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Completion of Ontologies and Ontology Networks

by

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Abstract

The World Wide Web contains large amounts of data, and in most cases this data has no explicit structure. The lack of structure makes it difficult for automated agents to understand and use such data. A step towards a more structured World Wide Web is the Semantic Web, which aims at introducing semantics to data on the World Wide Web. One of the key technologies in this endeavour are ontologies, which provide a means for modeling a domain of interest and are used for search and integration of data.

In recent years many ontologies have been developed. To be able to use multiple ontologies it is necessary to align them, i.e., find inter-ontology relationships. However, developing and aligning ontologies is not an easy task and it is often the case that ontologies and their alignments are incorrect and incomplete. This can be a problem for semantically-enabled applications. Incorrect and incomplete ontologies and alignments directly influence the quality of the results of such applications, as wrong results can be returned and correct results can be missed. This thesis focuses on the problem of completing ontologies and ontology networks.

The contributions of the thesis are threefold. First, we address the issue of completing the is-a structure and alignment in ontologies and ontology networks. We have formalized the problem of completing the is-a structure in ontologies as an abductive reasoning problem and developed algorithms as well as systems for dealing with the problem. With respect to the completion of alignments, we have studied system performance in the Ontology Alignment Evaluation Initiative, a yearly evaluation campaign for ontology alignment systems. We have also addressed the scalability of ontology matching, which is one of the current challenges, by developing an approach for reducing the search space when generating the alignment.

Second, high quality completion requires user involvement. As users' time and effort are a limited resource we address the issue of limiting and facilitating user interaction in the completion process. We have conducted a broad study of state-of-the-art ontology alignment systems and identified different issues related to the process. We have also conducted experiments to assess the impact of user errors in the completion process.

While the completion of ontologies and ontology networks can be done at any point in the life-cycle of ontologies and ontology networks, some of the issues can be addressed already in the development phase. The third contribution of the thesis addresses this by introducing ontology completion and ontology alignment into an existing ontology development methodology.

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Populärvetenskaplig sammanfattning

Föreställ dig att vi är intresserade av att ta reda på hur många Oscarsnomineringar och priser som varje skådespelare i någon film har haft. Om vi försöker ta reda på den här informationen på Internet skulle vi troligen behöva besöka flera webbplatser eftersom ingen av de befintliga webbplatserna ger oss informationen direkt. Till exempel skulle vi först behöva besöka en webbplats som innehåller en lista med namn på alla skådespelarna i filmen. Därefter skulle vi behöva besöka en annan webbplats som har en lista över Oscarsnomineringarna genom åren. Till sist kan vi kombinera informationen från de ovanstående webbplatserna, och räkna antalet nomineringar per skådespelare.

Om denna information finns tillgänglig på webben, varför kan inte besvarandet av frågan automatiseras? På grund av den arkitektur och design som webbplatser använder idag är informationen inte direkt användbar av automatiserade agenter. Innehållet på en webbplats som kan tolkas av agenten innehåller vanligtvis bara den information som behövs för att korrekt representera webbplatsen i en webbläsare. Ett sätt att hantera detta på är att även inkludera maskinläsbar information som beskriver innehållet på webbplatsen. På så sätt kan automatiserade agenter förstå den information som en webbplats innehåller. Vidare kan de relatera och kombinera den med information från andra webbplatser kodade på liknande sätt och besvara frågan självständigt. Detta är ett av målen för den semantiska webben, som ska vara en förlängning av den nuvarande webben, så att kunskapen och informationen är läsbar och förståelig för maskinerna. En av de tekniker som används för att uppnå detta är ontologier. Ontologier gör det möjligt att ange ordförråd som används för att beskriva information på webben. De gör det möjligt att definiera termer och relationer mellan dem, vilket en automatiserad agent kan använda för att tolka innehållet på webbplatsen. Ontologier är emellertid ofta inte fullständiga vilket kan leda till ofullständiga resultat. I de fall då det är nödvändigt att kombinera information från flera webbplatser, som i vårt exempel, kan det vara så att ontologier använder olika termer för att definiera samma begrepp. Till exempel kan en webbplats använda termen skådespelare medan den andra kan använda termen artist för att beskriva begreppet skådespelare. Denna heterogenitet gör det svårt att kombinera information från flera källor. Därför är det nödvändigt att identifiera sambandet mellan termer av de ontologier som används av olika webbplatser. Uppsättningen av dessa relationer kallas en justering.

Inriktningen på denna avhandling är att komplettera ontologier och ontologinätverk, dvs. ontologier kopplade till justeringar. Högkvalitativ komplettering och justering av ontologier kräver användarens engagemang för att bestämma om ett visst förhållande håller i en ontologi eller mellan ontologier eftersom det kräver kunskap om den domän som ontologierna beskriver. Bidragen av denna avhandling är följande. Först utformade vi metoder för att komplettera den vanligaste typen av relationer i ontologier, dvs is-a-

relationer. Is-a-relationer används för att beskriva att ett visst begrepp är en sidotyp av (mer specifik än) någon annan (t ex ett träd är en växt). Därefter är det ett problem att beräkning av justeringarna kräver att man jämför alla termer i en ontologi med alla termer i en annan ontologi som kan kräva mycket tid och beräkningsresurser. Därför diskuterar vi en metod som skulle begränsa antalet jämförelser till endast de som är bra kandidater. Vidare tittade vi på hur vi kan hjälpa användaren i kompletteringsprocessen så att han/hon inte är överväldigad av förslagen från systemen. Slutligen såg vi på hur vi kan integrera kompletteringen och justeringen av ontologier i utvecklingsfasen för ontologierna och därigenom garantera en högre kvalitet på ontologierna.

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List of publications

Included papers

- Paper I P. Lambrix, F. Wei-Kleiner, and Z. Dragisic. **Completing the is-a structure in light-weight ontologies**, Journal of Biomedical Semantics, volume 6, number 12, 2015.
- Paper II P. Lambrix, Z. Dragisic, and V. Ivanova. **Get My Pizza Right: Repairing Missing is-a Relations in *ALL* Ontologies**, In Proceedings of the 2nd Joint International Semantic Technology Conference – JIST 2012, volume 7774 of Lecture Notes in Computer Science, pages 17–32, Nara, Japan, 2012. (revised)
- Paper III A. Chiatti, Z. Dragisic, T. Cerquitelli, and P. Lambrix. **Reducing the search space in ontology alignment using clustering techniques and topic identification**, In Proceedings of the 8th International Conference on Knowledge Capture – K-CAP 2015, paper 21, Palisades, NY, USA, 2015. (revised)
- Paper IV Z. Dragisic, V. Ivanova, H. Li, and P. Lambrix. **Experiences from the Anatomy track in the Ontology Alignment Evaluation Initiative**, submitted.
- Paper V Z. Dragisic, V. Ivanova, P. Lambrix, D. Faria, E. Jiménez-Ruiz, C. Pesquita. **User Validation in Ontology Alignment**, In Proceedings of the 15th International Semantic Web Conference – ISWC 2016, volume 9981 of Lecture Notes in Computer Science, pages 200–217, Kobe, Japan, 2016.
- Paper VI Z. Dragisic, P. Lambrix, and E. Blomqvist. **Integrating Ontology Debugging and Matching into the eXtreme Design Methodology**, In Proceedings of the 6th Workshop on Ontology and Semantic Web Patterns – WOP 2015, volume 1461 of CEUR Workshop Proceedings, paper 1, Bethlehem, PA, USA, 2015.

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- P. Lambrix, F. Wei-Kleiner, Z. Dragisic, and V. Ivanova. **Repairing Missing Is-a structure in ontologies is an abductive reasoning problem**, In Proceedings of the 2nd International Workshop on Debugging Ontologies and Ontology Mappings – WoDOOM 2013, volume 999 of CEUR Workshop Proceedings, pages 33–44, Montpellier, France, 2013.
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Part I

Summary

Chapter 1

Introduction

1.1 Motivation

The World Wide Web (WWW) is a network of web sites interconnected via hyperlinks. It is growing rapidly and as of May 2017 it is estimated to contain more than 1 billion web sites [2, 4]. Data on the WWW is available in different formats, such as documents, databases, images and videos. Often, this data has only limited structure. For example, web pages are often only semi-structured, containing just enough machine-readable meta-data for the correct presentation of a web site in a browser. The actual content (body) of web-pages is human-readable and often has no explicit structure.

The lack of structure makes the automation of more sophisticated queries – which require the understanding of the meaning of the data – a problem. As a result, large amounts of useful data on the WWW are not being used to their full potential. For example, querying for the age of a person in a document that contains the birth year of that person would already pose a difficulty for an automated agent. The agent would not have an understanding of the concept of age and how it relates to the birth year. In order to achieve queries like this, a preprocessing step such as knowledge extraction is often required. However, in many cases these preprocessing steps are incomplete and inaccurate and require human intervention to validate the extracted knowledge.

In some cases it may be necessary to combine information from multiple sources to answer a specific query. For example, in order to answer a query such as “Which actor from the movie Inception has the most Academy Award nominations?” we might have to access information on two separate web pages, one containing the cast of Inception and one with the list of all Academy Award nominees. To answer such queries it is necessary to navigate to multiple data sources and assemble the information. These data sources can be heterogeneous, having different data models or data in different formats, which would limit an automated agent’s ability to answer

such queries.

To deal with these issues Berners-Lee et al. [15] proposed the idea of a Semantic Web. It is supposed to be an extension of the WWW that would structure meaningful information on the Web, thus making it possible for automated agents to execute more sophisticated tasks. In order to do this, current human-readable content on the WWW has to be annotated with semantic labels which would be used by automated agents to extract meaning. Technologies used to achieve this include Extensible Markup Language (XML) and Resource Description Framework (RDF), which provide the necessary syntax for defining semantic labels, as well as a framework for defining statements about resources on the WWW. In addition, the vision of the Semantic Web is a Web of linked data where such annotated data is published and linked with other data on the Semantic Web.

The Semantic Web also provides support for modelling the domain of interest, i.e. describing which types of objects (i.e. concepts) exist, which kinds of properties they possess and how they relate to each other. This is done using ontologies, which provide the means for defining a formal vocabulary for a domain of interest. On top of this, ontologies also allow for inference and reasoning, which makes it possible to infer implicit knowledge from ontologies. Ontologies enable automated agents to acquire an understanding of the underlying data. They also provide a vocabulary for communication with other agents which can be used for data integration.

With the increase in popularity of the Semantic Web, more and more ontologies have been developed. Therefore, it is of no surprise that there are multiple ontologies for the same domains, with overlapping information. For example, there are a number of repositories for biomedical ontologies such as Open Biological and Biomedical Ontologies (OBO) Foundry, BioPortal, and Unified Medical Language System (UMLS). These ontologies are often used, for example, for annotating data resources, searching, or analysis of data. However, these ontologies were developed by different groups or organizations, with different applications for and points of view on the domain. In addition, the Semantic Web is decentralized and there are no naming standards when it comes to semantic labels. Therefore, two sources might use different labels for the same concept, which can cause problems when integrating information from multiple data sources.

Ontology matching attempts to solve this problem. The goal of ontology matching is to identify inter-ontology relationships. Knowledge of the inter-ontology relationships is important in many cases, for example in cases where it is necessary to use multiple ontologies, e.g., companies may want to use community standard ontologies in conjunction with company-specific ontologies. Other examples are integration, search and analysis of data in cases where different data sources in the same domain have been annotated with different but similar ontologies. The inter-ontology relationships known as mappings or correspondences define relations between entities in the ontologies (such as concepts, relations and instances). A set of map-

pings (correspondences) is called an alignment. Ontologies together with the alignments between them form ontology networks. Finding the alignment between ontologies requires knowledge about the domain of ontologies, therefore making user intervention necessary. However, there are a number of ontology matching tools that can facilitate the process for the user by providing mapping suggestions which the user must then approve or reject.

Developing and aligning ontologies is not an easy task, and the resulting ontologies and ontology networks are often incorrect or incomplete which might lead to wrong conclusions being derived or valid conclusions being missed. Defects in ontologies and ontology networks can take different forms ranging from those that are easy to detect and resolve, such as syntactic defects that represent errors in syntax in the ontology representation, to more severe ones such as semantic and modelling defects. Semantic defects represent problems within the logic of the ontology, while examples of modelling defects are missing or wrong relations. Domain knowledge is required to detect and resolve modelling defects. In this work, we focus on incomplete ontologies and ontology networks, specifically ontologies with missing relations. In addition to being problematic for the correct modelling of a domain, incomplete ontologies also influence the quality of semantically-enabled applications.

When used in semantically-enabled applications, incomplete ontologies can lead to valid conclusions being missed. In ontology-based search, queries are refined and expanded by moving up and down the hierarchy of concepts. Incomplete structure in ontologies affects the quality of the search results. As an example, suppose we want to find articles in PubMed [5] using the Medical Subject Headings (MeSH) [3] term *Scleral Diseases*. PubMed is a database of abstracts primarily from the life sciences literature and MeSH is a thesaurus used for indexing PubMed records. By default the query will follow the hierarchy of MeSH and include more specific terms for searching, such as *Scleritis*. If the relation between *Scleral Diseases* and *Scleritis* were missing in MeSH, we would miss 1142 articles in the search result, which is about 59% of the original result¹.

