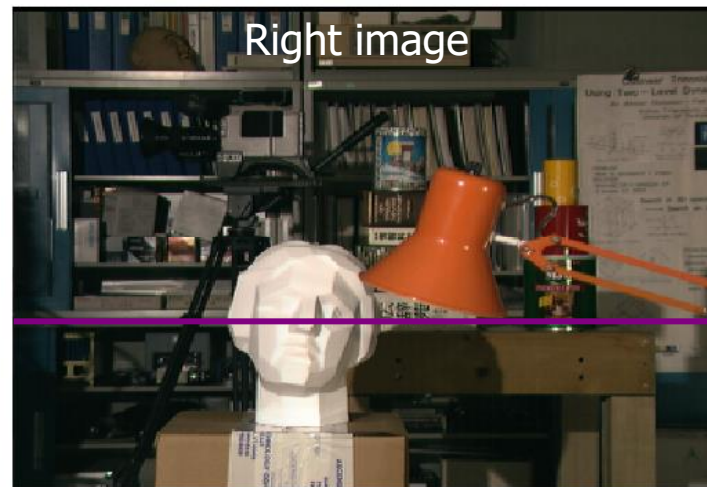
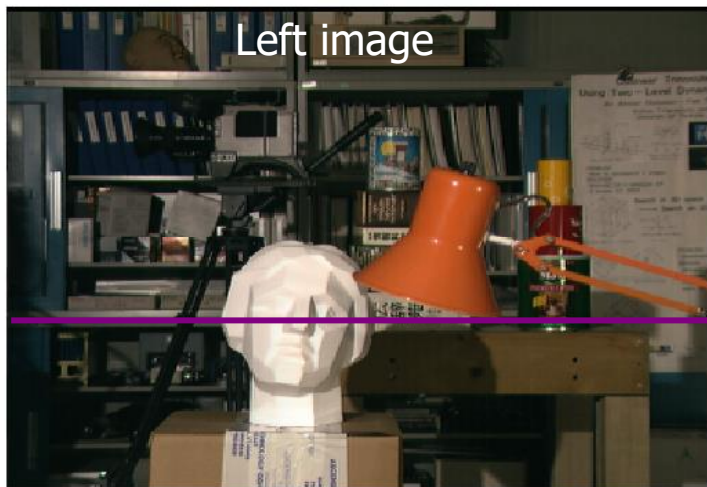


$W = 3$

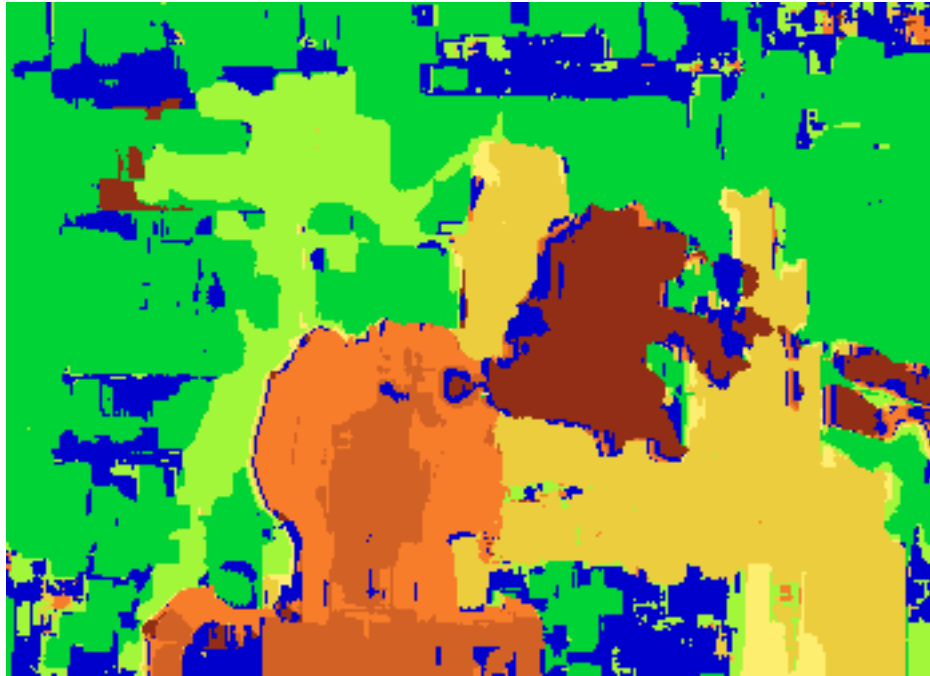


$W = 20$

Want window large enough to have sufficient intensity variation, yet small enough to contain only pixels with about the same disparity.



Results with window search



Window-based matching
(best window size)



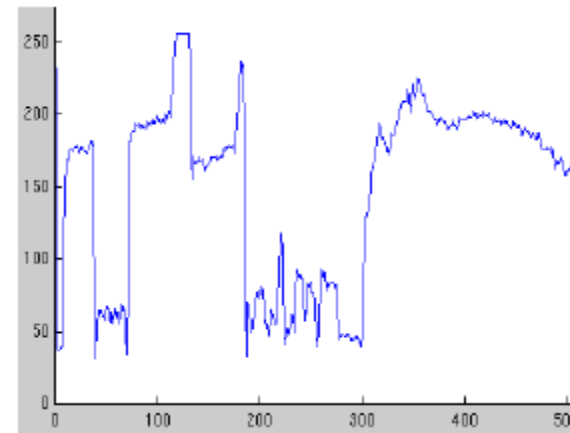
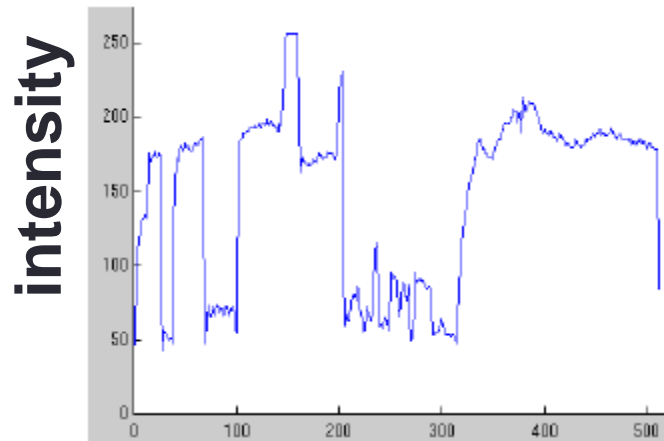
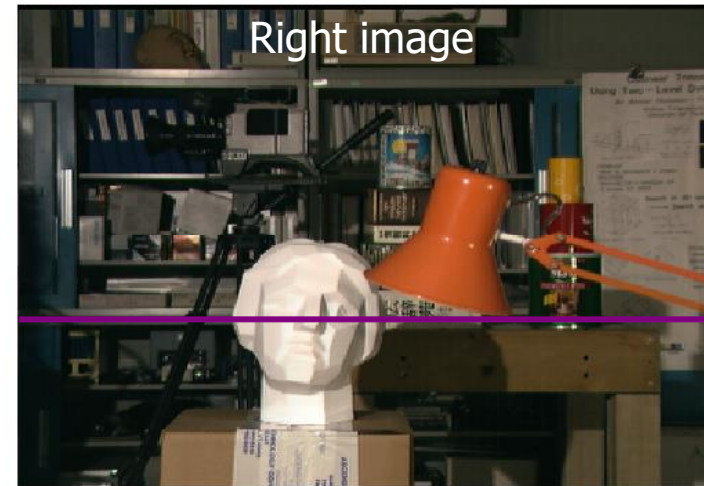
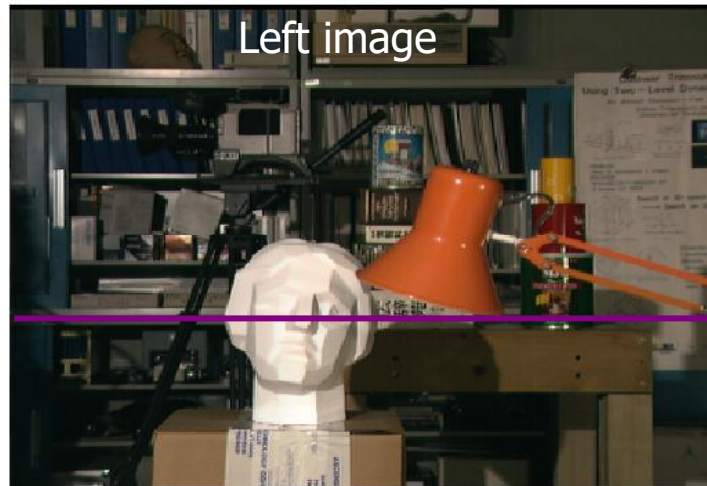
Ground truth

Better solutions

- Beyond individual correspondences to estimate disparities:
- Optimize correspondence assignments jointly
 - Scanline at a time (e.g. dynamic programming)
 - Full 2D grid (e.g. graph cuts)
 - Approximate 2D solution (e.g. semi-global matching)

Scanline stereo

- Try to coherently match pixels on the entire scanline
- Different scanlines are still optimized independently



