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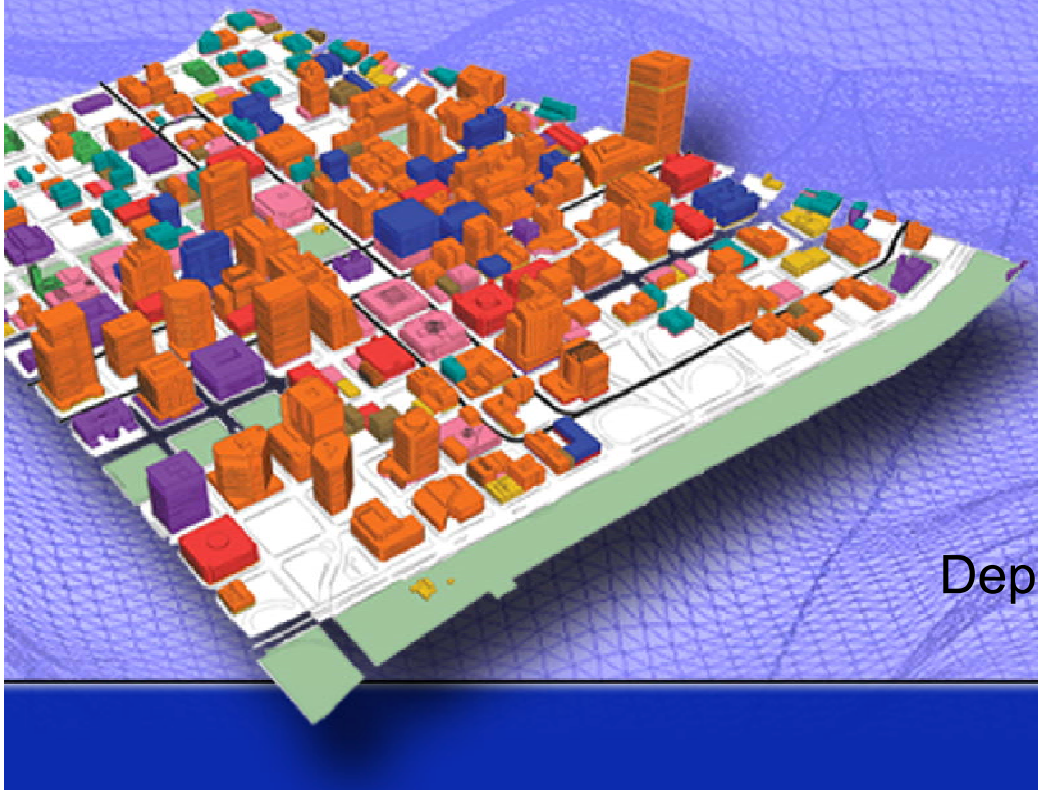
Spatial and Moving Objects Databases: State of the Art and Future Research Challenges



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Abstract

Spatial databases are full-fledged databases that, in addition, enable the storage, retrieval, manipulation, querying, and analysis of geometries like points, lines, and regions representing, for example, the geometries of cities, roads, and states respectively. More complex examples are spatial partitions representing spatial subdivisions like the counties in Florida and the election districts in Gainesville, and spatial graphs representing spatial networks like transportation networks and pipeline systems. Moving objects databases also deal with geometries but focus on the change of their location and/or shape and/or extent over time. Examples are moving points representing cell phone users, moving lines representing traffic congestions, and moving regions representing hurricanes. The objective of this tutorial is to highlight the state of the art of spatial and moving objects databases, and indicate their future research challenges. The focus is on data models, querying, data structures, algorithms, and system architectures. The tutorial will show that spatial data types and spatiotemporal data types provide a fundamental abstraction for modeling the geometric structure of objects in space, the temporally evolving structure of objects in space and time, their relationships, properties, and operations. These data types develop their full expressive power if they are integrated as abstract data types into databases and their query languages.

Outline

1. Introduction
2. Spatial Data Modeling
3. Spatiotemporal Data Modeling
4. Open Research Topics

Outline

Outline - Introduction

- Spatial and spatiotemporal data are ubiquitous
- Application examples
- Spatial and moving objects databases as interdisciplinary research fields
- Colloquial example queries
- Definition of spatial and spatiotemporal database systems

Spatial and Spatiotemporal Data are Ubiquitous (I)

- 80% of all available data have either an explicit or an implicit geographical reference

- Explicit geographical references
  - Actual geometries (spatial structures) of geographical objects
  - Examples: city boundaries, lakes, railroads, landmarks, school districts

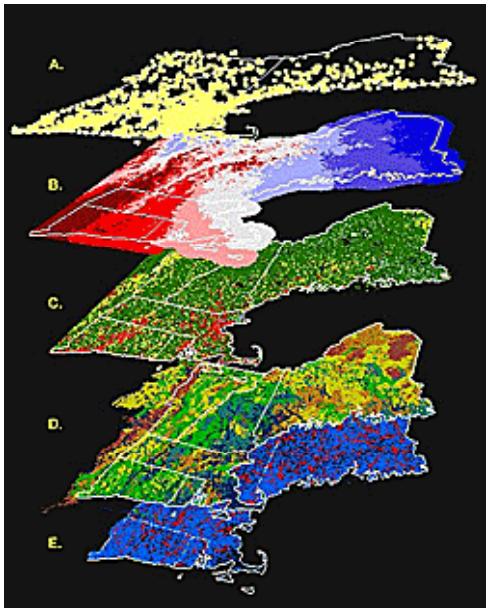
- Implicit geographical references
  - Textual references to the names and descriptions of geographic objects
  - Examples: zip codes, street names, city names, land parcel numbers
  - Geocoding: Google Map, MapQuest, Bing Maps, etc.

Spatial and Spatiotemporal Data are Ubiquitous (II)

- Adding time lets spatial objects move
  - Continuous evolution of geometries over time: movement, motion
  - Examples: hurricanes, traffic, whales, glaciers

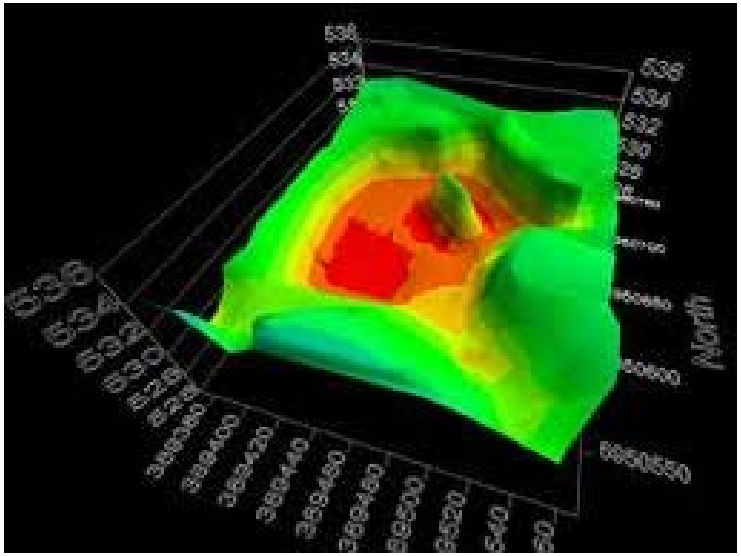
- Conclusions
  - Efficient and user friendly handling of large spatial data volumes is an important task of database technology
  - Understanding of spatial and spatiotemporal data is needed

Applications for Spatial Databases (I)



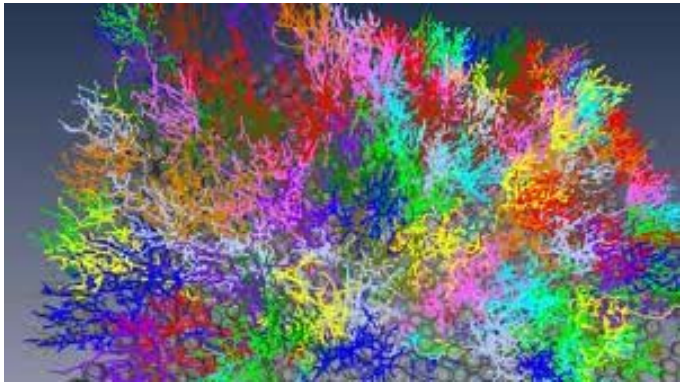
Data management foundation for Geographical Information Systems (GIS)

DNA helix

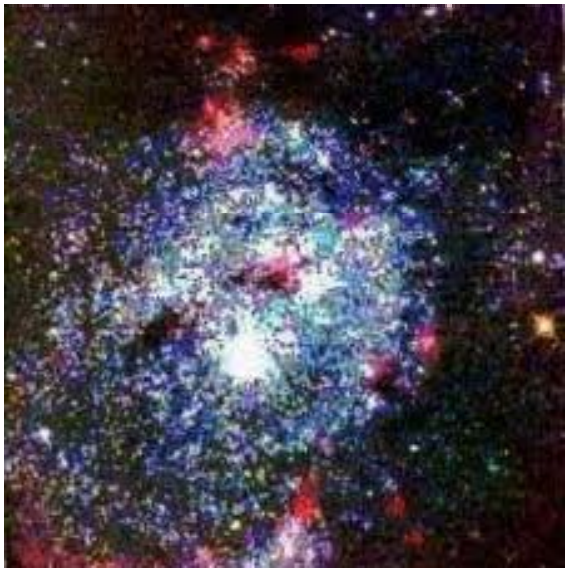


Spatial analysis

Applications for Spatial Databases (II)



The brain's complex network of 70 billion neurons and thousands of kilometers of circuits



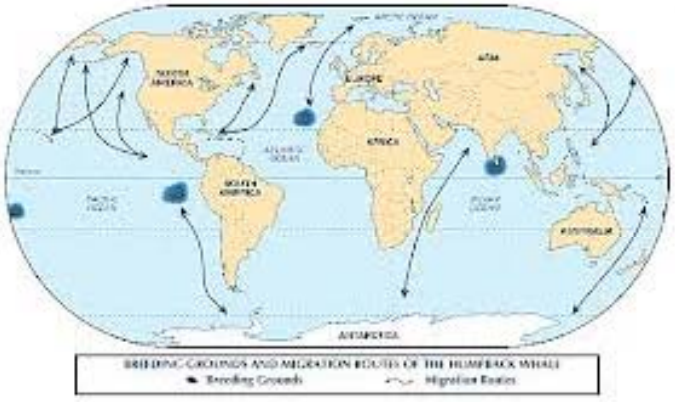
The Bubble complex (the Hodge object), a star cluster, in NGC 6946

A street map

Applications for Moving Objects Databases (I)

Traffic congestion research

Car navigation system



Migration routes of whales

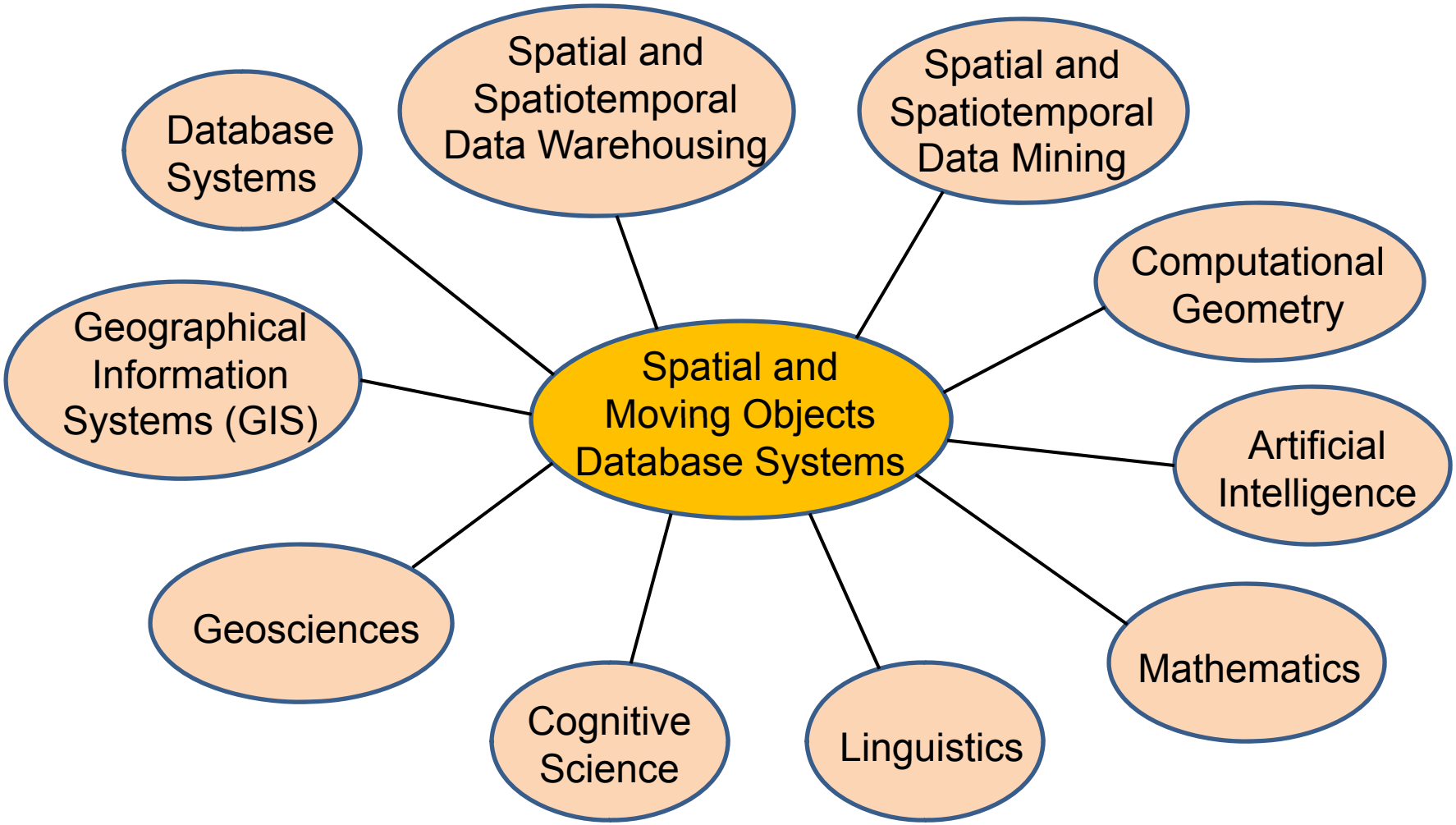
Applications for Moving Objects Databases (II)

Hurricane research

Movement of planets

Material flow in transportation pipelines (electricity, water, oil)

Spatial and Moving Objects Databases as Interdisciplinary Research Fields



User Groups and Spatial Queries of Interest (I)

Mobile phone user: Where is the nearest gas station? Is there a pet-food vendor on my way home?

Army field commander: Has there been any significant enemy troop movement since last night?

Insurance risk manager: Which houses on the Mississippi River are most likely to be affected by the next great flood?

Medical doctor: Based on this patient's Magnetic Resonance Imaging (MRI), have we treated somebody with a similar condition?

Molecular biologist: Is the topology of the amino acid biosynthesis gene in the genome found in any other sequence feature map in the database?

Astronomer: Find all blue galaxies within two arcmin of quasars.

Climatologist: How can I test and verify my new global warming model?

User Groups and Spatial Queries of Interest (II)

Pharmaceutical Researcher: Which molecules can dock with a given molecule based on geometric shapes?

Sports: Which seats in a baseball stadium provide best view of pitcher and hitter? Where should TV camera be mounted?

Corporate supply manager: Given trends about our future customer profile, which are the best places to build distribution warehouses and retail stores?

Transport specialist: How should the road network be expanded to minimize traffic congestion?

Urban sprawl specialist: Is new urban land development leading to the loss of rich agricultural land.

Ski resort owner: Which mountains on our property are ideal for a beginner's ski run?

Farmer: How can I minimize the use of pesticide on my farm?

Golf entrepreneur: Where do I build a new golf course which will maximize profit given the constraints of weather, Environmental Protection Agency pesticide regulations, the Endangered Species Act, property prices, and the neighborhood demographic profile.

Emergency service: Where is the person calling for help located? What is the best route to reach her?

User Groups and Spatiotemporal Queries of Interest (I)

Moving Point Entities	*Questions*
People: politicians, terrorists, criminals	■ When did Bush meet Arafat? ■ Show the trajectory of Lee Harvey Oswald on November 22, 1963.
Animals	■ Determine trajectories of birds, whales, . . . ■ Which distance do they traverse, at which speed? How often do they stop? ■ Where are the whales now? ■ Did their habitats move in the last 20 years?
Satellites, spacecraft, planets	■ Which satellites will get close to the route of this spacecraft within the next four hours?
Cars: taxi cabs, trucks	■ Which taxi is closest to a passenger request position? ■ Which routes are used regularly by trucks? ■ Did the trucks with dangerous goods come close to a high-risk facility?
Airplanes	■ Were any two planes close to a collision? ■ Are two planes heading toward each other (going to crash)? ■ Did planes cross the air territory of state X? ■ At what speed does this plane move? What is its top speed? ■ Did Iraqi planes pass the 39th degree?
Ships	■ Are any ships heading toward shallow areas? ■ Find "strange" movements of ships, indicating illegal dumping of waste.
Military vehicles: rockets, missiles, tanks, submarines	■ All kinds of military analyses.

User Groups and Spatiotemporal Queries of Interest (II)

Moving Region Entities	*Questions*
Countries	▪ What was the largest extent ever of the Roman Empire? ▪ On which occasions did any two states merge (e.g., reunification)? ▪ Which states split into two or more parts? ▪ How did the Serb-occupied areas in former Yugoslavia develop over time? When was the maximal extent reached?
Forests, lakes	▪ How fast is the Amazon rain forest shrinking? ▪ Is the Dead Sea shrinking? ▪ What is the minimal and maximal extent of river X during the year?
Glaciers	▪ Does the polar ice cap grow? Does it move? ▪ Where must glacier X have been at time Y (backward projection)?
Storms	▪ Where is the hurricane heading? When will it reach Florida?
High/low pressure areas	▪ Where do they go? Where will they be tomorrow?
Scalar functions over space (e.g., temperature)	▪ Where has the 0-degree boundary been last midnight?
People	▪ Movements of the Celts in the second century B.C.
Troops, armies	▪ Hannibal traversing the Alps. Show his trajectory. When did he pass village X?
Cancer	▪ Can we find in a series of X-ray images a growing cancer? How fast does it grow? How big was it on June 1, 1995?
Continents	▪ History of continental shift
Diseases	▪ Show the area affected by mad cow disease for every month in 1998.
Oil spills	▪ Which parts of the coast will be touched tomorrow?

What is a Spatial Database System?

- A spatial database system is a database system.
- It offers spatial data types (SDTs) in its data model and query language.
- It supports spatial data types in its implementation, providing at least spatial indexing and efficient algorithms for spatial joins.

From: R.H. Güting. An Introduction to Spatial Databases. *VLDB Journal (Special Issue on Spatial Databases)*, 3(4):357-399, 1994.

What is a Moving Objects Database System?

- A moving objects database system is a spatial database system.
- In addition, it offers spatiotemporal data types (STDTs) for moving objects (including operations and predicates) in its data model and query language.
- It supports spatiotemporal data types in its implementation, providing at least spatiotemporal indexing and efficient algorithms for spatiotemporal joins.

