Bauhaus-Universität Weimar
Faculty of Media
Degree Programme Computer Science and Media

Modelling Development of Countries in Historical Geographic Information Systems

Master's Thesis

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Selbstständigkeitserklärung

Hiermit versichere ich, dass ich die vorliegende Masterarbeit selbstständig und nur unter Zuhilfenahme der angegebenen Quellen erstellt habe.

Weimar, 6. June 2016 Marcus Kossatz

Acknowledgements

Helau

Chapter 1

Introduction

La Géographie n'est autre chose que l'Histoire dans l'espace,
de même que l'Histoire est la Géographie dans le temps.

Geography is nothing but History in space,
the same way as History is Geography over time.

– Élisée Reclus: "L'Homme et la Terre" (1908)

long and aspiring text about human life, the question of where, when, what and how?

time and space are everywhere, highly related to our lives and objects we perceive time personal time points of major life events, ...-¿ events, can trigger other events periods of studying, working, ... -¿ collection of events with similar characteristics world: every major issue has a time scale climate change (decades) climate tipping points (years) climate tipping points (years) economic meltdown (months) infectious diseases (weeks) disasters (days) -¿ time not easy to scale and to grasp space location of major life events (static) travel routes (dynamic) not always easy to grasp (exact location of monument is simple, but exact location of problematic area with fremdenfeindlichen hintergrund or historic countries are hard to set) event locations are sometimes not related to their consequences (e.g. Conferences of Tehran or Casablanca (1943) discussed how to deal with Germany after planned victory in WWII) motivation for spatio-temporal queries exploration of German history using historical maps of 1800, 1850, 1900 and 1950 each map has both temporal and spatial information in it but how to tell a story with that? more realistically, maps from 1871, 1919, 1933, 1945 and 1949, because of major events (founding of German Reich, end of WWI, beginning of Nazi dictatorship, end of WWII, founding of two German nations -¿ for one country might be suitable exploration of European or history would need a world map for each year how to see what has changed? -¿ inefficient how to know what is important? is that a reasonable way of storing information if one information set is with a high probability almost the same as the time point before? -¿ redundancy key problem model of historic maps at time points (-¿ snapshot model) given information at time point t1 and t2 How to know the status at time point t1 ¡ tm ¡ t2? -¿ It is impossible solution: away from snapshot based modeling of history to change-based modeling initial state ti, changes at point t1 and t2 How to know the status at time point t1 ¡ tm ¡ t2? -¿ it is ti + changes at t1 =¿ definition of each time point in history

research object of this thesis change over time of space of countries history of countries, their names and their borders and their relationships to each other visualize these changes and edit them (interface) Web-based historical geographic information system (WHGIS)

research questions of the thesis How to design and implement WHGIS? How to create an interface not just to explore historical changes? How to deal with uncertainty and fuzziness in history? Can researchers actually interact with such a system? How to design an interface that matches the mental model of a DH user of editing changes over time?

study of existing approaches, techniques and projects GIS: acquisition, management, analysis and presentation of spatial information handling of the spatial domain: extension to HGIS some systems allow presentations, but have very difficult interfaces no system that allows editing historical borders in time and space

1.1 Motivation

1.2 Research Questions

1.3 Overview

Chapter 2

Basics

This chapter will lay the theoretical foundation of this Master's Thesis and will embed it into the context of current research. The title of this work is:

Modelling Development of Countries in
Historical Geographic Information Systems

It includes the domain (*history of countries*) and the system to acquire, model, manage and visualize data of the domain: *Historical Geographic Information Systems* (HGIS).

The first section of this chapter will define HGIS and related terms. Afterwards, concepts to model time and space in an information system are introduced. Data sources suitable for input into an HGIS are listed in the next section, followed by techniques to manage and analyse the data. A special focus lies on concepts to visualize spatial and temporal data, explained in the next section. The chapter closes with possible HGIS applications and introduces the tool that is used in this thesis: HistoGlobe.

2.1 Historical Geographic Information Systems

> *"All human actions takes and makes place. The past is the set of places made by human action. History is a map of these places. The past thus exists not in time but in space."*

– Philip J. Ethington in [Eth07, précis]

An Historical Geographic Information System helps to answer research questions about how geographical phenomena have developed over time. To understand how it works, it is important to understand the four parts of the word: The research fields *history* and *geography* and the concepts of *information* an *systems*.

2.1.1 History

History is "an ideal field for thinking long and hard about important questions" [AHA]. The Greek word *Ιστορια / historia*, meaning "finding out, learning through research, narration of what is learned", is the origin[1] and it signifies the two main modern usage forms of the term: To research about and learning something and to tell a story. There are many different definitions of the word *history*[2]. The main goal of history is to study processes in the past to understand the situation in the present and make reasonable decisions for the future. The American Historical Association has developed the "five C's of historical thinking [that] together describe the shared foundations of [the] discipline" [AHA]:

Change over time The lives of people, their languages and their cultures are continuously changing. Describing these historical changes, triggered by historical events happed in the past, is a major goal of history. Snapshots in the form of historical maps or historical photography are used to tackle this task.

Context is an important element of historical thinking. The goal is to travel back in time to the moment of the event and recreate the world based on primary sources. The understanding of the historical context is crucial for the understanding of the event.

Causality The overall goal of each science is to answer the *why*-question concerning an event or a process. For historians that means to reasonably explain an historical event or process based on evidence. The problem is that history is not a science that can alter experimental conditions to extract new information, in a way that e.g. experiments in physics work. Historians have to focus on the interpretation of primary sources, which inherently yields multiple explanations for a single event.

[1] *History*, Dictionary.com, based on Random House Dictionary, 2015, URL: `http://dictionary.reference.com/browse/history`, last access: 23.10.2015

[2] *History*, Merriam Webster – an Encyclopædia Britannica Company, URL: `http://www.merriam-webster.com/dictionary/history`, last access: 23.10.2015

Contingency is a derived aspect from this problem. Each event has a whole network of prior conditions, because the world is highly interconnected. A slight change in one prior condition could have led to a completely different outcome of the event and a different state of the world.

Complexity The intrinsic human need for order conflicts with the complexity of history and their events and processes, because of its contingency. It is questionable if all details about events in the world are scientifically explainable.

Historical research is conducted by studying and interpreting primary sources, such as written documents, verbal texts, speeches, photographs, audio, video or historical maps. This signifies that most historical research is qualitative. The main organization principle in history is periodization: classifying events and processes to describe broader long-term changes and to explain complex phenomena [KH08, pp.4-7]. A special focus in this thesis is laid on historical maps as primary source to extract spatial information.

2.1.2 Geography

The term "geography" comes from Greek *γεωγραφια / geographia* , literally "describing the earth." [3] It is a science that studies the interplay between the landscapes and environments of the Earth (*physical geography*) on the one hand and the people, their cultures, societies and economies (*human geography*) on the other. That means geography is an interdisciplinary field between natural and social sciences [RGS].

Geographical research aims to understand where things are found, why they are there and how they developed over time. It focuses on the interconnectivity between elements of physical and human geography, which gets expressed in Tobler's First Law of Geography: "Everything is related to everything else, but near things are more related than distant things." [4]

Geographers use different technology and techniques to analyze geographic processes and to answer their research questions. The oldest and most important among those are maps. A map is a graphical expression of something that is not tangible: a part of the real world.

[3] *Geography*, Dictionary.com, based on Random House Dictionary, 2015, URL: `http://dictionary.reference.com/browse/geography`, last access: 23.10.2015

[4] "A computer movie simulating urban growth in the Detroit region", Waldo Tobler, 1970 Economic Geography, 46(2): 234-240.

A map shows the physical, environmental, political, economical or social properties of the Earth in order for the user of the map to get the most relevant information for his task, may it be orientation, learning or teaching. The "art and science of making maps" is the field of *cartography*[5]. Since maps visualize a model, they have a natural constraint: "No map can perfectly replicate the real world, since it inevitably generalizes, abstracts and approximates the complexity of the reality" [KH08, p. 181].

Comparison between geography and history Both research fields utilize maps for their research questions, which is the main commonality for the work of this thesis. However, the nature of both fields are also very different, illustrated in table 2.1.

geography	difference	history
where	dimension	when
exact, statistical	character	complex, fuzzy
mainly quantitative	research	qualitative
spatial proximity of conditions	causal explanation	temporal sequence of events
spatial differentiation	explanation	temporal differentiation
clustering	ordering	periodization
mostly visual (maps)	expression	mostly verbal (texts)
high (GIS)	digitalization potential	low (digital humanities)

Table 2.1: differences between history and geography
[KH08, pp. 2-4]

Whereas geography answers the questions *where?*, history focuses on *when?* – but the ultimate goal for both sciences is to answer the question *why?*

2.1.3 Information

The terms "signs", "data", "information" and "knowledge" are sometimes used interchangeably and there is no coherent definition for any of them. However, all describe different concepts. This explanation seen in figure 2.1 is based on the work of [Dra].

[5] *History of maps and cartography*, James S. Aber, URL: `http://academic.emporia.edu/aberjame/map/h_map/h_map.htm`, last access: 24.10.2015

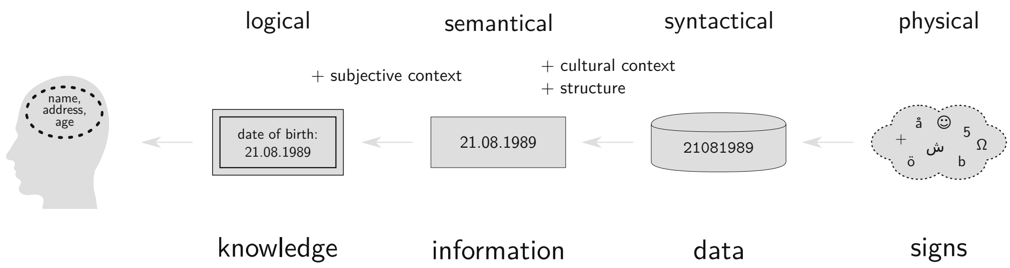


Figure 2.1: signs, data, information and knowledge

A *sign* is the physical representation of something in the real world. Since the real world is continuous, literally anything can be seen as a sign, so there are uncountably infinitely many different signs. *Data* is a subset of all possible signs and represents the syntactical level of what an information system deals with. Data itself does not have any meaning, but as soon as it is organized, it becomes *information*. However, information is sensitive to its cultural context. The string `14.07.1789` is useful and understandable for people in countries that use the date format `DD.MM.YYYY`. However, for people in Belize and the USA, that use the format `MM.DD.YYY`, this might just be a random string of numbers without any meaning, and therefore no information – although it is the same data. If information is visualized to and understood by a human and it can be integrated into his or her larger subjective context, it is *knowledge* [Nak]. The goal of a visualization is to present as much information as possible in a way that it can be transformed into knowledge by the viewer.

2.1.4 System

A *system* is an organized structure containing *elements* or *components* that are directly or indirectly *related* to and *interconnected* with each other. The elements and their relations form the whole of the structure. The surrounding of the system is its *environment*. There is an *internal state* at any point of the system's existence. This state only changes when it gets influenced by stimuli of its environment. *Emergent properties* characterize a system. They are independent from properties of the element of the system, e.g. water is liquid at room temperature, but the elements it consists of, hydrogen and oxygen, are a gas. Each system is both part of a larger system and can be decomposed into subsystems. Therefore, systems form a hierarchy.

A system has defined spatial and temporal boundaries. There are two types: *open systems* allow exchange of energy or information with their environment, whereas idealized *close systems* naturally do not interact with and are not influenced by its environment. Based on the black box principle the inner working of a closed system can not be seen from the outside [Bus].

2.1.5 Definition and Motivation

An *information system* (IS) is an application that is dealing with the acquisition, management, analysis and presentation of information. It is the unity of all its components and their interaction with each other [Zwa]. If the majority of the information in a system has a spatial relation to the Earth, its surface, its lithosphere, atmosphere or the social or economical structure of its habitation, it is a *geographic information system* (GIS). The data objects in the system are called *geo-objects* [Bol08]. If the information additionally has a temporal dimension, e.g. via time stamps or time spans, which enable to trace developments of geo-objects, it becomes an *temporal* or *historical geographic information system*. [GG14].

HGIS react on the spatial turn of history: the integration of geographic methods in historical research. It aims to discover the power of cartographic representation: "The spatial turn in the humanities must [...] understand the role of space in human events" [BCH10]. At the same time, they are the product of the temporal run in GIS: the coexistence of space (where things are) and time (what has changed over time) [Sol14, p. 45]. With HGIS it is possible to analyze how "spatial patterns change over time in order to better understand large-scale Earth processes" [Peu99]. Since "the world never stands still", but "the retention of information relating to past events [is] an important element of human representation of the world", the dimension of time has to be integrated into a GIS [Peu99].

Historical Geographic Information Systems consist of mainly four components: The acquisition part describes everything that is related to the input of *spatio-temporal data*. It is physically stored and logically managed in a *spatio-temporal database*. It will be analyzed regarding different aspects of the task in order to make sense of them: Transforming them into information that can be used to answer the question of the user. The resulting information will be presented on a display suited for space (e.g. a map) and time (e.g. a timeline). From the visualization the viewer can extract *spatio-temporal knowledge*. All components will be explained in more detail in this chapter.

HGIS are also called *Spatio-Temporal Information Systems* (STIS) [PTKT04].

2.2 Modelling Time and Space

A model tries to replicate a part of the real world. A data model abstracts a part of the world, identifies the most essential elements and their relation to each other and conceptualizes them e.g. in an *Entity Relationship Model*. In an HGIS, the data model should contain entities and relations to explain spatial-temporal phenomena in the real world. Based on the theory of the *Triadic Framework*, there are three components involved: space (3 dimensions), time (1 dimension) and attribute (multiple dimensions). All of these dimensions can change independently from each other [OS01, p. 53].

The remaining part of the section will introduce ways to separately represent time and space in an information system.

2.2.1 Representation of Space

The information system needs to unambiguously locate each geo-object on, underneath or close to the Earth's surface using *geographic coordinates*. They allow to locate an object directly in the coordinate system of the geodetic datum. In order to do that, a geo-object has to be expressed in the coordinate system of the Earth.

2.2.1.1 Geospatial Data Model

To model the Earth in an information system, its actual shape has to be analyzed. It is measured by scientists in the field of *geodesy* is rather complicated. In the Babylonian Empire ($\approx$ 2000-539 BC) the theory of the Earth being a flat disc surrounded by an infinite body of water evolved. The Greek scientists Pythagoras and Aristotle (340 BC) rejected this theory and proved the earth to be a three-dimensional spherical object. It took almost 2000 years until Sir Isaac Newton (1687) reasoned that due to the centrifugal forces of the rotating Earth the shape has to flattened at the poles and is therefore better described as an *ellipsoid* with two radii: the polar radius (r_p) and the slightly larger equatorial radius (r_e) [Bol08, pp. 69-77].

However, the model disregards that the surface of the Earth is not flat but consists of deep oceanic trenches and high mountains. Therefore the gravitational field of the Earth is not homogeneous either: the actual *mean sea level*, the reference surface for the height ofgeoobjects from 106 meter below to 85 meter above the uniform sea level of the ellipsoid model. These discoveries in the 20th century led to the complex *geoid* model (see figure 2.2). The latest and most accurate measurements for the shape of the Earth are the result of the GOCE satellite launched in March 2009 [Uot, Fra].