Matching using Epipolar Lines

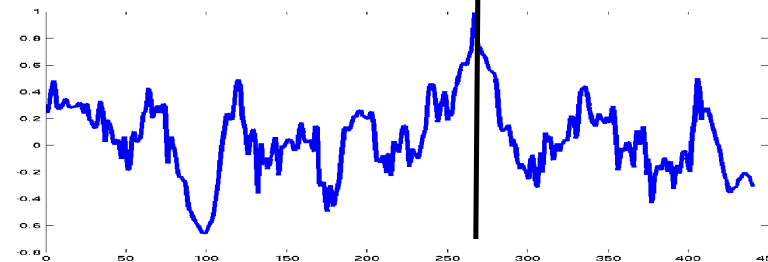
Left Image



Right Image



For a patch in left image
Compare with patches along
same row in right image



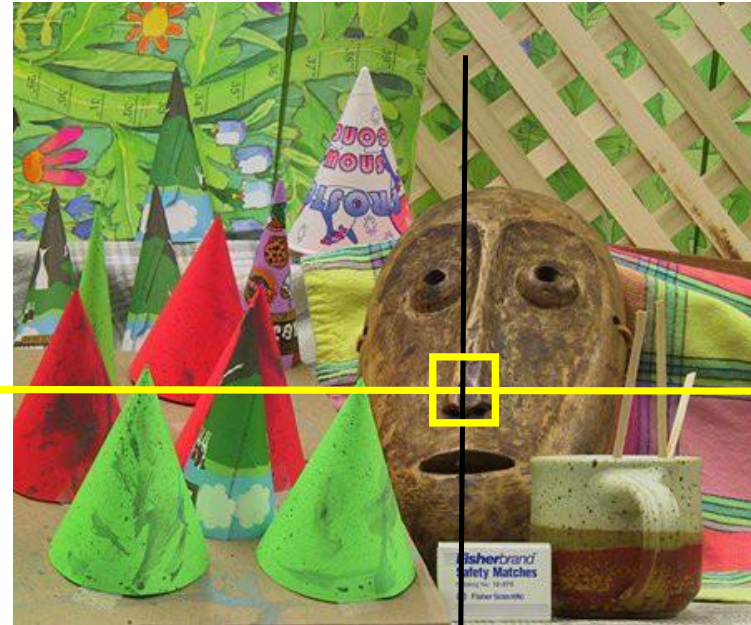
Match Score Values

Matching using Epipolar Lines

Left Image

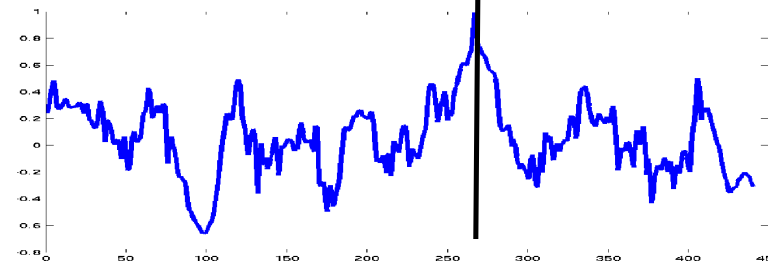


Right Image



Select patch with highest
match score.

Repeat for all pixels in
left image.

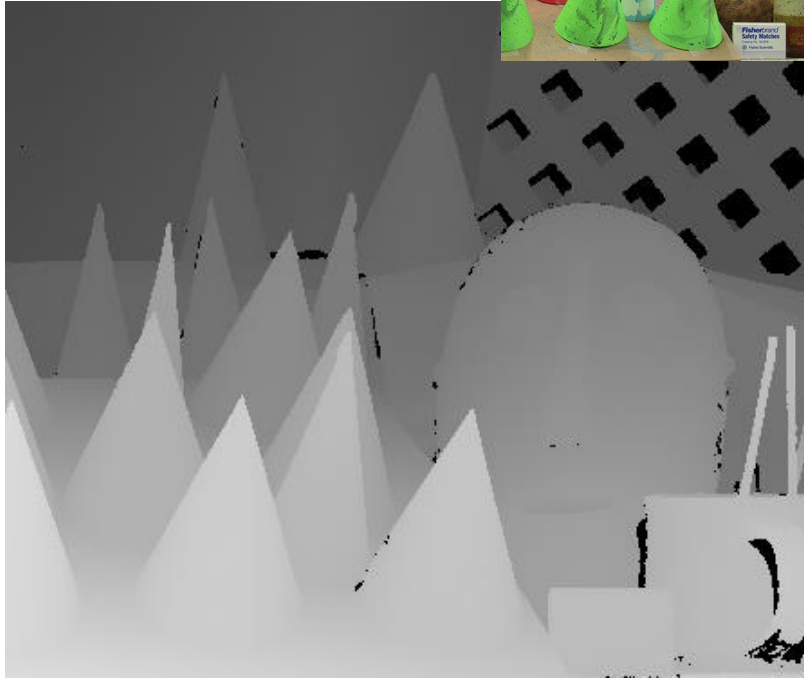


Match Score Values

Example: 5x5 windows NCC match score



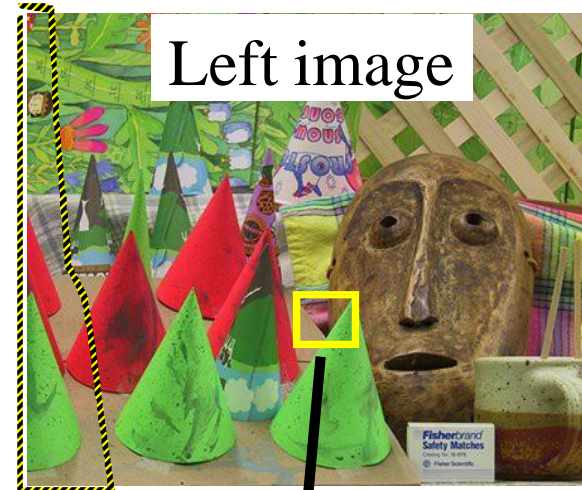
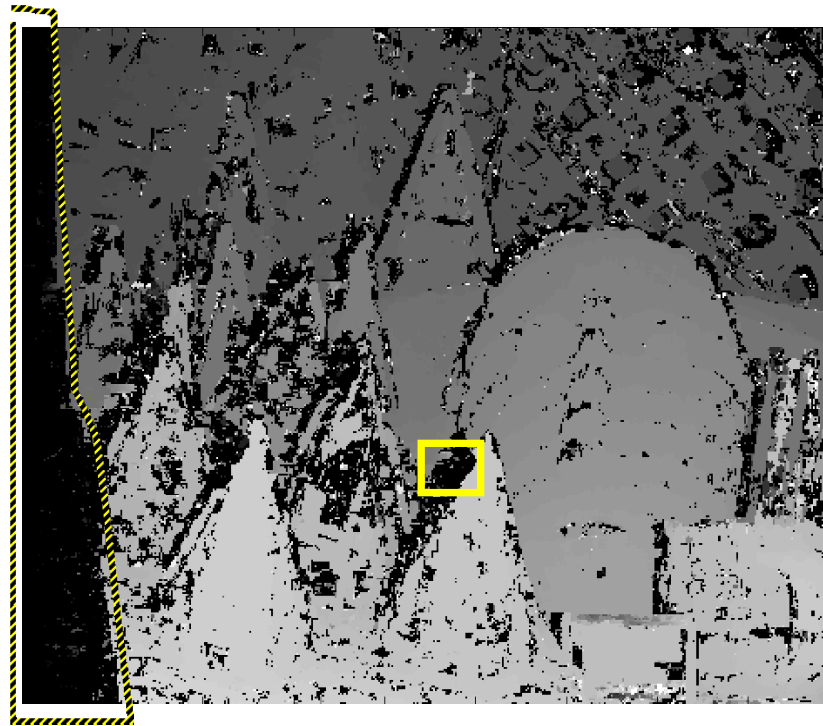
Computed disparities



Ground truth

Black pixels: bad disparity values,
or no matching patch in right image

Occlusions: No matches

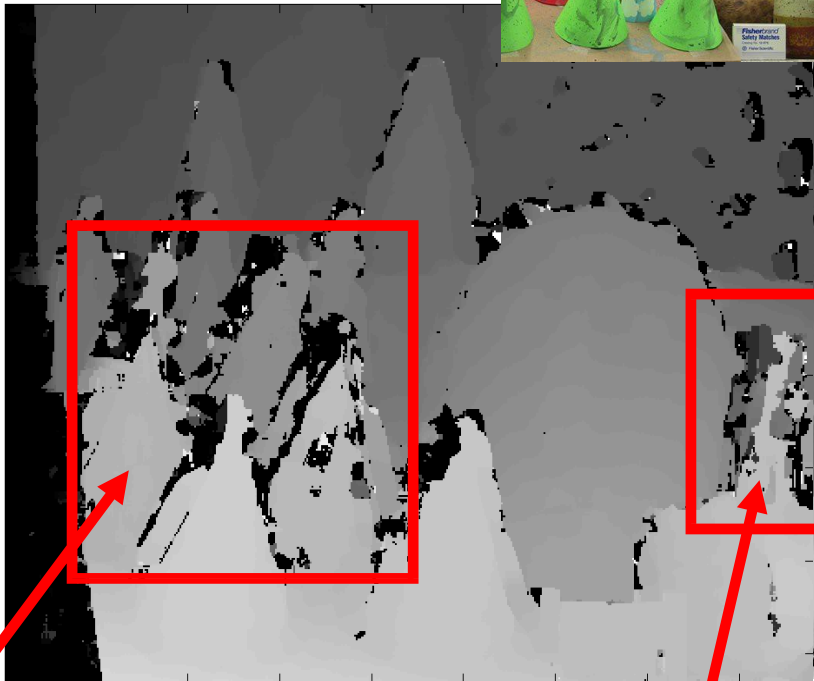


Effects of Patch Size



5x5 patches

Smoother in some areas



11x11 patches

Loss of finer details

Adding Intra-Scanline Consistency

So far, each left image patch has been matched independently along the right epipolar line.

