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Visualizing and Editing the Evolution of Countries in Time and Space

Master's Thesis

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Hiermit versichere ich, dass ich die vorliegende Masterarbeit selbstständig und nur unter Zuhilfenahme der angegebenen direkten und indirekten Quellen erstellt habe. Diese Arbeit wurde in gleicher oder ähnlicher Form noch bei keinem anderen Prüfer als Prüfungsleistunf eingereicht und ist noch nicht veröffentlicht.

Statement of Authorship

Hereby I declare that I completed this Master's Thesis on my own and that information which has been directly or indirectly taken from other sources has been noted as such. Neither this, nor a similar work, has been published or presented to an examination committee.

Weimar, 6. June 2016

Marcus Kossatz

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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

domain: evolution of countries in time and space -¿ names and territories -¿ modelling, visualizing and !!! editing !!!

1.1 Motivation

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

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:

Visualizing and Editing the
Evolution of Countries in Time and Space

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.

extension of Hivent model to actors

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.

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.

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[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

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 $\gamma\epsilon\omega\gamma\rho\alpha\varphi\iota\alpha$/ *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. 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 answering 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.

Whereas geography answers the questions *where?*, history focuses on *when?* – but the ultimate goal

[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.

[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

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]

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].

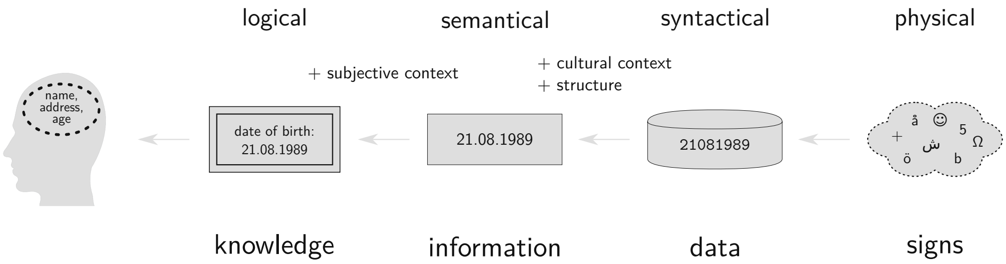


Figure 2.1: signs, data, information and knowledge

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 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 *Historical Geographic Information System* [GG14] or alternatively *Spatio-Temporal Information Systems* (STIS) [PTKT04].

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].

HGIS are rather recent tools and used mostly in *Digital Humanities* as a digital tool to answer research questions in the traditional fields of humanities: "situating history in its geographical context and using geographic information to illuminate the past" [KH08, p. 3]. Some interesting research questions that could be answered using HGIS could be:

- Did the European Union help to bring peace on the European continent? *(political)*
- Is there a coherence between life expectancy and fertility rate? *(social)*
- What is the effect of global warming on the melting of glaciers? *(physical)*
- What was the effect of Bismarck's foreign policy on peace in Europe? *(historical)*

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

2.1.6 Components

Information systems in general are based on a data model — HGIS in particular on a *spatio-temporal data model*, introduced in section 2.3. On top of that, there are different components. One way to classify them is using the four-component model:

1. **Input**: Primary acquision of spatio-temporal data, i.e. historical events, historical and current countries and their territories.
2. **Management**: Physical storage and logical management of the data in a spatio-temporal database, using a structure that fits the spatio-temporal data model.
3. **Analysis**: Gaining spatio-temporal information by cleaning, transforming or combining the data in database.
4. **Presentation**: Visualization of information on different displays, e.g. a map and a timeline, transforming information into spatio-temporal knowledge.

2.1.7 Applications

"Today, operational temporal GIS does not exist". This quote summarizes the state of the art in this field. The main reasons are "the complexity of integrating space and time and the lack of standards" [Raz12, p. 5].

However, there are numerous project that use HGIS for one specific research question. A large collection them can be found in [KH08] and [GG14]. A famous visualization combining time and space Napoleons Moscow Campaign by Charles Minard from 1869 (see figure 2.2). The "best statistical graphic ever drawn" [6] shows the number of men in Napoleon's 1812 Russian campaign army, their movements, as well as the temperature they encountered on the return path [KH08, pp. 188-191].

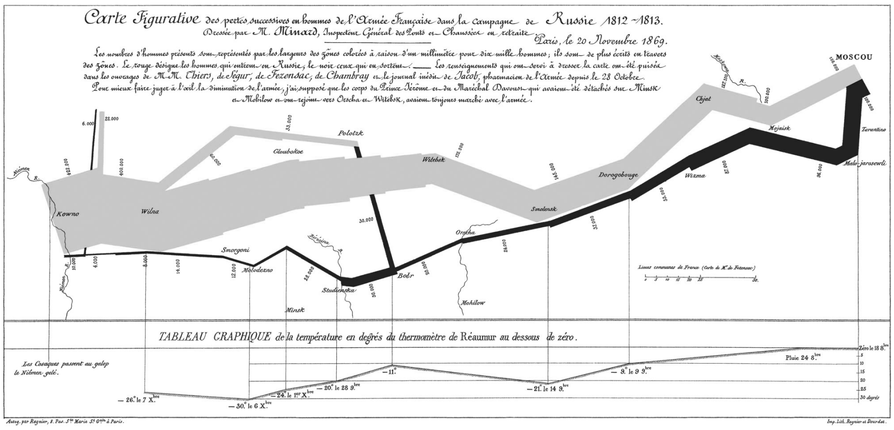


Figure 2.2: Napoleons Moscow Campaign [7]

The *Great Britain Historical GIS Project* (GBHGIS) [8] combines statistical data with territorial units of the United Kingdom, e.g. to analyze net migration in the districts in UK. The data is collected by the *British Ordnance Survey*, who automatically detect spatial changes to the geography and land use of the United Kingdom using aerial photography [9].

The *National Historical Geographic Information System* (NHGIS) [10] provides the digital boundaries of the United States of America and census data for each year since 1790. While the data in the system is extensive, the interface to analyze and use the data is very frustrating to use: A tutorial is necessary to go through the selection process. To download data, a user has to register, receive an email with a link to download a compressed file which has to be decompressed and then loaded into a GIS software to be visualized.

HGIS are not widely accepted in the humanities. One reason is the nature of the qualitative historical research: 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*. Information systems on the other hand have a logical architecture and, to be as precise and accurate as possible. Analysis is based on mathematical functions – an information system is

[6] *The Visual Display of Quantitative Information* (p. 40), Edward R. Tufte, 2001

[7] *Minard.png* Charles Minard, 1869, URL: `https://commons.wikimedia.org/wiki/File:Minard.png`, last access: 03.11.2015,

[8] *Great Britain Historical Geographical Information System (GBHGIS)*, Ian Gregory & Humphrey R. Southall, University of Portsmouth, since 1994, URL: `http://www.port.ac.uk/research/gbhgis/`, last access: 02.11.2015

[9] *British Ordnance Survey*, URL: `https://www.ordnancesurvey.co.uk/education-research/research/automatic-change-detection.html`, last access: 02.11.2015

[10] *Welcome to NHGIS*, Minnesota Population Center, University of Minnesota, since 2007, URL: , last access: 02.11.2015

quantitative in its entire nature [KH08, p. 2].

2.1.8 Data Sources

This HGIS needs data about historical countries, their names and borders and historical events that lead to historical changes of these countries. There are a lot of free and open sources for geographic data about the current countries, their names and borders. One of the most exhaustive collections of geographic data in public domain is hosted by Natural Earth [11]. 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 [12].

However, data about historical countries and events are not as straightforward to aquire, because of the mostly qualitative nature of historical research (see section 2.1.1). The most exhaustive free and open source of historical is the *Wikipedia* and their article categories, e.g. `armistices` or `treaties` [13]. All sorts of historical events can be found, even translated into different languages. Some information is structured in information boxes, e.g. some historical treaties have a name, an image, a location, a signature and an effect date, an overview about treaty conditions and signatories. Particularily interesting for this thesis are articles about historical countries [14], because they contain the name of the country and meta information, e.g. their historical successors and predecessors. Building an open-source Historical Geographic Information System on the basis of Wikipedia would be a huge project with significant impact on the world of free and open education — however, it would also be a big challenge: Wikipedia is incomplete, not all historical countries and events necessary to model the history of the world are available. It is also inconsistent, because not all articles about historical countries and events are structured, especially not to those who actually have an influence on a territorial change of a country, e.g. a border agreement. Retrieving, parsing and processing this information is a big challenge. Also the problem of accuracy and quality of information in the Wikipedia due to their open source nature has to be considered. Overall, using the Wikipedia as a data source for this thesis is not feasible, but is subject to further research.

Historical maps The most problematic data to acquire is about the territories and borders of historical countries. There is no primary data source for that, so the only way to retrieve a border is to extract it from an historical map.

They also can be found on Wikipedia, or in historical map colletions, e.g. *OldMapsOnline*. The project

[11] *Natural Earth*, URL: `http://www.naturalearthdata.com/downloads/`, last access: 30.10.2015

[12] *Planet OSM*, URL: `http://planet.openstreetmap.org/`, last access: 30.10.2015

[13] *Category:Treaties*, Wikipedia, the free encyclopedia,
URL: `https://en.wikipedia.org/wiki/Category:Treaties`, last access: 13.05.2016

[14] *List of former sovereign states*, Wikipedia, the free encyclopedia, URL: `https://en.wikipedia.org/wiki/List_of_former_sovereign_states`, last access: 13.05.2016

is developed "out of a love of history and heritage of old maps" and currently stores about 400000 historical maps [15]. There are five steps to retrieve a border with points in geographic coordinates from an historical map.

1. **Digitization**: If the map is on paper, it has to be scanned in the best possible quality. The result is a raster graphic.
2. **Georeferencing**: The historical map has to fit as good possible on the reference map. This requires to manually define a set of reference points which are used to transform the map into the geographic coordinate system. This process is error-prone, especially if the projection of the historical map is not known and the map itself is not accurate [Kno02, pp. xvii]. The outcome is a raster graphic in which each pixel is assigned a geographic coordinate.
3. **Preprocessing**: The raster image has to be be processed so that the desired border stands out and can be traced in the next step. This happens via greyscale conversion, thresholding or the Canny Edge Detector. This results in a monochrome graphic in which the desired border must be uninterrupted and clearly be seen.
4. **Line detection**: By selecting a start and an end point of the border, the line gets traced automatically. This step vectorizes one particular feature, a borderline, from the raster graphic and produces a polyline in geographic coordinates.
5. **Postprocessing**: In the last step, the polyline can be adapted: The line can be simplified to reduce unnatural artifacts and the position of border points can be manually edited. The final output of the whole process is a polyline whose points are expressed in the geographic coordinate system which can be used in the system as a border of an historic country.

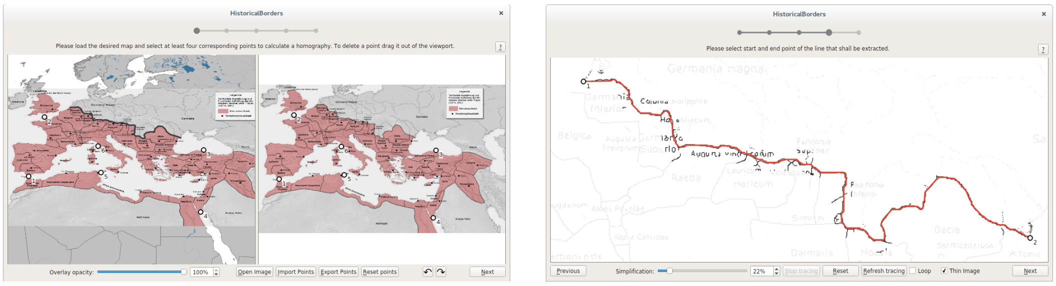
This process was developed in a preceding *HiBo* project (see figure 2.3).

Manual data input For the domain of this HGIS, the evolution of countries over time, there is no complete dataset available. Therefore, the system developed in this thesis needs to have an interface to enter historical data. The user needs to have an interface to enter information about historical events that change territories and names of historical countries. This data has to be acuired either from primary historical sources directly, or from free online sources. Next to Wikipedia, there are other collections of historical events, e.g. *Correlates of War* [17] for quantitative data about international relations.

[15] *Old Maps Online*, URL: `http://www.oldmapsonline.org/`, last access: 13.05.2016

[15] *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

[17] *Data Sets*, Correlates of War, URL: `http://www.correlatesofwar.org/data-sets/folder_listing`, last access: 13.05.2016



(a) Georeferencing (b) Semi-automatic digitizing

Figure 2.3: Semi-automatic extraction of a border from a map of the Roman Empire [16]

2.2 Time and Space

This section will explain ways to separately represent time and space in an information system. It will first explain the geospatial data model used in traditional GIS and then introduce maps as the representation of spatial information. In the second part of the chapter, models to represent the temporal dimension are introduced.

2.2.1 Model of Geographical Space

HGIS need to unambiguously locate geo-objects on, underneath or close to the Earth's surface using *geographic coordinates*. They express an object directly in the coordinate system of the Earth. To understand that, a model of the Earth has to be developed, the *geodetic datum*, that needs to fit the real shape of the Earth as accurately as possible.

The shape of the Earth measured in the field of *geodesy* is very complicated. In the Babylonian Empire (≈ 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 be 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 of objects varies 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 2.4). 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].

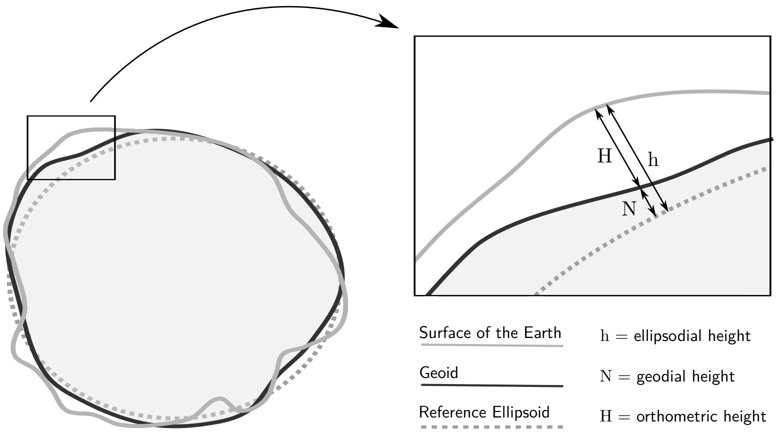


Figure 2.4: The geoid model, differences are exaggerated, [Bol08, Fig. 3-6, p. 75]

Geographic coordinate system The basis for the geospatial data model is the reference ellipsoid. It is represented in a three-dimensional *spherical coordinate system*. The *North* and the *South Pole* are defined as the two surface points closest to the Earth's center opposite to each other. The *Equator* is the line equidistant to the two poles and 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 Greenwich (London, United Kingdom) is used. Based on these two lines, each point in the spherical coordinate system can be unambiguously defined by [Bol08, pp. 26-28]:

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

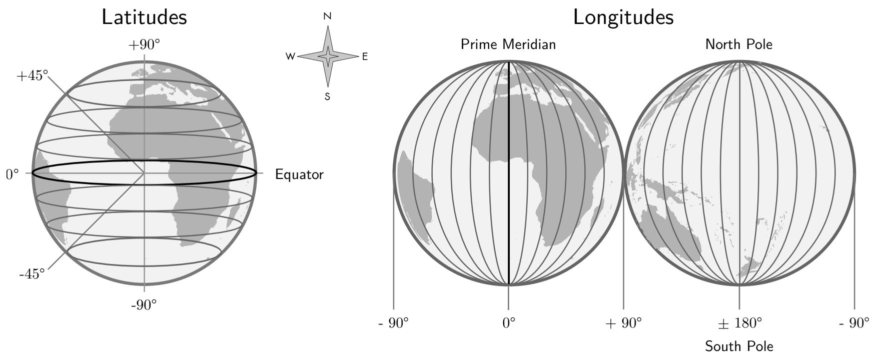


Figure 2.5: geographic coordinates using latitude and longitude

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].

