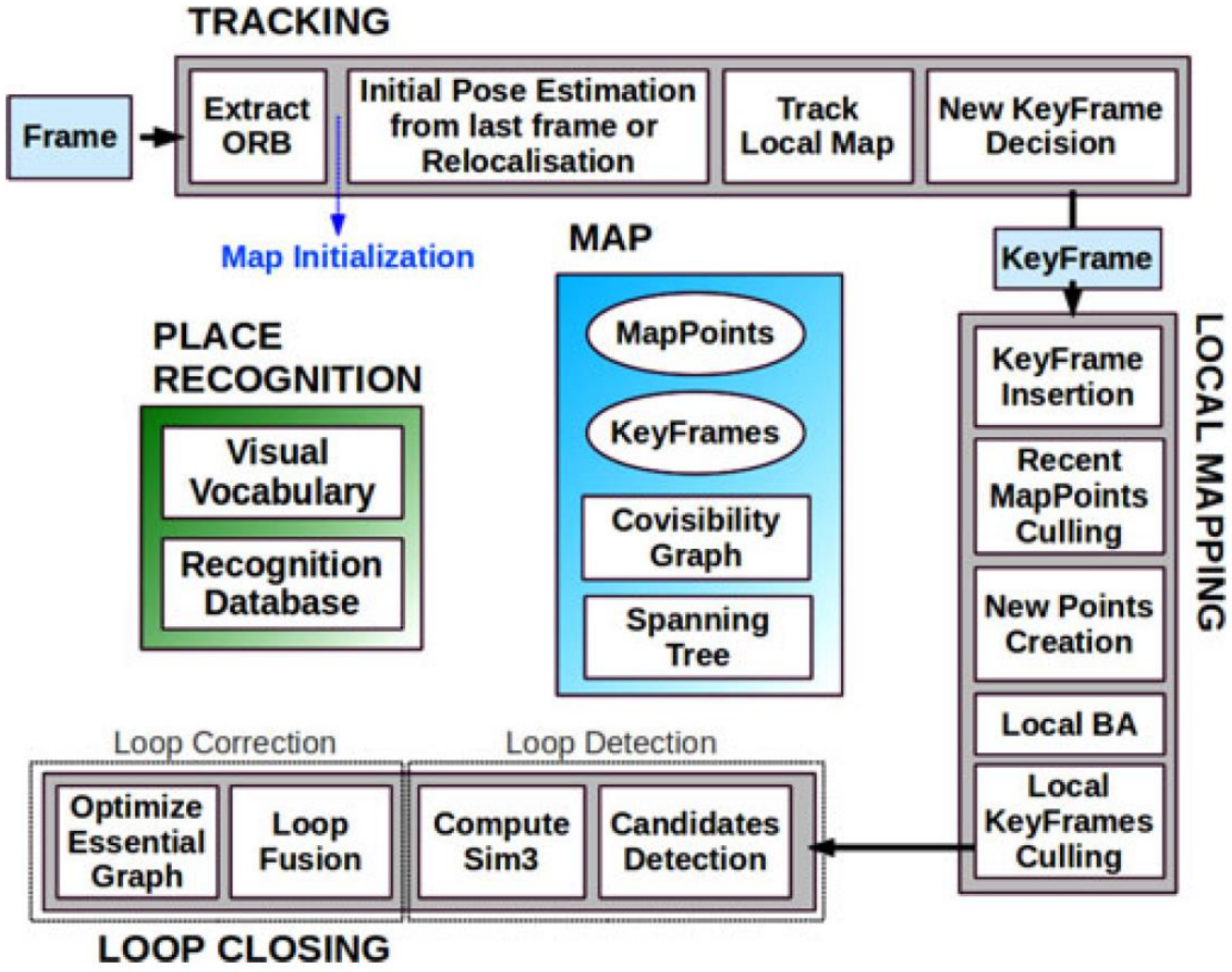
# Robotic Navigation and Exploration

Week 8: ORB SLAM

Min-Chun Hu anitahu@cs.nthu.edu.tw
CS, NTHU

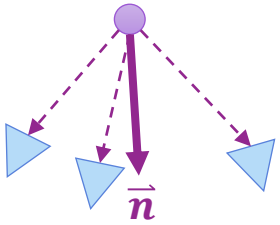
# ORB-SLAM Structure

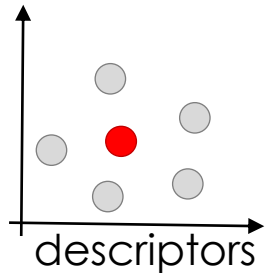


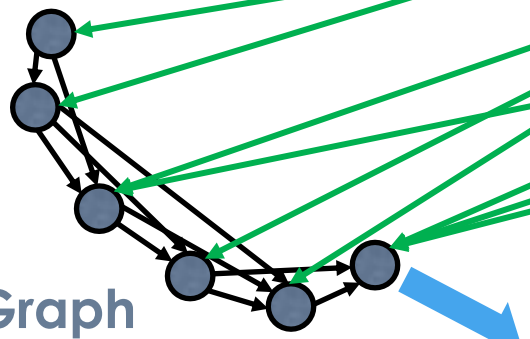
# Data Structure

**Map Point**

| | | | | | | |
|---|---|---|---|---|---|---|
| Descriptors | $dp_1$ | $dp_2$ | $dp_3$ | $dp_4$ | $dp_5$ | … |
| Viewing Direction | $n_1$ | $n_2$ | $n_3$ | $n_4$ | $n_5$ | … |
| 3D Position | $(x_1, y_1, z_1)$ | $(x_2, y_2, z_2)$ | $(x_3, y_3, z_3)$ | $(x_4, y_4, z_4)$ | $(x_5, y_5, z_5)$ | … |
