Semantic Annotation for Medieval Cartography

The Example of the Behaim Globe of 1492

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Abstract:
The Behaim Globe of 1492 is the oldest extant globe of the earth. It is an early masterpiece of different scientific and technological achievements; nowadays it is a famous exhibit of the Germanic National Museum in Nuremberg. Its map image is primarily Ptolemaic, including elements of medieval universal cartography and of portulans. Its luxurious decoration shows 100 pictorial illustrations plus sixty banners and coats of arms, more than 2000 place names, and more than 50 long legends. The Behaim Globe is one of the very few existing cartographical works where different traditions of late medieval mapmaking are bound together.

Starting with a database of digital images of its surface, a comprehensive catalogue of all visually relevant places including text fields is built up by means of a domain ontology for medieval cartography in description logics (OWL-DL). Up to now, nearly 3000 instances (catalogue entries) have been created. Today it is a common practice to unite generic concepts and properties for objects, time and space, events, actors, processes, etc., in a reference ontology such that domain specific concepts are derived from the generic ones. The CIDOC CRM is such a reference ontology; our implementation, the Erlangen CRM/OWL, provides a semantic base for the cartographic domain ontology, suitable for automatic reasoning.

Furthermore, the globe provides a georeferential organization of information which opens up a new dimension for semantic indexing. Historical maps are cognitive maps in the first place, which require a formal qualitative representation of (abstract) regions, their relative positions, but also direction, orientation, and distance. Represented by specific datatypes with constraint solvers, their integration with a logical representation framework leads to a system of hybrid reasoning for processing complex spatial queries over the Behaim globe instance base.

CIDOC 2010
ICOM General Conference
Shanghai, China
2010-11-08 – 11-10

1 BEHAIM's globe and medieval cartography

1.1 MARTIN BEHAIM and the globe of 1492

The BEHAIM Globe of 1492 is the oldest extant globe of the earth; today it is one of the most prominent exhibits of the Germanic National Museum (GNM) in Nuremberg. The merchant and seafarer MARTIN BEHAIM, born in 1459, was an offspring of a noble Nuremberg family, then on leave from his business in Lisbon. Obviously, he was an important person at the Portugese court, because he received a knighthood by king João I. in 1485. During his stay in Nuremberg between 1491 and 1493 he managed to convince leading members of the city council to finance the manufacturing of the globe under his direction. The decisive reasons are still unknown, but many inscriptions on the globe indicate an economic motivation in the first place. With its impressive visual appearance it may have helped to attract potential investors in German-Portugese commercial seafaring.

With a diameter of 50 cm the globe is rather large, exhibiting an image of the earth at the turn to the modern age, which is primarily affected by Ptolemaic cartography (fig. 1), but it also carries elements of portulans (sea charts) and of medieval universal cartography. First of all, the globe was put on display at a prominent place in the Nuremberg city hall and it got a new metal stand with an engraved horizon in 1510. In 1493, MARTIN BEHAIM returned to Portugal and he died in Lissabon in 1507. Whereas the final financial account on the globe of 1494 indicates clearly which craftsmen were involved in its making [38], the BEHAIM globe must be regarded as a joint achievement of the Nuremberg humanist circle. It is an early masterpiece of many kinds of scientific and technological achievements, establishing the intellectual and economic leadership of Nuremberg in late medieval Germany.

BEHAIM's globe provides the last pre-columbian account of the late medieval knowledge of the world in a georeferenced arrangement. At the same time, there are indications of the upcoming change to a more "modern" empirical, scientific image of the earth. Not the quality of the information, but its quantity and selection make the globe an important primary source for historical research. It is one of the very few existing cartographical works where different traditions of mapmaking are bound together: Ptolemaic mapping with elements of medieval universal cartography and of portulans.

As there is no modern comprehensive scholarly edition of BEHAIM's globe, we initiated some preparatory work in cooperation with the GNM which includes the present investigation on semantic annotation and reasoning. The best research summary of the state of the art around 1990 is given by the catalogue to the GNM exhibition "Focus Behaim Globus" in 1992 [4]. Nevertheless, in some regards the only, but partially outdated monograph by RAVENSTEIN (1908) [41] is still important, which contains a facsimile drawing of globe gores in original size, based on a copy of the globe from 1847 made for the French National Library in Paris, well as a summary paper by Muris [35]. (For comprehensive accounts of BEHAIM's biography, the history of the globe and its reception cf., e.g., Braeunlein [39] and Pohle [39].)

