SAND2014-19280C

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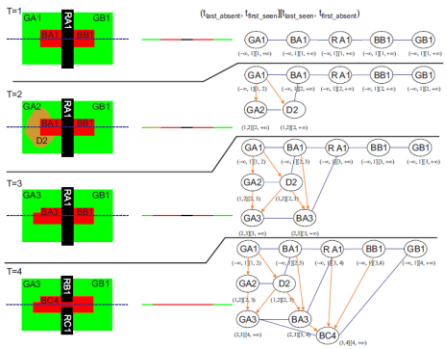

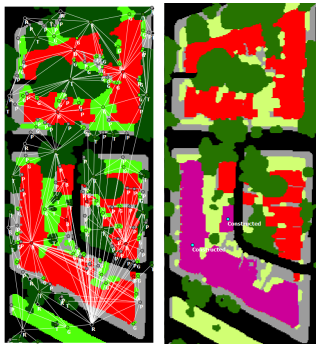


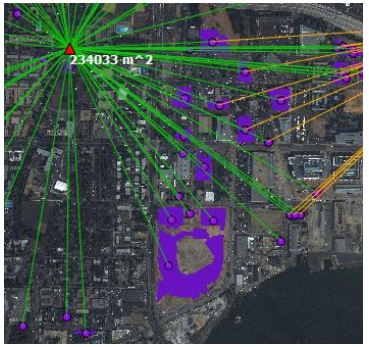


# A Computational Framework for Ontologically Storing and Analyzing Very Large Overhead Image Sets

Randy C. Brost, Ph.D.

November 4, 2014

U.S. DEPARTMENT OF ENERGY

NNSA National Nuclear Security Administration

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- Ojas Parekh
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- Sandia LDRD Office.

# Overview

Sandia National Laboratories

- Motivation.
- Computation.
- Results.
- Discussion.

# Motivation

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GeoGraphy

Motivation:

- Overwhelming remote sensing data.
- Wide-area search is tedious, error-prone.
- Reasoning over time is even more difficult.
- We don't want to miss important items (proliferation, weapons production…).

General approach:

- Automatically find items of potential interest.
- "Cue" to user for review.

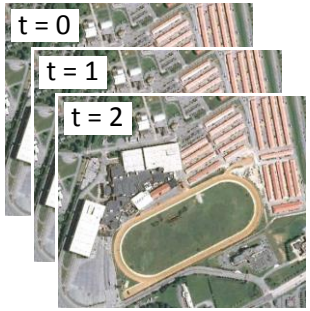
Types of questions:

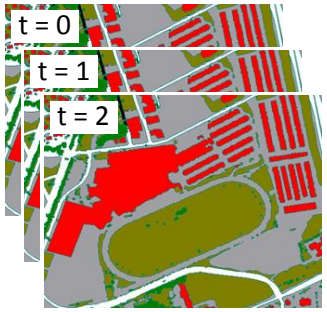
- Geospatial: Find all power plants.
- Temporal: Find all changes.
- Geospatial-temporal: Find all power plants that changed.
- Multi-modality: Find new construction near points of interest.
  Find industrial facilities with unusual emissions.

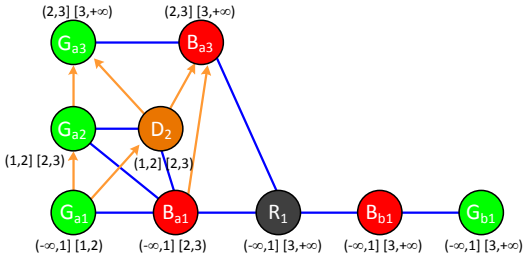
# Overview

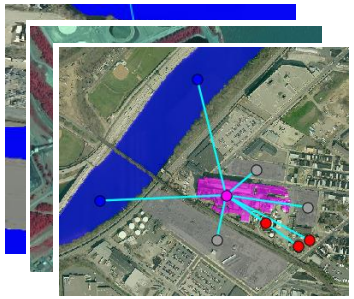
- Motivation.
- Computation.
- Results.
- Discussion.

# Geospatial-Temporal Graph Data Flow



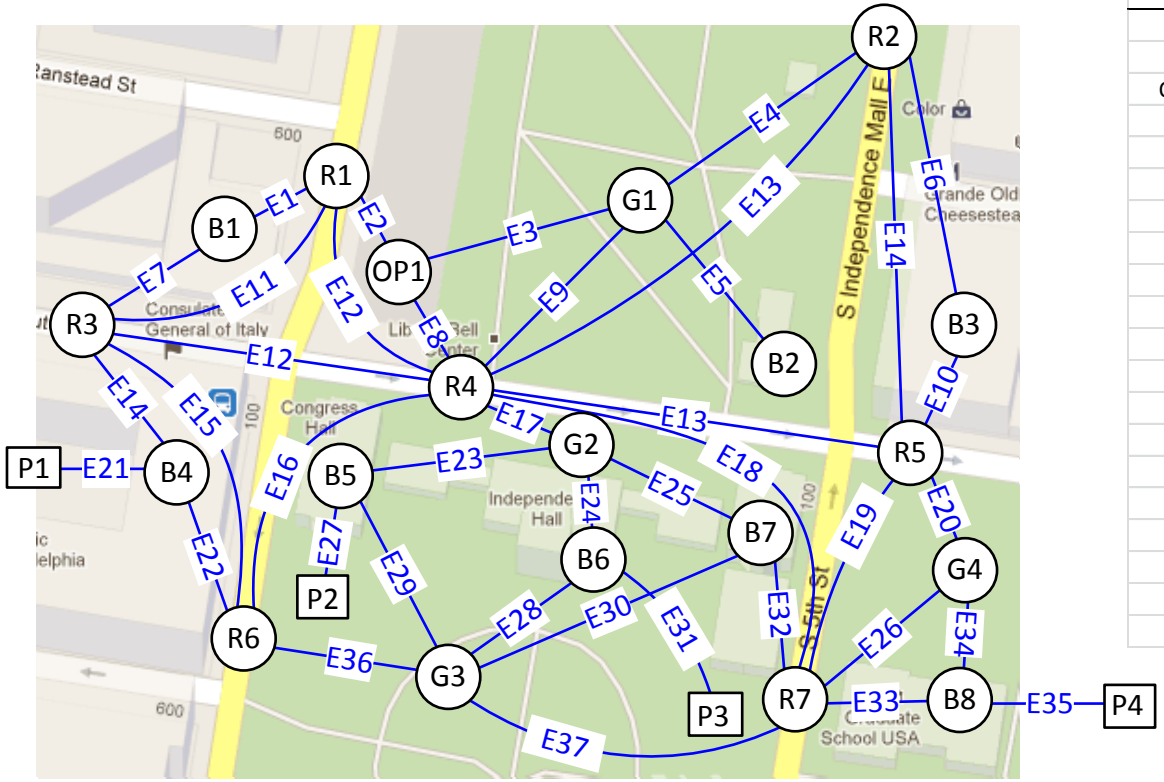
Remote Sensing → Primitive Recognition (U. Vermont) → Spatiotemporal Graph → Spatial, Temporal, Spatiotemporal → Matches

Query:
- Spatial parameters
- Temporal parameters
- Subgraph pattern
- Algorithm control

→ **Change Detection**

# Example Geospatial Semantic Graph

Independence Hall, Philadelphia:




Region node table:

| id | type | area | centroid x | centroid y |
|---|---|---|---|---|
| B1 | building | 3200 | -75.14900 | 39.94939 |
| R1 | road | 1800 | -75.14910 | 39.94949 |
| OP1 | paved | 4700 | -75.14935 | 39.94934 |
| G1 | grass | 22000 | -75.15010 | 39.94944 |
| R2 | road | 1900 | -75.15060 | 39.94999 |
| R3 | road | 1100 | -75.14885 | 39.94934 |
| R4 | road | 2200 | -75.14980 | 39.94924 |
| B2 | building | 780 | -75.15045 | 39.94931 |
| B3 | building | 6000 | -75.15075 | 39.94944 |
| B4 | building | 12000 | -75.14895 | 39.94884 |
| B5 | building | 2100 | -75.14920 | 39.94899 |
| G2 | grass | 7700 | -75.14990 | 39.94906 |
| R5 | road | 870 | -75.15065 | 39.94896 |
| B6 | building | 2000 | -75.15000 | 39.94889 |
| B7 | building | 3150 | -75.15040 | 39.94884 |
| G4 | grass | 15300 | -75.15080 | 39.94869 |
| R6 | road | 1970 | -75.14905 | 39.94844 |
| G3 | grass | 25000 | -75.14960 | 39.94829 |
| R7 | road | 1810 | -75.15050 | 39.94834 |
| B8 | building | 2700 | -75.15090 | 39.94819 |

Point node table:

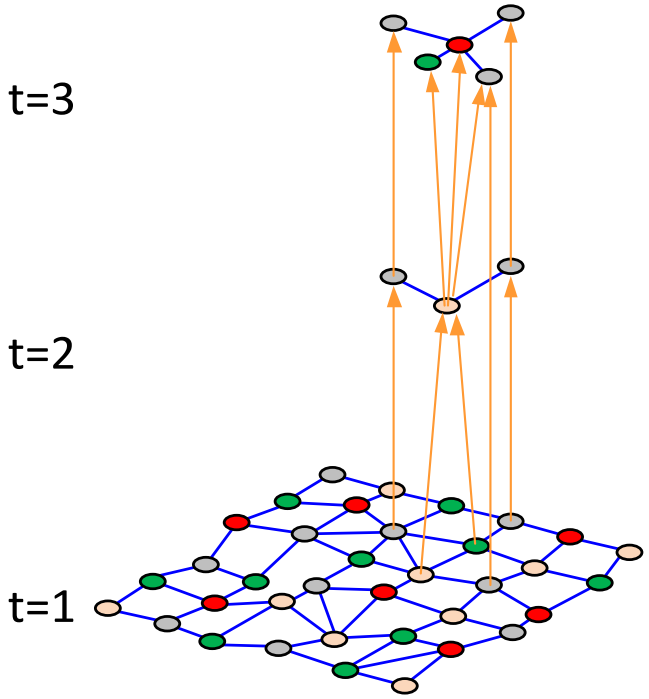
| id | Name | Address | Latitude | Longitude |
|---|---|---|---|---|
| P1 | Consulate of Italy | 150 S. Independent Mall West #1026 | -75.14895 | 39.94884 |
| P2 | Congress Hall | 41 N 6th Street | -75.14920 | 39.94899 |
| P3 | Independence Hall | 520 Chestnut Street | -75.15000 | 39.94889 |
| P4 | Graduate School USA | 150 S. Independence Mall West #674 | -75.15090 | 39.94819 |

Edge table:

| edge_id | node_1 | node_2 |
|---|---|---|
| E1 | B1 | R1 |
| E2 | R1 | OP1 |
| E3 | OP1 | G1 |
| E4 | G1 | R2 |
| E5 | G1 | B2 |
| E6 | R2 | B3 |
| E7 | R3 | B1 |
| E8 | OP1 | R4 |
| E9 | R4 | G1 |
| . | . | . |
| . | . | . |
| . | . | . |

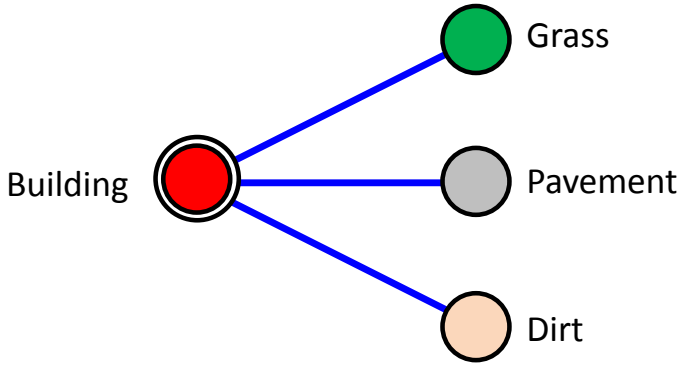
# Representing Change Over Time

- Encode change:
  - Node attributes include duration seen.
  - Only construct new nodes for changes.
  - “Changed-to” arcs encode time evolution.
  - Graph complexity focuses on change areas.

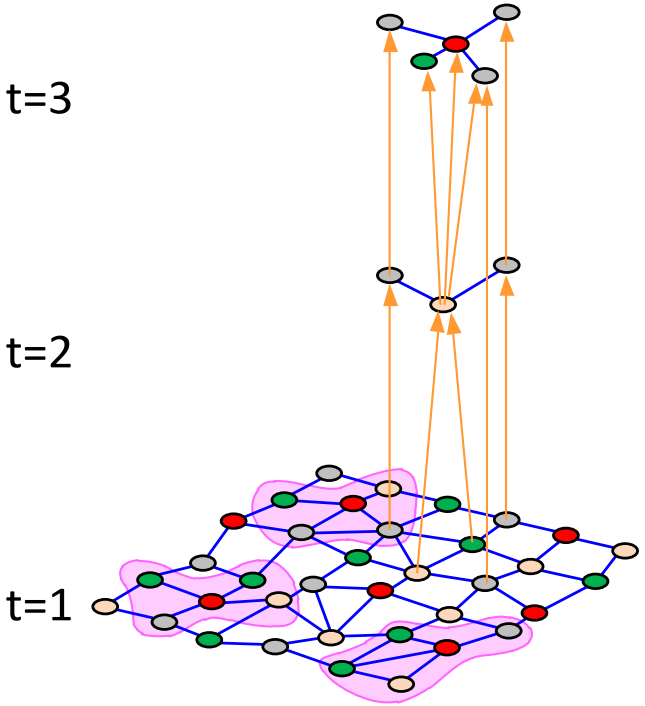


# Signature Search

- A signature encodes a desired question.
- Example: “Where are buildings with nearby grass, pavement, and dirt?

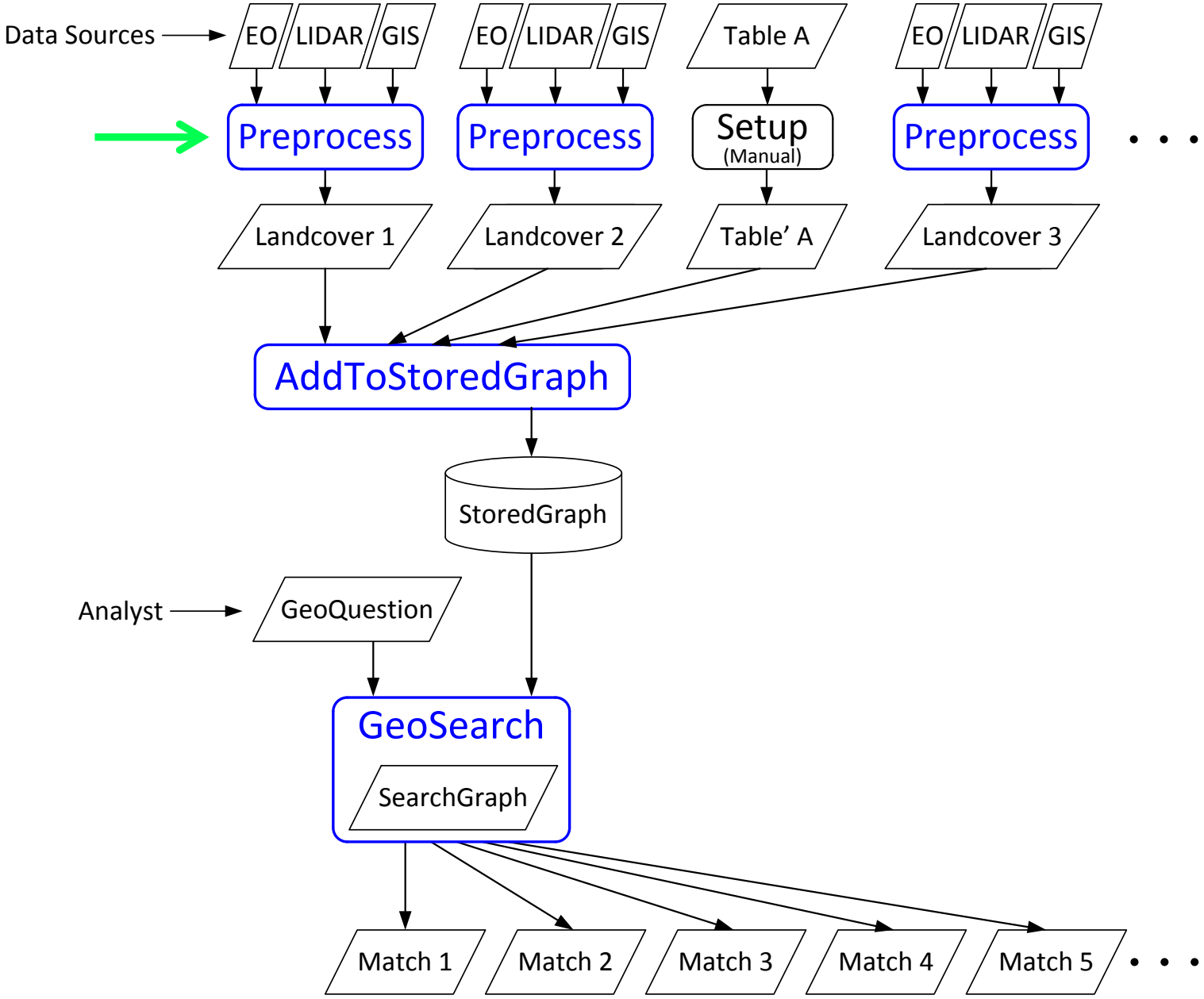



Query Template

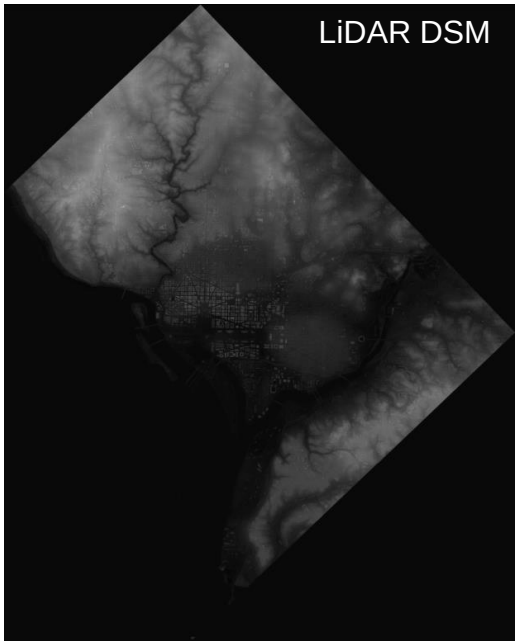



Search Results

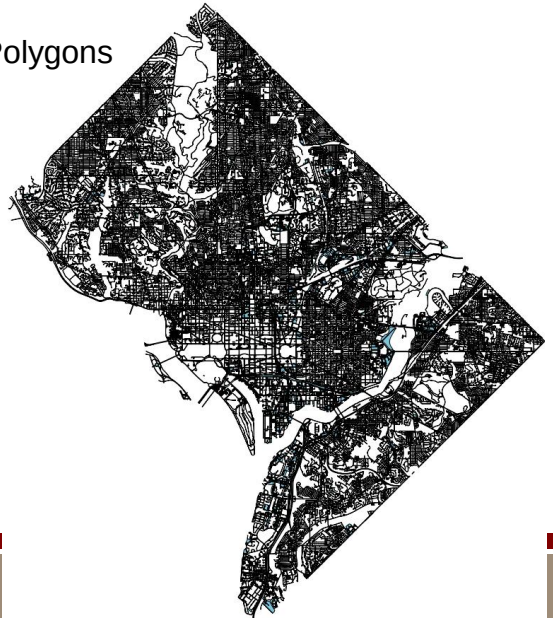
# Primary Data Flow



# Input Data


GIS Road Polygons



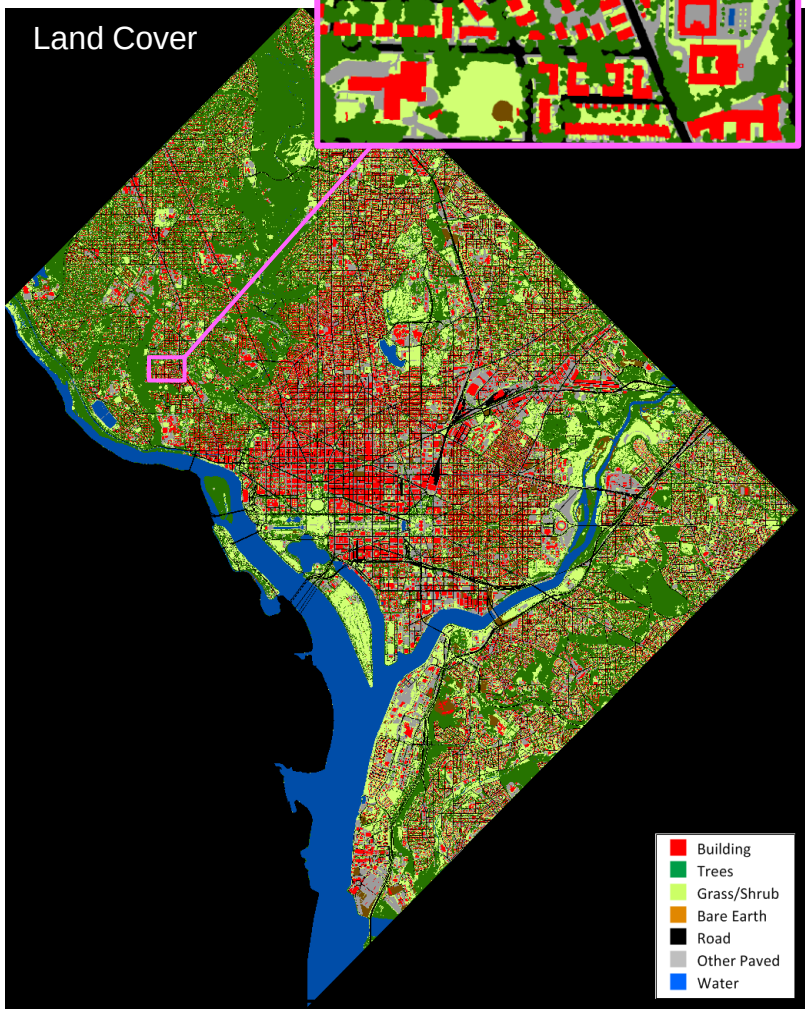
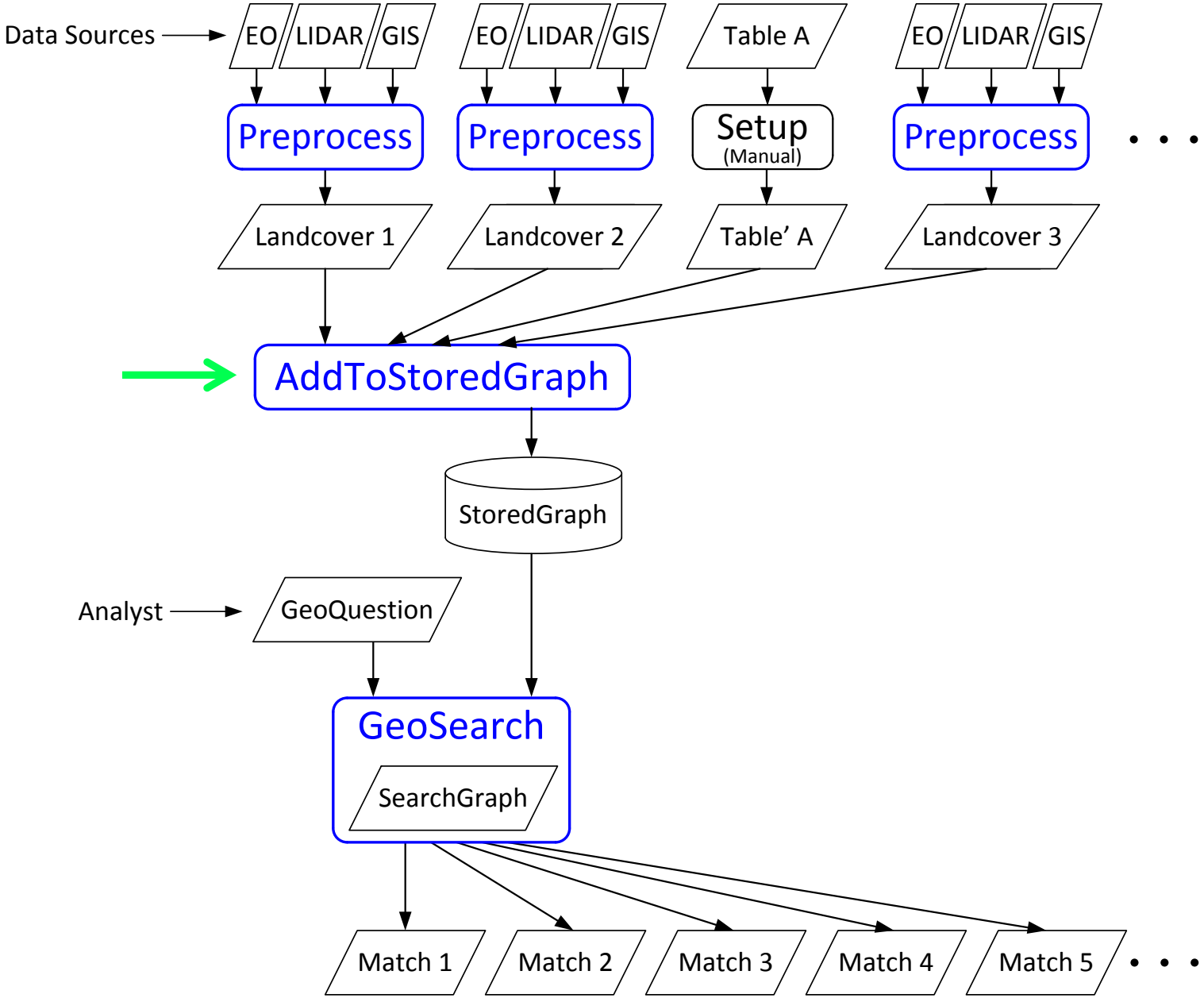



Image data and processing by University of Vermont Spatial Analysis Lab [O'Neil-Dunne 2012].

