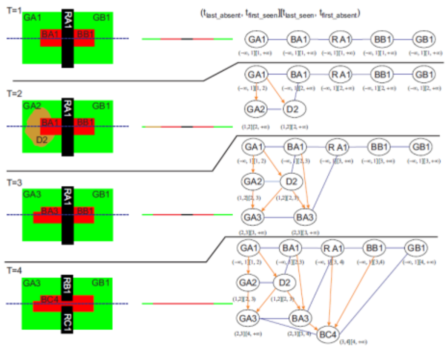
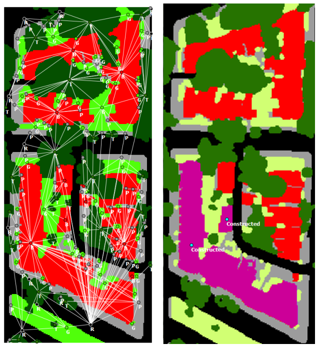
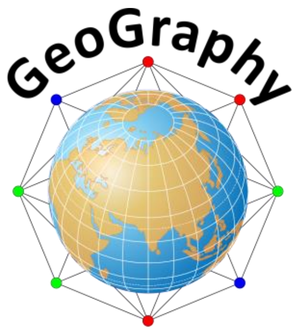
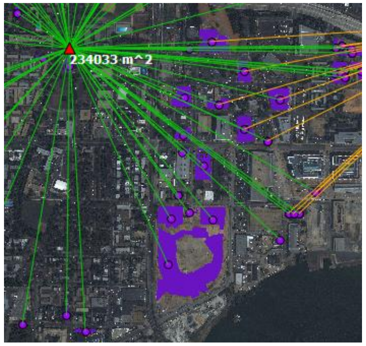
Exceptional service in the national interest

Sandia National Laboratories

DigitalGlobe

Geospatial-Temporal Semantic Graphs for Remote Sensing Data Analysis

Lawrence Livermore National Laboratory

Los Alamos NATIONAL LABORATORY EST.1943

Sandia National Laboratories

Randy C. Brost

July 23, 2015

U.S. DEPARTMENT OF ENERGY

NNSA National Nuclear Security Administration

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Team

Tri-Lab PIs:

- Randy Roberts, LLNL
- Randy Brost, SNL
- Paul Pope, LANL
- Danny Rintoul, SNL

Universities:

- Jarlath O-Neil-Dunne, UVM
- Sean MacFaden, UVM
- Taylor Engel, UVM
- Mike Richardson, RIT

Support:

- DOE NA-22 Office of Non-Proliferation, Jim Peltz, Program Manager
- Sandia LDRD Office.

Team:

- Craig Blackhart, LANL
- Michelle Carroll, SNL
- Debbie Dennison, LLNL
- Luci Gaines, LANL
- John Goforth, LLNL
- Art Jolly, LLNL
- Will McLendon, SNL
- Dan Morrow, SNL
- Jo Ellen Neuman, LLNL
- Ojas Parekh, SNL
- Drew Patterson, SNL
- David Perkins, SNL
- Lakshman Prasad, LANL
- Jorge Roman, LANL
- Shelly Spearing, LANL
- Diane Woodbridge, SNL

Overview

- Motivation.
- Computation.
- Example Results.
- Extensions.
- Discussion.

Motivation

Motivation:

- Overwhelming remote sensing data.

General approach:

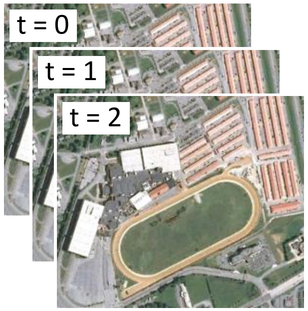
- Automatically find items of potential interest.
- "Cue" to user for review.

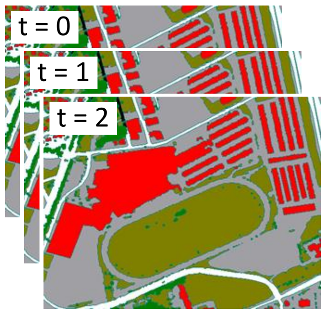
Types of questions:

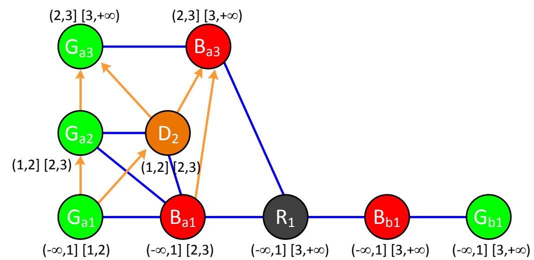
- Geospatial: Find all power plants.
- Temporal: Find all changes.
- Geospatial-temporal: Find all power plants that changed.
- Multi-modality: Find new construction near points of interest.
  Find industrial facilities with unusual emissions.

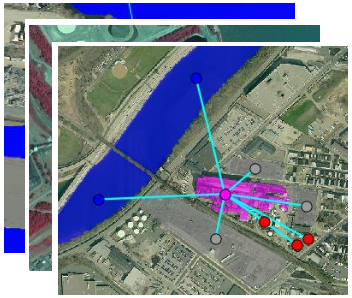
In sum: Make remote sensing data searchable, over space, modality, and time.

Geospatial-Temporal Graph Data Flow







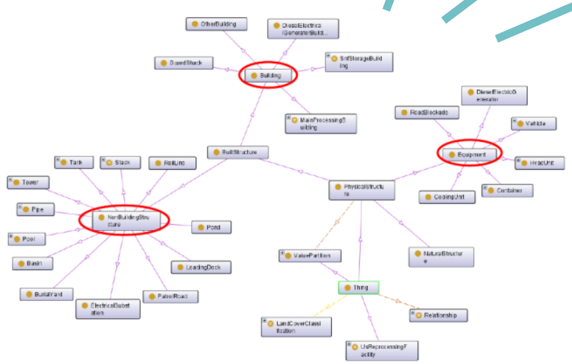


Remote Sensing → Region Classification → Spatiotemporal Graph → Spatial / Temporal / Spatiotemporal Matches

Change Detection

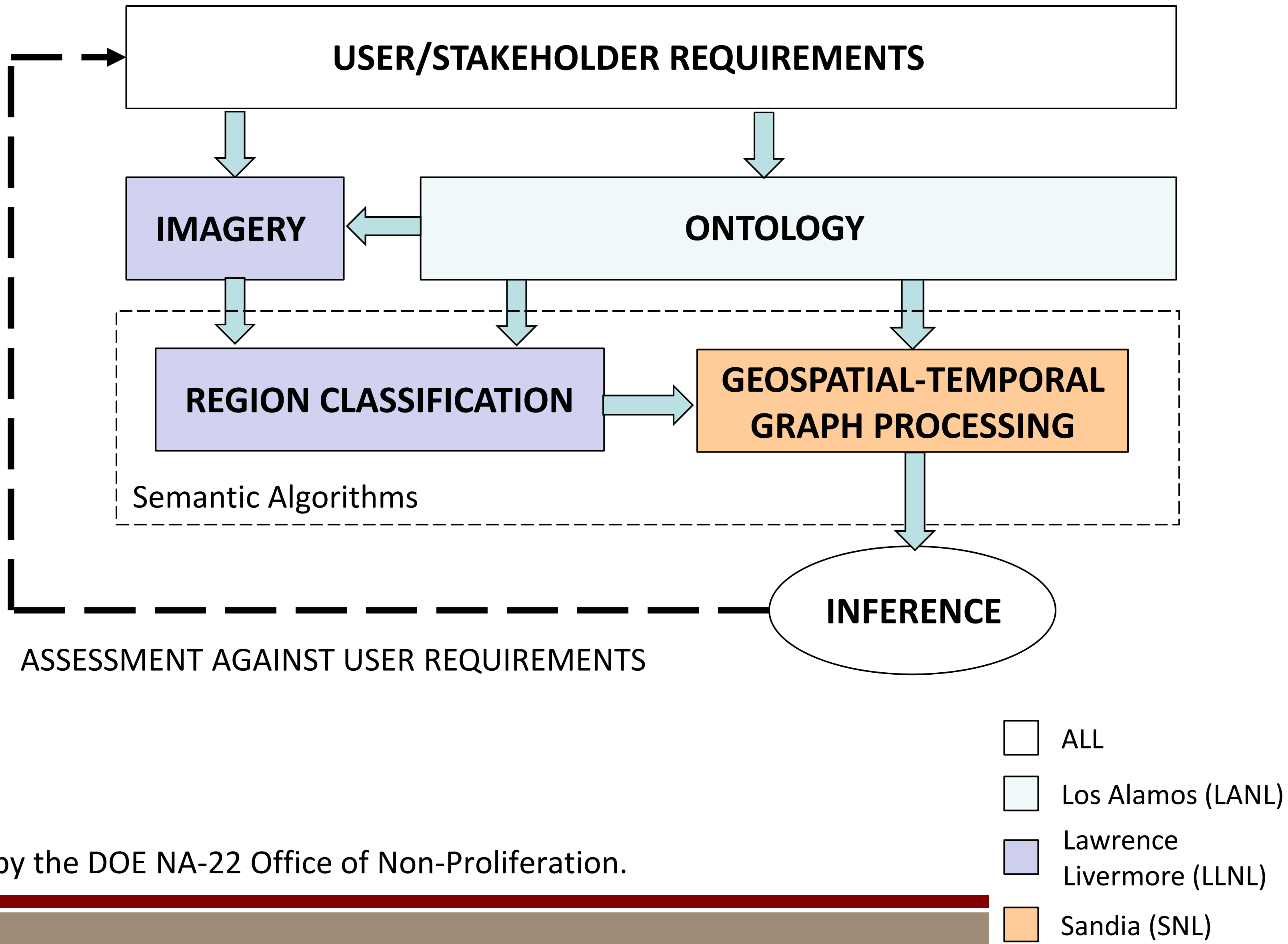
Query:

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



Ontology

Tri-Lab Project Overview



Funded by the DOE NA-22 Office of Non-Proliferation.

Ontology Engineering

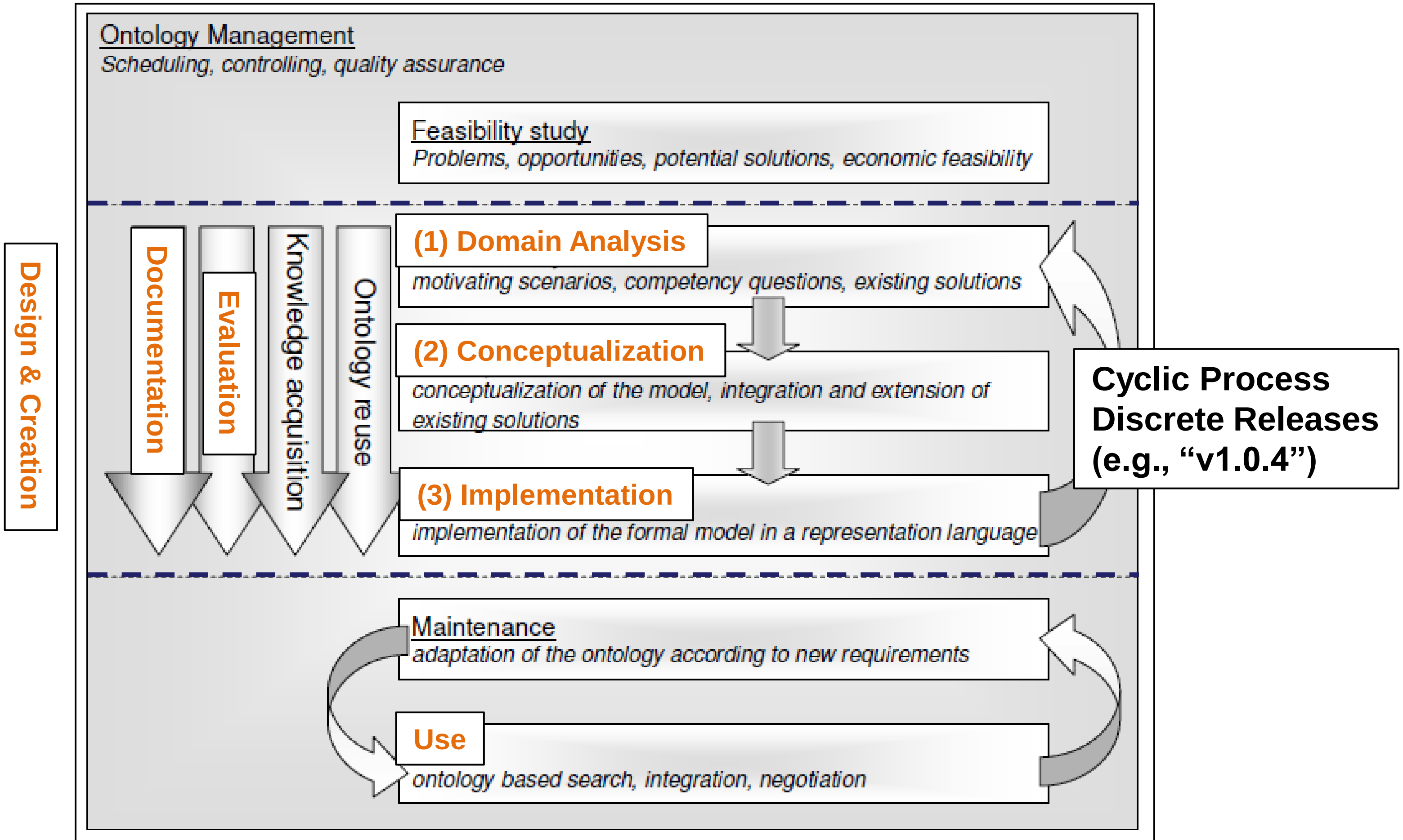
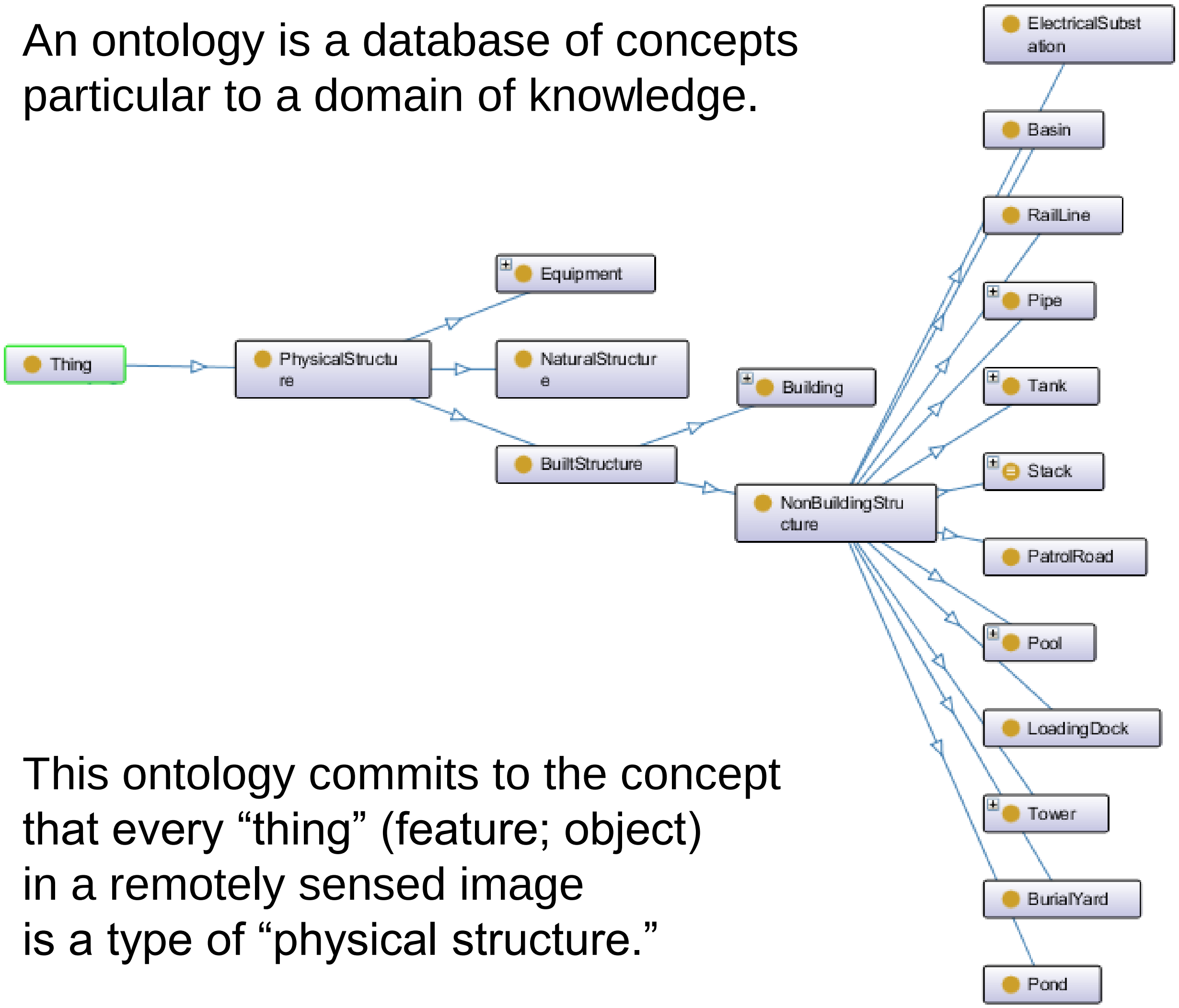


Fig. 1. Ontology Engineering Activities

(adapted from Simperl and Tempich, 2006)

Ontology

An ontology is a database of concepts particular to a domain of knowledge.



This ontology commits to the concept that every “thing” (feature; object) in a remotely sensed image is a type of “physical structure.”

Benchmark Imagery Suite

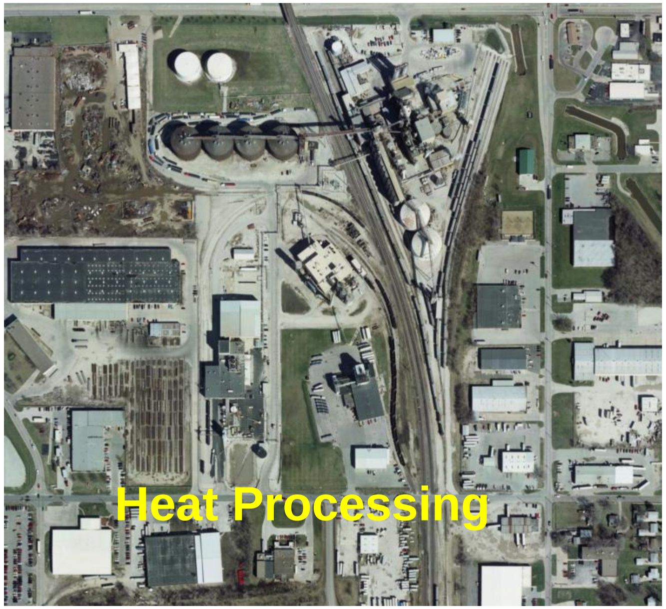
<u>A task-specific test data set:</u>

- VIS and VIS/NIR aerial images:
  - Chemical Processing (27) —refineries, …
  - Heavy Manufacturing (31) —steel foundries, …
  - Heat Processing (37) —power plants, …
  - Mechanical Processing (83) —aluminum processing, …
  - Semiconductor (12) —chip companies, …
- Synthetic images (38 fictitious electrical power plants).
- LiDAR elevation rasters (16 of the real facilities).

Benchmark Image Examples

Image properties:

- Orthorectified GeoTIFF.
- Near-nadir viewing angle.
- Area: 1 to 1.6 km^2.
- GSD: 0.3 to 1m.



