VAN course
Lesson 12

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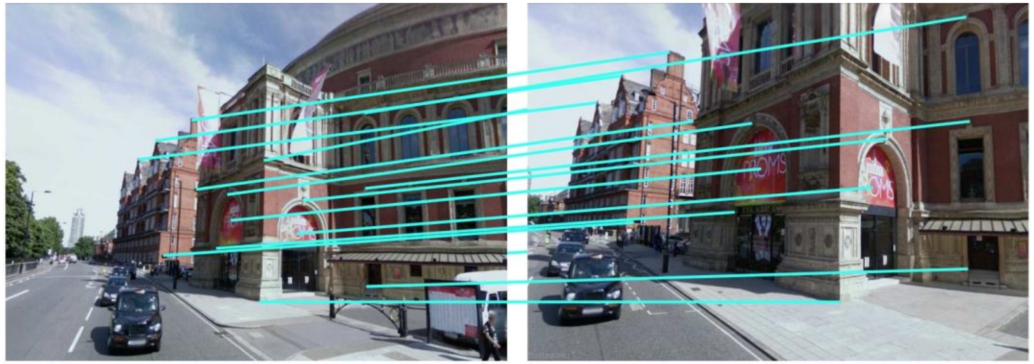
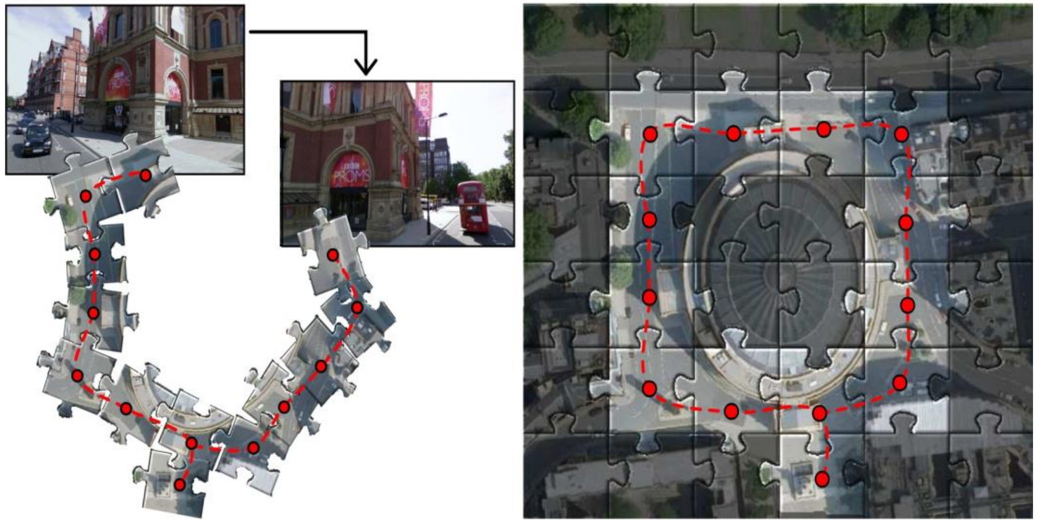
Loop Closure

Loop Closure

- Problem: Navigation drifts
  - We can reduce it, but not eliminate the problem
- If we revisit a location it can help
  - Shorter path to origin in the pose graph
  - Constraints propagate to other vertices
  - Vertices get a ‘second opinion’
- This is called a “**Loop Closure**”



