III: Small: A Theory of Topological Relations for Compound Spatial Objects

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**Accomplishments**

*What are the major goals of the project?*

The goal was to develop a comprehensive theory for topological relations among spatial objects that have holes. Such
a scenario is commonplace with objects that are extracted from geosensor networks, and only insufficiently addressed by spatial-relation theories that address hole-free regions.

*What was accomplished under these goals (you must provide information for at least one of the 4 categories below)?*

**Major Activities:**

This project developed a spatial theory for objects that may have holes and separations and the topological relations between such complexly structured objects. Such objects and their relations often occur in data extracted from geosensor networks, but also exist in administrative spatial configurations, such as the level of political subdivisions. While the existing models for simple regions—disk-like and simply connected—are more compact and more elegant, the large variety of different configurations that may occur for complex spatial regions may require more detail.

**Specific Objectives:**

Results are also posted and maintained at the project's web site http://www.spatial.maine.edu/~max/holesAndParts.html

1. **A Model for Complexly Structured Regions**

These results (including many figures) were published in [1], listed in Key Outcomes.

The foundation for complexly structure regions is an inventory of thirteen types of basic holed or separated regions. The rationale is whether a region’s parts are properly connected (pc) or closure-connected (cc).

The compound object model enables the construction of objects within a planar or a spherical embedding space. It has five components: (1) the cardinality of touching boundary segments, (2) implied external separations, (3) the relation-constrained set operations, (4) the sequence of intersections along boundaries, and (5) the sequence around boundary-boundary intersections. The five components are orthogonal (i.e., none of the five can be replaced by a combination of the other four). While not all five components are needed for the construction of all complex regions, some complex regions cannot be constructed without the entire toolset. The compound object model that uses cardinality-enhanced relations, together with the relation-constrained set operations and the two sequences is referred to as COM+.

The model also yields the novel concept of complement regions. An object’s complement provides critical information for the dependencies of topological relations. For a simple region embedded on the sphere S2, the closure of its complement gives the relation’s dual. For the any basic holed or separated region, the closure of a complement links holed regions with corresponding separated regions.

2. **Topology of Entire Spatial Scenes**

These results were published in [2], listed in key outcomes.

A major intellectual finding relates to capturing the topology of entire spatial scenes, not only binary relations between spatial objects. We found that a complete capture of the topology of an entire spatial scene needs two components: (1) the topological hull to capture surrounded components (not only those surrounded by a single spatial object, but also those surrounded by a collection of connected objects) and (2) an account for the occurrence of intersections between
the boundaries of regions. Topological hull and sequence of boundary-intersections are orthogonal (i.e., the information captured by one cannot be replaced by the information captured by the other). When used together, information about the topological hulls and boundary sequences capture the topology of entire spatial scenes. The model we developed allows for the comparison of spatial scenes and enables the construction of a topologically unambiguous depiction of spatial scenes.

3. Oriented Regions

These results were published in [3], listed in Key Outcomes.

The scene topology model enabled us to develop a novel approach for representing spatial features that are commonly thought-of as being linear. Typical spatial models represent them as directed lines, which adds complexity in spatial data types and their spatial relations. Lines also abstract away a linear feature's width. The model that underlies the scene representation allows to keep for such linearly-conceptualized features as roads and rivers their extend, while including the features' directions. While this was not foreseen initially, this result is an indication of the large value of the scene topology model.

4. The Topological Relation Surrounds

These results were published in [4], listed in Key Outcomes.

A unique feature of configurations with holes is the spatial relations surrounds (and conversely surrounded by), which is not part of the standard set of binary topological relations. We formalized an algebraic construction for the relation surrounds within a partition and provided a complementary graph-theoretic approach for the detection of the surrounds conditions created by the operations within the algebra. Four refinements of a surrounds relations were identified: (1) a holed configuration that surrounds nothing, (2) a holed configuration that surrounds an object without direct contact, (3) a holed configuration that surrounds an object with partial contact, and (4) a holed configuration that surrounds an object with full contact.