Region Classification

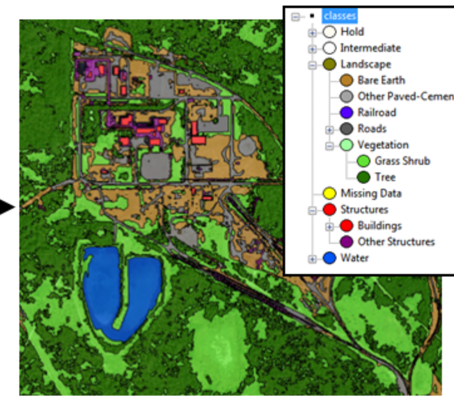
<u>We use eCognition* software to create land classification maps:</u>

Rule Sets

Analysis Software

- An example rule -

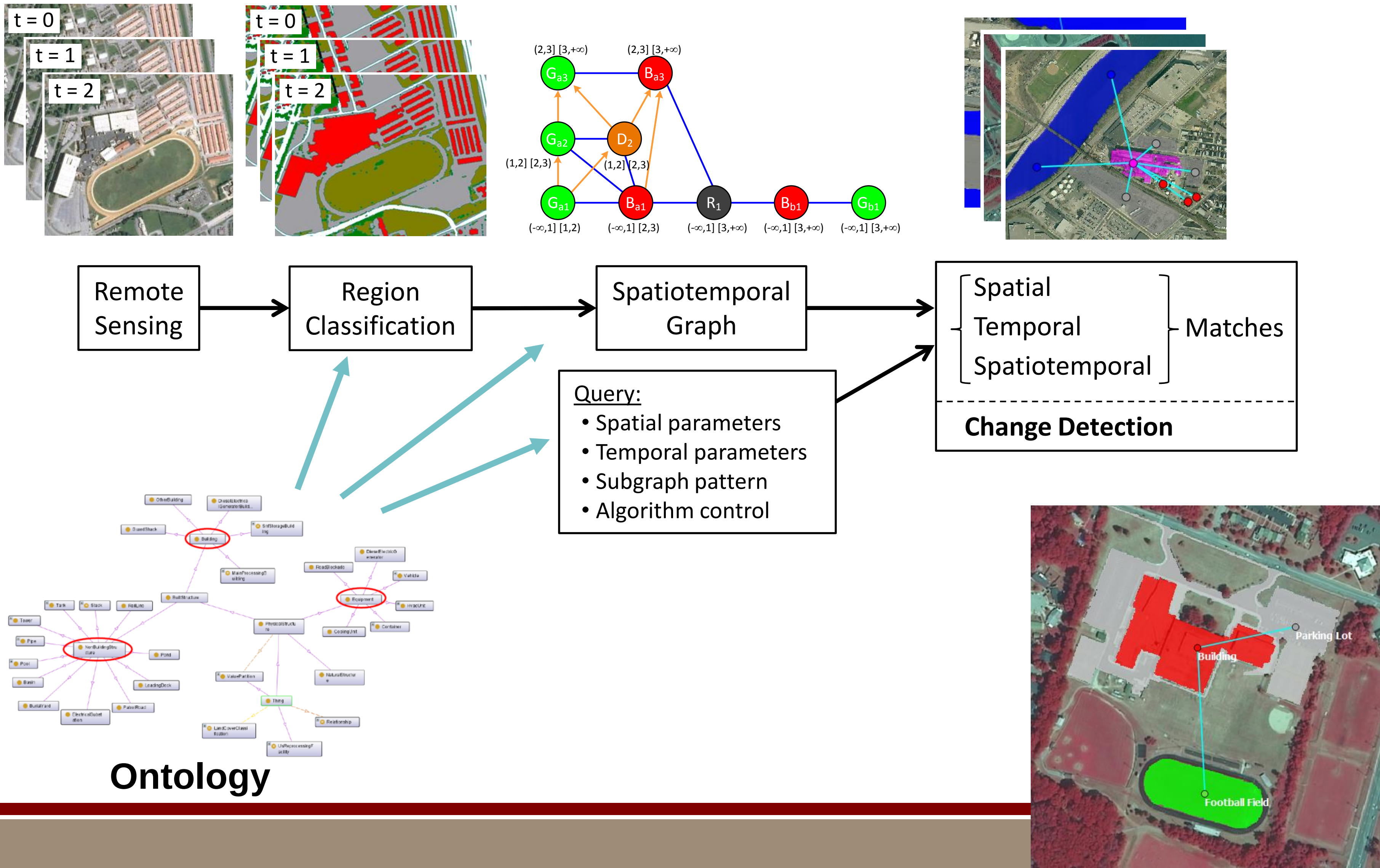
IF
0m < LiDAR < 2m
AND
0.1 < NIR
AND
50< Blue < 100
AND
area > 1000 m^2
THEN
Object = LAKE



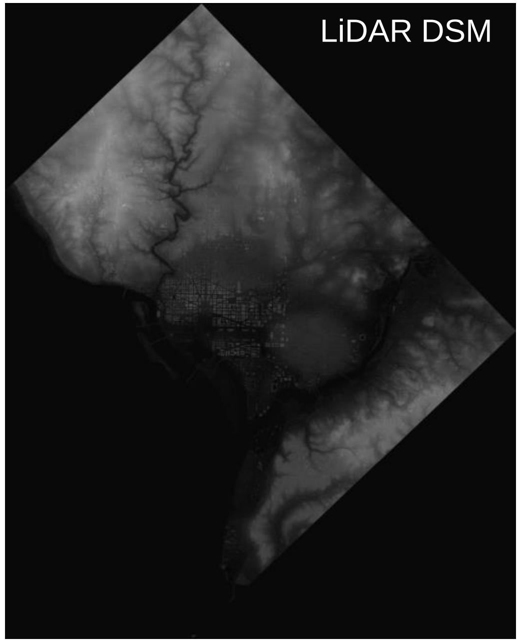
Posterized image

*eCognition is used throughout the project, by LLNL, SNL and U. Vermont

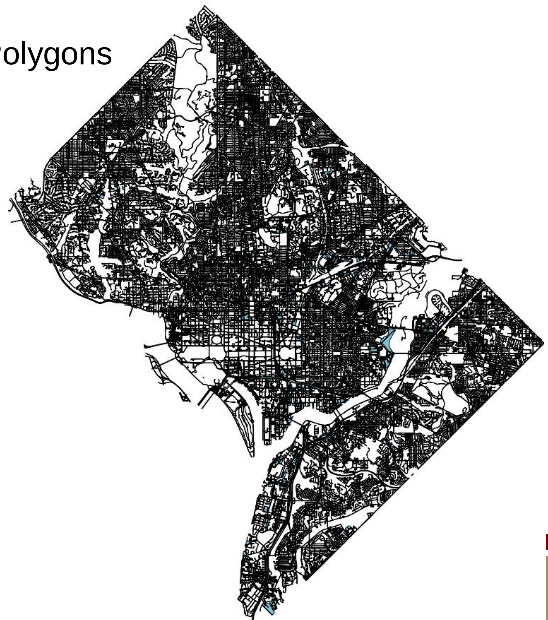
Geospatial-Temporal Graph Data Flow



Input Data



GIS Road Polygons



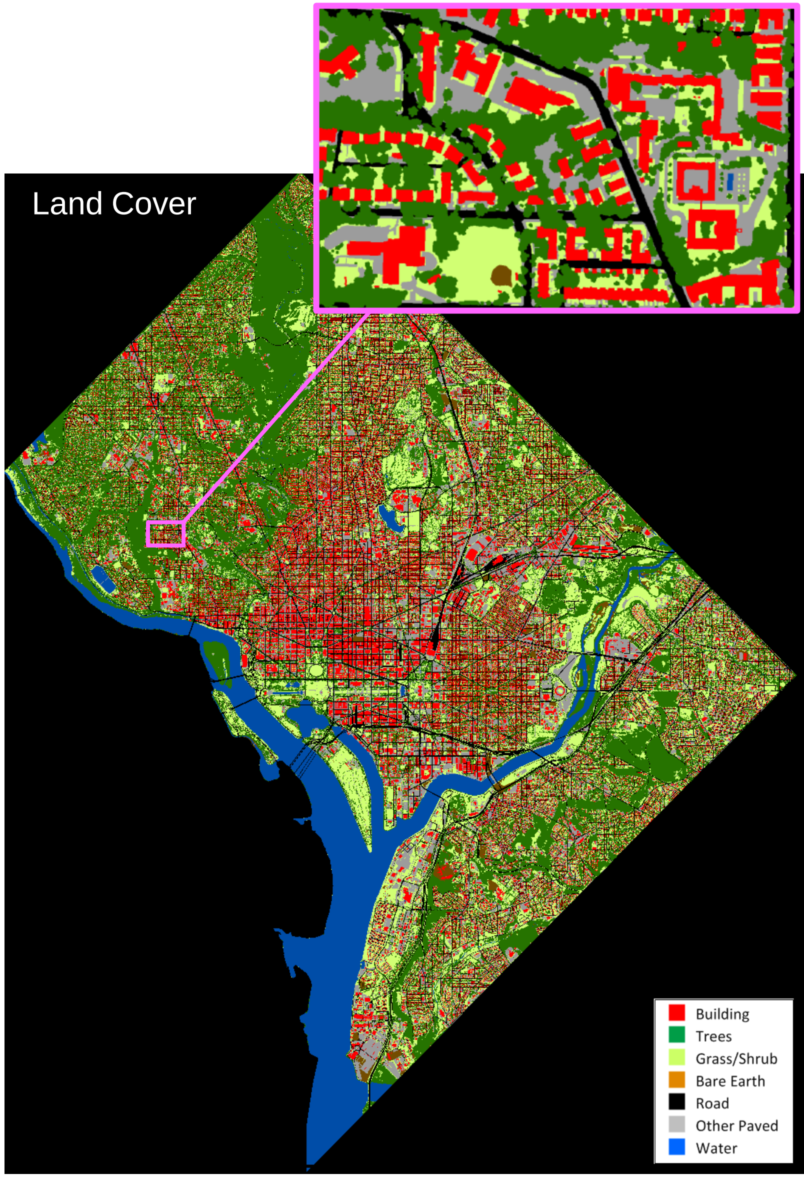


Image data and processing by University of Vermont Spatial Analysis Lab [O'Neil-Dunne 2012].

[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.

Systematic Land Cover Classification

Steps:

1. Assemble input:
   - RGB+IR imagery, near nadir.
   - LiDAR data.
   - GIS road centerlines or polygons (if available).
2. Construct normalized digital surface model (nDSM).
3. Using nDSM, split image into “Tall” vs. “Short.”
4. Using RGB+IR, split out “Tree” from Tall.
5. Using geometric morphology and LiDAR texture, split out “Building” from Tall.
6. Using morphology and LiDAR, split remaining Tall into “Wall” and “Other Structure.”
7. Using GIS road data, split out “Road” from Short.
8. Using RGB+IR, split remaining Short into “Grass/Shrub,” “Dirt,” “Water,” and “Other Paved.”
9. Output posterized file.

Work is proceeding at UVM, LLNL, and SNL evaluating this procedure.

This is a refinement of O'Neil-Dunne, et al, “An Object-Based System for LiDAR Data Fusion and Feature Extraction,” Geocarto 2012.

Example from UVM

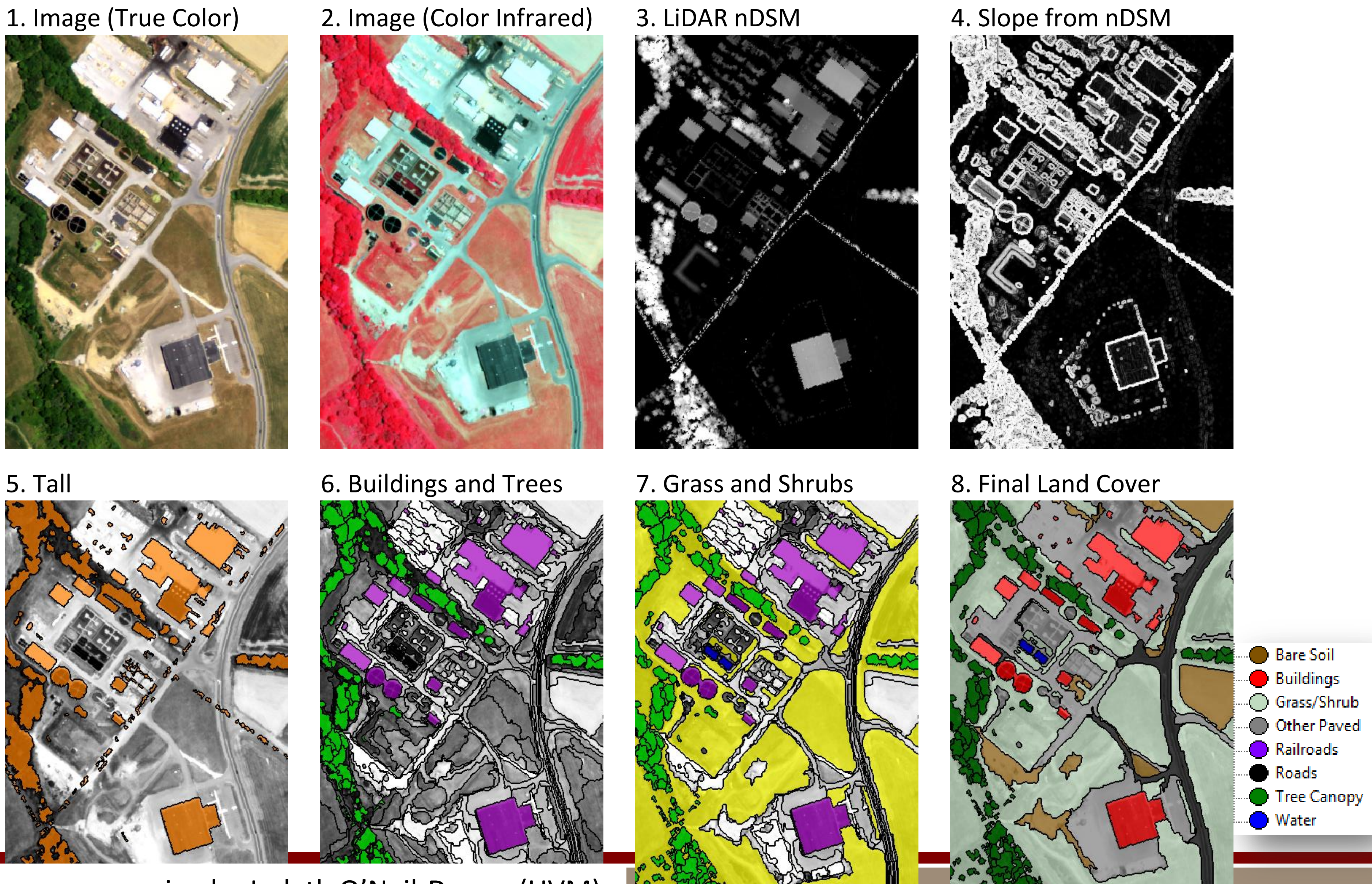
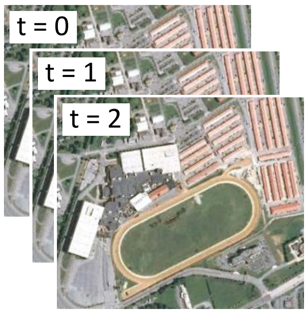
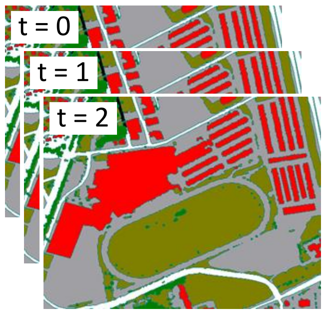
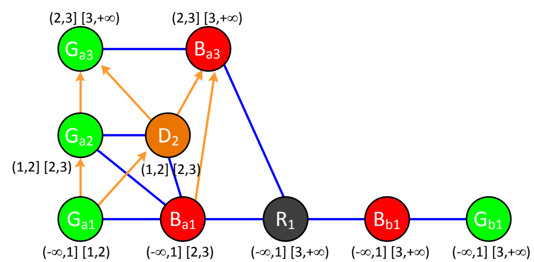


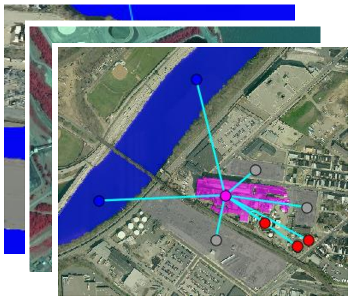
Image processing by Jarlath O'Neil-Dunne (UVM).

Geospatial-Temporal Graph Data Flow









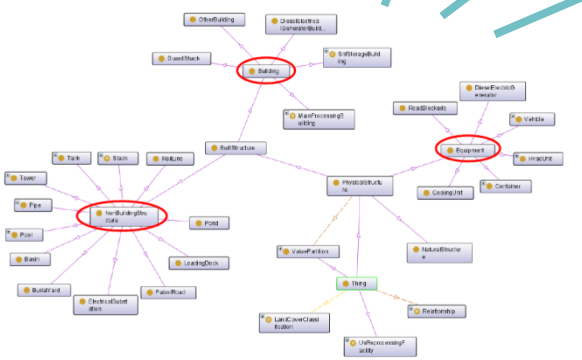
Remote Sensing → Region Classification → Spatiotemporal Graph →

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

→

Spatial / Temporal / Spatiotemporal — Matches

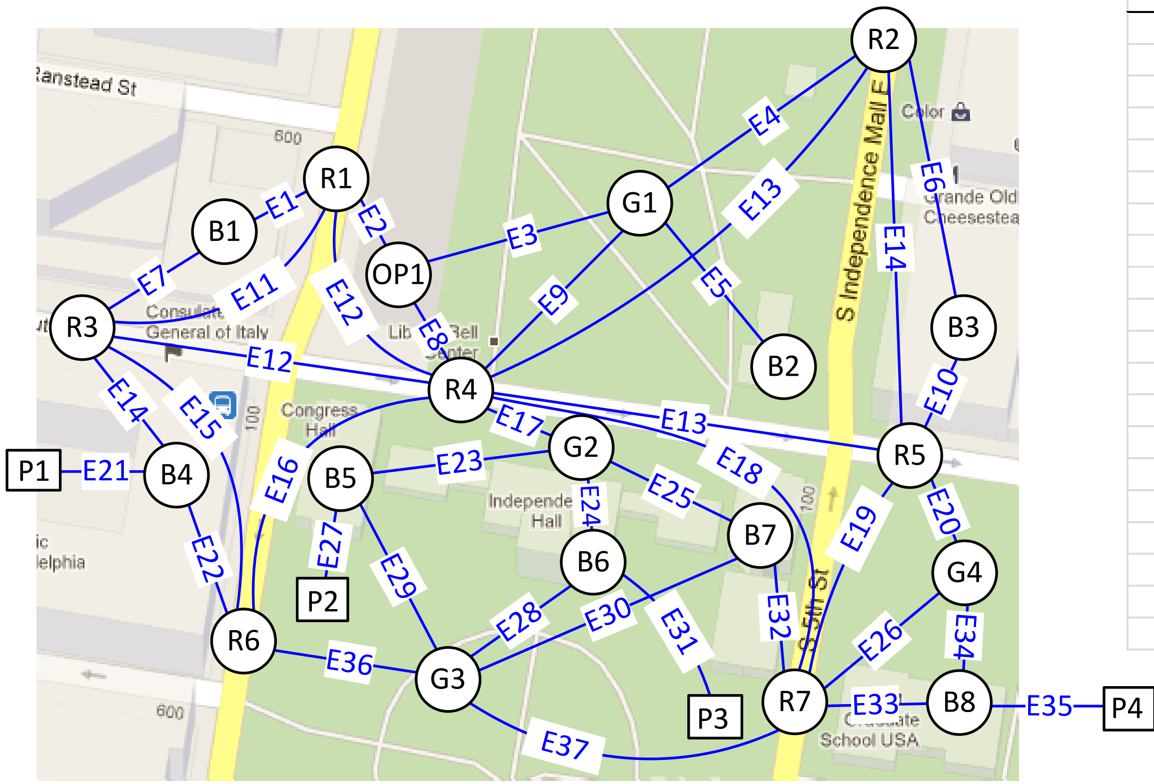
Change Detection



Ontology

Example Geospatial Semantic Graph

Independence Hall, Philadelphia:



Map data ©2014 Google

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

Region node table:

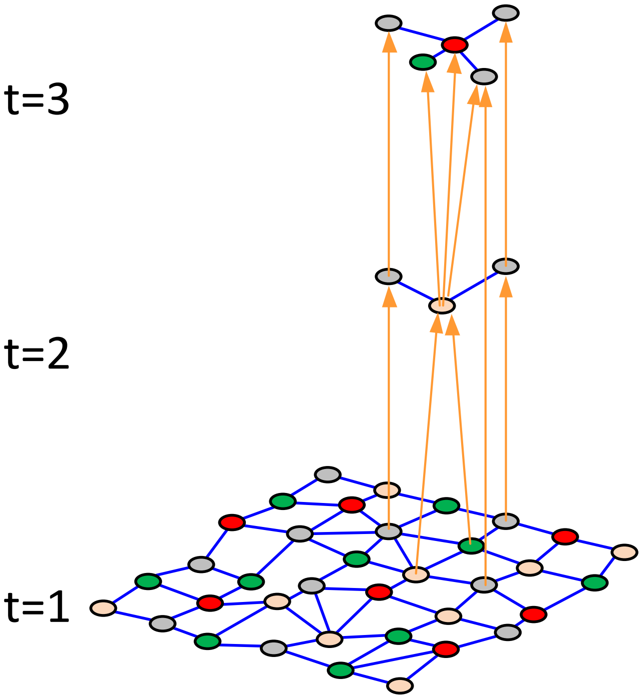
id	type	area	centroid x	centroid y
B1	building	3200	-75.14900	39.94939
R1	road	1800	-75.14910	39.94949
OP1	paved	4700	-75.14935	39.94934
G1	grass	22000	-75.15010	39.94944
R2	road	1900	-75.15060	39.94999
R3	road	1100	-75.14885	39.94934
R4	road	2200	-75.14980	39.94924
B2	building	780	-75.15045	39.94931
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

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
.	.	.
.	.	.
.	.	.

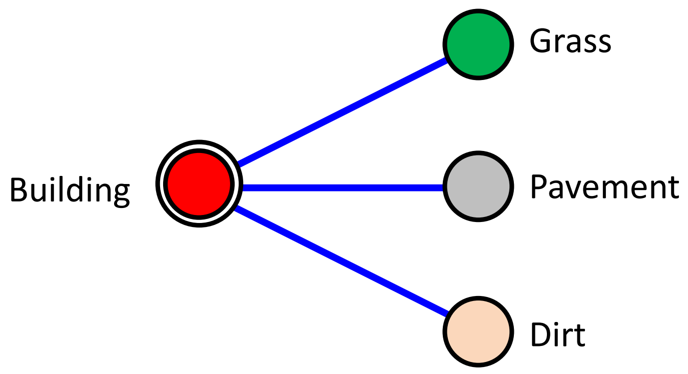
Representing Change Over Time

- 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.

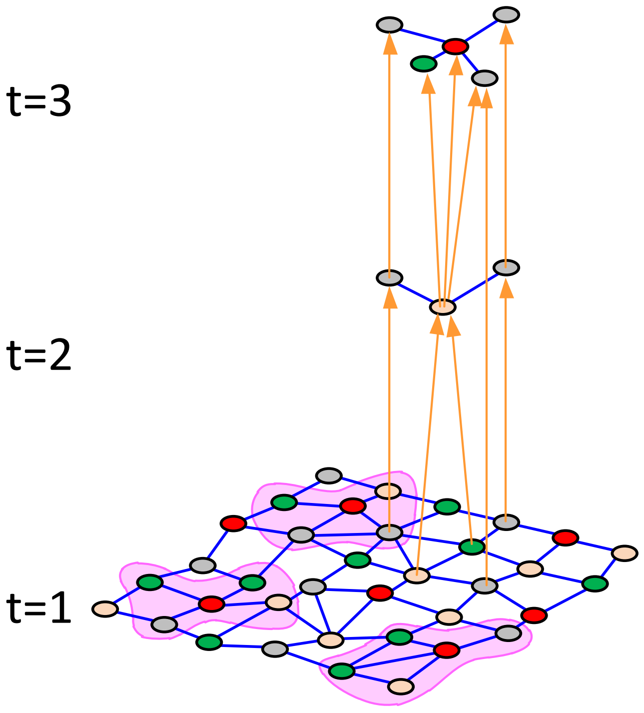


Signature Search

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



Query Template



Search Results

Overview

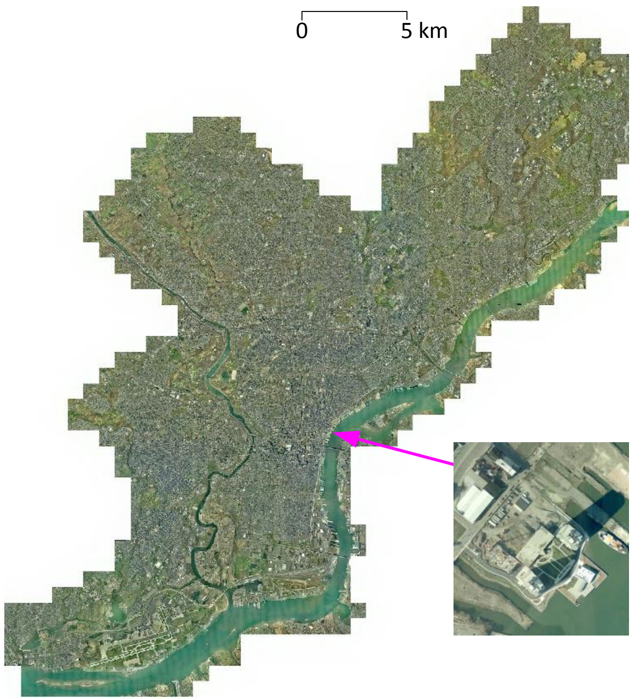
- Motivation.
- Computation.
- Example Results.
- Extensions.
- Discussion.