Goals of this Tutorial

- Provide an overview and understanding of the essential concepts of spatial and moving objects database systems
  - What is special with spatial (geometric) data?
  - What is special with spatiotemporal data?
- Emphasize the importance of spatial and spatiotemporal data types to model and query (moving) geometries in databases
- Modeling and conceptual aspects are the focus of this tutorial but not implementation aspects

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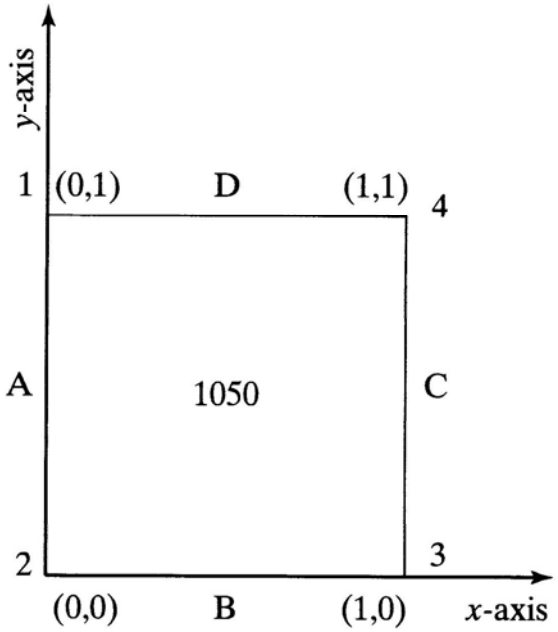
Outline – Spatial Data Modeling

- How spatial data should not be represented
- Spatial data types
- Geometric set operations
- Metric operations
- Topological relationships
- Directional relationships
- Spatial querying

How Spatial Data should NOT Be Represented (I)

- Example: Census block, and how we would perhaps like to store it in a table



Census_blocks

Name	Area	Population	Boundary
1050	1	1839	Polyline((0,0),(0,1),(1,1),(1,0))

- Problem: *Polyline* is not a built-in data type

How Spatial Data should NOT Be Represented (II)

❖ First solution ever proposed: Create a set of tables with shared attributes

Census_blocks

Name	Area	Population	boundary-ID
340	1	1839	1050

Polygon

boundary-ID	edge-name
1050	A
1050	B
1050	C
1050	D

Edge

edge-name	endpoint
A	1
A	2
B	2
B	3
C	3
C	4
D	4
D	1

Point

endpoint	*x*-coor	*y*-coor
1	0	1
2	0	0
3	1	0
4	1	1

How Spatial Data should NOT Be Represented (III)

- Problems
  - Polyline representation is *scattered* over *several* (!) tables
  - How do we know that these four tables represent a polyline?
  - The relational algebra and SQL do not provide geometric operations
  - SQL queries, if possible, are low-level queries
  - Even if so, it would not be clear how to apply these geometric operations to the tables
  - Only chance
    - Expensive joins needed to obtain full information about the polyline
    - All tuples have to be loaded into main memory for further processing
    - Tuples have to be transformed into a geometric data structure
    - Geometric operations have to be applied to geometric data structure

How Spatial Data should NOT Be Represented (IV)

- Conclusions
  - This solution is highly inefficient
  - Table representation does not allow the application of geometric operations.
  - Whole approach is unusable
  - An object concept is needed
  - Spatial and spatiotemporal data are/form complex application objects and are not an accumulation of their constituent parts
  - The relational data model and relational database systems cannot and should not be used to represent complex application objects like spatial and spatiotemporal data

What are Spatial Data Types? (I)

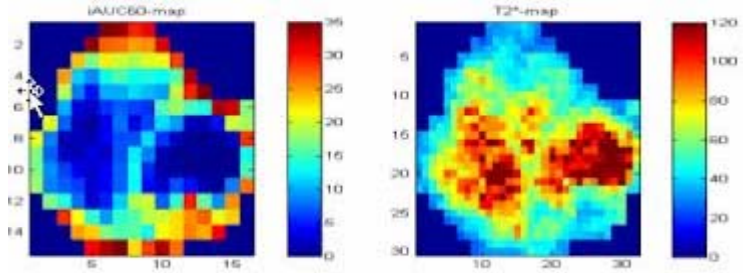
- Spatial data types
  - are special data types needed to model geometry and to suitably represent geometric data in database systems
  - Examples: point, line, region; partition (map), graph (network)
  - provide a *fundamental abstraction* for modeling the geometric structure of objects in space, their relationships, properties, and operations
  - are an important part of the data model and the implementation of a spatial DBMS
- The definition of SDTs
  - is to a large degree responsible for a successful design of spatial data models
  - decisively affects the performance of spatial database systems
  - exerts a great influence on the expressiveness of spatial query languages
  - should be independent from the data model used by a DBMS

What are Spatial Data Types? (II)

- Conclusions
  - An understanding of SDTs is a prerequisite
    - for an effective construction of important components of a spatial database system like spatial index structures, optimizers for spatial data, spatial query languages, storage management, graphical user interfaces
    - for a cooperation with extensible DBMS providing spatial type extension packages like spatial data blades, cartridges
  - The definition and implementation of spatial data types is probably the most fundamental issue in the development of spatial database systems

Which Spatial Data Need to Be Represented? (I)

- Two kinds of representations of spatial phenomena (vector/raster debate)
  - objects in space (entity-oriented / feature-based view)
    → vector data, boundary representation
    → spatial database systems
  - space itself (space-oriented / position-based view)
    → raster data, bitmap data, pixel data
    → image database systems



- We consider
  - modeling single, self-contained spatial objects
  - modeling spatially related collections of spatial objects

Which Spatial Data Need to Be Represented? (II)

Fundamental abstractions for modeling single, self-contained objects

point

city
castle
lighthouse
church

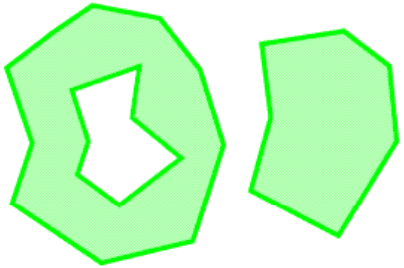
(location of object in space but not its extent relevant)

line

highway
river
cable
route

(connections in space, movement through space)

region

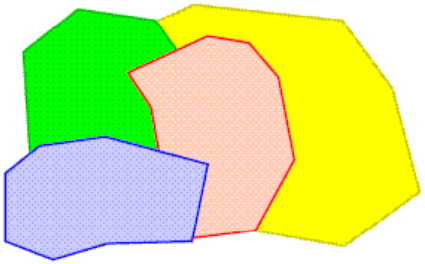


city
lake
district
forest
cornfield

(extent of an object relevant)

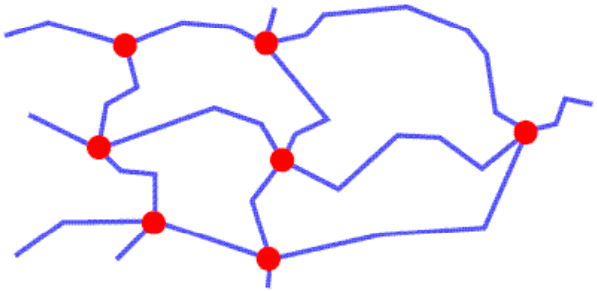
Fundamental abstractions for modeling spatially related collections of objects

partition



land use
districts
wards
countries
speech areas

Spatially embedded *network* (graph)



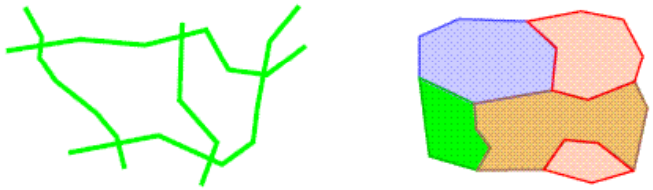
highways
railways
rivers
electricity
phone

Others: nested partitions, digital terrain models

A Three-Level Model for Phenomena in Space

Structure modeling

Structure objects

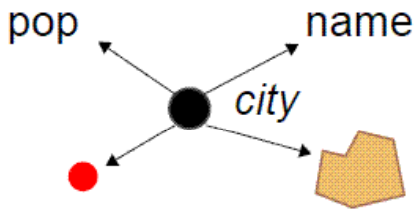


Structure types: sets, sequences, partitions, networks

Operations: overlay, shortest_path

Object modeling

Spatially-referenced objects

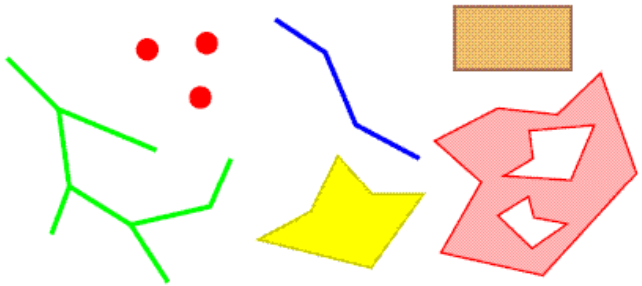


Object types: city, state, river

Operations: lies_in: city → state, flow: river → line)

Spatial modeling

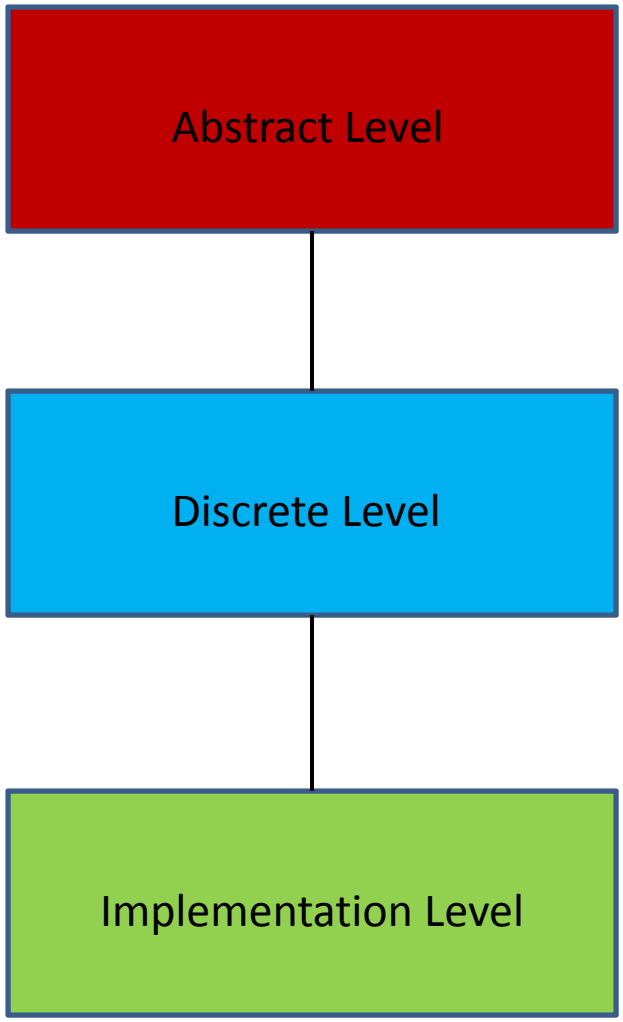
Spatial objects



Spatial data types: point, line, polygon

Operations: point-in-polygon test, intersection

Abstraction Levels for Data Type Design and Implementation



- Spatial/ST data types
- Abstract line, region, volume, surface, moving point, moving region
- Definitions based on mathematics (e.g., point set theory, point set topology, algebraic topology)
- Spatial/ST operations and predicates
- No consideration of implementation aspects

- Finite representations of spatial data types
  - Discrete data structures for SDTs/STDTs
  - Discrete line, region, volume, surface , moving point, moving region
- Algorithms for spatial/ST operations and predicates on finite representations

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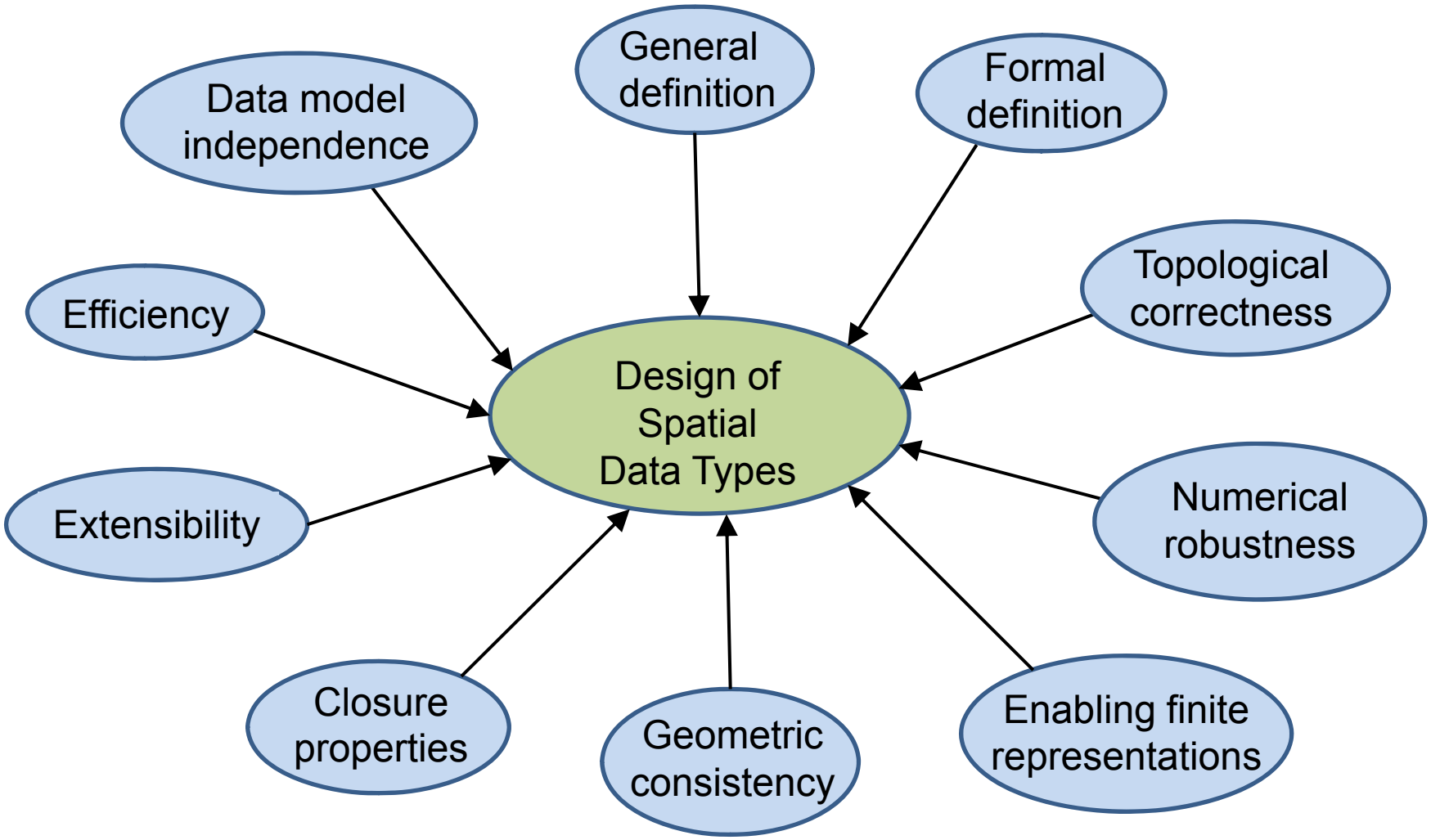
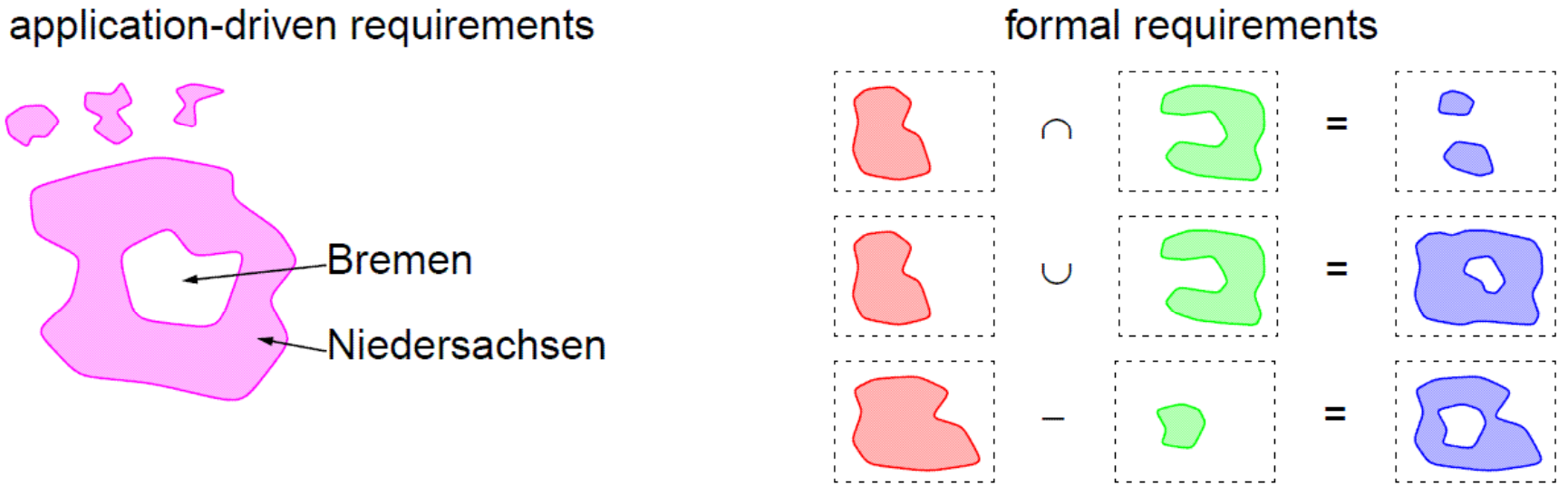
- Geometric data structures
  - In a programming language (C++, Java)
  - Array structures, no pointer structures
- Geometric algorithms
  - Methods from Computational Geometry

Design Criteria for Modeling Spatial Data Types



Closure Properties

❖ General definition/structure of spatial objects

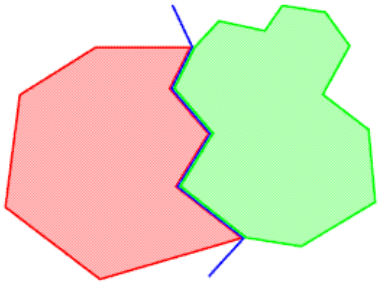


→Spatial objects must be closed under set operations on the underlying point sets

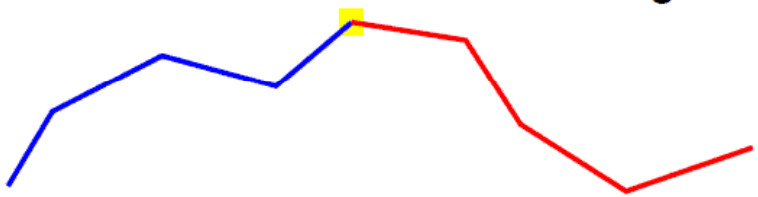
Geometric Consistency

❖ Support of geometric consistency constraints for spatially related objects

adjacent regions



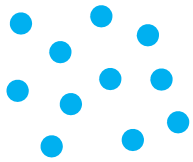
meeting lines

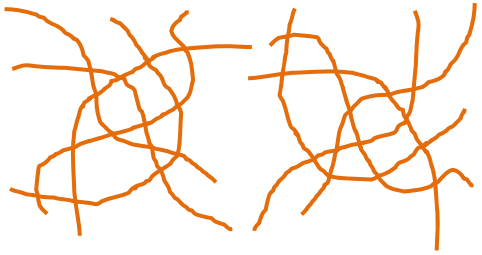


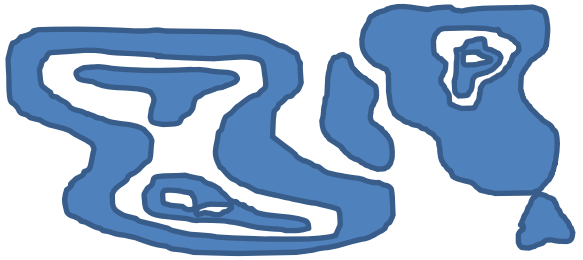
→SDT definition must offer facilities to enforce topological consistency constraints

Spatial Data Types – Intuitive Definition (I)

- Data type point: A (complex) point object consists of a finite number of single points.
- Data type line: A (complex) line object consists of a finite number of blocks (connected components). Each block consists of a finite number of disjoint or meeting continuous curves.
- Data type region: A (complex) region object consists of a finite number of disjoint or 0-meet faces (sub-regions). Each face consists of an outer cycle and a finite (zero, one, or more) number of disjoint or 0-meet hole cycles (holes).







