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

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Signature of Submitting Official (signature shall be submitted in accordance with agency specific instructions)	Max J Egenhofer

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:

Specific Objectives:

Significant Results:

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.

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 represening 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, separted, 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.

Key outcomes or Other achievements:

[1] M. Dube, M. Egenhofer, J. Lewis, S. Stephen, and M. Plummer, Swiss Canton Regions: A Model for Complex Objects in Geographic Partitions, in *Conference on Spatial Information Theory -- COSIT 2015*, Santa Fe, NM, *Lecture Notes in Computer Science*, Springer, September 2015 (in press).

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

[2] J. Lewis, M. Dube, and M. Egenhofer, The Topology of Spatial Scenes in R2, *Conference on Spatial Information Theory -- COSIT 2013*, Scarborough, UK T. Thenbrink, J. Stell, A. Galton, and Z. Wood (eds.), *Lecture Notes in Computer Science*, Vol. 8116, Springer, pp. 495-515, September 2013.

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

[3] J. Lewis and M. Egenhofer, Oriented Regions for Linearly Conceptualized Features, in: *Geographic Information Science -- Eighth International Conference, GIScience 2014*, Vienna, Austria

M. Duckham, K. Stewart, and E. Pebesma (eds.), *Lecture Notes in Computer Science*, Vol. 8728, Springer, pp. 333-348, September 2014

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

[4] M. Dube and M. Egenhofer, Surrounds in Partitions, *in: ACM SIGSPATIAL GIS 2014 -- 22nd ACM SIGSPATIAL International Conference on Advances in Geographic Information Systems*, Dallas, TX

Y. Huang, M. Schneider, M. Gertz, J. Krumm, and J. Sankaranarayanan (eds.), pp. 233-242, November 2014.

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

[5] G. Camara, M. Egenhofer, K. Ferreira, P. Andrade, G. Queiroz, A. Sanchez, J. Jones, and L. Vinhas, Fields as a Generic Data Types for Big Spatial Data, in: *Geographic Information Science -- Eighth International Conference, GIScience 2014*, Vienna, Austria, M. Duckham, E. Pebesma, K. Stewart, and A. Frank (eds.), *Lecture Notes in Computer Science*, Vol. 8728, Springer, pp. 159-172, September 2014.

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

[6] M. Dube and M. Egenhofer, An Ordering of Convex Topological Relations, in: *Geographic Information Science -- Seventh International Conference, GIScience 2012*, Columbus, OH, N. Xioa, M.P. Kwan, M. Goodchild, and S. Shekhar (eds.), *Lecture Notes in Computer Science*, Vol. 7478, Springer, pp. 72-86, September 2012.

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

[7] M. Egenhofer, Qualitative Spatial-Relation Reasoning in Design, in: *Studying Visual and Spatial Reasoning for Design Creativity,* J. Gero (ed.), Springer Science+Business Media, Dordrecht, 2015.

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 resarch 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, Stearns, 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.

Angelo, M., B. Batchelder, J. Haddad, A. Nantkes, J. Wheeler, and C. Wursten. (2013) Solving Hydroelectricity's Fish Problem. *A Journal of Explorations* 22.1, J. Swist (ed.), University of Maine, 287-295.

Barrett, J. (2013) Identifying Viable Symbols within 3D Qualitative Direction Partitions. *A Journal of Explorations* 22.1, J. Swist (ed.), University of Maine, 122-136.

Burris, C. (2013) Merit of the Judging/Perceiving Pole. *A Journal of Explorations* 22.1, J. Swist (ed.), University of Maine, 244-252.

Campbell, M. (2013) Identifying Languages based on Conditional Probability and Frequency Distribution. *A Journal of Explorations* 22.1, J. Swist (ed.), University of Maine, 147-160.

Guay, B. (2013) Detectability Levels of the Human Ear: Using a Range of Frequencies, Harmonics, Octaves, and Tones. *A Journal of Explorations* 22.1, J. Swist (ed.), University of Maine,167-176.

Lim, O. (2013) Biocapacity: The Earth's Natural Countdown. *A Journal of Explorations* 22.1, J. Swist (ed.), University of Maine, 177-193.

Barrett, J., S. Decker, D. Ewer, P. Nason, and L. Shaheed. (2012) Of Ecology and Climate Change: Past, Present, and Future. *A Journal of Explorations* 21.1, J. Swist (ed.), University of Maine, 292-317.