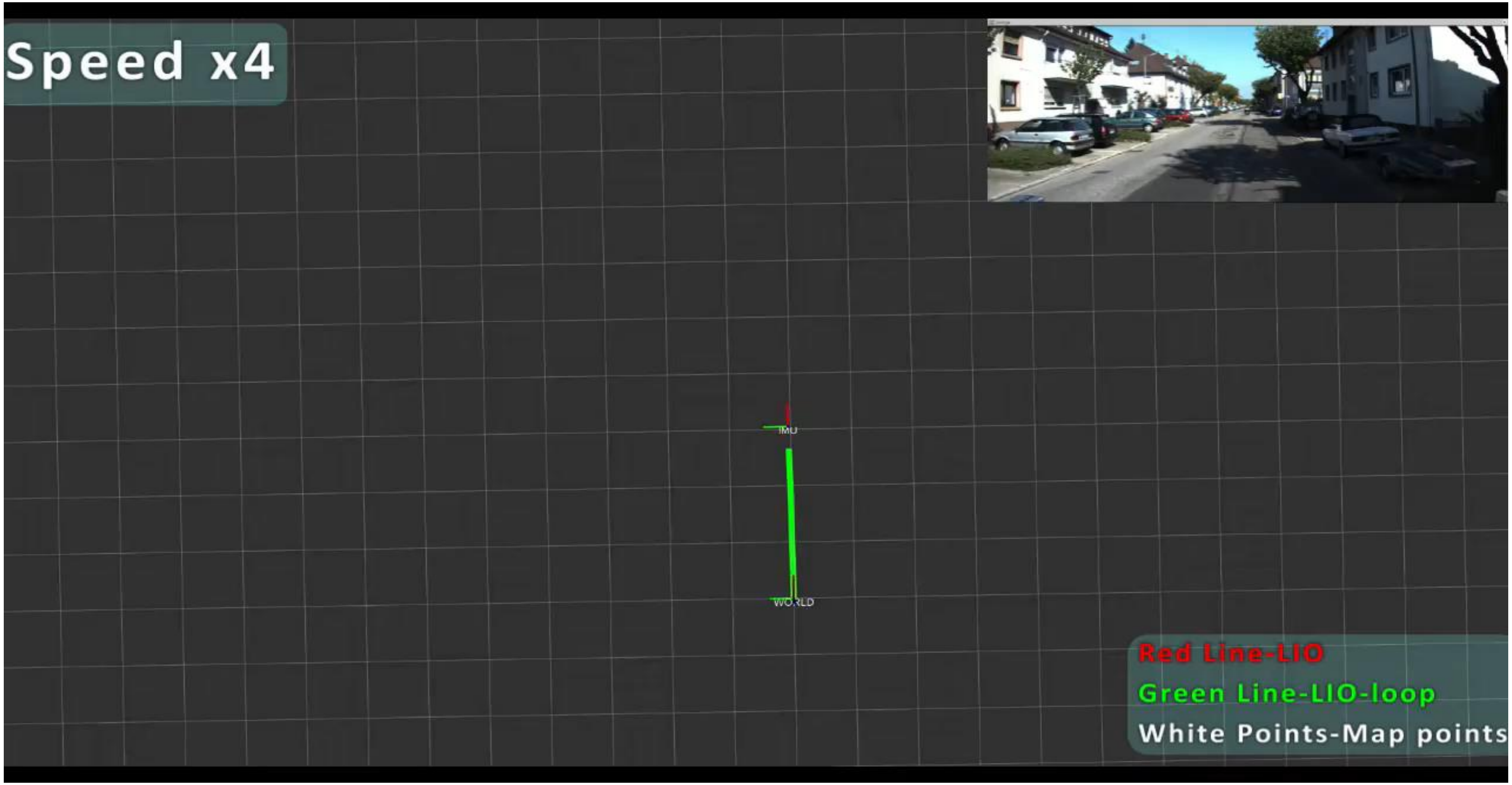
(a) Robust local motion estimation



(b) Mapping and loop-closure detection (c) Global optimisation

Images from: ChIi09thesis – “Applying Information Theory to Efficient SLAM”, 2009