1.2 The map image of Behaim's globe

The map image of the globe is primarily Ptolemaic, as an inscription on the globe itself says; on the first glance it appears as a large Ptolemaic world map drawn on a sphere. This is in particular the case for the depiction of Europe, North Africa, the Near East and Asia, which is far too much extended to the east. In its western and northern parts it had been completed by results of recent experience, and in the cartographically still untapped east by literary resources. The space between the western coast of Europe and the eastern coast of Asia is full of fanciful islands from medieval tradition, such as Antilia and St. Brendan's island. In view of the extent of Portugese exploration, the map is surprisingly inaccurate and partially out of date, especially in relation to the west coast of Africa. There are several hints to Portugese expeditions along the African coast — in one case there is also a claim of BEHAIM's participation — where captured coast locations are marked by Portugese flags, and the sea route to India appaears obvious. Nevertheless, it is remarkable that no notice is taken of the recently discovered islands far to the west of the Atlantic ocean. The socalled Columbus letter had been printed 1493 in Barcelona for the first time, so it must have been known, but underestimated in Nuremberg, a European trade capital with excellent communication links.

The globe is luxuriously decorated. It contains more than 2000 place names, 100 pictorial illustrations plus over sixty banners and coats of arms and more than 50 long inscriptions, many of which are only partially recognizable and have even been overwritten. Most of the pictorial and text elements conform to the tradition of encyclopedic medieval mappae mundi [12], dealing with the Christian salvific history, with tales from antiquity such as the story of Alexander the Great, with peculiarities and fabulous monsters of foreign countries, their inhabitants, plants and animals. Many inscriptions talk in particular about overseas trade, explorations and famous travels, referring to reports like that of Marco Polo and Mandeville, and quoting classical geographic texts by Strabo, Plinius and Ptolemy, and Isidore of Seville's encyclopedia.

What can be said about the cartographic sources for BEHAIM's globe?

The "Geographikè Hyphegesis" by KLAUDIOS PTOLEMAIOS (around 100–180 A.D., Alexandria) is first of all an instruction how to make maps. In its second to eighth book it contains coordinates of more than 8000 places between the Canaries (0° longitude) and East Asia (180°) as well as Central Africa (-15° latitude) and Northern Europe/Asia (65°), according to which regional maps can be constructed. All Ptolemaic world maps show considerable distortions: The Mediterranean is far too long such that Italy extends more from west to east than from north to south, and Asia extends too far to the east — on BEHAIM's globe even 230°. Cipangu (Japan) is located where on a modern globe Central America is found.

Ptolemy's Geography was brought to Italy by Byzantine emigrants around 1400. Also in the Latin editions the southern part of the world map shows only Northern Africa and the Indian Ocean as a semi-enclosed sea bordered by an unknown south continent which connects East Africa to East Asia. But there are exceptions: The world maps by HENRICUS MARTELLUS, who worked in Florence around 1490, two of which are extant in London and Yale, are more similar to BEHAIM's globe, in particular w.r.t. Asia and the Indian Ocean. Africa is shown with the Cape of Good Hope and its overall shape is even more precise than on the globe.

In contrast to the land-based Ptolemaic maps, portulans are constructed according to the practice of navigation with a compass and show only the coast lines, but with high precision (a comparison of 15 portulans by means of 350 identifiable points showed a maximum point error of ±40 km, which corresponds to 1/3° on a great circle [34]). They have been constructed in a systematic way; a system of rhumb lines originates from compass roses, and they contain a distance scale: direction and distance are essential for navigation [42, 31]. But precise determinations of position on board of a ship were not possible before the Portugese began with systematic astronomical navigation. Here BEHAIM may have had influence, because his native city of Nuremberg was the European center of the production of high precision measurement instruments.

The claim put up by some authors that portulans were used as models for the globe is rather improbable, because the map is surprisingly inaccurate and partially out of date, especially in the display and the toponyms of the West African coast, where BEHAIM points out his personal experience. But we find some of their typical iconographic elements such as flags, coats of arms, and tents on the globe.

The same observation holds for the influence of medieval mappae mundi, which is exhibited by the globe's encyclopedic character with many long explanatory inscriptions, but also in numerous miniatures. But in addition to Christian themes and those of classical antiquity shown on those maps we find an increasing number of secular subjects. There are biblical themes such as the evangelists and Noah's ark on Mount Ararat, but also Alexander's military expedition, many animals on land and sea, trading ships and an ice bear hunter with bow and arrow. The majority of the long inscriptions have secular content as well: texts referring to the globe itself, literary sources on geography and science, travel reports, and BEHAIM's own African journey. Most of them are close to Africa and Asia and report of peculiar properties of foreign countries, their climate, the inhabitants with their habits, their nutrition and their religions, but also of monsters and anthropophages, and any important information for travellers and merchants — about animals, plants, spices and other merchandise like furs, ivory, gold and precious stones. A extended text describes long distance trade between Asia and Europe with ten intermediate stops and all who make profit. Travelling times and places with specific geographic features such as the magnetic islands are pointed out. The legendary king priest John who was supposed to be an ally in the East against islamic countries, is mentioned several times.

Among the cartographic sources — besides the Ptolemaic-style Martellus maps — a late descendant of the circular medieval world maps deserves to be mentioned: Evidently BEHAIM was familiar with a large circular world map by the Venetian cartographer FRA MAURO which had been ordered by the Portugese king Alfonso in 1459. FRA MAURO's maps, one of which is on display in Venice [14], have also been influenced by oriental traditions — islamic with their orientation to the south instead of the east, and even Chinese — and show many similarities with the globe.

