

Fernando Silva Parreiras

Marrying Model-Driven Engineering and Ontology Technologies: The TwoUse Approach

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Promotionskommission

Vorsitzender:	Prof. Dr. Jürgen Ebert
Berichterstatter:	Prof. Dr. Steffen Staab
	Prof. Dr. Uwe Assmann
	Prof. Dr. Daniel Schwabe

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For wherever your treasure is,
that is where your heart will be too.
Luke 12:34

Abstract

The semantic web and model-driven engineering are changing the enterprise computing paradigm. By introducing technologies like ontologies, metadata and logic, the semantic web improves drastically how companies manage knowledge. In counterpart, model-driven engineering relies on the principle of using models to provide abstraction, enabling developers to concentrate on the system functionality rather than on technical platforms.

The next enterprise computing era will rely on the synergy between both technologies. On the one side, ontology technologies organize system knowledge in conceptual domains according to its meaning. It addresses enterprise computing needs by identifying, abstracting and rationalizing commonalities, and checking for inconsistencies across system specifications. On the other side, model-driven engineering is closing the gap among business requirements, designs and executables by using domain-specific languages with custom-built syntax and semantics.

In this scenario, the research question that arises is: What are the scientific and technical results around ontology technologies that can be used in model-driven engineering and *vice versa*? The objective is to analyze approaches available in the literature that involve both ontologies and model-driven engineering. Therefore, we conduct a literature review that resulted in a feature model for classifying state-of-the-art approaches. The results show that the usage of ontologies and model-driven engineering together have multiple purposes: validation, visual notation, expressiveness and interoperability.

While approaches involving both paradigms exist, an integrated approach for UML class-based modeling and ontology modeling is lacking so far. Therefore, we investigate the techniques and languages for designing integrated models. The objective is to provide an approach to support the design of integrated solutions. Thus, we develop a conceptual framework involving the structure and the notations of a solution to represent and query software artifacts using a combination of ontologies and class-based modeling. As proof of concept, we have implemented our approach as a set of open source plugins – the TwoUse Toolkit.

The hypothesis is that a combination of both paradigms yields improvements in both fields, ontology engineering and model-driven engineering. For MDE, we investigate the impact of using features of the Web Ontology Language in software modeling. The results are patterns and guidelines for designing ontology-based information systems and for supporting software engineers in modeling software. The results include alternative ways of describing classes and objects and querying software models and metamodels. Applications show improvements on changeability and extensibility.

In the ontology engineering domain, we investigate the application of techniques used in model-driven engineering to fill the abstraction gap between ontology specification languages and programming languages. The objective is to provide a model-driven platform for supporting activities in the ontology engineering life cycle. Therefore, we study the development of core ontologies in our department, namely the core ontology for multimedia (COMM) and the multimedia metadata ontology. The results are domain-specific languages that allow ontology engineers to abstract from implementation issues and concentrate on the ontology engineering task. It results in increasing productivity by filling the gap between domain models and source code.

Zusammenfassung

Wissenschaftliche und wirtschaftliche Initiativen haben immer mehr Interesse an der Integration von Ontologien und Software-Entwicklung. Das World Wide Web Consortium (W3C) und die Object Management Group (OMG) haben in den letzten Jahren Arbeitsgruppen zur Erforschung des Zusammenwirkens des Semantischen Webs und der Software-Entwicklung ins Leben gerufen.

Bezüglich der Integration von Ontologien und modellgetriebener Software-Entwicklung entstehen permanent Gebiete zur Erforschung neuer Technologien, die die Erhöhung des Abstraktionsgrades bereitstellen. Obwohl Ontologien in der Informatik zu den konzeptuellen Modellen gehören, werden sie anders und mit verschiedenen Technologien im Vergleich zur klassenbasierten und objektorientierten Softwareentwicklung eingesetzt.

In diesem Szenario ist die Fragestellung für die Forschung: Welche wissenschaftlichen und technischen Ergebnisse im Bereich von Ontologien und zugehörigen Werkzeugen existieren, die in modellgetriebener Software-Entwicklung und dem Entwurf von Ontologien eingesetzt werden können? Ziel dieser Arbeit ist es, Ansätze in der Literatur zu untersuchen, die die Integration beider Bereiche ermöglicht. Deshalb führen wir eine Literaturrecherche durch, die als Ergebnis eine Klassifizierung von modernen Entwicklungsansätzen liefert. Die Ergebnisse zeigen, dass der gemeinsame Einsatz von Ontologien und modellgetriebener Software-Entwicklung verschiedenen Zwecken dient: Der Validierung von visuellen Notationen, der Erhöhung der Ausdruckskraft vieler Sprachen in der Software-Entwicklung und der Interoperabilität.

Während Ansätze zur Einbeziehung beider Paradigmen existieren, ist ein integriertes Konzept für die klassenbasierte Modellierung und den Entwurf von Ontologien bisher nicht vorhanden. Daher untersuchen wir ebenfalls die Techniken und Sprachen zur Gestaltung integrierter Modelle. Das Ziel ist, ein Konzept für die Gestaltung von integrierten Lösungen zu erstellen. Daher haben wir ein Konzept entwickelt, das die Strukturen und die Notationen bietet, um Softwareartefakte unter Verwendung einer Kombination aus On-

tologien und klassenbasierter Modellierung zu repräsentieren und anzufragen. Wir haben eine Reihe von frei verfügbaren Komponenten (Plugins) als Machbarkeitsnachweis unserer Vorgehensweisen entwickelt, zusammen bilden sie das TwoUse Toolkit.

Die Hypothese dieser Arbeit ist, dass eine Kombination der beiden Paradigmen Verbesserungen in beiden Bereichen, sowohl im Entwurf von Ontologie als auch in der modellgetriebenen Software-Entwicklung, bringt. Bezüglich modellgetriebene Software-Entwicklung untersuchen wir den Einfluss der Verwendung von Ontologiesprachen in der Software-Modellierung. Die ausgearbeiteten Ergebnisse beinhalten Muster und Richtlinien für die Gestaltung ontologie-basierter Software, darüber hinaus wird so den Entwicklern eine umfassende Unterstützung in der Softwaremodellierung geboten. Die Ergebnisse umfassen alternative Wege zur Beschreibung von Klassen und von Objekten sowie von Anfragen an Softwaremodelle oder Beschreibung von Software-sprachen. Zu erkennen sind Verbesserungen in den Bereichen Veränderbarkeit und Erweiterbarkeit von Anwendungen. Für den Entwurf von Ontologien stellen wir Techniken vor, welche in der modellgetriebenen Software-Entwicklung benutzt werden, um die Abstraktionsebene zwischen Ontologie-Spezifikations-sprachen und Programmiersprachen zu erhöhen.

Für den Ontologie-Entwurf untersuchen wir die Anwendung von Techniken der modellgetriebenen Software-Entwicklung, um die Lücke zwischen abstrakten Ontologie-Spezifikationen und des Zugriffs durch Implementationsschnittstellen zu schließen. Das Ziel ist, eine Plattform bereitzustellen, die den Entwicklungsprozess von Ontologien unterstützt. Um dieses Ziel zu erreichen, analysieren wir Ontologien und zu deren Entwicklung vorgesehene Werkzeuge, die im WeST Institut an der Universität Koblenz-Landau entwickelt wurden, z.B. Werkzeuge für die Ontologie COMM (core ontology for multimedia) und die Multimedia-Metadata Ontologie. Die Ergebnisse unserer Ansätze sind domänenspezifische Sprachen, die die Entwickler von Ontologien nutzen, um sich auf die Ontologie-Entwicklung zu konzentrieren anstatt Implementationsschnittstellen zu verstehen. Daraus ergibt sich eine Steigerung der Produktivität.

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Fundamentals

Introduction

1.1 Motivation

Among recent attempts to improve productivity in software engineering, model-driven engineering (MDE) is an approach that focuses on the design of artifacts and on generative techniques to raise the level of abstraction of physical systems [2]. As model-driven engineering gains momentum, the transformation of artifacts and domain-specific notations become essential in the software development process.

One of the pre-existing modeling languages that boosted research on MDE is the Unified Modeling Language (UML). UML is a visual design notation [3] for designing software systems. It is a general-purpose modeling language, capable of capturing information about different views of systems, like static structure and dynamic behavior.

In addition to general-purpose modeling languages, MDE relies on domain-specific languages (DSL). Such languages provide abstractions and notations for modeling specific aspects of systems. A variety of domain-specific languages and fragments of their models is used to develop one large software system.

Among artifacts produced by multiple modeling languages, MDE faces the following challenges [4]: support for developers; interoperability among multiple artifacts and formal semantics of modeling languages. Addressing these challenges is crucial for the success of MDE.

In contrast, issues like interoperability and formal semantics motivate the development of ontology web languages. Indeed, the World Wide Web Consortium (W3C) standard Web Ontology Language (OWL) [5], together with automated reasoning services, provides a powerful solution for formally describing domain concepts in an extensible way, thus allowing for precise specification of the semantics of concepts as well as for interoperability between ontology specifications.

Ontologies provide shared domain conceptualizations representing knowledge by a vocabulary and, typically, logical definitions [6, 7]. OWL provides

a class definition language for ontologies. More specifically, OWL allows for the definition of classes by required and implied logical constraints on the properties of their members.

The strength of OWL modeling lies in disentangling conceptual hierarchies with an abundance of relationships of multiple generalization of classes (cf. [8]). For this purpose, OWL allows for *deriving* concept hierarchies from logically precisely defined class axioms stating necessary and sufficient conditions of class membership. The logics of class definitions may be validated by using corresponding automated reasoning technology.

Ontology engineers usually have to cope with W3C standard specifications and programming languages for manipulating ontologies. The gap between W3C specifications and programming language leads ontology engineers to deal with multiple languages of different natures. For instance, W3C specifications are platform independent, whereas programming languages include platform specific constructs.

Indeed, addressing these issues has been one of the objectives of model-driven engineering. MDE allows for developing and managing abstractions of the solution domain towards the problem domain in software design, turning the focus from code-centric to transformation-centric.

Understanding the role of ontology technologies like knowledge representation, automated reasoning, dynamic classification and consistency checking in MDE as well as the role of MDE technologies like model transformation and domain-specific modeling in ontology engineering is essential for leveraging the development of both paradigms.

For example, UML and OWL constitute modeling approaches with strengths and weaknesses that make them appropriate for specifying distinct aspects of software systems. UML provides means to express dynamic behavior, whereas OWL does not. OWL is capable of inferring generalization and specialization between classes as well as class membership of objects based on the constraints imposed on the properties of class definitions, whereas UML class diagrams do not allow for dynamic specialization/generalization of classes and class memberships or any other kind of inference *per se*.

Though schemas [9] and UML extensions (UML profiles) for OWL ontologies exist, an integrated usage of both modeling approaches in a coherent framework has been lacking so far. This thesis unveils research problems involving the composition of these two paradigms and presents research methods to assess the application of a novel framework integrating UML class-based models and OWL ontologies and technologies.

Investigating the composition of UML class-based modeling and ontology technologies requires a systematic procedure to address a series of research questions. Firstly, we need to characterize the fundamental concepts and technologies around UML class-based modeling and OWL ontologies and to elicit the requirements of an integrated framework. Consequently, we need to specify a framework that realizes the integration of both paradigms and fulfills the requirements previously elicited.

To analyze the impact of an integrated approach, we need to apply it in both domains: model-driven engineering and ontology engineering. In the domain of model-driven engineering, we apply the proposed framework to address shortcomings of software design and software languages. Our aim is to reduce complexity and to improve reusability and interoperability.

In the domain of ontology engineering, we tackle issues addressing the gap in clarity and accessibility of languages that operate ontologies, e.g., ontology translation languages or ontology APIs generation. Our framework is then used to support the development of platform independent models, aiming at improving maintainability and comprehensibility.

In the following subsections, we describe the motivation for investigating an integration between UML class-based modeling and OWL in Section 1.2. In Section 1.3, we present the guidelines for reading this thesis and in Section 1.4, we present the publications covering parts of this thesis.

1.2 Research Questions

Over the last decade, the Semantic Web and the software engineering communities have investigated and promoted the use of *ontologies* and of UML class-based modeling as modeling frameworks for the management of schemas. While the foci of these communities are different, the following question arises:

Question I *What are the commonalities and variations around ontology technologies and model-driven engineering?*

By identifying the main features of both paradigms, a comparison of both leads to the following sub-questions:

Question I.A *What are the scientific and technical results around ontologies, ontology languages and their corresponding reasoning technologies that can be used in model-driven engineering?*

Question I.B *What are the scientific and technical results around UML class-based modeling that can be used in ontology engineering?*

While investigating this problem, our goal is to analyze approaches that use both UML class-based technologies and ontology technologies and to identify patterns involving both paradigms. The result of such analysis is a feature model, described in Chapter 4.

The feature model reveals the possible choices for an integrated approach of OWL ontologies and model-driven engineering and serves as a taxonomy to categorize existing approaches. Furthermore, the classification allows for eliciting requirements for a composed approach.

We carry out exploratory research by conducting a domain analysis over approaches involving UML class-based technologies and ontology technologies found in the literature. Domain analysis addresses the analysis and modeling of variabilities and commonalities of systems or concepts in a domain [10].

The research result is a descriptive model characterized by a feature model for the area of marrying UML class-based modeling and ontology technologies.

While there exist mappings between these modeling paradigms [1], an analysis of the outcome of an integrated approach for UML class-based modeling and OWL is lacking so far. The challenge of this task arises from the large number of differing properties relevant to each of the two modeling paradigms.

For example, UML modeling provides means to express dynamic behavior, whereas OWL 2 does not. OWL is capable of inferring generalization and specialization between classes as well as class membership of objects based on restrictions imposed on properties of class definitions, whereas UML class diagrams do not allow for dynamic specialization/generalization of classes and class memberships or any other kind of inference *per se*.

Contemporary software development should make use of the benefits of both approaches to overcome their restrictions. This need leads to the following question:

Question II *What are the techniques and languages used for designing integrated models?*

To address this question, we use the requirements resulting from Problem I to propose a framework comprising the following building blocks: (i) an integration of the structure of UML class-based modeling and OWL; (ii) the definition of notations for denoting integrated artifacts; and (iii) the specification of a query solution for retrieving elements of integrated artifacts. Together, these building blocks constitute our original approach to Transform and Weave Ontologies and UML class-based modeling in Software Engineering — *TwoUse* (Figure 1.1).

We analyze the impact of the TwoUse approach with case studies in the domain of model-driven engineering and ontology engineering.

Applying TwoUse in Model-Driven Engineering

In UML class-based modeling, software design patterns provide elaborated, best practice solutions for commonly occurring problems in software development. However, software design patterns that manage variants delegate the decision of what variant to choose to client classes. Moreover, the inevitable usage of several software modeling languages leads to unmanageable redundancy in engineering and managing the same information across multiple artifacts and, eventually, information inconsistency. The growing demand for networked and federated environments requires the convergence of existing web standards and software modeling standards.

In contrast, the strength of OWL modeling lies in disentangling conceptual hierarchies with multiple generalization of classes [8]. OWL allows for *deriving* concept hierarchies from logically precisely defined class axioms stating necessary *and* sufficient conditions of class membership.

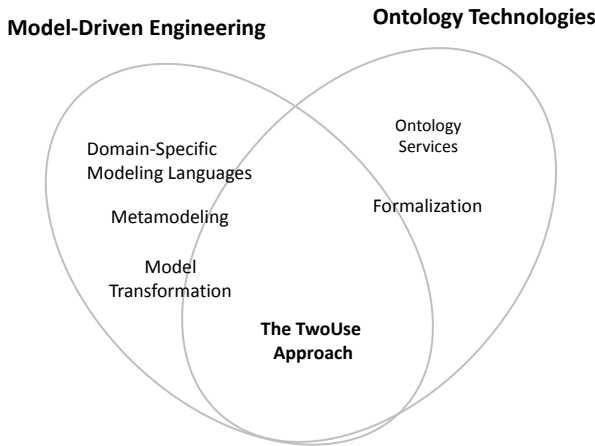


Fig. 1.1. Context of the Thesis.

OWL provides exclusive features that distinguish it from class-based modeling languages: class expressions, individual equality and class expression axioms. Hence, the following question arises:

Question III *What is the structural impact of using OWL constructs in designing software artifacts?*

To address this problem, we work on identifying patterns at the modeling level as well as at the language level. At the modeling level, we analyze the situation where the decision of what class to instantiate typically needs to be specified at a client class. We investigate the following question:

Question III.A *How to determine the selection of classes to instantiate using only class descriptions rather than by weaving the descriptions into class operations?*

In systems that rely on ontologies, i.e., in ontology-based information systems, the question is the following:

Question III.B *How to reuse existing knowledge captured by domain ontologies in the specification of functional algorithms of ontology-based information systems?*

At the language level, to support the interrelationships of software modeling languages in distributed software modeling environments, we need to answer the following question:

Question III.C *what and how ontology technologies can help existing modeling languages in managing the same information across multiple artifacts?*

The hypothesis is that an ontology-based approach improves software quality and provides guidance to software engineers. To test the hypothesis, at the modeling level, we analyze the TwoUse approach with three case studies: software design pattern, designing of ontology-based information systems and model-driven software languages.

At the modeling level, we analyze the application of TwoUse in addressing drawbacks of software design patterns and in design ontology-based information systems. At the language level, we analyze the application of TwoUse in addressing the transformation and matching of modeling languages into OWL.

Applying TwoUse in Ontology Engineering

In ontology engineering, the design of ontology engineering services [11] have drawn the attention of the ontology engineering community in the last years. However, as ontology engineering services get more complex, current approaches fail to provide clarity and accessibility to ontology engineers who need to see and understand the semantic as well as the lexical/syntactic part of specifying ontology engineering services. Ontology engineers use services in an intricate and disintegrated manner, that draws their attention away from the core task proper down into the diverging platform details.

From this scenario, the problem of supporting generative techniques in ontology engineering services emerges, adding expressiveness without going into platform specifics, i.e.,

Question IV *how to fill the abstraction gap between specification languages and programming languages?*

We propose a representation approach for generative specification of ontology engineering services based on model-driven engineering (MDE). In order to reconcile semantics with lexical and syntactic aspects of the specification, we integrate these different layers into a representation based on a joint meta-model.

The hypothesis is that filling the gap between ontology specification languages and general purpose programming languages helps to improve productivity, since ontology engineers do not have to be aware of platform-specific details. Moreover, it simplifies the tasks of maintenance and traceability because knowledge is no longer embedded in the source code of programming languages.

We validate our approach with three case studies of three ontology engineering services: ontology mapping, ontology API generation and ontology modeling.

For ontology mapping, we present a solution for ontology translation specification that intends to be more expressive than current ontology mapping

languages and less complex and granular than programming languages to address the following question:

Question IV.A How to fill the abstraction gap between ontology mapping languages and programming languages?

For ontology API generation, we present a model-driven solution for designing mappings between complex ontology descriptions and object oriented representations – the *agogo* approach – and tackle the following problem:

Question IV.B What are the results of applying MDE techniques in ontology API development?

For ontology modeling, we present a model-driven approach for specifying and encapsulating descriptions of ontology design patterns and address the following problem:

Question IV.C How to allow declarative specifications of templates and tools to test these template specifications and realizations?

1.3 Road Map

Figure 1.2 depicts the road map for this thesis, positioning the research questions presented in this chapter. In Part I, we present the fundamental concepts and analyze state-of-the-art approaches. Chapter 2 and Chapter 3 describe the concepts and technologies around MDE and ontologies, respectively. In Chapter 4, we present the commonalities and variations of both paradigms, analyze existing work in this area and elicit the requirements for an integrated solution.

Part II describes the role of MDE techniques (DSL, model transformation and metamodeling) and ontology technologies (reasoning services, query answering) in an integrated approach. In Chapters 5 and 6, we describe the conceptual architecture of our approach. Chapter 7 presents the TwoUse Toolkit – the implementation of the conceptual architecture.

We use the TwoUse toolkit to realize case studies from the model-driven engineering and ontology engineering domains. Part III assembles case studies that use our approach at the modeling level and at the language level. Chapter 8 analyzes the application of TwoUse in software design patterns and in Chapter 9, we present the application of TwoUse in ontology-based information systems. Chapter 10 describes the usage of TwoUse to support software developers in integrating software languages.

Part IV presents an analysis of employing our approach in ontology engineering services. We address the need for multiple languages for ontology mapping in Chapter 11. Chapter 12 presents a domain specific language for specifying ontology APIs. Chapter 13 use templates for encapsulate complexity of ontology design patterns.

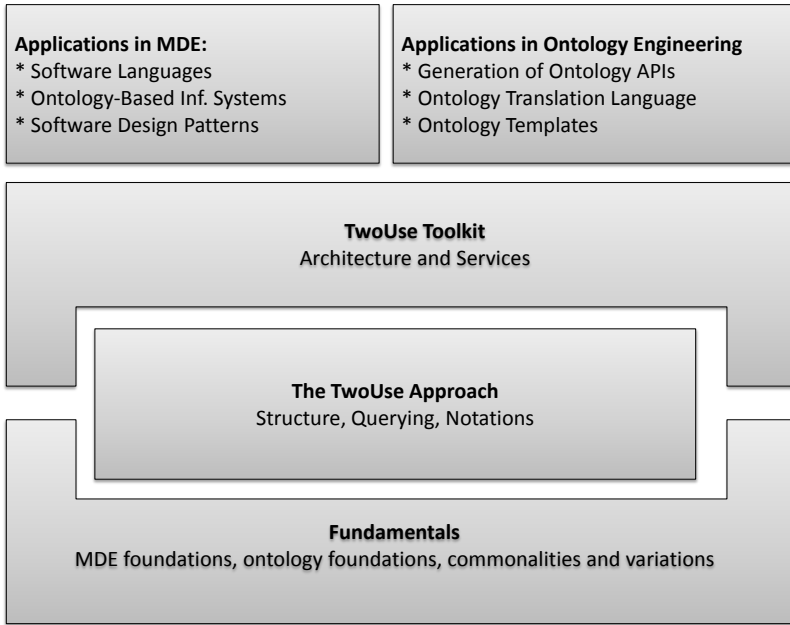


Fig. 1.2. Road Map of this Thesis.

1.4 Communications of this Thesis

We have communicated the research presented in this thesis through conference papers, a journal paper, conference tutorials, conference demonstrations and bachelor/master theses. In the following, we list the publications according to the chapters covering the respective contributions.

Chapter 3: Silva Parreiras, F., Staab, S., Ebert, J., Pan, J.Z., Miksa, K., Kuehn, H., Zivkovic, S., Tinella, S., Assmann, U., Henriksson, J.: Semantics of Software Modeling. In: Semantic Computing. Wiley (2010) 229–248

Chapter 4: Silva Parreiras, F., Staab, S., Winter, A.: On marrying ontological and metamodeling technical spaces. In: Proceedings of the 6th joint meeting of the European Software Engineering Conference and the ACM SIGSOFT International Symposium on Foundations of Software Engineering, 2007, Dubrovnik, Croatia, September 3-7, 2007, ACM (2007) 439–448

Chapters 5, 6, 9: Parreiras, F.S., Staab, S.: Using ontologies with UML class-based modeling: The TwoUse approach. Data & Knowledge Engineering **69**(11) (2010) 1194 – 1207

Chapter 7 Silva Parreiras, F., Walter, T., Gröner, G.: Filling the gap between the semantic web and model-driven engineering: The TwoUse toolkit. In:

Demo and Posters Proceedings of the 6th European Conference on Modelling Foundations and Applications, ECMFA 2010, Paris, France, June 15-18, 2010. (2010)

- Chapter 8: Silva Parreiras, F., Staab, S., Winter, A.: Improving design patterns by description logics: A use case with abstract factory and strategy. In: Proceedings of Modellierung 2008, Berlin, Germany, March 12-14, 2008. Number 127 in LNI, GI (2008) 89–104
- Chapter 11: Silva Parreiras, F., Staab, S., Schenk, S., Winter, A.: Model driven specification of ontology translations. In: Proceedings of Conceptual Modeling - ER 2008, 27th International Conference on Conceptual Modeling, Barcelona, Spain, October 20-24, 2008. Number 5231 in LNCS, Springer (2008) 484–497
- Chapter 12: Silva Parreiras, F., Walter, T., Staab, S., Saathoff, C., Franz, T.: APIs a gogo: Automatic generation of ontology APIs. In: Proceedings of the 3rd IEEE International Conference on Semantic Computing (ICSC 2009), September 14-16, 2009, Santa Clara, California, USA, IEEE Computer Society (2009) 342–348
- Chapter 13: Silva Parreiras, F., Groener, G., Walter, T., Staab, S.: A model-driven approach for using templates in OWL ontologies. In: Knowledge Management and Engineering by the Masses, 17th International Conference, EKAW 2010, Lisbon, Portugal, October 11-15, 2010. Proceedings. Volume 6317 of LNAI, Springer (2010) 350–359

We presented parts of this work in the following tutorials:

- Silva Parreiras, F., Walter, T., Wende, C., Thomas, E.: Model-Driven Software Development with Semantic Web Technologies. In: Tutorial at the 6th European Conference on Modelling Foundations and Applications, ECMFA 2010, Paris, France, June 15-18, 2010. (2010)
- Silva Parreiras, F., Walter, T., Wende, C., Thomas, E.: Bridging Software Languages and Ontology Technologies. In: SPLASH '10: Proceedings of the ACM international conference companion on Object oriented programming systems languages and applications companion, October 17, 2010, Reno/Tahoe, Nevada, USA., ACM (2010) 311–315
- Gasevic, D., Silva Parreiras, F., Walter, T.: Ontologies and Software Language Engineering. In: Tutorial at Generative Programming and Component Engineering (GPCE'10) co-located with Software Language Engineering (SLE 2010), October 10, 2010, Eindhoven, The Netherlands. (2010)
- Staab, S., Walter, T., Gröner, G., Silva Parreiras, F.: Model Driven Engineering with Ontology Technologies. In: Reasoning Web. Semantic Technologies for Software Engineering, 6th International Summer School 2010, Dresden, Germany, August 30 - September 3, 2010. Tutorial Lectures. LNCS 6325 Springer (2010) 62–98

The implementation of the approach described in this thesis served as basis for the following bachelor thesis, *Studienarbeiten* or *Diplomarbeiten*:

- Saile, David: Integrating TwoUse and OCL-DL. *Studienarbeit*.
- Schneider, Mark: SPARQLAS - Implementing SPARQL Queries with OWL Syntax. *Studienarbeit*. [In German]
- Fichtner, Vitali: Developing a semantic Environment for analyzing Software Artifacts. Bachelor Thesis. [In German]
- Schneider, Carsten: Towards an Eclipse Ontology Framework: Integrating OWL and the Eclipse Modeling Framework. *Diplomarbeit*. [In German]

Moreover, the implementation of the approach led to the development of a free open-source set of tools for designing models combining model-driven engineering and OWL – the TwoUse toolkit¹.

¹ <http://twouse.googlecode.com/>

Model-Driven Engineering Foundations

Summary. This chapter discusses the state of the art for model-driven engineering. We inspect approaches, abstractions, and techniques constituting MDE, describe them with respect to their concepts and relationships, and investigate the conceptual structure that underpins MDE in this state-of-the-art review. The result is a static structural model represented by UML class diagrams.

2.1 Introduction

Raising the level of abstraction is one of the basic principles of software engineering. It eliminates complexity that is not inherent in software artifacts. The idea is to selectively abstract away from non-fundamental aspects and to concentrate on the essential aspects of software artifacts.

Approaches that aim at reducing complexity have an impact upon software productivity. In productivity models, complexity metrics compose the cost metrics together with resources and personnel [12].

Model-driven engineering (MDE) is an approach that uses models, notations and transformation rules to raise the level of abstraction of a physical system [2] aiming at improving productivity.

In this chapter, we present the fundamental concepts of the model-driven engineering structure. In Section 2.2, we use the concept of *megamodel* [13] to present a description of the structure of MDE. We use this structure to group concepts around ontology technologies and model-driven technologies in Section 2.3.

2.2 Model-Driven Engineering Structure

Model-driven techniques provide management, transformation and synchronization of software artifacts. The objective is to factorize complexity into different levels of abstraction and concern, from high-level conceptual models down to the individual aspects of target platforms.

There is a consensus in the literature about the cornerstones of MDE: (1) languages comprising: models that represent real-world elements, metamodels to describe the structure of models and language semantics; (2) and transformations between languages. Schmidt [2] argues that model-driven engineering technologies should combine domain-specific modeling languages and transformation engines to address platform complexity. For Kent [14], MDE requires a family of languages, transformations between languages and a process associated with the conception of languages and transformations. In this chapter, we concentrate on the structural specification of model-driven engineering.

An instance of MDE is the Model-Driven Architecture (MDA) [15], which is based on OMG's Meta-Object Facility. It frequently includes UML as its modeling language and a common pipeline of managing and transforming models [16]: A platform-independent model (PIM) is transformed into a platform-specific model (PSM) and eventually into an executable representation (code), being the target platform.

Favre [13] proposes a descriptive model that specifies the concepts that are the cornerstones of MDE: model, metamodel, modeling language and model transformation. This descriptive model is called *megamodel* (Figure 2.1). We extend this model later to illustrate the relationships between MDE concepts and ontology technologies.

In the following section, we analyze and describe the concepts and relations depicted in the Figure 2.1.

2.2.1 Models

The notion of *model* accepted in MDE is that a model is a simplification of a physical system. Apostel [17] uses the word “simplification” to denote a viewpoint of a system from a certain scale where the system is controlled with a certain purpose in mind. This notion is aligned with Rothenberg's definition in which a model is a representation of the reality for a given purpose [18].

The UML specification [3] corroborates this notion describing a model as an abstraction of a physical system. Bezivin [19] and Favre [13] use the association `representedBy` or `representationOf` to connect the system under study to a model. Thus, a system can have multiple models depending on the viewpoint. For example, developers can use the UML and Java to represent different viewpoints of the real-world system *e-shop* (Figure 2.2).

Notice that Favre specifies the notion of a model as a relation to the system because a system can play the role of a model. For example, a Java program can be a model of a system and can also serve as a system for a UML model of the Java program.

2.2.2 Metamodels

While models describe a specific abstraction of reality, metamodels are models of languages used to define models [13, 20]. For example, the structure of the UML language is the metamodel of UML diagrams (Figure 2.3). Thus, we infer that a given UML class diagram conforms to the UML metamodel, i.e., a model conforms to its metamodel.

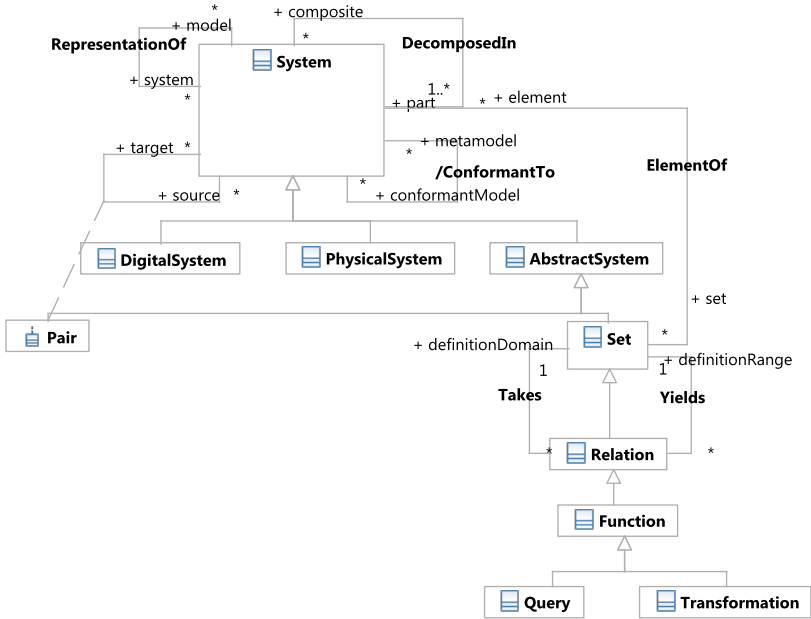


Fig. 2.1. Main Concepts of Megamodel.

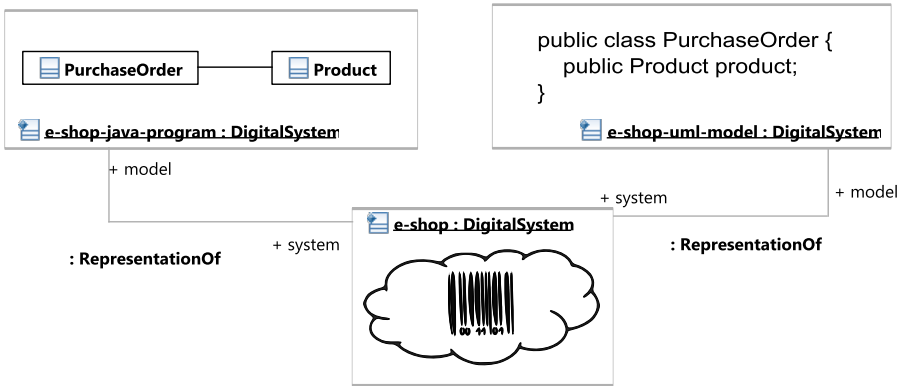


Fig. 2.2. Notion of RepresentationOf in Megamodel.

Metamodel-based approaches are based on a staged architecture of models and metamodels, where the structure of lower level models is defined by higher level metamodels. This staged architecture defines a layered structure, which is applied to define domain-specific languages and general-purpose languages, e.g., UML. Figure 2.4 illustrates a layered structure using UML as metamodeling language.

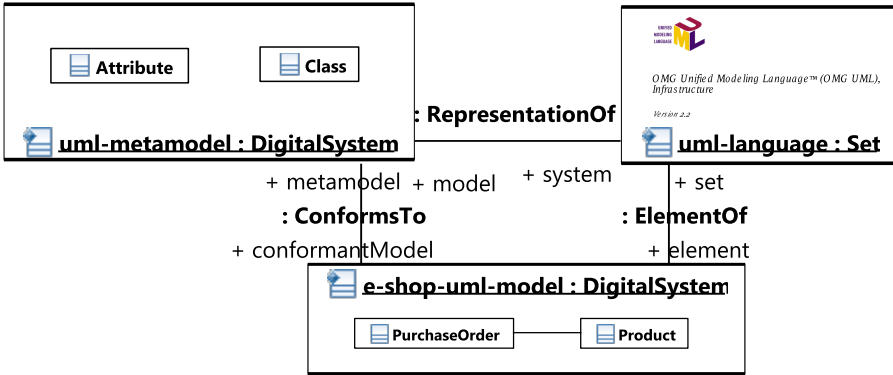


Fig. 2.3. Notion of ConformsTo in Megamodel.

At the top level (M3) is situated the Meta Object Facility [9] (MOF), which is a class-based modeling language that defines itself. Language specifications like the UML specification are viewed as (linguistic) instances [21] of the MOF situated on the metamodel level (M2). The model level (M1) contains concrete models defined by metamodels on M2. These models represent real world systems situated on M0.

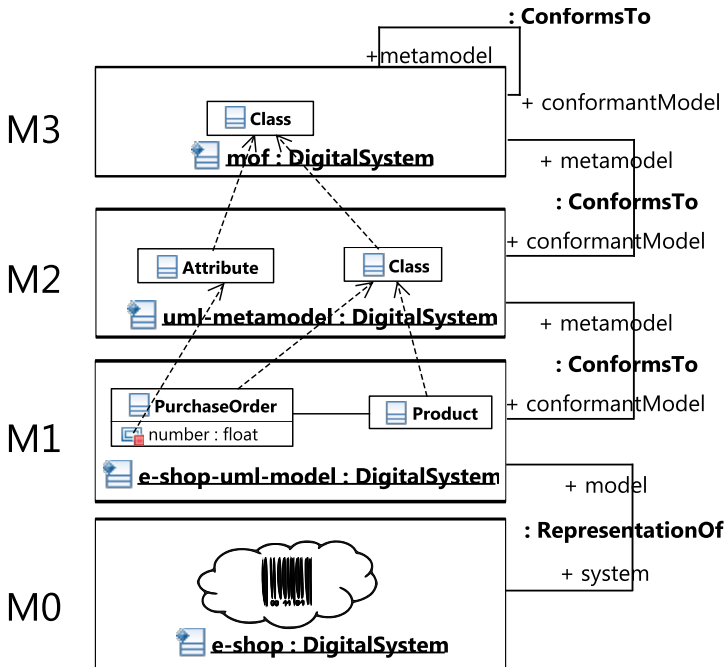


Fig. 2.4. Layered Architecture.

EMOF

Metamodeling rely in constructs like **package**, **class**, **inheritance**, **property** and **operation**. Therefore, OMG reuses common core packages of UML 2.0 and MOF 2.0 to define the essential constructs of MOF – EMOF. These essential constructs are reused by multiple modeling languages, query languages and transformation languages and comprise the core constructs for defining metamodels. Figure 2.5 shows the main classes of EMOF.

A **Package** contains **Types** or nested **Packages**. **DataType** and **Class** are specializations of **Type**. A **class** contains properties and operations. An **Operation** specifies the behavioral features of classifies. An operation specifies a type (**Classifier**), **Parameters** and constraints for executing a behavior.

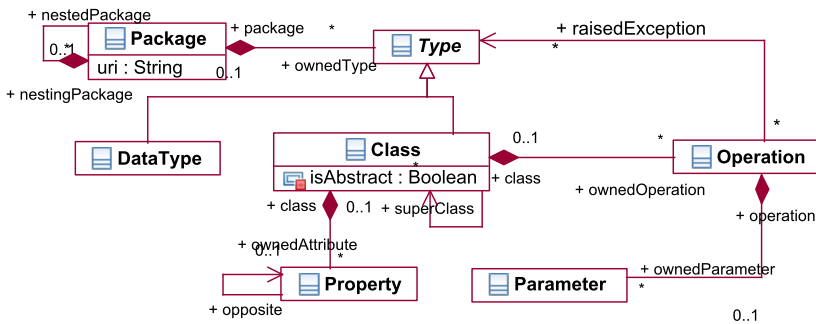


Fig. 2.5. EMOF classes.

Ecore

Ecore is an implementation of EMOF defined in the Eclipse Modeling Framework [22]. Ecore addresses practical issues regarding the structure of EMOF. For example, while EMOF defines one class for defining properties, Ecore defines two types of structural features: attributes and references. The practical aspects inherent in Ecore make it more suitable for adoption.

Figure 2.6 presents the main classes of Ecore. The class **EModelElement** allows to tag model elements with names. **EPackage** is an **EModelElement** that contains classifiers and sub-packages. Properties are defined by references and attributes as structural features. An **EReference** is a type of structural feature that has as type an **EClass**. An **EAttribute** is a type of structural reference that has as type an **EDataType**.

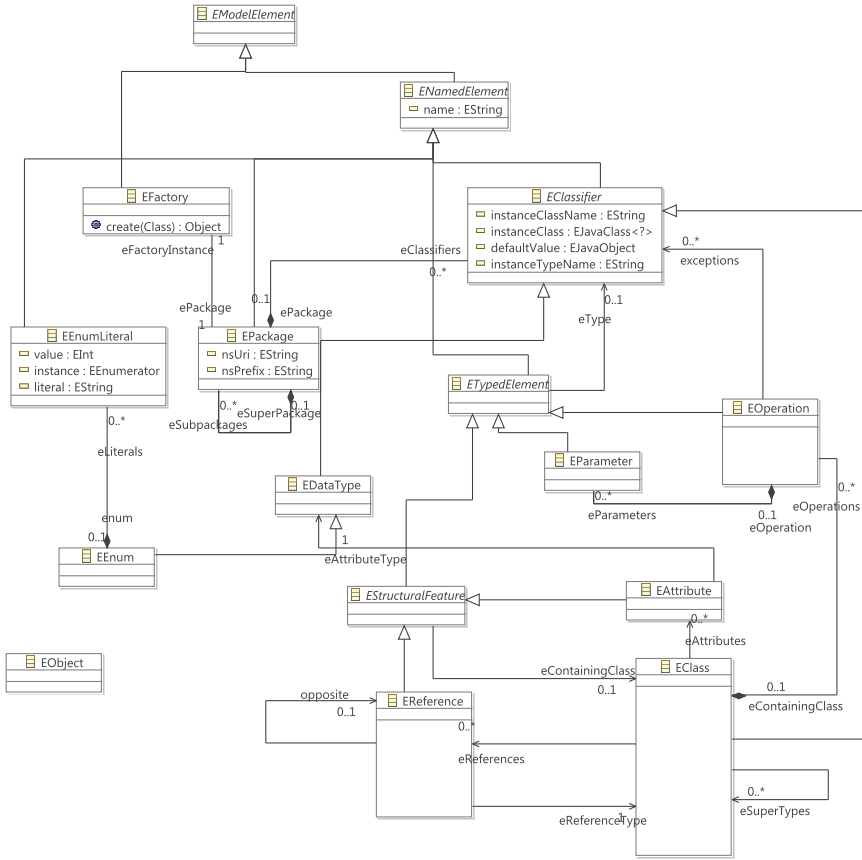


Fig. 2.6. Ecore Structure.

2.2.3 Modeling Languages

Favre defines the role of a language in megamodeling as an abstract system comprising a set of elements [13] or a set of coordinated models [23].

In the realm of modeling languages, i.e., languages for defining models, we identify two categories of languages according to the purpose of usage: general-purpose modeling languages (GPML) and domain-specific modeling languages (DSML).

General-purpose modeling languages (GPML) provide constructs to represent multiple aspects of a system. For example, the Unified Modeling Language (UML) and the Extensible Markup Language (XML) are general-purpose modeling languages used to model a wide variety of systems.

In contrast to GPML, domain-specific modeling languages (DSML) capture the essential concepts of a limited domain. They address specific applications. An Example of DSML is the W3C HyperText Markup Language (HTML).

According to Atkinson and Kühne [21], a language definition covers four components: (i) an abstract syntax, realized by metamodels in MDE, (ii) a concrete

syntax which renders the concepts defined in the metamodel, (iii) well-formedness, defined by constraints on the abstract syntax and (iv) the semantics describing the meaning of the concepts. For Harel and Rumpe [24, 25], a modeling language consists of a syntactic notation, its semantics and semantic mappings that relate the syntactic expressions to the semantic domain. In the next subsections, we describe these components and illustrate them with examples.

Figure 2.7 depicts the relationships and concepts for defining a modeling language using the megamodel structure. The UML metamodel defines the model of the e-shop domain. This model is the input of an injector that serializes the input e-shop UML model into a textual representation of UML (`e-shop.uml.text`). This textual model conforms to the EBNF grammar for UML. A mapping function connects the e-shop UML model to an equivalent representation (`fol-representation`) in first-order logics (FOL), giving semantics to the UML language.

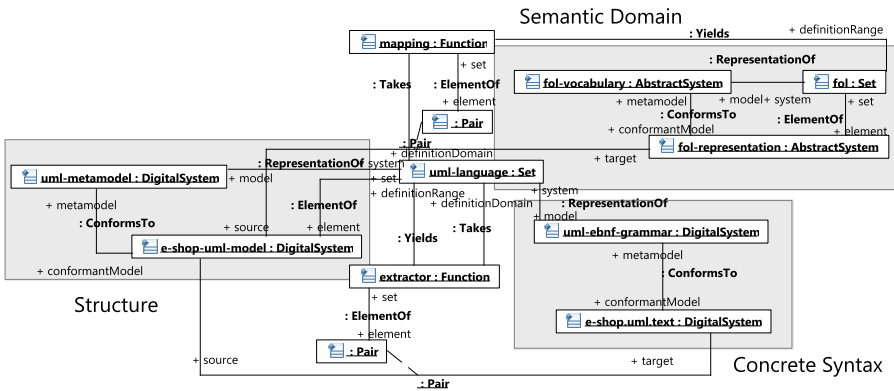


Fig. 2.7. Structure, Semantics and Syntax of the UML Language.

Syntax

The syntax provides a structure for arranging the elements of a given language. It comprises the symbols and signs that represent the language concepts. We identify two types of syntax: textual syntax and diagrammatic syntax.

A textual syntax comprises elements in the form of sequences of characters. A textual syntax defines the valid combinations of words and sentences. Examples of textual notations are the Human-Usable Textual Notation (HUTN) [26], HTML and XML.

A diagrammatic syntax, in contrast, comprises elements in the form of pictorial signs. Examples of diagrammatic notations are UML and the Business Process Modeling Notation (BPMN) [27].

Abstract Syntax

Model-driven engineering as promoted by the OMG is based on UML diagrams as model descriptions. UML class diagrams are a means for describing applica-

tion domains and software systems in the instance-schema-metaschema dimension (ISM-dimension). UML Class diagrams have their roots in entity-relationship (ER) descriptions of database schemas, on the one hand, and in design notations for object-oriented programs, on the other hand.

The OMG Meta Object Facility (MOF) is the relevant subset of UML to describe abstract syntax during metamodeling. In other words, in model-driven engineering, metamodels serve as abstract syntax, whereas models serve as snapshots of languages.

A snapshot is the static configuration of a system or model at a given point in time [28]. It consists of objects, values and links that represent the instances of a metamodel.

Semantics

The semantics of a modeling language allows for determining the truth value of elements in the model with respect to the system being defined. In other words, the semantics of a modeling language provides the meaning to its syntactical elements by mapping them to a meaningful representation [25, 29]. France *et al.* [30] and Harel and Rumpe [24] denominate the target of these mappings semantic model or semantic domain. For Harel and Rumpe [24], the semantic definition of a language comprises a semantic domain and a semantic mapping from the syntax to the semantic domain.

For example, the UML specification [3] defines the semantics of the UML language by explaining each UML modeling concept using natural language. In a formal approach, Berardi [31] defines the semantics of UML class diagrams by mapping UML class diagram constructs to first-order logic (FOL) formulas and, more specifically, to its fragment description logics (see Chapter 3).

2.2.4 Model Transformations

A transformation definition is a set of transformation rules that together describe the conversion of one model in the source language into another related model in the target language [16].

A transformation rule is a function that takes as input one or more model elements of a language and generates one or more model elements of a target language. For example, the transformation model

$$uml: Class(?x) \rightarrow mof: Class(?x)$$

produces one MOF class for each UML class, i.e.,

$$uml: Class(Product) \rightarrow mof: Class(Product)$$

The Object Management Group (OMG) defines a standard model transformation language within the MOF metamodeling environment: Query/View/Transformation (QVT) [32]. The call for proposal of the QVT language encouraged the development of other transformation languages: AGG [33], GReTL [34] and ATL [35].

2.2.5 Query Languages

In order to manipulate models, one requires a language capable of specifying query operations. In common MOF modeling practice, the Object Constraint Language (OCL) [36] is the textual query language used to specify such queries.

Beyond querying, OCL may also be used to specify invariants on classes and types in the class model, to describe pre- and post conditions on operations and methods, and to specify initial and derived rules over a UML model.

The OCL syntax differs from SQL and SPARQL. Indeed, SQL and SPARQL do not require a starting point for query, i.e., it takes a global point of view. OCL, on the other hand, takes the object-oriented point of view, starting the queries from one given class.

In OCL, expressions are written in the context of an instance of a specific class [36]. The reserved word `self` is used to denote this instance.

OCL expressions may be used to specify the body of query operations. Since OCL is a typed language, i.e., each OCL expression is evaluated to a value, expressions may be chained to specify complex queries or invariants.

Let us consider the example of an international e-shop system. A snippet of the corresponding UML class diagram is presented in the Figure 2.8.

The class `TaskCtrl` is responsible for controlling the sales orders. A `SalesOrder` can be a `USSalesOrder` or a `CanSalesOrder`, according to the `Country` where the `Customer` lives.

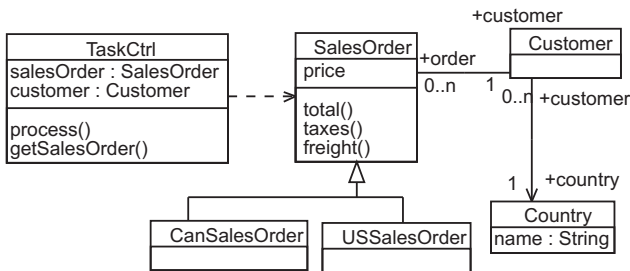


Fig. 2.8. UML Class Diagram of an E-Shop System.

The operation `getSalesOrder()` queries the country of the customer and returns the subclass of `SalesOrder` to be instantiated (either `CanSalesOrder` or `USSalesOrder`). Following the example mentioned above, the target operation may be denoted by the following OCL expression:

```

context TaskCtrl :: getSalesOrder () : OclType
body:
  if customer.country.name = 'USA' then
    USSalesOrder
  else
    if customer.country.name = 'Canada' then
      CanSalesOrder
    endif
  endif
  
```

endif

The example above illustrates the usage of reflection in OCL to deliver the right type. The usage of OCL reflection capabilities is common in model transformations. OCL defines a predefined class called `OclAny`, which acts as a superclass for every type except for the OCL pre-defined collection types. Hence, features of `OclAny` are available on each object in every OCL expression, and every class in a UML model inherit all operations defined on `OclAny`. We highlight two of these operations:

- `oclIsTypeOf(typespec: OclType): Boolean`: evaluates to **true** if the given object is of the type identified by `typespec`;
- `oclIsKindOf(typespec: OclType): Boolean`: evaluates to **true** if the object is of the type identified by `typespec` or one of its subtypes.

We exemplify these operations as follows. The first one evaluates to true if we have an instance of `SalesOrder` and ask whether it is an instance of `SalesOrder`. The second one evaluates to true if we have an instance of `USSalesOrder` and ask whether it is an instance of `USSalesOrder` or if we have an instance of `USSalesOrder` and ask whether it is an instance of `SalesOrder`, *but not the opposite*.

Semantics

The specification of OCL is given in natural language, although an informative semantics based on [37] is part of the specification. Beckert *et al.* [38] propose a translation of OCL into first-order predicate logics. Bucker presents a representation of the semantics of OCL in higher-order logic [39].

2.3 Technical Spaces

The concept of megamodel as used by Favre is platform-independent. Applying this structure into a set of technologies yields a technical space. Kurtev *et al.* [23] have coined the term *technical space* to organize concepts and to compare sets of solutions. A technical space comprises a framework for specifying models and metamodels, and a set of functions that operate on these models.

A common characteristic among several technical spaces is the organization of modeling levels. A technical space usually comprises a *metametamodel* (M3) that defines itself and defines metamodels (M2). Metamodels define models (M1) that represent systems (M0). Additionally, a technical space has a set of languages associated with it. In the context of the MDE structure presented in Section 2.2, we consider two types of languages: query languages and transformation languages.

Figure 2.9 shows the MOF Technical Space. In MOF, the metametamodel is MOF itself and an example of metamodel is UML. The query metamodel is OCL, whereas examples of transformation metamodels are ATL and QVT.

2.4 Conclusion

This chapter describes the main concepts and techniques around model-driven engineering. It provides the fundamental understanding about the role of model-driven

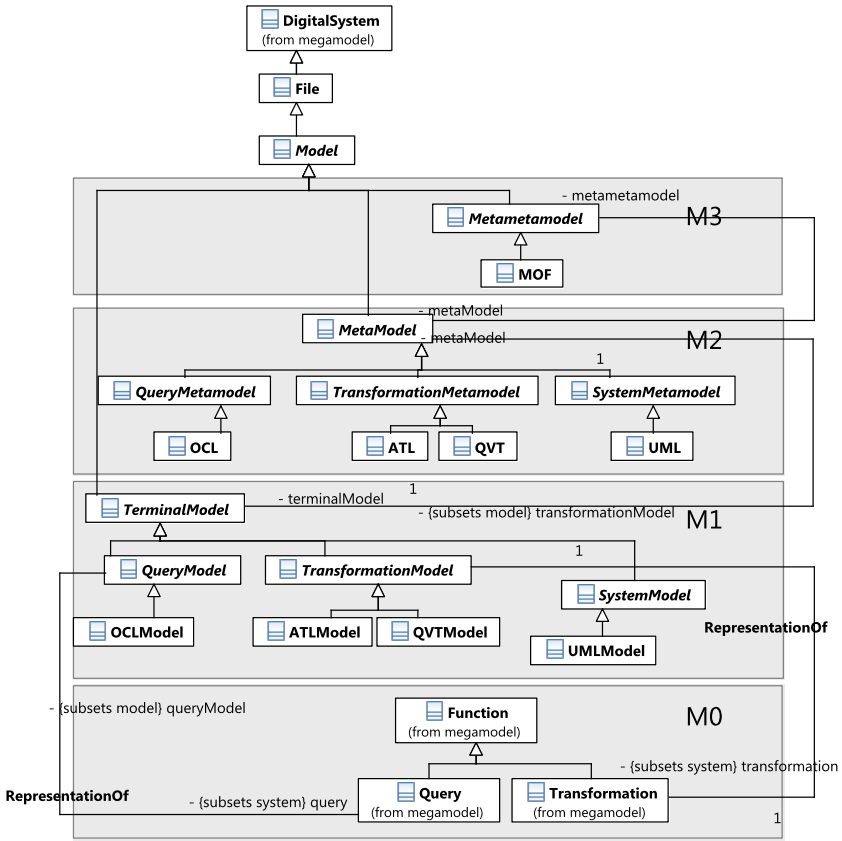


Fig. 2.9. MOF Technical Space.

engineering in software engineering. The contribution is a descriptive model connecting the main concepts of MDE that can be used to model further technical spaces. We use the descriptive model in further chapters for organizing the concepts and technologies presented in this thesis.

Ontology Foundations

Summary. Ontology technologies organize system knowledge in conceptual domains according to its meaning. It addresses various software engineering needs by identifying, abstracting and rationalizing commonalities, and checking for inconsistencies across system specifications. This chapter describes the state of the art of ontology technologies. The result is an outline of the languages and services around the Web Ontology Language. Additionally, we arrange these blocks using a model-driven perspective.

3.1 Introduction

Ontologies play a fundamental role in bridging computing and human understanding. The field of artificial intelligence has been studying ontologies under multiple perspectives like knowledge engineering and natural-language processing.

Ontology languages have constructs similar to UML class-based modeling, e.g., classes, properties and data cardinalities. Indeed, ontology languages provide various means for describing classes to the extent that explicit typing is not compulsory.

This chapter gives an overview of the scientific and technical results around ontologies, ontology languages and their corresponding reasoning technologies used in model-driven engineering. We introduce the concept of ontology in Section 3.2. Section 3.3 presents the W3C standard ontology language for ontology-based information systems – the Web Ontology Language. Section 3.4 describes ontology services like reasoning and querying. In Section 3.6 we describe the rule language for the semantic web.

Figure 2.4 presents the stack of technologies described in this chapter above in colored boxes. In Section 3.8, we describe the relations between these technologies using technical spaces.

3.2 Ontology

The word ontology has its origin in philosophy, and it denotes the philosophical study of the nature of existence. In this sense, ontology involves identifying the

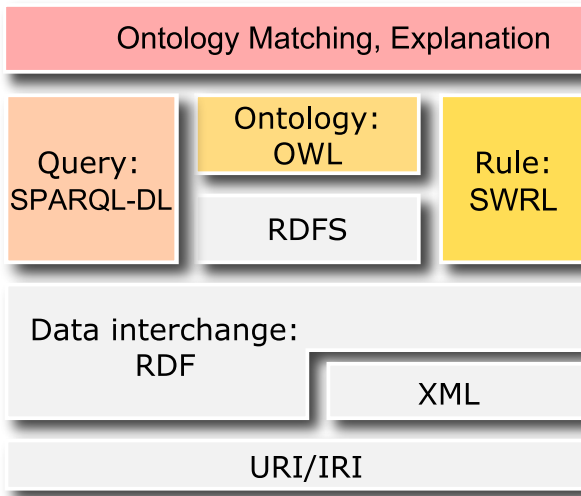


Fig. 3.1. Semantic Web Stack Covered in this Chapter.

fundamental categories of things. For example, ontological categories might be used to group objects as essential or existential, abstract or concrete.

Computer science took the term ontology and attributed a technical meaning to it: “An ontology is an explicit specification of a conceptualization” [6]. Studer *et al.* [40] argue that this specification is also formal, i.e., An ontology is an “explicit and formal specification of a conceptualization” [41].

In the semantic web field, ontologies provide shared domain conceptualizations representing knowledge by a vocabulary and, typically, logical definitions [6] to model the problem domain as well as the solution domain. Developers usually use ontologies as domain models for ontology-based information systems.

3.2.1 Ontology Modeling

The Web Ontology Language (OWL) [5] provides a class definition language for ontologies, i.e., OWL allows for the definition of classes by required and implied logical constraints on properties of their members.

The process of modeling ontologies exhibits a couple of overlaps with the development of conceptual models [42]. Requirements elicitation is followed by the design phase, where classes and relationships are defined similarly as in a UML class diagram. This stage, however, is followed by another step that depends on the ontology modeling paradigm and its corresponding language.

In the realm of description logic based ontologies [43], the strength of ontology modeling lies in disentangling conceptual hierarchies with an abundance of relationships of multiple generalization of classes. For this purpose, description logics allow for deriving concept hierarchies from logically precisely defined class axioms, stating necessary and sufficient conditions of class membership.

In the realm of logic programming-based ontologies [44], the strength of ontology modeling lies in a formally integrated consideration of expressive class and rule definitions.

In both paradigms, the structure of class definitions may be validated by introspecting the model, using corresponding reasoning technology. In the first model of description logics, this is indeed the focus of its reasoning technology while, in the second model, the focus of the corresponding reasoning technology is on reasoning with objects in a logical framework.

An ontology constitutes a formal conceptual model. Hence, its core concerns, i.e., formal definitions of classes and relationship, are germane to the software engineering community. However, ontologies have always been used differently than conceptual models in software and data engineering. Hence, the perspectives on modeling and using ontologies are slightly twisted if compared to conceptual models such as UML class diagrams.

For the sake of illustration, Figure 3.2 depicts an incomplete specification of the example presented in the Figure 2.8 using a description logic syntax. The identifier `Customer` is used to declare the corresponding class (3.1) as a specialization of `Thing` (\top), since classes in OWL are specializations of the reserved class `Thing`. The class `Consumer` has a restriction on property `country` with exactly one `Country` (3.2). The class `Country` *contains* the individuals `USA` and `CANADA` (3.3). `USSalesOrder` is defined as a subclass of a `SalesOrder` with at least one restriction on the property `country`, the value range must include the country `USA` (3.4). The description of the class `CanSalesOrder` is analogous. The intersection of both classes is empty (\perp), i.e., they are disjoint (3.6). The class `SalesOrder` is equal to the union of `CanSalesOrder` and `USSalesOrder`, i.e., it is a complete generalization of both classes (3.7).

3.3 The Ontology Web Language

The language and reasoning paradigm that has been predominantly used and researched is the family of description logic languages covered by the W3C recommendation Web Ontology Language (OWL) [5]. Description logic languages allow for capturing the schema in the “terminological box” (T-Box) and the objects and their relationships in the “assertional box” (A-Box). The terminological box captures knowledge about the class level, i.e., independent of a given situation.

The sub-languages of OWL (or profiles) differ in the set of modeling constructs they support. Depending on the exact configuration of allowed modeling primitives, a profile requires sound and complete reasoning algorithms that are NLogSpace-Complete (OWL 2 QL), PTime-Complete (OWL 2 EL and OWL 2 RL), NExpTime-Complete (OWL DL) or 2NExpTimeComplete (OWL 2) [45].

Each OWL sub-language corresponds to a given set of constructs in description logics. For example, OWL 2 EL corresponds to the description logic language $EL++$ and OWL DL corresponds to $SHOIN(D)$. OWL 2 extends both and it corresponds to $SROIQ(D)$ (see [43] for more about description logics).

3.3.1 OWL 2 Syntax

In order to save and share OWL 2 ontologies, one requires a concrete syntax for OWL 2. There are multiple concrete syntax notations for OWL 2: RDF/XML syn-

$$Customer \sqsubseteq \top \quad (3.1)$$

$$Customer \sqsubseteq = 1country.Country \quad (3.2)$$

$$\{USA, CANADA\} \sqsubseteq Country \quad (3.3)$$

$$USSalesOrder \sqsubseteq SalesOrder \sqcap \exists customer.(Customer \sqcap \exists country.\{USA\}) \quad (3.4)$$

$$CanSalesOrder \sqsubseteq SalesOrder \sqcap \exists customer.(Customer \sqcap \exists country.\{CANADA\}) \quad (3.5)$$

$$CanSalesOrder \sqcap USSalesOrder \sqsubseteq \perp \quad (3.6)$$

$$SalesOrder \equiv CanSalesOrder \sqcup USSalesOrder \quad (3.7)$$

$$customer \equiv order^- \quad (3.8)$$

$$country \equiv customer^- \quad (3.9)$$

$$SalesOrder(ORDER1) \quad (3.10)$$

$$Customer(HANS) \quad (3.11)$$

$$country(HANS, CANADA) \quad (3.12)$$

$$Customer(JOHN) \quad (3.13)$$

$$country(JOHN, USA) \quad (3.14)$$

$$customer(ORDER1, JOHN) \quad (3.15)$$

Fig. 3.2. E-Shop Example with Description Logic Syntax.

tax, OWL/XML syntax, Manchester Syntax, Functional Syntax and Turtle. Each of these notations is suitable for a specific purpose. In this work, we use the OWL 2 Functional Syntax due to its axiomatic nature, facilitating the analysis of the OWL 2 formal structure.

An OWL 2 Vocabulary $\mathcal{V}_O = (\mathcal{V}_{cls}, \mathcal{V}_{op}, \mathcal{V}_D, \mathcal{V}_{dp}, \mathcal{V}_{ind}, \mathcal{V}_{lt})$ is a 6-tuple consisting of the following elements:

1. \mathcal{V}_{cls} is a set of named classes, class expressions and the built-in classes `owl:Thing` and `owl:Nothing`.
2. \mathcal{V}_{op} is a set of object properties, including the built-in object properties `owl:topObjectProperty` and `owl:bottomObjectProperty`.
3. \mathcal{V}_{dp} is a set of data properties, including the built-in data properties `owl:topDataProperty` and `owl:bottomDataProperty`.
4. \mathcal{V}_{ind} is a set of individuals.
5. \mathcal{V}_{dt} is a set of datatypes.
6. \mathcal{V}_{lt} is a set of literals.

Given the vocabulary \mathcal{V}_O , we use the following convention in the tables 3.1 to 3.4:

- OP indicates an object property;
- OPE indicates an object property expression;
- DP indicates a data property;
- DPE indicates a data property expression;
- C indicates a class;

- CE indicates a class expression;
- DT indicates a datatype;
- DR indicates a data range;
- a indicates an individual (named or anonymous);
- It indicates a literal.

In order to illustrate the equivalences between OWL 2 and description logics, we present a list of OWL 2 axioms with their corresponding representation in description logics. Tables 3.1, 3.2 and 3.3 present lists of axioms for class expressions, object properties and data properties. Table 3.4 presents the list of assertions and Table 3.5 the list of class expressions.

OWL 2 Syntax	Description Logic Syntax
SubClassOf(CE_1 CE_2)	$CE_1 \sqsubseteq CE_2$
EquivalentClasses($CE_1 \dots CE_n$)	$CE_1 \equiv \dots \equiv CE_n$
DisjointClasses($CE_1 \dots CE_n$)	$CE_1 \sqcap \dots \sqcap CE_n \equiv \perp$
DisjointUnion(C $CE_1 \dots CE_n$)	$CE_1 \sqcup \dots \sqcup CE_n \equiv C$ and $CE_1 \sqcap \dots \sqcap CE_n \equiv \perp$

Table 3.1. Syntax of Class Expression Axioms.

OWL 2 Syntax	Description Logic Syntax
SubObjectPropertyOf(ObjectPropertyChain ($OPE_1 \dots OPE_n$) OPE)	$OPE_1 \circ \dots \circ OPE_n \sqsubseteq OPE$
SubObjectPropertyOf(OPE_1 OPE_2)	$OPE_1 \sqsubseteq OPE_2$
EquivalentObjectProperties($OPE_1 \dots OPE_n$)	$OPE_1 \equiv \dots \equiv OPE_n$
DisjointObjectProperties($OPE_1 \dots OPE_n$)	$OPE_1 \sqcap \dots \sqcap OPE_n \equiv \perp$
InverseObjectProperties(OPE_1 OPE_2)	$OPE_1 \equiv OPE_2^-$
ObjectPropertyDomain(OPE CE)	$\exists OPE.\top \sqsubseteq CE$
ObjectPropertyRange(OPE CE)	$\top \sqsubseteq \forall OPE.CE$
FunctionalObjectProperty(OPE)	$\top \sqsubseteq \leq 1 OPE$
InverseFunctionalObjectProperty(OPE)	$\top \sqsubseteq \leq 1 OPE^-$
ReflexiveObjectProperty(OPE)	$\top \sqsubseteq \exists OPE.Self$
IrreflexiveObjectProperty(OPE)	$\exists OPE.Self \sqsubseteq \perp$
SymmetricObjectProperty(OPE)	$OPE \sqsubseteq OPE^-$
AsymmetricObjectProperty(OPE)	$OPE \sqsubseteq \neg OPE^-$
TransitiveObjectProperty(OPE)	OPE^+

Table 3.2. Syntax of Object Property Axioms.

OWL 2 Syntax	Description Logic Syntax
SubDataPropertyOf($DPE_1 DPE_2$)	$DPE_1 \sqsubseteq DPE_2$
EquivalentDataProperties($DPE_1 \dots DPE_n$)	$DPE_1 \equiv \dots \equiv DPE_n$
DisjointDataProperties($DPE_1 \dots DPE_n$)	$DPE_1 \sqcap \dots \sqcap DPE_n \equiv \perp$
DataPropertyDomain($DPE CE$)	$\exists DPE.Literal \sqsubseteq DR$
DataPropertyRange($DPE DR$)	$Literal \sqsubseteq \forall DPE.DR$
FunctionalDataProperty(DPE)	$Literal \sqsubseteq \leq 1 DPE$
DatatypeDefinition($DT DR$)	$DT \equiv DR$

Table 3.3. Syntax of Data Property Axioms.

OWL 2 Syntax	Description Logic Syntax
SameIndividual($a_1 \dots a_n$)	$a_1 \doteq \dots \doteq a_n$
DifferentIndividuals($a_1 \dots a_n$)	$a_1 \neq \dots \neq a_n$
ClassAssertion($CE a$)	$CE(a)$
ObjectPropertyAssertion($OPE a_1 a_2$)	$OPE(a_1, a_2)$
NegativeObjectPropertyAssertion($OPE a_1 a_2$)	$\neg OPE(a_1, a_2)$
DataPropertyAssertion($DPE a lt$)	$DPE(a_1, lt)$
NegativeDataPropertyAssertion($DPE a lt$)	$\neg DPE(a_1, lt)$

Table 3.4. Syntax of Assertions.

3.3.2 OWL 2 Semantics

OWL 2 corresponds to the description logic $SROIQ(D)$ [46] and has a model-theoretic semantics defined by interpretations [47]. Model-theoretic semantics allows for interpreting unambiguously the legitimate expressions of a given language; for evaluating the truth of a language statement under a particular interpretation; and for carrying out automated reasoning with these statements [48].

An interpretation is a pair $\mathcal{I} = (\Delta^{\mathcal{I}}, \cdot^{\mathcal{I}})$, where $\Delta^{\mathcal{I}}$ is the domain and $\cdot^{\mathcal{I}}$ is the interpretation function that satisfies the conditions described in Tables 3.7 - 3.11. We say an interpretation \mathcal{I} satisfies an ontology \mathcal{O} if and only if it satisfies every axiom in \mathcal{O} .

3.3.3 World Assumption and Name Assumption

Analyzing the semantics of OWL, we can see that OWL does not assume unique names for individuals. For example, according to the definition of functional properties in Table 3.8 ($\forall x, y_1, y_2 : (x, y_1) \in (OPE)^{\mathcal{I}}$ and $(x, y_2) \in (OPE)^{\mathcal{I}}$ implies $y_1 = y_2$), for the two pairs of functional object property assertions $p(x, y_1)$ and $p(x, y_2)$, it is inferred that y_1 and y_2 are the same individual. The knowledge base becomes inconsistent only if it is asserted that y_1 and y_2 are different individuals ($y_1 \neq y_2$).

OWL 2 Syntax	Description Logic Syntax
ObjectIntersectionOf($CE_1 \dots CE_n$)	$CE_1 \sqcap \dots \sqcap CE_n$
ObjectUnionOf($CE_1 \dots CE_n$)	$CE_1 \sqcup \dots \sqcup CE_n$
ObjectComplementOf(CE)	$\neg CE$
ObjectOneOf($a_1 \dots a_n$)	$\{a_1, \dots, a_n\}$
ObjectSomeValuesFrom($OPE CE$)	$\exists OPE.CE$
ObjectAllValuesFrom($OPE CE$)	$\forall OPE.CE$
ObjectHasValue($OPE a$)	$OPE.\{a\}$
ObjectHasSelf(OPE)	$\exists OPE.Self$
ObjectMinCardinality($n OPE$)	$\geq n OPE$
ObjectMaxCardinality($n OPE$)	$\leq n OPE$
ObjectExactCardinality($n OPE$)	$= n OPE$
ObjectMinCardinality($n OPE CE$)	$\geq n OPE.CE$
ObjectMaxCardinality($n OPE CE$)	$\leq n OPE.CE$
ObjectExactCardinality($n OPE CE$)	$= n OPE.CE$
DataSomeValuesFrom($DPE_1 \dots DPE_n DR$)	$\{\exists DPE_1.DR\} \dots \{\exists DPE_n.DR\}$
DataAllValuesFrom($DPE_1 \dots DPE_n DR$)	$\{\forall DPE_1.DR\} \dots \{\forall DPE_n.DR\}$
DataHasValue($DPE lt$)	$DPE.\{lt\}$
DataMinCardinality($n DPE$)	$\geq n DPE$
DataMaxCardinality($n DPE$)	$\leq n DPE$
DataExactCardinality($n DPE$)	$= n DPE$
DataMinCardinality($n DPE DR$)	$\geq n DPE.DR$
DataMaxCardinality($n DPE DR$)	$\leq n DPE.DR$
DataExactCardinality($n DPE DR$)	$= n DPE.DR$

Table 3.5. Syntax of Class Expressions.

OWL 2 Syntax	Description Logic Syntax
DataIntersectionOf($DR_1 \dots DR_n$)	$DR_1 \sqcap \dots \sqcap DR_n$
DataUnionOf($DR_1 \dots DR_n$)	$DR_1 \sqcup \dots \sqcup DR_n$
DataComplementOf(DR)	$\neg DR$
DataOneOf($lt_1 \dots lt_n$)	$\{lt_1, \dots, lt_n\}$

Table 3.6. Syntax of Data Ranges.

In contrast, according to the semantics of UML-class based modeling, the model would be inconsistent since it is assumed by default that y_1 and y_2 are different individuals.

Another important assumption is whether the set of instances is considered complete or not (world-assumption). The underlying semantics of UML-based class modeling assumes that the set of instances of a given model is complete, i.e., the set of instances has exactly one interpretation. In this one interpretation, the classes and relations in the model are interpreted by the objects and tuples in the instance.

Description Logic Syntax	Semantics
$CE_1 \sqsubseteq CE_2$	$(CE_1)^{\mathcal{I}} \subseteq (CE_2)^{\mathcal{I}}$
$CE_1 \equiv \dots \equiv CE_n$	$(CE_j)^{\mathcal{I}} = (CE_k)^{\mathcal{I}}$ for each $1 \leq j \leq n$ and each $1 \leq k \leq n$
$CE_1 \sqcap \dots \sqcap CE_n \equiv \perp$	$(CE_j)^{\mathcal{I}} \cap (CE_k)^{\mathcal{I}} = \emptyset$ for each $1 \leq j \leq n$ and each $1 \leq k \leq n$ such that $j \neq k$
$CE_1 \sqcup \dots \sqcup CE_n \equiv C$ and $CE_1 \sqcap \dots \sqcap CE_n \equiv \perp$	$(CE_1)^{\mathcal{I}} \cup \dots \cup (CE_n)^{\mathcal{I}} = (C)^{\mathcal{I}}$ and $(CE_j)^{\mathcal{I}} \cap (CE_k)^{\mathcal{I}} = \emptyset$ for each $1 \leq j \leq n$ and each $1 \leq k \leq n$ such that $j \neq k$

Table 3.7. Semantics of Class Expression Axioms.

Description Logic Syntax	Semantics
$OPE_1 o \dots o OPE_n \sqsubseteq OPE$	$\forall y_0, \dots, y_n : (y_0, y_1) \in (OPE_1)^{\mathcal{I}}$ and ... and $(y_{n-1}, y_n) \in (OPE_n)^{\mathcal{I}}$ implies $(y_0, y_n) \in (OPE)^{\mathcal{I}}$
$OPE_1 \sqsubseteq OPE_2$	$(OPE_1)^{\mathcal{I}} \subseteq (OPE_2)^{\mathcal{I}}$
$OPE_1 \equiv \dots \equiv OPE_n$	$(OPE_j)^{\mathcal{I}} = (OPE_k)^{\mathcal{I}}$ for each $1 \leq j \leq n$ and each $1 \leq k \leq n$
$OPE_1 \sqcap \dots \sqcap OPE_n \equiv \perp$	$(OPE_j)^{\mathcal{I}} \cap (OPE_k)^{\mathcal{I}} = \emptyset$ for each $1 \leq j \leq n$ and each $1 \leq k \leq n$ such that $j \neq k$
$\exists OPE. \top \sqsubseteq CE$	$\forall x, y : (x, y) \in (OPE)^{\mathcal{I}}$ implies $x \in (CE)^{\mathcal{I}}$
$\top \sqsubseteq \forall OPE. CE$	$\forall x, y : (x, y) \in (OPE)^{\mathcal{I}}$ implies $y \in (CE)^{\mathcal{I}}$
$\top \sqsubseteq \leq 1 OPE$	$\forall x, y_1, y_2 : (x, y_1) \in (OPE)^{\mathcal{I}}$ and $(x, y_2) \in (OPE)^{\mathcal{I}}$ implies $y_1 = y_2$
$\top \sqsubseteq \leq 1 OPE^-$	$\forall x_1, x_2, y : (x_1, y) \in (OPE)^{\mathcal{I}}$ and $(x_2, y) \in (OPE)^{\mathcal{I}}$ implies $x_1 = x_2$
$\top \sqsubseteq \exists OPE. Self$	$\forall x : x \in \Delta^{\mathcal{I}}$ implies $(x, x) \in (OPE)^{\mathcal{I}}$
$\exists OPE. Self \sqsubseteq \perp$	$\forall x : x \in \Delta^{\mathcal{I}}$ implies $(x, x) \notin (OPE)^{\mathcal{I}}$
$OPE \sqsubseteq OPE^-$	$\forall x, y : (x, y) \in (OPE)^{\mathcal{I}}$ implies $(y, x) \in (CE)^{\mathcal{I}}$
$OPE \sqsubseteq \neg OPE^-$	$\forall x, y : (x, y) \in (OPE)^{\mathcal{I}}$ implies $(y, x) \notin (CE)^{\mathcal{I}}$
OPE^+	$\forall x, y, z : (x, y) \in (OPE)^{\mathcal{I}}$ and $(y, z) \in (OPE)^{\mathcal{I}}$ implies $(x, z) \in (CE)^{\mathcal{I}}$

Table 3.8. Semantics of Object Property Axioms.

Therefore, the lack of information in the set of objects and values that are instance of a UML-class based model is interpreted as negative information, since there is only one interpretation and everything that does not belong to this interpretation belongs to its complement (closed-world assumption).

In contrast, OWL assumes incomplete knowledge by default. The set of individuals, literals and property assertions has many different interpretations. Therefore, the absence of information in this set is only the evidence of lack of knowledge (open-world assumption).

Description Logic Syntax	Semantics
$DPE_1 \sqsubseteq DPE_2$	$(DPE_1)^{\mathcal{I}} \subseteq (DPE_2)^{\mathcal{I}}$
$DPE_1 \equiv \dots \equiv DPE_n$	$(DPE_j)^{\mathcal{I}} = (DPE_k)^{\mathcal{I}}$ for each $1 \leq j \leq n$ and each $1 \leq k \leq n$
$DPE_1 \sqcap \dots \sqcap DPE_n \equiv \perp$	$(DPE_j)^{\mathcal{I}} \cap (DPE_k)^{\mathcal{I}} = \emptyset$ for each $1 \leq j \leq n$ and each $1 \leq k \leq n$ such that $j \neq k$
$\exists DPE.Literal \sqsubseteq DR$	$\forall x, y : (x, y) \in (DPE)^{\mathcal{I}}$ implies $x \in (DR)^{\mathcal{I}}$
$Literal \sqsubseteq \forall DPE.DR$	$\forall x, y : (x, y) \in (DPE)^{\mathcal{I}}$ implies $y \in (DR)^{\mathcal{I}}$
$Literal \sqsubseteq \leq 1 DPE$	$\forall x, y_1, y_2 : (x, y_1) \in (DPE)^{\mathcal{I}}$ and $(x, y_2) \in (DPE)^{\mathcal{I}}$ implies $y_1 = y_2$
$DT \equiv DR$	$(DT)^{\mathcal{I}} = (DR)^{\mathcal{I}}$

Table 3.9. Semantics of Data Property Axioms.

Description Logic Syntax	Semantics
$a_1 \doteq \dots \doteq a_n$	$(a_j)^{\mathcal{I}} = (a_k)^{\mathcal{I}}$ for each $1 \leq j \leq n$ and each $1 \leq k \leq n$
$a_1 \neq \dots \neq a_n$	$(a_j)^{\mathcal{I}} \neq (a_k)^{\mathcal{I}}$ for each $1 \leq j \leq n$ and each $1 \leq k \leq n$ such that $j \neq k$
$CE(a)$	$(a)^{\mathcal{I}} \in (CE)^{\mathcal{I}}$
$OPE(a_1, a_2)$	$((a_1)^{\mathcal{I}}, (a_2)^{\mathcal{I}}) \in (OPE)^{\mathcal{I}}$
$\neg OPE(a_1, a_2)$	$((a_1)^{\mathcal{I}}, (a_2)^{\mathcal{I}}) \notin (OPE)^{\mathcal{I}}$
$DPE(a_1, lt)$	$((a_1)^{\mathcal{I}}, (lt)^{\mathcal{I}}) \in (DPE)^{\mathcal{I}}$
$\neg DPE(a_1, lt)$	$((a_1)^{\mathcal{I}}, (lt)^{\mathcal{I}}) \notin (DPE)^{\mathcal{I}}$

Table 3.10. Semantics of Assertions.

Each of these approaches (OWA and CWA) has its proper place. OWA serves to describe knowledge in an extensible way, since OWL is monotonic. The OWA is suitable to represent the core knowledge of a domain.

Closed-world assumption is appropriate for defining integrity constraints and validation based on negation as failure (NAF). The Negation as failure inference allows for deriving the negation of a proposition if it is not possible to obtain the affirmation of this proposition.

Let us use the example depicted in Table 3.2. We consider the following instances and property assertions: `country(JOHN, USA)`, `country(HANS, CANADA)`. Under the CWA, querying the ontology for customers who are *not* American (`Customer` \sqcap \neg `country`.{USA}?) produces HANS. Since there is no fact about HANS being American, it is derived that he is not. The same query under OWA would produce no results, since there are no facts asserting that HANS is not American. To achieve the same result, we need to close the domain.

There are OWL constructs that can be used to constrain the interpretation to a defined set of individuals, i.e., to *close the domain* (closed-domain assumption). Figure 3.3 shows axioms used to close the domain of the ontology presented in the

Description Logic Syntax	Semantics
$CE_1 \sqcap \dots \sqcap CE_n$	$(CE_1)^{\mathcal{I}} \cap \dots \cap (CE_n)^{\mathcal{I}}$
$CE_1 \sqcup \dots \sqcup CE_n$	$(CE_1)^{\mathcal{I}} \cup \dots \cup (CE_n)^{\mathcal{I}}$
$\neg CE$	$\Delta^{\mathcal{I}} (CE)^{\mathcal{I}}$
$\{a_1, \dots, a_n\}$	$\{(a_1)^{\mathcal{I}}, \dots, (a_n)^{\mathcal{I}}\}$
$\exists OPE.CE$	$\{x \mid \exists y : (x, y) \in (OPE)^{\mathcal{I}} \text{ and } y \in (CE)^{\mathcal{I}}\}$
$\forall OPE.CE$	$\{x \mid \forall y : (x, y) \in (OPE)^{\mathcal{I}} \text{ implies } y \in (CE)^{\mathcal{I}}\}$
$OPE.\{a\}$	$\{x \mid (x, (a)^{\mathcal{I}}) \in (OPE)^{\mathcal{I}}\}$
$\exists OPE.Self$	$\{x \mid (x, x) \in (OPE)^{\mathcal{I}}\}$
$\geq n OPE$	$\{x \mid \#\{y \mid (x, y) \in (OPE)^{\mathcal{I}}\} \geq n\}$
$\leq n OPE$	$\{x \mid \#\{y \mid (x, y) \in (OPE)^{\mathcal{I}}\} \leq n\}$
$= n OPE$	$\{x \mid \#\{y \mid (x, y) \in (OPE)^{\mathcal{I}}\} = n\}$
$\geq n OPE.CE$	$\{x \mid \#\{y \mid (x, y) \in (OPE)^{\mathcal{I}} \text{ and } y \in (CE)^{\mathcal{I}}\} \geq n\}$
$\leq n OPE.CE$	$\{x \mid \#\{y \mid (x, y) \in (OPE)^{\mathcal{I}} \text{ and } y \in (CE)^{\mathcal{I}}\} \leq n\}$
$= n OPE.CE$	$\{x \mid \#\{y \mid (x, y) \in (OPE)^{\mathcal{I}} \text{ and } y \in (CE)^{\mathcal{I}}\} = n\}$
$\{\exists DPE_1.DR\} \dots \{\exists DPE_n.DR\}$	$\{x \mid \exists y_1, \dots, y_n : (x, y_k) \in (DPE_k)^{\mathcal{I}} \text{ for each } 1 \leq k \leq n \text{ and } (y_1, \dots, y_n) \in (DR)^{\mathcal{I}}\}$
$\{\forall DPE_1.DR\} \dots \{\forall DPE_n.DR\}$	$\{x \mid \forall y_1, \dots, y_n : (x, y_k) \in (DPE_k)^{\mathcal{I}} \text{ for each } 1 \leq k \leq n \text{ and } (y_1, \dots, y_n) \in (DR)^{\mathcal{I}}\}$
$DPE.\{lt\}$	$\{x \mid (x, (lt)^{\mathcal{I}}) \in (DPE)^{\mathcal{I}}\}$
$\geq n DPE$	$\{x \mid \#\{y \mid (x, y) \in (DPE)^{\mathcal{I}}\} \geq n\}$
$\leq n DPE$	$\{x \mid \#\{y \mid (x, y) \in (DPE)^{\mathcal{I}}\} \leq n\}$
$= n DPE$	$\{x \mid \#\{y \mid (x, y) \in (DPE)^{\mathcal{I}}\} = n\}$
$\geq n DPE.DR$	$\{x \mid \#\{y \mid (x, y) \in (DPE)^{\mathcal{I}} \text{ and } y \in (DR)^{\mathcal{I}}\} \geq n\}$
$\leq n DPE.DR$	$\{x \mid \#\{y \mid (x, y) \in (DPE)^{\mathcal{I}} \text{ and } y \in (DR)^{\mathcal{I}}\} \leq n\}$
$= n DPE.DR$	$\{x \mid \#\{y \mid (x, y) \in (DPE)^{\mathcal{I}} \text{ and } y \in (DR)^{\mathcal{I}}\} = n\}$

Table 3.11. Semantics of Class Expression.

Figure 3.2. One may declare that the set of all existing individuals comprises $\{\text{HANS}, \text{JOHN}, \text{ORDER1}, \text{USA}, \text{CANADA}\}$ (Line 3.16). Moreover, because of the non unique name assumption, we have to assert that all individuals are different from each other (Line 3.17). Additionally, we declare that the classes `SalesOrder`, `Customer` and `Country` are disjoint from each other (Line 3.18) as well as the subclasses of `SalesOrder` are (Line 3.19).

By adding these axioms, we can also deliver the same results of CWA using OWA in the query aforementioned. We can infer that `HANS` does not live in `USA`, since `HANS` is a `Customer`, a `Customer` muss live in exactly one country (3.2), `HANS` lives in `CANADA`, and `CANADA` is different from `USA`.

However, closing the domain does not imply CWA because NAF is not in place. For example, if we remove the object property assertion `country(HANS, CANADA)` and ask the same query, using CWA, the result is still `HANS` because the lack of information about `HANS`. By using OWA, there are no results, since the lack of information about `HANS` is not enough to infer that he is not American.

$$\{HANS, JOHN, ORDER1, USA, CANADA\} \equiv \top \quad (3.16)$$

$$HANS \neq JOHN \neq ORDER1 \neq USA \neq CANADA \quad (3.17)$$

$$SalesOrder \sqcap Customer \sqcap Country \equiv \perp \quad (3.18)$$

$$CanSalesOrder \sqcap USSalesOrder \equiv \perp \quad (3.19)$$

Fig. 3.3. Closing the Domain of E-Shop with OWL Axioms.

Research in the field of combining description logics and logic programming [49] provides solutions to support OWL reasoning with CWA. Different strategies have been explored like adopting an epistemic operator [50, 51] or extending OWL with the specification of external predicates that implements the idea of Negation As Failure [52].

The CWA and OWA are not contradictory. Recent results [53] show that it is possible to control the degree of incompleteness in an ontology obtaining a more versatile formalism. Such “under specification” can be used to allow reuse and extension and does not mean insufficiency. Again using our example, suppose we define an incomplete list of countries part of the North American Free Trade Agreement (NAFTA) comprising only Canada and USA, because these are the countries the store ships to, and we do not need to know the others. If the store starts shipping to Mexico at some point in time, a query about whether Mexico is a member of NAFTA returns *undefined*, which is reasonable, providing that our list of NAFTA countries is incomplete and does not include Mexico.

3.4 Ontology Services

Ontology-Based Information Systems [11] provide users with a set of functionalities to manage ontologies – ontology services.

Tran *et al.* [11] described a set of ontology services for supporting ontology engineering. In this thesis, we concentrate on the following services: reasoning and querying.

3.4.1 Reasoning Services

Reasoning services are services provided by reasoning systems with respect to the ontology. Standard reasoning services are services available in all reasoning systems, whereas non-standard reasoning services are extensions of basic reasoning services.

The standard reasoning services for TBox are satisfiability and subsumption. A class C is unsatisfiable ($C \sqsubseteq \perp$) with respect to an ontology \mathcal{O} if C is empty (does not have any instances) in all models of \mathcal{O} . Satisfiability checking is useful for verifying whether an ontology is meaningful, i.e., whether all classes are instantiable.

Subsumption is useful to hierarchically organize classes according to their generality. A class C is subsumed by another class D with respect to an ontology \mathcal{O} if the set denoted by C is a subset of the subset denoted by D for every model of \mathcal{O} .

The standard reasoning services for ABox are instance checking, consistency, realization and retrieval. *Instance checking* proves whether a given individual i belongs to the set described by the class C . An ontology is *consistent* if every individual i is instance of only satisfiable classes. The *realization* service identifies the most specific class a given individual belongs to. Finally, the *retrieval* service identifies the individuals that belong to a given concept.

3.4.2 Querying

Querying ontologies is a research field that comprises multiple techniques and languages. We limit the scope of our analysis to two languages, conjunctive query and the SPARQL-like language SPARQL-DL. We address conjunctive queries because they have been the querying mechanism for description logic based knowledge bases. The reason for using SPARQL is that it is a W3C standard query language [54], and it includes the definition of graph pattern matching for OWL 2 Entailment Regime [55].

Conjunctive Query

Conjunctive queries correspond to the conjunctive existential subset of first-order logic formulas, i.e., disjunction (\vee), negation (\neg), or universal quantification (\forall) are not allowed. The body of a conjunctive query consists of one or more atoms binding variables or literal values to class expressions or property expressions in the ontology [56].

For example, the query

$$Q(x, y) : \neg Customer(x) \wedge hasOrder(x, y)$$

is a query for any instance of the concept *Customer* (x is a distinguished variable) that have some order (y is a non-distinguished variable).

Let $\mathcal{V}_{\mathcal{O}} = (\mathcal{V}_{cls}, \mathcal{V}_{op}, \mathcal{V}_{dp}, \mathcal{V}_{ind}, \mathcal{V}_D, \mathcal{V}_{lit})$ be an OWL vocabulary. Let $\mathbf{x} \equiv \{y_1, \dots, y_n\}$ and $\mathbf{y} \equiv \{x_1, \dots, x_n\}$ be sets of distinguished and non-distinguished variables. A conjunctive query $Q(s_i)$ is a conjunction of atoms in the form:

$$Q(s_i) \leftarrow \bigwedge P_i(s_i) \cup \bigwedge P_i(c_i) \text{ where}$$

- $P \in \mathcal{V}_{cls} \cup \mathcal{V}_{op} \cup \mathcal{V}_{dp} \cup \mathcal{V}_D$
- $s \equiv \mathbf{y} \cup \mathbf{x}$
- $c \in \mathcal{V}_{ind} \cup \mathcal{V}_{lit}$

An answer of a conjunctive query Q w.r.t. ontology is an assignment σ of individuals to distinguished variables, such that $\mathcal{I} \models Q(x\sigma, y)$.

SPARQL

SPARQL 1.0 [54] is the triple-based W3C standard query language for RDF graphs. The semantics of SPARQL 1.0 is based on graph pattern matching and does not take into account OWL, although the specification allows for extending the SPARQL basic graph matching. SPARQL 1.1 [54] will address this problem by specifying an OWL entailment regime for SPARQL [55].

Sirin and Parsia [57] have done preliminary work on answering full SPARQL queries on top of OWL ontologies on SPARQL-DL. Next, we describe the abstract syntax of SPARQL-DL and its semantics.

SPARQL-DL Abstract Syntax

The abstract syntax of SPARQL-DL comprises basically the extension of the OWL abstract syntax to cover the usage of variables and blank nodes for classes, properties, individuals and literals. Let $\mathcal{V}_{\mathcal{O}} = (\mathcal{V}_{cls}, \mathcal{V}_{op}, \mathcal{V}_{dp}, \mathcal{V}_{ap}, \mathcal{V}_{ind}, \mathcal{V}_D, \mathcal{V}_{lit})$ be an OWL vocabulary. Let \mathcal{V}_{bnode} and \mathcal{V}_{var} be the set of blank nodes and set of variables. A SPARQL-DL query atom q is of the form:

$$q \leftarrow \text{Type}(a, C) \mid \text{PropertyValue}(a, p, v) \mid \text{SameAs}(a, b) \mid \text{DifferentFrom}(a, b) \mid \\ \text{ClassExpressionAxioms}(CE_1, \dots, CE_n) \mid \text{ObjectPropertyAxioms}(OPE_1, \dots, OPE_n) \\ \text{DataPropertyAxioms}(DPE) \mid \text{Annotation}(s, p_a, o)$$

where $a, b \in \mathcal{V}_{ind} \cup \mathcal{V}_{bnode} \cup \mathcal{V}_{var}$, $v \in \mathcal{V}_{ind} \cup \mathcal{V}_{lit} \cup \mathcal{V}_{bnode} \cup \mathcal{V}_{var}$, $p \in \mathcal{V}_{op} \cup \mathcal{V}_{dp} \cup \mathcal{V}_{var}$, $CE \in \mathcal{V}_{cls} \cup \mathcal{V}_{var}$, $s \in \mathcal{V}_{cls} \cup \mathcal{V}_{op} \cup \mathcal{V}_{dp} \cup \mathcal{V}_{ap} \cup \mathcal{V}_{ind} \cup \mathcal{V}_D$, $p_a \in \mathcal{V}_{ap}$, $o \in \mathcal{V}_{cls} \cup \mathcal{V}_{op} \cup \mathcal{V}_{dp} \cup \mathcal{V}_{ap} \cup \mathcal{V}_{ind} \cup \mathcal{V}_D \cup \mathcal{V}_{lit}$. A SPARQL-DL query Q is a finite set of SPARQL-DL query atoms and the query is interpreted as the conjunction of the elements in the set.

For example, the query

`Type(?x, ObjectHasValue(country, USA))`

returns all individuals that have the individual USA as value of the property `country`.

The semantics of SPARQL-DL extends the semantics of OWL to provide query evaluation. We say that there is a model of the query $Q = q_1 \wedge \dots \wedge q_n$ ($\mathcal{I} \models \sigma Q$) with respect to an evaluation σ iff $\mathcal{I} \models \sigma q_i$ for every $i = 1, \dots, n$.

A solution to a SPARQL-DL query Q with respect to an OWL ontology \mathcal{O} is a *variable mapping* $\mu : \mathcal{V}_{var} \rightarrow \mathcal{V}_{uri} \cup \mathcal{V}_{lit}$ such that $\mathcal{O} \models \mu(Q)$.

3.5 Ontology Engineering Services

On top of core ontology services, ontology engineers count on functionalities to support the ontology development life cycle [11]. Two ontology engineering services are particularly useful for application in UML class-based modeling: explanation and ontology matching.

3.5.1 Explanation

Users rely on reasoning services for classification and consistency checking. However, in case of inconsistencies in ontologies with a large amount of classes, users need to identify which constructs are causing the inconsistencies. Therefore, research on explanations of inferred assertions is gaining attention.

Explanations can be seen as a form of *debugging* ontologies. It consists of identifying and computing justifications, i.e., the set of axioms causing the subsumption. There are distinguishing methods for computing a simple justification or all justifications [58, 59].

Black Box Method for Single Justification

The algorithm of a black-box technique for computing a justification comprises two steps. Firstly, axioms of an ontology \mathcal{O} are inserted into a new ontology \mathcal{O}' until a class C becomes unsatisfiable with regard to \mathcal{O}' . Secondly, irrelevant axioms are pruned until concept C becomes satisfiable, i.e., a single minimal justification is achieved.

Computing All Justifications

Once a single justification is achieved, one requires other techniques to compute the remaining justifications. Please refer to Kalyanpur *et al.* [59] for a description of a variation of the Hitting Set Tree (HST) algorithm [60] for finding all justifications.

3.5.2 Ontology Matching

Ontology matching is the discipline responsible for studying techniques for reconciling multiple resources on the web. It comprises two steps: match and determine alignments and the generation of a processor for merging and transforming [61]. Matching identifies the correspondences. A correspondence for two ontologies A and B is a quintuple, including an id, an entity of ontology A, an entity of ontology B, a relation (equivalence, more general, disjointness) and a confidence measure. A set of correspondences forms an alignment. Correspondences can be done at the schema-level (metamodel) and at the instance-level (model).

Matchings can be based on different criteria: name of entities, structure (relations between entities, cardinality), background knowledge like existing ontologies or wordnet. Techniques can be string-based or rely on linguistic resources like wordnet.

Furthermore, matchings are established according to the different structures that are compared. There are three techniques for comparing structures: internal structure comparison, relational structure comparison and extensional techniques. Internal structure comparison includes the comparison of property, key, datatype, domain and multiplicities. Relational structure comparison comprises the comparison of the taxonomic structure between the ontologies.

Finally, the extensional techniques cover the usage of extensional information, e.g., formal concept analysis for comparison.

3.6 Rules

Efforts in extending the expressiveness of the OWL language has led to the combination of OWL with the unary/binary Datalog sublanguages of RuleML [62]: The Semantic Web Rule Language (SWRL) [63].

A drawback of SWRL rules is that they are undecidable in general. Nevertheless, Motik *et al.* have identified the decidable subset of OWL, usually called description logic safe rules [64]. Although a syntax for description logic safe rules is not part of the OWL 2, standard existing work [65] defines such a syntax which is supported by the de facto standard OWL application program interface (OWL API) [66]. Thus, engineers can use description logic safe rules over reasoners that implement the tableau algorithm for description logic safe rules extension to OWL.

A rule comprises an antecedent and a consequent. Antecedents and consequents are composed by a set of atoms. An atom has the form $P(x)$ where P can be a class expression, data range, object property expression, data property expression, `sameAs` construct, `differentFrom` construct or built-ins and x are variables or named individuals.

The model-theoretic semantics for SWRL extends the semantics of OWL [47] to define extensions of OWL interpretations that map variables to elements of the ontology (bindings). Hence, an interpretation satisfies a rule *iff* every binding that satisfies the antecedent also satisfies the consequent [63].

3.7 Metamodels for Ontology Technologies

The definition of metamodel for ontology technologies enables the specification of model transformations of software engineering artifacts into OWL-related languages. For example, the transformation of UML class diagrams into OWL uses transformation rules based on the metamodel of both languages. In the next subsections, we give an overview of existing metamodels for OWL-related specifications.

3.7.1 OWL Metamodels

The following section presents a short description of the most prominent OWL metamodels, namely the *OMG OWL Metamodel* [1], the *NeOn OWL Metamodel* [67] and the *W3C OWL 2 Metamodel* [68].

We do not to describe these metamodels completely. Instead, we concentrate on two central constructs: classes and properties. Please refer to the citations for more details.

OMG OWL Metamodel

The *OMG OWL Metamodel* is part of the *OMG Ontology Definition Metamodel* [1]. It has a large number of classes, since it imports the *OMG RDFS Metamodel*. Thus, some relations between classes are described in the RDFS Metamodel and reused in the OWL Metamodel.

For example, Figure 3.4 and Figure 3.5 depict the Class Description Diagram and the Properties Diagram respectively. The Domain and range of properties are specified in the RDFS Metamodel, depicted in the Figure 3.6.

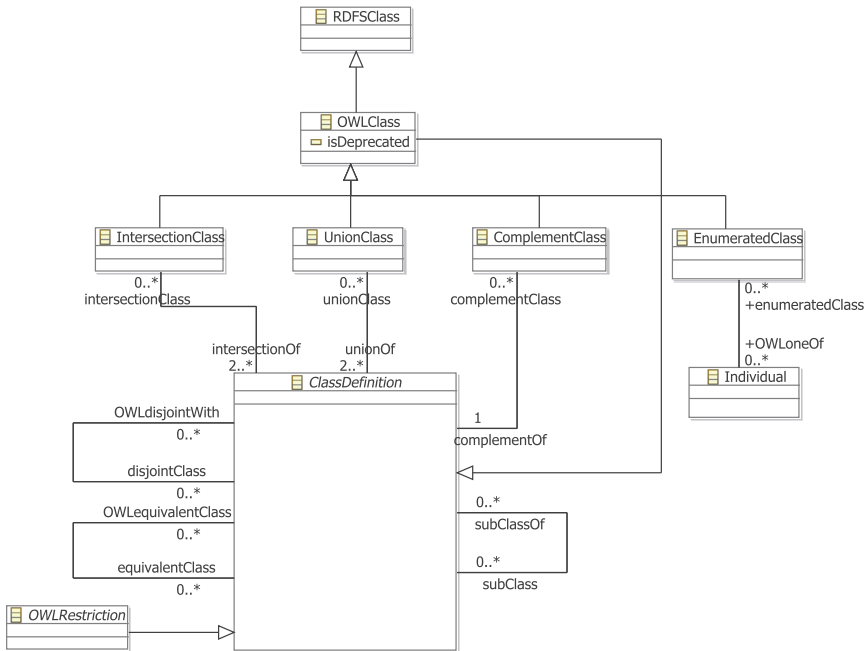


Fig. 3.4. OWL Class Descriptions of the OMG OWL Metamodel [1].

The OMG metamodel has public acceptance as standard and popularity. Nevertheless, the OMG metamodel introduces unnecessary complexity in dealing with RDF without any gain. Furthermore, the OMG metamodel does not provide support for OWL 2.

NeOn OWL Metamodel

The *NeOn Metamodel* [67] is a concise metamodel able to cover the OWL-DL functional syntax. Figure 3.7 and Figure 3.8 depict the OWL class hierarchy and the property diagram respectively. The relationship between *Class* and *Property* is direct, since the NeOn OWL Metamodel does not provide support for RDFS.

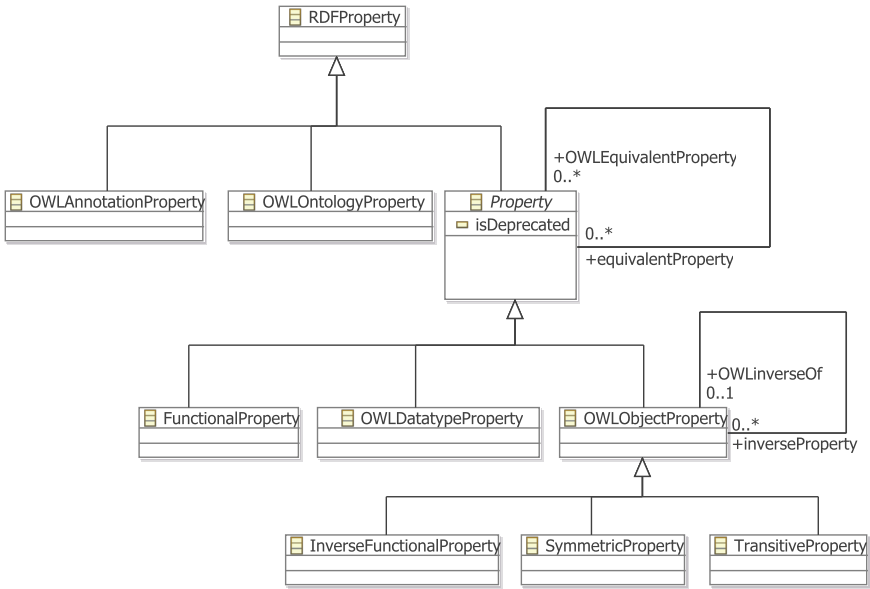


Fig. 3.5. OWL Properties of the OMG OWL Metamodel [1].

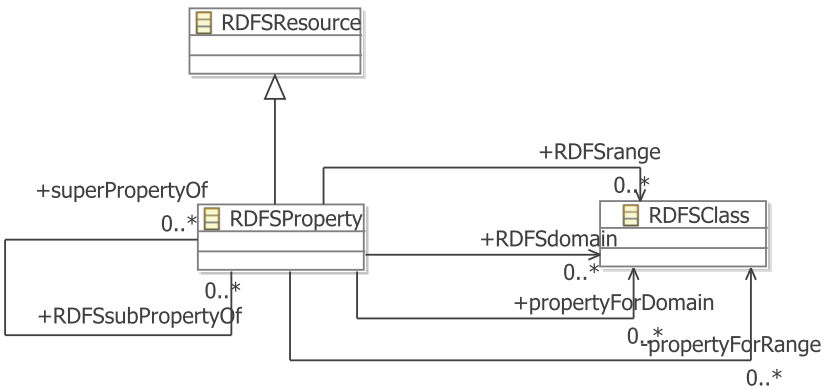


Fig. 3.6. RDFS Properties of the OMG OWL Metamodel [1].

The NeOn OWL Metamodel is smaller on the number of classes and simpler, since it is not attached to the RDF metamodel. However, the NeOn metamodel does not cover OWL 2 constructs.

W3C OWL 2 Metamodel

Improvements on the OWL language led the W3C OWL Working Group to publish working drafts of a new version of OWL: *OWL 2* [68]. OWL 2 is fully compatible

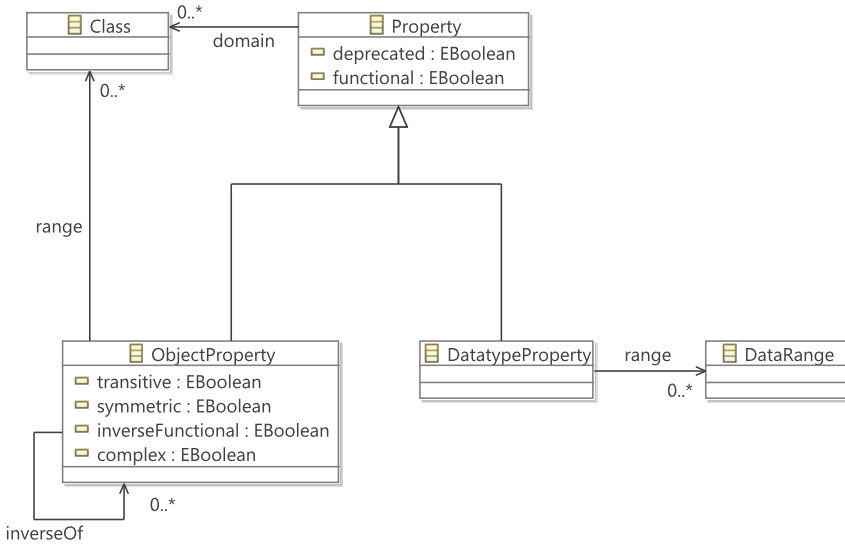


Fig. 3.7. OWL Class Descriptions of the NeOn Metamodel.

with OWL-DL and extends the latter with limited complex role inclusion axioms, reflexivity and irreflexivity, role disjointness and qualified cardinality restrictions.

The OWL 2 Metamodel is considerably different from the aforementioned metamodels for OWL. Constructs like Axiom and OWLEntity play central roles and associations between classes and properties are done by axioms. Figures 3.9 and 3.10 exemplify such constructs.

SWRL Metamodel

The SWRL metamodel (Figure 3.11) is an extension of the OWL 2 metamodel to provide support for OWL Rules. Brockmans *et al.* [69] have defined a metamodel for SWRL rules.

In the SWRL metamodel, a Rule is a subclass of OWLAxiom, which is defined as an element of an Ontology. A Rule contains an Antecedent and a Consequent, and those contain atoms. An Atom factors out OWL 2 axioms that can be used in SWRL rules like OWLClass and ObjectProperty.

3.7.2 SPARQL Metamodel

In addition to OWL and SWRL, we capture the structure of the SPARQL language using a metamodel. Since the SPARQL specification does not recommend a structural specification of the SPARQL language, we have designed the SPARQL metamodel based on the SPARQL EBNF Syntax.

Figure 3.12 presents the main classes of the SPARQL metamodel. A SPARQL query comprises a prologue, where namespaces are declared, and the query body.

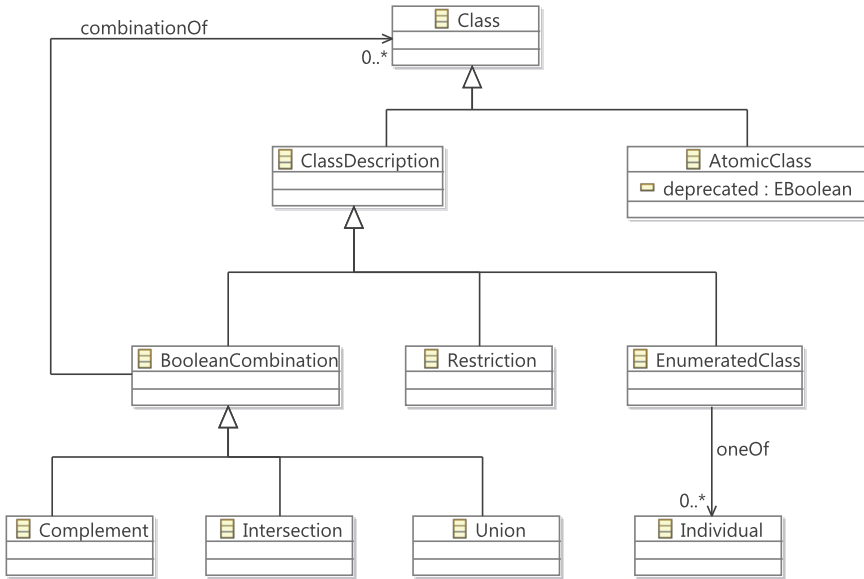


Fig. 3.8. OWL Properties of the NeOn Metamodel.

There are multiple types of SPARQL queries: DESCRIBE, CONSTRUCT, SELECT and ASK.

SPARQL queries have a WHERE clause, where the conditions are defined in the form of graph pattern. A graph pattern contains a triple block of subjects, properties, objects. In SPARQL queries, variables and blank nodes may occur in any position of the triples.

3.8 Ontological Technical Spaces

In order to organize the concepts presented in this chapter, we use the notion of technical spaces presented in Chapter 2. Figure 3.14 presents the description logics technical space.

The description logics technical space uses the description logic terminology as schema for defining knowledge bases as well as the SPARQL-DL or the conjunctive query vocabulary for defining queries. Query models are representations of evaluation functions that map variables into elements of a knowledge base.

The description logics technical space is an abstract technical space which is realized by the serialization of text files. OWL includes a set of concrete syntax notations for modeling OWL ontologies underpinned by description logics. Figure 3.15 depicts the relationships between OWL and description logics under the model-driven structure. The Java language is used to create Java programs that realize the idea of a reasoner and of a query engine. OWL reasoners take as input an OWL ontology written using, e.g., the OWL 2 Functional Syntax and generate a knowledge Base

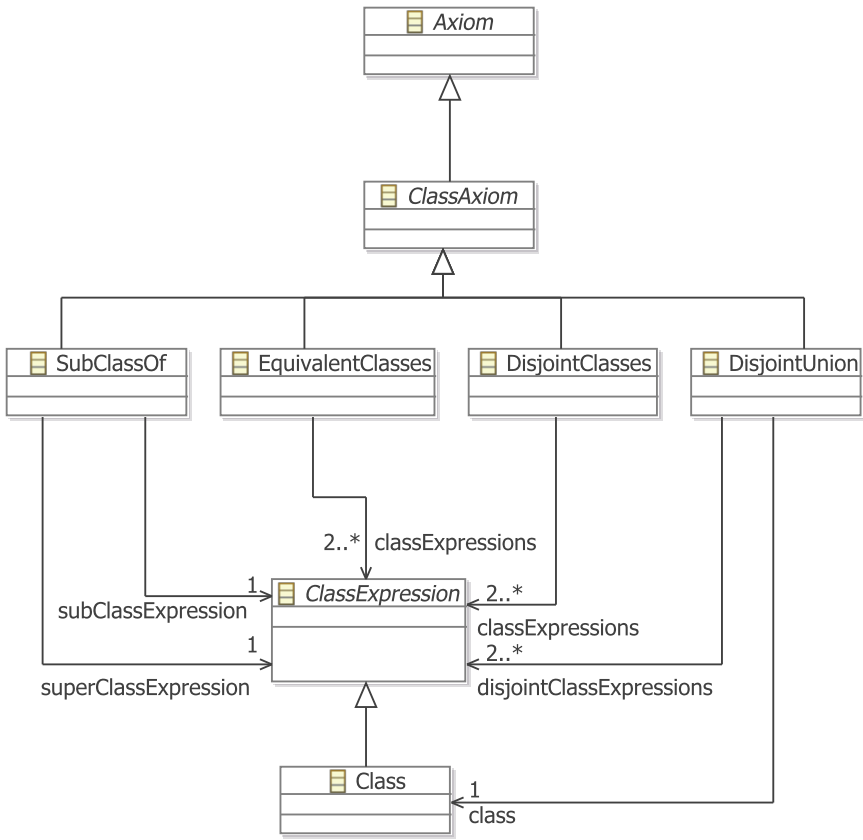


Fig. 3.9. OWL Class Descriptions of the OWL 2 Metamodel.

in memory for applying description logic algorithms. The same principles apply to query engines.

As defined in Section 3.7, there exist multiple MOF metamodels for ontology technologies and these are the main artifacts for model-driven engineering. Figure 3.16 depicts ontology technologies defined based on three technical spaces: MOF, EBNF and description logics technical space. MOF-based models of OWL ontologies and queries are defined using ontology-related MOF-metamodels. These models are serialized using projectors that generated textual representations of ontologies and queries. The textual file is the input artefact for reasoners, query engines and ontology services.

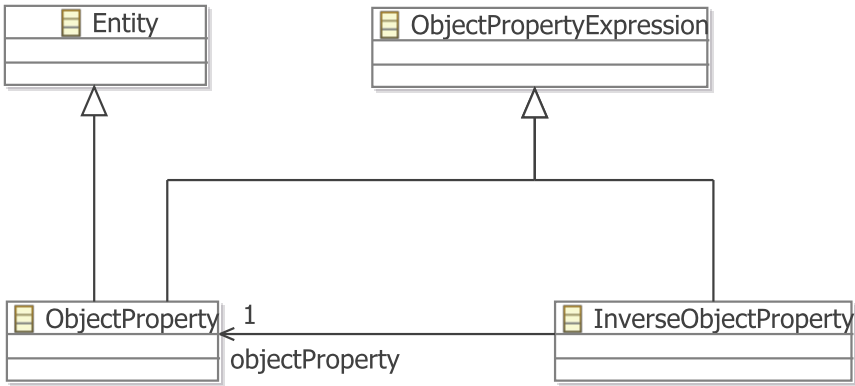


Fig. 3.10. OWL Properties of the OWL 2 Metamodel.

3.9 Conclusion

This chapter describes the main technologies of the semantic web stack related to ontology technologies. Additionally, we group languages and techniques according to the model-driven engineering structure. The contribution is a model-driven viewpoint of ontology technologies. We refer to these concepts and techniques later as we describe the integration with model-driven engineering.

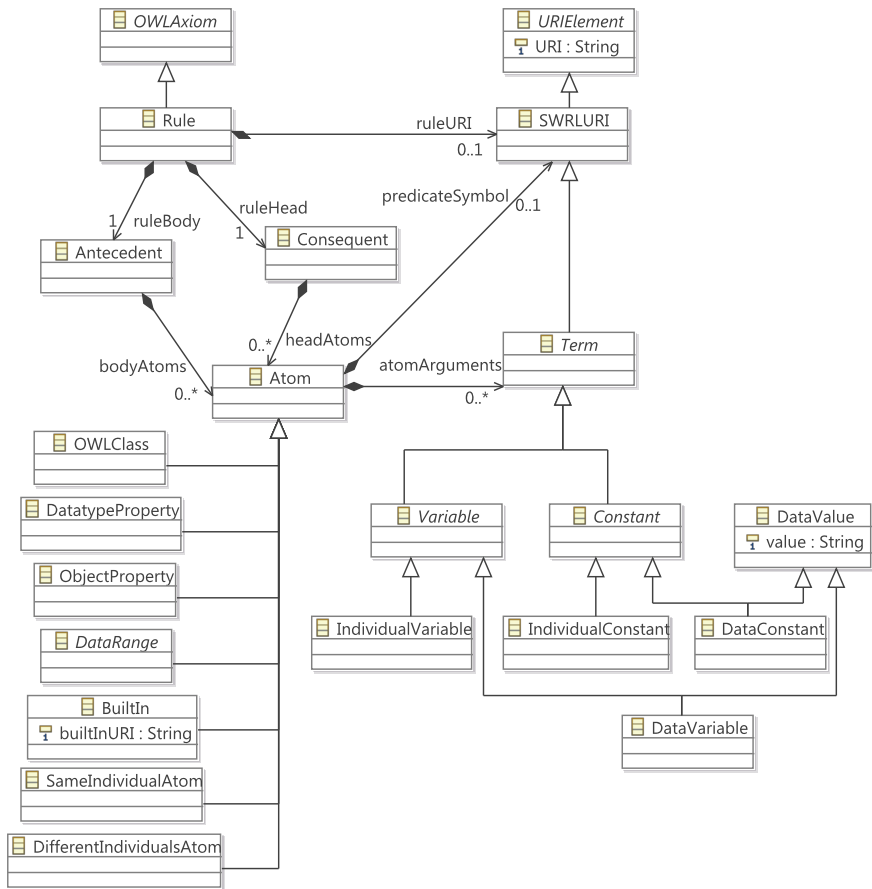


Fig. 3.11. Snippets of the SWRL Metamodel and the Connections with the OWL Metamodel.

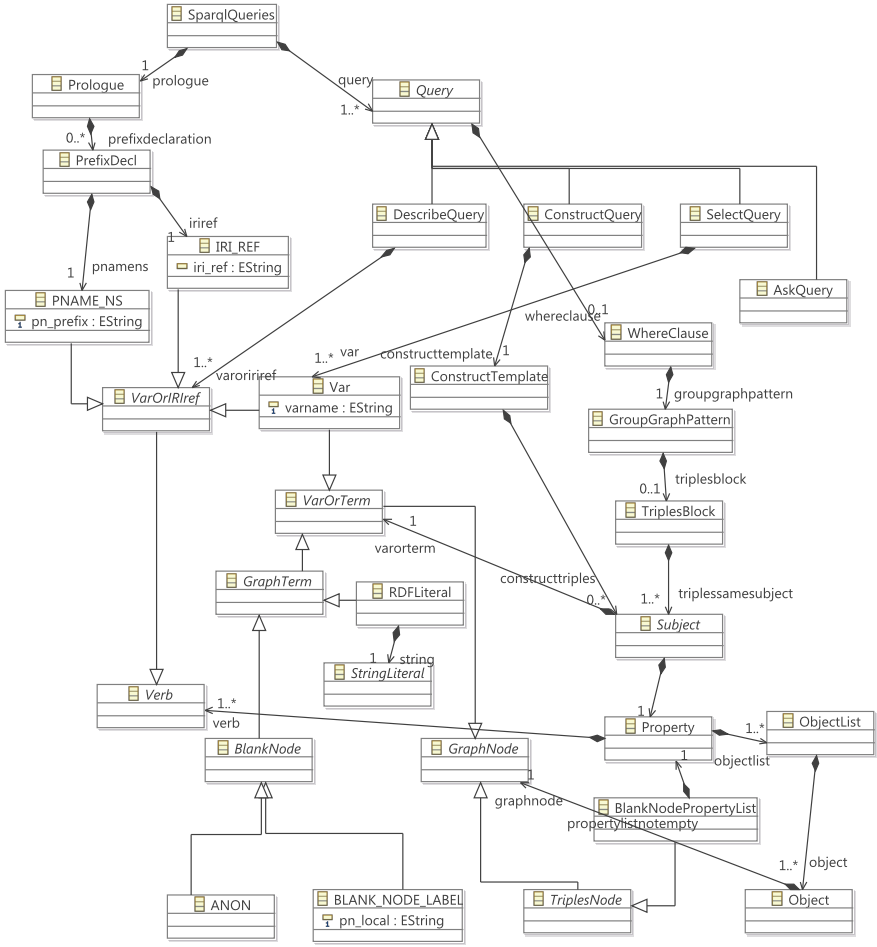


Fig. 3.12. Snippets of the SPARQL Metamodel.

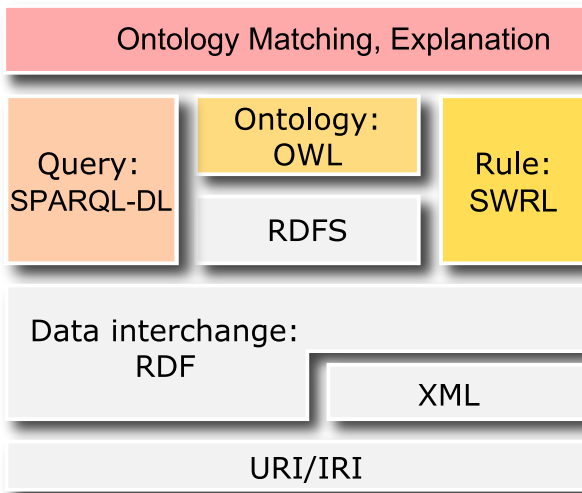


Fig. 3.13. Semantic Web Stack Covered in this Chapter.

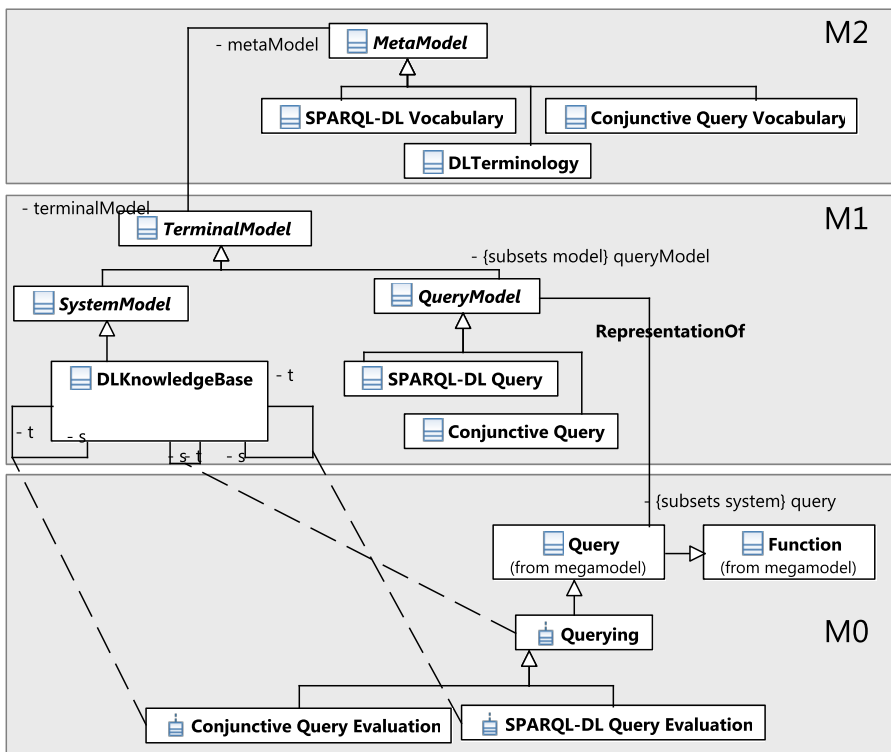


Fig. 3.14. The Description Logics Technical Space.

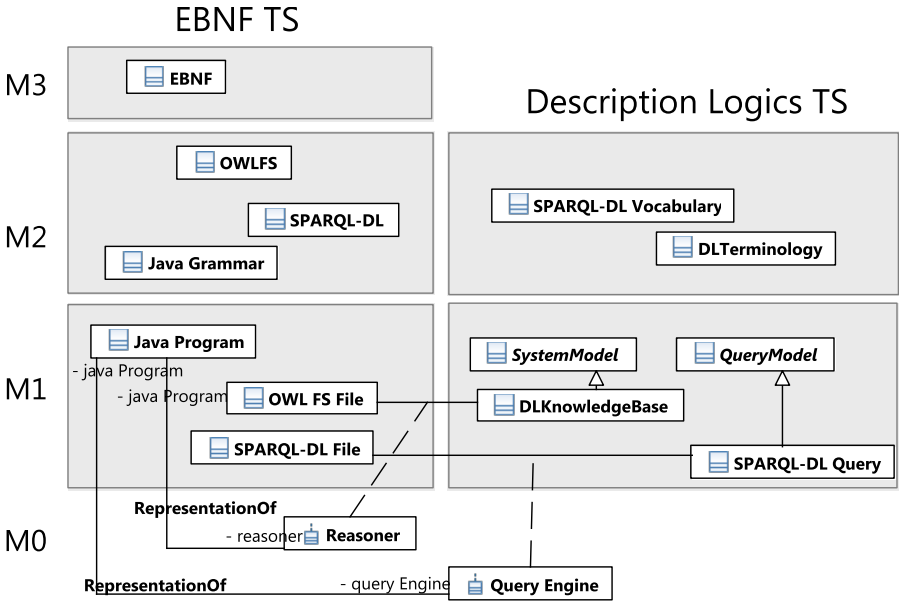


Fig. 3.15. Relation between the EBNF Technical Space and the Description Logics Technical Space.

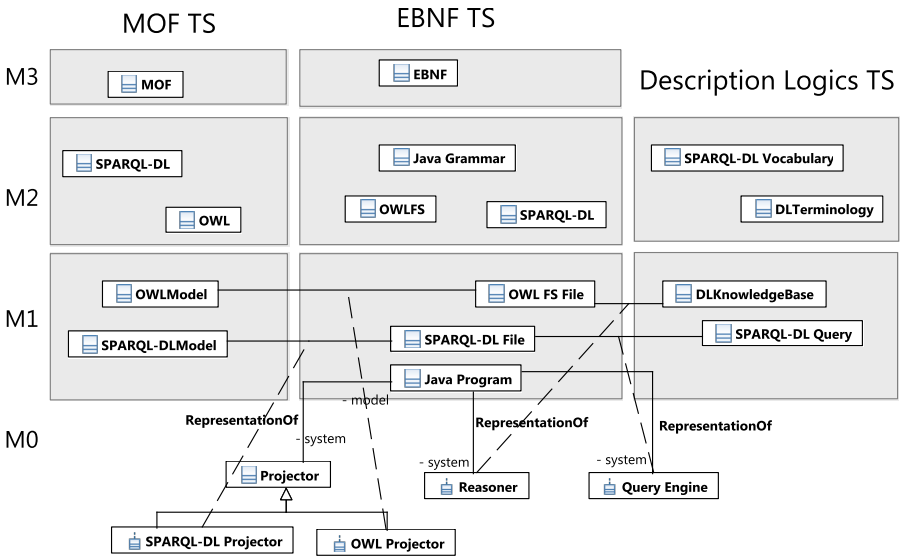


Fig. 3.16. Model-Driven Viewpoint of Ontology Technologies.

Towards Marrying Ontology Technologies and Model-Driven Engineering

Summary. In this chapter, we present a literature review and describe a domain analysis of ontological technical spaces and MOF technical space, explaining the features of the different paradigms. We analyze their similarities and describe frequently used patterns for transformations between instantiations of metamodeling technical spaces and ontological technical spaces¹.

4.1 Introduction

Ontology technologies and model-driven engineering have distinct foci. For example, MOF targets automating the management and interchange of metadata, whereas knowledge representation focuses on semantics of the content and on automated reasoning over that content [72].

While the focus of these communities is somewhat different, the following question arises: What are the commonalities and variations around ontology technologies and model-driven engineering?

MDE can be based on the *MOF Technical Space* (cf. Section 2.3)(MMTS) as well as on the *Ontological Technical Space* (cf. Section 3.8)(OTS). Figure 4.1 illustrates an example indicating the use of OTSs in the MDE process. The classical MDE transformations, residing in the MOF technical space, are extended by further transformations, making use of OTSs.

Further transformation into other technical spaces may provide additional analysis and implementation support, not as efficiently available in metamodeling technical spaces. Current MDE uses semi-formal metamodels instead of formal specification languages as support for describing models [73]. In the Figure 4.1, EMOF is transformed into an ontological representation in OWL, e.g., for model checking. The resulting ontology describes a submodel of EMOF, that enables logic-based model analysis and serves as knowledge base for a reasoner.

In order to improve the understanding of the space composed by MMTS and OTS (MMTS+OTS), we compare MMTS+OTS approaches by using a feature model

¹ This chapter contains work of the paper “On Marrying Ontological and Metamodeling Technical Spaces” presented at ESEC-FSE’07 [70] and EU STReP MOST Deliverable D1.1 “Report on Transformation Patterns” [71].

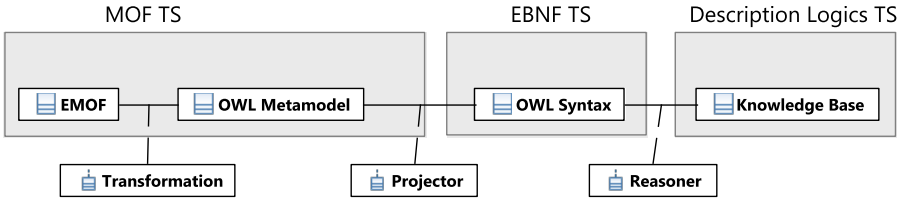


Fig. 4.1. Marrying MMTS and OTS.

and validate the model offering a survey and categorization of a number of existing approaches.

We organized the chapter as follows: we define basic similar concepts between UML class-based modeling and OWL modeling in Section 4.2. Section 4.3 presents an understanding of the domain in the form of a feature model. We apply this model categorizing related approaches in Section 4.4.

4.2 Similarities between OWL Modeling and UML Class-Based Modeling

Despite having distinct purposes, OTS and MMTS share similar constructs. Recent approaches presented similarities between MOF and RDF [74], between OWL/RDF and Object-Oriented Languages [75] and between UML and OWL [1, 76]. We summarize them in the Table 4.2. For the subtleties, please refer to the cited papers.

Table 4.1. OTS and MMTS: Comparable Features.

UML Class-based Modeling	OWL
package	ontology
class	class
instances and attribute values	individuals and data values
association, attribute	property
datatypes	datatypes
subclass, generalization	subclass, sub-property
enumeration	enumeration
navigable, non-navigable	domain, range
disjointness, cover	disjointness, disjoint union
multiplicity	cardinality

These similarities allows for translating UML class-based modeling into description logics, which gives UML class-based modeling a model-theoretic semantics. For

example, the work of Berardi *et al.* [31] investigates the translation of UML Class Diagrams into \mathcal{DLR}_{ifd} , an expressive yet decidable description logic.

Figure 4.2 depicts distinguishing features of UML Class Diagrams (\mathcal{DLR}_{ifd}), OWL-DL ($\mathcal{SHOIN}(\mathbf{D})$), OWL 2 ($\mathcal{SROIQ}(\mathbf{D})$) and \mathcal{ALCQI} , a fragment supported by state-of-the-art reasoning services that \mathcal{DLR}_{ifd} has in common with $\mathcal{SROIQ}(\mathbf{D})$. Considering Figure 4.2, UML class diagrams (\mathcal{DLR}_{ifd}) differentiate from OWL-DL ($\mathcal{SHOIN}(\mathbf{D})$) by representing n-ary relations, functional dependencies on n-ary relations, identification constraints, limited complex role inclusion, role disjointness, qualified cardinality restrictions, cardinality restrictions, role hierarchy, nominals, transitive properties, reflexivity.

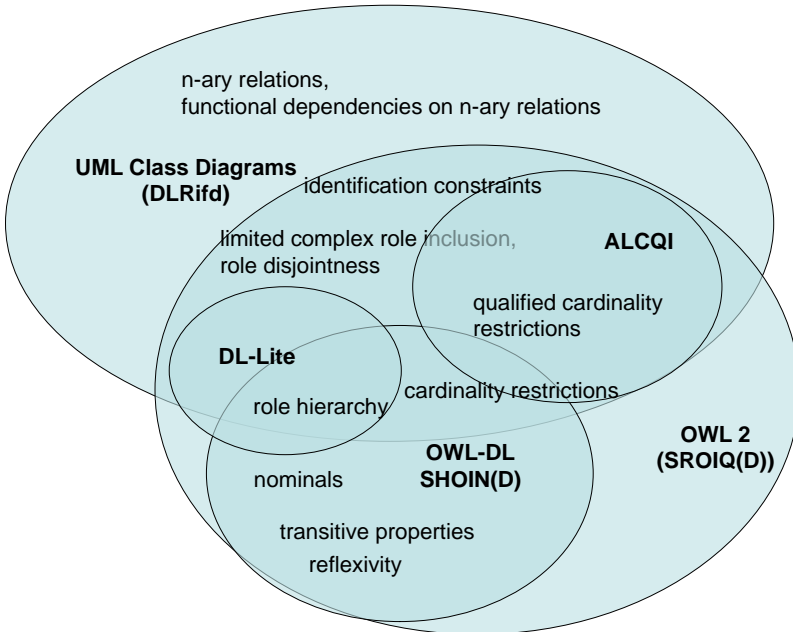


Fig. 4.2. Comparing UML Class Diagrams, OWL-DL, OWL 2 and DL-Lite.

State-of-the-art automated reasoning systems do not support all constructs of UML Class Diagrams (\mathcal{DLR}_{ifd}). However, by dropping functional dependencies and identification constraints, one achieves \mathcal{ALCQI} . \mathcal{ALCQI} is the most expressive fragment in common between UML class diagrams (\mathcal{DLR}_{ifd}) and OWL 2 ($\mathcal{SROIQ}(\mathbf{D})$). Automated reasoning systems [79] support constructs of OWL-DL ($\mathcal{SHOIN}(\mathbf{D})$), OWL 2 ($\mathcal{SROIQ}(\mathbf{D})$) and consequently \mathcal{ALCQI} .

Notice that we compare the language constructs and we do not consider OCL. Rahmani *et al.* [80] describe an adjustable transformation from OWL to Ecore and identified that it is possible to represent most OWL constructs with Ecore and OCL invariants. However, such a transformation has the purpose of aligning OWL constraints with OCL invariants and does not cover OWL reasoning services like realization and instance checking.

4.3 Commonalities and Variations

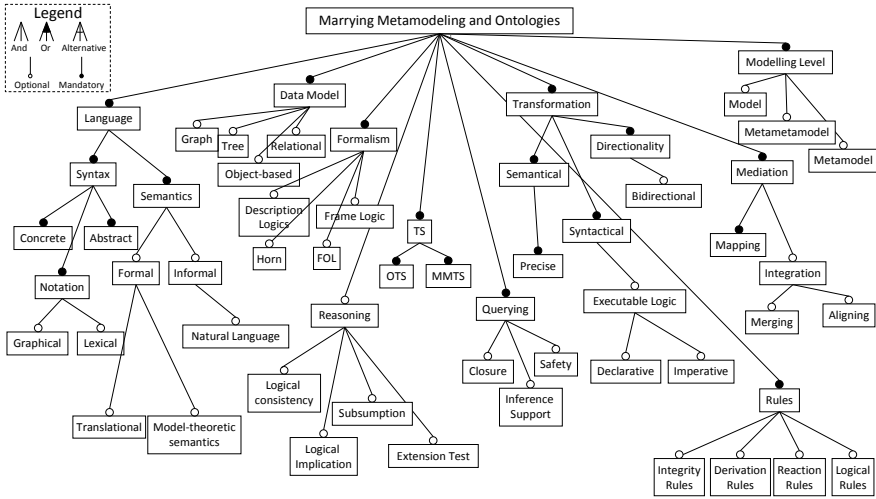


Fig. 4.3. Snippet of the Feature Model of Bridging OTS and MMTS.

In this section, we present a domain analysis of MMTS+OTS approaches. Domain analysis is concerned with analyzing and modeling the variabilities and commonalities of systems or concepts in a domain [10].

The product of such analysis is a feature model, described in this section. A feature model comprises a feature diagram, depicted in the Figure 4.3, the description of the features and examples. The feature model reveals the possible choices for a MMTS+OTS approach and also serves as a taxonomy to categorize approaches involving both paradigms. We describe the features on Figure 4.3 in the next sections.

4.3.1 Language

The choice of a language shapes the message exchange between agents. A language is defined based on:

1. a concrete syntax describing the way in which the language elements appear in a human-readable form. Extended BNF is frequently used to describe the concrete syntax of lexical notations. In the case of graphical notations, natural language and symbols are used to describe what graphical symbols represent information, and how these symbols are laid out. A particular case of concrete syntax is a serialization syntax, which allows the language expressions to be made persistent or interchanged between tools. XML can be used as serialization syntax. Syntactical variations may co-exist for one given language.
2. an abstract syntax of a language portraying the elements that compose the language, and the possible combination of these elements. Abstract syntax graphs, metamodels and Extended BNF are commonly used to represent the abstract syntax of a language.

3. the semantics of a language attributes meaning to the language primitives and its vocabulary. This attribution can be done by the means of a formal language, using mathematics, or an informal language, using natural language. The relevant formal semantics for MMTS+OTS are [81]:
 - *Model-theoretic semantics.* Model-theoretic semantics assigns meaning to a set of logical sentences by considering *all* possible interpretations that may be given to its atomic elements. Such a set of logical sentences is then satisfiable if there is an interpretation that will render all the sentences to become true (please refer to Section 3.3.2).
 - *Axiomatic semantics.* Axiomatic semantics is based on methods of logical deduction from predicate logic. The semantic meaning of a program is based on assertions about relationships that remain the same each time the program executes.
 - *Translational semantics.* Another way of giving a semantics to a language is translating expressions from one language into another language that has a defined semantics.

The abstract syntax characterizes the primitives of a language. The concrete syntax realizes the primitives by a concrete notation. The semantics assigns meaning to the primitives, and the models constructed using these primitives.

Let us consider three examples: UML is a modeling language with a graphical notation, an informal semantics described in natural language (there exist translational semantics approaches for UML), uses a metamodeling approach to describe its abstract syntax, as well as natural language and symbols to describe the concrete syntax.

OWL is an ontology modeling language with a lexical notation, formalized by description logics. It is a subset of first-order predicate logics with a model-theoretic semantics. OWL's concrete and abstract syntax are specified by Extended BNF.

RDF(S) is a language based on triples as the abstract syntax graph, with a concrete lexical notation and a formal axiomatic semantics [82].

4.3.2 Formalism

We define the term “formalism” as formal language used to precisely define concepts of the world. A formalism is the basis for reasoning over models. We distinguish between four formalisms applicable to MMTS+OTS:

- *First-Order Logic.* First-Order Logic is a logical language able to express relations between individuals using predicates and quantifiers [83].
- *Description Logics.* Description Logics are a family of knowledge representation formalisms aimed at unifying and giving a logical basis to frame-based systems, semantic networks, object-oriented representations, semantic data models, and type systems [43]. Core to each language from this family is its capability to express class definitions by restrictions on relationships to other classes and by inheritance relations. Though the exact expressiveness varies, all description logic languages are subsets of first-order predicate logics.
- *Horn Rules.* Horn rules restrict first-order predicate logics to axioms of a particular form. Though horn rules are in general Turing powerful, in a practical

situation it is possible to oversee deductive consequences and to reason efficiently with terms (i.e., kind of objects).

While horn rules can be given a model-theoretic semantics, e.g., first-order predicate logics, in order to handle negation efficiently, most approaches select specific interpretation functions in order to decide upon satisfiability (or inconsistency).

- *Frame Logic*. Frame Logic is a syntactically more expressive variant of horn rules. It constitutes a deductive, object oriented database language combining declarative semantics and the expressiveness of deductive database languages with the data modeling capabilities supported by the object oriented data model [44].

Ontologies and models written in a given language, e.g., OWL, are usually translated to one or more formalisms, e.g., *SHOIN(D)*, a member of the family of description logic languages, to realize reasoning.

4.3.3 Data Model

A data model is an underlying structure mandating how data is represented. The data model provides a basis for organizing the primitive elements of a language. This organization is used by the abstract syntax of the language to relate the primitives. We differentiate four data models:

1. *Graph*: consisting of (hyper-)edges and nodes.
2. *Tree*: constituting a restricted graph data model having a hierarchical organization of the data.
3. *Object-based*: organizing data according to the object-oriented paradigm.
4. *Relational*: organizing data in relations.

A modeling approach can be seen from the point of view of data models. For instance, the UML class diagram is commonly seen either as a graph data model or as an object data model.

OWL is primarily based on unary relations (i.e., logically-defined classes) and binary relations (i.e., relationships between objects), but there are alternative access methods, e.g., via Java object APIs or querying through the SPARQL, graph data model query language.

RDF(S) constitutes a graph data model, but it can also be seen as a kind of object model or a kind of constrained relational model.

4.3.4 Reasoning

Each type of reasoning is based on a formalism, typically a logical language, to deduce (infer) conclusions from a given set of facts (also called assertions) encoded in a model. Standard reasoning services include:

1. *Logical consistency*. Logical consistency checks whether a set of logical sentences, i.e., a logical theory, has an interpretation, i.e., admits a model.
2. *Logical implication*. Given a set of logical sentences as a premise (i.e., a “theory”), another set of logical sentences may be implied as a conclusion because every model of the premise is also a model of the conclusion.

3. *Subsumption*. Subsumption is a special case of checking logical implications. Subsumption tests whether one class definition is more specific than another one — given a set of logical sentences as background theory. Subsumption tests can be used to generate a sound and complete classification of a set of class definitions.
4. *Extension test*. An extension test checks whether a tuple is contained in a logical relation. Specifically, it tests whether an instance belongs to the extension of a class, which is a unary relation.

Indeed, all standard reasoning services in first-order predicate logics (and in description logics, specifically) that are illustrated here can be based on consistency checking.

In horn rules formalisms, reasoning is defined either based on resolution or based on naïve bottom-up evaluation.

4.3.5 Querying

Querying plays an important role for accessing and bridging between technical spaces. The work by Haase *et al.* [84] comparing aspects of query languages for ontologies have been used to identify features of querying:

1. *Inference support*. A query engine may access only explicitly available data (e.g., SPARQL [54]), or it may include facts derived by using a reasoner (e.g., OWL-QL [85] or SAIQL [86]).
2. *Closure*. A query language may represent the results of a query on a model (i.e., a kind of database) either in the same format as the model itself (usual) or in a different paradigm. For instance, the earliest RDF query languages returned results as variable bindings, i.e., as relations rather than graphs, while SPARQL may return results in its native paradigm, i.e., as a graph.
3. *Safety*. A query language is considered safe, iff a syntactically correct query returns a finite set of results.

Queries are expressed in a language, over a data model, in a modeling level, and can use a reasoning service. For example, OCL can be used as a query language with lexical notation over a UML object data model.

SPARQL is a query language with lexical notation over RDF graph data model without reasoning support (according to the version 1.0 of SPARQL specification [87]) and with results being either represented as relations or as graphs.

4.3.6 Rules

Rules are present inside technical spaces as well as in transformations between them. Rule languages can be considered to include a querying mechanism over a data model. The term “rules” is ambiguous and includes in its range:

1. *Integrity constraints*. Integrity constraints restrict the number of possible interpretations. They do not add inferences, but they signal exceptions.
2. *Derivation rules*. Integrity constraints comprise one or more conditions from which a fact is derived as conclusion iff the rule holds.

3. *Reaction rules.* Reaction rules have as a core feature their reactivity. They comprise a triggering event and a condition that carries out a triggered action iff the rule holds.
4. *Logical rules.* Logical rules describe a logical axiom that holds.

For example, OCL is a language with lexical notation, uses metamodeling to represent its abstract syntax and has translational semantics into first-order logics. It serves to write integrity constraints and derivation rules as well. Part of the UML specification called Action Semantics could be used to specify reaction rules.

F-Logic rules [44] are logical rules that can be considered to constitute derivation rules and that can be configured to model integrity constraints.

DL-safe rules [64] are a logical rule mechanism for a subset of OWL allowing for sound and complete reasoning with class definitions and a restricted rule language that defines specific logical axioms.

ATL [35] and QVT [32] are languages with lexical notation, metamodeling abstract syntax and they can be used to write transformation rules.

4.3.7 Transformation

A transformation definition is a set of transformation rules that together describe the conversion of one model in the source language into another related model in the target language [16]. Concerning MMTS+OTS, we distinguish between three aspects of transformations:

1. *Semantic.* The semantic aspect of a transformation differs between precise transformation or approximative transformations. Approximative transformations give up on soundness (rarely) or completeness (more often) in order to speed up subsequent querying or reasoning. Precise transformations are sound and complete.
2. *Syntactic.* We distinguish between (i) graph-based syntactic transformation, which draws on the theoretical work on graph transformations, operating on typed, attributed, labeled graphs (e.g., UMLX [88] and GReTL [34]); and (ii) hybrid syntactic transformations, which involve declarative and prescriptive notations. ATL [35] is an example of a hybrid language.
3. *Directionality.* Directionality concerns the generation of models in different directions based on the definition of a transformation. Bidirectional transformations are sufficient to transform forward and backward between source and target models. Examples include QVT and UMLX [88]. Unidirectional transformations allow for transformations in exactly one direction, such as ATL, in general.

A transformation language requires querying over a data model and transformation rules to manipulate the source and target metamodels. For example, an ATL transformation has a lexical notation, precise semantics, hybrid syntax and is composed by transformation rules using OCL as a query language over UML object models.

4.3.8 Mediation

Mediation is the process of reconciling differences between heterogeneous models. Mediation plays a central role in MMTS+OTS, as models in different languages must coexist. A mediation consists of:

1. *Integration*. Integration focuses on interoperability between models so that they work together effectively. It comprises:
 - *Aligning*. Aligning preserves the source models and produces a new model containing additional axioms to describe the relationship between the concepts from the source models.
 - *Merging*. Merging refers to the creation of one new merged model from two or more source models. The merging process can involve aligning as a step.
2. *Mapping*. Mappings are declarative specifications of the correspondences between elements of the two models. In the transformation process, the mapping specification precedes the transformation definition.
3. *Composition*. Composition comprises the combination of elements that conform to overlapping concepts in different source models. Usually, each source model handles a different dimension of the overlapping elements. A weaving process does not necessarily produce a merged mediation, but it can produce a model with new knowledge based on the source models.

Both integration and composition make use of mappings to specify overlaps. A transformation usually takes as input the source models and the mappings to generate the target models.

4.3.9 Modeling Level

Considering that “everything is a model” in model-driven engineering, these models are organized according to their conformance. Such an organization is defined by [19] as follows:

1. System: corresponding to the executable system, the runtime instances.
2. Model: defining the circumstances under which a system operates and evolves.
3. Metamodel: defining the constructs to design models.
4. Metametamodel: defining the constructs to design metamodels.

This organization corresponds to the OMG layered metamodel architecture: the metametamodel level (M3), the metamodel level (M2), the model level (M1) and the runtime instances (M0). Each modeling level is described using a language and is organized according to a data model (please refer to Section 11.3.2 for an example of the OMG layered metamodel architecture).

Figure 4.4 shows a layered architecture of the features presented in this section according to the abstraction level. Each layer exploits facilities of the layers below. It shows how the features are organized to realize each of the technical spaces.

4.4 The State of the Art of Integrated Approaches

In this Section, we apply the model presented in Section 4.3 to MMTS+OTS approaches found in the literature. As an example, we identify major categories that group related work. Each category corresponds to one configuration of our feature model.

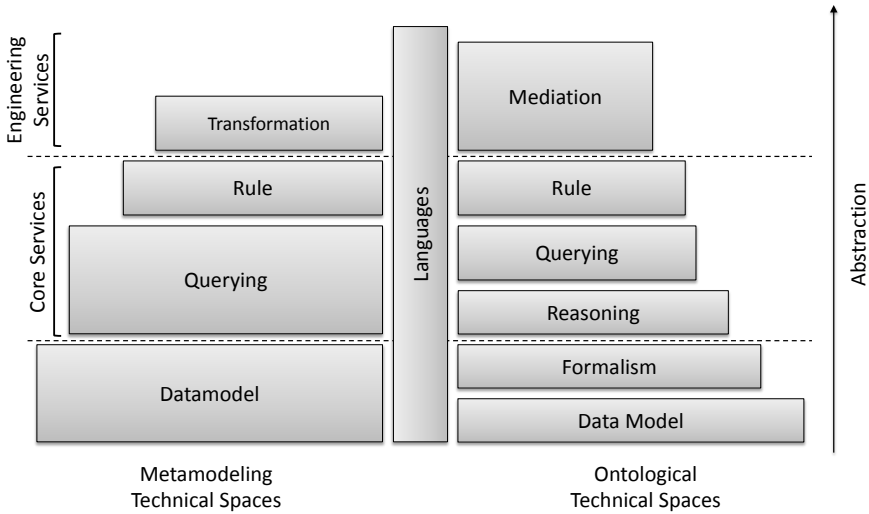


Fig. 4.4. Organization of Features According to Technical Space.

4.4.1 Model Validation

This category assembles the works that use automated reasoning techniques for checking and validation of models in formal languages. It implies aligning the source model and the target model by a mapping. A *unidirectional transformation* approach takes the mapping and uses transformation rules to generate the models. Queries against a reasoner serve to verify the models.

Approaches for validating models verify specification against design. The description logics technical spaces, however, have specifically been defined to validate the *internal* consistency of a set of class definitions. To exploit this model of validation, one may transform a part of a given MDE-based model, e.g., a UML class diagram, into a set of OWL class definitions (cf. [31]) and one may check class hierarchy relationships, property hierarchies as well as the logical consistency of instantiating classes.

Berardi *et al.* [31] provide automated reasoning support for detecting relevant properties of UML class diagrams, e.g., implicit consequences, refinement of properties and class equivalence. This work consists of aligning a UML class diagram (independent of modeling level) and a DL *ALCQI* knowledge base. A precise automatic unidirectional transformation generates an *ALCQI* knowledge base that corresponds to the UML class diagram.

We illustrate this process using the simple diagram depicted in the Figure 4.5. The diagram shows that a *WebPortalAccount* is a particular kind of *UserAccount* and that each *UserAccount* is owned by one and only one *User*. Additionally, there

exist two types of users: *Researcher* and *Student*. A *Researcher* can have only one *WebPortalAccount*. The association class *Uses* specializes the association class *Owns*.

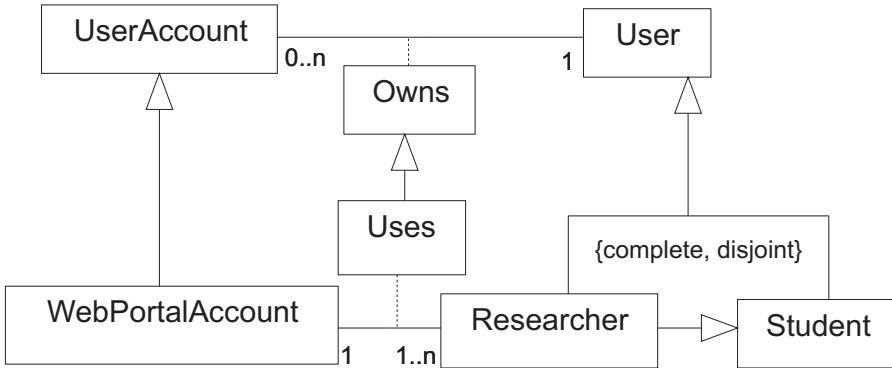


Fig. 4.5. Checking consistency of UML models.

After applying the transformation from UML into a description logic model, such as OWL (more specifically, Berardi *et al.* [31] mapped it into \mathcal{ALCQI}), we ask the reasoner to verify the model. By reasoning over such a diagram, we discover undesirable characteristics. For instance, the class *Researcher* must be empty and, hence, cannot be instantiated. The reason is that the disjointness constraint asserts that there is no *Researcher* that is also *Student*. Furthermore, since the class *User* is made up by the union of classes *Researcher* and *Student*, and since *Researcher* is empty, the classes *User* and *Student* are equivalent, implying redundancy.

By dropping the generalization *Student-Researcher*, we arrive at a valid model. If we invoke the reasoner one more time, we can refine the multiplicity of the role *Researcher* in the association *uses* to *1*. *Owns* is a generalization of *Uses*, hence every link of *Uses* is a link of *Owns*, since every *Account* is owned by exactly one *User*, necessarily every *WebPortalAccount* is used by at most one *Researcher*, since *WebPortalAccount* is a subclass of *Account*.

Straeten [89] proposes an approach to detect and resolve inconsistencies between versions of UML models, specified as a collection of class diagrams, sequence diagrams and state diagrams. She presents a UML Profile able to describe the evolution of the models.

Ren *et al.* [90] propose an approach for validating refinements of BPMN diagrams with OWL based on the execution set semantics. The OWL ontology serves to identify the invalid execution set in the refined BPMN diagram according to the abstract BPMN diagram.

The configuration of this category uses the following features (Figure 4.6): (i) a model at a given modeling level (model, metamodel or metametamodel), written in a graphical language, using an object data model; (ii) a target model, written in a language with model-theoretic semantics and lexical notation, including one formalism, reasoning capability, querying with closure, inference support and safe; (iii) a mapping specification describing the links between the models; (iv) a unidi-

rectional, declarative and precise transformation definition, which includes transformation rules and querying.

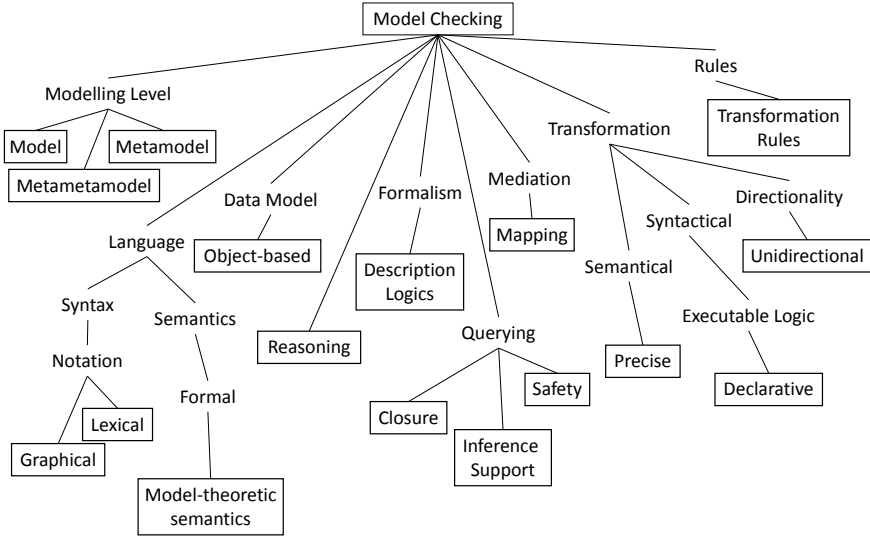


Fig. 4.6. Feature Model Configuration for Model Checking.

4.4.2 Model Enrichment

This category comprises the approaches that make use of ontologies to infer knowledge from the MMTS models and convert these inferences back as facts in the new MMTS models. The main difference between this category and the former is the bidirectional transformation and the application of transformation rules and reasoning on the OTS side. First, the MMTS model is transformed into an OTS model. On the OTS side, inference services and transformation rules are used to make explicit the assertions that are implicit in the MMTS. Then, the resulting OTS model is transformed back.

Let us illustrate this process with an example of mappings between two MMTS models, depict in the Figure 4.7. Let us assume that we have two models capturing bibliographical references. On the left side, we have the model M_a with the class `Publication`, which generalizes `Article` and `Thesis`, which generalizes `MScThesis` and `PhDThesis`. On the right side, we have the model M_b with the classes `Entry` and `Thesis`. At the center, we have the mapping M_{ab} with the association class `MScThesis2Thesis`, mapping a `MScThesis` onto a `Thesis`, and the association class `PhDThesis2Thesis`, mapping a `PhDThesis` onto a `Thesis`.

After translating both models into RDF models, we can use TRIPLE [91], a RDF query, inference, and transformation language, to apply the transformation rules depicted in 4.7, corresponding to the `MScThesis2Thesis` and `PhDThesis2Thesis` labels. This resulting query is translated back into MMTS model M_b .

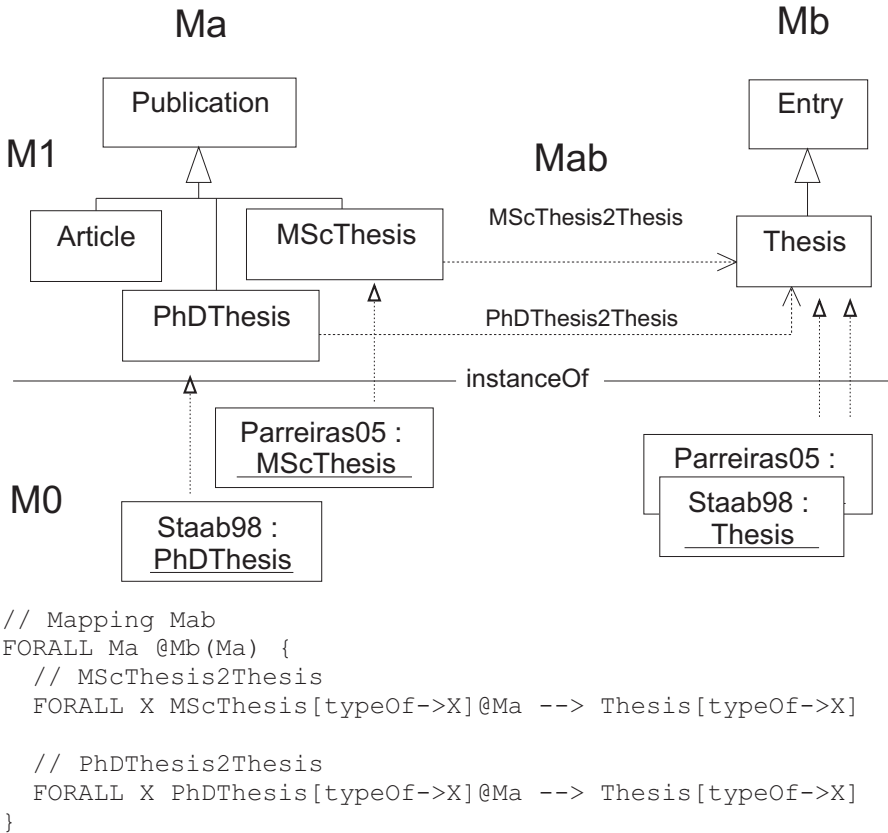


Fig. 4.7. Mapping between two models Ma and Mb.

The works that fit in this category have different facets. Billig *et al.* [92] use TRIPLE to generate mappings between a PIM and a PSM using a feature model that describes user requirements as input. It comprises a transformation from MMTS into OTS (TRIPLE), the generation of the mappings, the transformation into a PSM under OTS and the transformation OTS to MMTS of the PSM. Roser and Bauer [93] propose a framework to automatically generate model transformations inside a MMTS using the OTS; Kappel *et al.* [94] provide an approach for model-based tool integration. It consists of transforming two MMTS metamodels into ontologies, using reasoning services and generating mapping between the two MMTS.

The configuration of features in this category includes (Figure 4.8): (i) a model at a given modeling level (model, metamodel or metametamodel), written in a given language, using an object data model; (ii) a target model, written in a given logical language, reasoning capability, querying with closure, inference support and safety; (iii) a mapping specification describing the links between the models; (iv) a bidirectional declarative transformation definition, which includes transformation rules and querying; (v) logical rules and reasoning to make the knowledge explicit on the OTS side.

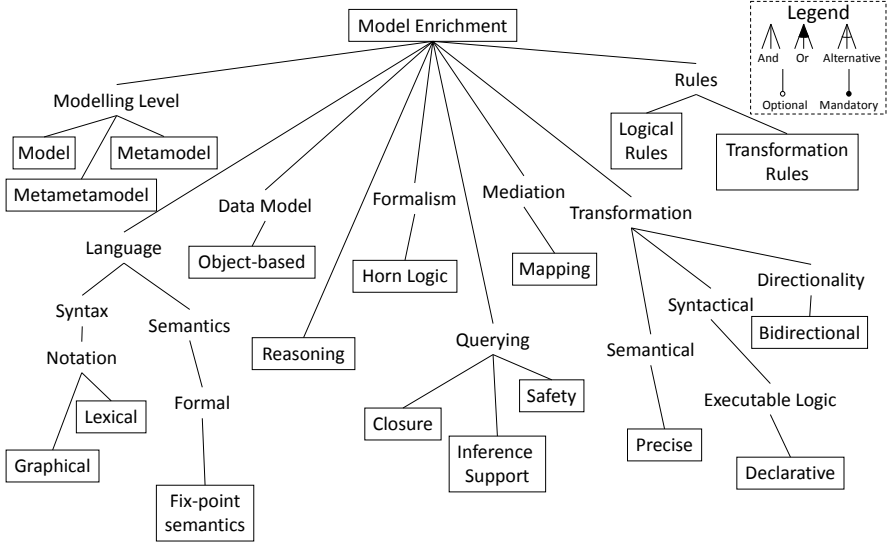


Fig. 4.8. Feature Model Configuration for Model Enrichment.

4.4.3 Ontology Modeling

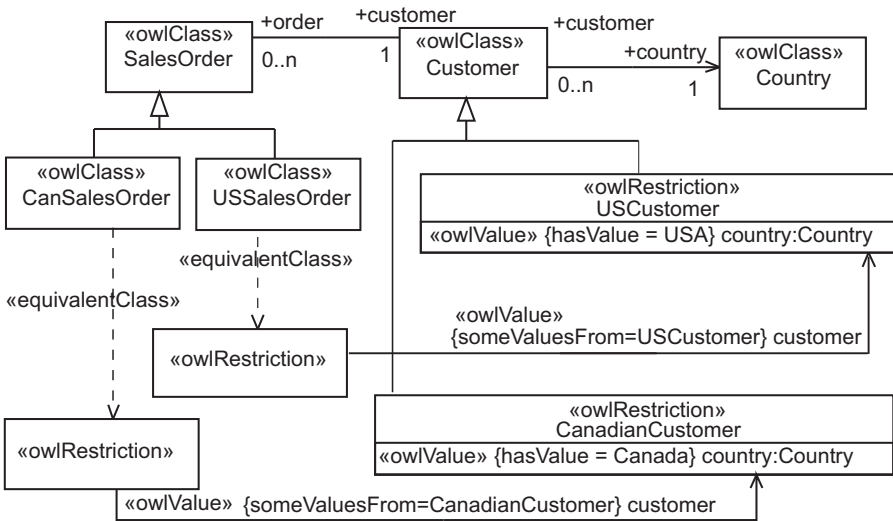


Fig. 4.9. Ontology Modeling with UML Profile.

This category assembles the efforts into giving a graphical notation to ontology modeling. Referring to our feature model, this category embraces the usage of MMTS

graphical notations to design OTS ontologies. It requires integration, bidirectional transformation, the model level, transformation rules and querying. It is the only one that does not involve reasoning.

Cranefield and Purvis [95] and Falkovych *et al.* [76] advocate the usage of UML without extensions as Ontology Representation Language capable of representing ontologies.

Extensions of the Unified Modeling Language for ontology development were proposed [96], culminating in a new metamodel into the MDA family of modeling languages - the Ontology Definition Metamodel [1, 67, 97]. These approaches use UML extension mechanisms (UML Profile) to represent the ontology, a mapping onto the ODM and a transformation from the ODM into the serialization syntax of the OWL ontology language. Figure 4.9 depicts the example of a UML class diagram representing an OWL ontology using the ODM UML profile for OWL.

The configuration of this category includes (Figure 4.10): (i) a model written in a given language with graphical notation from MMTS; (ii) a target model written in a given language and including one formalism from OTS; and (iii) a mapping specification describing the links between the models.

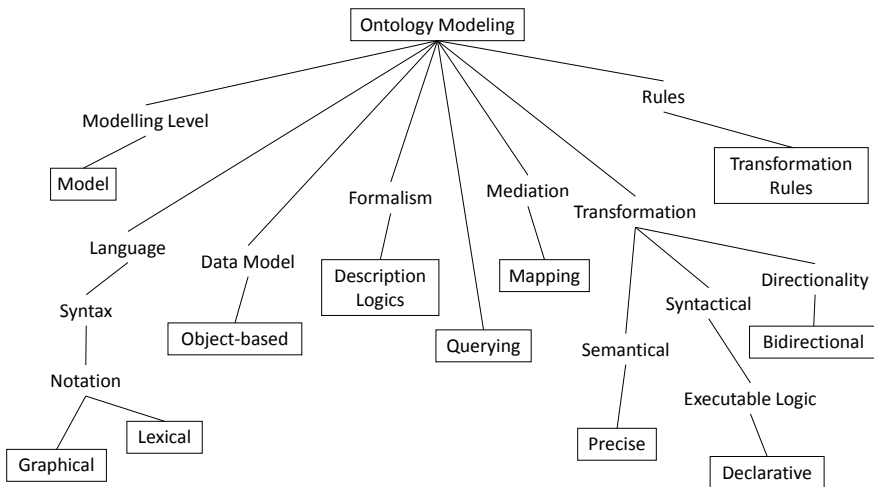


Fig. 4.10. Feature Model Configuration for Ontology Modeling.

4.5 Existing Work on Classifying Integrated Approaches

Research on the understanding of the large number of possible relations between OTS and MMTS is not new. Uschold and Jasper [98] propose a framework for understanding the ontology application scenarios outside the artificial intelligence community. Despite presenting application scenarios of ontologies in software development, the work does not explore the domain modeling community within software engineering.

Tetlow *et al.* [73] propose ideas based on how semantic web technologies can be applied in systems and software engineering and examples of these ideas. Such work does not present a framework pointing ways of integration. It serves as a research agenda instead, involving applications in the software engineering process.

Happel *et al.* [99] categorize ontologies in software engineering, distinguishing between four groups: Ontology-driven development (ODD), Ontology-enabled development (OED), Ontology-based architectures (OBA), Ontology-enabled architectures (OEA). Our work takes a more detailed view into ODD and OBA groups.

Bézivin *et al.* [100] bridge model engineering and ontology engineering using a M3-Neutral infrastructure. They consider software engineering and ontology engineering as two similarly organized areas, based on different metametamodels (M3-level).

4.6 Conclusion

In this chapter, we have illustrated commonalities and variations of using metamodeling technical spaces (MMTS) with ontological technical spaces (OTS). The basic pattern is that next to existing technical spaces of established metamodeling frameworks, new technical spaces are positioned that either enrich or exploit the software engineering capabilities by or for ontology technologies. We have identified the main characteristics of such approaches and designed a feature model to enlighten the possible conceptual choices. We have applied our model illustrating the usage of ontology technologies.

Conclusion of Part I

In this part, we have used the concept of megamodeling to provide a descriptive model for specifying the structure of MDE approaches (research question I). We use this model to describe the relationship between concepts of MDE and ontologies. Moreover, we use the approach to specify the relations between metamodeling technical spaces and ontological technical spaces.

Additionally, we propose a classification for existing approaches that use MDE and ontologies and identify patterns for transformations between both paradigms, addressing the research questions I.A and I.B. The analysis of existing work resulted in the identification of requirements for the integration of MDE and ontology technologies.

The TwoUse Approach

The TwoUse Conceptual Architecture

Summary. The next software engineering era will rely on the synergy between both model-driven engineering and ontology technologies. However, an approach that allows for exploiting the uniqueness of each paradigm has been missing so far. This chapter defines an integration between OWL and UML class-based modeling. It comprises an integration of existing metamodels and UML profiles, including relevant (sub)standards such as OCL. The result is a model-driven architecture for specifying integrated systems¹.

5.1 Introduction

UML class-based modeling and OWL comprise similar constituents: classes, associations, properties, packages, types, generalization and instances [1]. Despite the similarities, both approaches come with restrictions that may be overcome by an integration.

On the one hand, a key limitation of UML class-based modeling is that it allows only for static specification of specialization and generalization of classes and relationships, whereas OWL provides mechanisms to define these in a dynamic fashion. In other words, OWL allows for recognition of generalization and specialization between classes as well as class membership of objects based on conditions imposed on the properties of class definitions.

On the other hand, UML provides means to specify dynamic behavior, whereas OWL does not. The Object Constraint Language (OCL) [36] complements UML by allowing the specification of query operations, derived values, constraints, pre and post conditions.

Since both approaches provide complementary benefits, contemporary software development should make use of both. The benefits of an integration are twofold. Firstly, it provides software developers with additional modeling facilities. Secondly, it enables semantic software developers to use object-oriented concepts like operation

¹ This chapter contains work of the paper “Using Ontologies with UML Class-based Modeling: The TwoUse Approach” published in the Journal Data & Knowledge Engineering [101].

and polymorphism together with ontologies in a platform independent way. These considerations have led us to investigate the following challenge: How can we develop and denote models that benefit from advantages of the two modeling paradigms?

We present TwoUse in this chapter as follows: Section 5.2 describes the requirements for integrating ontology technologies and model-driven engineering. Section 5.3 presents and explains the building blocks of TwoUse. In Section 5.4 we present the metamodeling infra-structure for UML class-based models and OWL. In Section 5.5, we describe the notations for designing TwoUse models.

5.2 Requirements for Integrating Ontology Technologies and Model-Driven Engineering

Section 4.4 presents in the state-of-the-art research and MDE approaches that use OWL technologies and *vice versa*. However, the relationships between the two paradigms are still under exploration. In this section, we present the requirements for an integrated framework. These requirements are extended and refined in Part III and Part IV where we present the case studies.

5.2.1 Usage of Ontology Services in MDE

In addition to model validation and model enrichment, ontology technologies have more to offer. The integration between MDE and ontology technologies enables extending UML class-based modeling with OWL constructs and using ontology services to support the MDE process.

Integrate OWL Constructs in UML Class-Based Modeling

While mappings from one modeling paradigm to the other one have been established a while ago (see Section 4.4.1), the task of an integrated language for UML class-based modeling and OWL models is missing so far.

Such an approach simplifies the modeling task by introducing intuitive constructs that require complex OCL expressions otherwise, and it enables the definition of domain models enriched by formal class descriptions. Moreover, the usage of OWL class expressions allows decoupling class selection from the definition of query operations in client classes.

Such an integration is not only intriguing because of the heterogeneity of the two modeling approaches, but it is now a strict requirement to allow for the development of software with thousands of ontology classes and multiple dozens of complex software modules in the realms of medical informatics [102], multimedia [103] or engineering applications [104].

Usage of ontology services in UML class-based modeling

In addition to integrating OWL constructs in UML class-based modeling, the usage of ontology services (see Section 3.4) is essential for realizing the potential of ontology technologies. Therefore, one requires model transformations that transform integrated models into OWL ontologies.

Moreover, the integration between UML class-based modeling and OWL needs to cover the usage of ontology services at runtime as well as in design time. Thus, developers specify queries that use ontology services over the OWL representation. These queries are the interface between users and ontology services. The results generated by ontology services should be compatible with existing languages used to operate UML class-based models, e.g., OCL.

The intended benefit is that developers will not have to program by having to enumerate actions class-by-class. Instead they will rely on the ontology engine to perform generic operations to retrieve classes that satisfy ontological relationships with other classes, so that developers can focus only on the application specific actions.

5.2.2 Usage of MDE Techniques in OWL Ontology Engineering

MDE Support for Ontology Modeling

Research on ontology engineering has been inspired by the advances in software engineering over the years. For example, current approaches (see 4.4.3) use the graphical notation of UML to design OWL ontologies to support the ontology development life cycle. Moreover, as in software engineering, the usage of design patterns in ontology engineering is an established practice [105].

As new modeling techniques in model-driven engineering emerge, it is desirable to analyze the application of MDE techniques in ontology modeling. For example, the usage of domain-specific modeling is a promising approach for improving the usability of the OWL language by providing users with syntactical shortcuts. Moreover, the usage of templates in UML class-based modeling for reusing pieces of models is an accepted practice for improving reusability.

Usage of Domain Specific Modeling for Ontology Engineering Services

Currently, the development of ontology engineering services needs to manage multiple languages for defining services. For example, modelers of ontology matching services need to manage different languages: (1) an ontology translation language to specify translation rules and (2) a programming language to specify built-ins, when the ontology translation language does not provide constructs to completely specify a given translation rule. This intricate and disintegrated manner draws their attention away from the alignment task proper down into diverging technical details of the translation model.

Addressing this issue allows developers to concentrate on constructs related to the problem domain, raising the abstraction level. Moreover, by defining domain concepts as first-class citizens, developers may reuse these domain concepts on different situations. It helps to improve productivity, since modelers will not have to be aware of platform-specific details and will be able to exchange translation models even when they use different ontology translation platforms.

5.3 Addressing the Requirements with the TwoUse Approach

We build the TwoUse approach based on four core ideas:

1. As abstract syntax, it provides an integrated *MOF based metamodel* as a common backbone for UML class-based modeling and OWL modeling (Section 5.4).
2. As concrete syntax, it uses pure UML, Ecore, an *UML profile* supporting standard UML2 extension mechanisms and a textual concrete syntax to write integrated models (Section 5.5).
3. It provides a canonical *set of transformation rules* in order to deal with integration at the semantic level.
4. It provides a novel SPARQL-like language to write queries and constraints over OWL ontologies, SPARQLAS (Chapter 6).

To give an idea of the target integration, let us consider the simple example of E-Shop (please consult Figure 2.8 on Page 21). Instead of defining the operation `getTypes()` in the class `SalesOrder` using OCL, a more transparent and maintainable solution will use the expressiveness of the OWL language. Using the querying service, a query retrieves the OWL subclasses of `SalesOrder` a given instance fulfills the logical requirements of. The body of the `getTypes()` operation will then be specified by:

```
context SalesOrder
def getTypes(): Set(Class)
  ?self type ?T
  ?T subclassOf SalesOrder
```

As specified above, to identify which subclasses are applicable, we use the variable `?T` to get all types of `?self` that are subclasses of `SalesOrder`. We explain these and other expressions in Section 6.3.

The usage of the variable `?self` means that at the implementation level, we consistently correlate class instances with individuals in the ontology. That is, for every object in the system, we generate a corresponding individual in the ontology. As the classification of these individuals depends on structural relationships between objects, we need to update the individual information whenever changes in the object state occur.

The advantage of this integrated formulation of `getTypes()` lies in separating two sources of specification complexity. First, the classification of complex classes remains in an OWL model. The classification is re-useable for specifying other operations, and it may be maintained using diagram visualizations as well as decidable, yet rigorous reasoning models. Second, the specification of the business logic itself remains in OCL specifications. It becomes smaller, more understandable and easier to maintain.

Figure 5.1 presents a model-driven view of the TwoUse approach. TwoUse uses UML profiles for class diagrams and textual notations for designing combined models (Syntax). These notations are input for model transformations that generate TwoUse models conforming to the TwoUse metamodel (Structure). The TwoUse metamodel provides the abstract syntax for the TwoUse approach. Further model transformations take TwoUse models and generate the OWL ontology and Java code (Platform-Specific Artifacts and the Semantic Web Stack).

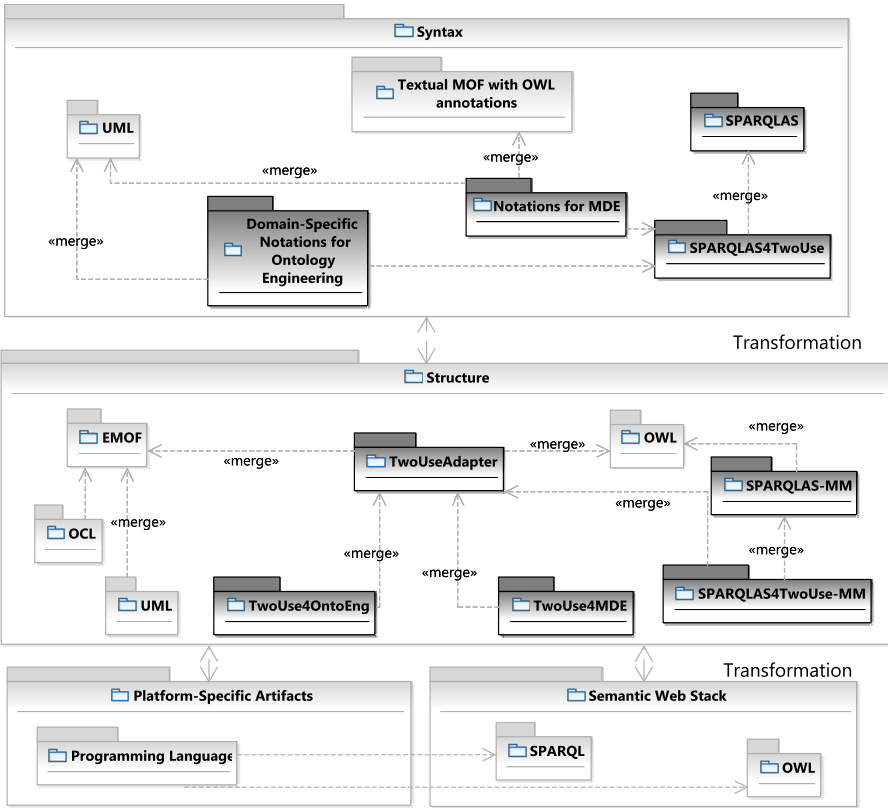


Fig. 5.1. The TwoUse Conceptual Architecture.

We correlate the building blocks in the Figure 5.1 with the requirements presented in Section 5.2 to show how TwoUse realizes the integration of MDE and ontology technologies. Table 5.1 depicts a traceability matrix and correlates the requirements (columns) with the building blocks (rows).

Extended languages for MDE (syntax and structure) and the TwoUse adapter allow for using OWL constructs in UML class-based modeling, whereas the SPARQLAS language enables the usage of ontology services. Domain-specific languages and the TwoUse adapter realizes the usage of MDE techniques for supporting ontology engineering.

5.4 Metamodeling Architecture

In this Section, we describe the concepts with respect to the integration of UML class-based modeling and OWL in the form of metamodels. The advantage of having an integrated metamodel is threefold:

- It enables the verification of well-formed models integrating both paradigms.

Requirements	OWL Constructs in UML class-based modeling (5.2.1)	Ontology services in UML class-based modeling (5.2.1)	MDE Support for Ontology Modeling (5.2.2)	Domain Modeling for Ontology Engineering Services (5.2.2)
Building Blocks				
Notations for MDE	X			
Domain-Specific Notations for Ontology Engineering				X
SPARQLAS		X		
SPARQLAS4TwoUse		X		
TwoUseAdapter	X	X	X	X
TwoUse4OntoEng			X	X
TwoUse4MDE	X	X		
SPARQLAS-MM		X	X	
SPARQLAS4TwoUse-MM		X	X	

Table 5.1. Traceability Matrix: Correlating Building Blocks with Requirements.

- It provides a common structure for supporting multiple notations.
- It realizes the mapping between UML class-based constructs and OWL constructs.

5.4.1 The TwoUse Metamodel

The TwoUse metamodel provides the abstract syntax integrating UML class-based modeling, OWL and a SPARQL-like query language. The abstract syntax provides an abstraction over the concrete syntax notations used in TwoUse.

The TwoUse metamodel provides the integration between common constructs in OWL and UML class-based modeling: package, class, property, instance and datatype. Basically, we compose classes from the Ecore metamodel with classes from the OWL metamodel.

We use model adaptation as composition technique to integrate the OWL metamodel and the Ecore metamodel. It consists of applying the Object Adapter Pattern [106] to *adapt* classes of the OWL metamodel to corresponding classes of the Ecore metamodel (see Table 4.2 for common features between UML class-based modeling and OWL). The Object Adapter Pattern allows us to compose objects within *Adapters*, called TwoUse classes.

Following the nomenclature of Gamma *et al.* [106], *Target* classes represent the interfaces from the Ecore metamodel (EPackage, EClass, EDatatype, EAttribute, EReference, EEnum, EEnumLiteral and EObject). *Adapter* classes are prefixed with TU and suffixed with Adapter (TUPackageAdapter, TUClassAdapter, TUDatatypeAdapter, TUAttributeAdapter, TUReferenceAdapter, TUEnumAdapter, TUEnumLiteralAdapter and TUObjectAdapter). *Adaptee* classes are classes of the OWL 2 metamodel.

Figure 5.2 illustrates the principle of model adaptation. We adapt the class `Class` from the OWL 2 metamodel for the class `EClass` from the Ecore metamodel. In the class `TUClassAdapter`, we implement the operations defined in the class `Ecore::EClass`.

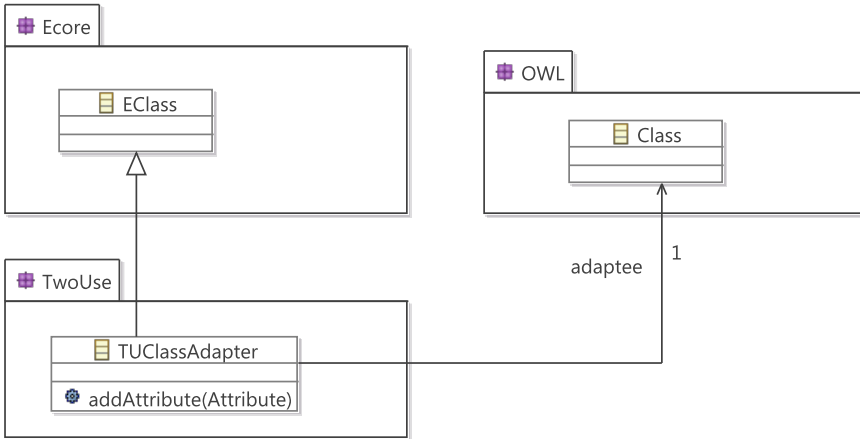


Fig. 5.2. Adapting the OWL Class for UML class-based modeling.

For example, the class `Ecore::EClass` defines the operation `addAttribute` for inserting attributes into a class. The class `TUClassAdapter` implements this operation as described in Listing 5.1. The implementation creates instances of the OWL 2 metamodel corresponding to the mappings between UML class-based modeling and OWL. In this example, for the addition of an attribute in a class in UML class-based modeling, we need to create two OWL axioms: one asserting the domain of the dataproperty and another asserting the range of the dataproperty.

Listing 5.1. Implementing the operation `addAttribute` in the class `TUClassAdapter`

```

1 public void addAttribute(Attribute attribute) {
    // DataPropertyDomain
    DataPropertyDomain dpd = owl2fsFactory
        .createDataPropertyDomain();
5 dpd.setDataPropertyExpression(attribute.getName());
  dpd.setDomain(eclass.getName());
  ...

    // DataPropertyRange
10 DataPropertyRange dpr = owl2fsFactory
        .createDataPropertyRange();
  dpr.setDataPropertyExpression(attribute.getName());
  dpr.setRange(attribute.getEAttributeType().getName());
  ...

```

15

```

    attributes.add(attribute);
}

```

Figure 5.3 depicts the mappings for the TwoUse metamodel using a simplified notation that associates the interfaces in the UML class-based metamodel to the corresponding concepts in the OWL 2 metamodel. As we have mentioned, this integration is independent of metamodeling level, i.e., it works for MOF, UML and any UML-class based modeling systems.

5.5 Syntax

5.5.1 UML Profile for OWL

The TwoUse approach provides developers with UML profiling as concrete syntax for simultaneous design of UML models and OWL ontologies, exploiting the full expressiveness of OWL (*SRITQ(D)*) and allowing usage of existing UML2 tools. We reuse the UML profile for OWL proposed by OMG [1] and introduce stereotypes to label integrated classes.

We use the UML profile for OWL proposed by OMG [1] for designing OWL ontologies using UML notation. We call the UML class diagram with elements stereotyped by a UML Profile for OWL a *hybrid diagram*. The hybrid diagram comprises three viewpoints, illustrated in the Figure 5.4: (1) the UML view, including OCL, (2) the OWL view and its logical class definitions and (3) the TwoUse view, which integrates UML classes and OWL classes and, relying on SPARQLAS, defines query operations that use ontology services (Chapter 6).

Considering the example of E-Shop (Figure 5.4 on Page 83), the OWL view consists of nine classes, five of which are named classes and four are unnamed classes. The restriction classes are required for reasoning on the subclasses `USSalesOrder` and `CanSalesOrder`. The UML View comprises six classes. The TwoUse view will contain five classes and the SPARQLAS query operation.

A TwoUse class is the bridge that links OWL elements with SPARQLAS expressions. To be compatible with tools that support UML2 extension mechanisms, developers annotate the UML element `OpaqueBehavior` with the stereotype `<<SPARQLASQuery>>` and define the SPARQLAS query as the body of the opaque behavior.

Table 5.2 illustrates the mappings between the UML Profile for OWL (hybrid diagram) and the TwoUse metamodel. Any class that has the stereotype `<<owlClass>>` in the hybrid diagram is mapped onto a TwoUse class. Any class with the stereotype `<<owlRestriction>>` and its properties `<<datatypeProperty>>` or `<<objectProperty>>` are mapped onto OWL classes and properties. Any class without any stereotype results in a regular class (`Ecore::EClass`). A TwoUse package is any package that has TwoUse classes. The UML Opaque behaviors stereotyped as `<<SPARQLASQuery>>` are mapped onto SPARQLAS.

5.5.2 Pure UML Class Diagrams

We have explored additional notations with increasing expressiveness, presented next. In addition to the UML Profile for TwoUse, one may use the pure UML

UML Class Diagram	TwoUse metamodel
UMLPackage	TUPackageAdapter
UMLClass	Ecore::EClass
(owlClass)UMLClass	TUClassAdapter
(owlRestriction)UMLClass	OWL::Class
(owlRestriction)UMLClass.(datatypeProperty)UMLProperty	OWL::DataProperty
(owlRestriction)UMLClass.(objectProperty)UMLProperty	OWL::ObjectProperty
(owlClass)UMLClass.(owlDataProperty)UMLProperty	TUAttributeAdapter
(owlClass)UMLClass.(owlObjectProperty)UMLProperty	TUReferenceAdapter
(owlIndividual)InstanceSpecification	TUObjectAdapter
(dataRange)Enumeration	TUEnumAdapter

Table 5.2. Mapping between the UML Profile for OWL (hybrid diagram) and the TwoUse Metamodel.

class diagram notation to model OWL ontologies with SPARQLAS expressions at class operations or use a textual syntax to design class-based models with OWL descriptions.

To let UML2 users develop ontology-based information systems, pure UML class diagrams may be used. Developers who do not need the full expressiveness of OWL can use this approach without having to handle the OWL syntax.

Model transformations transform the UML class diagram into a TwoUse model to support SPARQLAS expressions over the OWL translation of the UML class diagram. In this case, developers attach SPARQLAS expressions to the body of opaque behavior of class operations. Each UML class will be a TUClassAdapter. For transforming UML class diagrams into ontologies, we follow the rules defined in [1]².

5.5.3 Textual Notation

As alternative to graphical languages, we have defined a textual notation for specifying UML class-based models together with OWL. This approach is useful for experienced developers who work more productively with textual languages than visual languages.

In the following, we illustrate the textual notation with our running example. Again, each class is a TUClassAdapter. In this case, the textual notation allows for exploring the full expressiveness of OWL. The textual notation is a combination of the Java-like syntax and the OWL Manchester Syntax [107] (see Appendix A.1 for the EBNF grammar).

```

package PurchaseOrder // package name
PurchaseOrder // namespace prefix
"http://org.example/PurchaseOrder.ecore" //
namespace URI

```

² In this case, the expressiveness of the generated OWL ontology is limited to the description logic $\mathcal{ALCOIQ}(\mathcal{D})$, since \mathcal{DLR}_{ifd} is not supported by state-of-the-art DL-based reasoning systems [31].

```

{
5
  class TaskCtrl {
      reference SalesOrder salesOrder (0..-1);
      reference Customer customer (0..-1);

10
  }

  class SalesOrder {
      attribute EFloat price (0..1);

15
      reference Customer customer (1..1) opposite
          orders;

      operation EClass (0..-1) getTypes();
      operation EFloat total();
20
      operation EFloat taxes();
      operation EFloat freight();
  }

  class CanSalesOrder extends SalesOrder
      [equivalentTo [SalesOrder and [customer some
25
        [country value CANADA]]]] {}

  class USSalesOrder extends SalesOrder [equivalentTo
      [SalesOrder and [customer some [country value
30
        USA]]]] {}

  class Customer {
      reference SalesOrder orders (0..-1)
          opposite customer;
35
      reference Country country (1..1);
  }

  enum Country {
      1 : USA = "USA";
      2 : Canada = "Canada";
40
  }
}

```

The textual notation uses constructs familiar to programmers and enables developers to write class descriptions in a human readable way.

5.6 Conclusion

In this chapter, we have introduced a technique for integrating existing UML class-based metamodels and OWL metamodels. We describe the usage of the Adapter

design pattern to compose similar constructs between the OWL 2 metamodel and the Ecore metamodel. Moreover, we have defined notations for creating integrated models. As we apply our approach in Part III and Part IV, we will extend the integrated metamodel according to application requirements.

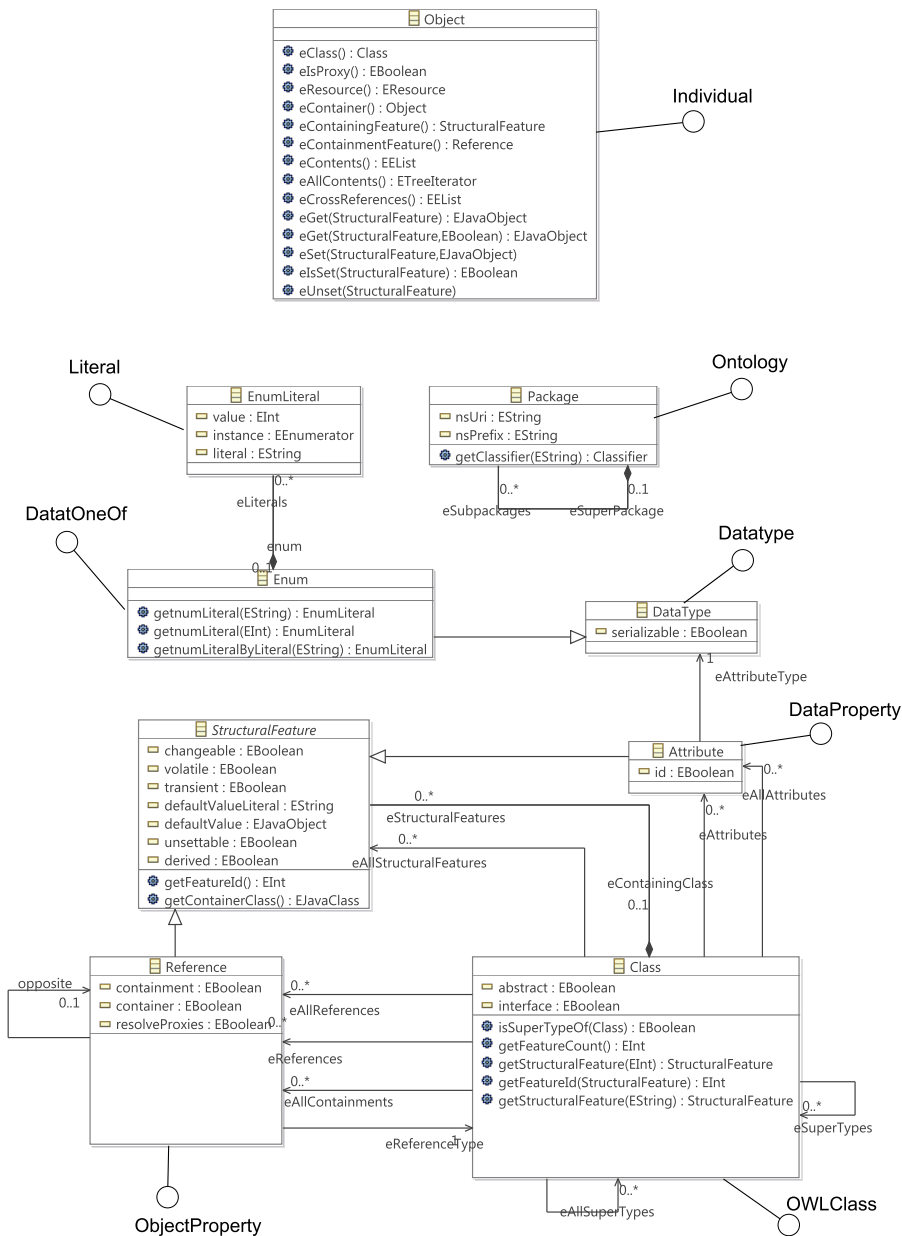


Fig. 5.3. The OWL 2 Metamodel Adapted for the UML Class-Based Metamodel – the TwoUse Metamodel.

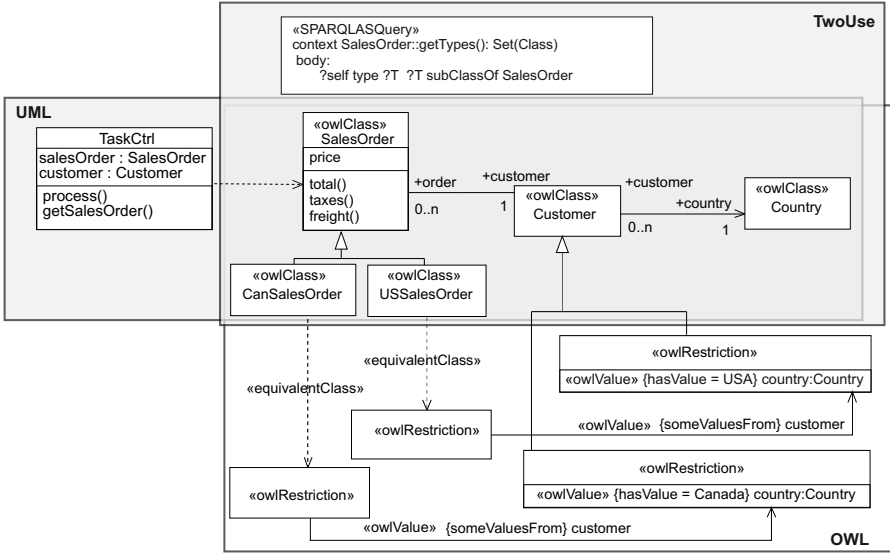


Fig. 5.4. UML class Diagram Profiled with Uml Profile for OWL and TwoUse Profile.

Query Languages for Integrated Models

Summary. After providing a unified view of metamodels and addressing the integration of modeling languages in the previous chapter, this chapter describes a querying approach to support developers in querying integrated models. We examine a combination of existing approaches and introduce our solution for querying integrated models¹.

6.1 Introduction

To exploit integrated models, it is important to enable engineers with the proper tools to manage and understand models. An important service for developers to gain insight into their models and to manage models is integrated querying.

In order to be able to query integrated models, a query framework needs to be integrated on the metamodeling level. A querying framework provides engineers with support for using existing approaches and for addressing modeling decisions.

In this chapter, we investigate the possibilities for querying elements of the combined metamodel in a flexible manner using or combining existing languages.

We structure this chapter as follows: in Section 6.2, we analyze the combination of existing query languages for UML class-based modeling and OWL. In Section 6.3, we present a concise query language for querying OWL ontologies: SPARQLAS. We extend SPARQLAS for supporting integrated models in Section 6.4: SPARQLAS4TwoUse.

6.2 Combining Existing Approaches

The OCL language provides the definition of functions and the usage of built-in functions for defining query operations in UML class diagrams, whereas SPARQL-DL provides a powerful language to query resources in OWL ontologies, allowing

¹ This chapter contains work of the EU STReP MOST Deliverable D1.2 “Report on Querying the Combined Metamodel” [108] and of the paper “Using Ontologies with UML Class-based Modeling: The TwoUse Approach” published at the Data & Knowledge Engineering Journal [101].

for retrieving of concepts, properties and individuals. While OCL assumes Unique Name Assumption (UNA) OWL may mimic it using constructs like `owl:AllDifferent` and `owl:distinctMembers`.

A combination of existing languages reflects configurations for querying integrated models. Figure 6.1 presents an architecture for querying integrated models. These configurations can be realized by adopting current approaches or combining different assumptions and reasoning services. We describe these configurations in the following sections.

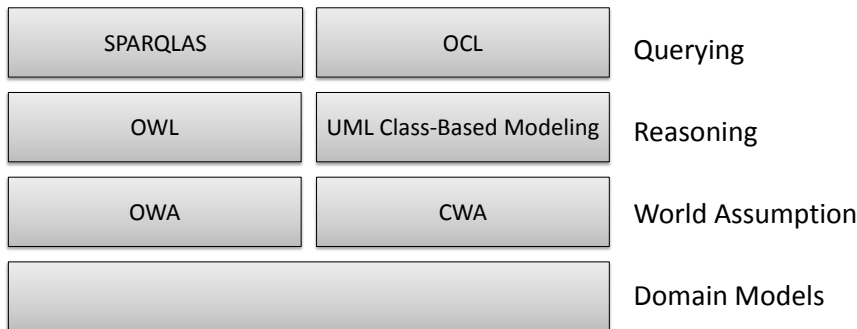


Fig. 6.1. Existing Approaches for Querying Models.

Using SPARQL over OWL with OWA

Among existing RDF based query languages for the semantic web, SPARQL is the W3C recommendation. It is based on triples patterns and allows for querying the vocabulary and the assertions of a given domain.

Restrictions on the SPARQL language, i.e., entailment regimes, allow for querying OWL ontologies, including TBox, RBox and ABox. One implementation is SPARQL-DL [57](see Section3.4.2 for a description of SPARQL-DL).

SPARQL-DL enables querying OWL ontologies using the Open World Assumption. It is current available with the Pellet Reasoner [79].

Using SPARQL over OWL with CWA

Polleres et al. [109] have explored the usage of the SPARQL language in combination with closed-world reasoning in SPARQL++. SPARQL++ extends SPARQL by supporting aggregate functions and built-ins. SPARQL++ queries can be formalized in HEX Programs or description logic programs. However, SPARQL++ covers only a subset of RDF(S) and how it could be extended towards OWL is still an open issue.

Using OCL over UML class-based modeling with CWA

This is the standard application of OCL as a query language. Query operations may be defined and used as helpers for OCL queries and constraints. Default values as well as initial and derived values can be defined by using UML and OCL.

Using OCL and SPARQL over OWA and UML class-based modeling

In some cases, a combination of UML class-based modeling and OWL is desired, e.g., for defining complex class descriptions or reuse existing ones. To make usage of behavioral features like query operations, helpers and built-ins, UML class-based modeling comes into play.

In the next section, we present our approach for such a combination. Our approach allows for describing query operations using SPARQL-like syntax. Query operations are written in SPARQL-like notation and are translated into SPARQL and execute against an OWL knowledge base. The results are used as input for OCL query operations that allows the usage of helpers, query operations and built-ins defined in OCL.

6.3 Querying Ontologies Using OWL syntax: SPARQLAS

Writing SPARQL queries for OWL can be time-consuming for those who work with OWL ontologies, since OWL is not triple-based and requires reification of axioms when using a triple-based language.

Therefore, we propose SPARQLAS, a language that allows for specifying queries over OWL ontologies with the OWL syntax [110]. SPARQLAS uses the OWL Functional Syntax as well as OWL 2 Manchester Syntax and allows using variables whenever an entity (Class, ObjectProperty, DataProperty, NamedIndividual) or a literal is allowed.

In the following, we illustrate the SPARQLAS concrete syntax with examples in Section 6.3.1, present the main classes of the SPARQLAS metamodel in Section 6.3.2 and exemplify the transformation of SPARQLAS into SPARQL in Section 6.3.3.

6.3.1 SPARQLAS Concrete Syntax

For creating SPARQLAS queries, we adopt the existing standard concrete syntax notations for OWL 2. Users can write SPARQLAS queries using the OWL 2 Functional Syntax [68] or the OWL 2 Manchester-like Syntax [107]. Appendix A.3 and Appendix A.2 specify the EBNF grammar for both notations.

Listing 6.1 and Listing 6.2 present the same query using the two different notations. The query results in all subclasses of a class that have, as the value of the property `customer`, a customer who lives in USA.

Listing 6.1. Example of SPARQLAS Query with Functional Syntax

```
1 Namespace ( = <http://www.example.org/customer#> )
   Select ?x
```

```

Where (
  SubClassOf (
5     ?x
      ObjectSomeValuesFrom(
          customer
          ObjectIntersectionOf(
10         Customer
          ObjectHasValue(country USA)
      )
  )
)

```

Since SPARQLAS copes with the OWL 2 syntax, it does not provide support for SPARQL solution sequences and modifiers (ORDER BY, OFFSET) or optional values (OPTIONAL). Schneider [110] presents an analysis of these constructs and the details about the mappings between SPARQLAS and SPARQL.

Listing 6.2. Example of SPARQLAS Query with Manchester-like Syntax

```

1 Namespace: <http://www.example.org/customer#>
  Select ?x
  Where: ?x subClassOf (customer some (Customer and (country
    value USA)))

```

6.3.2 SPARQLAS Metamodel

The SPARQLAS metamodel extends the OWL 2 metamodel [68] for including support for variables. Figure 6.2 depicts the additional classes in the SPARQLAS metamodel used for supporting the usage of variables. In the appendix, Figure A.1 depicts the complete SPARQLAS metamodel.

The class `Variable` is a term that has a symbol as property, which represents the variable (e.g., `?x`). Specializations of the class `Variable` define the existing variable types: `ClassVariable`, `ObjectPropertyVariable`, `DataPropertyVariable`, `IndividualVariable` and `LiteralVariable`. All these classes extend the class `Variable` and the corresponding class in the OWL 2 metamodel. For example, the class `ClassVariable` extends the class `Variable` as well as the class `ClassExpression`. Therefore, users can use variables whenever class expressions fit.

6.3.3 Transformation from SPARQLAS to SPARQL

SPARQLAS queries are translated into SPARQL queries to be executed by SPARQL engines that support graph pattern matching for OWL 2 entailment regime [55]. The model transformation comprises the implementation of the mappings from the OWL 2 structural specification to RDF Graphs (please consult [111] for the list of mappings).

For the sake of illustration, Listing 6.3 presents the corresponding SPARQL query for the SPARQLAS query defined in Listing 6.1 and 6.2. The SPARQL syntax uses triples to reify class expressions defined in the SPARQLAS queries.

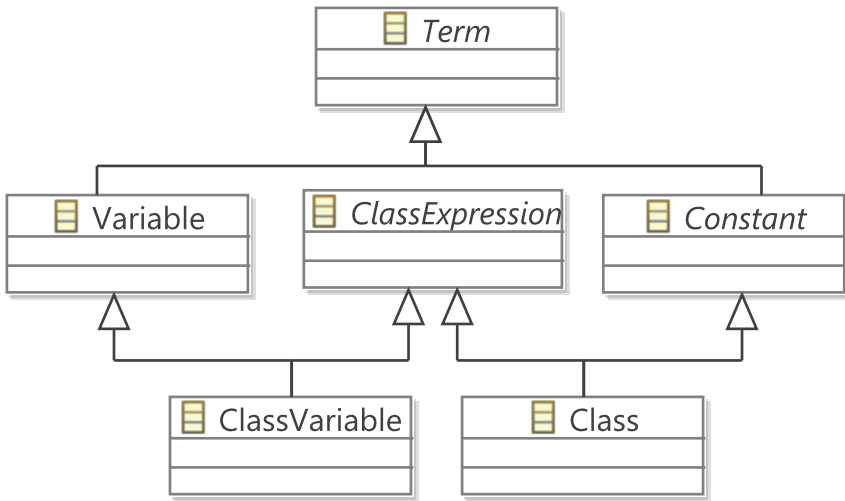


Fig. 6.2. Variables in the SPARQLAS Metamodel.

Listing 6.3. SPARQL Query Generated from the SPARQLAS Query

```

1 PREFIX rdf: <http://www.w3.org/1999/02/22-rdf-syntax-ns#>
  PREFIX rdfs: <http://www.w3.org/2000/01/rdf-schema#>
  PREFIX owl: <http://www.w3.org/2002/07/owl#>
  PREFIX xsd: <http://www.w3.org/2001/XMLSchema#>
5 PREFIX : <http://www.example.org/customer#>

SELECT DISTINCT ?x
WHERE {
  ?x rdfs:subClassOf [
10   rdf:type owl:Restriction ;
     owl:onProperty :customer ;
     owl:someValuesFrom [
       rdf:type owl:Class ;
       owl:intersectionOf [
15         rdf:first :Customer ;
           rdf:rest [
             rdf:first [
20               rdf:type owl:Restriction ;
                 owl:onProperty :country ;
                 owl:hasValue :USA
             ] ;
           rdf:rest rdf:nil
         ] ;
       ] ;
     ] ;
  ] ;
25 ]
}

```

```

    ]
}

```

6.4 Querying Integrated Models: SPARQLAS4TwoUse

An adaptation of SPARQLAS allows for defining the body of query operations in integrated models using an OWL-like language. Such an approach enables users to use ontology services integrated with UML class-based modeling, as depicted in the Figure 5.4.

For this purpose, we need first to compose the TwoUse metamodel with the SPARQLAS metamodel. Figure 6.3 depicts the navigation from the class `TUAdapterClass` to the query definition `SPARQLAS::Query`. The `TUAdapterClass` extends the `EClass`, with contains operations. An `Operation` extends a model element which contains constraints. A constraint contains as body an expression. The `ExpressionInSPARQLAS` defines a SPARQLAS Query.

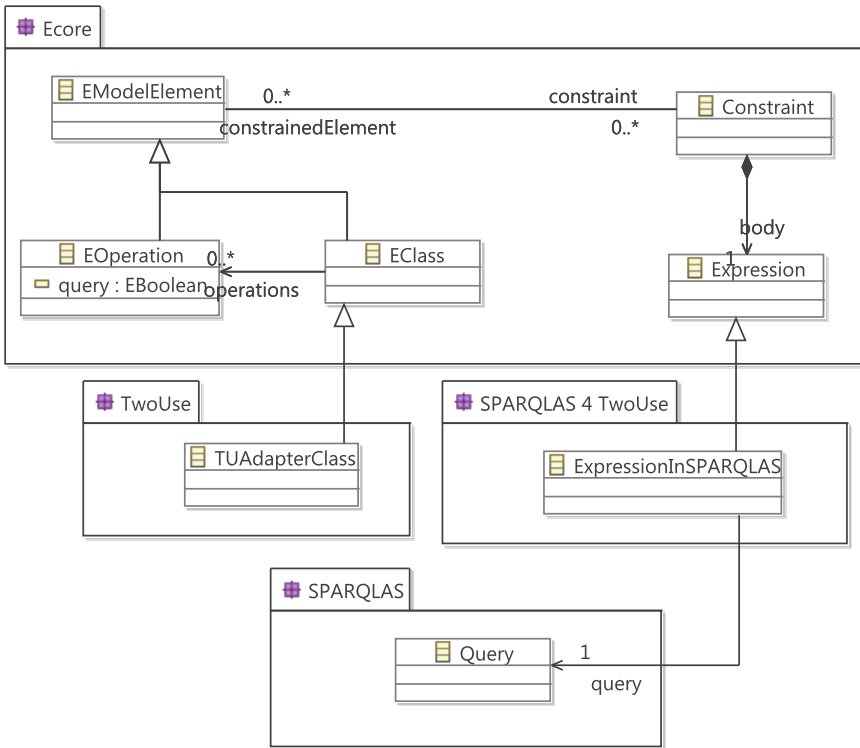


Fig. 6.3. Composing the SPARQLAS Metamodel and the TwoUse Metamodel.

The Variable ?self

Unlike in SPARQLAS, the expressions are written in the context of an instance of a specific class in SPARQLAS4TwoUse. We use the same rationale as OCL and reserve the variable `?self` for referring to the contextual instance. For example, the SPARQLAS4TwoUse query in Listing 6.4 evaluates to `John` if the contextual instance of the class `SalesOrder` is `ORDER1` (see Table 3.2 for the running example).

Listing 6.4. Example of SPARQLAS Query with Manchester-like Syntax

```

1 context SalesOrder :: getCustomer() : Customer
   Namespace: <http://www.example.org/customer#>
   Select ?c
   Where: ?self :customer ?c

```

SPARQLAS queries operate on the modeling layer (M) as well as on the snapshot layer (M-1). In the Figure 6.4, we present an object diagram representing a possible snapshot for the running example.

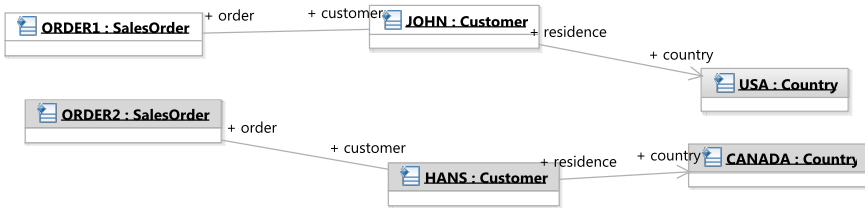


Fig. 6.4. Snapshot of the Running Example.

The result of SPARQLAS queries is mapped from OWL onto UML class-based modeling, i.e., although all OWL expressions like property chains and universal quantification can be used to write SPARQLAS queries, only classes, instances and literals can be delivered as the result.

Table 6.1 presents results of evaluating SPARQLAS expressions considering the snapshot depicted in the Figure 6.4. We take two objects of the snapshot (`ORDER1`, `ORDER2`) and bind them to the predefined variable `self`. For example, for the expression `?self type SalesOrder` where `?self` is bound to `ORDER1`, the result is `true`.

Since the results of SPARQLAS4TwoUse queries are transformed back from OWL into UML class-based modeling, the results can be used by OCL expressions that utilize query operations defined in SPARQLAS4TwoUse. For example, the OCL expression `self.getTypes().size()`; evaluates to 3 if the contextual instances are `ORDER1` (`Thing`, `SalesOrder`, `USSalesOrder`). Consequently, OCL expressions can use query operations defined in SPARQLAS4TwoUse as input (see Figure 6.5).

Context object SPARQLAS Expression	ORDER1	ORDER2
?self type SalesOrder	true	true
?self type USSalesOrder	true	false
?self type ?C	SalesOrder, USSalesOrder	SalesOrder, CanSalesOrder
?self inverse order ?c	John	Hans
?self directType ?C	USSalesOrder	CanSalesOrder

Table 6.1. Evaluation of SPARQLAS Expressions According to The Running Example Snapshot.

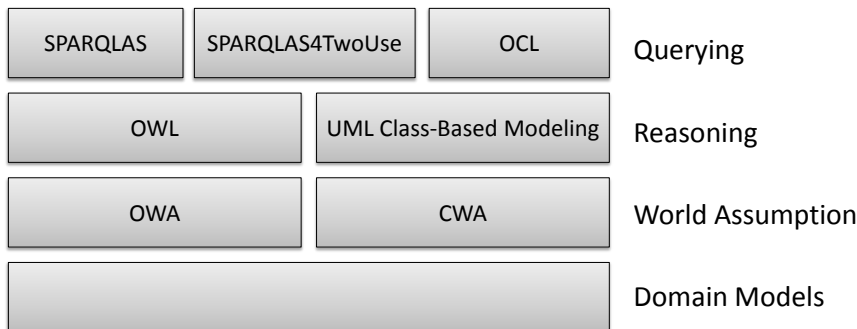


Fig. 6.5. Positioning SPARQLAS4TwoUse among Existing Approaches.

6.5 Conclusion

This chapter analyzes how current approaches can serve to query UML class-based modeling and OWL and possible combinations. The query languages SPARQLAS and OCL may be used according to different requirements to query OWL and UML class-based modeling respectively.

The adaptation of SPARQLAS, SPARQLAS4TwoUse, allows the definition of query operations for TwoUse classes that rely on ontology reasoning services. The combination of OCL and SPARQLAS4TwoUse allows for using the results of ontology reasoning services as input of OCL queries.

Realizing the TwoUse Conceptual Architecture: The TwoUse Toolkit

Summary. The gap between the specification of standards and the implementation of standards in a programming language leads to adaptation penalties when new versions are available. Among the possible solutions for raising the level of abstraction from code to standard specification, a framework that allows the integration of multiple standards at the design level is lacking so far. In this chapter, we present a generic architecture for designing artifacts using multiple standard languages, turning the focus from code-centric to transformation-centric. We test this architecture by instantiating its conceptual blocks in an integrated development environment – the TwoUse Toolkit¹.

7.1 Introduction

Although the interest in integrating ontology technologies and software engineering has gained more attention, practitioners lack tool support. Although guidelines for model transformations and implementations of these transformations exist, a comprehensive framework dedicated to fill the gap between model-driven engineering and ontology technologies is lacking so far. Ontology engineering environments [113] support exclusively ontology development and do not provide support for OMG standards.

Providing a framework for integrating MDE and ontology technologies requires dealing with the following challenges:

- Seamless integration between UML class-based modeling languages and OWL. Developers should be able to design models seamlessly in different formats like Ecore, UML, XML and OWL.
- Modeling Design Patterns. Integrated frameworks should provide developers with capabilities for reusing existing knowledge from other projects in the form of design patterns.

¹ This chapter contains work of the tool demonstration “Filling the Gap between the Semantic Web and Model-Driven Engineering: The TwoUse Toolkit” at ECMFA2010 [112].

- Integration with existing standard and recommendations such as SWRL [63] and OCL [36]. Developers should be able to work with semantic web languages (OWL, SWRL and SPARQL) as well as with software languages (UML and OCL).

In this chapter, we present a generic architecture to implement OWL-related standard specifications and model-driven techniques in an integrated engineering tool, turning the focus from code-centric to transformation-centric. It comprises a set of model transformations, graphical and textual editors and reasoning services.

We organize this chapter as follows. In Section 7.2, we describe the use cases for such an architecture based on the requirements specified in Section 5.2 and correlate use cases and requirements in Section A.7. We describe the generic architecture in Section 7.3. In Section 7.4, we describe an instantiation of the generic architecture for development of model-driven applications and ontology-based information systems – the TwoUse Toolkit.

7.2 Use Case Descriptions

In Section 5.2, we present the requirements for an integrated approach. Figure 7.1 depicts the use cases (UC) to address those requirements. It gives an overview of actors and their relation to the use cases. Appendix A.6 presents the description of these use-cases

Designing integrated UML class diagram or integrated Ecore models (UC *Design Integrated Model*) enables the integration of OWL constructs in UML class-based modeling. By specifying SPARQLAS4TwoUse query operations at classes (UC *Specify Query Operations*), software engineers can define queries over ontologies and thus use classification and realization to improve software quality (see case studies 8 and 9). Moreover, when ontology engineers transform Ecore-based models and metamodels into OWL (UC *Transform to OWL*), it allows the usage of explanation (UC *Explain Axiom*), querying (UC *Query UML class-based models*) and ontology matching (UC *Compute Alignments*) for supporting software engineers in debugging and maintenance.

The Usage of SPARQLAS for querying OWL ontologies applies the principles of MDE (domain-specific modeling and model transformation) to enable ontology engineers to write SPARQL queries without having to deal with the reification of OWL axiom in RDF triples (UC *Query OWL ontologies*). Moreover, the design and generation of ontology engineering services (UC *Design Ontology Engineering Service*) counts on domain-specific modeling and model transformation to generate platform-specific artifacts and raises the level of abstraction (see case studies 12, 11 and 13).

7.3 A Generic Architecture for MDE and Ontology Engineering

The architecture of an integrated environment for OWL modeling and UML class-based modeling serves as a guideline for the development of artifacts for ontology

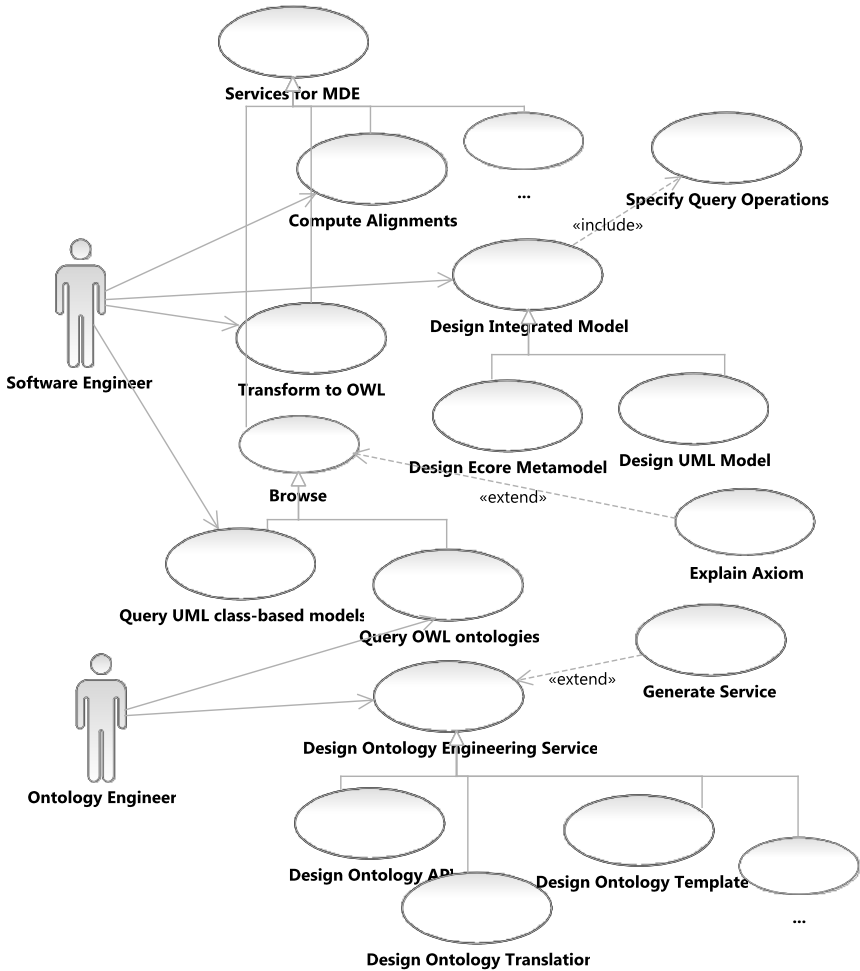


Fig. 7.1. Use Case for a Generic Architecture for MDE and Ontology Engineering.

engineering that use model-driven technologies and artifacts for model-driven engineering that use ontology technologies. It comprises a layered view according to the degree of abstraction of the components. Components of higher layers invoke components of lower layers.

Figure 7.2 depicts the generic architecture for developing integrated artifacts. It comprises a set of core services, services for ontology engineering, services for MDE and a front-end layer.

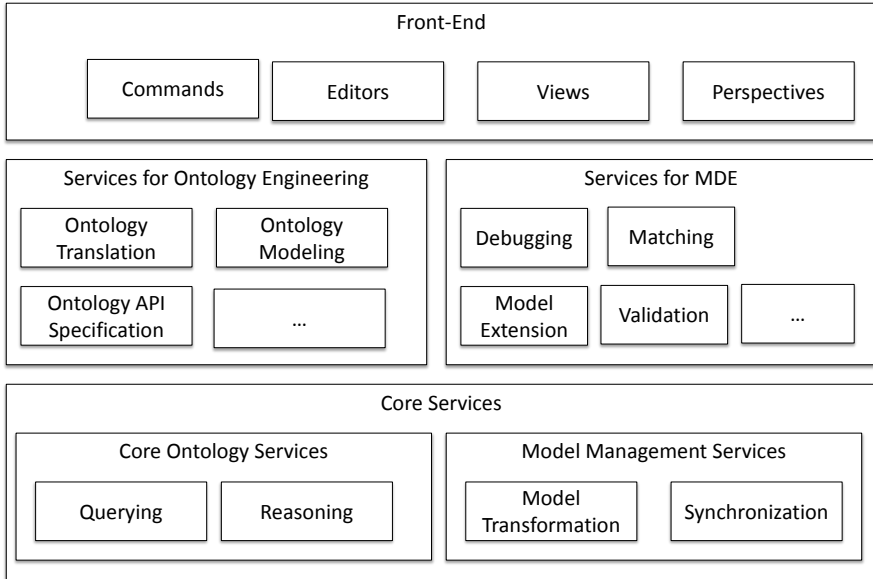


Fig. 7.2. A Generic Architecture for MDE and Ontology Engineering.

7.3.1 Core Services

The core services comprise the core ontology services and the model management services. The core ontology services correspond to the ontology services described in Section 3.4 and cover querying and reasoning.

The model management services involve model transformations and the synchronization of the source and target model. For example, when transforming a UML class diagram into OWL, one requires that the generated OWL ontology keeps synchronized with changes on the source model.

7.3.2 Engineering Services

Services for Ontology Engineering

Engineering services assemble the services for ontology engineering and the services for MDE. Among the services for ontology engineering, we highlight three services that use model-driven technologies to support ontology engineering: ontology translation, ontology modeling and ontology API specification. Further ontology engineering services are described in [11].

The ontology modeling service provides the structure for designing ontologies. It covers the support for ontology design patterns and the validation and verification of well-formedness constraints.

Ontology translation enables the translation of a source ontology into target formalisms. It adopts a dedicated language for defining mappings of multiple natures: semantic, syntactic and lexical.

Ontologies require dedicated APIs to encapsulate the complexity of concepts and relations. Therefore, to facilitate the adoption of these ontologies, ontology engineers specify which ontological concepts and roles require operations for creation, update and deletion. The ontology API service supports this task.

Services for Model-Driven Engineering

Among the services for MDE, we have identified the following services that use ontology technologies to support MDE: debugging, matching, validation and extension. Debugging allows for supporting software engineers in identifying the model elements that underpin a logical conclusion. For example, it consists of pointing out the assertions that support a given statement.

The matching services consist of applying ontology matching techniques [61] to identify similar concepts or relations in multiple models (see Section 3.5.2 for ontology matching techniques).

Finally, the model extension service controls the integration between OWL and UML class-based modeling. It manages the extension of UML class diagrams and textual Ecore notation with OWL axioms and the specification of a SPARQLAS4TwoUse query as the body of query operations.

7.3.3 Front-End

The layer **Front-End** is the interface between services and ontology engineers / software engineers. It comprises editors, views, commands and perspectives.

The editors enable engineers to create and update artifacts written in ontology languages as well as in software languages. For example, the OWL2FS editor enables ontology engineers to create OWL ontologies using the OWL 2 functional syntax.

Commands comprise the actions that engineers execute to manipulate artifacts. For example, to evaluate a given query operation, ontology engineers execute the command `evaluate` that requests the instance specifications to be used as the snapshot and invokes the model extension to control the applicable model transformations.

The component **View** provides engineers with multiple types of visualizations of artifacts. For example, engineers require the visualization of classes in a class hierarchy or the results of a query in a grid.

Perspectives arrange views and editors in the workbench. It consists of supporting the organization of the front-end services according to engineers needs.

7.4 Instantiating The Generic Model-Driven Architecture: The Twouse Toolkit

TwoUse toolkit is an open source tool that implements the research presented in this thesis. It is an instantiation of the generic architecture and an implementation of current OMG and W3C standards for designing ontology-based information systems

and model-based OWL ontologies. It is a model-driven tool to bridge the gap between semantic web and model-driven engineering.

TwoUse toolkit building blocks are (Figure 7.3):

- A set of textual and graphical editors. TwoUse relies on textual and graphical editors for editing and parsing W3C standard languages (OWL 2 and SPARQL), OMG standards (UML, MOF and OCL) as well as other domain-specific languages.
- A set of model transformations. Generic transformations like “Ecore to OWL” allow developers to transform any software language into OWL. Specific transformations like “UML to OWL” and “BPMN to OWL” allow developers to create ad-hoc OWL representations of software models.
- A set of ontology services like reasoning, query answering and explanation.

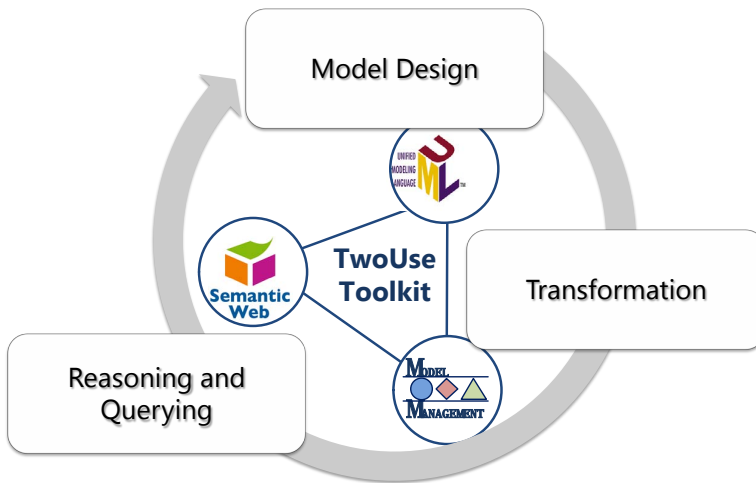


Fig. 7.3. The TwoUse Toolkit.

Figure 7.6 depicts the TwoUse instantiation of the generic architecture (Figure 7.2). It comprises core services, services for ontology engineering and model-driven engineering and a front-end.

Core Services

The TwoUse toolkit uses the implementation of SPARQL-DL and the OWL 2 reasoner provided by the Pellet reasoner [79] as components for realizing the core ontology services. The model transformation component consists of a set of model transformations implemented using the Java language [114] as well as the model transformation language ATL [35]. The synchronization service maintains the dependencies between the source artifacts and the target artifacts. For example, when engineers use a SPARQLAS query, a corresponding SPARQL query is generated and executed. The synchronization service maintains the generated SPARQL query

updated in case of changes on the SPARQLAS query. It basically implements the observer pattern [106] to notify state changes on the source model.

Services for Engineering

The services for ontology engineering cover concrete applications of the TwoUse toolkit. We detail each of these applications in Part IV.

The services for model-driven engineering cover explanation, ontology matching and the TwoUse metamodel. The explanation service uses ontology services to help software engineers in pinpointing statements. The TwoUse toolkit covers the following types of explanation: unsatisfiability, class subsumption, instantiation and property assertion. The matching service uses the Ontology Alignment API [115] to support engineers in identifying similar constructs over multiple metamodels. We illustrate the application of these services in Chapter 10.

Figure 7.4 depicts a snapshot of the TwoUse Toolkit showing the view Explanation. The result of the explanation is shown in the console with links to the class on the UML class diagram.

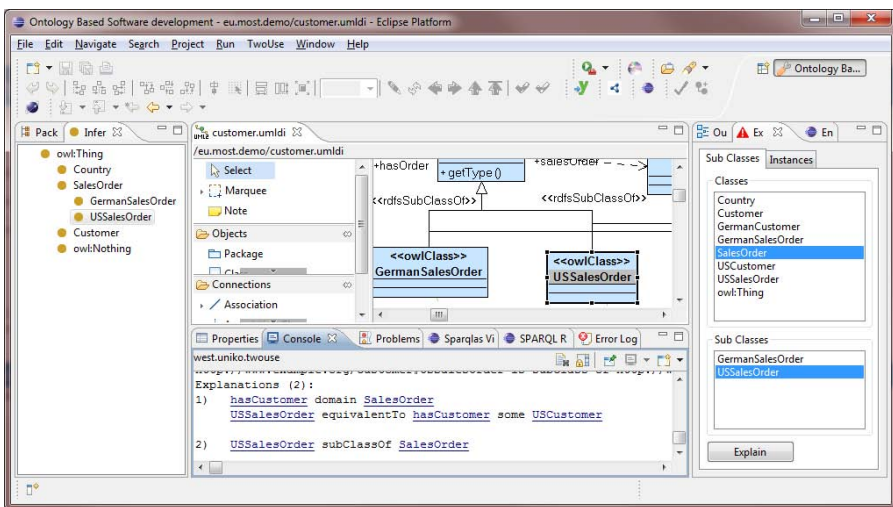


Fig. 7.4. TwoUse Toolkit Snapshot: Explanation Service.

Front-End

The front-end is the interface of the TwoUse toolkit to engineers. It comprises multiple editors that implement W3C standard languages and OMG standards as well as other domain-specific languages. We define three views to help engineers in visualizing models: a hierarchy of the inferred classes (Figure 7.5), a user interface for explanation and for query results. The commands involve transforming models into OWL, executing queries and generating services and code. We group the editors, views and commands under two perspectives: ontology-based model design and model-driven ontology development.

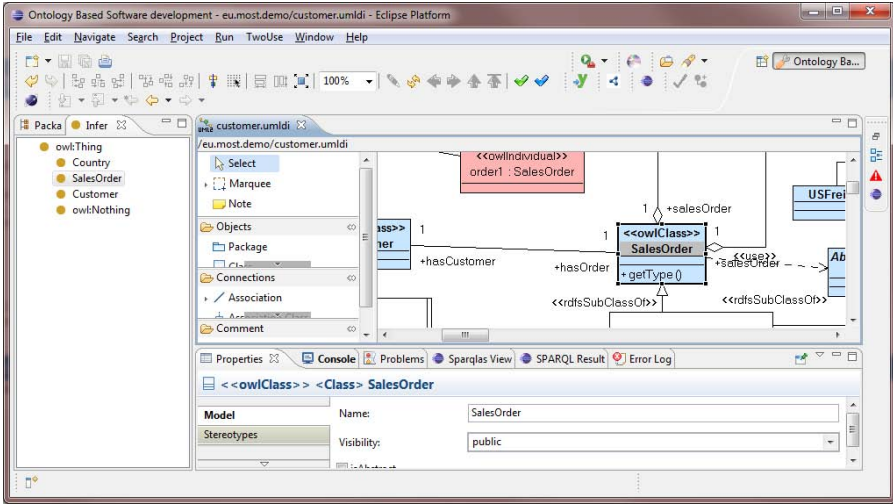


Fig. 7.5. TwoUse Toolkit Snapshot: View Inferred Class Hierarchy.

We implement the TwoUse toolkit on top of the Eclipse Rich Client Platform [116] as an open-source tool under the eclipse public license. It is available for download on the Project Website².

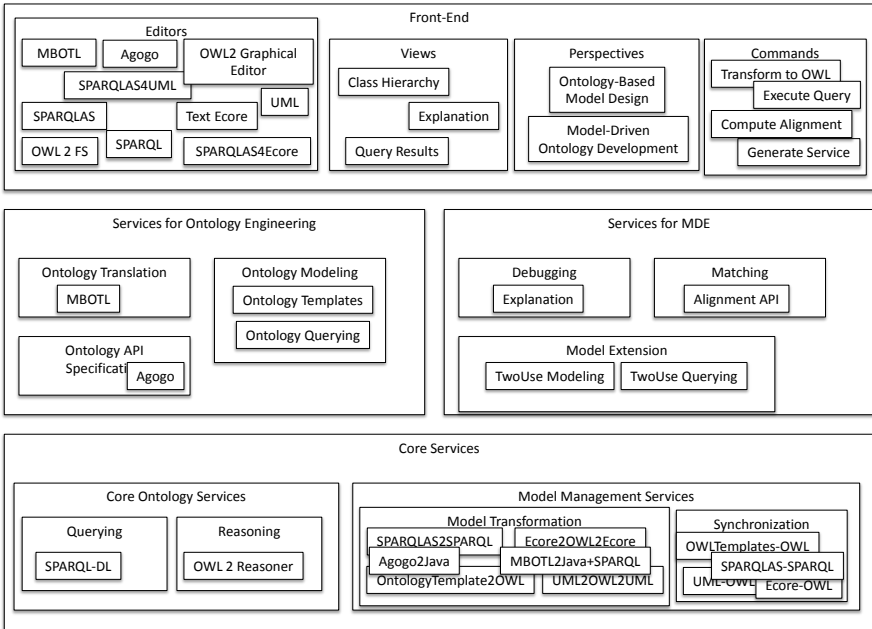


Fig. 7.6. Instantiation of the Generic Architecture: The TwoUse Toolkit.

² <http://twouse.googlecode.com/>

7.5 Conclusion

In this chapter, we have specified a generic architecture for integrated approaches. The architecture fulfills the requirements defined in Section 5.2. We validated the architecture by instantiating it as an implementation of the conceptual architecture – the TwoUse Toolkit.

Conclusion of Part II

This part presents TwoUse as a solution for developing and denoting models that benefit from the advantages of UML class-based modeling and OWL modeling (Research Question II). We describe the main building blocks of a conceptual architecture covering an integration of UML class-based modeling, OWL and a query language for OWL. Moreover, we specify a generic architecture for implementing the conceptual architecture and describe an instantiation of the generic architecture - the TwoUse Toolkit.

Applications in Model-Driven Engineering

Improving Software Design Patterns with OWL

Summary. This chapter tackles problems in common design patterns and proposes OWL modeling to remedy these issues. We exploit the TwoUse approach and integrate OWL with UML class-based modeling to overcome drawbacks of the strategy pattern, that are also extensible to the abstract factory pattern. The results are ontology-based software design patterns to be used with software design patterns ¹.

8.1 Introduction

Design patterns [106] provide elaborated, best practice solutions for commonly occurring problems in software development. During the last years, design patterns were established as general means to ensure quality of software systems by applying reference templates containing software models and their appropriate implementation to describe and realize software systems.

In addition to their advantages, Gamma *et al.* [106] characterize software design patterns by their consequences including side effects and disadvantages caused by their use. In this chapter, we address the drawbacks associated with pattern-based solutions for variant management [118]. Design patterns rely on basic principles of reusable object design like manipulation of objects through the interface defined by abstract classes, and by favoring delegation and object composition over direct class inheritance in order to deal with variation in the problem domain.

However, the decision of what variation to choose typically needs to be specified at a client class. For example, solutions based on the strategy design pattern embed the treatment of variants into the client's code, leading to an unnecessary tight coupling of classes. Gamma [106] identifies this issue as a drawback of pattern-based solutions, e.g., when discussing the strategy pattern and its combination with the abstract factory pattern. Hence, the question arises of how the selection of specific classes could be determined using only their descriptions rather than by weaving the descriptions into client classes.

¹ This chapter contains work of the paper “Improving Design Patterns by Description Logics: A Use Case with Abstract Factory and Strategy” presented at Modellierung'08 [117].

Here, *description logics* come into play. Description logics, in general, and OWL as a specific expressive yet pragmatically usable W3C recommendation [5] allow for specifying classes by rich, precise logical definitions [43]. Based on these definitions, OWL reasoners infer dynamically class subsumption and object classification.

The basic idea of this chapter lies in decoupling class selection from the definition of client classes at runtime by exploiting OWL modeling and reasoning. We explore a slight modification of the strategy pattern and the abstract factory pattern that includes OWL modeling and that leads to a minor, but powerful variation of existing practices: the *Selector Pattern*. To realize the *Selector Pattern*, we apply the TwoUse approach.

This chapter is organized as follows. We present an example demonstrating the application of the strategy and abstract factory patterns to solve a typical implementation problem in Section 8.2. The example illustrates the known drawbacks of the state-of-the-art straightforward adoption of these patterns. Then, we present a solution extending the existing patterns by OWL modeling in Section 8.3. We explain how our revision modifies the prior example and how it addresses the issues raised in the example. We describe an abstraction of the modified example, i.e. the selector pattern, in Section 8.4. We present its structure, guidelines for adoption, consequences and related works. A short discussion of open issues concludes this chapter in Section 8.6.

8.2 Case Study

This section presents a typical case study of design patterns involving the strategy and abstract factory pattern. To illustrate an application of such patterns, we take the example of an order-processing system for an international e-commerce company in the United States [119]. This system must be able to process sales orders in different countries, e.g., the US and Germany, and handle different tax calculations.

Design patterns rely on principles of reusable object-oriented design [106]. In order to isolate *variations*, we identify the *concepts* (commonalities) and concrete implementations (*variants*) present in the problem domain. The **concept** generalizes common aspects of **variants** by an abstract class. If several variations are required, the variations are subsumed to contextual classes, which delegate behavior to the appropriate variants. These variants are used by *clients*.

8.2.1 Applying the Strategy Pattern

Considering the principles above, we identify the class `SalesOrder` as a *context*, `Tax` as a *concept*, and the classes `USTax` and `GermanTax` as the *variants* of tax calculation. Since tax calculation varies according to the country, the strategy pattern allows for encapsulating the tax calculation, and letting them vary independently of the *context*. The resulting class diagram is depicted in the Figure 8.1.

To specify operations, we use the Object Constraint Language (OCL) [36]. The `TaskController` requires the operation `getRulesForCountry`, which returns the concrete strategy to be used. The specification must include criteria to select from the strategies. In our example, the criterion is the country where the customer of a sales order lives in.

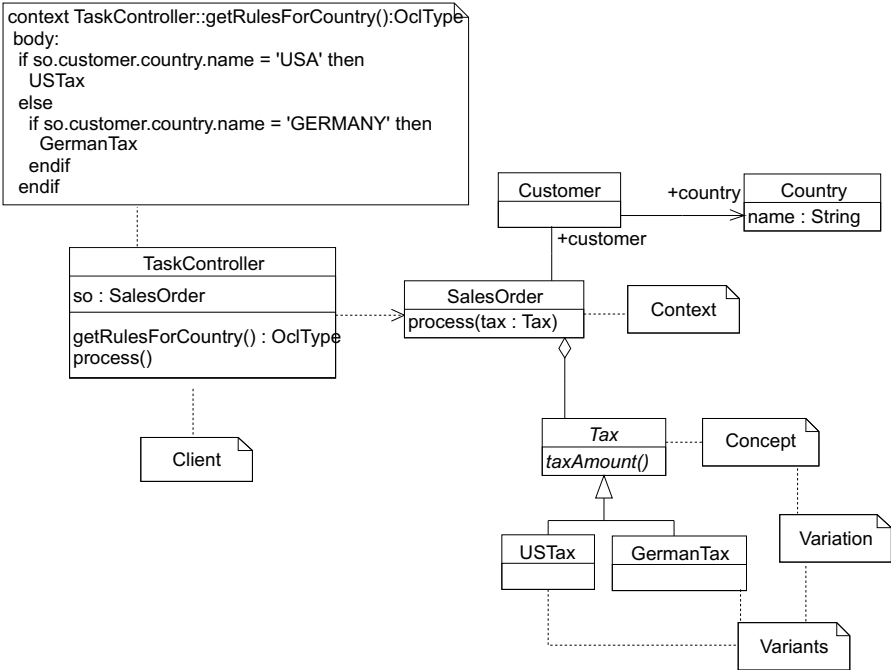


Fig. 8.1. Application of the Strategy Pattern in the Running Example.

The drawback of this solution is that, at runtime, the *client* TaskController must decide on the *variant* of the *concept* Tax to be used, achieved by the operation `getRulesForCountry`. Nevertheless, it requires the *client* to understand the differences between the variants, which increases the coupling between these classes.

Indeed, the decision of whether a given object of **SalesOrder** will use the class **GermanTax** to calculate the tax depends on whether the corresponding **Customer** lives in Germany. Although this condition refers to the class **GermanTax**, it is specified in the class **TaskController**. Any change in this condition will require a change in the specification of the class **TaskController**, which is not intuitive and implies an undesirably tight coupling between the classes **GermanTax**, **Country**, and **TaskController** (cf. Figure 8.2).

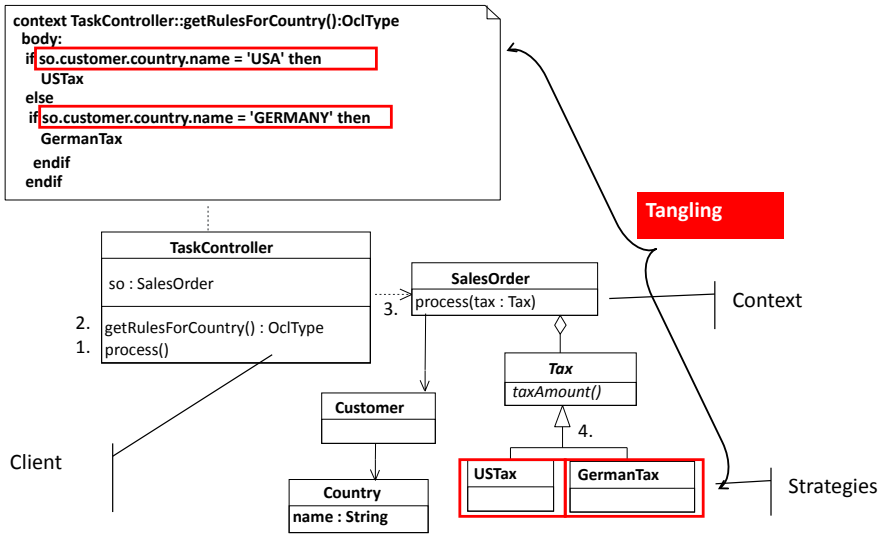


Fig. 8.2. Drawbacks of the Strategy Pattern.

8.2.2 Extending to the Abstract Factory

When the company additionally needs to calculate the freight, new requirements must be handled. Therefore, we apply again the strategy pattern for freight calculation. As for the tax calculation, the *context* SalesOrder aggregates the *variation* of freight calculation, USFreight and GermanFreight generalized by the *concept* Freight (cf. Figure 8.3).

As we now have families of objects related to USA and Germany, we apply the abstract factory pattern to handle these families. The abstract factory pattern provides an interface for creating groups of related *variants* [106].

As one possible adaptation of the design patterns, the *client* (TaskController) remains responsible for selecting the *variants* of the *concept* AbstractFactory to be used, i.e., the family of strategies, and passes the concrete factory as a parameter to the class SalesOrder. The class SalesOrder is associated with the class AbstractFactory, which interfaces the creation of the strategies Tax and Freight. The concrete factories USAbsFact and GermanAbsFact implement the operations to create concrete strategies USFreight, GermanFreight, GermanTax and USTax.

The adaptation of the design patterns used as the example introduces a configuration object [119] to shift the responsibility for selecting variants from one or several clients to a Configuration class, as depicted in the Figure 8.3. The class Configuration decides which variant to use. The class SalesOrder invokes the operation getRulesForCountry in the class Configuration to get the variant. These interactions are also depicted in a sequence chart in the Figure 8.4.

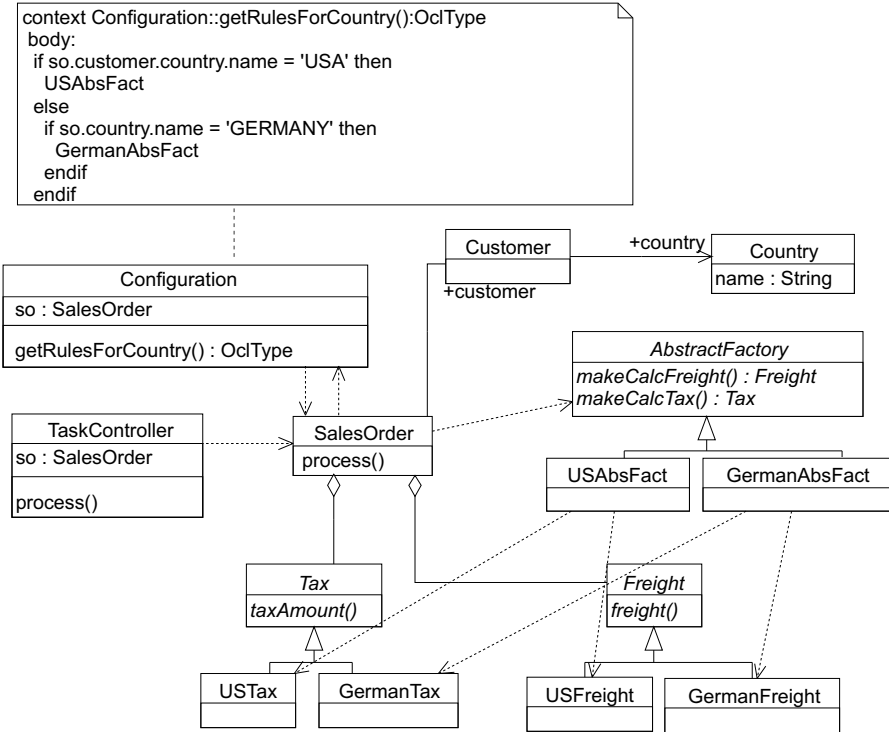


Fig. 8.3. Strategy and Abstract Factory Patterns with Configuration Object.

8.2.3 Drawbacks

In general, the strategy pattern solves the problem of dealing with variations. However, as documented by Gamma [106], the strategy pattern has a drawback. The clients must be aware of variations and of the criteria to select between them at runtime, as described at the end of Section 8.2.1.

When combining the strategy and the abstract factory pattern, the problem of choosing among the variants of the `AbstractFactory` remains almost the same. Indeed, the abstract factory pattern assembles the families of strategies. Hence, the client must still be aware of variations.

The solution using the class `Configuration` does not solve this problem either, i.e., the coupling migrates. As the `Configuration` must understand how the variants differ, the selection is transferred from the client `TaskController` to the class `Configuration`.

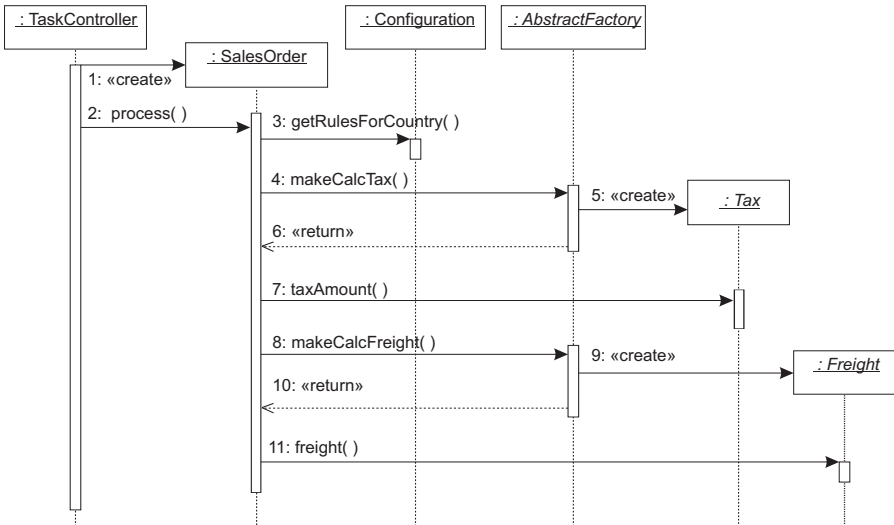


Fig. 8.4. UML Sequence Diagram of Strategy and Abstract Factory Patterns with Configuration Object.

Furthermore, each occurrence of the strategy and the abstract factory patterns increases the number of operations that the class `Configuration` must be able to handle. It makes the specification of such a class complex, decreasing class cohesion.

Thus, a solution that reuses the understanding of the variations without increasing the complexity is desirable. Furthermore, such a solution should allow to decide on the appropriate variants as late as possible. Separating the base of decision from the decision itself will provide an evolvable and more modular software design. In the next section, we describe how `TwoUse` provides such a mechanism.

8.3 Application of the TwoUse Approach

A solution for the drawbacks presented at the end of Section 8.2 is to dynamically classify the *context*, and verify if it satisfies the set of requirements of a given *variant*. To do so, one requires a logical class definition language that is more expressive than UML, e.g., the Web Ontology Language (OWL) [5].

To benefit from the expressiveness of OWL and UML modeling it is necessary to weave both paradigms into an integrated model-based approach, e.g., by using the `TwoUse` modeling approach (see Chapter 5).

8.3.1 OWL for Conceptual Modeling

OWL provides various means for expressing classes, which may also be nested into each other. One may denote a class by a class identifier, an exhaustive enumeration of individuals, a property restriction, an intersection of class descriptions, a union of class descriptions or the complement of a class description.

For the sake of illustration, an incomplete specification of the E-Shop example using a description logic syntax repeated here. The identifier *Customer* is used to declare the corresponding class (8.1) as a specialization of *Thing* (\top), since all classes in OWL are specializations of the reserved class *Thing*. The class *Country* contains the individuals *USA* and *GERMANY* (8.2). The class *USCustomer* is defined by a restriction on the property *hasCountry*, the value range must include the country *USA* (8.3). The description of the class *GermanCustomer* is analogous (8.5). *USSalesOrder* is defined as a subclass of a *SalesOrder* with at least one *USCustomer* (8.4). The intersection of both classes is empty (\perp), i.e., they are disjoint (8.7). The class *SalesOrder* is equal to the union of *GermanSalesOrder* and *USSalesOrder*, i.e., it is a complete generalization of both classes (8.8).

$$Customer \sqsubseteq \top \quad (8.1)$$

$$\{USA, GERMANY\} \sqsubseteq Country \quad (8.2)$$

$$USCustomer \sqsubseteq Customer \sqcap \exists hasCountry\{USA\} \quad (8.3)$$

$$USSalesOrder \sqsubseteq SalesOrder \sqcap \exists hasCustomer.USCustomer \quad (8.4)$$

$$GermanCustomer \sqsubseteq Customer \sqcap \exists hasCountry\{GERMANY\} \quad (8.5)$$

$$GermanSalesOrder \sqsubseteq SalesOrder \sqcap \exists hasCustomer.GermanCustomer \quad (8.6)$$

$$GermanSalesOrder \sqcap USSalesOrder \sqsubseteq \perp \quad (8.7)$$

$$SalesOrder \equiv GermanSalesOrder \sqcup USSalesOrder \quad (8.8)$$

Notations for OWL modeling have been developed, resulting in lexical notations (cf. [5, 120]) and in UML as visual notation (cf. [1, 69, 97]). When modeling the problem domain of our running example using a UML profile for OWL [1], the diagram looks as depicted in the Figure 8.5. The number relates the list of DL statements above to the corresponding visual notation.

8.3.2 TwoUse for Software Design Patterns: the Selector Pattern

To integrate the UML class diagram with patterns (cf. Figure 8.3) and the OWL profiled class diagram (cf. Figure 8.5), we rely on the TwoUse approach. We use UML profiles as concrete syntax, and allow for specifying UML entities and OWL entities using one hybrid diagram. These entities are connected using the UML profile and SPARQLAS queries. This hybrid diagram, i.e., a UML class diagram with profiles for OWL and TwoUse is mapped later onto the TwoUse abstract syntax.

The approach enables the modeler to use SPARQLAS4TwoUse expressions to describe the query operations of classes that have both semantics of an OWL class and a UML class in the *same* diagram. Moreover, this operation can query the OWL model, i.e., invoke a reasoning service at runtime that uses the same OWL model.

Hence, we can achieve dynamic classification writing SPARQLAS4TwoUse query operations in the *context* to classify the *variation* in the OWL model in runtime. The result is returned as a common object-oriented class.

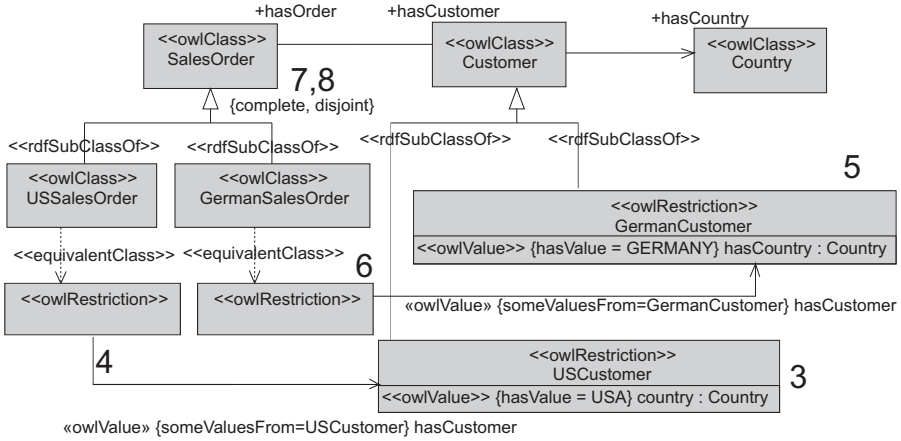


Fig. 8.5. Domain Design by a UML Class Diagram Using a UML Profile for OWL.

Structure

The hybrid diagram is depicted in the Figure 8.6 and in the Figure 8.7. The classes **Customer** and **Country** are OWL classes and UML classes, i.e., they are hybrid TwoUse classes. They are used in the OWL part of the model to describe the variations of the context **SalesOrder**. The TwoUse profile provides a mapping between the names in OWL and in UML in such a way that class names in both OWL and UML are preserved.

The concrete factories, i.e. the variants to be instantiated by the client **TaskController** are TwoUse classes as well. The concrete factories are described based on the restrictions on the class **SalesOrder** which must also exist in both paradigms. In the OWL part of the model, the concrete factories specialize the **SalesOrder**, but in UML, they specialize the class **AbstractFactory**. Hence, they do not inherit the methods of the class **SalesOrder**, because the associations between the variants and the context happen only in OWL part of the model.

Participants and Collaborations

The TwoUse approach preserves the signature and behavior of existing pattern implementations, as only the body of the operation `getRulesForCountry` is affected. The class **Configuration** is no longer needed, as the selection is moved to querying the OWL part of the model (cf. the query in the Figure 8.6).

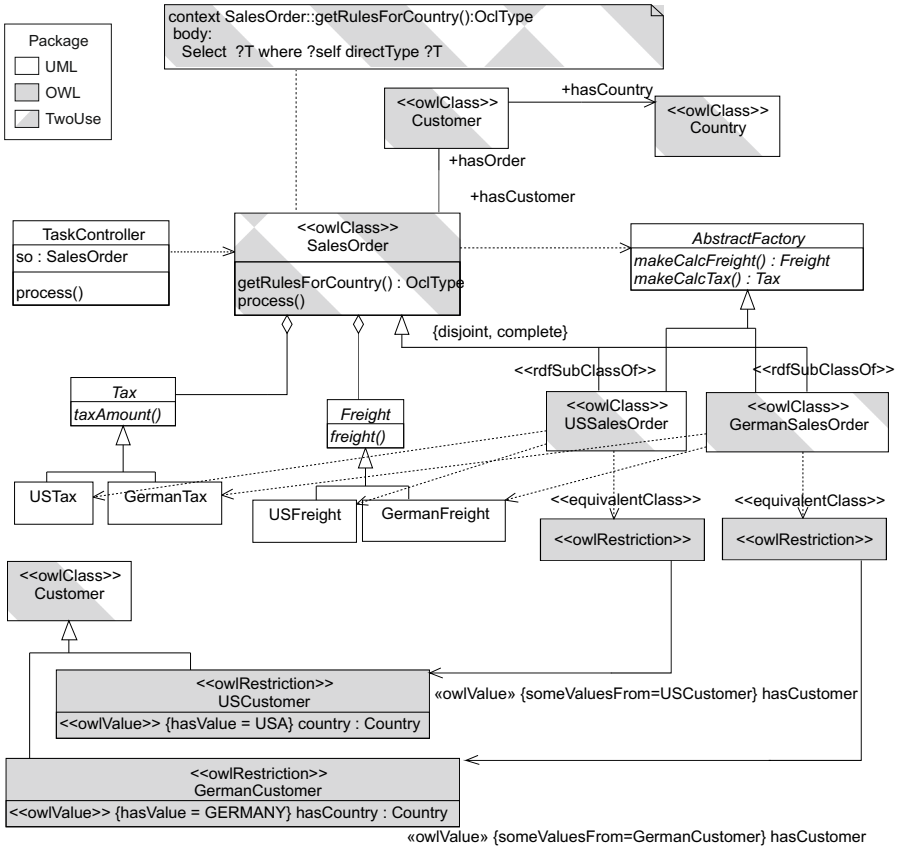


Fig. 8.6. Profiled UML Class Diagram of an Ontology-Based Solution.

As depicted in the Figure 8.8, the class `TaskController` invokes the operation `process` in the class `SalesOrder` (2), which invokes the operation `getRulesForCountry` (3). This operation calls SPARQLAS4TwoUse query operations. The SPARQLAS4TwoUse operations use reasoning services to classify dynamically the object `SalesOrder` to the appropriate subclass. The resulting OWL class, i.e., `USSalesOrder` or `GermanSalesOrder`, is mapped onto a UML class and is returned. The remaining sequence (5-12) remains unchanged.

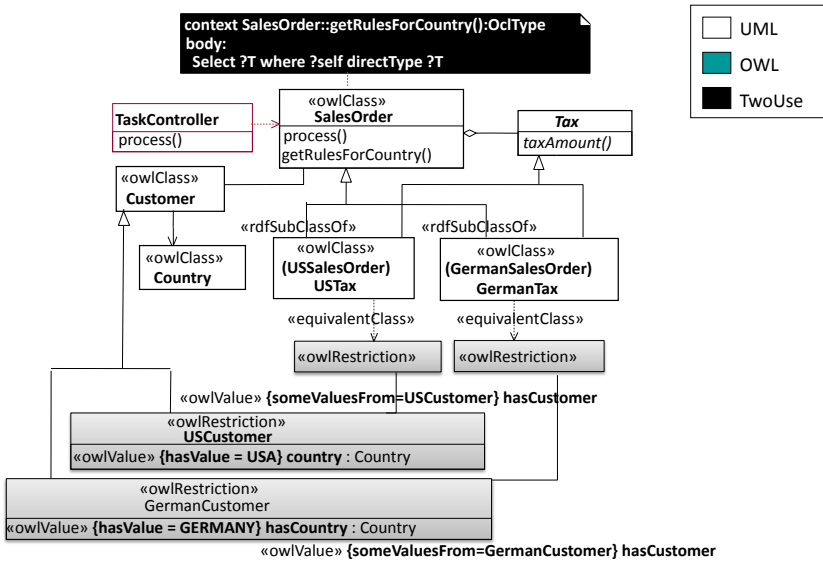


Fig. 8.7. Profiled UML Class Diagram with the Strategy Pattern.

For instance, let `ORDER1` be a `SalesOrder` with the property `customer` being `HANS` with the property `country` being `GERMANY`. The call `ORDER1.getRulesForCountry()` results in an object of type `GermanSalesOrder`.

Comparison

In the strategy and abstract factory solution, the decision of which *variant* to use is left to the *client* or to the *Configuration* object. It requires associations from these classes (`TaskController` and `Configuration` respectively) with the concepts (`Tax` and `AbstractFactory` respectively). Furthermore, the conditions are hard-coded in the client's operations.

The *TwoUse*-based solution cuts these couplings, as the selection is done at the OWL concept level, without any impact on the UML level, allowing the OWL part of the model to be extended independently.

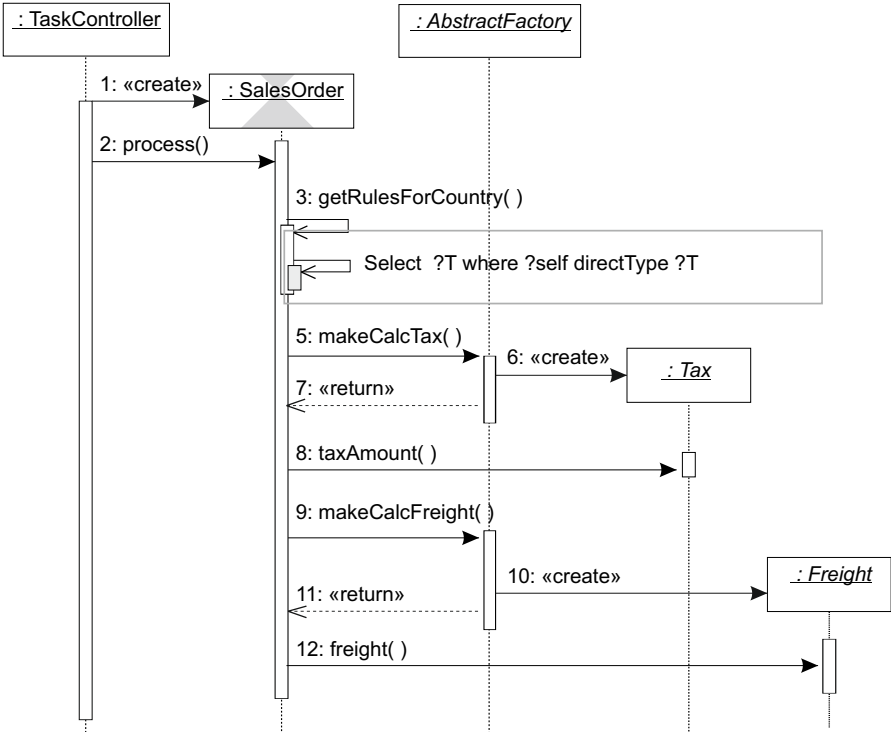


Fig. 8.8. Sequence Diagram of an OWL-Based Solution.

The descriptions of the classes `USSalesOrder` and `GermanSalesOrder` are used for the Reasoner to classify the object dynamically. As the classification occurs at the OWL level, resulting OWL classes are transformed into UML classes. Hence, the conditions are specified as logical descriptions.

When evolving from Figure 8.1 to Figure 8.3, the OWL part of the model does not change. Thus, new patterns can be applied without additional effort in modeling the OWL domain.

8.4 Validation

After analyzing the case study of composing OWL and design patterns in Section 8.3, we abstract repeatable arrangements of entities and propose a design pattern supported by OWL to address decision of variations — *the selector pattern*.

The selector pattern provides an interface for handling variations of context. It enables the context to select the appropriated variants based on their descriptions. Selections in the selector pattern are encapsulated in appropriate SPARQLAS-queries against the concept, facilitating a clear separation between the base of decision and the decision itself.

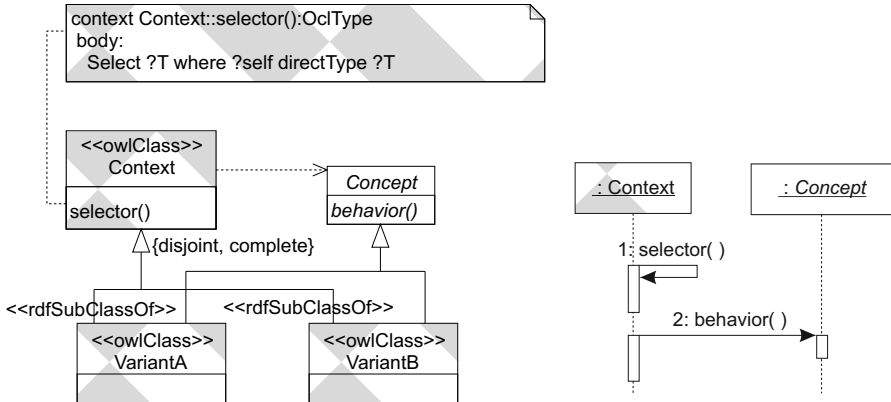


Fig. 8.9. Structure, Participants and Collaborations in the Selector Pattern.

8.4.1 Participants and Collaborations

The selector pattern is composed by a *context* (e.g., `SalesOrder` in the Figure 8.6), the specific *variants* (e.g., `USAbsFact` and `GermanAbsFact` in the Figure 8.6) of this context and their respective descriptions, and the *concept* (e.g., `AbstractFactory` in the Figure 8.6), which provides a common interface for the variations (Figure 8.9). Its participants are:

- `Context` maintains a reference to the `Concept` object.
- `Concept` declares an abstract method `behavior` common to all variants.
- `Variants` implement the method `behavior` of the class `Concept`.

The *Context* has the operation `select`, which uses SPARQLAS operations to call the reasoner and dynamically classify the object according to the logical descriptions of the variants. A *Variant* is returned as the result (Figure 8.9). Then, the *Context* establishes an association with the *Concept*, which interfaces the variation.

8.4.2 Applicability

The selector pattern is applicable:

- when the strategy pattern is applicable (cf. [106]);
- when the decision of what variant to use appears as multiple conditional statements in the operations;
- when exposing complex and case-specific data structures must be avoided.

The selector pattern preserves the interactions of the patterns strategy and abstract factory, studied in this chapter. The following steps guide the application of the selector pattern:

1. Design the OWL part of the model using a UML profile for OWL, identifying the concept and logically describing the variations;
2. Map the overlapping classes in UML and in OWL using a UML profile;
3. Write the operation in the *Context* class corresponding to the operation selector using SPARQLAS expressions.

8.4.3 Drawbacks

The proposed solution may seem complex for practitioners. Indeed, applying the selector pattern requires sufficiently deep understanding by the developers about topics like open and closed world assumption, class expressions and satisfiability, in addition to the knowledge about SPARQLAS4TwoUse. Moreover, the diagram presented by Figure 8.6 is visibly more complex than the corresponding version without patterns, although applying aspect oriented techniques can minimize this problem.

Further, calls from OCL to SPARQLAS4TwoUse may return OWL classes that are not part of the TwoUse model. This implies a dynamic diffusion of OWL classes into the UML model which must either be accommodated dynamically or, which needs to raise an exception.

Therefore, class descriptions must be sufficient for the reasoner to classify the variant, i.e., classes and properties needed to describe the variants must also exist at the OWL level. When this is not possible, the reasoner cannot classify the variants correctly.

8.4.4 Advantages

The application of the selector pattern presents the following consequences:

Reuse. The knowledge represented in OWL can be reused independently of platform or programming language.

Flexibility. The knowledge encoded in OWL can be modeled and evolved independently of the execution logic.

Testability. The OWL part of the model can be automatically tested by logical unit tests, independently of the UML development.

Easy Adoption. Expanding Figure 8.3 with Figure 8.6 and Figure 8.4 with Figure 8.8 in the motivating example, show that the changes required by applying the selector pattern in existing practices are indeed minor.

UML paradigm dominance. The concrete cases are bound to the context only in OWL. It has no impact on the UML part of the model. The programmer freely specifies the SPARQLAS operation calls when applicable.

8.5 Related Work

State-of-the-art approaches require hard-coding the conditions of selecting a particular variant [119]. Our approach relies on OWL modeling and reasoning to dynamically subclassify an object when required.

The composition of OWL with object-oriented software has been addressed by [121] and [122]. We address this composition at the modeling level in a platform independent manner [16].

8.6 Conclusion

We have proposed a novel way of reducing coupling in important design patterns by including OWL modeling. We have proposed an ontology-based software design pattern called selector pattern and discuss the impact of adopting the new approach.

The application of TwoUse can be extended to other design patterns concerning variant management and control of execution and method selection. Software design patterns that factor out commonality of related objects, e.g., prototype, factory method and template method, are good candidates.

Modeling Ontology-Based Information Systems

Summary. Developers of ontology-based information systems have to deal with domain knowledge represented in ontologies and domain logic represented by algorithms. An approach that allows developers to reuse knowledge embedded in ontologies for modeling algorithms is lacking so far. In this chapter, we apply the TwoUse approach for enabling developers of ontology-based information systems to reuse domain knowledge for modeling domain logic. It results in improvements in maintainability, reusability and extensibility ¹.

9.1 Introduction

The development of ontology-based information systems has gained momentum as users increasingly consume applications relying on semantic web technologies. For example, a core ontology-based information system for the Semantic Web is the semantic annotation of formulas, text or image, which transforms human-understandable content into a machine understandable form.

The development of these applications requires software engineers to handle software artifacts and the ontologies separately. For instance, software engineers cannot use OWL class expressions in the body of operations that indeed relies on information contained in the ontology. Therefore, software engineers have to define the conditions for selecting classes twice, firstly in the ontology and secondly in the body of operations. This process is error-prone and requires the synchronization of both definitions in case of changes.

In this chapter, we analyze the application of the TwoUse approach for integrating the ontologies in the development of ontology-based information systems. TwoUse enables ontology engineers to specify conditions reusing the knowledge encoded in the ontology.

This chapter is structured as follows: Section 9.2 describes the domain of the case study and analyzing current modeling techniques. In Section 9.3, we apply

¹ This chapter contains work of the paper “Using Ontologies with UML Class-based Modeling: The TwoUse Approach” published at the Data & Knowledge Engineering Journal [101].

the TwoUse approach for integrating domain ontologies and software specification. Section 9.4 analyzes the application of the TwoUse approach according to ISO 9126 non-functional software requirements, and it describes the limitations.

9.2 Case Study

We describe the case study in the context of the semantic multimedia tools in this chapter. The K-Space Annotation Tool (KAT) [123] is a framework for semi-automatic and efficient annotation of multimedia content that provides a plug-in infrastructure (analysis plug-ins and visual plug-ins) and a formal model based on the Core Ontology for Multimedia (COMM) [124].

Analysis plug-ins provide functionalities to analyze content, e.g., to semi-automatically annotate multimedia data like images or videos, or to detect structure within multimedia data. However, as the number of available plug-ins increases, it becomes difficult for KAT end-users to choose appropriate plug-ins.

For example, semantic multimedia developers provide machine learning based classifiers, e.g., Support Vector Machines (SVM), for pattern recognition. There are different recognizers (object recognizers, face detectors and speaker identifiers) for different themes (sport, politics and art), for different types of multimedia data (image, audio and video) and for different formats (JPEG, GIF and MPEG). Moreover, the list of recognizers is continuously extended and, like the list of multimedia formats, it is not closed but, by sheer principle, it needs to be open.

Therefore, the objective is to provide KAT end-users with the functionality of automatically selecting and running the most appropriate plug-in(s) according to the multimedia data captured by the ontology. Such improvement enhances user satisfaction, since it prevents KAT end-users from employing unsuitable recognizers over multimedia data.

In the following, we consider three recognizers that work over soccer videos: highlight recognizer, jubilation recognizer and goal shots detector. A highlight recognizer works on detecting sets of frames in videos with high changing rates, e.g., intervals where the camera view changes frequently in a soccer game. A jubilation recognizer analyzes the video and audio, searching for shouts of jubilation. Finally, a goal shots detector works on matching shouts of jubilation with changes in camera view to characterize goal shots.

9.2.1 UML class-based software development

We apply an extensible approach to model recognizer variations, namely an adaptation of the strategy pattern [106]. The strategy pattern allows for encapsulating recognizers uniformly, as depicted in the Figure 9.1.

Figure 9.1 depicts the KAT domain in the UML class diagram. It is a complex domain since KAT uses the COMM ontology that comprises multiple occurrences of ontology design patterns, e.g., *semantic annotation* used in the running example.

Users select KAT algorithms for SVM recognition and, consequently, the class controller invokes the method `run()` in the class `kat_algorithm` (Figure 9.1). The method `run()` invokes the method `getRecognizers()`, which uses reflection to get a


```

        ) )
    then
        _r->including(goal_shots_detector)
    else if
20    _i.annotated_data_role->exists ( adr |
        adr.video_data->exists ( v |
            v.ocllsTypeOf(video_data) ) )
    then
        _r->including(highlight_recognizer)->union(
25    _r->including(jubilation_recognizer))
    else
        _r
    endif
endif)->asSet ()

```

In fact, the OCL expressions in Listing 9.1 contain class descriptions in some sense. For example, the classes `highlight_recognizer` and `jubilation_recognizer` need a `kat_algorithm` with some `annotated_data_role` with some `video_data` (Lines 19-24). The description of a `goal_shots_detector` is complicated (Lines 7-15), since it needs a `soccer_video`, that is a subclass of `video_data`, with some `semantic_annotation` with some `highlight`, and with some `semantic_annotation` with some `jubilation`.

Indeed, the UML/OCL approach has limitations:

- It restricts information that can be known about objects to object types, i.e., known information about objects is limited by information in object types (or in object states when using OCL).
- Class descriptions, e.g. `goal_shots_detector` (Lines 7-16), are embedded within conditional statements that are hard to maintain and reuse. In scenarios with thousands of classes, it becomes difficult to find those descriptions, achievable only by text search.
- OCL lacks of support for transitive closure of relations [89, 125]. It makes expressions including properties like `part-of` more complex.

9.2.2 Ontology-Based Software Development

OWL Modeling

Instead of hard-coding class descriptions using OCL expressions, a more expressive and extensible manner of modeling data provides flexible ways to describe classes and, based on such descriptions, it enables type inference.

Therefore, one requires a logical class definition language that is more expressive than UML class-based modeling. Indeed, OWL provides various means for describing classes. One may denote a class by a class identifier, an exhaustive enumeration of individuals, property restrictions, an intersection of class descriptions, a union of class descriptions, or the complement of a class description.

For the sake of illustration, we use description logic syntax to specify the KAT domain as follows. KAT uses the COMM ontology [124] as a conceptually sound model of MPEG-7 and as a common but extensible denominator for different plugins exchanging data.

For example, the classes `jubilation` and `highlight` are subclasses of `kat_thing`(1). A `soccer_video` is a subclass of `video_data`(2). A `highlight_annotation` is a `semantic_annotation` that `setting_for` some `highlight` (3). A `highlight_video` is equivalent to a `video_data` that `setting` some `highlight_annotation`(4). A `jubilation_video` is similarly described (5). A `highlight_recognizer` is a subclass of a `kat_algorithm` and is equivalent to a `kat_algorithm` that defines some `annotated_data_role` that is `played_by` some `video_data`(7).

$$jubilation, highlight \sqsubseteq kat_thing \quad (9.1)$$

$$soccer_video \sqsubseteq video_data \quad (9.2)$$

$$highlight_annotation \equiv semantic_annotation \\ \sqcap \exists setting_for.highlight \quad (9.3)$$

$$highlight_video \equiv video_data \sqcap \exists setting.highlight_annotation \quad (9.4)$$

$$jubilation_video \equiv video_data \sqcap \exists setting.jubilation_annotation \quad (9.5)$$

$$soccer_jub_hl_video \equiv soccer_video \sqcap highlight_video \sqcap jubilation_video \quad (9.6)$$

$$highlight_recognizer \equiv kat_algorithm \\ \sqcap \exists defines(annotated_data_role \sqcap \exists played_by.video_data) \quad (9.7)$$

$$goal_shots_detector \equiv kat_algorithm \\ \sqcap \exists defines(annotated_data_role \sqcap \exists played_by.soccer_jub_hl_video) \quad (9.8)$$

Table 9.1. Specifying KAT with Description Logic Syntax.

OWL is compositional, i.e., OWL allows for reusing class descriptions to create new ones. A look at the class `soccer_jub_hl_video`(6) shows that it is equivalent to an intersection of `soccer_video`, `highlight_video` and `jubilation_video`, i.e., a soccer video with `highlight` and `jubilation`. Thus, it becomes easier to describe the class `goal_shots_detector`(8), which is a subclass of a `kat_algorithm` and is equivalent to a `kat_algorithm` that defines some `annotated_data_role` that is `played_by` some `soccer_jub_hl_video`. Moreover, OWL allows for defining properties as transitive, simplifying query expressions. The reader may compare these reusable class definitions against the involved and useable implicit definition of distinctions provided in Listing 9.1 (Lines 6-25).

OWL Reasoning

OWL ontologies can be operated on by reasoners providing consistency checking, concept satisfiability, instance classification and concept classification. The reasoner performs model checking to the extent that entailments of the Tarski-style model theory of OWL are fulfilled. For instance, it is possible to verify whether it is possible to apply `goal_shots_detector` to images (consistency checking)(the answer is ‘no’ if `goal_shots_detector` is disjoint from image recognizers) or whether a given instance is a `soccer_jub_hl_video`(instance classification). It is possible to ask a reasoner to classify the concepts of the ontology and find that `highlight_video` and `jubilation_video` are both superclasses of `soccer_jub_hl_video` (concept classification).

More specifically, given that we know an object to be an instance of `highlight_video`, we can infer that this object has the property `setting` and the value of `setting` is an individual of `highlight_annotation`. Conversely, if we have an object of `video_data`, which has the property `setting` and the value of `setting` associated with such an individual is a `highlight_annotation`, we can infer that the prior individual is an instance of `highlight_video`. This example illustrates how to define OWL classes like `highlight_video` by necessary and sufficient conditions.

To sum up, OWL provides important features complementary to UML and OCL that improve software modeling: it provides multiple ways of describing classes; it handles these descriptions as first-class entities; it provides additional constructs like transitive closure for properties; and it enables dynamic classification of objects based upon class descriptions.

The need for an integration emerges since OWL is a purely declarative and logical language and not suitable to describe, e.g., dynamic aspects of software systems such as states or message passing. Thus, to benefit from inference, one must decide at which state or given which trigger one should call the reasoner. In the next section, we address this issue among others, proposing ways of integrating both paradigms using the TwoUse approach.

9.3 Application of the TwoUse Approach

We apply the TwoUse approach described in Part II to enable engineers to design and integrate UML models and OWL ontologies, exploiting the full expressiveness of OWL ($SR\mathcal{OIQ}(\mathcal{D})$) and allowing usage of existing UML2 tools.

To give an idea of the integration, we use the example of the E-Shop domain. Instead of defining the query operation `rNames` using UML/OCL expressions, we use the expressiveness of the OWL language together with SPARQLAS4TwoUse. Querying an *OWL reasoning service*, it is possible to ask which OWL subclasses of `kat_algorithm` describe a given instance, enabling dynamic classification. Such expression will then be specified by:

```
1 context kat_algorithm
  def rNames(): Set(Class)
    ?self type ?T
    ?T subclassOf kat_algorithm
```

As specified above, to identify which subclasses are applicable, we use the variable `?T` to get all types of `?self` that are subclasses of `kat_algorithm`.

The advantage of this integrated formulation of `rNames` lies in separating two sources of specification complexity. First, the classification of complex classes remains in an OWL model. The classification reuses the COMM model and it is re-useable for specifying other operations; it is maintainable using graphical notations; and it is a decidable, yet rigorous reasoning model (see Figure 9.2). Second, the specification of the execution logic remains in the UML specification (Sequence Diagram in the Figure 9.1).

9.3.1 Concrete Syntax

Figure 9.2 shows a snippet of the UML class diagram for the case study. In this snippet, the OWL view consists of five classes. The UML View comprises the seven classes depicted in the Figure 2.8 and the TwoUse view contains six classes and a SPARQLAS query expression.

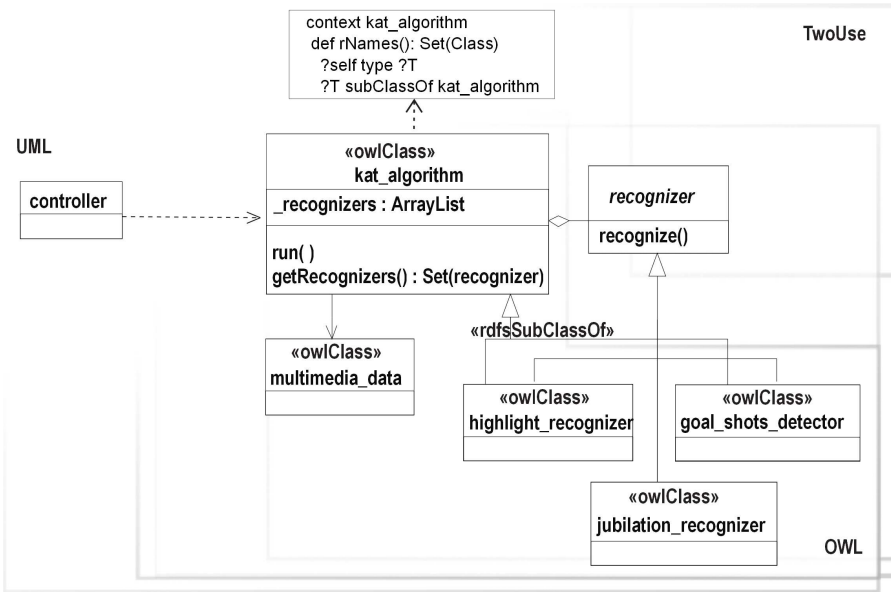


Fig. 9.2. UML Class Diagram of KAT.

Another way of integrating ontologies in the development of ontology-based information systems is using the textual syntax. Listing 9.2 presents the equivalent of the UML class diagram defined using the textual syntax for Ecore and includes the OWL class expressions (between brackets).

Listing 9.2. Modeling KAT using the textual language

```

1 class controller {}
  class kat_algorithm extends core:algorithm {
    attribute recognizer recognizers (0..-1);
    operation void run();
5   operation recognizer (0..-1) getRecognizers();
    operation rNames(): Set(OclType)
      Select ?T where ?self type ?T ?T subClassOf
        kat_algorithm;
  }
  ...
10 abstract class recognizer {

```

```

    operation void recognize();
}
class highlight_annotation [equivalentTo
    [core:semantic_annotation and [dsn:setting_for some
    highlight]]] {}
class highlight_video [equivalentTo [core:video_data and
    [dsn:setting some highlight_annotation]]]{}
15 class jubilation_video [equivalentTo [core:video_data and
    [dsn:setting some jubilation_annotation]]]{}
class soccer_jub_hl_video [equivalentTo [ soccer_video and
    highlight_video and jubilation_video]]]{}
class highlight_recognizer extends kat_algorithm ,
    [subClassOf [dns:defines some
    [core:annotated_data_role and [played_by some
    core:video_data]]]]]{}
class jubilation_recognizer extends kat_algorithm ,
    [subClassOf [dns:defines some
    [core:annotated_data_role and [dns:played_by some
    core:video_data]]]]]{}
class goal_shots_detector extends kat_algorithm ,
    [subClassOf [dns:defines some
    [core:annotated_data_role and [dns:played_by some
    soccer_jub_hl_video]]]]]{}

```

9.3.2 Abstract Syntax

The TwoUse abstract model is generated as output of model transformations that take as input models defined using any of the notations supported by TwoUse. Figure 9.3 depicts an excerpt of the abstract model for the running example.

9.3.3 Querying

Table 9.2 lists results of evaluating SPARQLAS expressions considering the snapshot depicted in the Figure 9.4. We take two objects of the snapshot (`alg1`, `alg2`) and bind them to the predefined variable `self`. For example, for the expression `self.owl:InstanceOf(highlight_recognizer)` where `self` is bound to `alg1`, the result is `true`.

9.4 Validation

Based on the case study, we analyze how TwoUse features reflect development-oriented non-functional requirements according to a quality model covering the following quality factors: maintainability, efficiency (ISO 9126 [126]), reusability and extensibility [127]. The decision of using UML with OWL does not affect other ISO 9126 quality factors.

Context object SPARQLAS Expression	alg1	alg2
?self directType highlight_recognizer	true	true
?self directType goal_shots_detector	false	true
?self type ?T	algorithm, description, highlight_recognizer, jubilation_recognizer, method	algorithm, description, highlight_recognizer, jubilation_recognizer, goal_shots_detector, method
?self type ?T ?T subClassOf algorithm	highlight_recognizer, jubilation_recognizer	highlight_recognizer, jubilation_recognizer, goal_shots_detector
?self directType ..t ?a type ..t	alg1, alg2	alg1, alg2
?self directType ?T	highlight_recognizer	goal_shots_detector

Table 9.2. Evaluation of SPARQLAS expressions according to the KAT snapshot.

Maintainability

We analyze maintainability with regard to analyzability, changeability and testability as follows.

Analyzability. In case of failure in the software, developers have the possibility of checking the consistency of the domain and then use axiom explanation to track down failure, which helps to improve failure analysis efficiency.

Changeability. The knowledge encoded in OWL evolves independently of the execution logic, i.e., developers maintain class descriptions in the ontology and not in the software. Since the software does not need recompilation and redistribution, the work time spent to change decreases.

Testability. Developers used queries declared in unit tests to test ontology axioms, enabling test suites to be more declarative.

Reusability

Extending the COMM core ontology allows developers to reuse available knowledge about multimedia content, semantic annotation and algorithm. Furthermore, developers can reuse the knowledge represented in OWL independently of platform or programming language.

Moreover, developers rely on usage of class descriptions to semantically query the domain. Semantic query plays an important role in large domains like KAT (approx. 750 classes). For example, it is possible to reuse algorithm descriptions applicable to videos. By executing the query

```

1 ?T subClassOf (defines some (annotated_data_role and
    (played_by some video)))

```

using SPARQLAS, developers see that the classes `highlight_recognizer`, `jubilation_recognizer` and `goal_shots_detector` are candidates to reuse. Such a semantic query is not possible with UML/OCL.

Extensibility

When the application requires it, developers can be more specific by extending existing concepts and adding statements. By adding new statements, developers update the OWL ontology which does not require generating code if the UML model is not affected. For example, if developers identify that an algorithm works better with certain types of videos, developers extend the algorithm description.

9.4.1 Limitations

By weaving UML and OWL ontologies, TwoUse requires sufficient understanding of developers about class expressions and satisfiability. There is a trade-off between a concise and clear definition of syntax that is unknown to many people as in Table 9.1 versus an involved syntax that people know. From past experiences, we conclude that, in the long term, the higher level expressivity will prevail, as developers are willing to learn a more expressive approach.

Indeed, we have defined multiple notations according to different developers' needs, but this does not prevent them from understanding the semantics of OWL constructs. This shortcoming is minimized in case of ontology-based information systems, since software developers are familiar with OWL.

9.5 Conclusion

In this chapter, we show how our approach yields improvements on the maintainability, reusability and extensibility for designing ontology-based information systems, which corroborates literature on description logics [128]. TwoUse allows developers to raise the level of abstraction of business rules until now embedded in OCL expressions.

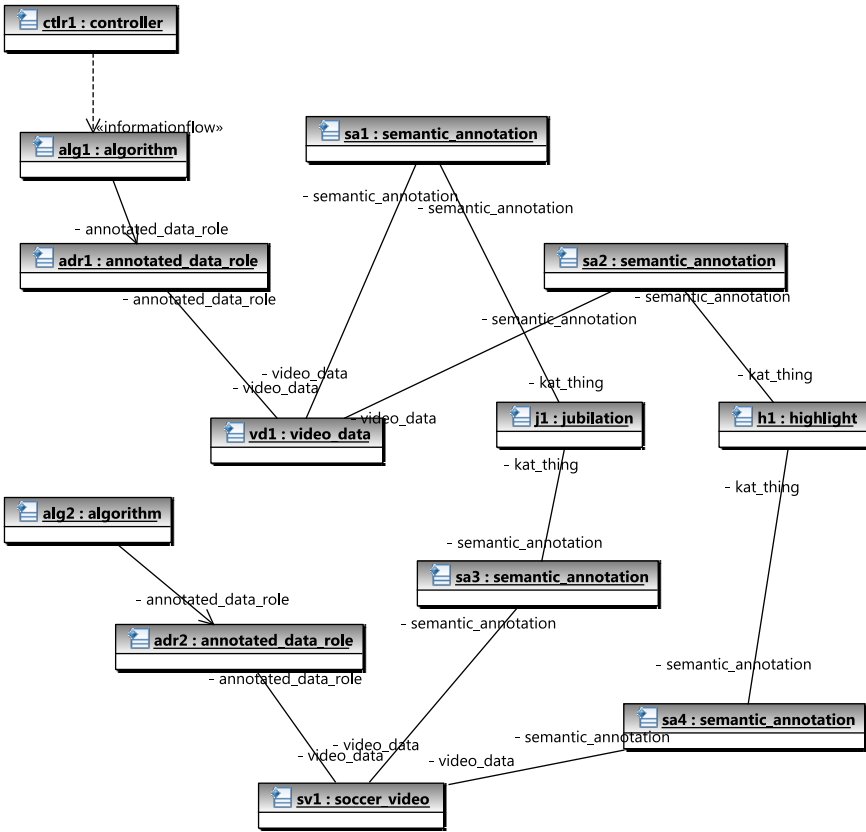


Fig. 9.4. Snapshot of KAT (M0).

Enabling Linked Data Capabilities to MOF Compliant Models

Summary. In the software development process, there are standards for general-purpose modeling languages and domain-specific languages, capable of capturing information about different views of systems like static structure and dynamic behavior. In a networked and federated development environment, modeling artifacts need to be linked, adapted and analyzed to meet information requirements of multiple stakeholders. In this chapter, we present an approach for linking, transforming and querying MOF-compliant modeling languages on the web of data. We propose the usage of semantic web technologies for linking and querying software models. We apply the proposed framework in a model-driven software.

10.1 Introduction

In a model-driven architecture, software engineers rely on a variety of languages for designing software systems. As different stakeholders need different views of information, the software development environment needs to encompass a myriad of general-purpose and domain-specific languages with complementary and overlapping applications.

Since it is not feasible to capture all aspects of software into only one single model, contemporary model-driven architectures includes numerous notations to serve according to the software development task. The inevitable usage of multiple languages leads to unmanageable redundancy in developing and managing the same information across multiple artifacts and, eventually, information inconsistency. With the growing demand for networked and federated environments, the question arises about what and how existing web standards can help existing modeling standards in fulfilling the requirements of a *web of models*.

Semantic web technologies [41] and linked open data (LOD) principles [129] enable any kind of data to be represented, identified, linked and formalized on the web. The same data can be adapted for use according to the software engineer's perspective.

The interest on this topic motivated the Object Management Group (OMG) to issue a request for proposal aiming at defining a structural mapping between Meta Object Facility (MOF) models and Resource Description Framework (RDF)

representations [130]. This mapping should make possible to apply LOD principles to MOF compliant models and to publish MOF compliant models as LOD resources.

In a collaborative environment, developers need to be able to create architectures with information expressed in multiple modeling languages. According to the development phase, developers rely on multiple languages for modeling distinct aspects of the system.

OWL [5] provides a powerful solution for formally describing domain concepts in networked environments. OWL is part of the semantic web stack, is compatible with RDF and with LOD principles. OWL's objective is to provide evolution, interoperability, and inconsistency detection of shared conceptualizations.

Although transformations from the MOF metamodel to OWL have been proposed before, addressing the aforementioned problems requires a coherent framework comprising techniques not only for transforming but for extending, linking and querying MOF compliant models.

In this chapter, we propose TwoUse as a framework for supporting interrelationships of modeling languages in distributed software modeling environments. We present this chapter as follows: Section 10.2 describes the running example used through the chapter and analyzes the requirements to be addressed. Section 10.3 describes the application of the TwoUse approach. We analyze the approach on Section 10.4 and the related work in Section 10.5. Section 10.6 finishes the chapter.

10.2 Case Study

As a case study, we use the development of the TwoUse toolkit, i.e., “we eat our own dog food”. As described in Chapter 7, the TwoUse Toolkit is a model-driven implementation of current OMG and W3C standards for designing ontology-based information systems and model-based OWL ontologies.

TwoUse's development life cycle comprises five phases: requirement specification, analysis, design, code and management. Figure 10.1 depicts these phases and the artifacts generated in each phase. In the requirement specification phase, developers use UML use case diagrams and a domain-specific language for specifying requirements. These requirements are realized by Business Process Model Notation (BPMN) and UML component diagrams in the analysis phase. During the design phase, developers specify metamodels, generations for those metamodels, model transformations and in the case of editors, the grammar specification. At the end of the development life cycle, these artifacts are transformed to source code and the dependencies between TwoUse plug-ins are captured by eclipse manifest files. Finally, the management phase controls the development life cycle and provides versioning.

Figures 10.3, 10.2 and 10.4 depict three concrete diagrams and show how they depend on each other. The UML use case diagram depicts use cases from the perspective of two actors: software engineer and ontology engineer (Figure 10.3). Software engineers use the TwoUse toolkit to extend UML or Ecore models with OWL annotations, to transform either of these metamodels into OWL and subsequently to query them. Ontology engineers use a textual or graphical editor to design an OWL ontology to be queried afterwards.

The BPMN diagram shows the realization of these use cases from the perspective of the software engineer (Figure 10.3). Concretely, software engineers open the

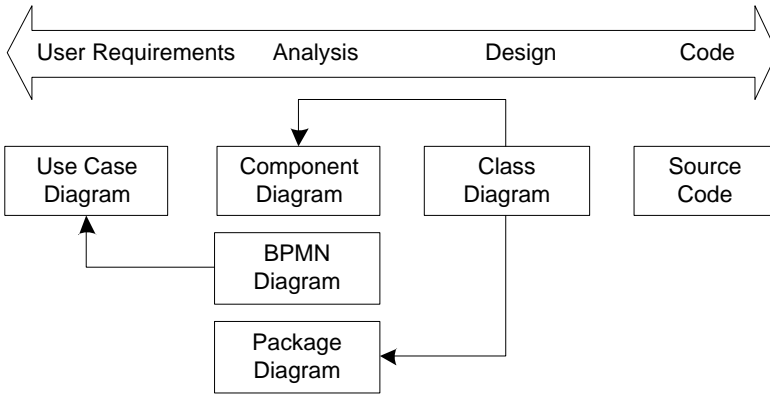


Fig. 10.1. Development Life Cycle of the TwoUse Toolkit.

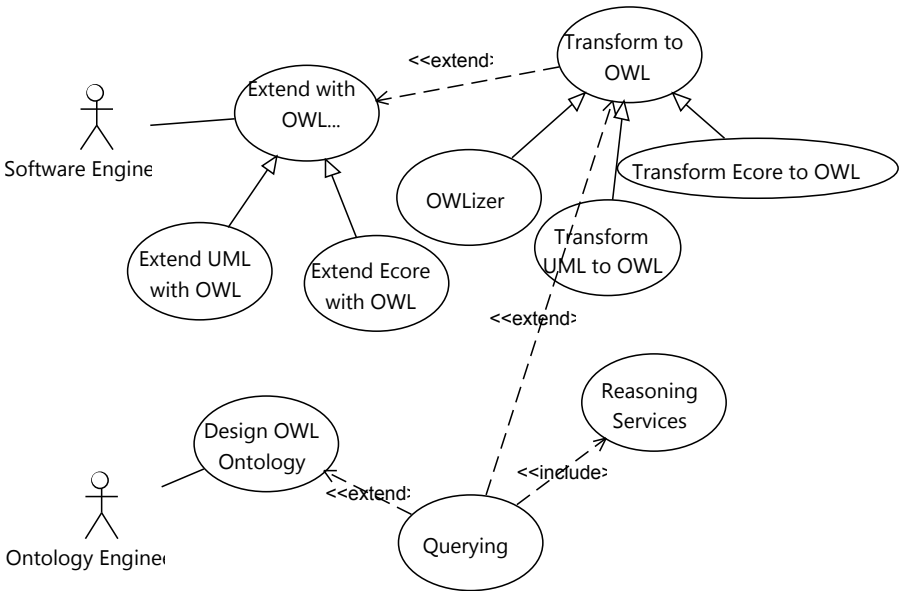


Fig. 10.2. Snippets of Use Case Diagram from TwoUse Toolkit.

perspective “ontology development” to start editing and querying models and meta-models in OWL format.

The component diagram shows the internal structure and dependencies of component in the TwoUse architecture (Figure 10.4).

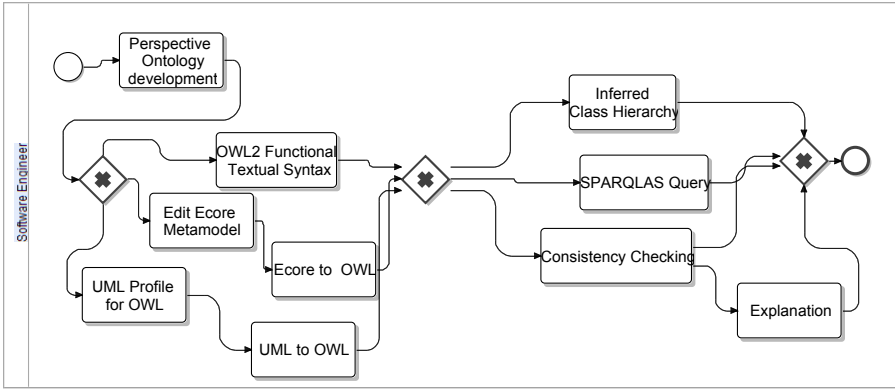


Fig. 10.3. Snippets of BPMN Diagram from TwoUse Toolkit.

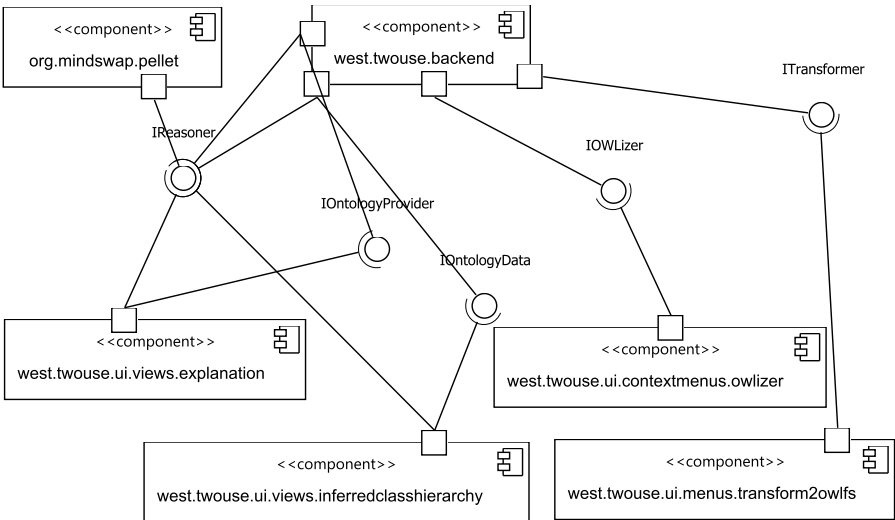


Fig. 10.4. Snippets of Component Diagram from TwoUse Toolkit.

The TwoUse toolkit development life cycle relies on multiple models to provide viewpoints according to the development phase. For example, testers are interested in the information flow to realize functionalities provided by the system. Software engineers are interested in the impact of changing a given component or task. Other software engineers are interested in a modular view of the system for coordinating deliverables.

10.2.1 Requirements

Based on demand identified in developing the TwoUse toolkit, we identify three fundamental requirements for realizing a linked-open data environment in model-driven engineering:

RQ1: Model and Metamodel Interoperability. Multiple metamodels may define the same concepts in different ways. Therefore, one needs to extend existing meta-modeling frameworks (e.g., EMOF) to include support for primitives for relating different representations, thus allowing for integrate models that conform to heterogeneous metamodels.

RQ2: Techniques for composition of models and metamodels. For semi automatically integrating modeling languages, one requires alignment techniques that allow for identifying equivalences over multiple languages and represent these equivalences (linking).

RQ3: Integration Management. To achieve interoperability of modeling languages, one needs to control all stages of linking modeling languages. Models and metamodels must be *transformed* into the same representation. After the composition takes place developers can create or execute *queries* over artifacts.

Addressing these requirements allows for achieving the following features:

Consistent view over multiple MOF Models: Based on an integration of multiple (MOF-based) languages, it is possible to have a consistent view over multiple artifacts.

Query Answering: Based on underlying formal semantics and constraints, it is possible to define queries over multiple artifacts. For example, it is possible to answer questions like: What is the effect of updating the plug-in pellet? Which case tests must be executed if this plug-in is updated? Moreover, it enables the identification of the impact of some model components upon others (Impact Analysis) and thus the identification of cyclic dependencies or other unexpected consequences.

10.3 Application of the TwoUse Approach

In this section, we describe how we exploit the TwoUse approach to address the requirements described in the previous section. We present how to extend and transform modeling languages into OWL. We illustrate how to query and manage links between modeling languages.

In the next subsections, we show how we apply the TwoUse components described in Chapter 7 to realize linked data capabilities to MOF languages. The approach consists of the following components (1) model extension, (2) model transformation, (3) matching, and (4) querying (please refer to Section 7.3 for the components of the generic architecture).

10.3.1 Model Extension

OWL specifies class expression axioms, object property axioms and individual axioms that serve to link similar classes and individuals over multiple metamodels and models. Because of OWL 2 expressiveness, it is possible to combine class expressions and axioms to express equivalencies between classes.

Figure 10.5 shows snippets of the UML and BPMN metamodels. From the UML metamodel, it depicts classes of the Use Case package and the Activity package. From the BPMN metamodel, it depicts classes that describe tasks and message edges. A

look at both metamodels shows correspondences between the activity package and the BPMN metamodel. For example, the UML class **Activity** is equivalent to BPMN class **BpmnDiagram**.

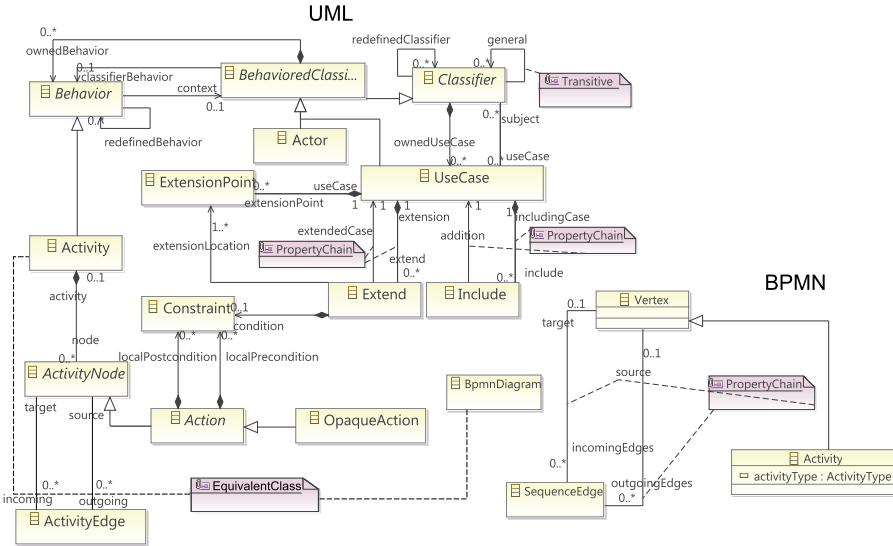


Fig. 10.5. Snippet of BPMN metamodel and UML metamodel for Use Cases.

In Listing 10.1, we present examples using OWL 2 syntax of constructs that can serve to link Ecore metamodels with OWL. In Line 1, we describe the equivalence of a UML **Activity** and **BpmnDiagram**. The equivalence of the set of individuals of the class **OpaqueAction** and the set of individuals of the class **Activity** where the property **activityType** is set to **Task** in the BPMN metamodel is defined in Line 2. Lines 3 and 4 characterize the property **general** of the UML metamodel as transitive. In Line 5, we derive a new property in the BPMN metamodel based on a property chain, i.e., a composition of the properties **outgoingEdges** and **target** are properties of **successorActivities**. For instance, $outgoingEdges(x, y), target(y, z) \rightarrow successorActivities(x, z)$. Similarly, a property chain **ancestorNodes** for the UML metamodel is defined in Line 6. The equivalence of the defined property chains is expressed in Line 7.

Listing 10.1. Linking Ecore metamodels with OWL.

```

1 EquivalentClasses (uml:Activity bpmn:BpmnDiagram)
EquivalentClasses (uml:OpaqueAction ObjectSomeValuesFrom
    (bpmn:activityType bpmn:Task))
TransitiveObjectProperty (uml:general)
SubObjectPropertyOf( ObjectPropertyChain
    (bpmn:outgoingEdges bpmn:target)
    bpmn:sucessorActivities)
5 SubObjectPropertyOf( ObjectPropertyChain (uml:outgoing
    uml:target) uml:sucessorNodes)
SubObjectPropertyOf( ObjectPropertyChain (uml:include
    uml:addition) uml:includeUseCases)
SubObjectPropertyOf( ObjectPropertyChain
    (ObjectInverseOf(uml:addition) uml:includingCase)
    uml:includingUseCases)
EquivalentObjectProperties (uml:sucessorNodes
    bpmn:sucessorActivities)

```

At the model level, developers can link models elements (metamodel instances) using OWL constructs. The `SameIndividual` axioms allow to define the equality of individuals in order to assert that instances of different metamodels are the same. For example, if we have a UML package called `west.twouse.backend`, we can assert that this package is the same as the Java package with the same name – `SameIndividual(uml:west.twouse.backend java:west.twouse.backend)`.

Additionally, OWL 2 provides constructs to enrich Ecore metamodels and extend its expressiveness. For example, object property axioms aim at characterizing object properties like the definition of sub-property relations and the expression of reflexive, irreflexive, symmetric, asymmetric and transitive properties.

Another benefit of extending Ecore with OWL is monotonicity, i.e., adding further axioms to a model does not negate existing entailments. We can extend Ecore metamodels with OWL without invalidating any existing assertions. Thus, OWL provides a non-invasive way to integrate same or similar concepts of different modeling languages.

In order to extend the expressiveness of Ecore metamodels, we use the textual notation defined in the TwoUse approach (Chapter 5).

By extending the Ecore metamodel with OWL, we enable developers with primitives for connecting metamodels like property equivalence, class equivalence and individual equality, addressing the requirement RQ1.

10.3.2 Model Transformation

Based on the mappings between UML class-based modeling and OWL ontology, we develop a generic transformation to transform any Ecore Metamodel/Model into OWL TBox/ABox – OWLizer [131]. Figure 10.6 depicts the conceptual schema of transforming Ecore into OWL.

A model transformation takes a language metamodel and the annotations as input and generates an OWL ontology where the concepts, enumerations, properties and datatypes (terms) correspond to classes, enumerations, attributes/references

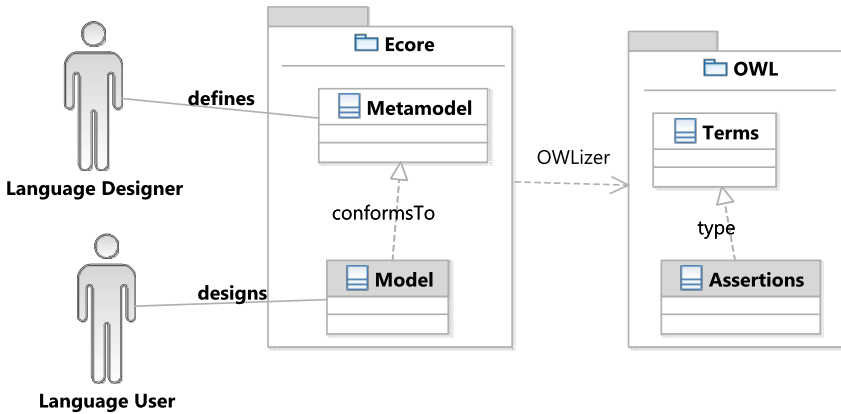


Fig. 10.6. Mapping Ecore and OWL.

and datatypes in the language metamodel. Additionally, the transformation takes the language model created by the language user and generates assertions in the OWL ontology.

The structural mapping from Ecore-based metamodels and models to OWL makes Ecore models in general data available as federated, accessible and query-ready LOD resources. Multiple UML models can be transformed into a common representation in OWL ontologies according to this structural mapping. Having models represented in OWL ontologies, one might connect these ontologies and process these ontologies in a federated way.

Thus, the resulting OWL representations address the requirement RQ3 defined in Section 10.2.1.

10.3.3 Matching

In a model-driven paradigm, resources that are expressed using different modeling languages must be reconciled before being used. As described previously (see Section 3.5 in Chapter on Ontology Foundations), ontology matching allows for identifying correspondences of elements between two ontologies.

The quality of the correspondences depends on the applied criteria and technique. For example, if we apply only string matching, it generates a false positive correspondence between the UML Activity and the BPMN Activity. However, if we apply structure-based techniques and analyze the structure of the UML class Action and the BPMN class Activity, we see that both have similar structures (both have one superclass with two associations with the same cardinalities). However, the UML class Action is abstract and the BPMN class Activity is concrete. So, we could assert that the class Activity is a subclass of class Action.

Automatic matching techniques can be seen as support but should be assisted by domain experts, because of false positive matches. For example, the correspondence between BpmnDiagram and UML Activity is hard to catch automatically.

Ontology matching capabilities address the requirement RQ2 by identifying correspondences in order to link between (meta) models.

10.3.4 Querying with SPARQLAS

As described in Section 6.3, SPARQLAS allows for specifying queries using the OWL syntax for querying OWL ontologies. Listing 10.2 shows a SPARQLAS query about use cases that include other use cases. In this example, we ask about the individuals ?x whose type is an anonym class where the transitive property includeUseCase has as a value some use case.

Listing 10.2. Use Cases that includes some other use case

```

1 Namespace: uml = <http://www.eclipse.org/uml2/3.0.0/UMI#>
Select ?x
Where:
    ?x type (UseCase and includeUseCase some UseCase)

```

With SPARQLAS, we cover the requirement RQ3 by providing distributed query facilities for models and metamodels that are represented in OWL.

10.4 Validation

In order to validate our approach, we applied it in the TwoUse Toolkit. Table 10.4 presents the list of artifacts part of the development process of TwoUse Toolkit and the corresponding metrics. TwoUse Toolkit is a model-driven approach, i.e., each artifact listed below has an Ecore metamodel. For each artifact, we present the number of classes on the metamodel and the number of instances.

Table 10.1. TwoUse Measurement.

Phase	Artifact	Classes	Instances
User Requirements	Requirements specification	24	212
	UML diagrams	261	174
Analysis	BPMN diagram	24	754
Design	Metamodel	23	5370
	Generator specification	20	3374
	Grammar specification	38	7611
	Model transformation	46	8043
Code	manifest specification	53	2824
Management	Versioning and development life cycle	22	7032

Using our approach, we are able to extract information about the Ecore metamodels and models listed in Table 10.4, partially fulfilling requirement RQ3. Our approach for transforming Ecore-compliant metamodels and models captures all Ecore constructs. Thus, transformations from OWL back to Ecore can be done lossless.

After extracting metamodel/model information from TwoUse artifacts, we used ontology matching techniques to identify correspondences between metamodels, fulfilling the requirement RQ2. For Ecore metamodels and models, we have used string distance method that analyzes the similarities between names of elements. Additionally, we have used the class structure alignment method for establishing alignments based on the comparison of class properties.

Ontology matching techniques still generate false positives. Thus, it is necessary that domain experts assist the ontology matching process at the metamodel level (M2) by manually determining which of the identified correspondences should be implemented. At the modeling level (M1), this problem is minimized by alignment rules that query the metamodels. For example, if an instance *x* of UML metaclass `OpaqueAction` has the same name as an instance of the BPMN metaclass `Activity`, then they are the same activity.

Once that domain experts have acknowledged which correspondences should take place, the axioms for realizing the correspondences are generated, fulfilling the requirement RQ2. Listing 10.3 presents sample axioms for linking model and metamodel. Equivalent classes or class expressions are connected by the construct `EquivalentClasses`, whereas individuals with the same name are connected by the construct `SameIndividual`.

Listing 10.3. Sample of Linking Ecore metamodels with OWL.

```

1 EquivalentClasses (uml:Activity bpmn:BpmnDiagram)
EquivalentClasses (uml:ActivityNode bpmn:Vertex)
EquivalentClasses (uml:OpaqueAction ObjectSomeValuesFrom
    (bpmn:activityType bpmn:Task))
    EquivalentDataProperties (uml:name bpmn:name)
5 SameIndividual (uml:west.twouse.reasoner
    srs:west.twouse.reasoner)
SameIndividual (mf:west.twouse.reasoner
    srs:west.twouse.reasoner)
SameIndividual (uml:ReasoningServices
    srs:ReasoningServices)

```

Finally, we present the specification of queries mentioned at the beginning of this Section, fulfilling the requirement RQ3. Listing 10.4 presents the SPARQLAS query for determining which tasks realize the use case `Querying`. The usage of the transitive property and property chain for `includeUseCases` simplifies the query. Moreover, the query works for Activity Diagrams and BPMN Diagrams, since both are integrated.

Listing 10.4. Which Tasks realize Use Case `Querying`?

```

1 Namespace: = <http://www.eclipse.org/uml2/3.0.0/UMI#>
Select ?name
Where: _:u name "Querying"^^xsd:string
    _:u includeUseCases ?uc
5    ?uc ownedBehavior ?act

```

```

?act node ?node
?node type OpaqueAction
?node name ?name

```

Listing 10.5 presents an example of querying involving both levels (metamodel M2 and model M1) at the same time. It uses the alignments presented above, i.e., individuals of class `UseCase` and class `Component` are the same as individuals of classes `UseCase` and `Component` with the same name. Moreover, it uses an anonym property that corresponds to a property chain of the property `uml:includingCase` and the inverse of the property `uml:addition`.

Listing 10.5. What Use Cases to test If the component `west.twouse.reasoner` is updated?

```

1 Namespace: uml = <http://www.eclipse.org/uml2/3.0.0/UML#>
  Namespace: srs = <http://west.uni-koblenz.de/SRS#>
  Namespace: mf =
    <http://west.uni-koblenz.de/EclipseManifest#>
  Select ?name
5 Where: ?component mf:name
    "west.twouse.reasoner"^^xsd:string
    ?component srs:requirement ?requirement
    ?requirement srs:useCase ?uc
    ?uc uml:name ?name
  Union:
10    ?uc (inverse uml:addition o uml:includingCase) ?iuc
    ?iuc uml:name ?name

```

10.4.1 Limitations

Since there exist multiple strategies for matching and aligning ontologies, it is possible that false positive matches occur. For example, OWL classes with the same name are matched as equivalent, if one uses a string based matching technique, although the two concepts are semantically different. Thus, domain experts must be involved to validate the results of matching and alignments.

10.5 Related Work

The integration of software artifacts has been the topic of works including [132,133]. However, these approaches presented dedicated extractors for specific systems like bug tracking and version control but not for software models. Moreover, neither of these approaches presents formats for publishing data suitable to the linked-data approach, i.e., they do not share the principles of interoperability for connecting federated software models across the Web.

Kiefer *et al.* [134] and Iqbal *et al.* [135] explore semantic web approaches for transforming software artifacts such as data from version control systems, bug tracking tools and source code into linked data. Both approaches use artifact-specific extractors and thus work only for a fixed number of software artifacts. We propose

a generic approach for transforming and managing any MOF metamodel in a web format.

The OMG ontology definition metamodel [1] specifies mappings between OWL and UML. In this chapter, we present a general approach for mapping arbitrary Ecore models into OWL. We provide the means to express any MOF metamodel in its equivalent OWL.

The OMG Request For Proposal for MOF to RDF Structural Mapping in support of Linked Open Data [130] aims at defining a structural mapping between OMG-MOF models and RDF. This work can be seen as a response to this request. We propose an approach that can serve as a benchmark for future proposals.

10.6 Conclusion

In this chapter, we propose an approach to enable analysis, federation and querying of models expressed in MOF compliant languages, including OMG standards and domain-specific languages. The contribution in this chapter shows that the usage of the Ontology Web Language for specifying metamodels is a viable solution to achieve interoperability and shared conceptualizations. The role of OWL is not to replace MOF or the Object Constraint Language, since OWL addresses distinct requirements, specially concerning networked environments. OWL should complement the spectrum of software modeling languages in a unified architecture.

Conclusion of Part III

In this part, we have analyzed the impact of using OWL constructs and OWL ontology services in software modeling languages (addressing research problem III).

We used class expressions to decouple class selection from OCL expressions embedded in query operations (addressing research problem III.A) and improve software design patterns that address variant management.

When applying it in ontology-based information systems, the usage of SPARQLAS4TwoUse for integrating queries over ontologies with operations impacts on maintainability, reusability and extensibility (addressing research problem III.B).

Moreover, the transformation of MOF-based software languages into OWL supports software development by allowing developers to extract software engineering data using SPARQL-like queries over multiple software artifacts (addressing research problem III.C).

Applications in the Semantic Web

Model-Driven Specification of Ontology Translations

Summary. The alignment of different ontologies requires the specification, representation and execution of translation rules. The rules need to integrate translations at the lexical, the syntactic and the semantic layer requiring semantic reasoning as well as low-level specification of ad-hoc conversions of data. Existing formalisms for representing translation rules cannot cover the requirements of these three layers in one model. We propose a metamodel-based representation of ontology alignments that integrate semantic translations using description logics and lower level translation specifications into one model of representation for ontology alignments ¹.

11.1 Introduction

The reconciliation of data and concepts from ontologies and data repositories in the Semantic Web requires the discovery, the representation and the execution of ontology translation rules. Although research attention is now devoted to the discovery of alignments between ontologies, a shallow inspection of ontology alignment challenges reveals that there does not exist *one* accessible way of representing such alignments as translation rules [137].

The reason is that alignments must address ontology translation problems at different layers [138, 139]:

1. At the *lexical layer*, it is necessary to arrange character sets, handling token transformations.
2. At the *syntactic layer*, it is necessary to shape language statements according to the appropriate ontology language grammar.
3. At the *semantic layer*, it is necessary to reason over existing ontological specifications and data in both the source and the target ontologies.

For addressing ontology translation problems at the semantic layer, existing frameworks provide reasoning in one or several logical paradigms, such as description logics [140, 141] or logic programming [142–144]. For addressing ontology trans-

¹ This chapter contains work of the paper “Model-Driven Specification of Ontology Translations” presented at ER’08 [136].

lation problems at lexical and syntactic layers, alignment frameworks take advantage of platform-specific implementations, sometimes abstracted into translation patterns [145, 146] or into logical built-ins [144].

Such hybrid approaches, however, fail to provide clarity and accessibility to the modelers that need to see and understand translation problems at semantic, lexical and syntactic layers. Indeed, modelers need to manage different languages: (1) an ontology translation language to specify translation rules and (2) a programming language to specify built-ins, when the ontology translation language does not provide constructs to completely specify a given translation rule. This intricate and disintegrated manner draws their attention away from the alignment task proper down into diverging technical details of the translation model.

Filling the gap in the ontology translation domain between ontology mapping languages and general purpose programming languages helps to improve productivity, since modelers will not have to be aware of platform-specific details and will be able to exchange translation models, even if they use different ontology translation platforms. Moreover, maintenance and traceability are facilitated because knowledge about mappings is not longer embedded in the source code of programming languages.

We propose a platform independent approach for ontology translations, based on model-driven engineering (MDE) of ontology alignments. The framework includes a language to specify ontology translations – the Model-Based Ontology Translation Language (MBOTL). In order to reconcile *semantic* reasoning with idiosyncratic *lexical* and *syntactic* translations, we integrate these three translation problems into a representation based on a joint metamodel. The joint metamodel comprises, among others, the OWL 2 metamodel and the OCL metamodel to support specification, representation and execution of ontology translations.

The chapter is organized as follows: The running example and the requirements for ontology translation approaches are explained in Section 11.2. Our solution is described in Section 11.3, followed by examples in Section 11.4. In Section 11.5 we discuss the requirements evaluation and in Section 11.6, we present related work. The conclusion, Section 11.7, finishes the chapter with an outlook to future work.

11.2 Case Study

We consider two ontologies of bibliographic references from the test library of the Ontology Alignment Evaluation Initiative (OAEI) [137] to demonstrate the solution presented in this chapter: the reference ontology (#101) and the Karlsruhe ontology (#303). Canonical mappings covered by examples in this chapter and snippets of the source and target ontologies using the Manchester OWL Syntax [120] are shown in the Figure 11.1. Please refer to OAEI for complete ontologies.

By examining the mapping between ontology #101 and ontology #303, it becomes clear that translations are required in order to realize the mapping. Individuals of the classes `Chapter` and `InBook` in ontology #101 are translated into individuals of the class `InBook` in the ontology #303. Values of the object property `month` having a Gregorian month, e.g., “-01”, are translated into the equivalent unabbreviated form, e.g., “January”. Values of the data property `pages` in ontology #303 can be calculated by subtracting the value of the data property `initialPage` from the value of the property `endPage` in ontology #101.

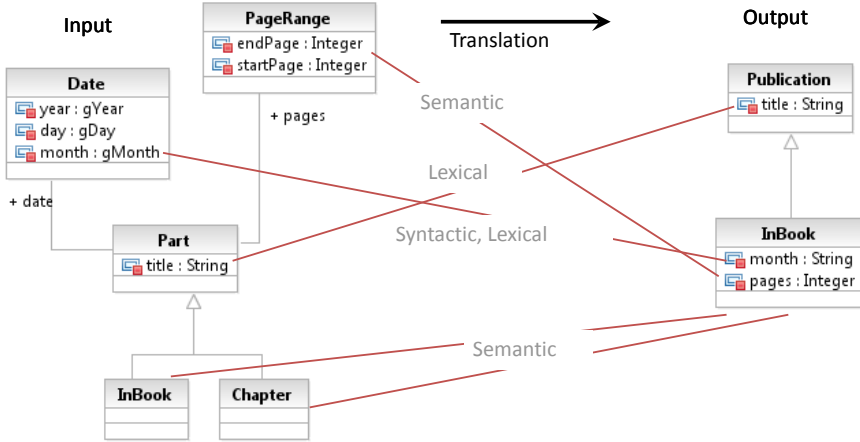


Fig. 11.1. Ontology Mapping Challenge for the Running Example.

We define the translation rules explained above by the following logical rules. All variables are treated as universally quantified and prefixed with a question mark. Let *builtin: notShortened* be a built-in function that returns the unabbreviated month, *builtin: toUpper* be a built-in function to capitalize strings, *builtin: -* be a subtractor function, *s* be the namespace prefix of the source ontology #101, and *t* be the namespace prefix of the target ontology #303, the translation rules can be written as follows:

$$\begin{aligned}
 t: \text{InBook}(?x) \wedge t: \text{month}(?x, ?m) \wedge t: \text{title}(?x, ?n) \wedge t: \text{pages}(?x, ?p) \leftarrow \\
 (s: \text{InBook}(?x) \vee s: \text{Chapter}(?x)) \wedge s: \text{month}(?x, ?y) \wedge \\
 \text{builtin: notShortened}(?y, ?m) \wedge s: \text{title}(?x, ?z) \wedge \\
 \text{builtin: toUpper}(?z, ?n) \wedge s: \text{pages}(?x, ?w) \wedge s: \text{startPage}(?w, ?a) \wedge \\
 s: \text{endPage}(?w, ?e) \wedge \text{builtin: -}(?e, ?a, ?p). \quad (11.1)
 \end{aligned}$$

The translation rule of authors is not trivial either. While in ontology #101 the authors are collected by recursively matching the property *first* of the class *PersonList*, in ontology #303 it is a matter of cardinality of the object property *author*. Let *list: contains* be the built-in able to filter a list structure into object properties, the referred rule can be written as follows:

$$\begin{aligned}
 t: \text{Book}(?x) \wedge t: \text{author}(?x, ?u) \leftarrow \\
 s: \text{Book}(?x) \wedge s: \text{author}(?x, ?y) \wedge \text{list: contains}(?y, ?u). \quad (11.2)
 \end{aligned}$$

However, built-ins are black boxes that conceal knowledge about algorithms, compromising traceability and maintenance. Therefore, an approach able to specify rules and built-ins without code specifics is required.

From inspecting these examples, we illustrate requirements for a platform independent ontology translation approach addressing translation problems at the following ontology translation layers proposed by Corcho and Gómez-Pérez [138] based on Euzenat [139]: the lexical layer, the syntactic layer, the semantic layer and the pragmatic layer. Since the pragmatic layer addresses the meaning of representation in a given context, it is similar to the semantic layer from the point of translation decisions. In this chapter, we refer to both layers as semantic layer.

1. The lexical layer deals with distinguishing character arrangements, including:
 - a) *Transformations of element identifiers*. They are required when different principles are applied to named objects, for example, when transforming the value of the data property title into capital letters.
 - b) *Transformations of values*. They are necessary when source and target ontologies use different date formats, for example, when transforming a Gregorian month into an unabbreviated form.
2. The syntactic layer covers the anatomy of the ontology elements according to a defined grammar. The syntactic layer embraces:
 - a) *Transformations of ontology element definitions*. They are needed when the syntax of source and target ontologies are different, e.g., when transforming from OWL RDF syntax into OWL XML syntax.
 - b) *Transformations of datatypes*. They involve the conversion of primitive datatypes, e.g., converting string datatype to date datatype.
3. The semantic layer comprises transformations dealing with the denotation of concepts. We consider the following aspects:
 - a) *Inferred knowledge*. Reasoning services are applied to deduce new knowledge, for example, inferring properties from class restrictions.
 - b) *Transformations of concepts*. It takes place when translating ontology elements using the same formalism, e.g., translating a concept from Karlsruhe's OWL ontology for bibliographic references into one or more concepts in the INRIA's OWL ontology.

The translation problems are classified in non-strict layers, e.g., one rule commonly addresses more than one translation problem. For example, in Rule 2, the built-in `toUpper` solves a translation problem at the lexical layer, the translation of months happens at the syntactical layer and is achieved by the built-in `notShortened` and, finally, the translation of the union of individuals of the classes `Chapter` and `LnBook` in ontology #101 into individuals of the class `LnBook` in ontology #303 appears at the semantic layer.

An orthogonal classification of ontology translation problems is given by Dou *et al.* [143]. From their point of view, ontology translation problems comprise dataset translation, ontology-extension generation and querying. This chapter concentrates on dataset translation, i.e., translation of instances, leaving the model-driven engineering of the remaining problems for future work.

11.3 Application of the TwoUse Approach

The proposed ontology translation approach relies on advances in model-driven engineering (MDE) with support for ontology reasoning services [147]. We define here

the Model-Based Ontology Translation Language (MBOTL) comprising (1) a textual concrete syntax used to write translation rules, (2) an integrated metamodel as abstract syntax to represent the translation rules as models, (3) an extensible model library to provide built-in constructs and (4) model transformations yielding translational semantics.

Figure 11.2 relates MBOTL with existing approach with respect to abstraction and expressiveness. Languages for specifying translation rules like F-logic and RDF abstract from platform details, but they are not as powerful as programming languages. The usage of a domain specific language for ontology translation (MBOTL) provides the right trade-off between abstraction and expressiveness.

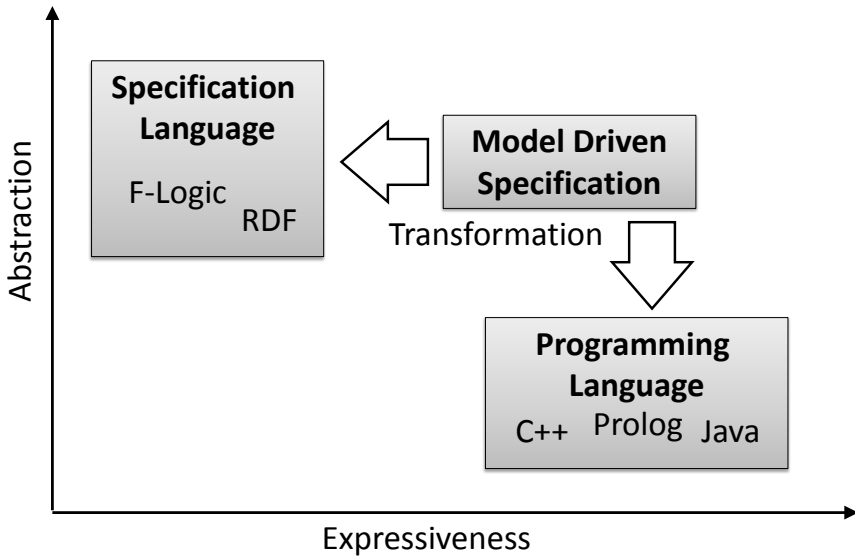


Fig. 11.2. Abstraction vs. Expressiveness.

11.3.1 Concrete Syntax

While visual notations are effective in communicating models, textual notations are preferable to express more complex structures. The following subsections present the anatomy of the translation rules, alluding to the requirements presented in Section 11.2.

Dealing with Translation Problems at Semantic Layer

In order to extract information from the source ontology, we need a query language able to determine which datasets are to be translated. We use OCL expressions [36] to formulate queries. Indeed, OCL has been used in MDE for specifying constraints and queries that are side effect free operations. As OCL is originally designed for UML or MOF, we provide a transformation from OCL to SPARQL.

Ontology translation problems at the semantic layer are treated by querying individuals of the source ontology using OCL queries and matching target individuals. These assumptions have been used by model transformation languages like OMG MOF Query/View/Transformation (QVT) [32] and the Atlas Transformation Language (ATL) [35]. We base MBOTL upon the ATL concrete syntax to specify ontology translations.

The example depicted in the Figure 11.3 illustrates the concrete syntax. A rule `Conference2Conference` is defined for translating individuals of the class `Conference` in ontology `#101` into individuals of the class `Conference` in ontology `#303`.

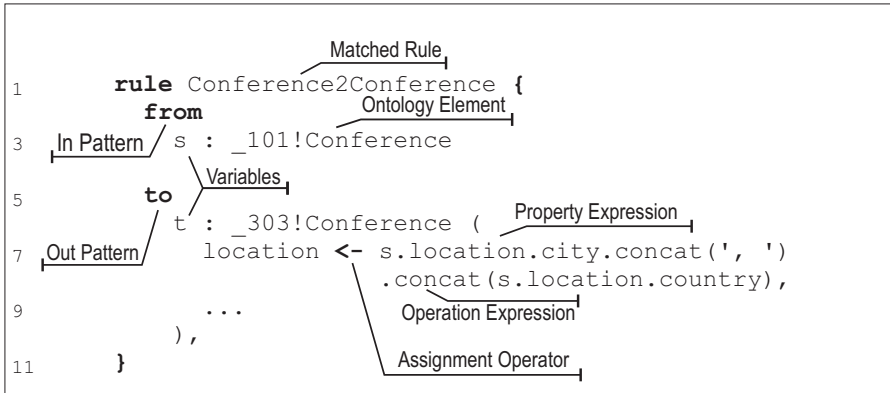


Fig. 11.3. Example of a Translation Rule.

In OCL, a dot-notation is used to navigate through properties. In the scope of our extension of OCL, a property can be an OWL data property, an OWL object property, a predefined operation or a helper. A helper is a user defined side effect free query operation belonging to a defined class in one of the given ontologies.

For example, in the expression `s.location`, `s` is a reference to an individual of the class `Conference` with `location` resulting in a value of the class `Address`. The navigation can also end with an operation evaluation, as depicted in the Figure 11.3, where the operation `concat` is used to concatenate the properties `city` and `country`.

Addressing Translation Problems at Lexical and Syntactic Layers

Ontology translation problems at lexical and syntactic layers are supported by employing operations or helpers. For example, for the type `string`, the operation `toUpper()` returning a string object with capital letters is available. Thus, the evaluation of `s.title.toUpper()` capitalizes the value of the property `title`.

The operation `toUpper()` is an example of predefined operation. The set of predefined operations is available in the OCL library (M1 layer). These operations are applicable to any type in OCL. Additionally, it is possible to specify *ad hoc* operations, the so-called helpers.

11.3.2 Metamodels

The textual concrete syntax for ontology translation specification presented in the previous section has an integrated metamodel as equivalent abstract syntax. The integrated metamodel consists of the following metamodels: MOF metamodel [9], OCL metamodel [36], OWL metamodel [1], and part of the ATL metamodel [35].

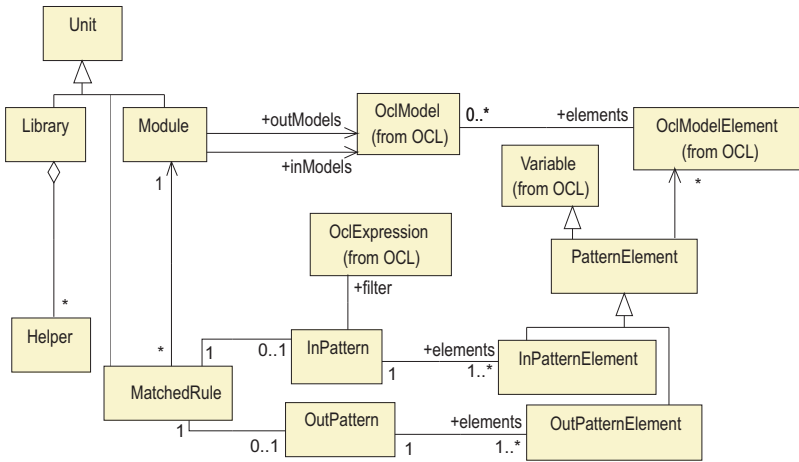


Fig. 11.4. Fragment of the ATL Metamodel.

The translation metamodel (Figure 11.4) allows for describing translations between two ontologies by a model. A translation is characterized as a `Module` relating source ontologies (`inModels`) and target ontologies (`outModels`). A `MatchedRule` is a specific translation rule that has a pattern for the input model (`inPattern`) and a pattern for the output model (`outPattern`). The `InPattern` has one or more elements that are OCL variables (`Variable`). Variables are bound to model elements (`OclModelElement`). The `InPattern` has an `OclExpression` acting as query to refine individuals of the `OclModelElement`.

Since each expression in OCL has a type, we need a type metamodel (Figure 11.5). The expression evaluation produces a value of type of the expression. The type `TUClassAdapter` is the particular composition of the OWL class with the MOF class. This composition allows for applying side effect free operations into individuals of OWL classes.

Figure 11.5 depicts additionally another part of the integrated metamodel, namely the package `Expressions` of the extended OCL metamodel. The class `OclExpression` enables MBOTL to define the abstract syntax for OCL expressions. The integration with the OWL metamodel is accomplished by expressions of the type

PropertyCallExp. Such expression allows for navigating through OWL properties, as explained in Sect. 11.3.1.

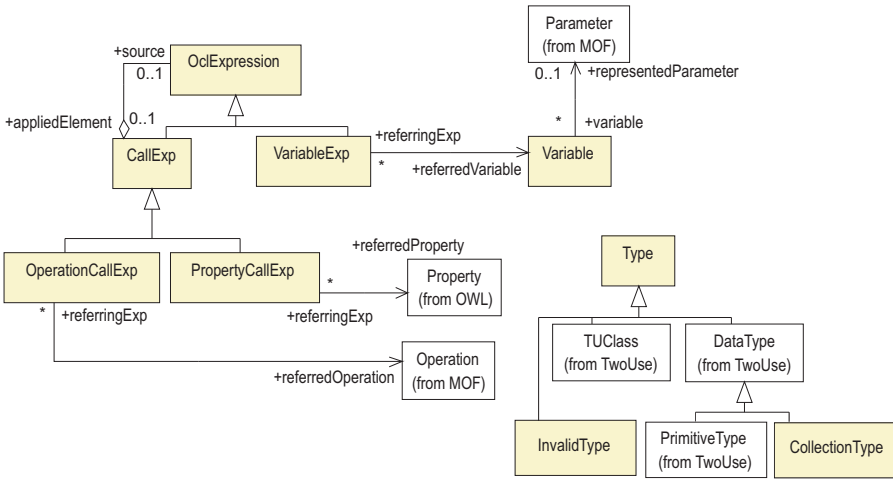


Fig. 11.5. Snippet of the Package Type and Package Expressions of the OCL Metamodel.

The operation call expressions (OperationCallExp) support the declaration of built-in operations and helpers. An operation call expression evaluates to the result of a class operation, providing that such operation is side effect free. This resource is particularly relevant in the scope of ontology translation, i.e., it enables queries to invoke built-in reasoning operations or helpers.

11.3.3 Model Libraries

The model libraries define a number of datatypes, class identifiers and operations that must be included in the implementation of MBOTL. These constructs are instances of an abstract syntax class. The foundation library exists at the M1 level, where the abstract syntax (metamodel) exists at M2 level. The foundation library is composed of the XML Schema Datatypes library, the RDF library, the OWL library and the OCL library.

An example of M1 object of the extended OCL library is the construct `oclAny`. All types inherit the properties and operations of `oclAny`, except collection types. This invariant allows for attributing predefined operations to classes. The OCL library is based on the standard OMG OCL library [36].

11.3.4 Semantics

The semantics of MBOTL is defined by the semantics of the languages comprising the integrated metamodel (Section 11.3.2).

MBOTL is translated into a target language (SPARQL and Java). Regarding the target languages, the semantics of SPARQL is described by entailment regimes, whereas the semantics of Java can be defined by providing an Abstract State Machine [148]. More specifically, the SPARQL basic graph pattern is described according to an entailment regime. Indeed, SPARQL-DL [57] provides an entailment regime for OWL-DL.

11.3.5 Ontology Translation Process

In order to guide the user from the ontology translation specification until the running code, the ontology translation process covers the following steps:

1. *Specification of Ontology Translation.* The ontology translation rules and helpers are specified by the user using MBOTL.
2. *Specification of Model Transformations.* In order to have a running implementation of ontology translation, the ontology translation specification model is transformed into models for a given platform. The model transformation specification mapping the MOBTL model onto platform specific models must be specified here. Our framework provides model transformations from MOBTL into SPARQL and Java as target platforms. Notice that other target platforms like F-Logic and Java can be considered.
3. *Transformation into Target Platform.* Three transformations take place at this step. Firstly, the ontology translation specification in the concrete syntax (MOBTL file) is injected into a model conforming with the integrated meta-model, i.e., the ontology translation specification model. The second transformation is responsible for generating models according to the target metamodels, e.g., SPARQL and Java metamodels. Thirdly, SPARQL queries in the SPARQL concrete syntax and Java code are extracted from the SPARQL and Java MOF-based models.

11.3.6 Implementation

The implementation comprises (1) the environment to specify ontology translations and (2) transformations into ontology translation engines in order to realize ontology translation. Figure 11.7 depicts a screen shot of the MBOTL implementation on TwoUse toolkit.

Taking the ontology translation specification model as a source model, we use the Atlas Transformation Language [35] framework to define model transformations into models for an ontology translation platform (2). We use SPARQL and Java as target languages and the Jena framework as a ontology translation solution. The Jena framework includes an API for OWL ontologies and reasoners, as well as a SPARQL engine.

Elements of the ontology translation specification model concerning translation problems at the semantic layer are transformed by ATL into SPARQL CONSTRUCT queries. The SPARQL engine can be extended using custom SPARQL filter functions — as foreseen as an extension hook in the SPARQL standard, but also using so called *predicate functions*. Predicate functions are not matched against the knowledge base like normal RDF predicates, but evaluated in Java code. Filter

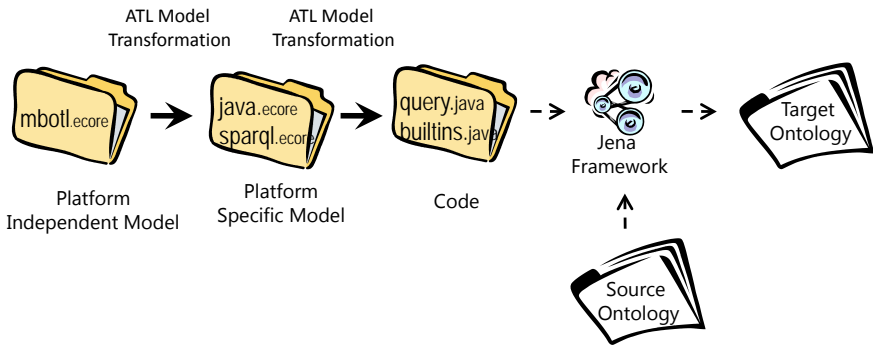


Fig. 11.6. Ontology Translation Process.

and predicate functions are used to handle translation problems at the lexical and syntactic layer. These functions are defined in the ontology translation specification model and have the Java code automatically generated by the ATL transformation.

The next section illustrates our approach by addressing the translation problems presented in Section 11.4, specifying the translation rules and transforming the ontology translation specification into SPARQL and Java code.

11.4 Examples

This section presents rules integrating translation problems at semantic, syntactic and lexical layers, according to the problems presented in Section 11.2.

Example 1: Semantic, syntactic and lexical translations

The classes `Chapter` and `InBook` in ontology #101 are translated into the class `InBook` in the ontology #303. The translation rule uses a helper to transform a Gregorian month, e.g., “-01”, into its equivalent unabbreviated form, e.g., “January”. This helper is applicable only to the `gMonth` datatype. Using MBOTL, we can specify both the rule and the helper — and hence lexical, syntactical and semantical translations — using an integrated framework. The helper is shown on top of listing 11.1, followed by the translation rule.

Listing 11.1. Semantic, syntactic and lexical translations with MBOTL

```

1 helper context _101!gMonth
  def: notShortened() : String =
    Sequence{ 'January', 'February', 'March' }->at(
      Sequence{ '--01', '--02', '--03' }->indexOf(self.toString()))

```

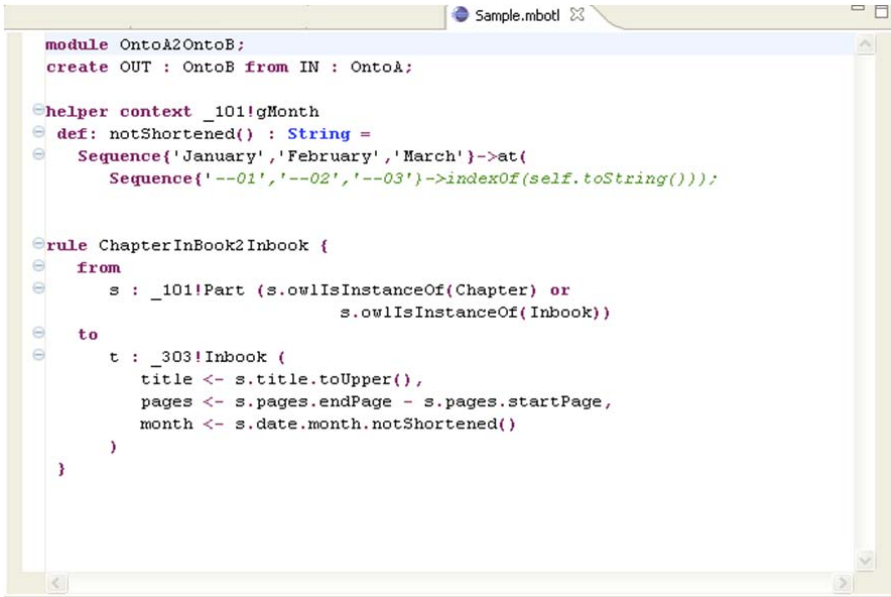


Fig. 11.7. Screenshot of MBOTL.

```

5
rule ChapterInBook2Inbook {
  from
    s : _101!Part (s.owlIsInstanceOf(Chapter) or
                  s.owlIsInstanceOf(Inbook))
10  to
    t : _303!Inbook (
      title <- s.title.toUpper(),
      pages <- s.pages.endPage - s.pages.startPage,
      month <- s.date.month.notShortened(),
15  )
}

```

After specifying mappings with MBOTL, we transform MBOTL specification into suitable languages for execution. Our implementation uses SPARQL queries for semantic mappings and Java code for syntactic translations.

In this example, the rule `ChapterInBook2Inbook` is transformed into a SPARQL query (Listing 11.2), whereas the helper `notShortened` is transformed into Java code (Listing 11.3). The Java code extends a suitable SPARQL engine, in this case Jena.

Listing 11.2. SPARQL query corresponding to `ChapterInBook2Inbook`

```

1 CONSTRUCT {?x rdf:type _303:Inbook. ?x _303:title ?y.
           ?x _303:pages ?z. ?x _303:month ?w}
WHERE {
  ?x rdf:type _101:Part.

```

```

5  {?x rdf:type _101:Chapter UNION ?x rdf:type _101:Inbook}
   ?x _101:title ?u. ?u userdef:toUpper ?y.
   ?x _101:pages [rdf:type _101:Page;
                 _101:startPage ?w; _101:endPage ?u].
   ?z userdef:difference (?u ?w).
10 ?x _101:date [rdf:type _101:Date; _101:month ?m].
   ?m userdef:notShortened ?w.
}

```

In Lines 1 and 2 of Listing 11.2, the pattern in the target ontology is specified. It is filled with variable bindings obtained from the pattern in Lines 4-11. Variables in SPARQL are denoted with a question mark. In Line 5 we see the disjunction of chapter and book. In Lines 7-8, the start and end page properties of the complex “Page” concept in the source ontology is matched. They are used to compute the simpler page length in the target ontology using a predicate function in Line 9. Analogously, the abbreviated date is matched and mapped in Lines 10-11.

As an example of the translation of a helper, we show a part of the Java code resulting from transforming `notShortened` into a Jena predicate function in Listing 11.3.

Listing 11.3. Automatically generated Java code for the function `notShortened`

```

1 public class NotShortened extends PFuncSimple {
   /** Implements Sequence{ 'January', 'February', 'March' }
   */
   private List colLit1() {
     List /*(String)*/ myList = new ArrayList( /*String*/);
5     myList.add( "January" );
     myList.add( "February" );
     myList.add( "March" );
     return myList;
   }
10
   /** Implements Sequence{ '--01', '--02', '--03' } */
   private List colLit2() {
     List /*(String)*/ myList = new ArrayList( /*String*/);
15     myList.add( "--01" );
     myList.add( "--02" );
     myList.add( "--03" );
     return myList;
   }
20
   private QueryIterator execFixedSubj(Node subject,
                                     Node object, Binding binding,
                                     ExecutionContext execCxt) {
25
   /** Implements the built-in notShortened() : String */
   return new QueryIterSingleton (
     colLit1().size() > colLit2().indexOf(this.toString())
     ?((String) colLit1().get(colLit2().indexOf(this.toString())))

```

```

    : "", execCxt);
  }
30 }

```

Example 2: Semantic and syntactic translation of complex structures

In the ontology #101, the class `Article` has the property `author` with the range of type `PersonList`. `PersonList` has a property `first` with the range of type `Person` and a property `rest` with the range of type `PersonList`.

This rule relies on a helper, able to match elements recursively. In this case, the helper algorithm must add the current value of the property `first` to the collection of authors and verify whether the value of the property `rest` is `nil`, returning in this case the collection. Otherwise, the helper is invoked until value `nil` is found.

As we can see from the examples, helpers are used for lexical and syntactical translations (Example 1) and semantic translations (Example 2).

11.5 Analysis

In response to the requirements deduced in Section 11.2, Table 11.1 shows use cases according to each requirement and where to find the corresponding examples in this chapter.

Table 11.1. Satisfying Ontology Translation Requirements.

Requirement (Section 11.2)	Use Case	Implementation
1.(a)	converting to capital letters	Listing 11.1, Line 12
1.(b)	converting date formats	Listing 11.1, Line 14
2.(b)	converting <code>gMonth</code> to <code>String</code>	Listing 11.1, Line 14
3.(a)(b)	Union of <code>Chapter</code> and <code>InBook</code>	Listing 11.1, Line 8-9

Translation problems of lexical nature, e.g., converting a string to an uppercase string, are managed by using predefined OCL operations applied to specific types of objects, in this example a string type. It is also possible to write functions, i.e., helpers, to perform *ad hoc* operations. For example, the helper `notShortened` (Listing 11.1) allows for converting date formats, i.e., replacing a value of `gMonth` type to the unabbreviated form.

Translation problems inherent in the syntactic layer are handled distinctly. For example, datatype conversions are achieved by invoking predefined operations, e.g., `toString()` (Listing 11.1).

Translation problems at the semantic layer, regarding datasets of ontologies with different vocabularies but the same formalism is demonstrated by the running example. In Listing 11.1, the individuals of the class `Chapter` in ontology #101 and the individuals of the class `InBook` are translated into individuals of the class `InBook` in ontology #303.

Limitations

Our approach has restrictions reflected by the ATL metamodel. With ATL, it is possible to realize only unidirectional translations. A bidirectional translation must be accomplished by two unidirectional translations.

Moreover, at the current state of development, it is not possible to validate or to reason over translation models. In other words, it is not possible to test the translation model without transforming it into the target platform (SPARQL and Java).

11.6 Related Work

Since related work has been done in the field of ontology alignment, we group works according to semantic, syntactic and lexical layers.

Among works covering lexical and syntactic translations, Model transformation languages like OMG Query/View/Transformation (QVT) [32] and Atlas Transformation Language (ATL) [35] allow for defining how to transform MOF-based models using declarative and imperative constructs. Nevertheless, they do not support the OWL metamodel and do not provide description logic constructs. Our contribution extends the ATL solution by integrating with the OWL metamodel and providing such constructs.

The work of Atzeni *et al.* [149] is based on a metamodel approach with models described in terms of the constructs they involve, taken from a given set of predefined ones. However, the work is in the scope of databases and does not support reasoning at the semantic layer.

Among works covering semantic reasoning capabilities, C-OWL [140] and the ontology mapping system proposed by Haase and Motik [141] are formal solutions for ontology mapping with description logic expressiveness. The mappings are based on subsumption relationships of concepts between ontologies. Notwithstanding, the usage of built-ins to express lexical and syntactic translation problems is not possible. A metamodeling-based approach of Haase and Motik [141] is provided by Brockmans *et al.* [150]. Although the usage of built-ins in mapping rules is allowed, the latter approach does not provide the means to specify built-ins without recourse to programming languages, whereas MBOTL allows for specifying *ad hoc* functions by helpers.

Among works covering lexical, syntactic and semantic translations, MAFRA [145] and RDFT [146] are frameworks enabling dataset translations. Nonetheless, both are based on RDF Schema and neither they provide the expressiveness of OWL nor support reasoning capabilities of description logic inference engines.

OntoMorph [142] and the framework proposed by Dou [143] for ontology translation rely on First Order Logic (FOL) expressiveness to specify translation rules. Our approach counts on the decidable subset of FOL, the description logic $\mathcal{SHOIN}(\mathbf{D})$, with complete and sound automated reasoning services for addressing semantic translation problems. Moreover, while the first solution relies on PowerLoom and the latter on Web-PDDL, we propose a platform independent model-based translation language, flexible enough to cope with different knowledge representation systems.

OntoMap [144] is a mapping solution allowing for visual specification of mappings, with a limited number of translation functions. Snoogle [151] is an ontology

translation tool that enables the use of SWRL rules to express translations and alignments between geospatial ontologies. While in both approaches it is possible to use custom plug-ins, the user has to write functions using Java and the Jena framework. In contrast, our approach allows for specifying mapping rules and functions in a platform independent and integrated way.

Corcho and Gómez-Pérez [152] propose ODEDialect, a set of declarative languages to specify ontology translations. However, it is a platform specific approach based on Java that exposes users to the complexity of programming languages, whereas MBOTL allows modelers to concentrate on business logics instead.

11.7 Conclusion

This chapter presents a solution for ontology translation specification that aims at being more expressive than ontology mapping languages and less complex and fine-grained than programming languages. The solution is comprised of a concrete syntax, an integration metamodel covering OWL, MOF, OCL and ATL metamodels and model transformations from MBOTL into SPARQL and Java. We validate our solution against canonical ontology translation problems organized in three layers – lexical, syntactic and semantic.

Automatic Generation of Ontology APIs

Summary. When developing application programming interfaces of ontologies that include instances of ontology design patterns, developers of ontology-based information systems usually have to handle complex mappings between descriptions of information given by ontologies and object oriented representations of the same information. In current approaches, annotations on API source code handle these mappings, leading to problems with reuse and maintenance. We propose a domain-specific language to tackle these mappings in a platform independent way – *agogo*. Agogo provides improvements on software engineering quality attributes like usability, reusability, maintainability, and portability ¹.

12.1 Introduction

Upper level ontologies and domain ontologies comprise occurrences of a variety of ontology design patterns (OPs) [105]. These ontologies are generally large and densely axiomatized. Therefore, in comparison with generic solutions like RDF or OWL APIs, the development of dedicated application programming interfaces (APIs) eases the adoption of this kind of ontologies.

When developing such dedicated APIs, developers of ontology-based information systems face the challenge of mapping descriptions of complex relations or entities to object oriented (OO) representations thereof. For example, core ontologies such as COMM [124], X-COSIMO [154] or Event-Model-F [155] represent complex objects, e.g., a multimedia annotation, a conversation among participants or an event decomposition. Such objects are not represented by a single instance of a class but by ontology design patterns involving a number of connected (linked) instances.

The task of implementing object manipulation functionality becomes complex as well. For example, the specification of creation or deletion of multimedia objects is spread out in a number of connected (linked) data instances using decompositions, descriptions and segments.

¹ This chapter contains work of the paper “APIs *a gogo*: Automatic Generation of Ontology APIs” presented at ICSC’09 [153].

Specifying interfaces for manipulating ontologies should provide constructs that enable to handle complex structures defined by ontologies. Accordingly, such constructs need to map from a single programming object to multiple RDF statements.

Current approaches store annotations as plain text on API source code to handle these mappings. These approaches have the following disadvantages (Figure 12.1):

- Low level of abstraction. When it comes to complex mappings between ontology classes and OO classes, current approaches require developers to deal with platform-specific details like database connection, data validation, deviating attention from the mappings.
- No portability. The APIs are tightly coupled to programming languages and cannot be easily ported to other programming platforms.
- Low reuse rate. Mappings between ontology classes and OO classes are in the form of annotations. These annotations are stored as plain text and to be reused, they have to be copied instead of being referred.
- Hard maintenance. Changes of mappings on the ontology usually imply changing all occurrences of a given Java annotation, since mappings are stored as annotations and must be copied to be reused.

```

package de.unikoblenz.isweb.fpi;
import java.util.Collection;
import net.java.rdf.annotations.complex;
//<http://events.semantic-multimedia.org/ontology/2008/12/...
@complex(")?subject <http://www.w3.org/1999/02/22-rdf-syntax-ns#type> <http://
public class Event {

    @complex(")?subj <http://www.loa-cnr.it/ontologies/DUL.owl#isEventIncludedIn> ?
        "?obj <http://www.w3.org/1999/02/22-rdf-syntax-ns#type> <http://events
            <http://www.loa-cnr.it/ontologies/DUL.owl#classifies> ?decomp
        "?decompositionDesc <http://www.w3.org/1999/02/22-rdf-syntax-ns#type> <
            <http://www.loa-cnr.it/ontologies/DUL.owl#classifies> ?sut
        "?compositeRole <http://www.loa-cnr.it/ontologies/DUL.owl#classifies> ?sut

    Collection<FDecomposition> decompositions;

    @complex("<http://events.semantic-multimedia.org/ontology/2008/12/...
    String name;

    public void SetFDecomposition(FDecomposition d) {

    }

}

```

Fig. 12.1. Limitations of Current Approaches.

Indeed, addressing these issues has been one of the objectives of the field of model-driven engineering (MDE) [14], i.e., to develop and manage abstractions of the solution domain towards the problem domain in software design. Considering

the expansion and usage of MDE techniques, we investigate the following problems in this chapter: What MDE techniques address the aforementioned issues? What are the results of applying these techniques in ontology API development?

Tackling the aforementioned problems results in improving the usability, maintainability and portability of ontology API specifications. It enables developers to concentrate on the mappings instead of taking care of problems inherent in programming. By considering mappings as first-order objects rather than as annotations, developers can keep track of mapping ontology elements like classes and properties. Finally, by introducing an abstraction from the programming language, it allows developers to generate APIs for different programming languages or domain-specific APIs.

We extend the TwoUse approach and introduce *agogo*, an approach that provides a development environment for API developers to handle complex mappings, to define and to reuse complex OPs, and to automatically generate ontology API code. Moreover, we present results of comparing *agogo* with existing ontology API code, showing drastic reduction in size.

We organize this chapter as follows: After introducing the challenges and benefits of *agogo*, we analyze current approaches in Section 12.5. We derive requirements based on our experience in developing APIs for core ontologies (COMM [124], X-COSIMO [154], Event-Model-F [155]) in Section 12.2. Section 12.3 presents the techniques and artifacts used by *agogo* to tackle those requirements. We describe how *agogo* uses these techniques and artifacts by example in Section 12.3.2. In Section 12.4, we analyze how the *agogo* approach allows for improving quality of ontology APIs based on the quality characteristics introduced in this section. Finally, Section 12.6 concludes this chapter.

12.2 Case Study

From the set of ontology design patterns found in the COMM ontology, we use the Semantic Annotation Pattern to illustrate the solution presented in this chapter. The basic rationale applies to any other pattern used in COMM, X-COSIMO [154] and Event-Model-F [155]. Figure 12.2 illustrates the semantic annotation pattern as defined by the COMM ontology and the desired classes of the API in the programming model.

The pattern describes the annotation of a multimedia item with some label, e.g., the annotation of a part of a photo with a label pointing to a person – Carsten (not included in the Figure 12.2). This association is embodied through a **semantic-annotation** that satisfies a **method** (e.g., algorithms for image recognition) that defines a **semantic-label-role** as well as an **annotated-data-role**. The **multimedia-data** has to play the **annotated-data-role**, which identifies the part of the image that is annotated. The depicted particular has to play the **semantic-label-role**, e.g., the instance **Carsten**.

The COMM API comprises mappings between such patterns and Java objects. For instance, objects of the class `SemanticAnnotation` represent instantiations of the pattern **semantic-annotation**. The mapping is achieved by implementing the intended behavior for create, read, update, and delete operations (CRUD) that affect the knowledge base accordingly:

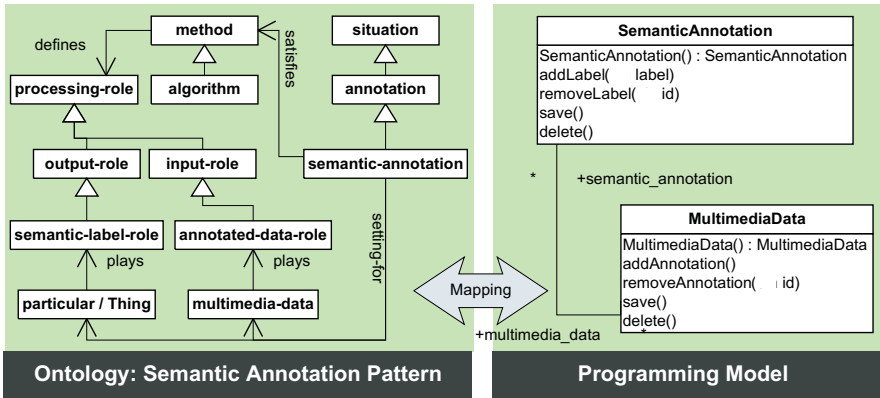


Fig. 12.2. Ontology and API for the Semantic Annotation Pattern.

Create: The construction of a *new* object, i.e., an object representing data that is *not yet present* in the knowledge base, needs to result in the correct and complete instantiation of an ontology pattern.

Read: The construction of an object based on *existing* data in the knowledge base. Although similar from an application programming interface point of view, the underlying operation in the knowledge base is fundamentally different. In this case, the knowledge base is queried for the instance of a pattern, and all involved resources and statements required to fully instantiate the object.

Update: The update of an object needs to result in the replacement of information in the knowledge base. Thereby, developers need to implement distinct update behaviors. For example, the class `MultimediaData` implements a method to add a `SemanticAnnotation`. This method either adds a semantic label to an existing `SemanticAnnotation` for the image or creates a new instance of a `SemanticAnnotation`.

Delete: The deletion of an object has different implications. For instance, the deletion of `SemanticAnnotation` results in the deletion of the *relation* between the image and Carsten as expressed by the instance of the pattern. In another scenario, developers may want to delete the image and Carsten as well or to delete the representation of Carsten.

Based on our experience in developing the core ontologies COMM, X-COSIMO and Event-F and their APIs, we have identified problems and derived the following requirements:

RQ1. Emphasis on domain concepts. When programming ontology APIs, developers have to deal with aspects inherent in programming languages like database access coding or data validation coding. For example, for each mapping, developers have to write code for handling access to the knowledge base. These tasks divert developers' attention from the specification of ontology APIs.

Moreover, currently, developers have to redundantly implement programming code for validating the correct instantiation of objects, e.g., code that checks whether all required information is available in an object. In our example, the Java class `SemanticAnnotation` needs to provide code that checks whether all information for a correct instantiation of the *Semantic Annotation Pattern* is available. The instan-

tiation of this pattern without both the part of the image and the depicted person makes no sense.

RQ2. Patterns as first-class citizens. Currently, when specifying standard behaviors for CRUD operations, developers have no choice but tangling the specification over the classes that implement the pattern. Thus, developers cannot reuse these operations across software projects or programming languages.

RQ3. Support for debugging. The ontology API code consists of complex queries. Such queries are typically represented as strings and are not always recognized by programming languages or programming environments during compile time. This makes debugging particularly hard for two reasons: First, the programming environment gives no hints for syntax errors during compile time. Accordingly, developers can track syntax errors only at runtime. Second, even at runtime, semantic errors are hard to recognize. For instance, the following SPARQL-query has the correct syntax but does not return any results due to the mistyped concept name *semantic-an(n)otation*: “*select ?s where {?s a comm:semantic-anotation}*”

RQ4. Change management. As the programming code references ontology concepts that the programming environment ignores, refactoring code in case of ontology changes is difficult. For instance, if a developer changes the ontology concept *semantic-annotation* to *Annotation*, associations in the programming code (e.g. annotations, query strings, URI strings) need to be updated manually.

RQ5. Generation of APIs for the same ontology or for different platforms. Currently, mappings cannot be reused in other programming languages, since they are implemented by programming code and specific means provided by a programming language, e.g. Java annotations.

The problems that motivate these requirements impair the development of ontology APIs by retarding their availability, affecting the adoption of the respective ontologies. Moreover, having families of APIs for a given ontology or APIs for different platforms is implausible due to the effort needed.

To enforce the importance of these requirements, we analyze the current COMM API. The current COMM ontology has 702 classes while its API has 34 packages, 294 classes, 1823 functions and 11597 non-commenting source statements (NCSSs).

12.3 Application of the TwoUse Approach

agogo is an application of the TwoUse approach for automatically generating OWL APIs on demand. To tackle the problems presented in the previous section, *agogo* relies on technologies regularly applied in model-driven development: metamodeling, concrete syntax and model transformations.

Agogo's metamodel and concrete syntax constitute a domain-specific language (DSL) that provides an abstraction layer over programming languages, encapsulating redundant data validation or implementation behavior. The DSL simplifies the process of specifying ontology APIs by focusing on domain concepts (RQ1).

Moreover, the usage of metamodels allows for defining concepts in a structured way, improving maintainability (RQ4). For example, elements of the ontology API specification are maintained as single units instead of being stored in annotations.

The definition of constraints on concepts in the *agogo* metamodel improves design time checking, i.e., it enables API developers to validate API specifications against these constraints, minimizing errors at runtime (RQ3).

The concrete syntax for ontology API specification enables users to model patterns as first-class citizens (RQ2). For example, developers specify CRUD operations and patterns using SPARQL syntax independently from the class definition. