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METHODS FOR CREATING AND USING GEOSPATIO-TEMPORAL SEMANTIC WEB

Doctoral Dissertation

Tomi Kauppinen

Aalto University
School of Science and Technology
Faculty of Information and Natural Sciences
Department of Media Technology

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Doctoral Dissertation

Tomi Kauppinen

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Abstract

This dissertation discusses the problems and the methods of creating and using ontologies in the area of digital cultural heritage. One of the problems is that content annotations in semantic cultural heritage portals commonly make spatiotemporal references to historical regions and places using names whose meanings are different in different times. For example, historical administrational regions such as countries, municipalities, and cities have been renamed, merged together, split into parts, and annexed or moved to and from other regions. The contribution of this dissertation to this problem is to develop methods which can be used to model, produce and utilize geospatio-temporal ontologies. The resources in geospatio-temporal ontologies can be used as annotation terms for describing content, and also for seeking information. The main point of this dissertation is to describe schemas, models and methods that produce and utilize a geospatio-temporal ontology. The schemas and the models are used as inputs for the methods. These methods generate identifiers for spatio-temporal instances, and also relationships between them. In this work, historical Finnish municipalities were modeled and geospatio-temporal descriptions for them created from a filled-up schema. Methods enriched the models by creating geospatio-temporal relationships between these temporal municipalities. The resulting collection of models are referred to as the Finnish Spatio-temporal Ontology (Suomen ajallinen paikkaontologia, SAPO). Specific relationships of the geo-spatiotemporal instances provided the basis for novel recommendation, data mining and visualization schemes. The results of the experiments were promising. For example, with the help of the ontology a user has the ability to retrieve also the content annotated to a historic region even if she searches using a contemporary name of the same or partially overlapping region. The work contributes also to modeling and reasoning about imprecise temporal intervals. A set of different measures based on analyzing two fuzzy temporal intervals are presented and evaluated in the work. The use of a combination of different measures for calculating relevance between temporal intervals was found out to perform best.

Keywords geoinformation, time, change, ontologies, spatiotemporal reasoning

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Työn ohjaaja	

Tiivistelmä

Väitöskirjan tutkimusongelmat ja menetelmät liittyvät ontologioiden tuottamiseen ja hyödyntämiseen digitaalisen kulttuuriperinnön alueella. Eräs ongelmista on se, että kulttuuriaineistojen annotoinneissa käytetään usein historiallisten alueiden ja paikkojen nimiä, joiden merkitys voi vaihdella ajan kuluessa. Monet hallinnolliset alueet kuten valtiot, kunnat ja kaupungit ovat vaihtaneet nimiään. Lisäksi monet niistä ovat yhdistyneet, jakautuneet, luovuttaneet alueita tai vastaanottaneet alueita. Väitöskirjan kontribuutio tähän ongelmaan on kehittää menetelmiä, joiden avulla voidaan mallintaa, tuottaa ja käyttää geospatio-temporaalisia ontologioita. Menetelmät tuottavat spatio-temporaalisia resursseja ja niiden välisiä suhteita. Työssä esitellään myös menetelmien soveltamista suomalaisten historiallisten kuntien mallintamiseen. Menetelmillä tuotettiin Suomen ajallinen paikkaontologia (SAPO), joka koostuu ajallisista kunnista sekä niiden välisistä peittävyys-suhteista (overlap-relations). Jokaisella ajallisella kunnalla on lisäksi oma globaali, geospatio-temporaalinen tunnisteensa, johon voidaan viitata esimerkiksi kulttuuriaineistoja annotoitaessa. Ajallisten kuntien välisiä suhteita on sovellettu ja evaluoitu väitöskirjassa suosittelu-, visualisointi-, ja tiedonlouhintajärjestelmissä. Testeissä geospatio-temporaalisen ontologian käyttö osoittautui lupaavaksi. Ontologian avulla käyttäjälle voidaan esimerkiksi suositella hänen hakuterminä käyttämäänsä paikkaa peittäviin historiallisiin paikkoihin annotoituja sisältöjä, esimerkiksi alueen vanhoja ilmakuvia. Väitöskirja käsittelee myös epätäsmällisten ajanjaksojen mallintamista sekä niihin liittyvää päättelyä ja tiedonhakua. Väitöskirjassa esitellään ja evaluoidaan eri mittoja, jotka perustuvat kahden sumean aikajakson analysointiin. Näiden mittojen painotetun yhdistelmän todettiin suoriutuvan parhaiten epätäsmällisten ajanjaksojen välisen relevanssin laskennassa.

Asiasanat paikkatieto, aika, muutos, ontologiat, spatio-temporaalinen päättely

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Preface

The provenance of this dissertation is indebted to many people. First, I should acknowledge the influence of my supervisor Prof. Eero Hyvönen especially for helping me to understand and reshape the research questions, and for all our conversations about the work in its various phases.

I acknowledge Jari Väätäinen from the Geological Survey of Finland (GTK)[1] for his essential work in providing and extending the knowledge base of changes which is a crucial part behind the Finnish Spatio-temporal Ontology (SAPO). I acknowledge Panu Paakkarinen for his outstanding contributions related to the different phases of evaluations and for building demonstration applications. I also acknowledge Riikka Henriksson for collaboration and for our many conversations concerning research.

I wish to acknowledge Tuukka Ruotsalo for all our conversations about research and especially for always emphasizing the importance of evaluation. I acknowledge Stina Westman and Mari Laine-Herdandez for conversations about evaluation metrics that helped me to understand the characteristics of each metrics. I wish to acknowledge Heini Kuittinen for our in-depth discussions about fuzzy temporal intervals and for collaboration in conducting user evaluations.

I wish to acknowledge Jouni Tuominen, Robin Lindroos and Kim Viljanen for collaboration concerning the development of ontology publication services in various phases of the work. I acknowledge Eetu Mäkelä and Jussi Kurki for collaboration and for many technical innovations that helped me to build applications for evaluation purposes. I wish to acknowledge Reetta Sinkkilä for collaboration and for her contributions in context navigation that helped me to understand the essential features of the SAPO ontology and to develop it further. I acknowledge Christine Deichstetter for her great efforts related to

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[1] http://www.gtk.fi/

historic overlay maps. I also acknowledge Glauco Mantegari for intensive collaboration concerning the modeling of imprecise time periods.

I acknowledge Matias Frosterus, Katariina Nyberg, Anu Yli-Salmi, Tuomas Palonen, Joeli Takala and Katri Seppälä for reading and commenting the introduction and many of the manuscripts of the articles of this dissertation. I acknowledge Jan Kallenbach and Mark van Assem for all our fruitful discussions about research. I also acknowledge Prof. Pirkko Oittinen for her important advices concerning the final steps of the work. I acknowledge pre-examiners Prof. Matti Nykänen and Docent Dr. Vesa A. Niskanen for their valuable comments that helped to enhance the content of this dissertation.

I also acknowledge all colleagues in the Department of Media Technology and especially colleagues in the Semantic Computing Research Group (SeCo) for co-operation, fruitful discussions and valuable comments concerning the different phases of the research. The research was initiated in the National Semantic Web Ontology Project in Finland[2] (FinnONTO) 2003–2007, 2008-2010 funded mainly by the Finnish Funding Agency for Technology and Innovation (Tekes) and continued in the EU project SmartMuseum[3] supported within the IST priority of the Seventh Framework Programme for Research and Technological Development. I gratefully acknowledge the support of the partners[4] of FinnONTO, e.g. the Geological Survey of Finland (GTK)[5] and the National Land Survey of Finland (MML)[6] for close co-operation and for providing datasets.

I thank my father Matti and my brother Sami for their continuous support. This dissertation is dedicated to the memory of my mother Elli and her vision for this world. I am grateful for her irreplaceable support and for our long discussions. Most of all, I acknowledge Lili and Inka, for they are the ones who have made and who continue to make the time of my life meaningful.

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[2] http://www.seco.tkk.fi/projects/finnonto/
[3] http://smartmuseum.eu/
[4] http://www.seco.tkk.fi/partners/
[5] http://www.gtk.fi/
[6] http://www.maanmittauslaitos.fi/

Contents

List of Publications

This thesis consists of an overview and of the following publications which are referred to in the text by their Roman numerals.