2 The cognitive map approach, visual analysis and the catalogue of places

2.1 Cognitive maps

Structuring knowledge accroding to cognitive criteria, i.e., strategies of perception, learning, memory and associative reasoning, was familiar to medieval cartographers. To mention only two examples, St. Augustine and Hugo of St. Victor deal in-depth with the associative organization of memory and in particular with the spatial mapping of knowledge elements to architectonical structures.

“In the last analysis all maps are cognitive maps” — this thesis put up by BLAKEMORE und HARLEY [3] indicates an important topic of recent research in the history of cartography. Georeferencing, i.e. reference to geographical locations, is the underlying principle for organizing and presenting all kinds of information in maps, historical and modern ones. Persons, buildings and other artifacts, historical and fictuous events are recognized at certain places, associated with them, and henceforth memorized and retrieved; temporal courses of events are mapped into spatial relations. TOLMAN [46] was the first to introduce the term “cognitive map” to denote the cognitive representation of space and of spatial relations, first of all on the individual level, later on augmented by a layer of social communication. KITCHIN and BLADES [28] and MACEACHREN [32] provide a representative and comprehensive overview from the viewpoint of psychology and cognitive science.

Easy access to cognitive mapping can be achieved by investigating the questions of “where”, “what”, and “when” systematically. For the “where”, i.e. spatial information in a proper sense, we presuppose naming (“appellation”) as an elementary means to determine identity. For a description of places, depending on the frame of reference, a specification of states or processes, and of distance and direction must be added. An example of a process specification would be a route description, how a certain place can be reached. “What” — the objective — and “when” become important for the solution of spatial problems: a set of suitable properties must be given which are useful to find a solution by means of cognitive mapping. In other words, first of all, we have to identify the elements which are necessary for an *epistemological* organization of spatial knowledge. In a second step we need to develop a formal representation suitable for computational processing. Obviously, *regions* and their relative positions play a key role as well as directions or *orientation*, resp., and *distance*. To perceive these elements, to identify them and to refer to them in discourse is an accomplishment in abstraction which has in any case also a cognitive foundation. In order to meet objections against this approach as ahistorical, we are convinced that there are basic epistemological expressions of spatial orientation which are to a large extent invariant to cultural conditions.

So, basically we are considering the assembly of maps and their description in terms of those primarily qualitative categories with (qualitative) spatial reasoning in mind. In combination with the descriptive modelling approach for maps as presented in section 2.3, an operationalization of these elements allows for new logical connections and hence to answer complex queries.

2.2 Digitization of the map image

The surface of the globe is made of paper and it was painted by the Nuremberg artist GEORG GLOCKENDON [38]. Due to awkard placements for centuries and some failed restoration attempts, where the biggest damage was done by boiled linseed oil, the conservation state of the sphere, which shows deformations of up to 2 cm, and hence its visual appearance, is rather poor.

Currently there are two series of photographs which cover the complete surface: a series of excellent black and white photos taken in 1940 and colour photographs taken in polarized light in 1990 for the preparation of the exhibition “Focus Behaim-Globus” in 1992. The latter ones show a lot of details which cannot be recognized in normal lighting. They were used for the production of photogrammetrically orthonormalized globe gores in orginal size, generated by a computer-controlled analog optical device at the Technical University of Vienna [27, 30, 29].

The starting point for a thorough investigation of the globe is a database of digital images of its surface. So, besides the original black and white and colour photographs, we digitized the films of the gores, which have about DIN A4 size per half gore of 30° with the optimal film resolution (later on, also the Technical University of Vienna digitized the images, but those were never delivered to the museum, cf. [11]). Due to many problems which can be recognized on the extant photographs, but cannot be solved with digital image processing, in cooperation with the museum we submitted a proposal for a new digital photographic record and 3D modelling with tenfold resolution.

With the goal of a — digital and printed — scholarly edition in mind, the first interpretation step consists of a paleographic analysis and a new reading of all inscriptions and a standardized description of all 110 miniatures, followed by a scholarly commentary. Here, ULRICH KNEFELKAMP has already performed the essential preparatory work at the end of the 1980s. As far as the inscriptions are concerned, we can distinguish three groups: one or two words, usually place or person names (*Venedig, Insule martini, konik organ*), short texts, i.e., phrases or single sentences (*Di santig wüstung, alexanders altar, der heilige 3 drei / konig einer aus india*) and ca. 50 long texts, most of them written in ocean areas. It is immediately conspicuous that besides a very early handwriting there are about six different handwritings which originate from the 16th to 19th century. Most of the texts written by the latter hands are palimpsests or overwritings, i.e., there is an older inscription underneath, parts of which are still visible at the borders or between the lines. It is still an open question — if an answer can be found at all — whether the overwritings are just reproductions of already partially rotten inscriptions. What had been changed or supplemented, and why? And there are places where one can recognize faint traces of inscriptions which are no longer legible. Among the minatures there are depictions of humans, animals, monsters, ships, buildings, town silhouettes and fortifications, banners and coats of arms, but also of astronomical objects such as the signs of the zodiac, sun, moon, and planets. We also find whole scenes like people kneeing in front of a ruler’s tent in Africa. The biggest ship is depicted in the Indian Ocean at a place, which at that time the Portugese had not yet reached! In about the same region on FRA MAURO’s map there is also a ship accompanied by an inscription pointing to the expeditions of the Chinese admiral ZHENG HE...