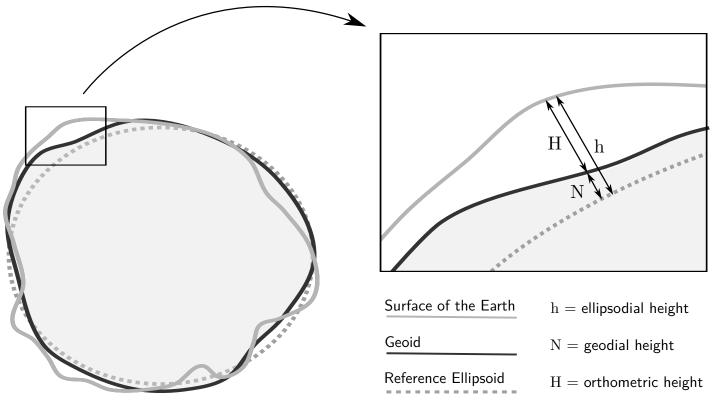


Figure 2.2: The geoid model, differences are exaggerated
based on [Bol08, Fig. 3-6, p. 75]

Geographic coordinate system The reference ellipsoid is the basis for the model that is used to determine an object's position relative to the Earth's surface. It is represented in a three-dimensional *spherical coordinate system*.

This ellipsodial model defines the *North Pole* and the *South Pole* as the two surface points closest to the Earth's center and the *Equator* as the line equidistant to the two poles and therefore dividing the world in a *Northern* and *Southern Hemisphere*. Additionally, the *Prime Meridian* is defined as the line perpendicular to the Equator, running from the North to the South Pole. Since there are infinitely many lines like this, its definition is arbitrary, but by convention, the line running through Greenwhich, London, United Kingdom is used.

Based on these two lines, each point in the spherical coordinate system can be unambiguously defined by three values (see Figure 2.3):

1. The rotation angle along the Equator, defining its longitude: $\gamma = [-180° \ldots +180°]$
2. The rotation angle along the Prime Meridian, defining its latitude: $\phi = [-90° \ldots +90°]$
3. The distance to the origin: $r \in \mathbb{N}_0$

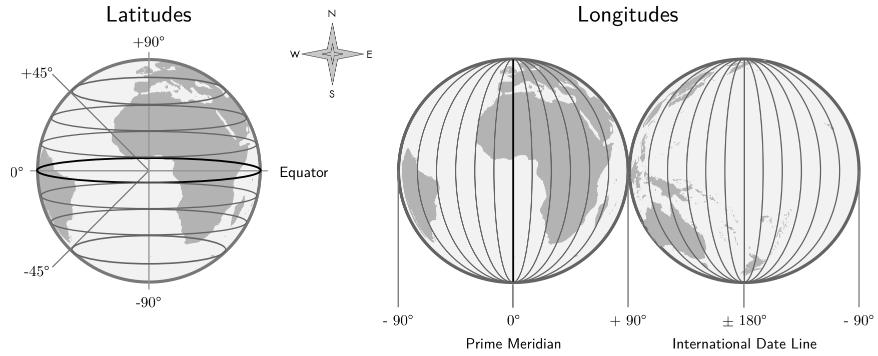


Figure 2.3: Geo-coordinates using latitude and longitude
based on [Bol08, pp. 26-28]

Lines of constant latitude are running horizontally and are called *parallels*, lines of constant longitude are *meridians* appearing in vertical direction. All parallels are circles with their center on the axis between the poles. No two parallels intersect. The longest parallel is the Equator (0° latitude). All meridians have the same length.

Geographic coordinates are usually recorded either in degree-minutes-second (`DMS`, e.g. `50° 58' 22''`) or in decimal degree (`DD`, e.g. `50.973`) notation [Bol08, pp. 30, 79].

Geodetic datum One main task of a GIS is to accurately visualize the Earth on a map. Since the Earth is an inhomogeneous three-dimensional shape but the output medium is a two-dimensional computer screen or piece of paper, it has to be transformed. First the Earth has to be modeled using the *geodetic datum*. It consists of two parts: The approximation of the Earth's surface in a the Cartesian coordinate system with the origin and a set of reference points used to accurately locate a point.

Geodetic datums can be very accurate in one region of the world, i.e. the model fits the real geoid very well, but inaccurate in another region. This is the main reason why there are a lot of different geodetic datums used in the world. The same coordinates in two different geodetic datums define two different points on Earth. In order to be accurate is essential to know the geodetic datum of the coordinates [Bol08, p. 80].

The *World Geodetic System 1984 (WGS84)* is a model that found worldwide acceptance and is used in all major Web-based mapping services like *OpenStreetMap* and is implemented in the GPS unit of all major smart phones.

2.2.1.2 Raster and Vector Model

Geographical features like cities, houses or country borders are infinite in detail. But storage in a computer system is finite. In order to model these continuous phenomena in an information system, a relevant subset of them has be sampled to create discrete spatial data. It can be represented in a raster or in a vector model.

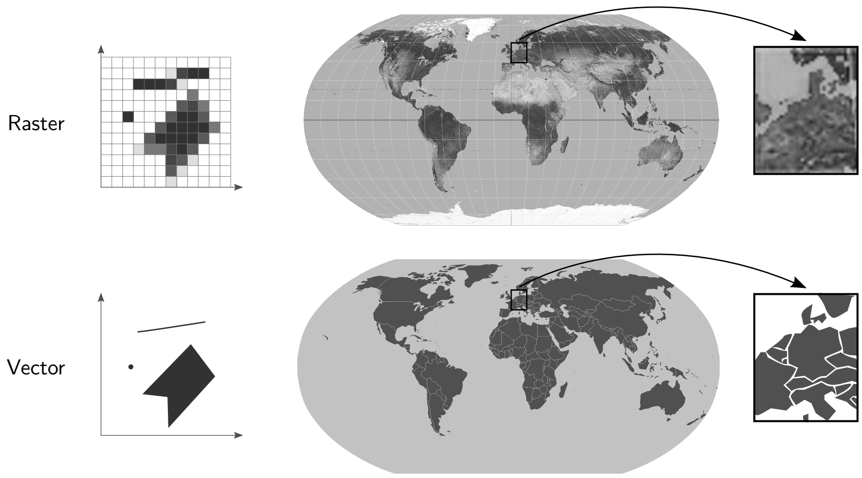


Figure 2.4: Comparison of the raster and the vector model

The *raster model* contains a regular grid with a fixed *cell dimension*. Each cell has a certain value, e.g. a color value, height or population density. The raster model is simple and allows straightforward rendering: only affine transformations have to be applied in order to project e.g. two raster map layers on top of each other. The main disadvantage of the raster model is its fixed resolution: it can not be scaled up without losing quality [Bol08, pp.42-48]. Raster graphics are used by most map engines for the basic map layer in form of map tiles, e.g. in OpenStreetMap or the satellite image of the Earth by NASA in Google Maps.

In the two-dimensional *vector model*, each object is a mathematically described geometric primitive. There are three basic primitives (figure 2.5):

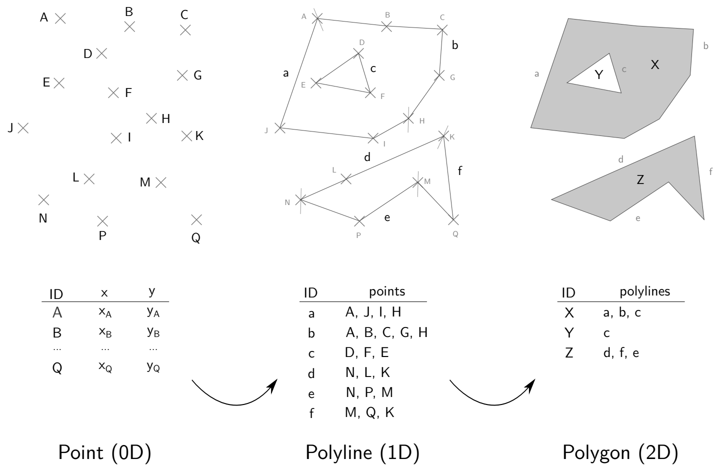


Figure 2.5: The basic geometric primitives point, polyline and polygon

0D A *point* is the fundamental object in vector geometry. It has no dimension, no size and is only defined by its position, specified in geographic coordinates. One point is independent from all other ones. Points can be used e.g. to represent a landmark.

1D A *polyline* is constructed by an ordered set of points with at least one start and one end point. A street can be expressed by a polyline.

2D A *polygon* is an ordered set of polylines creating a closed area. A polygon can be *simple*, *weakly simple* or *complex* (see figure 2.6). A lake can be described by a polygon.

Additionally, a *polypolyline* represents multiple separate lines belonging to one logical entity, e.g. an interrupted highway. In the same way, a *polypolygon* describes the union of multiple separate areas, e.g. a set of islands of an archipelago.

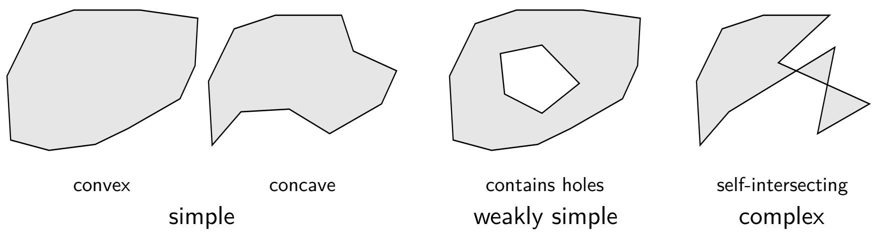


Figure 2.6: Different properties of polygons

Scale-independence is one of the biggest advantages of a vector model. The data model is more compact in comparison to the raster model. On the other hand, the model can become very complex. Since vector data has to be rasterized to be shown on the screen, the computational effort increases with complexity [Bol08, pp.33-42].

Vector models are suitable to represent phenomena in real world that can easily to discretized, e.g. the boundaries of a national park. Common file types for vector data with spatial reference are the open file formats GeoJSON (`.geojson`)[6] and Scalable Vector Graphics (`.svg`)[7] or ESRI Shapefiles (`.shp`)[8].

2.2.1.3 Geospatial Topology

Topology is the study of position, how objects are spatially arranged and relatively positioned to each other. It does not include measures like distances or angles. Two objects are said to be topologically equivalent, if they can be deformed into each other, e.g. an ellipse can be stretched into a circle.

A *geospatial topological vector model* defines the relationship between geospatial objects, i.e. equals, disjoint, intersects, touches / neighbors, contains, covers, within, interior & boundary [CFO93].

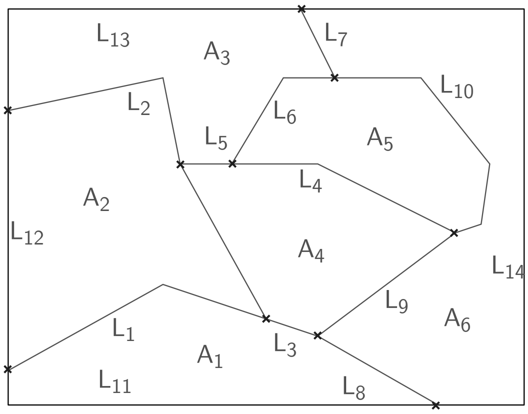
The 2D vector model from subsection 2.2.1.2 can be extended with a topology, if the geometries are represented in a planar topological vector model. The elements in this topological space are nodes (0D), edges (1D) and meshes (2D) and they correspond directly to the geometric primitives stated above. A topological vector model has strict connectivity (a "clean" geometry), if no two edges intersect without a node at their intersection point (planar), each interior edge has exactly two adjacent areas and each edge contains at least two nodes [Bol08, pp.37-39].

The topological vector model has a great asset: if an edge between two adjacent areas changes, the connectivity and adjacency does not change and therefore also the topology

[6] *GeoJSON*, IETF Geographic JSON Working Group, URL: `http://geojson.org/`, last access: 30.10.2015

[7] *W3C SVG Working Group*, IETF Geographic JSON Working Group, URL: `http://www.w3.org/Graphics/SVG/`, last access: 30.10.2015

[8] *ESRI Shapefile Technical Description*, ESRI White Paper, July 1998, URL: `http://www.esri.com/library/whitepapers/pdfs/shapefile.pdf`, last access: 30.10.2015



edge	area1	area2
L_1	A_1	A_2
L_2	A_2	A_3
L_3	A_1	A_4
...	...	...
L_{14}	A_6	-

Figure 2.7: An example of a topological vector model and an adjacency table

stays constant. The lookup for neighboring areas is very fast if the topology ensures strict connectivity: The neighbors of an area can be found in the adjacency table. Potentially problematic is the creation of a clean geometry: it can be cumbersome and require a lot of manual adjustment, for example ensuring strict connectivity by manually connecting nodes.

2.2.2 Representation of Time

Unlike in space, time knows only one dimension, which makes modelling simpler. Time is represented by timestamps, with a certain granularity (year, month, day, hour, minute, second, millisecond).

However, there are several different types of time. The simplest categorization is between a discrete *event* and a continuous *process*. Events can happen at a certain *time point* or like processes in a *time interval* or *time period*, defined by two time points. An information system that stores events with a significant outcome regarding the geo-objects in the system, is an *event-based historical geographic information system*. On the other hand, a *process-based historical geographic information system* models mainly processes as a series of events of one kind regarding a small set of geo-objects [Sol14, chapter 2, pp. 47-49].

When storing time related information in an information system, it is furthermore important to distinguish between the time that was true in reality (*valid time* or *world time*) and the time it was stored in the database (*transaction time* or *database time*) [OS01, p. 69].

The Taxonomic Model of Time by [Fra98] classifies time not only into discrete and continuous, but also by the "nature of time": a consecutive development on the time axis, defined by start and end, defines *linear time*. In a contrary, *cyclic time* has no predefined order and events reoccur on a regular cyclic basis.

Temporal Topological Relations The topological relationship between two time points t_1 and t_2 is straightforward. Since they are discrete elements and therefore isomorphic to the space of integers, there are three different order onsrelations:

1. $t_1 < t_2$: the first event happens before the second event
2. $t_1 > t_2$: the first event happens after the second event
3. $t_1 = t_2$: the first and the second event happen at the same time

For time spans, there are six possibile temporal topological relations (table 2.2). Except for `equals`, each of them has an inverse, yielding a total of 13 different relations.

relation	symbol	visualization
X before Y	`X < Y`	X Y
X meets Y	`X m Y`	X Y
X overlaps Y	`X o Y`	X Y
X equals Y	`X = Y`	X Y
X starts Y	`X s Y`	X Y
X during Y	`X d Y`	X Y
X ends Y	`X e Y`	Y X

Table 2.2: Temporal relations of time spans
based on [all]

2.3 Spatio-Temporal Data Models

"Geography differs from geometry because
in geography, space in indivisibly coupled with time"

– Don Parkes & Nigel Thrift (1980)

A HGIS needs to handle the development of geo-objects over time. Developments are driven by *changes* to the state of an object. According to the Triadic Framework time, space and attribute are independent from each other. However, in order to trace spatial and attribute changes over time, the dimensions have to be related to each other. This section introduces different approaches to maintain these relations.

Throughout the lifetime of a geo-object, it appears at some point, might undergo several changes and might disappear at some other time point. The data model has to be able to effectively and efficiently manage those changes. There are mainly two kinds: *Discrete changes* are based on the idea of a *state machine*: At any point in the lifetime, an object is in a certain state. It stays there until an event occurs that suddenly changes the object into a new state at a discrete time point. As an example, if an armistice agreement between two former war parties A and B contains a deal to cede parts of the territory of A to become territory of B, this territorial change is sudden. On a contrary, an object can gradually change according to a *continuous process*, e.g. the change of the coastlines of landmasses [Peu99].