The Geodetic Datum is the digital model of the analogue Earth. It consists of two parts: The approximation of the Earth's surface in a the Cartesian coordinate system with the origin in the Earth's center 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 in the GPS unit of major mobile devices.

Raster and Vector Model The real world is infinite in detail, but storage in a computer system is finite. In order to model continuous geographical 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.

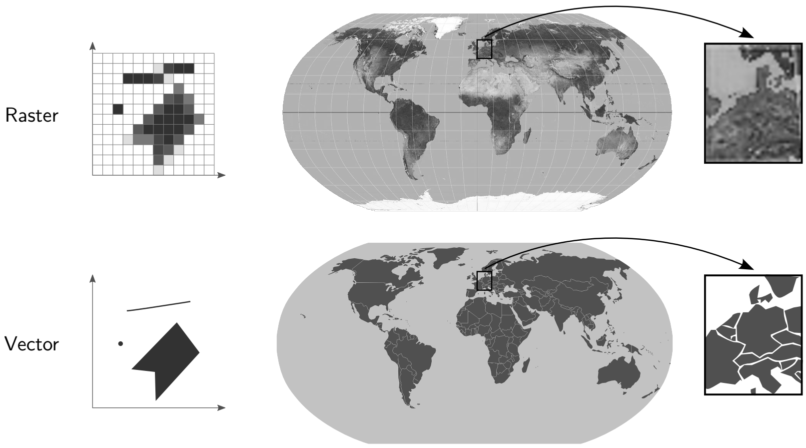


Figure 2.6: Comparison of the raster and the vector model

The *raster model* contains a regular grid with a fixed *cell dimension*. Each cell has a certain value, e.g.

a color value. The model is simple and allows straightforward rendering: only affine transformations have to be applied in order to project 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 for map tiles by most map engines, e.g. in OpenStreetMap or the satellite image by NASA in Google Maps.

In the two-dimensional *vector model*, each object is a mathematically described geometric primitive. All of them can be expressed by three basic primitives (figure 2.7):

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 others. Points can be used to represent the location of an event.

1D A *polyline* is constructed by an ordered set of points with at least one start and one end point. A border line 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 2.8). The territory of a country without islands can be described by a polygon. If a country does have islands or overseas territories, a *polypolygon* represents multiple separate polygons belonging to one logical entity.

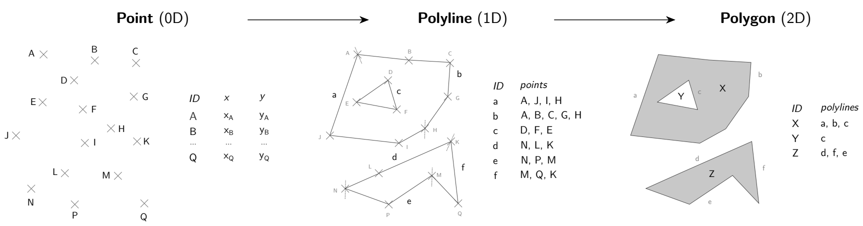


Figure 2.7: The basic geometric primitives point, polyline and polygon

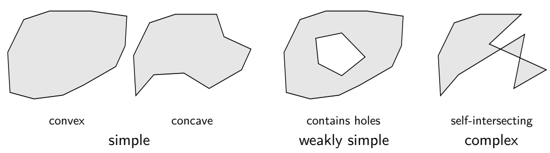


Figure 2.8: Different properties of polygons

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 that can easily to discretized, e.g. the boundaries of a country. Common file types for vector data with spatial reference are the open file format GeoJSON (`.geojson`) [18] or ESRI Shapefiles (`.shp`) [19].

2.2.2 Presentation of Geographic Space

The most common ways to present geographic space are two-dimensional *maps* and three-dimensional *globes*. The HGIS in this thesis will use a map to show the evolution of countries over time. A map is a discrete graphical expression of the geographical features 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.

A map is typically structured according to the *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. A *legend* including the scale bar and north arrow shall explain all symbols used on the map and give orientation. In interactive web based systems, there should 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].

Leaflet.js is "an open-source JavaScript library for mobile-friendly interactive maps" [20] that offers functionality to embed a map with a chosen projection in on the client-side of a web based information system, use own map tiles, symbols and markers on the map and tools for zooming and panning.

Map projections Since the Earth is three-dimensional, but the map on the computer screen only two-dimensional, the model of the Earth has to be projected onto the map. But as previously discussed in subsection 2.2.1, the Earth is an inhomogeneous spherical object with a curved surface whereas the map is flat [Bol08, p.79]. That is why some features of the Earth will be distorted on the map: An *equivalent projection* preserves the area sizes of features on the map, whereas a *conformal projection* preserves angles and the shapes of objects. Every map projection that is area-preserving distorts shapes at the same time, and each shape-preserving map distrots areas to some degree. There is no perfect map projection. [Geo].

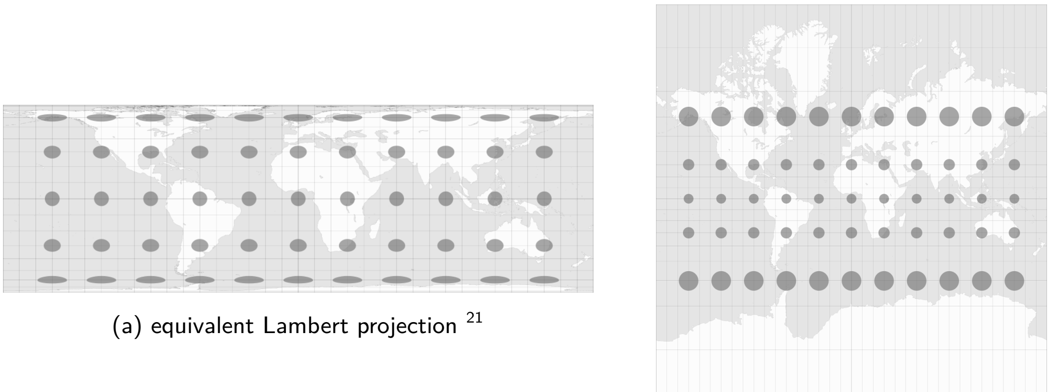
[18] *GeoJSON*, IETF GeoJSON Working Group, URL: `http://geojson.org/`, last access: 30.10.2015

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

[20] *Leaflet - JavaScript library for interactive maps*, URL: `http://leafletjs.com/`, last access: 02.11.2015

[21] *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

[22] *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



(a) equivalent Lambert projection [21]

(b) conformal Mercator projection [22]

Figure 2.9: Comparison of equivalent and conformal map projections

A compromise between preserving areas and shapes is the *Robinson projection*. It is neither conformal, nor equivalent, but provides a reasonable trade-off between both properties.

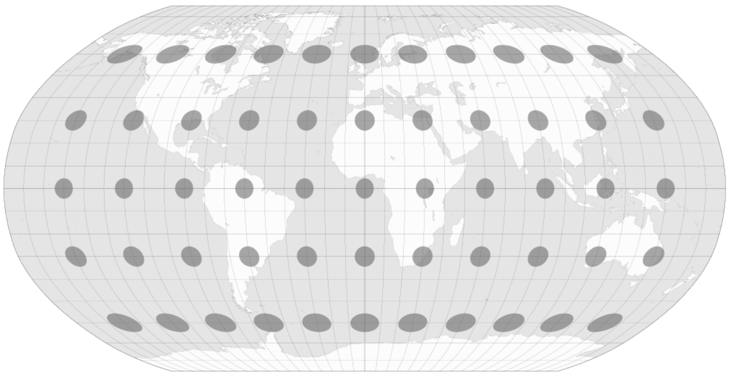


Figure 2.10: Robinson projection [23]

2.2.3 Model of Historical Time

Time is an abstract concept that "can be perceived only by its effects" [Lan89, p. 27]. Many philosophers and scientists have been developing models to work with time. In this case, the model needs to be appropriate to both represent time in an historical sense in interplay with geographical space.

excerpted from an official document of the United Nations prior to 17. September 1987.

[23] *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

A popular model is *Cartographic Time*, where time is seen as the "fourth cartographic dimension", is suitable for spatio-temporal information systems [Lan89, p. 28]. Whereas space is represented by geo-objects on a map, time may be seen as versions or states on a timeline, separated by events that change one state to another state. Unlike space, time knows only one dimension. The position of an event on the timeline is described by its date using a reasonable sampling unit like century, year, day, hour or millisecond [Lan89, p. 32].

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].

The Taxonomic Model of Time by [Fra98] classifies time not only into discrete and continuous, but also by the *nature of time* or *time order*: 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. The other two types, *branching time* and *multi-dimensional time*, are more complex and not relevant for this thesis.

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 number space of integers, there are three different order relations:

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 [All84]

2.2.4 Presentation of Historical Time

In contrast to space, time does not have an intrinsic representation. However, the most common form to visualize cyclic time is on a cyclic display, e.g. a time wheel or a clock. Linear time is very often visualized on a *timeline*. The purpose of a timeline is to show events as time points or processes as time intervals in chonological order. A timeline additionally shows time markers showing a certain date to support orientation. A timeline uses a certain time scale:

- On a *linear* timeline, the distance between any two time points is directly proportional to their actual temporal distance.
- A *logarithmic* timeline uses a logarithmic function to scale the depicted time. Relative to a reference point on the timeline, e.g. the timeline center, the further away a time point, the further away its position on the timeline – however, the distance between the time point and the reference point does not increasy linearily, but logarithmically. That means, events that are further away do not appear as far. This time scale accounts for logarithmic human perception: events that happened 20 years ago do not seem to be twice as long ago as events happening 10 years ago [DISP08].
- A timeline can also have an *irregular* scale, e.g. to have the same absolute distance of events on the timeline. This is useful if the distribution of the events on the timeline are far from homogeneous.

The visualization of time can be separate from the spatial dimension, according to the Triadic Framework, e.g. with a timeline. In another approach, space and time can also be coupled and displayed in the same presentation display, e.g. in a space-time cube [Häg70].

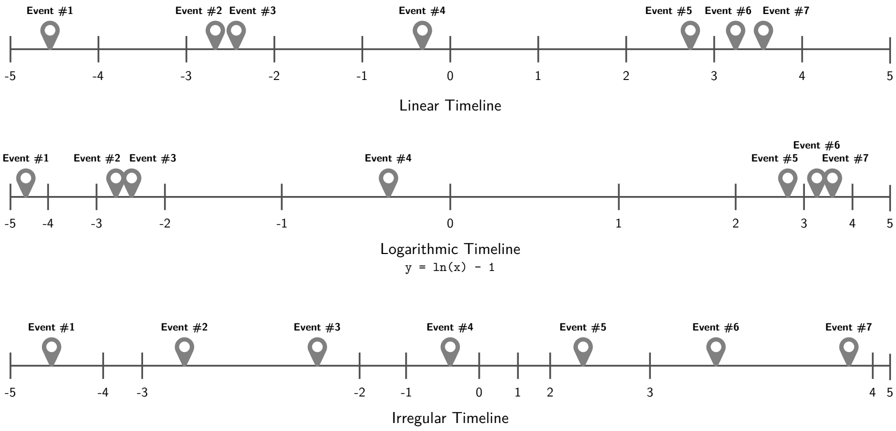


Figure 2.11: Comparison between a linear, a logarithmic and an irregular timeline

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 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. Historical Geographic Information Systems can be used to explain spatial-temporal phenomena in the real world. Therefore, it needs to handle the development of geo-objects and their attributes over time. Developments are driven by *changes* to the state of an object.

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]. However, in order to trace spatial and attribute changes over time, the dimensions have to be related to each other.

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.

This section introduces different spatio-temporal data models to maintain relations between time and space of an entity.

2.3.1 Snapshot Model

One of the simplest, oldest and most frequently used 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].

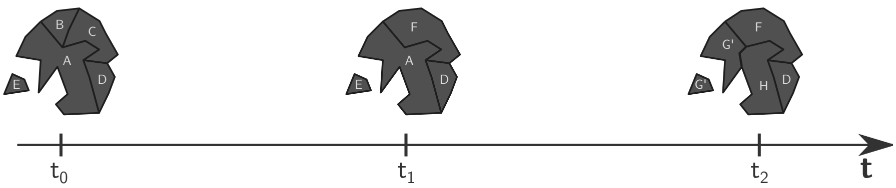


Figure 2.12: The Snapshot Model by [Lan88]

The model allows to retrieve the state of the system at a defined time point t_i. However, 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 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 the domain of this thesis.

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].

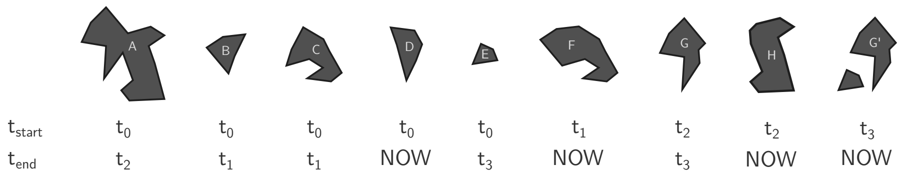


Figure 2.13: The Simple Time-Stamping method by [HW90]

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 ($B + C \rightarrow G$) or if two are successors ($B \rightarrow G$) and one just stops to exist ($C \rightarrow \emptyset$). The model is also redundant: if a geo-object replaces another one ($B \rightarrow G$), 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? This problem is addressed in the *Three-Domain Model* by [Yua96a, Yua96b]. 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".
- 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. One limitation of the model is that it only traces spatial attributes over time. In an alternative model by [CT95], the *thematic domain* is added to fully describe a spatio-temporal object and trace also aspatial attributes that can change over time, e.g. the name of an entity.