2.3 Knowledge representation: Conceptual modelling and the catalogue of places

Next, a comprehensive catalogue of all visually relevant places on the globe's surface has to be built up on the basis of a systematic classification of all visual object types and properties, representing geographic and non-geographic entities, anchored in positions on the associated map images. The goal is the semantic annotation of historical maps in general by means of a conceptual model. Up to now, nearly 3000 instances, i.e., catalogue entries, have been written, including all known historical transcriptions of the legends. So, the current catalogue of places covers about 70% of the globe's surface, but the remaining parts are not decorated as richly as the already recorded parts.

The entries of the catalogue of places consist of structured descriptions, a first version of which had been developed in a predecessor project [16] which attempted to make the results of the exhibition "Focus Behaim Globus" [4] available with an information system. These structured descriptions are built up in a systematic way along the paths provided by a conceptual model, now usually called a "formal domain ontology". To be precise, a formal ontology defines the terminological system of a domain of discourse [36] and it usually follows appropriate theories. In ideal cases it draws on their resp. context of justification and uses their underlying abstraction methods [33, 15]. Then we can say that a formal ontology represents the conceptual kernel of a domain theory, and we can also claim that it defines the representation of semantics of a domain with the terminologically controlled linking of concepts, sometimes also called "sense-relational semantics".

A conceptual model consists of a hierarchy of concepts (classes) from general to specific ones, to which properties are associated in such a way, that the class definitions are abstractions over explicitly named properties. From the definitional viewpoint the essential, necessary properties may be supplemented by sufficient ones. Extensionally, a concept or class consists of all individuals ("particulars") which are given by filled-in schemata of — at least the necessary — properties, socalled instances. So, an entry in the catalog of places is nothing else than such an instance. It is important to notice that in our case the formal description aims directly at the visual appearance of items on a map in terms of properties and concepts. We distinguish between geographic (e.g., *continent*, *river*, *settlement*) and non-geographic concepts (e.g., *banner*, *ruler*, *castle*, and including readings of the inscriptions), which in turn have superconcepts (e.g., *building* for *castle*), as shown in fig. 2. An instance of the concept *continent* would be *Africa* with appropriate property values for size, position, etc. Modelling of further properties of the globe such as materials, production processes, etc., and also of its role in the urban and scholarly discourse is, although important, currently not included, but may be subject of future extensions.

For the representation of formal ontologies, conceptual models and associated object descriptions, we use knowledge representation languages from the family of description logics [1]. Those are decidable sublanguages of first-order logic for which efficient reasoning algorithms are available which guarantee complete and correct inferences from complex, logically composed queries [10]. Within this framework, we implemented our domain ontology, derived from an earlier class and property hierarchy in an object-oriented programming language (Common LISP Object System), in the description logic CLASSIC [5] first, which has recently been actually remodelled in the Semantic "Web Ontology Language" OWL-DL [44] and integrated with CIDOC CRM (cf. 3.1), comprising concepts of the mentioned three map types as well as the nongeographical iconographic concepts and the inscriptions. For the description logic language OWL-DL powerful inference engines, such as Racer (`http://www.racer-systems.com/`; 27.07.2010) [22] or Pellet (`http://clarkparsia.com/pellet`; 27.07.2010) [43] are available. They enable automatic structuring of a body of formalized knowledge by computing the subsumption of concepts and properties as well as the classification of object descriptions and processing of complex, logically composed queries. Furthermore, there are powerful graphical editors with integrated reasoners such as Protégé [37] for the development of formal ontologies in OWL-DL.

3 Conceptual modelling with CIDOC CRM

3.1 CIDOC CRM as a formal reference ontology

Any domain ontology — in our case for the history of cartography — makes use of generic concepts for time and space, events, actors, processes, etc., which are fundamental for conceptual modelling not only in scientific, but also in common sense domains as well. Furthermore, the fundamental mathematical concepts required for formal modelling such as number, set, relation, but also mereology (part-whole relations) must be available. So, formal reference ontologies containing just generic concepts and properties were developed. Different domain ontologies can be “plugged in” such that the domain specific concepts are derived as specialisations of the generic ones. From a technical perspective, reference ontologies are particularly relevant because they provide a basis for semantic interoperability, e.g., for data integration and comprehensive information retrieval.