The spatio-temporal data models developed in the previous 30 years differ mostly in the organizing dimension: In *location-based* models time is an attribute of a geo-object. On a contrary, *time-based* approaches handle events and processes that change objects suddenly or gradually. *Entity-based* models represent geo-objects as own entities. Spatial changes over time are related to these entities, but they are not attributes and therefore independent.

2.3.1 Snapshot Model

One of the simplest, oldest and most frequently used data models is based on the idea of *snapshots*: At a certain time point t_i, a new layer gets created. It stores the full picture of the current state of all geo-objects [Lan88].

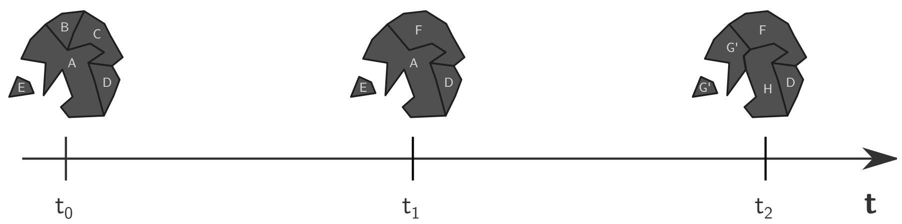


Figure 2.8: The Snapshot Model by [Lan88]

The model allows to easily retrieve the state of the system at a defined time point t_i, it is also its biggest limitation: for all other time points $t \neq t_i$ that are not covered by a snapshot, it is impossible to retrieve the state of the system, because the data model does not record any changes. This is an integral problem of the model and can not be solved. The original model is also redundant, because objects that have not changed from one snapshot to the next one are duplicated. However, there have been improvements made, e.g. by [Arm92].

Historical maps are examples for snapshots: They show the state of the world at one particular point in history, e.g. Europe 1919 and Europe 1945. However, with no additional information, it is impossible to deduct how Europe looked like in 1939. Therefore, this model is not suitable for this domain.

2.3.2 Simple Time-Stamping

This problem is solved by assigning a geo-object a period of existance by two additional attributes: at the *start date* t_{start} the object gets created and at the *end date* t_{end} it is ceased. If an object still exists its cessation date gets a special value, e.g. `NOW` [HW90].

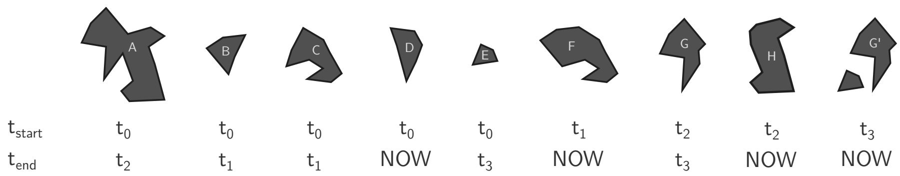


Figure 2.9: The Simple Time-Stamping method by [HW90]

The *Simple Time-Stamping* method is also location-based and tracks discrete changes of objects. Given full and integer information, the state of the system at each time point t_i can be retrieved: All geo-objects for which $t_{start} \leq t_i < t_{end}$ are active, all others are inactive. However, this retrieval is cumbersome, because without efficient data structures every time the date changes, it has to be checked for each geo-object if its state has changed.

Another problem of the model is that it does not allow for tracing the development of objects in different states. As an example, at time point t_1 the geo-objects B and C cease and G starts. Visually, G is a successor of B and C, but this historical relationship can not be deducted directly from the model. This shortcoming can be resolved by adding a reference to the predecessor and the successor of the object.

This model alone is not suitable for the domain of this thesis, because it is impossible to say what exactly has happened at a certain time point. Given the example above, it is unclear if two objects unified to a new one $(B + C \to G)$ or if two are successors $(B \to G)$ and one just stops to exist $(C \to \emptyset)$. The model is also redundant: if a geo-object replaces another one $(B \to G)$, then the end date of B is the same as the start date of G.

2.3.3 Event-Based Spatio-Temporal Data Model

A time-based approach addresses exactly those shortcomings: They explicitly represent events or processes in the data model and associate all objects that change according to them. One example of this approach is the *Event-Based Spatio-Temporal Data Model* (ESTDM) for geospatial raster data by [PD95].

At one defined time point t_b, a snapshot gets stored. This *base map* contains the current state of the map, i.e. the current value of each raster cell `(x,y)`. From that moment on, the system stores events that change the values of certain cells. Such an event has a time stamp (`t`) and a list of components associated with it. A component represents a new value (`v`) and knows which raster cells (`x`, `y`) change their value to `v`.

The method uses the following data structures: a header file contains information about the thematic domain, a pointer to the base map and to the first and last element of the event list. This doubly-linked list stores all events chronologically. Therefore, each event knows its preceding and succeeding event via a `prev` respectively `next` pointer.

If the time point of an event is reached, all its components are executed, i.e. the relevant raster cells change their value. The system follows the `next` pointer to know which event is waiting to be executed next. Since a change is relative to the previous change, not to the base map, change tracking is efficient.

The concept of the ESTDM suits the problem domain really well: An historical event changes the geometry of certain objects suddenly. The model explicitly represents these discrete changes. However, it does not work for vector data. The authors have explicitly stated that "the design of such a [vector-based] model is not seen as a straightforward task", because of the problem "how to maintain the integrity of spatial topology as it changes [...] The solution will require a more complex definition of components within individual events" [PD95, p. 21].

2.3.4 Three-Domain Model

An event-based STDM for vector geometry including lines and polygons has to answer the following questions: What uniquely identifies a geo-object? What kind of spatial, topological and attribute changes can happen to an object? Which of these maintain the identity and which create a new object? [Yua96b]

This problem is addressed in the *Three-Domain Model* by [Yua96a]. The model is based on abstract entities that represent a spatio-temporal object. It handles the three domains identity, space and time separately:

- The *semantic domain* holds an entity uniquely identifiable. An object in this domain corresponds to a human concept, e.g. a "country". It handles attributes of the area, but not the spatial and temporal properties.
- The *spatial domain* represents geospatial objects in vector format, e.g. a polygon describing the territory of a country.
- The *temporal domain* stores all temporal objects, e.g. time points of an historical events, or time intervals of a war.

The model is not specific, but more a general abstract framework to handle space, time and identity. This makes the model very flexible, e.g. it can handle discrete and continuous changes, relative and absolute time, world and database time.

2.3.5 History Graph Model

Most of the data models introduced so far cover only static changes of geo-objects. [key] identified three different types of temporal behaviour of changing objects:

- Dynamic objects that change continuously.
- Static objects that change according to events with duration (processes).
- Static objects that change according to sudden events.

Based on this observation he developed a data model that can handle all three kinds of temporal behaviour: The *History Graph Model*. It manages objects and events separetly from each other. An object can only be in three different states:

1. An object is *static*, if it currently does not change. This is called an *object version*. The version has an interval associated to it representing the duration of the object version, until it changes the next time. If the object is dynamic and changes continuously, the duration is zero.

2. If an object is currently *changing*, it is in an *object transition*. The transition has an associated interval as well, whose duration is zero if it is a sudden change. Additionally, a transition links the relevant objects to each other creating a historical predecessor-successor-relationship.

3. An object that is currently not active, is *ceased* and not visible on the map.

The history of a geo-object is a chronologically ordered set of versions and transitions, that can be visualized in a graph (see figure 2.10).

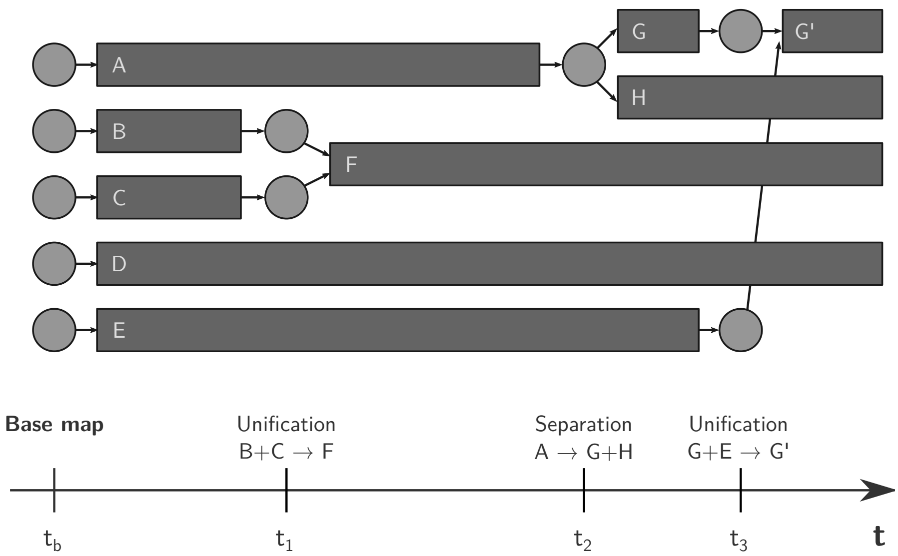


Figure 2.10: The History Graph model

The model defines six basic types of temporal changes that can happen (see figure 2.11):

- **Creation**: A new object is created.
- **Alteration**: A property of an object (e.g. geometry) changes.
- **Cessation**: An object is ceased.
- **Reincarnation**: An object that has previously been ceased is recreated.
- **Split/Deduction**: An object is divided into two or more new objects or one or more objects are deducted from an existing one.

- **Merge/Annexation**: Two or more objects are joined together to a new object or one or more objects are annexed to another object.

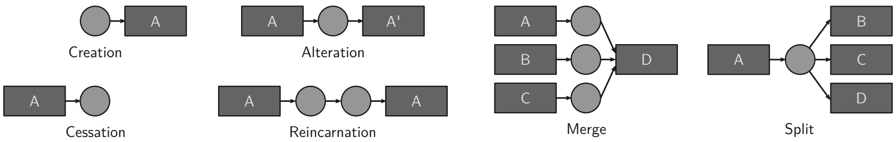


Figure 2.11: Types of changes in the History Graph model

The History Graph model can be seen as an extension to the ESTDM. It combines the advantages of event-based and entity-based spatio-temporal data models, supports discrete and continuous changes and relative and absolute time. The main improvement is that the historical development of a geo-object can directly be derived from the model, because objects are linked to their precedessors and successors. The History Graph model can tell a story.

Other popular spatio-temporal data models that are not covered in this work, because they were not seen as relevant for the domain, include the *Space-Time Composite* model, the *Grid Model* and the *Amendment Vector Model*. Overviews about these and other spatio-temporal data models can be found in [Zha11], [PTKT04] and [Peu99].

2.4 System Components

HGIS like any other system four components trallala und hoppsassa

2.4.1 Input

Spatial Data for a GIS can either be acquired from existing sources or retrieved manually. One of the most exhaustive collections of geographic data in public domain is hosted by Natural Earth [9]. There is physical data (e.g. coastlines, rivers, or glacier areas) and cultural data (e.g. political borders, cities, roads, airports or timezones). OpenStreetMap also opens its database to the public [10]. Additionally there is free geodata for special purposes, like

[9] *Natural Earth*, URL: `http://www.naturalearthdata.com/downloads/`, last access: 30.10.2015
[10] *Planet OSM*, URL: `http://planet.openstreetmap.org/`, last access: 30.10.2015

regions or statistical data for the USA [11] or terrain models and administrative regions for Germany [12].

2.4.2 Management

Database Management Systems

Version Management database has to be updates when change occurs versioning methods relation-level versioning rollback: new event -¿ new snapshot type of change (added, altered/updated, deleted, restored) tuple-level versioning store changes with event time =¿ time slices can be derived from the information about changes (+) less redundancy, less data (-) weaker performance on retrieval attribute versioning -¿ extension of tuple-level versioning: separation entity ¡-¿ attribute changes stored in attributes

international boundary has different states: event old b. new b. active - valid - old legal document invalid - old new demarcation invalid draft -¿ invalid old quality control invalid valid new -¿ stati: valid, draft, revised, approved = valid check on consistency -¿ only one version accessible to public

Spatio-Temporal Queries

historical R-tree assign timestamp t_i -¿ active objects = [o_1, 0_2, ... , o_n] (+) fast handling of timestamp (-) redundancy, because of repeating objects

MV3R tree (Tao & Papadios, 2001) version copy (+) less redundant

A *Database Management System* (DBMS) is a software system for the administration of data, i.e. storage, retrieval, validation of data and their relations. A DBMS has the task to maintain security, performance, stability and allow multi-user access on the same data, following the *client-server* principle.

Data and functions are separated from each other using a *multi-tier architecture* that is best visualized in an example of a Web-based GIS: The Web browser on the client side hosts the map including content and the tools in the user interface. If the user interacts with a tool

[11] *Free GIS Data - GIS Data Depot*, geocommunity, URL: `http://data.geocomm.com/catalog/index.html`, last access: 30.10.2015

[12] *Dienstleistungszentrum des Bundes für Geoinformation und Geodäsie*, Geodatenzentrum, URL: `http://www.geodatenzentrum.de/geodaten`, last access: 30.10.2015

the client sends a request to the Web server for new data. The processing layer on the server checks the request and forwards it to the DBMS which translates the request into a query to the database. The result will be handed back to the processor that transforms the data into information and sends it to the client. On the map the new information will be shown.

Following this principle multiple clients can independently from each other get new data from the server, but also multiple processing layers for different purposes can simultaneously request data fro the database, ensured by the DBMS. Another advantage of the clear separation between the data (*model*), the user interface (*view*) and the processing layer (*controller*) follows directly from the *model-view-controller pattern*: One part can be changed without interfering the other parts, e.g. if the map interface changes, the data can stay untouched and an implementation of a new database technology has no consequences to the interface.

There are mainly two types of DBMS: the most common *relational* database and *object-relational* databases that are inspired by the features of object-oriented programming paradigms. Pure *object-oriented* databases will not be covered in this section.

Relational databases Databases are built around logical entities that have a discrete set of attributes associated with them, e.g. a city (entity) has a name, a location, a major, a state it belongs to etc. For each member of the entity there is one value for each attributes (e.g. the name of the city is Weimar) which is of a certain data type (integer, decimal, string, boolean, etc.). Entities is a database are represented in a table with rows (one row per member), columns (one column per attributes) and cells (attribute value for this member). Each entity has one attribute that unambiguously identifies each record in the table, the *primary key*.

In a *Relational Database Management System* (RDBMS), entities can be related to each other by three types of relations:

1. If each member of one entity has directly one member from another entity associated, it is a direct attributional relation (*1:1*), e.g. each city has exactly one major.
2. If each member can have several members of another entity related to it, there is a one-to-many (*1:n*) relationship, e.g. each state can have many cities, but a city can only be in one state.
3. If multiple members from one entity can be related to multiple members of another

entity, it is called many-to-many relation (*m:n*), e.g. each river can flow through several states and each state can have several rivers.

The relations are implemented via their primary keys. Many-to-many relationships require another connection table that uses the primary keys from both entities as *foreign keys* in the new table and links them, e.g. if river `r` flows through countries `x` and *y*, the connection table would have one record linking `r` to `x` and one linking `r` to `y`. The entities and their relations are visualized in an *entity-relationship model* (E-R model), as seen in figure 2.12.

