A Graph-Based Memetic Approach to Sketch Geolocation

Andrew R. Buck and James M. Keller

Department of Electrical and Computer Engineering
University of Missouri
Columbia, Missouri, USA

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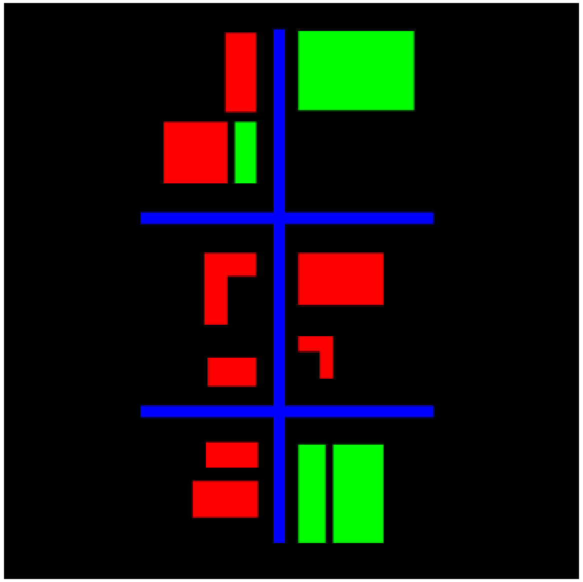
Outline

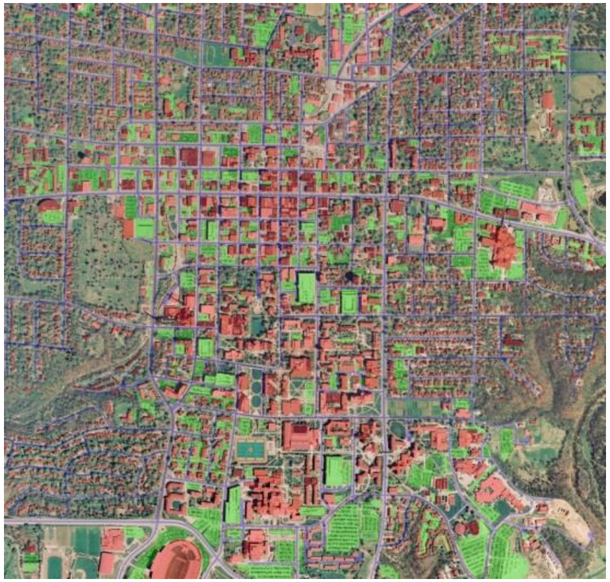
- Problem Overview
  - Scene Matching based on Spatial Relations
- An Evolutionary Algorithm
  - Global Search Strategy
  - Local Search Strategy
  - Combined Memetic Approach
- Experimental Results
- Conclusions

Problem Overview

- Scene Matching
  - Hand Drawn Sketch
  - Segmented Satellite Image



Where in the image does the sketch come from?



Combinatorial Optimization

- Given a target sketch of objects,

$$\mathcal{X}_T = (o_1, \ldots, o_N)$$

... and a set of reference objects,

$$\mathcal{X}_R = (x_1, \ldots, x_M)$$

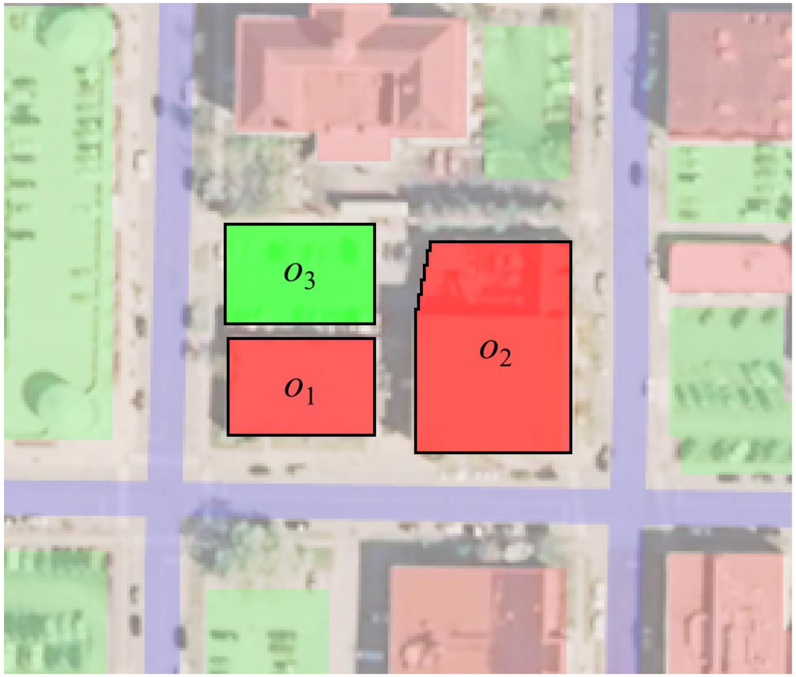
what is the set of objects from $\mathcal{X}_R$ that best matches $\mathcal{X}_T$?

