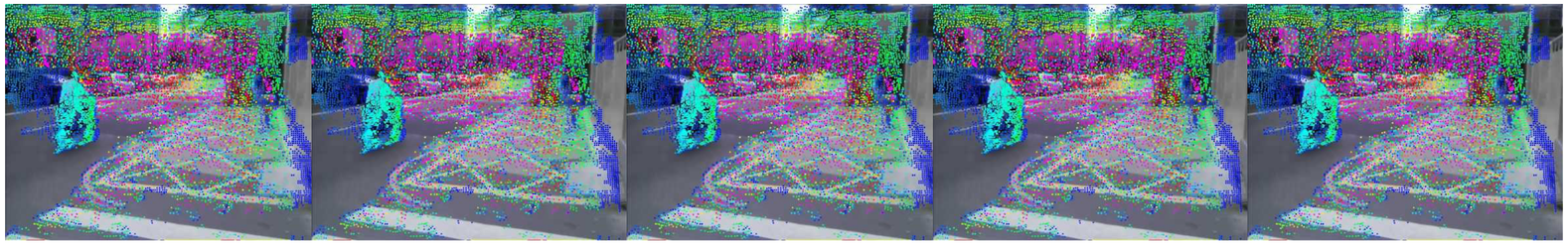
THE UNIVERSITY OF BRITISH COLUMBIA

CPSC 425: Computer Vision



Lecture 16: Multiview Reconstruction

Menu for Today

Topics:

- **Stereo, Optical Flow** recap
- **Multiview Reconstruction**
- **Quiz 5** on Thursday
- Visual **Classification**

Readings:

- **Today's** Lecture: Szeliski 11.4, 12.3-12.4, 9.3, 5.1-5.2

Reminders:

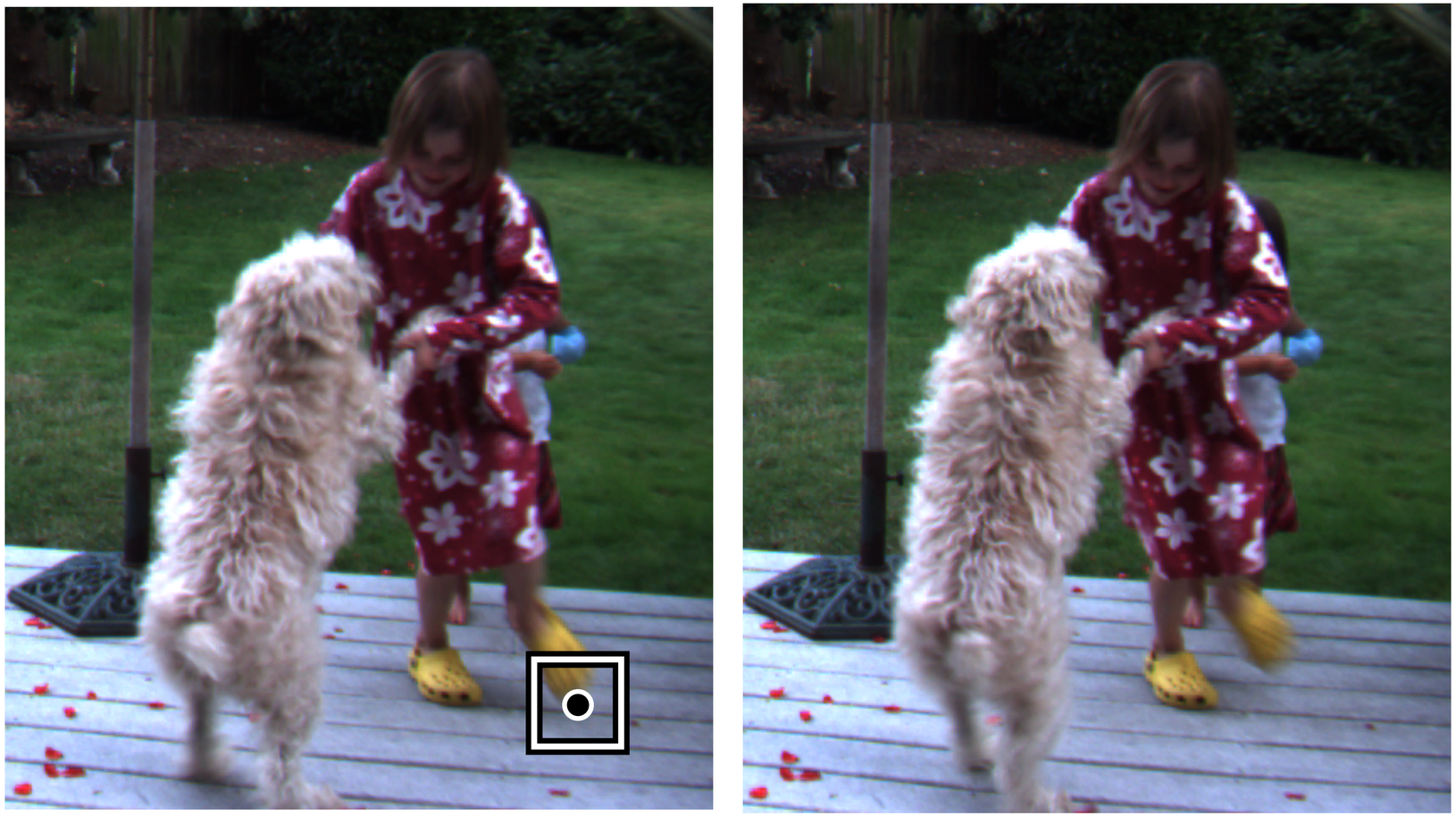
- **Assignment 4**: due Thursday
- **Assignment 5**: Scene Recognition with Bag of Words is now available

2-view Rigid Matching

- **1D search**, points constrained to lie along epipolar lines

2-view Non-Rigid Matching

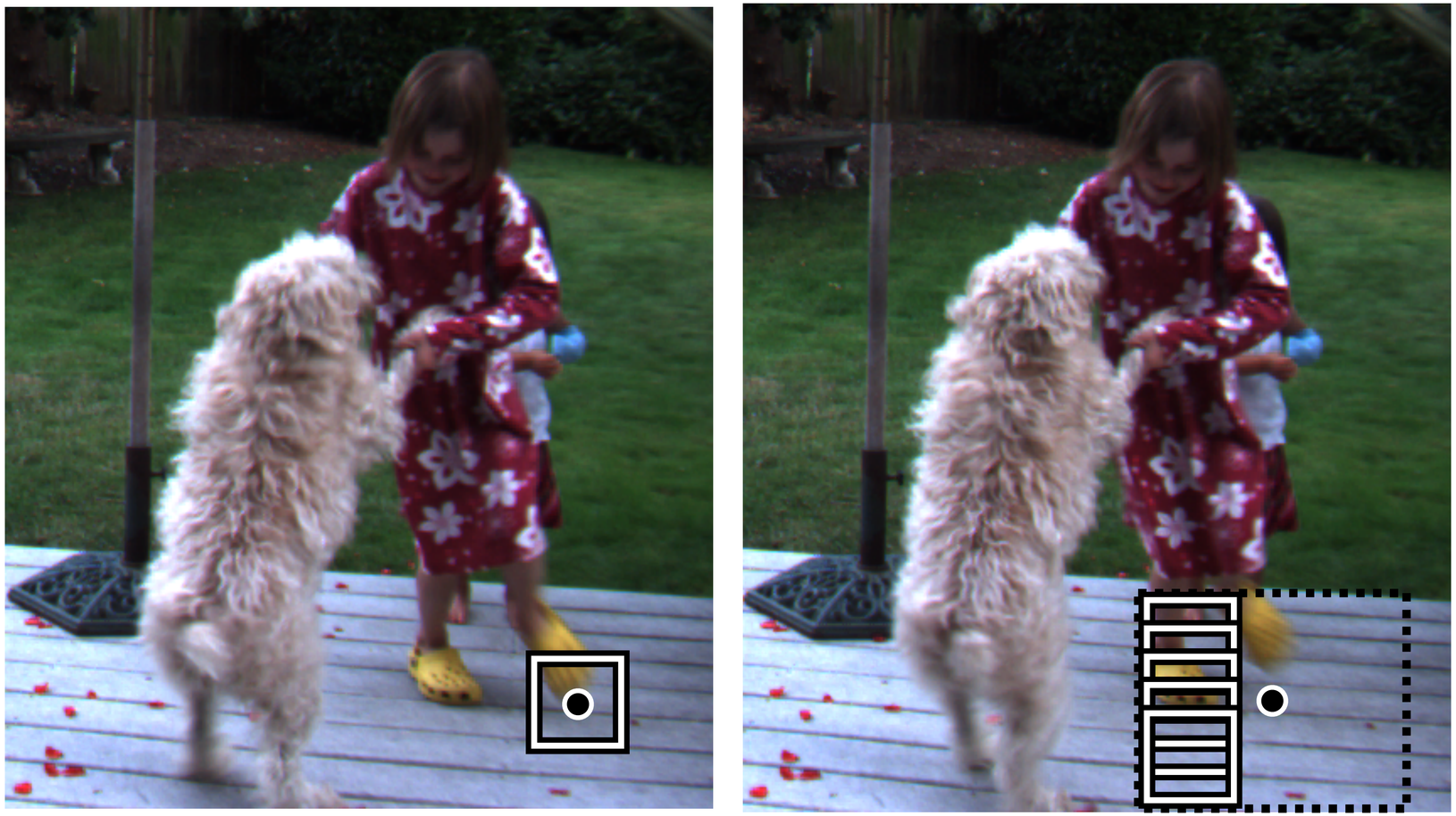
- **2D search**, points can move anywhere in the image



[vision.middlebury.edu/flow]

2-view Non-Rigid Matching

- **2D search**, points can move anywhere in the image



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2-view Non-Rigid Matching

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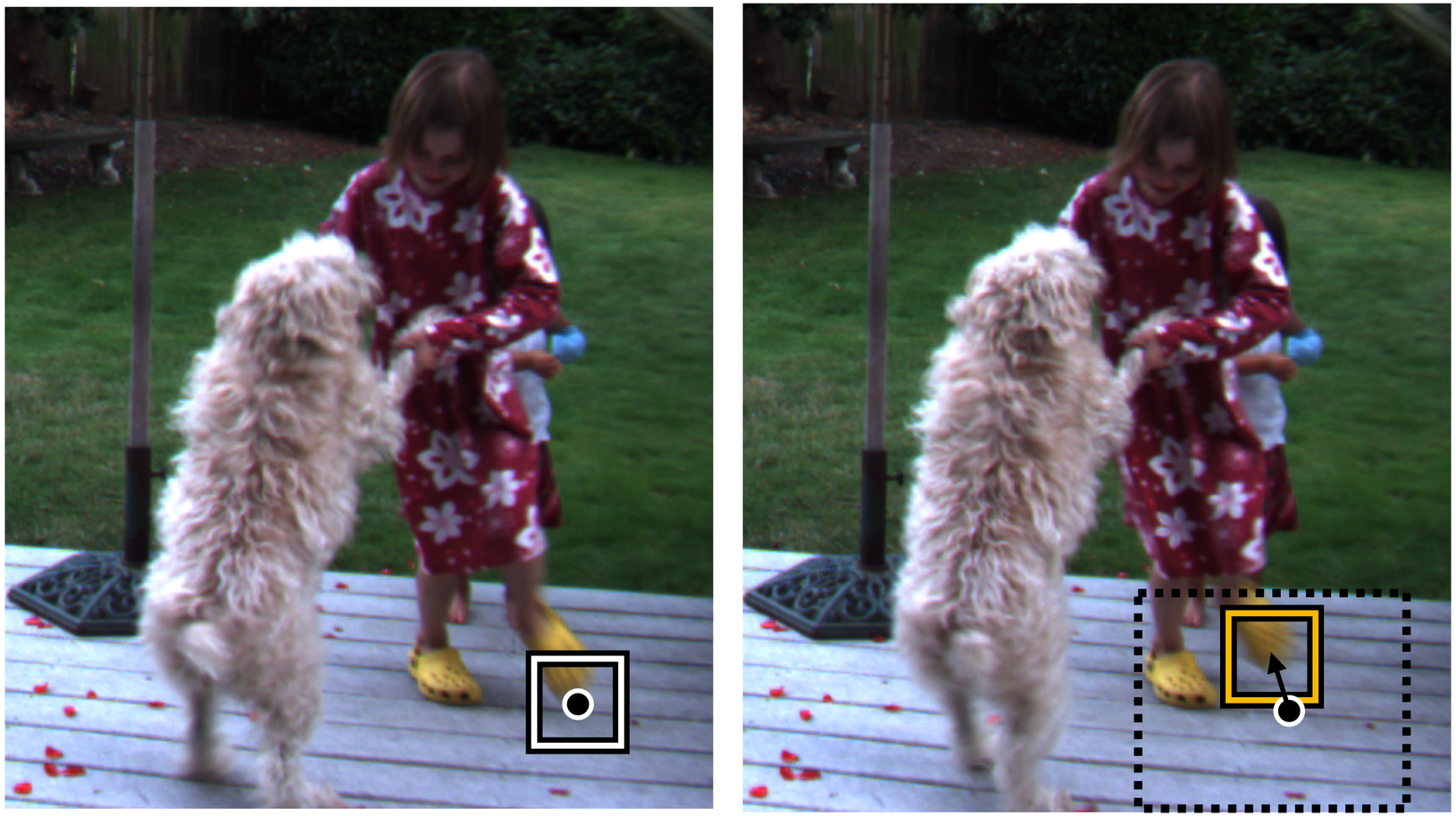