[O'Neil-Dunne 2012] O'Neil-Dunne, et al, An object-based system for LiDAR data fusion and feature extraction, Geocarto (28), pp. 227–242, 2012.

# Primary Data Flow



# Example Scenario

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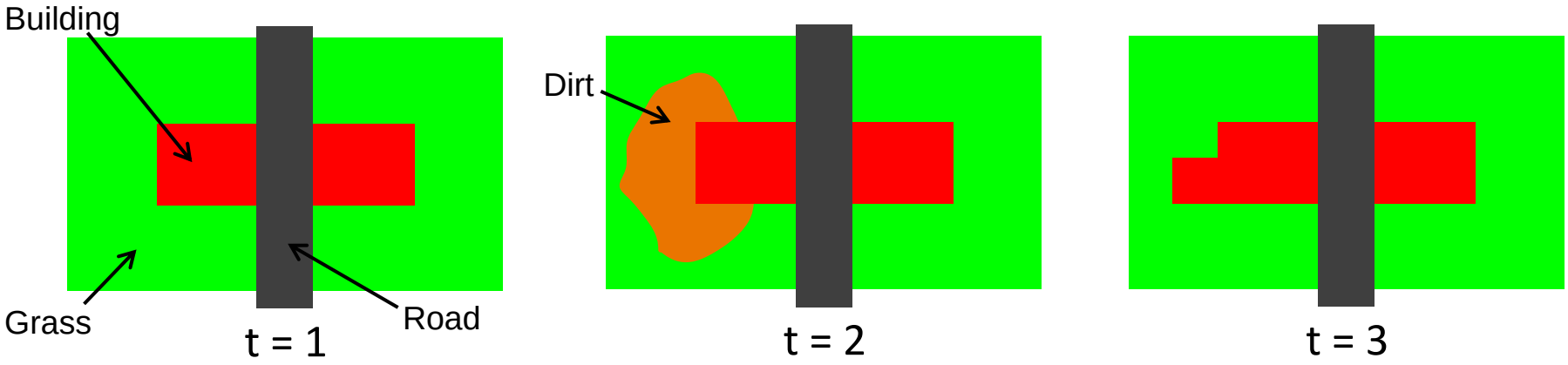
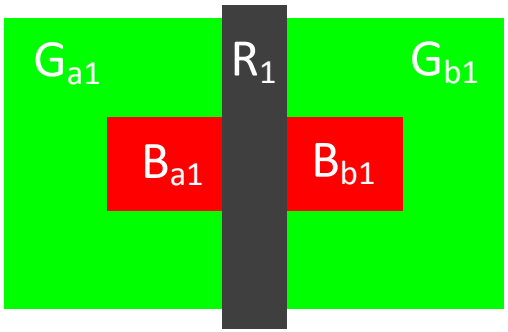
Data sequence:



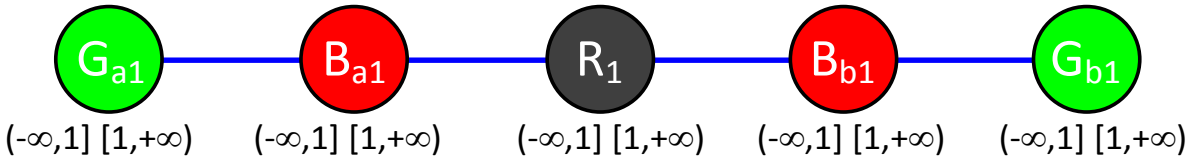
# StoredGraph Construction

Sandia National Laboratories

Start with land cover #1:




t = 1




Each node has several attributes:
area, centroid, moments, eccentricity, orientation, bounding box, etc...

Legend:

G Durable nodes

Adjacency edges

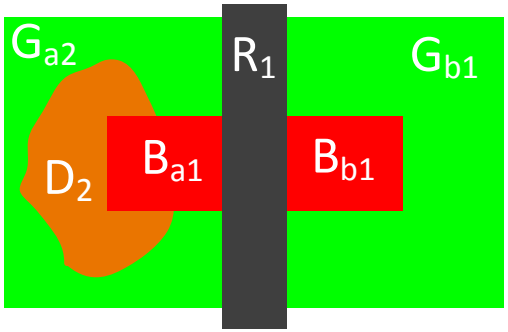
Data semantics:

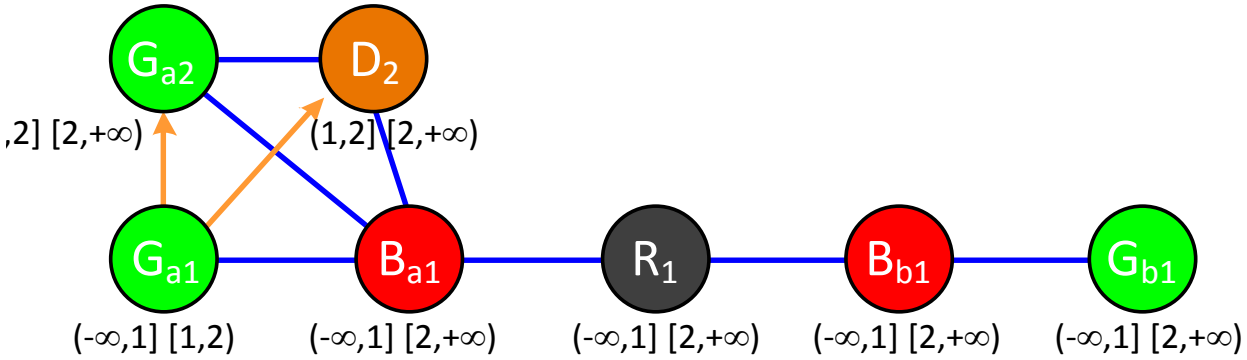
| | |
|---|---|
| Building | B |
| Grass | G |
| Dirt | D |
| Road | R |

* Road↔Grass edges omitted for clarity throughout.

# StoredGraph Construction

Add land cover #2:




Data semantics:

| | |
|---|---|
| Building | B |
| Grass | G |
| Dirt | D |
| Road | R |

Legend:

G Durable nodes

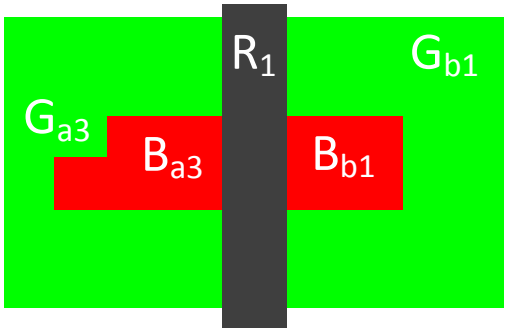
Adjacency edges

Change edges

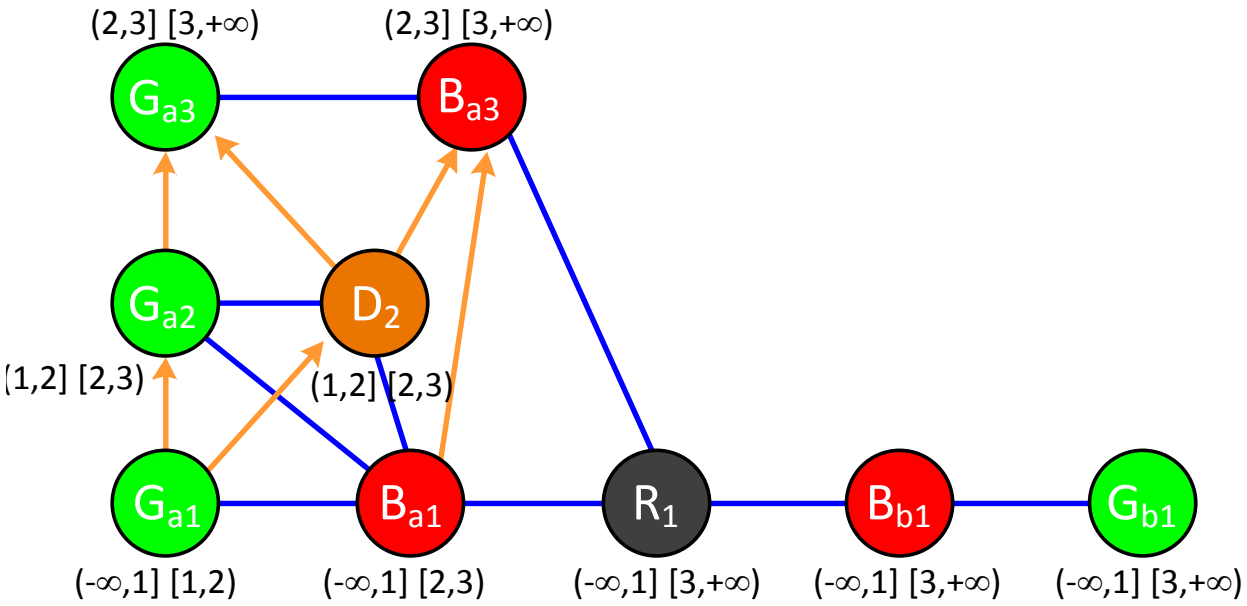
# StoredGraph Construction

Sandia National Laboratories

Add land cover #3:




t = 3




Data semantics:

| | |
|---|---|
| Building | B |
| Grass | G |
| Dirt | D |
| Road | R |

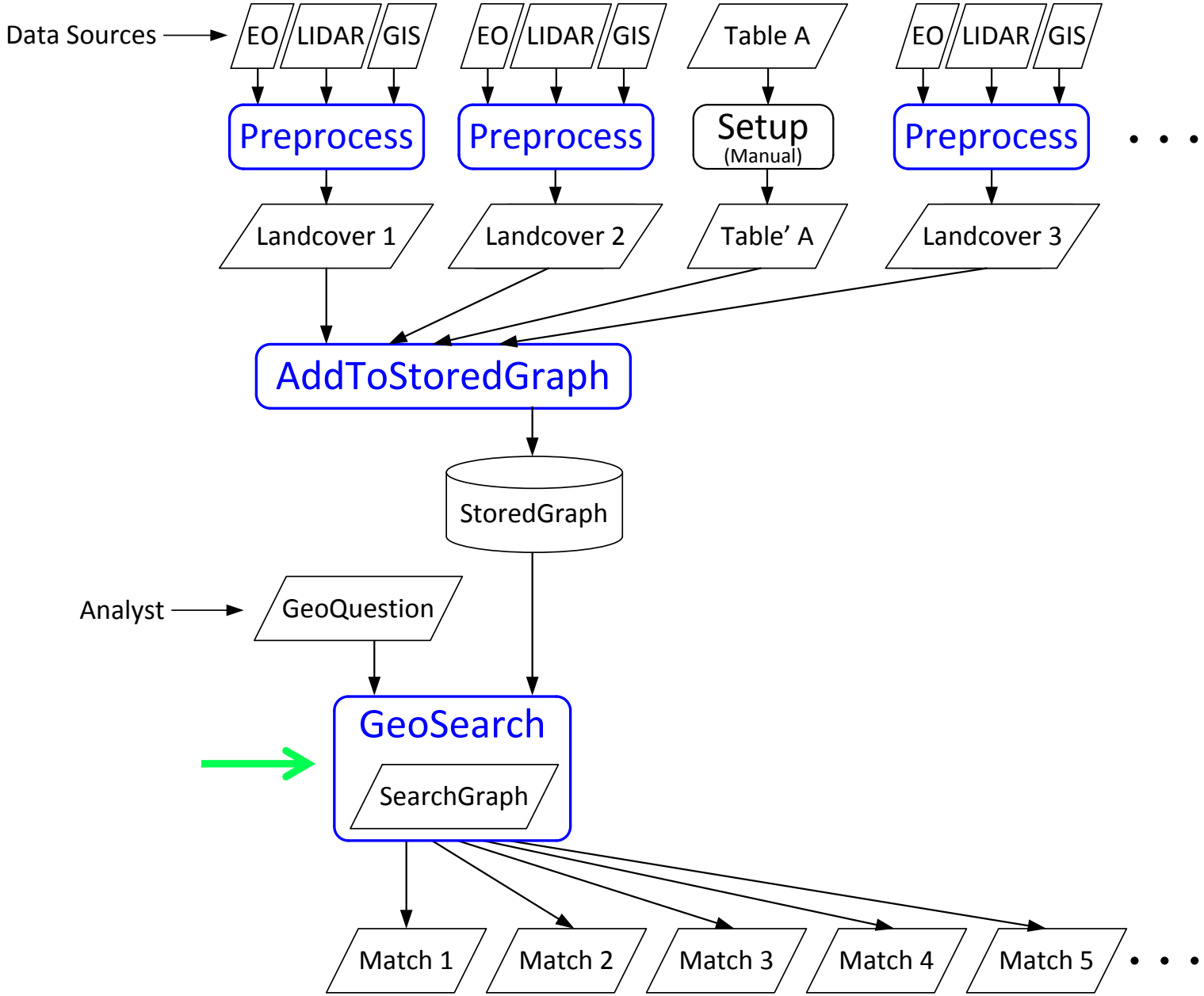
Legend:

G Durable nodes

Adjacency edges

Change edges

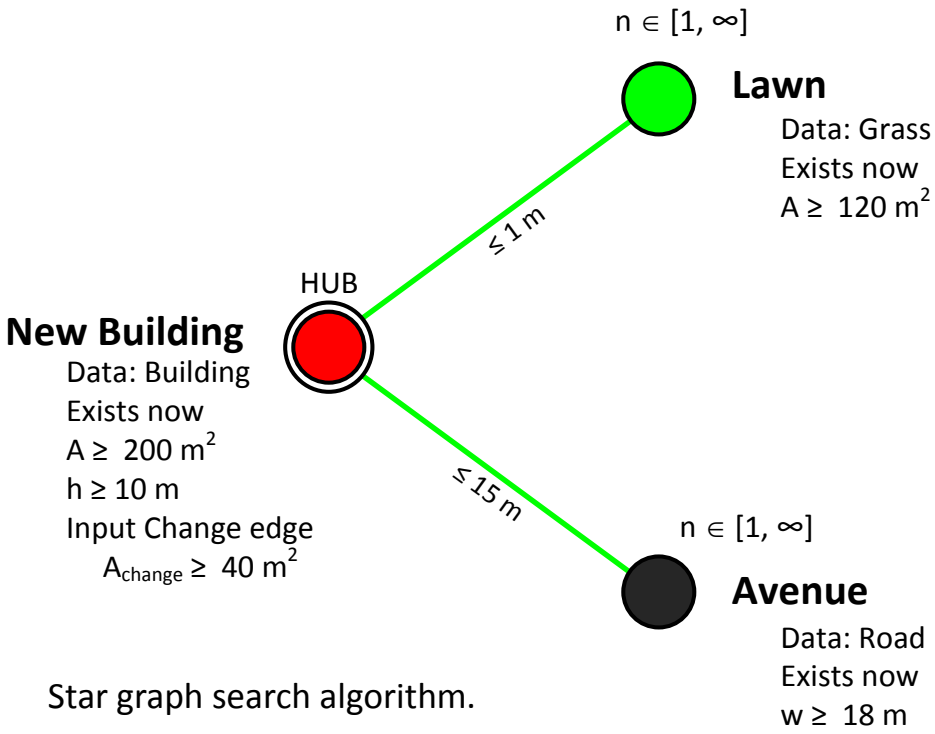
# Primary Data Flow



# Query Definition

Question: Where is a new luxury office building?

Star graph template:




Star graph search algorithm.

Question semantics:

| | |
|---|---|
| New Building | N |
| Lawn | L |
| Avenue | A |

Data semantics:

| | |
|---|---|
| Building | B |
| Grass | G |
| Dirt | D |
| Road | R |

This configuration is consistent with a luxury office building.

# Search Graph Source: StoredGraph

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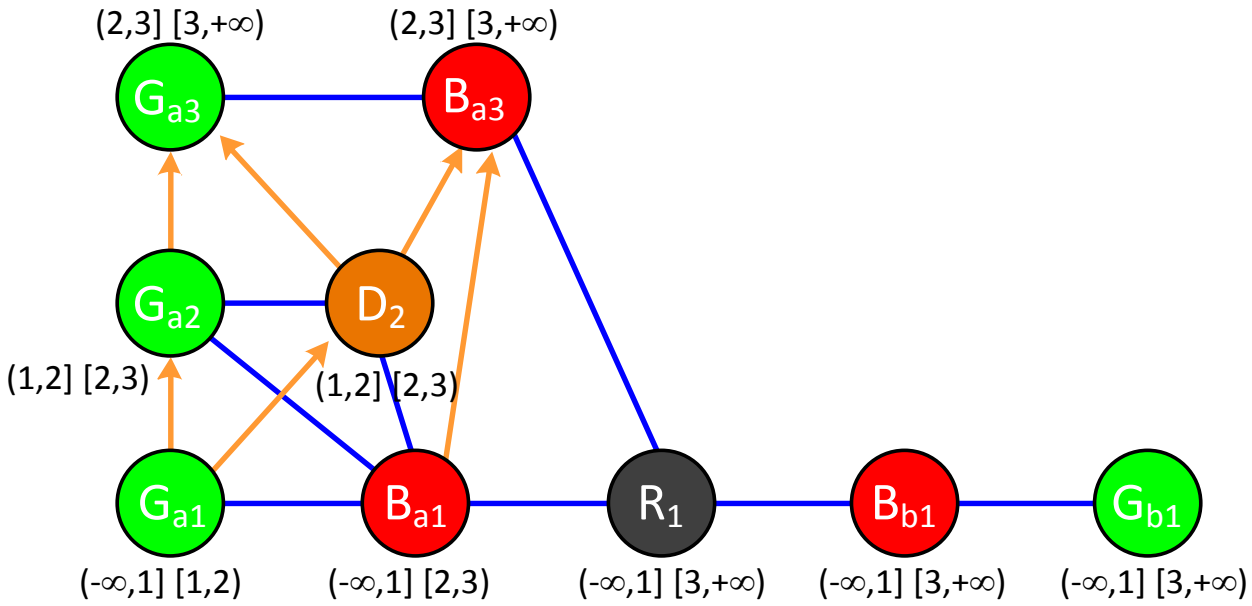
Available StoredGraph:




Legend:

- G — Durable nodes
- Adjacency edges
- Change edges

Data semantics:

| | |
|---|---|
| Building | B |
| Grass | G |
| Dirt | D |
| Road | R |

# Constructed SearchGraph

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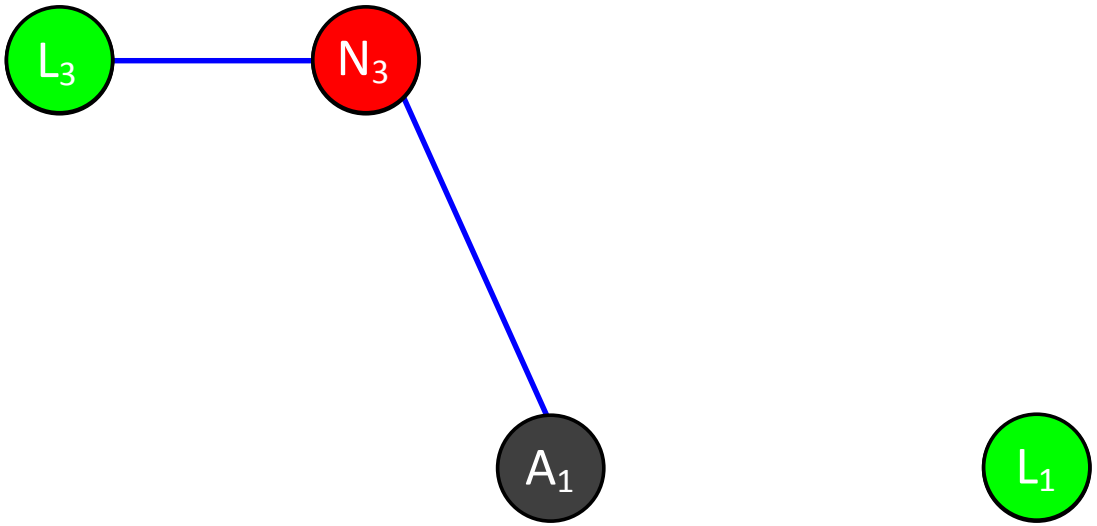
<u>After adding edges:</u>

Signature nodes:
- New Building
- Lawn
- Avenue

Signature edges:
- New Building ↔ Lawn
- New Building ↔ Avenue




<u>Question semantics:</u>

| | |
|---|---|
| New Building | N |
| Lawn | L |
| Avenue | A |

SearchGraph only contains elements relevant to the question.

Semantics are now in terms of the question.