Incomplete alignment in an ontology network might also lead to incomplete results when, for example, an ontology network is used for integrating heterogeneous sources that are annotated using the ontologies in the network. Let us imagine that we have another data source that is annotated with the National Cancer Institute (NCI) Thesaurus and which we want to integrate with PubMed. One way to achieve this is by establishing an alignment between MeSH and NCI Thesaurus. For example, the NCI Thesaurus contains the concept *Sclera Disorder*, which corresponds to *Scleral Diseases* in MeSH. If this correspondence is included in the alignment then we could query PubMed for articles on scleral diseases using the concept *Sclera Disorder* from NCI Thesaurus, and conversely we could query our data source using the MeSH concept *Scleral Diseases*. However, if this correspondence

¹PubMed accessed on 09-05-2017

were missing then our query would not return any results (assuming that the correspondence is not implicitly derivable from the network).

Completing ontologies and ontology networks consists of two phases, detection and repair. In the detection phase missing relations are detected, and in the repairing phase the detected missing relations are made derivable in the ontology or ontology network. Ontology matching can be seen as a special case of ontology completion, where the inter-ontology relationships are the focus of the completion.

There are different ways to detect missing relations. One way is inspection by domain experts. Another way is using linguistic patterns, e.g. if we have concepts X and Y in the ontology and a statement “ X such as Y ” in some text, then a relation Y is-a X is a possible relation in the ontology. Ontology matching often utilizes string matching techniques, where concepts with similar labels are matched. Although there are many approaches for detecting missing relations, these approaches, in general, do not detect *all* missing relations. For instance, although the precision for the linguistic patterns approaches is high, their recall is usually very low.

In the following example, we discuss a process of completion of an ontology network that consists of two ontologies. Figure 1.1 shows parts of NCI Thesaurus and the Adult Mouse Anatomy (AMA) ontology concerning joints, which is relevant to our discussions. In order to establish an ontology network it is necessary to find the alignment between the two ontologies. For example, we can identify a number of correspondences between two ontologies, such as equivalence relations: *Joint* $\equiv$ *joint*, *Ankle Joint* $\equiv$ *ankle joint*, *Elbow Joint* $\equiv$ *elbow joint*, *Shoulder Joint* $\equiv$ *shoulder joint*.

In addition, we can detect a number of missing relations in the AMA ontology. Let us assume that the detection phase of the completion of the AMA ontology yielded 6 missing is-a relations. Is-a relations ($\sqsubseteq$) are relations between concepts which define that some concept is a subconcept (more specific) of some other concept e.g. *Tree* $\sqsubseteq$ *Plant*. The detected missing is-a relations are: *wrist joint* $\sqsubseteq$ *joint*, *hip joint* $\sqsubseteq$ *joint*, *knee joint* $\sqsubseteq$ *joint*, *elbow joint* $\sqsubseteq$ *joint*, *ankle joint* $\sqsubseteq$ *joint* and *shoulder joint* $\sqsubseteq$ *joint*. In the ideal case, where our set of missing is-a relations contains *all* missing is-a relations, the repairing phase is easy. We just add all missing is-a relations to the ontology and a reasoner can compute all logical consequences. However, when the set of missing is-a relations does not contain all missing is-a relations – and this is the common case – there are different ways to repair the ontology. The missing is-a structure in the example can be repaired by adding *limb joint* $\sqsubseteq$ *joint*. This is-a relation is correct according to the domain and constitutes a new is-a relation that was not derivable from the ontology and was not originally detected by the detection algorithm. To illustrate why *limb joint* $\sqsubseteq$ *joint* repairs the detected missing is-a structure, consider the missing is-a relation *wrist joint* $\sqsubseteq$ *joint*. Since the relation *wrist joint* $\sqsubseteq$ *limb joint* is already derivable from the ontology, adding *limb joint* $\sqsubseteq$ *joint* would make *wrist joint* $\sqsubseteq$ *joint* derivable in the ontology. Similar reasoning holds for

Figure 1.1. Parts of National Cancer Institute (NCI) Thesaurus and Adult Mouse Anatomy – AMA ontology concerning joints.

the other missing is-a relations in the set. We also note that from a logical point of view, adding *limb joint* $\sqsubseteq$ *joint of rib* also repairs the missing is-a structure. However, from the point of view of the domain, this solution is not correct. Therefore, as is the case for all approaches for dealing with modelling defects, a domain expert needs to validate the logical solutions.

1.2 Problem formulation

As the previous discussion pointed out, incomplete ontologies and ontology networks can lead to incomplete results in semantically-enabled applications. To deal with this problem it is necessary to detect and resolve missing relations in the ontologies and ontology networks. Therefore, the goal of this work is to address different issues in completing ontologies and ontology networks. The main research question is:

How to complete ontologies and ontology networks?

More specifically, the thesis addresses three aspects of completing ontologies and ontology networks, which are represented with three subquestions:

- 1) How can the missing is-a structures and alignments in ontologies and ontology networks be completed?

In this work we focus on completing the is-a structures in ontologies and alignments. The **is-a** relation is the most common type of relation found in ontologies. For example, in the SNOMED Clinical Terms (SNOMED CT) [6] ontology, which is the largest collection of medical terms in the world with more than 300,000 concepts, is-a relations make up around one quarter of all statements about concepts and relations in the ontology. Equivalence correspondences between concepts are the most common type of correspondences currently supported by the majority of existing systems, as well as the most commonly evaluated type of correspondences at the Ontology Alignment Evaluation Initiative (OAEI), which is a yearly evaluation campaign for ontology matching systems.

We can divide the completing of ontologies and ontology networks into completing the ontologies and completing the relations between ontologies (i.e. alignment).

- 2) How to limit and facilitate user interaction in the completion process?

User validation is a necessary phase of the completion process, as only domain-correct relations should be added to ontologies and ontology networks. However, a user's time and effort are limited resources and therefore it is necessary to consider strategies and approaches which would both limit interaction with the user and facilitate the user's involvement. The relevance of user involvement is evidenced by the fact that nearly half of the future challenges of the ontology matching area [111] are directly related to it.

- 3) How can the completion process be integrated into the ontology development phase?

While the completion of ontologies and ontology networks can be done at any point in the life-cycle of ontologies and ontology networks, some of the issues can be addressed early, in the development phase. While most methodologies for developing ontologies include a quality assurance step, very little existing work provides details on how this can be achieved. In a study [112] of larger ontology development projects it was found that while most of the projects used some form of methodology, quality checking and evaluation of the resulting ontologies was commonly omitted.

1.3 Research method

In the thesis we use a number of different research methods combining formal methods, implementation, and simulation. For all of the papers, a literature survey has been conducted in order to get a better overview of existing work related to the problem being studied. In Paper I and Paper II, which are concerned with completing the is-a structures in ontologies, we have used mathematical modelling to formalize the problem of completing the is-a structures in ontologies. We then proceeded by designing algorithms to solve the formalized problem. Some of the properties of the algorithms, such as soundness and completeness, were validated using mathematical proofs. Two tools were developed based on the designed algorithms. The development of the tools followed the prototyping software development methodology where a working version of the tool was developed, reviewed, and then further enhanced based on the review. The approach for completing ontologies was evaluated using a tool in an evaluation similar to a simulation, where we evaluated our methods in a controlled environment. The benefit of using simulations is a high level of precision, while its main drawback is limited realism. In order to increase the realism in our experiments we used real-world ontologies. Similarly, in Paper III we used simulation to evaluate our approach to reducing the search space.

We have conducted a case study related to the anatomy track of the OAEI in Paper IV. It analyzed the last 10 instances of the track. A case study is a qualitative research method which is used for gaining an in-depth understanding of the studied context as well as its dynamics [38]. The major disadvantage of the case study approach is that it is difficult to generalize. The case study research method was also used in Paper VI to evaluate our approach to integrating ontology matching and debugging into an ontology development methodology.

In Paper V, in which we aim to identify requirements for user validation in ontology alignment, we have conducted a type of systematic literature review which was intended to identify the requirements. We have also conducted a number of simulations to measure the impact of user errors on on-

tology alignment. The systematic literature review can be used to identify gaps in current research, summarize existing evidence of some phenomenon, or provide a framework or guidelines for new research [72]. The major advantage of a systematic literature review is that it gives an overview of the studied research question over a range of settings and empirical methods [72]. However, its drawback is that it requires more effort.

1.4 Contributions

The contributions of this thesis are as follows:

With respect to the question *How can the missing is-a structures and alignments in ontologies and ontology networks be completed?*

- We have formalized the problem of completing the is-a structures in ontologies as a generalized TBox abduction problem (GTAP) which is an extension of a TBox abduction problem [40]. Further, we introduced different preference criteria that are relevant to completing the is-a structure. These criteria also account for knowledge added to an ontology, in contrast to preference criteria in logic-based abduction, which usually emphasise only the solution size. We have developed algorithms for completing the is-a structures in more expressive ontologies. In this thesis we considered logic-based ontologies in the $\mathcal{EL}$ family and $\mathcal{ALC}$, for which we developed two algorithms. We have developed two systems based on these algorithms and evaluated them against a number of ontologies with different levels of expressivity. In the experiments we have shown that our approach, in addition to repairing the ontology, also adds new knowledge that was not previously detected in the detection phase. While the approaches for completing is-a structures in ontologies discuss completion of individual ontologies, they are also applicable to ontology networks. In this case an ontology network can be treated as a single ontology and the discussed approaches would work across ontologies.
- With respect to the alignment, we have conducted an empirical study of the last 10 instances of the anatomy track and 2 instances of the anatomy task in the interactive track in OAEI. The study analyses the participating systems, the types of techniques used, and their performance. In addition, we have analyzed the general trends as well as common mistakes and rarely found correspondences.
- In order to address the problem of scalability of alignment algorithms, we have developed a method for reducing the search space when generating mapping suggestions. The method is based on clustering techniques. With this method we were able to generate partitions that allowed for high quality alignments with a highly reduced effort for computation of the parts of the ontologies in the partition.

With respect to the question *How to limit and facilitate user interaction in the completion process?*

- We have conducted a qualitative study of the state-of-the-art ontology alignment systems to identify requirements for user validation in ontology alignment. The identified requirements pertain to three aspects of the user validation process: user, system services and user interface. In addition, we have also conducted experiments to analyse the impact of user errors on the ontology alignment process. While the requirements are discussed in the context of ontology alignment, they are directly applicable to the user validation phase in ontology completion.
- The methods that have been developed for reducing the search space when generating mapping suggestions in addition to reducing the computational effort for the parts of ontologies also impacts the user validation phase, as fewer mapping suggestions will be generated by the tool, thus requiring less user input for the validation.

With respect to the question *How can the completion process be integrated into the ontology development phase?*

- We have shown how both ontology completion and ontology matching can be integrated into a state-of-the-art ontology development methodology, thus addressing the issue of the quality of ontologies already in the development phase. In addition to completion, the proposed solution addresses other types of defects such as syntactic and semantic defects. The proposed approaches were evaluated in a case study based on a real-world ontology.

1.5 Thesis outline

The rest of the thesis is organized as follows:

Chapter 2 provides background on ontologies and description logics. In addition, the chapter discusses ontology debugging, ontology completion and ontology matching, and gives details on abductive reasoning in logic-based ontologies.

Chapter 3 gives a summary of the included works.

Chapter 4 covers an overview of related work with focus on completing ontologies and ontology networks.

Chapter 5 provides a discussion of the included works as well as directions for future work.

Chapter 2

Background

This chapter presents background on areas that are relevant for this thesis. The chapter is organized as follows. First, in Section 2.1 we present the ontologies and discuss components, uses and a classification of ontologies. In Section 2.2 we provide some details about description logics and present variants of description logics relevant to this work. Reasoning in description logics is discussed in Section 2.3. The section introduces tableaux reasoning, which is an approach to reasoning in description logics that is used in this thesis. Details about different defects in ontologies are given in Section 2.4. Section 2.5 gives an overview of abduction problems in description logics and discusses preference criteria on solutions to abductive queries. Finally, in Section 2.6 we present an overview of the ontology matching process including the steps in the process and basic matching strategies.

2.1 Ontologies

The term ontology comes from philosophy, where it is the study of existence and the nature of being. It tries to answer questions such as “What does it mean to exist?” or “What can be said to exist?”. In computer science the term was first used by McCarthy [92] in 1980 when discussing a new form of logic, where he suggested that ontologies can be used as a way of expressing commonsense knowledge. However, ontologies were still discussed in philosophical terms until the mid 80s when Alexander et al. [9] proposed a language for encoding ontological knowledge about the domain. This is recognized as the first use of the term *ontology* from a computer science perspective and a step away from philosophy [122]. Since then ontologies were adopted in many computer science communities, specifically in Artificial Intelligence, where ontologies became one of the important knowledge representation formalisms.

There are a number of definitions of ontologies in computer science. One of the first ones is by Neches et al. [94] which states: “An ontology defines

the basic terms and relations comprising the vocabulary of a topic area as well as the rules for combining terms and relations to define extensions to the vocabulary”. Probably the most cited definition in literature is by Gruber [49], where an ontology is defined as “an explicit specification of a conceptualization”. Studer et al. [116] extended this definition and defined an ontology as “a formal, explicit specification of a shared conceptualization”.