ICOM-CIDOC’s “Conceptual Reference Model” (CRM) (registered as ISO Standard 21127 “Information and documentation — A reference ontology for the interchange of cultural heritage information”. For further details cf. `http://www.cidoc-crm.org/`; 27.07.2010) [8, 45] is such a reference ontology with an emphasis on cultural heritage documentation. We developed an implementation of the standard in OWL-DL, the “Erlangen CRM/OWL” [17] (implementation available at `http://erlangen-crm.org/`; 27.07.2010.), which is very well suited to provide a generic semantic base for the BEHAIM cartographic domain ontology such that its concepts and properties are derived from the more general ones in CRM. Whereas many applications of CRM aim at the representation of entire collection items, in our case the CRM is used for fine-grained semantic labelling of the details of a complex object.

Interoperability comes in if there are other ontologies, e.g., for biographic information, which have been connected to the CRM in the same way. In this case the CRM serves as a mediator for queries addressing persons presented on the globe, e.g. sovereigns, to access their biographical data. With the planned embedding in the WissKI framework system (`http://www.wiss-ki.eu/`; 27.07.2010.), we also get access to various authorities for named entities for free. If there are similar place catalogues for other maps, a variety of comparisons of texts and images comes within reach and an opportunity for a new quality of comparative work will become possible.

3.2 Conceptual modelling and embedding in CRM

The design decision for the conceptual model of the globe, was, as mentioned in section 2.3, to focus on visual items, each occupying a certain region on its surface. Because the globe contains iconographic elements of all three medieval map types, it should be suitable as a kernel for a formal ontology for the whole of medieval cartography. Starting with a set of characteristic properties, we defined a class hierarchy as the basis for the formal ontology in OWL-DL. The basic distinction, as shown in fig. 2, is between geographic and non-geographic regions.

For geographic regions, we make a further distinction between contiguous and non-contiguous ones, and among those, whether they represent land or water areas. The most important terminal classes for contiguous land regions are named regions, settlements, mountains, forests, deserts, capes, and islands, for water regions we have sea, oceans, currents, lakes, and rivers.

Non-geographic regions are either carrying text or images. Besides the great circles — equator, ecliptic, and meridian — we distinguish between various kinds of miniatures: signs of governance (banners, coats of arms, thrones, tents), astronomical signs (signs of the zodiac, planets), animals (land, sea, and fabulous), people (rulers, bishops, saints, and others), buildings (fortifications, cities, monuments, tombs), ships, and scenes composed of several iconic elements.

To serve as a domain ontology embedded in CRM, appropriate CRM (super-) concepts — and properties — had to be identified as anchors for these classes or subtrees of the class hierarchy, resp. With the decision to focus on the visual items, only the globe as a whole is represented as an (E22) Man-Made Object (a concept name in CRM) and as such it is an (E84) Information Carrier. In the actual model, physical properties such as materials like the paint and anything related to the conservation state — scratches, fadings, bleached spots — are not yet attributed to parts of the surface, but only to the globe as a whole. Hence, disregarding physical features of the parts for the time being, the primary interfaces between the CRM and the BEHAIM region subtree are (E38) Visual Item and (E53) Place, as can be seen in fig. 3, a screen shot taken from the Protégé editor. As places, all instances, i.e. entries in the catalogue of places, are at the same time georeferenced and therefore carry positions.

As a next step, the inscriptions, written in early modern German, will have to be tagged and indexed semantically w.r.t. Named Entities and technical terms. The approach developed in our WissKI project [18, 19] will be taken up for this task, but a lot of adaptation is required because the linguistic resources such as taggers and partial parsers are not directly applicable to the actual linguistic variety. Furthermore, a facility to display different historical readings — of which there are about ten, at least partial ones — in parallel will be important for research.

4 Query processing and reasoning

In our view, the ultimate goal of formal classification and semantic labeling of objects is to make their descriptions accessible to reasoning. Of course, many — simple and composite — questions could be asked directly by means of SQL, if the object descriptions were stored in a relational database, as long as they refer directly to the classes and properties used and do not require any kind of advanced knowledge processing like terminological inference. Logical inference comes into appearance with more composite questions for object classes and their partial descriptions and with complex feature-logical compositions, e.g. consistency checks and automatic object classification. “Intelligent” search requires content-based inferences within hierarchies of concepts and properties, as well as formal logical reasoning. By this means, claims of validity and justifications can be included in the course of processing. Some examples of queries which require in-depth reasoning are: *What is the object at (X,Y)? Where are Nuremberg coats of arms? Which signs of governance are named? Which animals can be seen in Africa? Where are references to travel reports?*

In our current development environment, queries to a reasoner (Racer, Pellet or any other OWL-DL conformant reasoner) can be posed via Protégé through the DIG reasoner interface [2], which is also available in the WissKI system. Without any doubt, any logical query language syntax is not what can be offered to an end user, therefore we plan to implement a form-based query interface for the WissKI system. A decisive idea for systematizing queries has been developed under the title of “query patterns” by Constantopoulos et al. [7]: “Query patterns enable effective information tools and provide guidance to users interested in posing complex questions about objects. Semantically, query patterns represent important questions, while syntactically they impose the correct formulation of queries.” The authors identified 23 typical query patterns for the cultural heritage domain and arranged them into successive representation layers “so as to expose dominant information requirements on one hand, and structures that can support effective user interaction and efficient implementation of query processing on the other”. Originally, those patterns had been defined in terms of Datalog rules and also reformulated as SPARQL queries. It is still to be determined how far these generic patterns will have to be completed by specific ones from the cartographic domain in general. For queries including spatial relations definitely extensions are mandatory as outlined in the last sections of this paper.