Overview

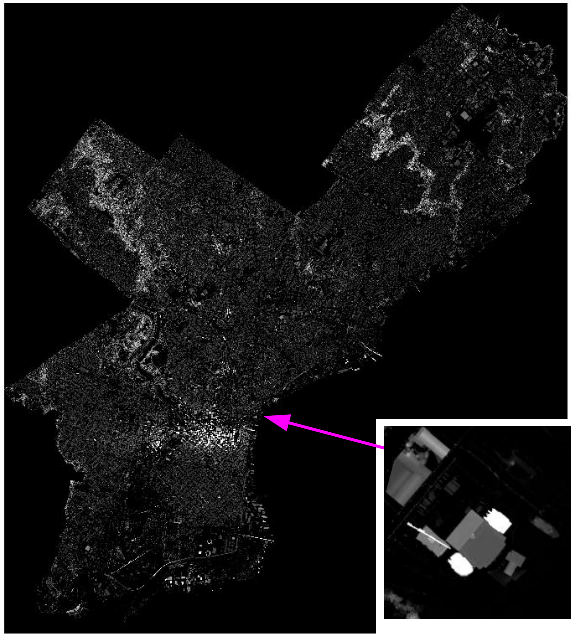
- Motivation.
- Computation.
- Example Results.
  - Data.
  - Power plants.
  - Refineries.
  - Change analysis.
  - New complex.
- Extensions.
- Discussion.

Philadelphia 2008

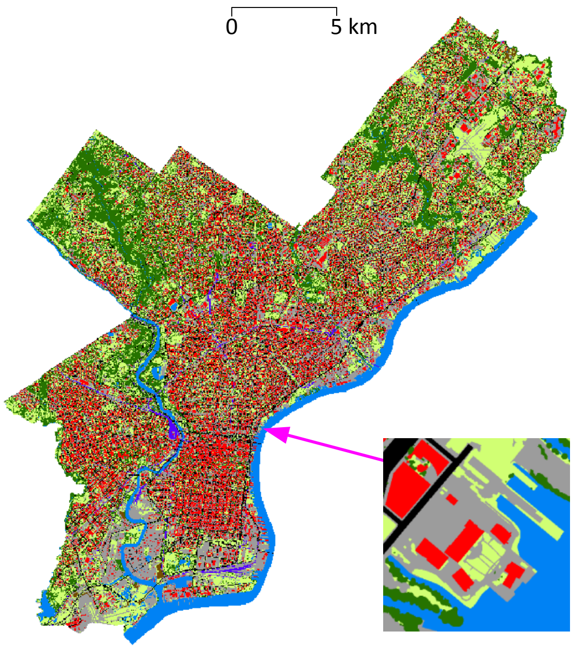
Primary input:



Optical Image



LiDAR nDSM



Land Cover

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

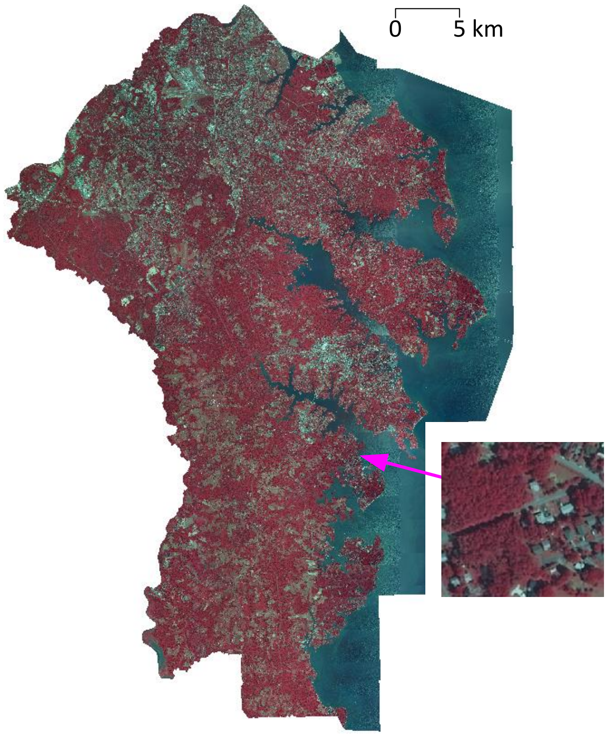
Pixel size 0.3 m
89,540 × 100,294 pixels
(9.0 Gpix)
2,084 MB

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

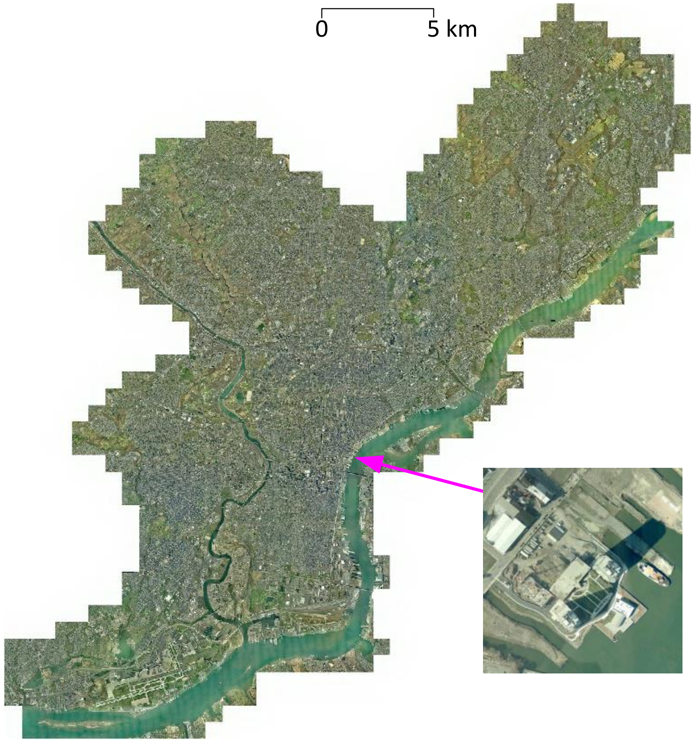
Image data provided by the University of Vermont.

Three Data Regions

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.

Image data provided by the University of Vermont.

Overview

- Motivation.
- Computation.
- Example Results.
  - Data.
  - → Power plants.
  - Refineries.
  - Change analysis.
  - New complex.
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Power Plant Search

Query specification:

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

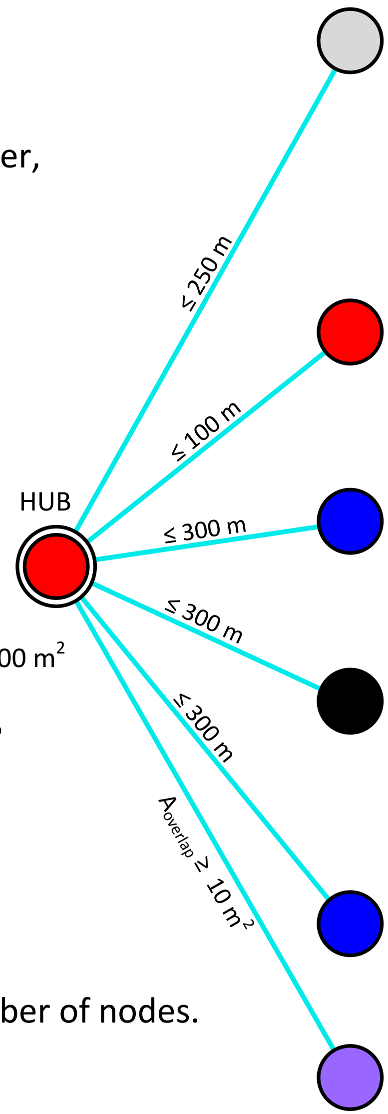
Question semantics:

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

Heat Building
Data: Building
Not circular
$2{,}800\ m^2 \le A \le 60{,}000\ m^2$
$h_{max} \ge 50$ m
$h_{max} / h_{median} \ge 1.75$



Transformer $n \in [1, \infty]$ (required)
Data: Other Paved
Chunk (15 × 15)
$A \ge 5{,}000\ m^2$
Eccentricity ≤ 3.5
$12\ m \le h_{max} \le 35\ m$
At least 5 m^2 above 10 m

Tank $n \in [0, 6]$ (optional, limited)
Data: Building
Circular
$90\ m^2 \le A \le 3{,}000\ m^2$

Evaporation Pond $n \in [0, \infty]$ (optional)
Data: Water
$1{,}500\ m^2 \le A \le 19{,}500\ m^2$
Eccentricity ≤ 6.0

Coal Pile $n \in [0, \infty]$ (optional)
Data: Dirt
$A \ge 30{,}000\ m^2$
Eccentricity ≤ 3.0
$[R\ G\ B]_{max} \le 0.4$

Body of Water $n \in [0, \infty]$ (optional)
Data: Water
$A \ge 20{,}000\ m^2$

Constructed $n \in [0, 0]$ (forbidden)
Data: Building
$A \ge 100\ m^2$
New, Extended, Changed

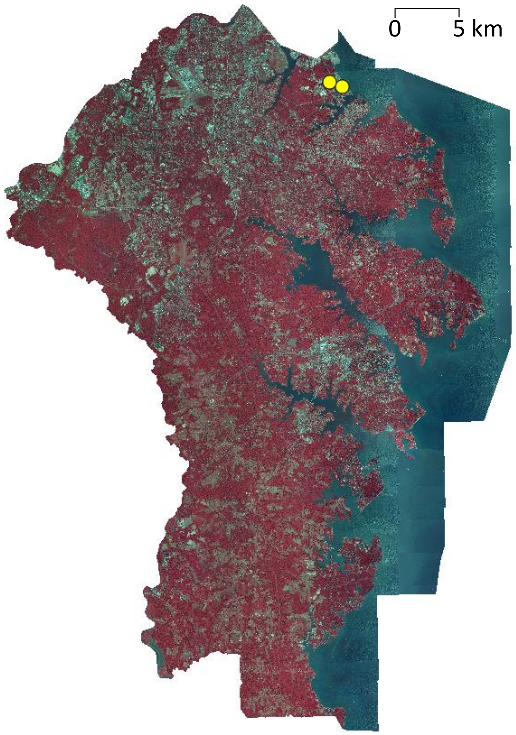
Star graph search.

Sort matches by number of nodes.

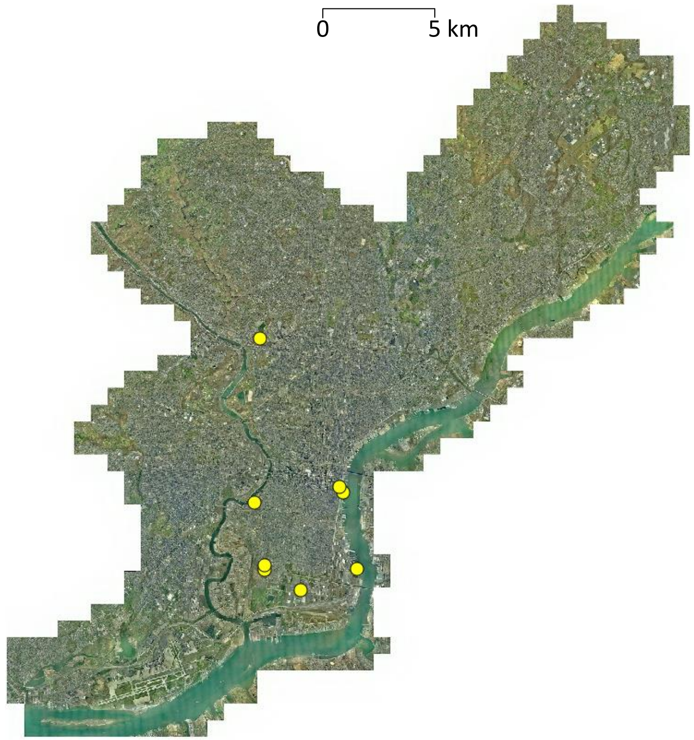
Note: "Exists Now" is omitted for clarity.

Power Plant Search

Search results:



Anne Arundel County, MD



Philadelphia, PA

Washington, DC

Input:

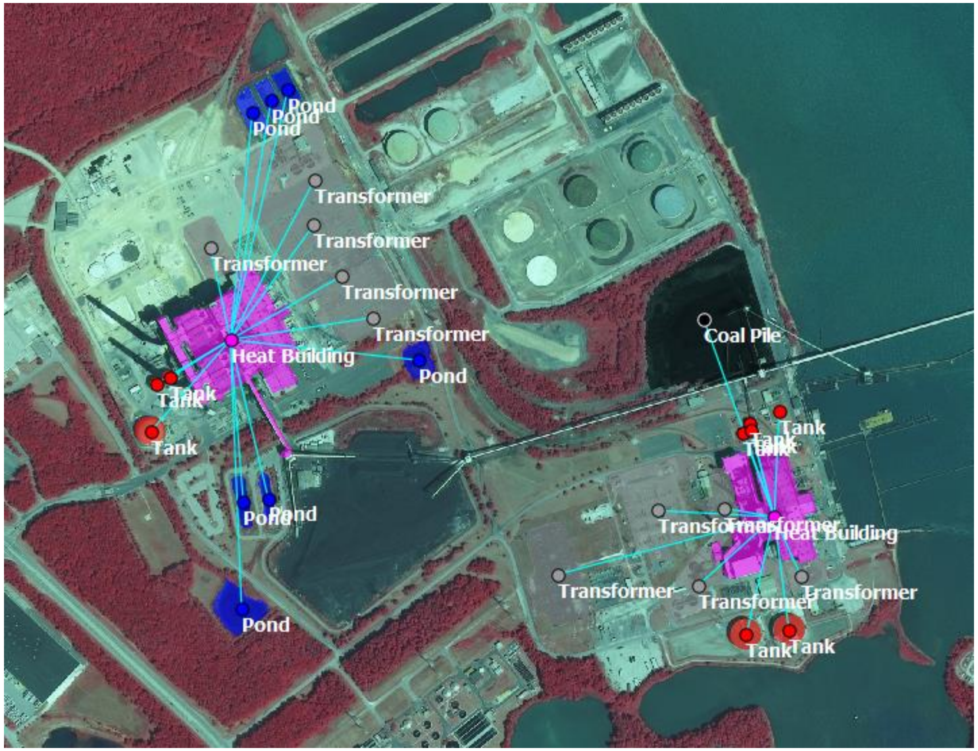
2,067	km^2 total area
135 billion	Pixels
3.6 million	Features

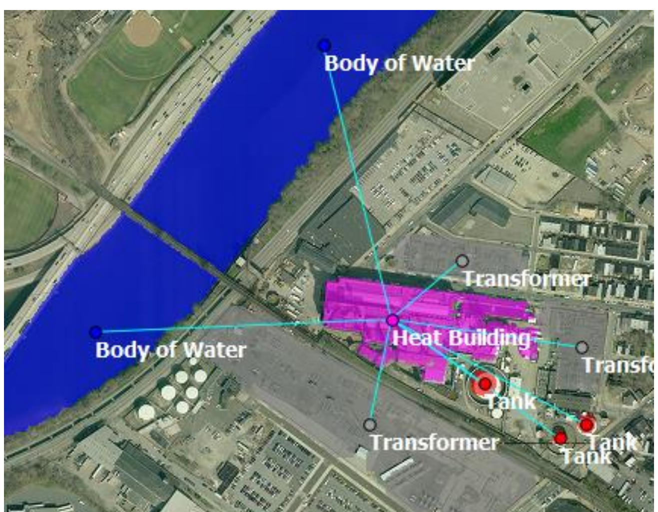
Output:

6	True positives
9	False positives
2	False negatives
(2	Invisible)

Image data provided by the University of Vermont.

Power Plant Results: True Positives





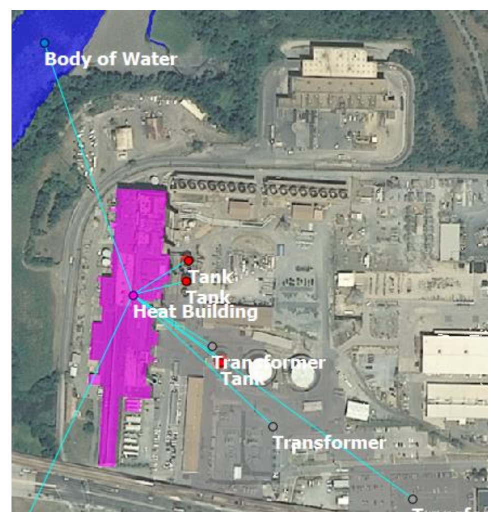


Image data provided by the UVM.

Power Plant Results: False Positives

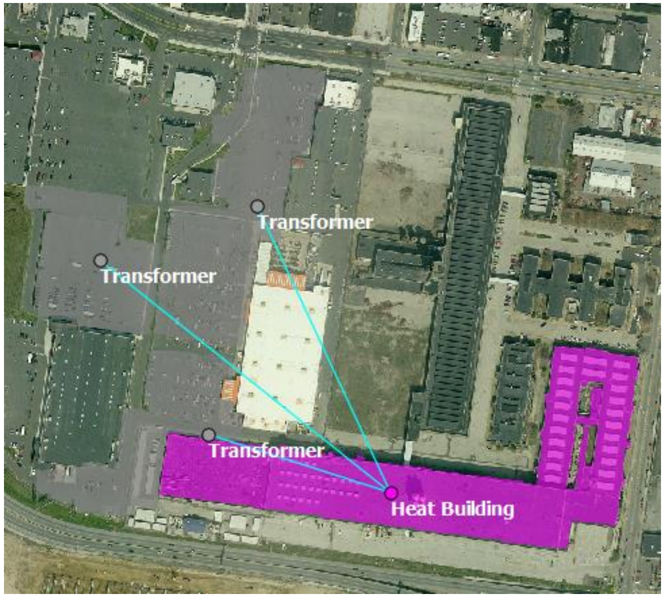
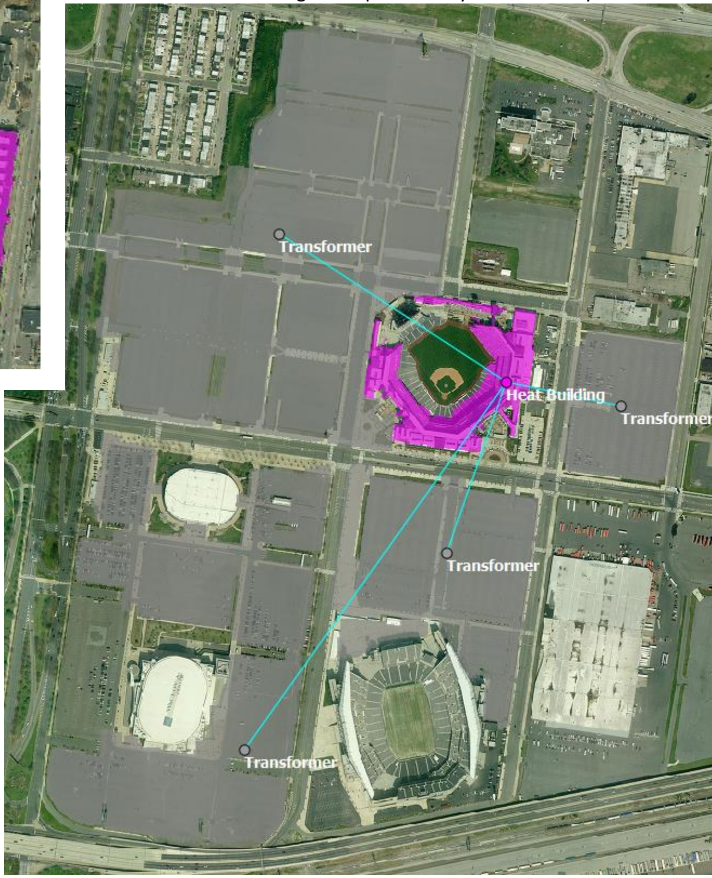
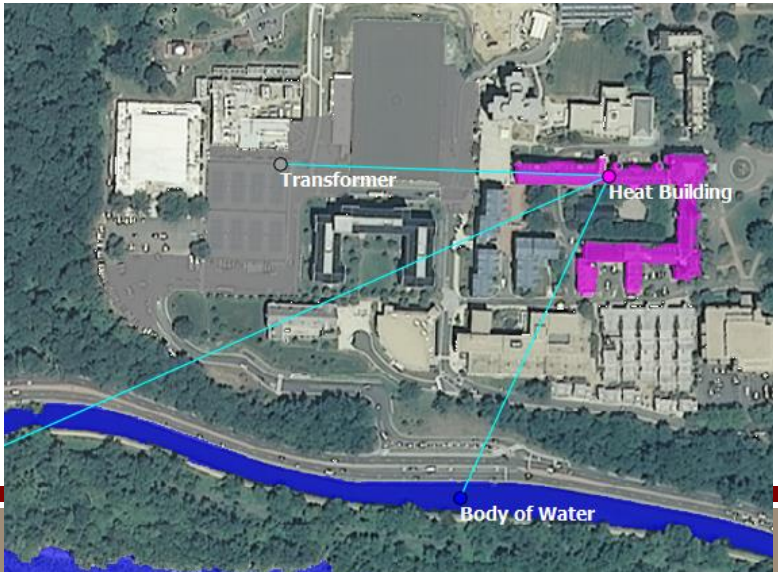


Image data provided by the University of Vermont.





A better transformer filter would eliminate these.

Overview

- Motivation.
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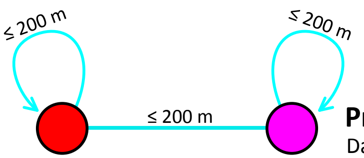
  - Change analysis.
  - New complex.
- Extensions.
- Discussion.