The findings about the surrounds relations are particularly important as past models that attempted to consider regions with holes could not distinguish whether an object is located in a holed region's inner exterior (i.e., the hole) or in its outer exterior (i.e., outside). Our model overcomes this shortcoming.

5. Fields as a Foundational Model for Geosensed Spatial Data

These results were published in [5], listed in Key Outcomes.

Since the motivation for holed and separated regions stems from the extraction and analysis of data from geosensor networks, the PI, with collaborators in Brazil, explored a first model for spatial fields that can yield spatial regions (simple, holed, separated, or combined). We developed a generic data type for fields that can represent different types of spatiotemporal data, such as trajectories, time series, remotely sensed images, and climate data. To assess its power of generality, we showed how to represent existing algebras for spatial data with the Fields data type. The paper also demonstrated that array databases are an excellent support for processing big spatial data through a prototype developed by the Brazilian collaborators.
6. Similarity of Spatial Relations

These results were published in [6,7], listed in Key Outcomes.

When conveying spatial information verbally (e.g., through spatial queries or on verbal descriptions of spatial configurations), the terms available in natural languages often do not have the granularity to distinguish all the details that computational model of spatial relations typically capture. In order to provide a mapping from a modeled topological relation onto an appropriate natural-language term, we studied the distribution of these relations along their conceptual neighborhood graph, which is a computational rationale for determining most similar relations. Without conducting human subjects experiments, sixteen English-language spatial prepositions for region-region relations were analyzed for their corresponding topological relations, each of which was found to represent a convex subset within the conceptual neighborhood graph of the region-region relations. The resulting lattice of the convex subgraphs enables an algorithmic approach to explaining unknown prepositions.


http://www.spatial.maine.edu/~max/RC82.html


http://www.spatial.maine.edu/~max/RC77.html


http://www.spatial.maine.edu/~max/RC78.html


http://www.spatial.maine.edu/~max/RC80.html

http://www.spatial.maine.edu/~max/RC79.html


http://www.spatial.maine.edu/~max/RC76.html


http://www.spatial.maine.edu/~max/Aix.pdf

*What opportunities for training and professional development has the project provided?*

2 PhD students were mentored on research, including research publications.

Matthew Dube served as volunteer research mentor during the past three summers for eleven Upward Bound Students from Maine and Massachusetts who attended Portland High, Oxford Hills Comprehensive, Steams, Mattanawcook Academy, Bangor High, Central High, Mount View High, Lowell High, Lawrence High, Nokomis High, and Penobscot Valley High. These students developed individual research projects, published in UMaine's *A Journal of Explorations*. For authors and titles of the mentored projects see http://www.spatial.maine.edu/~matthew.dube/index_files/cv.htm.


* How have the results been disseminated to communities of interest?

Through publications and presentations at all key conferences in geographic information science.

**Products**

**Books**

**Book Chapters**

**Conference Papers and Presentations**


### Inventions

### Journals

### Licenses

### Other Products

### Other Publications

### Patents

### Technologies or Techniques

### Thesis/Dissertations

### Websites

## Participants/Organizations

### What individuals have worked on the project?

<table>
<thead>
<tr>
<th>Name</th>
<th>Most Senior Project Role</th>
<th>Nearest Person Month Worked</th>
</tr>
</thead>
<tbody>
<tr>
<td>Egenhofer, Max</td>
<td>PD/PI</td>
<td>8</td>
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<td>Camara, Gilberto</td>
<td>Faculty</td>
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<td>Dube, Matthew</td>
<td>Graduate Student (research assistant)</td>
<td>12</td>
</tr>
<tr>
<td>Lewis, Joshua</td>
<td>Graduate Student (research assistant)</td>
<td>12</td>
</tr>
</tbody>
</table>

**Full details of individuals who have worked on the project:**

Max J Egenhofer  
**Email:** max@spatial.maine.edu  
**Most Senior Project Role:** PD/PI
Nearest Person Month Worked: 8

Contribution to the Project: Project leader, supervised PhD students, authored and coauthored publications.