I Tomi Kauppinen and Eero Hyvönen. Modeling and Reasoning about Changes in Ontology Time Series. Chapter 11 in Ontologies: A Handbook of Principles, Concepts and Applications in Information Systems, pp. 331–339. Rajiv Kishore, Ram Ramesh, Raj Sharman (editors). ISBN: 0-387-37019-6. Integrated Series in Information Systems, Springer-Verlag, 2007.

II Tomi Kauppinen, Jari Väätäinen, and Eero Hyvönen. Creating and Using Geospatial Ontology Time Series in a Semantic Cultural Heritage Portal. In The Semantic Web: Research and Applications, Proceedings of the 5th European Semantic Web Conference 2008 (ESWC 2008), pp. 110–123, Tenerife, Spain, LNCS 5021, Springer-Verlag, 2008.

III Tomi Kauppinen, Riikka Henriksson, Reetta Sinkkilä, Robin Lindroos, Jari Väätäinen and Eero Hyvönen. Ontology-based Disambiguation of Spatiotemporal Locations. In Proceedings of the 1st International Workshop on Identity and Reference on the Semantic Web (IRSW2008), Tenerife, Spain, 2008, CEUR Workshop Proceedings, ISSN 1613-0073, online http://ceur-ws.org/Vol-422/irsw2008-submission-8.pdf.

IV Tomi Kauppinen, Kimmo Puputti, Panu Paakkarinen, Heini Kuittinen, Jari Väätäinen and Eero Hyvönen. Learning and Visualizing Cultural Heritage Connections between Places on the Semantic Web. In Proceedings of the Workshop on Inductive Reasoning and Machine Learning on the Semantic Web (IRMLeS2009), Heraklion, Crete, Greece, CEUR Workshop Proceedings, ISSN 1613-0073, online CEUR-WS.org/Vol-474/paper7.pdf.

V Tomi Kauppinen, Panu Paakkarinen, Eetu Mäkelä, Heini Kuittinen, Jari Väätäinen, and Eero Hyvönen. Geospatio-temporal Semantic Web for Cultural Heritage. In Digital Culture and E-Tourism: Technologies, Applications and Management Approaches. Miltiadis Lytras, Ernesto Damiani, Lily Diaz and Patricia Ordonez De Pablos (editors), IGI Global, 2010 (accepted for publication).

VI Tomi Kauppinen, Glauco Mantegari, Panu Paakkarinen, Heini Kuittinen, Eero Hyvönen, and Stefania Bandini. Determining Relevance of Imprecise Temporal Intervals for Cultural Heritage Information Retrieval. International Journal of Human-Computer Studies, In Press, Accepted Manuscript, Elsevier, 2010.

VII Eero Hyvönen, Eetu Mäkelä, Tomi Kauppinen, Olli Alm, Jussi Kurki, Tuukka Ruotsalo, Katri Seppälä, Joeli Takala, Kimmo Puputti, Heini Kuittinen, Kim Viljanen, Jouni Tuominen, Tuomas Palonen, Matias Frosterus, Reetta Sinkkilä, Panu Paakkarinen, Joonas Laitio, and Katariina Nyberg: CultureSampo—Finnish Culture on the Semantic Web 2.0. In Proceedings of the Museums and the Web 2009, Indianapolis, USA, 2009.

VIII Jouni Tuominen, Tomi Kauppinen, Kim Viljanen, and Eero Hyvönen: Ontology-Based Query Expansion Widget for Information Retrieval. In Proceedings of Scripting and Development for the Semantic Web Workshop at the ESWC, Heraklion, Greece, 2009, CEUR Workshop Proceedings, ISSN 1613-0073, online CEUR-WS.org/Vol-449/ShortPaper1.pdf.

IX Eero Hyvönen, Eetu Mäkelä, Tomi Kauppinen, Olli Alm, Jussi Kurki, Tuukka Ruotsalo, Katri Seppälä, Joeli Takala, Kimmo Puputti, Heini Kuittinen, Kim Viljanen, Jouni Tuominen, Tuomas Palonen, Matias Frosterus, Reetta Sinkkilä, Panu Paakkarinen, Joonas Laitio, Katariina Nyberg: CultureSampo—A National Publication System of Cultural Heritage on the Semantic Web 2.0. In The Semantic Web: Research and Applications, Proceedings of the 6th European Semantic Web Conference (ESWC2009), pp. 851–856, Heraklion, Greece, Springer-Verlag, 2009.

Author's contribution

I The author was the principal writer of the study and responsible for the development of the method, measurements, implementation of the system and the results related to it. E. Hyvönen contributed at the idea stage especially regarding to the idea about the ontology time series and helped with the organization of the article. The author carried out the rest of the work.

II The author carried out all of the work related to the methods and their development and wrote the article. J. Väätäinen contributed to the creation of the data set by using the described schemas. E. Hyvönen contributed at the idea stage and helped with the organization of the article.

III This publication was the result of close co-operation between the authors. R. Henriksson wrote the chapter regarding the SUO ontology and R. Lindroos implemented the ONKI-Geo service. J. Väätäinen contributed as a domain expert. R. Sinkkilä implemented the IRMA-Sapo system. The author carried out the rest of the work. E. Hyvönen supervised the research.

IV The author was the principal writer of the study. K. Puputti and P. Paakkarinen jointly implemented the visualization of the results on a map. J. Väätäinen contributed as a domain expert. H. Kuittinen and E. Hyvönen contributed at the idea stage. The author carried out the rest of the work.

V The author was the principal writer of the study. P. Paakkarinen implemented the user interfaces for nearby searches and H. Kuittinen carried out the evaluation of the results of the nearby search. E. Hyvönen contributed at the idea stage and helped with the organization of the article. The author carried out the rest of the work.

VI The author was the principal writer of the study. G. Mantegari was responsible for the materials for the study and mainly designed the user interface for the evaluations. P. Paakkarinen implemented the user interface used in the evaluations and carried together with the author the calculation of evaluation results. H. Kuittinen carried out the user agreement results. E. Hyvönen contributed at the idea stage and helped with the organization of the article. The author carried out the rest of the work.

VII This study was a result of a close co-operation between several authors. The author lead and carried out activities related to map-based perspectives, especially historical areas, historical maps and nearby point of interest search.

VIII The author contributed to the development of the query expansion framework that makes use of a spatio-temporal ontology, and wrote the according section.

IX This paper discusses a demonstration system that is a result of a joint work. The author lead and carried out activities related to map views.

List of Abbreviations

AI	Artificial Intelligence
COA	Center of Area
GI	Geographic Information
GIS	Geographic Information Systems
GIR	Geographic Information Retrieval
INSPIRE	Infrastructure for Spatial Information in Europe
LR	Left-Right notation of fuzzy sets
MOM	Mean of maxima
OGC	Open Geospatial Consortium
ONKI	National Finnish Ontology Service
ONKI-Geo	ONKI Ontology Service for Geographical Data
OWL	Web Ontology Language
POI	Point of Interest
RDF	Resource Description Framework
RDFS	RDF Schema
SAPO	Finnish Spatio-temporal Ontology
SRS	Semantic Reference Systems
STIS	Spatio-temporal Information System
SPARQL	Simple Protocol and RDF Query Language
UI	User Interface
URI	Uniform Resource Identifier
W3C	World Wide Web Consortium
WGS84	World Geodetic System 1984
XML	Extensible Markup Language

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1 Introduction

1.1 Background and Motivation

Geospatial ontologies can be used to capture and describe semantics of places i.e. their properties and mutual relationships. By doing this intelligent applications can reason about locations and visualize locations and content related to them e.g. as maps [48, 77]. Providing rich descriptions of locations enables to distinguish between locations, helps to find out correct references, and aims to ensure the semantic interoperability [45, 54]. Construction and publication of geospatial ontologies with clear semantics aims to contribute to the *Semantic Geospatial Web* [24, 7].

However, this becomes very hard when the temporal dimension is added: knowledge about historical places and their relations is not readily available and hence methods for dealing with them are needed. Even in current historical geovocabularies and ontologies, such as the Getty Thesaurus of Geographic Names (TGN)[7], historical regions may be found, but the aspect of change is usually missing. Geographical places exist in both time and space [47]. Spatiotemporal ontologies target these kind of challenges [74, 33]. Hence in addition to geospatial ontologies there is a need for geospatio-temporal ontologies that define the temporality of places i.e. represent temporal parts [74] of places and their mutual relations.

Producing relationships to describe resources is a fundamental task in ontology construction for geospatial and temporal knowledge. There exist techniques for creating relationships (e.g. [23]) and for utilizing them e.g. in information retrieval [30]. A major difficulty with relationships is that they often lack knowledge about the grade of the relationship.