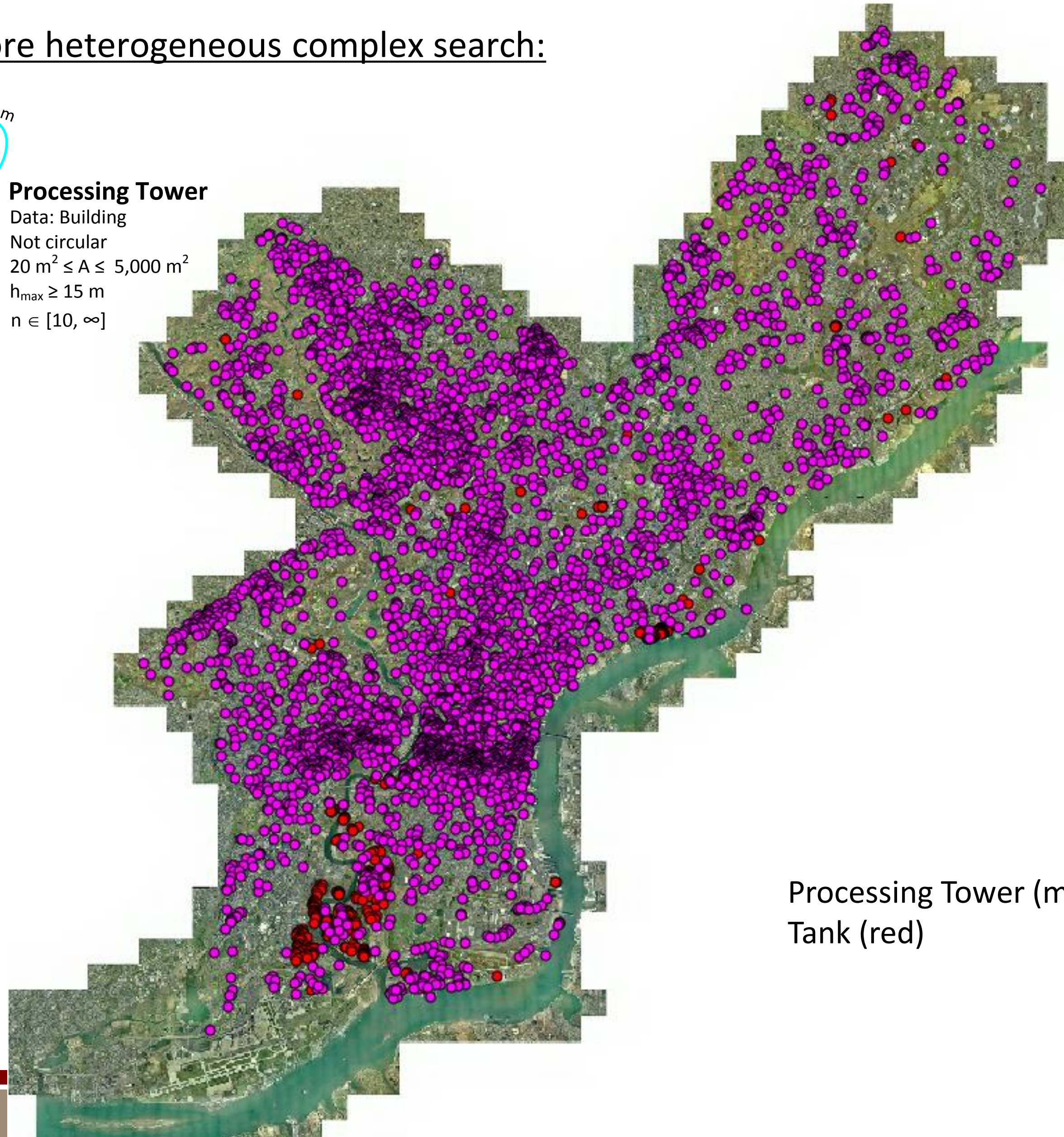
Large Refinery Search

SearchGraph, before heterogeneous complex search:



Tank
Data: Building
Circular
150 m^2 ≤ A ≤ 3,000 m^2
n ∈ [10, ∞]

Processing Tower
Data: Building
Not circular
20 m^2 ≤ A ≤ 5,000 m^2
h_{max} ≥ 15 m
n ∈ [10, ∞]

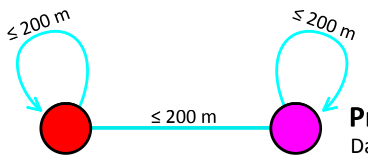


Processing Tower (magenta)	4,909
Tank (red)	371

Image data provided by UVM.

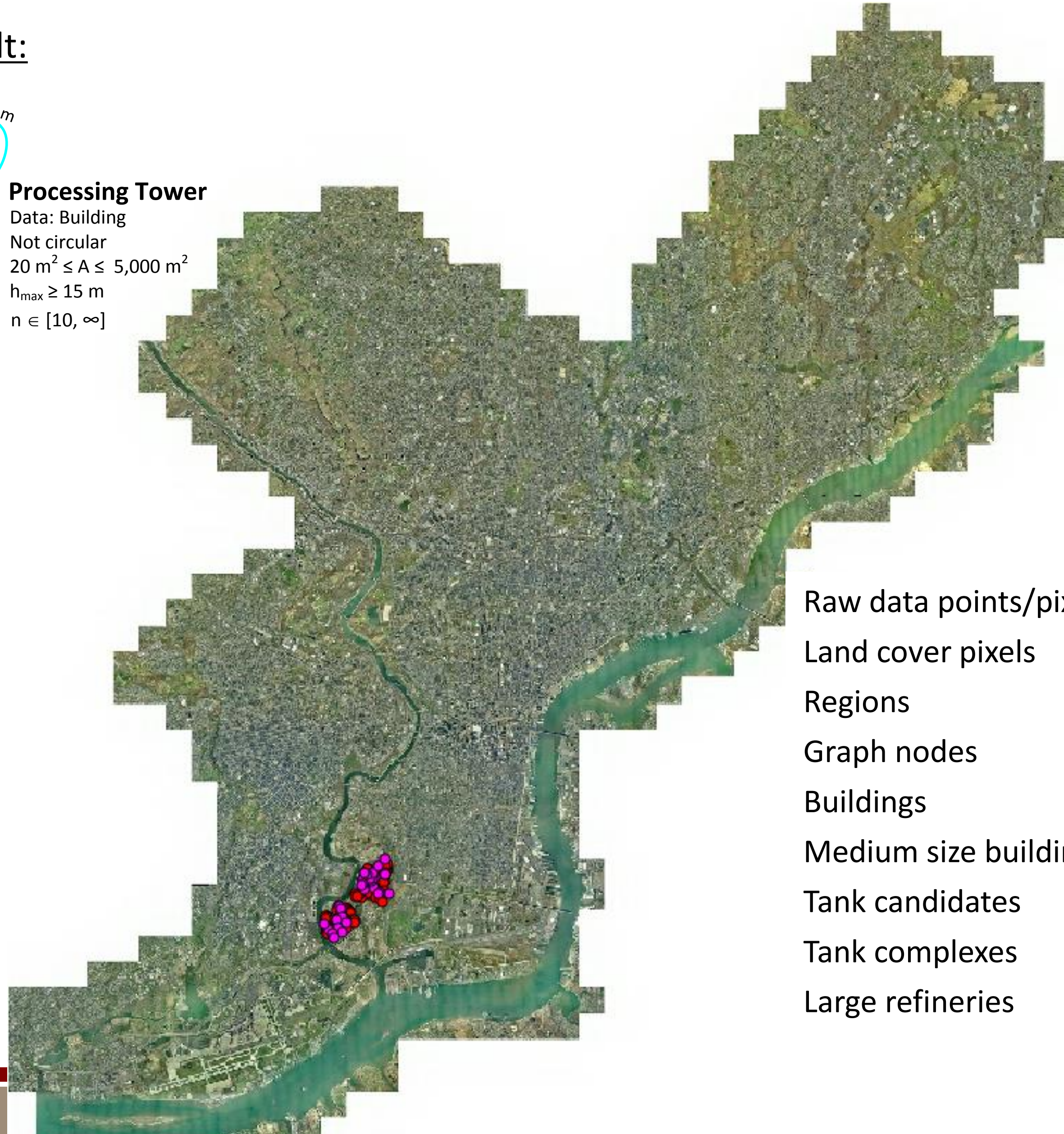
Large Refinery Search

Graph search result:



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

Image data provided by UVM.

Large Refinery Search

Refineries found:

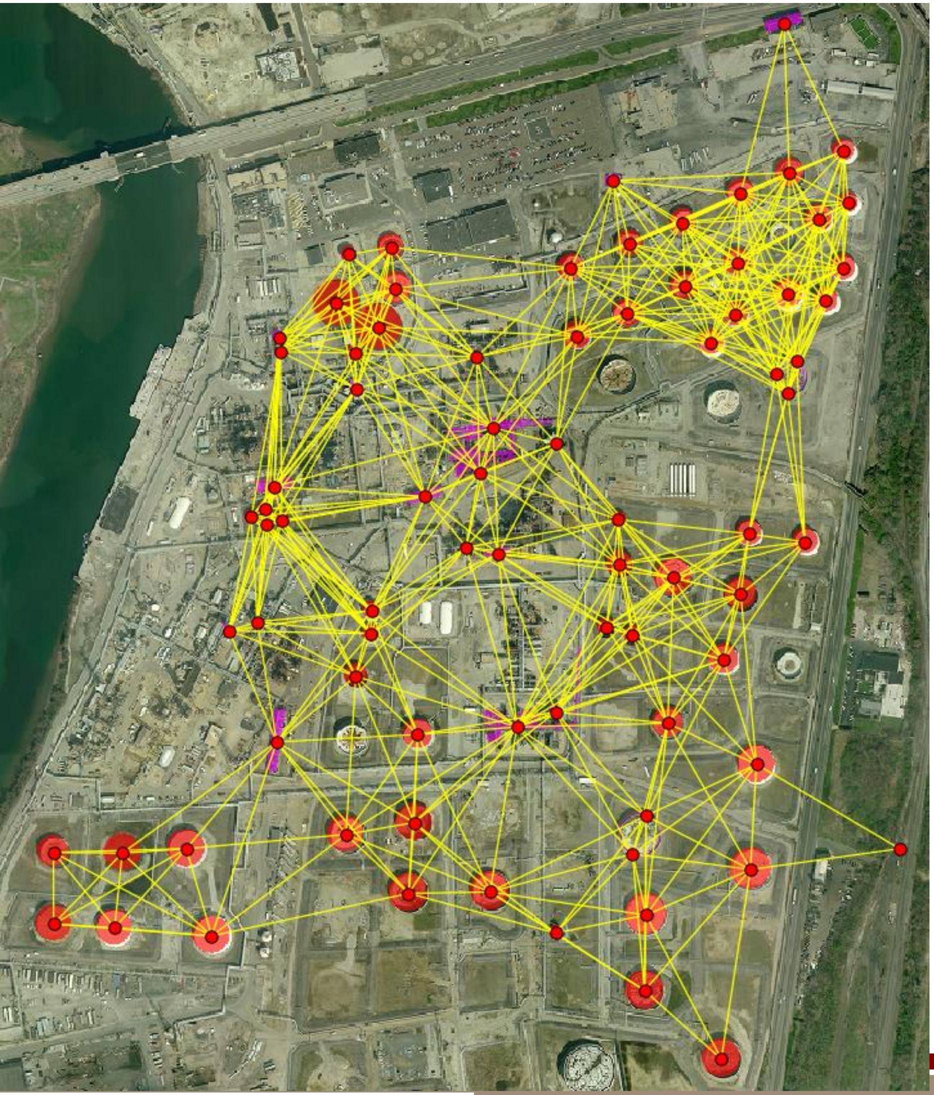


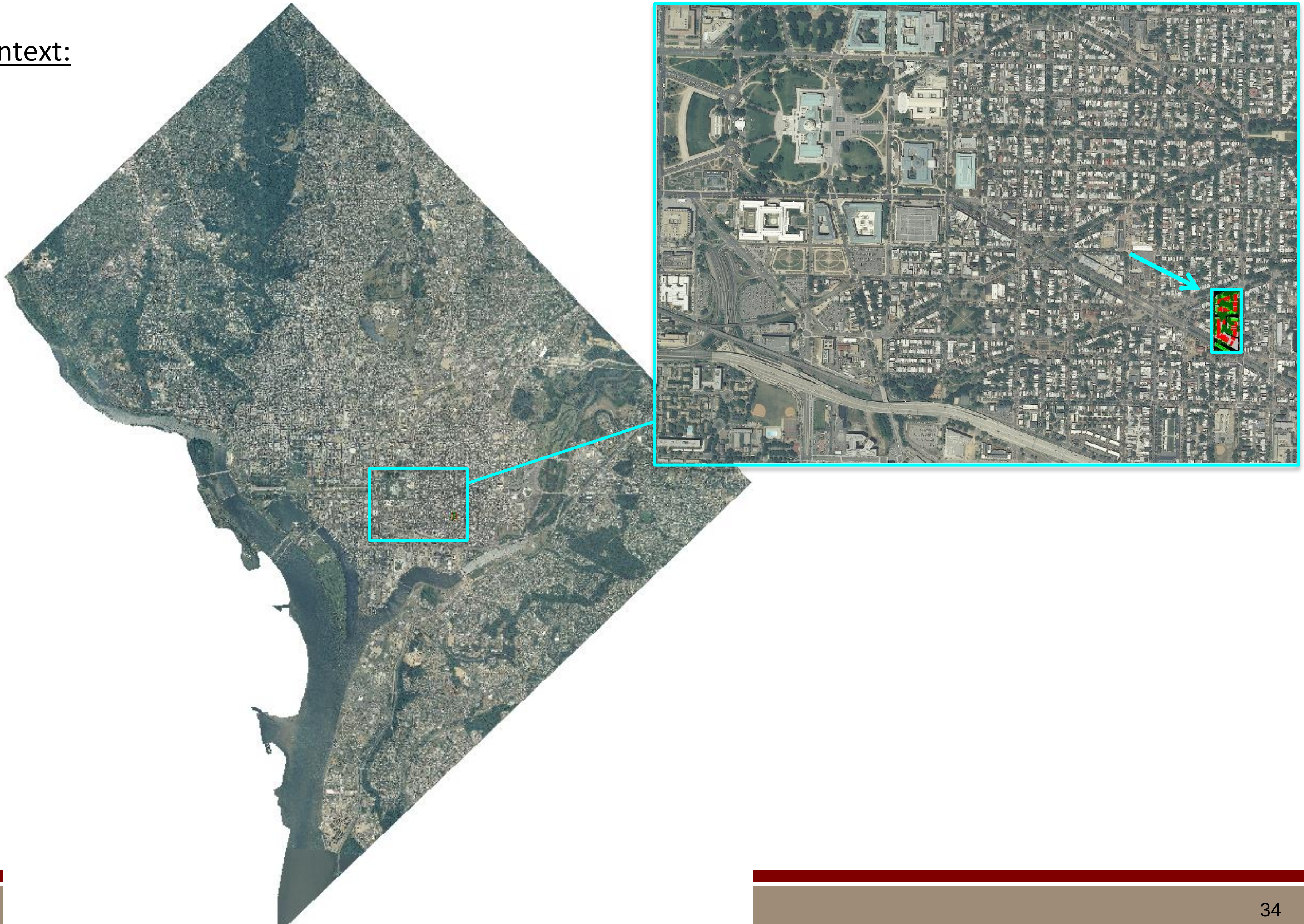
Image data provided by the University of Vermont.

Overview

- Motivation.
- Computation.
- Example Results.
  - Data.
  - Power plants.
  - Refineries.
  - Change analysis.
  - New complex.
- Extensions.
- Discussion.

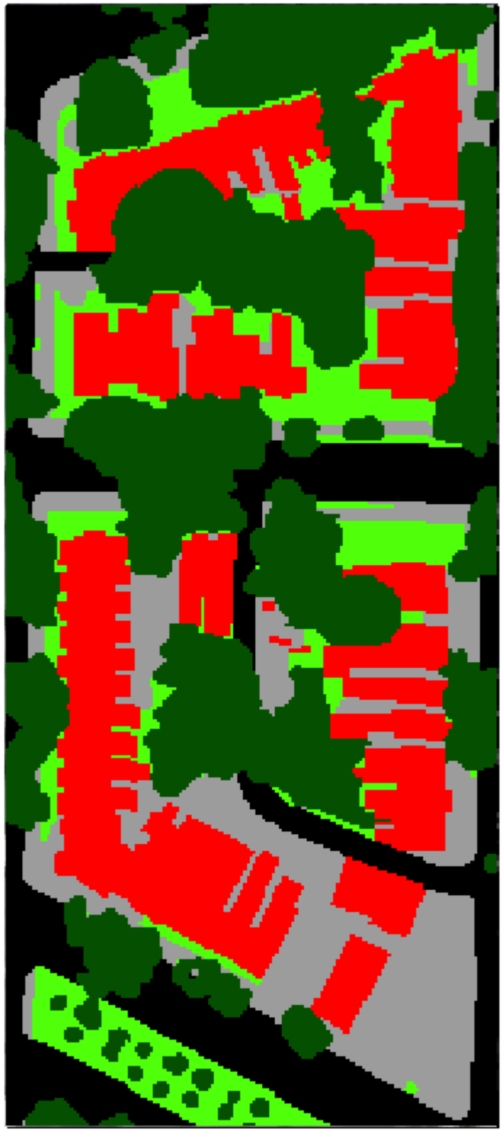
Simple Change Example

Context:



Simple Change Example
(NA-22 Project)

Resulting land cover:



2006

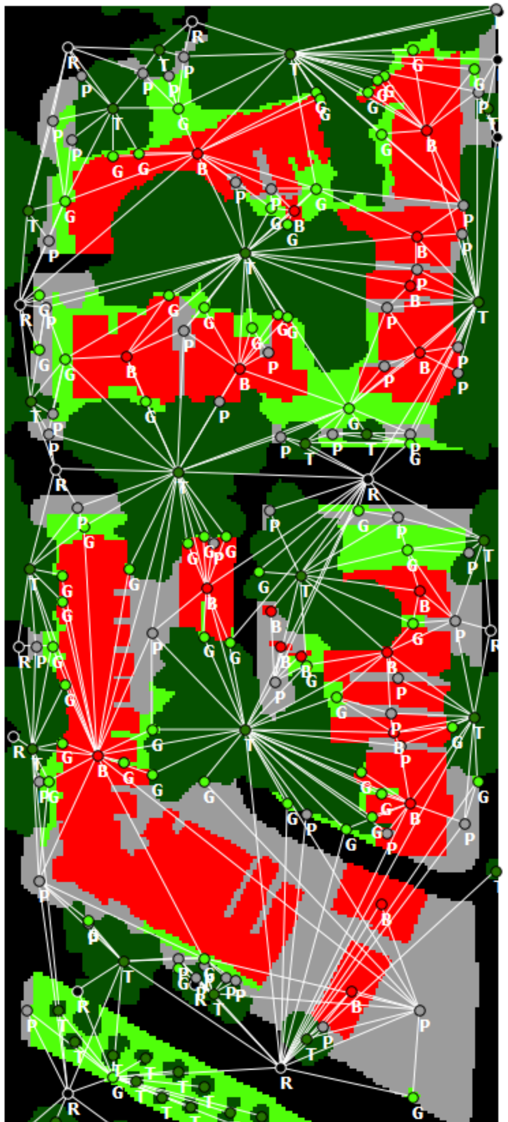
2011

StoredGraph in Three Time Slices

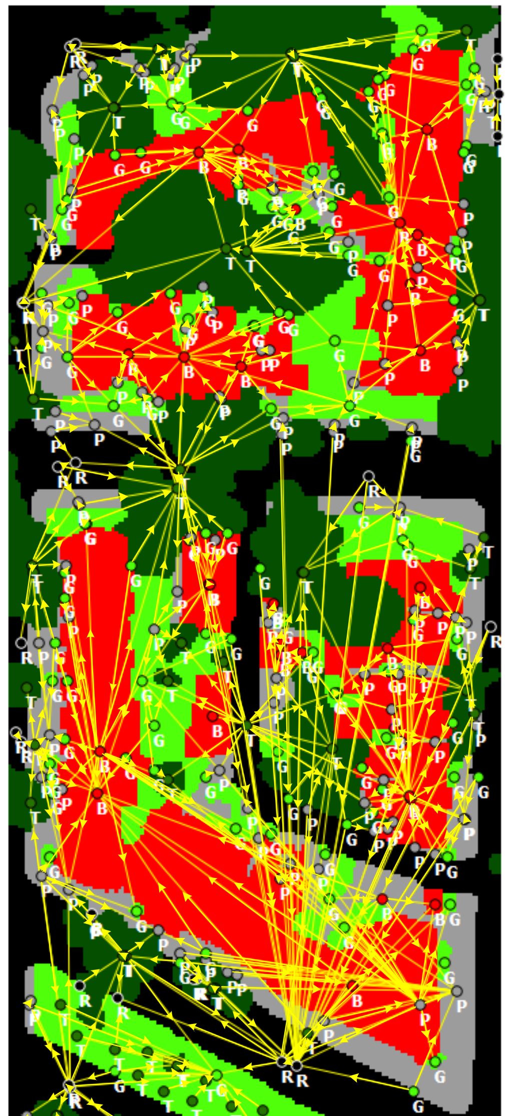
(NA-22 Project)