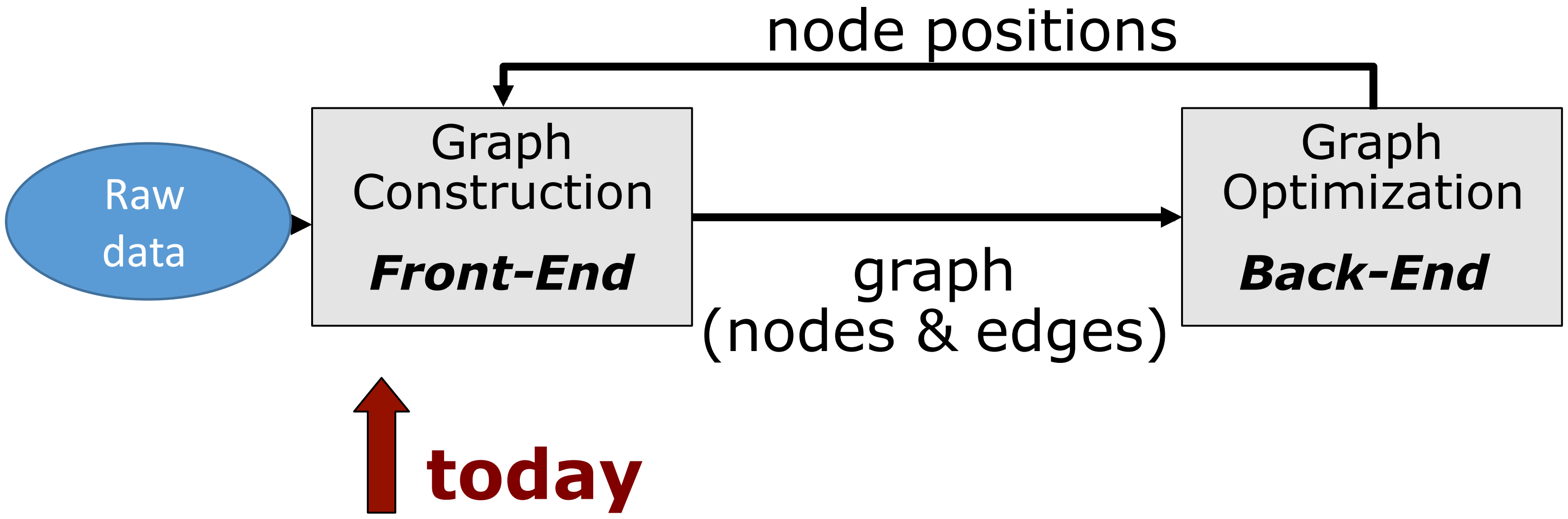
Loop Closure



https://www.youtube.com/watch?v=LVbzuyOCCaM

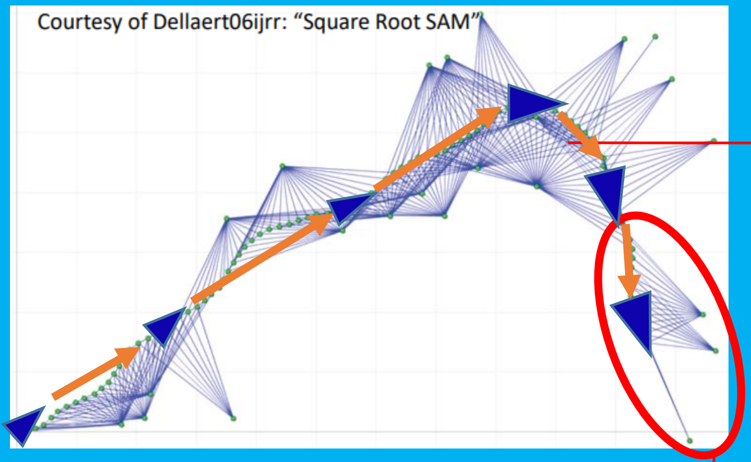
Loop Closure

- When implementing an online system:
  - Front end
    - Find new graph edges
    - To previous vertex: Stereo tracking, PnP, factor graph (Ex 1-3)
    - To old known vertices: Loop closure (Ex. 5)
  - Backend
    - Global optimization – Pose graph (Ex. 4)