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[7] http://www.getty.edu/research/tools/vocabulary/tgn/

In this dissertation we describe methods for modeling, creating, visualizing, sharing, and applying a geospatio-temporal ontology which represents places and their temporal parts, and binary and graded relationships between them. The idea is that these will contribute to building the *Geospatio-temporal Semantic Web*. We also provide results of testing how spatial relations help in ranking relevant information objects related to a given place and its historical versions. One of the main practical contributions of this dissertation is the creation, publication and applications of the Finnish Spatio-temporal Ontology (SAPO). Moreover, we introduce a method to calculate the relevance between two given temporal intervals concerning a spatially restricted region and present its evaluation results.

To summarize, we target the following two research questions, which are divided into more specific research questions:

1. How semantics of changes concerning geospatial regions can be modeled and applied?

    (a) How can changes be used in automatic geospatio-temporal ontology construction?

    (b) How can a geospatio-temporal ontology be used in cultural heritage applications, e.g. in recommendation, query expansion and in data mining?

2. How imprecision of time periods can be modeled and applied?

    (a) How can imprecise time periods be used in cultural heritage information retrieval?

    (b) How does the use of different measures of temporal relevance affect the results in information retrieval in terms of precision and recall?

1.2 Objectives

In this dissertation the objective is to present and evaluate new methods for creating graded relationships for geospatial and temporal ontologies. More specifically, we focus on the following themes concerning geospatial and temporal relations:

Graded geospatial overlap relations. We describe how geographic regions can be related to each other based on changes and properties concerning them. Especially, the focus is on creation of graded geospatial overlap relations.

Change chains. Changes concerning geographic regions frequently form chains. We exploit these chains in order to create global overlap relations between regions.

Geographic information retrieval. Geospatial relations can be used to solve semantic mismatches between a query and annotations; it is natural to try to enhance geographic information retrieval with relations. We study this and present evaluation results.

Cultural connection pattern discovery. Geographic regions are related not only through their spatial properties but also through cultural connections between them. We study utilization of data mining techniques together with ontology-based knowledge to discover and visualize these cultural connections.

Graded temporal overlap relations. Knowledge concerning temporal intervals and their mutual relationships is often imprecise and subjective. Our objective is to study how this imprecision can be modeled using fuzzy sets. We also study how the mutual relevance of two temporal intervals can be measured concerning a spatially restricted region.

Applications of geospatio-temporal ontologies. A geospatio-temporal ontology contains descriptions of, and relationships between historical places. We will discuss and show how historical places were visualized on maps together with related cultural heritage content.

1.3 Summary of Publications

Publication **I** presents the basic ideas behind modeling changes and the reasoning mechanisms to produce an ontology time series. Publication **II** presents how to do the schema-based modeling of changes in the geospatial domain, how to use this information to produce temporal parts of places, and finally how temporal parts are interlinked in a geospatial ontology time series. Publication **III** discusses publishing and utilization of geospatial ontologies, and specifically a geospatial ontology time series. Publication **IV** presents a combination of data mining together with ontology-based reasoning in order to find out cultural connections between places modelled using different semantic granularities. Publication **V** presents an application of geospatial and spatio-temporal ontologies in recommending relevant cultural information objects. Publication **VI** presents a method for measuring the relevance between given two fuzzy temporal intervals. Publications **VII** and **IX** present the semantic portal CULTURESAMPO which makes use of many of the presented methods. Publication **VIII** illustrates the use of spatio-temporal relations in query expansion.

1.4 Contributions of the Dissertation

The contributions of this dissertation can be summarized as follows:

- A novel method was developed for calculating a global overlap table between spatio-temporal resources (publication **I**).

- A novel technique and schemas were developed for creating a geospatio-temporal ontology (publication **II**).
- The Finnish Spatio-temporal Ontology SAPO was developed using the novel methods and published for public use (publications **II** and **III**).
- A new recommendation technique based on overlaps between spatio-temporal resources was developed (publications **II** and **V**).
- A new method for determining the temporal relevance between fuzzy temporal intervals was developed and evaluated (publication **VI**).
- An ontology-based data mining technique was developed that uses a spatio-temporal ontology to reveal multi-level and multi-relational data mining results (publication **IV**).
- The methods and techniques listed above were implemented and tested with thousands of annotations of cultural heritage content (publications **V**, **VII**, **VIII** and **IX**).

1.5 Structure of the Dissertation

In the following sections we will discuss different aspects of the Semantic Geospatial Web, namely, geospatial semantics, spatio-temporal and temporal data models, the idea of ontologies, and their realizations using Semantic Web standards, and finally discuss applying all these ideas in the area of cultural heritage. Throughout this introductory part we will provide links to publications of this dissertation. These publications explain the contributions of this dissertation w.r.t. the state-of-the-art in more detail.

2 The Semantic Geospatial Web

2.1 Need for Geospatial Semantics

There exist currently 192 member states in United Nations [8] i.e. countries which all divide into number of cities, municipalities and places of other types. The result is millions of places with even more different names for these places. Furthermore, different geographic shapes are identified, named and listed in various ways. The physical 3-dimensional world together with additional cultural dimensions form our world.

Geographic information (GI) is essential in searching for information and for sharing it. For example, every day, numerous geographical sensors and satellites produce a huge volume of spatial data and this data is increasingly available on the Web. Geographic Information Systems (GIS) deal with concepts of space and geographic data [31, 11], i.e. with geospatial concepts. The idea behind modern GIS systems is to [83] “geo-enable” the Web and allow for complex spatial information and services accessible and useful in all kinds of applications, e.g. online photo collections, navigation systems, and cultural heritage applications.

The Semantic Geospatial Web aims to bring together georeferenced content and the Semantic Web (see e.g. [24, 7]). All in all, the term Semantic Geospatial Web refers to the idea of the current state of the art, where Geospatial means that places play an important role in building the next generation web, and where the Semantic Web [10] provides the way to refer to these places and to be able to explicate relationships. It has been stated[24] that in order to build the Semantic Geospatial Web one needs to:

1. Develop spatial and terminological ontologies that have a formal semantics.

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[8] as of writing 2009, see http://www.un.org/en/members/growth.shtml

2. Represent semantics of concepts in those ontologies in a form that is available both to machines for processing and to people for understanding.
3. Be able to process geospatial queries against developed ontologies.
4. Evaluate the retrieval results based on the match between the semantics of a query (i.e. the expressed information need) and semantics of available information objects (the answer set) in some system.

The motivation for building up the Semantic Geospatial Web is to be able to answer more precisely to user's information needs by using the semantics of the queries and information objects. Hence ideally in this setting all relevant hits are found and there are no irrelevant hits, or at least they are minimized and ranked lower than relevant ones in an answer set. The aim is also to enable transactions between applications across different domains through improved interoperability and wide-spread usage of spatial terms and concepts with clear semantics [24].

2.2 Semantic Interoperability and Ontologies

The World Wide Web offers a lot of services where one can find location-related information to e.g. check bus time tables, see restaurants on a map, or browse Wikipedia[9] articles before a trip to a certain place. Navigation systems guide people from one place to another, whether they are walking or using a car. However, one problem is that these different systems are not always easily connected with each other as they do not "speak the same language", i.e. they do not share the same references to locations. The problem is hence the lack of interoperability, or more precisely the lack of *semantic interoperability*.

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[9] http://www.wikipedia.org

Even though it is hard [45, 54] to accurately define the notion of semantic interoperability, one can understand the underlying intuition based on software: it is unlikely that two agents could successfully interoperate by exchanging messages without sharing the same meaning for concepts in the messages [54]. This meaning can be expressed as concepts, i.e. classes and instances, and their mutual relationships, ontological structures and rules. For example, an ontology can specify the meaning of the term "forest" in one or more vegetation databases [53]. Defining ontologies is related to the Knowledge Representation (KR) field of the Artificial Intelligence (AI) research [67].

By publishing ontologies that contain this knowledge, applications can share the references to the concepts and also their incorporated meanings. This aims to enable semantic interoperability in e.g. geospatial applications. Indeed, one of the goals of the European initiative INSPIRE[10] is to enable interoperability between GIS systems hosted in different countries and organizations. In publication **III** we presented an ontology service intended for publishing spatio-temporal ontologies. The idea is that if organizations use the same URIs[11] for same geographic resources (like places), the integration of systems referring to these URIs is more straightforward.