Since countries, their territories and attributes can change independently over time, the data model used in this thesis will be built on top of the Three Domain Model.

2.3.5 History Graph Model

Most of the data models introduced so far cover only static changes of geo-objects. [Ren96] 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 2.14).

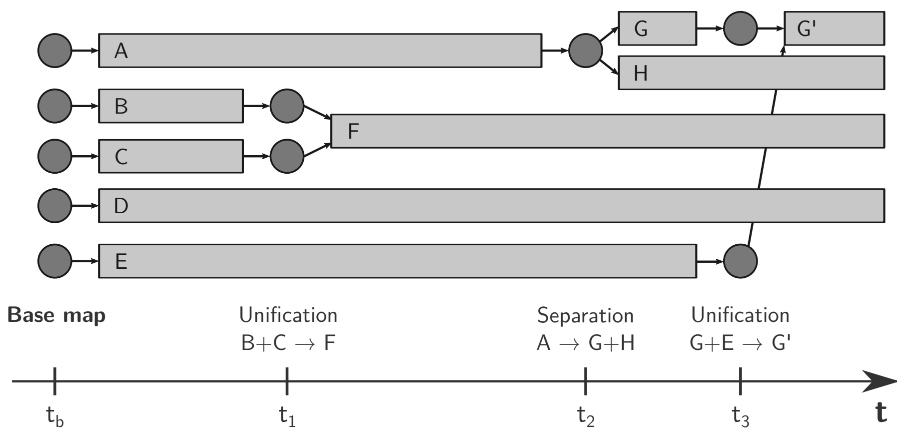


Figure 2.14: The History Graph model

The model defines six basic types of temporal changes that can happen (see figure 2.15):

- **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.

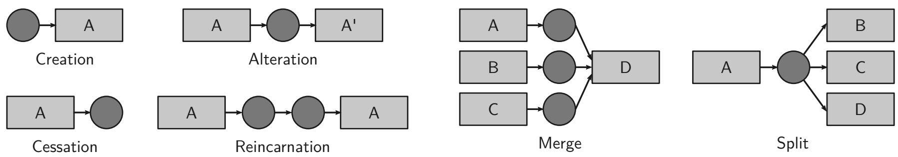


Figure 2.15: Types of changes in the History Graph model

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. This is the reason why this model is particularly suitable for the work of this thesis.

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 Database Management Systems

Information systems use databases for managing the data. A *Database Management System* (DBMS) is a software system for the administration of data, mainly storage and retrieval. There are mainly two types of DBMS: the oldest and most common ones are *Relational DBMS*. *Object-Oriented DBMS* werde developed to adapt concepts of object-oriented programming into the database world. The combination of both approaches are *Object-Relational DBMS*.

2.4.1 Relational Database Management Systems

RDBMS are built upon the concept of *entitities*, e.g. an `HistoricalCountry`, with *attributes*, e.g. `name` and attribute values of a simple data type, e.g. the character string `"Germany"`. Entities are represented in a table with one row for each *tuple* and one column for each attribute. An entity has one attribute that unambiguously identifies each tuple, the *primary key*, mostly a contiguous number.

Entities can be related to each other in three different kinds of *relations*:

`1:1` Direct attributional relation, e.g. one country has one head of state and vice versa.

`1:n` One-to-many relation, e.g. one country can have many cities, but each city can belong to only one country.

`m:n` Many-to-many relation, e.g. one country can have many rivers, but each river can also flow through multiple countries.

Entities and their relations are visualized in an *Entity-Relationship Model* (ER model). Data can be retrieved from and entered into a relational database using the *Structural Query Language* (SQL). The query to get the names of cities in `Germany` in alphabetical order is:

```
SELECT      city.id, city.name
FROM        (city JOIN country ON city.country = country.id)
WHERE       country.name = "Thüringen"
ORDER BY    city.name
```

The first RDBM developed was *Oracle*, released in 1979 [Ora]. Since then, the concept has been established as the state-of-the-art for databases. An example for a popular RDBMS used for Web-bases systems is *MySQL*, the "world's most popular open source database" [24].

2.4.2 Object-Oriented Database Management Systems

One problem with RDBMS is that attributes can only be assigned simple data types. Developers using object-oriented programming need to map the objects used in the application to tuples in the relational database – and vice versa data from the database needs to be transformed to objects in the application. This process can be cumbersome. OODBMS have been developed to address this problem and adopt the concepts of object-oriented programming for database management purposes [Dar].

- *Classes* are the structured representation of things in the real world of the same kind, with the same properties, e.g. a country, having a name and a territory. Classes in OODBMS relate to Entities in RDBMS.

[24] *MySQL :: About MySQL*, URL: `https://www.mysql.com/about/`, last access: 31.10.2015

- An *object* is an instance of a class, one specific thing with defined properties, e.g. the country of Germany with its territory. This correlates to a tuple in RDBMS.
  - The *attributes* of an object can not just be of a simple data type, but also instances of other classes, e.g. `country.territory` can be a `polypolygon` object. These complex data types are a major improvement compared to RDBMS.
  - Objects also have *methods* that can be called to do something with the object, e.g. `territory.getArea()` calculates the area size of a country.
- The internal state of an object can not be accessed from the outside. Methods are the only way to interact with an object. This is called *encapsulation* and maintains control over what can be done to and with an object and prevents corruption.
- According to the concept of *inheritance*, classes can be hierarchically structured, whereas the attributes and the methods of a *base class* are inherited to its *derived class*. As an example, an `Area` has a `name`, a `territory` and the method `getArea()` associated to it. A `Country` can be derived from the `Area`, inheriting both attributes and the method. Additionally, it can get an attribute `head_of_state`, which is specific to `Country`, but not to `Area`. The class `Ocean` can just as well be derived from `Area`.
- An associated concept is *polymorphism*: The same function can be called on different objects and the return value will be of the same type. However, internally it might be calculated differently. As an example, consider the classes `Polygon` and `Polypolygon`, both inherited the method `getArea()` from their base class `Geometry`. Whereas a polygon calculates its area directly based on its geometry, a polypolygon internally calles the function `getArea()` on all its associated polygons and sums up their areas.

OODBMS support all those concept and allow to store the objects used in the application directly in the database. Additionally, objects from the database can be accessed directly, there is no need for an additional query language [Dar].

2.4.3 Object-Relational Database Management Systems

ORDBMS combine the advantages of both worlds. Internally, it uses the established and efficient relational database for the data storage. The database model and the interaction with the data happens in an object-oriented way while supporting all of the concepts mentioned in the previous subsection 2.4.2. The most popular ORDBMS example for Web-based systems is *PostgreSQL*, "the world's most advanced open source database" [25].

[25] *PostgreSQL:*, The world's most advanced open source database, URL: `http://www.postgresql.org/`, last access: 31.10.2015

2.4.4 Spatio-Temporal Databases

Databases for HGIS have to deal with spatial, temporal and attribute data. According to the Triadic Frame, these aspects should be modeled separately from each other, as they can change independently.

Spatial data can easily become very large, because of the mass of very precise coordinate data. *Spatial databases* are specialized to work with spatial data: they process the data effieciently and to provide general data types, such as `Point` or `Polygon` and methods, e.g. to calculate the area or the distance between two points. *PostGIS* [26] is an extension for PostgreSQL that is especially utilized for handling spatial data.

Temporal data usually relates to events and processes. It is defined either by a time point or a time interval which is again defined by two time points. This is called a *bitemporal* element. A time point can be modeled in the database as an attribute of the complex `Date` type. For relational databases that only support simple data types, the date can be stored as a string or be expressed with a `long` integer (64 bit) $\forall n \in \mathbb{N} : n \in [-2^{63} \,..\, 2^{63} - 1])$ determining the number of milliseconds since 1st January 1970 (UNIX time) [Emi]. SQL was extended by features to handle time in a database, e.g. *SQL/MM* [Peu99, chapter 6].

Object-Oriented Spatio-Temporal Database Models The question is: How to implement the spatio-temporal data modles introduced in section 2.3 in a relational, object-oriented or object-relational database management system introduced in this section? While the implementation depends on the data model, there are common concepts and isses that have to be addressed.

When storing time related data, it is 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*). A property of spatio-temporal database models is whether valid and transaction time are supported.

Object-oriented concepts are more appropriate than the concept of relational databases, because of the complex nature of spatio-temporal data [PTKT04, section 3.9]. One of the first concepts was the concept of a *spatio-temporal object* combining geometrical and bitemporal properties in one object [WHM90].

A similar approach by [Raz12] is the *Spatio-Temporal Data Type* (STT). Time is not considered an attribute of space, but a separate class. They are aggregated in the `SpatioTemporal` class, using both spatial and bitemporal attributes. The model also provides spatio-temporal operators, e.g.

[26] *PostGIS*, URL: `http://postgis.net/`, last access: 31.10.2015

STT_intersects returns true if two SpatioTemporal objects intersect in time and space, i.e. their geometries intersect and the time intervals in which they are active overlap. These operators are very helpful when analyzing spatio-temporal data or checking for data integrity.

Version management An issue is how to perform retrospective updates. Given a database model that stores objects that are created, updated and destroyed by events. Object X is created at time point t_x. At time point t_y, X gets destroyed and replaced by object Y. If a new change that updates X to X' gets inserted at time point t_u in between, i.e. $t_x < t_u < t_y$, then the event at time point t_y is not correct anymore, because object X does not exist. The question is how to maintain data integrity on insertion, update and deletion from a spatio-temporal database? This issue has to be addressed using formal logic for temporal reasoning [Peu99, section 6].

2.5 HistoGlobe

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.

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

describe the components of the HG explicitally

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

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

usable User Interface for both navigation and editing -¿ problem: all interfaces are trés horrible!

module system

transition to concept chapter

Chapter 3

Development

The aim of this thesis is to create a Historical Geographic Information System to visualize and edit the evolution of countries in time and space. This is a complicated task, because both the reality and the human that should be able to use the system are complex. The task is to create an interface that a human can easily understand and use. For complex applications in which the interface matters, the methodologies of *Human Centered Design* are promising to achieve a good solution.

The development process is iterative divided in several phases. In each phase, the fidelty towards the final solution is increased. A phase starts with an initial set of requirements about the problem. In multiple iterations, an interface is developed that solves the problem. Each iteration has four steps: The requirements for the system are analyzed in the *planning* step. Afterwards, they translated into an abstract *design* which is realized in a specific *implementation* of the interface. Finally, this interface is tested with humans to find out how well it works. Based on the results of this *testing* step, the requirements are updated and the next iteration starts. This is repeated until a version of the interface is created that sufficiently solves the problem. Then the fidelity is increased, starting the next development phase.

The five phases in this thesis were:

1. **Idea**: The initial idea how to edit and visualize the history of countries.
2. **Paper Prototype**: The concept of the interface realized and tested on paper.
3. **Mockup Prototype**: The concrete workflow developed in a slide-based presentation.
4. **Web-Based Prototype**: The final version developed in a Web application.
5. **Extensions**: Design approaches how to fit the uncertain nature of history.

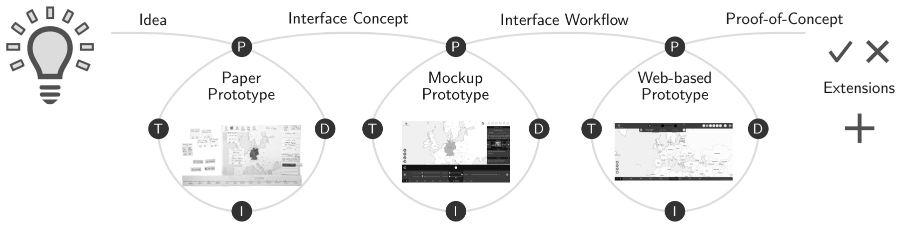


Figure 3.1: Human Centered Design process with five project phases

There are several models involved in the development of the software, each of them has to be developed or analyzed separately. The *data model* is an abstraction and simplification of the real world. The *Hivent Model* created in this thesis is explained in the first section 3.1 of this chapter. In iteractive computer systems, the *mental model* is the representation in the mind of the human about how the interface he or she is interacting with should work. On the other hand, the *conceptual model* describes the way the interface actually works. The goal of Human Centered Design is to match the conceptual model to the mental model. Section 3.2 outlines the gradual interface design process to reach this goal. In the application, the implemented *database model* has to match the abstract data model. The task for the *computational model* is to translate between the database model and the conceptual model. The working of the HistoGlobe application, including the computational model, is introduced in the last section 3.3 of this chapter.

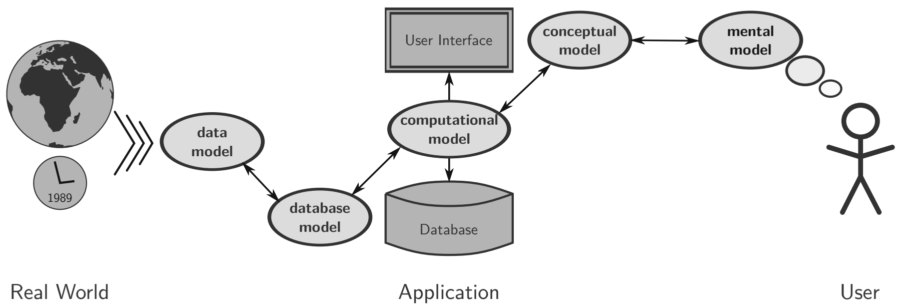


Figure 3.2: Relevant models for the system

3.1 Hivent Model

This section introduces the data model that represents countries and their evolution in time and space. In section 2.3, different spatio-temporal data models were introduced to solve this problem. The *Snapshot Model* is unsuitable for the problem space. *Simple Time-Stamping* is helpful to link countries to their history, but it does not explicitly model historical changes, which is desireable. For that purpose, the idea of the *Event-Based Spatio-Temporal Data Model* was developed, but since it only works for raster data, it is also not suitable for this thesis. This problem is solved in the *History Graph Model*. Additionally, the introduced temporal changes allow to represent historical changes and their influences on geographic entities directly in the model. Finally, the *Three-Domain Model* introduces a helpful concept to separate the spatial, temporal and thematic dimension of a spatio-temporal entity.

The *Hivent Model* is constructed from components of some of these models: An Event-Based Spatio-Temporal Data Model supporting vector data. It is organized according to the Three-Domain Model and allows to visualize the evolution on a History Graph. In the first section of this section, the main elements of the Hivent model are introduced. Afterwards, the preconditions are defined. Finally, the Historical Geographic Operations that describe changes of countries in time and space are explained.

3.1.1 Elements

The main elements of the the model are *Hivent*s, representing an historically significant happening and *Area*s, an abstract entity on a map with a name and a territory. An *Historical Change* is part of one Hivent and manipulates the history of one or more Areas.