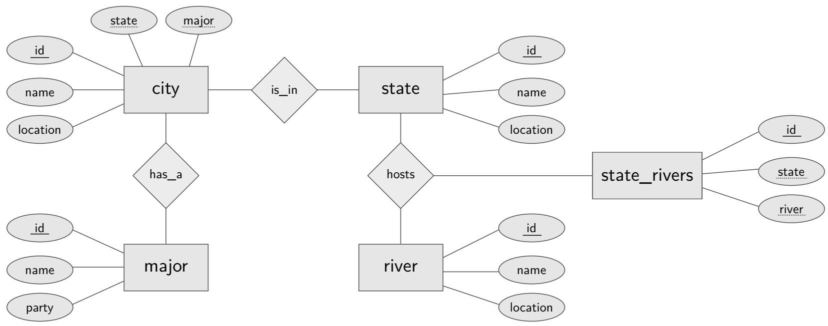


Figure 2.12: Example for a simple entity-relationship model.

Data can be retrieved from a database using the *Structural Query Language* (SQL). An example query to get the names of cities from the state `Thüringen` in alphabetical order is:

```
SELECT     city.id, city.name
FROM       (city JOIN state ON city.state = state.id)
WHERE      state.name = ‘‘Thüringen’’
ORDER BY   city.name
```

SQL can also be used to add or manipulate data in a database, e.g. with the `CREATE` or `INSERT INTO` commands.

The main goals for each database user is to maintain its correctness,consistency and simplicity and to reduce redundancy in the data. This can be achieved by *normalizing* the database:

1. To free the collection of relations from undesirable insertion, update and deletion dependencies.
2. To reduce the need for restructuring the collection of relations, as new types of data are introduced, and thus increase the life span of application programs.

3. To make the relational model more informative to users.

4. To make the collection of relations neutral to the query statistics, where these statistics are liable to change as time goes by. [13]

Two examples for RDBMS are *MySQL*, the "the world's most popular open source database" [14], and the serverless, zero-configuration library *SQLite* [15].

Object-relational databases Relational databases are well-suited to manage data in simple form without complex database user requirements. However, there can be more difficult queries to the database. Given the example in figure 2.12, a user would like to know all rivers that are in and close to the state `Thüringen`, i.e. they smallest distance between the river and the state border is less than 50 km. A query for that request should look like this:

```
SELECT    river.name
FROM      (river JOIN state JOIN state_rivers)
WHERE     state_rivers.state = state.id AND
          state_rivers.river = river.id AND
          state.name = ‘‘Thüringen’’ AND
          distance (state.location, river.location) < 20
ORDER BY  city.name
```

This query needs to call the function `distance`, but user-defined functions are not part of SQL. Also, the data type of the attribute `location` is not simple: it is not a single value, but rather a `polyline` or a `polygon`. Complex user-defined data types are also not integrated in SQL.

ORDBMS behave like RDBMS but can handle complex data. For that matter functionality from object-oriented programming are added, so it supports user-defined data types and functions and the principles such as *encapsulation* or *inheritance*. One famous example for object-relational databases is *PostgreSQL*, "the world's most advanced open source database" [16].

[13] *Further Normalization of the Data Base Relational Model*, E.F. Codd, [p. 34]
[14] *MySQL :: About MySQL*, URL: `https://www.mysql.com/about/`, last access: 31.10.2015
[15] *SQLite Home Page*, URL: `https://www.sqlite.org/`, last access: 31.10.2015
[16] *PostgreSQL: About*, URL: `http://www.postgresql.org/about/`, last access: 31.10.2015

Spatial databases GIS can deal with a lot of coordinate data. This amount of data has to be processed efficiently in order to maintain a good overall system performance. *Spatial databases* are specialized for this matter. They have predefined data types such as `point`, `polyline` or `polygon` and support spatial queries such as functions to solve the point-in-polygon problem or to calculate a distance between two polylines. *PostGIS* is an extension for PostgreSQL that is especially utilized for GIS [17]. *SpatiaLite* is a library for the same purpose, extending SQLite's relational database management system [18].

Spatio-Temporal Databases how to store and query spatial and temporal data?

static databases no updates, old information overwritten by new information -¿ not suitable for spatio-temporal object management static rollback approaches implementation of relation-level versioning change -¿ copy old data, change elements to new data =¿ complete new time slice (+) effective versioning (+) fast retrieval of state at time point x (-) highly redundant historical databases store valid state at a specific time point (valid time) store time slices valid for specific time steps or validity of objects between events -¿ changes only made with valid time temporal databases support both valid and transaction time retrieval of current state at given time step (+) supports retrieval of what was known to the database at given time point usage in knowledge and research database usage when different sources for same event are used -¿ supports different views on world

implementation using relational databases separation time and space in database

ER model for temporal objects example: administrative units units change borders and attributes over time units valid over certain period of time units have ancestors and successors -¿ units gain area from or loose area to one or several other units hierarchical structure of units (country -¿ state -¿ county -¿ city -¿ neighborhood -¿ ...) units can have additional attribute data (e.g. statistics per year) [OS01, p. 67-68]

2.4.3 Spatio-Temporal Object-Oriented Data Model

2D geometries + 1D time element: spatio-temporal atom event-based: new event =¿ new ST atom stacked on top of existing ones

[17] *PostGIS*, URL: `http://postgis.net/`, last access: 31.10.2015
[18] *SpatiaLite*, URL: `https://www.gaia-gis.it/fossil/libspatialite/index`, last access: 31.10.2015

implementation Spatio-Temporal Data Type (STT) time not as an attribute of space -¿ special entity spatio-temporal object model (everything is an object) separate classes for Space and Time -¿ aggregation to SpatioTemporal class each object with temporal and spatial extension (start + end date, full geo) operators for time and space time in YYY-MM-DD (ISO 8601 standard) 'NOW' = still existing = no end date [Raz12]

2.4.4 Analysis

analysis: determine, change, evaluate

analysis methods spatial analysis temporal analysis time series analysis process analysis (modification modeling + future forecasting) attribute analysis alteration of [OS01, p. 128]

spatial queries query of spatial properties and attribute values e.g. size of Germany in 1871 thematic queries query objects based on certain criteria (spatial and attribute) multi-criteria analysis e.g. all democratic countries larger than 10.000 km^2 statistical analysis artithmetic calculation and classification of characteristics of objects univariate, multivariate investigation e.g. What was the population density in Germany in 1945 compared to 1995 overlay/split aggregation and splitting of spatial components based on the layer principle e.g. Germany in 1945 gets split up into FRG and GDR by one polyline (inner German border) and one polygon (West Berlin) geometric-topological operations analyze the neighborhood relations between geometric objects e.g. is the geometry all countries at time point 1991 strictly connected? temporal analysis using spatial and temporal operators in figure e.g. in which year did the largest amount of border changes happen? [OS01, p. 129-140]

Multivariate Historical-Geographical Model multivariate features of a spatial object connection between temporal development of features geographical model location (geometry) neighborhood relation (topology) historical model object at different points in times [OS01, p. 128]

Spatial Queries / Operators and intersection not difference or (cascaded) union xor (inverted) symmetric difference

Temporal Queries / Operators

temporal logic rules and symbols represent time reason about time temporal operators ??? detail?

trajectories sequence of 2D or 3D locations of an object

Spatio-Temporal Queries / Operators when + where -¿ what when + what -¿ where where + what -¿ when

A GIS shall solve the problem for a user or answer his or her research question. Given a well-filled database with a working DBMS, the data might not answer the research question directly. It has to be sorted, selected or classified in order to convey the required information. For this process there are *spatial operations* on the data in the system. Several operations can be applied in a certain order [Bol08, pp. 321-325]. Both spatial and attribute data are analyzed to combine the dimensions *where?* and *what?* in order to answer the ultimate question *why?* something is the way it is [Kno02, p.xii-xvi].

An example is a system visualizing social developments on Earth. The researcher wants to divide the world into five regions with a similar life expectancy to see if there are spatial discrepancy of advances in global health. He or she has a GIS with all countries and their current life expectancy stored. In order to answer his or her research question, the following steps may be required

1. Extract the life expectancy value per country.
2. Classify the values on a discrete scale from very low to very high and put each country into one of the five classes.
3. Unify neighboring countries that are in the same class to get five world regions.
4. Name the five world regions.
5. Apply a color scheme to the classification and set the background color for each of the five world regions.
6. Create a legend with the classification and the explanation of the symbols.
7. Present the resulting map on the screen.

There are special operations for raster data, e.g. spatial interpolation, and for vector data.

Only explain those later that are really important!

graph / network analysis what is the shortest way from A to B? what is the fastest route from A via B1, B2, ..., Bn nack to A? (TSP)

Polygon geometry intersection, (cascaded) Union, (symmetric) difference

Polygon Clipping Sutherland-Hodgeman Weiler-Atherton

Topology analysis test for consistency, connectedness and completeness of topology

2.4.5 Presentation

spatio-temporal visualization ——————————

spatial domain 2D: map, different projections 3D: globe

temporal domain linear time time line time series: graph (t,y coordinate system) 2.5D map: temporal dimension on z axis or on surface space-time path cyclic time time series: polar diagram time wheel both mono-temporal: one layer -¿ one time point multi-temporal: one layer -¿ multiple time points [OS01, p. 144]

direct display of time on a map choropleth maps temporal diagrams change indicators

display mechanisms for visualizing temporal change change data additional to base map (diagrams, texts) static symbols thematic map, symbols: dates, routes, developments time sequence maps mono-temporal maps in sequence animations interactive visualization of time and space and attributes [OS01, p. 146-147]

other approaches scatterplot variation of two variables over time parallel coordinate plot variation of multiple variables over time time series graph variation of one variable over time

visualization in a way that people can understand it self-organizing map (SOM) nD variables -¿ 2D space + 2D color scheme

Scivis vs. Infovis

list of all possible spatial presentations -¿ only focus on maps list of all possible temporal presentations -¿ only focus on timelines

Cartographic visualizations are the interface between the GIS and the human. A map is is the common form. It is a discrete graphical expression of the continuous real world. The creation of a map is not just a scientific, but also a creative process: The form, function and interaction methods shall follow the purpose of the usage of the map.

There is no fixed guideline how to properly design a map, but there are typical elements that are part of every cartographic visualization.The main element is the map itself, using a specific map projection , a scale and an initial center point. A map is typically structured in a *layer* principle. Each layer is a transparent film showing one specific aspect, e.g. a physical layer showing coastlines, mountains or forests, a political layer showing international borders or a cultural layer showing cities or population densities. The layers are interchangeable, can be switched on and off and serve to serve a different visualization purpose. The map is designed using a certain color scheme, fonts and signatures for all the objects on the map.

Additionally there can be a *title* describing the purpose of the map. A *legend* including the scale bar and north arrow shall explain all symbols used on the map and give orientation. Depending on the degree of interactivity, there can be *menus* with different visualization options, e.g. panning and zooming on the map, switching map layers on and off or changing the color scheme of the map. [Bol08, pp. 159-166]

The main goal of map design is to give the user nothing but the necessary information he needs to satisfy his or her information need. The cartographer shall use techniques of *cartographic generalization* to minimize information on the map and maximize the knowledge to be extracted from the map. Simplification, smoothing or aggregation help to reduce amount of information. Enlarging, widening or displacement help to focus on the important areas of the map. Selection and classification help the user to get an overview of the information. [KW05]

Leaflet.js is "an open-source JavaScript library for mobile-friendly interactive maps" [19] that offers functionality to embed a map with a chosen projection in an HTML document, use own map tiles, symbols and markers on the map and tools for zooming and panning. The same service is provided by *OpenLayers*, a "A high-performance, feature-packed library for all your mapping needs" [20], just with more features and users.

2.4.5.1 Maps

maps are means and products of GIS

scientific visualization vs. information visualization tangible objects abstract concepts with

[19] *Leaflet - JavaScript library for interactive maps*, URL: `http://leafletjs.com/`, last access: 02.11.2015
[20] *OpenLayers 3 - Welcome*, URL: `http://openlayers.org/`, last access: 02.11.2015

inherent form without inherent form e.g. CT scan of human body e.g. flow of refugees -¿ 3D globe: inherent form, direct representation of Earth -¿ scientific visualization -¿ 2D map and time: no inherent form resp. abstract concept =¿ information visualization

tasks of visualization present (what? where? when? how?) analyze (e.g. what is the best? where is the most? when was the first?) explore (why?)

interactive map enhances human cognition (panning, zooming, changing map layers, time point, data source, ...) and lets him gain knowledge about the domain

maps contain symbols and elements ... blaaa ...

traditional paper maps vs. modern digital maps

classical map		modern	
character	restriction	character	improvement
static	only discrete point in time	dynamic	higher sample rate for continuou
isolating	only part of geographical space in 2D	multi-dimensional	multiple levels of detail, possibilit
selective	only one layer	inclusive	change layers and perspectives
passive	only sending information	interactive	direct manipulation and explorat

Table 2.3: Innovation of modern digital maps
alternation of [Kar12] and [OS01, p. 145]

modern digital maps can show changes in time and space due to their dynamic, multi-dimensional, inclusive and interactive nature.

Map Projections Based on the geodetic datum a three-dimensional representation of the Earth in form of a globe would be a possible medium to view the planet. When seen perpendicular onto the world, a globe represents sizes, shapes, distances and directions of objects close to the viewpoint with a reasonable accuracy. However, they are very space-consuming and cumbersome. For a precise measurement of distances, following a route or examining a terrain model, the globe would have to be very large. Therefore, the desired medium for practical purposes is a two-dimensional map.

The basic problem to be solved is that the Earth is a spherical object, its surface is curved and it is therefore not straightforward to project it onto a flat 2D map. The meridians which are lines of equal value converge at the poles. Neighboring meridians (distance: 1°) have a distance of 111 km at the Equator and 0 km at the poles. They do not form a right-angled grid with the parallels and therefore no Cartesian coordinate system. This is the reason why the geometries of the spherical Earth will be distorted when displayed on a flat 2D Cartesian coordinate system. [Bol08, p.79]

There are two main classifications of map projections: The *projection family* with respect to the geometric shape used for the transformation: *cylindrical*, *conical* and *azimuthal* or *planar projection*). Secondly, the *distortion characteristics* with respect to the map property that is preserved. There are *equivalent*, *conformal*, *equidistant*, *zenithal* and compromise projections. Most families and characteristics can be mixed, e.g. it is possible to create a cylindrical, a conical and an azimuthal equivalent map projection [Kry].

Projection Families The basis of geometrical map projections are *developable surfaces* onto which the ellipsoidal model of the Earth is projected. The are mainly three geometric shapes that are used as reference surfaces: cylinders, cones and planes. The model is fitted in or on the surface touching it in at least one point or line. The idea is that there is a projection source from which rays are shot through the ellipsoid on the surface, projecting each point of the ellipsoid onto the surface (as seen in figure 2.13). This principle is known from the ray casting technique in computer graphics [Geo].

In praxis, also pure mathematical map projections are used, e.g. pseudocylindrical, sinusoidal or Mollweise projections. They are much more complex and have the goal to reduce the overall distortion [Bol08, p.99].