Spatial Data Types – Intuitive Definition (II)

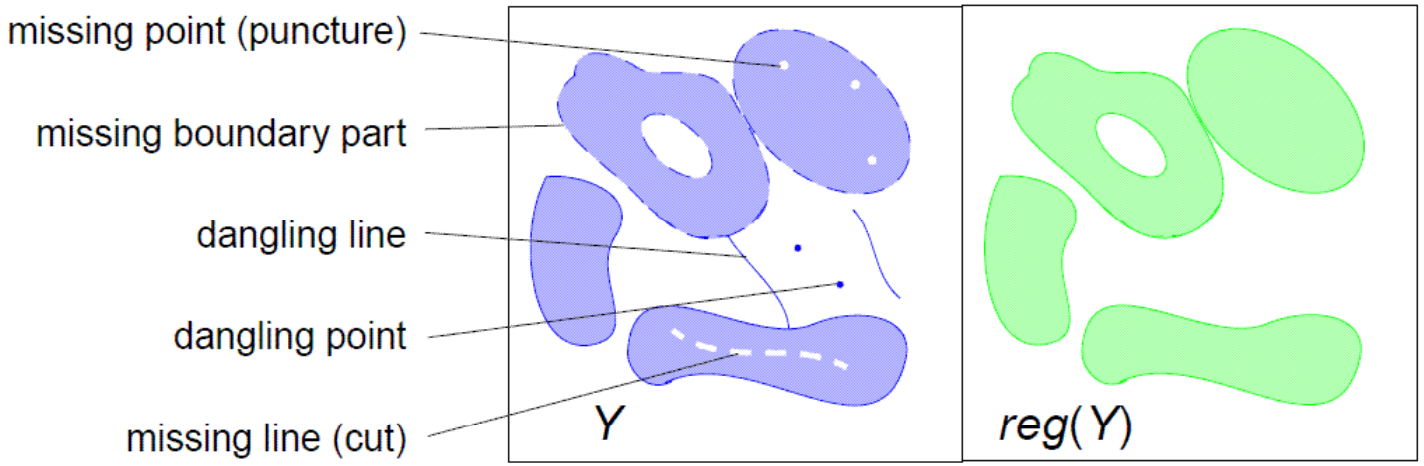
- Advantages of these definitions
  - Intersections of two line objects can be represented as a single complex point object
  - No dependence of the object-oriented type constructors (set, list, array) of the data model of the deployed database system
  - No distribution of the single points of the result in several tuples of a relational table
  - Several disjoint rivers can be represented as a single line object (waterways)
  - Multiple components and holes in regions are needed since
    - this guarantees the closure properties of spatial data types
    - this is required by spatial applications (e.g., Italy with mainland, offshore islands, and the Vatican)

Why Do We Need a Formal Definition of SDTs?

- Better understanding of the complex semantics of spatial objects and operations at the discrete level
- Formal definition of SDTs should be directly usable for a formal definition of corresponding spatial operations and predicates
- Clarity and consistency of the conceptual user view of SDTs
- A first step towards a standardization of spatial data types (achieved)
- Formal specification of SDTs for a possible implementation at the implementation level

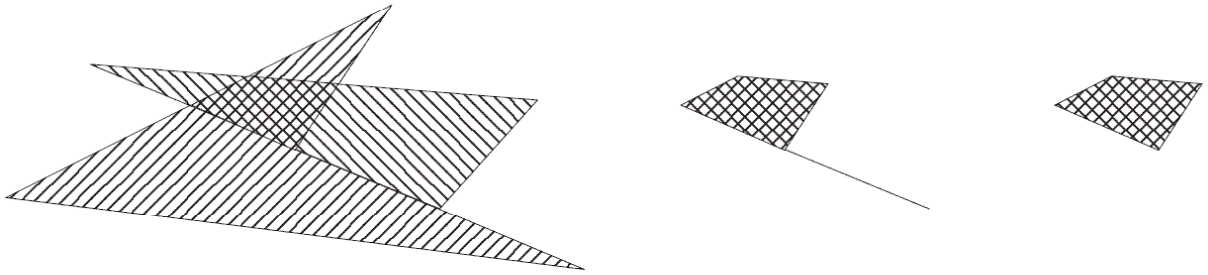
Point Set Theory (I)

- Basic assumption: space is composed of infinitely many points (Euclidean plane IR^2) and contains a set of spatial objects
- Each spatial object *Y* can be regarded as the point set occupied by that object ($Y \subset IR^2$)
- Use of set operations $\cup$, $\cap$, $-$ for constructing new spatial objects
- Possible anomalies



Point Set Theory (II)

- Possible anomalies (*continued*)



Two intersecting *Regions* objects

Conventional intersection

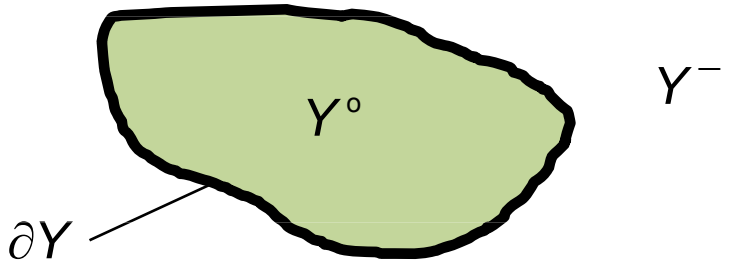
Regularized intersection

- Ambiguities when defining topological relationships
  - Let *A* and *B* two spatial objects, and let *points* be a function that provides the point set of a spatial object
  - $A = B := points(A) = points(B)$
    $A \text{ inside } B := points(A) \subseteq points(B)$
    $A \text{ intersects } B := points(A) \cap points(B) \neq \varnothing$
  - The definitions of = and *inside* are both covered by the definition of *intersects*

Point Set Topology (I)

- Same basic assumptions as point set theory but investigates topological structures of a point set

  boundary (∂Y), *interior* (Y°), *closure* ($\overline{Y}$), *exterior* (Y^-)



$$\overline{Y} = Y^\circ \cup \partial Y \quad Y^\circ \cap \partial Y = \emptyset \quad Y^- \cap \partial Y = \emptyset \quad Y^\circ \cap Y^- = \emptyset$$

$$\mathbb{R}^2 = Y^\circ \cup \partial Y \cup Y^-$$

- Point set topology investigates properties that are independent of an underlying distance or coordinate measure (metric) and that are preserved under continuous topological transformations

Point Set Topology (II)

- Regularization of point sets to avoid anomalies
- Spatial regions are defined as regular closed sets
- Y is a regular closed set if $Y = \overline{Y^{o}}$
- Effect of the *interior* function: elimination of dangling points, dangling lines and boundary parts
- Effect of *closure* function: elimination of cuts and punctures by appropriately adding points, adding missing boundary points
- Regularization function $reg(Y) := \overline{Y^{o}}$
- Geometric set operations are equated with regular set operations (A, B regular closed sets)

$A \oplus B := reg(A \cup B)$ $\quad A \otimes B := reg(A \cap B)$ $\quad A \ominus B := reg(A - B)$

Formal Definition of Spatial Data Types

- The spatial data type *point* is defined as

  point = $\{P \subset \mathrm{IR}^2 \mid P \text{ is finite}\}$

- The spatial data type *line* is defined as

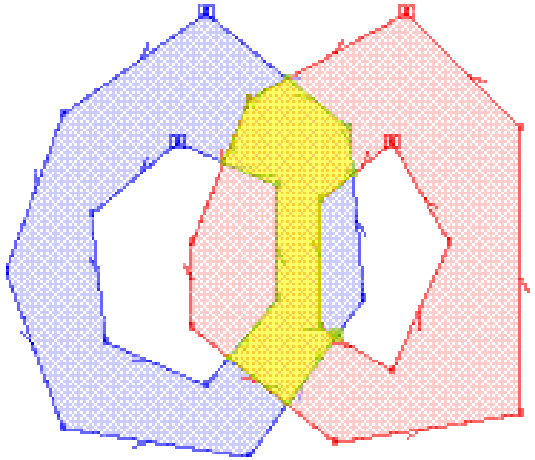
$$\begin{aligned} line = \{L \subset \mathbb{R}^2 \mid\ & \text{(i)}\ \ L = \textstyle\bigcup_{i=1}^{n} f_i([0,1]) \text{ with } n \in \mathbb{N}_0 \\ & \text{(ii)}\ \ \forall\, 1 \le i \le n : f_i : [0,1] \to \mathbb{R}^2 \ \text{ is a continuous mapping} \\ & \text{(iii)}\ \forall\, 1 \le i \le n : |f_i([0,1])| > 1\}. \end{aligned}$$

- The spatial data type *region* is defined as

$$\begin{aligned} region = \{R \subset \mathbb{R}^2 \mid\ & \text{(i) } R \text{ is regular closed} \\ & \text{(ii) } R \text{ is bounded} \\ & \text{(iii) The number of connected sets of } R \text{ is finite}\} \end{aligned}$$

Geometric Operations (I)

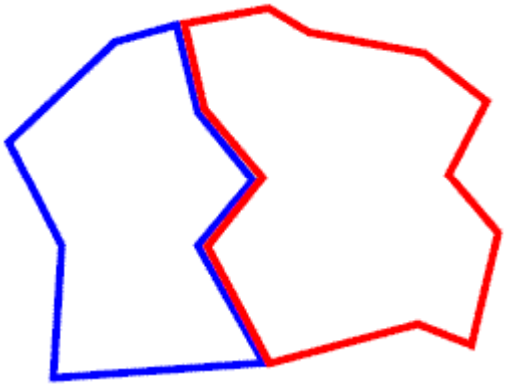
- Geometric union, geometric intersection, and geometric difference (geometric set operations) of two spatial objects of the same spatial type
  union, *intersection*, *difference* : $\alpha \times \alpha \rightarrow \alpha$ for all $\alpha \in$ {*point*, *line*, *region*}



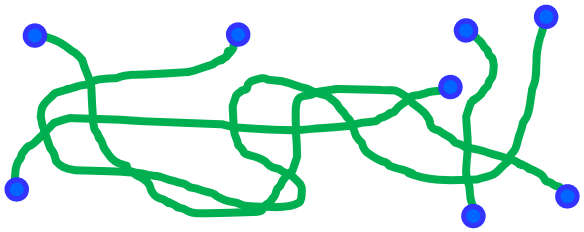
- Formal definition the geometric set operations for α = *region*
  - *union*(*A*, *B*) := $A \oplus B$
  - *intersection*(*A*, *B*) := $A \otimes B$
  - *difference*(*A*, *B*) := $A \ominus B$

Geometric Operations (II)

- Geometric intersection of two spatial objects of different spatial data types
  intersection: $\alpha \times \beta \rightarrow \alpha$ for all $\alpha, \beta \in \{$*point*, *line*, *region*$\}$ and $\alpha \neq \beta$
- Computation of the common boundary of two spatial objects
  commonBorder: $\alpha \times \beta \rightarrow$ *line* for all $\alpha, \beta \in \{$*line*, *region*$\}$ and $\alpha \neq \beta$

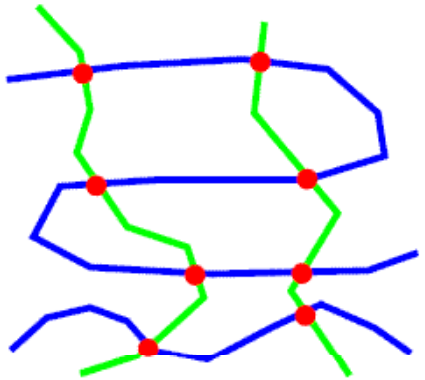


- Computation of the boundary of a spatial object
  - *boundary*: *region* $\rightarrow$ *line*
  - *boundary*: *line* $\rightarrow$ *point*

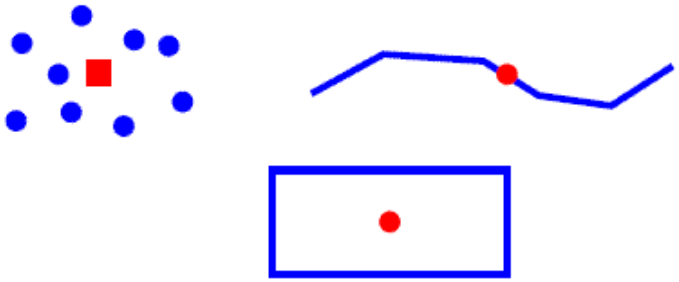


Geometric Operations (III)

- Computation of the common boundary points of two spatial objects
  commonPoints: $\alpha \times \beta \rightarrow$ *point* for all $\alpha, \beta \in$ {*line*, *region*} and $\alpha \neq \beta$

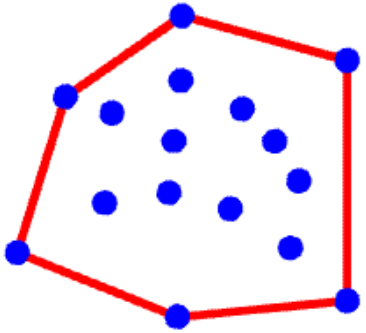


- Computation of the center of a spatial object
  center: $\alpha \rightarrow$ *point* for all $\alpha \in$ {*point*, *line*, *region*}



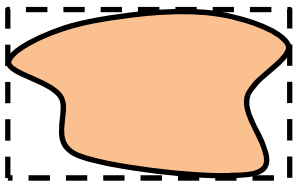
Geometric Operations (IV)

- Computation of the convex hull of a point object
  convexHull: *point* $\rightarrow$ *region*



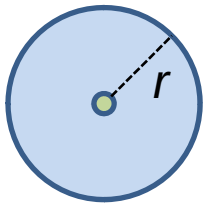
- Computation of the minimum bounding box (rectangle) of a spatial object, that is, its smallest enclosing and axis-parallel rectangle

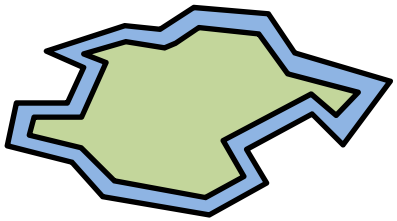
  box: $\alpha \rightarrow$ *region* for all $\alpha \in$ {*point*, *line*, *region*}



Geometric Operations (V)

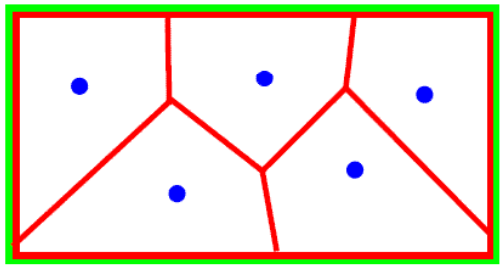
- Zooming a spatial object by a factor
  scale : $\alpha \times$ *float* $\rightarrow \alpha$ for all $\alpha \in$ {*point*, *line*, *region*}
- Rotation of a spatial object around a point by a given angle
  rotate : $\alpha \times$ *point* $\times$ *float* $\rightarrow \alpha$ for all $\alpha \in$ {*point*, *line*, *region*}
- Moving a spatial object by a defined vector
  translate : $\alpha \times$ *point* $\rightarrow \alpha$ for all $\alpha \in$ {*point*, *line*, *region*}
- Creation of a region object (a buffer) that contains all points in a certain distance from a spatial input object (a negative distance lets the input object shrink)
  bufferZone : $\alpha \times$ *float* $\rightarrow$ *region* for all $\alpha \in$ {*point*, *line*, *region*}



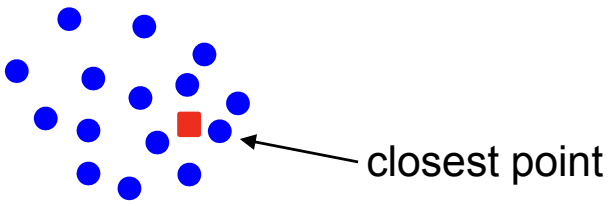



Geometric Operations (VI)

- Voronoi operation: For a given set *S* of points in the plane, the Voronoi diagram associates with each point *p* from *S* the region consisting of those points of the plane that are closer to *p* than to any other point in *S*



- The closest operation yields a point object whose point components are nearest to a given single *reference point*
  closest : *point* × *point* → *point*



Metric Operations (I)

- Computation of the area of a region object
  area: *region* $\rightarrow$ *float*
- Computation of the length of a region boundary
  perimeter: *region* $\rightarrow$ *float*
- Computation of the length of a line object
  length: *line* $\rightarrow$ *float*
- Computation of the largest Euclidean distance between any of two points of a spatial object
  - *diameter*: *region* $\rightarrow$ *float*
  - *diameter*: *line* $\rightarrow$ *float*
  - *diameter*: *point* $\rightarrow$ *float*
  - In summary: *diameter*: $\alpha \rightarrow$ *float* for all $\alpha \in$ {*point*, *line*, *region*}

Metric Operations (II)

- Ideas for new unary distance operations
  minIntraDist,
  maxIntraDist,
  minInterDist,
  maxInterDist: $\alpha \rightarrow$ *float* for all $\alpha \in$ {*point*, *line*, *region*}

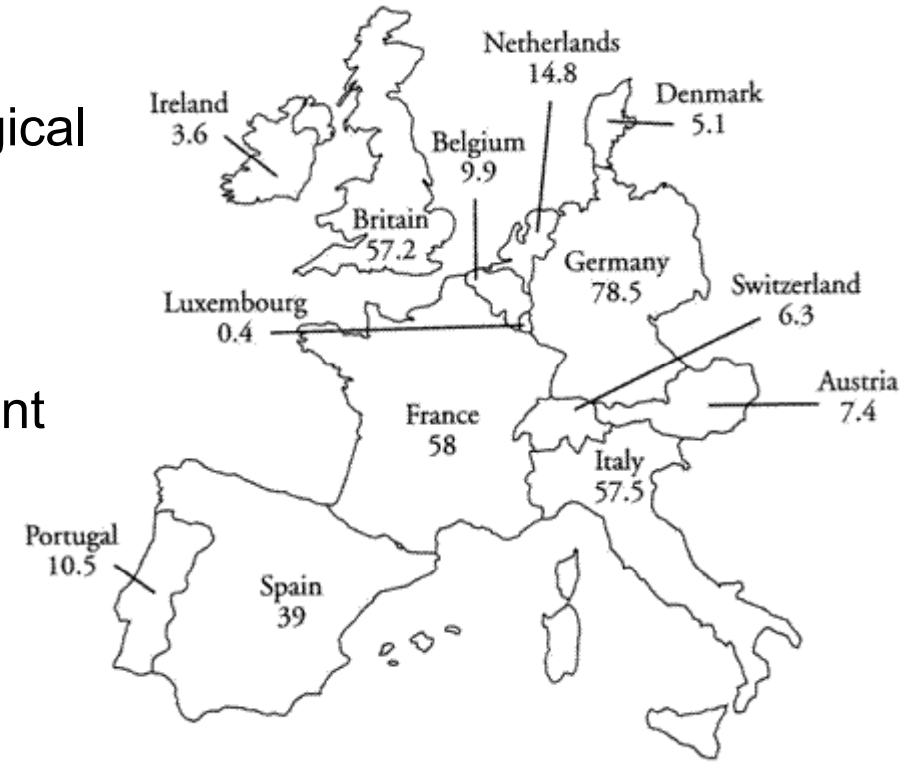
- Minimum/maximum Euclidean distance computation between two spatial objects
  dist, *maxDist* : $\alpha \times \beta \rightarrow$ *float* for all $\alpha, \beta \in$ {*point*, *line*, *region*}