Hivents are the main organizing elements of the data model. The word is an acronym for ***Hi***storical e***vent***. It represents a significant happening in history, e.g. a treaty, bill or declaration. The focus in this work is on events that influence the geopolitical situation on Earth. An Hivent happens at one particular point in time and space and introduces historical changes to countries.

Areas represent one identical current or historical country with a *name* and a *territory* on the map. The name of the Area consists of a common *short name*, e.g. "Germany" and a *formal name*, e.g. "Federal Republic of Germany". The *territory* of the Area is described by a polypolygon, a set of weakly simple polygons to support enclaves and exclaves. The polylines of the polygons consist of an ordered set of points that represent the country border. The borders of a country are either *interior*, i.e. bordering another country, or a *coastline*, bordering a body of water. Additionally, each Area is keeps references to the *start change* and *end change*, the historical changes that created or ceased the Area, and to all *update changes* that change the territory and name of the Area.

Historical Changes influence the development of an Area over time. Throughout the lifetime of an Area, it is created at some point t_s, then its territory and short name can change multiple times $t_i : t_s < t_i$ and at some point $t_e : t_s < t_i < t_e$ it ceases. Since all changes in this model are sudden, there are only two possible states an Area can be in: It is *active*, if at the current time point it is historically existing and it is *inactive* if it does not. Each area is uniquely identified by its formal name. That means, the short name can change, but as soon as the formal name of an area changes (e.g. "German Empire" to "Federal Republic of Germany"), it is considered a "new" Area.

Each Historical Change belongs to exactly one Hivent, inheriting its time point at which the change happens. The change is described by a Historical Geographic Operation introduced in section 3.1.3.

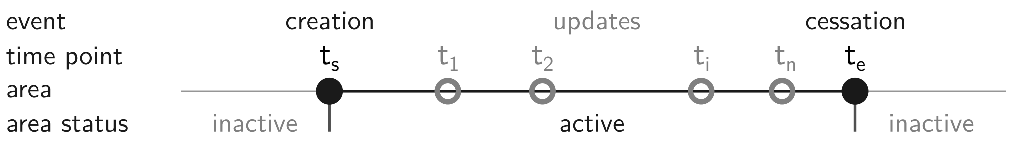


Figure 3.3: Three event types that change Areas, resulting in two different area states

3.1.2 Preconditions

> *In the beginning God created the heavens and the Earth*
> *Now the Earth was formless and empty [...]*
> *And God said, "Let there be light" — and there was light.*
>
> – Genesis 1:1, The First Book of Moses, Old Testament

There are five axoims and two assumptions that are the basis of the spatio-temporal system developed in this thesis. The theoretical foundation is the model of the Earth, its curved surface that can be projected on a two-dimensional map using a map projection, as introduced in sections 2.2.1 and 2.2.2.

Axiom 1 *The Earth's surface has an invariant area size, i.e. it does not change over time.*

Axiom 2 *Each Area in the spatio-temporal system is located directly on the surface of the Earth.*

These axiom sets the spatial foundation of the system: a constant dimension of the map and Areas covering the map. The basis of the temporal part of the system is content of the next three axioms:

Axiom 3 *The spatio-temporal system has an initial state at time point t_0. At this initial state, there exists exactly one Area, denoted by Ω and referred to as the* universe *Area. It has no name and its territory covers the whole surface of the Earth.*

Axiom 4 *At each time point $t_i \geq t_0$ an Historical Change can be introduced.*

Axiom 5 *At each time point $t_i \geq t_0$ each point on the surface of the Earth is covered by exactly one territory of exactly one Area.*

As it has been defined in section 3.1.1, an Historical Change can create, manipulate and cease Areas on the Earth's surface. According to axoim 5, each change introduced in the system must maintain the spatial integrity on the map: When an Area with a territory is created on the map, the Area claiming this territory before has to cease this territory. Formally, it can be said that each change consists of a set of old Areas A that are manipulated, a set of new Areas B that are created in the change, and an operation $\rightarrow_C$ describing the change. Each Area $A_i \in A$ and $B_i \in B$ has a territory A_i^T respectively B_i^T. For each change introduced in the system, the territories of the old Areas must have the same size than the territories of the new Areas to maintain the spatial integrity of axiom 5:

$$\bigcup_{i=1}^{n} A_i^T = \bigcup_{i=1}^{n} B_i^T \tag{3.1}$$

The first Historical Changes introduced in the system at time point t_0 are the creation of all bodies of water, including the oceans and lakes, denoted as W. Each Area $W_i \in W$ is created with their name and territory cut out of Ω. The result is that at t_0, the map is divided into water (W) and land (Ω). Land can at any point in time be either *claimed*, i.e. it is currently occupied by the territory of exactly one active Area, or on a contrary be *unclaimed*, i.e. belonging to Ω. It is a subtractive data model, because each new Areas territory is cut out of Ω.

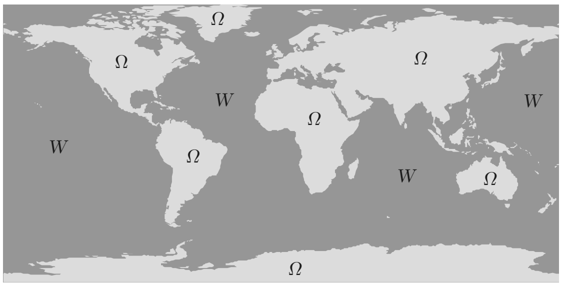


Figure 3.4: The initial state of the world map at time point t_0

In the real world, the name of a country changes according to sudden events, e.g. a declaration or a governmental bill. The territory can change either because of a geographical processes, e.g. the sea level rise influencing the change of the coastline, or according to a historical event, e.g. a treaty. The Hivent model is based on two assumptions that simplify the model and keep the problem space clear:

Assumption 6 *The territory of a country stops at the coastline.*

Assumption 7 *The spatial configuration of the Earth's surface, i.e. land, water and the coastlines, has not changed over time.*

Both assumptions are obviously wrong: In line with [Uni82], the territory of a country extends in a range of 3 to 12 miles (5 to 20 kilometers) into international waters. They are constantly changing and so does the distribution of land and water on Earth. However, the assumptions allow the Hivent Model to focus only on discrete historical changes and not on long-term processes. In this data model, the temporal behavior of an Area can therefore be described as a *static object that changes according to sudden events*.

3.1.3 Historical Geographic Operations

Respecting the preconditions, there are several different types of changes that can occur to a set of Areas. All possible changes can be expressed with only five spatio-temporal operations that are called *Historical Geographic Operations* (HG Operations). The first four change the identity of a set of Areas and therefore establish historical predecessor-successor-relationships. They are always symmetric, i.e. if one old Area is replaced by one new Area, the old Area is the historical predecessor of the new Area and vice versa the new Area is the successor of the old Area.

UNI – Unification A set of old Areas unifies to one new Area. The old Areas cease, becoming the historical predecessors of the new Area. This new Area receives a new name and its territory is the union of the territories of the old Areas.

In 1922, the Russian SFSR, the Transcaucasian SFSR, the Ukrainian SSR and the Byelorussian SSR unified and formed the Union of Soviet Socialist Republics (USSR).

INC – Incorporation One or more old Areas are incorporated into another Area that stays active. Its territory is enlarged by the union of the territories of the old Areas. The old Areas are historical predecessors of the new Area.

In 1990, the territory of the German Democratic Republic (East Germany) became part of the Federal Republic of Germany (West Germany). Although this event is known as the *German Reunification*, it is historically an incorporation of East Germany into West Germany [Jan].

SEP – Separation As the inverse of unification, one old Area is preceded by multiple new Areas. Each new Area gets a new name, receives a part of the territory of the old Area, and the old Area as its only historical predecessor.

In 1993, the Czech and Slovak Federal Republic, commonly known as Czechoslovakia, dissolved into present-day Czech Republic and Solvak Republic, creating two new countries out of one old.

SEC – Secession As the inverse of incorporation, one or more new areas are ceded from a previously exising area that stays active. Each new Area gets a new name, receives the previously existing Area as the only historical predecessor and a part of its territory.

In 2008, the Republic of Kosovo declared independence from Serbia and has since then partially received international recognition. Unlike in the case of separation, Serbia stays as country, keeping its name, but ceding a part of its territory to Kosovo.

NCH – Name Change An Area changes its short name but preserves its identity.

A recent change happened on 5. May 2016: The cabinet of Czech Republic approved that the country will now offically be called "Czechia". However, the formal name stays "Czech Republic", which preserves its identity.

HG Operations can be combined when they happen at the same time, e.g. if one Area incorporates another Area and thereby changes its short name, this is a combination of `INC + NCH`. When West Germany incorporated East Germany in 1900, it was from that moment on just called Germany.

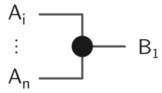
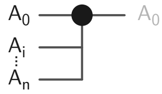
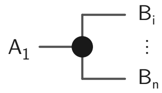
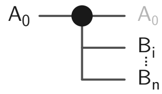
	operation	visualization	historical relationship[2]
`UNI`	Unification		$A_i \leftrightarrow_H B_1$
`INC`	Incorporation		$A_i \leftrightarrow_H A_0$
`SEP`	Separation		$A_1 \leftrightarrow_H B_i$
`SEC`	Secession		$A_0 \leftrightarrow_H B_i$
`NCH`	Name Change		$\emptyset$

Table 3.1: The five HG Operations

3.1.4 Edit Operations

The Historical Geographic Operations are valuable, because they can describe all possible changes in the evolution of countries in time and space. They are really well understood from the system point of view and are therefore the basis for the Hivent Model. However, the purpose of the HGIS developed in this thesis is to provide a well understood user interface to introduce historical changes to countries. Throughout the development process, interviews with historians and other researchers in humanities at University of Virginia were conducted, to understand their mental model about the task. In the interviews it turned out that the HG Operations are not suitable to be used for human edit purposes, because of their low-level nature. One example is that the operations do not provide a straightforward way to create a new country on previously unclaimed land. The same is true for changing the formal name of an Area.

Therefore, this thesis introduces a second set of high-level operations to introduce changes to countries on the map: the *Edit Operations* in table 3.2 have proven to be understandable in several user studies:

[2] $A_i \leftrightarrow_H B_i$ denotes: $\forall i \in [1..n]$: A_i is historical predecessor of B_i and B_i is successor of A_i

CRE	Create	a new Area with a new name and territory on the map.
MRG	Merge	two or more Areas to a new Area. The name has to be set manually, the territory is automatically unified.
DIS	Dissolve	one Area into two or more new Areas, manually setting their new territory and name.
CHB	Change Borders	between two neighboring Areas by defining the territory that changes sides.
REN	Rename	an Area and set a new formal name, short name or both.
CES	Cease	an Area by deleting it from the map, leaving unclaimed land.

Table 3.2: The six Edit Operations

Change direction An important issue is the difference between a *forward* and a *backward change*. The general idea of the Hivent Model is to start at one initial time point t_0 and to consecutively add historical changes at time points $t_i > t_0$ that manipulate the current state into the future. A state is invariant until a new historical change is inserted that manipulates it again. For researching purposes this is not suitable, because the current state $t_c : t_c > t_0$ of the map is known. The problem is to describe states in the past. For this purpose the concept of a backward change comes into play: An historical change that manipulates a set of old Areas to a set of new Areas is inserted at time point t_i, but into the past ($t_0 < t_i < t_c$). As an example: Given the initial state 10.06.2016 with present-day Germany created on 03.10.1990 on the map. The user wants to enter the German Reunification. The interface must support separating Germany into East and West, but indicating that this was the state *before* 1990 and the original state was *after* this date. This is complicated, because the conceptual, data and computational model have to support it.

Inverse operations Related to this problem is the fact that just like the HG Operations in the previous section, also the Edit Operations have inverses: A `CRE` can be inverted with a `CES` and a `MRG` with a `DIS` operation. `CHB` and `REN` can be inverted with themselves,

Error correction Correcting wrong information in an event-based system is important to understand: Given time point t_y and an Area A with the name X. If X happens to be wrong, it means that the historical change at time point $t_x : t_x < t_y$ that created the name X into Area A is erroneous and has be corrected. Correcting a state means correcting the event that created this state.

3.2 User Interface

The Hivent Model presented in the previous section serves as the data model for HistoGlobe, the application in which the work of this thesis is implemented. Developing the system bottom-up from the data model to the interface might not lead to usable system. Human Centered Design promotes a top-down process from the user via the interface into the core of the application. This section illustrates the iterative design process for this thesis seen in figure 3.1. The two main use cases for HistoGlobe that are focused in this thesis are:

1. **Understanding** the history of countries.
2. **Editing** the spatio-temporal evolution of countries with historical changes.

For both use cases a visualization and interaction was designed. The interviews with humanity researchers confirmed that the combination of a map and a timeline are a very appropriate and intuitive way to interactively visualize the history of countries. Thefore, the main concept of HistoGlobe introduced in section 2.5 does not need to be changed. However, two necessary extension modules have emerged: The *HistoGraph* introduced in section 3.2.1 visualizes the history of countries on a graph. Next to the normal browsing mode, the *Edit Mode* is proposed in section 3.2.2. It uses the six Edit Operations to introduce historical changes to the current state on the map. The gradual process from the inital idea to the final user interface implemented in HistoGlobe is illustrated in the last section 3.2.3.

3.2.1 HistoGraph

Based on the idea of the History Graph Model (section 2.14), the linguistically and conceptually related *HistoGraph* visualizes the evolution of countries in time, without any spatial relation. The edges of the graph represent an Area, the nodes a HG Operation. The graph shows the predecessor-successor-relationships between Areas. This is easily possible, because in the Hivent Model an Area keeps references to the historical changes creating, updating and ceasing the Area (section 3.1.1). The two-dimensional HistoGraph has an horizontal orientation. It expands the timeline: the x-axis of the graph refers to one time point. The y-axis has no spatial or temporal relation, its dimension changes depending on how much space the visualization needs. The graph uses the visualization approach of the five HG Operations (table 3.1), including the following symbols (table 3.3):

——	Area	
●	Identity-changing HG Operation	`UNI`, `INC`, `SEP`, `SEC`
○	Property-changing HG Operation	`NCH`
◉	A combination of both	e.g. `INC + NCH`

Table 3.3: symbols used in the HistoGraph

Each uninterrupted horizontal line refers to exactly one Area. If an horizontal line leads straight through a circle, the identity of the Area is preserved in the operation. New Areas resulting from an identity-changing HG Operation emerge from the circle with a vertical line, indicating a sudden change with zero duration. From this line, the new Areas branch out right-angled. The HistoGraph is created from one particular reference Area. It visualizes historically related Areas in one direction: into the past, it recursively plots the predecessors on the graph, but not the predecessors successors. Into the future, the successors of the reference Area are plotted recursively, but not their predecessors.