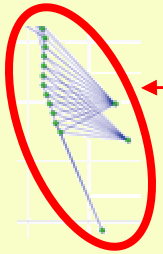


Courtesy of Cyrill Stachniss

Loop Closure

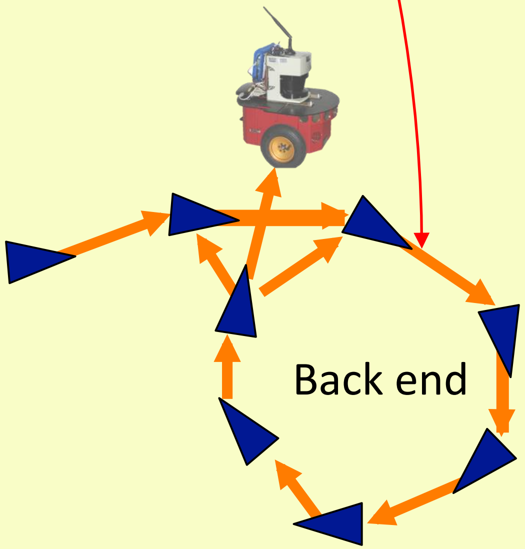


We wish to solve the whole bundle



Front end

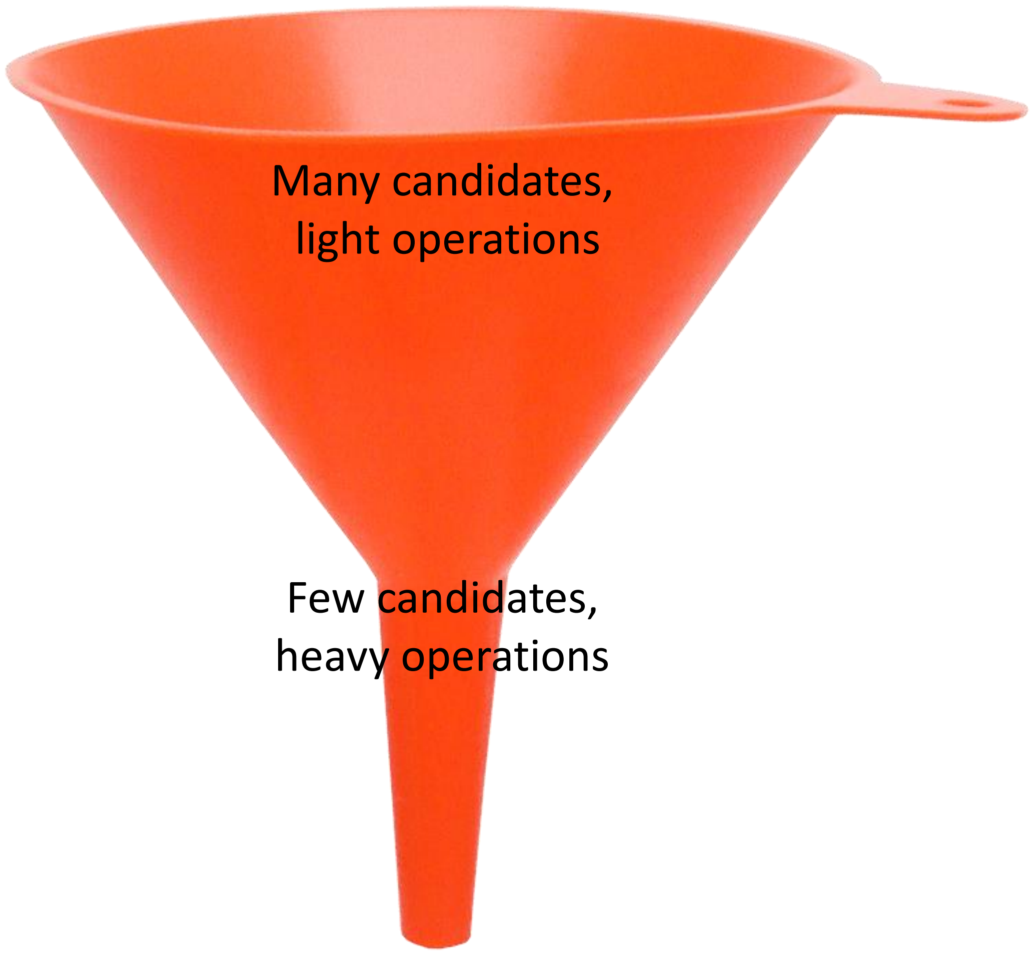
We settle for those
sub problems



And it works!

Loop Closure

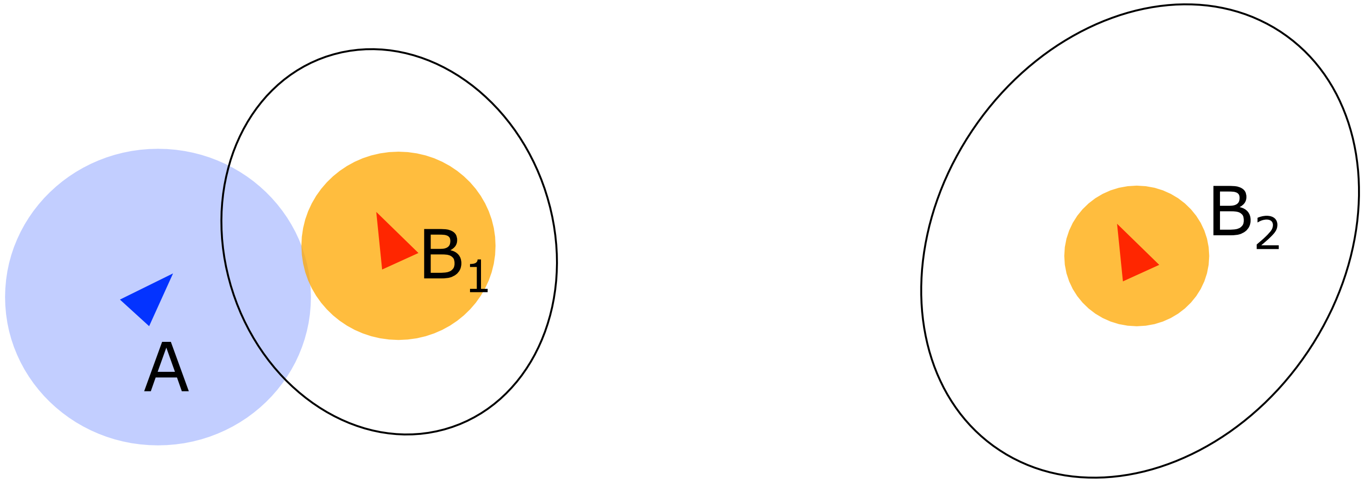
- How can we spot a loop closure?
  - Find candidates (light):
    - Using our navigation system
    - Global image descriptor
  - Validate candidates (heavy):
    - 3D points clouds matching using ICP
    - Descriptor-based matching
  - Calculate edges and factors:
    - Find transformation using matches/ICP
  - Outlier removal:
    - Olson’s method



Loop Closure - Geometric intersection

Geometric intersection: Where to Search for Matches?

- Consider uncertainty of the nodes with respect to the current one



Views may overlap

Views cannot overlap

- “Intersection” means that B pose **is** pose A with high probability
- Note: even if location overlaps, pose may not.

Loop Closure - Geometric intersection

- We wish to find: $\Delta x^T \Omega_{n|i} \Delta x < d$

  Where: $\Delta x = t2v(X_i^{-1} X_n)$

  and $\Omega_{n|i}$ is the conditional information matrix of $x_n | x_i$
- This requires marginalization to remove all other x_j
- Inverting the full Ω is too expensive for front-end.
- Fast approximation:
  - Find shortest path using Dijkstra
  - Compose the incremental covariance along the path.

Assume $\mathbf{x} \sim \mathcal{N}(\mathbf{m}_x, \mathbf{\Sigma}_x)$ and $\mathbf{y} \sim \mathcal{N}(\mathbf{m}_y, \mathbf{\Sigma}_y)$ then