- Computation of the direction between two single points as the angle $0 \leq \alpha < 360$ between them
  direction : *point* $\times$ *point* $\rightarrow$ *float*

- Number of components (points, blocks, faces) of a spatial object
  noOfComps: $\alpha \rightarrow$ *integer*

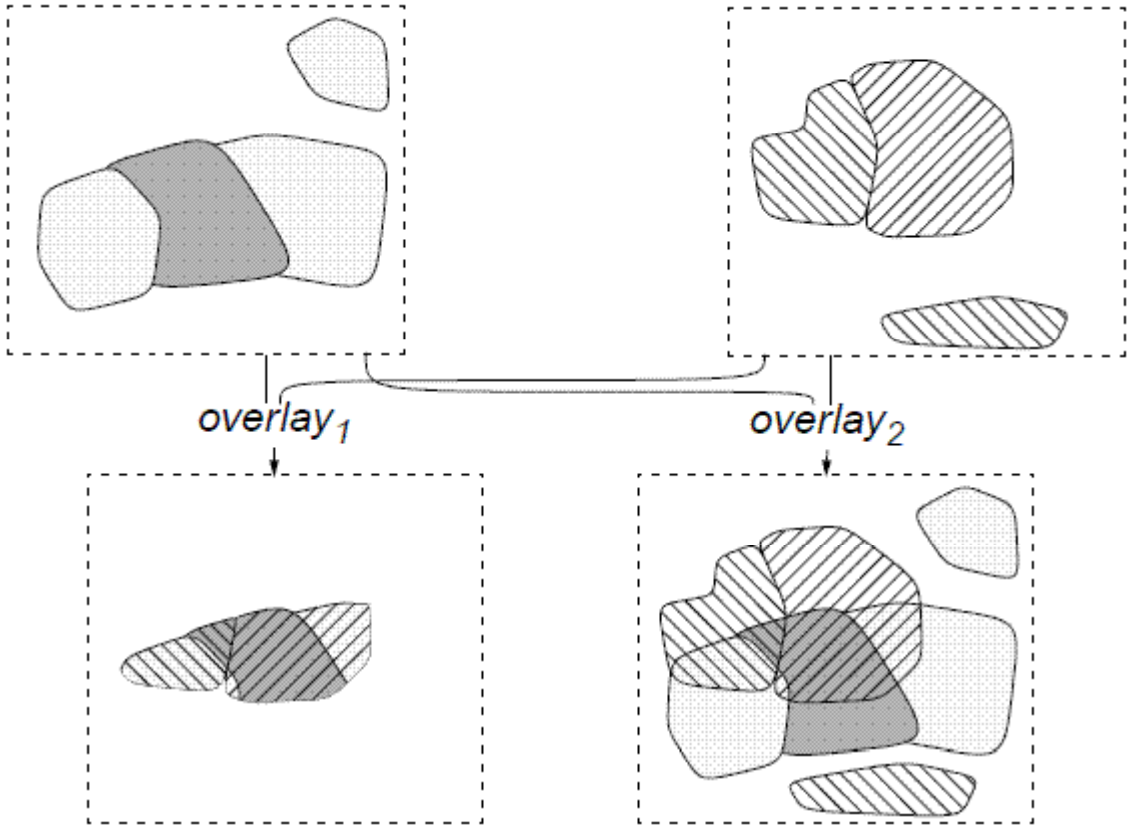
Spatial Partitions and Their Operations (I)

- Spatial partition: subdivision of the plane into pairwise disjoint regions where each region is associated with an attribute (label) having a simple or even complex structure
- Partition constraints maintain topological relationships between regions
  - Interiors of different region objects must be disjoint
  - Different region objects are adjacent (they meet) or they are disjoint
- Important example of a spatial connectivity structure



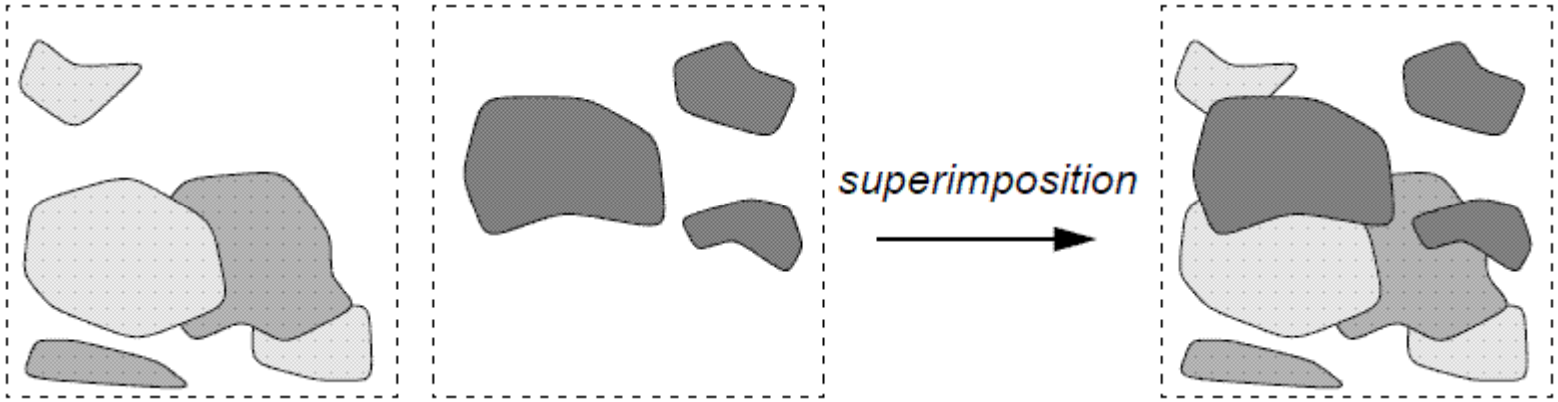
Spatial Partitions and Their Operations (II)

- The *overlay* operation transparently lays two partitions of different themes on top of each other and combines them into a new spatial partition.



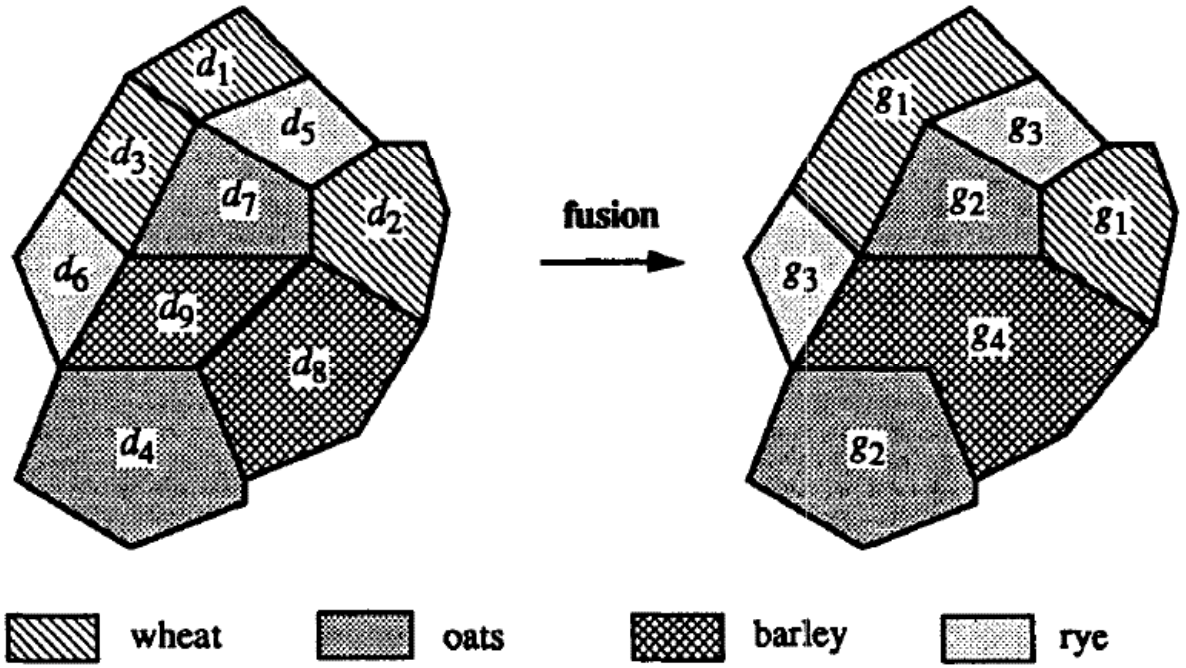
Spatial Partitions and Their Operations (III)

- The *superimposition* operation superimposes the spatial objects of a spatial partition on another spatial partition in order to cover and erase parts of the other partition.



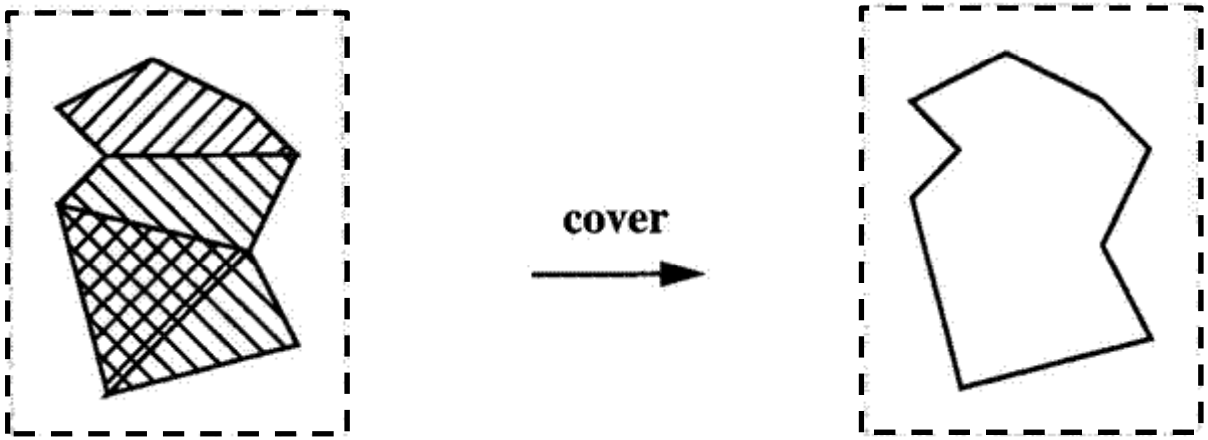
Spatial Partitions and Their Operations (IV)

- The *fusion* operation merges the region objects of a spatial partition on the basis of the equality of a non-spatial attribute. For each group of equal non-spatial objects, a spatial object is created as the geometric union of the set of spatial objects of each group.
- Example: Compute the spatial partition with the regions of the same land use



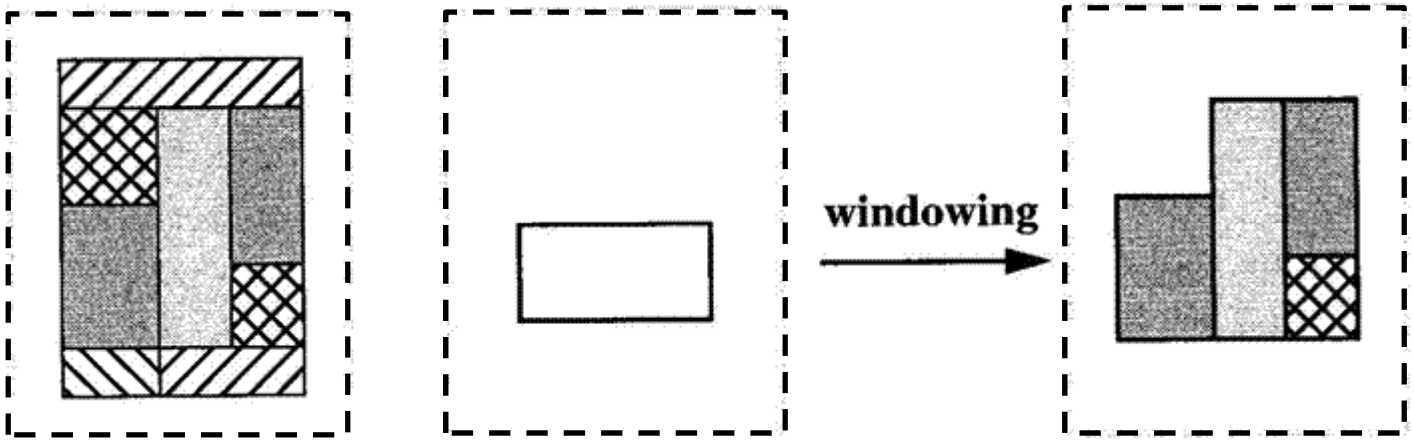
Spatial Partitions and Their Operations (V)

- The *cover* operation yields a spatial partition with a single region object as the geometric union of all region objects of a spatial partition.



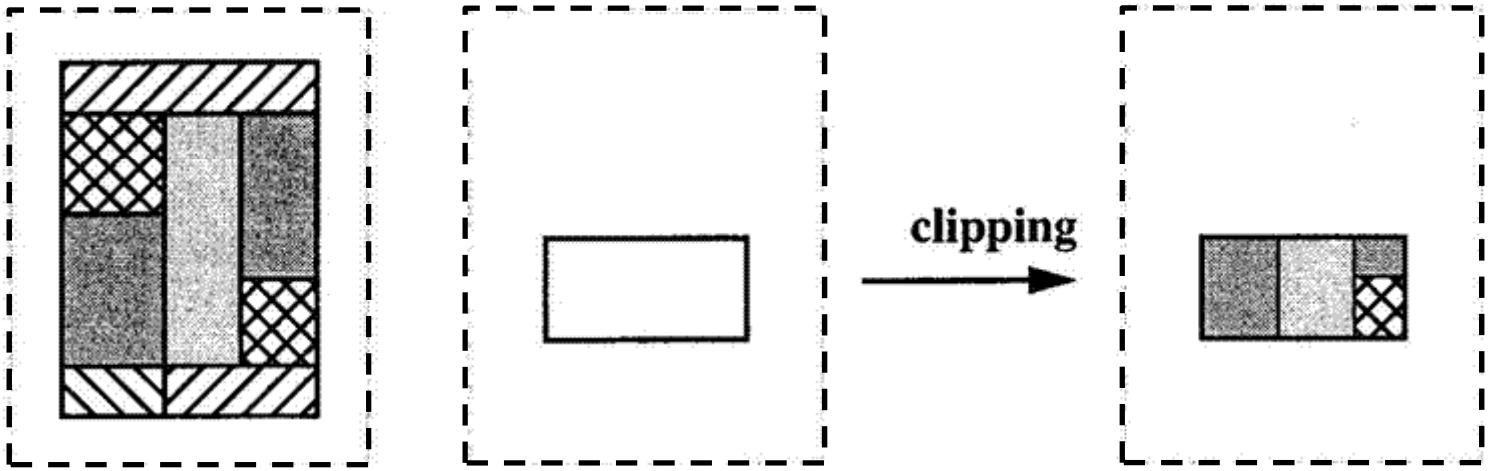
Spatial Partitions and Their Operations (VI)

- The *windowing* operation retrieves those regions of a spatial partition whose intersection with a given window (rectangle, circle, polygon) is not empty.



Spatial Partitions and Their Operations (VII)

- The *clipping* operation selects those parts of a spatial partition which lie inside a given window (rectangle, circle, polygon).

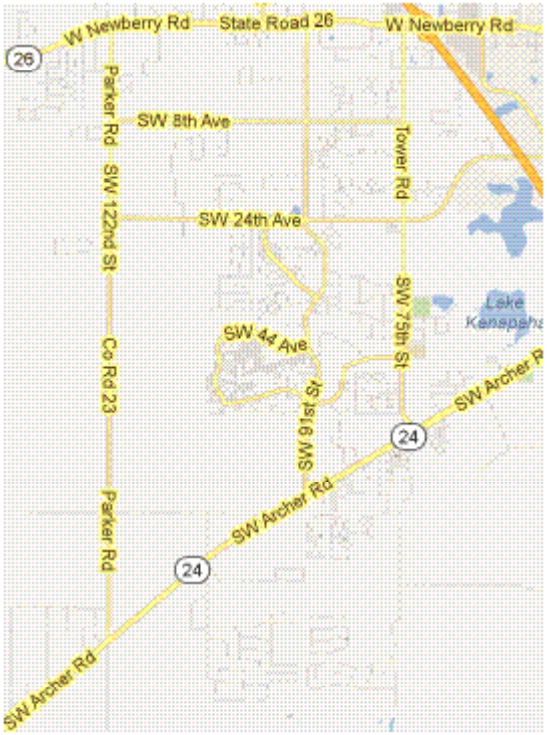


- Observation: The formal definition of all application-specific operations on spatial partitions can be derived from three fundamental operations
  - intersection
  - relabel
  - refine

Spatial Networks and Their Operations (I)

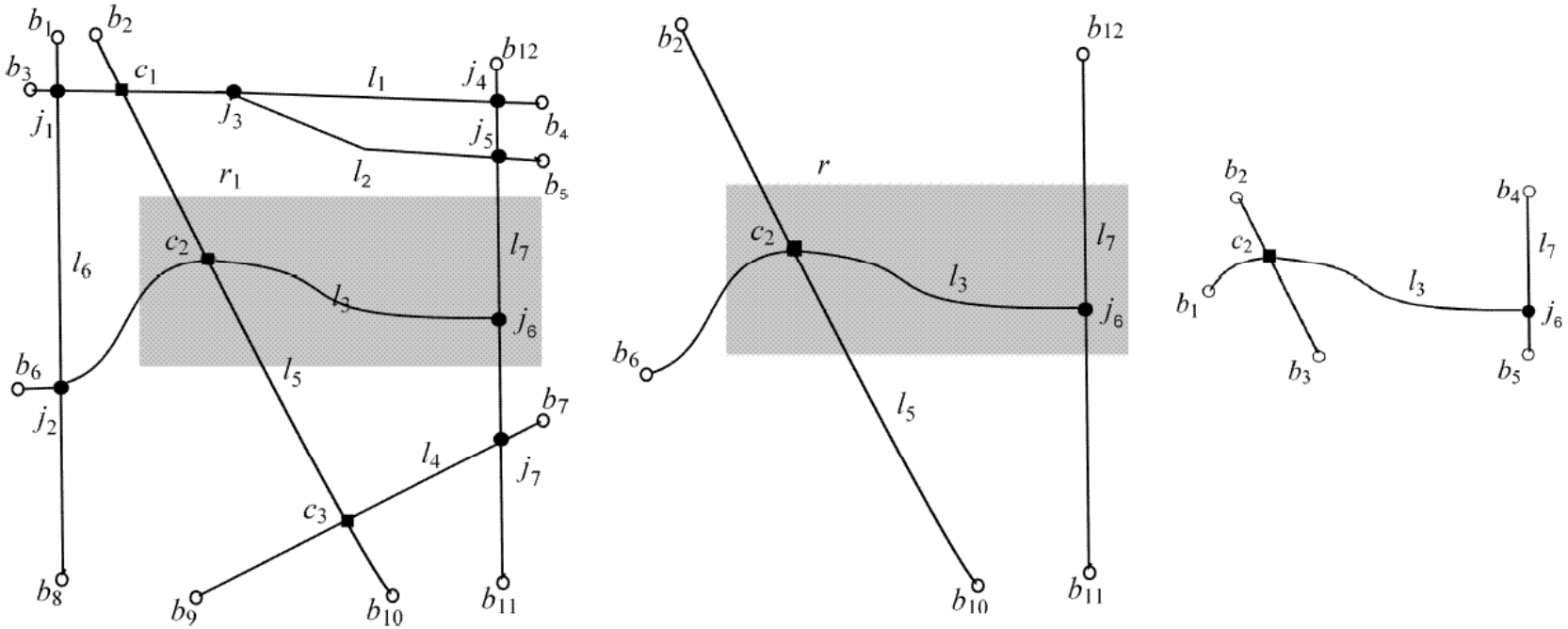
- Spatial network: spatially embedded graph in the plane consisting of pairwise disjoint, continous lines where each line is associated with an attribute (label) having a simple or even complex structure

- The *shortest path* (*shortest route*) operation determines the shortest path between any two network points with respect to
  - network distance
  - time
  - slope
  - any weight on which a distance metric can be defined
  - a combination of weights



Spatial Networks and Their Operations (II)

- *Windowing* and *clipping* again, but now applied to spatial networks (Euclidean range query)



Spatial Networks and Their Operations (III)

- The operations *spatial network union*, *spatial network intersection*, and *spatial network difference* compute the union, intersection, and difference of two spatial networks of the same label type or different label types.
  - *Spatial network intersection*: Given a bus route network and a taxi network. Which roads do they share?
  - *Spatial network union*: Given a bus route network and a metro network. Which locations can a passenger reach?
  - *Spatial network difference*: Given a bus route network and a taxi network. Which locations can taxis but not buses reach?