There are many definitions of ontologies. First of all, it is important to notice that in philosophy "ontology" has a specific meaning that should not be confused with the meaning of "ontology" in computer science. Studying ontology is a part of a branch called metaphysics in the philosophical tradition [80]. Ontology is what a certain philosopher accepts to exist in the world. In other words, ontology describes what there is. For example, ontology can contain material objects and sets, and nothing else. The fundamental idea of ontology is that everything that does not exist is left out, and everything that does exist is included.

Perhaps most commonly used definition of "ontology" in computer science states that an

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[10] Infrastructure for Spatial Information in Europe, http://inspire.jrc.it/

[11] Uniform Resource Identifier, see http://www.w3.org/Addressing/

ontology is an explicit specification of a conceptualization [34] meaning that an ontology explicitly specifies a representation of a piece of conceptualized knowledge. Another definition [49] states that “the term ontology usually refers to a set of distinct objects resulting from an analysis of a domain, or microworld”. In publications **I**, **II**, **III**, **IV**, **V** and **VI** we used the term ontology in a meaning common in the Semantic Web field: “*[ontology refers to] a set of knowledge terms, including the vocabulary, the semantic interconnections and rules of inference and logic, for some particular topic*” [38].

This definition of the ontology is close to that of controlled vocabularies and thesauri. Generally, a controlled vocabulary aims to identify index terms with a clear semantic meaning, and to harmonize indexing concepts, and to use concepts rather than words in information retrieval [6]. page 170 Building thesauri is based on this idea: a thesaurus 1) provides a standard vocabulary for indexing and searching, 2) helps users in query formulation by locating a right term, and 3) provides classified hierarchies with a possibility to broaden or narrow a query based on the hierarchical relations according to users’ needs [28]. However, ontologies provide formally defined semantics which enables reasoning in more elaborate forms, e.g. using transitive relations. An example of a typical reasoning task is as follows: if *Helsinki* is part of *Finland*, and if *Finland* is part of *Europe*, then one can reason that *Helsinki* is part of *Europe*.

Developing an ontology includes [63] 1) defining classes in the ontology, 2) arranging the classes in a taxonomic, usually subclass-superclass hierarchy, 3) defining properties and describing allowed values for these properties and 4) filling in the values for the properties for instances. It is also notable that ontologies need to evolve over time: ontologies are altered to correct errors, to accommodate new information, or to adjust the representation of the domain as the world changes [36]. This is some times called ontology evolution, which has been defined [62] as the ability to manage ontology changes and their effects by creating and maintaining different variants of the ontology.

In this dissertation, ontology evolution is studied in publications **I** and **II** by modelling of historical places using a time series of location ontologies each of which is valid during a limited period of time. The next ontology in the series is needed whenever a set of simultaneous changes in the modeled domain occurs. This kind of evolution of ontology time series is due to changes in the underlying domain and should not be confused with ontology versioning [52], database schema evolution, or such forms of ontology evolution that deal with ontology refinements or other changes in the conceptualization [51, 76].

2.3 Spatial Relationships

Places relate to each other in different ways: traditionally this has been modelled using spatial structures and relations. These spatial structures and their mutual relations are a most essential form of geographic knowledge, and can be represented as geospatial ontologies. Geospatial ontologies [26] define concepts that represent 1) things that have a location on the Earth's surface and 2) spatial relations between these things. These concepts are instances of classes such as *city*, *country*, *municipality*, and other core geographic concepts [39]. The traditional theories behind structures in geo-ontologies have a basis in topology (the theory of boundaries, contact, and separation), mereology (theory of parts and wholes) and geometry [58].

There are formalized attempts to represent essential spatial relations like the Region Connection Calculus RCC-8 [65] and its extensions [16, 15] that are interested in *mutually exhaustive and pairwise disjoint* (MEPD) binary relations for pairs of spatial regions [16]. RCC-8, for example, offers eight qualitative relations for reasoning about regions.

These qualitative, topological relations (overlaps, disjoint, etc.) form a subset of spatial relationships. Figure 2.1 depicts an example of topological relationships between two objects A and B. Objects A and B are said to *overlap*, or to *intersect*, namely, 1) the boundaries of A and B coincide in two points, 2) A and B share some of their interiors, and 3) boundaries of A and B run through the other objects' interior (the boundary of A to the interior of *B* and vice versa) [22].

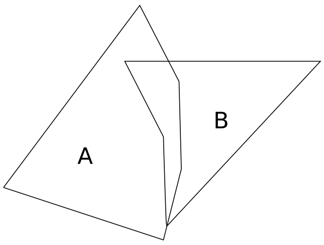

Figure 2.1: Two intersecting objects A and B. [22]

RCC-8 differentiates in total the following eight relations: *disconnected (DC), externally connected (EC), equal (EQ), partially overlapping (PO), tangential proper part (TPP), tangential proper part inverse (TPPi), non-tangential proper part (NTPP),* and *non-tangential proper part inverse (NTPPi).* These relations are depicted in Figure 2.2, which illustrates the differences in their semantics. In this dissertation we define the term overlap region to refer to the region where both of the two regions have points. If two regions share an overlap region, then there is an *overlap*-relation between them. In this sense e.g. two externally connected regions *X* and *Y* (*X EC Y*) do not share a point and hence there is no *overlap*-relation between them in our model.

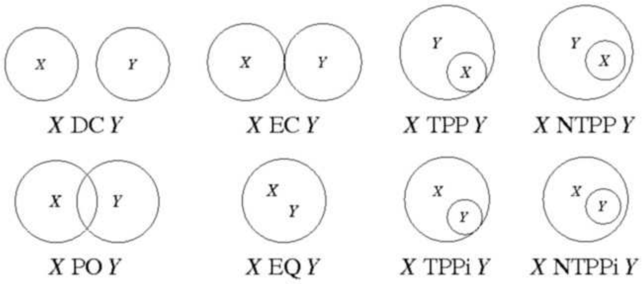

Figure 2.2: The eight binary relations of the RCC-8. [65]

Moreover, there are other spatial relations such as relations expressing directions (north of, south of, etc.) or distances (far, close) [29]. Distance relations *far* and *close* have a quantitative basis. For example, all objects lying within some radius from a given query point (e.g. the proximity of the user's location) can be considered as being close, and similarly all other objects can be regarded as being far. The search results for a given spatial query could then be ranked based on these qualitative relations that have a quantitative basis. For example, a system could first list the objects of interest that are close. Using more categories (quite close, close, quite far, far, etc.) would allow more fine-tuned ranking.

2.4 Querying for Geographic Information

Information retrieval is a process where a user expresses her information need and as a result gets information that more or less satisfies this need. A query q is the formulation of this user information need, expressed e.g. as a set of query terms [6]. A query can be composed of a single keyword (i.e. term), multiple keywords or more complex expressions. Retrieved documents can then be ranked according to their relevance to the query.

An ontology contains definitions of classes and instances, and relationships between them. An ontology can be used to expand a set of concepts in the user's original query with related concepts in an ontology [84]. As a result the additional relevant documents are retrieved by the query in addition to those that would be retrieved already by the original, non-expanded query. The assumption hence is that the user has not originally represented her information need sufficiently, because she is not aware of all the relevant query terms. It has been found out [84, 85] that using thesauri and ontologies in query expansion work best when the original queries contain only few terms.

For example, a spatial query usually includes one or more spatial terms [30]: in a query "museums near Helsinki" not only Helsinki is a relevant spatial term but also its suburbs and neighboring municipalities. This area of information retrieval dealing with spatial terms is called Geographic Information Retrieval (GIR). Spatial terms, i.e. geographical places, do not exist just in space but also in time [47]. This is especially true for museum collections where objects have references to places from different times. This sets the requirement to utilize also relations between historical places and more contemporary places in geographic information retrieval through query expansion.

In practice this means that the original query containing e.g. one place instance q_{place} is expanded to contain those place instances q_i that overlap q_{place}. A practical example[12] of this is depicted in Figure 2.3 showing places (municipalities) near the current border between Finland and Russia. A municipality called Imatra *overlaps* many historical municipalities, namely Ruokolahti, Jääski, and Joutseno. Over time there have been also different partonomy hierarchies i.e. these municipalities have been *part of* Finland, contemporary Russia and even *part of* USSR until 1991.