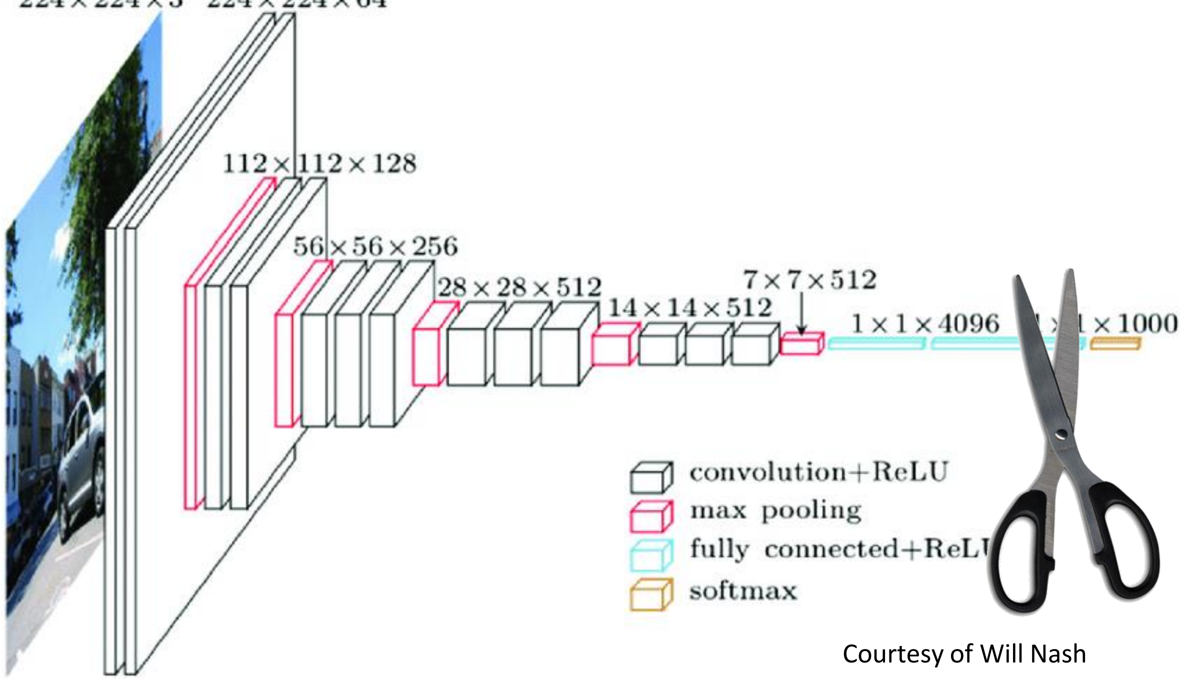
$$\mathbf{Ax} + \mathbf{By} + \mathbf{c} \sim \mathcal{N}(\mathbf{Am}_x + \mathbf{Bm}_y + \mathbf{c}, \mathbf{A\Sigma}_x\mathbf{A}^T + \mathbf{B\Sigma}_y\mathbf{B}^T)$$

$$x + y \sim N(m_x + m_y, \Sigma_x + \Sigma_y)$$

Loop Closure - Global image descriptor

- For every image:
  - Calc a global image descriptor
  - i.e. the hidden layers of a CNN
  - Save in database
- For new image:
  - Compare descriptor to database
  - Find candidates using a threshold

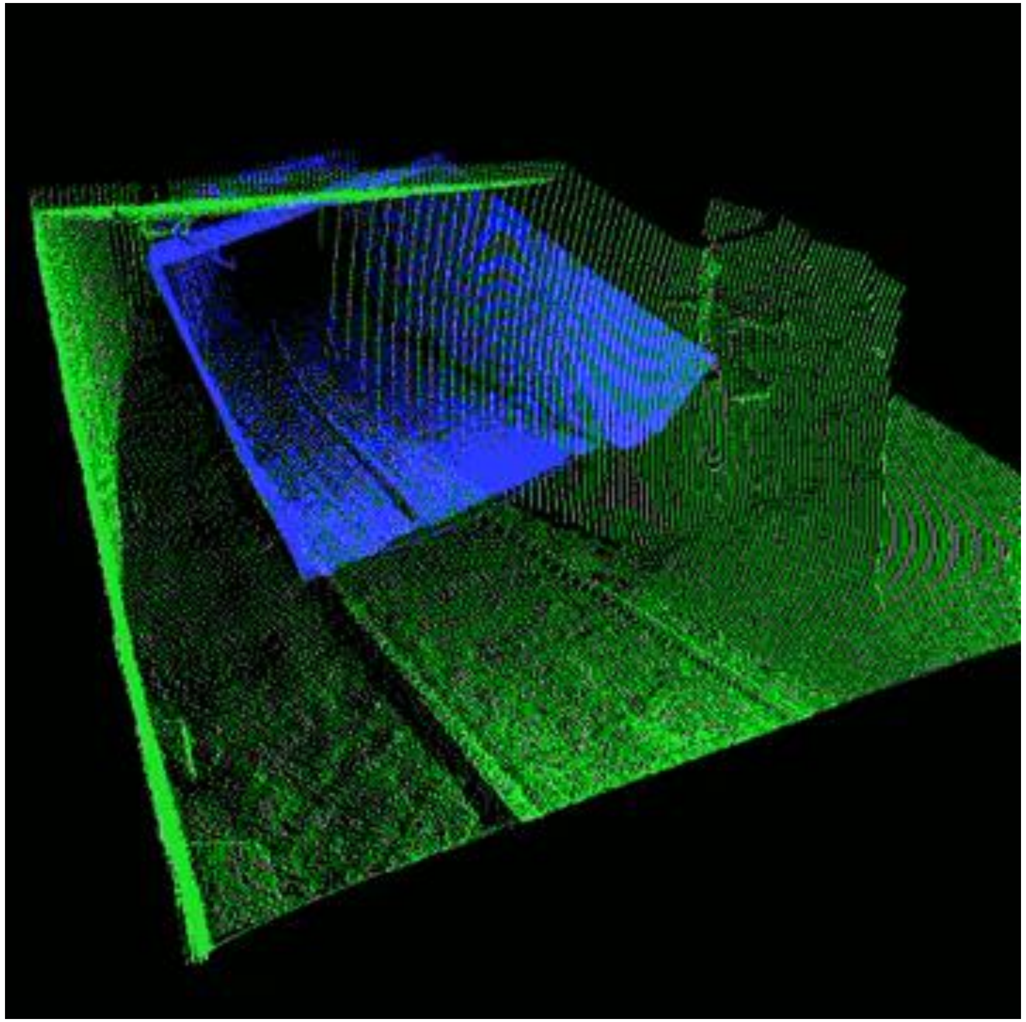
VGG convolutional neural network for Image Recognition