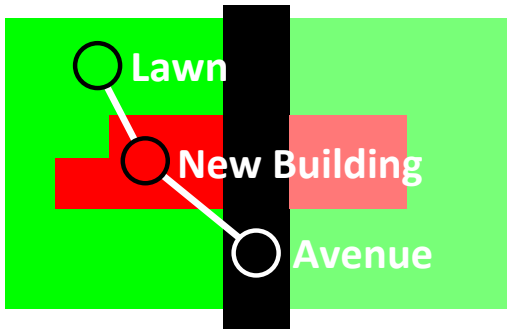
<u>Legend:</u>

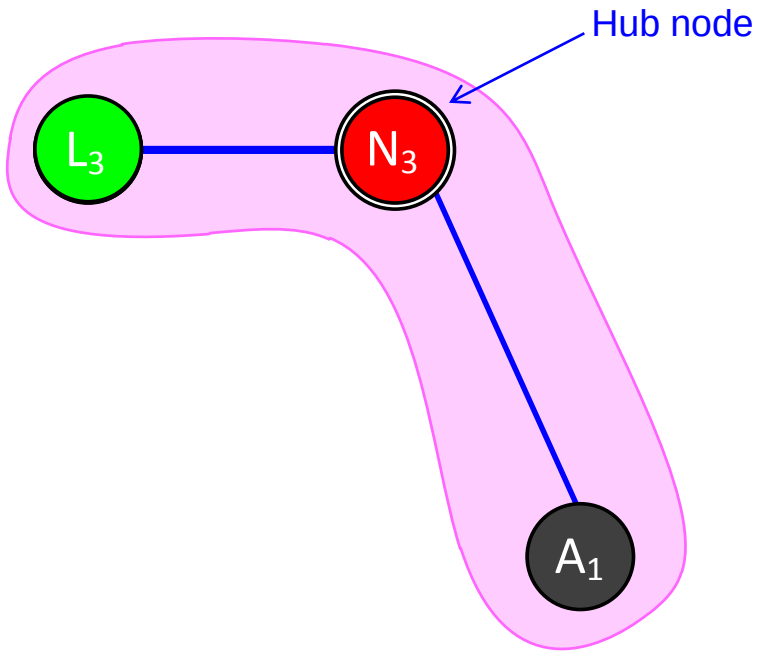
G Nodes

Edges

# Search Result

Matches found:




Remarks:

- This match is consistent with hypothesized signature.
- It does not "prove" this is a luxury office building --- this template might also match a movie star's mansion.

# Graph Search

Sandia National Laboratories

Initial implementation [Watson 2010]:

- Subgraph isomporhism.
- NP-complete! [Cook 1971, Ullmann 1976]

Current approach:

- Identify relevant portion of StoredGraph.
- Lazy constraint, distance edge evaluation, with caching.
- Simple graph search algorithms:
  - Star graph.
  - Connected component.
  - Interrupted star, using transitive closure.
- Postprocessing calculations.

[Cook 1971] S. A. Cook, "The Complexity of Theorem-Proving Procedures," 3rd ACM Symposium on Theory of Computing, pp. 151–158, 1971.

[Ullmann 1976] J. R. Ullmann, "An Algorithm for Subgraph Isomorphism," Journal of the ACM 23(1), pp. 31–42, 1976.

[Watson 2010] J. P. Watson, “Complex Signature Detection Using Geospatial/Temporal Semantic Graphs,” Simulations, Algorithms, and Modeling Program Review Meeting (SAM2010), April 2010.

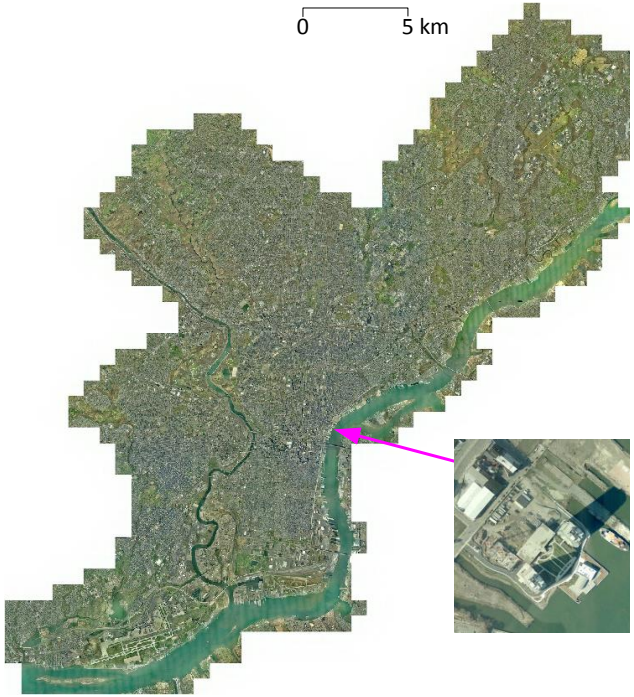
# Overview

Sandia National Laboratories

- Motivation.
- Computation.
- Results.
  - Data.
  - Power Plant Search.
  - Refinery search.
  - Change Analysis.
  - New Building complex search.
- Discussion.

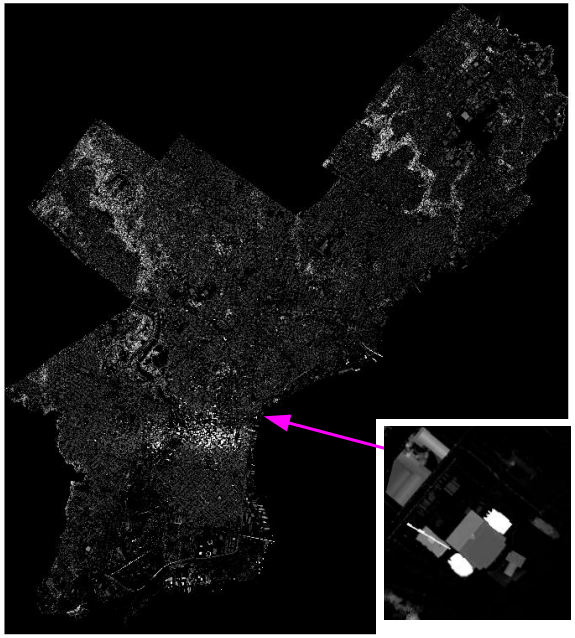
# Philadelphia 2008

Primary input:



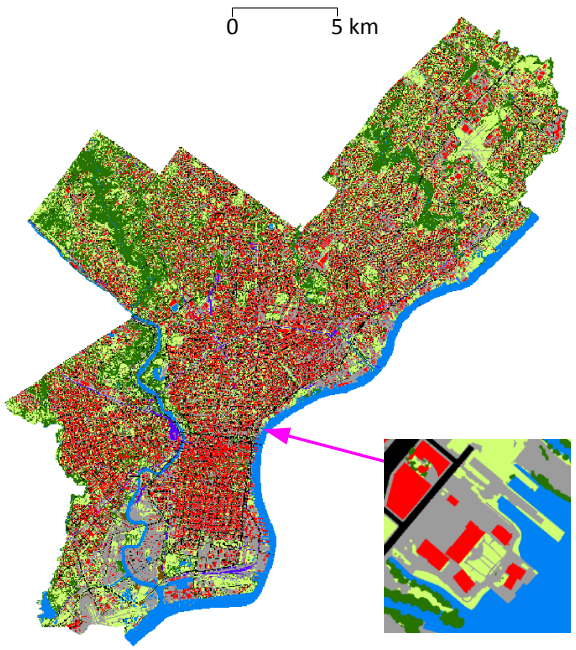

Optical Image

Pixel size 0.1 m
307,531 × 330,033 pixels
(101.5 Gpix)
7,669 MB



LiDAR nDSM

Pixel size 0.3 m
89,540 × 100,294 pixels
(9.0 Gpix)
2,084 MB




Land Cover

Pixel size 0.3 m
89,548 × 100,303 pixels
(9.0 Gpix)
8,775 MB

# Three Data Regions

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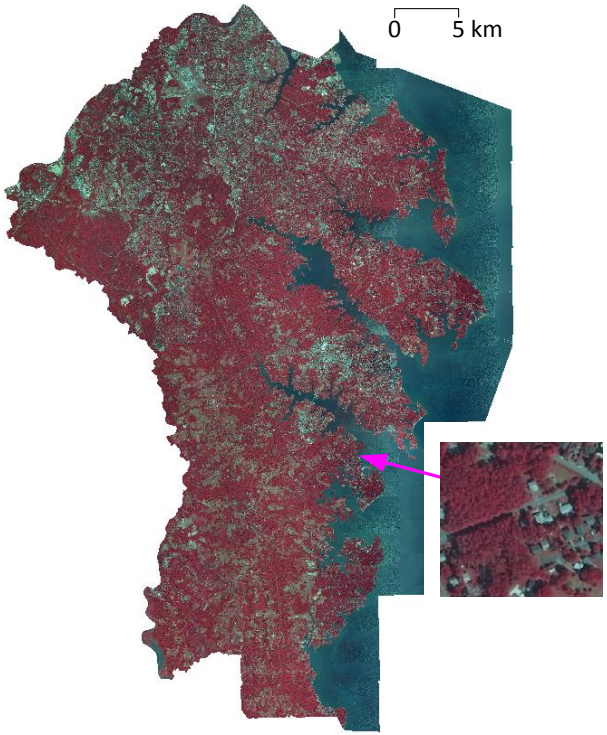
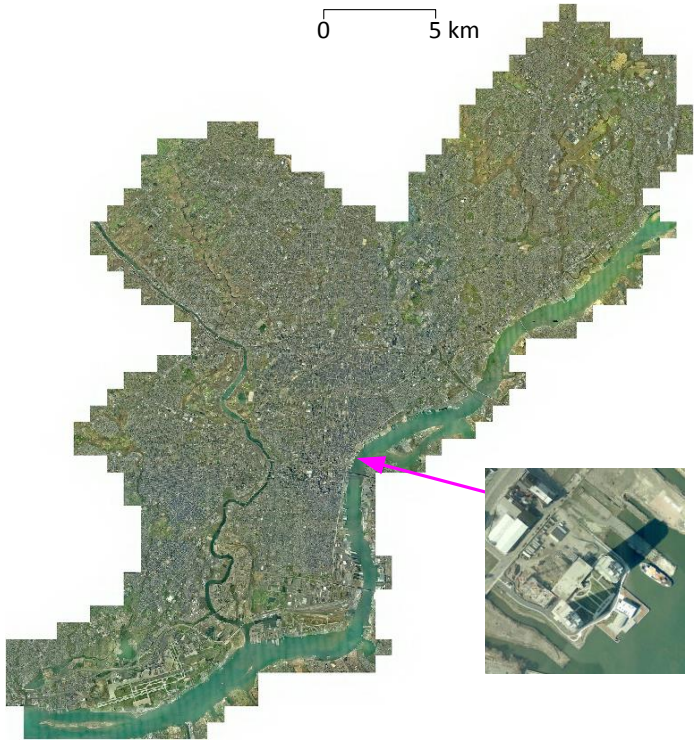
Search results:




Anne Arundel County, MD




Philadelphia, PA


Washington, DC

Total:

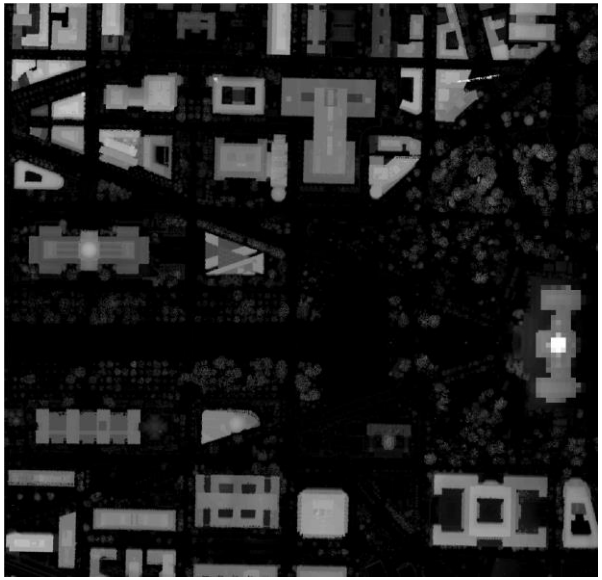
| | |
|---|---|
| 2,067 | $km^2$ total area |
| 135 billion | Pixels |
| 3.6 million | Features |

Total file size was about 88 GB.

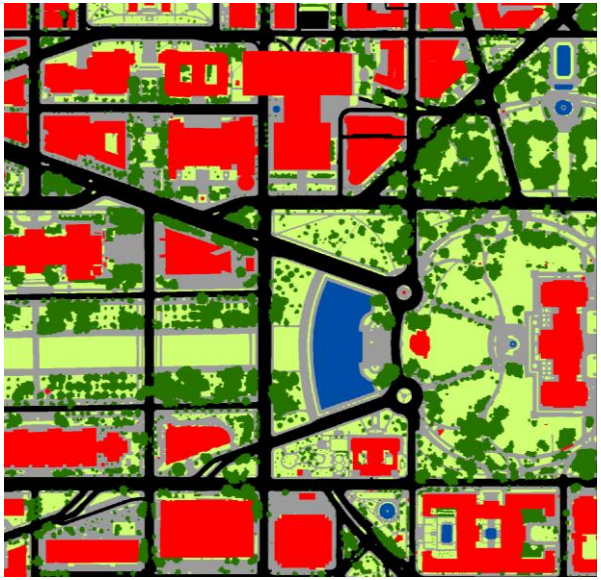
# Washington, DC Data

Zoomed in:

RGB+IR Optical Image



LiDAR Height Map (nDSM)



Posterized Land Cover

All of our wide-area data sets include this level of detail (roughly).

# Power Plant Search

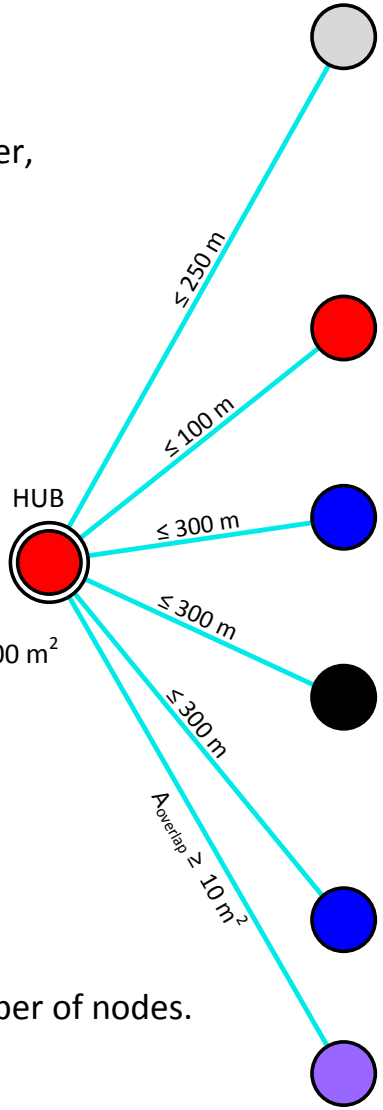
Sandia National Laboratories

Query specification:

A power plant is a heat building with a transformer, and optional storage tank, evaporation pond, coal pile, body of water.

Question semantics:
Heat Building
Transformer
Cooling Tower
Evaporation Pond
Body of Water
Coal Pile
Storage Tanks
Processing Tower
Pipe Network
⋮

Data semantics:
Building
Road
Other Paved
Grass/Shrub
Trees
Dirt
Water




**Transformer** n ∈ [1, ∞] (required)
Data: Other Paved
Chunk (15 × 15)
A ≥ 5,000 m²
Eccentricity ≤ 3.5
12 m ≤ $h_{max}$ ≤ 35 m
At least 5 m² above 10 m

**Tank** n ∈ [0, 6] (optional, limited)
Data: Building
Circular
90 m² ≤ A ≤ 3,000 m²

**Evaporation Pond** n ∈ [0, ∞] (optional)
Data: Water
1,500 m² ≤ A ≤ 19,500 m²
Eccentricity ≤ 6.0

**Coal Pile** n ∈ [0, ∞] (optional)
Data: Dirt
A ≥ 30,000 m²
Eccentricity ≤ 3.0
$[R\ G\ B]_{max}$ ≤ 0.4

**Body of Water** n ∈ [0, ∞] (optional)
Data: Water
A ≥ 20,000 m²

**Constructed** n ∈ [0, 0] (forbidden)
Data: Building
A ≥ 100 m²
New, Extended, Changed

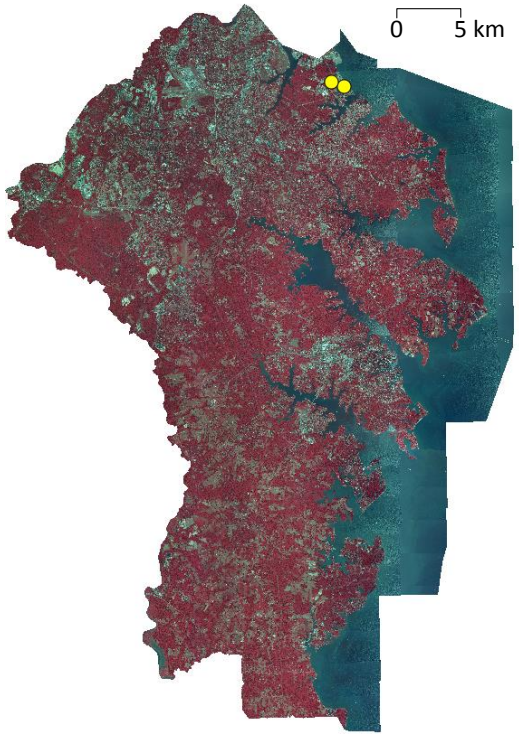
Star graph search.

Sort matches by number of nodes.

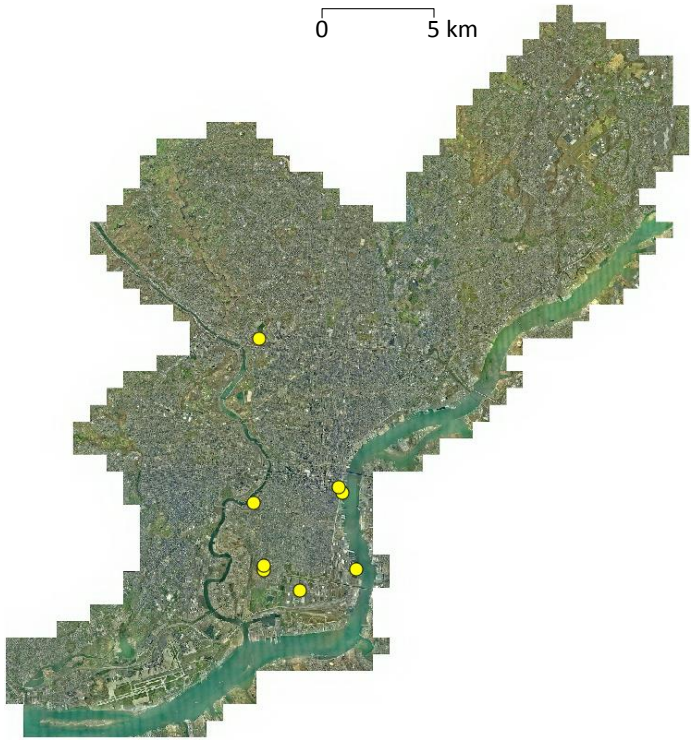
Note: "Exists Now" is omitted for clarity.

# Power Plant Search

Search results:




Anne Arundel County, MD




Philadelphia, PA


Washington, DC

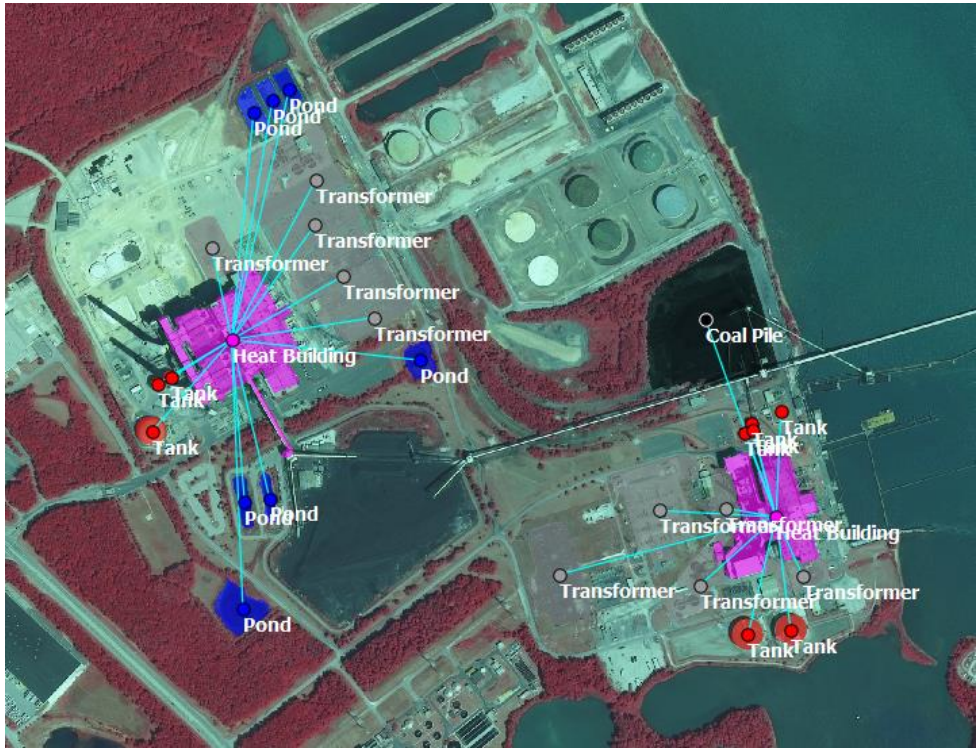
Input:

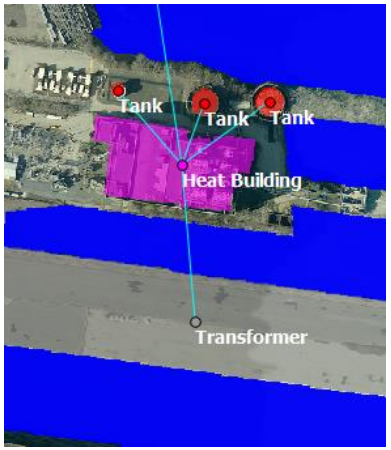
| | |
|---|---|
| 2,067 | $km^2$ total area |
| 135 billion | Pixels |
| 3.6 million | Features |

Output:

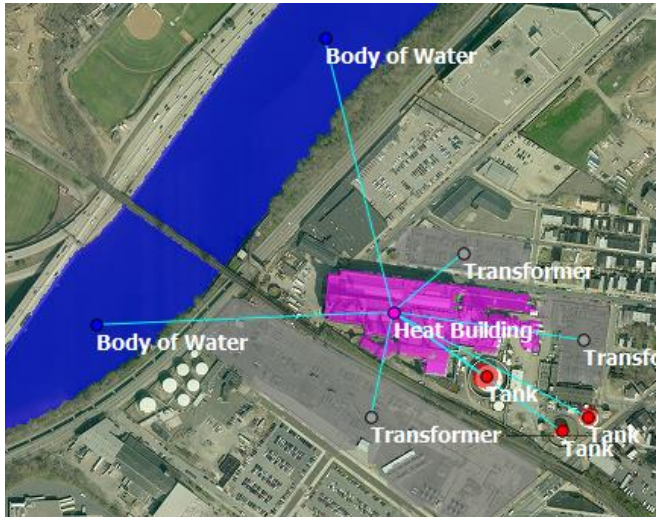
| | |
|---|---|
| 6 | True positives |
| 9 | False positives |
| 2 | False negatives |