5 Spatial reasoning: Topology and orientation

The globe is also an excellent example of georeferential organization of information which opens up a new dimension for semantic indexing. Landmarks, buildings, persons, historical or fictional events are perceived at certain places, are associated with them, are memorized and recalled accordingly. History and histories are anchored in space; episodes are mapped into spatial relations. So, pre-modern maps are cognitive maps in the first place; cognitive relations have priority over geographic precision. This indicates a specific need for the formal representation of (abstract) regions, their relative positions among each other, but also direction, orientation, and distance. We want to describe maps in terms of these primarily qualitative categories and to carry out qualitative reasoning for query processing.

The question for a formal-logical representation of cognitive categories, in particular for the representation of qualitative spatial knowledge and inference, makes only sense if in the context of research there is a set of complex questions to a cartographic database which can be answered otherwise only with a high demand of resources or cannot be answered at all. As a feasibility study, we investigated how to extend the domain model of the BEHAIM globe with spatial knowledge in terms of the mentioned cognitive categories to enable queries of the following kinds (for details cf. [25], ch. 3.): In deictic questions, spatial properties of known objects in question are asked for. In iterative questions, the objects are unknown and have to be identified in terms of certain spatial properties. Such spatial properties are topological ones, e.g.

neighbourhood, borderlines, the interior or exterior of regions, or set-based, e.g. intersection, containment or identity, or metric, e.g. direction and distance.

On the technical level, topological and orientation relations as well as distance and size can be represented by specific datatypes and processed by special constraint solvers. The integration with a logical representation framework leads to a system of hybrid reasoning which has been prototypically implemented in description logics as an extension of the cartography ontology and tested with the BEHAIM globe instance base. *“Which regions are east of the Azore islands? ”* is a typical geographical query to demonstrate the feasibility of our approach.

5.1 Topological description and reasoning

There are several formal approaches to qualitative theories of geographic (Euclidean) space which are suitable for spatial reasoning (cf., e.g. [13], [48], [23]). LAURE VIEU has elaborated a theory which is particularly well suited for our approach [47], where, on the basis of mereology as an axiomatized part-whole relation, she provided a formalization of topological concepts as well as geometrical concepts, in particular distance and orientation in first-order logic.

The “Region Connection Calculus” (RCC), an elementary topological theory with regard to qualitative spatial reasoning, has been developed by ANTHONY COHN et al. [6]. Based on a concept of *topological regions*, the spatial relations between two regions have been analyzed and it has been shown that the eight relations in fig. 4 constitute an exhaustive and pairwise disjoint system. The abbreviations are: DC = *disconnected from*, EC = *externally connected to*, PO = *partially overlaps*, EQ = *is identical with*, TPP = *tangential proper part of*, NTTP = *nontangential proper part of*. From the — logically formulated — theorems of the socalled RCC8 theory a composition table can be derived which simplifies reasoning with these relations considerably. The answer to a query such as “Given $R1(x,y)$ and $R2(y,z)$, what is the relation between x and z, where $R1$ and $R2$ are relations of the calculus? ” can be determined by a simple lookup in a table, where rows and columns are marked with the mentioned relations, instead of calling a resource consuming automatic proof procedure. As for the topological relations between two regions, four cases can be distinguished: identical (EQ), disjoint (DC, EC), overlapping (PO) and contained (N/TPP/I). The regions, here ideally represented by circles or ellipses, are regarded as point sets in mathematical topology and can be deformed elastically. The “topological mapping” preserves particular properties of the point sets: borderline points are mapped to borderline points, neighbouring points stay neighbours and the borderline stays closed. Obviously, regions with an “inner hole” are not topologically equivalent to simply connected regions.

Three elements are required for relations of direction or *orientation*: A primary object, a reference object, and a reference system. A reference system can either be extrinsic such as a given coordinate system or a system of rhumb lines on a portulan, or deictic.

Qualitative relations of *distance and size* can be specified in an absolute or relative scale. Absolute scales arrange — in a given frame of reference — qualitative specifications such as “near” and “distant” or “large” and “small” in an absolute partial order. In the relative case objects are always described in relation to other objects. In qualitative comparisons, the kinds of objects as well as granularity play an essential role for plausibility.

5.2 Implementation of spatial reasoning

In general, on medieval maps only large regions like the continents Asia, Africa and Europe have clear borderlines; in a few cases the (seven) climatic zones are drawn. For smaller regions, polygons have to be introduced. In many cases, rectangles will suffice, because reference objects such as miniatures and inscriptions can easily be enclosed, and processing will be simplified (for the algorithmic treatment of flat and spheric maps in "computational geometry" cf. e.g., [26, 40]; for an application on the BEHAIM globe also [25]).