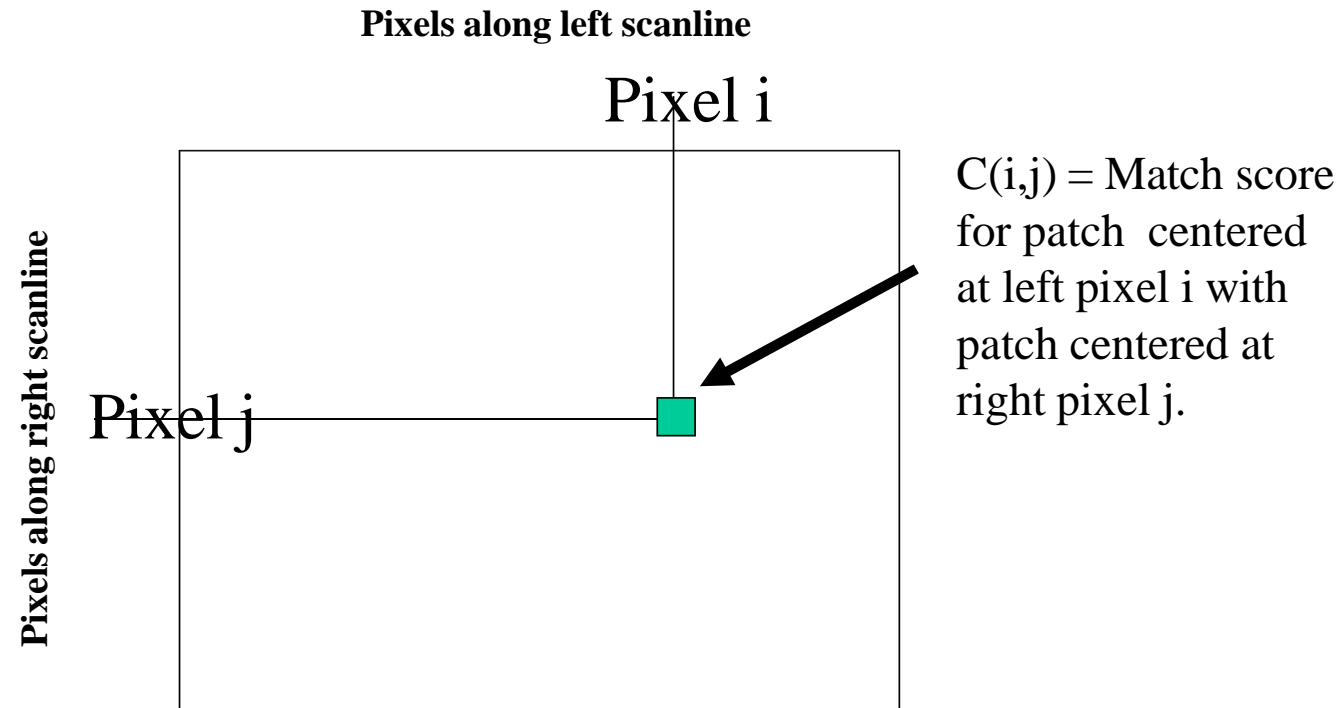
This can lead to errors.

We would like to enforce some consistency among matches in the same row (scanline).

Disparity Space Image

First we introduce the concept of DSI.

The DSI for one row represents pairwise match scores between patches along that row in the left and right image.

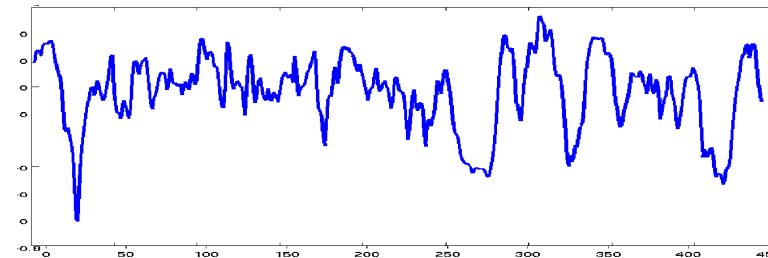


Disparity Space Image (DSI)

Left Image



Right Image



Dissimilarity Values
(1-NCC) or SSD

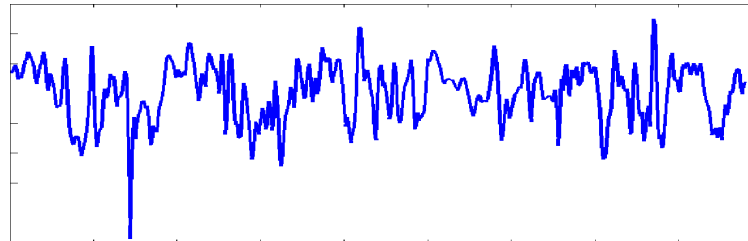
Robert Collins
CSE486, Penn State

Disparity Space Image (DSI)

Left Image



Right Image



Dissimilarity Values
(1-NCC) or SSD

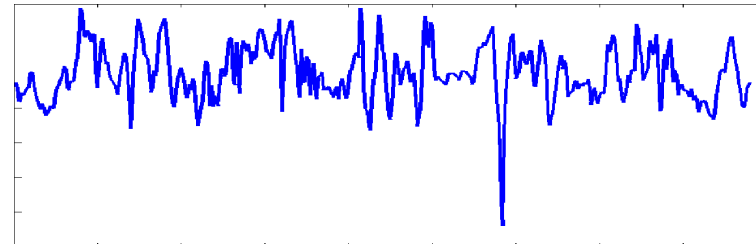
Robert Collins
CSE486, Penn State

Disparity Space Image (DSI)

Left Image



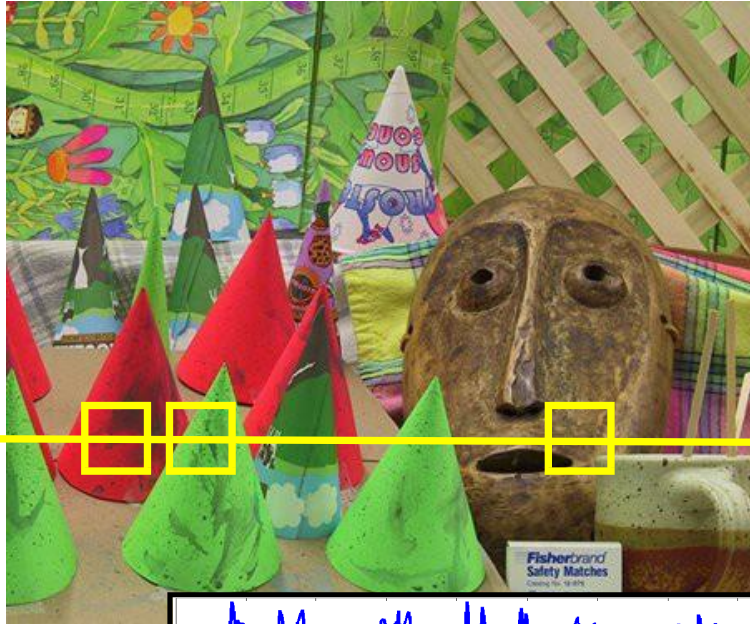
Right Image



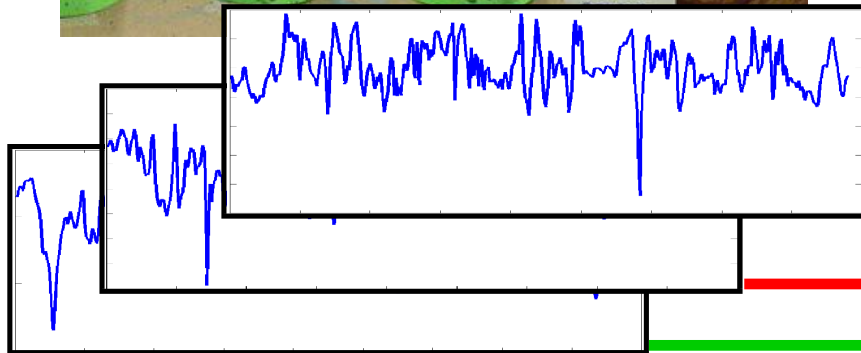
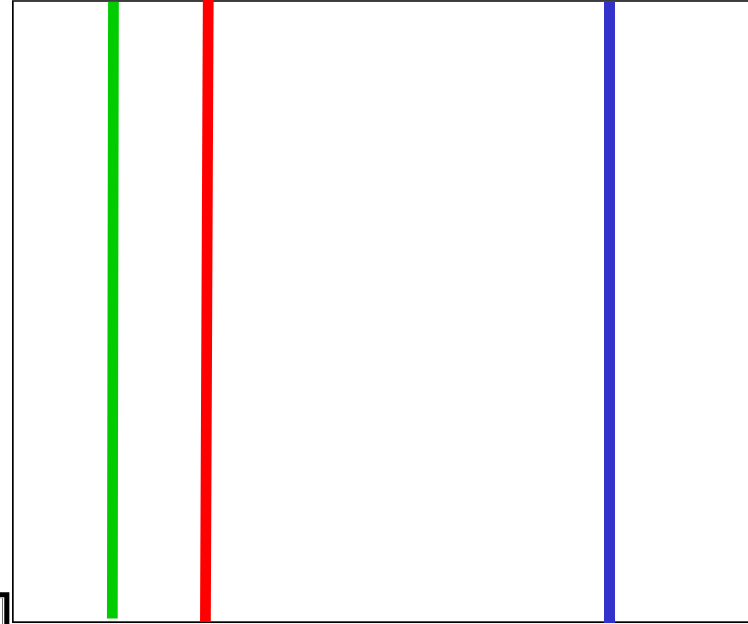
Dissimilarity Values
(1-NCC) or SSD

Disparity Space Image (DSI)