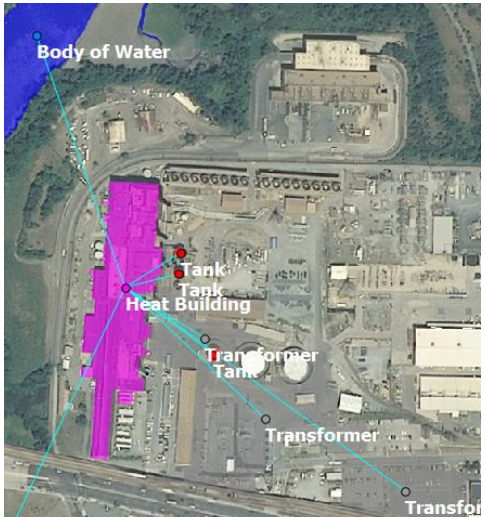
# Power Plant Results: True Positives



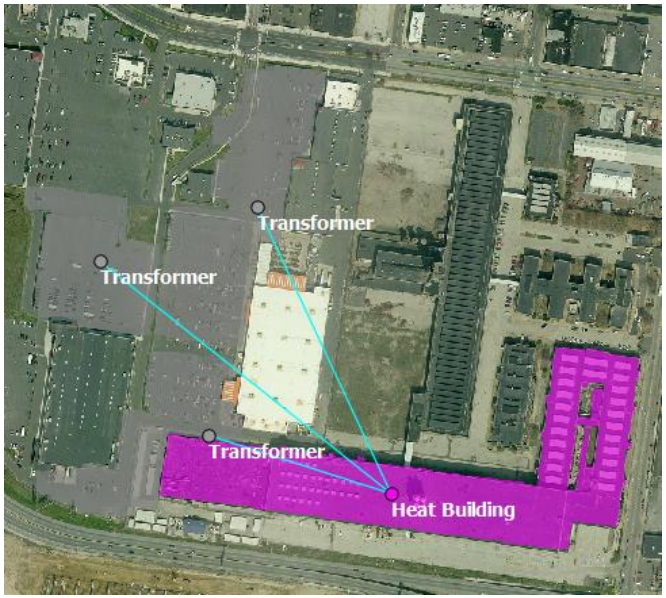



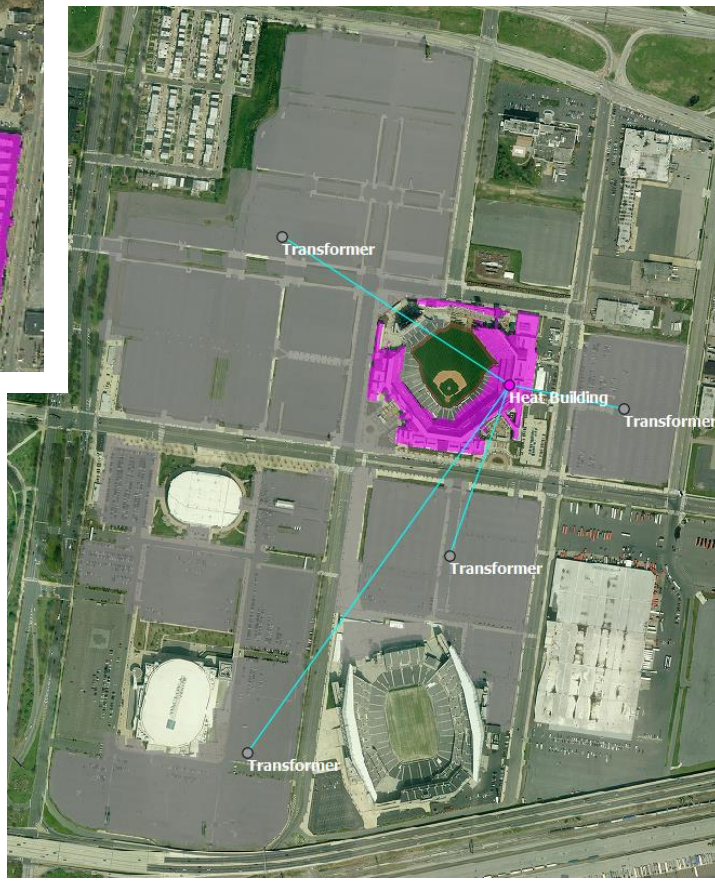

Note that power plants were found despite several land cover classification errors.

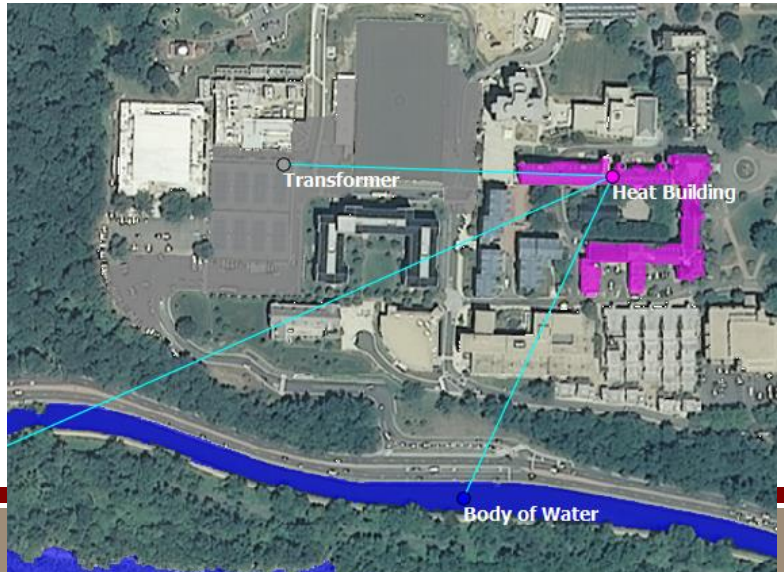



# Power Plant Results: False Positives

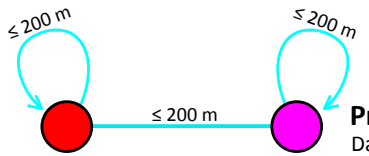



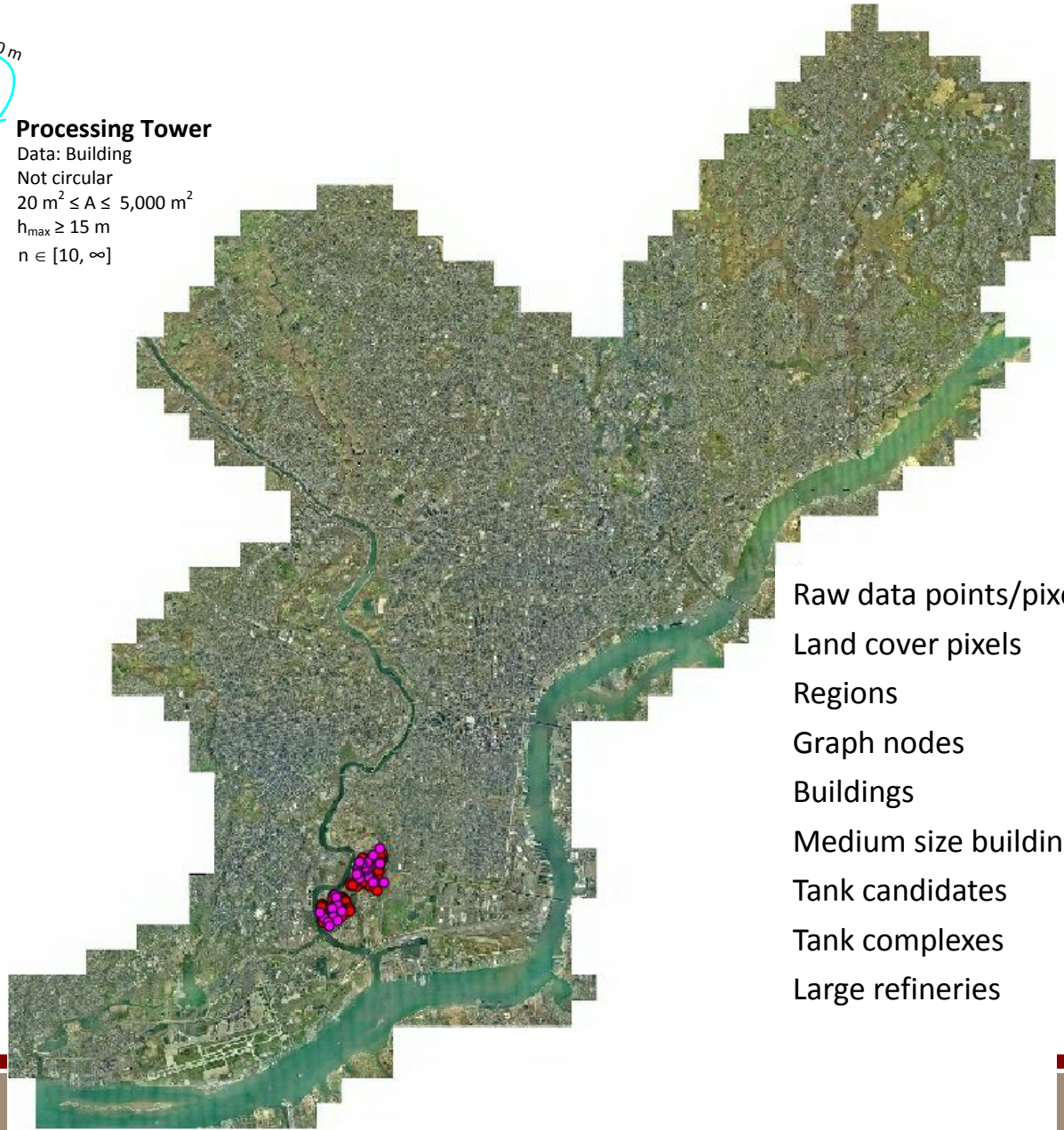

A better transformer filter would eliminate these.

# Large Refinery Search




**Tank**
Data: Building
Circular
150 $m^2 \leq A \leq$ 3,000 $m^2$
$n \in [10, \infty]$

**Processing Tower**
Data: Building
Not circular
20 $m^2 \leq A \leq$ 5,000 $m^2$
$h_{max} \geq 15$ m
$n \in [10, \infty]$



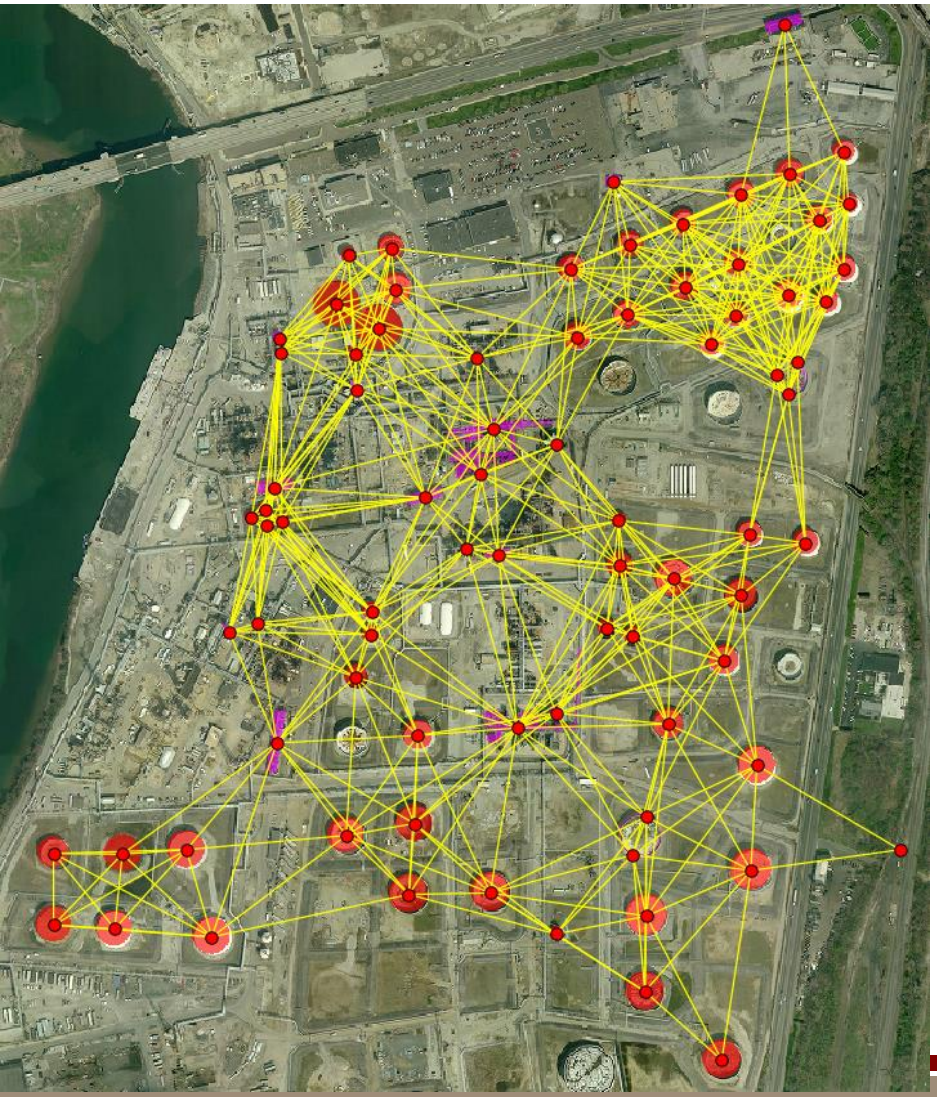
0 False positives
0 False negatives

| | |
|---|---|
| Raw data points/pixels | 101,495,378,523 |
| Land cover pixels | 8,981,933,044 |
| Regions | 1,133,822 |
| Graph nodes | 1,133,822 |
| Buildings | 154,062 |
| Medium size buildings | 87,170 |
| Tank candidates | 371 |
| Tank complexes | 28 |
| Large refineries | 2 |

# Large Refinery Search

Sandia National Laboratories

Refineries found:



# Large Refinery Search

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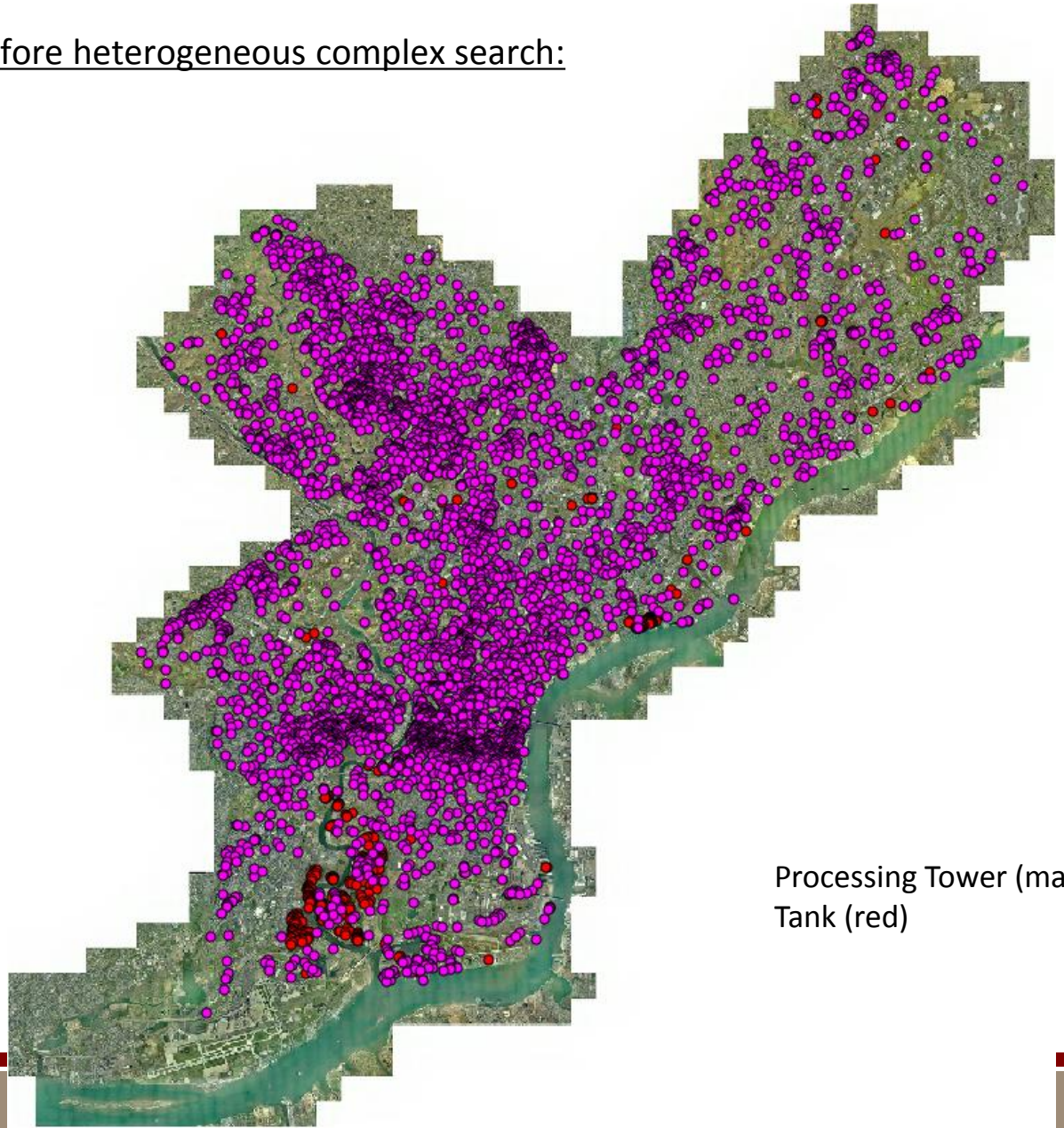
SearchGraph, before heterogeneous complex search:



| | |
|---|---|
| Processing Tower (magenta) | 4,909 |
| Tank (red) | 371 |

# Simple Change Example

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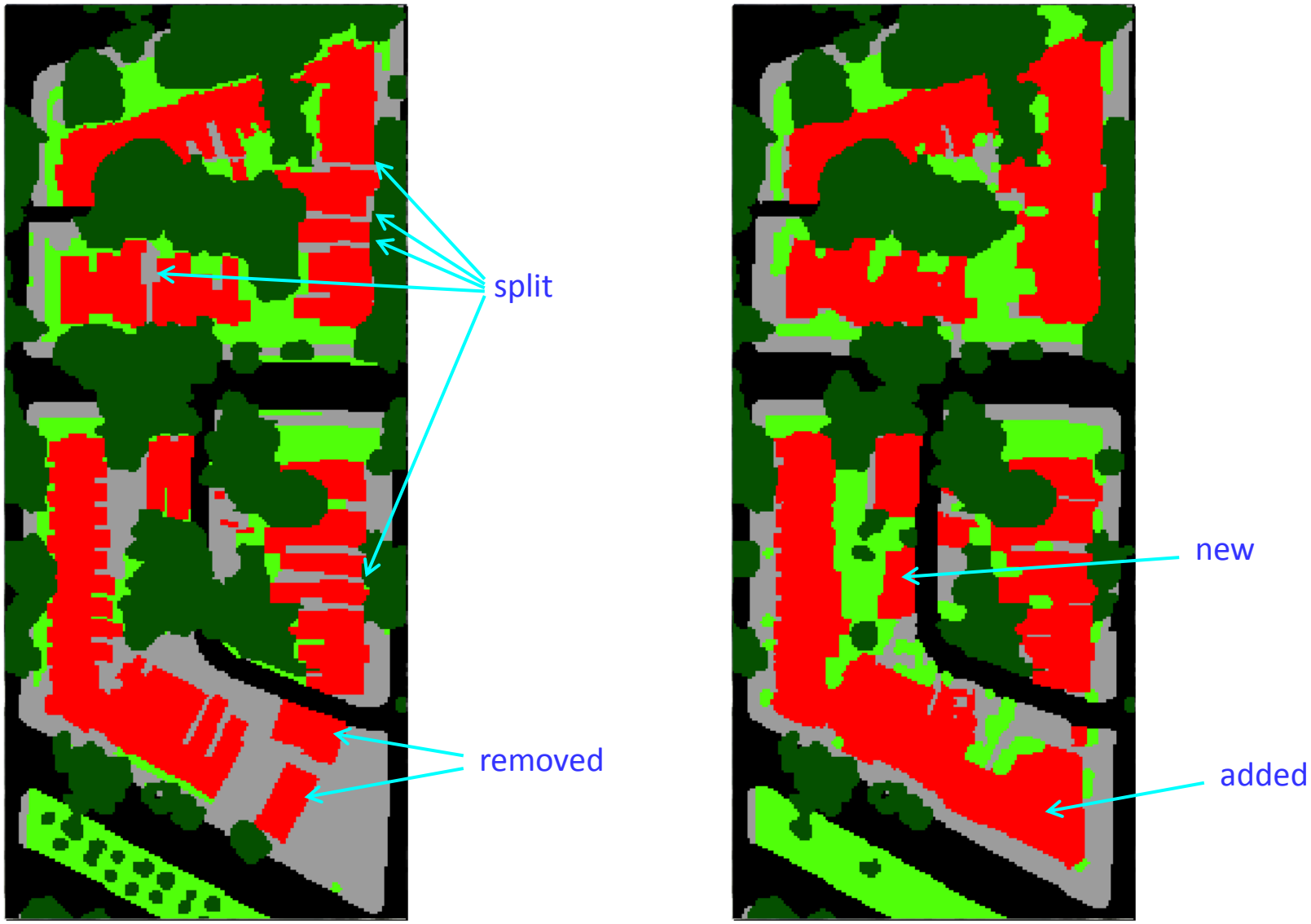
Context:

# Simple Change Example

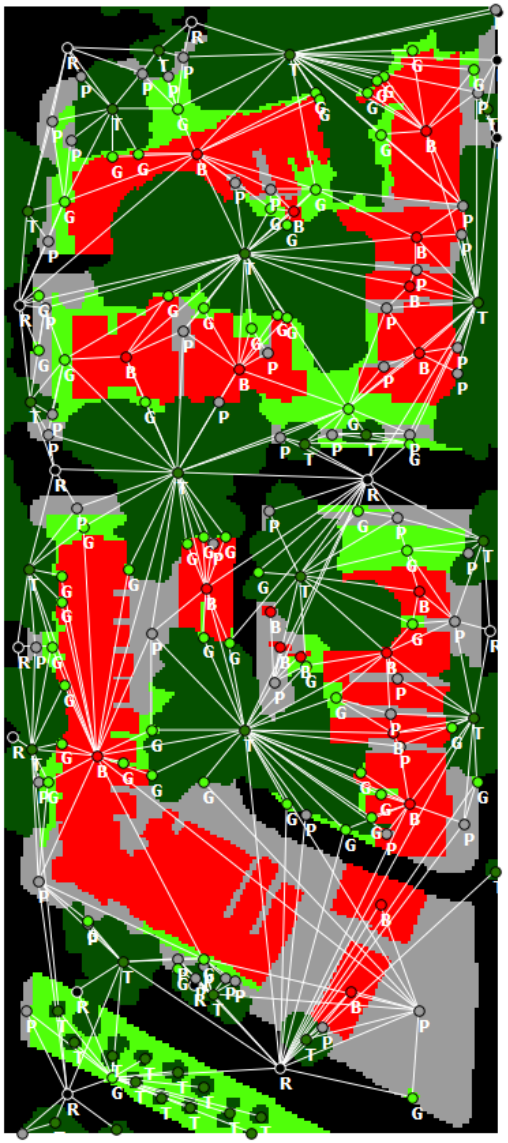
Input land cover:



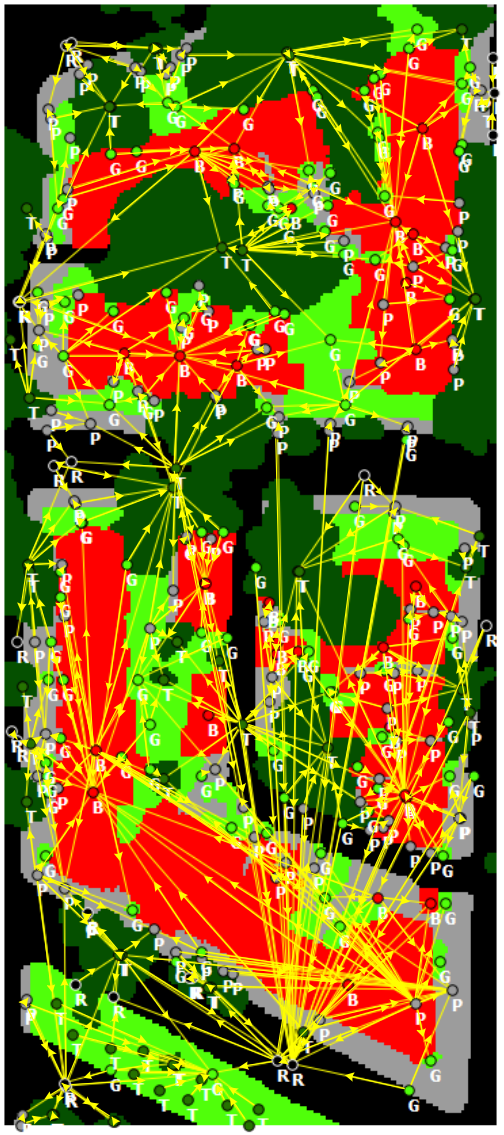
# Graph-Based Analysis

342 nodes
808 adjacency edges
559 change edges
0 distance edges

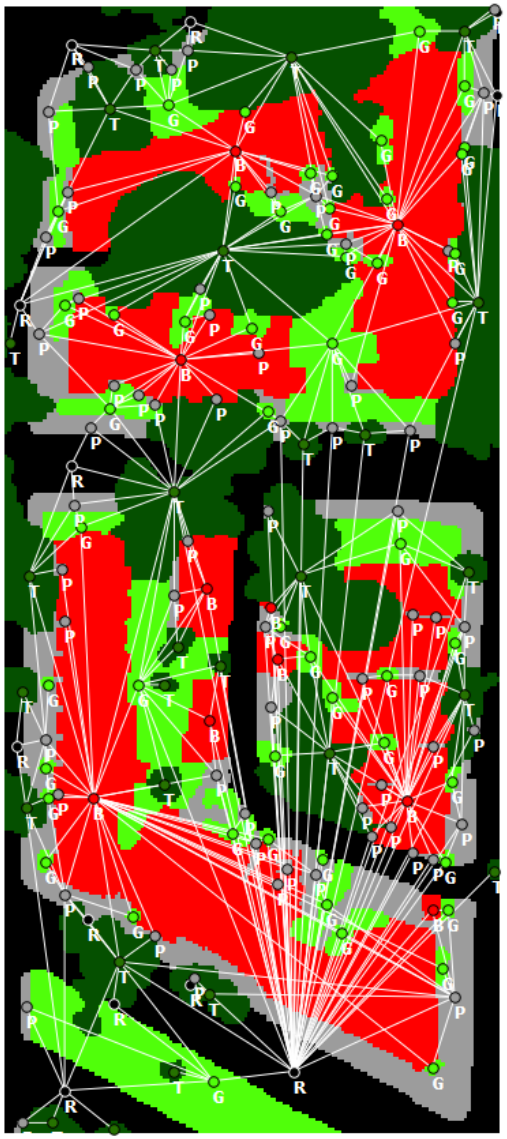
Geospatial-temporal graph:



2006 Adjacency



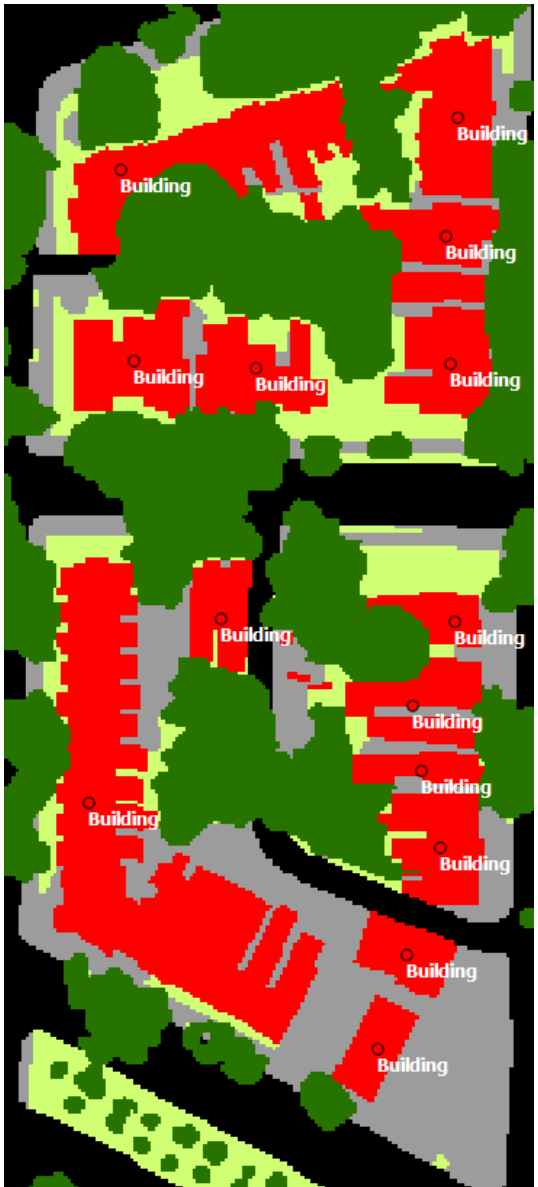
2006 → 2011 Change



2011 Adjacency

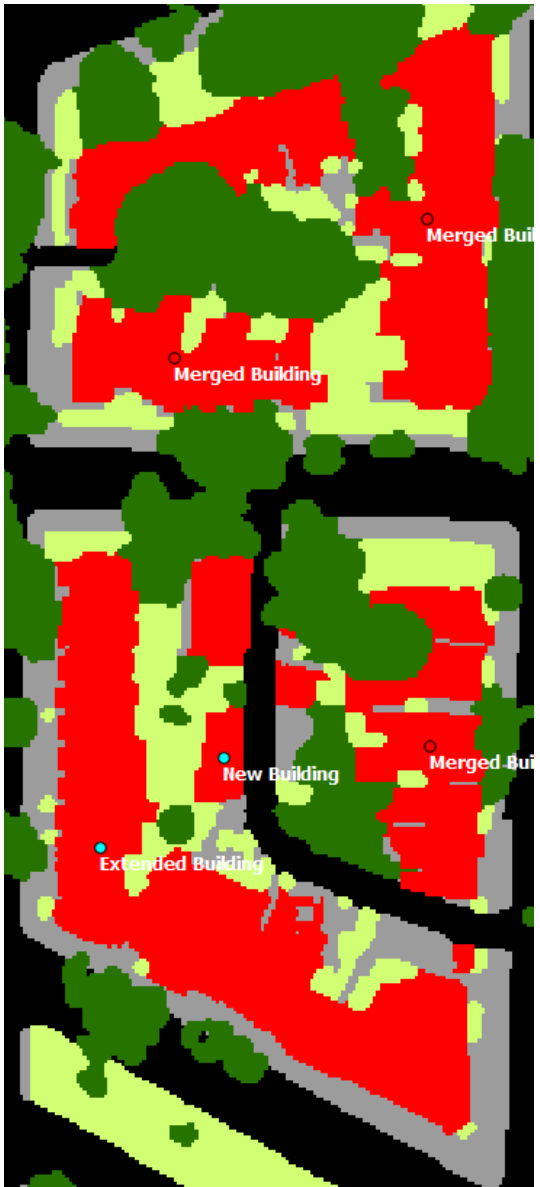
# Simple Change Example – Graph-Based

Before graph-based change analysis:





Graph-based diagnosis:

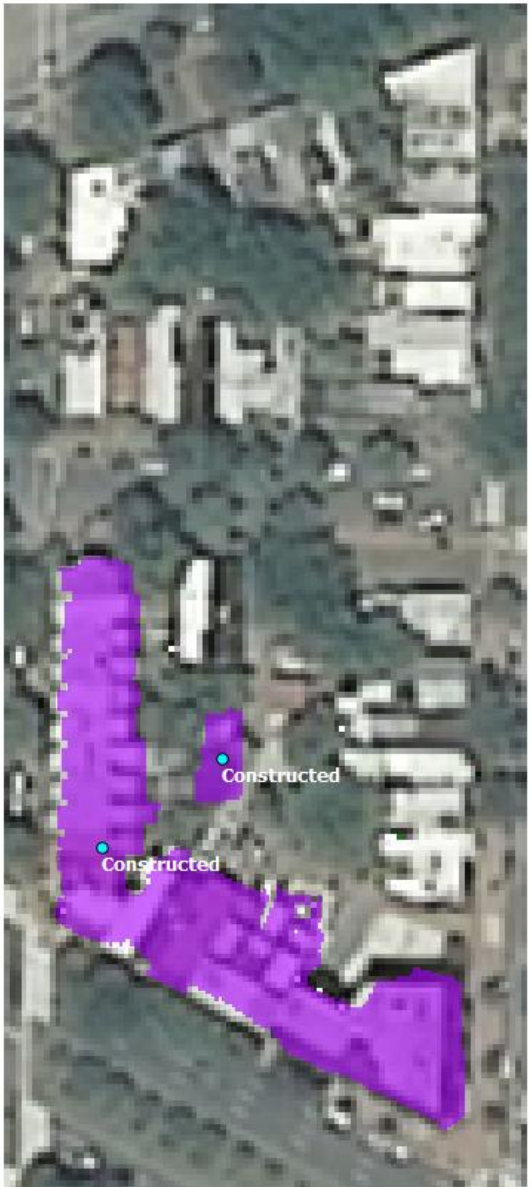


# Differentiating Important Change

Significant change diagnosis:

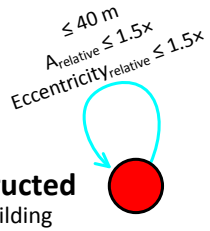


Shown over latest image:



# New Complexes

Seek complexes of new buildings, across the entire city:




**Constructed**
Data: Building
Exists now
$A \geq 100\ m^2$
New, Extended, Changed
$n \in [5, \infty]$

2006*

2011



2006*



2011

* Image from DigitalGlobe.

# Overview

- Motivation.
- Computation.
- Results.
- Discussion.

# Summary

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What we have shown:

- Imagery + LiDAR + GIS ⇒ Land cover model [O'Neil-Dunne 2012].
- Sequence of above ⇒ Geospatial-temporal graph.
- Given query, spatial search for power plants, refineries, high schools…
- Given query, spatial-temporal search for change, construction complexes…
- Over a wide area (2,067 $km^2$, 135 billion pixels, 3.6 million graph nodes).

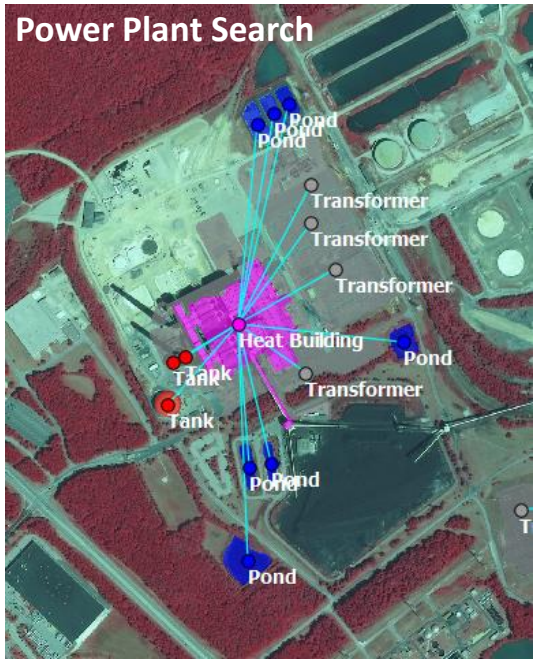
What we have NOT shown:

- Continent-scale robust image pre-processing.
- Recognition scope.
- User-friendly query construction.
- Complex multi-step change analysis.

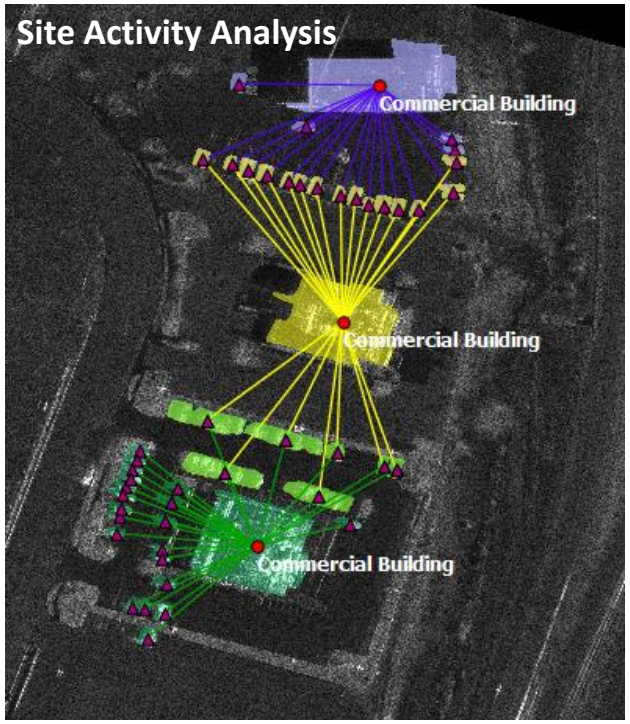
} Areas of on-going work.

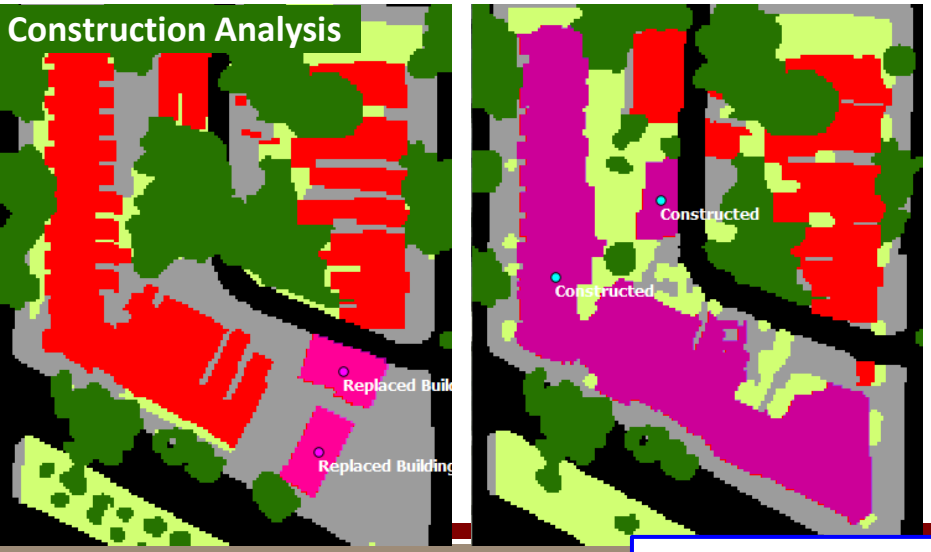
[O'Neil-Dunne 2012] O'Neil-Dunne, et al, An object-based system for LiDAR data fusion and feature extraction, Geocarto (28), pp. 227–242, 2012.

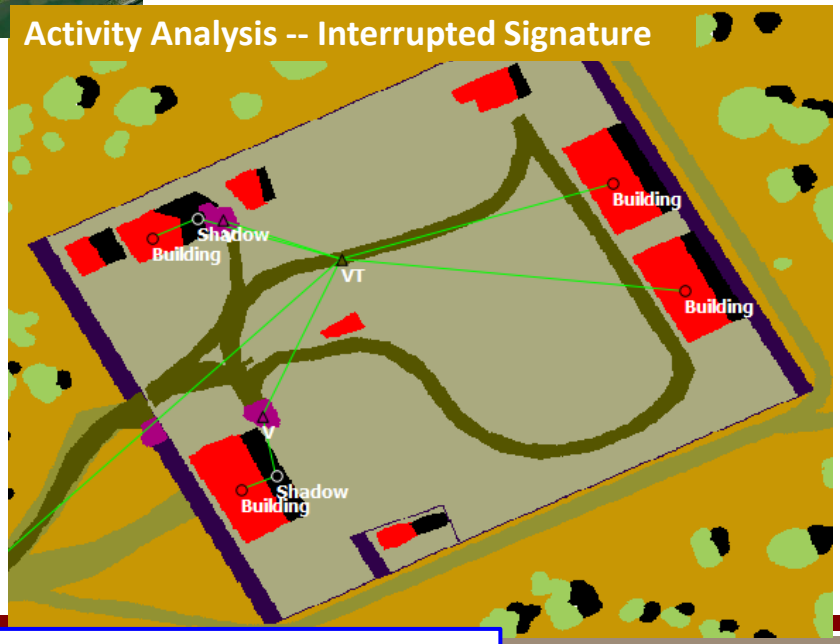
# Diversity of Problems








All of these were solved by the same code.

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# BACKUP SLIDES

# Discussion

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- Graph-based search tolerates varying topology.
- Query templates do not need to specify particular shapes, or all features.
- Search can tolerate some pre-processing errors.
- Change detection can be challenging if data methods are not consistent across time.
- Our approach is to assemble simple pieces into an effective sequence.
- We did not attempt to optimize run time.
- Our search approach exploits context, and can be viewed as analogous to context-based image preprocessing (GEOBIA), at a higher level of abstraction.

# Comparison to GEOBIA*

Same as:

- Analyzes multi-modality overhead image data.
- Includes shrink/grow operations.
- *Future: Direct output of graph tables.*

System Difference:

- Rule sets must be programmed for a new query.
- Queries with multi-constraint filtering or variable topology require difficult manual setup.
- Re-usable distance edges.
- *Quality score/sort.*

Mathematical Difference:

- Heterogeneous complex.
- Temporal graph, chronology representation.
- Explicit representation of multi-step change.
- Interrupted star algorithm.
- Infer connected tree.
- *Multi-step sequence analysis.*
- *Forward/backproject, with temporal feasibility.*
- *Path sequence analysis.*

Shortfalls:

- Shape file input.
- Particular functions.

…eCognition might output graph tables directly.

* Geospatial Object-Based Image Analysis, particularly eCognition. See GEOBIA 2014 for recent publications. Preliminary.

# Comparison to Spatial SQL Databases*

Same as:

- Superset of SQL. *(Future: Spatial SQL.)*
- R trees.
- Coarse/fine tests.
- Star-graph equivalent through complex query.

Shortfalls:

- Shape file input.
- Particular functions.

…would be resolved by converting to Spatial SQL.

System Difference:

- Direct scan from raster image.
- Lazy constraints (circularity, height, RGB, *shape scan, transformer*).
- Caching.
- Some variables, such as area, pre-computed.
- Provenance fetch.
- Re-usable distance edges.
- Temporal chronology representation/history.
- Chunking to provide separation of joined spatial regions into semantic components.
- Some queries conceptually simpler (?).
- *Quality score/sort.*

Mathematical Difference:

- Transitive closure.
- Heterogeneous complex.
- Temporal graph, automatic change analysis.
- Interrupted star algorithm.
- Infer connected tree.
- *Multi-step sequence analysis.*
- *Forward/backproject, with temporal feasibility.*
- *Path sequence analysis.*
- Heterogeneous relation types: Distance, change, adjacency , spatiotemporal constraints, *is-a, component-of.*
- *Layers of abstraction.*

* Preliminary. Further, graph databases, semantic graph databases not addressed here.

# Key Data Structures

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## StoredGraph

- Accumulates all observed data.
- Large, persistent.
- Semantics match data: Building, Trees, Grass_Shrub, Dirt, Road, Other_Paved, Water, …[1]

## GeoQuestion

- Defines semantics of interest.
  Example: "Where are high schools?" ⇒ Classroom_Building, Football_Field, Parking_Lot.
- Defines signature: items and relationships.
- Defines desired search procedure.

## SearchGraph

- Parts of the StoredGraph relevant to the question.
- Smaller, with full topology.
- Semantics match question: Classroom_Building, Football_Field, Parking_Lot.[1]

## Match

- A set of SearchGraph nodes and edges, satisfying the signature.

1. Contrast with:
   - Kolas, Dean, and Hebeler, "Geospatial semantic web: architecture of ontologies," IEEE Aerospace Conference, page 10, 2006.
   - Arpinar, et al, "Geospatial ontology development and semantic analytics," Transactions in GIS, 10(4):551–575, 2006.
   - Ashish and Sheth, eds, Geospatial Semantics and the Semantic Web, Springer, 2011.

# StoredGraph Representation

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Data semantics.

Node types:

- Region, Durable (building, tree,…).
- Region, Ephemeral (cloud, tire tracks,...).
- Point, Durable (hospital name and address,…).
- Point, Ephemeral (concert date and location,…).
- Ensemble (high school complex,…). [PENDING]

Attributes:

- Region: class, area, eccentricity, orientation,…
- Point: specialized semantics. [FULL-FEATURED PENDING]
- All have back-pointers to original data.

Time attributes:

- Durable: $(t_{last.absent}, t_{first.seen}]$ $[t_{last.seen}, t_{first.absent})$.
- Ephemeral: t
- Also parameter history (durable only).

Edge types:

- Adjacency.
- Distance.
- Change.
- Component-Of. [PENDING]

# GeoQuestion Representation

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GeoQuestion

- Semantics: Node, edge "roles."
- SearchGraph node specs.
- SearchGraph edge specs.

} These define the SearchGraph.

- Search method type and parameters.
- Postprocessing options.
- Quality spec (not implemented).

The design of an effective user interface to design queries remains an important topic for PANTHER research.

# GeoQuestion Details

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GeoQuestion

- Bookkeeping: Name, directory.
- Node role map.
- Edge role map.
- List of SearchGraphNodeSpecs
  - List of LazyConstraintSpecs
- List of SearchGraphEdgeSpecs
  - List of InterNodeConstraintSpecs
- GraphSearchMethodEnum
  - Entire graph.
  - Connected components:
    - Min, max components allowed.
  - Star Graph, Interrupted Star:
    - Hub role
    - List of SpokeSpecs (spoke role, min/max counts).
    - List of SpokeConstraintSpecs (spoke role, other role, list of InterNodeConstraintSpecs)
- List of PostprocessMatchSpec (calculation type, roles to consider, min/max limits).
- Quality spec (not implemented).

We do not expect analysts to program this!

The design of an effective query input method is an important PANTHER research topic.

# SearchGraph Representation

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SearchGraph

- Lightweight nodes.
- Can be viewed as a graph with colored nodes and edges.
- Attributes not included, but points back to original StoredGraph nodes.
- Full topology included in memory.
- Typically much smaller than StoredGraph.
- It is convenient to think of SearchGraph as subset of StoredGraph.
- But in general, StoredGraph nodes map many-to-many to SearchGraph nodes.
- Also has edges that may not exist in the StoredGraph.

# Match Representation

Match

- A set of SearchGraph nodes and edges.
- Associated post-process results (quality score, etc).

# AddToStoredGraph Summary

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1. Read data file name and auxiliary info.
2. Add provenance lookup pointers to StoredGraph.
3. Scan the image, adding nodes and adjacency edges to StoredGraph.
   - Perform change analysis for each node, creating change edges.

Use streaming algorithms to process very large files without exceeding memory.

# AddToStoredGraph Context

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Context: For each input data set:

1. Prepare the input.
2. Add auxiliary provenance files.
3. Run AddToStoredGraph program.

…Repeat as new data arrives.

# AddToStoredGraph Algorithm

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Input:

- Posterized image file.
  *or*
  csv table file.
- Companion file explaining time window, background information.