The behavior of the HistoGraph is shown in figure 3.5 at the example of present-day Germany and its state history since the end of World War II. This history was driven by six historical events, which provide examples for all five HG Operations. They are listed in table 3.4.

Hivent date	Hivent description	HG Operations
05.06.1945	In the Berlin Declaration the total dissolution of the Third Reich is confirmed. It separates into multiple parts, returning the territories annexed by the German Reich in World War II. The rest is controlled by the British, French, American and Soviet occupation zone.	`SEP`
16.02.1946	The Saar Protectorate is entangled from the French Zone of Occupation Germany, creating an own country.	`SEC`
28.05.1949	The Federal Republic of Germany (West Germany) is created from the British, American and French Zone of Occupation.	`UNI`
07.10.1949	The German Democratic Republic (East Germany) is created from the Soviet Zone of Occupation.	`UNI`
01.01.1957	The Saar Treaty ("Little Reunification") joins the Saar Protectorate as the Bundesland Saarland in West Germany.	`INC`
03.10.1990	In the German Reunification, East Germany joins West Germany. The Federal Republic of Germany is now just called "Germany".	`INC + NCH`

Table 3.4: Historical events in German state history since 1945

The example hosts a special case: in October 1949, East Germany was created from the Soviet Zone of occupation. Both Areas have the same territory, but a different short and formal name. A `NCH` can not be performed, because the identity is not preserved: The German Democratic Republic is a new Area. However, the change can be described by a `UNI` of only one Area (Soviet Zone), creating a new Area (East Germany) and establishing a historical relationship between both.

The graph plots Germany first. Since it does not have any successors, the plot goes only one way, historically backwards: East Germany and the Saar Protectorate were incorporated into Germany, so they are plotted. All emerged from the four post-war occupation zones, which are also plotted. All of the four occupation zones themselves originated from the German Reich. However, the German Reich dissolved into many more Areas, e.g. the Memel territory. They are not included in the graph, because they are not predecessors of any Area that is a recursive predecessor of present-day Germany.

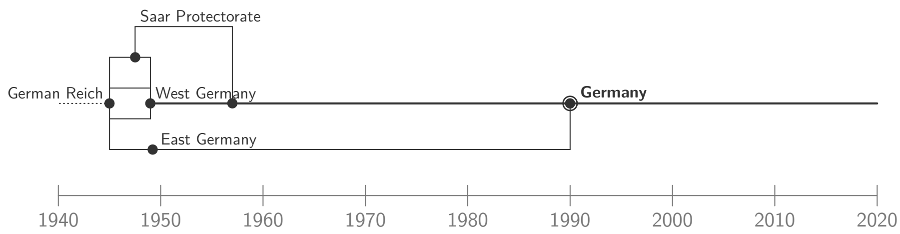


Figure 3.5: The concept of the HistoGraph at the example of the history of Germany since 1945

Many problems of the graph visualization are apparent in this example: Circles my overlap, if many operations happen in a short period of time – in this case between 1945 and 1949. The name "West Germany" collides with the vertical line indicating the incorporation of the Saar Protectorate, which should also be avoided. Additionally, the names of the Areas of the four post-war occupation zones can not be shown in the Graph, because there is no space for them. One more important aspect can be seen in the creation of West Germany in 1949: A `UNI` operation unifies three old Areas to one new Area. This could be visualized symmetrically with a straight line from the midmost incoming Area line into the circle to the outgoing Area line of the new Area. This would give the impression that this midmost Area has the same identity than the newly created Area, which is not the case. In general, the circle for `UNI` and `SEP` operations with an odd number of old respectively new Areas must be displaced off the center to emphasize that the identity has changed. All these issues are not in the scope of this thesis and subject to future work in the field of Information Visualization.

3.2.2 Edit Mode

The user interface of HistoGlobe has two modi: The browsing mode to view the evolution of countries on a map with a timeline and the *Edit Mode* to introduce historical changes to Areas. This mode is proposed in this section. The Human Centered Design process produced an interface that allows to intuitively edit Hivents, Areas and historical changes directly in HistoGlobe, without the need to write data into tables or forms. The conceptual model of the interface promotes six Edit Operations, introduced in section 3.1.4. They describe one historical change that transforms a set of old areas into a set of new areas, using internally the HG Operations (see section 3.1.3). In the interface, the historical change is prepared in a workflow of four steps:

1. `SELECT_OLD_AREAS`: The user selects the old Areas that will be changed in the Edit Operation.
2. `CREATE_NEW_TERRITORIES`: For each new Area resulting from the Edit Operation, the user creates a polypolygon describing the territory of the Area.
3. `CREATE_NEW_NAMES`: Afterwards the user writes the name of each new Area directly on the map. This finalizes the set of new Areas for the historical change.

4. ADD_CHANGE: Finally, the historical change has to be added to an Hivent that introduces it and inherits the time point to it. The user either selects an existing Hivent or creates a new one. All the information necessary for the spatio-temporal Hivent Model are completed.

For each Edit Operation, the requirements for the steps are different. Not all operations need all steps and some data is processed automatically. Table 3.5 presents an overview about the behaviour of each operation in the first three steps. The last step is the same for each operation: Each historical change has to be added to an Hivent.

	SELECT_OLD_AREAS	CREATE_NEW_TERRITORIES	CREATE_NEW_NAMES
CRE	–	create a territory of the new country on unclaimed land and/or overlapping existing countries	create a name of the new country
MRG	select the countries to be merged	– automatic unification of territories of selected countries	create a name of the merged country
DIS	select a country to be dissolved	create a territory for each new country	create a name for each new country
CHB	select two neighboring countries to change their border	create the new border between both countries the territory for both countries will be created automatically	–
REN	select a country to change its name	–	create a new name of the country
CES	select a country to cease it	–	–

Table 3.5: The requirements of each step for the Edit Operations

3.2.3 Design Iterations

The previous sections introduced the concepts of the HistoGraph and the Edit Mode. This section illustrates the Human Centered Design process integrating both concepts into the existing user interface of HistoGlobe. In each phase, interviews with students and employees of Scholar's Lab at University of Virginia were conducted to determine what works well and what has to be improved.

Initial interviews The first phase, four researchers were asked about their opinions on the idea of HistoGlobe, potential use cases and the concept of the Edit Mode. The idea proved popular, especially for students and teachers in school, historically interested people in general and also for scholars in digital humanities. All researchers agreed that the key to successful Edit Mode is usability, because editing data in time and space is a challenging task. A main concern is uncertainty in historical research: Almost all sorts of information – temporal, spatial and attribute – are potentially uncertain. A good user interface for researchers therefore has to support uploading historical sources and indicating uncertainty. The Edit Operations from section 3.1.4 resulted from the initial interviews.

Paper Prototype From the results of the inital interview, the first interface concept for the Edit Mode was developed and transformed into a paper prototype. It is an interface out of paper that is very fast to create and allows to identify flaws in the concept early in the design process. In this process, two paper prototype iterations were created. Both iteration took about three full work days: one day to create the conceptualize and create prototype, half a day to conduct the study with three people, and one and a half days to analyze the results and rethink the concept.

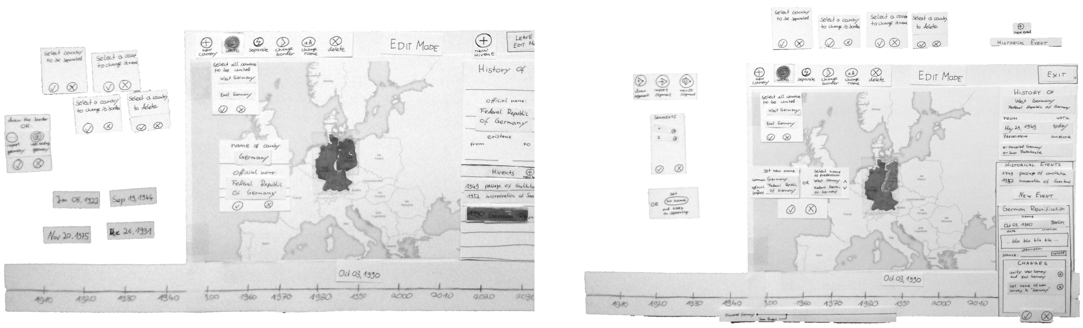


Figure 3.6: The two iteration of the paper prototype for the Edit Mode

The interface consists of a map of Europe, a timeline centered at 1975 and the buttons with a set of dialogs for the for the Edit Mode. Both prototypes were evaluated with three test subjects that had to solve four tasks covering different use cases and operations:

1. 1300: Rename incorrectly spelled name of Switzerland on the map (*correction*)
2. 1990: Unite East and West Germany (*forward change*)
3. 1993: Separate the Soviet Union into Russia, Estonia, Latvia, etc. (*forward change*)
4. 1944: Change the border between Finland and the Soviet Union before 1944 (*backward change*)

Most parts of the interface concept were understood and all subjects could solve the first three tasks. However, there were also problems:

1. There difference between Hivents, the history of a country and an historical change was unclear.
2. The border drawing dialoge was imagined to be very complex.
3. The backward change was not understood
4. Correcting the name Switzerland by changing the event that created it in 1300 caused confusion.

The main finding of this step was that depending on the task, there is both an Hivent-based and an Area-based mental model of the task. This became apparent in the German Reunification Hivent: Some users started the unification operation first, and added West and East Germany afterwards – and some selected first West Germany, then initiated a unification operation and then added East Germany. From that finding arose that the interface has to support both an Hivent-based and an Area-based approach to introduce historical changes and correct information on the map.

Mockup Prototype The main part of the design process was spent on the mockup prototypes. Their purpose is to rapidly develop an interface workflow that is understandable by the users. The prototypes were created in *LibreOffice Impress*, an open-source slide-based presentation tool. The interface is simulated on slides: the map is a background image, the timeline, the set of buttons and dialogs for the Edit Mode and HistoGraph are modelled with geometric elements: lines, circles and rectangles. Interactivity is simulated by linking a click on an element to a different slide that shows the effect of the operation. This allows to model sudden changes in the interface.

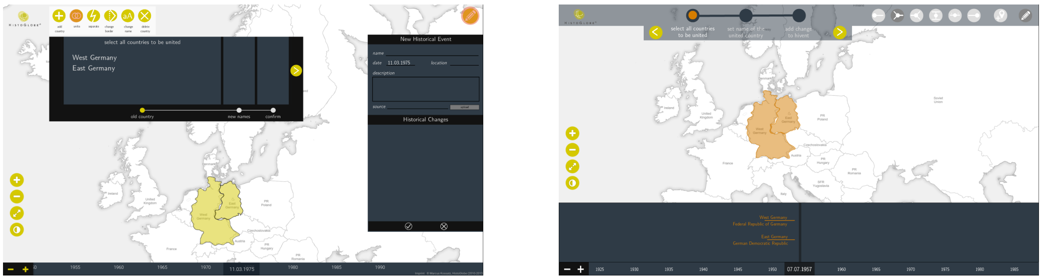


Figure 3.7: Two iteration stages of the mockup prototype for the Edit Mode

Creating the mockup prototype took longer than a paper prototype, but would have still been much faster than actually implementing an interactive Web-based interface. Each prototype iteration was tested with multiple subjects and similar tasks as for the paper prototype. From one test to the next one changes to the interfaces were made. Some interesting quotes from the users were:

"this was much easier than I thought"

"the interface is very clear and graphically pleasing"

"it's looking good"

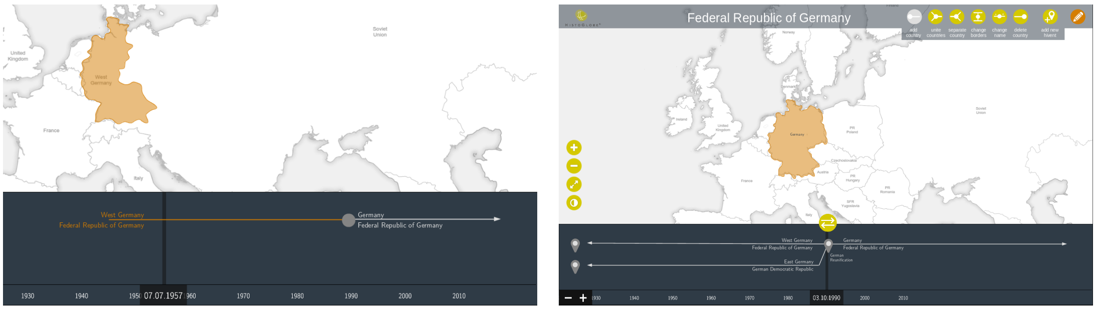
"there is a training session needed"

"the logic makes sense, it is just very complex"

"a nice tutorial and a good documentation are necessary"

The main evolution was from a separate dialogue window for the Edit Operation workflow to an intergrated workflow window in the title bar. Also the HistoGraph was introduced to visualize the historical change at while editing it. A lot of smaller design issues, e.g. position of buttons, font sizes or color schemes were identified and fixed. But also conceptual issues arose.

Especially the problem to initiate a backward change (see section 3.8) proved to be very difficult. Two design solutions were developed: First, instead of initializing a change in 1990 to separate Germany into East and West, the user can introduce two creation events for the two German states in May and October 1949. The interface needs to provide a visual clue that after creating West Germany, this Area can only be active until 1990, because then another Area, present-day Germany, uses its territory (see figure 3.8a). The change from West Germany to Germany will be created automatically. The second approach is to introduce a button that flippes an Edit Operation that has just been created (see figure 3.8b) – in this case the `DIS` operation introduced to secede East Germany from Germany will be flipped into a `UNI` operation to incorporate East Germany into Germany. This approach makes use of the fact that each Edit Operation and has an inverse, as explained in section 3.1.4. However, this flipping requires the introduction of additional creation events: West and East Germany were introduced in the change, but only the event that ceases both of them (`INC` of West Germany into East Germany). They also need a creation event, otherwise they would be active backwards all the way to t_0, the initial state of the system.



(a) Visual clue: predefined and of Area (b) Create backward change by flipping Edit Operation

Figure 3.8: Two approaches for editing changes backwards

The prototype was very valuable for the development process. In a total of two weeks, an interface concept and workflow was designed that proved to be understandable by the users.

Final Web-based prototype The main advantage of the design process is that it prevents major redesigns of the final Web-based prototype. After three months of implementation of the final system, the interface looks very similar to the last version of the mockup prototype. The original main elements of the interface are the map, the timeline with the Now Marker indicating the current date of the visualization and the control buttons for zooming the map and the timeline. They are preserved and extended by new interface elements for the Edit Mode. Their interaction and behavior are introduced in this section at the example of the fictional secession of Scotland from the United Kingdom in 2018. The HistoGraph was not implemented, because of the conceptual problems mentioned in section 3.2.1 that have to be solved first.