These definitions are related by the idea of conceptualization, i.e. an abstraction or a simplified view of the domain in question. The specification of this conceptualization should be explicit, i.e. the types of concepts, their relations and their use should be explicitly defined and formal, meaning that they are machine readable [116]. Studer et al. [116] also emphasized the need for this conceptualization to be “shared”, meaning that it is the result of a consensus and does not only encode the knowledge of a single individual.

Ontologies differ in the kind of knowledge they can represent. Given this, different ontology components can be identified (e.g. [41, 76, 114]). Corcho et al. [24] define a minimal set of components that different kinds of ontologies share:

- Concepts (classes) – represent types of objects in the domain. Objects can be both abstract and concrete, as well as simple or complex, e.g. Man, Endocarditis, Carditis, PathologicalPhenomenon.
- Instances (individuals) – represent instantiations of concepts, i.e. actual objects, for example John. The assertion Man(John) represents that John is an instance of concept Man.
- Relations (properties, roles) – represent relations between concepts in the domain. Stevens et al. [114] define two types of relations:
 - taxonomical – which represent relations that organize concepts into hierarchies. The two most used types of these are specialization relations (is-a, subconcept, subclass) and partitive relations (part-of). For example, Endocarditis is-a Carditis represents a specialization relation which defines that Endocarditis is a type of Carditis. An example of a partitive relation is the relation Lower jaw part-of Jaw.
 - associative – which relate concepts across concept hierarchies (e.g. is-caused-by, has-associated-process, etc.).
- Axioms – model statements which are always true in a domain and which cannot be defined by other components [24]. Axioms are used to define such statements as cardinality restrictions (Man has exactly one Jaw), disjoint concepts (Endocarditis is not a Fracture) as well as general statements about the domain (e.g. Endocarditis is-a InflammatoryProcess and has-location Endocardium). These kinds of statements are useful for verifying if the knowledge in the ontology is consistent as well as for inferring new knowledge not explicitly defined in the ontology [24].

2.1.1 Use of ontologies

Ontologies have a number of uses, such as the following [75]:

- they are used as a means of communication between people and organizations;
- they enable knowledge reuse and sharing;
- they provide a basis for interoperability between systems;
- they are used for data integration;
- they are used as a repository of information.

In addition to being a key technology for the Semantic Web, ontologies are used in a variety of areas:

- Software Engineering – ontologies can be used in all phases of the software engineering life-cycle, e.g. as a means for representing different artefacts of a development process [55]. Ontologies are also used to support the systematic review process in Software Engineering [27];
- Artificial Intelligence – ontologies provide means for representing common sense knowledge [89];
- Computer Security – ontologies are used to encode properties of resources and different threats [58, 71];
- Biomedicine – ontologies are often used as knowledge repositories and as a means for data integration across heterogeneous data sources [96].

2.1.2 Classifications

Depending on the expressiveness of the knowledge representation formalism used for defining ontologies, a number of categories of ontologies can be defined. One of the first such classifications was introduced by Lasila and McGuinness [88] (later extended by Uschold and Gruninger [117]). This work defined an ontology spectrum which spans from inexpressive, lightweight ontologies represented in informal languages to very expressive ontologies represented in formal languages.

- Glossaries and Data Dictionaries – represent the simplest types of ontologies, essentially a list of terms. An example of this kind of ontology is a controlled vocabulary. In the case of glossaries, terms are associated with a meaning specified in natural language.
- Thesauri and taxonomies – represent ontologies that are lists of terms with a fixed set of relations between them. For example thesauri can define relations such as hyponym, antonym, synonym (e.g. WordNet [8]). In the case of taxonomies, terms are organized into an is-a hierarchy.

- Ontologies represented using metadata, XML, schemas and data models – ontologies in this category can define concept hierarchies, attributes, relations and axioms.
- Ontologies represented using logical languages – represents the most expressive kind of ontologies based on a formal language (logic). The formal languages provide syntax and well-defined semantics as well as reasoning mechanisms such as consistency checking. Description logics is an example of a formal language widely used for defining ontologies.

A similar classification is given by Lambrix [75], where ontologies are classified based on the components and the information they contain.

2.2 Description Logics

Description logics is a family of formalisms used for representing knowledge in an application domain. In description logics an application domain is defined in terms of concepts that are used to describe entities in the domain. One of the main reasons for the popularity of description logics in knowledge representation systems is the emphasis on reasoning capabilities, which allow inference of implicit knowledge from explicitly defined descriptions.

There are three main building blocks in description logic languages [11]:

- Atomic concepts – unary predicates, representing types or sets of objects in the domain, e.g. *Professor*, *Course*, *ResearchProject*.
- Atomic roles – binary predicates, representing binary relations between the objects in the domain, e.g. *teaches*, *worksOn*.
- Individuals – constants, representing actual objects in the domain, e.g. *john*, *mary*, *semanticweb101*.

The vocabulary of a description logic language can be defined as a triplet (N_C, N_R, N_I) where N_C is a set of atomic concepts, N_R is a set of atomic roles and N_I is a set of individual names. Complex concept and role descriptions in the application domain are formed by combining basic building blocks and logical constructors such as conjunction ($\sqcap$), disjunction ($\sqcup$), existential quantification ($\exists$), etc.

The semantics of concept descriptions are defined in terms of interpretations. An interpretation $\mathcal{I}$ consists of a non-empty set $\Delta^{\mathcal{I}}$ and an interpretation function $\mathcal{I}$, which assigns to each atomic concept $A \in N_C$ a subset $A^{\mathcal{I}} \subseteq \Delta^{\mathcal{I}}$, to each atomic role $r \in N_R$ a relation $r^{\mathcal{I}} \subseteq \Delta^{\mathcal{I}} \times \Delta^{\mathcal{I}}$, and to each individual name $a \in N_I$ an object $a^{\mathcal{I}} \in \Delta^{\mathcal{I}}$.

A knowledge base in description logics is an ordered pair $(\mathcal{T}, \mathcal{A})$ consisting of a terminological component called TBox ($\mathcal{T}$) and an assertional component called ABox ($\mathcal{A}$).

TBox <i>UndergraduateCourse</i> $\sqsubseteq$ <i>Course</i> <i>GraduateCourse</i> $\sqsubseteq$ <i>Course</i> <i>Researcher</i> $\equiv \exists \text{worksOn}.\text{ResearchProject}$ <i>Teacher</i> $\equiv \exists \text{teaches}.\text{Course}$ <i>Professor</i> $\sqsubseteq (\exists \text{teaches}.(\text{UndergraduateCourse} \sqcup \text{GraduateCourse})) \sqcap$ ($\exists \text{worksOn}.\text{ResearchProject}$)
ABox <i>Professor</i> (<i>john</i>) <i>Course</i> (<i>semanticweb101</i>) <i>teaches</i> (<i>john</i> , <i>semanticweb101</i>)

Figure 2.1. A knowledge base – example.

A TBox contains a finite set of terminological axioms i.e. statements about how concepts and roles relate to each other. These axioms, in the general case, are of the form:

$$\begin{aligned} C &\sqsubseteq D \quad (r \sqsubseteq s) \\ C &\equiv D \quad (r \equiv s) \end{aligned}$$

where C and D are concepts (atomic or complex) and r and s are roles (atomic or complex) [11]. Axioms of the first type are called subsumption axioms (also known as inclusions, specializations, is-a relations). Regarding the semantics, an interpretation $\mathcal{I}$ satisfies a subsumption axiom $C \sqsubseteq D$ ($r \sqsubseteq s$) if it holds that $C^{\mathcal{I}} \subseteq D^{\mathcal{I}}$ ($r^{\mathcal{I}} \subseteq s^{\mathcal{I}}$). If an interpretation $\mathcal{I}$ satisfies an axiom (or set of axioms) then $\mathcal{I}$ is a model of this axiom (or a set of axioms). Axioms concerning concepts are also known as general concept inclusions (GCI) while axioms concerning roles are known as general role inclusions (GRI). Axioms of the second type are equivalence axioms. An interpretation $\mathcal{I}$ satisfies an equivalence $C \equiv D$ ($r \equiv s$) if it holds that $C^{\mathcal{I}} = D^{\mathcal{I}}$ ($r^{\mathcal{I}} = s^{\mathcal{I}}$). Equivalence $C \equiv D$ ($r \equiv s$) can also be represented with two subsumption axioms: $C \sqsubseteq D$ and $D \sqsubseteq C$ ($r \sqsubseteq s$ and $s \sqsubseteq r$). If the left hand side of an equivalence axiom is an atomic concept then these axioms are also known as concept definitions.

An ABox contains assertional knowledge, i.e. statements about the membership of individuals to concepts (concept assertions) and relations between individuals (role assertions). For example, *Professor*(*john*), *Course*(*semanticweb101*) are concept assertions and *teaches*(*john*, *semanticweb101*) is a role assertion where *john* and *semanticweb101* are individuals, *Professor* and *Course* are atomic concepts and *teaches* is an atomic role. An interpretation $\mathcal{I}$ is a model of an ABox if for every concept assertion $C(a)$ it holds that $a^{\mathcal{I}} \in C^{\mathcal{I}}$ and for every role assertion $r(a, b)$ it holds that $(a^{\mathcal{I}}, b^{\mathcal{I}}) \in r^{\mathcal{I}}$. An interpretation is a model for a knowledge base if it is a model for the TBox and the ABox.

An example description logic knowledge base is given in Figure 2.1. In this example, *Course*, *UndergraduateCourse*, *GraduateCourse*, *Teacher*, *ResearchProject*, *Researcher*, and *Professor* are atomic concepts, *teaches*

Table 2.1. The $\mathcal{EL}$ family – Syntax and Semantics.

Name	Syntax	Semantics
top	$\top$	$\Delta^{\mathcal{I}}$
bottom	$\perp$	$\emptyset$
nominal	$\{a\}$	$\{a^{\mathcal{I}}\}$
conjunction	$C \sqcap D$	$C^{\mathcal{I}} \cap D^{\mathcal{I}}$
existential restriction	$\exists r.C$	$\{x \in \Delta^{\mathcal{I}} \mid \exists y \in \Delta^{\mathcal{I}} : (x, y) \in r^{\mathcal{I}} \wedge y \in C^{\mathcal{I}}\}$
GCI	$C \sqsubseteq D$	$C^{\mathcal{I}} \subseteq D^{\mathcal{I}}$
equivalence axioms	$C \equiv D$	$C^{\mathcal{I}} = D^{\mathcal{I}}$
RI	$r_1 \circ \dots \circ r_k \sqsubseteq r$	$r_1^{\mathcal{I}} \circ \dots \circ r_k^{\mathcal{I}} \subseteq r^{\mathcal{I}}$

and *worksOn* are atomic relations and *john* and *semanticweb101* are individuals. The TBox contains three subsumption axioms, related to concepts *UndergraduateCourse*, *GraduateCourse*, and *Professor*, and two concept definitions (equivalence axioms) for concepts *Teacher* and *Researcher*. In natural language, the terminological axioms can be read as follows. Undergraduate course and graduate course are types of courses. A professor is someone who teaches some undergraduate or graduate course and works on a research project. However, not everyone who works on a research project and teaches such courses is a professor, therefore only the subsumption relation is used. Furthermore, teacher is defined as someone who teaches some course and a researcher is someone who works on some research project.

The ABox contains three assertions, two of which represent concept assertions, namely that *john* is a professor and that *semanticweb101* is a course. Furthermore, the ABox also contains a role assertion which states that *john* teaches the *semanticweb101* course.

As mentioned in the previous section, ontologies can be specified using description logics. In this case, concepts, relations, instances and axioms in ontologies map to concepts, roles, individuals and axioms in description logics, respectively.

There are different variants of description logics depending on which kind of logical constructors they allow. The supported logical constructors in a language have direct consequences on the properties of the language such as decidability, termination and completeness of reasoning. In this work we focus on two variants, the $\mathcal{EL}$ family and $\mathcal{ALC}$.

2.2.1 $\mathcal{EL}$ family

The $\mathcal{EL}$ family of description logics includes three variants: $\mathcal{EL}$, $\mathcal{EL}^+$ and $\mathcal{EL}^{++}$. For the description logics $\mathcal{EL}$ and $\mathcal{EL}^+$ the concept constructors are

Table 2.2. $\mathcal{ALC}$ – Syntax and Semantics.

Name	Syntax	Semantics
top	$\top$	$\Delta^{\mathcal{I}}$
bottom	$\perp$	$\emptyset$
conjunction	$C \sqcap D$	$C^{\mathcal{I}} \cap D^{\mathcal{I}}$
disjunction	$C \sqcup D$	$C^{\mathcal{I}} \cup D^{\mathcal{I}}$
concept negation	$\neg C$	$\Delta^{\mathcal{I}} \setminus C^{\mathcal{I}}$
existential restriction	$\exists r.C$	$\{x \in \Delta^{\mathcal{I}} \mid \exists y \in \Delta^{\mathcal{I}} : (x, y) \in r^{\mathcal{I}} \wedge y \in C^{\mathcal{I}}\}$
universal restriction	$\forall r.C$	$\{x \in \Delta^{\mathcal{I}} \mid \forall y \in \Delta^{\mathcal{I}} : (x, y) \in r^{\mathcal{I}} \rightarrow y \in C^{\mathcal{I}}\}$
GCI	$C \sqsubseteq D$	$C^{\mathcal{I}} \subseteq D^{\mathcal{I}}$
equivalence axioms	$C \equiv D$	$C^{\mathcal{I}} = D^{\mathcal{I}}$

the top concept $\top$, conjunction, and existential restriction. For $\mathcal{EL}^{++}$, we additionally have the bottom concept $\perp$, nominals, and a restricted form of concrete domains. In this thesis, we consider the version of $\mathcal{EL}^{++}$ without concrete domains. For the syntax and semantics of the different constructors see Table 2.1.