| Associated Key Frames | $[fid_1, fid_2, \dots]$ | $[fid_1, fid_2, \dots]$ | $[fid_1, fid_2, \dots]$ | $[fid_1, fid_2, \dots]$ | $[fid_1, fid_2, \dots]$ | … |



**Graph**

Covisibility Graph
Spanning Tree
Essential Graph

**Keyframe**

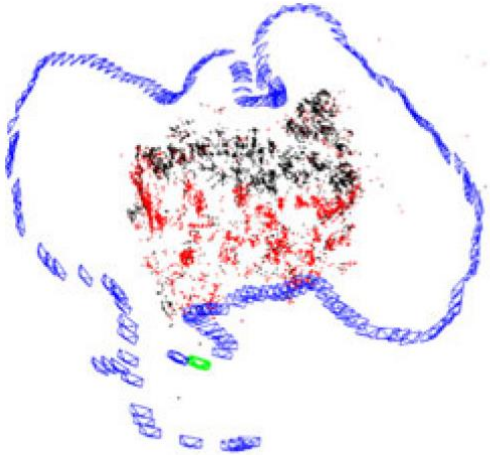
| | | | | | | |
|---|---|---|---|---|---|---|
| Associated Map Points | $mid_1$ | $mid_2$ | $mid_3$ | $mid_4$ | $mid_5$ | … |
| Descriptors | $dp_1$ | $dp_2$ | $dp_3$ | $dp_4$ | $dp_5$ | … |
| Key Points | $(u_1, v_1)$ | $(u_2, v_2)$ | $(u_3, v_3)$ | $(u_4, v_4)$ | $(u_5, v_5)$ | … |