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2-view Non-Rigid Matching

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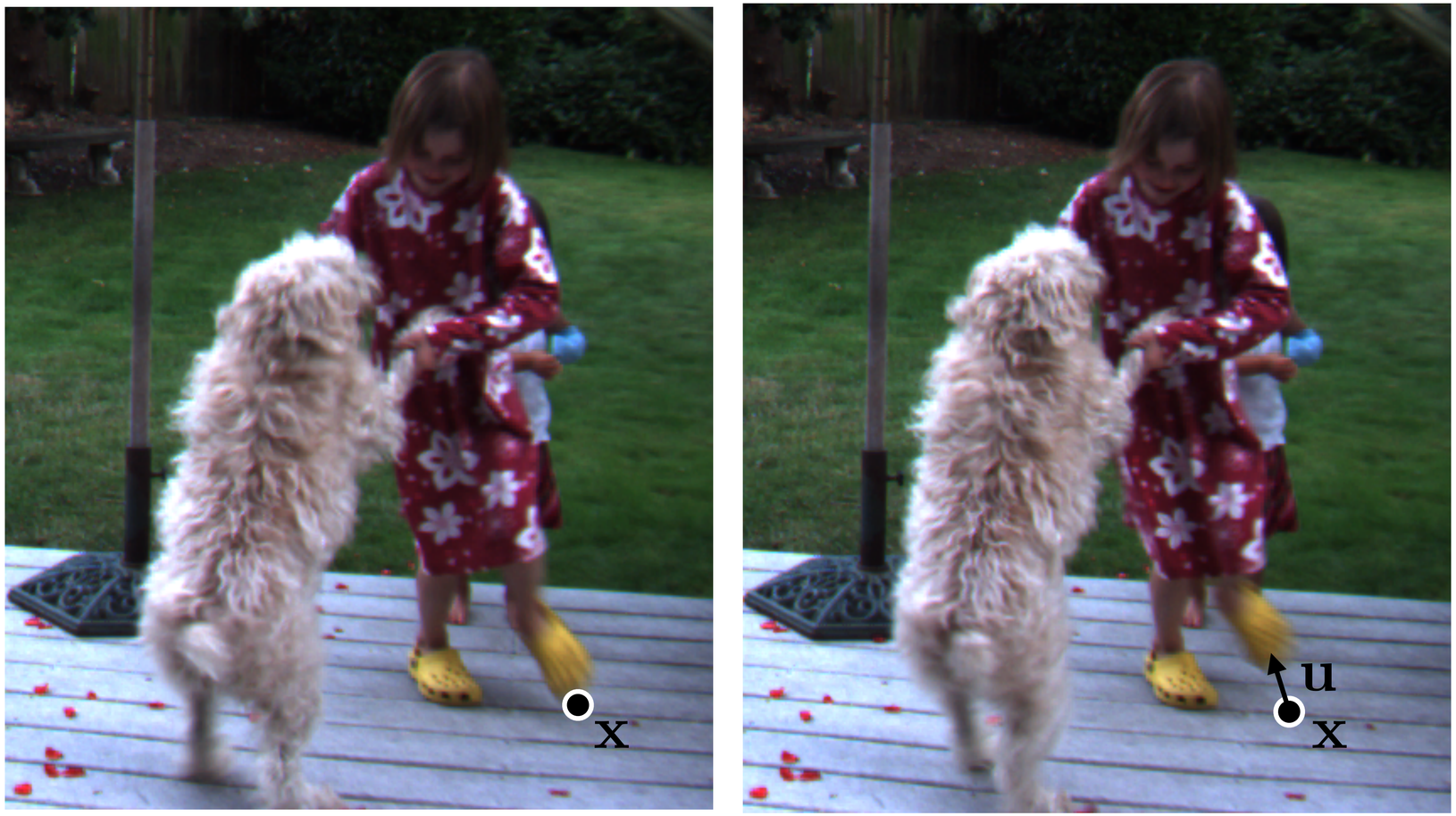
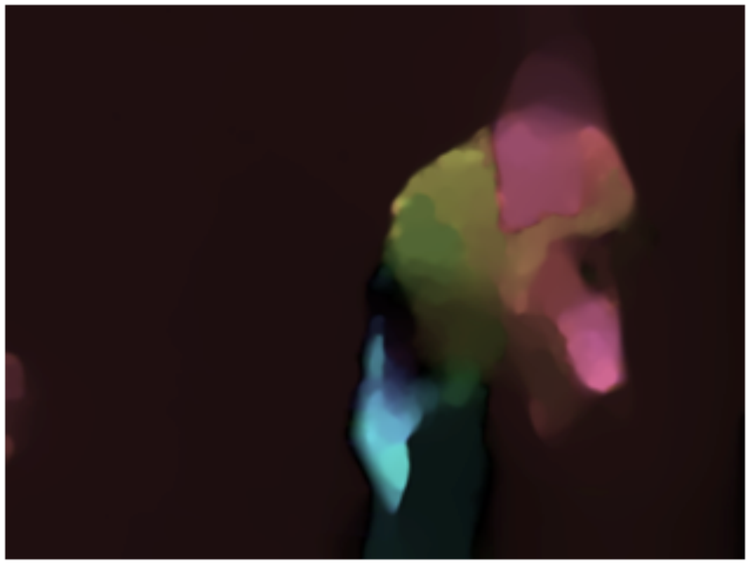
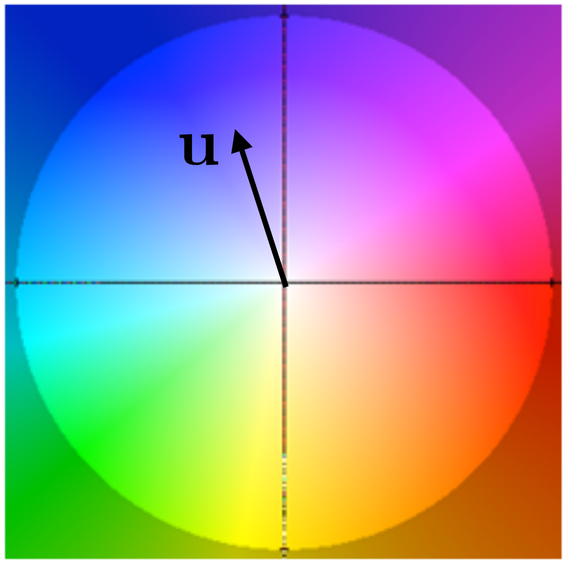


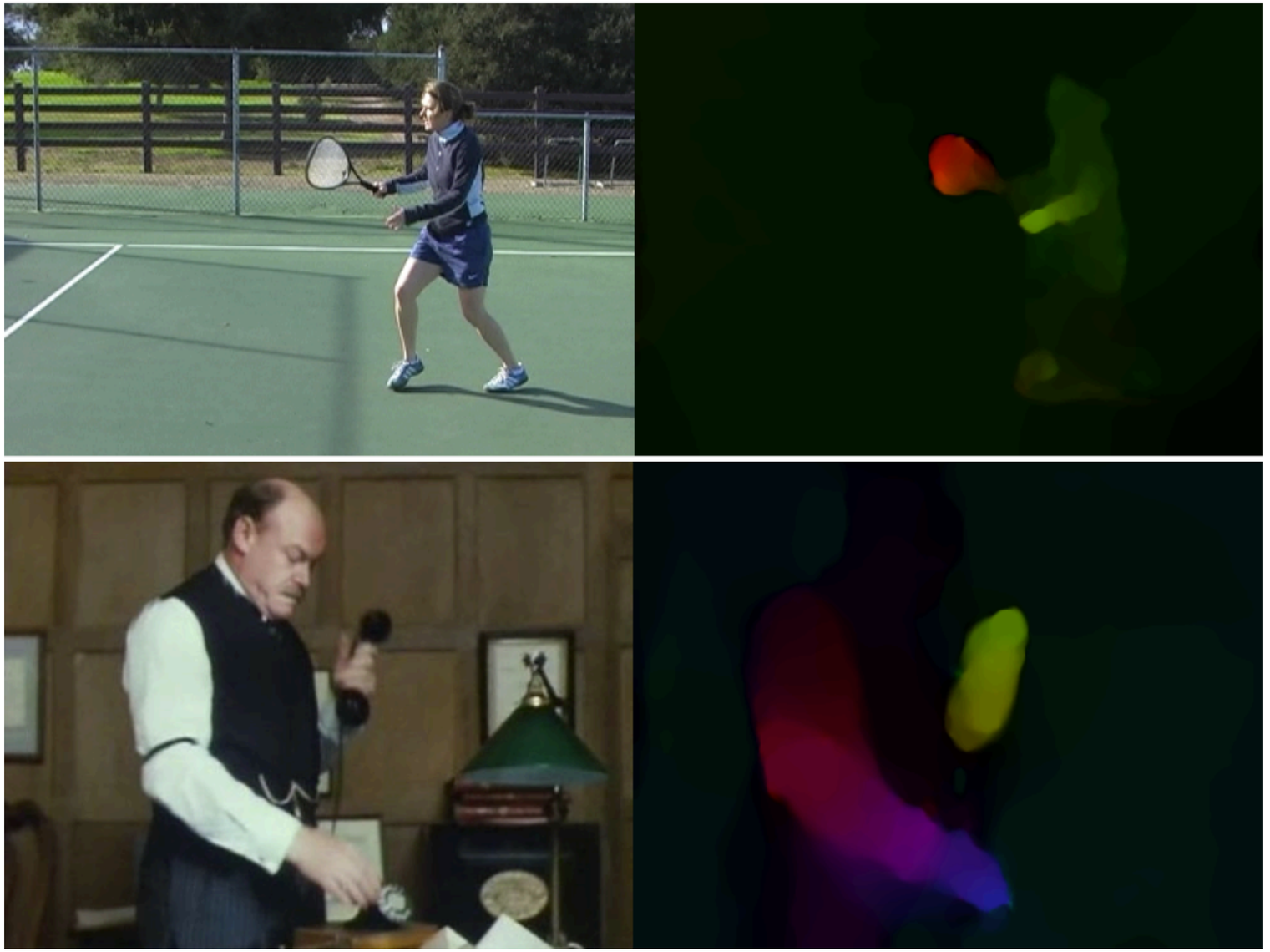
[vision.middlebury.edu/flow]

Optical Flow: Example 1





Optical Flow: Example 2



[Brox Malik 2011]

Optical Flow Recap

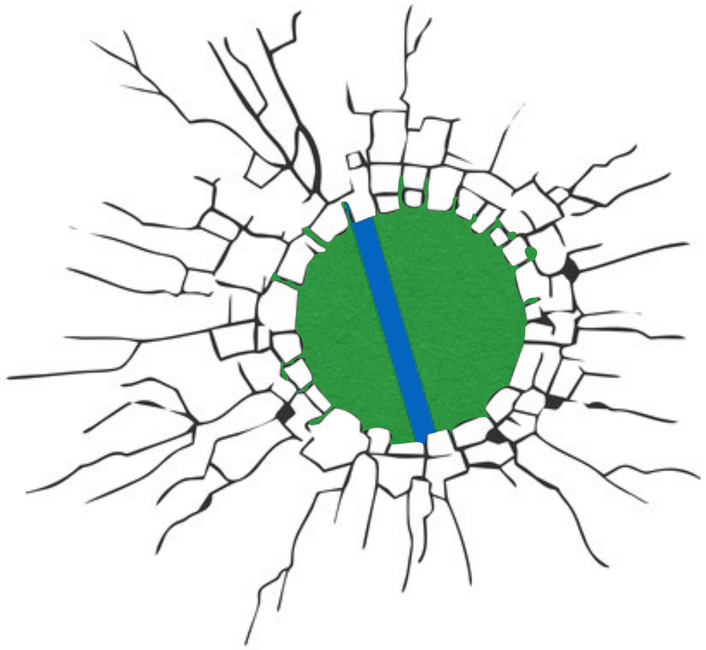
Optical Flow the apparent motion of all pixels in an image between a pair of image frames

Brightness Constancy a point on an object has the same intensity as it moves (in x, y, t)

Optical Flow Constraint the derivative of brightness constancy at a point, relates image gradients in x, y, t and flow vector u,v

$$I_x u + I_y v + I_t = 0$$

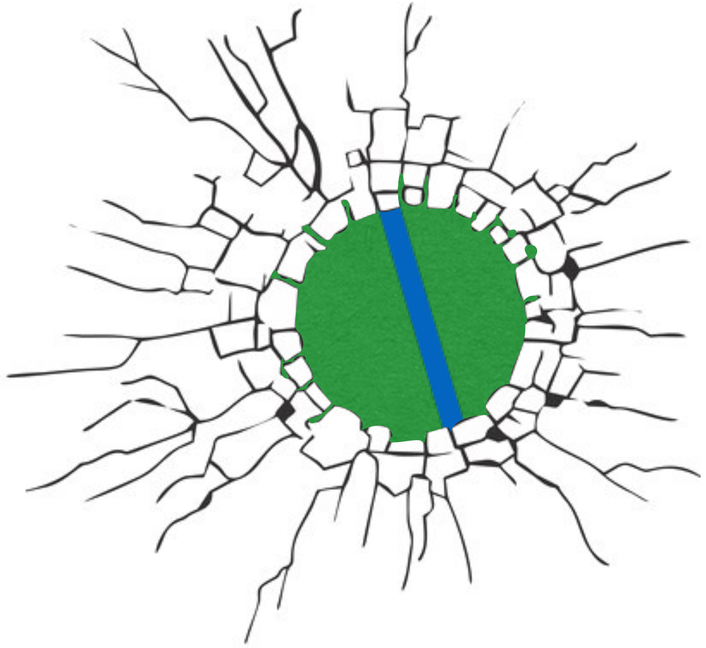
Aperture Problem



In which direction is the line moving?