Left Image



DSI

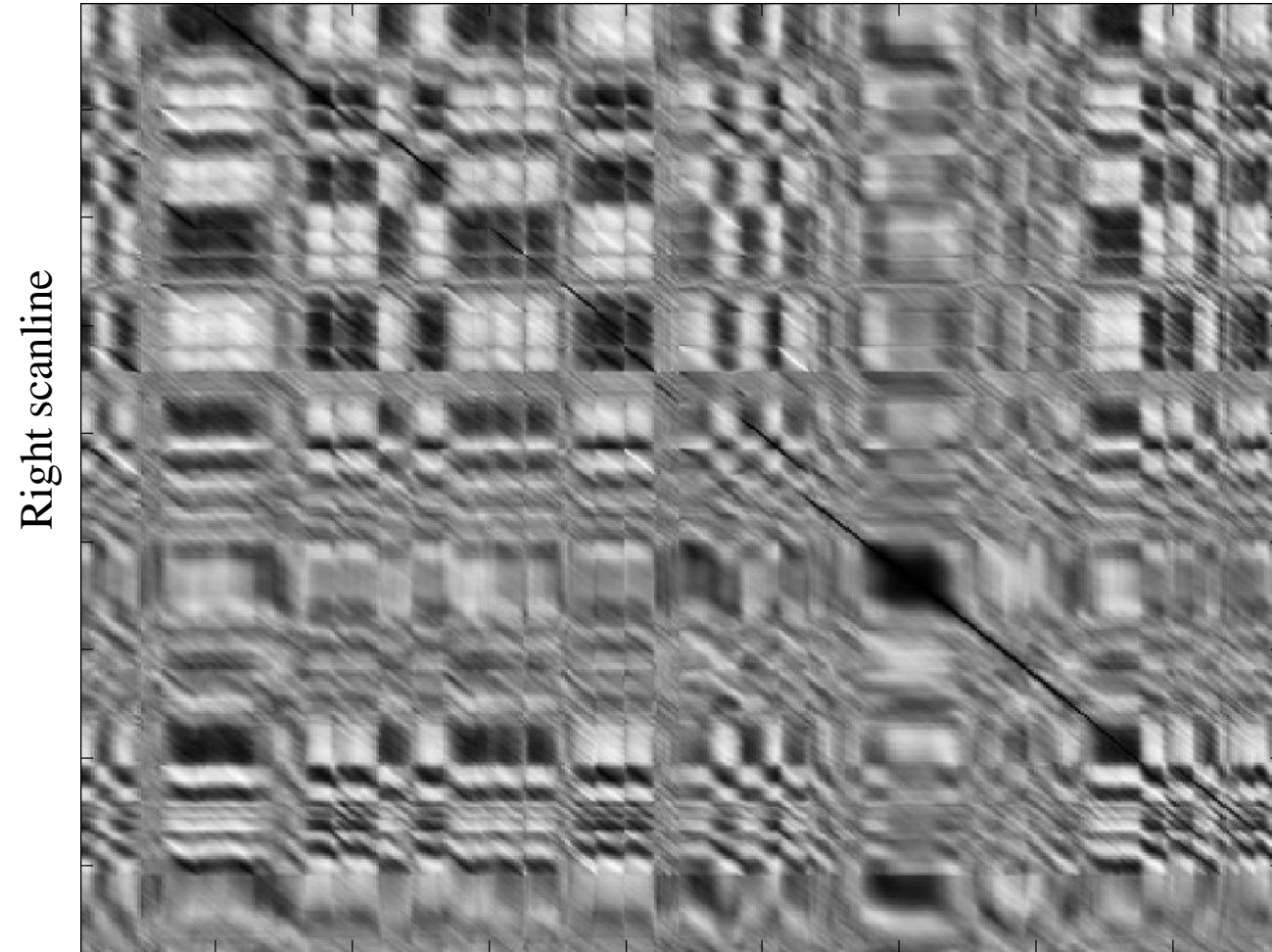


Dissimilarity Values

Enter each vector of
match scores as a
column in the DSI

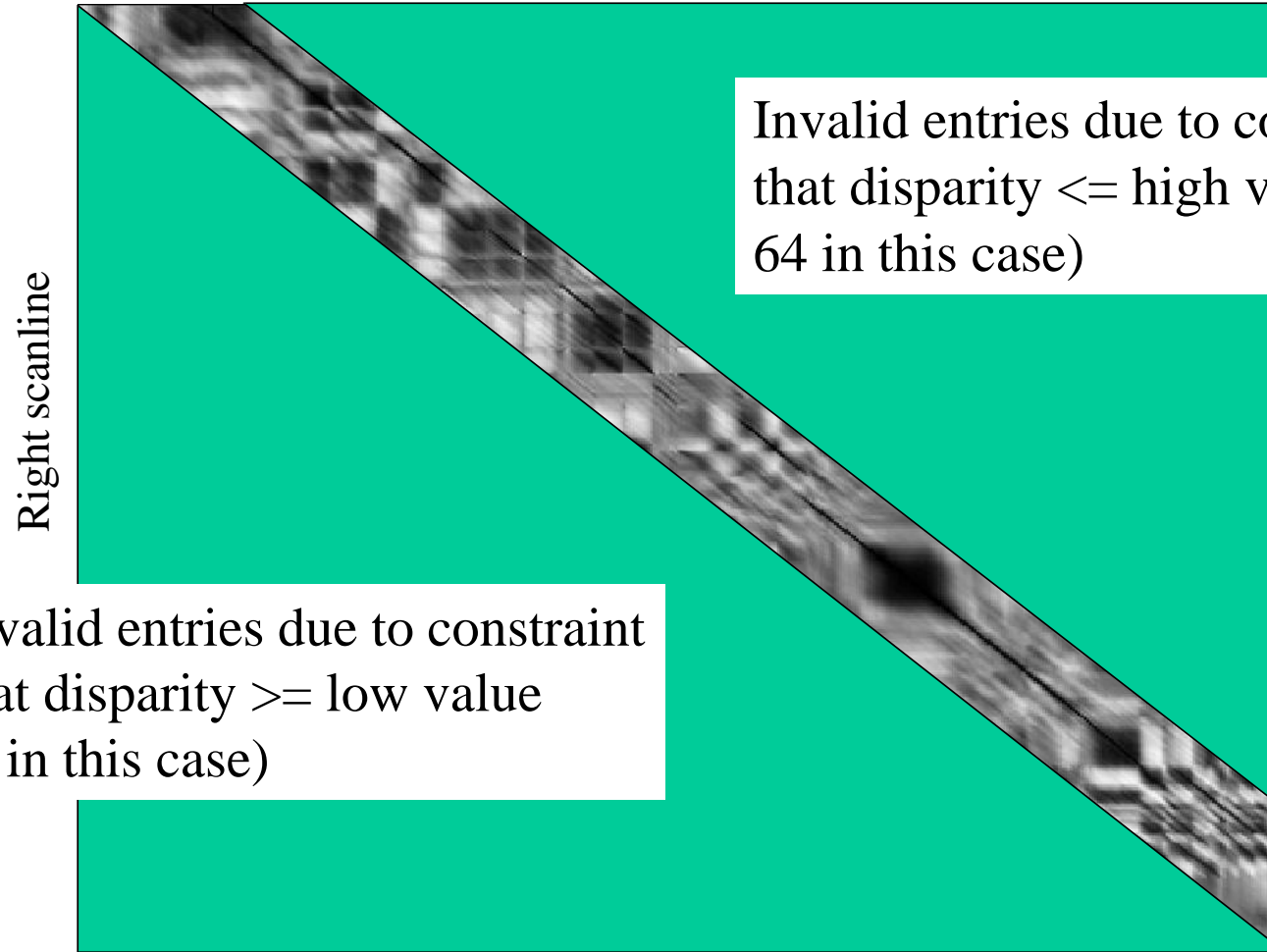
Disparity Space Image

Left scanline



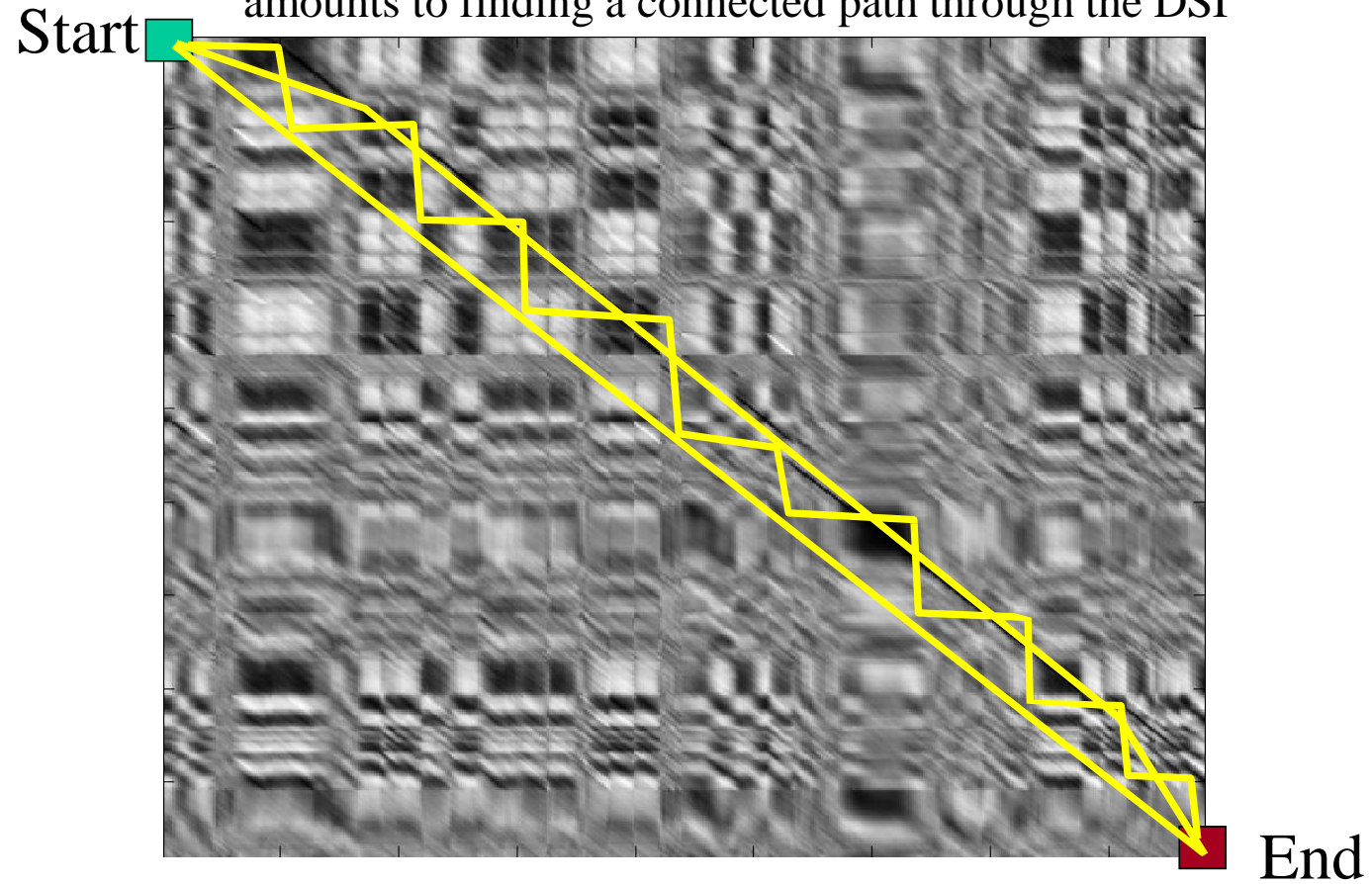
Disparity Space Image

Left scanline



DSI and Scanline Consistency

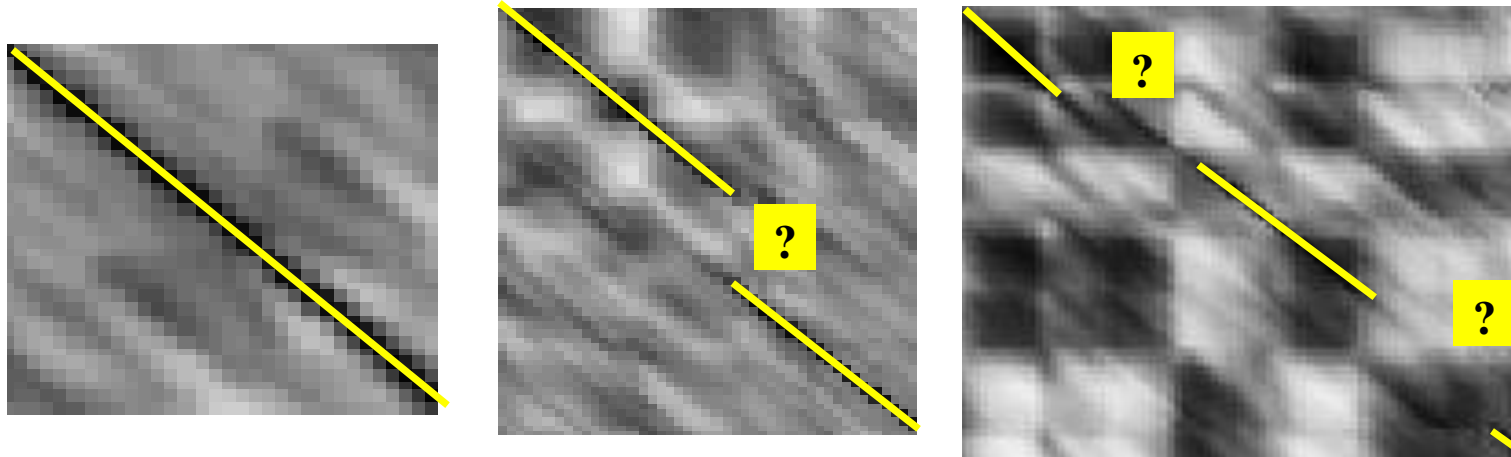
Assigning disparities to all pixels in left scanline now amounts to finding a connected path through the DSI



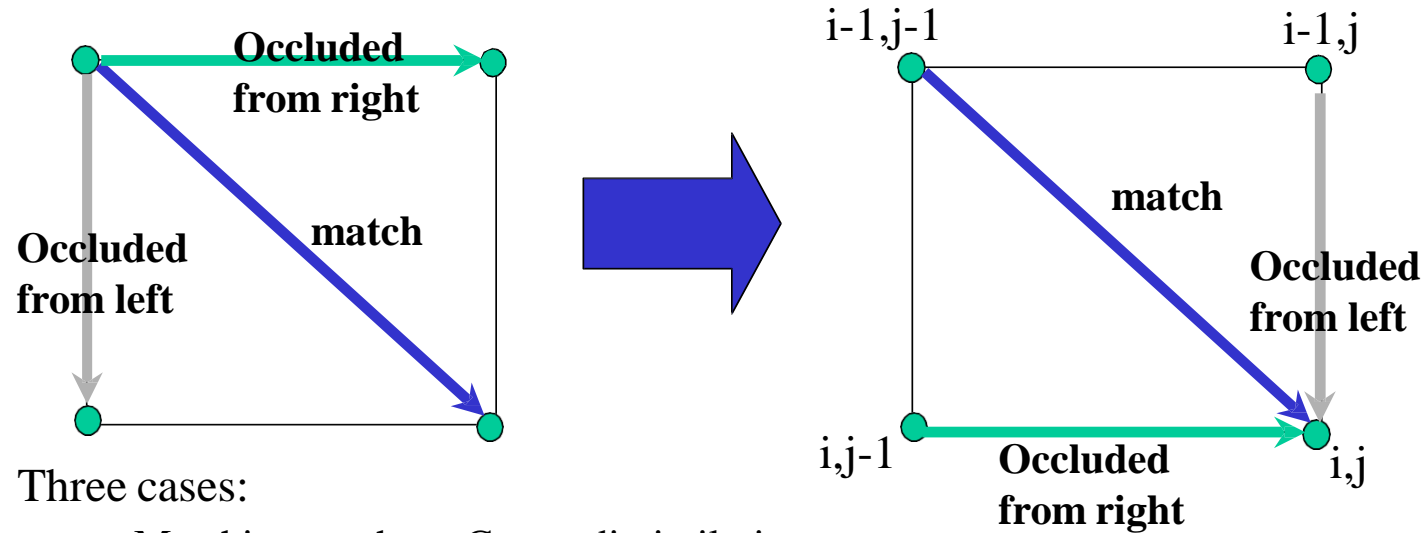
Lowest Cost Path

We would like to choose the “best” path.

Want one with lowest “cost” (Lowest sum of dissimilarity scores along the path)