Camera Pose $(q_1, q_2, q_3, t_x, t_y, t_z)$

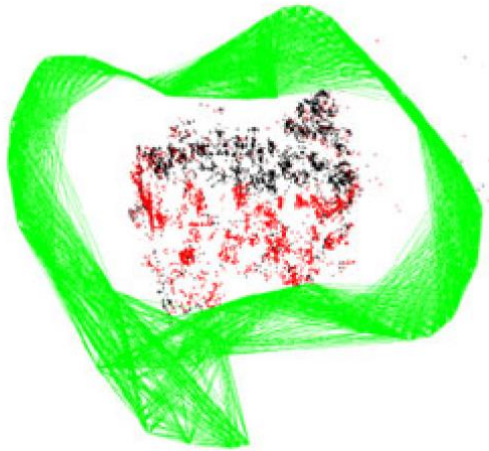
Camera Intrinsic $(f_x, f_y, c_x, c_y)$

# Covisibility Graph and Essential Graph

- In covisibility graph, the connected keyframe nodes share points observations.
- ORB-SLAM also maintain an incremental spanning tree. In tracking process, the new keyframe inserts into the node with most shared point observations.
- When performing the global pose graph optimization, the essential graph is built by the spanning tree, the subset of edges with high covisibility (>100) and the loop closing edges.