Image Credit: Ioannis (Yannis) Gkioulekas (CMU)

Aperture Problem



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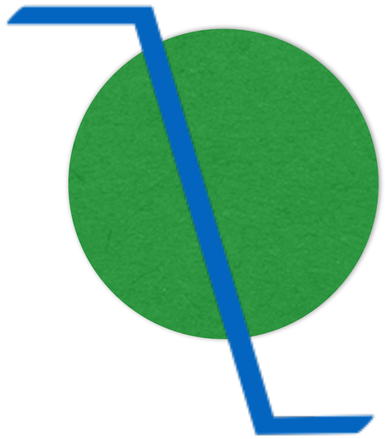

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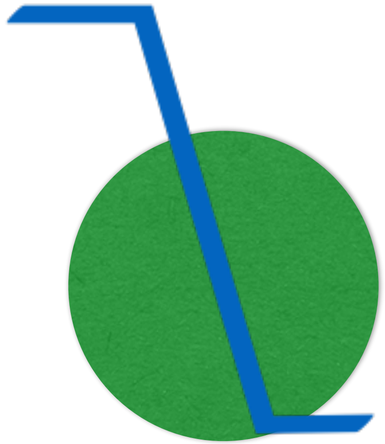

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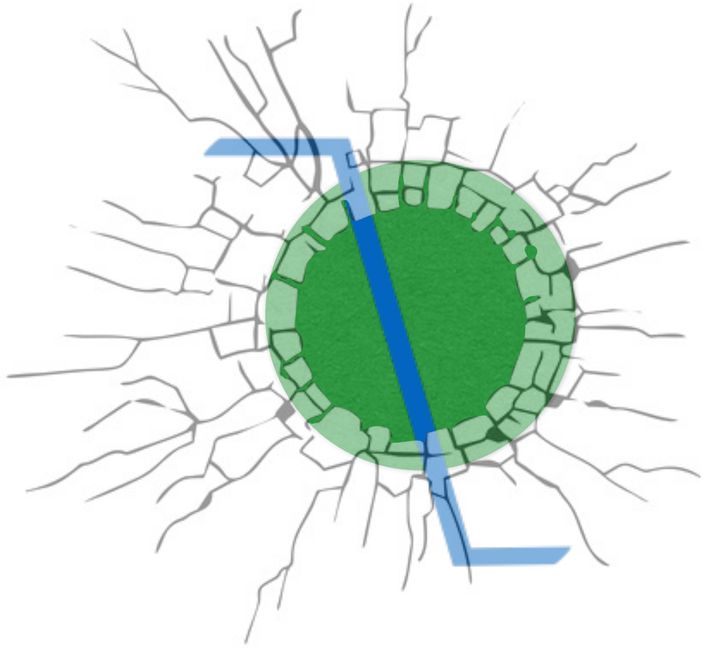

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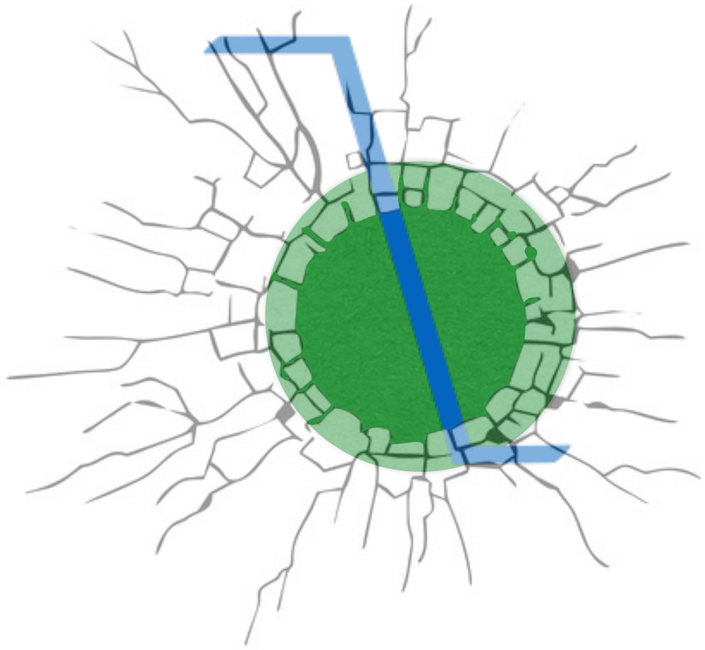

Image Credit: Ioannis (Yannis) Gkioulekas (CMU)

Optical Flow Algorithms

Flow Ambiguity component of velocity parallel to an edge is not defined by the above constraint → aperture problem

Lucas Kanade resolves the ambiguity by adding multiple pixels (each with 1D optical flow constraint) → linear system to solve for 2D flow

Other flow algorithms (e.g., Horn Schunck) use **priors over the 2D flow field** (e.g., smoothness)

Multiview + Sparse SFM

- Multiview Image Alignment, Residuals, Error Function
- Structure from Motion (SFM)
- Bundle Adjustment, Pose Estimation, Triangulation

[Szeliski 11.4]

Multiview Image Alignment

- Align a set of images given a motion model (e.g., planar affine)

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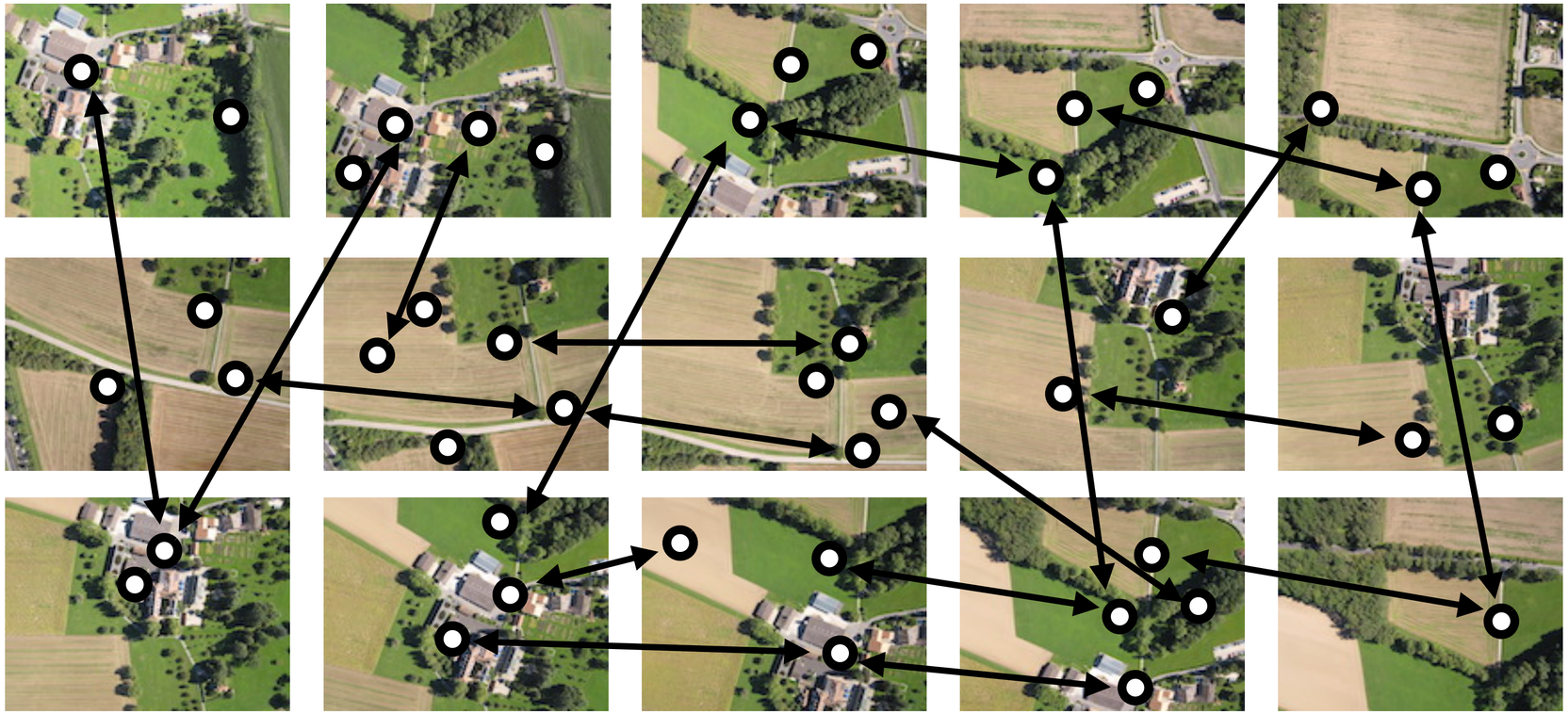
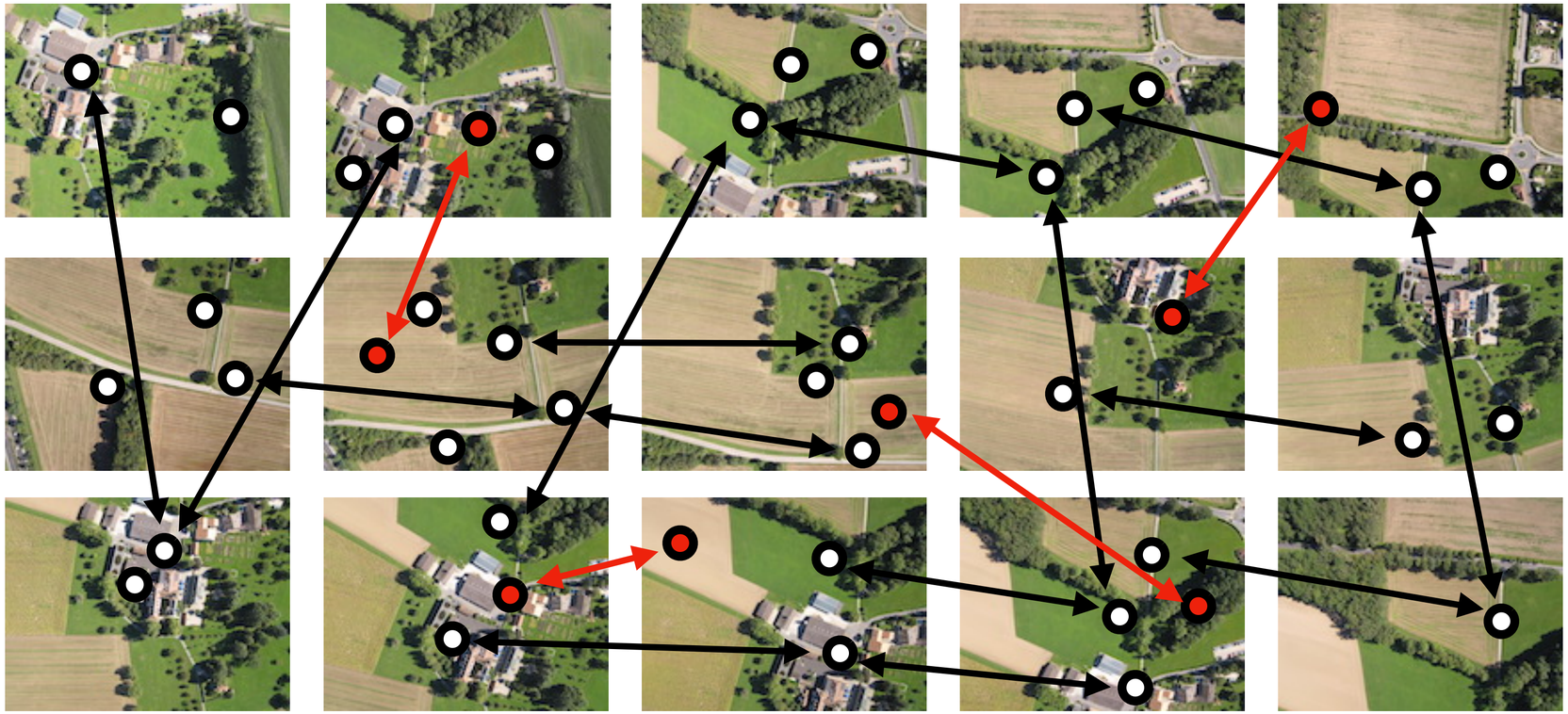


Step 1: Find all matches between images using SIFT

Multiview Image Alignment

- Align a set of images given a motion model (e.g., planar affine)



Step 1: Find all matches between images using SIFT

Step 2: Remove incorrect matches using RANSAC

Multiview Image Alignment

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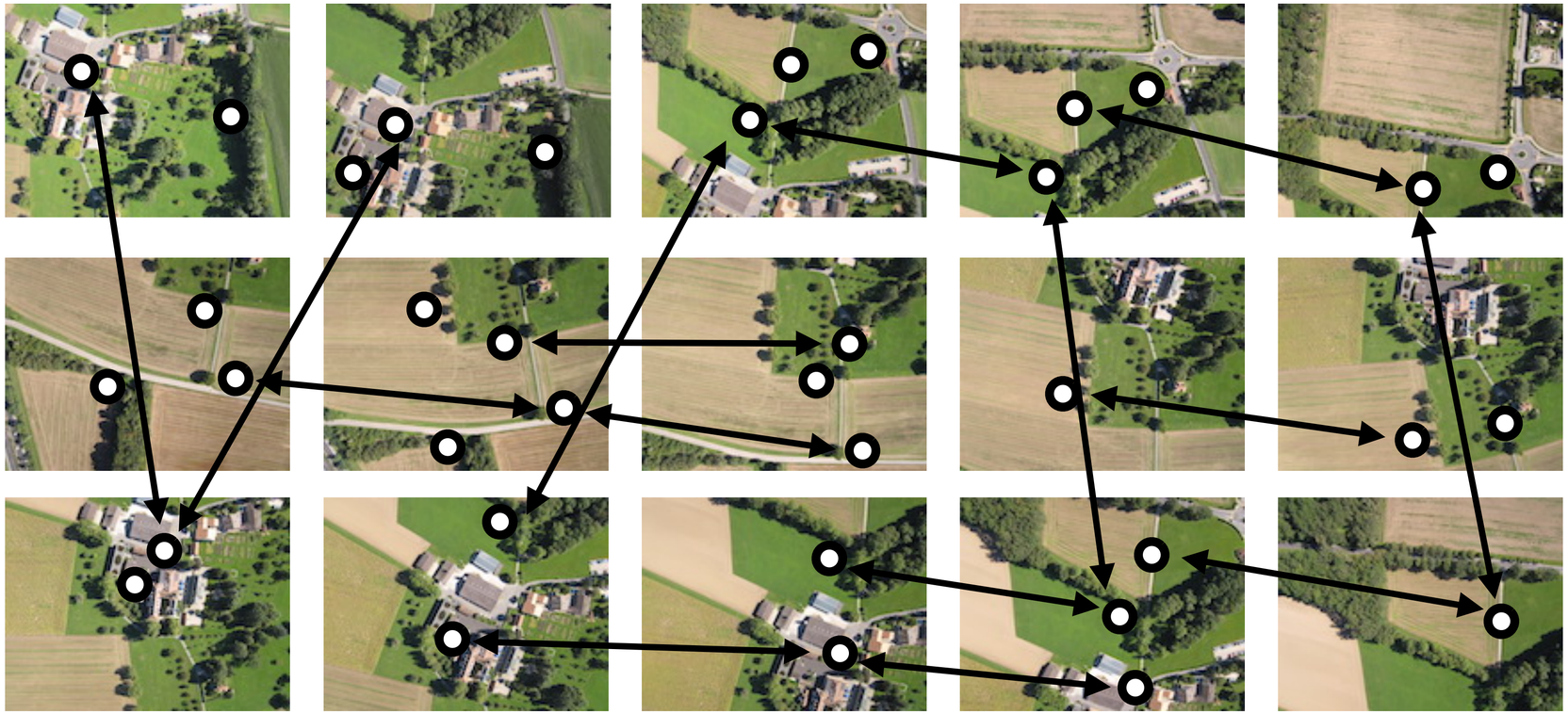