Cox et.al. Stereo Matching

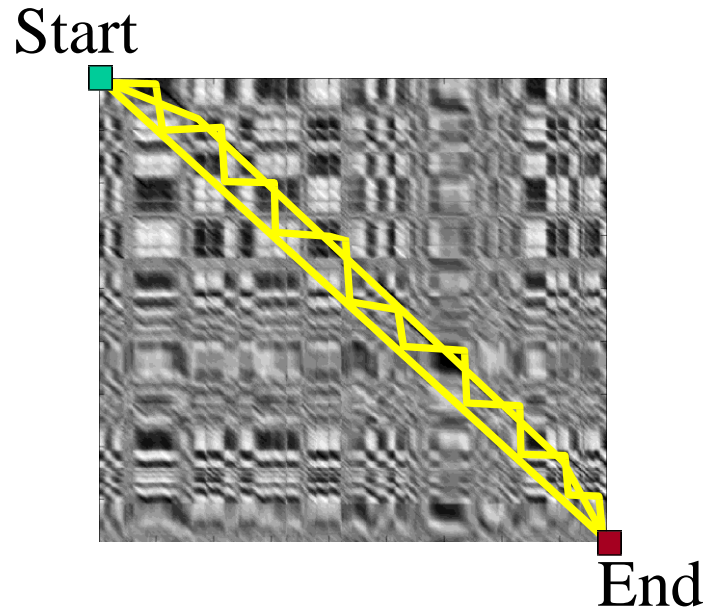


Three cases:

- Matching patches. Cost = dissimilarity score
- Occluded from right. Cost is some constant value.
- Occluded from left. Cost is some constant value.

$$C(i,j) = \min([C(i-1,j-1) + \text{dissimilarity}(i,j) \\ C(i-1,j) + \text{occlusionConstant}, \\ C(i,j-1) + \text{occlusionConstant}]);$$

Cox et.al. Stereo Matching



Recap: want to find lowest cost path from upper left to lower right of DSI image.

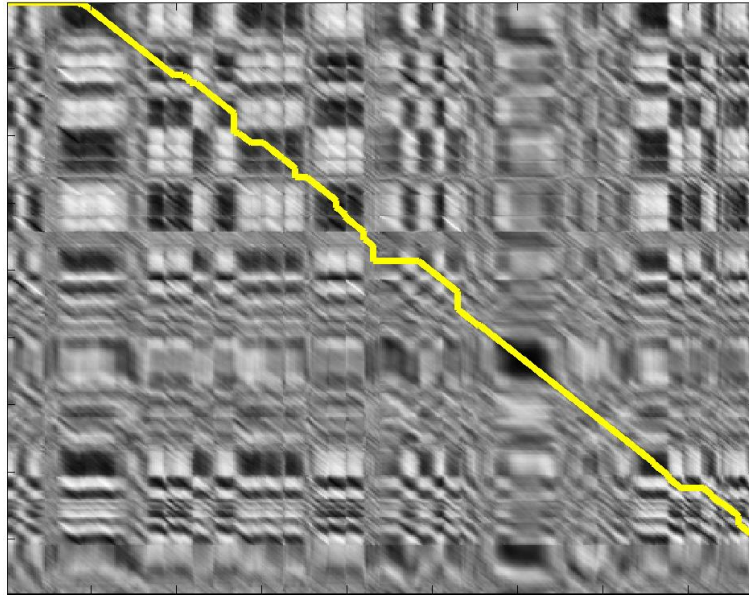
At each point on the path we have three choices: step left, step down, step diagonally.