342 nodes
808 adjacency edges
559 change edges
0 distance edges

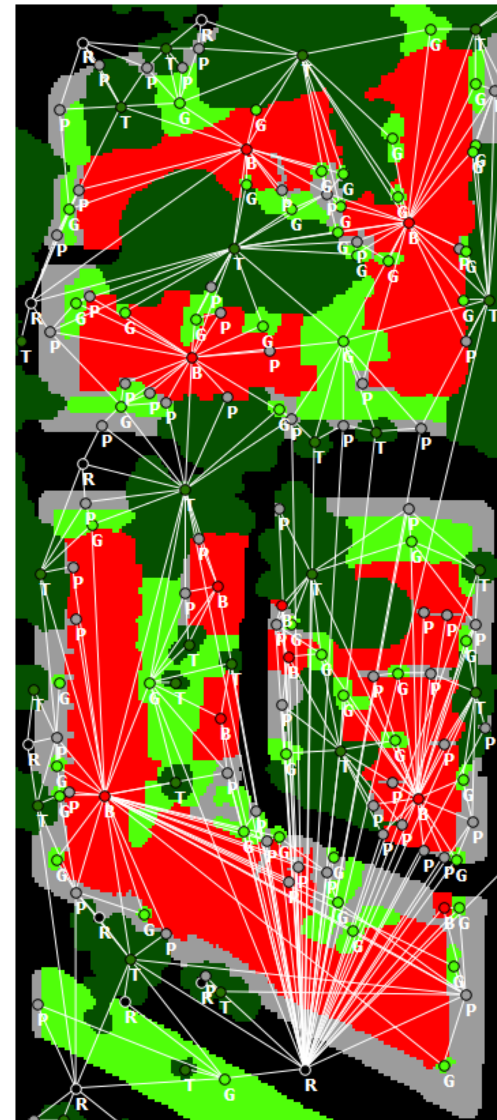
<u>Geospatial-temporal graph:</u>



2006 Adjacency



2006 → 2011 Change

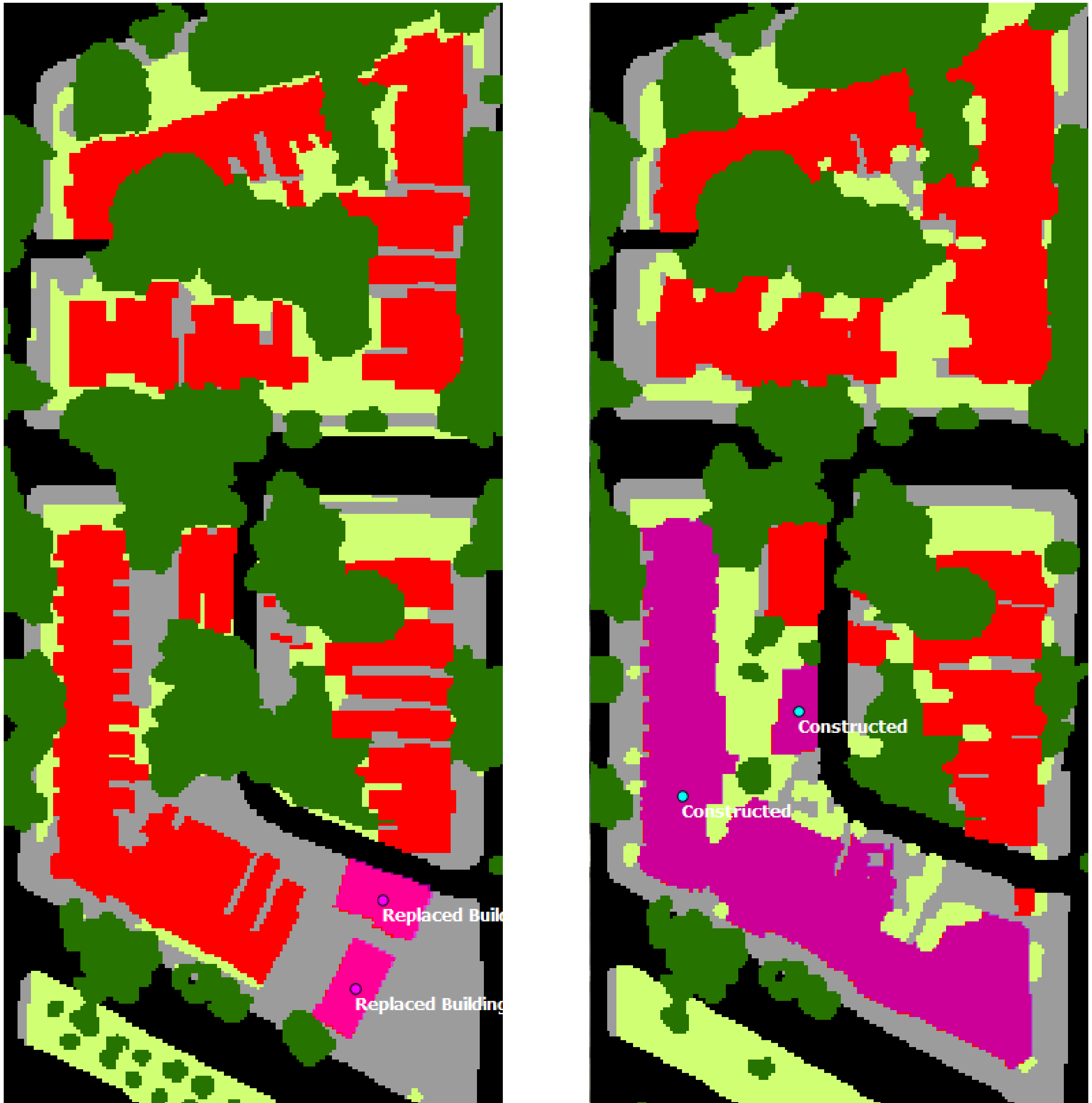


2011 Adjacency

Differentiating Important Change

(NA-22 Project)

Graph-based change analysis results:

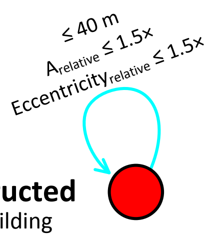


Overview

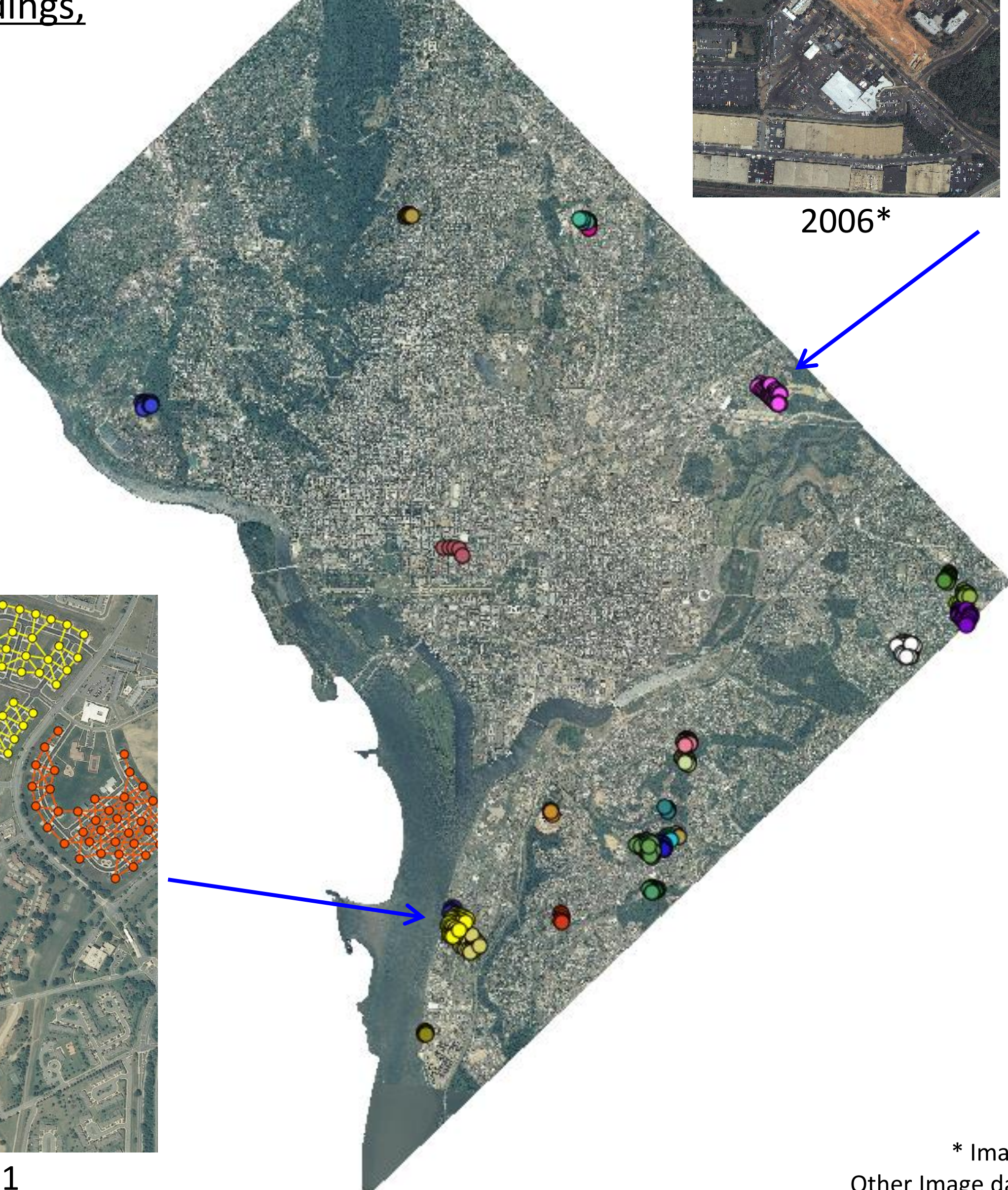
- Motivation.
- Computation.
- Example Results.
  - Data.
  - Power plants.
  - Refineries.
  - Change analysis.
  - New complex.
- Extensions.
- Discussion.

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.
Other Image data provided by UVM.

Overview

- Motivation.
- Computation.
- Example Results.
- Extensions.
- Discussion.

Overview

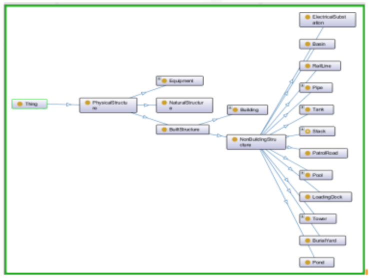
- Motivation.
- Computation.
- Example Results.
- Extensions.
  - Query generation.
  - Semantic refinement: Chunks, path network.
  - Search writeback and re-use.
  - Quality scoring.
  - Activity analysis.
- Discussion.

Approaches to Query Construction

Methods:

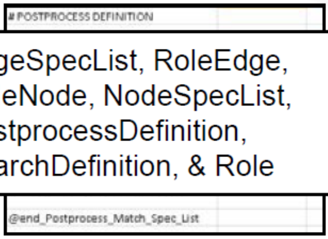
- GeoQuestion csv file code.
- Definition with GUI.
- Query-by-example.
- Generation from ontology.

Ontology to Query Generation



Knowledge Base
Protégé
Craig Blackhart

O2Geo
Perl
Shelly Spearing



EdgeSpecList, RoleEdge, RoleNode, NodeSpecList, PostprocessDefinition, SearchDefinition, & Role

GeoQuestion input (7 CSVs / query)
MS Excel
SNL and LANL

Geospatial Data & posterizations
LLNL & U.Vt

Cyclic Process
Discrete Releases
(e.g., "v1.0.4")

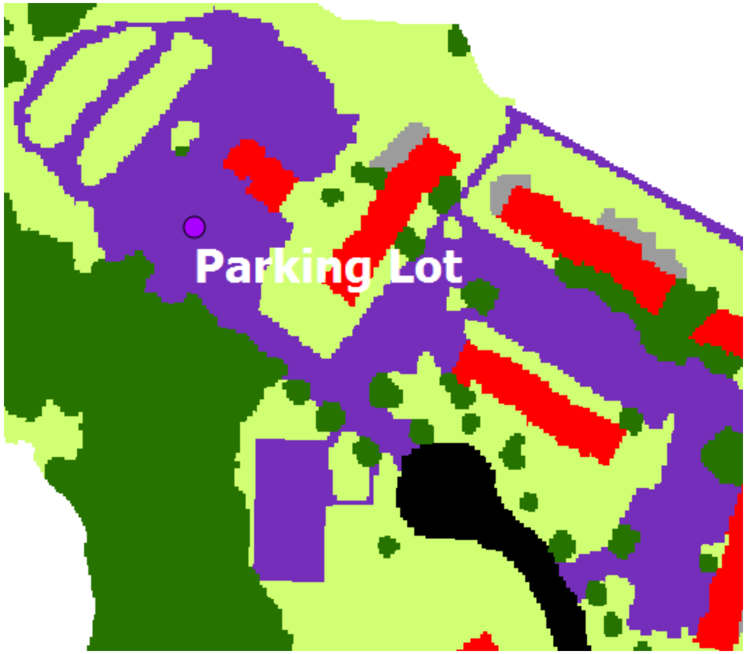
GeoGraphy
Randy Brost, et al.

Search output
List of matches

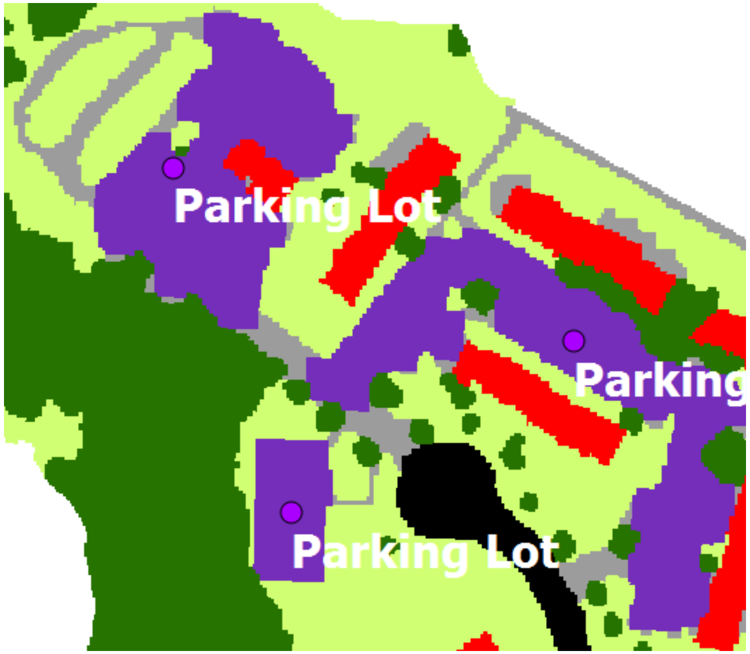
Chunk Operation

Chunking breaks up linked regions into significant sub-regions:

Before Chunking



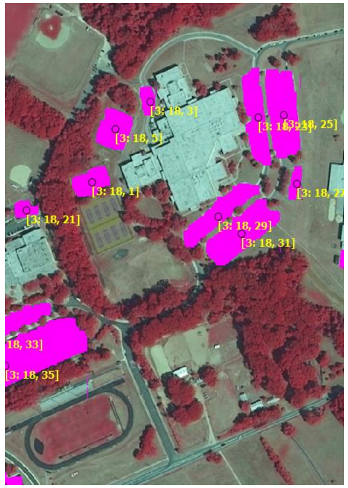
After Chunking



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

Multi-Step GeoSpatial-Temporal Search

Pre-processing:



Search results can be written back to the graph, used as components of later searches.

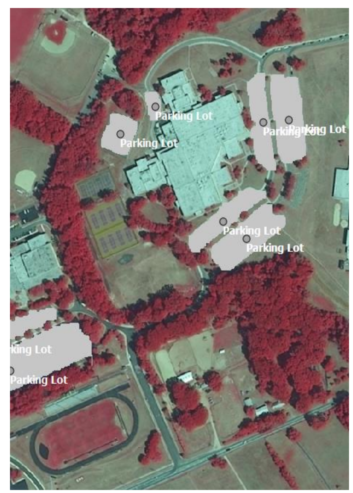
Advantages:

- Batch "micro-searches."
- Smaller, modular queries.
- Log analyst feedback.
- Search re-use.
- Hierarchical semantics.
- Expands scope of possible searches.

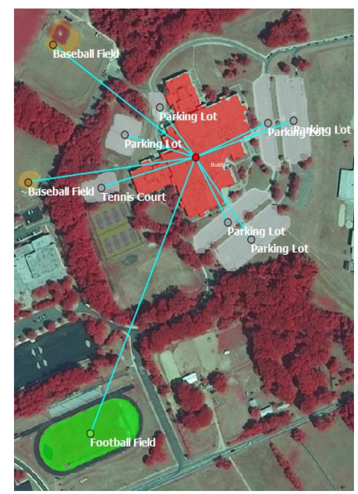
Interactive:

Search 1

Search 2



Search 3

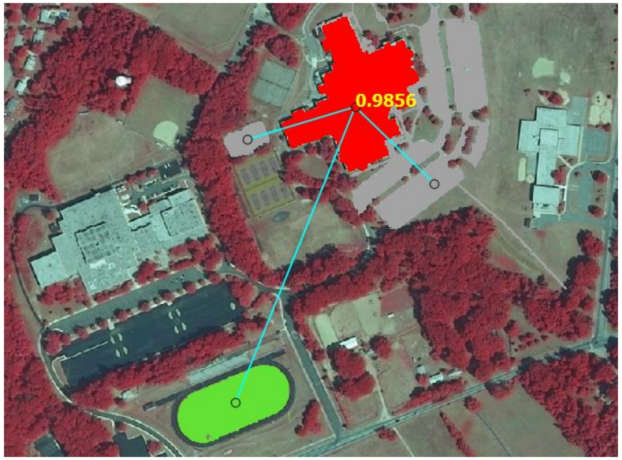


Search 4
(Using results from 1, 2, 3)

Match Quality Scoring

Example output:

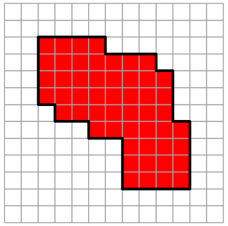
High School



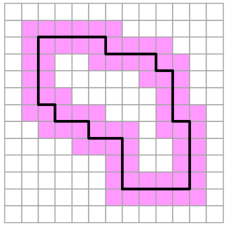
Middle School

Elementary School

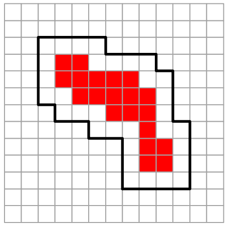
Shape error model:



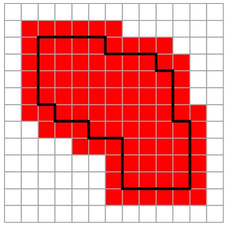
Nominal



Boundary Uncertainty

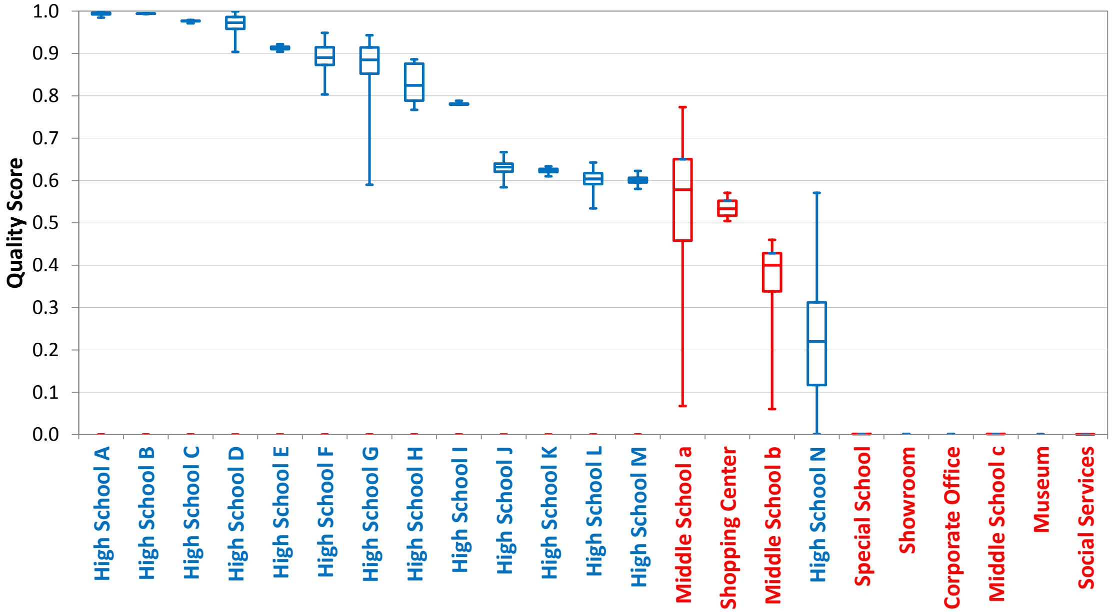


Minimum Area



Maximum Area

Results:



Sandia PANTHER Project

Goal:

Develop tools to aid understanding of voluminous remote sensor data, focusing on activity.

Main pillars:

- SAR image pre-processing (Sensor Exploitation).
- Signature search and trajectory analysis (Discrete Analytics).
- Human factors studies (Human Analytics).

Goal is to increase human analyst understanding and situational awareness.

Notes:

- Kristina Czuchlewski is the Principle Investigator.
- Supported by the Sandia LDRD office as a Grand Challenge – a substantial internal investment.
- PANTHER's signature search approach employs geospatial-temporal semantic graphs to analyze activity patterns.
- The projects are complementary: The NA-22 project focuses on durable objects, while PANTHER focuses on activity.

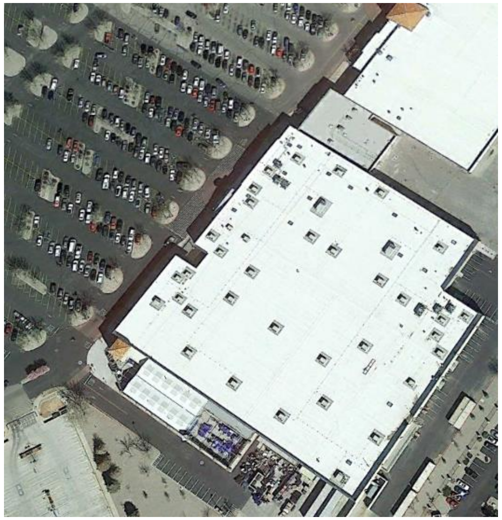
Why Activity Analysis?

Activity can help understand what's happening.

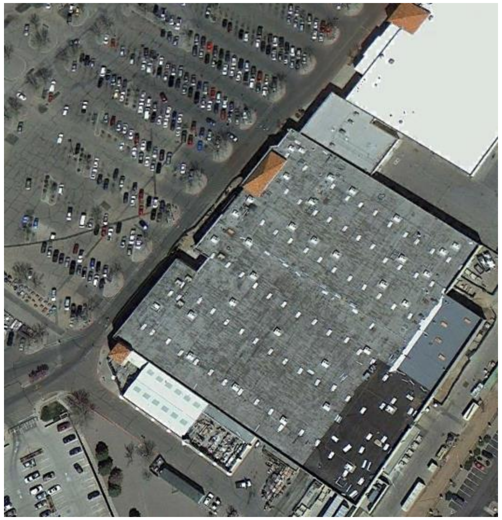
Successful?