Step 1: Find all matches between images using SIFT

Step 2: Remove incorrect matches using RANSAC

RANSAC recap

- RANSAC solution for Similarity Transform (2 points)

RANSAC recap

- RANSAC solution for Similarity Transform (2 points)

4 inliers (red, yellow, orange, brown),

4 outliers (blue, light blue, purple, pink)

RANSAC recap

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RANSAC recap

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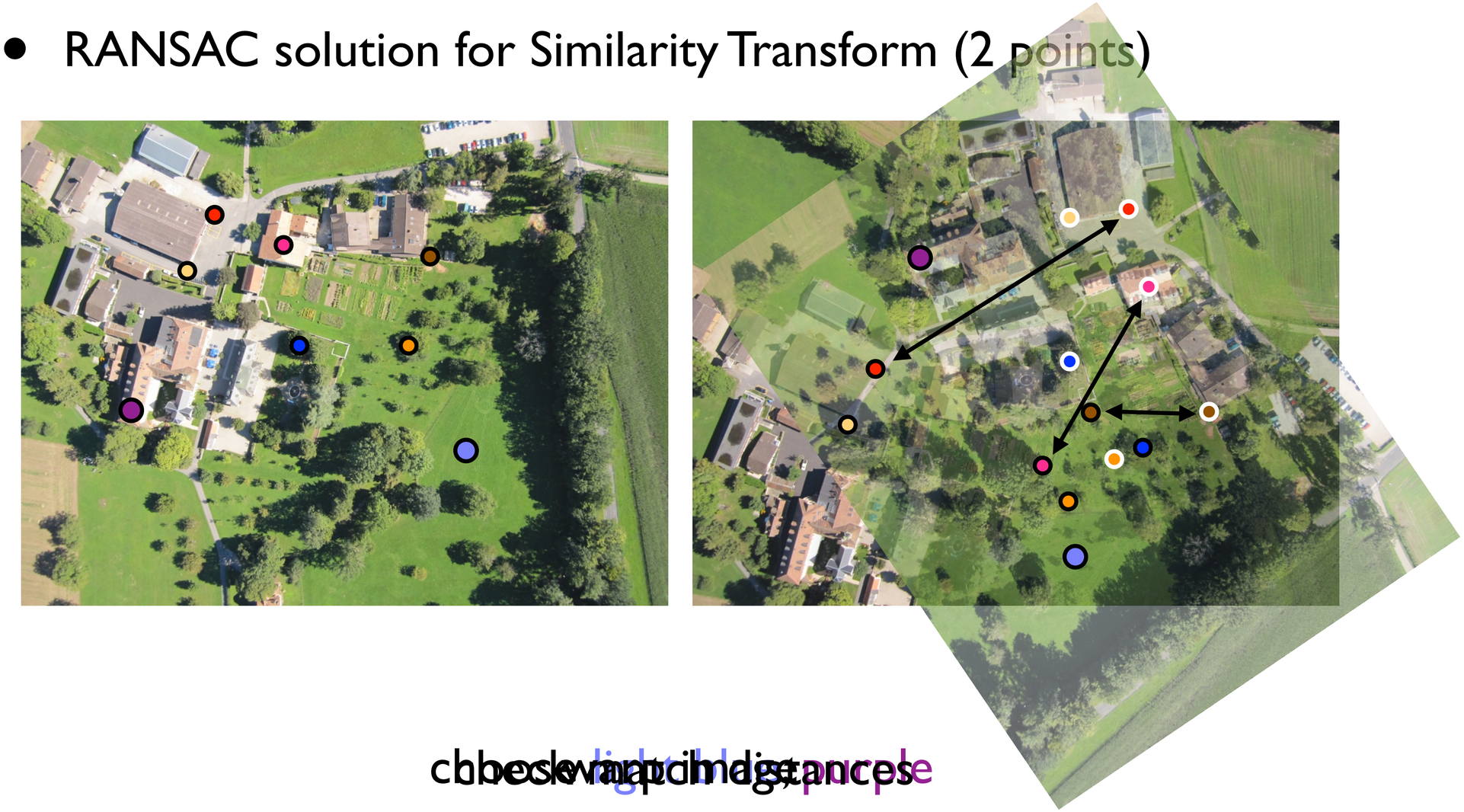


choose random matches

check warp distances

light blue, purple

#inliers = 2

RANSAC recap

- RANSAC solution for Similarity Transform (2 points)

RANSAC recap

- RANSAC solution for Similarity Transform (2 points)

check overlap in pink blue

#inliers = 2

RANSAC recap

- RANSAC solution for Similarity Transform (2 points)

RANSAC recap

- RANSAC solution for Similarity Transform (2 points)

check overlap, image areas

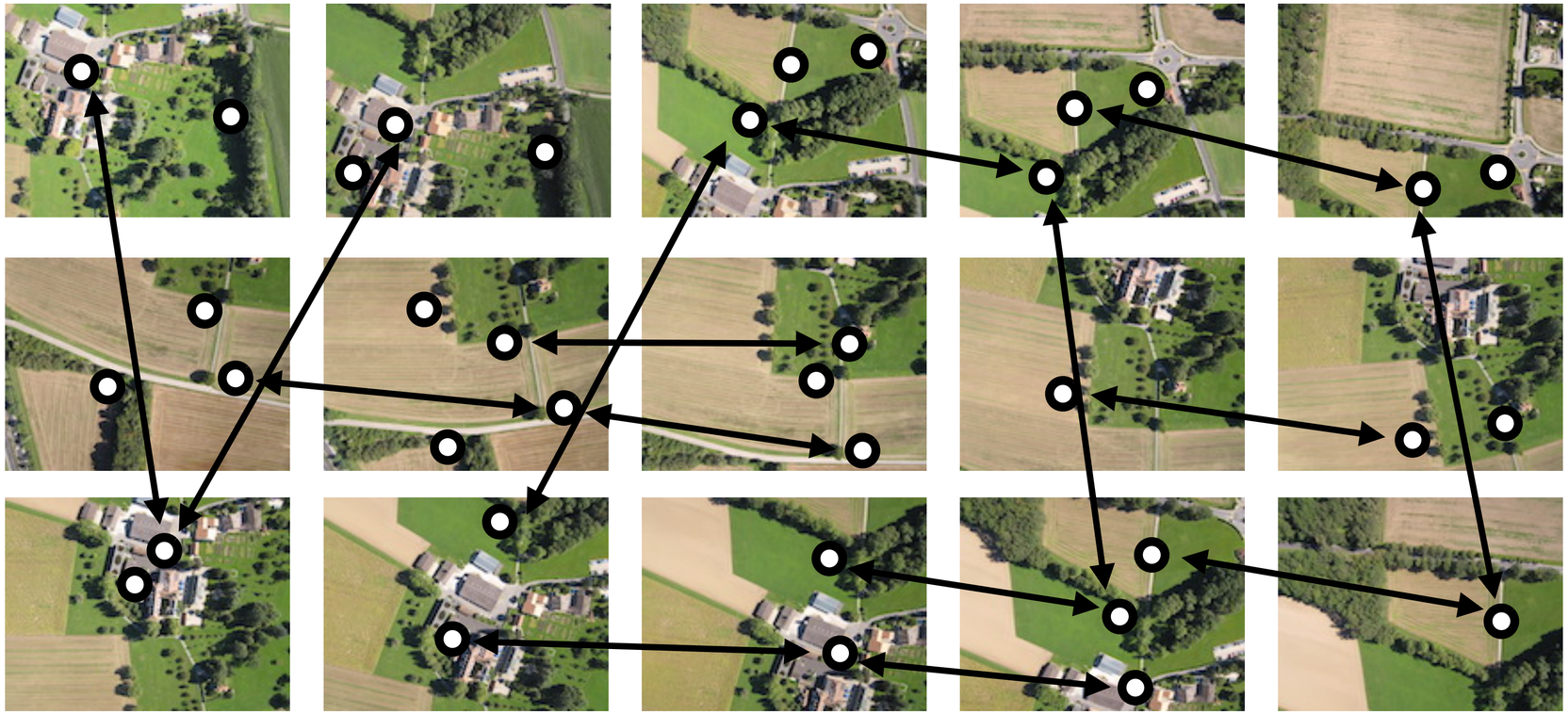
#inliers = 4

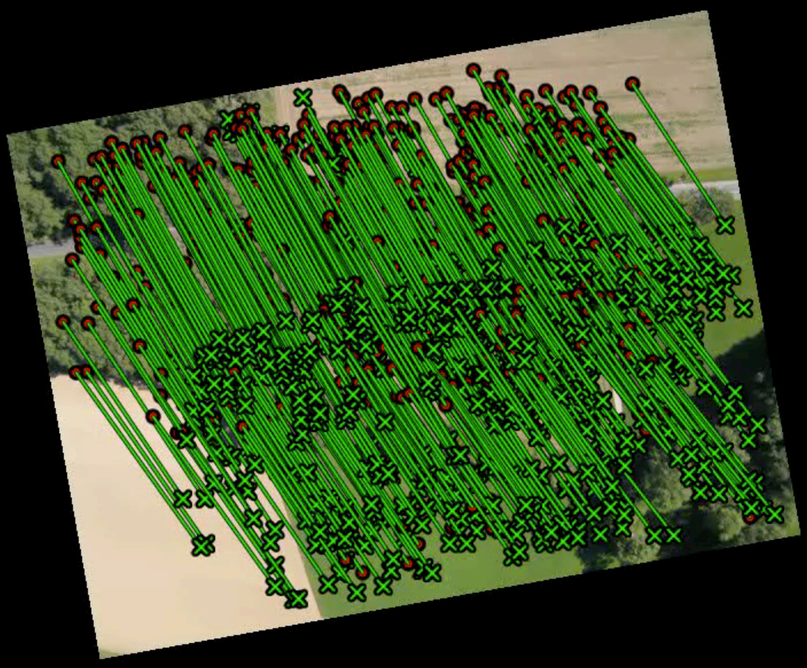
RANSAC recap

- RANSAC solution for Similarity Transform (2 points)

Planar Image Alignment

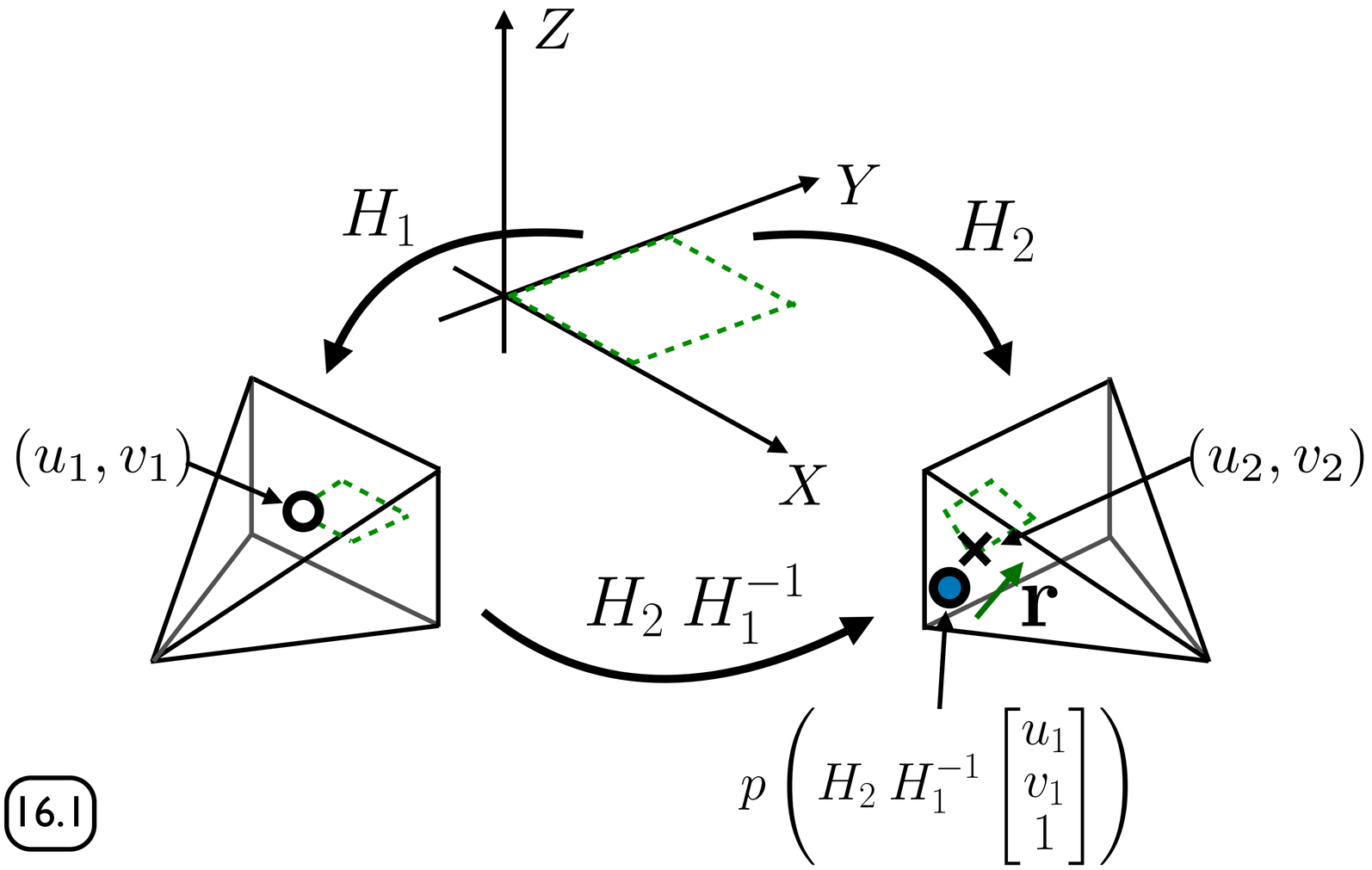
- Given a clean set of correspondences, align all images