Each choice has a well-defined cost associated with it.

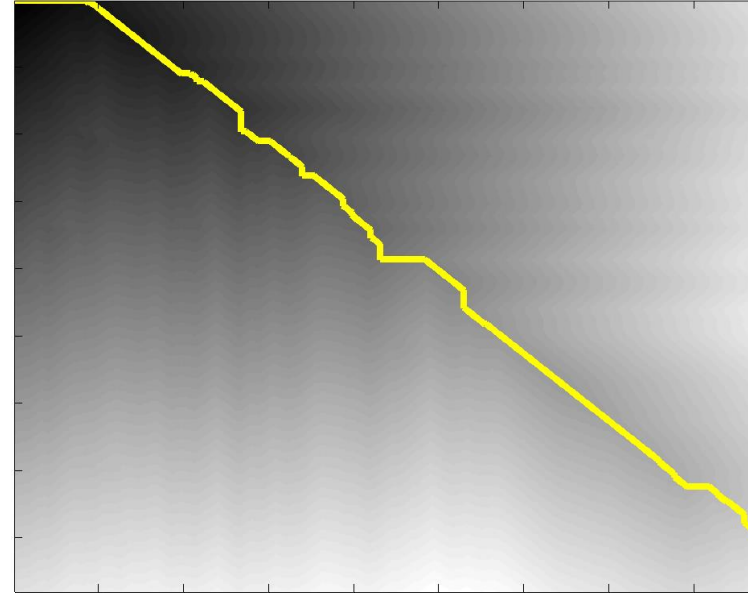
This problem just screams out for Dynamic Programming!
(which, indeed, is how Cox et.al. solve the problem)

Real Scanline Example

DSI



DP cost matrix
(cost of optimal path from each point to END)



Every pixel in left column now is marked with either a disparity value, or an occlusion label.

Proceed for every scanline in left image.

Example

Result of DP alg



Result without DP (independent pixels)



Result of DP alg. Black pixels = occluded.

Occlusion Filling

Simple trick for filling in gaps caused by occlusion.



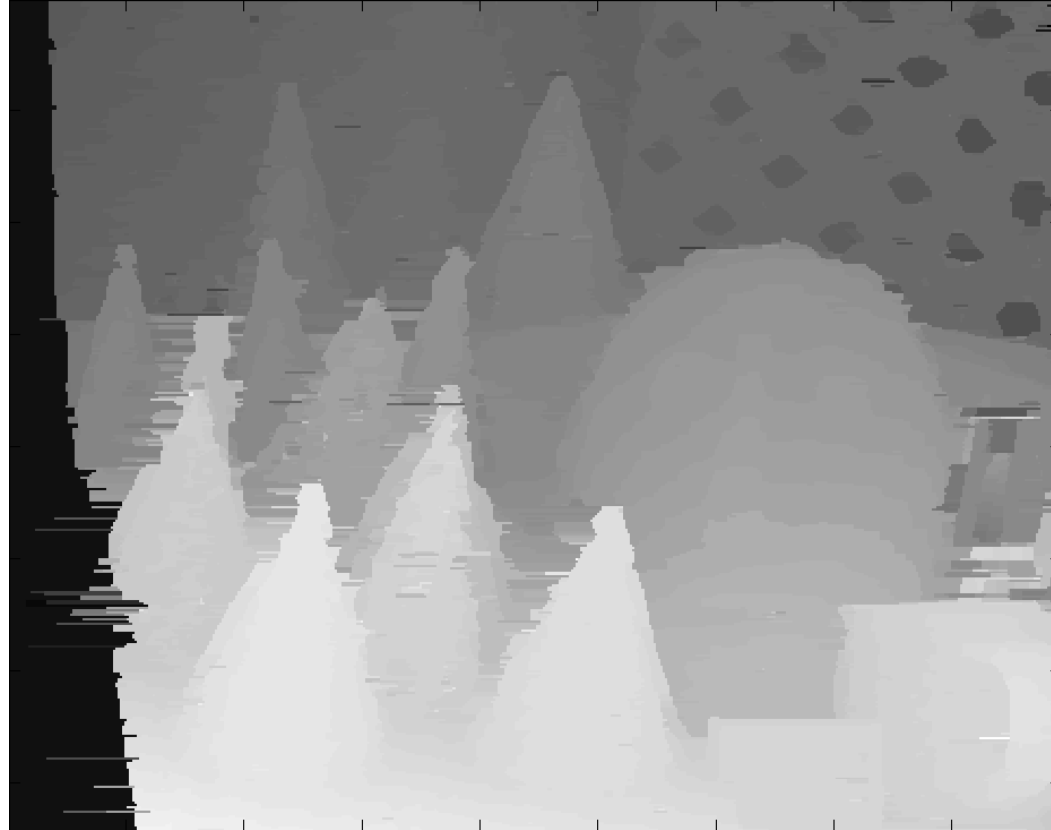
 = left occluded

Fill in left occluded pixels with value from the nearest valid pixel preceding it in the scanline.



Similarly, for right occluded, look for valid pixel to the right.

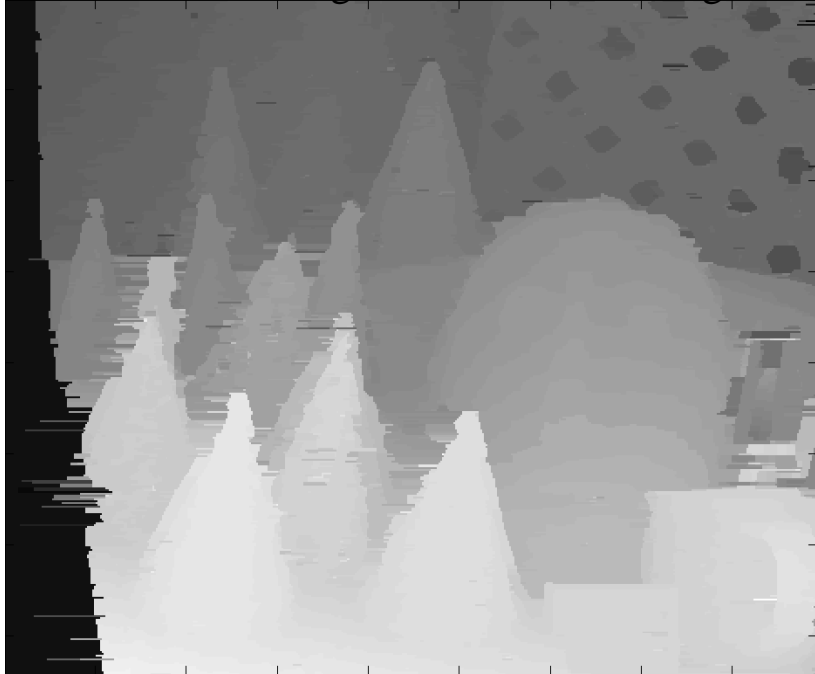
Example



Result of DP alg with occlusion filling.

Example

Result of DP alg with occlusion filling.

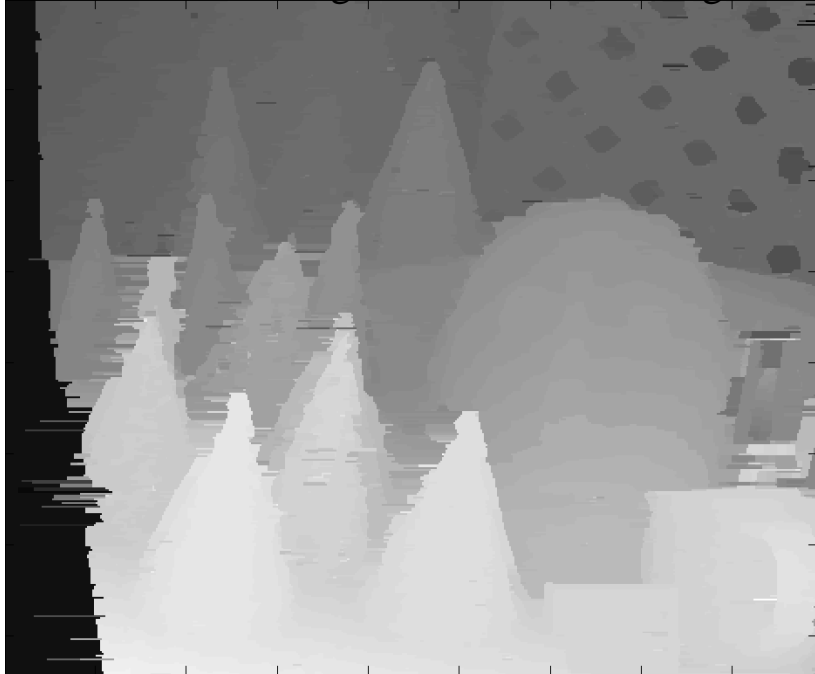


Result without DP (independent pixels)