Algorithm (for image):

Write observation context to StoredGraph.
Scan image file lines, grouping pixels into regions. ← Streaming algorithm allows very large images to be processed without exceeding memory.
Each time a durable region* $R_i$ closes:
  Use $R_i$'s bounding box to look up candidate overlap nodes in the StoredGraph.
  Analyze whether $R_i$ is new, a repeat, or a change to a previous node.
    New $\Rightarrow$ write $R_i$ node to StoredGraph.
    Repeat $\Rightarrow$ update time history of existing StoredGraph node.
    Change $\Rightarrow$ write $R_i$ node to StoredGraph, and
      for each overlapping prior node:
        write change edge to $R_i$ and update prior node's time history.

* Ephemeral region and point nodes are simpler.

# GeoSearch Algorithm

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Primary steps:

1. Load data, construct GeoQuestion.
2. Construct SearchGraph.
   - Nodes
     - SQL query constraints.
     - Lazy-evaluated node constraints.
   - Edges
     - Generate node pairs.[1]
     - Evaluate inter-node constraints.
     - If passes, construct edge.
3. Graph search.
   - Graph search algorithm → set of Matches.
   - Postprocess each match, filter by result.
   - Quality scoring and sorting.*
4. Save results to database.*

* Not implemented yet.

1. Among other techniques, R-Trees are used to limit average-case complexity. See:
Guttman, "R-Trees: A Dynamic Index Structure for Spatial Searching," ACM SIGMOD 1984, p. 47.
Boost Geometry Library. http://www.boost.org (2013).

# GeoSearch Detail: Graph Search Algorithms

- **Subgraph isomorphism** – General template match (not supported).[1]
- **Connected components** – Find groups of related items.[2]
- **Star graph** – Hub and spokes, with various constraints.
- **Interrupted star** – Allows interruption of hub and/or spokes.
- **Heterogeneous complex** – Useful when there is no obvious hub.

1. Ullmann, "An algorithm for subgraph isomorphism", Journal of the ACM 23 (1): 31–42, 1976.

2. Hopcroft and Tarjan, "Efficient algorithms for graph manipulation," Communications of the ACM 16(6), 372-378, June 1973.

# GeoSearch Detail: Star-Graph Search

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Input:

- Hub role $r_h$.
- Spoke specs: { <role $r_j$ , $n_{j.\min}$ , $n_{j.\max}$>,… } ← Spoke $[n_{j.\min}, n_{j.\max}]$ interval enables:
  - Variable match topology (set $n_{j.\min} \neq n_{j.\max}$).
  - Allowable and preferred configurations.
  - Optional items (set $n_{j.\min} = 0$).
  - Forbidden items (set $n_{j.\max} = 0$).
- Spoke-to-spoke constraints.

Algorithm:

For each candidate hub node $h_i \in \mathcal{H}$:

Walk neighbors of $h_i$, collect candidate spoke nodes $\{s_j\}$.

Check spoke-to-spoke constraints, mark $s_j$ nodes that pass.

Discard unmarked nodes from $\{s_j\}$.

Check $[n_{j.\min}, n_{j.\max}]$ bounds:

If not met, discard hub $h_i$.

Else assemble star $\mathbf{S}_i \leftarrow h_i \cup \{s_j\}$, add $\mathbf{S}_i$ to match list $\mathcal{M}$.

endfor

Return $\mathcal{M}$.

- This algorithm solves a restricted class of problems.
- More efficient than general subgraph isomorphism.
- More flexible than subgraph isomorphism (see above).
- Narrower class of templates.
- Geospatial problems allow edge replacement.

# GeoSearch Detail: Post-Processing Algorithms

- Count nodes – Count nodes in match
  - Optional node filtering.
  - Min/max thresholds.
- Sum area – Sum node area in match, with optional filtering.
  - Optional node filtering.
  - Min/max thresholds.
- Break cycles – Removes redundant chain edges (preliminary).

# Land Cover Primitive Recognition

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Steps:

1. Assemble input:
   - RGB+IR imagery.
   - LiDAR data.
   - GIS road polygons.
2. Construct normalized digital surface model (nDSM).
3. Using nDSM, identify buildings and trees.
4. Using RGB+IR, identify grass, bare earth, water, impervious.
5. Using GIS data, distinguish roads from other paved.

Primitive recognition algorithm and data results due to Jarlath O'Neil-Dunne, et al, University of Vermont Spatial Analysis Lab.

For details, see O'Neil-Dunne, et al, "An Object-Based System for LiDAR Data Fusion and Feature Extraction," Geocarto International, 2012.

# Input

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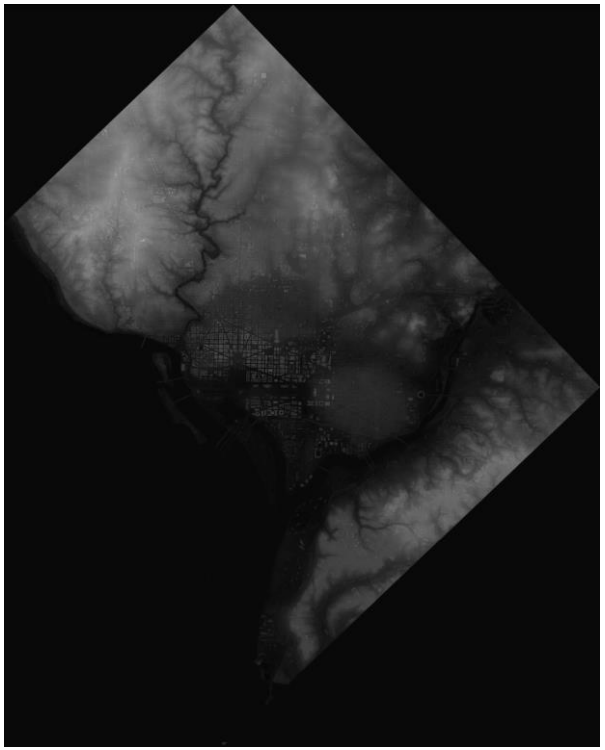
Washington, DC example:

4-Band (RGB+IR) Imagery

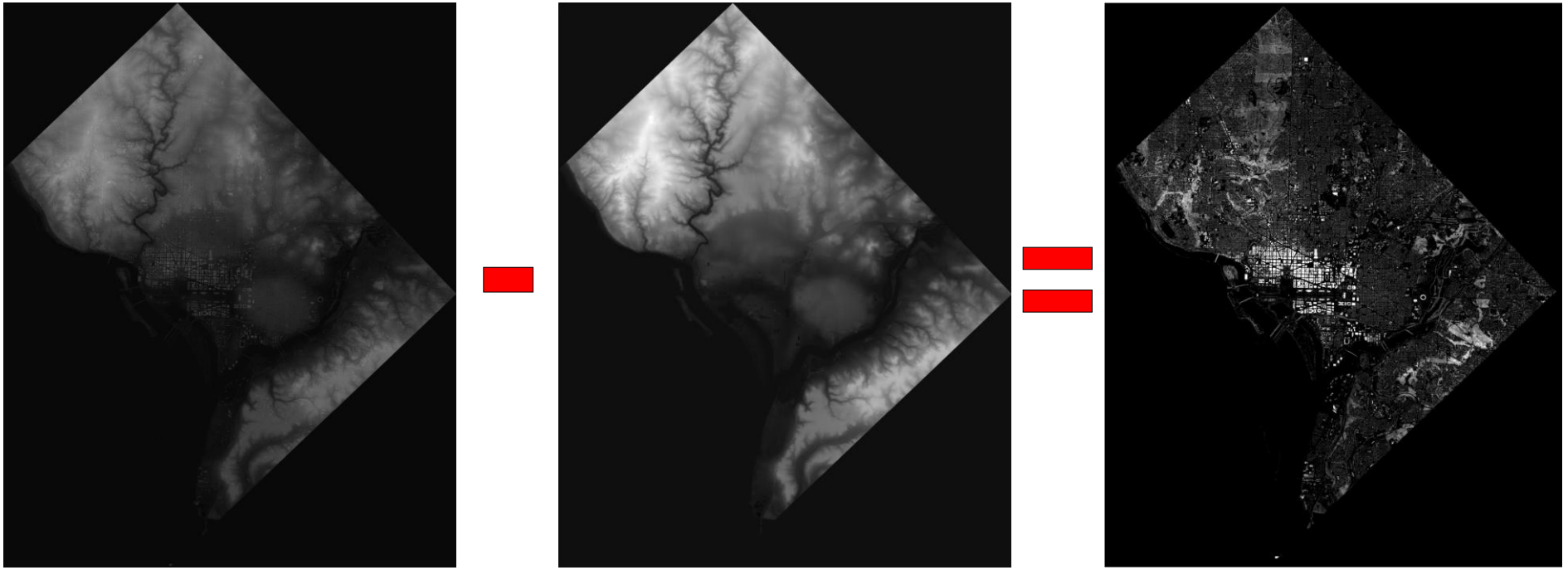


Digital Surface Model, from LiDAR

GIS Road Polygons

Data provided by Jarlath O'Neil-Dunne at the University of Vermont Spatial Analysis Lab.

# nDSM Generation



Digital Surface Model
(DSM)

Digital Elevation Model
(DEM)

Normalized Digital Surface Model
(nDSM)

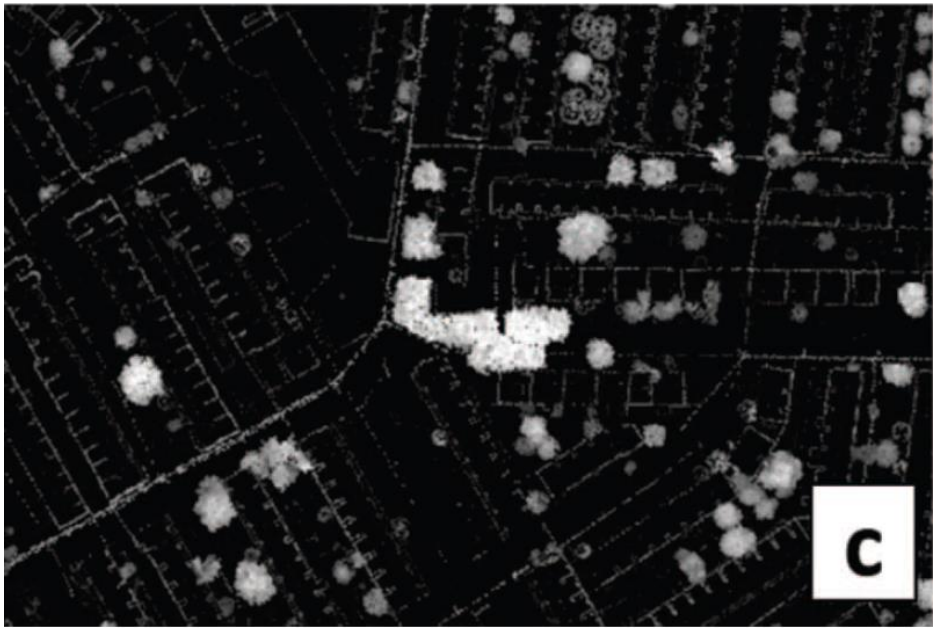
Data provided by Jarlath O'Neil-Dunne at the University of Vermont Spatial Analysis Lab.

# Building and Tree Segmentation

Sandia National Laboratories

Distinguishing buildings and trees:

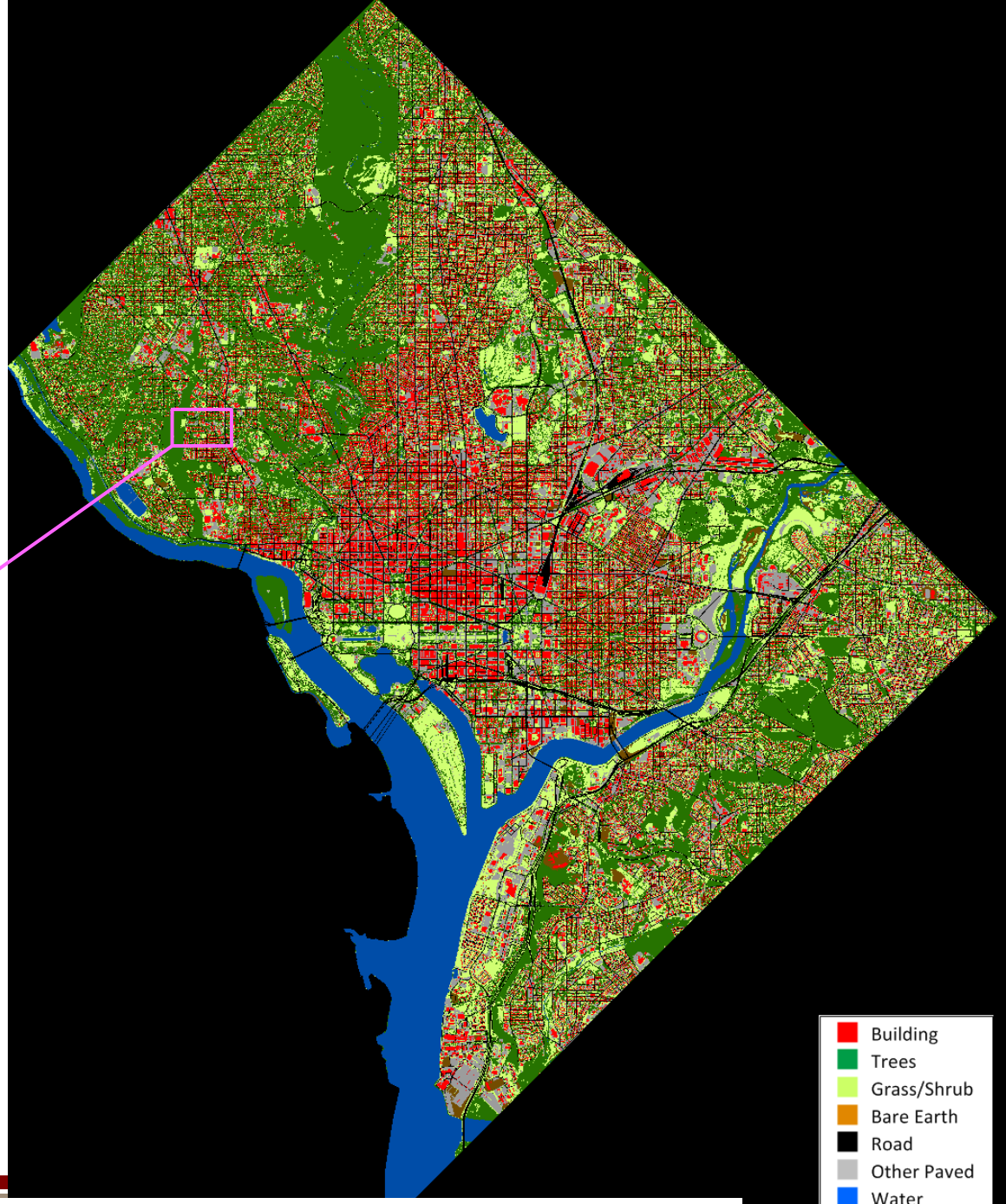

Z Height




Z Deviation

From O'Neil-Dunne, et al, “An Object-Based System for LiDAR Data Fusion and Feature Extraction,” Geocarto International, 2012.

# Output

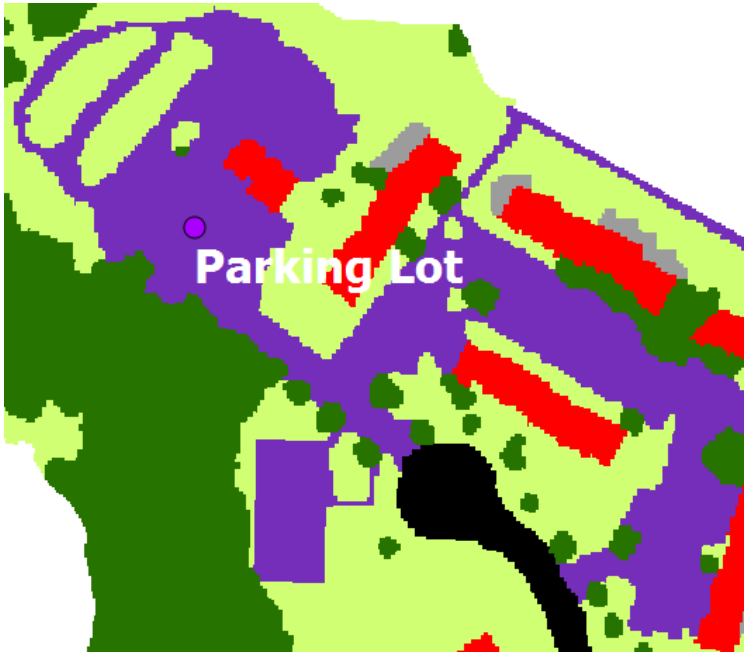



Data provided by Jarlath O'Neil-Dunne at the University of Vermont Spatial Analysis Lab.

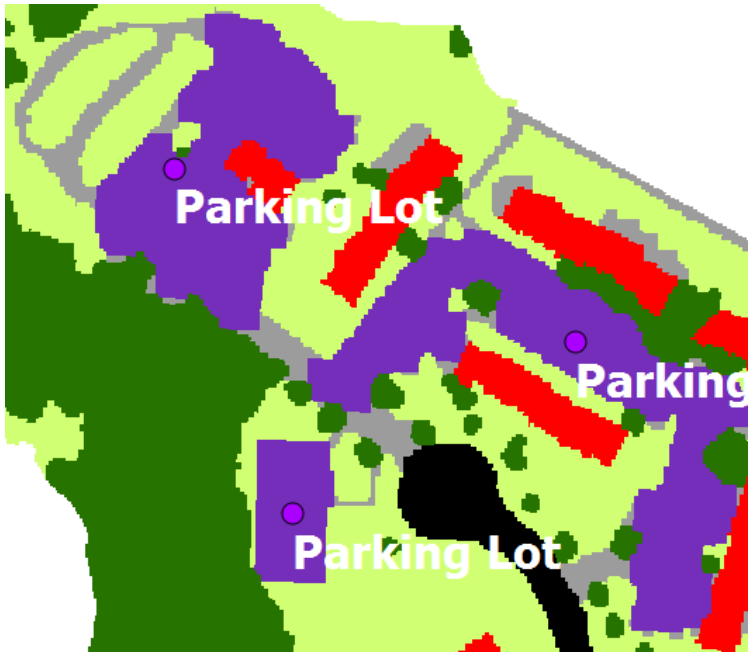
# Chunk Operation

Chunking breaks up linked regions into significant sub-regions:

Before Chunking




After Chunking




Implemented by a geometric shrink/grow operation, with controllable magnitude.

# GeoGraphy Code Implementation

Sandia National Laboratories

Implementation details:

- C++, a few scripts.
- Third-party libraries:
  - Boost (www.boost.org) - Smart pointers, Program options, R-trees, variable data types.
  - SQLite (www.sqlite.org) – Lightweight and efficient SQL database storage.
  - GDAL (www.gdal.org) – Tools for abstracting geospatial data.
- Roughly 53,000 lines of C++ code, 370 files.
- Three major applications, six supporting utility programs.
- Externalized semantics.
- Maturity level:
  - Code runs fully automatically.
  - Single processor, single thread – multi-processor speedups deferred.
  - Input format designed for programmers.
  - Output rendering capabilities support technical communication.
  - No interface built for user community.

# Data Collected

Sandia National Laboratories

GeoGraphy

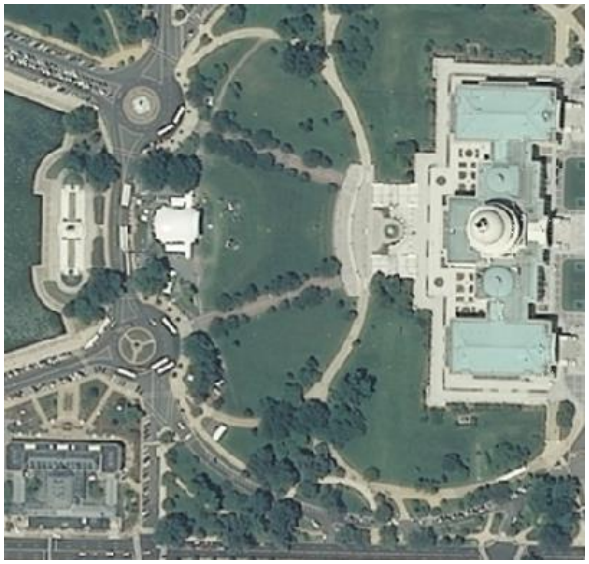
Data sets in hand:

- Single time:
  - Anne Arundel County.
  - Greater Baltimore
    (Baltimore City, Baltimore County, Howard County, Anne Arundel County).
- Two-time:
  - Washington, DC.
  - Philadelphia (2nd-generation pre-processing):
    - Improved feature recognition.
    - Railroad separated from road.
    - Shapes based on prior landcover, vary only if significant change.
- The above include provenance data (imagery, LiDAR, GIS).
- Also prepared many sample tiles of varying size, for development.

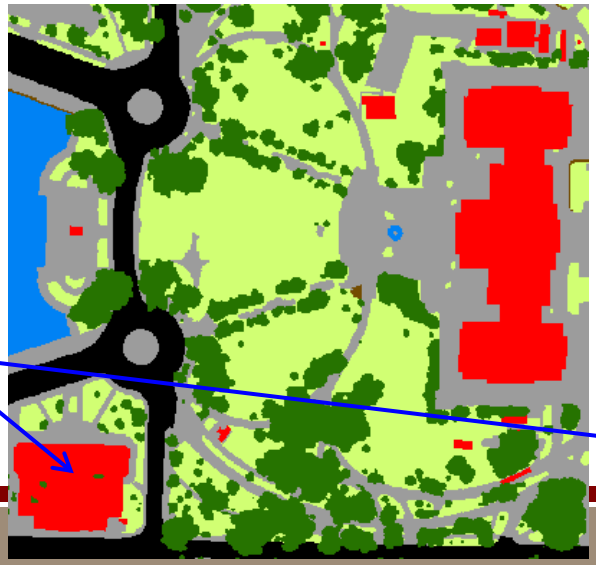
# Washington, DC Data

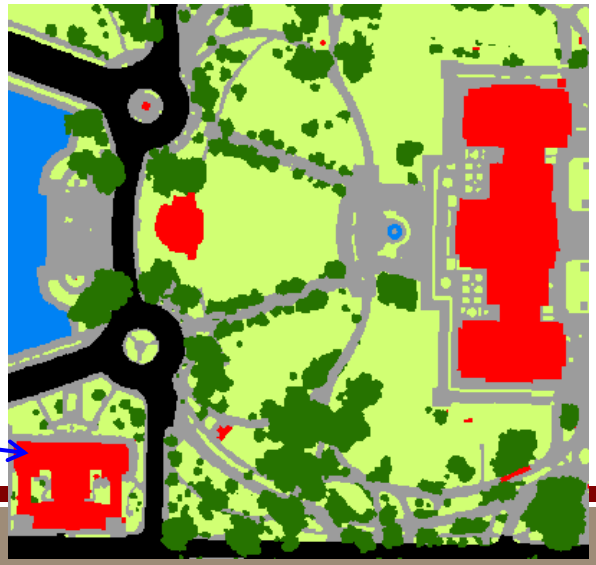
Comparing 2006 and 2011:

2006



2011





Difference in precision causes pseudo-change.