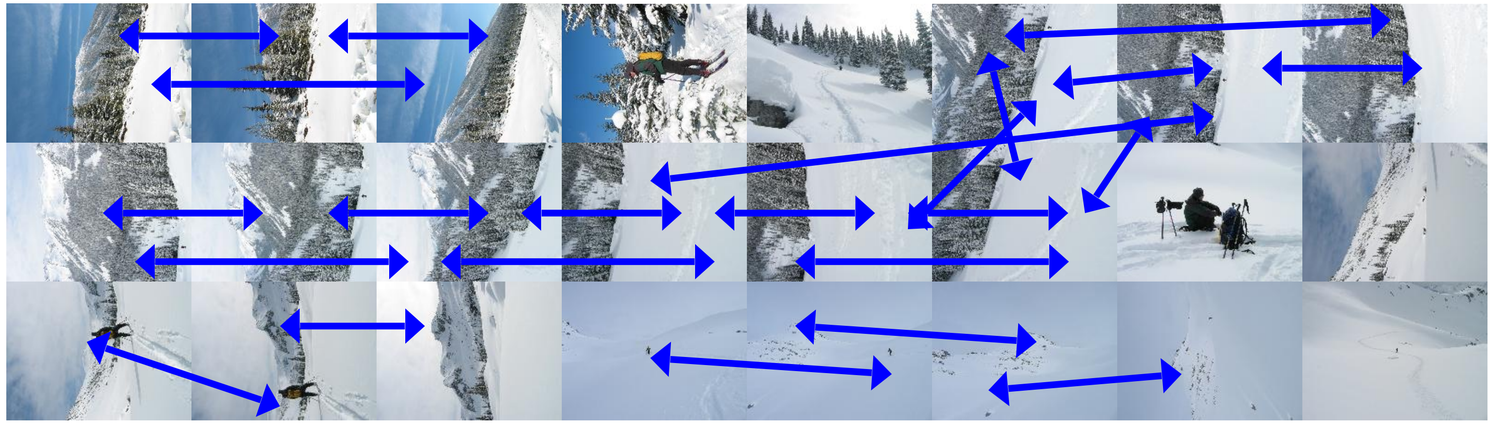
Multiview Image Alignment

- Residual = vector between observed feature and projection

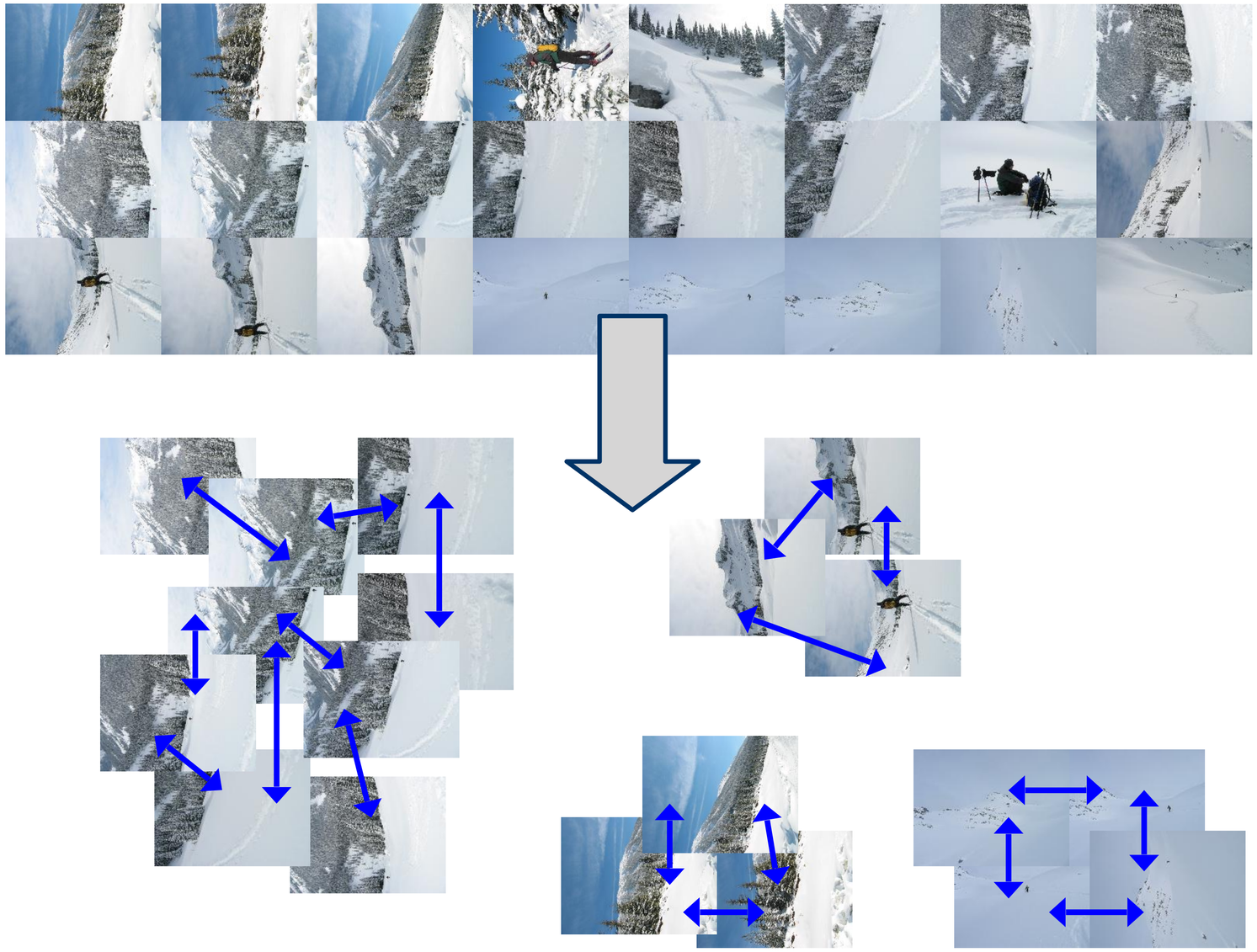


16.1

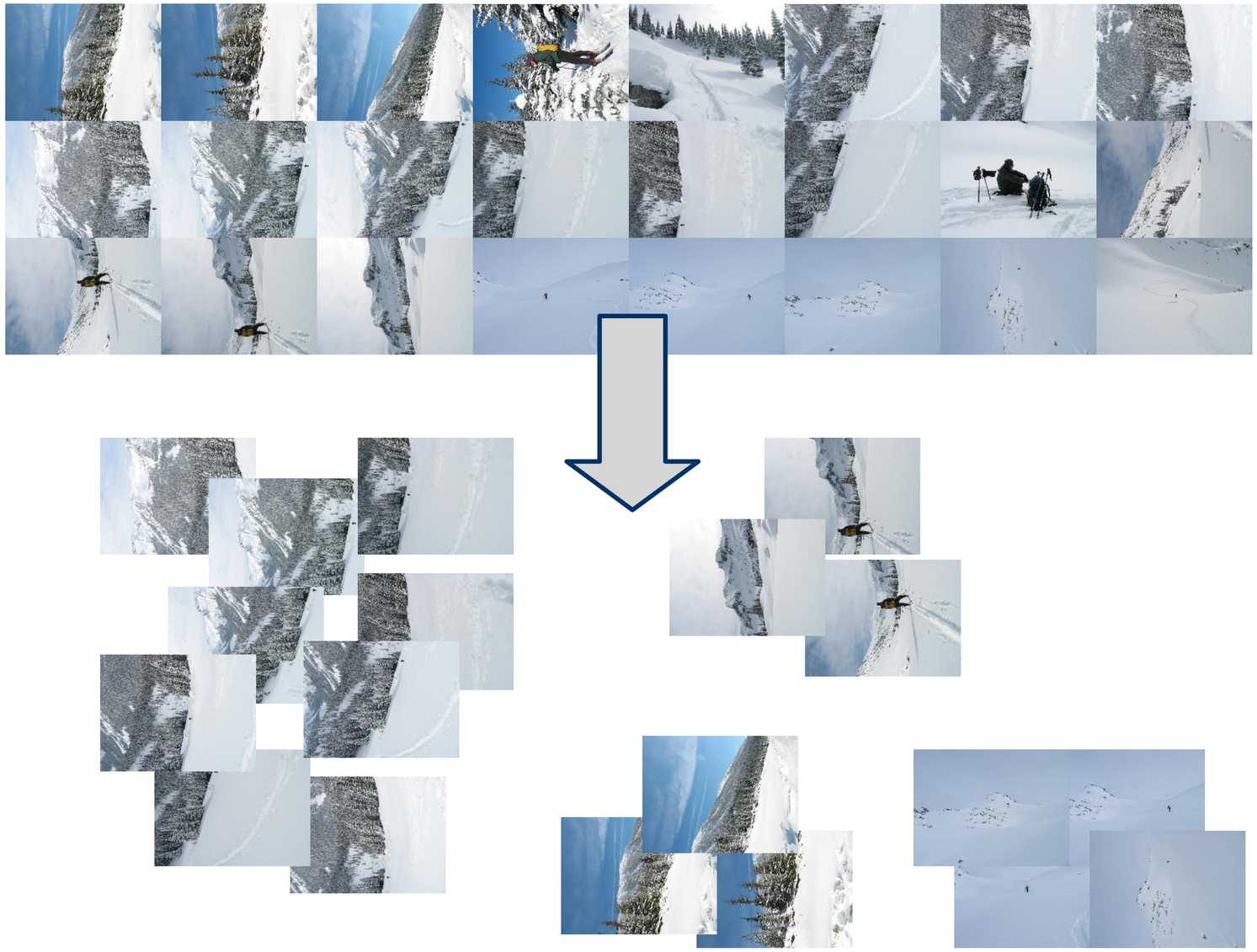
Panorama Recognition



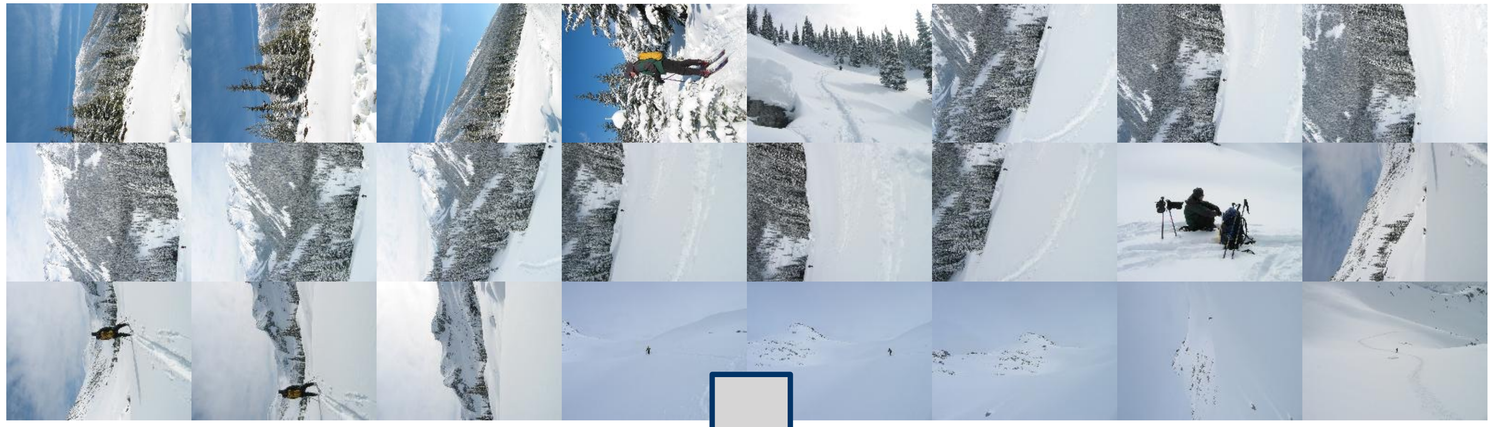
Panorama Recognition

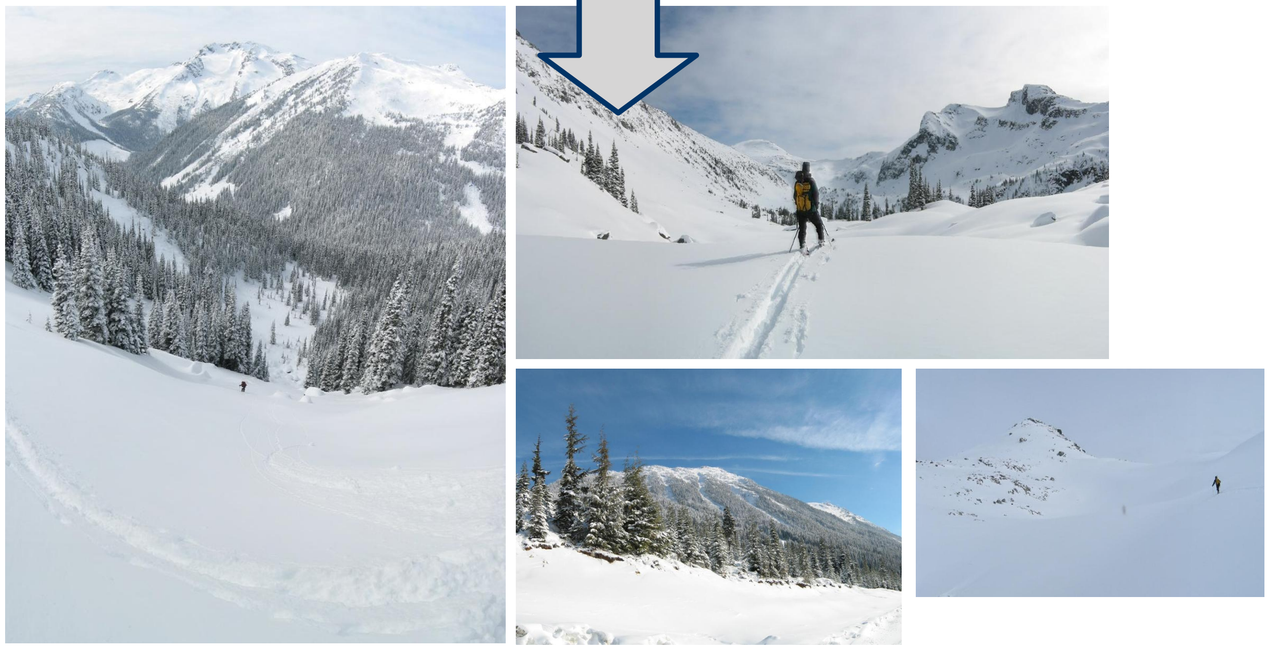


Panorama Recognition



Panorama Recognition





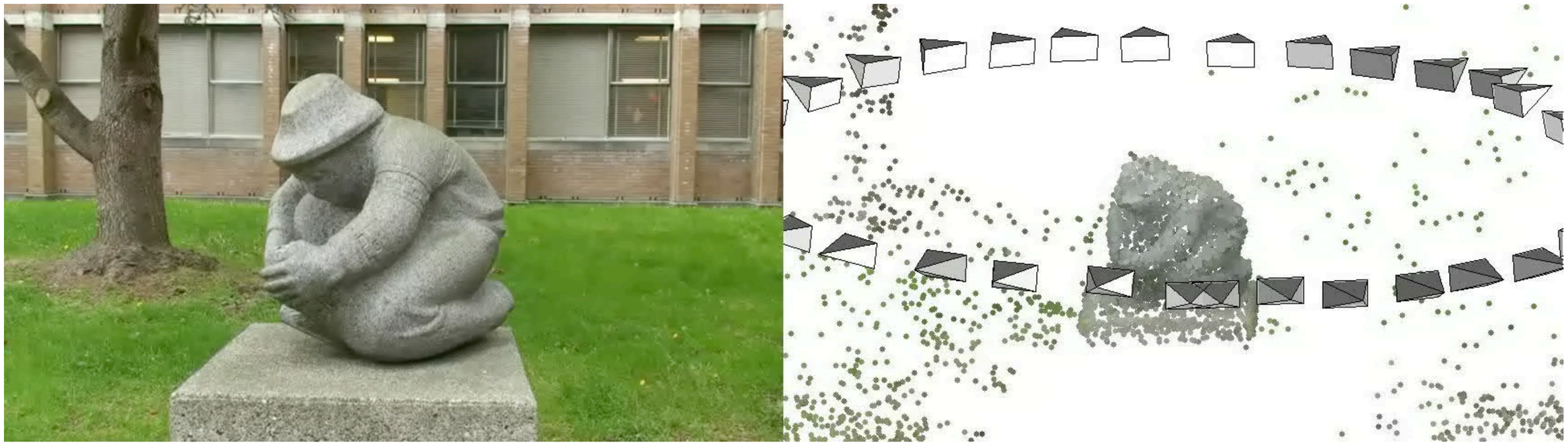
Panorama Stitching

- We can concatenate pairwise homographies, but over time multiple pairwise mappings accumulate errors
- We use global alignment (bundle adjustment) to close the gap

Structure from Motion

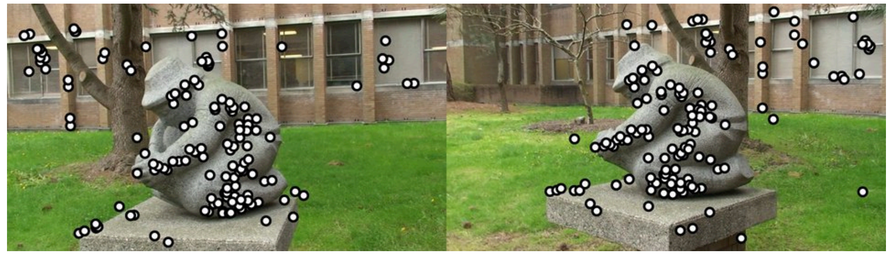
Given an (unordered) set of input images, compute cameras and 3D structure of the scene

Structure from Motion



2-view Structure from Motion

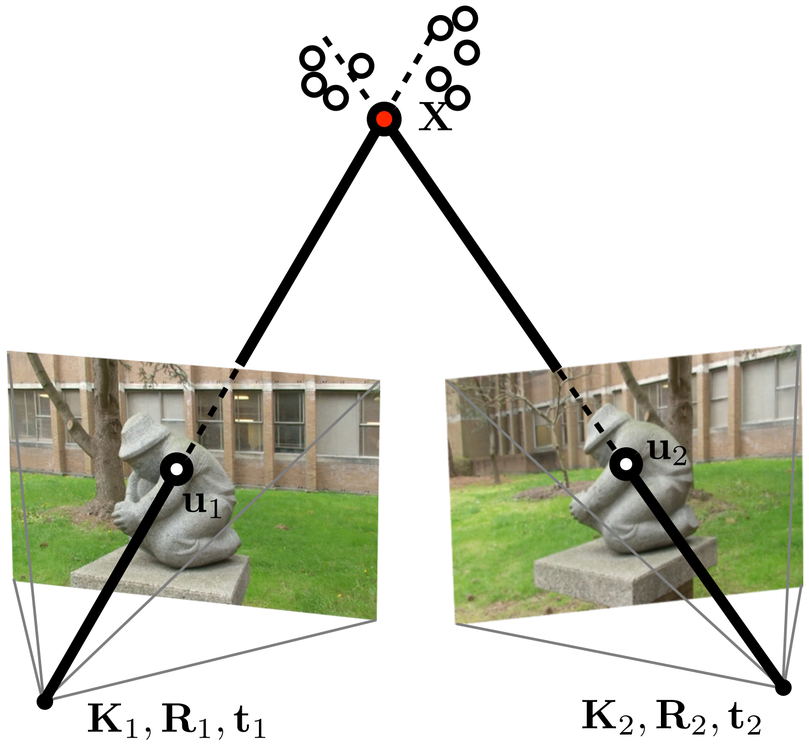
- We can use the combination of SIFT/RANSAC and triangulation to compute 3D structure from 2 views