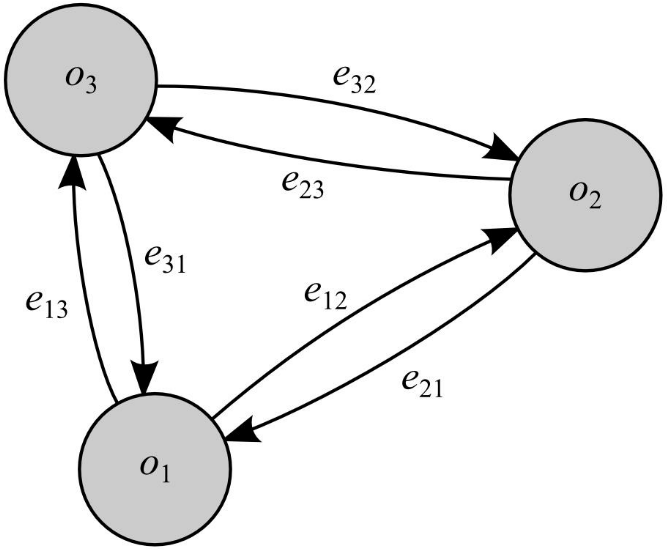
$$\Gamma = \left(x_{(1)}, \ldots, x_{(N)}\right)$$

- Constrained optimization
  - Solutions should be in a similar configuration
  - Object types should match (*e.g.* buildings, parking lots)

Representing Object Sets

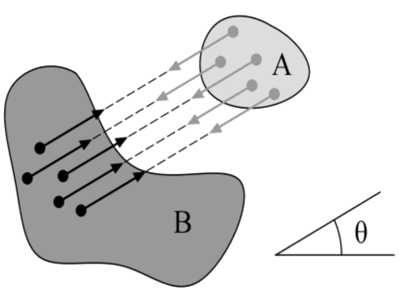
- Object sets are represented as graphs
  - Vertices → Objects
  - Edges → Spatial relationships

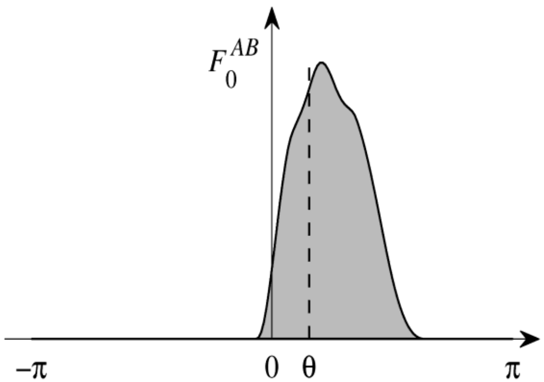


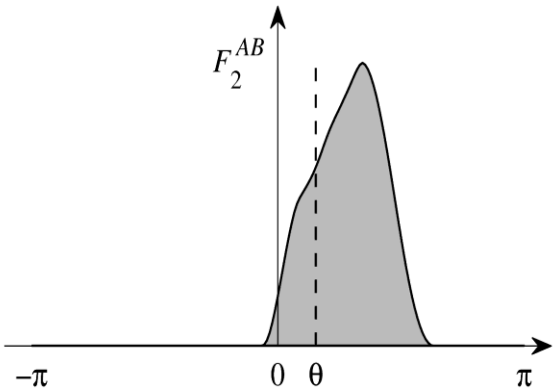


Histograms of Forces

- The histograms of forces (HoF) capture the relative spatial position between two objects
- A force histogram $F_r^{AB}(\theta)$ is a way of representing the degree of truth of the statement, "A is in direction θ from B."
  - $r = 0$ gives the histogram of constant forces
  - $r = 2$ gives the histogram of gravitational forces



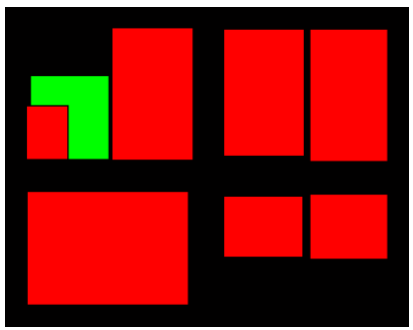


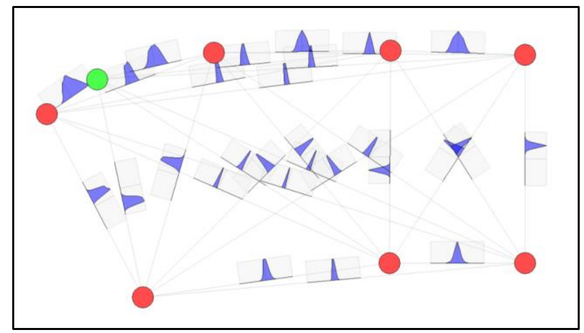


Attributed Relational Graphs

- We create attributed relational graphs (ARGs) for the target sketch and reference database