# Graph Construction

Large graphs constructed so far:

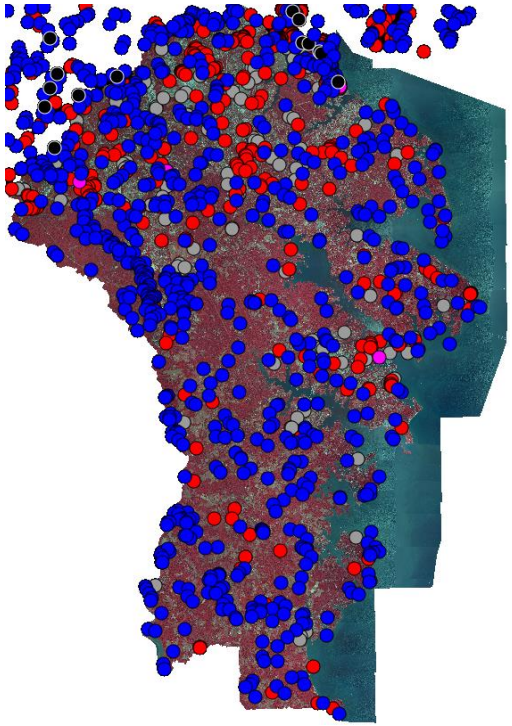
| | Landcover Pixels* | Nodes | Graph File |
|---|---|---|---|
| ▪ Single-time: | | | |
| ▪ Anne Arundel County. | 4.1 GPix | 1,204,087 | 1.6 GB |
| ▪ Greater Baltimore (sliced). | 11.3 GPix | 3,488,712 | 4.5 GB |
| ▪ Two-time: | | | |
| ▪ Washington, DC. | 1.0 GPix | 1,326,212 | 1.7 GB |
| ▪ Philadelphia. | 3.8 GPix | 1,540,909 | 2.0 GB |

* Only includes land-area pixels, not blank filler space.

# Power Plant SearchGraph

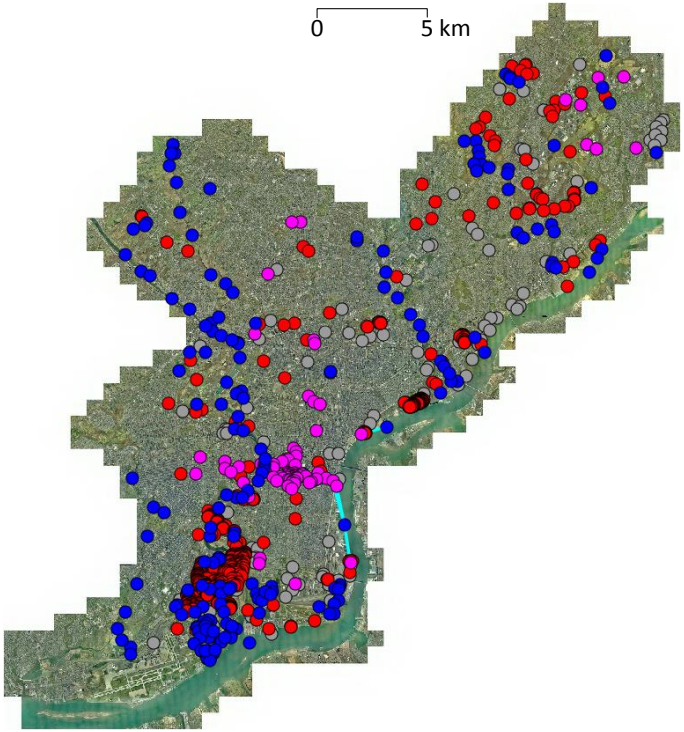
Sandia National Laboratories

SearchGraph, before star graph search algorithm:



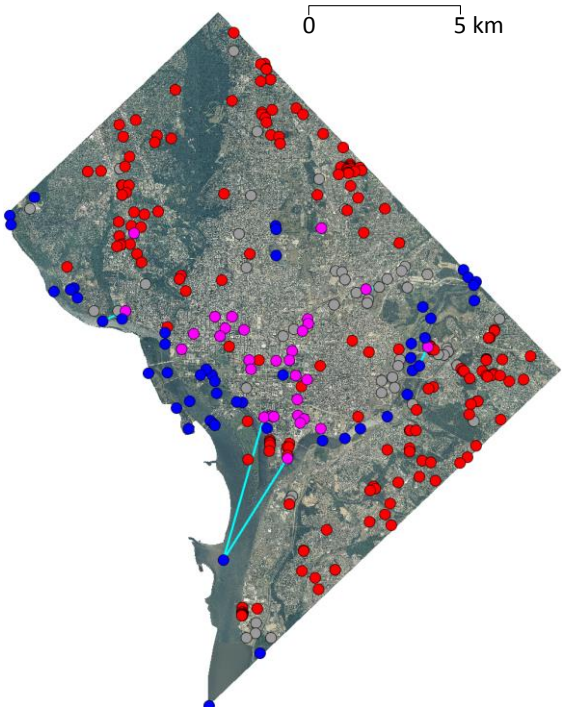
Anne Arundel County, MD

| | |
|---|---|
| Heat Building (magenta) | 5 |
| Transformer (grey) | 128 |
| Tank (red) | 500 |
| Evaporation Pond (blue) | 774 |
| Coal Pile (black) | 14 * |
| Body of Water (blue) | 62 |




Philadelphia, PA

| | |
|---|---|
| Heat Building (magenta) | 77 |
| Transformer (grey) | 104 |
| Tank (red) | 520 |
| Evaporation Pond (blue) | 138 |
| Coal Pile (black) | 0 |
| Body of Water (blue) | 53 |




Washington, DC

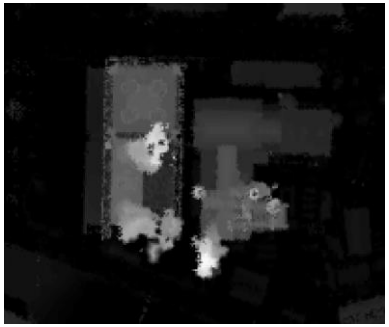
| | |
|---|---|
| Heat Building (magenta) | 31 |
| Transformer (grey) | 52 |
| Tank (red) | 174 |
| Evaporation Pond (blue) | 20 |
| Coal Pile (black) | 0 |
| Body of Water (blue) | 31 |

(Rejected construction nodes not shown.)

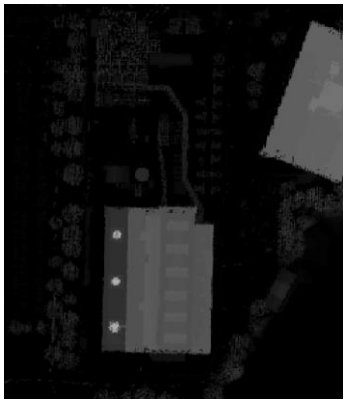
# Individual Heat Buildings – Correct

Sandia National Laboratories

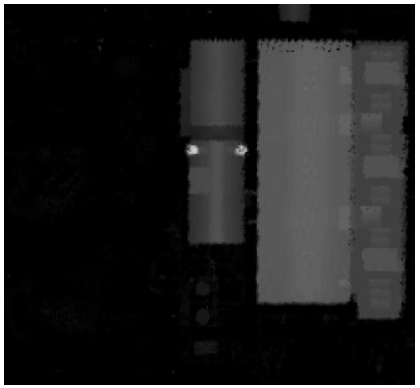
A: Capitol Power Plant




B: Buzzard Point Power Plant

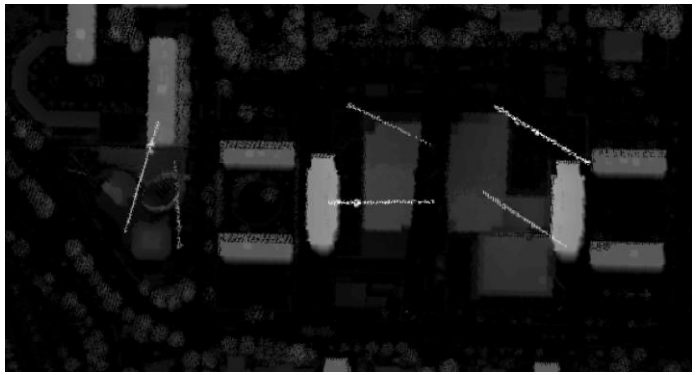



C: Surprise Power Plant

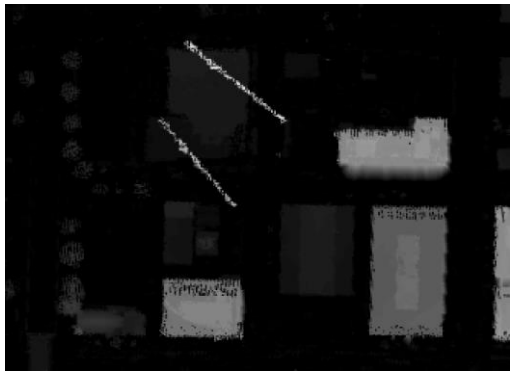


# Individual Heat Buildings – False Positive

D



E



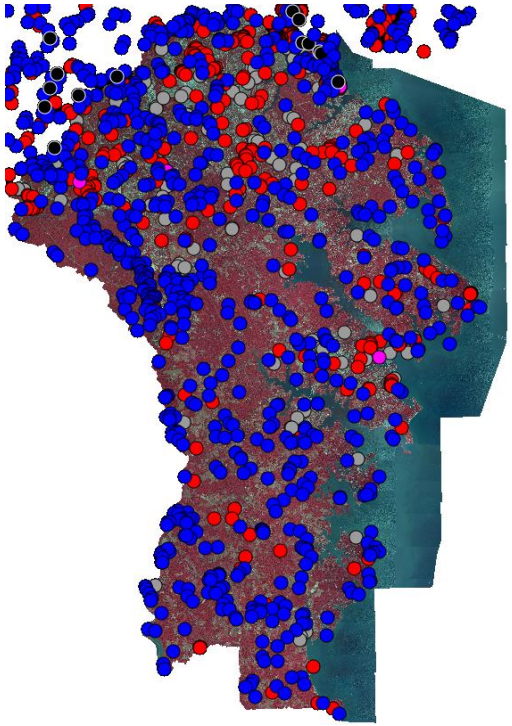
Construction cranes are interpreted as thin tall building components (like exhaust stacks).

Note: This reinforces the importance of providing provenance back-pointers to the user.

# Power Plant SearchGraph

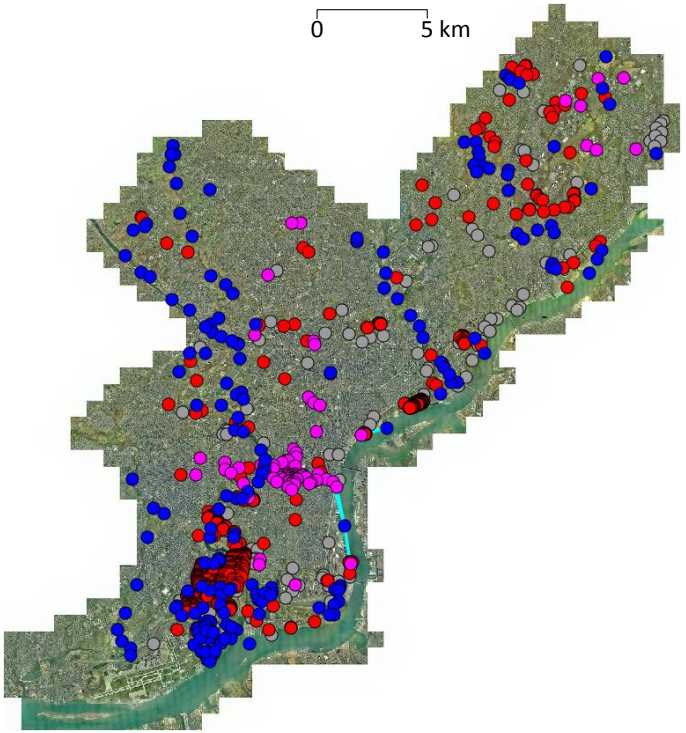
Sandia National Laboratories

SearchGraph, before star graph search algorithm:



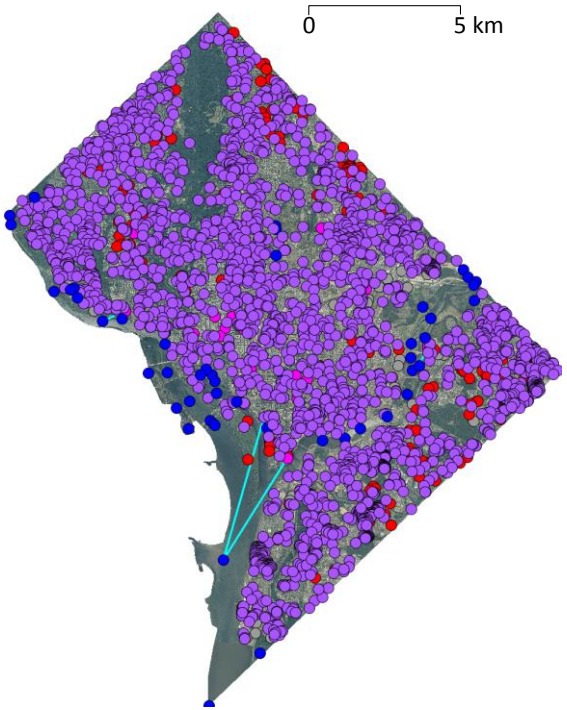
Anne Arundel County, MD

| | |
|---|---|
| Heat Building (magenta) | 5 |
| Transformer (grey) | 128 |
| Tank (red) | 500 |
| Evaporation Pond (blue) | 774 |
| Coal Pile (black) | 14 * |
| Body of Water (blue) | 62 |
| Constructed (purple) | N/A |




Philadelphia, PA

| | |
|---|---|
| Heat Building (magenta) | 77 |
| Transformer (grey) | 104 |
| Tank (red) | 520 |
| Evaporation Pond (blue) | 138 |
| Coal Pile (black) | 0 |
| Body of Water (blue) | 53 |
| Constructed (purple) | N/A |




Washington, DC

| | |
|---|---|
| Heat Building (magenta) | 31 |
| Transformer (grey) | 52 |
| Tank (red) | 174 |
| Evaporation Pond (blue) | 20 |
| Coal Pile (black) | 0 |
| Body of Water (blue) | 31 |
| Constructed (purple) | 5,979 |

* Some coal piles due to image clipping.

# A Predicted False Negative

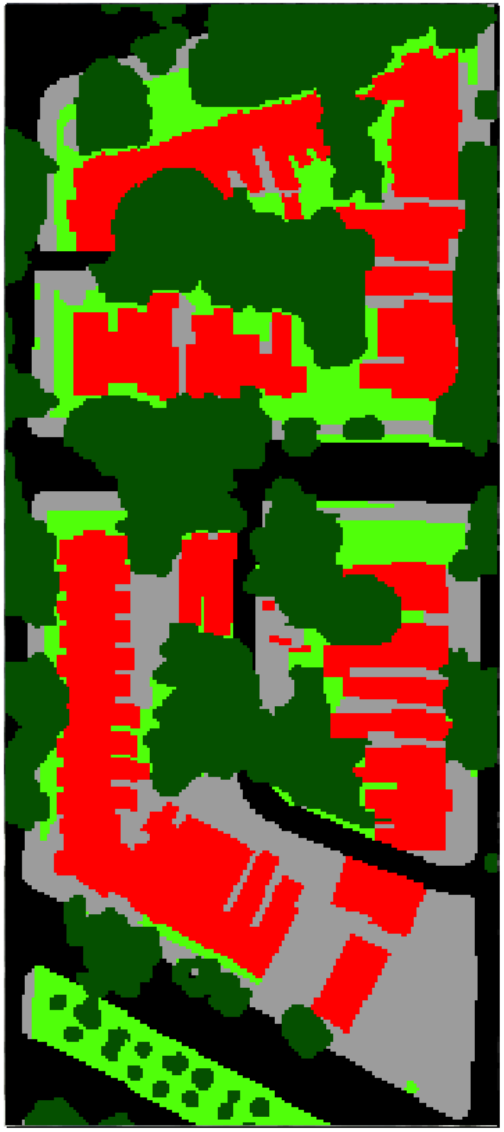
Sandia National Laboratories

If we searched for medium-to-small refineries, this would be missed:

The pipe network caused tanks and processing towers to be linked into one large region. Redefining the query to utilize chunking is likely to solve this.

# Simple Change Example

Resulting land cover:

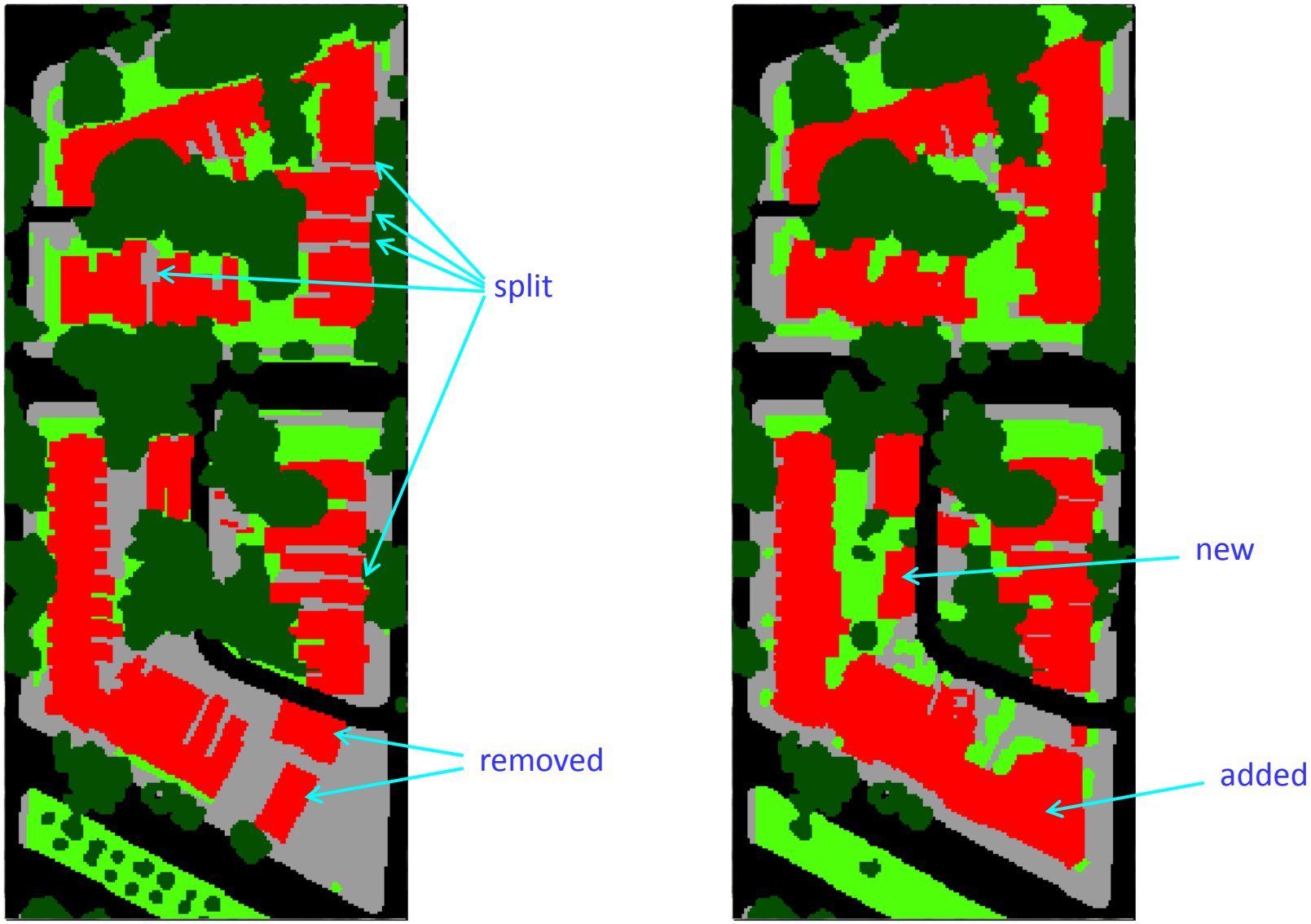


2006

2011

# Geometric Change Analysis

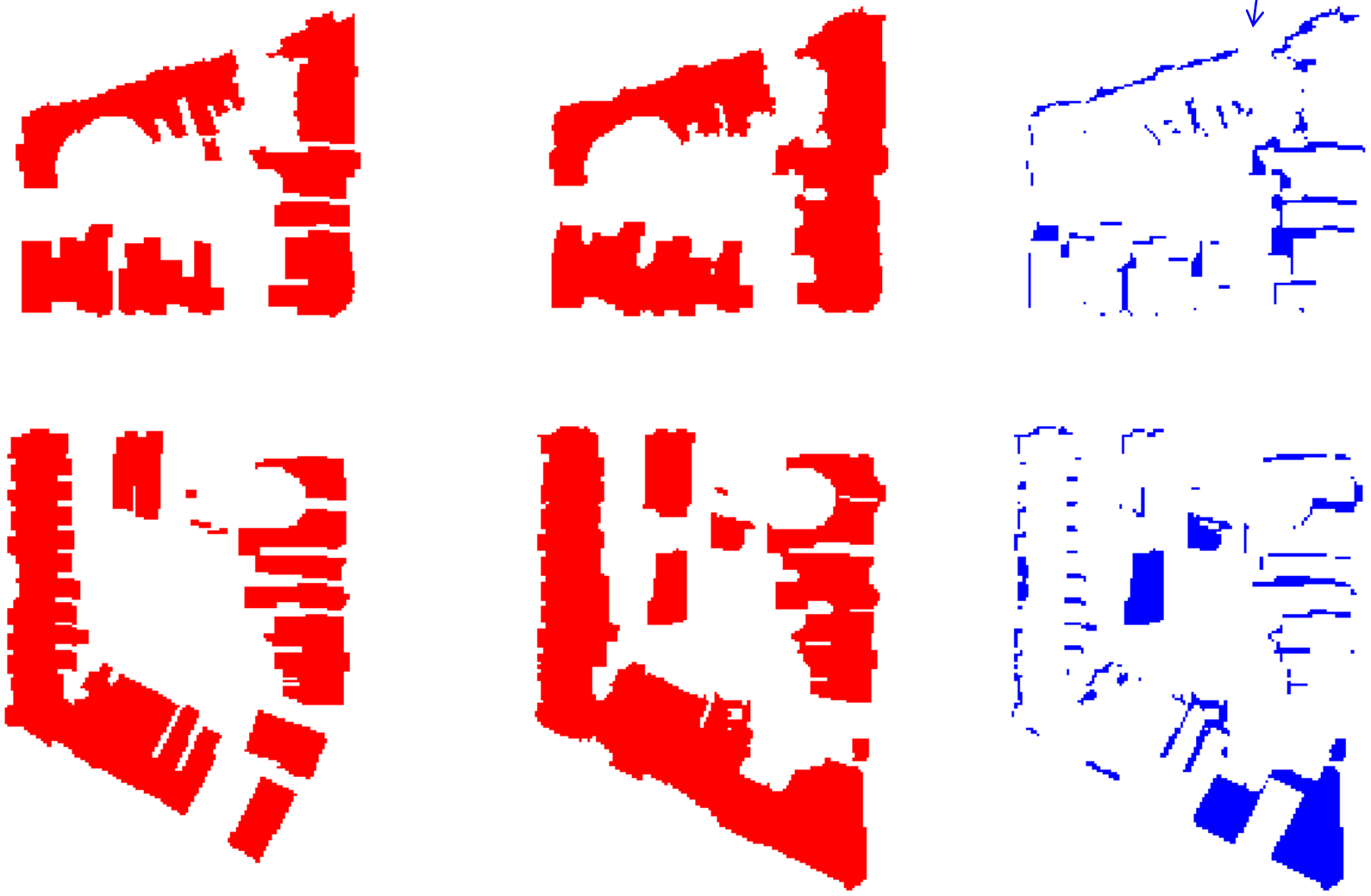
Input land cover:



# Geometric Change Analysis

Ghost boundaries result from sensor noise and registration error.