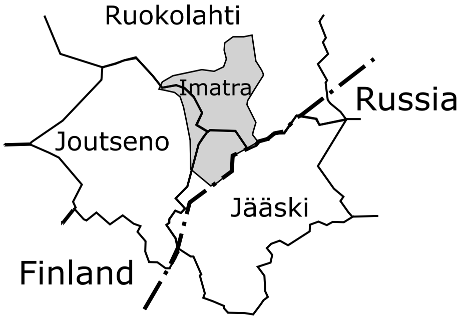

Figure 2.3: An example of overlapping places.

Publication **I** showed how quantified overlap relations[13] can be calculated for historical regions. The quantified overlap relation states how much two regions overlap, in addition to stating that they overlap qualitatively. The idea is that by utilizing the quantified overlap-relation one gets the probability that a point *x* is in a region *A* given that the point is in region *B*, i.e. $P(A|B)$. For example, assume that Ruokolahti (existed between years 1940–1947) overlaps 60% of Imatra (1948–1973). This means that if there are photos annotated using Imatra (1948–1973) they have a 60% probability of being in the region

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[12] Figure is originally drawn by Jari Väätäinen for publication **V**.

[13] Note that in publication **I** we used term *covers* for this relation.

of Ruokolahti (1940–1947), assuming that the photos are evenly distributed.

Conducting a retrieval performance evaluation gives an idea about how precise (precision) an answer set is to a given query. The evaluation also depicts how many of the relevant items have been retrieved (recall) (see e.g. [6], page 74). This evaluation measures how well an information retrieval system performs. For example, concerning spatial queries one can examine whether using a spatial overlap relation is good for enhancing queries or not. In publication **V** we showed that by using *overlaps*-relations one can increase the recall without sacrificing the precision too much.

The standard calculation of precision and recall evaluates the performance of methods based on binary relevant vs. non-relevant distinction. In contrast, the generalized precision and recall [50] uses multiple grade relevance assessments, e.g. in range [0,1]. The generalized precision and recall is intended to reward methods retrieving highly relevant documents. Indeed, in many research settings gradation of relevance of information objects have been used (as noticed in [68], page 2133). Publication **VI** shows how graded relevance was used in analyzing the relationship between two historical, temporal intervals concerning a restricted spatial area (Ancient Milan).

3 Spatio-temporal Data Modeling

3.1 Representing Change

The world is constantly changing both physically and culturally. Earthquakes, volcanic eruptions, movement of tectonic plates, and erosion, for example, reshape Earth. Changes happen also at a cultural level: e.g. different countries and regions are merged, split and renamed due to reorganizations. The world is full of events like this (as discussed e.g. in [75]). For example, *Budapest* was formed via the unification of the former towns *Buda* and *Pest*, the *Czech Republic* and the *Slovak Republic* were formed through the separation of *Czechoslovakia*. In 2003 the *Federal Republic of Yugoslavia* was reconstituted as the *State Union of Serbia and Montenegro*. Later on, in 2006 the single country the *State Union of Serbia and Montenegro* in turn was split into two separate countries, *Montenegro* and *Serbia*. These changes are depicted in Figure 3.1 where the x-axis depicts time and the y-axis the relative sizes of the countries. The *Federal Republic of Yugoslavia*, the *State Union of Serbia and Montenegro*, *Montenegro* and finally *Serbia* are typical individuals of a place ontology.

In essence, these changes in political regions over time result in new borders, sizes, shapes and place names for regions they concern. These regions, before and after the changes, may have different relationships with other regions, and they have unique extensions in the space-time-continuum. Hence there is a need for representing changes, and also to model geospatial entities (e.g. administrational units) of different times.

Modeling changes, however, is not trivial. There has been an active philosophical discussion about how and whether things of the world endure or perdure as time goes by (see e.g. [74, 33]). According to three-dimensionalism, things have only spatial parts, they endure, and are wholly present throughout the time interval of their existence. Four-

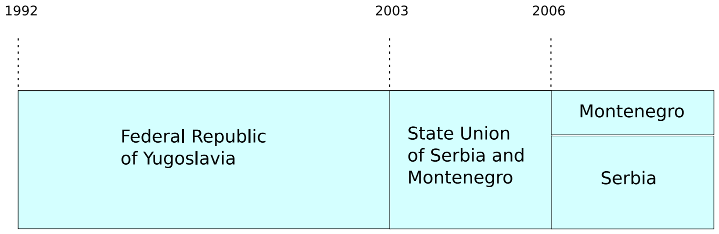

Figure 3.1: Montenegro, Yugoslavia and Serbia over time and space.

dimensionalism challenges this view by asserting that things also have temporal parts in addition to their spatial parts. For example, the notion of a person has temporal parts such as childhood and death. According to this view, things can be seen as “space worms” that spread out in spacetime. In the SNAP/SPAN-approach [33], both views are supported by a combination of a three-dimensional SNAP-ontology and a four-dimensional SPAN-ontology.

In general, spatio-temporal data models combine ontologies of space and time and form the core of a Spatio-Temporal Information System (STIS) [64]. The aim in STIS is to maintain integrity of databases even if there are spatial changes occurring over the time. For this purpose spatio-temporal data models define data types, relationships, operations, and rules.

Change has been seen as one of the most important issues in geospatial ontologies. For example, the NCGIA[14] Initiative 21 workshop defined [57] a hierarchical ontology structure for categorizing geographic changes. These change types include e.g. processes, which divide to natural processes (flooding, erosion, etc.), tides, seasons, and property changes (like temperature change, land use change, color change).

However, these change types do not include any types for modeling spatial changes over time, like *merges* and *splits*. A recent study [23] addressed changes in topological re-

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[14] National Center for Geographic Information and Analysis, http://www.ncgia.ucsb.edu/

lations as they occur when splitting a region into two. The result is a study about what qualitative inferences can be made about binary topological relations when one region is cut into two pieces. In publication **II** we present a method and schemas for maintaining knowledge about changes and for producing a geospatial ontology time-series using a method presented in publication **I**. While the work done in [23] considered producing qualitative knowledge out of knowledge about spatial changes, the method described in publication **I** produces (in addition) quantitative knowledge about overlap relationships between regions, i.e. how much two regions overlap.

3.2 Representations of Time

Time is one of the central concepts in many of the ontologies representing the world. For example, when concerning historical places, one needs to somehow model also time, not just places. Event-based systems also need a theory and a model of time to adapt [59]. There are many theories of time. A straightforward theory of time says that time "flows inexorably forward, and that events are associated with either points or intervals in time, as on a timeline" [49]. Moreover, this understanding of time assumes that events precede one another in the case that the flow of time leads from the first event to the second. This is, however, just one of the many theories. Due to the importance of modeling time, there has been an extensive amount research concerning the general properties of time. There have been e.g. discussion [4, 81] whether the basic primitive is the interval (period) or the point. Selecting whether to use intervals [3], time points [73] or both to represent time is an example of the fundamental decision to be taken when modeling temporal entities. Allen's temporal interval algebra, for example, has been used to model actions and events [5].

Other properties for time are characterized by whether time is discrete or dense, bounded or unbounded and what type of precedence the time ontology allows: linear, branching, parallel or circular (cyclic). Allen's theory [3] of relations between intervals has been a basis for many other theories and methods concerning time. In the Allen Algebra the basic structure is aRb where R denotes a relation in the set of the 13 primitive interval relations that exclusively correspond to every possible simple qualitative relationship that may exist between a pair of convex intervals. The relations of the Allen Algebra can be used in reasoning in a well-grounded manner. For example, from *a before b* we can infer *b after a*. The variables *a* and *b* are time intervals, for example *a*="20th century" and *b*="21st century".

Formalisms using the Allen Algebra are based on crisp, exact and known boundaries of time intervals and they enable encoding of qualitative relations between time intervals. The 20th century is an example of a time period with exact boundaries, i.e. we know this period has a beginning time (1900-01-01) and an end time (1999-12-31). However, beginning and ending times of intervals might be unknown [83]. Another challenge is that many time intervals are somewhat imprecise [83, 61] meaning that their beginning and ending times are inherently gradual. For example, the concept *fin de siècle* refers to the end of the 19th century but it is unclear what is the exact year this period started. Nevertheless, it may be agreed that the end of the 19th century does not start before year 1850. Other examples containing imprecision are e.g. geological periods like *ice age* or periods related to cultures, such as *the Bronze Age*, or to events like wars, e.g. *the First World War* or *the Falklands War*. Moreover, wars have start and end times, but the exact values for these times may depend on the country participating a war.