From an implementation viewpoint, the spatial concepts and properties can be encapsulated in a domain of specific "concrete" object types with predefined predicates and relations and possibly further functions, which come with special problem solving methods (RCC8). Such an abstract datatype, sometimes also called a "concrete domain", can be combined with a description logic system in such a way that the reasoning process becomes hybrid. The spatial inferences are delegated to a "black box" which returns its results to the description logic reasoner.

For our first experimental implementation of spatial reasoning, the BEHAIM globe domain ontology had been translated into the description logic language CLASSIC, which provides an interface for extensions with concrete domains. Using the computational geometry algorithms implemented by JELINEK [25], we defined an abstract data type (a different modelling approach had been chosen by the Hamburg research group of VOLKER HAARSLEV and RALF MÖLLER [20, 21]), which allows in addition to topological modelling to comprise orientation, scaling and distance [9]. As for scaling, groups of objects of similar size can be established, e.g., continent vs. archipelago, mountains vs. cape, forest, or city, and in analogy, the same holds for distance. So it is possible to pose queries on the level of topological and other spatial predicates which are decided externally, i.e., by means of methods of the concrete domain. Some examples of typical hybrid spatial-conceptual queries are: *Which geographic regions are within the African continent? Which regions are south of the Azores and west of the Canaries? What is east of the Black Sea? Which cities in the continent of Asia are closer than 50 units east the Caspian Sea?* .

So the inital claim has been met that a rational reconstruction of cognitive maps is possible on an epistemological level, comprising the elements necessary to organize spatial knowledge. With the presented operationalization, qualitative inferences can be drawn automatically. Now, the next step will be to transfer it to the conceptual model in OWL-DL, extended by a comprehensive spatial "concrete domain". The only obstacle to be overcome is the fact that OWL-DL does not support "concrete domains", but the specification of OWL 2 supports such datatypes directly. At the time of this writing, we are not aware of any OWL 2 reasoner which is yet able to support them.

6 Conclusion

To facilitate the comparison of different maps, e.g., of the BEHAIM globe with a Martellus map, in addition to a parallel — scaled — presentation, transformations must be supported, in particular for historical maps which have not been designed with a mathematical projection. For this purpose, we provide the program module MapViewer [24] which offers methods based on image registration.

An extremely important question for future research is how to represent diachronic concepts, i.e., concepts whose meaning has changed over time, as a basis for diachronic knowledge models. There is no doubt that in the period between the High Middle Ages and the Renaissance, the interpretation of many of the represented objects and states of affairs is subject to change. Not only geographic facts are affected by changes in historical semantics, but also many presentations with encyclopedic and narrative content. The problem how this observation can be captured with formal languages for knowledge representation has hardly been addressed. In any case, the representation of concepts will have to be combined with an internal representation of time, which, from the viewpoint of formal logic will have many similarities with the representation of space as outlined above.

Last but not least, deductive methods are complementary to, and not a replacement for the “ars inveniendi”, but they can reveal new, implicit states of affairs in a given data base and therefore have a high potential for the induction on innovative research questions.

Acknowledgement. The authors are indebted to Bernhard Schiemann and Tobias Scharpff for helpful comments and hints. Tobias helped also with the implementation of the domain ontology in OWL-DL.