Burris, C. (2012) Exploring the Methods of Differential Calculus through the Brachistochrone Problem. *A Journal of Explorations* 21.1, J. Swist (ed.), University of Maine, 130-142.

Lim, O. (2012) The Gerrymandered States of America: An Attempt to Reverse the Election of 2008 in Favor of the Minority Candidate. *A Journal of Explorations* 22.1, J. Swist (ed.), University of Maine, 151-166.

Lopez-Cornier, B. (2011) An Algorithm for Determining Convexity within an Arbitrary Network. *A Journal of Explorations* 20.1, R. Pyles (ed.), University of Maine, 118-135.

Tiv, C. (2011) Using Taylor Series to Approximate an Indefinite Integral (Anti-derivative). *A Journal of Explorations* 20.1, R. Pyles (ed.), University of Maine, 136-148.

Barrett, J. (2014). Determining Topological Relations between Digital 3D Objects from Qualitative Metric Information. Journal of Explorations 23(1): 228-240.

Chan, J. (2014). Partitioning New England to Represent Republican Populations. Journal of Explorations 23(1): 261-274.

Guay, B. (2014). Discrimination of Equally Tempered Tones and Chords. Journal of Explorations 23(1): 122-135.

Simpson, N. (2014). Raster Relations Revisited: Expanding Spatial Possibilities through Constraint Relaxation. Journal of Explorations 23(1): 241-252.

*** 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

M. Dube and M. Egenhofer (2012). *An Ordering of Convex Topological Relations*. Geographic Information Science -- Seventh International Conference, GIScience 2012`. Columbus, OH. Status = PUBLISHED; Acknowledgement of Federal Support = Yes

G. Camara, M. Egenhofer, K. Ferreira, P. Andrade, G. Queiroz, A. Sanchez, J. Jones, and L. Vinhas (2014). *Fields as a Generic Data Type for Big Spatial Data*. Geographic Information Science -- Eighth International Conference, GIScience 2014. Vienna, Austria. Status = PUBLISHED; Acknowledgement of Federal Support = Yes

M. Dube, J. Barrett, and M. Egenhofer (2015). *From Metric to Topology: Determining Relations in Discrete Space*. Conference on Spatial Information Theory -- COSIT 2015. Santa, Fe, NM. Status = ACCEPTED; Acknowledgement of Federal Support = Yes

J. Lewis and M. Egenhofer (2014). *Oriented Regions for Linearly Conceptualized Features*. Geographic Information Science -- Eighth International Conference, GIScience 2014. Vienna, Austria. Status = PUBLISHED; Acknowledgement of Federal Support = Yes

M. Egenhofer (2011). *Reasoning with Complements*. Advances in Conceptual Modeling -- Recent Developments and New Directions. Brussels, Belgium. Status = PUBLISHED; Acknowledgement of Federal Support = Yes

M. Dube and M. Egenhofer (2015). *Surrounds in Partitions*. ACM SIGSPATIAL GIS 2014 -- 22nd ACM SIGSPATIAL International Conference on Advances in Geographic Information Systems. Dallas, TX. Status = PUBLISHED; Acknowledgement of Federal Support = Yes

M. Dube, M. Egenhofer, J. Lewis, S. Stephen, and M. Plummer (2015). *Swiss Canton Regions: A Model for Complex Objects in Geographic Partitions*. Conference on Spatial Information Theory -- COSIT 2015. Santa, Fe, NM. Status = ACCEPTED; Acknowledgement of Federal Support = Yes

J. Lewis, M. Dube, and M. Egenhofer (2013). *The Topology of Spatial Scenes in R2*. Conference on Spatial Information Theory -- COSIT 2013. Scarborough, UK. Status = PUBLISHED; Acknowledgement of Federal Support = Yes

Inventions

Journals

Licenses

Other Products

Other Publications

Patents

Technologies or Techniques

Thesis/Dissertations

Websites

Participants/Organizations

What individuals have worked on the project?

Name	Most Senior Project Role	Nearest Person Month Worked
Egenhofer, Max	PD/PI	8
Camara, Gilberto	Faculty	1
Dube, Matthew	Graduate Student (research assistant)	12
Lewis, Joshua	Graduate Student (research assistant)	12

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

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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

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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

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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

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What other organizations have been involved as partners?

Name	Type of Partner Organization	Location

INPE	Other Organizations (foreign or domestic)	Brazil

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 clolsely 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.

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.