- The operation *spatial network buffer* considers a spatial network as a line object and computes a buffer around it.
  - Example: Given a bus route network. Compute the region that represents its “zone of attraction”.

Spatial Networks and Their Operations (IV)

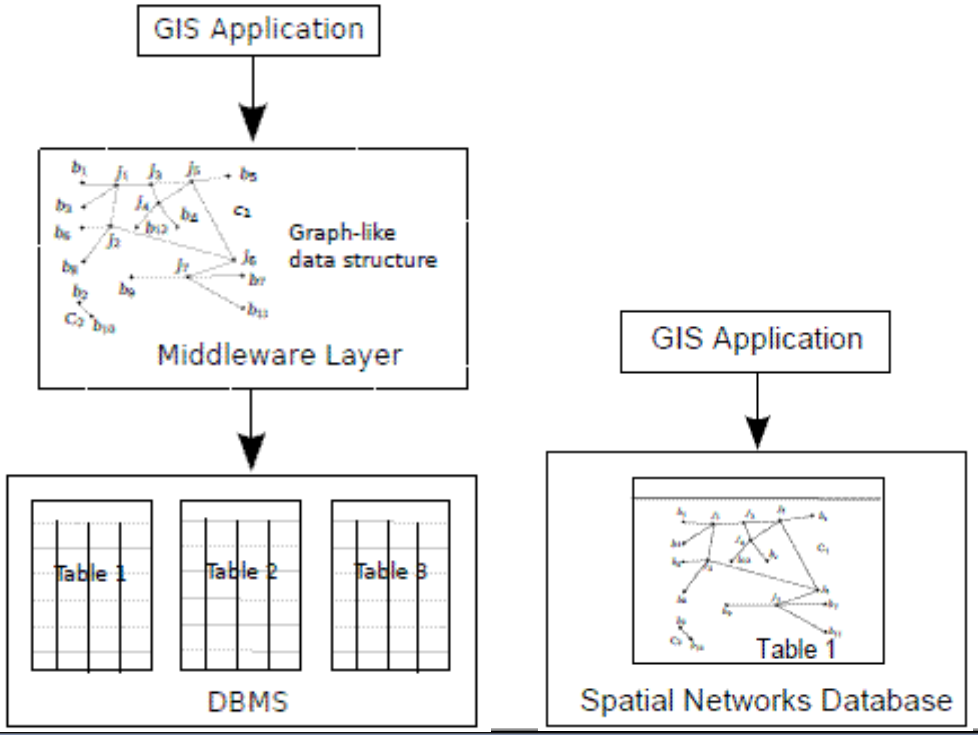
- The operation *get graph* extracts the graph structure of a spatial network.
- The operation *network distance* determines the distance between two points in a network.
  - Important for network range queries: Determine the spatial network that has a distance *d* from a network point *s*
- The operation *length* sums up the length of all edges of a spatial network
  - What is the overall length of the bus network in Gainesville?
- The operation *maxDist* determines the maximum distance within a spatial network
  - What is the farthest distance in the bus network?
- The operation *get transfer points* determines the common points of two different spatial networks where one can transfer from one network into the other.
- Many more operations …

Spatial Networks and Their Operations (V)

- Spatial network modeling in a database context
  - Very few interesting models exist but they are incomplete
  - Still a lot of effort needed
- Spatial network representation in a database context
  - Poor: network data are spread over a large collection of tables
  - Expensive joins needed to bring data together
  - Network operations cannot be applied to these representations
- Spatial network querying in a database context
  - Formulation of network queries is difficult
  - No spatial network queries possible since network operations are missing
  - High-level spatial network query language is missing
- Spatial network algorithms in a database context
  - A number of efficient spatial network algorithms is available
  - However: they depend on a particular spatial network database system

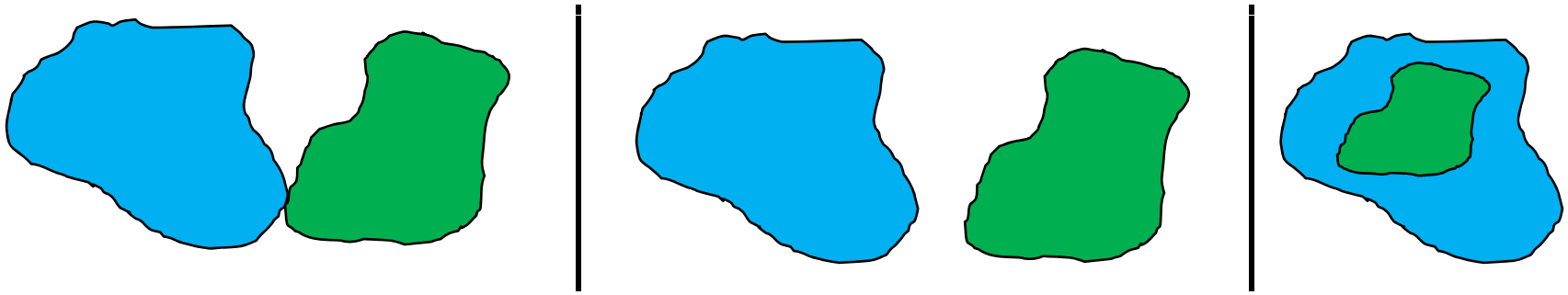
Spatial Databases cannot Store Spatial Partitions and Spatial Networks

- Both are highly complicated connectivity structures
- Both have complex operations involving large volumes of data
- Both are **not** *first-class citizens* in spatial databases



Topological Relationships (I)

- Topological relationships characterize the relative position of two spatial objects towards each other
- Examples:



meet *disjoint* *inside*

- Needed for spatial joins and spatial selections

```
SELECT cname, sname
FROM cities, states
WHERE loc inside territory
```

Topological Relationships (II)

- Requirements of a model for topological relationships
  - All topological relationships must be mutually exclusive
  - The set of topological relationships must be complete

- Proposed models:
  - 9-Intersection Matrix model (9IM)
    - based on point set theory and point set topology
    - takes into account the topological invariants of the intersections of the boundary, interior, and exterior of one spatial object with the corresponding components of another spatial object
  - Region Connection Calculus (RCC)
    - based on spatial logic, “pointless” approach
    - axiomatic approach to formulating topological relationships and reasoning about spatial data

Topological Relationships (III)

❖ 9-intersection matrix ($A, B \in \{point, line, region\}$)

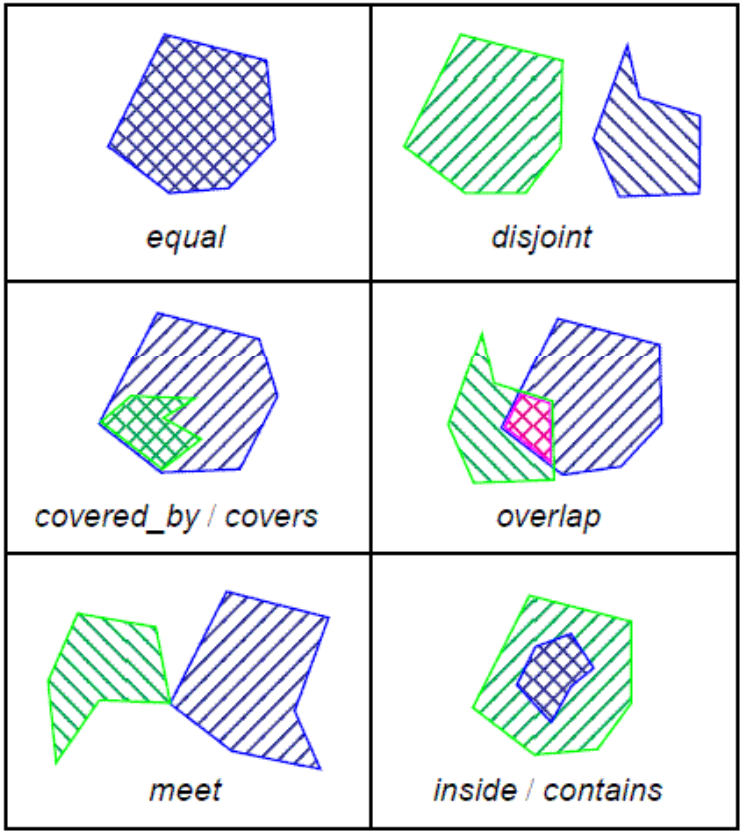
$$\begin{pmatrix} A^\circ \cap B^\circ \neq \varnothing & A^\circ \cap \partial B \neq \varnothing & A^\circ \cap B^- \neq \varnothing \\ \partial A \cap B^\circ \neq \varnothing & \partial A \cap \partial B \neq \varnothing & \partial A \cap B^- \neq \varnothing \\ A^- \cap B^\circ \neq \varnothing & A^- \cap \partial B \neq \varnothing & A^- \cap B^- \neq \varnothing \end{pmatrix}$$

$$\begin{pmatrix} 0 & 0 & 1 \\ 0 & 0 & 1 \\ 1 & 1 & 1 \end{pmatrix} \quad \begin{pmatrix} 0 & 0 & 1 \\ 0 & 1 & 1 \\ 1 & 1 & 1 \end{pmatrix} \quad \begin{pmatrix} 1 & 1 & 1 \\ 1 & 1 & 1 \\ 1 & 1 & 1 \end{pmatrix} \quad \begin{pmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

disjoint *meet* *overlap* *equal*

$$\begin{pmatrix} 1 & 0 & 0 \\ 1 & 0 & 0 \\ 1 & 1 & 1 \end{pmatrix} \quad \begin{pmatrix} 1 & 1 & 1 \\ 0 & 0 & 1 \\ 0 & 0 & 1 \end{pmatrix} \quad \begin{pmatrix} 1 & 1 & 1 \\ 0 & 1 & 1 \\ 0 & 0 & 1 \end{pmatrix} \quad \begin{pmatrix} 1 & 0 & 0 \\ 1 & 1 & 0 \\ 1 & 1 & 1 \end{pmatrix}$$

inside *contains* *covers* *coveredBy*



Topological Relationships (IV)

- Finding topological relationships: proof-by-constraint-and-drawing
- Phase 1
  - Starting point: $2^9 = 512$ possible matrices
  - Find constraint rules that must hold for valid topological relationships
    - Example: the intersection of the exteriors of two spatial objects is always non-empty (eliminates 256 matrices immediately)
    - Constraints are type-combination specific
  - Apply constraint rules one after the other and remove matrices that do not fulfill them
- Phase 2
  - For the remaining matrices, draw prototypical spatial configurations in the Euclidean plane to verify the existence of the corresponding topological relationships

Topological Relationships (V)

❖ Number of topological relationships for two simple spatial objects

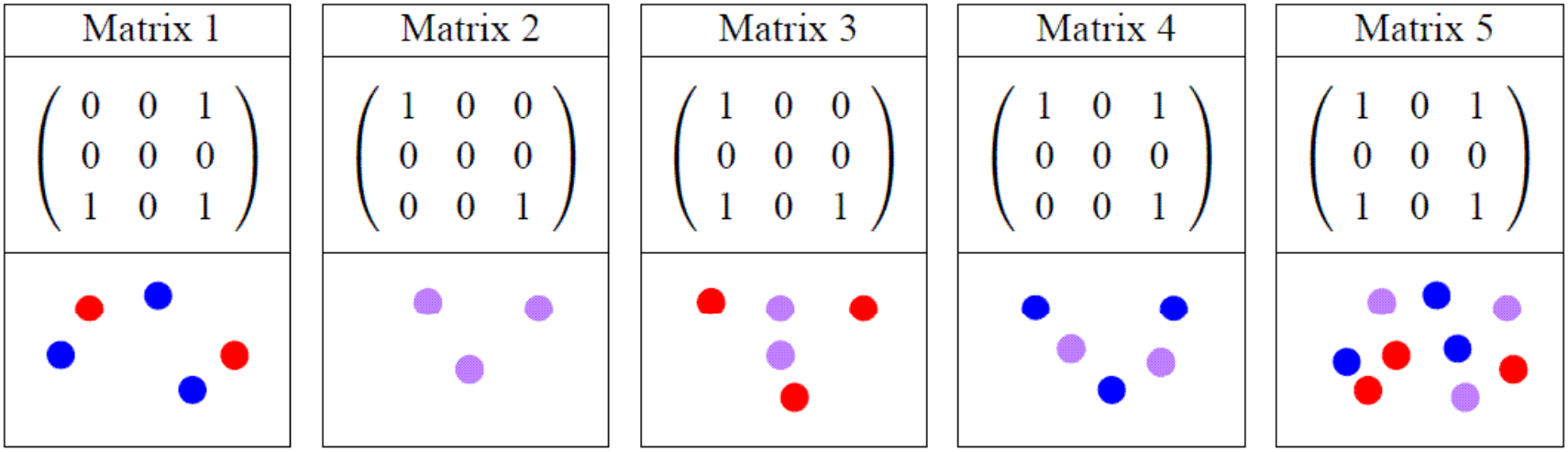
	Simple Point	Simple Line	Simple Region
Simple point	2	3	3
Simple line	3	33	19
Simple region	3	19	8

❖ Number of topological relationships for two complex spatial objects

	Complex Point	Complex Line	Complex Region
Complex point	5	14	7
Complex line	14	82	43
Complex region	7	43	33

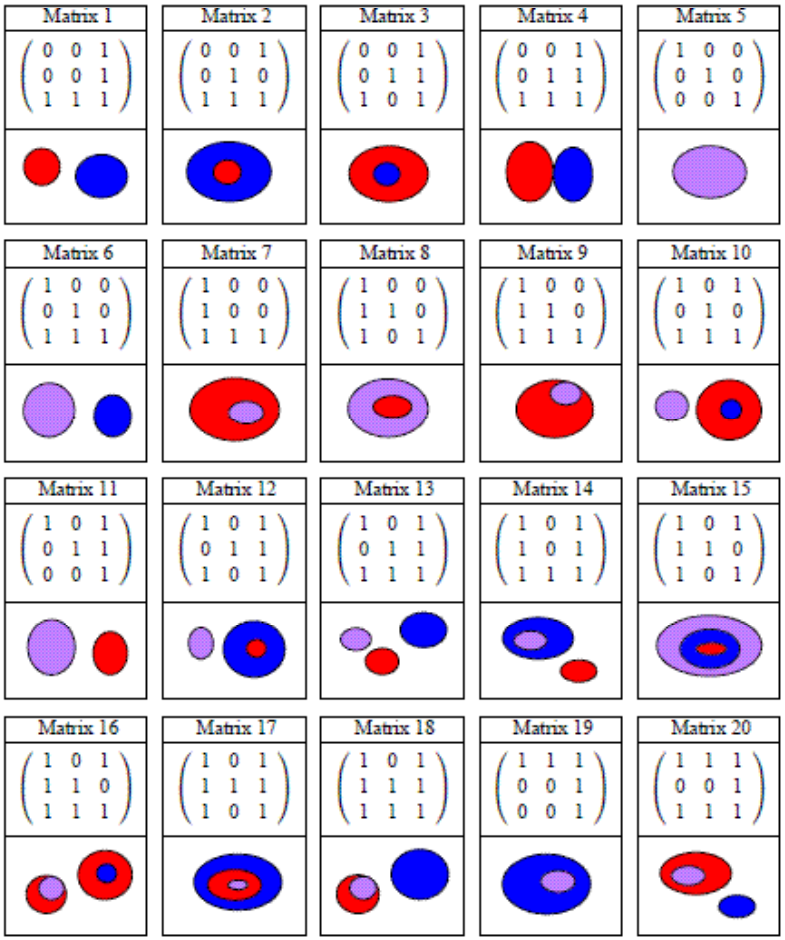
Topological Relationships (VI)

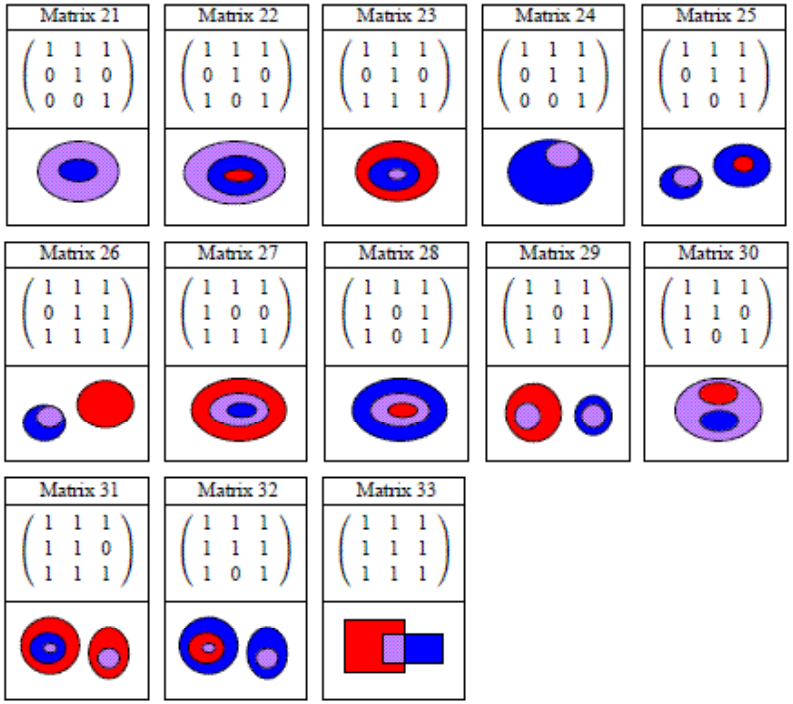
❖ Example 1: Topological relationships between two complex point objects



Topological Relationships (VII)

❖ Example 2: Topological relationships between two complex region objects





Topological Relationships (VIII)

- Problem: too many topological relationships that the user cannot handle
- Solution: clustering rules that put similar topological relationships together into a topological cluster predicate