Geometric subtraction:



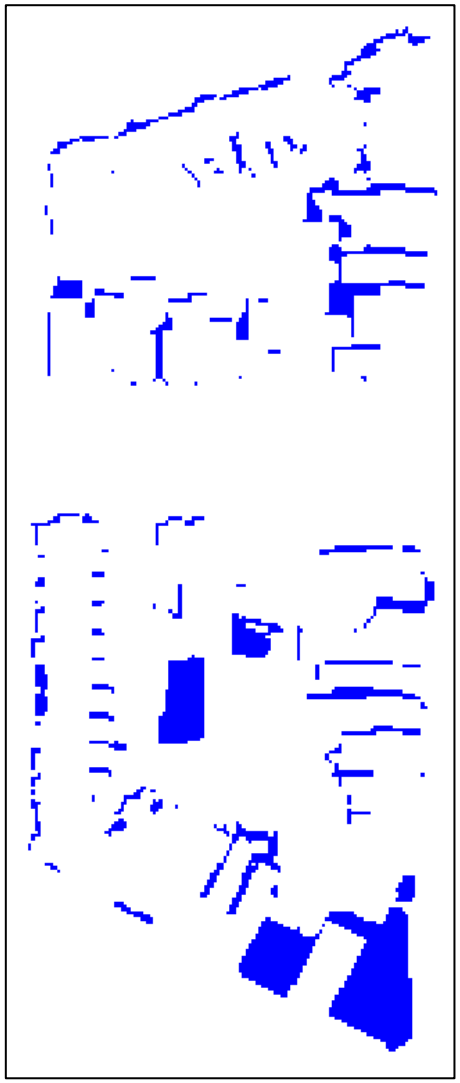
2006 Buildings

2011 Buildings

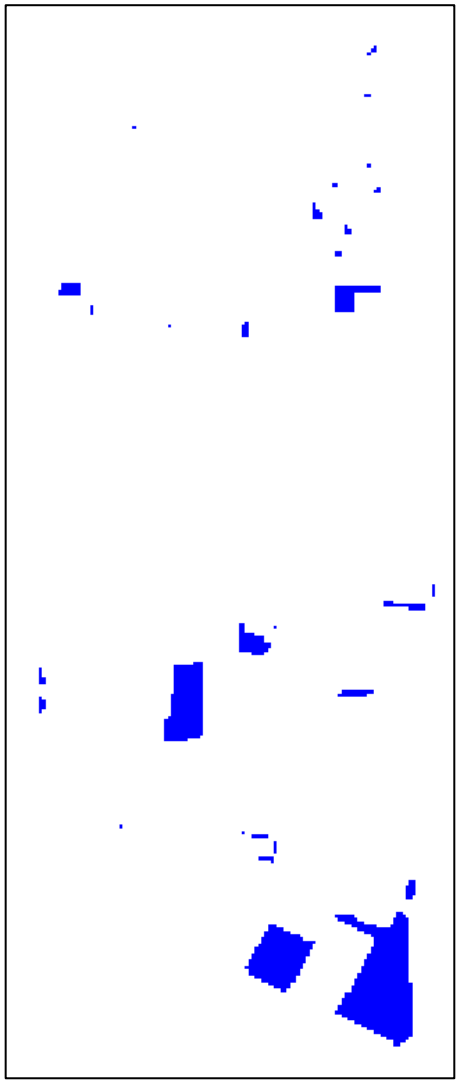
2011 minus 2006

# Geometric Change Analysis

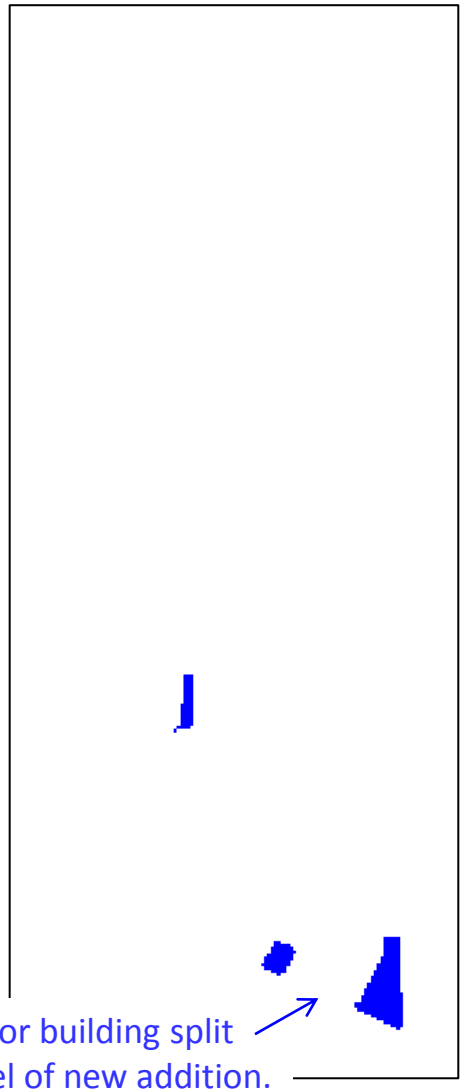
Shrinking to remove ghost boundaries:



2011 minus 2006



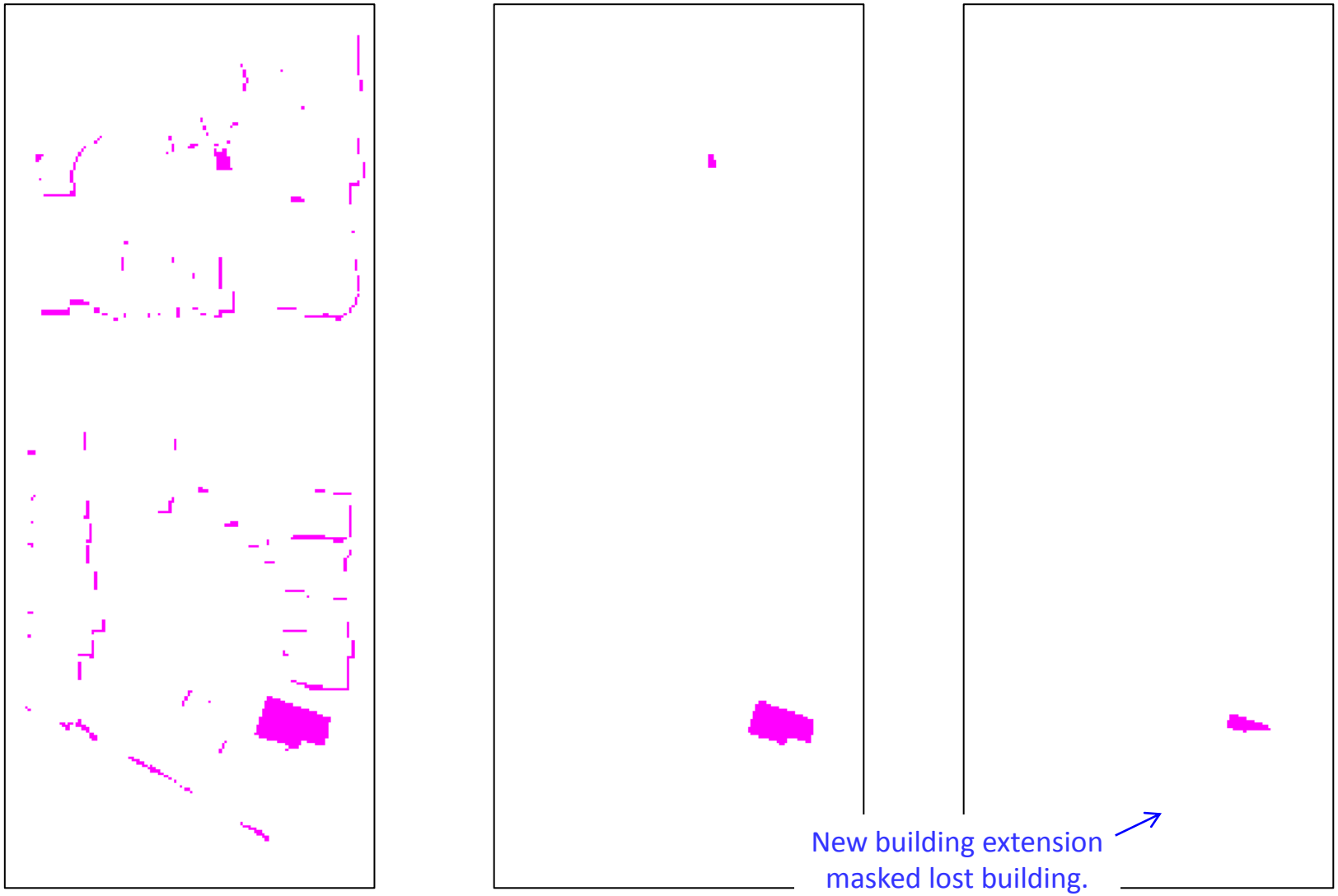
Shrink 1 Pixel




Shrink 4 Pixels

# Geometric Change Analysis

Finding lost buildings (old minus new):




2006 minus 2011 | Shrink 1 Pixel | Shrink 4 Pixels

# Geometric Change Analysis Results

Input land cover:

removed

missed this one

2006

new

added split in two; misses interior change section.

2011

Change results do not match full shape.

# Review of Change Analysis Methods

Approaches to change detection:

1. Pure pixel-based change analysis.
   - Simple, but image changes can result from illumination, color balance, moving shadows, etc., which are not real changes in the world.

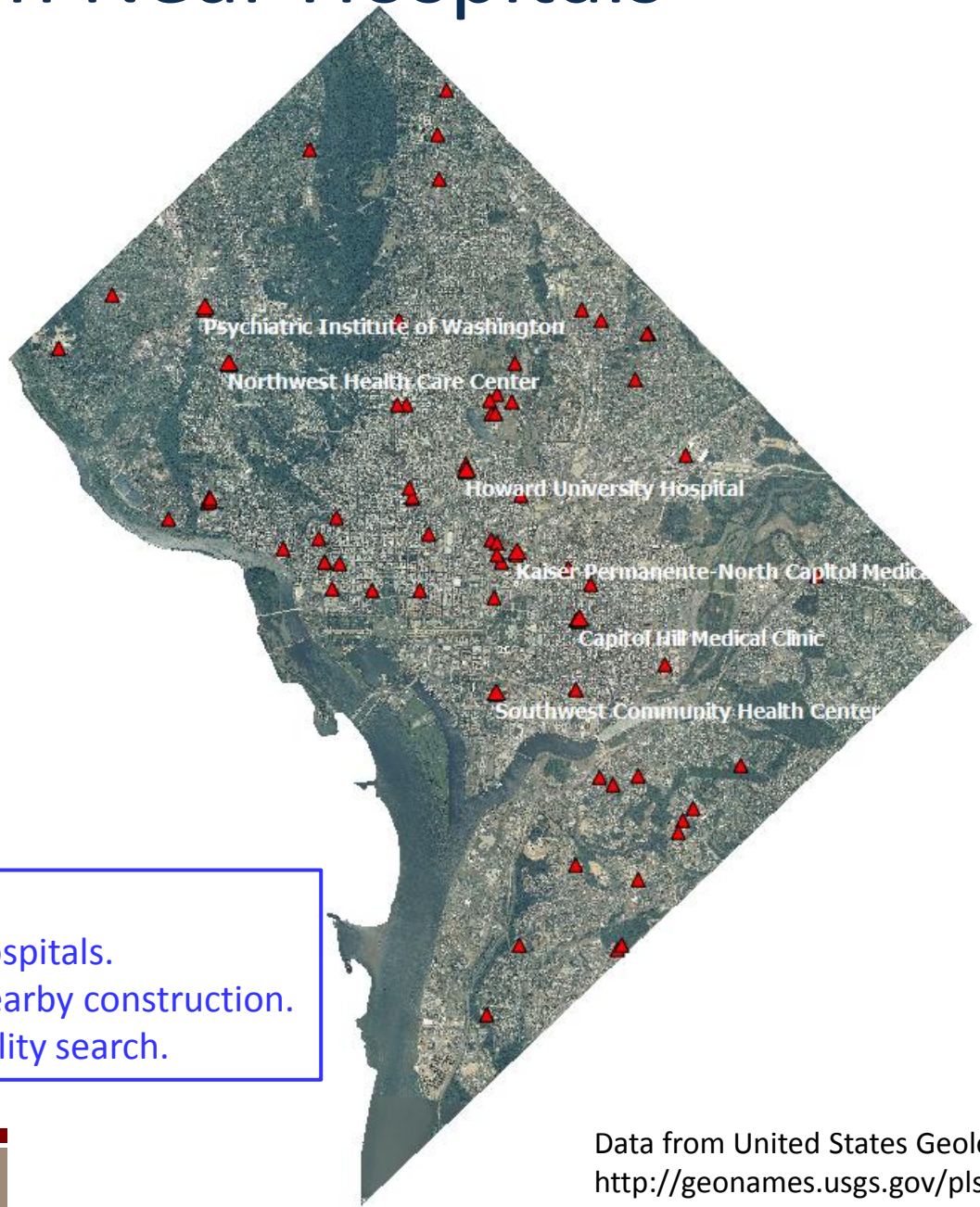
2. Geometric feature-based change analysis.
   - Better, but noise and geometric interference can lead to confusing or misleading results.

3. Graph-based change analysis.
   - Can reject false change, clarify change relationships, and present correct before/after representations.

# Construction Near Hospitals

Sandia National Laboratories

Hospitals in the DC area:




Goals:

1. Find construction near hospitals.
2. Estimate magnitude of nearby construction.
3. Demonstrate multi-modality search.

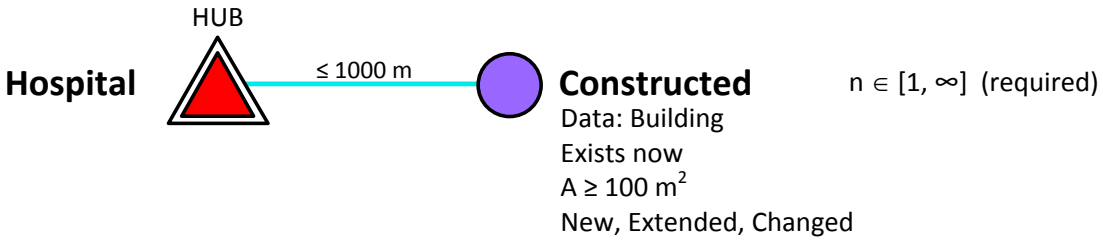
Data from United States Geological Survey.
http://geonames.usgs.gov/pls/gnispublic

# Construction Near Hospitals

Query specification:

How much construction has occurred within 1 km of each hospital?

Question semantics:
Building
Changed Building
Extended Building
Merged Building
New Building
Replaced Building
Constructed
Hospital
⋮




Data semantics:
Building
Road
Other Paved
Grass/Shrub
Trees
Dirt
Water
Hospital

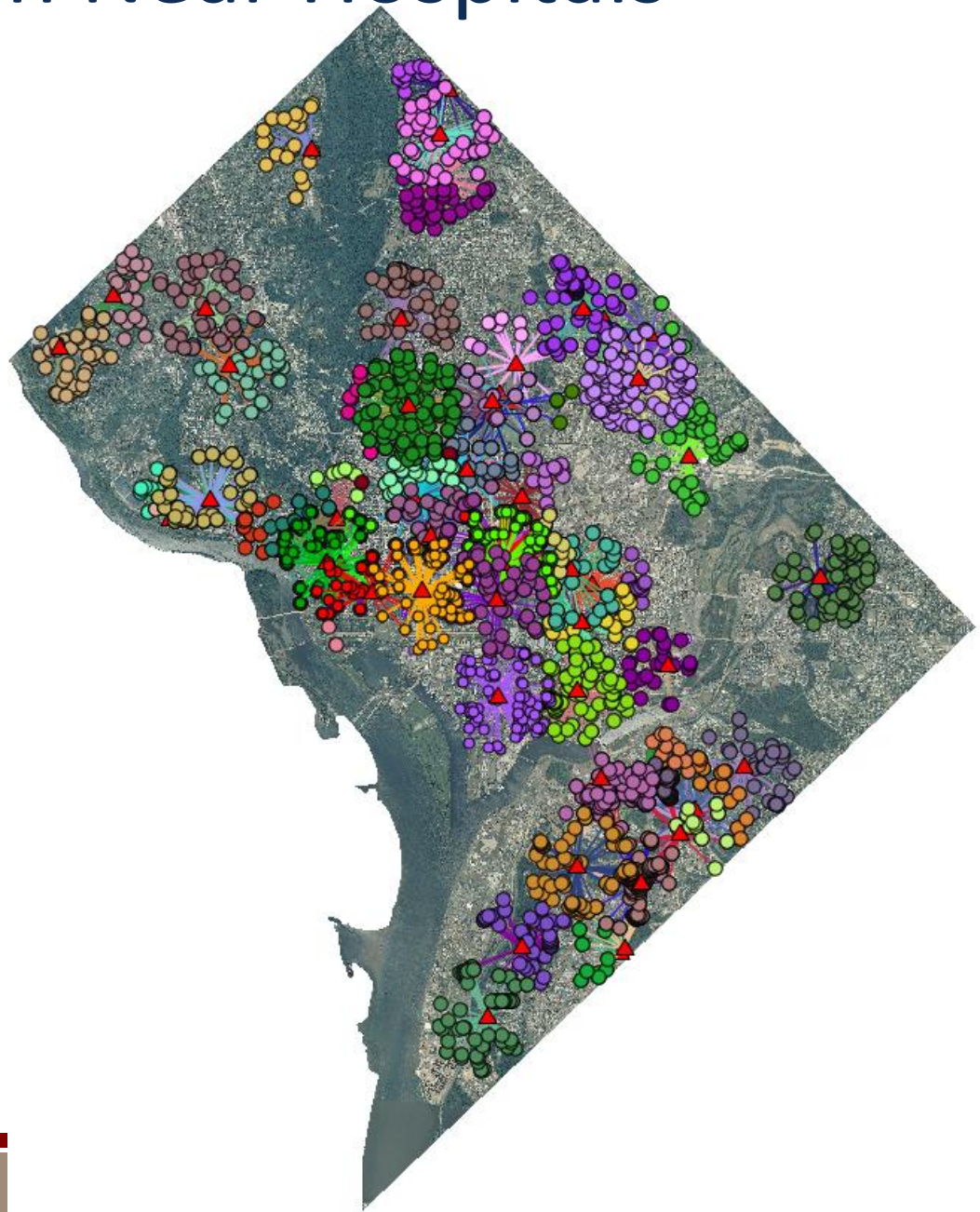
Star graph search.

Rank in order of most construction first.

# Construction Near Hospitals

Sandia National Laboratories

All matches:



# Construction Near Hospitals

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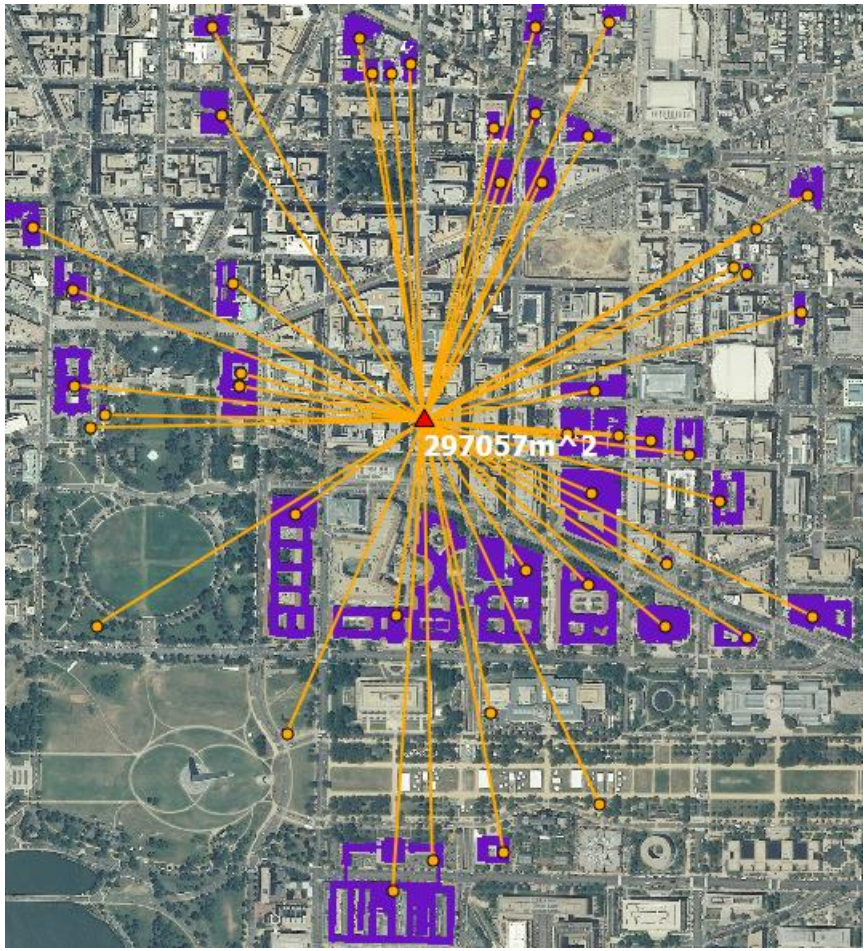
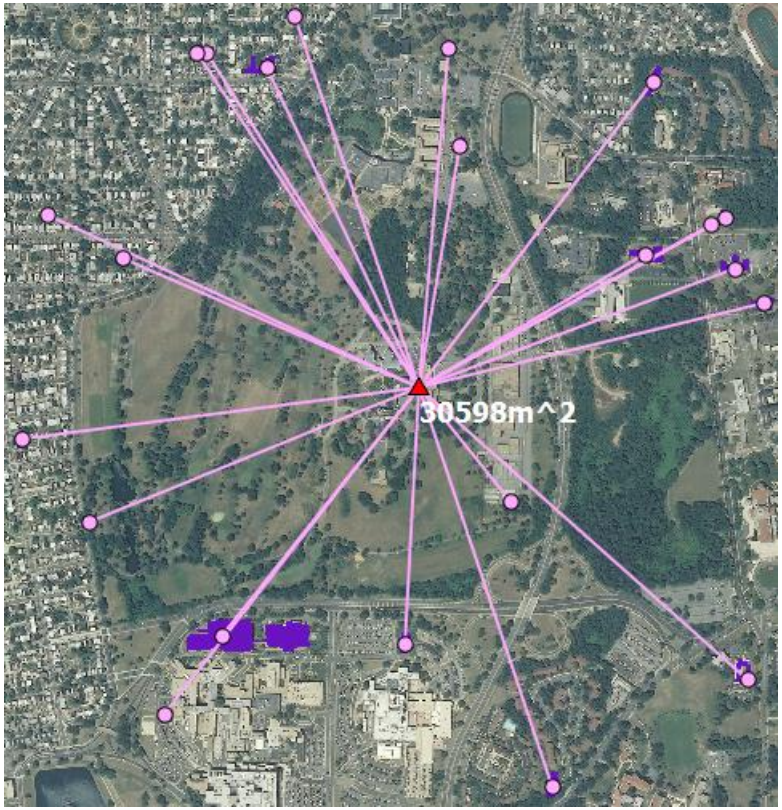
Select two for close examination:

# Construction Near Hospitals

Sandia National Laboratories

Hospital with different amounts of nearby construction:*




One computation includes:

- Temporal change detection.
- Construction diagnosis.
- Image and text data.
- Post-processing numerical sum.

* Includes pseudo-construction. See above.