In $\mathcal{EL}$, a TBox can contain two types of axioms: general concept inclusions of the form $C \sqsubseteq D$ (where C and D are $\mathcal{EL}$ concepts) and equivalence axioms of the form $C \equiv D$. An equivalence axiom $C \equiv D$ can also be represented with two GCIs, $C \sqsubseteq D$ and $D \sqsubseteq C$.

In the case of $\mathcal{EL}^+$ and $\mathcal{EL}^{++}$, TBoxes may also contain role inclusions (RIs) of the form $r_1 \circ \dots \circ r_m \sqsubseteq s$ (where r_i and s are role names).

2.2.2 $\mathcal{ALC}$

Description logic $\mathcal{ALC}$ was introduced by Schmidt-Schauß and Smolka [106]. The logical constructors in $\mathcal{ALC}$ are concept conjunction, disjunction, negation, and universal quantification. In the general case, description logic $\mathcal{ALC}$ allows general concept inclusions of the form $C \sqsubseteq D$, where C and D are $\mathcal{ALC}$ concepts. The syntax and semantics of the logical constructors in $\mathcal{ALC}$ are given in Table 2.2.

In this thesis we consider ontologies that can be represented by a TBox that is an acyclic terminology. An acyclic terminology is a finite set of concept definitions (i.e. equivalence axioms of the form $C \equiv D$, where C is an atomic concept) that contains neither multiple definitions nor cyclic definitions. A cyclic definition is a definition which defines concepts in terms of themselves or in terms of concepts that indirectly refer to them [11].

2.3 Reasoning in description logics

Knowledge bases usually contain implicit knowledge that is not explicitly defined using terminological or assertional axioms. In the example in Figure 2.1 it is easy to see that *Professor* is a *Researcher*, given that he/she works on a *ResearchProject*, and as a consequence *john* is also an instance of the concept *Researcher*. However, this knowledge is not explicitly defined in the knowledge base. In order to infer this implicit knowledge, knowledge representation systems based on description logics enable a number of reasoning tasks.

Reasoning tasks in description logics can be divided into two categories: reasoning tasks for concepts and reasoning tasks for ABoxes [11]. Reasoning tasks for concepts include checking [11]:

- Satisfiability – a concept C is satisfiable w.r.t. a TBox T if there exists a model $\mathcal{I}$ of T such that $C^{\mathcal{I}}$ is non-empty. A TBox is said to be incoherent if it contains an unsatisfiable concept.
- Subsumption – a concept C is subsumed by D w.r.t. a TBox T if $C^{\mathcal{I}} \subseteq D^{\mathcal{I}}$ holds in every model $\mathcal{I}$ of T . This can also be written as $T \models C \sqsubseteq D$.
- Equivalence – a concept C is equivalent to D w.r.t. a TBox T if $C^{\mathcal{I}} = D^{\mathcal{I}}$ holds in every model $\mathcal{I}$ of T .
- Disjointness – a concept C is disjoint from concept D w.r.t. a TBox T if $C^{\mathcal{I}} \cap D^{\mathcal{I}} = \emptyset$ holds in every model $\mathcal{I}$ of T .

Reasoning tasks for ABoxes include the following tasks [11]:

- Instance checking – checking if an assertion α is entailed by an ABox $\mathcal{A}$ ($\mathcal{A} \models \alpha$), i.e. that every model of $\mathcal{A}$ is also a model of α .
- Realization – given an individual a and a set of concepts, the task is to identify the most specific concepts C such that $\mathcal{A} \models C(a)$ where the most specific concepts are those that are minimal w.r.t. the subsumption ordering.
- Retrieval – represents retrieval of all individuals of some concept, i.e. for a given concept C the idea is to identify all a such that $\mathcal{A} \models C(a)$.
- Knowledge base consistency – a knowledge base is consistent if there exists an interpretation $\mathcal{I}$ that satisfies both T and $\mathcal{A}$.

The reasoning tasks are closely related and can often be reduced from one to the other. For example, a concept C is subsumed by D if $C \sqcap \neg D$ is unsatisfiable. Given this, reasoning algorithms usually provide the means for solving only one reasoning task, while the others are solved by reduction to it.

$\sqcap$ -rule:	if the ABox contains $(C_1 \sqcap C_2)(x)$, but it does not contain both $C_1(x)$ and $C_2(x)$, then these are added to the ABox.
$\sqcup$ -rule:	if the ABox contains $(C_1 \sqcup C_2)(x)$, but it contains neither $C_1(x)$ nor $C_2(x)$, then two ABoxes are created representing the two choices of adding $C_1(x)$ or adding $C_2(x)$.
$\forall$ -rule:	if the ABox contains $(\forall r.C)(x)$ and $r(x, y)$, but it does not contain $C(y)$, then this is added to the ABox.
$\exists$ -rule:	if the ABox contains $(\exists r.C)(x)$ but there is no individual z such that $r(x, z)$ and $C(z)$ are in the ABox, then $r(x, y)$ and $C(y)$ with y an individual name not occurring in the ABox, are added.

Figure 2.2. Transformation rules (e.g. [12]).

There are a number of reasoning algorithms for description logics, and in the following section we introduce the tableaux reasoning algorithm which is used in the thesis.

Tableaux reasoning

Checking satisfiability of concepts in ontologies represented in the studied description logics can be done using a tableau-based algorithm (e.g. [12]). To test whether a concept C is satisfiable, such an algorithm starts with an ABox containing the statement $C(x)^1$ where x is a new individual. It is usually assumed that C is normalized to negation normal form, i.e. negations can only appear in front of atomic concepts. This is done by applying De Morgan's laws and rules for quantifiers. For example, the negation normal form of $\neg(C \sqcup \exists r.D)$ would be $\neg C \sqcap \forall r.\neg D$. Next, consistency-preserving transformation rules are applied to the ABox. Figure 2.2 lists the rules for description logic $\mathcal{ALC}$. The $\sqcap$ -, $\forall$ - and $\exists$ -rules extend the ABox while the $\sqcup$ -rule creates multiple ABoxes representing different choices for the disjunction. The algorithm continues applying these transformation rules to the ABox until no more rules apply. This process is called completion, and if one of the final ABoxes does not contain a contradiction – clash (we say that it is *open*), then satisfiability is proven, otherwise unsatisfiability is proven.

One way of implementing this approach is through completion graphs, which are directed graphs in which every node represents an ABox. Application of the $\sqcup$ -rule produces new nodes with one statement each, while the other rules add statements to the node on which the rule is applied. The ABox for a node contains all the statements of the node as well as the statements of the nodes on the path to the root. Satisfiability is proven if at least one of the ABoxes connected to a leaf node does not contain a contradiction, otherwise unsatisfiability is proven.

In order to take subsumption axioms and concept definitions in the TBox into account, ABoxes have to be expanded with statements of the form $x : \neg C \sqcup D$ for every individual x in the ABox, for each axiom $C \sqsubseteq D$ in

¹These statements are also written as $x : C$.

Figure 2.3. Completion graph for $\text{Professor} \sqcap \neg \text{Teacher}$.

the TBox. This is often a costly task, and different methods are used to minimize the need for such expansions.

In this thesis we assume that an ontology is represented by a knowledge base containing a TBox that is an acyclic terminology and an empty ABox. In this case reasoning can be reduced to reasoning without the TBox by unfolding the definitions. However, for efficiency reasons, instead of running the previously described satisfiability checking algorithm on an unfolded concept description, the unfolding is usually performed on demand within the satisfiability algorithm. When dealing with acyclic TBoxes, concept definitions are unfolded on demand as follows:

- If the TBox contains an axiom of the form $A \equiv B$ and an ABox contains a statement $x : A$ then statement $x : B$ is also added to the ABox.
- If the TBox contains an axiom of the form $A \sqsubseteq B$ and an ABox contains a statement $x : A$ then statements $x : B$ and $x : \overline{A}$, where $\overline{A}$ represents a new concept name, are also added to the ABox.

It has been proven that satisfiability checking w.r.t. acyclic terminologies is PSPACE-complete in $\mathcal{ALC}$ [90].

Figure 2.3 shows a completion graph for subsumption checking of the relation $\text{Professor} \sqsubseteq \text{Teacher}$ with respect to the knowledge base in Figure 2.1. As explained earlier, the subsumption check can be reduced to a satisfiability check. Therefore, in order to prove that $\text{Professor} \sqsubseteq \text{Teacher}$ holds, it is necessary to prove that $\text{Professor} \sqcap \neg \text{Teacher}$ is unsatisfiable on an empty ABox, meaning that all leaf ABoxes contain a contradiction. The algorithm starts with the statement $x : \text{Professor} \sqcap \neg \text{Teacher}$ where x is a new individual. We continue by unfolding and applying $\sqcap$ -, $\forall$ - and $\exists$ -rules until no more unfoldings are possible and no more rules apply. In the completion graph in Figure 2.3 this is represented by steps (1) to (13) in ABox 1. Next, we apply a $\sqcup$ -rule which produces two new ABoxes containing statements from the initial ABox together with statements representing

different choices for the disjunction (statements (14) and (18)). The algorithm continues applying transformation rules, and after adding statement (17) in ABox 1.1 a clash is detected given that y is of type *Course* and $\neg\textit{Course}$ at the same time. The same clash is detected in ABox 1.2. Given that all leaf ABoxes are closed the subsumption is proven.

2.4 Debugging and completing ontologies

With the increasing presence of data sources on the Internet, more and more research effort has been put into finding possible ways of integrating and searching such (often heterogeneous) sources. Semantic Web technologies such as ontologies are becoming a key technology in this effort. As discussed in Chapter 1, high quality ontologies and ontology networks are important for acquiring reliable results in semantically-enabled applications. However, it is often the case that defects are introduced into ontologies, both in the development phase and in updates. One of the reasons for this is that the domain experts who usually develop ontologies lack expertise when it comes to knowledge representation paradigms, and are often unaware of good and bad practices for developing ontologies. As a result, the ontologies they produce often have defects ranging from simple syntactic errors to wrong use of language constructs. For example, ontology developers often mistake the relation *part-of* for the *is-a* relation. Another example of a defect is a situation in which domain experts introduce logical contradictions into the ontology.

In order to ensure high quality ontologies and ontology networks it is necessary to resolve these kinds of defects, which is the focus of ontology debugging and ontology completion. Ontology debugging and completing ontologies can be divided into two phases i.e. the detection phase and the repairing phase. In the detection phase, defects are detected using various techniques. The complexity of the detection phase varies with the types of defects.

In the repairing phase, the detected defects are repaired. The exact approach that is used to make the repair is dependent upon which kind of defects are debugged. For example, when dealing with ontology completion, i.e. missing relations, the idea is to add knowledge to the ontology that would make the missing relations derivable. One method for dealing with wrong relations is to remove relations that make the wrong relations derivable.

Classification of defects

There are three types of defects [66]:

- Syntactic defects – these represent syntactic errors, for example missing tags or incorrect format. This kind of defect is easy to detect and can be resolved using parsers and validators.

- Semantic defects – these defects can be further classified into:
 - unsatisfiable concepts – concepts to which no instance can belong, i.e. concepts that are equivalent to $\perp$. For example, let us consider an ontology with the following axioms:

$$\begin{aligned} Bird &\sqsubseteq FlyingAnimal \\ Penguin &\sqsubseteq Bird \sqcap \neg FlyingAnimal \end{aligned}$$

In this case concept *Penguin* is defined as a subconcept of *Bird* and a flightless animal ($\neg FlyingAnimal$). However, given that concept *Bird* is defined as a subconcept of *FlyingAnimal* it follows that *Penguin* is also a subconcept of *FlyingAnimal*. So in this case *Penguin* is at the same time a $\neg FlyingAnimal$ and a *FlyingAnimal*, which would mean that *Penguin* is equivalent to $\perp$ and therefore an unsatisfiable concept.

- incoherent ontologies – ontologies that contain an unsatisfiable concept. Therefore, the ontology from the previous example would be an incoherent ontology, given that it contains the unsatisfiable concept *Penguin*.
- inconsistent ontologies – ontologies which contain a contradiction, e.g. an instance of an unsatisfiable concept or an ontology from which it is possible to derive that $\perp \sqsubseteq \top$. In our case, if we add an instance of concept *Penguin* to the ontology from the example it would be inconsistent.

As introduced in Section 2.3, one of the reasoning tasks in ontologies is satisfiability checking, which can be used to detect defects of this kind. However, the repairing phase is not trivial and there are a number of different approaches to dealing with defects of this type (see Chapter 4).

- Modeling defects – these represent defects that are a result of modeling errors. Examples of this kind of defect are missing and wrong relations. Missing relations are the focus of ontology completion. This kind of defect requires domain knowledge to detect and resolve. In Figure 1.1, examples of missing is-a relations in the AMA ontology are *wrist joint* $\sqsubseteq$ *joint*, *hip joint* $\sqsubseteq$ *joint*, *knee joint* $\sqsubseteq$ *joint*, *elbow joint* $\sqsubseteq$ *joint*, *hindlimb joint* $\sqsubseteq$ *joint*, *forelimb joint* $\sqsubseteq$ *joint*.