Cluster predicate	Point/ Point	Line/ Line	Region/ Region	Point/ Line	Point/ Region	Line/ Region
$disjoint_c$	1	1–4	1	1, 2	1	1, 2
$meet_c$	–	5–32	2–4	3–6	2, 3	3–13
$covers_c$	–	49, 52, 69, 72	11, 21, 24	–	–	–
$coveredBy_c$	–	37, 38, 41, 42	6, 8, 9	–	–	15, 17, 28, 31
$inside_c$	3	34, 35, 39, 40	7	7, 8, 11, 12	4, 6	14, 16, 26, 27, 29, 30
$contains_c$	4	43, 46, 63, 66	19	–	–	–
$overlap_c$	5	44, 45, 47, 48, 50, 51, 53–62, 64, 65, 67, 68, 70, 71, 73–82	10, 12–18, 20 22, 23, 25–33	9, 10, 13, 14	5, 7	18–25, 32–43
$equal_c$	2	33, 36	5	–	–	–

Directional Relationships (I)

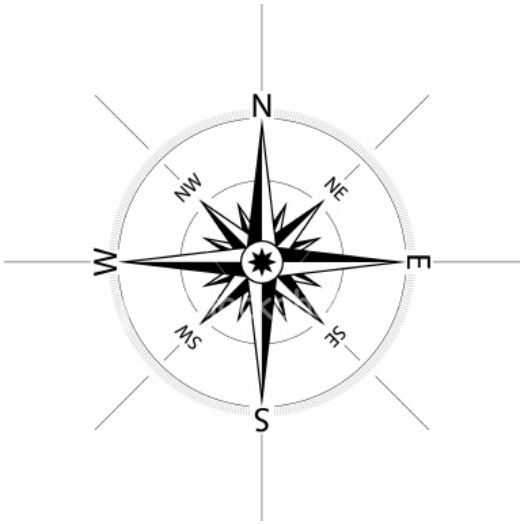
- Directional relationships characterize the directional orientation of two spatial objects towards each other
  - *absolute* directional relationships (cardinal directions): *north_of* and *southwest_of* with respect to a given reference or coordinate system
  - *relative* directional relationships: *in_front* and *left* with respect to an observer position

- Needed for spatial joins and spatial selections

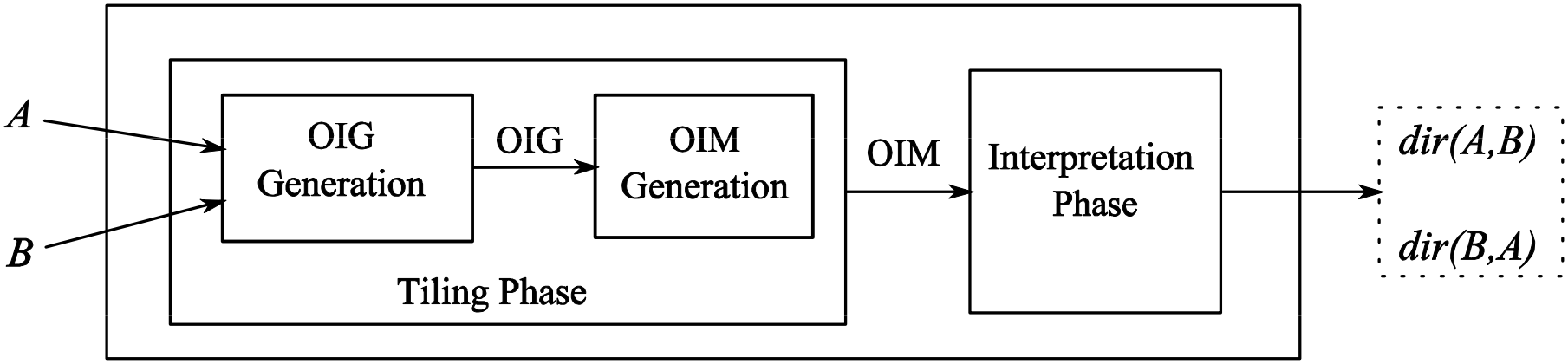
states(sname: varchar(50), territory: region)

```
SELECT s.sname
FROM states s,
        ( SELECT territory
          FROM states
          WHERE sname = 'Italy') t
WHERE s.territory northwest_of t.territory
```

Directional Relationships (II)

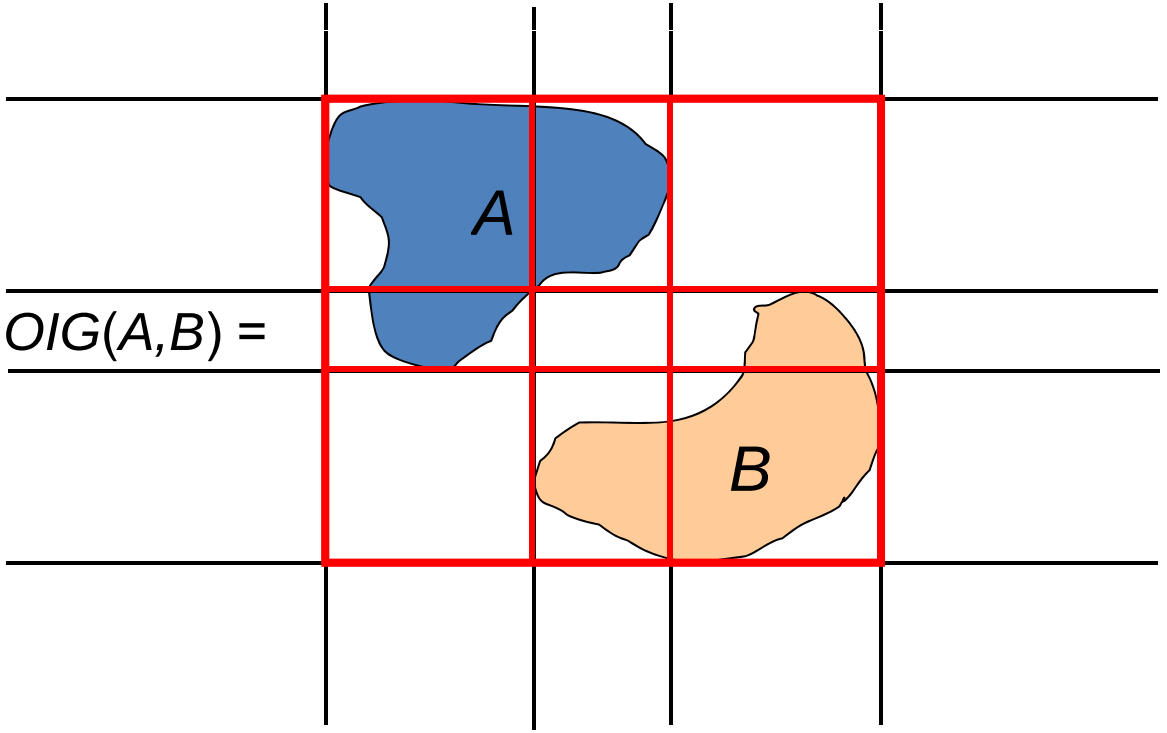


- Objects Interaction Matrix (OIM) model
  - Computational model for cardinal directions
  - Cognitive, subjective models can be built on top
- Two phases
  - Tiling Phase
  - Interpretation Phase



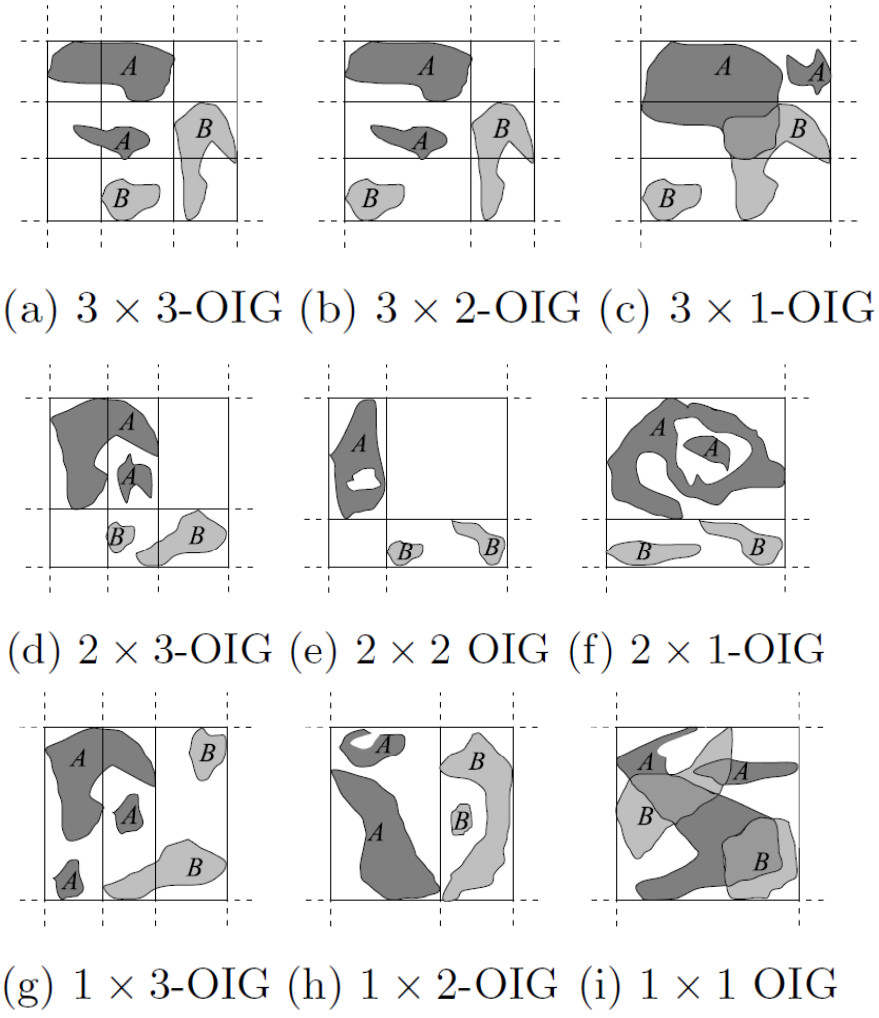
Directional Relationships (III)

- Tiling Phase
  - Determine Objects Interaction Grid (OIG) through partitioning lines
  - Determine Objects Interaction Grid Space (OIGS)



Directional Relationships (IV)

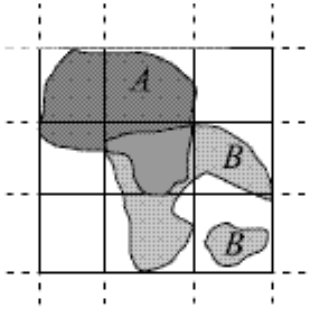
- Tiling Phase (*continued*)
  - 9 possible sizes of OIGs
  - $m \times n$-OIG for $m, n \in \{1, 2, 3\}$



Directional Relationships (V)

- Tiling Phase (*continued*)
  - Map OIG into an Objects Interaction Matrix (here: 3 × 3-matrix)

$$OIM(A,B) = \begin{pmatrix} \iota(A,B,t_{1,1}) & \iota(A,B,t_{1,2}) & \iota(A,B,t_{1,3}) \\ \iota(A,B,t_{2,1}) & \iota(A,B,t_{2,2}) & \iota(A,B,t_{2,3}) \\ \iota(A,B,t_{3,1}) & \iota(A,B,t_{3,2}) & \iota(A,B,t_{3,3}) \end{pmatrix}$$



$$\longrightarrow \begin{pmatrix} 1 & 1 & 0 \\ 1 & 3 & 2 \\ 0 & 2 & 2 \end{pmatrix}$$

  - Objects Interaction Function

$$\iota(A,B,t_{i,j}) = \begin{cases} 0 \text{ if } & A^\circ \cap t_{i,j}^\circ = \varnothing \ \wedge \ B^\circ \cap t_{i,j}^\circ = \varnothing \\ 1 \text{ if } & A^\circ \cap t_{i,j}^\circ \neq \varnothing \ \wedge \ B^\circ \cap t_{i,j}^\circ = \varnothing \\ 2 \text{ if } & A^\circ \cap t_{i,j}^\circ = \varnothing \ \wedge \ B^\circ \cap t_{i,j}^\circ \neq \varnothing \\ 3 \text{ if } & A^\circ \cap t_{i,j}^\circ \neq \varnothing \ \wedge \ B^\circ \cap t_{i,j}^\circ \neq \varnothing \end{cases}$$

Directional Relationships (VI)

- Tiling Phase (*continued*)
  - Numbers of possible $m \times n$-matrices

		n		
	×	1	2	3
	1	4	16	64
m	2	16	256	4096
	3	64	4096	262144

Total: 270756

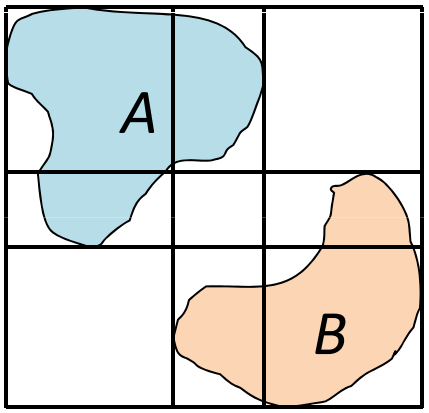
  - Numbers of valid OIMs for two complex/simple region objects

		n		
	×	1	2	3
	1	1/1	6/6	8/6
m	2	6/6	84/68	216/124
	3	8/6	216/124	1132/464

Total: 1677/805

Directional Relationships (VII)

- Interpretation Phase
  - Determine the location of each part of *A* and *B* in *OIM*(*A*, *B*)
  - Example



$$\begin{pmatrix} 1 & 1 & 0 \\ 1 & 0 & 2 \\ 0 & 2 & 2 \end{pmatrix}$$

  - *loc*(*A*, *OIM*(*A*, *B*)) = {(1, 1), (1, 2), (2, 1)}
  - *loc*(*B*, *OIM*(*A*, *B*)) = {(2, 3), (3, 2), (3, 3)}

Directional Relationships (VIII)

- Interpretation Phase (*continued*)
  - Set of basic cardinal directions CD = {*N*, *NW*, *W*, *SW*, *S*, *SE*, *E*, *NE*, *O*}
  - Determine the cardinal directions between the parts of *A* and *B* by an interpretation function ψ

$$\psi((i,j),(i',j')) = \begin{cases} \mathrm{N} & if \;\; i < i' \;\wedge\; j = j' \\ \mathrm{NW} & if \;\; i < i' \;\wedge\; j < j' \\ \mathrm{W} & if \;\; i = i' \;\wedge\; j < j' \\ \mathrm{SW} & if \;\; i > i' \;\wedge\; j < j' \\ \mathrm{S} & if \;\; i > i' \;\wedge\; j = j' \\ \mathrm{SE} & if \;\; i > i' \;\wedge\; j > j' \\ \mathrm{E} & if \;\; i = i' \;\wedge\; j > j' \\ \mathrm{NE} & if \;\; i < i' \;\wedge\; j > j' \\ \mathrm{O} & if \;\; i = i' \;\wedge\; j = j' \end{cases}$$

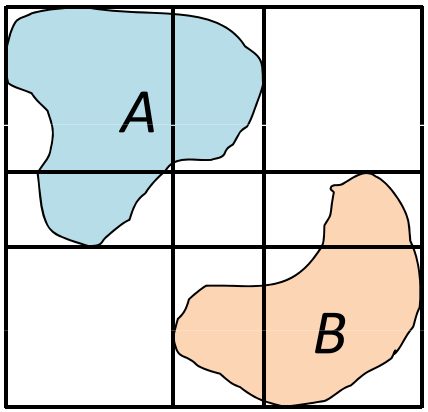
Directional Relationships (IX)

- Interpretation Phase (*continued*)
  - Interpretation table for the interpretation function ψ

(i,j) \ (i',j')	(1,1)	(1,2)	(1,3)	(2,1)	(2,2)	(2,3)	(3,1)	(3,2)	(3,3)
(1,1)	O	W	W	N	NW	NW	N	NW	NW
(1,2)	E	O	W	NE	N	NW	NE	N	NW
(1,3)	E	E	O	NE	NE	N	NE	NE	N
(2,1)	S	SW	SW	O	W	W	N	NW	NW
(2,2)	SE	S	SW	E	O	W	NE	N	NW
(2,3)	SE	SE	S	E	E	O	NE	NE	N
(3,1)	S	SW	SW	S	SW	SW	O	W	W
(3,2)	SE	S	SW	SE	S	SW	E	O	W
(3,3)	SE	SE	S	SE	SE	S	E	E	O

Directional Relationships (X)

- Interpretation Phase (*continued*)
  - Example (*continued*)



$$\begin{pmatrix} 1 & 1 & 0 \\ 1 & 0 & 2 \\ 0 & 2 & 2 \end{pmatrix}$$

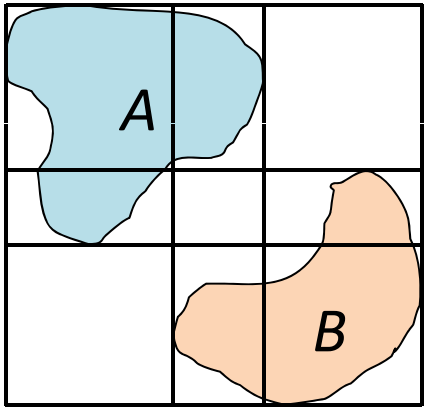
$\psi((1, 1), (2, 3)) = NW$
$\psi((1, 2), (3, 2)) = N$
...