3.3 Modeling Imprecision of Time Periods

The fuzzy set theory [87] enables modeling imprecise time ranges, such as "around 1950", that have vague boundaries. The resulting models are often called fuzzy temporal intervals [61, 83]. In the fuzzy set theory the grade of membership μ of an item x in given set A has a value in range [0,1], whereas in the traditional set theory an item x either belongs to a given set A or not. In other words, in the fuzzy set theory x more or less belongs to the set A.

For example, Visser [83] defines the fuzzy temporal interval T to be a trapezoidal fuzzy set, i.e. T is the quadruple

$$T = \langle T_{fuzzybegin}, T_{begin}, T_{end}, T_{fuzzyend} \rangle, \tag{3.1}$$

where $T_{fuzzybegin}$ is used to explicate the earliest start T, T_{begin} the latest start, T_{end} the earliest end, and finally $T_{fuzzyend}$ the time when the T has ended for sure.

To enable reasoning about fuzzy temporal intervals Nagypal and Motik [61] have introduced a mechanism based on fuzzy sets to evaluate whether Allen's temporal relationships such as INTERSECTS holds between two fuzzy temporal intervals. The result is a value explicating the level of confidence. Visser has proposed [83] to calculate the overlap between two fuzzy temporal intervals in order to calculate their mutual relevance. In publication **VI** fuzzy temporal intervals were applied in order to rank annotation time periods given a query time period. It was shown that a combination of weighted measures based on the overlap and closeness between two fuzzy temporal intervals confirms best to user opinions.

4 Semantic Web and Interoperability

4.1 The idea of the Semantic Web

The World Wide Web (WWW) contains a massive amount of documents in different formats such as in (X)HTML[15] and PDF[16]. In addition there are numerous formats for images, videos and audio. These documents are targeted to people and their semantics is not directly machine-processable.

The idea of the Semantic Web [10] is to describe knowledge about different domains in a machine-processable format. The goal is to build “the web of data (for computers)” in addition to the existing “web of documents (for humans)”. The idea is that intelligent, capable agents can utilize this knowledge in assisting people in their tasks [37]. Publication **V** discusses one such task: how geospatial and spatio-temporal ontologies can be applied in digital tourism.

Ontologies form a basis of the Semantic Web (see e.g. [25]). Ontologies define classes, individuals, properties and relationships that are used to represent things describing the world and relations between them. These things can be anything, such as organizations, persons, places, times, or events. By using relationships, persons can be related to e.g. the places they have been born in, or to their birth times. Publishing ontologies on the Semantic Web enables people and organizations to use shared ontologies in annotating e.g. photographs, videos, music, and other types of cultural objects.

The Semantic Web utilizes formats standardized by the World Wide Web Consortium (W3C)[17]. These include the syntactic layer, namely the Extensible Markup Language

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[15] Extensible HyperText Markup Language, see http://www.w3.org/MarkUp/Activity

[16] Portable Document Format

[17] http://www.w3.org/

(XML) [12], and languages for the semantic layer, namely the Resource Description Framework (RDF) [8], RDF Schema (RDFS) [13] and Web Ontology Language (OWL 2) [40].

RDF is intended to represent knowledge about how different things relate to each other. The representation is done using triples of the form <*S,P,O*> where *S* is the subject, *P* is the predicate and *O* is the object. A triple is also called an RDF statement, and it describes a resource (*S*), the resource's property (*P*), and the value of that property (*O*). For example, RDF triple <*geo:Finland,rdf:type,geo:Country*> states that *Finland* is a *country*. In RDF URIs are used to identify resources. URIs consist of a namespace[18], and a local name. Prefixes are often used to shorten URIs. For example, in *geo:Finland* there are two parts, *geo* for the prefix of the namespace, and *Finland* for the local name.

4.2 Using Semantic Web Technologies for Modeling Geospatial Semantics

In the geospatial domain, RDF provides means for assigning essential geographical properties to the URIs of the places. These can include e.g. coordinates of points or polygonal boundaries, place type, time span, size, names of the place in different languages, events related to regions, and mutual relationships between places. For example, Figure 4.1 depicts the triple <*geo:Finland,geo:partOf,geo:Europe*> which represents the fact that *Finland* is part of *Europe*.

An example from publication **I** gives an idea about using RDF in modeling changes. Merging of *East Germany* and *West Germany* is there modeled as follows using RDF. In Figure 4.2 the property *before* refers to the resources *East Germany* and *West Germany* that existed before this change (*geo:merge42*), and the property *after* refers to the new

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[18] For more information about namespaces see http://www.w3.org/TR/1999/REC-xml-names-19990114/.

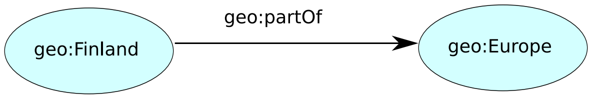

Figure 4.1: The partonomy relationship between Finland and Europe represented using an RDF triple.

resource *Germany* which exists after the merge. Publication **I** describes how these kind of descriptions of changes were used to produce knowledge about overlappings between regions (e.g. *Germany overlaps East-Germany*). Moreover, publication **II** discusses how the references to times in this kind of models of changes were used to infer time spans for the resources (e.g. timespan 1949–1990 for East Germany).

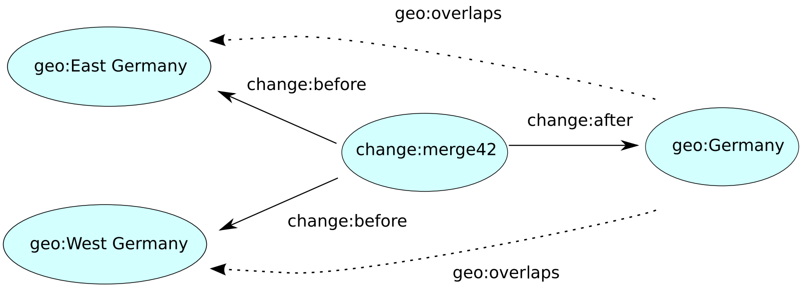

Figure 4.2: An event modeled using RDF. In this event *East Germany* and *West Germany* were merged to form *Germany*.

4.3 RDF in Modeling Imprecise Time Periods

Representing time in Semantic Web ontologies is not straightforward because the question of when a certain time was or will be is often uncertain, subjective or vague [61]. For example, it may not be known when exactly a given archaeological artifact was manufactured (uncertainty), when "The Middle Ages" was according to opinions of different historians (subjectivity), or when the spring starts (vagueness, imprecision).

RDF was used in annotating historical cultural heritage content in publication **VI** and hence there was a need for a model of time in RDF that would support imprecision. Annotations were originally made using CIDOC CRM [17] ontology. RDF was used to model imprecision of both the query times and the annotation times. We used a combination of regular expressions and string parsing techniques for determining fuzzy temporal intervals from the time labels of the query and the annotation times. The resulting fuzzy temporal intervals were saved as RDF triples.

We showed in publication **VI** that modeling imprecision of temporal intervals and using a combination of graded relevance measures was best in terms of precision and recall. Thus, it was shown that it is worthwhile to model vagueness and imprecision. Because the modeling was done using the Semantic Web standards, it was possible to publish resources, i.e. the time periods and the annotations, on the Semantic Web.

4.4 Publishing and Sharing Ontologies

One of the major problems in Semantic Web ontologies is that organizations commonly mint different URIs for the same resources [44]. One possible solution is to build coreference systems that offer mappings between different URIs. On the other hand, if organizations would retrieve URIs directly from commonly used ontology library systems and ontology servers offering a rich set of relationships between the URIs, then the integration of data sets could be more straightforward. The idea about ontology servers and libraries has been presented before [18] and ontology servers have been extensively compared in [1]. However, there is little work done for offering ontology services for semantic geospatial ontologies where there are specific needs for disambiguation among large amount of spatiotemporal instances [41, 56]. The SPIRIT spatial search engine [46] provides facilities to find web resources relating to places referred to in a query. The geo-ontology within this search engine is used for the purposes of information retrieval by modeling the geographical terminology and the spatial structure of places. It supports for example query disambiguation by recognizing the variant place names and historical alternatives.