2.5 Abduction in description logics

Logical abductive reasoning is a type of inference. The task of abductive reasoning is, given a set of formulas (theory T) and a formula that represents an observation (an abductive query O), to find a set of formulas (an explanation E) such that $T \cup E$ is consistent and $T \cup E \models O$. In some definitions,

logic-based abduction also includes a set of formulas H called hypotheses, from which explanations are formed. When it comes to abductive reasoning in description logics Elsenbroich et al. [40] defined the following categories of abductive reasoning:

- ABox abduction – abductively retrieving concept or role instances which, together with the knowledge base, would entail a given ABox assertion.
- Concept abduction – abductively finding concepts that are subsumed by a given concept C .
- TBox abduction – abductively retrieving relations which, together with the knowledge base, entail a given relation $C \sqsubseteq D$.
- Knowledge-base abduction – abductively retrieving a set of TBox and ABox assertions which, together with the knowledge base, entail an abductive query that can be either an ABox or TBox assertion.

In this thesis we focus on TBox abduction, which is defined as follows.

Definition 1 (TBox Abduction [40]) *Let $\mathcal{L}$ be a description logic, Γ a knowledge base in $\mathcal{L}$, and A, B concepts that are satisfiable w.r.t. to Γ and such that $\Gamma \cup \{A \sqsubseteq B\}$ is consistent. A solution to the TBox abduction problem for (Γ, A, B) is any finite set $S = \{E_i \sqsubseteq F_i \mid i \leq n\}$ of TBox assertions, such that $T \cup S$ is consistent and $T \cup S \models A \sqsubseteq B$. The set of all such solutions is denoted as $S_T(\Gamma, A, B)$.*

Constraints on solutions

Eiter and Gottlob [39] showed that computing all abductive solutions, even in propositional logic, is not possible or practical in all cases. Therefore, constraining solutions can significantly reduce the search space and allow practical use of logical-based abduction. Examples of constraints on solutions are subset minimality and minimum cardinality. A solution S is said to be subset minimal if no proper subset of S is a solution. In the case of minimum cardinality, solutions containing fewer formulas are preferred.

There are a number of restrictions that can be imposed on solutions of abductive problems in description logics. One such restriction is consistency, meaning that the union of the background theory (knowledge base) and the solution to the abduction problem should be consistent, e.g. $\top \sqsubseteq \perp$ does not hold in the knowledge base. However, Elsenbroich et al. [40] argue that inconsistent solutions can be valuable, as they could imply the need for a revision of a knowledge base. Other restrictions such as relevance and minimality can be used for restricting trivial solutions. Relevant solutions are those solutions which do not directly entail the abductive query. In other words, an abductive query needs to be a logical consequence of a union of a solution and a knowledge base and not only the solution. Elsenbroich et al.

Figure 2.4. Example of an alignment between two ontologies.

[40] distinguish between two types of minimality: syntactic minimality, in which case a solution has to be of minimal length, and semantic minimality², in which case a solution should only contain information which is necessary to make an abductive query a logical consequence of a knowledge base and a solution. For example, if A is found to be a solution to some abductive query then $A \cap B$ is not a semantically minimal solution, as it contains B which is extra information.

2.6 Ontology matching

Ontology matching or ontology alignment is a process of determining relationships between entities in ontologies, i.e. concepts, relations, instances and axioms. These relationships can be in the form of similarity values or as explicit relations such as equivalence, is-a or part-of relations. The inter-ontology relationships are called correspondences and the set of correspondences is called an alignment. The correspondences can be 1-to-1 (one-to-one) correspondences between entities in different ontologies, as well as 1-to-n (one-to-many), n-to-1 (many-to-one) and n-to-m (many-to-many) correspondences where multiple entities in one ontology are mapped to one or more entities in the other ontology. An ontology network is defined as a set of ontologies together with the alignments between these ontologies.

In Figure 2.4 we give an example of an alignment between the two ontologies introduced in Chapter 1. The correspondences are marked with dashed arrows. The alignment consists of 9 correspondences between concepts in two ontologies, 8 equivalence correspondences and a single is-a (subsump-

²This preference criterion is not directly related to semantic maximality, discussed later in this work.

Figure 2.5. Ontology matching framework [80].

tion) correspondence. Most of the correspondences map one concept to a single concept in the other ontology, except in the case of concept *joint* in AMA which is mapped to two concepts in the NCI ontology, *Joint* via an equivalence relation and *Joint By Site* via an is-a relation.

Figure 2.5 gives an example of a general ontology matching framework that many existing ontology matching systems follow. The framework consists of two parts. In Part I the correspondences are computed and in Part II the computed correspondences are presented to the user for validation.

Part I of the matching process consists of the following three main steps:

Preprocessing. In the preprocessing step input ontologies are prepared for the alignment. This may include, for example, checking the validity of the files and feature selection to select only features which can be used by the algorithms. Another example of preprocessing is search space selection to reduce the search space so that there is no need to look at all possible pairs of entities being matched.

Matching. The goal of this step is to compute similarity values between

entities from the input ontologies. The similarity values can be based on different aspects, such as linguistic properties or structure of the ontologies. We list the most common matching strategies:

- String-based strategies. The similarity between entities in the input ontologies is based on similarity between textual descriptions such as labels and definitions for relations, concepts or instances in the ontologies. For example, similarity can be defined as the number of matching contiguous sequences of n letters in two strings (*n-gram*). Another example would be defining the similarity between two strings as the minimum number of edits needed to transform one string to the other (*edit distance*).
- Structure-based strategies. These strategies take the structure of the ontologies into account. For example, two concepts can be considered to be more similar if the super-concepts or the sub-concepts of these concepts appear in an already-accepted correspondence.
- Constraint-based strategies. These strategies take into account different constraints on entities in two ontologies, such as data-types, cardinality, disjointness relation to other entities, etc. The more similar the constraints are, the more similar the entities are considered to be. For example, if two relations have similar data-types or similar cardinalities then these relations might be similar.
- Instance-based strategies. The similarity between two concepts is based on the number of shared instances of those two concepts.
- Use of auxiliary information. In some cases it may be possible to reuse external data sources as sources of domain knowledge for finding correspondences. For example, WordNet [8] can provide information about synonyms, hypo- and hypernyms of terms, and biomedical sources such as BioPortal [1], MeSH [3], and UMLS[7] can be used for matching biomedical ontologies.

Combining and Filtering. Most of the state-of-the-art systems allow combination of multiple matching strategies. Common approaches for combining results from multiple matchers include calculating the weighted-sum of the similarity scores from the selected matchers or selecting the maximum score among all of the matchers. Filtering is most commonly done using a threshold, i.e. correspondences with a similarity score above the defined threshold are accepted and passed to Part II of the process.

In Part II the correspondence suggestions from Part I are presented for validation to a user who makes a decision on their correctness with respect to the domain. Some ontology matching tools also provide different forms of conflict checking, with the aim of removing possible conflicts that the validated relations might cause in the ontologies. The matching process can be iterative, and the output from one iteration could be used as the input

to the next. The benefit of this approach is that the validated relations can guide the matching process.

The increased interest from the research community in ontology matching has led to the creation of the Ontology Matching Workshop, as well as the Ontology Alignment Evaluation Initiative (OAEI). OAEI is an evaluation campaign with the aim of comparing and assessing the strengths and weaknesses of both ontology matching systems, as well as different matching techniques. In addition to this, OAEI has also aimed at improving evaluation techniques for ontology matching. It consists of a number of different tests covering different types of matching tasks such as instance matching, interactive matching, and matching ontologies in different languages. A large number of the tasks have a reference alignment which has been manually curated.

In cases where the gold standard (reference alignment) exists, measures such as precision, recall and F-measure can be used to evaluate the quality of the alignment. The precision of an alignment is the number of identified correspondences that are correct, i.e. those that appear in the reference alignment, divided by the total number of identified correspondences in the alignment. The recall is the number of identified correct correspondences divided by the total number of correspondences in the reference alignment. F-measure is defined using the following formula:

$$F\text{-measure}_\alpha = (1 + \alpha) \cdot \frac{\text{precision} \cdot \text{recall}}{\alpha \cdot \text{precision} + \text{recall}}$$

The α parameter can be used to assign different weights to precision and recall. Recall and precision have equal weights when $\alpha = 1$.

Chapter 3

Summary of papers

The chapter presents summaries of the included papers. The papers can be divided into three groups. The first group of papers focuses on completion of ontologies. More specifically, Paper I and Paper II address the issue of completing the is-a structures in ontologies with a focus on ontologies represented in description logics. The second group of papers deals with ontology matching. Paper III addresses the issue of scalability of ontology matching algorithms by proposing a method for reducing the search space. Paper IV provides a study of one of the longest running tracks at OAEI. Finally, Paper V looks at the problem of user validation and discusses different issues related to user-interaction during the ontology matching process. The third group includes Paper VI which addresses the issue of quality of ontologies by proposing a method for integrating ontology debugging and matching into the ontology development phase. Full papers can be found in Part II of the thesis.

Paper I: Completing the is-a structure in lightweight ontologies

The paper [87] considers the problem of completing the is-a structures in ontologies represented in the $\mathcal{EL}$ family of description logics. The paper formalizes the problem as a generalized version of the TBox abduction problem (GTAP). We also discuss preference criteria for the solutions which, in addition to the size of a solution – a factor that is commonly addressed in abduction problems – also consider knowledge added to the ontology. The paper provides a complexity analysis for decision problems for the formalized problem, both with and without preference criteria. We have developed algorithms for solving GTAP which take as input a set of missing is-a relations and return a solution that is possibly more informative, thus adding new knowledge to the ontology which was not detected by detection algorithms.

Therefore, our approaches can also be applied for detection of missing is-a relations. We have developed a system for repairing the missing is-a structure and showed the usefulness of our approach in two experiments dealing with real-world ontologies. In both cases, in addition to repairing the missing is-a structure, our approach has also identified a number of new missing is-a relations which were not in the initial set of missing is-a relations and which represent new knowledge added to the ontologies.

Paper II: Get My Pizza Right: Repairing Missing is-a Relations in $\mathcal{ALC}$ Ontologies

In this paper (revision of [77]) we address the problem of completing the is-a structures in more expressive ontologies. The paper discusses an algorithm for solving GTAP in ontologies represented using $\mathcal{ALC}$ description logics. The algorithm for solving the problem is based on the tableaux reasoning algorithms. By finding ways of closing open branches in the tableaux we can produce solutions to the GTAP. The paper provides proofs for the soundness of our approach. We have also developed a system and conducted experiments using real-world ontologies. While the approach requires more time compared to the $\mathcal{EL}$ system, the $\mathcal{ALC}$ approach is more general and is applicable to more expressive ontologies.

Paper III: Reducing the search space in ontology alignment using clustering techniques and topic identification

The paper (revision of [21]) addresses the issue of scalability in ontology matching. We propose an approach for reducing the search space when generating correspondence suggestions. The method presented in the paper is based on clustering techniques and text mining techniques such as topic identification. Clustering techniques are used to partition the ontology, while topic identification methods are used to identify topics of each partition, thus making it possible to find mappable parts. We have conducted experiments using the alignments from the anatomy track from the OAEI. The experiments have shown that our methods achieve high precision while significantly reducing the effort, i.e. the number of comparisons a matching algorithm needs to perform. This indirectly reduces the manual effort as the user is presented with fewer correspondence suggestions. However, other techniques will still be needed for finding correspondences that are not in the mappable parts.

Paper IV: Experiences from the Anatomy track in the Ontology Alignment Evaluation Initiative

The paper [32] is a study of the last ten years of the anatomy track at the Ontology Alignment Evaluation Initiative, which is one of the longest running tracks of the campaign. First, we give details of the data sets used and summarize the evolution of the data set over the years. We then give an overview of all participating systems as well as the matching techniques they have used. We have conducted an analysis of the performance results for the period of 2007 to 2016, which gives an overview of the general trends. In addition, the paper provides an analysis of the most common mistakes as well as an analysis of the most commonly identified correspondences. This analysis has led to the identification of possible issues with the reference alignment and the ontologies. Finally, we propose possible changes and directions for the track.

Paper V: User Validation in Ontology Alignment

The paper [31] addresses the issue of user validation in ontology matching, which is considered to be one of the challenges facing the ontology matching community. We have conducted a literature study in order to identify issues related to user validation in ontology matching. The identified issues are related to three aspects of user validation: the profile of the user, the services of the alignment system, and its user interface. The study also discusses how state-of-the-art matching systems deal with these issues. In addition to the study, the paper describes experiments to assess the impact of user errors in the validation process on the quality of the alignment, as well as how systems deal with errors.

Paper VI: Integrating Ontology Debugging and Matching into the eXtreme Design Methodology

While quality of ontologies is often addressed in the existing methodologies for developing ontologies, a description of the specific steps that need to be performed is often lacking. The paper [33] describes an approach for integrating ontology debugging and ontology matching into the process of ontology development. With respect to ontology debugging, we looked at syntactic, and semantic defects as well as the issue of ontology completion. The focus of our approach is the eXtreme Design (XD) methodology, which

builds on the idea of reusing and specializing content patterns that cover certain modelling issues. We have conducted a case study on a real-world ontology developed using the XD methodology. The case study has shown that by integrating ontology debugging and matching it is possible to detect and repair a number of defects during the development phase, which would otherwise have ended up in the final ontology.