Figure 3.9: Initial state of the normal mode

The initial state of the user interface. Additional to the original elements, there is an edit button on the upper right corner. Clicking it enters the Edit Mode of the system.

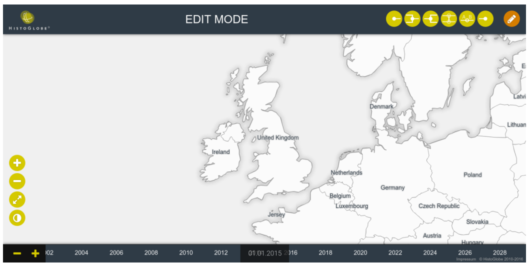


Figure 3.10: Initial state of the Edit Mode

In the Edit Mode, a title bar and six buttons for the Edit Operations are revealed. Clicking a button starts the operation workflow introduced in section **??**.

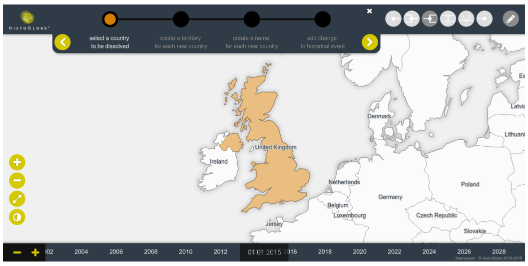


Figure 3.11: Step 1) `SELECT_OLD_AREAS`

A *Workflow Window* is guiding the user through the process of completing the historical change. It shows all the steps necessary for this Edit Operation. In the case of `DIS`, the user has to select the country to be dissolved by clicking it on the map. After the step is completed, clicking the next button in the workflow window procceeds to the next step. At each point in the workflow, clicking the back button reverts the previous action.

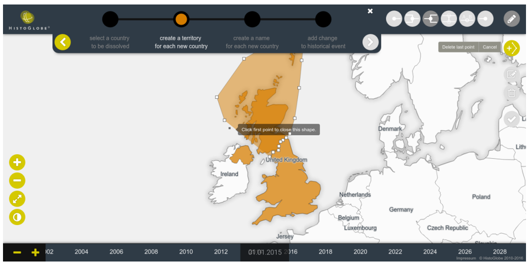


Figure 3.12: step 2) `SET_NEW_TERRITORIES`

In the second step, the user has to create the territory for each new Area that shall be created. Therefore, the *New Territory Tool* provides the functionality to create, manipulate and delete polylines by clicking and moving it directly on the map. The polypolygon drawn by the user is intersected with the old territory to create the territory of the new Area. After one new territory is created sucessfully, the second one can be taken from the remaining old territory by selecting it from the map. As soon as the whole old territory is distributed among the new Areas, the workflow proceeds to the next step.

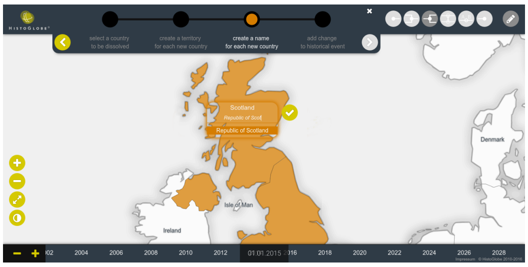


Figure 3.13: Step 3) `SET_NEW_NAMES`

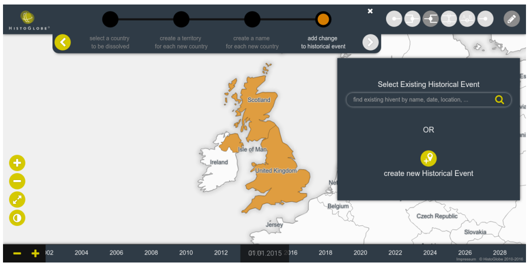


Figure 3.14: Step 4) `ADD_CHANGE`

In the next step, for each Area that has been created in the step before, a name has to be defined. The *New Name Tool* is a draggable input form with two lines, the upper one for the short name, the lower one for the formal name, the identity of the Area. Via instant search, the user can select existing country names from the database to be put in the New Name Tool. When clicking the confirm button, the short name is put directly on the map.

When all names are set, the Edit Operation is complete. In the last step of the workflow, it has to be added to an Hivent. The *New Hivent Box* offers two possibilities: the user can search for an existing Hivent and add the historical change to it, or create a new one.

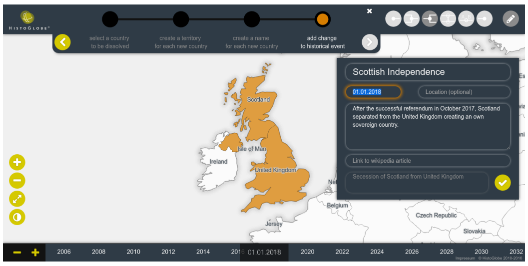


Figure 3.15: Step 4) `ADD_CHANGE`

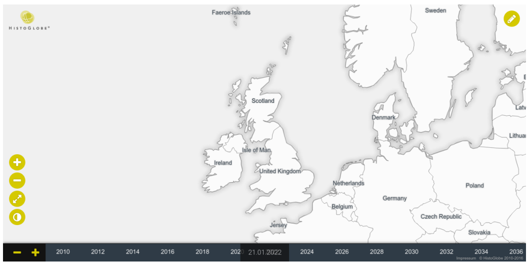


Figure 3.16: The final state with Scotland

The new Hivent created for that change is the "Scottish Independence" on 01.01.2018 with a description of the Hivent and possibly a location and a link to a wikipedia article. In the last line, the historical change "Secession of Scotland from the United Kingdom" is noted. Clicking the confirm button finalizes the workflow.

Clicking the edit button again leaves the Edit mode back to the normal view. Scotland and the United Kingdom are both visible on the map after 2018. When moving the timeline before 2018, Scotland is still part of the UK.

3.3 Application

HistoGlobe is a Web-based Historical Geographic Information System. The Data model and the conceptual model of the user interface were introduced in the first two sections of this chapter. This section introduces the underlying database model, a specific implementation of the data model, and the computational model that translates between the conceptual model and the database model of the system.

The first part provides an overview about the architecture of the system in section 3.3.1.

3.3.1 System Architecture

HistoGlobe uses a classical client-server architecture of a Web-based information system. The user opens the application and interacts with it through the user interface in a Web browser, the *client* side of the system. The Web *server* is a remote computer that hosts the database and the middleware. The user interacts with the interface, the client-side application sends a request to the Web server for new data. The middleware checks the request and queries the necessary data from the database. It transforms the data and sends it back to the client. The interface shows the new information.

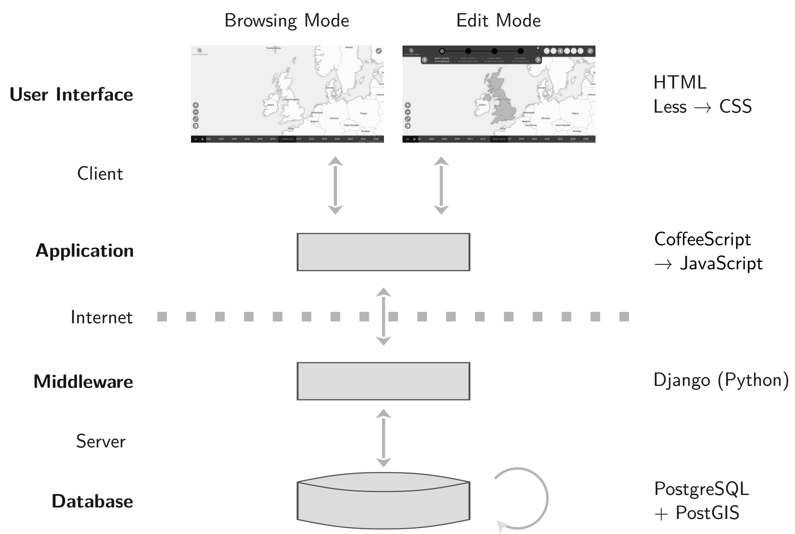


Figure 3.17: The system architecture of HistoGlobe

This clear separation between the data, the application and the user interaction in this chapter and in the system follows directly from the *model-view-controller* pattern: One part can be changed independently from the others parts: if the 2D map is replaced by a 3D globe, only the view changes, but the middleware and the database can stay untouched. Likewise, the implementation of a new database technology has no consequences to the view.

3.3.2 Hivent Database Model

From the system point of view, the underlying data model explained in section 3.1 has to be implemented in a database model. HistoGlobe uses *Django*, a free and open-source web framework [3], combined with *PostgreSQL* [4] , one of the most popular Object-Relational Database Management Systems introduced in section 2.4.3, on the server-side of the system. This allows HistoGlobe to take advantage of object-oriented concepts in a stable and fast relational database. Since the database is using a lot of geospatial data, the *PostGIS* is used as a spatial database extension for PostgreSQL [5].

With these tools at hand, the database model shown in figure 3.18 was developed. It is the final result of a highly iterative process that underwent many improvements and adpations to new requirements introduced in the Human Centered Design process. The model is structured in two parts: The lower part describes the semantic, spatial and thematic domain of Areas, their names and territories. The upper part represents the temporal domain that introduces changes to the entities of the other three domains. It is the core of the spatio-temporal *Hivent Database Model*.

Semantic, Spatial and Thematic Domain `Area` `universe`

`AreaName` `short_name` `formal_name`

`AreaTerritory` `geometry` `representative_point`

Temporal Domain `Hivent`

1. The *name* of the Hivent.
2. A textual *description* of the topic of the Hivent.
3. The point in time, identified by the Hivent *date*.
4. The Hivent *location*.
5. The *historical changes* resulting from the Hivent.

`HistoricalChange` `edit_operaton` -¿ 6 high-level Edit Operations

[3] *Django*, The Web framework for perfectionists with deadlines, URL: `https://www.djangoproject.com/`, last access: 27.05.2016

[4] *PostgreSQL:*, The world's most advanced open source database, URL: `http://www.postgresql.org/`, last access: 31.10.2015

[5] *PostGIS*, Spatial and Geographic Objects for PostgreSQL, URL: `http://postgis.net/`, last access: 27.05.2016

AreaChange hg_operaton -¿ 5 low-level Historical Geographic Operations

example German Reunification:

Hivent "German Reunification" 03.10.1990

HistoricalChange MRG

AreaChange INC NCH

OldArea DDR, east territory, "East Germany"

UpdateArea BRD: west territory -¿ full territory BRD: "West Germany" -¿ "Germany"

NewArea none

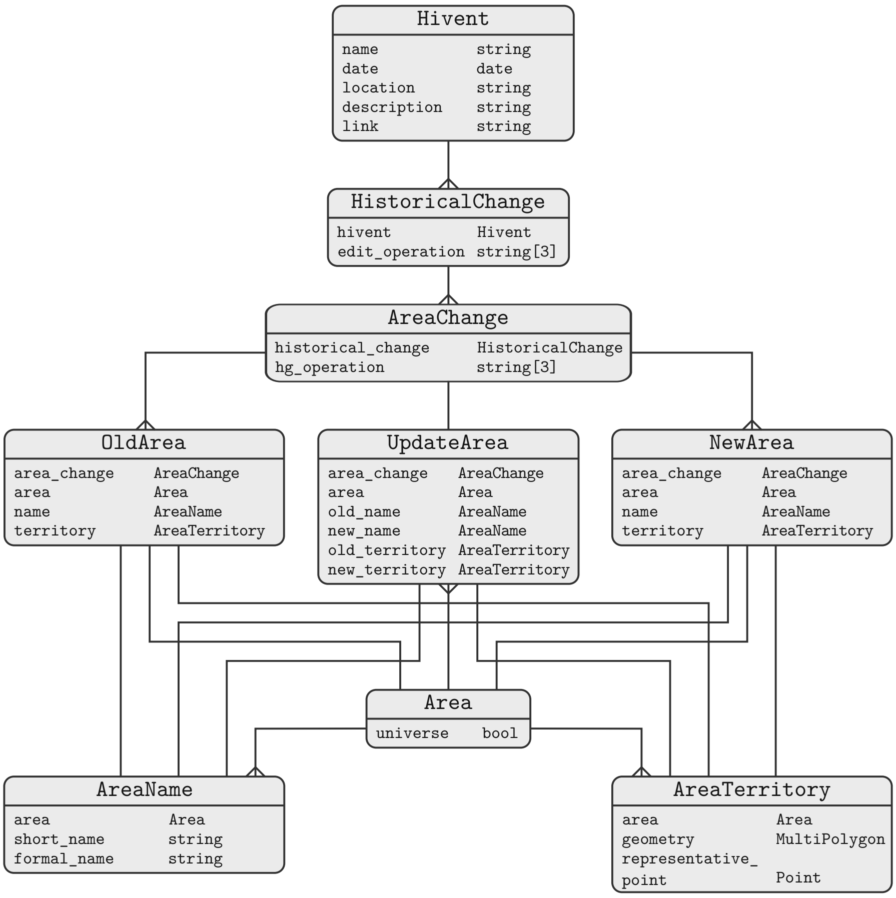


Figure 3.18: The Hivent Database Model

no transaction time, only valid / event time only world time is regarded, not database time.

view

get_all save_operation

3.3.3 Computational Model

Class diagram

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

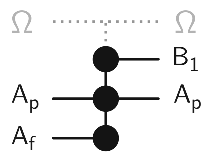
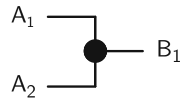
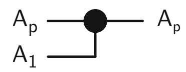
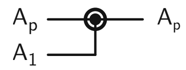
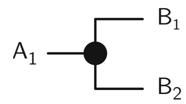
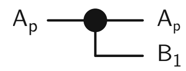
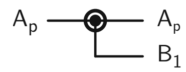
HistoGraph

LabelManager*

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

Reduction to HG Operations The conceptual model promotes six Edit Operations (see section 3.1.4) that humans can understand. The underlying data model is based on five HG Operations (see section 3.1) that can model all evolutionary changes to countries in time and space. The task for the computational model of HistoGlobe is to translate between both operation sets.

Each Edit Operation will internally be expressed by a set of Historical Geographic Operations that describe the change on a low level. Depending on the input of the user in the Edit Operation steps, there are different possibilities. They are introduced in table 3.3.3.