Funding Support: none

International Collaboration: No
International Travel: Yes, Austria - 0 years, 0 months, 5 days; Belgium - 0 years, 0 months, 2 days; United Kingdom - 0 years, 0 months, 4 days

Gilberto Camara
Email: gilberto.camara@inpe.br
Most Senior Project Role: Faculty
Nearest Person Month Worked: 1

Contribution to the Project: Co-authored a paper on the Field Model.

Funding Support: none known.

International Collaboration: Yes, Brazil
International Travel: Yes, Austria - 0 years, 0 months, 4 days

Matthew Dube
Email: Matthew_Dube@umit.maine.edu
Most Senior Project Role: Graduate Student (research assistant)
Nearest Person Month Worked: 12

Contribution to the Project: Senior graduate research assistant, develops, under PI's supervision, theories, writes papers, and made several conference presentations.

Funding Support: Graduate research assistantship UMaine

International Collaboration: No
International Travel: Yes, United Kingdom - 0 years, 0 months, 5 days

Joshua Lewis
Email: Joshua_Lewis@umit.maine.edu
Most Senior Project Role: Graduate Student (research assistant)
Nearest Person Month Worked: 12

Contribution to the Project: Developed, under the PIs supervision, the boundary-interactions.

Funding Support: Teaching Assistant

International Collaboration: No
International Travel: Yes, Austria - 0 years, 0 months, 4 days; United Kingdom - 0 years, 0 months, 4 days

What other organizations have been involved as partners?

<table>
<thead>
<tr>
<th>Name</th>
<th>Type of Partner Organization</th>
<th>Location</th>
</tr>
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</table>

https://reporting.research.gov/rppr-web/rppr?execution=e1s77
Full details of organizations that have been involved as partners:

**INPE**

**Organization Type:** Other Organizations (foreign or domestic)
**Organization Location:** Brazil

**Partner's Contribution to the Project:**
In-Kind Support
Facilities
Collaborative Research

**More Detail on Partner and Contribution:** The PI has a long-term research collaboration with Gilberto Camara at INPE. While during the project period no mutual visits occurred, we co-authored a paper on the Field Model.

What other collaborators or contacts have been involved?
Nothing to report

**Impacts**

**What is the impact on the development of the principal discipline(s) of the project?**

Through the dissemination of our results, the GIScience community has now a better understanding of spatial relations with complex objects. In particular the surrounds relations have the potential to become as critical in the future as the eight fundamental region-region relations.

**What is the impact on other disciplines?**

Since this part of geographic information science is closely linked to Computer Science, and since Oracle Spatial is headed by several UMaine Alumni, there is great potential that the surrounds relations will become available in commercial implementations in the future.

**What is the impact on the development of human resources?**

Two PhD students who were funded on this project, are still pursuing their dissertations. Matt Dube, who has published extensively, is on track to graduate in Spring 2016. He wants to pursue an academic career.

Joshua Lewis, albeit more junior, was already successful with two lead-authored papers at COSIT and GIScience, both with highly competitive reviewing. He also wants to pursue an academic career.

**What is the impact on physical resources that form infrastructure?**

Nothing to report.

**What is the impact on institutional resources that form infrastructure?**

Nothing to report.

**What is the impact on information resources that form infrastructure?**

All publications in pre-print version have been made available through the PI's web site and will remain there together with earlier material.
The dissertations of the two PhD students will be made available on-line through UMaine's Fogler library.

**What is the impact on technology transfer?**

No impact yet. There is, however, potential that the models developed may migrate into spatial-database products, like many other of our results in the past.

**What is the impact on society beyond science and technology?**

Nothing to report.

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**Changes/Problems**

**Changes in approach and reason for change**

Nothing to report.

**Actual or Anticipated problems or delays and actions or plans to resolve them**

Nothing to report.

**Changes that have a significant impact on expenditures**

Nothing to report.

**Significant changes in use or care of human subjects**

Nothing to report.

**Significant changes in use or care of vertebrate animals**

Nothing to report.

**Significant changes in use or care of biohazards**

Nothing to report.