Chapter 4

Related work

This chapter discusses related work on completing ontologies and ontology networks. We focus on the state-of-the-art work in completing the missing is-a structure and completing alignment, both of which were addressed in this thesis. In addition, the chapter gives an overview of existing methods for detection of missing is-a relations as well as other non-taxonomic relations that are related to the problem of ontology completion.

Our work on integrating ontology debugging and ontology matching into ontology development also addressed semantic defects in addition to the ontology completion problem. Therefore, in this chapter we provide an overview of existing methods for dealing with semantic defects. Finally, one of the contributions of the thesis is a formalization of the ontology completion problem as an abductive reasoning problem. In this chapter we look at related work on abductive reasoning in description logics.

4.1 Completing the missing is-a structure

There is not much work dealing with completing of missing is-a structures. This problem was addressed by Lambrix et al. [84] and Lambrix and Liu [83] in terms of taxonomies. Lambrix et al. [84] defined the problem of completing the is-a structure (called structural repairing). The problem can be seen as an abduction problem, however the authors' problem definition does not consider the role of a domain expert. The authors also introduced preference relations: axiom-preferred, information-preferred and strict-hierarchy-preferred. The axiom-preferred relation prefers repairs that do not contain redundant information, information-preferred prefers repairs that are more informative, and strict-hierarchy-preferred prefers repairs that do not change is-a relations in a taxonomy into equivalence relations. The solutions that are most axiom-preferred solutions would relate to a subset minimal solution in our setting. More informative solutions in our setting are a more strict version of information-preferred solution, since their work

considers only is-a hierarchies. The authors introduced an algorithm for generating repairs based on Source and Target sets with respect to the introduced preference relations. An extension of the algorithm was proposed which considers the influences of repairs for other missing is-a relations when repairing a missing is-a relation. In both cases, the user can only select a single relation per missing is-a relation. The approach is non-iterative and there is no guarantee that the final solution is skyline optimal as it might not be subset minimal. The paper also discusses an approach for recommending repairing actions which aims to minimize interaction with background knowledge. The algorithms were implemented in a system which was evaluated on the AMA ontology and the NCI-A ontology.

The work by Lambrix et al. [84] focused on repairing a single ontology. Lambrix and Liu [83] extended the work by considering repairing missing is-a structure in taxonomies that are part of taxonomy networks, i.e. taxonomies networked by alignments. In addition to extending algorithms for generating, recommending and executing repair actions to deal with taxonomies in this setting, the extension also considers the problem of detecting missing is-a relations. In this case, candidate missing is-a relations are is-a relations which are derivable from a taxonomy network but are not derivable from a taxonomy itself. The candidate missing is-a relations must then be validated by a domain expert to acquire a final set of missing is-a relations.

We note that the approaches presented in this thesis for completing an is-a structure can be used for completing taxonomies, and in that case our approach finds more informative solutions than the previously described approaches.

The work by Lambrix and Ivanova [79] further extends the previous work and presents a unified approach for repairing missing and wrong is-a relations as well as missing and wrong mappings in networked taxonomies. The implemented system was evaluated against a number of taxonomies as well as in a use case [63].

Ivanova and Lambrix [61] presented a unified approach for aligning and repairing taxonomies. In this work, the authors have integrated their approach for repairing missing and wrong is-a relations and mappings with an alignment component based on the previous work by Lambrix and Tan [86]. The alignment component is used for detecting additional candidate missing mappings. The candidate missing mappings are then validated and validated missing mappings are passed to the repairing component for repair.

4.2 Detecting missing relations

There are different approaches for detecting missing is-a relations. A number of these approaches deal with detecting missing is-a relations in ontology networks. An approach by Bada and Hunter [13] discusses a method for enriching Open Biomedical Ontologies (OBO). This approach deals with subject-property-object terms in these ontologies and introduces the concept

of nonalignments i.e. a subset of terms that have a subsumption relation between subjects but not between objects. This could imply that there are missing is-a relations between objects of terms in an nonalignment. Therefore, the next step is to use domain knowledge to determine if this is the case. If so, missing is-a relations need to be repaired. The authors propose two ways of repairing a nonalignment, either by adding is-a relations between objects or by removing is-a relations between subjects. As discussed in the previous section, a similar approach was used to detect missing is-a relations [83] and to detect both missing is-a relations and missing mappings in taxonomies [61, 63].

Bodenreider et al. [18] discuss and compare two different methods for aligning NCI-A and AMA ontologies, a lexical approach and a manual alignment. In the lexical approach, the first step is to identify mappings by matching pairs of concepts that match lexically. After that, a structural validation is executed which compares hierarchical relations among concepts in detected mappings across ontologies. In other words, if two concepts that appear in two mappings are related in one ontology then the concepts to which they map should also be related in the other ontology. If this is not the case, the mapping needs to be removed. Structural validation can also be used as a way of identifying candidate missing is-a relations. The pairs of concepts from mappings that cannot be structurally validated are candidate missing is-a relations.

Some approaches for detecting modeling defects focus on properties of the is-a relation. Guarino [50] suggests that the main reason that taxonomic information in ontologies is often complicated and difficult to understand is due to is-a overloading, i.e., linguistic definitions and properties of the is-a relation do not always reflect the ontological is-a relation. Therefore the author defines a number of ontology design principles which can be used to detect modeling defects in an ontology.

Keet [70] proposes methods for detecting and repairing flaws in object property expressions. Some examples of flaws are domain and range flaws, property characteristics flaws and property chain issues. The author defines two services for debugging these flaws, one dealing with property hierarchies and the other one dealing with property chains. The detection in these services is based on a number of tests that are run against property hierarchies and property chains. In addition, the author also specifies a number of guidelines on how to resolve situations where some test fails i.e. approaches for revising an ontology, which include changes in property expressions or class hierarchy.

Some of the ontology learning field's approaches to detecting relations between concepts in ontologies can be applied to detecting missing is-a relations. Ontology learning from text is discussed by Buitelaar et al. [20]. The authors cover a number of methods and applications for extracting ontology relations from text corpora. The methods in this area typically build upon established methods from computational linguistics and natural language

processing.

There are methods in computational linguistics which specifically deal with the detection of is-a relations. The work done by Hearst [57] specifies a number of lexico-syntactic patterns for detecting hyponym relations in a text corpus. The specified patterns describe relationships between noun phrases. An example of a simple pattern is “ NP_0 such as NP_1 and NP_2 ” in which case NP_1 and NP_2 could be identified as hyponyms of NP_0 . The author also describes a procedure for detecting new patterns where the idea is to first identify related terms given some lexical relation and then try to generalize parts of text where the detected related terms appear close to each other. While these types of patterns have a high precision, their recall is usually low.

Arnold and Rahm [10] propose three linguistically-based strategies for detecting relations between concepts in mappings. The first one, the compound strategy, suggests that a concept A subsumes another concept B if the name of B is a compound word which ends with the name of A . The other strategy is based on background knowledge. Background knowledge sources such as thesauri and dictionaries are queried for linguistic relationships between concept names. The relationships are then used to decide relations between concepts in an ontology, e.g. synonym relation relates to equivalence, hyponym relation relates to subsumption. The third strategy is the itemization strategy which suggests that an is-a relation exists between an itemization and items that it contains.

Two approaches for ontology extension based on linguistic methods are presented by Wächter et al. [118]. The methods were illustrated on Gene Ontology (GO). They relied on having a selection of PubMed articles related to each term in the ontology. According to the first method, superstring prediction, terms which are superstrings of terms in the ontology, are possible candidates for including in the ontology. The second method, term co-occurrence analysis, takes co-occurrence of terms in a scientific text as an indication of possible candidate terms.

There are a number of methods for detecting relations between concepts in ontologies based on machine learning techniques and statistical methods.

Maedche and Staab [91] discuss methods for extracting non-taxonomic relations from text based on association analysis. The input to the association analysis is a set of concept pairs, which in turn are acquired from a text processing component which associates concepts based on their linguistic dependency or heuristic correlations, e.g. concepts are coupled if they appear in the same sentence or prepositional phrases are coupled with adjacent noun phrases.

A supervised classification-based method for aligning ontologies is presented by Spiliopoulos et al. [113]. The features used in the classification algorithm take into account both properties of textual descriptions of concepts (such as names, labels and comments) and properties of textual descriptions of related concepts, i.e., concepts related via equivalence, disjointness or sub-

sumption axioms.

An approach for learning ontologies using probabilistic topic models is discussed by Zavitsanos et al. [123]. The approach uses Latent Dirichlet Allocation (LDA) [17] to identify topics from documents. The identified topics correspond to concepts in the new ontology. Conditional independence tests are then applied on the identified topics to detect taxonomic relations.

Cimiano et al. [22] present a method for learning taxonomic information from text based on Formal Concept Analysis (FCA) [46]. The inputs to the FCA are verb-subject, verb-object and verb-prepositional phrase pairs, which are acquired in a pre-processing phase. The output lattice from the FCA is transformed into a compacted partial order which corresponds to the resulting concept hierarchy.

Change management techniques from the ontology evolution area [56] can be used for detection of missing is-a relations. A process of adapting mappings in evolving ontologies is discussed by Dos Reis et al. [101]. The approach for adapting mappings is based on a categorization of ontology changes. The authors specified three algorithms that deal with mapping adaptation after removal, addition or revision of knowledge in an ontology.

4.3 Ontology matching

Ontology matching has been an active research area in the recent years. Interest within the community has lead to the creation of the Ontology Matching workshop, as well as the evaluation campaign OAEI, which have been run yearly since early 2000s. Together with other Semantic Web conference and workshops, these venues have been used to present a variety of approaches and systems for matching ontologies. There are a number of surveys on the state-of-the art (e.g. [65, 85, 95, 97, 109, 110, 111]) as well as books (e.g. [14, 41]) discussing different aspects of the field. However, even with more than 20 years of research there are still a number of challenges facing the community [110, 111]. The first challenge is related to the issue of evaluating large-scale ontology matching. This kind of evaluation requires substantial manual effort to build high-quality reference alignments. In addition, new measures besides precision and recall are needed which would take into account the usefulness of a produced alignment. Next, three challenges are related to issues of efficiency of ontology matching. The first challenge in this group is related to the efficiency of matching techniques with respect to runtimes as well as memory requirements. Next, matching with background knowledge poses a challenge since most existing methods find new correspondences but many of the suggestions are wrong. Therefore, better strategies for reusing background knowledge with focus on precision are needed. Matcher selection, combination and tuning is not a trivial task and as more and more matchers are being developed more work will be needed on techniques for selecting, combining and tuning matchers to take full advantage of the aggregation of matchers.

The next group of challenges is related to users of the systems. The first challenge is related to user involvement, i.e. systems need to provide decision support to the user in such a way that it is not overwhelming to the user. Interaction with the system needs to be natural and complete. More work is also needed on explanations of matching results. The explanations need to be concise, clear and precise. Allowing more people to vote and discuss correspondences can contribute to better alignment by lowering the impact of individual user errors. However, social and collaborative matching requires algorithms for ranking suggestions, voting strategies, and strategies to promote user participation.

Finally, the alignment management challenge relates to providing support and infrastructure for storing and sharing alignments.

Our work is related to a number of challenges. The work on reducing the search space for ontology matching relates directly to the challenge of efficiency of matching techniques. Shvaiko and Euzenat [111] suggest that the efficiency issues can be addressed by parallelization or distribution of matching tasks, approximation of matching results, modularization of ontologies or optimization of existing proven approaches. Our approach is based on modularization of ontologies. There have been a number of works [29, 59, 81, 107, 120] which use the modularization of ontologies to limit the search space and number of similarity computations.

Seddiqui and Aono [107] propose the of the Anchor-Flood algorithm which segments the input ontologies with respect to anchors. An anchor is a pair of similar concepts in two ontologies. The segments are then built around anchors by iteratively adding neighbouring concepts (children and parents) to concepts in the segments. The alignment is then produced by aligning concepts in anchored segments in two ontologies.

Another approach based on anchors was proposed by Wang et al. [120]. However, this approach does not require computation of segments in ontologies. In this case anchors are used to find ignorable similarity computations based on the concept hierarchy and locality of matching, i.e., most elements of one part of the ontology would match elements in one part of the other ontology.

The method proposed by Hu et al. [59] computes ontology partitions using a variant of ROCK [51], exploiting a link measure based on structural similarities between concepts. After identifying partitions in ontologies they are assigned RDF sentences from the ontologies and possibly further extended in order to preserve RDF sentences within the block.

In the context of schema-matching Do and Rahm [29] propose a fragment-based approach where the search space is reduced by matching non-overlapping subschemas. The matching is then done on similar subschemas which are, for example, those which have similar roots or context.

Other methods use the initial alignment to compute ontology partitions. Lambrix and Liu [81] use the initial alignment in the preprocessing step to partition the ontologies based on the structure of ontologies. In the GOMMA

system [48] partitions are contain concepts which have a good coverage of concepts appearing in the initial set of correspondences.

The Malasco system [98] is a modular system implementing three different partitioning approaches. The first approach iterates over RDF sentences and creates partitions with N triples. Other approaches reuse existing work on ontology partitioning presented by Stuckenschmidt and Klein [115] and Cuenca Grau et al. [26]. The author claims that the system achieved better precision when overlapping partitions were used.