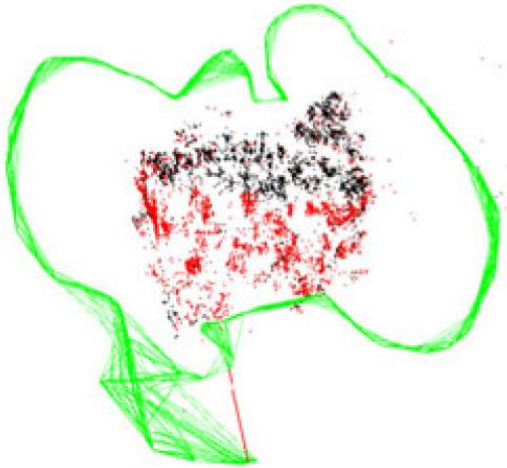


Keyframes



Covisibility Graph

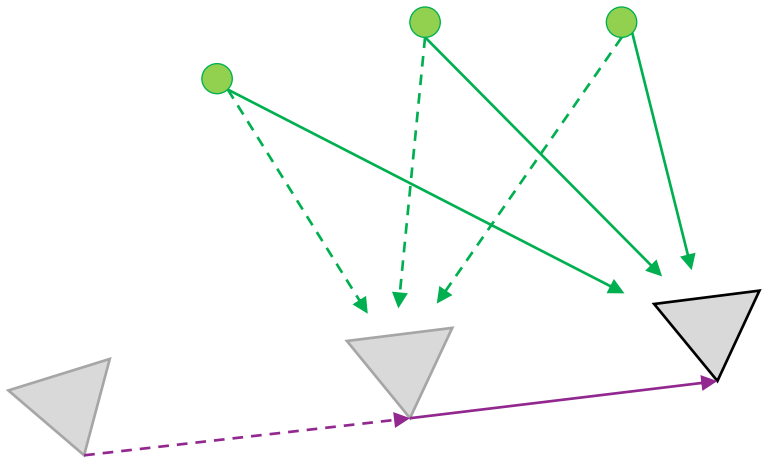
Spanning Tree



Essential Graph

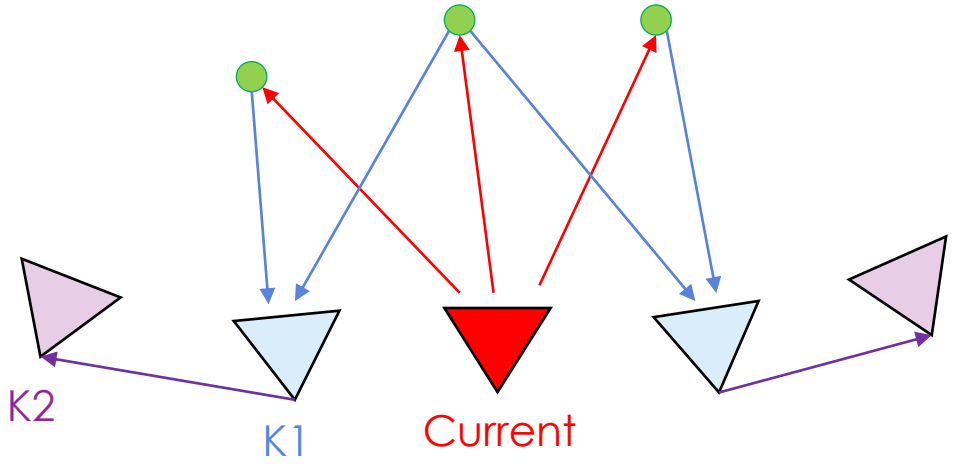
# Tracking – Initial Pose Estimation

- Utilize constant velocity motion model to predict camera pose.
- Search the matching points around the projected map points observed in the last frame.
- Optimize with found correspondences.



# Tracking – Track Local Map

- Get initial camera pose estimation and set of feature matches.
- Search more map point correspondences in the set of keyframes ***K1*** , which share map points with the current frame, and a set ***K2*** with neighbors to the keyframes ***K1*** in the covisibility graph.
- Motion-only Bundle Adjustment.

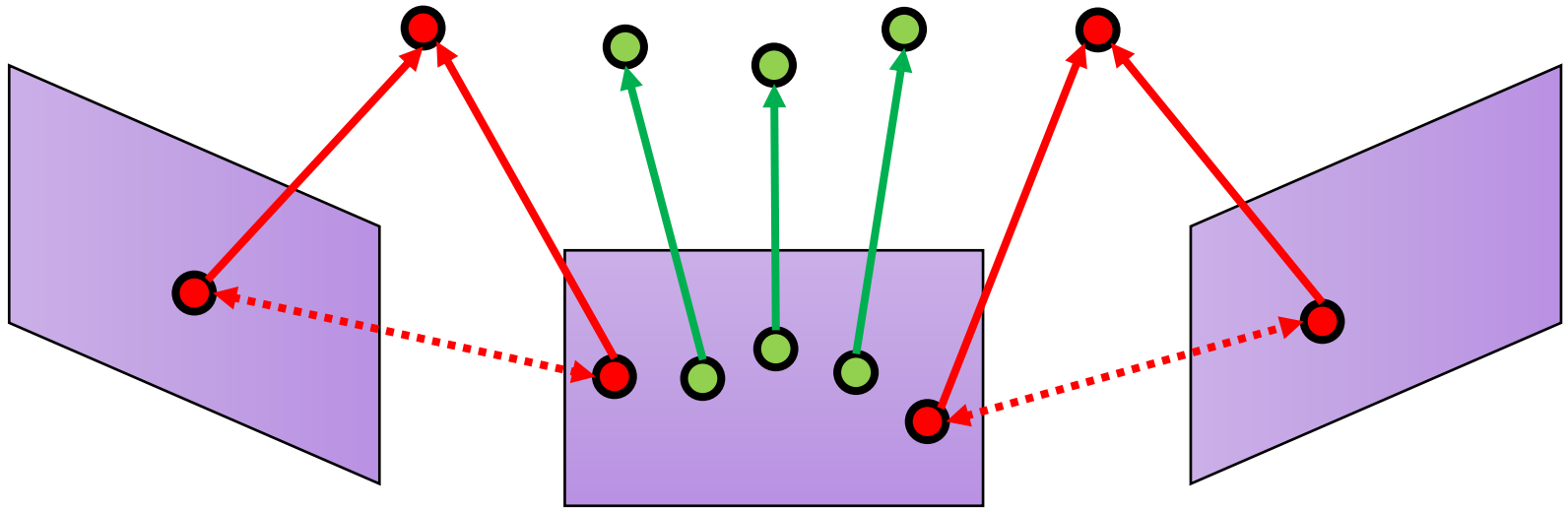



Bundle Adjustment over SE(3)

$$s\begin{bmatrix} u \\ v \\ 1 \end{bmatrix} = \begin{bmatrix} f_x & \gamma & u_0 \\ 0 & f_y & v_0 \\ 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} r_{11} & r_{12} & r_{13} & t_1 \\ r_{21} & r_{22} & r_{23} & t_2 \\ r_{31} & r_{32} & r_{33} & t_3 \end{bmatrix} \begin{bmatrix} x \\ y \\ z \\ 1 \end{bmatrix}$$