Raw SIFT matches

RANSAC for Epipolar Geom

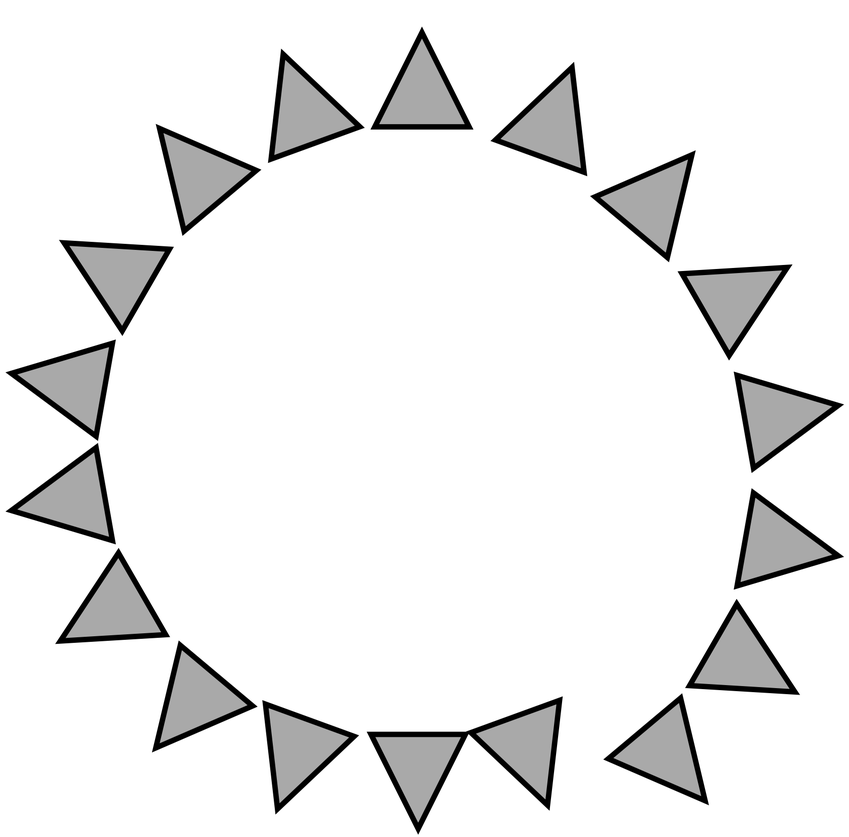
Extract R, t



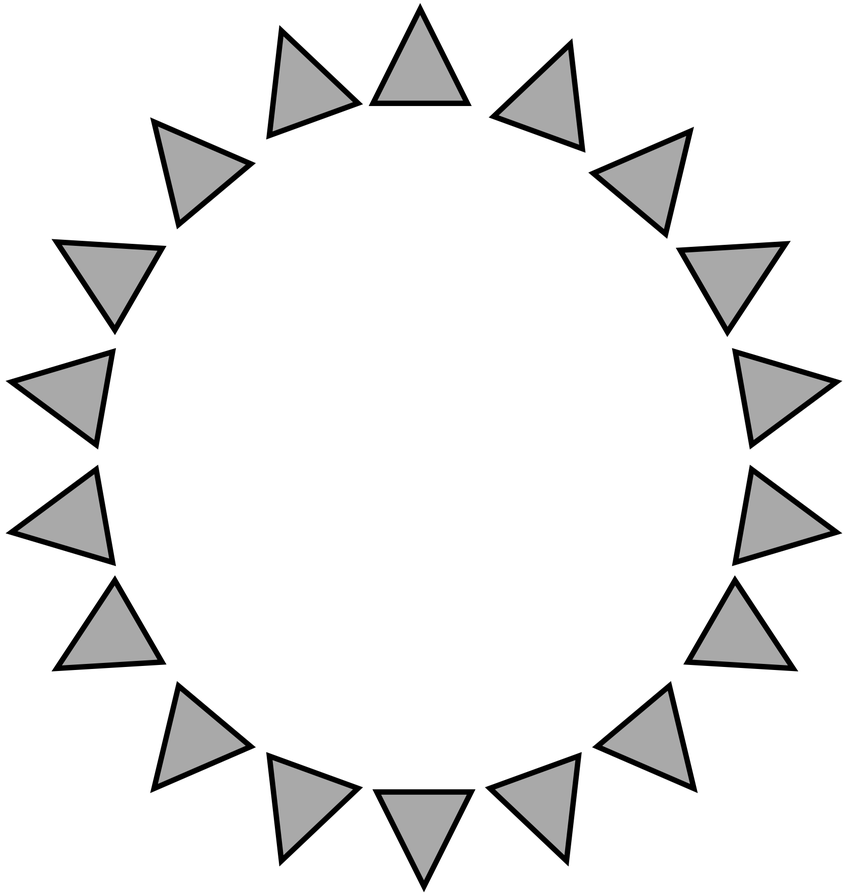
Triangulate to 3D Point Cloud

Global Alignment

- Concatenation of pairwise R, t estimates results in drift, e.g.,



Pairwise alignment



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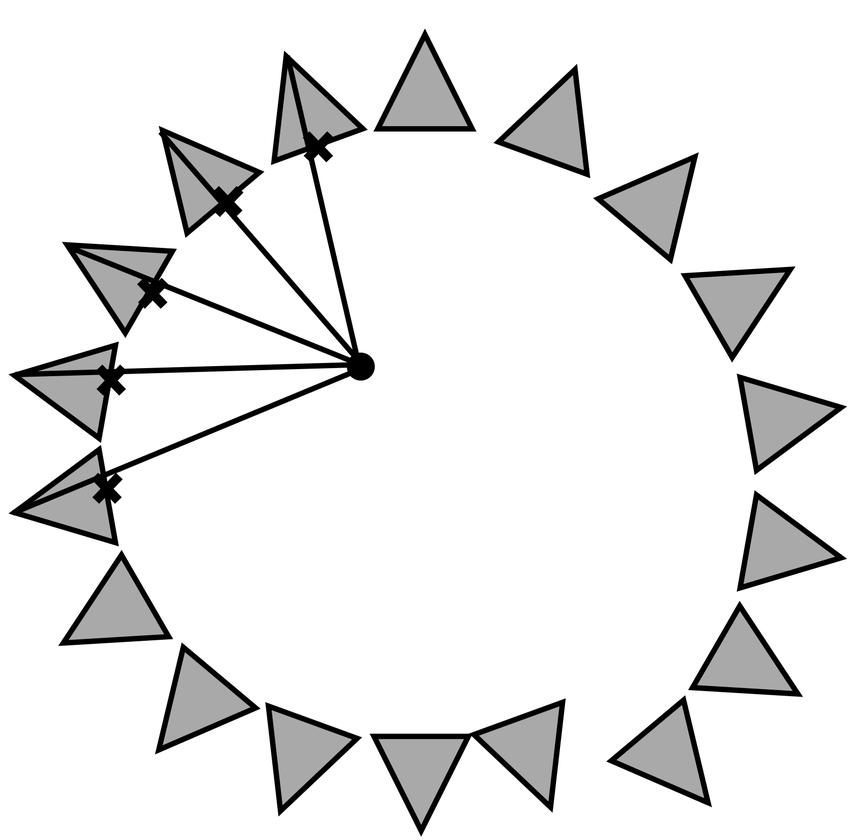
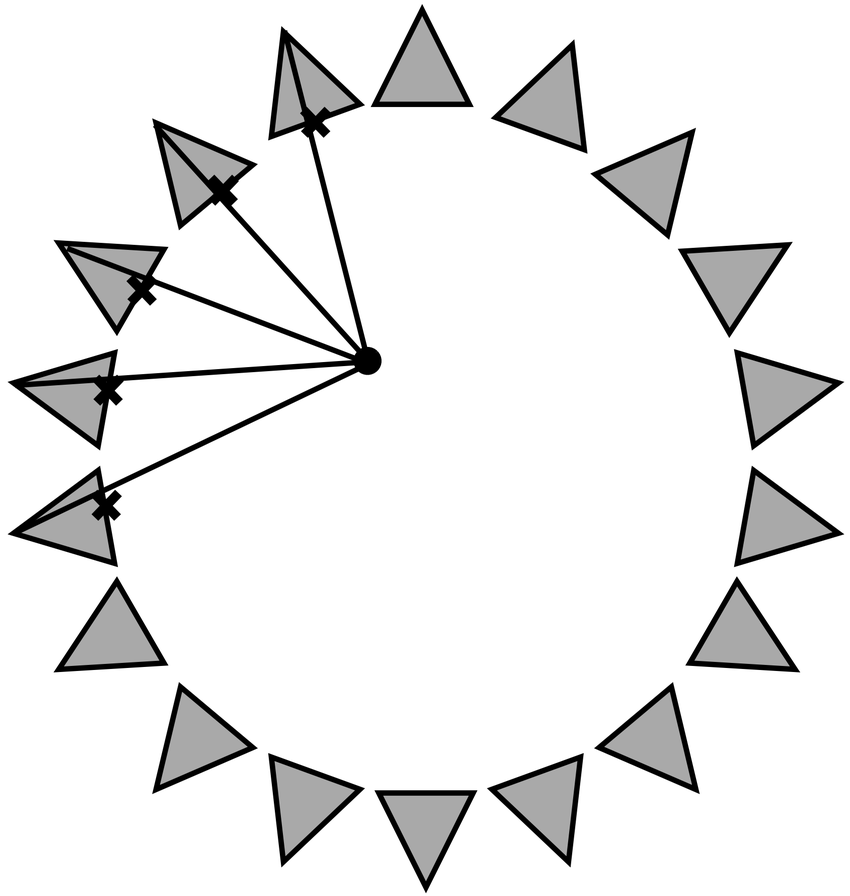


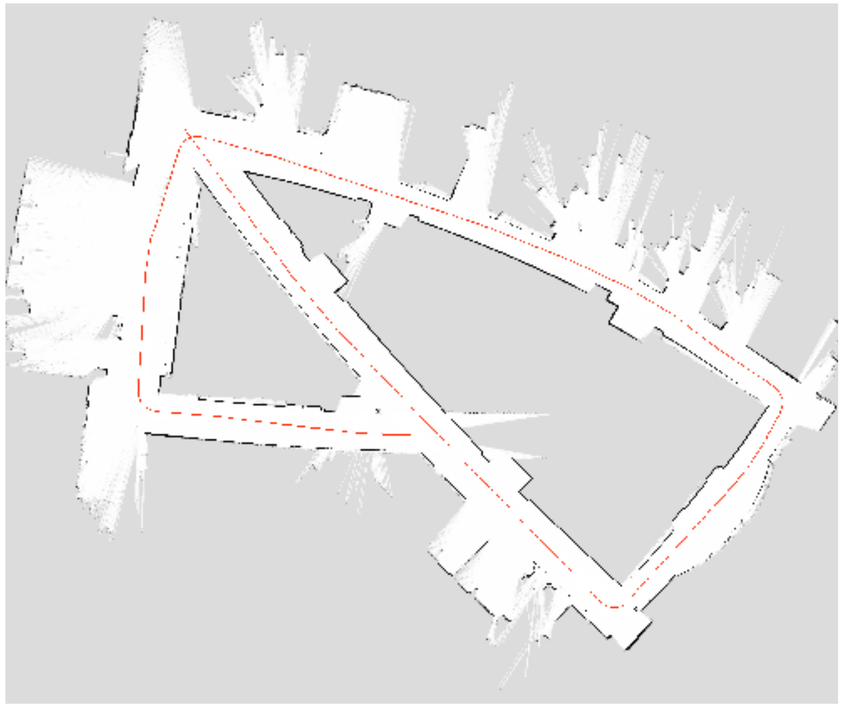
Pairwise alignment



Global alignment

Global Alignment

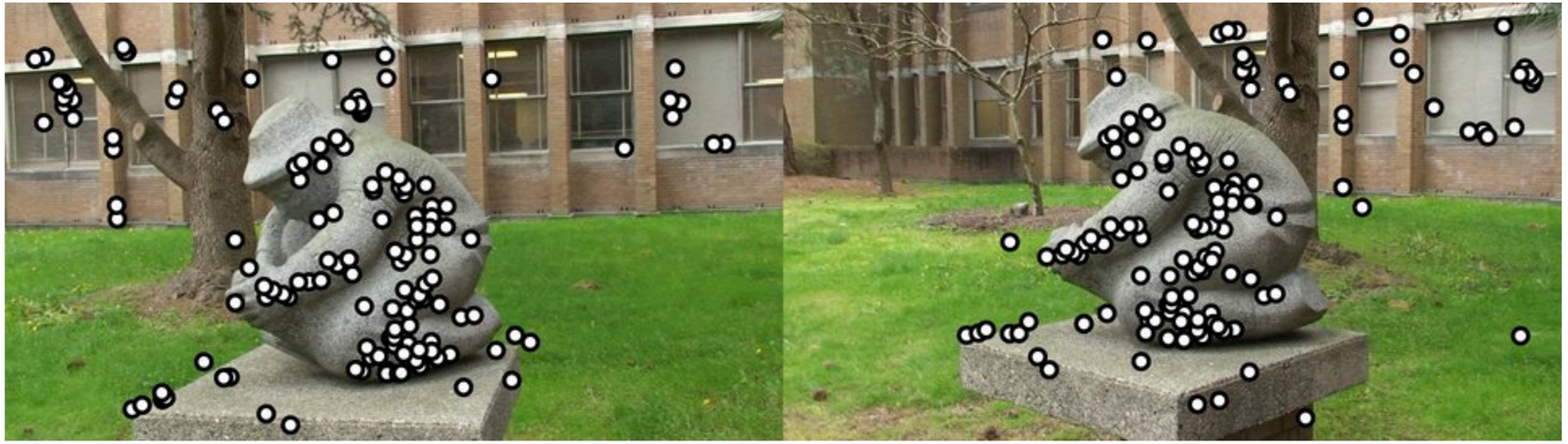
- In robotic navigation frame-frame alignment also causes drift



We can use **bundle adjustment** to close the gap

[Kaess Dellaert 2010]

RANSAC for 3D Matches

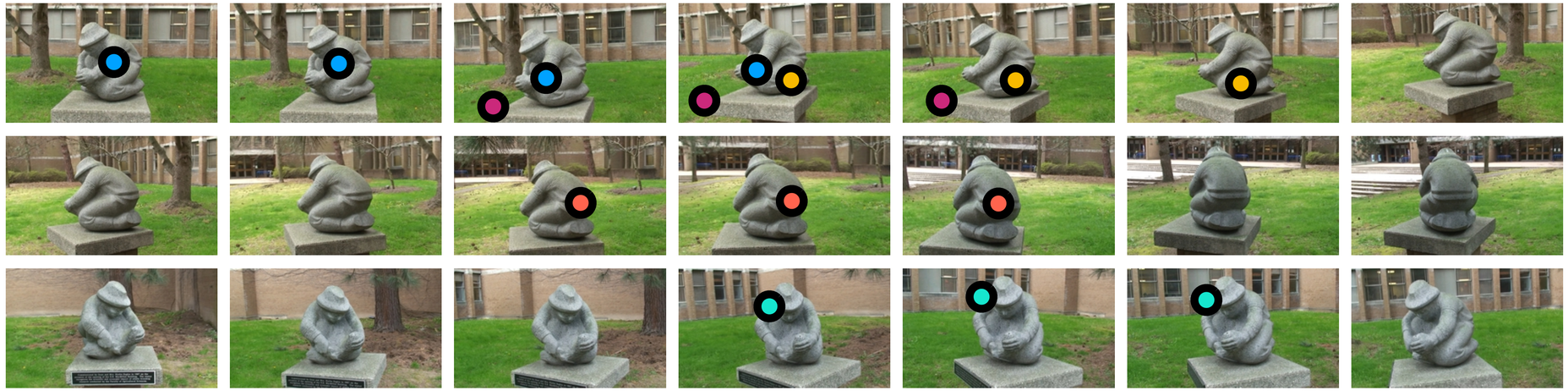


Raw feature matches (after ratio test filtering)

Solved for RANSAC inliers

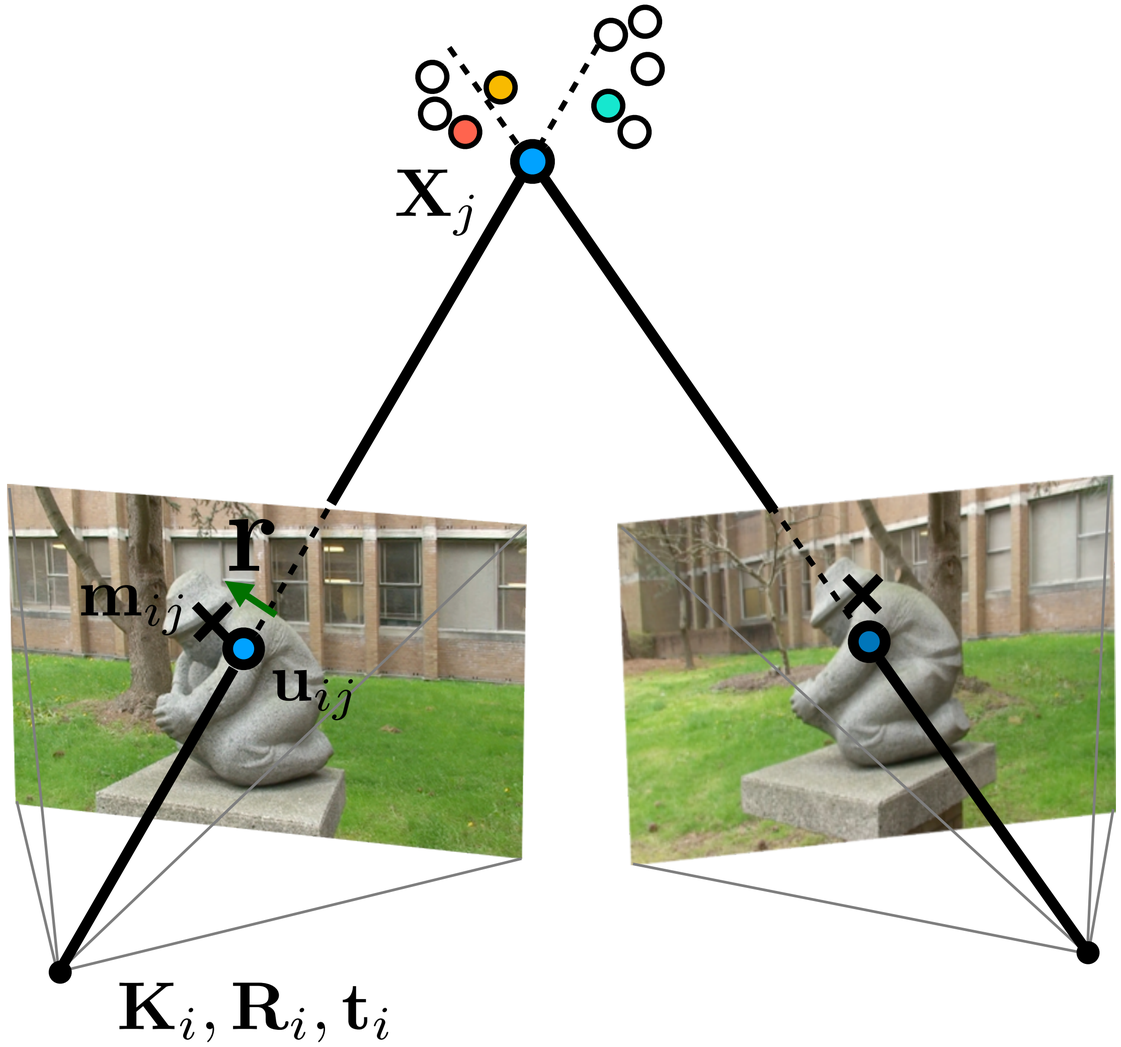
Feature Tracking

- Form feature tracks by combining pairwise feature matches



- Tracked features become individual 3D points in the reconstruction
- Features matched across 3 or more views provide strong constraints on the 3D reconstruction

Bundle Adjustment



- Minimise errors projecting 3D points into all images

$$e = \sum_{i \in \text{images}} \sum_{j \in \text{points}} |\mathbf{r}_{ij}(\mathbf{R}_i, \mathbf{t}_i, \mathbf{X}_j)|^2$$

[Szeliski 11.4]

Bundle Adjustment

- Full bundle adjustment (optimise all cameras and points):

$$e = \sum_{i \,\epsilon\, \text{images}} \sum_{j \,\epsilon\, \text{points}} |\mathbf{r}_{ij}(\mathbf{R}_i, \mathbf{t}_i, \mathbf{X}_j)|^2$$

- Triangulation (optimise points, fixed cameras):

$$e = \sum_{i \,\epsilon\, \text{images}} \sum_{j \,\epsilon\, \text{points}} |\mathbf{r}_{ij}(\mathbf{R}_i, \mathbf{t}_i, \mathbf{X}_j)|^2$$