Courtesy of Will Nash

Loop Closure - Validate candidates with ICP

- For any candidate-pair for edge:
  - Find the corresponding 3D point cloud
  - Optional: extract unique structures
    - Like trees of cars
    - Walls are large but with low information
  - Find transformation
    - Using ICP, RANSAC and least squares minimization
  - Evaluate edge
    - Matches percent
    - Mean distance
  - If it's good, set an edge
    - The factor is the calculated relative transformation



Courtesy of [Andreas Nuechter]

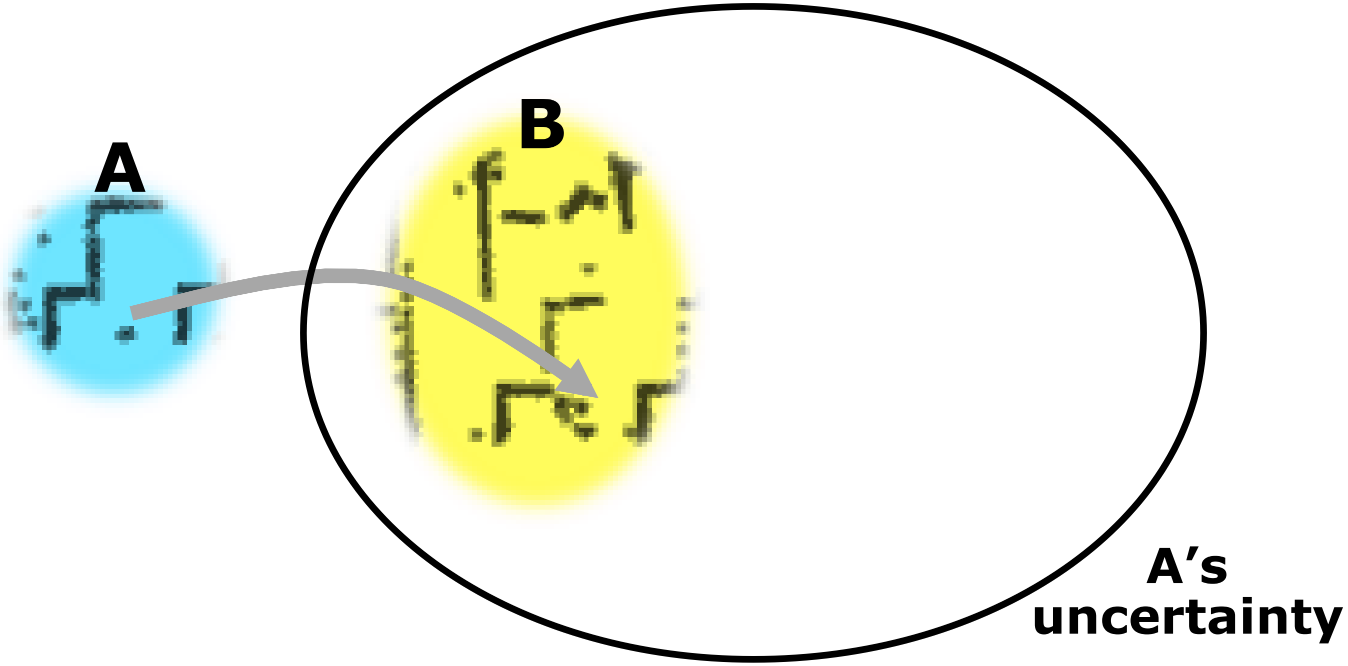
Loop Closure - Validate candidates with ICP

Problems

- ICP is sensitive to initial guess
- Make many initial guesses? Inefficient sampling
- Ambiguity in the environment