EditOp. (case)	old Areas	update Areas	new Areas	expression by HG Operations [6]	visualization
`CRE` (1)				Area B_1 is created with territory T. The part of T that is on previously unclaimed land (T_Ω) is seceded as B_1 from Ω. If T_Ω is empty, then B_1 is initialized with an empty territory. The rest of T covers some Areas A_p partially and some Areas A_f fully. For each A_p, the covered territory T_p is seceded and incorporated into B_1. Each A_f is completely incorporated into B_1.	
	n_f	n_p	1	`SEC` of B_1 from Ω `SEC` of T_p from A_p, `INC` of T_p into B_1 `INC` of A_f into B_1	
`MRG` (1)				Multiple Areas A_i are unified to B_1. The new Area receives a new name distinct from all the names of A_i.	
	$n \geq 2$	0	1	`UNI` of $\forall A_i$ to B_1	
`MRG` (2)				Multiple Areas A_i are unified, the resulting Area reuses the short and formal name of one of the old Areas (A_p) and therefore preserves it. The remaining Areas A_i are incorporated into A_p.	
	$n \geq 1$	1	1	`INC` of $\forall A_i$ into A_p	
`MRG` (3)				The same as the previous case, just that A_p receives a new short name and therefore an additional name change is required.	
	$n \geq 1$	1	1	`INC` of $\forall A_i$ into A_p `NCH` of A_p	
`DIS` (1)				Separate one Area A_1 into multiple new Areas B_i and define a territory and name for each of them. Each name is distinct from the name of the old Area.	
	1	0	$n \geq 2$	`SEP` of A_1 into $\forall B_i$	
`DIS` (2)				Separate multiple Areas B_1 from one initial Area A_p and define a territory and name for each of them. One of the separated Areas has the same short and formal name as A_p, so it continues its identity and preserves the Area. The remaining new Areas secede from A_p.	
	1	1	$n \geq 1$	`SEC` of $\forall B_i$ from A_p	
`DIS` (3)				The same as the previous case, just that A_p receives a new short name and therefore an additional name change is required.	
	1	1	$n \geq 1$	`SEC` of $\forall B_i$ from A_p `NCH` of A_p	

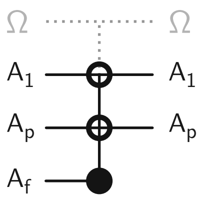
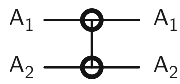
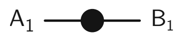
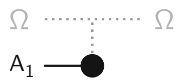
<table>
<tr><th>EditOp.
(case)</th><th>old
Areas</th><th>update
Areas</th><th>new
Areas</th><th>expression by HG Operations [6]</th><th>visualization</th></tr>
<tr><td rowspan="2">CHB (1)</td><td colspan="4">One existing Area A_1 is selected and its territory changes. Relative to the old territory some parts of the territory expanded (T_e) and some withdrew (T_w). The part of T_e that expanded into unclaimed land ($T_\Omega \in T_e$) is seceded from Ω and incorporated into A_1. The Areas A_f fully covered by T_e are incorporated into A_1, the Areas A_p partially covered by T_e secede this territory $T_p \in T_e$ to A_1. T_w will be incorporated into Ω, resulting in unclaimed land.</td><td rowspan="2"></td></tr>
<tr><td>n_f</td><td>$1 + n_p$</td><td>0</td><td>SEC of T_Ω from Ω, INC of T_Ω into A_1
SEC of T_p from A_p, INC of T_p into B_1
INC of A_f into B_1
SEC of T_w from B_1, INC of T_w into Ω</td></tr>
<tr><td rowspan="2">CHB (2)</td><td colspan="4">Two existing Areas A_1 and A_2 are selected and their common border changes. This results in a symmetrical change of territories, made up by two sets of territories: T_2 that previously belonged to A_1 and is now part of A_2 and T_1 for which the opposite is true. T_2 is seceded by A_1 and incorporated into A_2, the opposite happenes to T_1.</td><td rowspan="2"></td></tr>
<tr><td>0</td><td>2</td><td>0</td><td>SEC of T_2 from A_1, INC of T_2 into A_2
SEC of T_1 from A_2, INC of T_1 into A_1</td></tr>
<tr><td rowspan="2">REN (1)</td><td colspan="4">One Area A_1 is selected and both its short and formal name is changed. Therefore, a new Area B_1 is created as a direct successor of A_1. This is a special case of a unification with only one Area.</td><td rowspan="2"></td></tr>
<tr><td>1</td><td>0</td><td>1</td><td>UNI of A_1 to B_1</td></tr>
<tr><td rowspan="2">REN (2)</td><td colspan="4">One Area A_1 is selected and receives a new short name, but the formal name and therefore the identity is preserved. A_1 is updated.</td><td rowspan="2"></td></tr>
<tr><td>0</td><td>1</td><td>0</td><td>NCH of A_1</td></tr>
<tr><td rowspan="2">CES (1)</td><td colspan="4">One Area A_1 is selected and ceases by incorporating into the universe.</td><td rowspan="2"></td></tr>
<tr><td>1</td><td>0</td><td>0</td><td>INC of A_1 into Ω</td></tr>
</table>

Table 3.6: Translation from Edit Operations to HG Operations

[6] multiple HG Operations in one row happen exactly at the same time point, so they are combined

Functional description Each HG Operation can be described by a mathematical function. The following symbols are used in the equations:

A	set of old Areas that were active before the Historical Change
B	set of new Areas that are created in the Historical Change
n :	$n \in \mathbb{N}, n > 0$ total number of old respectively new Areas
i :	$i \in [\mathbf{1}..n]$ iterator for the current old respectively new Area
A_0/B_0	the first old respectively new Area ($i \geq 1 \Rightarrow$ not A_i/B_i !)
A_i/B_i	the current old respectively new Area ($i \geq 1 \Rightarrow$ not A_0/B_0 !)
A_i^T/B_i^T	the new territory of the current Area (a polypolygon)
A_i^N/B_i^N	the new name of the current Area (short and formal name)

$$(B_0) = UNI([A_1..A_i..A_n], B_0^N)$$
$$(A_0) = INC(A_0, [A_1..A_i..A_n])$$
$$([B_1..B_i..B_n]) = SEP(A_0, [[B_1^T, B_1^N]..[B_i^T, B_i^N]..[B_n^T, B_n^N]])$$
$$(A_0, [B_1..B_i..B_n]) = SEC(A_0, A_0^T, [[B_1^T, B_1^N]..[B_i^T, B_i^N]..[B_n^T, B_n^N]])$$
$$(A_0) = NCH(A_0, A_0^N)$$

Pseudocode description of the HG operations in an object-oriented manner. The existance of a class `Area` is assumed. Each `Area` object has the following member variables: a `name`, a `territory` and a list of historical `predecessors` and `successors`. Single capital letter variables (`A`/`B`) denote arrays of `Area` objects. Variables with a capital letter followed by a number or lowercase letter (e.g. `B0`) are single `Area` objects.

```
FUNCTION UNI(A, B0_name)
  # create new territory
  B0_territory = NEW Geometry # empty
  FOREACH Ai IN A
    B0_territory.union(Ai.territory)
  # create new area
  B0 = NEW Area(B0_name, B0_territory)
  # establish historical relationships
  FOREACH Ai IN A
    Ai.successors.add(B0)
    B0.predecessors.add(A1)
  # return new area
  RETURN B0
```

Listing 3.1: Unification

```
FUNCTION INC(A0, A)
  # update old area with new territory
  temp_terr = NEW Geometry # empty
  FOREACH Ai IN A
    temp_terr.union(Ai.territory)
  A0.territory = temp_terr
  # establish historical relationships
  FOREACH Ai IN A
    Ai.successor.add(A0)
    A0.predecessor.add(A1)
  # return new area
  RETURN A0
```

Listing 3.2: Incorporation

```
FUNCTION SEP(A0, B_data)
  # create each new Area
  B = []
  FOREACH Bi_data in B_data
    B.add(NEW Area(
      Bi_data.name, Bi_data.territory)
    )
  # establish historical relationships
  FOREACH Bi IN B
    A0.successors.add(Bi)
    Bi.predecessors.add(A0)
  # return new areas
  RETURN B
```

Listing 3.3: Separation

```
FUNCTION SEC(A0, A_territory, B_data)
  # update old area with new territory
  A0.territory = A_territory
  # create each new Area
  B = []
  FOREACH Bi_data in B_data
    B.add(NEW Area(
      Bi_data.name, Bi_data.territory)
    )
  # establish historical relationships
  FOREACH Bi IN B
    A0.successors.add(Bi)
    Bi.predecessors.add(A0)
  # return old and new areas
  RETURN [A0, B]
```

Listing 3.4: Secession

```
FUNCTION NCH(A0, A_name)
  # update old area with new name
  A0.name = A_name
  # return updated area
  RETURN A0
```

Listing 3.5: Name Change

Execute Historical Change execute function for all operations the same

```
## member variables
old_areas = []          # Area
new_areas = []          # Area
update_name = {
  area :          null  # Area
  old_name :      null  # AreaName
  new_name :      null  # AreaName
}
update_territory = {
  area :          null  # Area
  old_territory : null  # AreaTerritory
  new_territory : null  # AreaTerritory
}

## main function
FUNCTION execute(direction)

  # hide old areas
  FOREACH old_area IN old_areas
    IF direction IS 1 # forward change
      old_area.hide()
    ELSE              # backward change
      old_area.show()

  # show new areas
  FOREACH new_area IN new_areas
    IF direction IS 1 # forward change
      new_area.show()
    ELSE              # backward change
```

```
      new_area.hide()

  # check if the area name is updated
  IF update_name.area
    IF direction IS 1 # forward change
      update_name.area.name = new_name
    ELSE              # backward change
      update_name.area.name = old_name
    update_name.area.update()

  # check if the area territory is updated
  IF update_territory.area
    IF direction IS 1 # forward change
      update_territory.area.territory = new_territory
    ELSE              # backward change
      update_territory.area.territory = old_territory
```

Listing 3.6: class HGOperation

HistoGraph

```
FUNCTION plot(reference_area, plot_start_date, plot_end_date)
  # plot the current Area
  # logic is omitted

  # recursively plot in historically backward direction
  FOREACH predecessor IN reference_area.predecessors
    IF predecessor.end_date >= plot_start_date
      plot(predecessor)

  # recursively plot in historically forward direction
  FOREACH successor IN reference_area.successors
    IF successor.start_date <= plot_end_date
      plot(successor)
```

Listing 3.7: plotting Areas on the HistoGraph

store Hivents in DoublyLinkedList

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.

transition to next chapter

Chapter 4

Evaluation

MECE principle The MECE principle – mutually exclusive and collectively exhaustive – is used by the consulting company McKinsey for organizing large amounts of data and as a strategy for effective problem solving. The advantages of a MECE model are [For]:

- Each possible case in the real world can be mapped to a case in the model, because the model covers all possibilities (*collectively exhaustive*).
- A case in the real world can be expressed by exactly one case in the model, because there is only one possibility (*mutually exclusive*).
- The model is logical and comprehensive, can easily be understood and followed.

Mutual exclusion First it is to be shown that one operation can not be equivalently expressed by a combination of any other operations. This is obviously true for `CRE`, because all other operations require at least one old area as an input to the operation. Vice versa, `CES` is unique, because it is the only operation without any new areas. `ICH` could geographically be represented by a combination of `CES` of and `CRE`, but that would not create a historical relationship between both Areas. Since the other identity-changing operations require either multiple old or new areas and the last three operations are identity-preserving, `ICH` is also unique.

`UNI`, `INC`, `SEP` and `SEC` require either old or new areas and establish historical relationships by changing identities. That is why they can neither be replaced by `CRE`, `ICH` and `CES` (only one old and/or new area), nor by `NCH`, `BCH` and `TCH` (identity-preserving). It is trivial that no operation can be expressed by its inverse and an operation that requires one old area can not replaced by one that requires multiple and vice versa. Therefore, the only possible combinations left are `UNI` $\leftrightarrow$ `INC` and `SEP` $\leftrightarrow$ `SEC`. While geographically, they are equivalent, because they unite respectively separate the territory in the same way, they are historically distinct: While in `UNI` and `SEP`, no Area is preserved in the operation, `INC` and `SEC` represent one Area that incorporate one Area into respectively cede one Area from its own territory. This shows the mutual exclulsion of all identity-preserving operations.

It has already been argued that identity-preserving operations can not be expressed by a combination of any identity-changing ones. Also, `NCH` changes the name, whereas `TCH` and `BCH` manipulate the territory of an Area, so it is clear they can not replace each other. By intuition, `BCH` is the same as two `TCH` of both Areas affected by the `BCH`. Both operations do also not set up any historical relationship, so they are historically the same. However, geographically, two `TCH` of two neighboring countries would be redundant, since the territory ceded by one Area is exactly the same territory that is incorporate by the neighbor. Therefore it has been proofed that all operations are mututally exclusive.

Exhaustive collection Next it needs to be shown that all cases that can happen in the real world can be expressed using a combination of one of the ten HG Operations. The first aspect is the identity of an Area, representing a political entity in the real world. In the life cycle of an entity, it is established at one point t_s, its name and territory can change multiple times while being active $U : \forall t_u \in U : t_u > t_s$ and it ceases at some other point $t_e : t_s < \forall t_u \in U < t_e$.

In the real world, a political entity can be created in three ways:

1. If before the creation of the entity its initial territory was fully unclaimed, it does it have any historical predecessors and is created new. This is represented in the `CRE` operation.
2. If its initial territory was fully claimed by a set of entities, then all of these entities are historical predecessors.
   (a) If the entity originates from itself by changing its formal name, the territory remains unchanged. The `ICH` operation reflects that case.
   (b) An entitiy can also originiate from one entity that has dissolved into several subsequent entities, which is represented in the `SEP` operation.
   (c) Finally, an entity can originate from several entities unifying. The `UNI` operation models this case.
3. If the new entities territory was partially claimed and partially unclaimed, this process of creating entity A can be expressed by a combination of three operations:
   (a) `CRE` creates the temporary entity A_T with a new name and its territory on all unclaimed land that shall be occupied by A later.
   (b) The rest is currently territory of a set of entities B. For each entity $B_i \in B$, the part that shall be territory of A gets ceded from B_i with a `SEC` operation, creating a set of entities A_R. This operation establishes a historical relationship between B_i and A_i.

(c) A_T and all $A_i \in A_R$ are unified with `UNI` to the final entity A. A inherits its name from A_T and each Area $B_i \in B$ as a predecessor.

Throughout the lifetime of a political entity, the following changes can happen to it:

1. The entity can change its name. A change of the commonly known short name is represented by `NCH` and preserves its identity. A change of the long official or formal name creates a new Area (`ICH`).
2. The territory of the political entity can change.
   (a) If it expands into land that is not claimed by any other entity at this time point or if it is shrinking without influencing the territory of potentially neighboring entities, the `TCH` operation can be used.
   (b) If the entity incorporates a territory from or cedes a territory to one neighboring entity, then this change is modeled by a *BCH* operation.

is that historical relationships must always be established in both ways, i.e. $A \rightarrow_H B \Leftrightarrow A \leftarrow_H B$. There are five operations that set up an historical relationship and for all of them this is true. Regarding the Area name, it must be

name: no problem, can overlap territory: by precondition: can not overlap =¿ geometrical and topological integrity

investigate for each operation if it maintains integrity CRE ICH CES UNI, INC, SEP and SEC operate solely on NCH BCH TCH

compare 5 HG operations with temporal operations in History Graph Model

transition to extensions

-¿ 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]

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

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

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

The model is open to future extensions to account also for geographic changes and international sea borders.