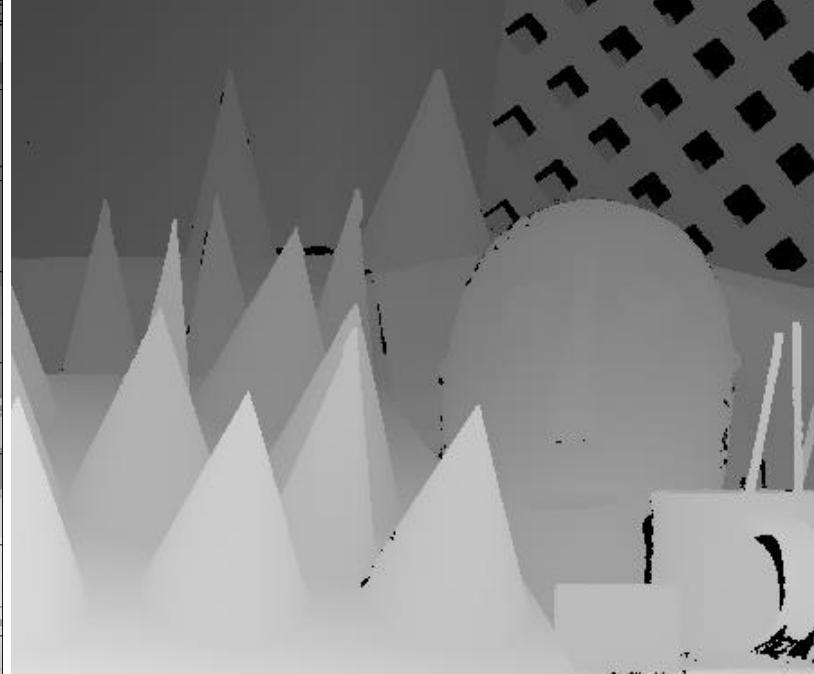


Example

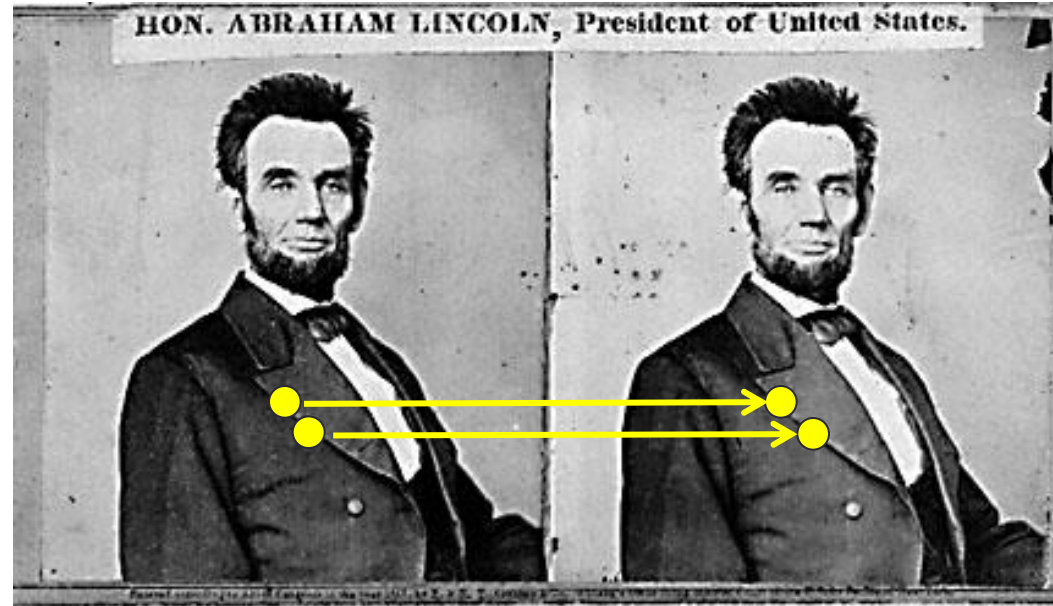
Result of DP alg with occlusion filling.



Ground truth

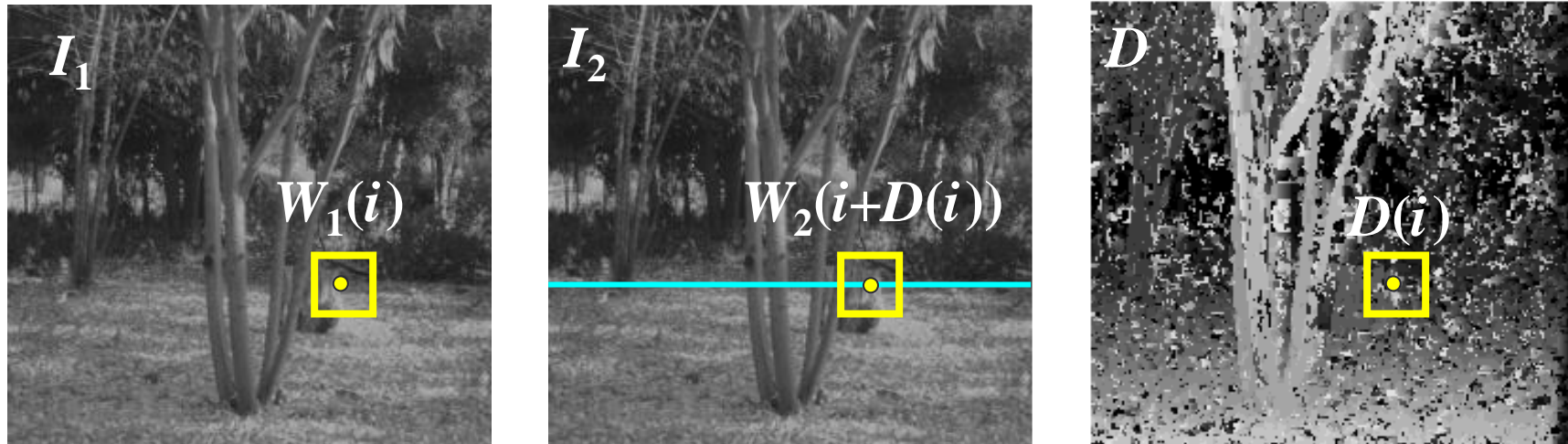


Stereo with 2D smoothness constraint



- 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

Optimizing for match quality *and* smoothness (in any direction)



$$E = \alpha E_{\text{data}}(I_1, I_2, D) + \beta E_{\text{smooth}}(D)$$

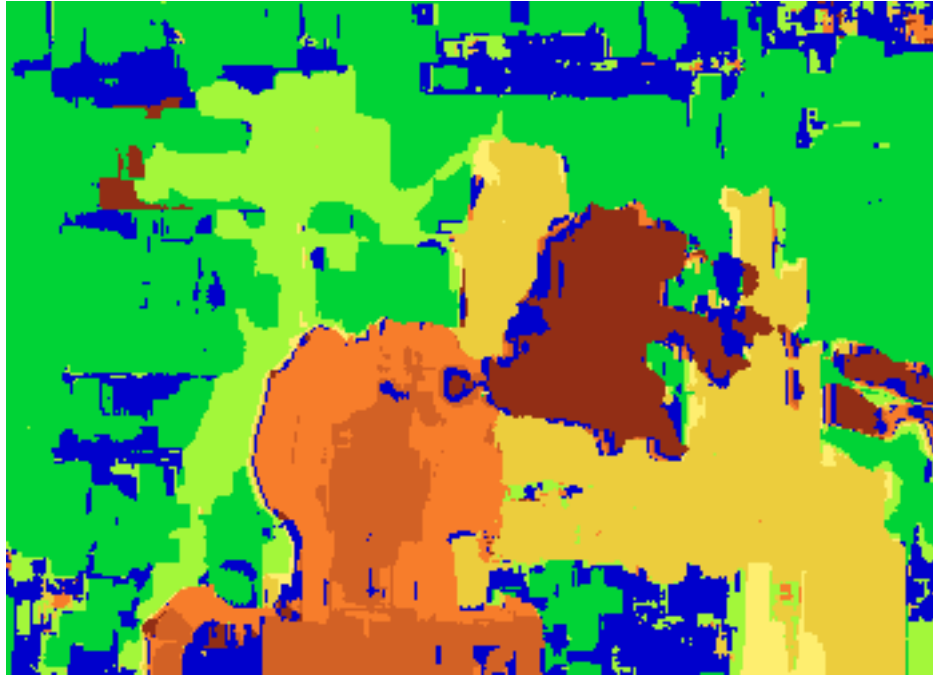
$$E_{\text{data}} = \sum_i (W_1(i) - W_2(i + D(i)))^2$$

$$E_{\text{smooth}} = \sum_{\text{neighbors } i, j} \rho(D(i) - D(j))$$

- Energy functions of this form can be minimized using *graph cuts*

Y. Boykov, O. Veksler, and R. Zabih, [Fast Approximate Energy Minimization via Graph Cuts](#), PAMI 2001

Results with window search



Window-based matching
(best window size)



Ground truth

Better results...



Graph cut method

Boykov et al., [Fast Approximate Energy Minimization via Graph Cuts](#),
International Conference on Computer Vision, September 1999.