Furthermore, in the thesis we focused on user validation, which relates to challenges of user involvement, explanation of matching results and social and collaborative matching. There have been earlier studies (e.g. [43, 44, 47, 62, 78, 42]) addressing different aspects of user involvement in the matching process. These usually only focus on a subset of the three aspects identified in Paper V, i.e. the profile of the user, user interface and system services. In addition, we focus only on user validation in ontology matching and not user involvement in general.

One of the earliest evaluations of user interfaces was conducted by Lambrix and Edberg [78]. The authors have evaluated two state-of-the-art systems for ontology merging in bioinformatics. The evaluation consisted of two parts. The first part evaluated systems w.r.t. predefined criteria using a literature study. In the second part the user interface was evaluated through a user study with 8 users from different backgrounds to evaluate relevance, efficiency and learnability of the user interface, as well as users' attitude towards it.

The work by Falconer and Storey [44] proposes a theoretical framework for cognitive support in ontology matching. The theoretical framework is based on literature, existing work on cognitive support and decision making as well as on a case study conducted by the authors. The authors define a set of requirements for four conceptual dimensions, User Analysis and Decision Making, Interaction, Analysis and Generation and Representation. Later work [43] focuses on cognitive difficulties in ontology matching and surveys the existing visual ontology matching tools which involve the user in the matching task. The work has shown that most tools at that developed with findings from behavioural user studies in mind which made it difficult to identify possible features which would improve the interaction.

Granitzer et al. [47] provide a set of requirements for visual ontology matching systems. The requirements are divided into process driven and user driven requirements. Process driven requirements are related to different steps in the alignment process such as search for candidate correspondences or similarity computation. User driven correspondences are related to the use of processes for ontology matching.

Ivanova et al. [62] provide a set of requirements for fostering user involvement in large-scale ontology matching. The work builds on requirements from the earlier work [44, 47] which are further extended and refined to address the issue of user involvement in large-scale ontology matching. In

addition, the authors have conducted a literature study as well as a heuristic evaluation and an observational study of state-of-the-art ontology matching systems to check the coverage of the requirements.

Euzenat and Shvaiko [42] give an overview of user involvement in the ontology matching process. The authors discuss interaction of individual users as well as interaction by sets of users, for example done through crowdsourcing or collaborative matching. In addition, the authors discuss different alignment explanation approaches and how they can facilitate user involvement in ontology matching.

4.4 Debugging semantic defects

Most of the work in debugging semantic defects aims at identifying and removing logical contradictions from an ontology. Standard reasoners are used to identify the existence of a contradiction, and provide support for resolving and eliminating it [45].

In works by Scholobach [104] and Schlobach and Cornet [105] minimal sets of axioms are identified which need to be removed to render an ontology coherent. This is done using the pinpointing algorithm. The idea behind this algorithm is that those axioms which are responsible for the incoherences should be removed with minimal intrusion in the ontology. In order to find these axioms, the algorithm first needs to find a minimal unsatisfiability-preserving sub-TBox (MUPS). A MUPS with respect to unsatisfiable concept A represents a minimal subset of TBox which contains A and is unsatisfiable. Generated MUPSs for all unsatisfiable concepts are used in the next step for the calculation of minimal incoherence preserving sub-TBoxes (MIPSSs). MIPSSs correspond to the minimal sets of axioms which cause the incoherence in the TBox. After finding the set of MIPSSs in the ontology, the decision regarding which axioms to remove has to be made. Therefore, Schlobach [104] introduces the concept of *cores* which represent sets of axioms that appear in one or more MIPSSs. The number of MIPSSs where some core appears represents an arity of a given core. The cores are then used by the algorithm to identify a set of pinpoints, i.e., axioms which need to be removed from an ontology to make it coherent.

Kalyanpur et al. [69] proposed two approaches for debugging unsatisfiable concepts, glass-box techniques and black-box techniques. The glass-box techniques can provide information about clashes (causes of defects) as well as a set of axioms which caused the clash. The clash information provides the user with information that is needed for debugging defects. The information usually includes names of concepts participating in the clash. The information about axioms participating in the clash is provided in the sets of support. These sets are formed during the execution of a reasoner. The reasoner needs to be extended in such way that it keeps extra information, which in the case of clash detection can be used to track the source axiom. The problems with the glass-box techniques are that they require reason-

ers which are capable of generating explanations and the memory overhead needed for dependency tracking.

The black-box techniques do not have these requirements. The main idea of black-box techniques is to divide unsatisfiable concepts into root concepts (those which are not dependent on any other unsatisfiable concept) and derived concepts (unsatisfiable concepts dependent on some other unsatisfiable concepts). The algorithm for searching for root/derived concepts is divided into two steps: detection of asserted dependencies and detection of inferred dependencies. The first step focuses on finding dependencies between unsatisfiable concepts among assertions within the ontology while the detection of inferred dependencies searches for dependencies among inferred structures of the ontology.

However, the presented techniques only provide the user with information which helps the user in understanding defects in an ontology. The actual repairing is done manually. Kalyanpur et al. [68] extended their work, proposing an approach to debugging unsatisfiable concepts similar to pinpointing [104, 105]. Their algorithm is based on *precise* MUPS, an extension of MUPS, which describes the specific parts of an axiom that make the axiom unsatisfiable. To get the *precise* MUPS, the search for the MUPS is done on a new knowledge base which is made by splitting axioms across conjunctions into shorter and simpler axioms. The axioms that are considered suitable for removal are acquired using a modified version of the hitting set algorithm [102], which takes into account a ranking of an axiom. The authors present a number of different ranking approaches, such as impact of removal, annotation information, number of times an axiom appears in an ontology, etc. In order to optimize the repairing process the authors reused the idea of root and derived unsatisfiable concepts [69]. The idea is that by repairing the root concepts a large portion of unsatisfiable concepts that were dependent on these concepts would also be repaired.

In the work by Haase and Stojanovic [52] the focus is on maintaining consistency as the ontology evolves. This is based on a formalization of the semantics of change for ontologies. Three types of consistency are formally defined: structural consistency, logical consistency, and user-defined consistency. The authors also discuss resolution strategies for each type of corresponding inconsistency. In the case of logical consistency, two alternatives for resolution are discussed. The first alternative is to identify a consistent ontology for a given change by removing one axiom at a time from an inconsistent ontology. The second alternative suggests that the resolution should be done by localizing the inconsistency i.e. identifying a minimal set of axioms that make the ontology inconsistent.

In works by Meilicke et al. [93] and Ji et al. [64] the setting is extended to repairing ontologies connected by mappings. In this case, semantic defects may be introduced by integrating ontologies. Meilicke et al. [93] address the problem of finding and repairing incoherences caused by the automatic mapping process. The proposed debugging algorithm is based on conflict

sets. Conflict sets extend the idea of diagnosis [102] where, given a set of components *COMP* and a set of observations *OBS*, the task is to identify a subset of erroneous components so that the remaining components are consistent. In the case of distributed ontologies, a set of components *COMP* represents a set of mappings between ontologies and a set of observations *OBS* is a set of concept subsumptions in the ontologies. The proposed algorithm returns minimal conflict sets, i.e., conflict sets whose subsets are not conflict sets. Thus, repairing one component from the minimal conflict set would repair the conflict. The decision on which mappings should be removed from the minimal conflict steps is based on the confidence value of each mapping, if specified, or on the WordNet [8] distances between concepts participating in the mapping.

Ji et al. [64] propose a relevance-directed approach for diagnosing and repairing ontology networks. Their approach is based on computing MUPS between sub-ontologies and is adapted from the algorithm proposed by Kalyanpur et al. [67], which is based on the hitting set algorithm [102]. The approach is relevance-directed as there are 3 strategies for computing MUPS: computing a single MUPS, computing some MUPS and some hitting sets, and computing all MUPS and all hitting sets. The decision on which strategy to use is made by a user given an ontology and his/her purpose.

Most approaches for debugging semantic defects return a list of possible diagnoses that can repair the ontology. However, not all of these are desired by the user. Shchekotykhin et al. [108] propose query strategies for interactive debugging of ontologies which, through a series of queries to the user, aim to identify the target diagnosis.

The work by Qi et al. [100] further characterizes the problem as mapping revision. The authors define a conflict-based mapping revision operator based on minimal conflict sets [93]. Using belief revision theory, the authors give an analysis for the logical properties of the revision algorithms.

Another approach for debugging mappings is proposed by Wang and Xu [119]. In this work, the authors define four types of defects in mappings, i.e. redundant mappings, imprecise mappings, inconsistent mappings and abnormal mappings. In addition, algorithms for detecting and diagnosing each type of defined defects are defined. The algorithms output warnings about detected defects as well as suggestions on how to debug them. The users have to manually execute the suggestions.

The work by Corcho et al. [25] deals with both modeling and semantic defects. The authors propose an approach for detecting modeling and semantic defects within an ontology based on patterns and antipatterns. The proposed patterns and antipatterns contain those patterns which have an impact on logical consequences and those which are supposed to improve the intended meaning of ontologies and their understandability. In addition to defining patterns and antipatterns, the authors also propose ways of solving the issues detected by the patterns and antipatterns. The work specifies a debugging strategy which defines the order in which a user should resolve

detected patterns and antipatterns.

Roussey and Zamazal [103] presented a method for detecting, without a reasoner, some of the antipatterns introduced by Corcho et al. [25]. The antipatterns are detected by running a SPARQL query on a transformed ontology. A transformed ontology is acquired from the original ontology by applying transformation rules that are designed to simplify class definitions, harmonize different implementation styles, and simulate inferences, thus avoiding the need for a reasoner.

Another work by Lambrix and Liu [82] considers both modeling and semantic defects, where the authors provide a method for repairing wrong missing is-a structure and wrong mappings in ontology networks. In addition to modeling defects, this method uses approaches for debugging semantic defects.

Poveda-Villalón et al. [99] present a web-based tool for validating ontologies against a catalogue of defined pitfalls. The pitfalls cover different categories of issues. These categories have to do with issues that are related to syntactic correctness of the ontology with respect to language specifications, documentation and clarity of the code, logical consistency, and modelling issues.

4.5 Abductive reasoning in description logics

Elsenbroich et al. [40] defined four different abductive reasoning tasks – concept abduction, ABox abduction, TBox abduction and knowledge base abduction.

Most existing approaches for description logic abduction focus on ABox and concept abduction and are mostly based on existing proof techniques such as semantic tableaux and resolution. Since the number of possible solutions can be infinite, these approaches introduce constraints on solutions.

Halland and Britz [53] propose a semantic tableaux approach for ABox abduction in $\mathcal{ALC}$. In their approach, the authors perform instance checking on an abductive query. After extracting a full completion graph, the algorithm generates a set of concept assertions for each open branch which would close that branch. This is done by taking negations of concept assertions in open branches. The solutions to the abductive query are then acquired by running the minimal hitting set algorithm [102] on these sets. This algorithm is sound but not complete and the solutions are not guaranteed to be semantically minimal.

The work by Klarman et al. [73] proposes both a semantic-tableaux and a resolution based approach for ABox abduction. The proposed approaches are goal-oriented, meaning that only actions which contribute to the solution are chosen in the proof procedures. This is done by using regular connection tableaux for the tableau-based approach or sets-of-support in the case of resolution proofs. Both approaches, however, require translation to first order logic (conjunctive normal form) and the solutions have to be translated

back to description logic. The method is both complete and sound for consistent and semantically minimal solutions. Since the set of solutions can contain some inconsistent and non-minimal solutions additional checks are required to guarantee consistency and minimality.

A practical approach for ABox abduction, based on abductive logic programming, was proposed by Du et al. [34]. This approach considers solutions over a finite set of concepts and roles called abducibles, which is in contrast to the work by Klarman et al. [73] where solutions can be formed using arbitrary concepts which can lead to infinitely many solutions when dealing with cyclic definitions. The proposed approach [34] uses existing abductive logic programming systems and therefore requires a transformation to a plain Datalog program. The solutions are consistent and minimal given a set of abducibles. In this case, allowed abducibles are atomic concepts or atomic roles. The approach does not guarantee completeness since the translation to a Datalog program is approximate and in some cases a solution would not be found. The authors extended their work [35] by allowing arbitrary concepts and roles as abducibles, such as complex concepts, negated roles, etc. This work was further extended [37] to deal with an ABox abduction problem where new individuals are allowed in solutions. For example, for abductive query $Person(Tom)$ in the case where the ontology contains $\exists hasParent.Person \sqsubseteq Person$ an intuitive minimal explanation is a set $\{hasParent(Tom, u), Person(u)\}$ where u is a new individual. As a consequence of this extension there can be infinitely many minimal solutions. To deal with this, the authors reduce the number of explanations which need to be computed by considering only representative solutions, that is solutions which are not subsumed by other minimal solutions. This approach was compared to the approach by Du et al. [34] in an experimental evaluation, which has shown that computing representative solutions is more efficient than computing minimal solutions.

There are a number of approaches which deal with the concept abduction problem as well as the conditionalised concept abduction problem, where the idea is for concepts C and D and a TBox T to identify a concept H such that $C \sqcap H \sqsubseteq D$ holds in T and $C \sqcap H \not\sqsubseteq \perp$.