  - Determine the cardinal directions $dir(A, B)$ between A and B

$dir(A, B) = \psi(loc(A, OIM(A, B)), loc(B, OIM(A, B)))$

Directional Relationships (XI)

- Interpretation Phase (*continued*)
  - Example (*continued*)



$$\begin{pmatrix} 1 & 1 & 0 \\ 1 & 0 & 2 \\ 0 & 2 & 2 \end{pmatrix}$$

$$\begin{aligned} dir(A, B) &= \psi(loc(A, OIM(A, B)), loc(B, OIM(A, B))) \\ &= \psi(\{(1, 1), (1, 2), (2, 1)\}, \\ &\quad \{(2, 3), (3, 2), (3, 3)\}) \\ &= \{\psi((1, 1), (2, 3)), \psi((1, 1), (3, 2)), \\ &\quad \psi((1, 1), (3, 3)), \ldots, \psi((2, 1), (3, 3))\} \\ &= \{NW, N, W\} \end{aligned}$$

$$\begin{aligned} dir(B, A) &= \psi(loc(B, OIM(A, B)), loc(A, OIM(A, B))) \\ &= \psi(\{(2, 3), (3, 2), (3, 3)\}, \\ &= \quad \{(1, 1), (1, 2), (2, 1)\}) \\ &= \{\psi((2, 3), (1, 1)), \psi((2, 3), (1, 2)), \\ &\quad \psi((2, 3), (2, 1)), \ldots, \psi((3, 3), (2, 1))\} \\ &= \{SE, S, E\} \end{aligned}$$

Directional Relationships (XII)

- Existential predicates

$$
\begin{aligned}
A\ north\_of\ B &\overset{\text{def}}{\Leftrightarrow} N \in dir(A,B)\\
A\ west\_of\ B &\overset{\text{def}}{\Leftrightarrow} W \in dir(A,B)\\
A\ south\_of\ B &\overset{\text{def}}{\Leftrightarrow} S \in dir(A,B)\\
A\ east\_of\ B &\overset{\text{def}}{\Leftrightarrow} E \in dir(A,B)\\
A\ origin\_with\ B &\overset{\text{def}}{\Leftrightarrow} O \in dir(A,B)\\
A\ northwest\_of\ B &\overset{\text{def}}{\Leftrightarrow} NW \in dir(A,B)\\
A\ southwest\_of\ B &\overset{\text{def}}{\Leftrightarrow} SW \in dir(A,B)\\
A\ northeast\_of\ B &\overset{\text{def}}{\Leftrightarrow} NE \in dir(A,B)\\
A\ southeast\_of\ B &\overset{\text{def}}{\Leftrightarrow} SE \in dir(A,B)
\end{aligned}
$$

- *dir*(*A*, *B*) = {*NW*, *N*, *W*} means

$$
\begin{aligned}
&A\ west\_of\ B \ \wedge\ A\ northwest\_of\ B \ \wedge\ A\ north\_of\ B \ \wedge\\
&\neg(A\ northeast\_of\ B) \ \wedge\ \neg(A\ east\_of\ B) \ \wedge\ \neg(A\ southeast\_of\ B) \ \wedge\\
&\neg(A\ south\_of\ B) \ \wedge\ \neg(A\ southwest\_of\ B) \ \wedge\ \neg(A\ origin\_with\ B)
\end{aligned}
$$

Directional Relationships (XIII)

- Similarly-oriented directional predicates

$$A\ northern\_of\ B \overset{\text{def}}{\Leftrightarrow} A\ north\_of\ B \vee A\ northwest\_of\ B \vee A\ northeast\_of\ B$$

- Strict directional predicates

$$\begin{aligned} A\ strictly\_north\_of\ B \overset{\text{def}}{\Leftrightarrow}\ & A\ north\_of\ B \wedge \\ & \neg(A\ south\_of\ B) \wedge \neg(A\ west\_of\ B) \wedge \\ & \neg(A\ east\_of\ B) \wedge \neg(A\ northwest\_of\ B) \wedge \\ & \neg(A\ northeast\_of\ B) \wedge \neg(A\ southwest\_of\ B) \wedge \\ & \neg(A\ southeast\_of\ B) \wedge \neg(A\ origin\_with\ B) \end{aligned}$$

- Surround directional predicates

$$\begin{aligned} A\ surrounds\ B \overset{\text{def}}{\Leftrightarrow} & A\ north\_of\ B \wedge A\ northeast\_of\ B \wedge A\ east\_of\ B \wedge \\ & A\ southeast\_of\ B \wedge A\ south\_of\ B \wedge A\ southwest\_of\ B \wedge \\ & A\ west\_of\ B \wedge A\ northwest\_of\ B \wedge A\ origin\_with\ B \end{aligned}$$

Spatial Querying (I)

- Tables
  - CREATE TABLE Country(name varchar(30), pop int, shape region);
  - CREATE TABLE River(name varchar(30), shape line);
  - CREATE TABLE City(name varchar(30), pop int, shape point);
- Q1: Find the names of all countries that are neighbors of the USA.

```
SELECT    C1.name AS neighbors
FROM      Country C1, Country C2
WHERE     C1.shape meets C2.shape AND C2.name = 'USA'
```

- Q2: The St. Lawrence River can supply water to cities that are within 300 km. Determine those cities and compute their distance from the river.

```
SELECT    C.name, dist(C.shape, R.shape) AS distance
FROM      City C, River R
WHERE     C1.shape inside bufferZone(R.shape, 300) AND
          R.name = 'St. Lawrence River'
```

Spatial Querying (II)

- Q3: List the length of the rivers in each of the countries they pass through together with the river name and the country name.

```
SELECT    R.name, C.name,
          length(intersection(R.shape, C.shape)) AS rLength
FROM      River R, Country C
WHERE     R.shape intersects C.shape
```

- Q4: List all countries, ordered by the number of adjacent countries.

```
SELECT    C.name, COUNT(C1.name) AS noOfNeighbors
FROM      Country C, Country C1
WHERE     C.shape meets C1.shape
GROUP BY  C.name
ORDER BY  noOfNeighbors DESC
```

Spatial Querying (III)

- Q5: List the names of the pairs of all countries that are separated by exactly one other country.

```
SELECT    C1.name, C3.name
FROM      Country C1, Country C2, Country C3
WHERE     C1.shape meets C2.shape AND C2.shape meets C3.shape
          AND C1.shape disjoint C3.shape
```

- Q6: List the names of all countries that are north of “Mexico”.

```
SELECT    C.name
FROM      Country C, Country C1
WHERE     C.shape north_of C1.shape AND C1.name = ‘Mexico’
```

Effect of strictly_north_of, northern_of, strictly_northern_of?

Spatial Querying (IV)

- Spatial data types
  - are specified as abstract data types (ADTs)
  - ADTs are used as attribute types in relational (or other) schemas
  - Internals of ADTs are invisible to the user
  - ADT implementations can be exchanged without the need to redefine database schemas and reformulate queries

- Spatial operations and predicates
  - are high-level methods
  - are embedded into an extension of the SQL query language
  - Algorithms for the operations and predicates are invisible to the user
  - Algorithms for the operations and predicates can be exchanged without the need to reformulate queries since the interfaces (signatures) stay the same

Outline

Outline – Spatiotemporal Data Modeling

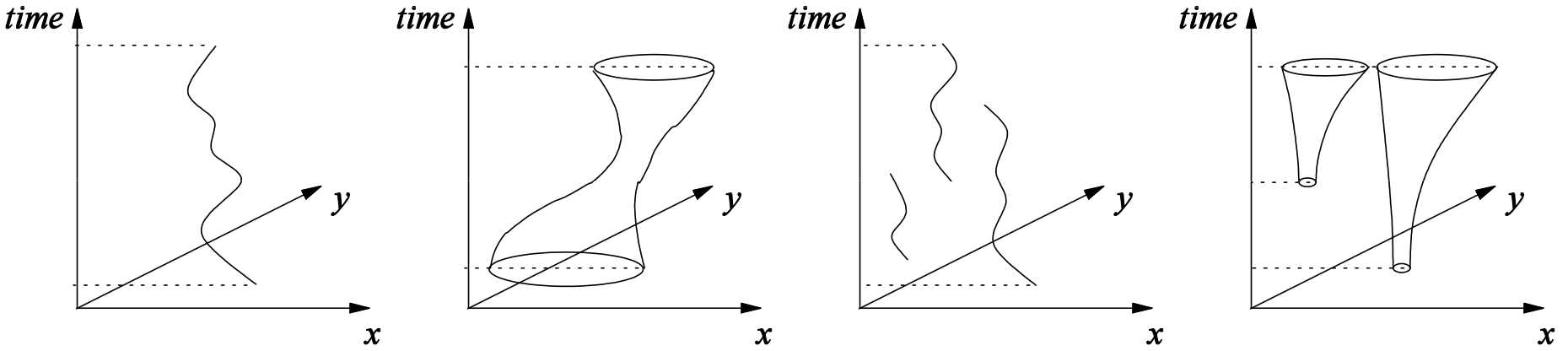
- What are Spatiotemporal Data Types?
- Uncertain Moving Objects
- Predictive Moving Objects
- Spatiotemporal Partitions and Moving Objects in Spatial Networks
- Spatiotemporal Operations
- Spatiotemporal Predicates
- Spatiotemporal Querying

What are Spatiotemporal Data Types? (I)

- Spatiotemporal data types are data types to represent moving objects.
- A moving object represents the *continuous* evolution of a spatial object over time.
- Moving point
  - Only time-dependent location is of interest
  - Examples: eyes of tropical cyclones, cell phone users, terrorists, whales
- Moving region
  - Also the time-dependent shape and/or areal extent is of interest
  - Examples: hurricanes, forest fires, oil spills, diseases, glaciers
- Moving line
  - The time-dependent shape and/or linear extent is of interest
  - Examples: traffic jams, front of an army; boundary of any moving region

What are Spatiotemporal Data Types? (II)

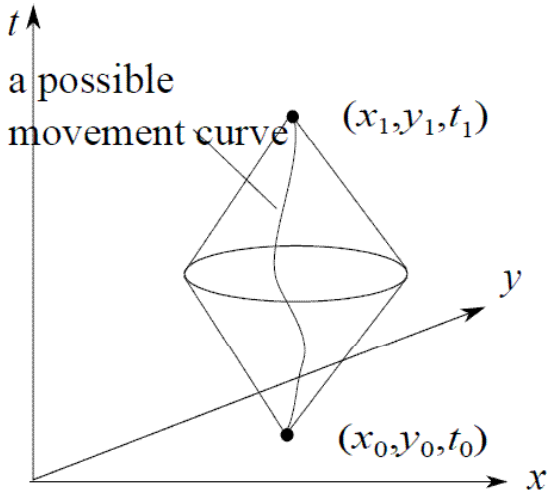
- Formally: Let $\alpha \in \{point, line, region\}$, and let *time* be the data type to represent time instants. Then a (historical) moving object *m* is a function of a spatiotemporal data type $\tau(\alpha) = time \rightarrow \alpha$.
  - $hmpoint = \tau(point) = time \rightarrow point$
  - $hmregion = \tau(region) = time \rightarrow region$
  - $hmline = \tau(line) = time \rightarrow line$

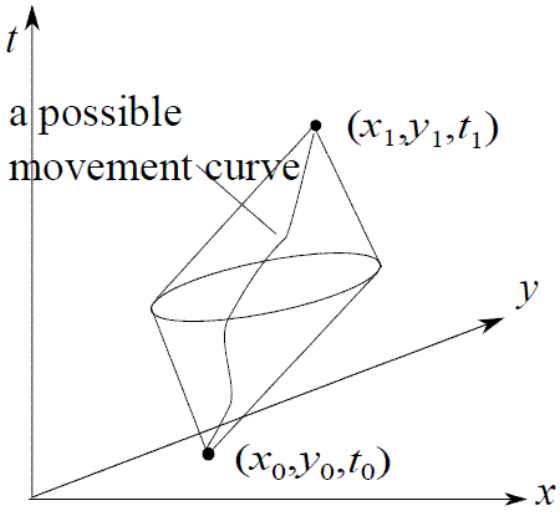


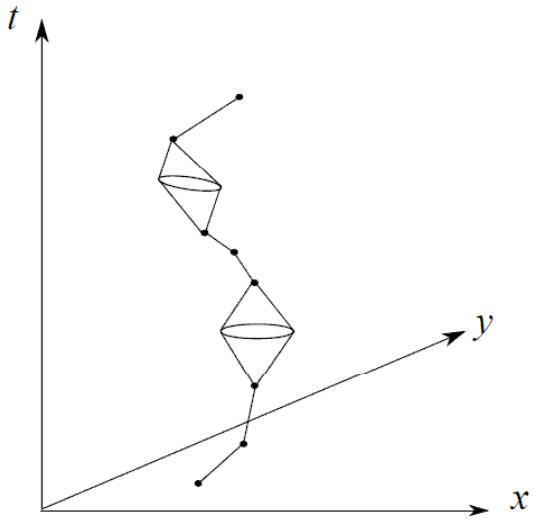
simple moving point | simple moving region | complex moving point | complex moving region

Uncertain Moving Objects

- A moving object $m \in \tau(\alpha)$ is a partial function and can have definition gaps
- If the maximum velocity of *m* is known, the uncertainty region of *m* can be computed as a space-time prism.

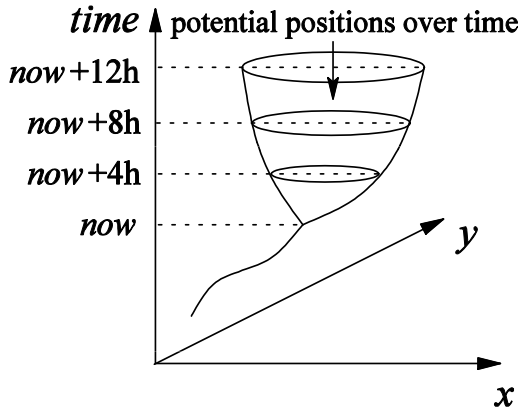






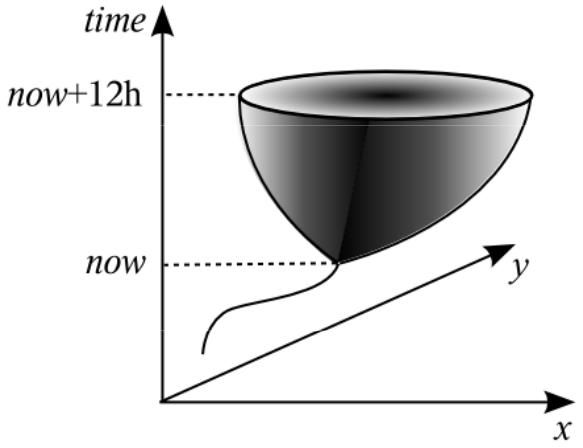
Predictive Moving Objects (I)

- Many applications are interested in a forecast of the (near) future temporal evolution of a spatial object (e.g., hurricane research, meteorology, fire management, disaster management, disease control)
- Example: Hurricane Ernesto (August 2012)
- Prediction is application-specific and afflicted with uncertainty
- Geometric aspect can be represented by spatiotemporal data types $\tau(\alpha)$



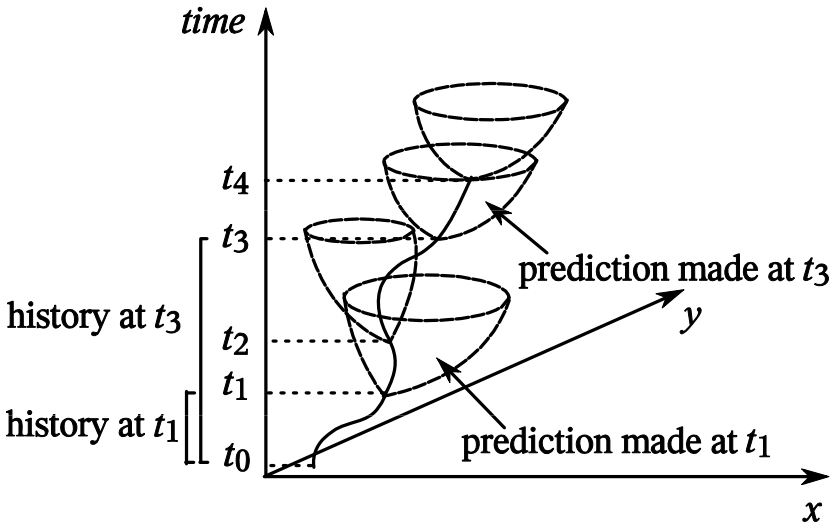
Predictive Moving Objects (II)

- Uncertainty aspect represented by a confidence distribution function that is assigned an domain/application-specific distribution function
- Nature of these functions: probabilistic, fuzzy, possibilistic, rough, …
- *Balloon* metaphor taken from hurricane research
  - Past movement of a hurricane resembles the string of a balloon
  - Future prediction of a hurricane resembles the body of a balloon
- Balloon object = historical moving object + predictive moving object (spatiotemporal snapshot)
- Observation: *dim*(historical moving object) ≤ *dim*(predictive moving object)



Predictive Moving Objects (III)

- Moving balloon objects represent the dynamics of moving objects as a continuous sequence of balloon objects
- Past movement is updated (historical accumulation)
- New predictions and employed prediction models are possible due to new insights and input factors
- Quality of predictions can be checked



Spatiotemporal Partitions and Moving Objects in Spatial Networks

- Spatiotemporal partitions (ongoing research)
  - represent the temporal evolution of spatial partitions
  - Maintain partition constraints over time
  - Examples: change of temperature zones (weather maps on TV), temporal evolution of icing, development of unemployment rate
- Moving objects in spatial networks (ongoing research)
  - Moving objects are spatially constrained
  - Movement of spatial objects depends on speed, slope, number of lanes, other moving objects, and so on
  - Examples: car navigation, location-based services, mobile computing, traffic jams, pipelines (water, oil, power), Internet
  - Continuous range queries interesting for car navigation
    Example: Permanently report the three nearest restaurants while driving

Spatiotemporal Operations (I)

- Operations for projection to domain/range
  - The operation *deftime* returns the times for which a moving object (seen as a function) is defined.

    deftime : $\tau(\alpha) \rightarrow$ *periods* [*periods* $\equiv$ type for interval sets]
  - The operation *rangevalues* returns the values assumed over time as a set of intervals.

    rangevalues : $\tau(\alpha) \rightarrow$ range(α) [1D]
  - The operation *locations* determines those components of the projection of a discretely moving point into the plane that form a *point* object.

    locations : τ(*point*) $\rightarrow$ *point*
  - The operation *trajectory* determines those components of the projection of a continously moving point into the plane that form a *line* object.

    trajectory : τ(*point*) $\rightarrow$ *line*

Spatiotemporal Operations (II)

- Operations for projection to domain/range (*continued*)
  - The operation *routes* returns the projection of a discretely moving line object.

    $routes : \tau(line) \rightarrow line$

  - The operation *traversed* returns the projection of a continuously moving line object.

    $traversed : \tau(\alpha) \rightarrow region$ for $\alpha \in \{line, region\}$

  - The operation *inst* yields the time component of a (*time*, *value*) pair.

    $inst : intime(\alpha) \rightarrow time$

  - The operation *val* yields the value component of a (*time*, *value*) pair.

    $val : intime\ (\alpha) \rightarrow \alpha$ [$intime = time \times \alpha$]

Spatiotemporal Operations (III)

- Operations for interaction with domain/range
  - The operation *atinstant* restricts a moving object to a given time instant, resulting in a (*time*, *value*) pair (time slice operator).

    $atinstant : \tau(\alpha) \times time \rightarrow intime(\alpha)$
  - The operation *atperiods* restricts a moving object to a given set of time intervals.

    $atperiods : \tau(\alpha) \times periods \rightarrow \tau(\alpha)$
  - The operations *initial* and *final* return the first and last (*time*, *value*) pair, respectively.

    $initial, final : \tau(\alpha) \rightarrow intime(\alpha)$
  - The operation *present* checks whether a moving object exists at a given time instant, or is ever present during a given set of time intervals, respectively.

    $present : \tau(\alpha) \times time \rightarrow bool$ $present : \tau(\alpha) \times periods \rightarrow bool$

Spatiotemporal Operations (IV)

- Operations for interaction with domain/range (*continued*)
  - The operation *at* restricts a moving object to a value in the range.

    $at : \tau(\alpha) \times \alpha \rightarrow \tau(\alpha)$ [1D] $at : \tau(\alpha) \times range(\alpha) \rightarrow \tau(\alpha)$ [1D]

    $at : \tau(\alpha) \times point \rightarrow \tau(point)$ [2D]

    $at : \tau(\alpha) \times \beta \rightarrow \tau(\gamma)$ [2D] with γ = if $dim(\alpha) \leq dim(\beta)$ then α else β

  - The operations *atmin* and *atmax* restrict a moving object to the times when it is minimal or maximal with respect to the total order on this space.

    $atmin, atmax : \tau(\alpha) \rightarrow \tau(\alpha)$ [1D]

  - The operation *passes* checks whether a moving object ever assumed (one of) the value(s) given as a second argument.