Loop Closure - Validate candidates with ICP
Ambiguities - Global Ambiguity

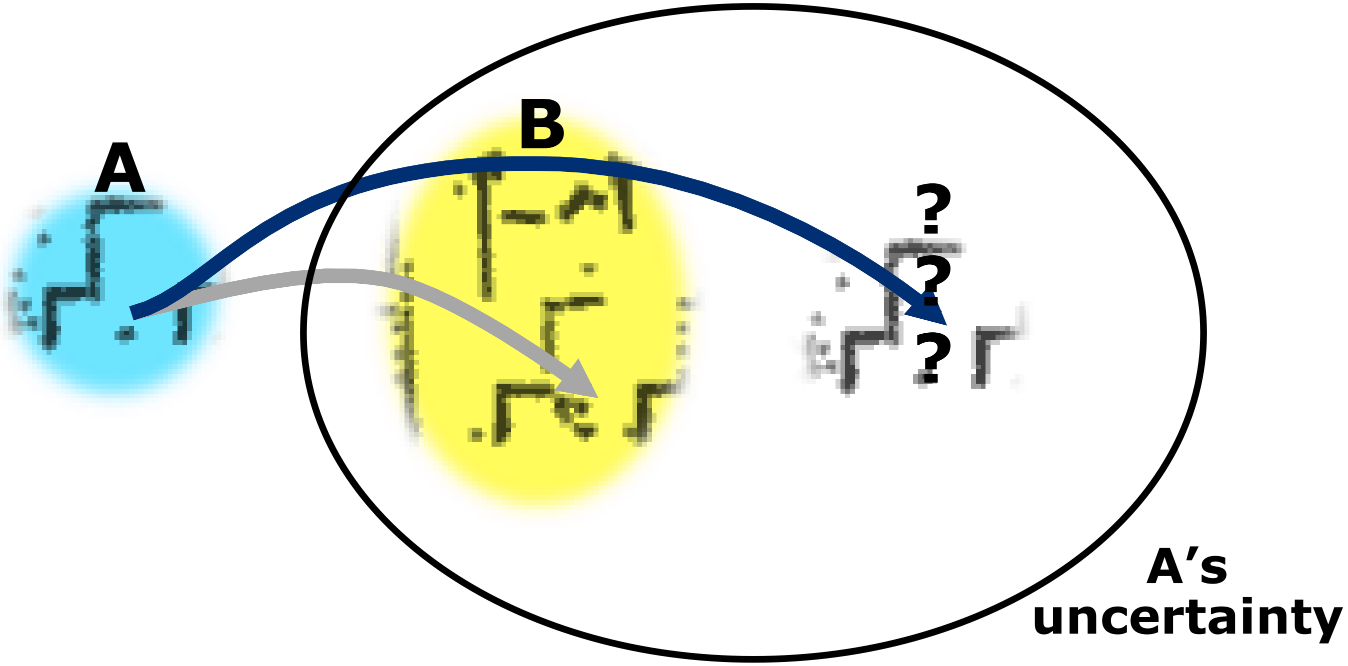
- B is inside the uncertainty ellipse of A
- Are A and B the same place?



Courtesy of Cyrill Stachniss

Loop Closure - Validate candidates with ICP Ambiguities - Global Ambiguity

- B is inside the uncertainty ellipse of A
- A and B might not be the same place



Courtesy of Cyrill Stachniss

Loop Closure - Validate candidates with ICP
Ambiguities - Global Ambiguity

- B is inside the uncertainty ellipse of A
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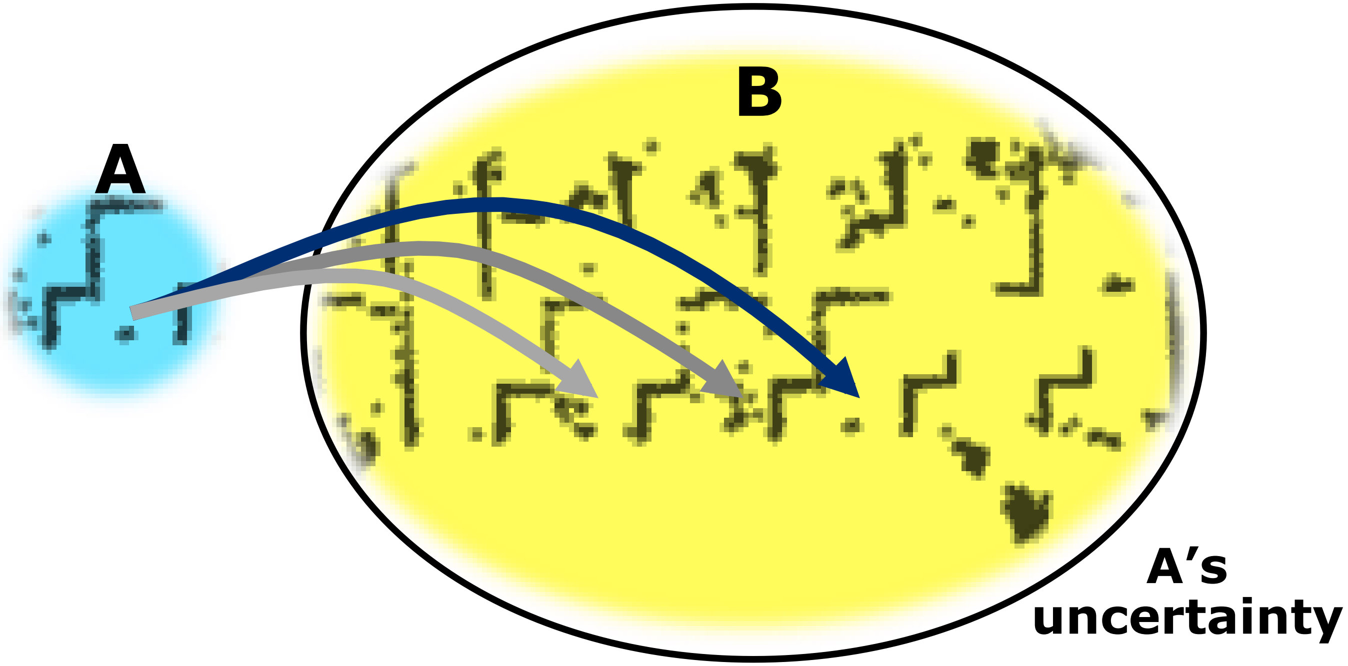
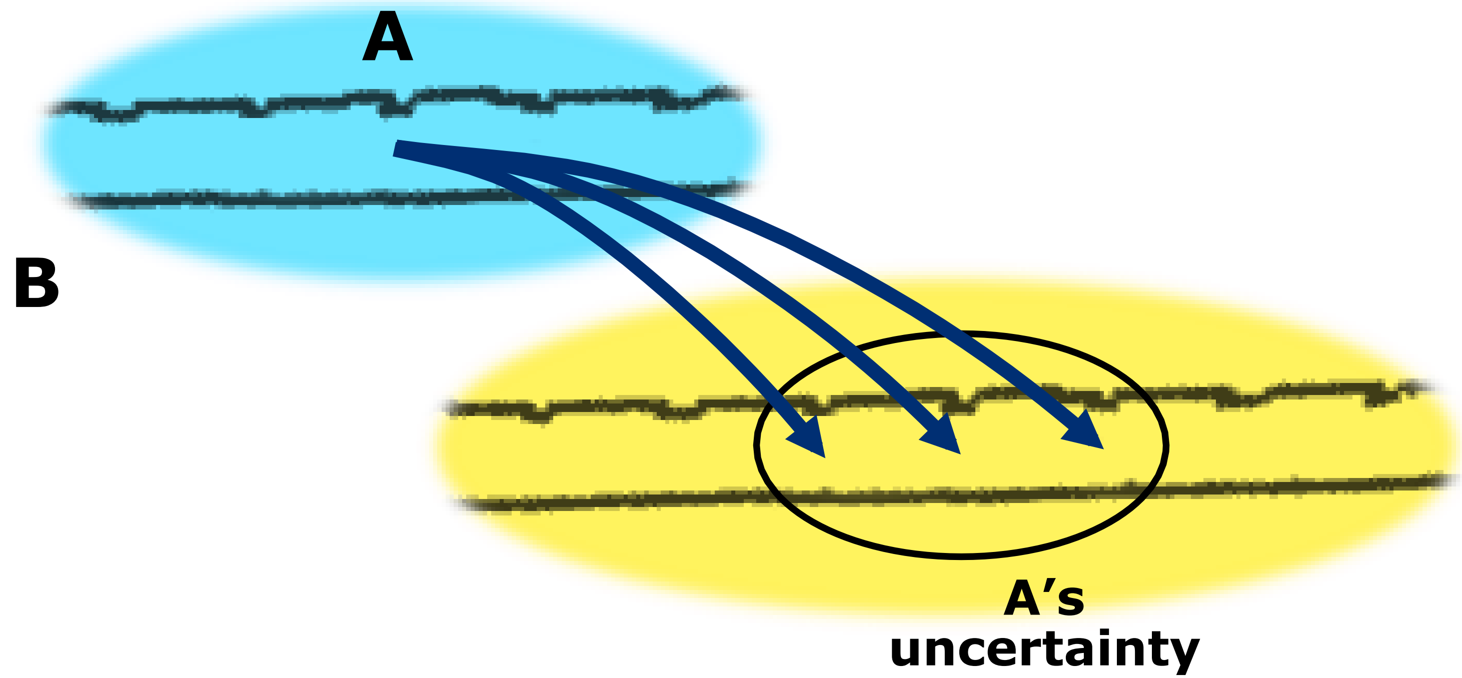


Courtesy of Cyrill Stachniss

Loop Closure - Validate candidates with ICP
Ambiguities - Local Ambiguity

- "Picket Fence Problem": largely overlapping local matches



Courtesy of Cyrill Stachniss

Loop Closure - Validate with descriptors

- For any candidate-pair for edge:
  - Extract features descriptors from both images
  - Find correspondences
    - Using ANN
  - Remove outliers, evaluate edge
    - With RANSAC and Consensus matching
  - If it’s good, set an edge
    - Calculated relative transformation
    - First with PnP
    - Then with small factor graph for the Cov matrix
  - Much more robust than point-cloud methods
    - Low ambiguity rate
    - Relative transformation may still be wrong