In order to utilize references (i.e. URIs) to instances of ontologies, these references need to be shared and published on the Semantic Web using e.g. ontology library systems such as the ONKI ontology service [43, 82] for this purpose. The browsing of classes and instances by using hierarchical and other relationships is typically provided by ontology browsers. Other application scenarios of ONKI include annotation (indexing) of content, disambiguation of concepts, and searching and fetching of concepts, their related concepts and properties.

Publication **III** presents ONKI-Geo, an ontology service intended for sharing spatio-temporal ontologies, and publication **VIII** presents a system that uses a spatio-temporal ontology to provide a query expansion machinery. Our approach is to provide a rich set of spatial and temporal properties for the place instances in order to facilitate the process of disambiguating between them e.g. for annotation purposes.

The Finnish Spatio-Temporal Ontology (SAPO) which was developed using the methods described in publications **I** and **II** has also been published[19] for open access in ONKI. It has a potential to be widely used across organizations that need to make references to historical regions.

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[19] http://www.yso.fi/onki/sapo/

5 Using Spatio-temporal Knowledge in the Cultural Heritage Domain

5.1 Modeling Cultural Heritage Resources

A large proportion of cultural resources such as museums, monuments, photographs, videos, artefacts, and books are geographically referenced, and thus should be identified by search terms that refer to locations [48, 77]. This is because the objects are produced, found or used in the referenced locations, or have some other relationship to the location in question. By georeferencing the resources [70], different spatial queries can be enabled in order to find interesting connections between places and related contents. In publications **II** and **V** we used instances of a spatio-temporal ontology in georeferencing cultural heritage resources. The spatio-temporal ontology connects places from different times, and can thus be used to connect also content from different times.

Moreover, annotations of cultural heritage content use different roles for locations. For example, CultureSampo (publications **IV**, **VII**, and **IX**) annotations include the following place roles:

- place of discovery	the place from where an object was found
- place of manufacture	the place where an object was manufactured
- place of acquirement	the place from where an object was acquired
- place of creation	the place where an object was created
- place of photographing	the place where a photograph was taken at
- place of subject	the place depicted in an object such as a painting
- place of usage	the place where an object was/is used
- place of context	the place relevant to an object in an unspecified way

The idea about using the place roles in annotations is depicted[20] in Figure 5.1. For example, a hat in the bottom left corner is annotated with Joutseno in the role *place of usage* while Jääski is in the same role in an annotation of the horn shown in the bottom right corner. Two different museum items were manufactured either in Imatra (a chair in 1957) or in an overlapping historical Ruokolahti (a shepherd's whistle in 1920).

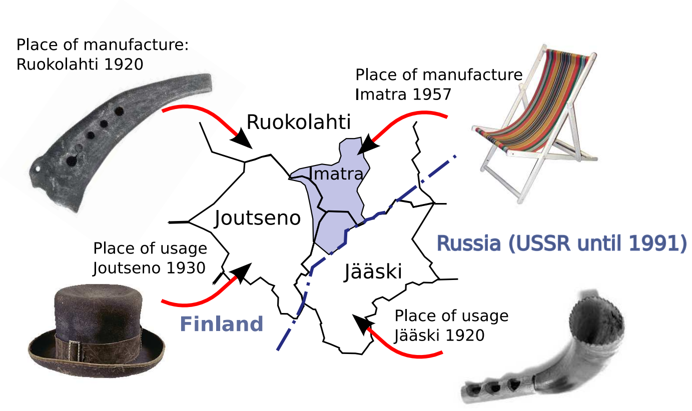

Figure 5.1: An example of annotations using place roles.

Ideally, cultural heritage collections need to represent spatio-temporal entities that consist of not just space but also events and actions happening in that space [20]. For example, Figure 5.2 depicts the life of Caesar seen as events. Both birth and death events happen in some point of space-time, and they are related to a number of other resources, such as Caesar's mother, Caesar himself, Brutus, and Brutus' dagger. Time is especially important for managing historical collections, for example in visualizing (see e.g. publication **VII** and [72]) them on a timeline. Chronological reasoning [21] of archaeological findings is another important usage for temporal knowledge in the cultural heritage domain.

There are many metadata metadata schema recommendations for the annotation of cultural content. These recommendations include, for instance, the Functional Requirements for Bibliographic Records (FRBR) [69], Categories for the Description of Works of Art (CDWA) [27], and CIDOC Conceptual Reference Model [19].

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[20] Figure is originally drawn by Jari Väätäinen for publication **IV**.

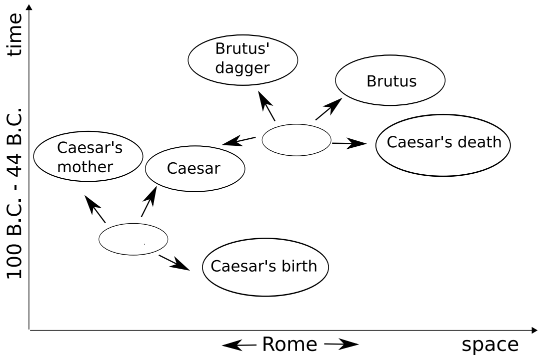

Figure 5.2: The life of Caesar seen as events. [20]

5.2 Applications Using Digital Cultural Heritage Collections

There is a strong trend of building up more and more location-aware cultural heritage services [79]. It has been suggested [60] that museums should publish their activities, collections, services, and products for the wide use of communities such as travellers. This can be done by e.g. offering specific points of interest (POI) with related text, navigation points, maps, and content organized by theme [78]. It is possible to put cultural heritage collections on a map [55] or provide a search of collections. Map visualization can be enabled for nearby photos of a location [35] or objects of interest can be recommended in a mobile setting [9, 2, 66]. A related effort is DBPedia Mobile [7] which uses Wikipedia data with a map-based search of information.

By sharing ontological references (such as geospatial objects), semantic interoperability can be obtained in different cultural heritage collections, and intelligent end-user services such as semantic search, recommendation, browsing and visualization can be facilitated [71, 42, 86]. For example, in the semantic portal MuseumFinland[21] [42] a location partonomy[22] was used for annotating museum artifacts with metadata about the place of manufacture and place of usage.

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[21] http://www.museosuomi.fi

[22] This partonomy is a part-of hierarchy of individuals of the classes Continent, Country, County, City, Village, Farm etc.

In publications **II**, **V**, **VII**, **VIII** and **IX** we discuss and present applications that make use of geospatio-temporal ontologies, and reasoning mechanisms in order to provide intelligent end-user services. These applications are published as part of the semantic portal CULTURESAMPO–Finnish Culture on the Semantic Web 2.0. The material used by the applications consists of heterogeneous cultural content which comes from collections of over twenty Finnish museums, libraries, archives, and other memory organizations. This content was annotated using RDF and references to various ontologies, such as the Finnish Spatio-Temporal Ontology (SAPO). The dataset is metadata of over 500,000[23] collection objects, e.g. artifacts, photographs, maps, paintings, poems, books, folk songs, videos, and millions of other reference resources such as places, times, etc.

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[23] As of writing 2009. However, the number is objects is increasing as new collections are added.

6 Discussion and Future Work

6.1 Research Questions Revisited

The research questions were originally listed in Section 1.1:

1. How semantics of changes concerning geospatial regions can be modeled and applied?
    (a) How can changes be used in automatic geospatio-temporal ontology construction?
    (b) How can a geospatio-temporal ontology be used in cultural heritage applications, e.g. in recommendation, query expansion and in data mining?
2. How imprecision of time periods can be modeled and applied?
    (a) How imprecise time period can be used in cultural heritage information retrieval?
    (b) How does the use of different measures of temporal relevance affect the results in terms of precision and recall?

Concerning the first research question, we provided an analysis of different kinds of changes concerning geospatial regions in publication **II**. This analysis yielded different change types. These change types were used when filling up the schema of changes. First of all, our focus was in GIS domain and hence change types in other domains were not in the scope of this dissertation. However, while this set of changes aimed at being the set of changes needed to model changes in administrative regions, it did not aim to model all the changes concerning regions in the GIS domain. Other changes could include e.g.

changes in land use, vegetation, inhabitation, and so on. Narrowing the scope was done because the intended usage of the changes was to use them together with spatial extensions of places in producing spatial overlap-relations through reasoning. Other types of changes would not have served for this purpose and hence they were left out. However, in some other reasoning and application scenarios other change types and extensions could be useful.