Colucci et al. [23] consider an approach to the conditionalized concept abduction problem. The approach they present uses a variation of the semantic tableaux and also proposes two labelling functions. The two labelling functions $T()$ and $F()$ represent true and false formulas in a tableaux. The solutions are formed from concepts which have at least one constraint in $F()$ of every open branch. This choice is non-deterministic and can be used to select solutions based on some criteria. The algorithm also contains a consistency check, which implies that the produced solutions are always consistent.

Another approach to conditionalized concept abduction in $\mathcal{ALN}$ description logics was proposed by Di Noia et al. [28]. This approach operates on concepts in conjunctive normal form and is based on a modified version of

the structural subsumption algorithm [19]. A structural subsumption algorithm is used to identify concepts H , which need to be conjoined with C so that $C \sqcap H \sqsubseteq D$ holds. The proposed algorithm returns irreducible solutions, i.e. solutions which are minimal conjunctions.

The complexity of concept abduction in the $\mathcal{EL}$ family of description logics is explored by Bienvenu [16]. The abduction problem discussed in the paper includes a set of possible hypotheses. The work focuses on three decision problems, i.e. existence (does a solution exist), relevance (does the hypothesis appear in some solution) and necessity (does the hypothesis appear in all solutions). The complexity of the decision problems is analysed in terms of a number of preference criteria, such as subset minimality, minimal cardinality and minimal weight. The analysis has shown that the complexity of concept abduction for the decision problems is equal to the complexity of abduction in propositional definite Horn theories in the case of $\mathcal{EL}$ and $\mathcal{EL}^+$. In the case of $\mathcal{EL}^{++}$ the complexity is the same as in the case of propositional Horn theories.

There has not been much work related to TBox abduction, which is the most relevant abduction problem for this thesis. The work by Hubauer et al. [60] proposes an automata-based approach to TBox abduction using abducibles. It is based on a reduction to the axiom pinpointing problem which is then solved with automata-based methods. Similarly to the approach presented by Du et al. [34], the abductive problem also contains a set of abducibles which in this case represent a set of axioms that can appear in solutions.

A recent approach by Halland et al. [54] considers the TBox abduction problem in $\mathcal{ALC}$ ontologies. The presented approach is based on tableaux reasoning, where the solutions to the abductive query are acquired by generating a set of axioms for each open branch in the full completion graph such that when the axioms are added to the knowledge base, it would close the open branch. The axioms which close open branches are of the form $C \sqsubseteq D$, where C is of the form A , $\neg A$ or $\exists r.T$ and D is of the form A , $\neg A$ or $\forall r.\top$ where A is an atomic concept and r an atomic role. Similarly to their previous approach [53] the authors use the minimal hitting set algorithm [102] to extract a solution from these sets of axioms.

The authors have also shown that their approach for solving a TBox abduction problem can be applied to the generalized version of a TBox abduction problem, which considers multiple subsumption axioms in the abductive query. In this case for an abductive query $\{C_1 \sqsubseteq D_1, \dots, C_n \sqsubseteq D_n\}$ the satisfiability checker needs to be run on input $(C_1 \sqcap \neg D_1) \sqcup \dots \sqcup (C_n \sqcap \neg D_n)$.

Both the approach for the TBox abduction problem and the generalized version of a TBox abduction problem require a post-processing step to test for semantic minimality, consistency and relevance. The approaches are sound and complete with respect to the allowed constructors for relations in the solution.

The presented approaches for description logic abduction mostly deal

with relatively inexpressive ontologies, such as $\mathcal{EL}$ and $\mathcal{ALC}$. However, the work by Donini et al. [30] describes a type of conditionalised concept abduction called structural abduction which is applicable to $\mathcal{SH}$. In this case, instead of finding concept H such that $C \sqcap H \sqsubseteq D$, the presented algorithm first finds places within a description of C where hypotheses variables can be added. Then, a solution is defined as a substitution of a set of variables with concepts which cause the new extended concept to be subsumed by D . A more recent approach [74] describes an approach using saturation-based reasoning for concept forgetting. The TBox abduction is defined as a form of concept forgetting problem and the solution contains only concepts appearing in the signature of abducibles. The approach is implemented for $\mathcal{ALCH}$.

The work by Du et al. [36] presents an approach for TBox abduction based on justification patterns. A justification pattern is acquired by introducing variables instead of concepts' names (respectively roles) into justifications for some concept inclusion. The axioms in the solution can contain arbitrary DL constructors.

The computational complexity of the generalized TBox abduction problem in the $\mathcal{EL}$ family of description logics was analysed by Wei-Kleiner et al. [121]. The analysis focused on three decision problems: existence (does a solution exist), relevance (does a set of axioms appear in some solution) and necessity (does a set of axioms appear in every solution). These problems relate to the problems discussed by Bienvenu [16], with the difference being that, rather than including a set of hypotheses our abduction problem includes an oracle function which returns true or false depending on whether or not an is-a relation is correct according to the domain. The computational complexity of these problems was explored with respect to the preference criteria presented in this thesis. The analysis has shown that skyline optimal solutions are the best choice in practice.

Chapter 5

Conclusions and Future Work

The World Wide Web (WWW) is growing rapidly. However, data on the WWW often has only limited structure. This limits the opportunities for automation of queries that require an understanding of the meaning of the underlying data, as well as queries which require data from multiple sources. As a consequence large amounts of useful data are not being used to their full potential. A step towards support for queries of this kind is the idea of the Semantic Web, which represents an extension of the current WWW. The Semantic Web aims at structuring the data, thus adding meaning to it, which would allow automated agents to execute more sophisticated queries.

Ontologies are one of the key technologies in this endeavour. Ontologies provide a means for modelling a domain of interest i.e. establishing a vocabulary of the domain. Ontologies and alignments between them can be used for data integration and as a basis for data interoperability.

However, ontologies and ontology networks are often incomplete, a consequence of which is that semantically-enabled applications that use such ontologies and ontology networks might omit relevant and correct results. Therefore, there is a need for high quality ontologies and alignments.

The focus of this thesis has been completion of ontologies and ontology networks. With respect to completing the ontologies, our work focused on is-a relations in ontologies, which are the most common type of relations found in ontologies. We considered ontologies represented in description logics, more specifically the $\mathcal{EL}$ family and $\mathcal{ALC}$ family of description logics. The $\mathcal{EL}$ family of description logics is highly relevant for the representation of lightweight ontologies and some of the major biomedical ontologies are represented in $\mathcal{EL}$. On the other hand, $\mathcal{ALC}$ is often considered a basic expressive description logic containing logical constructors such as disjunction, existential quantifier and universal quantifier, which sets a foundation for more expressive description logics.

We formalized the problem of completing the is-a structures in ontologies as a generalized version of the TBox abduction problem. In contrast to logic-based abduction where the idea is to identify solutions that are as small as possible, the goal of repairing missing is-a structure is to add more subsumptions to enrich the ontology. Therefore, our formalization also includes a preference criterion which emphasizes the informativeness, i.e. the knowledge added to the ontology. We have also developed algorithms for solving the GTAP in the $\mathcal{EL}$ family and $\mathcal{ALC}$ description logics. The $\mathcal{EL}$ algorithm relies on identifying logical patterns in normalized $\mathcal{EL}$ ontologies for extracting solutions to GTAP. In this case, the reasoner is used as a black box and the logical patterns are applied to the result of the reasoning process. On the other hand, the $\mathcal{ALC}$ algorithm is more general and is based on satisfiability checking using tableaux reasoning. This approach is a glass-box approach, as the logical patterns used to identify solutions to the GTAP are applied directly to the completion graph of a tableaux reasoner. The algorithms are iterative and in every iteration, except for the last, a more informative solution is acquired. We have implemented systems for completing $\mathcal{EL}$ and $\mathcal{ALC}$ ontologies based on our algorithms. The analysis and the experiments have shown that our approach for completing the is-a structures in ontologies is useful, as in the experiments we have identified a number of new is-a relations which were not detected by the detection algorithm. The iterative approach has also proven to be advantageous, as in subsequent iterations new knowledge was identified and solutions to some missing is-a relations were refined. Therefore, our approach for completing the is-a structures can be seen as a detection method where the input is a set of is-a relations that require inspection, and the output is new knowledge to be added to the ontology.

With respect to alignments, we have conducted a case study of the last 10 years of the anatomy track at Ontology Alignment Evaluation Initiative, which is one of the longest running tracks of the campaign. We studied system performance and also looked at the approaches used by the systems to get a better understanding of the state of the art and identify possible shortcomings and directions for improvement. Our analysis has shown that runtimes of the participating systems have improved significantly over the years. However, while the precision of the participating systems is usually very high, many of the systems fail in finding non-trivial correspondences, i.e. correspondences which cannot be found by simple string matching. For example, even after ten years of the track there are correspondences that were found by only a few systems.

Furthermore, we have also addressed the problem of scalability, which is one of the challenges facing the community. We have developed a method for reducing the search space for matching algorithms that is based on clustering and text mining. Clustering is used to partition the ontologies into smaller partitions. Text mining methods are then used to identify topics in the partitions. Therefore, the matching algorithms need only to compare

concepts in clusters with similar topics in two ontologies. Our evaluation has shown that our method cuts the search space significantly, thus reducing the effort for computation as well as validation while still maintaining high precision. However, other techniques will be needed to deal with the low recall, given that some concepts end up being outliers in the clustering phase.

User involvement is necessary to ensure high-quality completion of ontologies and ontology networks. We conducted a broad study which identified three aspects of user validation in ontology alignment, the user's profile, ontology alignment system services and their user interfaces. The services and the user interface were assessed in a qualitative evaluation of the state-of-the-art systems while the impact of user errors, as well as how systems cope with them, were evaluated in experiments where user interaction was simulated using an oracle.

The user profile is one of the key factors in user validation. With respect to the user profile, we have identified three different types of expertise: domain expertise of the user, technical expertise, and expertise with the alignment systems. These set the requirements on how the user interface should be implemented, which information can be shown, and the degree of complexity that can be included. To facilitate the validation process for the user, the user interface should provide components such as explanations of the correspondences, contextual information about the correspondences, the consequences of validating a correspondence, and should also provide mechanisms for annotating correspondences or enabling validation over multiple sessions. However, in all cases systems should not overwhelm the user with information, as users have limited working memory and limited availability. To deal with limited availability, systems can provide system services for prioritizing the correspondence suggestions that are presented to the user, and then extrapolate the user's input to similar correspondences (using methods such as feedback propagation). However, our experiments have shown that extrapolation can increase the impact of user errors, as erroneous user input will be extended to other correspondence suggestions. Therefore, systems need to find a balance in the number of suggestions passed to the user and the degree of extrapolation.

Completion of ontologies and ontology networks can be done at any point in their life-cycle, however some of the issues can be addressed early, in the development phase. Our work presents an approach for integrating ontology debugging, completion and alignment into the eXtreme Design Methodology (XD), which is an ontology development methodology based on reusing ontology patterns, i.e. small ontology fragments which represent general use cases. To evaluate the approach we applied it to an existing ontology which was developed using the XD methodology. Our analysis has found a number of issues with the developed ontology which could have been addressed in the development phase using our approach.

Future work

There are a number of directions that are interesting for future work. They focus on improvements to the current approaches as well as extensions such as dealing with more expressive languages, and different methodologies. Here we list some of the interesting directions for future work:

Completing the is-a structure

Our approach for repairing missing is-a relations can be regarded as a detection method given that solutions to GTAP often contain new is-a relations which were not detected by the detection algorithm. However, these detection mechanisms explore only small parts of ontologies that are related to is-a relations under inspection. Therefore, a detection component would be beneficial for our approach as it would identify additional missing is-a relations and provide a starting point for the process of completing ontologies. There are many approaches for detecting missing is-a relations in ontologies, some of which were described in Chapter 4.

Furthermore, it is necessary to evaluate the scalability of our approach to more expressive representation languages as well as different types of relations. Some scalability issues could be alleviated by considering modular approaches where algorithms are run only on the parts of ontologies that are relevant for a certain missing relation.

User validation in the completion process

Our work analysing user validation has identified three different types of user expertise. Users can have different types and different levels of expertise. In order to evaluate the interplay between different aspects of the system (user interface and system services) and their impact on different types and levels of user's expertise, it would be beneficial to conduct usability testing, which would provide a better understanding of the requirements for ontology matching systems for users with different expertise types and levels.

In addition, another interesting direction related to user validation is to evaluate different validation approaches, such as presenting a user with conflicting mappings, sets of similar mappings, or giving the user the ability to assign a confidence value instead of making a binary decision.

Partitioning the search space

In our approach for partitioning the search space in ontology matching after the clustering step it is necessary to find representative keywords in each cluster, which are then used to identify topics for each cluster. In the current implementation, topic identification, as well as mapping of clusters with similar topics, is done manually. Therefore, one direc-

tion for future work would be to look at approaches for automating this step.

Another future work direction would be to extend the current approach to increase recall. In this case we would have to consider outliers, which in the current approach are excluded from the partitions.

Quality assurance in ontology development methodologies

The proposed approach requires a set of different tools which need to be run on the target ontology in order to integrate the ontology patterns and repair different defects. Therefore, one direction for future work would be to develop a support tool for ontology development which would include the various steps discussed in our approach.

In addition, our approach for integrating ontology matching and ontology debugging into ontology development was applied on one methodology. Therefore, a more general method for quality assurance in ontology development is needed. This would also require conducting usability studies to evaluate the added value for users.

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