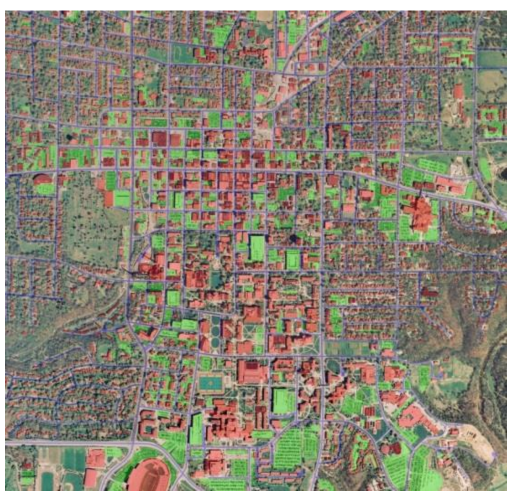
Target Sketch





G_T

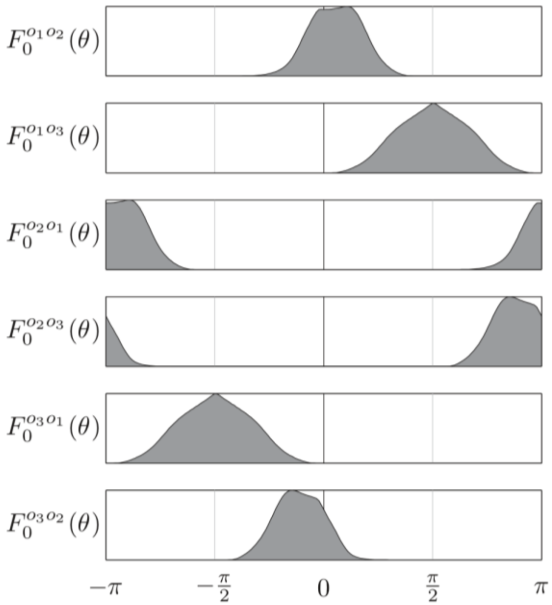
Reference Database



G_R

Comparing ARGs

- ARG similarity is computed as the average cross-correlation of corresponding histograms
  - ARGs must be complete graphs of the same size
  - Object correspondence is defined by vertex order



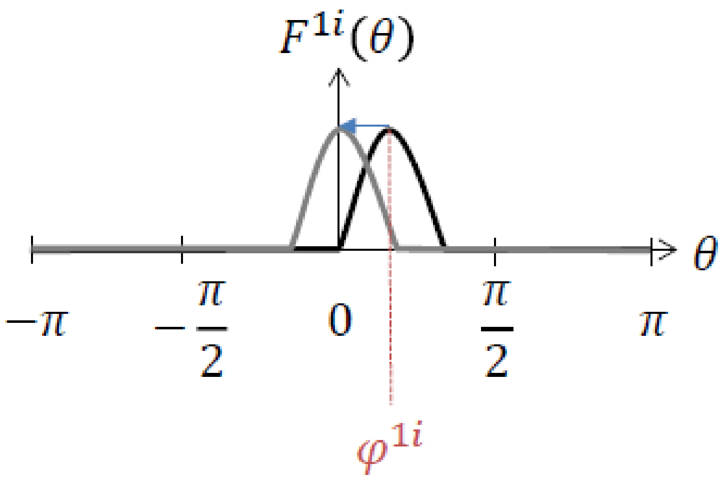
Normalized Cross-Correlation:

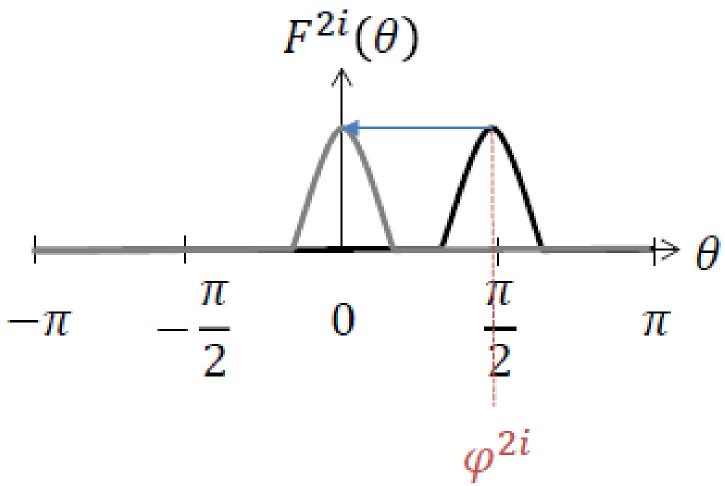
$$\psi_{\mathrm{CC}}\left(F_r^{1i}, F_r^{2i}\right) = \frac{\sum_\theta F_r^{1i}(\theta) F_r^{2i}(\theta)}{\sqrt{\sum_\theta \left(F_r^{1i}(\theta)\right)^2} \sqrt{\sum_\theta \left(F_r^{2i}(\theta)\right)^2}}$$

$$\psi_{\mathrm{Hist}}(h_{1i}, h_{2i}) = \frac{1}{2}\psi_{\mathrm{CC}}\left(F_0^{1i}, F_0^{2i}\right) + \frac{1}{2}\psi_{\mathrm{CC}}\left(F_2^{1i}, F_2^{2i}\right)$$

Handling Rotation

- F-Histograms need to be normalized to account for sketch rotation





$$d_{ij} = \varphi^{1i} - \varphi^{2i}$$

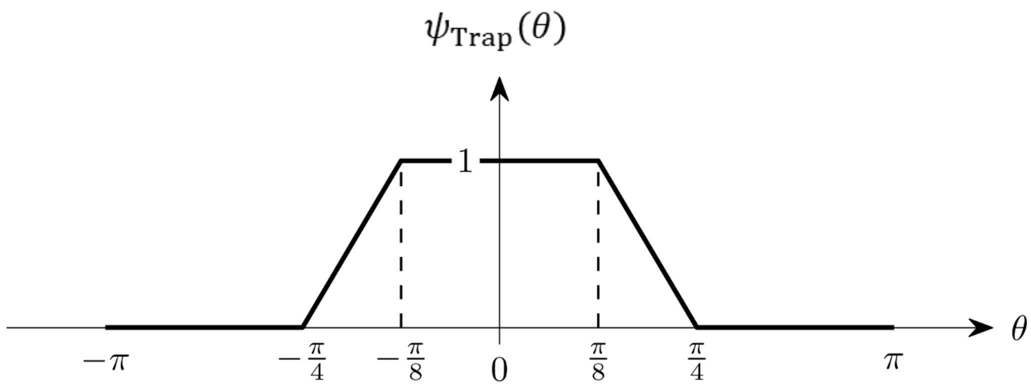
$$\boldsymbol{D} = (d_1, \dots, d_{N(N-1)/2})$$

Best rotation angle for the sketch:

$$\varphi^{\star} = \underset{d_i \in \boldsymbol{D}}{\arg\min} \left[\pi - \sum_{d_j \in \boldsymbol{D}} \left| \pi - |d_i - d_j| \right| \right]$$

Elastic Angles

- Each histogram pair is weighted by how far the angular difference is from the optimal rotation angle



- Overall fitness of a solution G_Γ is given by its similarity to G_T

$$\Psi(G_\Gamma) = \frac{N(N-1)}{2} \sum_{i=1}^{N(N-1)/2} \psi_{\text{Trap}}(\varphi^\star - d_i)\psi_{\text{Hist}}(h_{\Gamma i}, h_{Ti})$$

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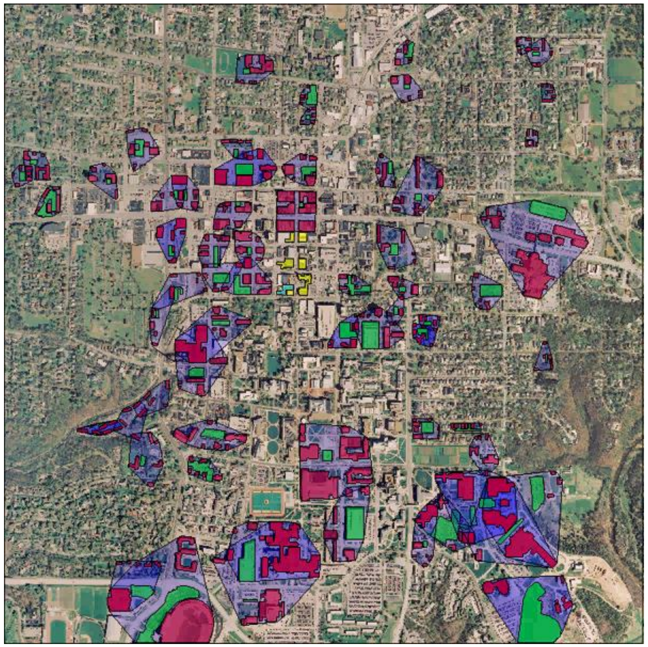
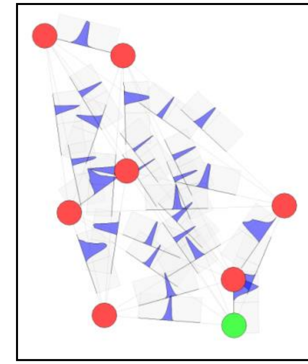
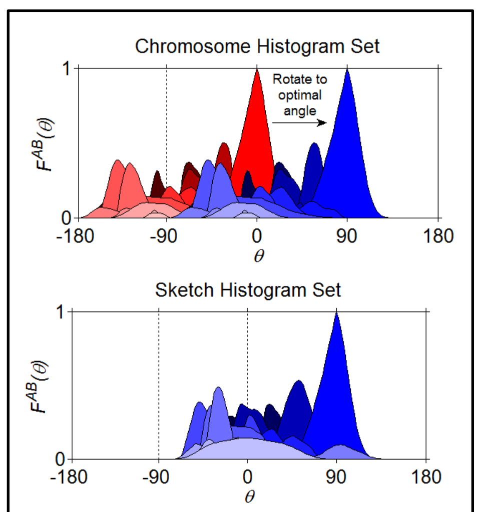
Global Search Strategy



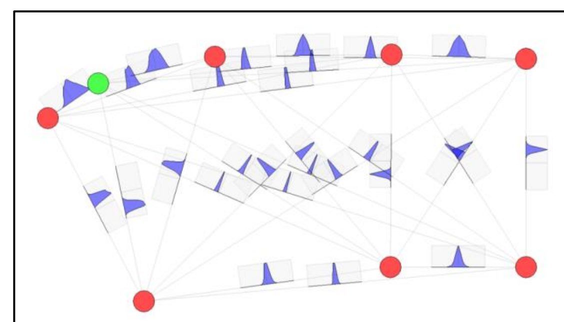
For each chromosome

Build ARG





Compare with sketch ARG to compute fitness

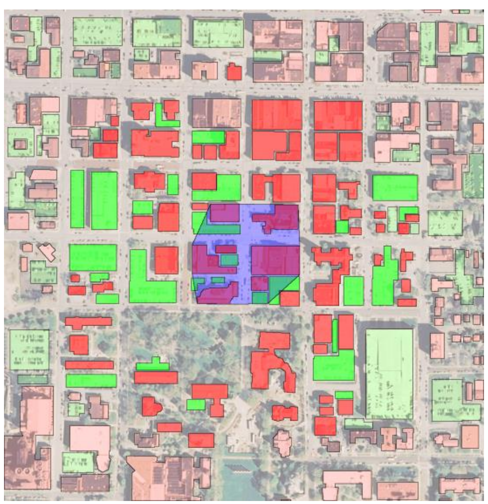


An evolutionary framework maintains a population of chromosomes which could match the sketch

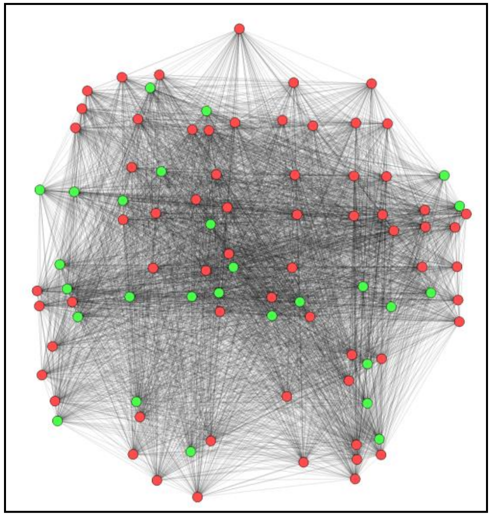
Local Search Strategy

For each chromosome…

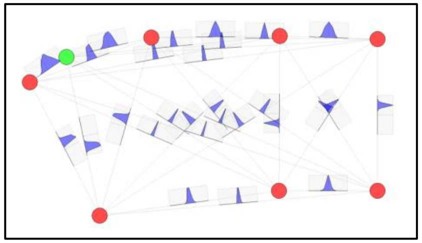
…get nearest neighbors for each chromosome



Build ARG



Use a local search strategy to find a new chromosome that more closely matches the sketch ARG



Exploration vs. Exploitation

- Traditional crossover and mutation tend to produce invalid solutions (graphs are incomplete)

- Exploration (Global search strategy)
  - Handled by the random initialization operator
    - New random individuals are added every few generations

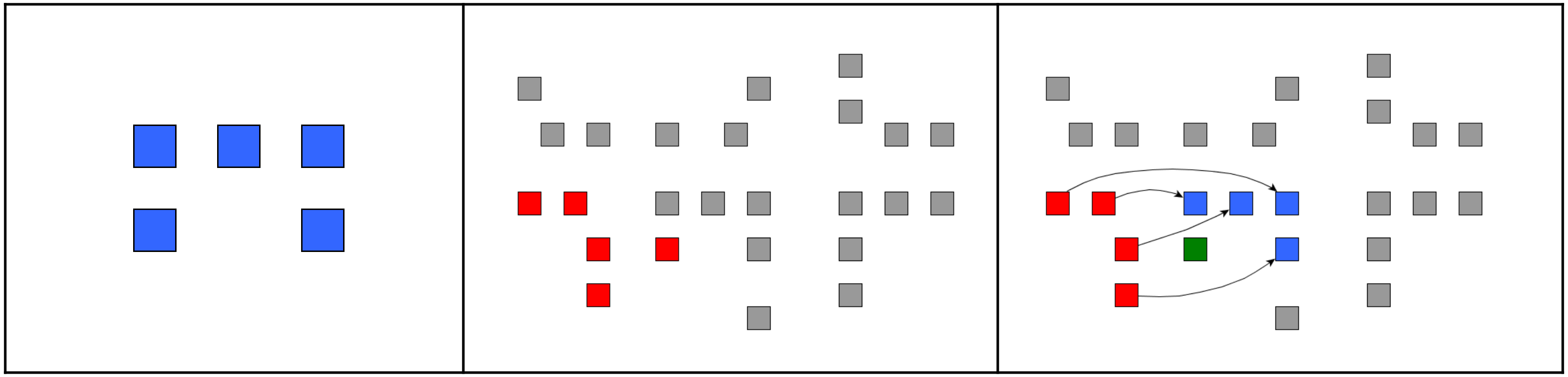
- Exploitation (Local search strategy)
  - Handled by the one-seed and VF2 local search operators
    - Good children replace their parents

Overall Algorithm

- Create an initial population of random chromosomes
- While stopping criteria is not met
  - For each chromosome, generate children using local search (exploitation)
  - If a child is more fit than its parent, it replaces the parent
  - Every few generations, replace the lowest scoring fraction of the population with new random individuals (exploration)
- Return top scoring individuals from the last generation

One-Seed Set Reconstruction

- A single seed object is kept from the chromosome, and the remaining objects are chosen to give the best match with the sketch



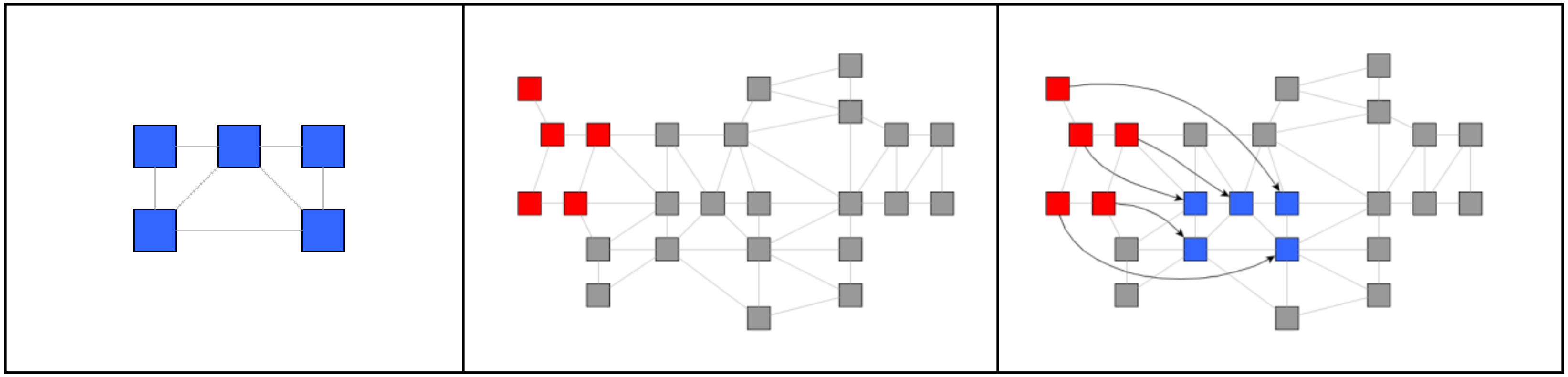
Sketch

"Nearly correct" Chromosome

Local Search

VF2 Subgraph Isomorphism

- The VF2 algorithm is used to find the subgraph which most closely matches the sketch



Sketch | "Nearly correct" Chromosome | Local Search

One-Seed vs. VF2

- One-Seed
  - Moves slowly through the search space
  - Builds up partial solutions one object at a time
  - Complexity is $O(N^5 K)$
    - N is sketch size and K is neighborhood size

- VF2
  - Searches the entire local neighborhood
  - Uses a state space representation and a set of feasibility rules to guide the search
  - Complexity
    - Best case is $O\left(N(K+N^2)\right)$
    - Worst case is $O\left(K!\,(K+N^2)\right)$

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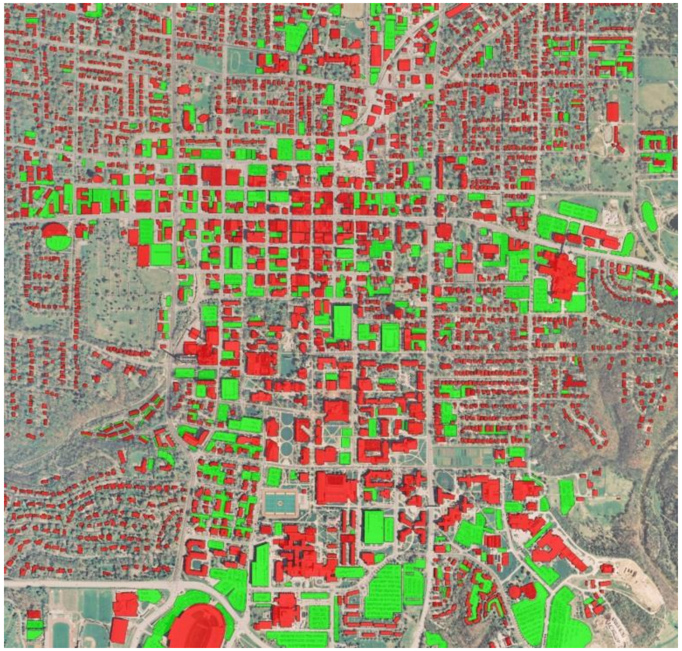
Experiments

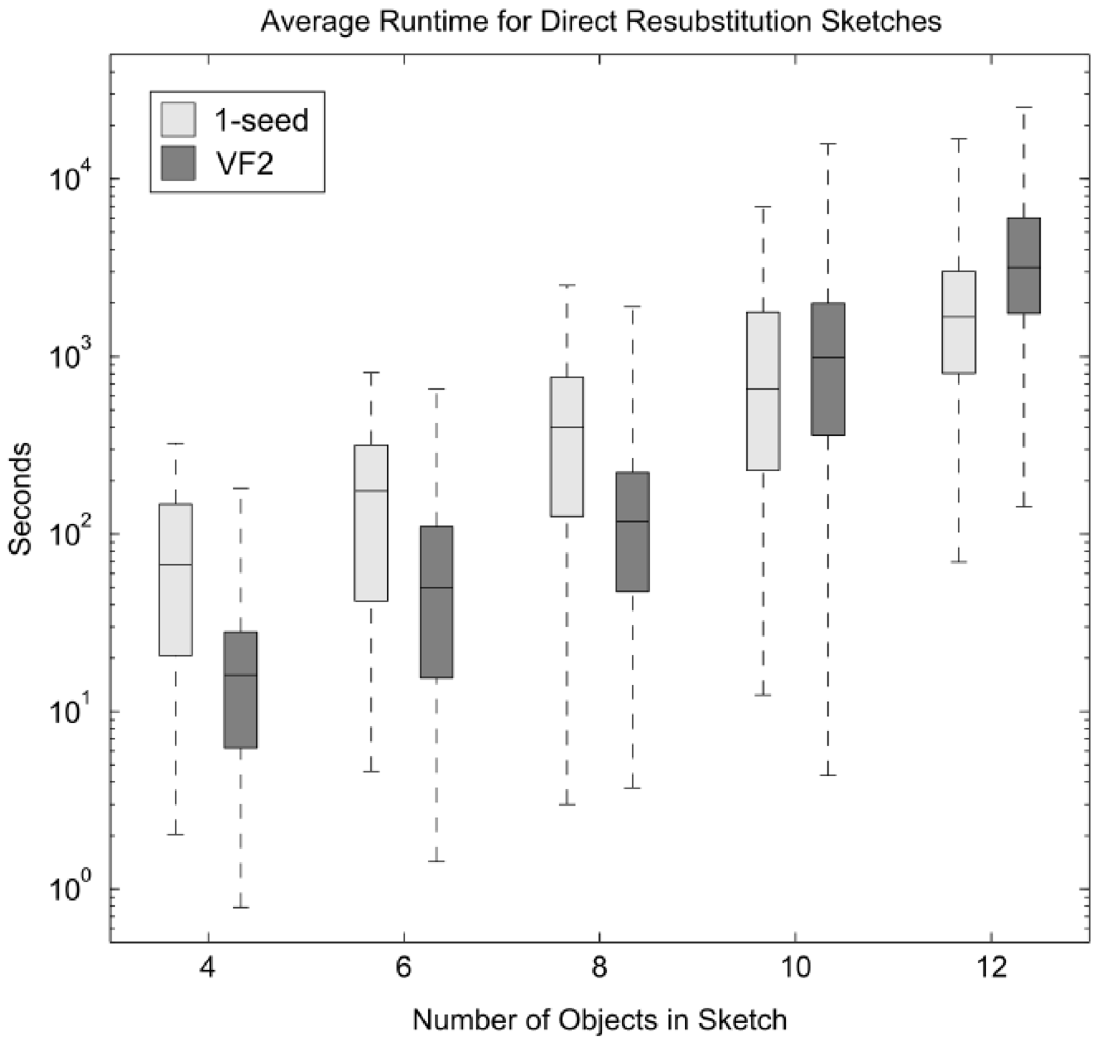
- Hand-segmented database of Columbia, MO
  - 2467 buildings
  - 378 parking lots
- Reference ARG pre-computed with 50 nearest neighbors
- 100 target sketches randomly generated for each test configuration:
  - 4, 6, 8, 10, and 12 objects
    - Direct resubstitution sketches
    - Transformed sketches



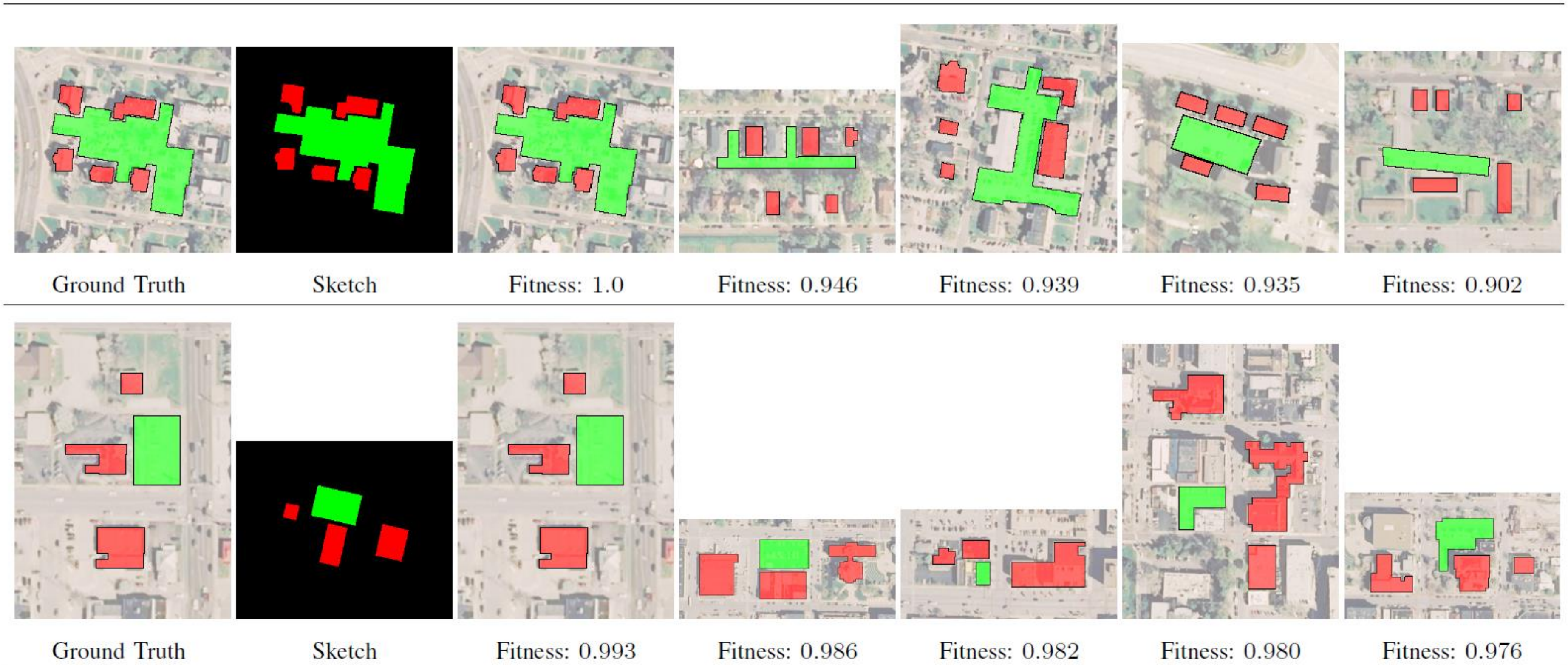
Accuracy Results

Mutation Method	Objects in Sketch	Percent Correctly Matched	
		Direct Resubstitution Sketches	***Transformed Sketches***
1-Seed	4	95.1%	80.6%
	6	98.5%	95.6%
	8	99.6%	93.4%
	10	94.8%	81.7%
	12	86.2%	87.2%
VF2	4	98.7%	80.4%
	6	96.6%	94.3%
	8	98.1%	86.0%
	10	90.8%	69.2%
	12	76.5%	78.8%

Runtime Results



Examples



Ground Truth
Sketch
Fitness: 1.0
Fitness: 0.946
Fitness: 0.939
Fitness: 0.935
Fitness: 0.902
Ground Truth
Sketch
Fitness: 0.993
Fitness: 0.986
Fitness: 0.982
Fitness: 0.980
Fitness: 0.976

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Conclusions

- Scene matching is a real-world problem with intuitive global and local search paradigms
  - A memetic framework can help combine multiple search strategies
- Evolutionary computation helps manage complexity in large search spaces
- Further improvements to the algorithm
  - $(\mu + \lambda)$ evolution strategy with appropriate diversity mechanisms
  - Tabu search to avoid researching regions

Thank You