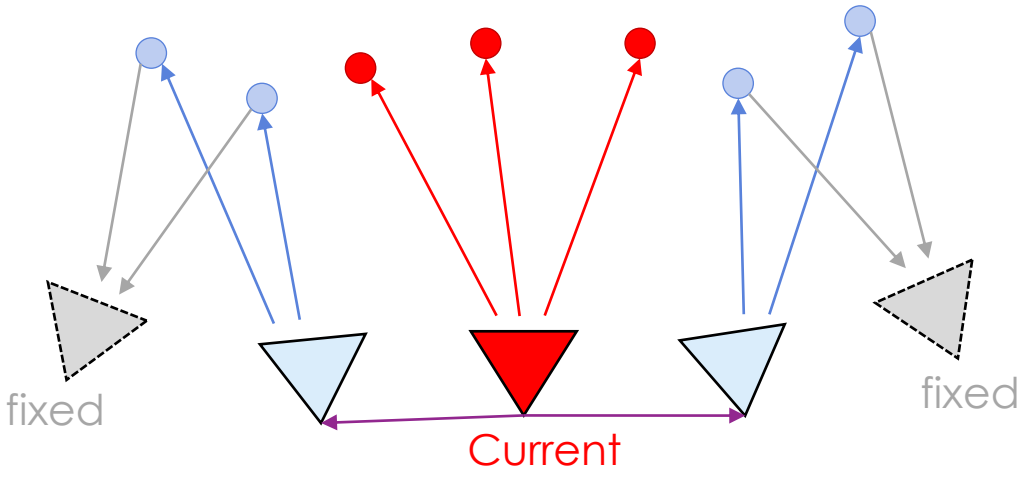
# Mapping – Create New Map Points

- Keyframe Insertion
  - For each unmatched ORB, search a match with other unmatched point in other connected keyframes Kc in the covisibility graph.
- Map Point Creation
  - Triangulting ORB from connected keyframes in covisibility graph.



# Mapping - Local Bundle Adjustment

- Optimize the currently processed keyframe, all the keyframes connected to it in the covisibility graph, all the map points seen by those keyframes.
- All other keyframes that see those points but are not connected to the currently keyframe are included in the optimization but remain fixed.

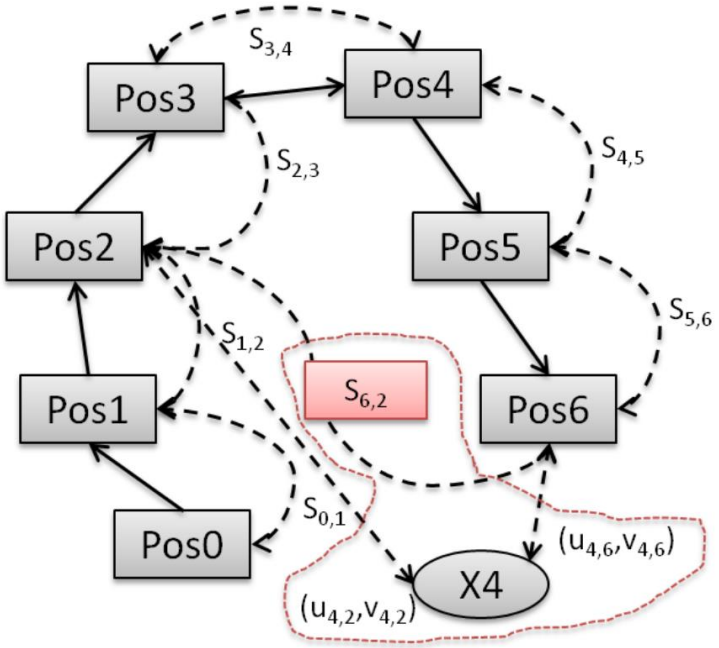



Bundle Adjustment over SE(3)