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.

Another constraint of the model is that it does only support coequal Areas and no hierarchies, e.g. a country consists of a set of states which consist of a set of counties. Also, independent Areas that overlap other areas, e.g. to visualize a disputed zone or the expansion of the rain forest, are not possible given the model.

The model can easily be extended to states, provinces or regions. Therefore, from now on the term

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

political unit instead of country is used to describe the object in the real world that is modeled by an Area in the system.

Hierarchical Areas CTR -¿ STA -¿ CTY -¿ CIT each level one layer aggregate geometry upwards

Overlapping Areas e.g. war zone, independent layer

border change: manipulate border, not territory

For precision purposes it would be important to be able to import existing geometries from external sources or to import an historical map and extract the territory from there. However, this was not in the scope of this thesis and has to be integrated in the future.

Chapter 5

Uncertainty

Every aspect of the development chapter 3 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 evolution 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].

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

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

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]

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

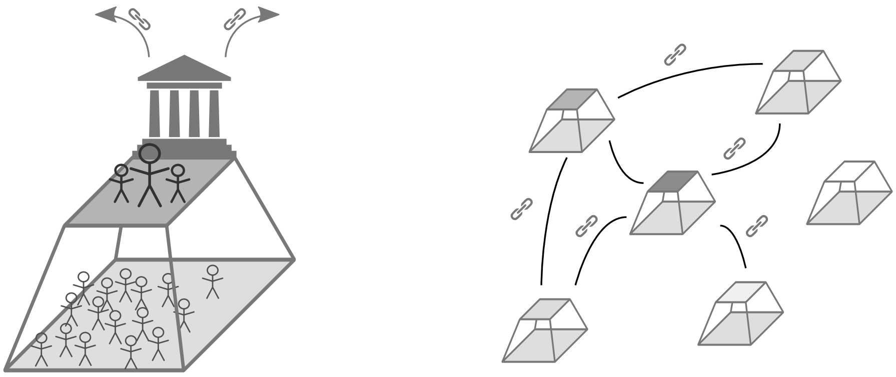


Figure 5.1: The Declaratory Theory (left) and the Constituitive Theory (right) of Statehood

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).

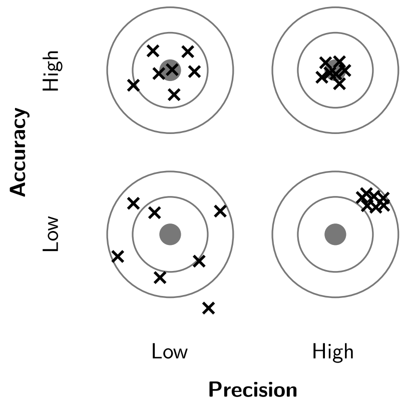


Figure 5.2: The difference between accuracy and precision

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 3 is evaluated in terms of 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.

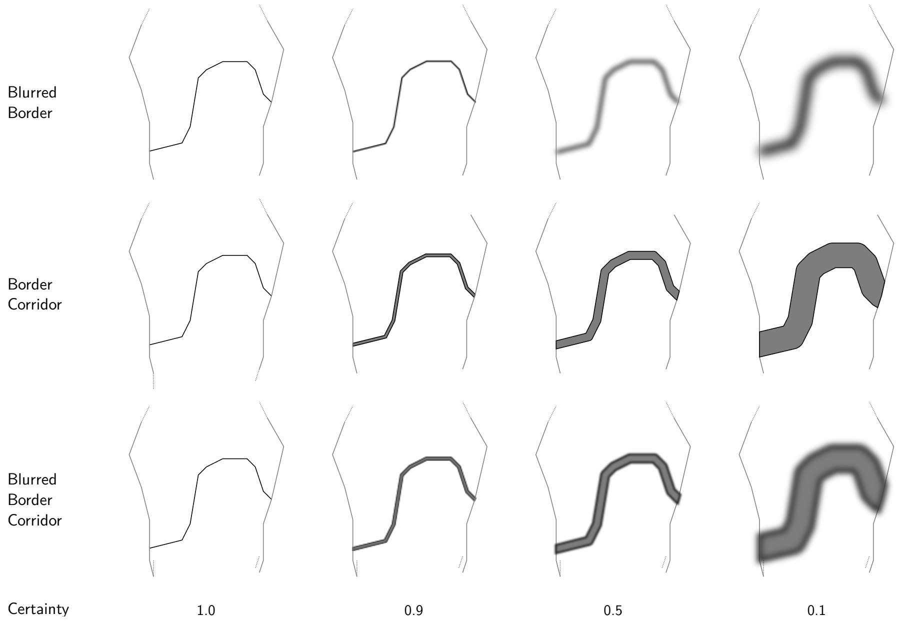


Figure 5.4: Three different methods to visualize uncertain courses of a border

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.

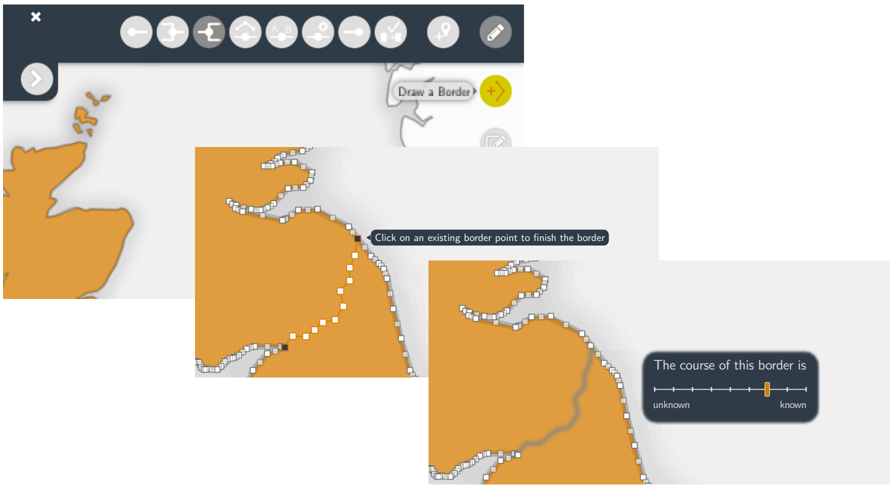


Figure 5.5: Drawing historical borders instead of full areas and definining a level of certainty.

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.

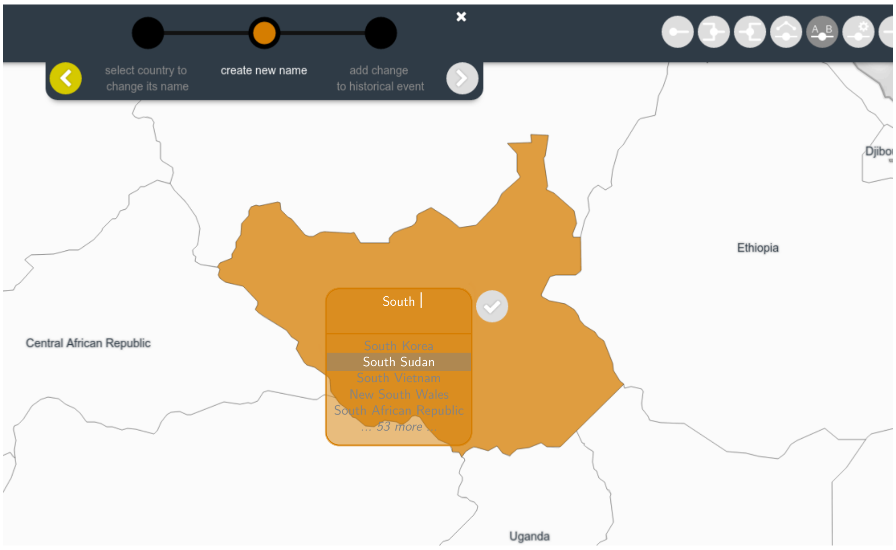


Figure 5.6: Getting suggestions for the name name from Wikipedia.

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.

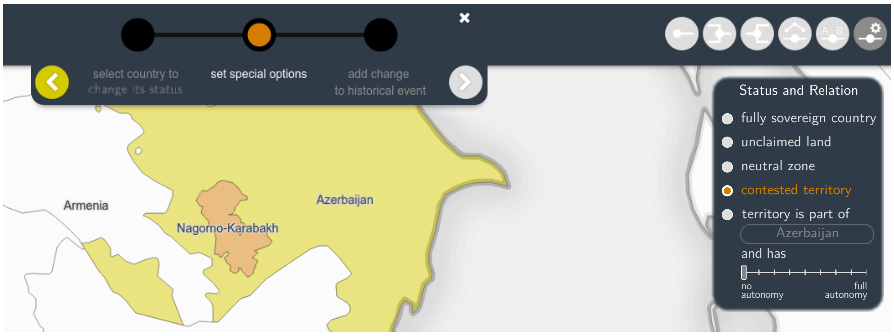


Figure 5.7: Defining a special status or relationship to a territory.

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.

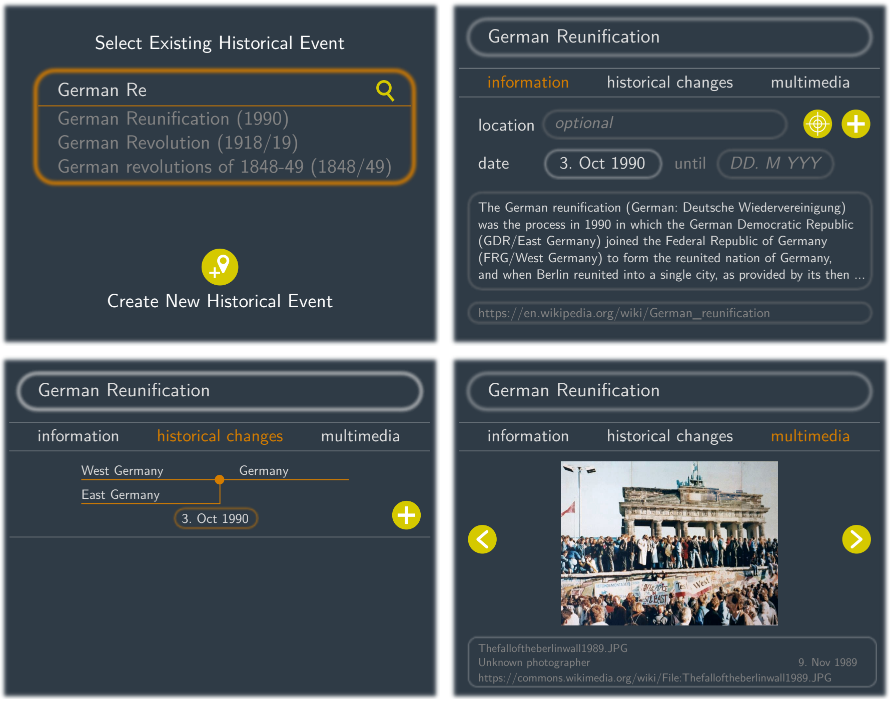


Figure 5.8: Creating a new Hivent and adding the newly created historical change.

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.

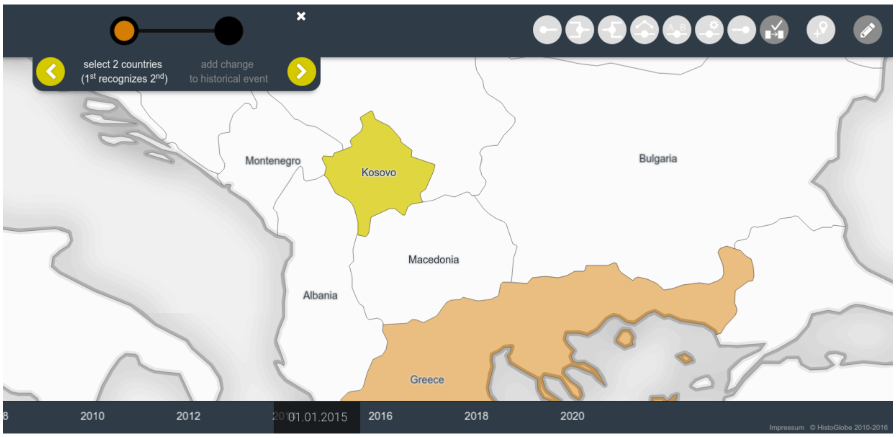


Figure 5.9: New edit operation: Recognition – sets up the recognition of one area to another.

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 3 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.

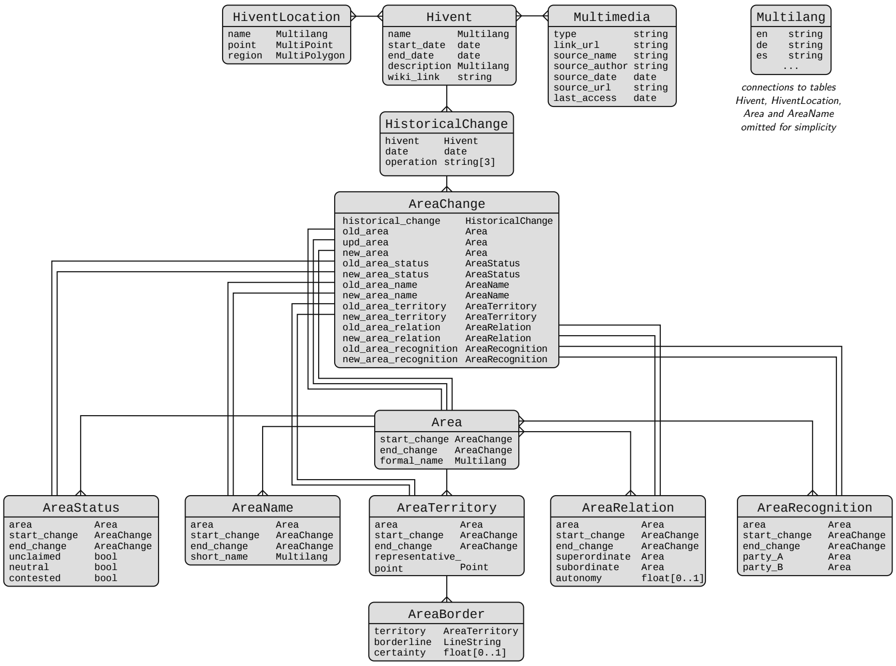


Figure 5.11: The new data model to support the developed approaches regarding uncertainty

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

extend the pure presentational purpose of st data to analytical purpose, e.g. where have most border changes take place in previous 200 years?

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]. 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

extend area model to hierachies (country -¿ states -¿ counties/cities)

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Stuff