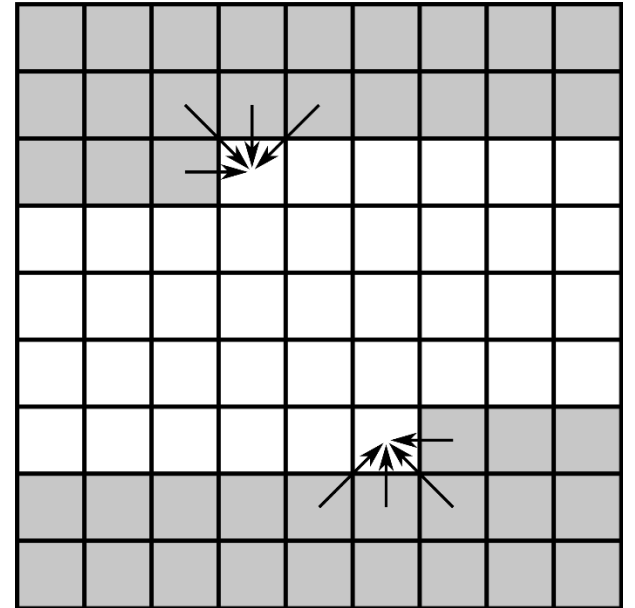
Ground truth

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

Semi-global matching

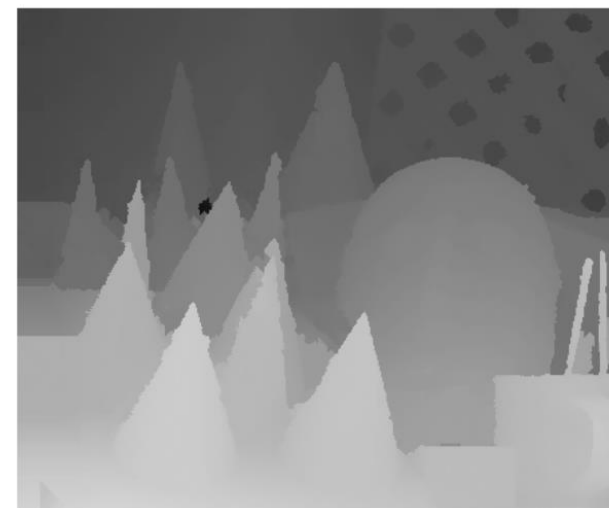
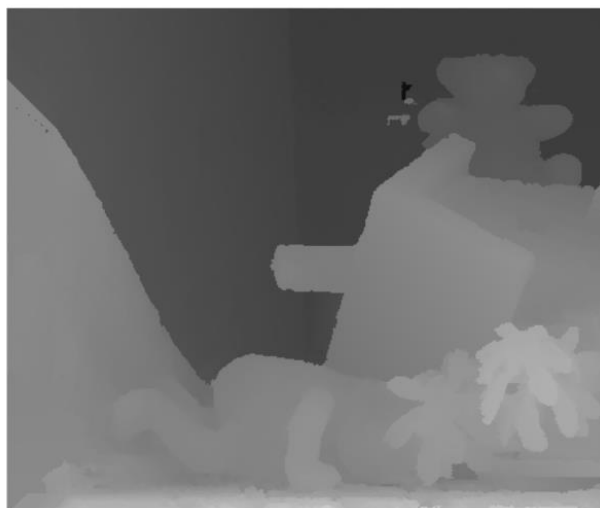
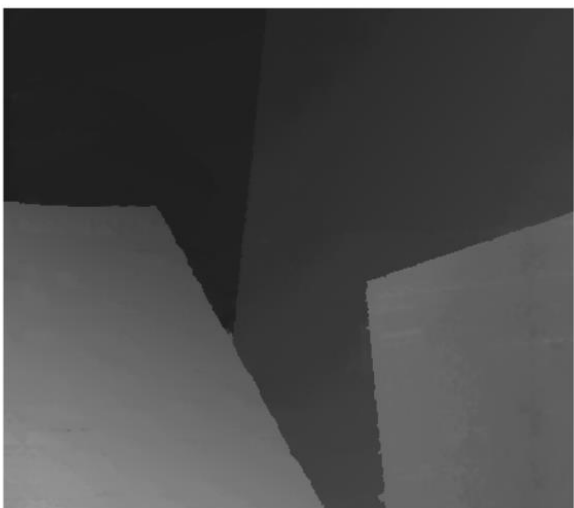
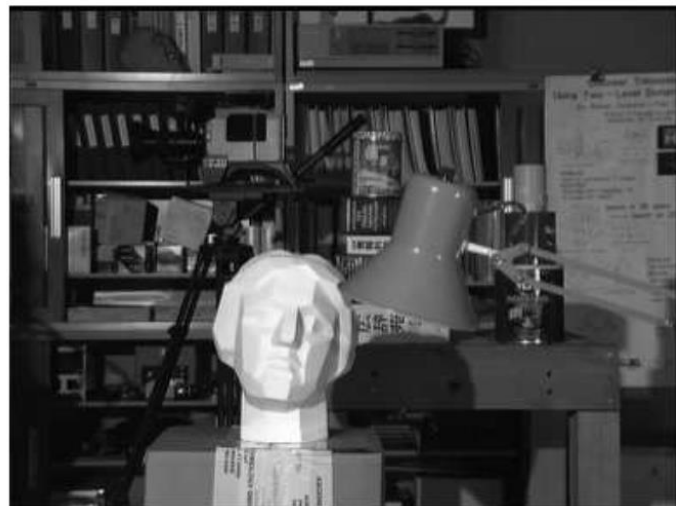
$$E(D) = \sum_{\mathbf{p}} (C(\mathbf{p}, D_{\mathbf{p}}) + \sum_{\mathbf{q} \in N_{\mathbf{p}}} P_1 \mathbb{T}[|D_{\mathbf{p}} - D_{\mathbf{q}}| = 1] + \sum_{\mathbf{q} \in N_{\mathbf{p}}} P_2 \mathbb{T}[|D_{\mathbf{p}} - D_{\mathbf{q}}| > 1])$$

- Approximate the full smoothness optimization by considering 8 or 16 directions in two or three passes.
- Optimization looks like scanline, dynamic programming stereo, but with a 2d notion of smoothness



Stereo Processing by Semi-Global Matching and Mutual Information. Hirschmuller, PAMI 2007. **3500+** citations

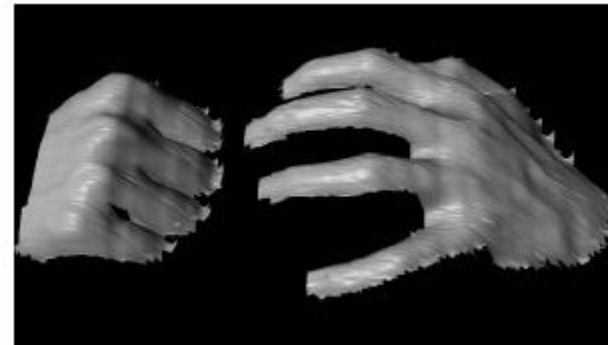
Semi-global matching



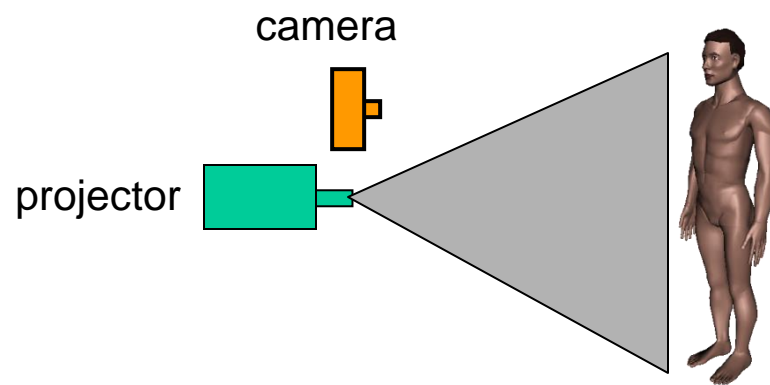
Stereo Depth Estimation Challenges

- Low-contrast ; textureless image regions
- Occlusions
- Violations of brightness constancy (e.g., specular reflections)
- Really large baselines (foreshortening and appearance change)
- Camera calibration errors

Active stereo with structured light



- Project “structured” light patterns onto the object
 - Simplifies the correspondence problem
 - Allows us to use only one camera



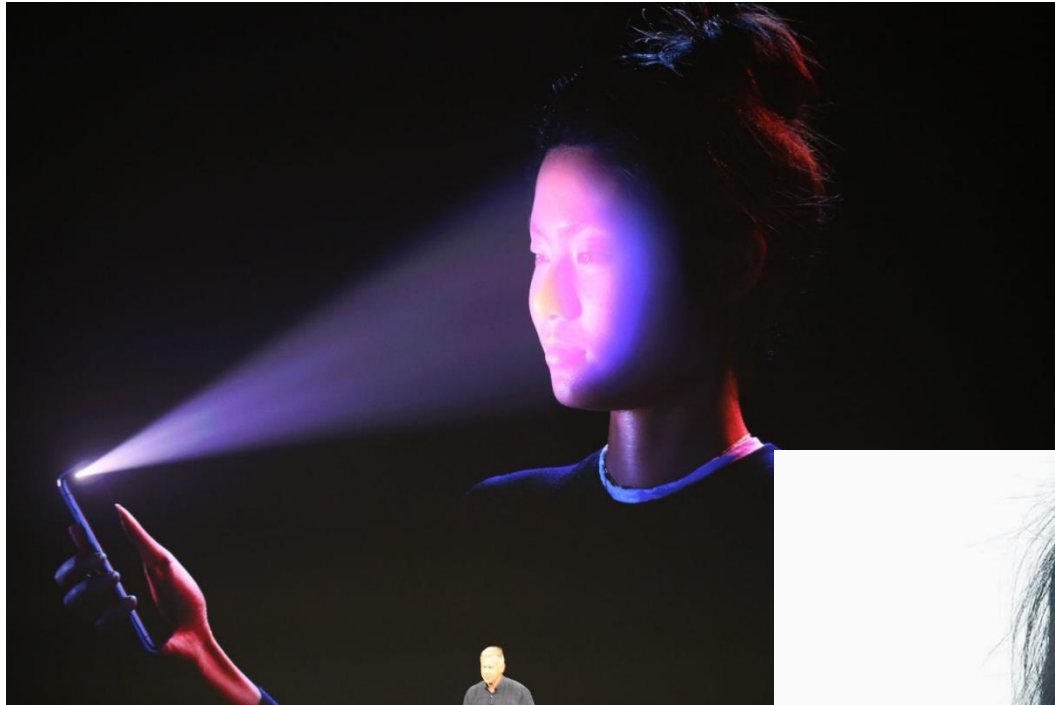
L. Zhang, B. Curless, and S. M. Seitz. [Rapid Shape Acquisition Using Color Structured Light and Multi-pass Dynamic Programming](#). *3DPVT* 2002

Kinect: Structured infrared light



<http://bbzipo.wordpress.com/2010/11/28/kinect-in-infrared/>

iPhone X



iPhone 12 switched to lidar
(time of flight)

Argo uses both

Examples of state of the art stereo and state of the art lidar