$$s\begin{bmatrix} u \\ v \\ 1 \end{bmatrix} = \begin{bmatrix} f_x & \gamma & u_0 \\ 0 & f_y & v_0 \\ 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} r_{11} & r_{12} & r_{13} & t_1 \\ r_{21} & r_{22} & r_{23} & t_2 \\ r_{31} & r_{32} & r_{33} & t_3 \end{bmatrix} \begin{bmatrix} x \\ y \\ z \\ 1 \end{bmatrix}$$

# Loop Closing – Similarity Transform

- Compute correspondences between ORB and map points in the current keyframe and the loop candidate keyframes to get 3d-to-3d transform.
- Iteratively finding the candidate scale, optimize the scale and find more correspondence points and optimize again.

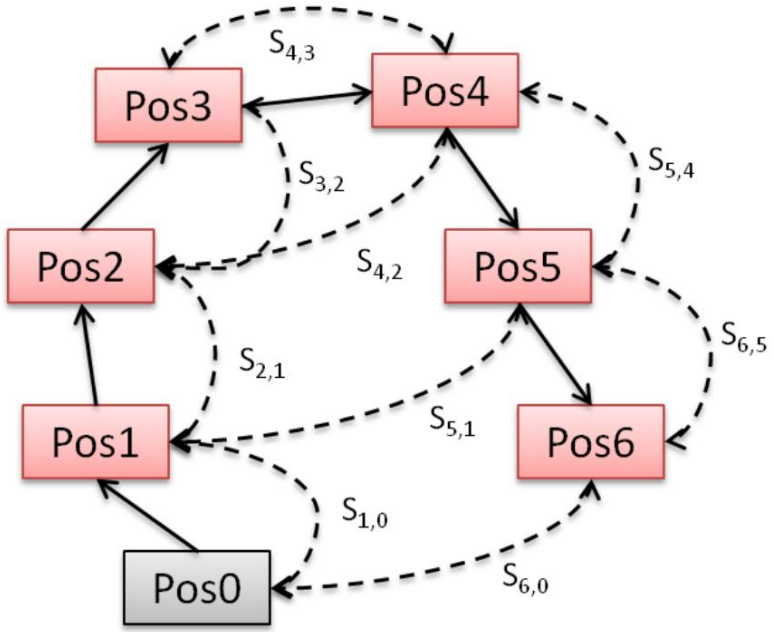



$$s\begin{bmatrix} u \\ v \\ 1 \end{bmatrix} = \begin{bmatrix} f_x & \gamma & u_0 \\ 0 & f_y & v_0 \\ 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} r_{11} & r_{12} & r_{13} & t_1 \\ r_{21} & r_{22} & r_{23} & t_2 \\ r_{31} & r_{32} & r_{33} & t_3 \end{bmatrix} \begin{bmatrix} x \\ y \\ z \\ 1 \end{bmatrix}$$

Relative Sim(3) Optimization

# Loop Closing – Fusion and Global Optimization

- Fuse the duplicated map points, insert edges to covisibility graph and propagate the scale information to correct the pose of neighbor keyframes.
- Perform global pose graph optimization.




$$s\begin{bmatrix} u \\ v \\ 1 \end{bmatrix} = \begin{bmatrix} f_x & \gamma & u_0 \\ 0 & f_y & v_0 \\ 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} r_{11} & r_{12} & r_{13} & t_1 \\ r_{21} & r_{22} & r_{23} & t_2 \\ r_{31} & r_{32} & r_{33} & t_3 \end{bmatrix} \begin{bmatrix} x \\ y \\ z \\ 1 \end{bmatrix}$$

Essential Graph Sim(3) Optimization