On Sunday:

Successful?

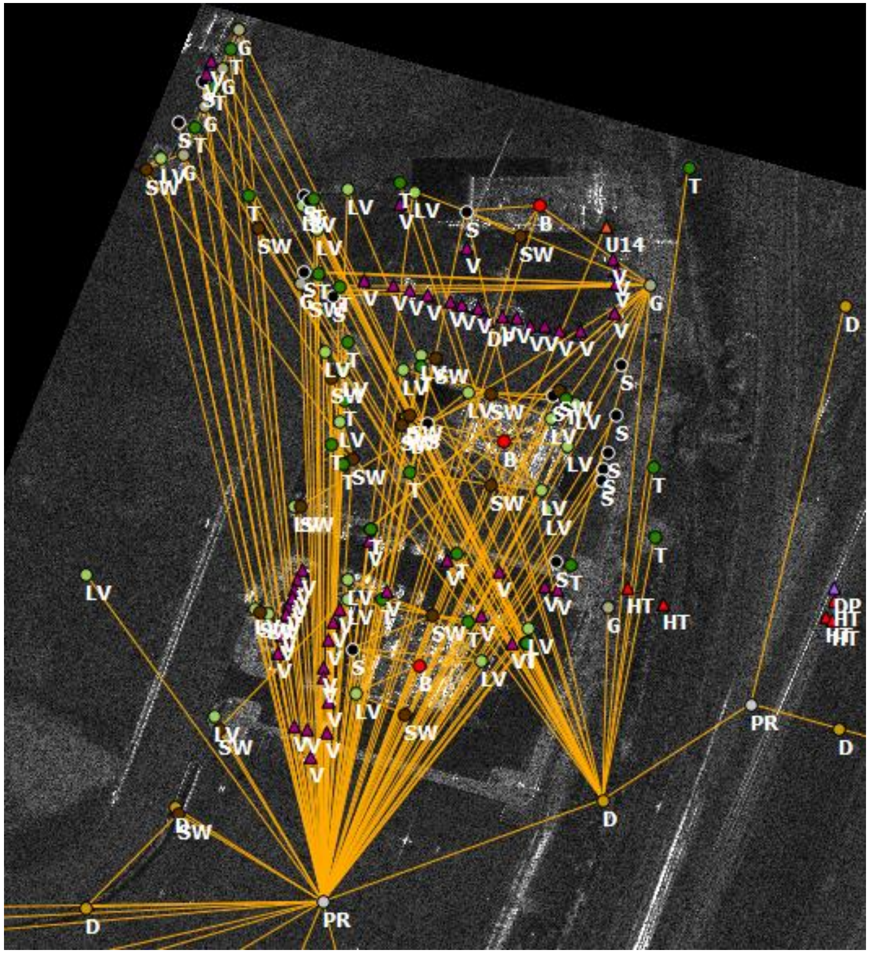


On Sunday:

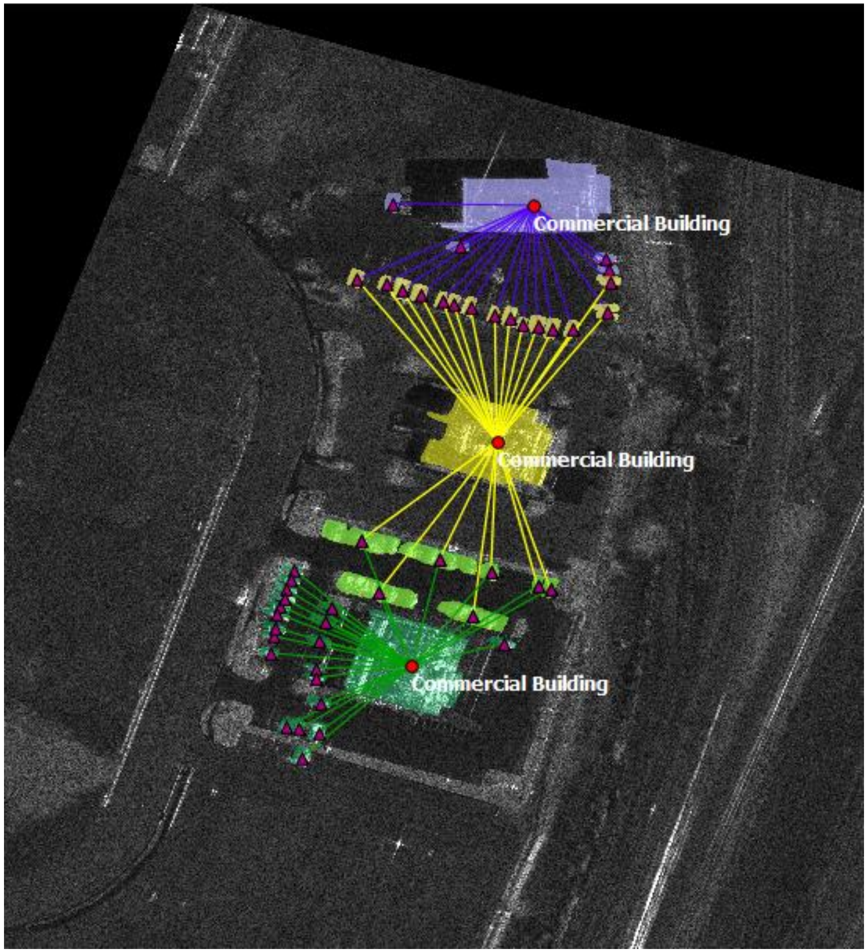


Example: Activity Search

Geospatial-temporal semantic graph:



Match results:



Goal is to find large buildings with substantial nearby vehicle activity, indicating a possible active business.

Note: Based on hand-annotated primitive features.

Overview

- Motivation.
- Computation.
- Example Results.
- Extensions.
- Discussion.

Overview

- Motivation.
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- Example Results.
- Extensions.
- Discussion.
  - → Recap.
  - Application.
  - Evaluation.
  - Data supply.

Recap

We have demonstrated:

- Imagery + LiDAR + GIS ⇒ Land cover [O'Neil-Dunne 2012].
- Sequence ⇒ Geospatial-temporal graph.
- Spatial search: power plants, refineries, high schools…
- Spatial-temporal search: change, construction complexes…
- Over a wide area (2,067 km^2, 135 billion pixels, 3.6 million graph nodes).
- Multi-modality.

We have NOT shown:

- Continent-scale robust image supply and pre-processing.
- Recognition scope.
- Complex temporal analysis.
- Open issues:
  Multiple hypotheses, match ambiguity, scale.

[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.

Overview

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Searching for a Site of Interest

- We have seen how this approach can solve a variety of search problems.
- Will it find proliferation sites of interest?
- We conducted a first experiment.

<u>Steps:</u>

1. Research sites, select candidates (LANL).
2. Obtain imagery and LiDAR (LLNL).
3. Image processing to find land cover (LLNL).
4. Construct geospatial-temporal graph (SNL).
5. Construct ontology, generate query (LANL).
6. Use query to search graph (SNL).

This problem motivates an interest in global imagery.

<u>Results:</u>

1. Code found site. ✓'s
2. Code did not find site in wide area where it was absent. ✓'s

Overview

- Motivation.
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  - Recap.
  - Application.
  - → Evaluation.
  - Data supply.

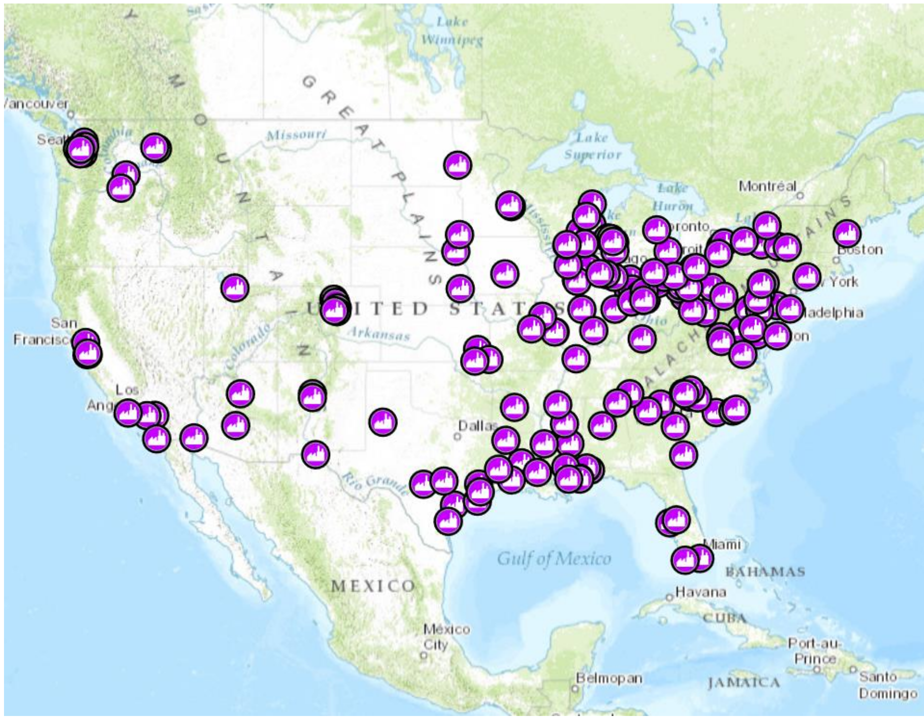
Evaluation

<u>We are developing our assessment strategy:</u>

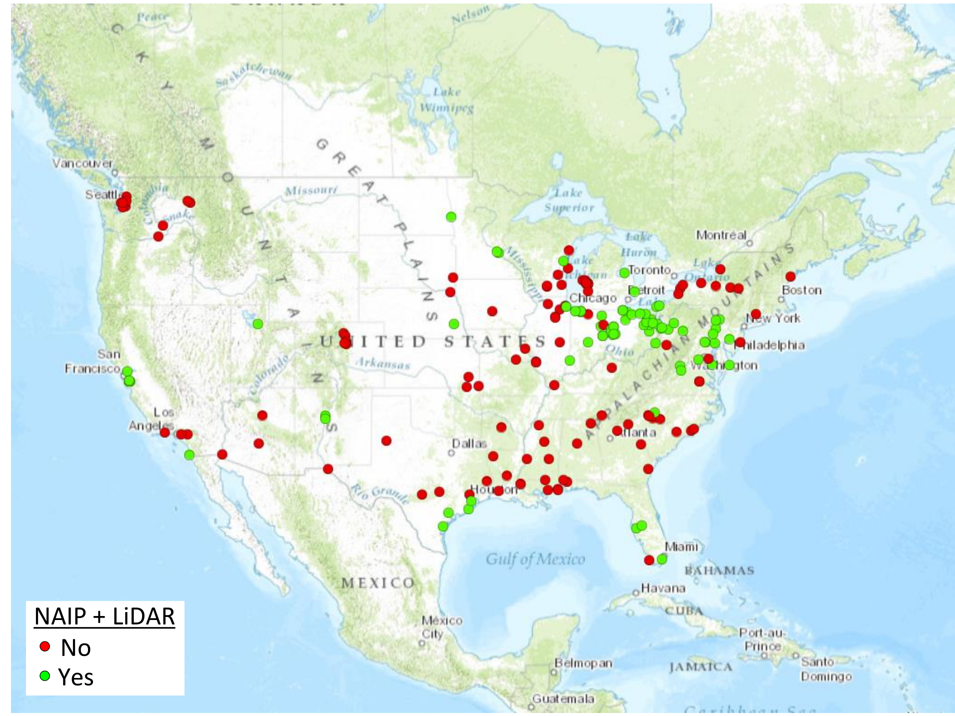
- By *assessment,* we mean essentially verification and validation (V&V).
  - Verification – “Are we building the thing right?”
  - Validation – “Are we building the right thing?”
- In research and development (R&D), requirements and metrics for evaluation evolve as the needs of stakeholders become clearer.
- Thus our strategy:
  1. Define algorithm requirements.
  2. Define metrics that quantify how well requirements are met.
  3. Evaluate performance wrt requirements.
  4. Determine if requirements or metrics require revision.
  5. Repeat until further changes are insignificant.
- Two phases:
  - A. Components: Image processing, ontology, graph search engine.
  - B. End-to-end: Probability of detection, false alarm rate, confidence levels.

UVM Analysis of Benchmark Sites

All sites:



80 locations with both NAIP and LiDAR:



We are aiming for a single rule set that will solve all these sites.

Maps provided by Jarlath O'Neil-Dunne (UVM).

Overview

- Motivation.
- Computation.
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  - Data supply.

A Possible Data Supply Pipeline

1. Wide-area collect.
2. Orthorectification.
3. Atmospheric correction.
4. 3d stereo.
5. Land cover.
6. (Count cars.)
7. Store, setup provenance metadata.
8. Graph construction, change analysis.
9. Micro-search, with writeback.
10. RSS feed of changes of interest.
11. Ready for user interface.

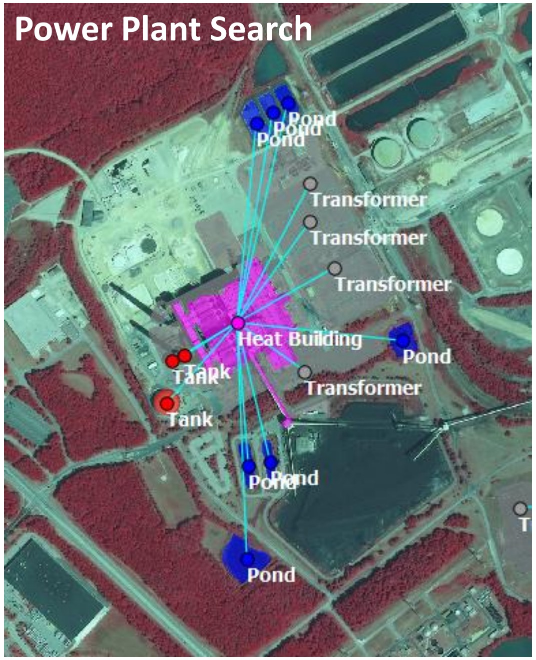
Questions:

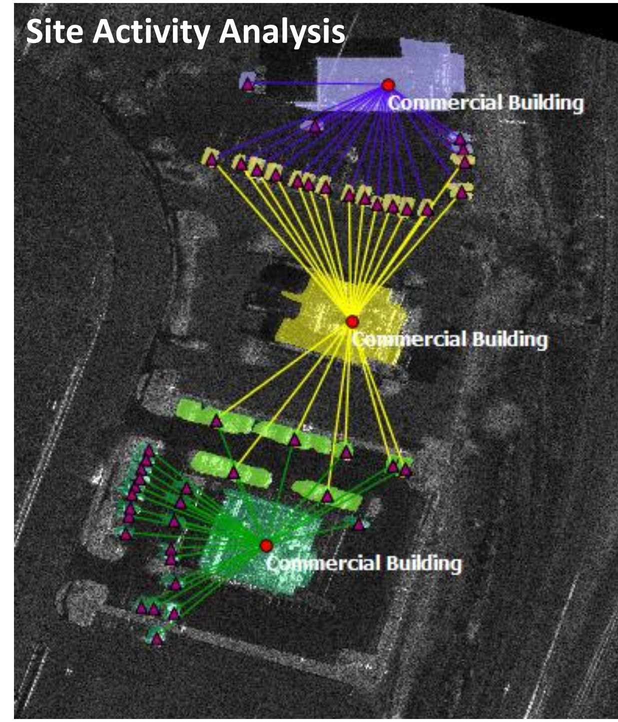
- Feasible? Automatic? Reliable? World-wide?
- Are you thinking something different?

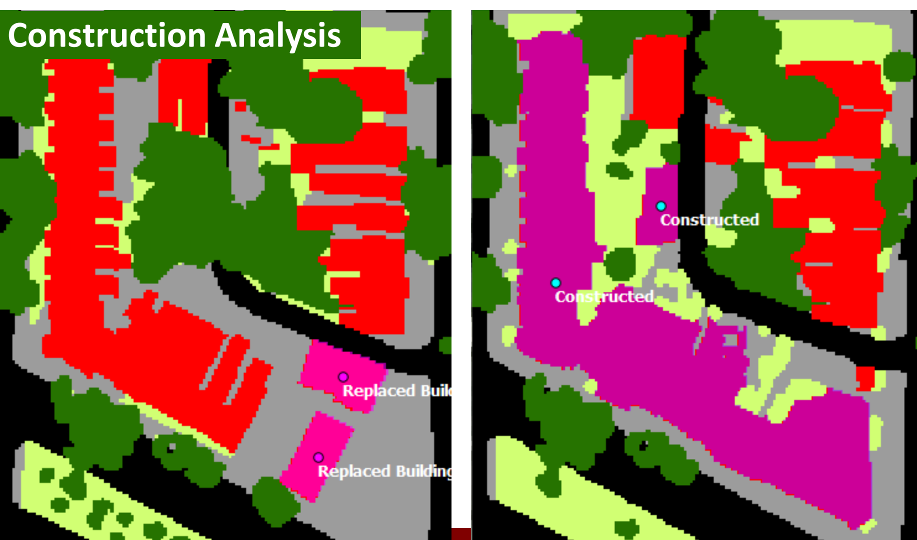
We're very interested in your thoughts!

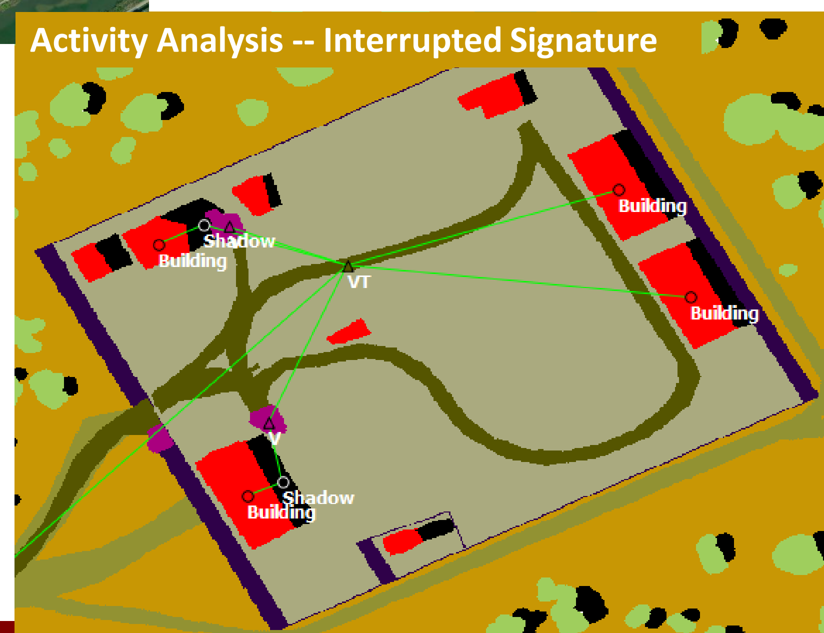
BACKUP SLIDES

Diversity of Problems









All of these were solved by the same code.

Some image data UVM.

Search Run Times

As of January 2014:

	Tri-Region*		Washington, DC**
Power Plant	15.0 hours	New Complex	1.7 hours
Refinery	8.9 hours		

Reported in BigSpatial paper (Nov 2014).

May 2014:

	Anne Arundel***
High School	11.6 hours

Improvement:

March 2015:

	Anne Arundel***
High School (batch)	0.1 hour
High School (interactive)	0.03 hour (less than 2 minutes)

All times are single-thread, single processor.

These algorithms are well-suited to parallel computation.

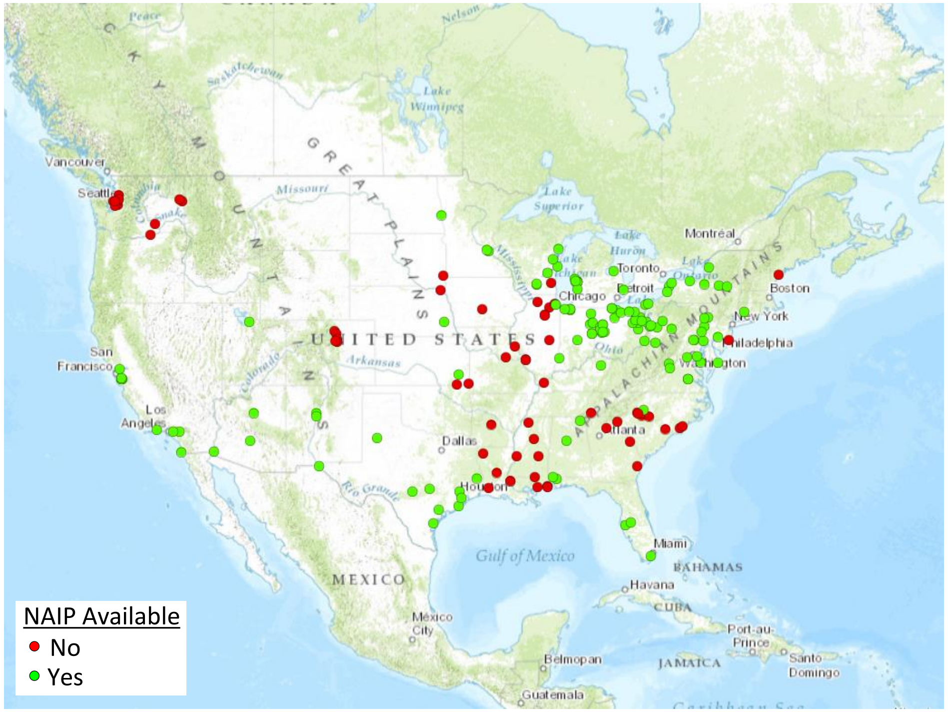
* Tri-Region: 2,067 km^2 area, over 9 billion land cover pixels, 3.5 million features.