    $passes : \tau(\alpha) \times \beta \rightarrow bool$ with γ = if $dim(\alpha) \leq dim(\beta)$ then α else β

Spatiotemporal Operations (V)

- Derivable spatiotemporal operations by temporal lifting: automatically derive spatiotemporal operations from spatial operations based on a clear semantics

- Examples
  - *dist*: *point* $\times$ *region* $\rightarrow$ *real*
    Dist: τ(*point*) $\times$ τ(*region*) $\rightarrow$ τ(*real*)
    Dist: *hmpoint* $\times$ *hmregion* $\rightarrow$ *hmreal*
  - *intersection*: *line* $\times$ *region* $\rightarrow$ *line*
    Intersection: τ(*line*) $\times$ τ(*region*) $\rightarrow$ τ(*line*)
    Intersection: *hmline* $\times$ *hmregion* $\rightarrow$ *hmline*
  - *area*: *region* $\rightarrow$ *real*
    Area: τ(*region*) $\rightarrow$ τ(*real*)
    Area: *hmregion* $\rightarrow$ *hmreal*

Spatiotemporal Operations (VI)

- Let $f : \alpha_1 \times \ldots \times \alpha_n \rightarrow \beta$ be a spatial operation with $\alpha_i \in \{point, line, region\}$ and $\beta \in \{point, line, region, int, real, bool\}$. Its corresponding temporally lifted version, that is, its corresponding spatiotemporal operation is defined by

$$\uparrow f : \tau(\alpha_1) \times \ldots \times \tau(\alpha_n) \rightarrow \tau(\beta)$$

with

$$\uparrow f(S_1, \ldots, S_n) := \{(t, f(S_1(t), \ldots, S_n(t))) \mid t \in time\}$$

- Examples
  - *Dist* = $\uparrow$*dist*
  - *Intersection* = $\uparrow$*intersection*
  - *Area* = $\uparrow$*area*

Spatiotemporal Predicates (I)

- Problem: Temporal lifting of spatial predicates does not lead to predicates
- Example:
  - Spatial predicate: *inside* : *region* $\times$ *region* $\rightarrow$ *bool*
  - Temporally lifted spatial predicate:
    $\uparrow$*inside* : τ(*region*) $\times$ τ(*region*) $\rightarrow$ τ(*bool*)
- A lifted spatial predicate yields a defined value only on the intersection of the domains of two moving objects.
- A spatiotemporal predicate is a function of type $\tau(\alpha) \times \tau(\beta) \rightarrow$ *bool* for $\alpha, \beta \in$ {*point*, *line*, *region*}.

Spatiotemporal Predicates (II)

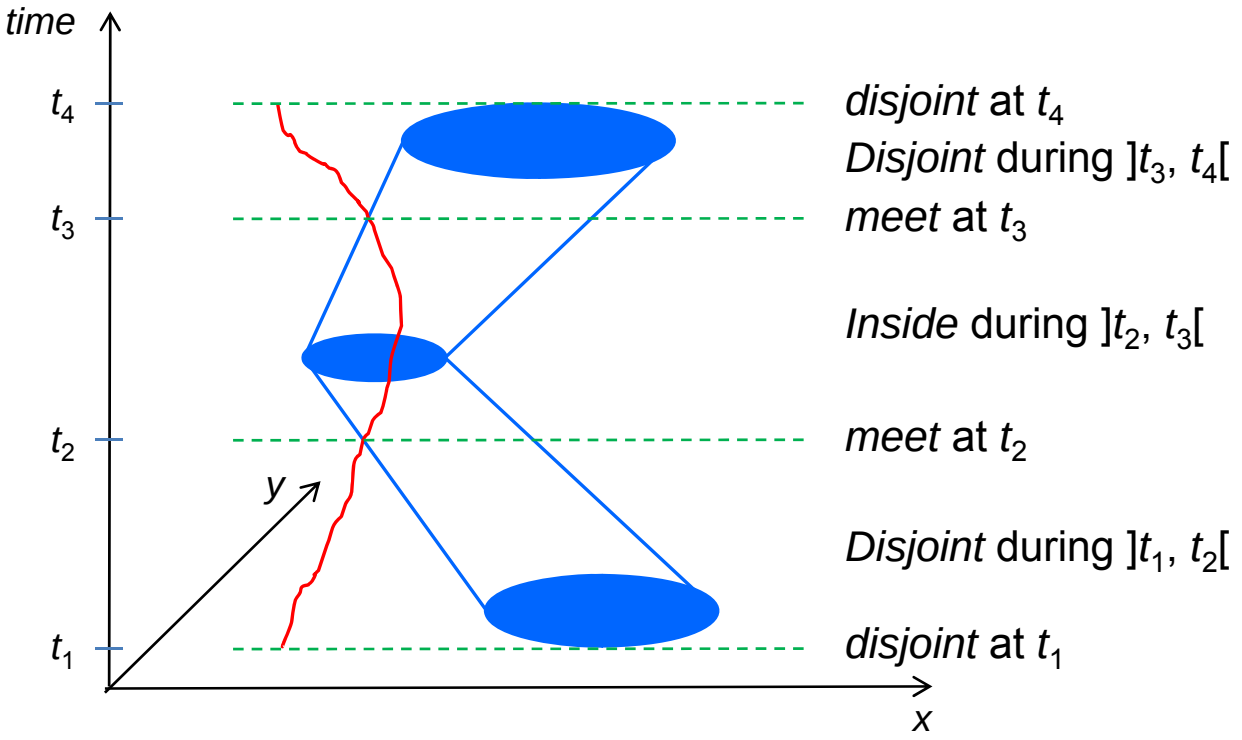
- Basic spatiotemporal predicates
  - defined by temporal lifting and temporal aggregation
  - each predicate has an own "preferred" temporal aggregation
  - Examples
    - *disjoint*: disjointedness required only on the common lifetime
    - *inside*: containment required only with respect to the lifetime of the first operand object
    - Define default expected aggregation behavior

$$
\begin{aligned}
Disjoint &:= \overline{disjoint} \\
Meet &:= \overleftrightarrow{meet} \\
Overlap &:= \overleftrightarrow{overlap} \\
Equal &:= \overleftrightarrow{equal} \\
Covers &:= \overrightarrow{covers} \\
CoveredBy &:= \overleftarrow{coveredBy} \\
Contains &:= \overrightarrow{contains} \\
Inside &:= \overleftarrow{inside}.
\end{aligned}
$$

- A spatiotemporal predicate describes the *continuous* development of the topological relationships of two moving objects over time.

Spatiotemporal Predicates (III)

❖ Example: air plane (red) crosses a hurricane (blue)



Spatiotemporal Predicates (IV)

- Let *P* be a basic spatiotemporal predicate, S_1 and S_2 be two moving objects, and *I* be a (half-) open or closed time interval. Then *predicate constriction* is defined as

  $P_I(S_1, S_2) := P(S_1|_I, S_2|_I)$

- Example (plane *F*, hurricane *H*)
  - *Inside*(*F*, *H*) = *false*
  - $Inside|_{]t2,\ t3[}(F, H) = true$
- Two classes of topological predicates
  - Instant predicates can be true for an instant time (but also for a period of time)

    equal, *meets*, *covers*, *coveredBy*
  - Period predicates can only hold for a period of time

    disjoint, *overlap*, *inside*, *contains*

Spatiotemporal Predicates (V)

- A spatiotemporal predicate is an *alternating temporal sequence* of topological relationships that hold over time intervals or at time points.
- A spatiotemporal predicate is an *alternating temporal sequence* of topological relationships and basic spatiotemporal predicates.
- Symbol “>>” is *temporal composition operator*
- Examples of spatiotemporal predicates for a moving point object and a moving region object
  - *Enter* := *Disjoint* >> *meet* >> *Inside*
  - *Cross* := *Disjoint* >> *meet* >> *Inside* >> *meet* >> *Disjoint*
  - *Leave* := *rev*(*Enter*)
  - *Cross* := *Enter* >> *Leave*
  - *TempLeave* := (*Meet* >> *Disjoint*)* >> *Meet*

Spatiotemporal Predicates (VI)

- Examples of spatiotemporal predicates for two moving region objects
  - *Touch* := *Disjoint* >> *meet* >> *Disjoint*
  - *Snap* := *Disjoint* >> *Meet*
  - *Release* := *Meet* >> *Disjoint*
  - *Bypass* := *Snap* >> *Release*
  - *Excurse* := *Meet* >> *Disjoint* >> *Meet*
  - *Into* := *meet* >> *Overlap* >> *coveredBy*
  - *OutOf* := *rev*(*Into*)

Spatiotemporal Predicates (VII)

- Examples of spatiotemporal predicates for two moving region objects (*continued*)
  - *Enter* := *Disjoint* >> *Into* >> *Inside*
  - *Leave* := *rev*(*Enter*)
  - *Cross* := *Enter* >> *Leave*
  - *Melt* := *Disjoint* >> *meet* >> *Overlap* >> *Equal*
  - *Separate* := *rev*(*Melt*)
  - *Spring* := *equal* >> *Overlap* >> *meet* >> *Disjoint*
  - *Graze* := *Disjoint* >> *meet* >> *Overlap* >> (*CoveredBy* >> *Overlap*)* >> *meet* >> *Disjoint*

Spatiotemporal Querying (I)

- Tables
  - CREATE TABLE Flight(id varchar(30), route hmpoint);
  - CREATE TABLE Weather(name varchar(30), kind varchar(50), extent hmregion);

- Q1: What are the departure and arrival times of flight LH 257, and how long is the part of the route of this flight that lies within France?

```
CREATE TABLE France AS
        (SELECT * FROM States WHERE sname = 'France');

SELECT      min(deftime(route)) AS departureTime,
            max(deftime(route)) AS arrivalTime,
            length(trajectory(Intersection(route, ^territory))) AS lenInFr
FROM        Flight, France
WHERE       id = 'LH 257';
```

Spatiotemporal Querying (II)

- Q2: When and where did flight LH 257 enter the territory of France?

```
SELECT    initial(at(route, territory)) AS entry,
          inst(entry) AS entryTime,
          val(entry) AS entryLocation,
FROM      Flight, France
WHERE     id = 'LH 257';
```

- Q3: Determine the time periods when snow storm 'Lizzy' consisted of exactly three separate areas.

```
CREATE TABLE Lizzy AS
      (SELECT extent
       FROM weather
       WHERE name = "Lizzy" and kind = "snow storm");

SELECT deftime(at(noOfComps(extent) = 3, TRUE))
FROM Lizzy;
```

Spatiotemporal Querying (III)

- Q4: Where was United Airlines flight 207 at time 8:00 am?

```
SELECT    val(atinstant(route, 8:00)) AS locAtEight
FROM      Flight
WHERE     id = 'UA 207';
```

- Q5: Where was United Airlines flight 207 between 7:00 am and 9:00 am?

```
SELECT    trajectory(atperiods(route, 7:00..9:00)) AS loc
FROM      Flight
WHERE     id = 'UA 207';
```

- Q6: Which planes ran into a hurricane?

```
SELECT    id
FROM      Flight, Weather
WHERE     kind = 'hurricane' AND
          route Disjoint >> meet >> Inside extent;
```

Spatiotemporal Querying (IV)

- DEFINE Enters AS Disjoint >> meet >> Inside;

- Q7: Which planes ran into a hurricane (reformulation)?

```
SELECT      id
FROM        Flight, Weather
WHERE       kind = 'hurricane' AND
            route Enters extent;
```

- Other definitions of complex spatiotemporal predicates

  DEFINE Leaves AS rev(Enters);

  DEFINE Crosses AS Enters >> Leaves;

  DEFINE Bypass AS Disjoint >> Meet >> Disjoint;

Spatiotemporal Querying (V)

- Q8: What is the number of planes that were entering snow storms or fog areas?

```
SELECT      count(*) as num
FROM        Flight, Weather
WHERE       kind = 'snow storm' OR kind = 'fog'
GROUP BY    route Enters extent;
```

- CREATE TABLE Bird(swarm varchar(40), movement hmpoint);

- Q9: Which swarms fly together, then take different routes for some time, and finally meet again?

```
DEFINE Remeets AS _ >> Meet >> Disjoint >> Meet >> _;

SELECT      A.swarm, B.swarm
FROM        Bird AS A, Bird AS B
WHERE       A.movement Remeets B.movement;
```

Outline

Outline – Open Research Topics

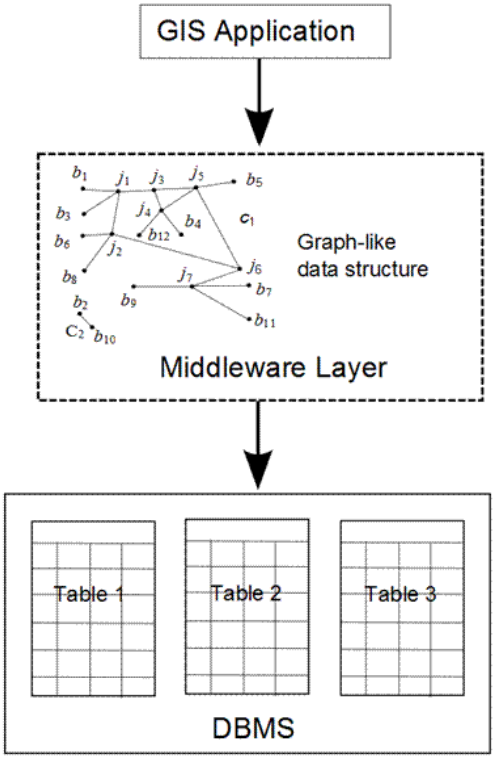
- Topics not covered in this tutorial
- Research challenges

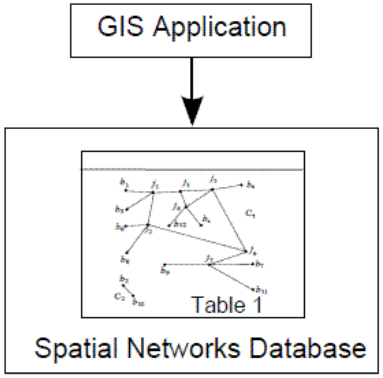
Topics Not Covered in this Tutorial

- Goal of the tutorial: Learn concepts first
- Data structure design for spatial and spatiotemporal data types
- Geometric algorithm design for spatial and spatiotemporal operations and predicates (require methods from Computational Geometry)
- Efficient implementation techniques for spatial and spatiotemporal joins
- Spatial and spatiotemporal query processing
- Spatial and spatiotemporal indexing

Research Challenges (I)

- Spatial partitions and spatial networks as *first class citizens* in spatial databases (Map Algebra)

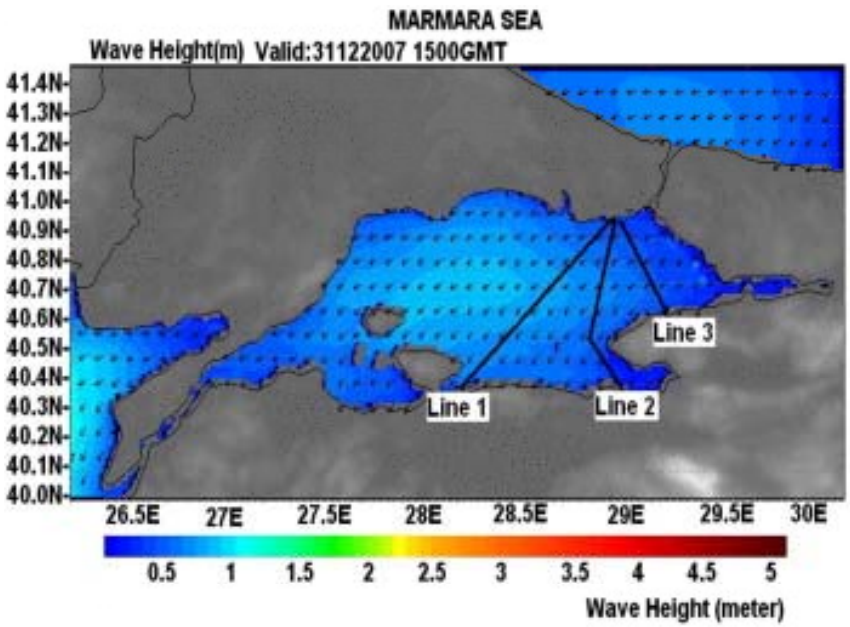


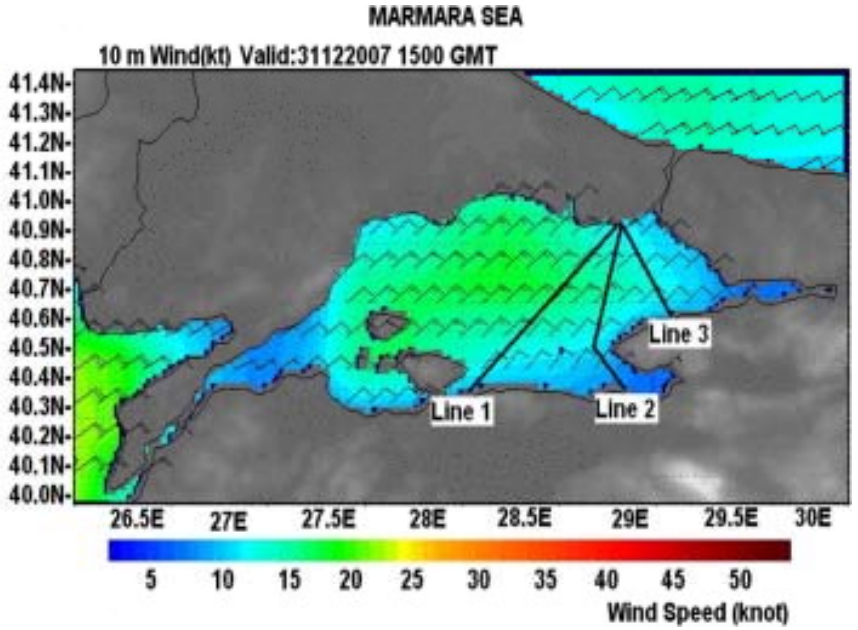


- Query languages for spatial partitions and spatial networks

Research Challenges (II)

❖ Vague and fuzzy spatial objects



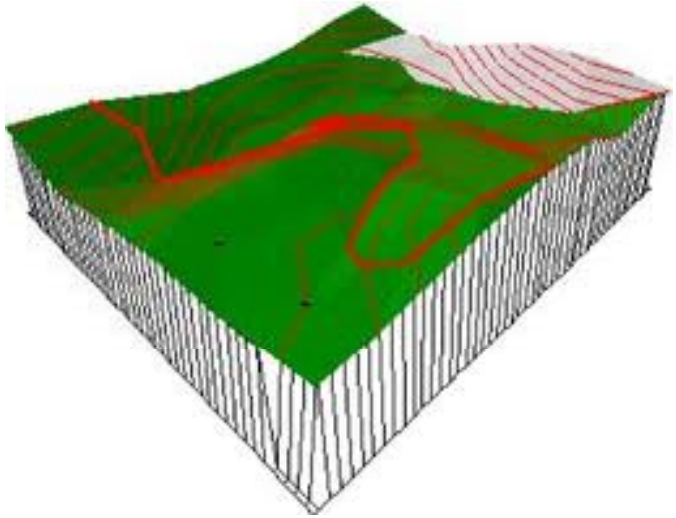


❖ Some models for fuzzy spatial objects available (especially from GIS field)

❖ Problem: Implementation of fuzzy spatial objects

Research Challenges (III)

- Three-dimensional spatial objects



- Applications: Meteorology, GIS, soil science, earth science
- Problem: Computational Geometry is immature with respect to three-dimensional data handling

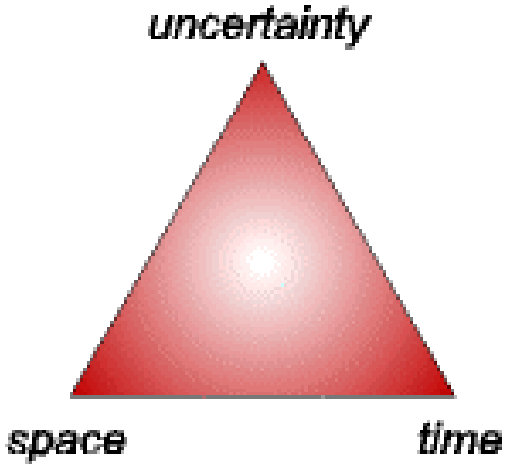
Research Challenges (IV)

- Moving objects (3D + time)

- Applications: Meteorology, hurricane research, tsunami research, earthquake research, volcano research
- Construction of moving objects from gridded sensor data (icing problem)

Research Challenges (V)

- STU objects (Space + Time + Uncertainty)



- Applications: Modeling of natural phenomena in general, geosciences, hurricane research, meteorology

Thank You for Your Attention and Interest!