Distortion characteristics To flatten a spherical surface onto a flat surface, transformations such as stretching, tearing or shearing have to be performed. A map projection is only accurate at the *standard lines*, i.e. the point(s) or line(s) where the developable surface touches or intersects the ellipsoid. In all other parts the map will in some ways be deformed. That causes distortion in at least one of the following properties of a map: shape (angle), size (area), direction or distance of features on the map. There is no perfect map projection. Each projection can preserve maximum two of these properties at a cost of distorting the others. The cartographer has to make a compromise and choose a set of characteristics that

[21] based on: *Coordinate Reference Systems*, QGis Documentation, URL: `http://docs.qgis.org/2.0/en/docs/gentle_gis_introduction/coordinate_reference_systems.html`, last access: 27.10.2015

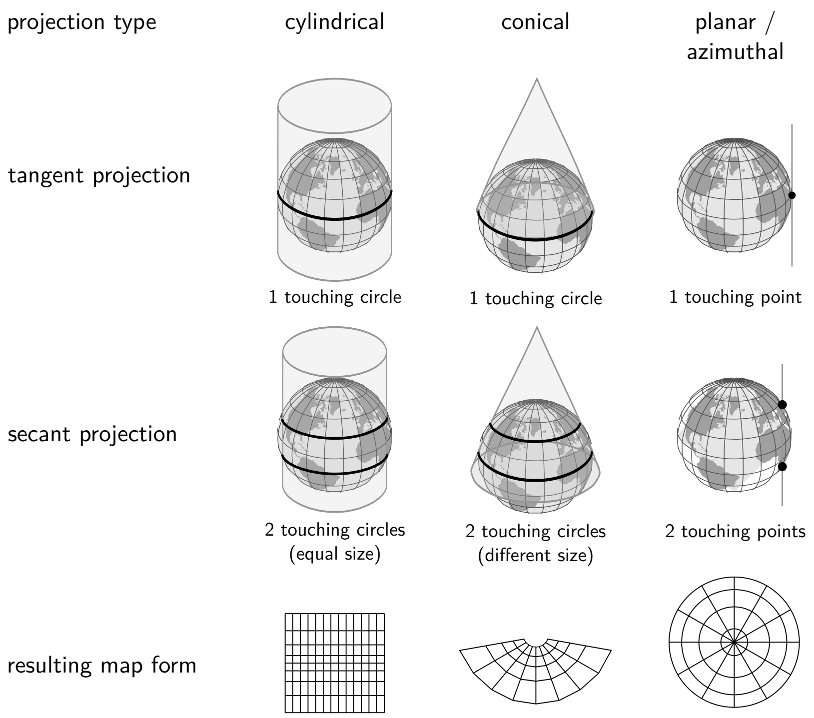


Figure 2.13: Three different developable surfaces for map projections [21]

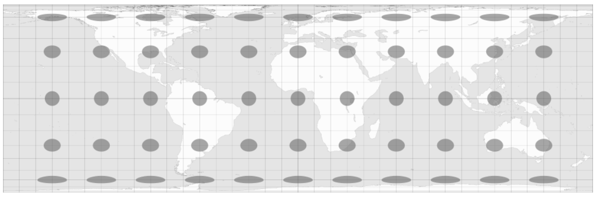
are important while accepting a distortion in the other properties.

Tissot's indicatrices visualize the distortion patterns in the form of ellipses on the map. Their size, shape and orientation are caused by the map projection and show the distortion at this point of the map. Using indicatrices the advantages and disadvantages of each map projection can be shown.

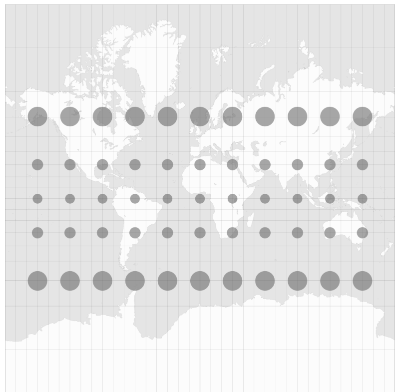
There are two mutual exclusive characteristics: *equivalent* and *conformal*. Equivalent projections preserve the sizes and areas of features on the map, whereas conformal projections preserves angles and the shapes of objects. Every map projection that is area-preserving distorts shapes at the same time, and vice versa [Geo].

[22] *Tissot indicatrix world map Lambert cyl equal-area proj*, Eric Gaba / Sting (Wikimedia), June 2008 URL: `https://commons.wikimedia.org/wiki/File:Tissot_indicatrix_world_map_Lambert_cyl_equal-area_proj.svg`, last access: 28.10.2015

[23] *Tissot indicatrix world map Mercator proj*, Eric Gaba / Sting (Wikimedia), September 2008 URL: `https://commons.wikimedia.org/wiki/File:Tissot_indicatrix_world_map_Mercator_proj.svg`, last access: 28.10.2015



(a) Lambert cylindrical projection [22]



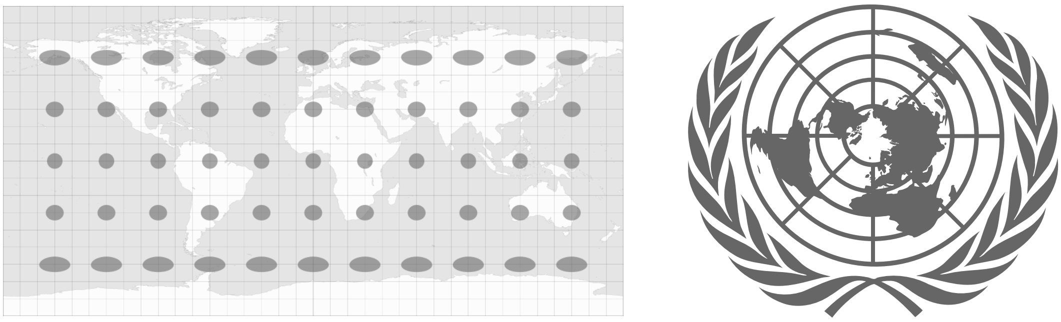
(b) Mercator cylindrical projection [23]

Figure 2.14: Comparison of equivalent and conformal map projections

The *Mercator projection* (figure 2.14b) is an angle-preserving map. It was used for nautical navigation because of a very helpful property: constant compass bearing. A straight line on a Mercator map crosses all meridians in the same angle, a so called *loxodrome*. A navigator only has to follow this line and never needs to reset the compass, because it will always point in the same direction. This is not the shortest way from A to B, but the easiest to navigate. The disadvantage of Mercator maps are the large area distortions towards the poles, which can be seen at the sizes of the ellipses. The best example visualizing the problem is Greenland: On the map it seems almost as large as Africa, whereas in reality Africa is 14 times larger than Greenland. [Geo]

This scale becomes obvious in the area-preserving *Lambert projection* (figure 2.14a). Tissot's indicatrices all have the same size, but their shapes get distorted towards the poles. This map shows the real size of Africa, but largely distorts the shape of Europe. However, for thematic mapping and teaching purposes equivalent projections are well-suited, because they accurately show the areas of the countries. [Geo]

The result of an *equidistant* projection is a map that in relation to the scale accurately shows the distances between certain points on the map.



(a) Equirectangular equidistant cylindrical projection [24] (b) Logo of the United Nations [25]

Figure 2.15: Two examples of equidistant map projections

Figure 2.15b shows a prominent example: The Unites Nations chose a map for their logo from which all points on the map have the correct distance to the North Pole. The equirectangular projection in Figure 2.15a has a slightly different property: any meridian is true to scale and therefore all distances along the meridians are accurate. However, the ellipses on the map are distorted in both shape and size, so the map is neither conformal nor equivalent. Air navigation charts or seismology make use of the equidistant property e.g. to show distances from major cities to the epicenter of an earthquake. [Geo]

Zenithal or *azimuthal* projections preserve directions from the center point to all other points on the map (see figure 2.16). It is only possible in the family of planar projections and can be combined with a conformal, equivalent and equidistant property. These maps are used whenever directional relationships are important, for example in navigational charts.

If no characteristic is explicitly important but the overall distortion shall be minimized, a *compromise projection* can be used. They do not preserve any property, but are a trade-off in the distortion of all other properties. The Robinson projection in figure 2.17 is a well-known example. All Tissot's indicatrices not on the Equator are distorted in size, shape and

[24] *Tissot indicatrix world map equirectangular proj*, Eric Gaba / Sting (Wikimedia), June 2008 URL: `https://commons.wikimedia.org/wiki/File:Tissot_indicatrix_world_map_equirectangular_proj.svg`, last access: 28.10.2015

[25] *Logo of the United Nations*, Shizhao (Wikimedia), 13.06.2007 URL: `https://commons.wikimedia.org/wiki/File:Logo_of_the_United_Nations_(B%26W).svg`, last access: 28.10.2015, Comment: This work is excerpted from an official document of the United Nations prior to 17. September 1987.

[26] *Lambert azimuthal equal-area projection SW*, Strebe (Wikimedia), 15. August 2011 URL: `https://commons.wikimedia.org/wiki/File:Lambert_azimuthal_equal-area_projection_SW.jpg`, last access: 28.10.2015

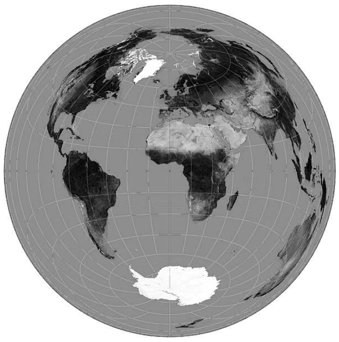


Figure 2.16: Lambert azimuthal (zenithal) equivalent projection [26]

direction, but compared to the Mercator or Lambert projection, the magnitude of distortion is lower.

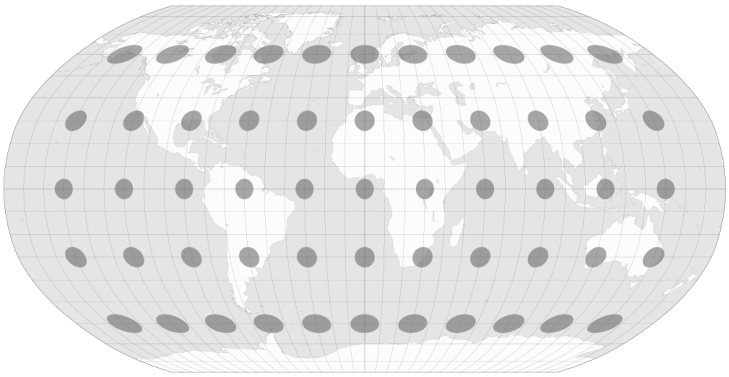


Figure 2.17: Robinson projection [27]

2.4.5.2 Timelines

2.5 Application

In summary, The research focuses on changes over time triggered by historical events happening in an historical context. There are currently no historical information systems that scientists of this field use for their research, it is rather based on primary and secondary

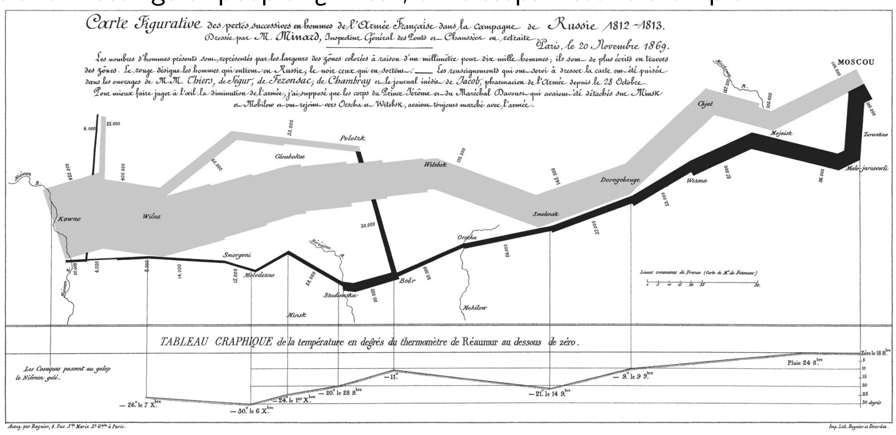
[27] *Tissot indicatrix world map Robinson*, Eric Gaba / Sting (Wikimedia), June 2008 URL: `https://commons.wikimedia.org/wiki/File:Tissot_indicatrix_world_map_Robinson_proj.svg`, last access: 28.10.2015

sources, e.h. historical documents, speeches or photography.

Historical or *temporal geographic information systems* (HGIS) combine elements of history and geography into one information system to be able to answer research questions for both historians and geographers: “situating history in its geographical context and using geographic information to illuminate the past.” [KH08, p. 3] This manifests the interdisciplinary nature of HGIS and making it also an interesting technology in the context of *digital humanities*, the intersection between humanities and computing. The main distinction to classical GIS is the integration of the component of time, making the system four-dimensional. HGIS collect, manage, analyze and present spatio-temporal information and models changes over time and space [Kno02, p. xii]

there is “not any operational temporal GIS” [Raz12, p. 5]

lifelines showing tracks, routes and meetings or people -¿ linear, time steps historic example:



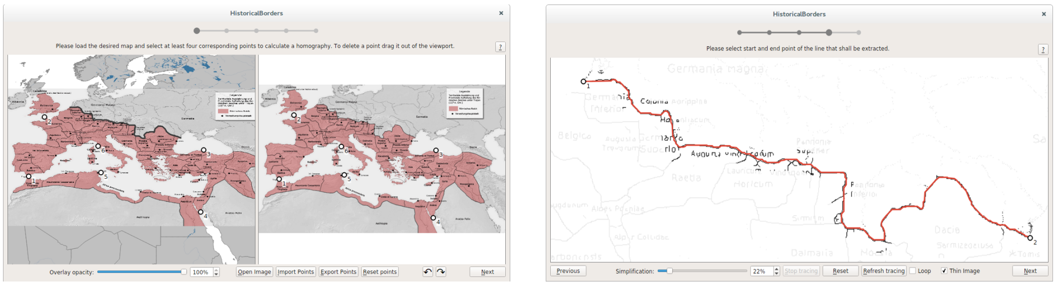
Napoleons Moscow Campaign [28] [KH08, pp. 188-191]

reason about historical events combine spatial and temporal and attributional information -¿ overlays e.g. Battlefield stories (what was the cause for the victory of party A?)

mapping historical maps (historical status) most part of the work: digitizing and systematizing primary source material into spatial and attribute data (geodata) -¿ georeferencing, semi-automatic feature extraction, manual data entry [Kno02, pp. xvii] There are several techniques to acquire geodata as a primary source, e.g. through surveying, aerial and satellite

[28] *Minard.png* Charles Minard, 1869, URL: `https://commons.wikimedia.org/wiki/File:Minard.png`, last access: 03.11.2015, Charles Minard’s 1869 chart showing the number of men in Napoleon’s 1812 Russian campaign army, their movements, as well as the temperature they encountered on the return path. Lithograph, 62 x 30 cm

imaging using remote sensing and photogrammetry [Bol08, p. 148-149, p. 213-216]. Spatial data from a hardcopy map can be gained by a two-step process that can be seen in figure 2.18: First project the map into the coordinate system of the world by *georeferencing*. The result is that each pixel of the raster graphic is assigned a geographic coordinate from the real world, so the geometry is given a spatial reference. Afterwards acquire the coordinates of the desired features on the map through semi-automatic digitizing [Bol08, p. 133-142].