The research question 1(a) deals with a reasoning task. Namely, the question was how the models of changes could be used to produce knowledge about geospatio-temporal entities and their relationships to each other. To answer this research question, a reasoning procedure was introduced in publication **I**. It was shown how descriptions of changes can be used to produce quantified overlap-relations between regions. Publication **II** showed how a set of schemas were used in collecting changes, and how resources representing temporal parts of places were created based on the changes.

The research question 1(b) deals with the potential applications. This question was targeted by building a set of applications using geospatio-temporal ontologies. These applications included recommendation systems based on overlap-relations, as discussed in publications **II** and **V**, visualization as discussed in publication **VII**, query expansion as discussed in publication **VIII**, and application in data mining as discussed in publication **IV**. In publication **V** the usefulness of using the overlap-relations in recommendation was tested with a set of oblique aerial photos. It was shown that the average recall increased without lowering the average precision when only those overlap-relations were used where the query region overlapped the recommended region with value 1.0, i.e. fully. Using overlap-values with lower values naturally lowered the average precision, but the recall increased accordingly. In this study we made the assumption that the aerial photos were evenly distributed. However, a more detailed study could be made where the actual distribution of the aerial photos is first examined and then used as a basis for this study. This was left out in our study because it turned out to be hard and in most of the cases impossible to find out the exact place where a historical aerial photo was taken at.

Another assumption was that the geospatio-temporal ontology included all the overlap-relations that there should be. However, during the process it came clear that there are still missing overlap-relations in SAPO due some unmodeled changes, and due to the limitations of the reasoning procedure. However, the missing ones seem to be mainly small areal changes. They would produce overlap-relations of grades near to 0, and are hence marginal compared to thousands of existing overlap-relations. Hence, even though SAPO does not contain absolutely the complete set of the possible overlap-relations, it turned out to be very useful according to the tests.

The second research question asked how to model the imprecision of time periods. In publication **VI** we presented a model and a method based on fuzzy sets for operating with imprecision. We also provided an application scenario in the cultural heritage domain, which answered the research question 2(a). It was shown how the combined measure performs best in cultural heritage information retrieval, which answered the research question 2(b). This measure combined weighted overlap and closeness-relations into one measure. While publication **VI** presented how the individual measures can be calculated, one could find out other ways of calculating them. Closeness, for example, could be calculated using some other formula than the fuzzy subtraction.

6.2 Research Evaluation

To evaluate the research we will also discuss the work in terms of its 1) significance, 2) internal validity, 3) external validity, 4) objectivity and confirmability, and 5) reliability and auditability [14]. The discussion is collected in the tables 6.2, 6.2, 6.2 and 6.2.

Criteria and relevant queries	Evidence in Study
1) Significance	
Is there theoretical significance?	Methods and schemas presented in publications **I** and **II** are novel and provide a theoretical basis for modeling spatio-temporal places, and for reasoning about changes.
Is there practical significance?	Methods were applied to produce the Finnish Spatio-temporal Ontology SAPO which has been published for open access. SAPO was also applied in several practical settings as shown in publications **II**, **IV**, **V**, **VII**, **VIII**, and **IX**, for example in the recommendation systems of CULTURESAMPO .

Table 6.1: Significance.

Criteria and relevant queries	Evidence in Study
2) Internal validity	
Do the methods work?	When presenting the methods we have given detailed examples so that a reader can try the methods herself, see publications **I**, **II**, **IV**, and **VI**.
Have rival methods been considered?	Publication **VI** compares different measures for calculating the temporal relevance. Methods presented in publications **I** and **II** are not easily compared with rival methods, because such complete methods did not exist before.
Has sufficient evidence been collected in evaluating the methods?	SAPO contains changes concerning a long time period, i.e. years 1865–2009, and SAPO was applied in real application scenarios. Concerning the evaluation in publication **VI** the evaluations were made by domain experts and end users. One could have had more test subjects (> 12). However, given that the evaluation took four hours in average, this was hard to organize.

Table 6.2: Internal validity.

Criteria and relevant queries	Evidence in Study
3) External validity	
Are the findings congruent with prior theory?	Methods build on existing theories, e.g. the probability theory in publication **I**, and the fuzzy set theory in publication **VI**.
Can the findings be applied elsewhere?	Modeling of changes of places is a problem in many countries, and is a concern in managing, searching and browsing cultural heritage collections. However, we did not test the suitability of the methods for other countries so this cannot be confirmed.

Table 6.3: External validity.

6.3 Limitations and Future Work

The data that was used to construct the Finnish Spatio-temporal Ontology SAPO currently covers Finnish administrative regions 1865–2009. The partonomy of SAPO is also restricted to three place type levels: country, province and municipality. There is a need to go further on into history and to model and instantiate also other historical place types. A natural next step would be to add historical and contemporary villages and city districts.

Changes that will happen in the future need to also be included in SAPO in order to maintain its usability in a variety of application scenarios. In practice, future changes need to be modelled using the schemas, the presented automated procedures need to be run, and results need to be published for open access.

SAPO is currently limited to Finland, but the models and the methods can be applied to

4) Objectivity and confirmability	
Are the study's methods described in detail?	One can try the methods manually, e.g. the procedures of how data was collected by using the schemas in publication **II**.
Are the researchers explicit about personal assumptions, values and biases?	Personality is always present, when one does research. However, the co-operation with domain experts and the use of external evaluators aimed to ensure that the research is objective.
5) Reliability and auditability	
Are the research questions clear?	The research questions were listed in Section 1.1.
Are basic constructs clearly specified?	The basic constructs of the research were detailed in publications **I**, **II**, **IV**, and **VI**.

Table 6.4: Objectivity/confirmability and reliability/auditability.

other countries as well. There are a lot of boundary changes to be modelled concerning different countries. For example in Japan the number of municipalities declined from about 71,000 in 1889, to about 1,700 in 2008 [32]. During this period many old municipal names were dissolved, and various new names were generated. In Japan, from the year 1999 until 2008 a total of 598 municipalities were formed by merging existing ones, out of which 330 kept their existing names and 268 got new names. Future work could include testing the methods and the models for countries such as Japan, and share the results on the Geospatio-temporal Semantic Web.

The European Union has defined a three-level hierarchical classification, the Nomenclature of Territorial Units for Statistics (NUTS)[24]. The NUTS subdivides each EU Member State into a number of regions, each of which is in turn subdivided further. Integrating the NUTS model with SAPO would serve statistics calculation purposes.

The calculation of relevance between imprecise time periods only considered a spatially restricted area in publication **VI**. Future work could include incorporating different cases of spatial relations, spatial distance, or cultural connections into the setting, and to find out how and what kind of effect they have in relevance calculation.

Visualization of polygonal boundaries of historical places was done in CULTURESAMPO as described in publications **II** and **VII**. The aim of the visualization was to be intuitive; i.e. a user could select a certain place, and see a historical and contemporary map at the same time. The user may also select two places from different time periods, and see how they overlap. A limitation here was the incompleteness of polygonal data, which made it impossible to provide this functionality for all places. Current boundaries also do not include enclaves i.e. external regions of a municipality. Future work could hence include digitalization of more polygonal boundaries and maps, and in more detail. This would further enable new kinds of applications where the user can compare more places and browse the content annotated to them and to their historical counterparts.

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[24] http://epp.eurostat.ec.europa.eu/portal/page/portal/region_cities/regional_statistics/nuts_classification.

7 Conclusions

This introduction to the dissertation provided discussion about the relationships of our contributions w.r.t. to geospatial semantics, spatio-temporal modeling, representations of imprecise time periods, publishing the results on the Semantic Web, and cultural heritage applications. We examined how ontological knowledge can be used to represent spatio-temporally referenced data and to enable and enhance search and browsing.

Concerning modeling of spatio-temporal regions we discussed representations of change, and their applications to cultural heritage information retrieval. These applications can be used e.g. for teaching where historic regions have been and how they are related with each other in a partonomy hierarchy, and for retrieving historical cultural content related to the regions. The relationships can be explicated for the user indicating whether the content has been found, used, manufactured, or located in a specific spatio-temporal region. Because one of the main results of this dissertation, the Finnish Spatio-temporal Ontology (SAPO), is published for open access, it has the potential to be widely used across organizations needing references to historical regions.

Imprecision of temporal intervals was modeled using fuzzy sets and a method was developed in order to obtain a better match between human and machine interpretations of periods in information retrieval. This method could be used in e.g. suggesting items from approximately the same period as the reference query period, and also for ranking the relevance of more distant periods of time.

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