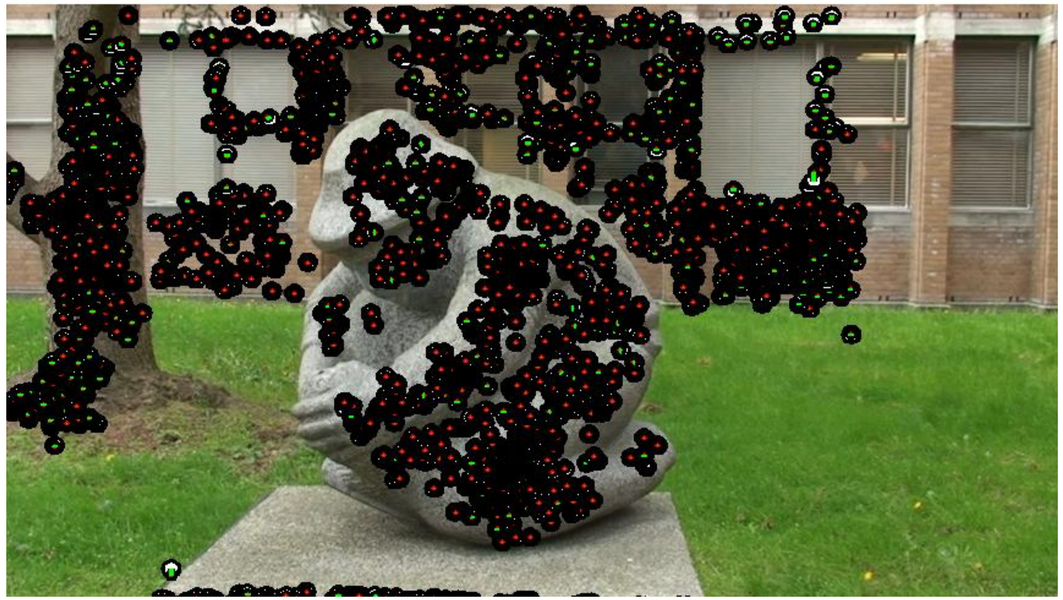
- Pose estimation for camera i:

$$e = \sum_{j \,\epsilon\, \text{points}} |\mathbf{r}_{ij}(\mathbf{R}_i, \mathbf{t}_i, \mathbf{X}_j)|^2$$

(optimised parameters are shown in red)

Bundle Adjustment

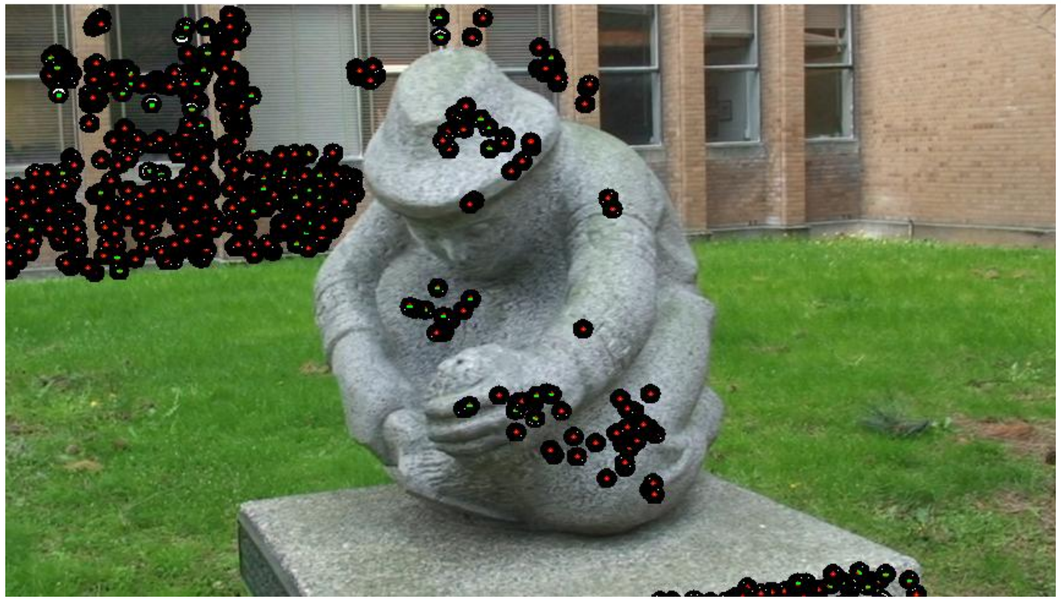
- Initialization with 3 views



Joint optimization of cameras and structure

Bundle Adjustment

- Add camera 4



Estimate camera pose, add new 3D points, jointly optimize

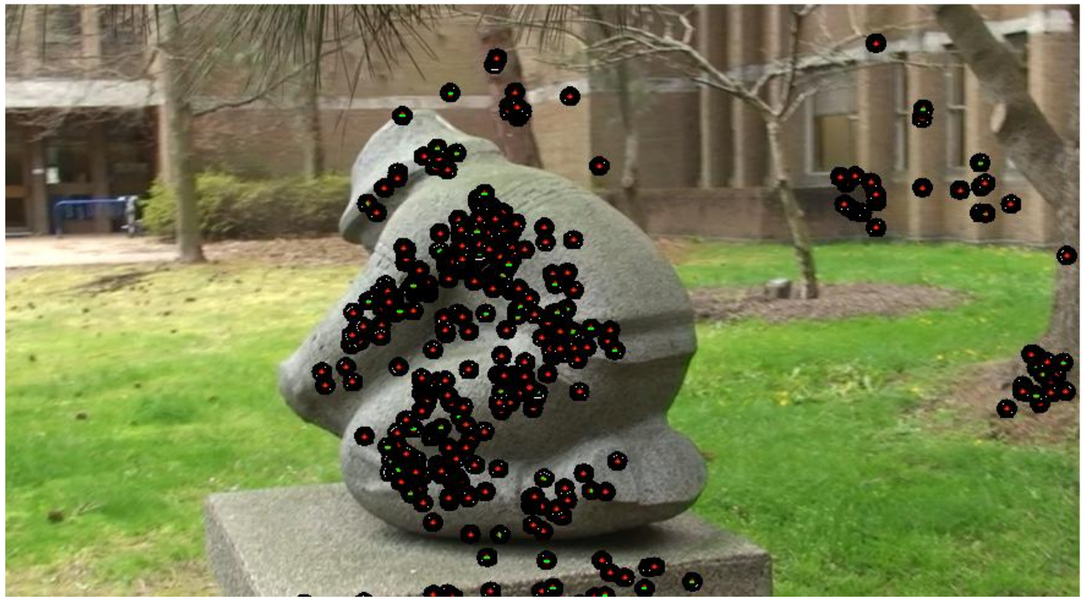
Bundle Adjustment

- Add camera 5

Estimate camera pose, add new 3D points, jointly optimize

Bundle Adjustment

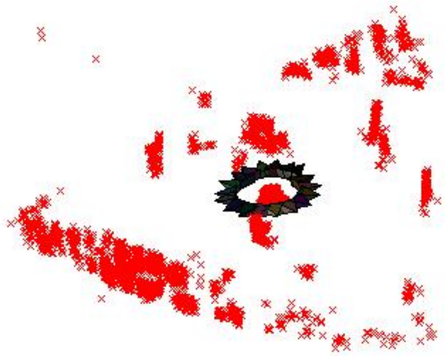
- Add camera 6



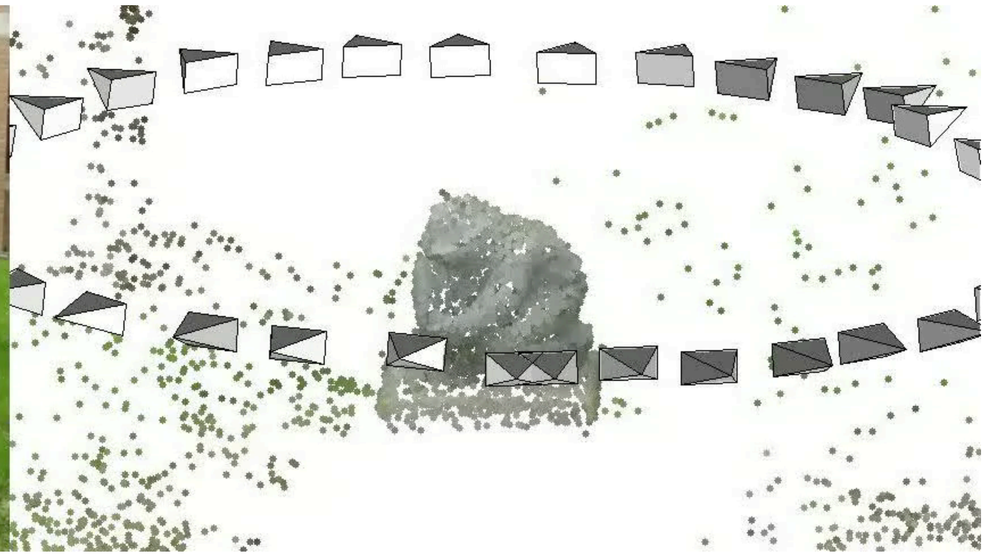
Estimate camera pose, add new 3D points, jointly optimize

Bundle Adjustment

- Add remaining cameras in same way



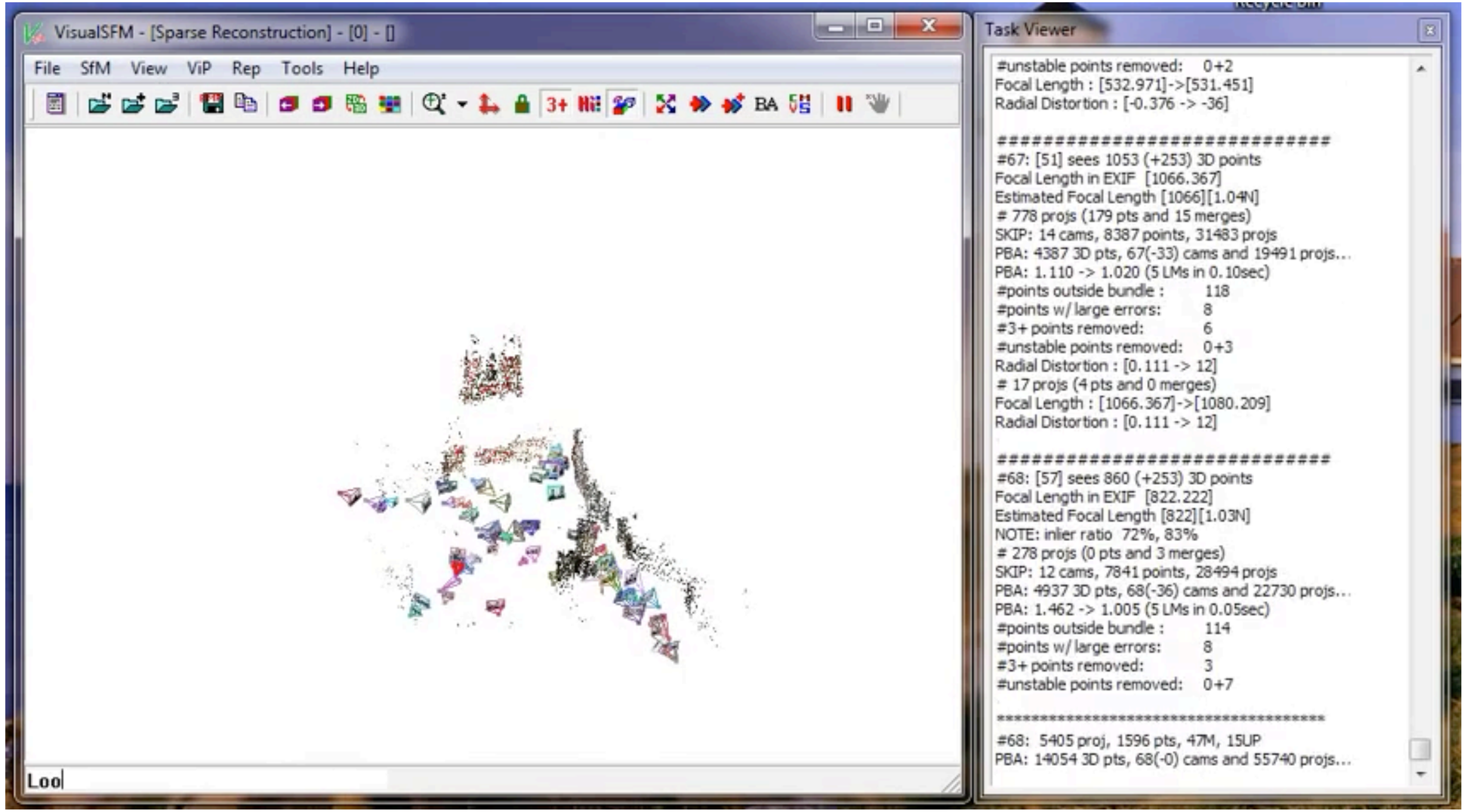
Structure from Motion



SFM recap

- Match features, e.g., SIFT, between all views
- Use RANSAC to reject outliers and estimate Epipolar Geometry / Camera matrices
- Form feature tracks by linking multiview matches
- Select an initialization set, e.g., 3 images with lots of matches and good baseline (parallax)
- Jointly optimize cameras R, t and structure X for this set
- Repeat for each camera:
  - Estimate pose R, t by minimising projection errors with existing X
  - Add 3D points corresponding to the new view and optimize
  - Bundle adjust optimizing over all cameras and structure

Visual SFM



[ccwu.me/vsfm]

Application: 3D from Internet Images

- Reconstruct 3D from unordered photo collections

[Building Rome in a Day, S. Agarwal et al 2009]

Menu for Today

Topics:

- **Stereo, Optical Flow** recap
- **Multiview Reconstruction**
- **Quiz 5** on Thursday
- Visual **Classification**

Readings:

- **Today's** Lecture: Szeliski 11.4, 12.3-12.4, 9.3, 5.1-5.2

Reminders:

- **Assignment 4**: due Thursday
- **Assignment 5**: Scene Recognition with Bag of Words is now available