(a) Georeferencing (b) Semi-automatic digitizing

Figure 2.18: Semi-automatic extraction of a border from a map of the Roman Empire [29]

HGIS projects usage: mostly quantitative research -¿ logical characteristics of information system)

large collection of research projects [KH08] [GG14]

"The Barrington Atlas of the Greek and Roman World" gazetteer: name of historic place -¿ map by map [Tal00] [30] solution think about how to represent historical knowledge in geographic context degree of certainty -¿ ironically: that has to be exact as well in a database table =¿ reason: careful conclusions from historical maps problem: tedious manual work 20 hour per map already digitized [Kno02, pp. 145]

show change over time (historical development) state-based approach (photography: validity period of geometries)

"Great Britain Historical GIS Project" (GBHGIS) [31] idea: combine statistical data with ter-

[29] *HiBo - semi-automatic extraction of borders from historical maps*, Project of: B. Weber, N. K. Dankwa, K. Singh and T. Kashyappan, supervised by: Prof. Volker Rodehorst and Marcus Kossatz, Bauhaus-Universität Weimar, February 2015, URL: `https://bitbucket.org/bastian_weber/hibo`, last access: 29.10.2015

[30] *Ancient World Mapping Center*, The University of North Carolina, URL: `http://awmc.unc.edu/`, last access: 03.11.2015

[31] *Great Britain Historical Geographical Information System (GBHGIS)*, Ian Gregory & Humphrey R.

ritorial units =¿ new analytical opportunities e.g. analyze net migration in the districts in UK -¿ snapshot model problem: "To map and spatially analyze data correctly, quantities must be linked to an accurate representation of the units for which they were collected." administrative units / districts fundamentally changed three times and slightly changed hundreds of times over the last 200 years statistical data is gathered per unit hardly any info about historical boundaries of districts (some by British Ordnance Survey, but not covering everything) =¿ results would be disproportional [Kno02, pp. 117-129] solution: aerial interpolation geostatistical interpolation discrete data proportional to source polygon (old geometry) -¿ reaggregate to target polygons (new geometry) =¿ prediction [Arc]

UK ordnance survey * automatic change detection `https://www.ordnancesurvey.co.uk/education-research/research/automatic-change-detection.html`

"National Historical Geographic Information System" (NHGIS) [32] idea: provide digital boundaries for each census year -¿ estimation of population of any year concept: composite map: each face represents an area that never changed -¿ composition to regions per year based on compositing information dealing with problem of varying administrative borders through aerial interpolation interface: very scientific a lot of options need tutorial to go through the selection need to register before downloading something get a link to download a file have to decompress it then load it into your preferred GIS -¿ incredibly frustrating !!!

This application does maps and timelines:

https://www.palantir.com/palantir-gotham/applications/

MAP The Map application delivers geospatial analytic capabilities. It combines the visualization of geo-located objects on a map with histogram, timeline and time wheel visualizations. A heatmap visualization illuminates the density of interesting objects on the map.

The imagery on the Map is fully pluggable, allowing users to switch between different sources of imagery, integrate private imagery, and create composite imagery sets that combine two or more sources of imagery.

KML and Shapefiles can be imported as independent map layers, and shapes contained in these layers can be used to select and filter objects that lie in a similar region (like a county,

Southall, University of Portsmouth, since 1994, URL: `http://www.port.ac.uk/research/gbhgis/`, last access: 02.11.2015

[32] *Welcome to NHGIS*, Minnesota Population Center, University of Minnesota, since 2007, URL: `http://www.port.ac.uk/research/gbhgis/`, last access: 02.11.2015

census plot, or state). Layers can be colored and labeled according to calculations performed on the data they contain.

Here is a group using the tool to do historical maps: http://envisioninghistory.org/

And here is a program I'm using for my dissertation. I don't know if it does timelines and maps, but I think it might.

http://www.tableau.com/

Here are some examples of what I'm doing with it:

And my dissertation website just for fun: http://nazitunnels.org

The major problem that lays in the nature of the qualitative historical research is that all historic sources are subjective and biased, their content may be fuzzy and they are definitely incomplete. So the knowledge that can be extracted from a source bears the integral problem of *uncertainty*. On the other hand there are information systems with a logical architecture, with the goal to be as precise and accurate as possible. Analysis is based on mathematical functions – in its entire nature an information system is quantitative. This contrast is the main problem why HGIS is not widely accepted yet [KH08, p. 2].

Another problem for historians is that they do not necessarily need a tool to better visualize existing knowledge (e.g. historical maps), but to generate new knowledge by analyzing spatio-temporal coherences or distributions in historical data. Spatio-temporal reasoning is still an open field and not easily possible with existing HGIS [KH08, p. 268], [GG14, p. xii].

Some interesting research questions that could be answered using HGIS could be:

- Did the European Union help to bring peace on the European continent or the other way around? (political)
- Is there a coherence between life expectancy and fertility rate on earth? (social)
- Does global warming speed up the melting of the glaciers? (physical)
- What was the contribution of Bismarck's foreign policy to a longer period of peace in Europe from 1871 to 1914? (historical)

Or on a more abstract level: Where and When has something changed and why did it change?

space-time premise by Gaddis 2002 time and space equal importance event what significantly has happend and by whom? (singularity!) process how something has happened? (event+activity =¿ trigger of process) change driven by process spatiotemporal data defines all above three

2.5.1 Digital Humanities

2.5.2 HistoGlobe

transition to concept chapter

Chapter 3

Concept

domain: development of countries in time and space

changed-based approach (historical event -¿ .. -¿ geometry changes) is there something ?!? -¿ MY APPROACH! usable User Interface for both navigation and editing -¿ problem: all interfaces are trés horrible!

no perfect data model possible, because a model is just an incomplete abstraction of the real world

map for spatial domain (x, y) timeline for temporal domain (t) -¿ 3D system

no transaction time, only valid / event time

space-time composite with lines

-¿ the whole earth is 100% covered by spatial objects (full topology) countries, debated territories, unknown land, water Newtons concept of absolute space?

ancestors successors layers of administrative units open to extension for additional attribute data (e.g. statistics)

geometries must be edited

requirements geographical knowledge contextualize / intersect historical sources accept imprecision prevent illusion of certainty

Application: HistoGlobe A distributed *Web Information System*, consists of a remote server side, on which the storage and management of the actual data happens, and the client side on which the user communicates with the system. It hosts the user interface that is rendered in a Web browser.

describe the components of the GIS explicitally hardware software data

collection management analysis output

research questions –¿ HGIS ¡– development of system historians / ME geographers (+) open source, direct manipulation, easy sharing and collaboration

interior borders of countries, which are straight lines between manually defined border points. =¿ vector model

countries with enclaves or islands are not topologically equivalent.

There are topological rules rules that can be applied, e.g. two neighboring countries (polygons) share one common border (polyline). That preserves the relationship between them if their common border changes.

=¿ event-based HGIS

only world time is regarded, not database time.

identity: formal name of an entity

store Hivents in DoublyLinkedList

borders: complex model: different states of boundaries: draft -¿ proposal -¿ dispute -¿

simplification: just active / inactive, normal / contested + level of certainty

Hivent-Based Three-Domain Spatio-Temporal History Graph Data Model for Vector Geometry ... or in short: HBTDSTHGDMVG

A main problem is to maintain the integrity of the spatial topology when a new change gets inserted not at the end of the list. A simple example shows that problem: Given geo-object X is part of the inital base configuration at change t_b. At a later change, e.g. t_y X gets replaced by object Y. If a new change that updates X to X' gets inserted before at time point $t_x < t_y$, then t_y is not integer anymore, because object X does not exist. That is why on insertion of a change, all succeeding changes have to be tested for integrity and it might be necessary to update later changes.

history graph model without changing state: active, inactive

3.1 Hivent

event which is in itself or whose outcome is historically significant (subjective) or with

WHAT? significant happening WHO? different actors WHEN? one point in time WHERE? mostly also point in space, sometimes different from area that event affects WHY? because

models historically significant happenings with a focus on those who influence the geopolitical history of countries.

In modern history, geopolitical changes of countries are manifested mostly in historical treaties which are the result of a conference or any other gathering of representatives of stakeholders of that initiated change. Since each of those treaties is signed on one particular day, in one particular place and has one particular name, the `Hivent` model seems appropriate.

However, the first question arises regarding the relevance of the location: While the exact position of the battlefield of Verdun or the place where John F. Kennedy was assassinated might very relevant to the event itself, the location of a governmental bill, a declaration of independence or a border convention might not play an important role and usually happens in a representative place, e.g. the parliament or the office of a president. In a lot of cases, it is much more important which territories an event actually influences instead of where it happened.

significant happening in time and space incluencing others central element in event based STDM

3.2 Area

model the main entity of the domain: historical or current countries. An `Area` represents one identical country, consisting at each time point of its existance of exactly one `AreaName` and one `AreaTerritory`. The model seems appropriate since the name and the territory of an area are exactly the two properties that are part of the domain.

abstract: area

defined by borders hierarchical structure

country borders coastlines interior disputed territories situation: n fully recognized countries and m non or partially recognized entities claim sovereignty over 1 territory territory is surrounded by disputed border question: does this disputed area claim sovereignty? [1]http://www.economist.com/blogs/economist-explains/2014/09/economist-explains-1 uncertain borders situation: n fully recognized countries commonly agree on a boundary between them, but the border is not clearly defined / fuzzy / uncertain states of borders planned agreed demarcated provisional valid vs. disputed

area territory -¿ geometry –¿ border -¿ representative point name -¿ short name -¿ formal name

enclaves exclaves

3.3 Hivent-Based Spatio-Temporal Data Model

3.4 Spatio-Temporal Operations

CRE UNI INC SEP SEC TCH BCH NCH ICH DES

inclusion of universe Ω: CRE = SEC from Ω DES = INC into Ω

MECE principle: Mutually Exclusive and Collectively Exhaustive

3.5 Edit Mode

user operations CRE UNI SEP TCH NCH DES — / / / / — HG operations CRE UNI INC SEP SEC TCH BCH NCH ICH DES

[1]`\unskip\penalty\@M\vrulewidth\z@height\z@depth\dpff`

area changes ADD DEL* DEL* DEL TCH TCH TCH NCH ADD DEL ADD, TCH, NCH, DES ADD TCH ADD* NCH? TCH DEL NCH? ADD*

Chapter 4

Development

distributed Web-based system classic approach: UI ¡-¿ Client (main program) ¡-¿ Server (middleware) ¡-¿ DB

4.1 System Architecture

graphic of basic system: UI Client-side mechanism Server-side mechanism Database

programming languages / Framworks Client HTML Less -¿ CSS CoffeeScript -¿ JavaScript Server Django -¿ Python PostgreSQL + PostGIS

4.2 Interface Design

4.2.1 Paper Prototype

description of process image of two prototypes

4.2.2 Mockup Prototype

description of process screenshot of two steps in between and of final version

4.2.3 Final Version

4.3 Client-Side Application

HistoGlobe

SpatialDisplay -¿ Map

TimeController ¡-¿ Timeline ¡-¿ NowMarker

HiventController AreaController ¡-¿ AreasOnMap HiventHandle AreaHandle Hivent HistoricalChange AreaChange Area AreaName AreaNameLayerOnMap AreaTerritory AreaTerritoryLayerOnMap

DatabaseInterface

EditMode -¿ EditOperation -¿ EditOperationStep NewTerritoryTool* NewNameTool NewHiventBox WorkflowWindow

HistoGraph

LabelManager*

important little utils Button, ButtonArea NumberInput, TextInput, TextInputArea Title Watermark DoublyLinkedList WithinTree Geometry -¿ Polypolygon -¿ Polygon -¿ Polyline -¿ Point

4.4 Server-Side Application

models

Hivent m HistoricalChange m ———AreaChange—— — — — — —-Area—- — m m m m AreaTerritory AreaName

view

get_all save_operation

-¿ Managing Vagueness, Uncertainty and Granularity in Spatial Information Systems (VUG) -¿ Karl Grasser (Diss. Santa Barbara) -¿ Fuzzy, Imprecice, proabilities vs. possibilities

big problem: why? intention and motivation of author? hard to find out... voice and perspective medieval maps: natural landmarks as border points =¿ inaccurate and imprecise perspective: who is making the map? (illiterates?) different names: US Civil War (North) vs. WWI (West) vs. Germanic War (Russia) WWII (West) vs. Great Fatherland War (Russia)

accepted uncertainty: date != exact timepoint, only D.M.Y location != exact location, only name of place

[Sol14, chapter 2, p. 51]

different states of boundaries: draft -¿ proposal -¿ dispute -¿

Chapter 5

Uncertainty

Every aspect of the concept (chapter 3) and the development (chapter 4) of this work is based on the prerequisite of full certainty of the data. That means both the Historical-Geographic Operations and the Hivent-Based Spatio-Temporal Data Model assume that the dates of the historical events, the names and territories of the historical and current areas and the historical relations between events and areas are accurate and reasonably precise (definitions see 5.2).

However, this assumption is far from valid. In historical research, uncertainty is one of the major problems (see 2.1.1) a historian has to deal with on a daily basis: sources, even primary sources, can be biased towards the author of the source, information can be imprecise or even inaccurate and information can be conflicting with other sources. This chapter explains problems with uncertainty in the domain of development of countries in time and space and develops approaches to deal with these problems.

5.1 Definition of a Country

The problem begins with the definition of a term that almost everybody in the world is familiar with: a "country". Since countries are the domain of this historical geographic information system, it must be possible to decide for each current and historic territorial entity in the world if it is or was a country or not. Therefore a clear and non-conflicting definition of a country is necessary. However, this is impossible to do.

The Oxford Dictionary definition of a country reads as follows:

> "The *territory* of a *nation*; a *region* constituting an *independent state*, or a region, province, etc., which was once independent and is still distinct in institutions, language, etc." [1]

This definition includes many different concepts and terms: the territory or region that the country is on, a nation or state, a population and a culture of the territory in terms of institutions or languages. While nation and state are commonly used as synonyms for countries, their meaning varies from case to case, as it will be examined in this section.

To understand what a country really is, the United Nations as an intergovernmental organisation are a valuable source. It was found after World War II (October 1945) and promotes international peace keeping, security, protection of human rights or humanitarian aid to all its member states which should coincide with all the countries in the world. The committee currently has 193 full member states and two permanent obervers: The Holy See (Vatican City) and the State of Palestine [Unib]. But these 195 members in total do not cover all places in the world – and also a membership in the United Nations does not mean that the question of statehood can simply be answered.

5.1.1 Special Cases

Examining the list of the UN member states yields several interesting observations and special cases, which can be classified by their membership status in the United Nations and their degree of international recognition.

UN observer states The *Holy See* is the juridcal and spiritual entity representing the territory of Vatican City. It is a fully recognized and sovereign state but is not a full member of the UN, because it has never applied for it. It is the by far smallest sovereign state in the world (0.44 m^2), is an enclave inside the city of Rome with a population of only 800 people, including 30 women [Vat].

[1] *country, n. and adj*, Oxford English Dictionary, URL: `http://www.oed.com/view/Entry/43085?`, last access: 2016-04-25

The *State of Palestine* has a population of 4.8 million people [Pal, as of 2016] and is also an UN observer state. However, it is totally different in terms of sovereignty: While it consists of the territories of the West Bank, East Jerusalem and the Gaza Strip, their borders were drawn in the 1949 Green Line Armistice Agreement but were never intended to be used as international boundaries [Amn]. Since then, the ongoing and complex conflict with the State of Israel lead to a difficult situations regarding the sovereignty over the territories. Therefore, the state has no clearly defined territoy. Moreover, while 114 states officially recognize the Palestinian state, almost all current main economic powers do not, including the Canada, France, Germany, Italy, the United Kingdom and the United States. None of them even voted in favor of Palestine receiving an observing status in the UN [Unia]. That means, unlike the Holy See, Palestine is not a fully sovereign and recognized state.

UN non-members with limited recognition *Kosovo* is a state Europe and and declared independence from Serbia in 2008. It has a clearly defined territory and a permanent population and is recognized by 111 UN member states. In order for Kosovo to become a full member of the United Nations, all permanent members of the security council (United Kingdom, France, Russia, China and the United States) must agree. But since Russia and China strongly support the territorial integrity of Serbia, they would veto Kosovos membership in the United Nations. Therefore, Kosovo is not even an observer state of the United Nations, although having about the same degree of international recognition as Palestine [Peo].