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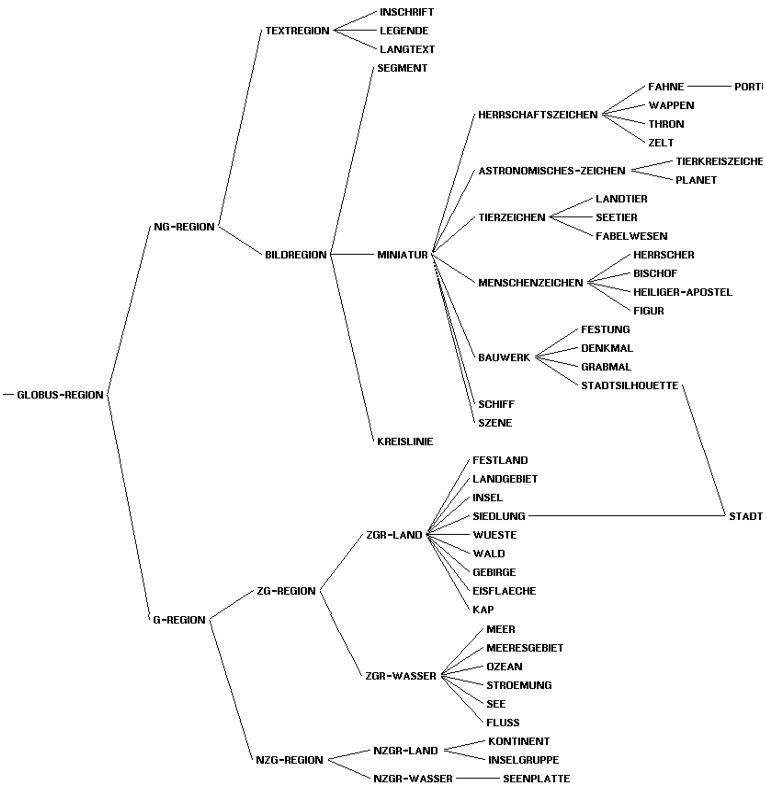
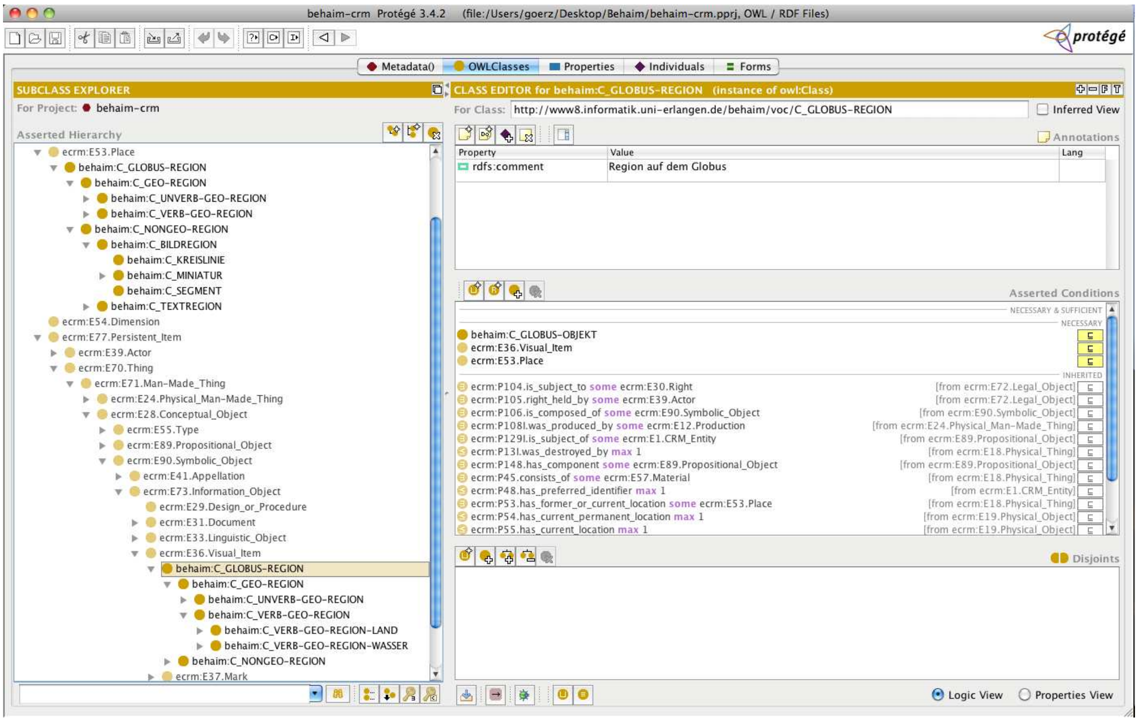
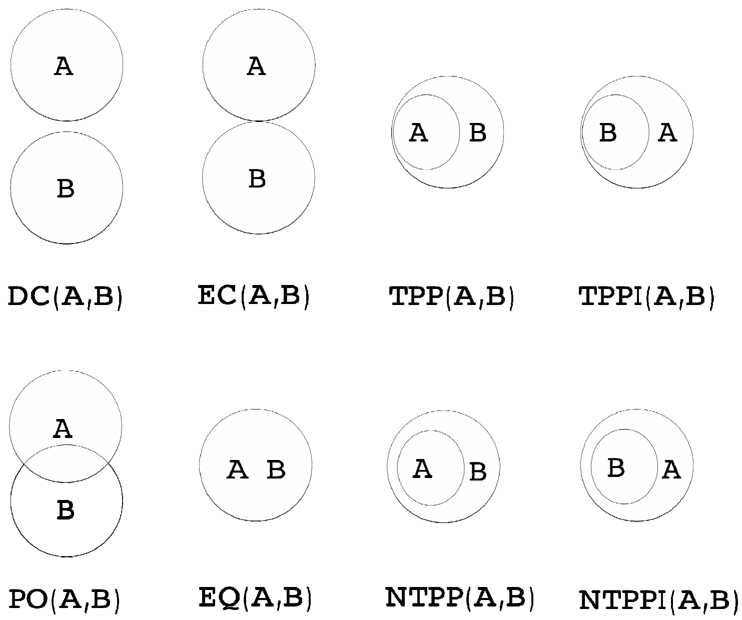
(1) Behaim globe in the exihibiton of the Germanic National Museum, Nuremberg



(2) Concept Tree



(3) Behaim domain ontology embedded in Erlangen CRM / OWL



(4) Topological relations of Region Connection Calculus RCC8