** Washington, DC: 177 km^2 area, almost 1 billion land cover pixels, 1.3 million features, two times (2006, 2011).

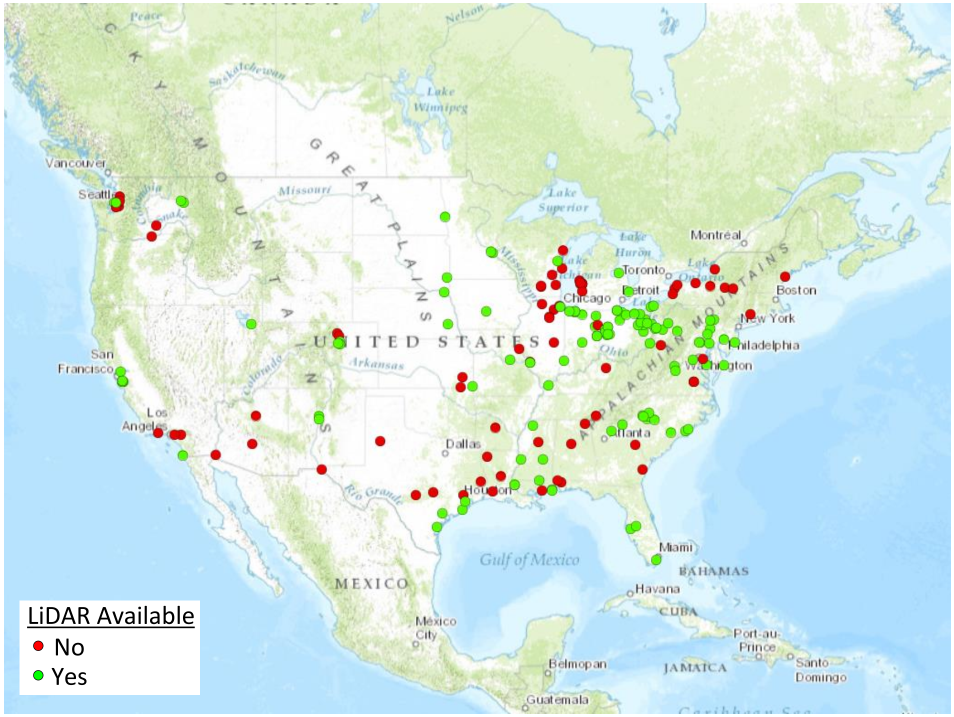
*** Anne Arundel County: 1,523 km^2 area, over 4 billion land cover pixels, 1.2 million features.

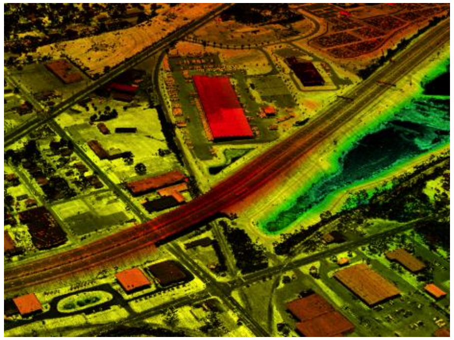
UVM: Survey of Supporting Data

124 locations with RGB+IR:



109 locations with LiDAR:

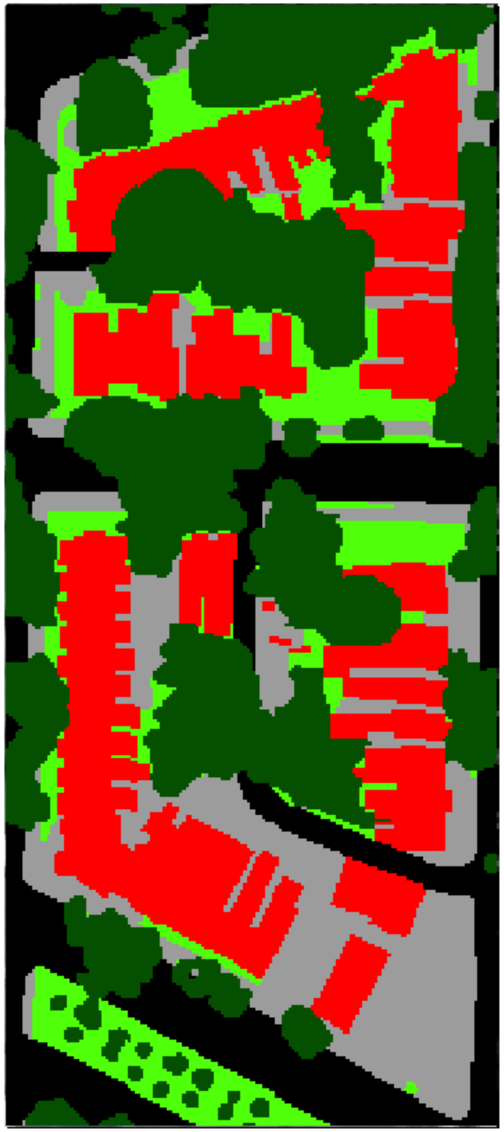




Maps provided by Jarlath O'Neil-Dunne (UVM).

Simple Change Example

Resulting land cover:



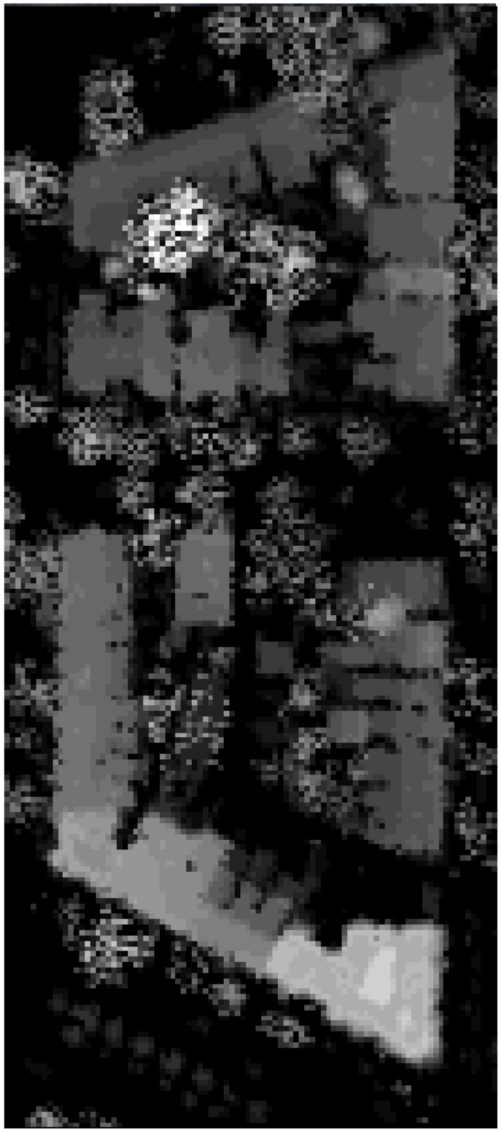
2006

2011

Simple Change Example
(NA-22 Project)

Input data:

2006 Quickbird



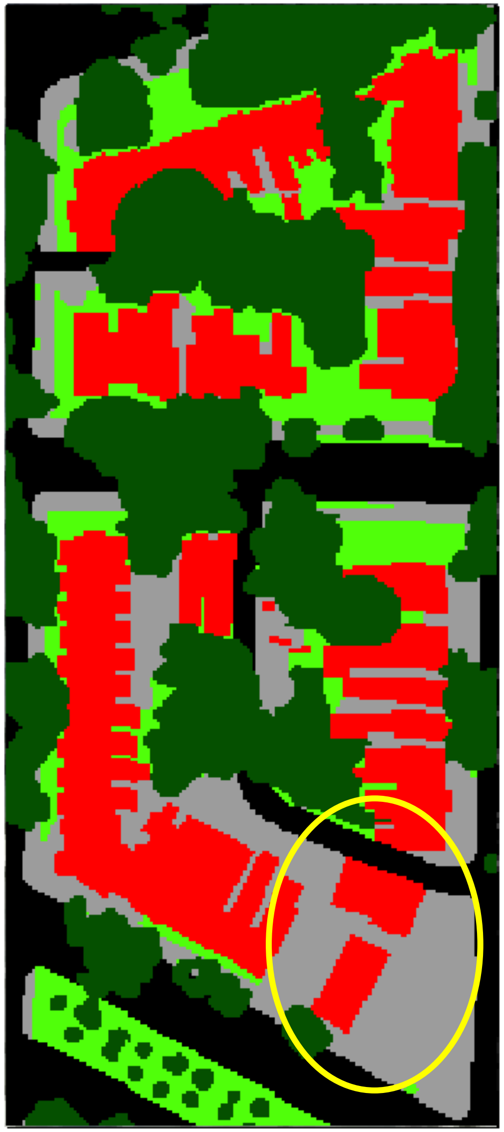
2008 LiDAR

2011 NAIP

Image/Landcover Discrepancy

Input data:

2006 Quickbird



2006

The 2006 land cover shows two previous buildings, but the 2006 image shows these already removed.

Reason:

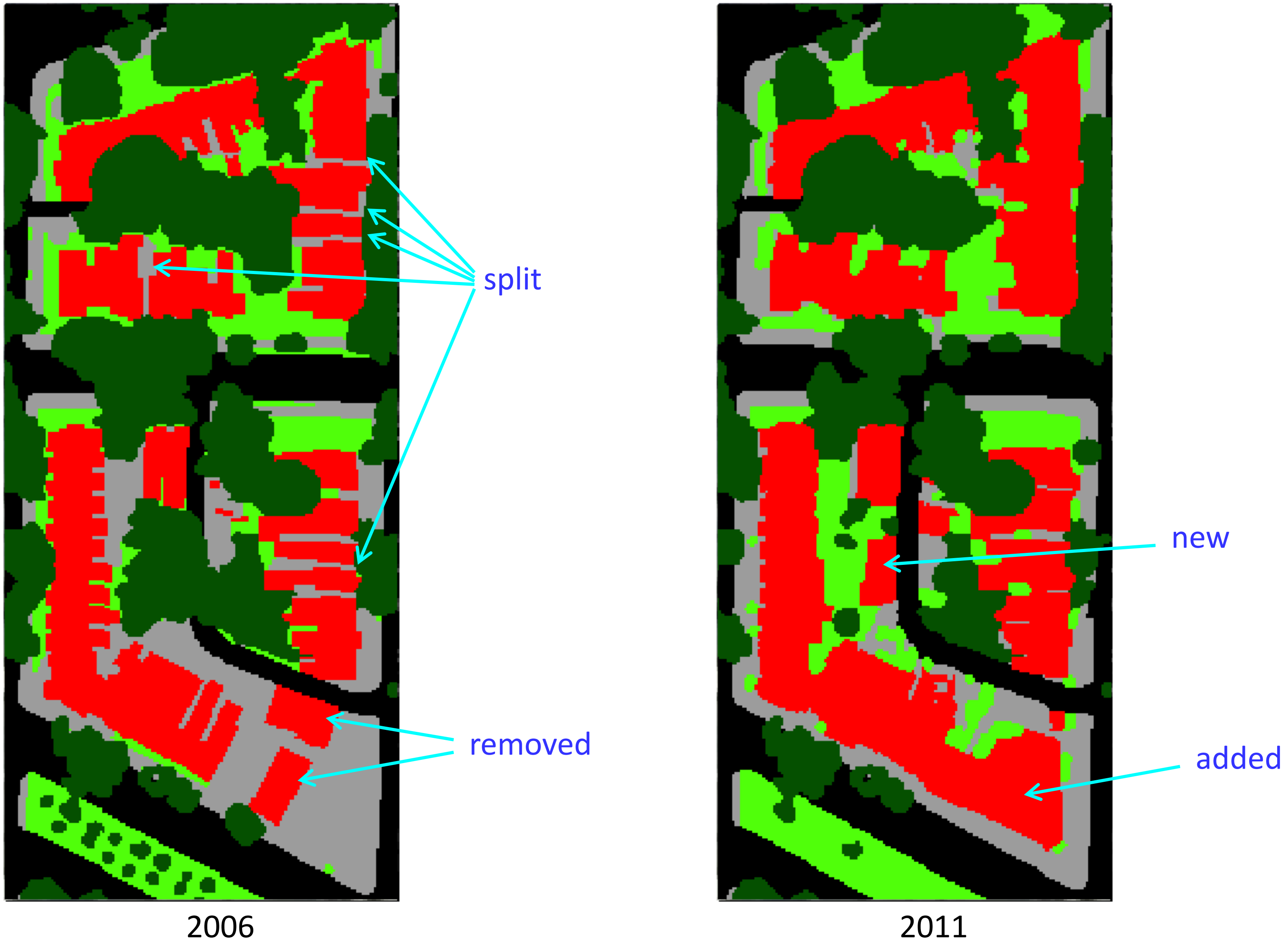
The land cover corresponds to a slightly different time than the 2006 Quickbird image.

Resolution:

We will treat the land cover data as the authority on the state of the world in 2006.

Geometric Change Analysis

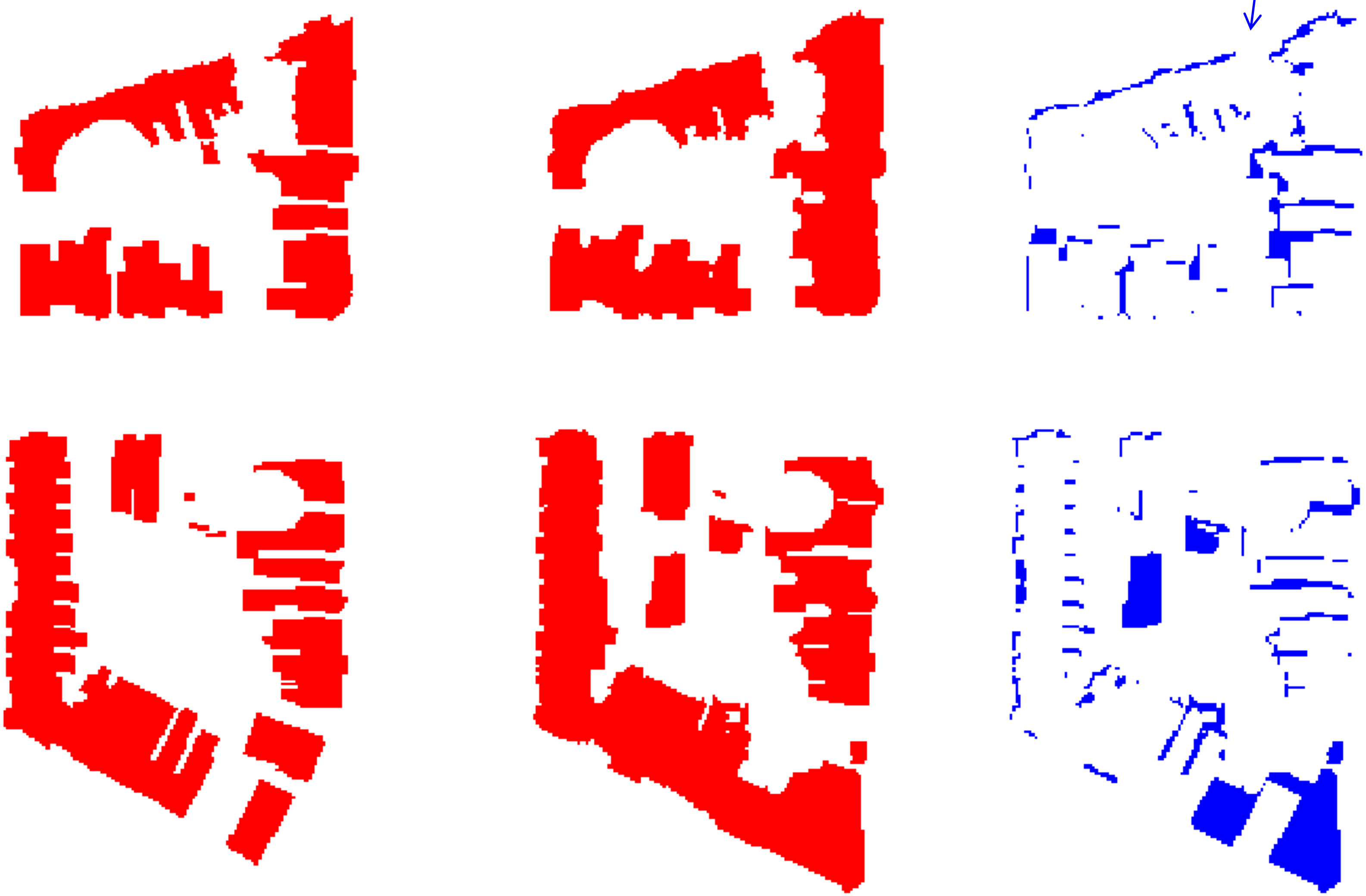
Input land cover:



Geometric Change Analysis

Ghost boundaries result from sensor noise and registration error.

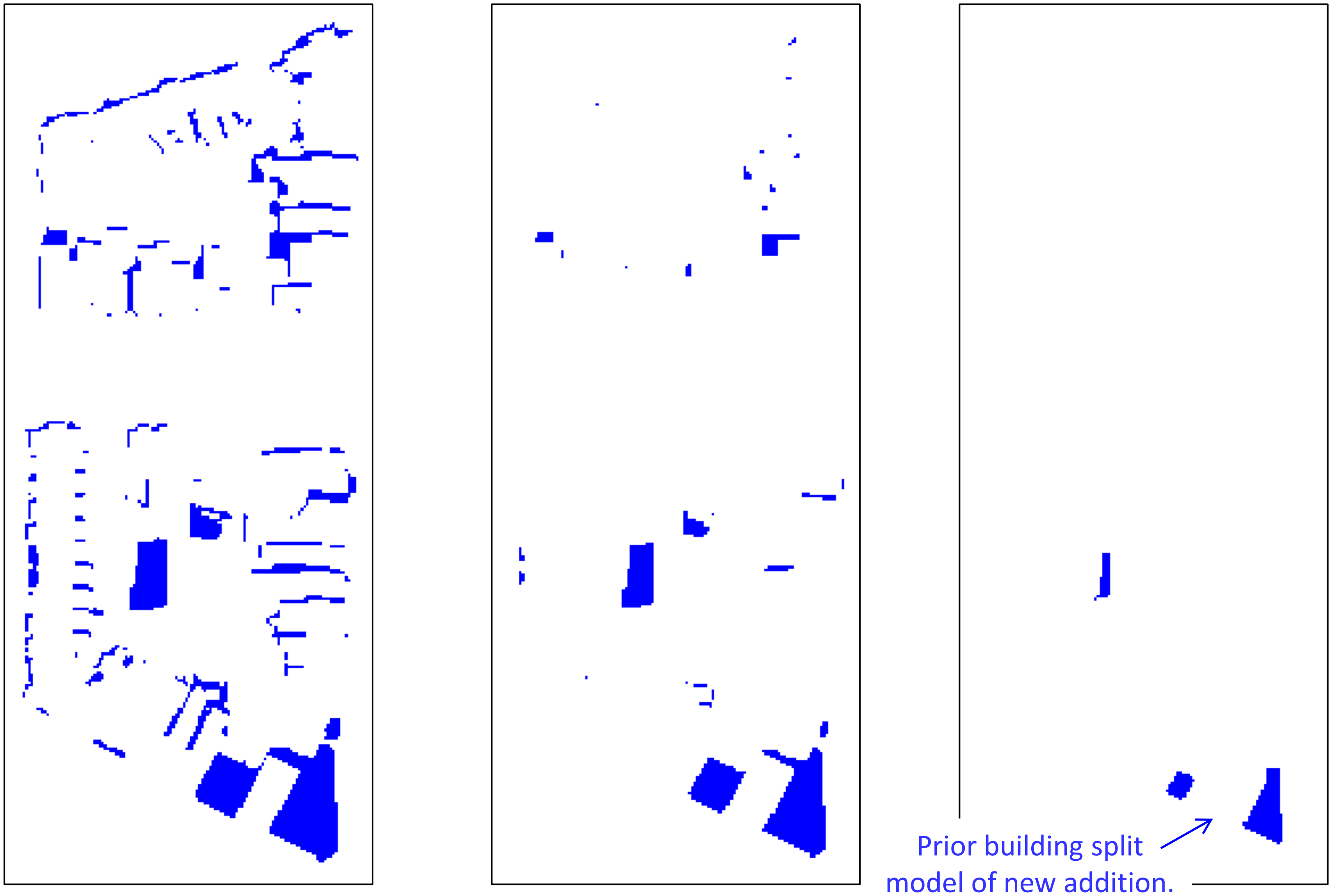
Geometric subtraction:



2006 Buildings | 2011 Buildings | 2011 minus 2006

Geometric Change Analysis

Shrinking to remove ghost boundaries:

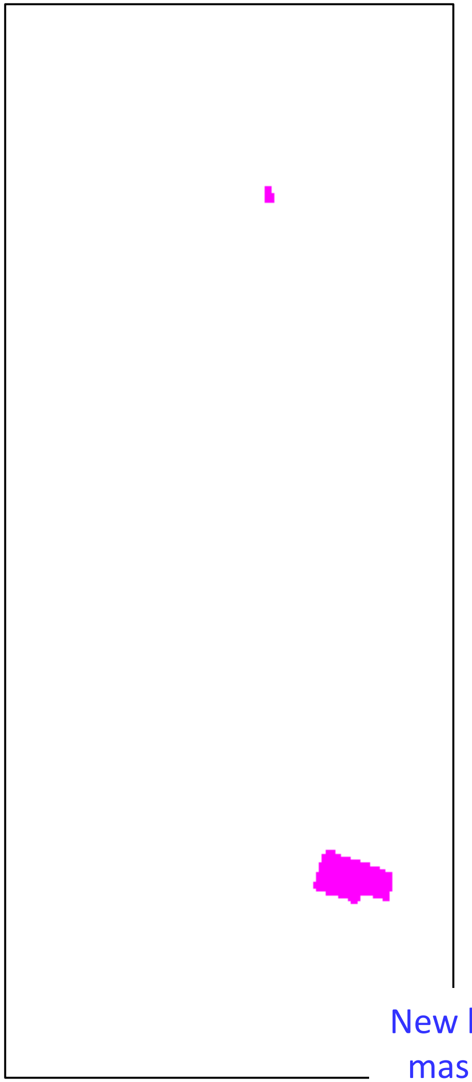


2011 minus 2006 | Shrink 1 Pixel | Shrink 4 Pixels

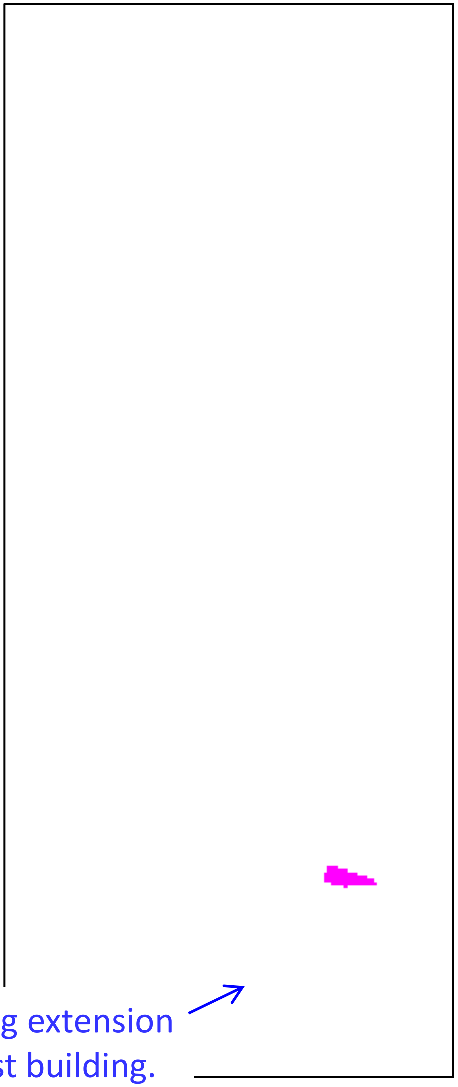
Geometric Change Analysis

Finding lost buildings (old minus new):

2006 minus 2011



Shrink 1 Pixel



New building extension masked lost building.

Shrink 4 Pixels

Geometric Change Analysis Results

Input land cover:

removed

missed this one

2006

Change results do not match full shape.

new

added

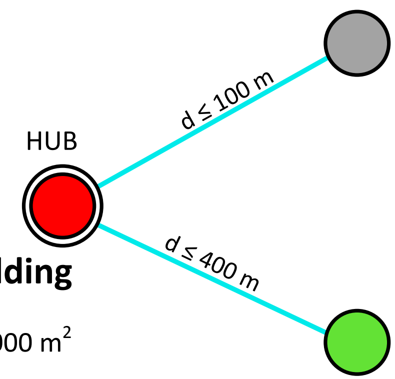
split in two; misses interior change section.

2011

Simple High School Search

<u>Query specification:</u>

A high school is a classroom building with a parking lot and football field.



Parking Lot
Data: Other Paved
Chunk (9 × 9)
$800\ m^2 \le A \le 52{,}000\ m^2$

$n \in [1, \infty]$ (required)
$10{,}000\ m^2 \le sum(Area)$

Classroom Building
Data: Building
$6{,}000\ m^2 \le A \le 35{,}000\ m^2$

Football Field
Data: Grass Shrub
$8{,}700\ m^2 \le A \le 10{,}300\ m^2$
$2.1 \le Eccentricity \le 2.6$
$480\ m \le Perimeter \le 800\ m$

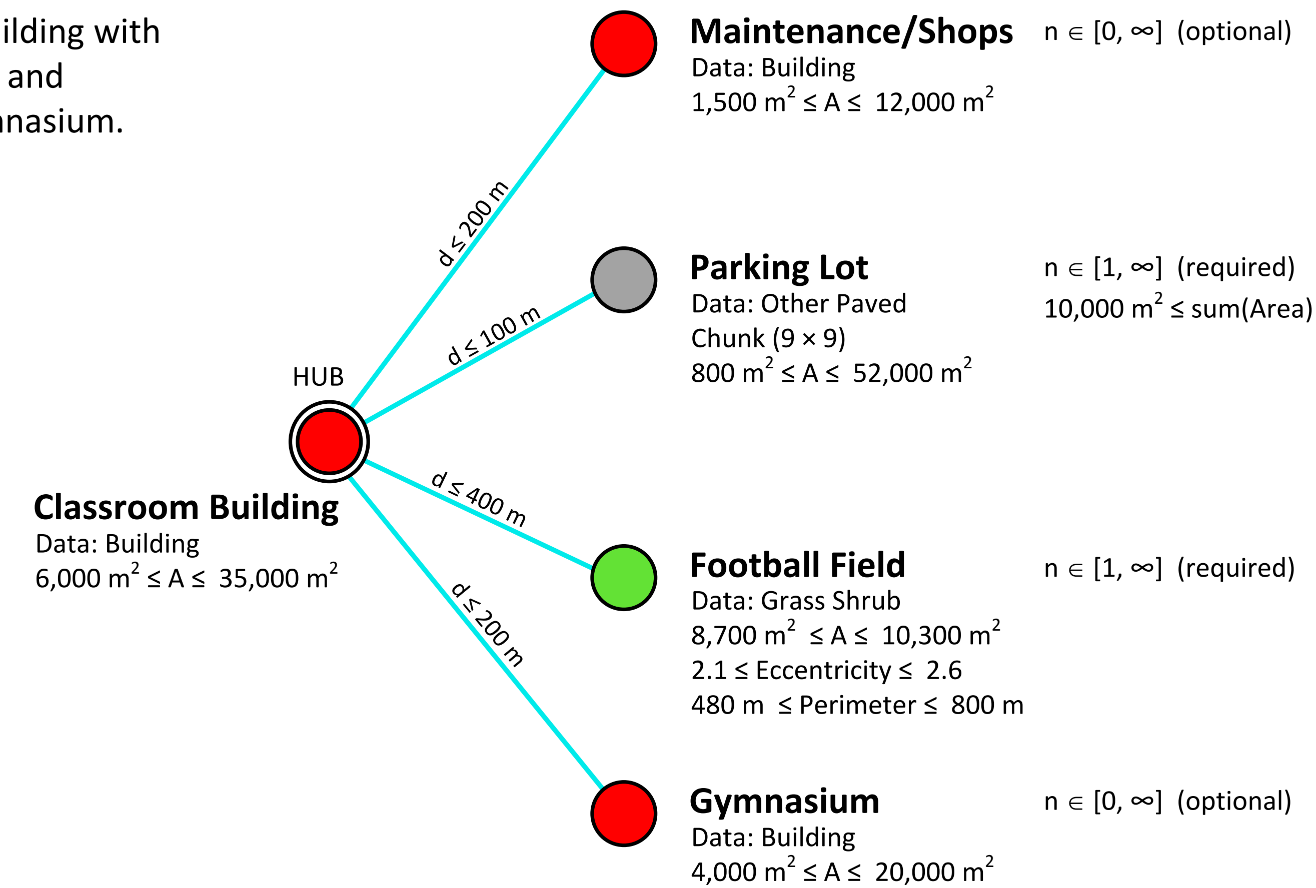
$n \in [1, \infty]$ (required)

Northeast High School

Simple High School, Extended

<u>Query specification:</u>

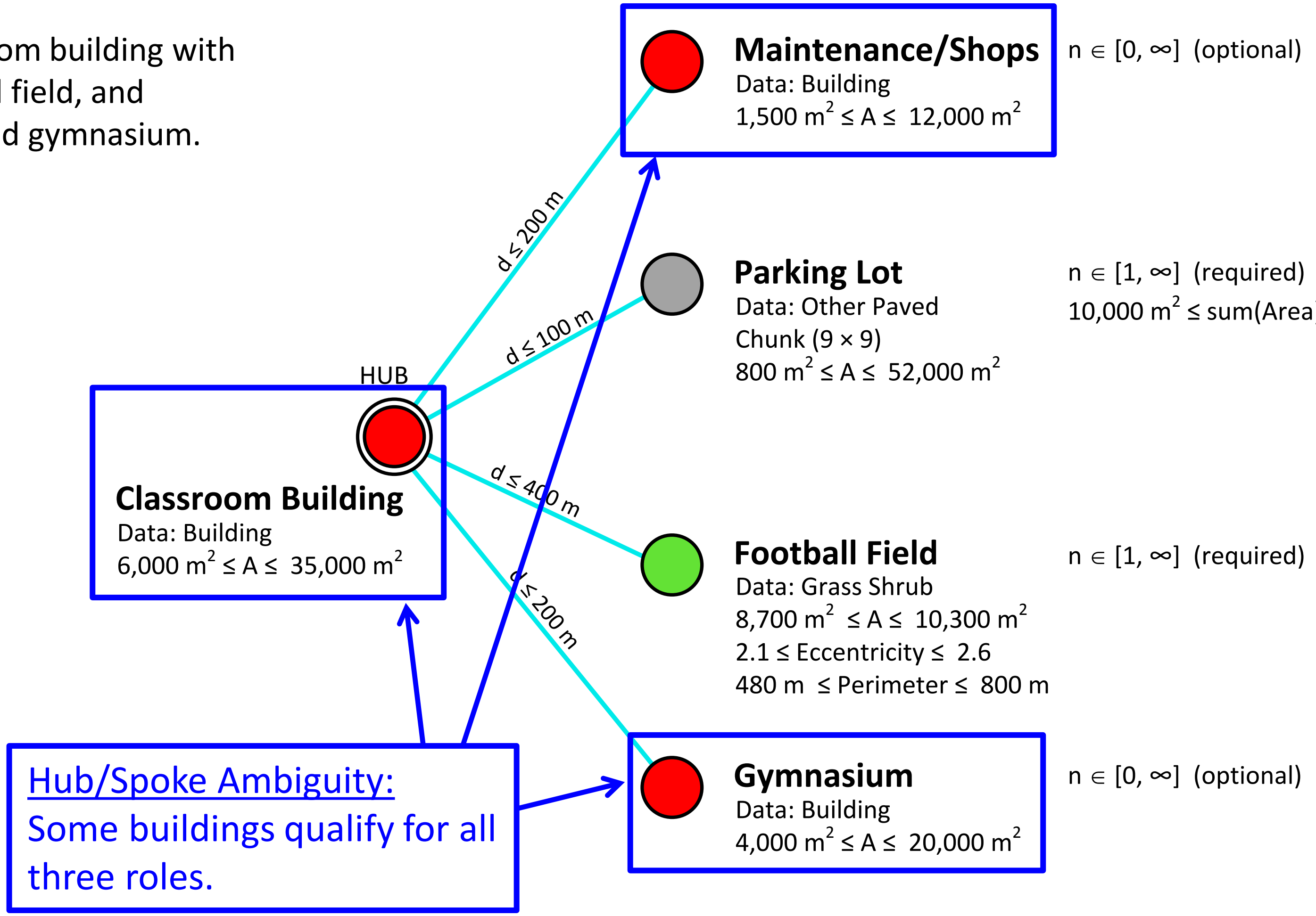
A high school is a classroom building with a parking lot and football field, and optional maintenance and gymnasium.



Hub/Spoke Ambiguity

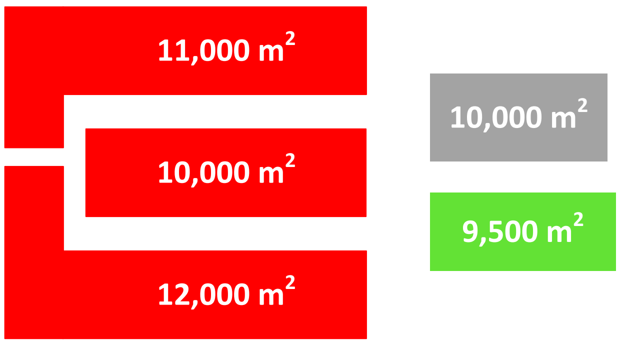
<u>Query specification:</u>

A high school is a classroom building with a parking lot and football field, and optional maintenance and gymnasium.

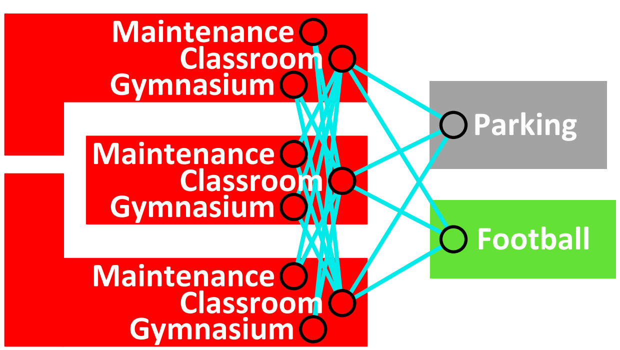


Ambiguous Hub/Spoke Search Result

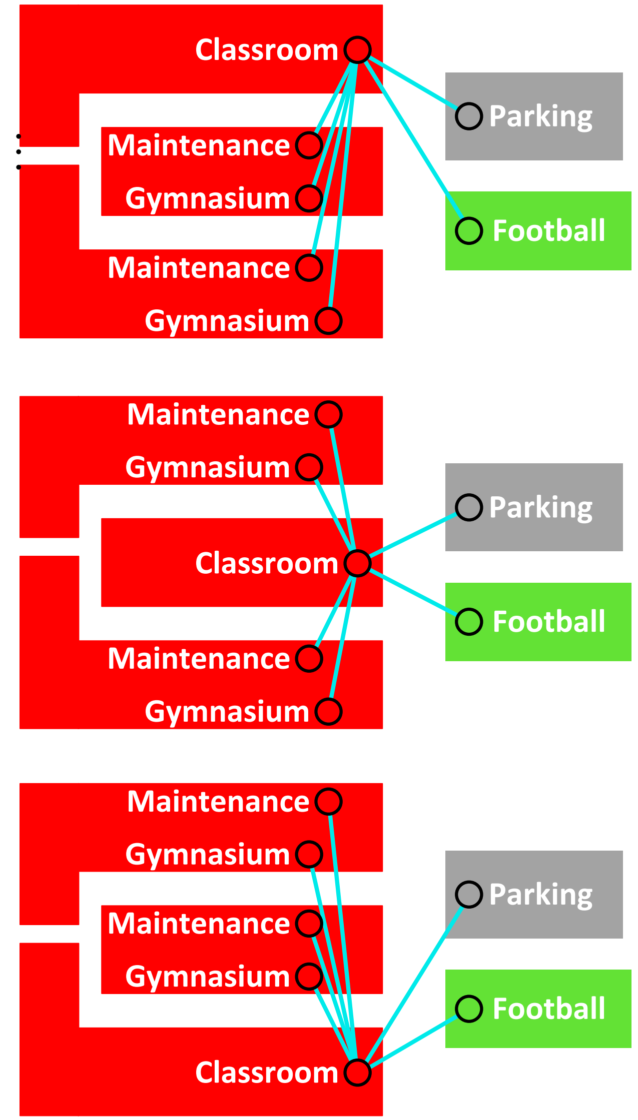
Scene:



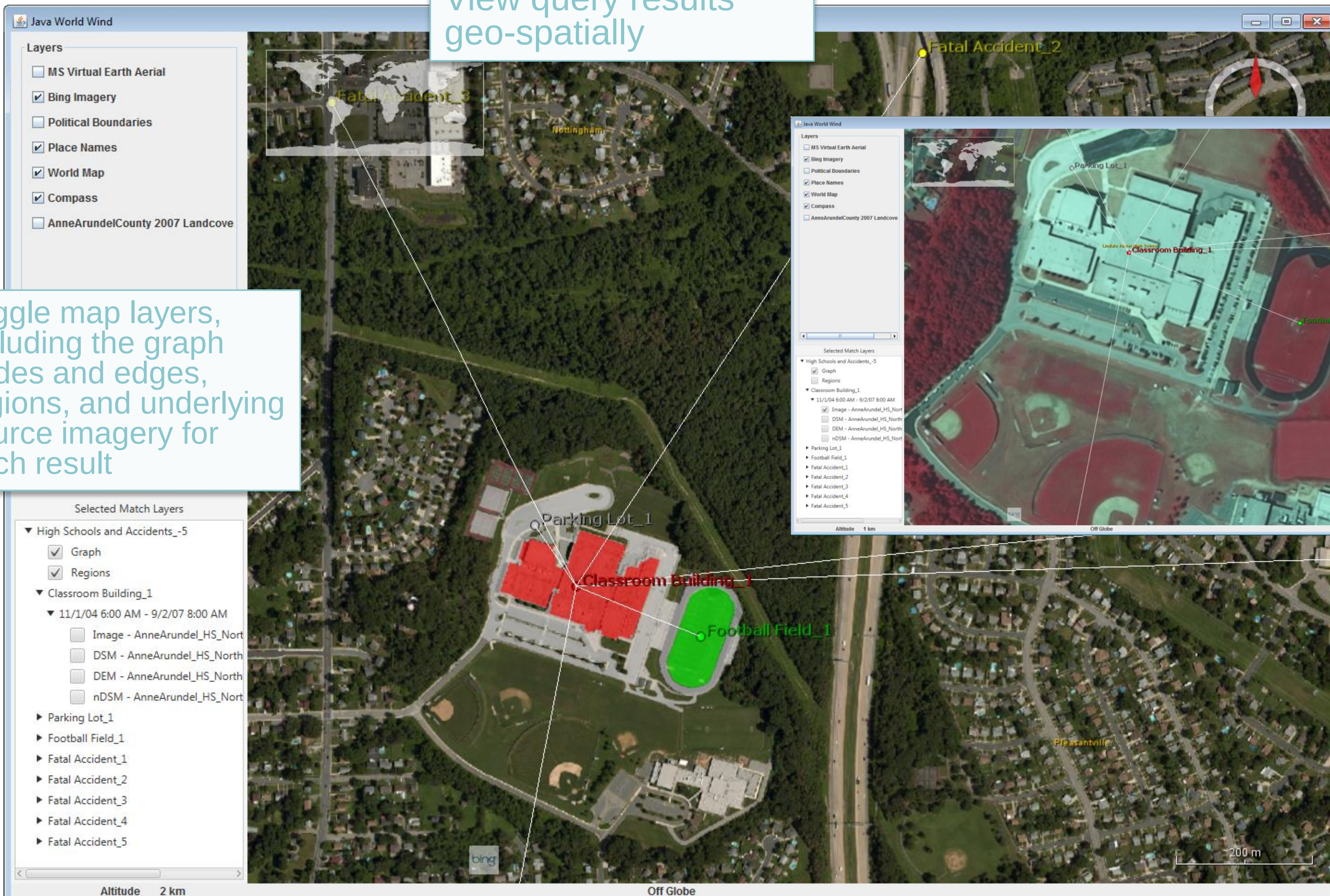
Search Graph:



Matches:



PANTHER UI Rendering Query Results

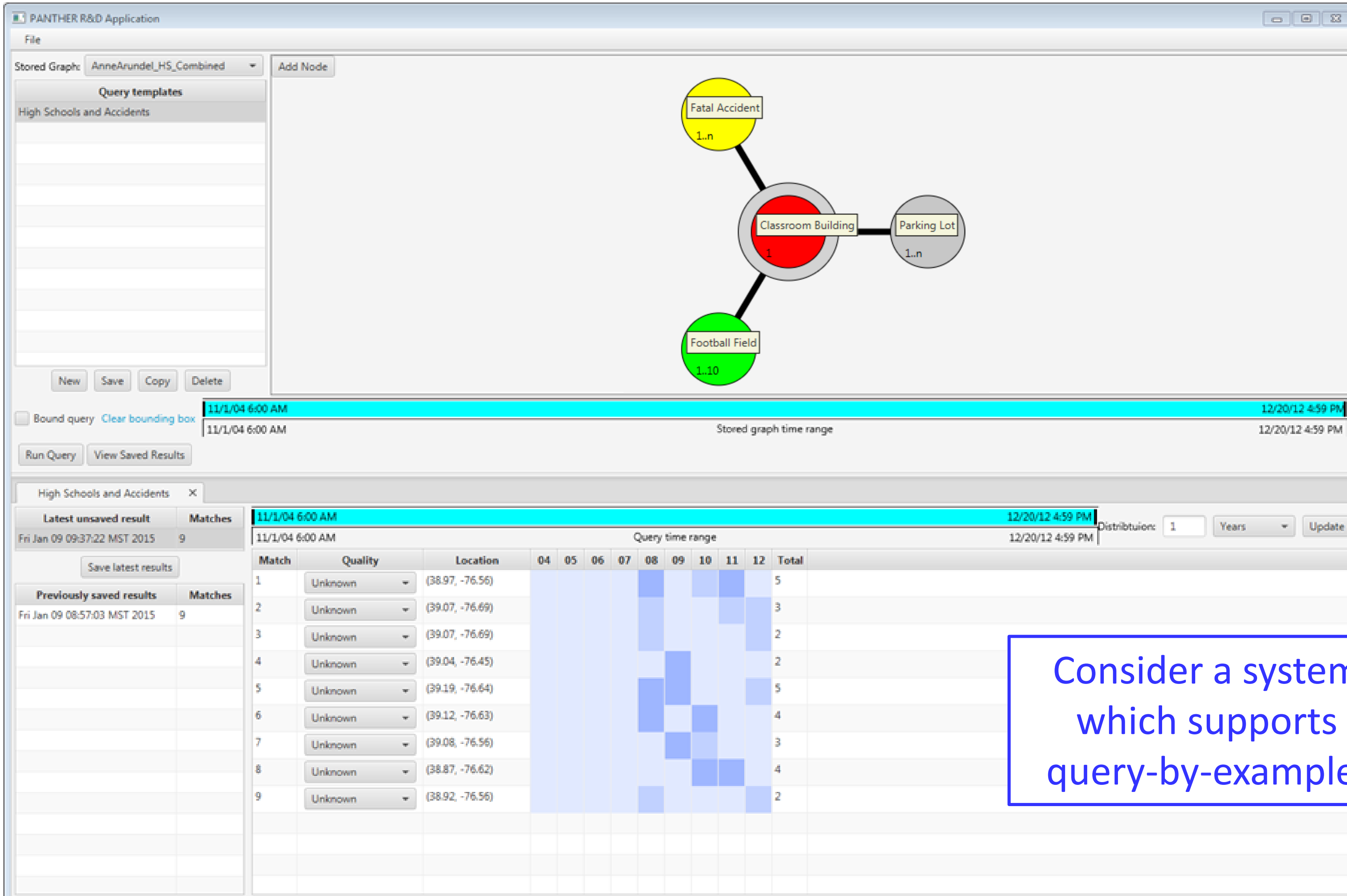


View query results geo-spatially

Toggle map layers, including the graph nodes and edges, regions, and underlying source imagery for each result

PANTHER user interface by Jamie Coram, David Perkins, and Dan Morrow (SNL).

PANTHER User Interface



Consider a system which supports query-by-example.

PANTHER user interface by Jamie Coram, David Perkins, and Dan Morrow (SNL).

Match Quality Scoring

Motivation:

- Some matches are more relevant than others.
- False negatives should be avoided.
- Widening search bounds captures false negatives, but also increases false positives.
- Quality scoring moves best matches to front, poor false positives to back of list. (Similar to web search*)

* Sergey Brin and Lawrence Page. The anatomy of a large-scale hypertextual web search engine. *Computer Networks and ISDN Systems 30 (1998) 107- 117*, 30:107–117, 1998.