The status of Taiwan is a very complicated issue. An overgeneralized description of the problem, which involves two territories and two political entities, is: There is the *People's Republic as China* (commonly known as China), with full control over mainland China, and the *Republic of China*, governing the island of Taiwan. However, both political entities claim each others land. That means, there are two states claiming the exact same territory. But, since 1971 the People's Republic of China is the representative of whole China in the United Nations, including the island of Taiwan. Because it is part of the Security Council, it successfully vetos membership requests of the Republic of China. Therefore, it can not be a member of the United Nations, although it operates like an independend country by international standards: They have an own jurisdiction, issue own passports and have unofficial diplomatic relations to most countries in the world. But officially, only 22 member states of the United Nations uphold diplomatic relations to Taiwan [Rep]. To all of these states the People's Republic of China does not have any diplomatic relations, which makes also them an only partially recognized state.

There are other non-member states of the United Nations which have not yet gained broad international recognition: the Sahrawi Arab Democratic Republic (recognized by 84 UN member states [Wes]), Abkhazia (6 [Glo]), South Ossetia (5 [BBCc]), the Turkish Republic of Northern Cyprus (1 [Leo15]), Nagorno-Karabakh Republic (0 [BBCa]), Transnistria (0 [Gut14]) and Somaliland (0 [BBCb]).

UN members with limited recognition In addition to the Republic of China, there are five other member states of the United Nations that are not fully recognized by all other UN members: Armenia (not recognized by Pakistan [Tod]), the Republic of Cyprus (not recognized by Turkey [Eur]), North and South Korea (officially Democratic People's Republic of Korea and Republic of Korea, mutual non-recognition [Dav]) and the State of Israel, which 32 UN member states do not recognize [Isr].

Special Territories Additionally to countries gaining for international recognition there are territories belonging to fully sovereign countries with a varying degree of sovereignty. For example Greenland is an autonomous country within the Kingdom of Denmark, but not a sovereign state and therefore not a member of the United Nations. The same applies to the Faroer Islands (part of Denmark) and numerous overseas territories of the United Kingdom, the French Republic and the Kingdom of the Netherlands in the Carribean, the Indian Ocean or the Southern Pacific Ocean. Moreover, there are five quasi-independent countries in a so called *Free Association*: Niue and Cook Islands are associated to New Zealand and not part of the United Nations. The Marshall Islands, the Federated States of Micronesia and Palau are associated to United States, but in contrast are full UN members [Won].

This incomplete and simplified list of special cases manifests the big problem that is associated with the terms "country", "state" or "nations": There is neither a *de jure* consistent definition nor a *de facto* consistent usage of these terms. Everything breaks down to two different concepts:

5.1.2 Declaratory vs. Constituitive Theory

The declaratory theory, established in the Montevideo Convention 1933 [Yal], gives each entity the right to declare a state if it matches all of the four requirements:

1. a clearly defined territory

2. a permanent population
3. a political representation / government
4. the *capacity* to enter diplomatic relations

These four requirements make sure that a state can exist physically and politically. However, it is worth noticing that this definition does not include any actual diplomatic relations to other states, but only the capacity to enter them. Therefore the existance of a state is independent from its recognition by other states. In other words: "A country is a country when it thinks it is a country."

In contrast, the constituitive theory requires exactly that: A state can only be considered as such if it is recognized by other states. However, it is not defined anywhere by how many other states [Law]. In short: "A country is a country when other countries think that country is a country." [CGP]

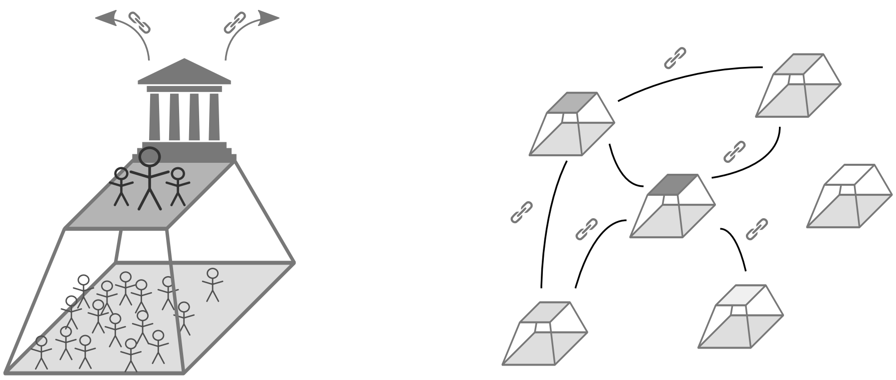


Figure 5.1: The Declaratory Theory (left) and the Constituitive Theory (right) of Statehood

Both theories have advantages and disadvantages, but the two main problems are:

1. Following the declarative theory, countries are self-classifying and potentially conflicting entities. The application of this measure would grant Kosovo, the Republic of China, Abkhazia or the Sarhawi Arab Democratic Republic full statehood. However, since their territories are contested, this would lead to overlapping territories with Serbia, China, Georgia and Morocco, which is impossible.

2. There is no superior organization that can judge if a country is a country or not. Even the United Nations fail to do so, because their membership requirements prevent states like Kosovo or the Republic of China from becoming full members. They also have no power to rule out problems regarding the independence of Transnistria or Somaliland.

Therefore it is impossible to objectivly classify an area as a country or not: nobody can say if Kosovo, the State of Palestine or Niue are countries or not. These theories have been introduced in the previous 80 years. For the time before that, a conflict-free decision of what is country is not just impossible, but also not justifyable because of a lack of jurisdiction.

That means, an historical geographic information system with the goal to visualize the development of the countries on Earth in time and space inevitably deals with uncertain information that certain parties see as wrong. Its data model can not perfectly fit self-classifying data and can not rely on an objective data source. The system has to contain approaches that deal with this problem.

5.2 Types of Uncertainty

In order to understand different types of uncertainty it is important to understand the concepts of *disagreement*, *precision* and *accuracy*.

The model in an information system tries to resemble the real world as good as possible and necessary – in this case the history of countries. If there is already a conflict in the real world, e.g. the Kasmir region which is claimed by both India and Pakistan as part of their territory, then this is a *disagreement* which also has to be proberly modeled as such in the system.

The better a model simulates the reality, the more *accurate* or correct it is. That means, the closer it gets to the target, the higher is the accuracy. *Precision* or exactness describes how similar the results are compared to each other, independent from the distance to the target. That means a precise model gets the same results over and over again (see figure 5.2).

If the border between the Principalities of Transsylvania and Wallachia is deducted from an historical map of 1600, the course of the border is is inaccurate to a certain degree, because the map does not show the real world correctly. However, it can be modelled in the system very precisely, because the coordinates of the border points are stored as floating point numbers in the data model. In contrast, there is currently no agreement upon territory of Palestine, although the different versions can be modelled very precisely. In order for the model to also be accurate in this case, it would need to support contested territories.

Hereafter the current data model introduced in section 4 is evaluated in terms of accuracy and precision.

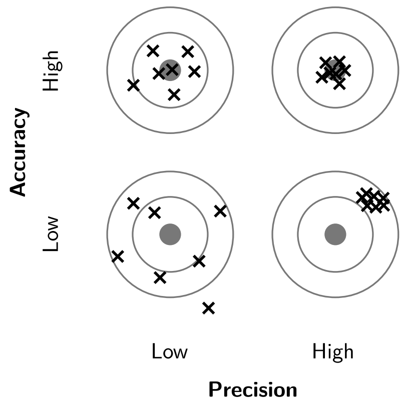


Figure 5.2: The difference between accuracy and precision

Hivents The model for historically significant happenings contains only the following meta information: name, date and location of the event. This has several shortcomings in terms of precision:

The name of an historical event can have different versions: a long, official version and a short common version. The commonly known "Treaty of Versailles" (1919) is officially called the "Treaty of Peace between the Allied and Associated Powers and Germany". Also the name is different in other languages affected by the treaty. Additionally, there can be different versions of the name from different perspectives, even within the same language, e.g. the "American Civil War" as it is known today was alternatively called "War Between the States", "War for Southern Independence" or "War of Northern Aggression" depending on the perspective. The `Hivent` model does not account for different languages and versions and is therefore not very precise.

The `Hivent.date` is supposed to represent the temporal dimension of an historical event. While an historical change itself is discrete and happens at exactly one time point, the historical event yielding this change might not. The "Congress of Vienna" which reordered the empires on the European mainland was one of the main historical events in modern European history. While the changes of the congress came into effect on 9. June 1815, the congress itself took place in Vienna from September 1814 until June 1815 which is also a timespan of interest. Another phenomenon becomes apparent in the "Convention for the Extension of Hong Kong Territory" (1898) which had a predefined length of 99 years. The treaty therefore has two dates in which historical changes happened: the date the treaty came into effect (Hong Kong becomes part of the United Kingdom) and the date it stopped being in effect (Hong Kong is handed over to China). Other interesting aspects are different calendar systems used in different parts of the world throughout history: the October Revolution in Russia (1917) happened in November in their Gregorian Calendar system, but in October in the Julian Calendar. Also timezones can play a crucial role: The German Instrument of Surrender ending World War II in Europe came into effect on 8. May 1945 at 23:01 Central European Time, so the 8. May is celebrated as the Victory Day in Western Europe. But in the Soviet Union and nowadays Russia that happened at 1:01 Moscow Time on 9. May 1945 which is why the celebration of the Victory Day there happens one day later. While the `Hivent.date` field in the data model works with timezones, it does not support different calendar systems or multiple dates associated with one `Hivent` which limits its precision.

The event location is represented by the `Hivent.location` name of a place, which can e.g. be a city, a battlefield or a region. The model is not very precise, because the actual geospatial location or region in which an historical event happened is not stored in the system. Additionally, it does not support names in different languages.

The even larger problem is an integral lack of accuracy: The whole nature of historical research is based on subjective interpretation of supposedly objective primary sources. But it is questionable if a source can actually be objective. Each bill, treaty or speech is written by somebody, each map was drawn by someone and has therefore a subjective note. Information in a primary source can be (un)intentionally incomplete, imprecise or inaccurate. The source can be biased towards the author, can contain secret passages not open to the public or its geographic information might be wrong. There are many problems involved in historical sources which makes the acquisition of objective historical data almost impossible. The further documents go back in time, the lower is the expected accuracy. Since all the information in the historical geographic information system is based on primary sources, the data in the system inherits these problems.

Areas Also the model of an abstract area, consisiting of a territory and a name, is problematic in terms of accuracy and precision. As it has been discussed in subsection 5.1 in detail, it is impossible to objectively model all areas free of conflicts. But the current model does not support the status of a territory as being contested Also, countries can be part of other autonomous (constituent) countries, like England is part of the United Kingdom of Great Britain and Northern Ireland or Greenland is part of Denmark. However, the data model does not support different levels of sovereignty, autonomy or international recognition.

The `AreaName` has the same problem than the `Hivent.name`: it differs among the languages or even among cultures using the same language. The model does not support that. But in one aspect it is more precise than for historical events, because it contains both the formal and the short name of a country.

More problematic is the `AreaTerritory`: Areas bordering international water have a constant coastline assuming that it has never changed. This is inaccurate, because coastlines gradually change all the time, therefore also the boundaries of the countries. The data model does support neither that nor international sea borders which are parts of a countries territory. The primary source for territories of countries are historical maps. They show the status of a country at one point in history or sometimes a territorial change. The process of extracting a boundary from an historical map is error-prone and yields to a loss of accuracy in each step on the way: digitizing, georeferencing and contour tracing. The level of inaccuracy depends on the resolution, the map projection and the colors used in the map. In the data model it is not possible to provide information about the expected accuracy of a territory.

Another problem is that the territory is stored as a whole polypolygon. Different parts of the border can have a different status, e.g. one part is a sea border, one is a well-established and demarcated border to neighboring country X and another part is a contested border to neighbour Y. The `AreaTerritory` data model does not account for these differences.

Accurately modelling contested territories is also problematic. It is based on the principle that there can not be overlapping territories at the same time. That means, a contested territory, for example China or occupied territories in the State of Palestine by the State of Israel can only exist once at the same time and therefore have to treated specially. But the data model does not support contested areas. To go even further, it is questionnable which areas should be included in the data model and which not. While it seems obvious to have Spain, Saudi-Arabia and Azerbaijan in the system, the question of whether or not to include the State of Palestine, Abkhazia, Somaliland or micronations like the Conch Republic in the Florida Keys is hard to answer.

Overall, the current data model poorly accounts for different levels of uncertainty in historical geographic information: imprecise and inaccurate sources, different viewpoints and interpretations, contested territories, changing coastlines or different languages. The question of the upcoming subsection is: How can the data model be extended in order to be more accurate and more precise?

5.3 Solution Approaches

In summary, the shortcomings of the current concept are:

1. General
   (a) only one language (English)
   (b) constant coastlines
2. Hivent
   (a) only one historical perspective on the Hivent name
   (b) only one discrete Hivent date
   (c) only one calendar system (Julian Calendar)
   (d) only location name, no connection to the map
3. Area
   (a) only one historical perspective on the Area name
   (b) all Areas on the same level (no dependencies)
   (c) no support for non-sovereign autonomous regions
   (d) no credibility of Areas existence (via international recognition)
   (e) only clear territories, no support for neutral zones or contested territories
   (f) no support for uncertain parts of a territory
   (g) no support for international sea borders

A higher accuracy in the data model usually leads to a higher complexity. This trade-off has to be thoroughly taken into consideration when supporting a new feature to make a model more accurate. This is why the following problems will be ignored in the rest of the thesis:

1b) Coastlines change continuously, therefore the Hivent-Based Spatio-Temporal Data Model is not suitable. A support for coastline changes would require another data model applied to coastlines. This is out of the scope of this thesis. One approach is to model international waters just like any other area with a name and a territory and change the boundaries according to an underlying continuous function. This way, the countries sharing that coastline as their international border would change likewise.

2a) The support for different historical perspectives on the same event, e.g. different names and descriptions or even different historical changes would create a research tool with great potential. It would enable the possibility for different versions of history based on alternative scenarios ("What if X would have (not) happened?"). However, this would significantly increase the complexity of the system and would also be very subjective.

2c) The introduction of different calendar systems would not increase the accuracy of the model significantly. The dates in the system must all stick to the Julian calendar, which is a reasonable requirement to avoid unnecessary complexity.

3a) see 2a)

3g) Currently each countries territory extends in a range of 3 to 12 miles (5 to 20 kilometers) [Uni82] into international waters. While this is important to accurately model a territory, it is complex, because not every country has signed the convention and each signing party can choose their range into international water. This would not just increase the complexity of the model but also create unfamiliar country territories.

In order to tackle the remaining shortcomings of the current concept, both the user interface and the data model have to be extended.

5.3.1 Extension of the Edit Mode

Two new operations (see figure 5.3) are introduced: `SCH` changes the status of an area and `REC` declares a new recognition, i.e. one country internationally recognizes another one.

Figure 5.3: Newly designed and extended buttons for edit operations.

Set New Territory Also the edit operation workflow gets changed. The second step (`SET_NEW_TERR`) defines the territory of the new area(s). Instead of drawing the whole territory as a set of polygons, the user draws one borderline at a time, geometrically as a polyline. This has the main advantage that each part of the border is treated separately.

The borderline is assigned a degree of certainty, in the interface controlled by a horizontal slider, in the model as a certainty value (`certainty` $\in\ ]0..1]$). Absolute certainty (1.0) creates a sharp and crisp line on the map. In case of uncertainty (`certainty` $\in\ ]0..1[$) three different visualization methods are introduced:

1. Blurred Border: The higher the uncertainty, the wider and more blurry the border.
2. Border Corridor: With increasing uncertainty, the offset around the actual border line extends. That creates a corridor in which the actual border is probably in.
3. Blurred Border Corridor: The combination of the first two approaches.

A simple model for the calculation of the blur factor, line width and offset distance is:

$$f(c) = -1 \cdot S \cdot ln(c) + I$$

where c is the certainty factor, $S > 0$ is a scaling factor and I is the inital value (for width: $1\ px$, for blur: 0, for offset: $0\ px$). In the example in figure 5.4 the scaling factor $S = 4$. In the Blurred Border Corridor method, the scaling factor for line width and the blur factor was halved. Further analysis and user testing are required in order to decide for one of the three approaches to be used in the system.

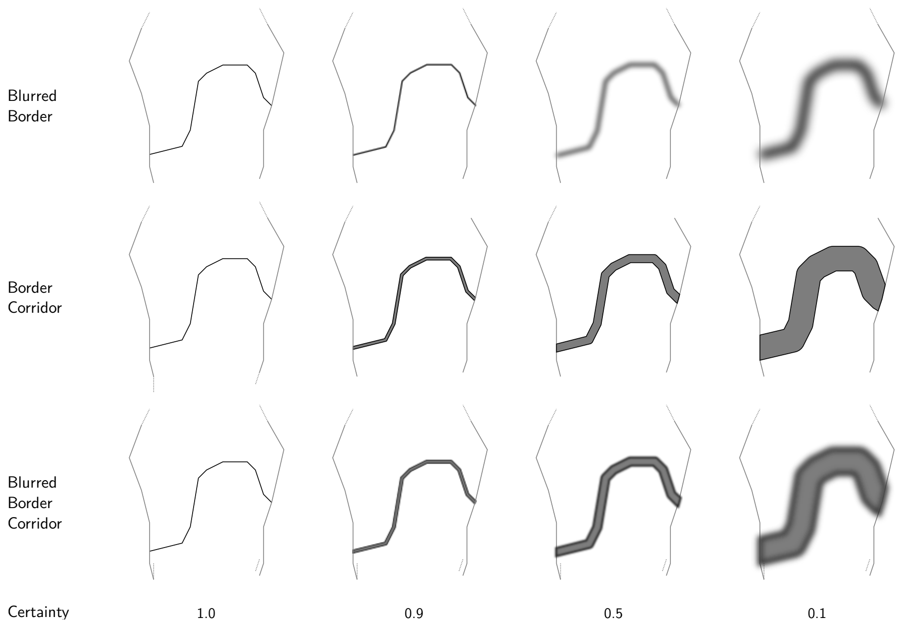


Figure 5.4: Three different methods to visualize uncertain courses of a border

Another advantage of the input of borderlines instead of territories is that once the model is further advanced, coastlines can be continuously changed according to an appropriate change model (see problem 1b). This can be applied solely to the coastlines without affecting the interior borders.

A new border point automatically snaps to an existing border point, if the mouse position is close enough to it (an appropriate threshold might be $5\ px$). This allows for a smooth workflow and is required to create closed polygons. In case the borderline is closed, it gets treated as a complete polygon and territory. When the user finished a territory by defining all surrounding polylines that create a closed ring, the polygon gets assembled. If a borderline meets another borderline at an interior node, the polyline gets split up into two parts so that each meeting point of borders is the start or end point of a polyline. This way integrity is maintained and each territory compounds of several polylines creating a set of closed polylines: a polypolygon.

Figure 5.5: Drawing historical borders instead of full areas and definining a level of certainty.

If the created territory overlaps with an existing territory, its intersection will created a separate territory. In the next step, this territory can then be defined as a contested area or defined as a part of another area. If the step yields an empty territory that was claimed before, it can later be defined as a neutral zone or unclaimed land.

Set New Name When defining the name of an area, the user will get actual name suggestion. These result from a collection of current and historical countries from Wikipedia. That saves time for researching short and formal names of areas. In the long run, the system can be synchronized with Wikipedia or even be designed as an extension for Wikipedia articles about current or historical countries.

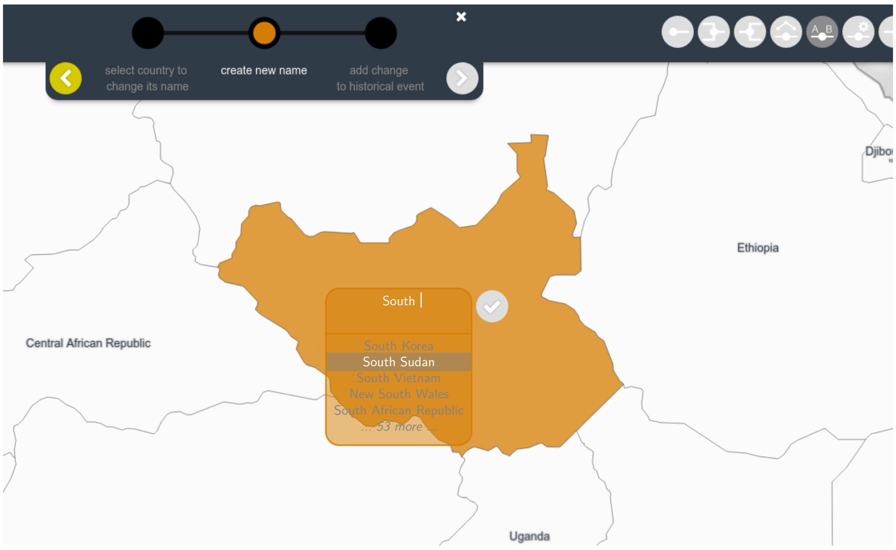


Figure 5.6: Getting suggestions for the name name from Wikipedia.

Set New Status To treat special areas differently, a new step in the edit operation workflow gets defined. After the territory and the name of a new area are defined, a special status can be assigned to it:

1. A *fully sovereign country* is a political entity with full sovereignty over its territory and people and significant international recognition, e.g. Estonia.
2. An *unclaimed land* is a territory that is not claimed by any political entity, e.g. currently Antarctica.
3. A *neutral zone* is often a buffer zone between two conflicting countries, e.g. the UN Buffer Zone in Cyprus.
4. A *contested territory* is claimed by at least two different political entities of the same hierarchical level, e.g. the Kashmir region between India and Pakistan. It is also suitable for areas that have claimed independence from a sovereign country but are not yet regonized as such, making their whole territory contested, e.g. Nagorno-Karabakh (see figure 5.7).

5. A territory can be a subordinate part of another country with a certain degree of autonomy ($\in [0..1]$). Fully subordinate parts of a country, like a US State or a German Bundesland have no autonomy (0). Autonomous countries within another country, like England to the United Kingdom or Greenland to Denmark, receive have certain a degree of autonomy ($\in]0..1[$). Full autonomy (1) would mean the territory is a fully sovereign country and the value can therefore not be set in the options.

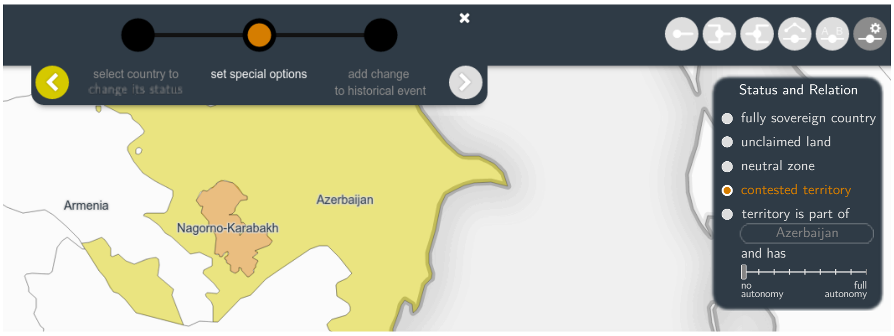


Figure 5.7: Defining a special status or relationship to a territory.

Add Historical Change The visualization of an Hivent gets split up into three parts:

1. An information section storing important meta data of the event location, the dates (timespan in which the event happened), a description and the lin kto the wikipedia article (if given).
2. A section storing all historical changes associated with that historical event. Each historical change is visualized and is assigned a date at which this event came into effect.
3. A multimedia section stores images, videos, audio files and documents and their sources associated to the historical event.

Similar to the extension of the area name step, also Hivent names can be chosen among a collection of Wikipedia articles describing historical events. Selecting a name from a wikipedia article automatically fills the information section and adds multimedia files from the wikipedia article. The historical change will automatically be entered in the section (see figure 5.8). With this separation, different historical changes at different dates can be associated with one historical events, largely increasing the `Hivent` data model.

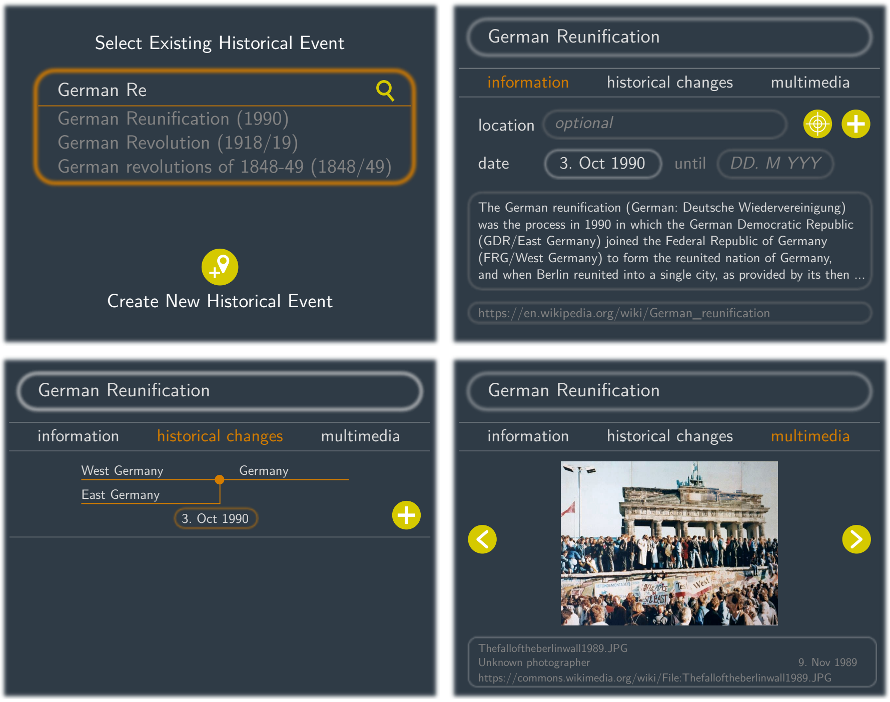


Figure 5.8: Creating a new Hivent and adding the newly created historical change.

New Area Recognition One new operation is to add the recognition of one country by another country. That is simply performed by selecting two areas on the map, whereas the first area recognized the second area. This is an historical change that can afterwards be attached to an Hivent.

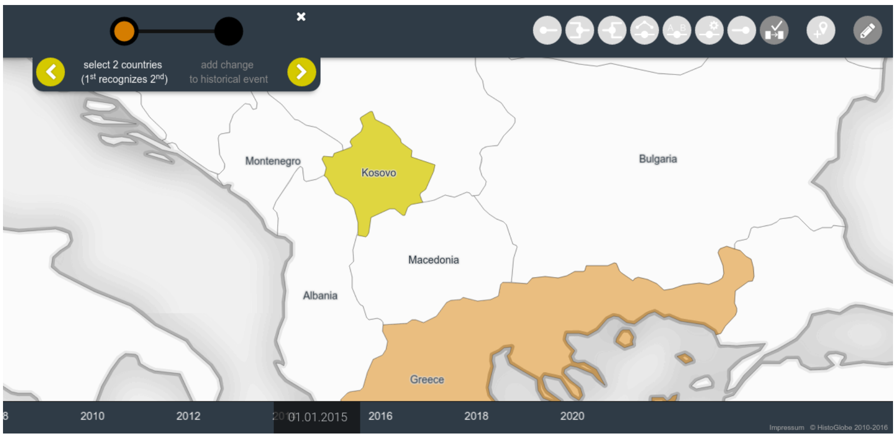


Figure 5.9: New edit operation: Recognition – sets up the recognition of one area to another.

Multi-language support In order to support different languages, a language selection is placed on the bottom right corner of the interface, on the timeline (see figure 5.10). This changes the language of the whole interface and loads the translations of the area names and the Hivent names, locations and descriptions in the newly created language. If a term is not defined in the language, the fallback language (English) is used instead.

Figure 5.10: Changing the language in the user interface.

5.3.2 Extension of the Data Model

To account for the changes in the interface, also the data model has to be adapted. The main changes to the original data model developed in section 4 are:

1. Creation of a `Multilang` entity to store a name of an Hivent, its location or an Area name in different languages.
2. Outsourcing of the `HiventLocation` into an own entity to identify a location with a name and a geospatial reference.
3. Creation of a `Multimedia` entity to manage multimedia files associated to an Hivent.
4. Attachment of a date to an `HistoricalChange`.
5. Inclusion of the `formal_name` into the `Area` model to emphasize it as the identifier of an area.
6. Creation of an `AreaBorder` with a `borderline`. A set of `AreaBorders` create one `AreaTerritory` which is associated to the Area. Each change of an `AreaBorder` creates one or two new `AreaTerritory`/ies.

7. Creation of an `AreaStatus` an an `AreaRelation` to account for special status of an area alone or in relation to another area with a certain level of autonomy.

8. Creation of an `AreaRecognition` to account for international recognition of one area to another one.

9. Adaption of the `AreaChange` entity to model a change of each possible property of an area.

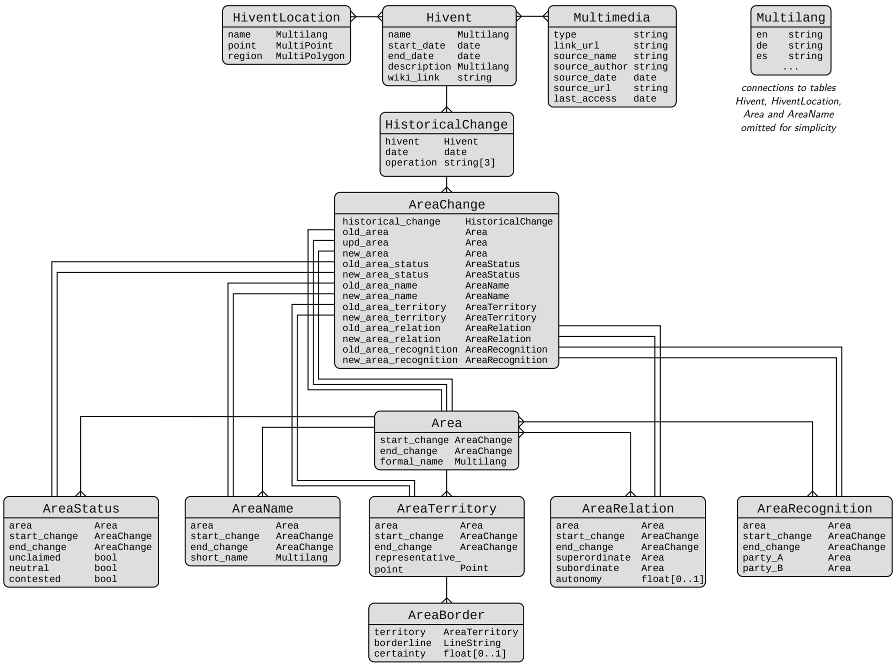


Figure 5.11: The new data model to support the developed approaches regarding uncertainty

Chapter 6

Summary

6.1 Results

Research Questions

6.2 Problems

6.3 Future Work

step further: temporal GIS to narrative GIS

idea: explain history with spatial narratives geographically contextualize events and interactions organizing principle: time

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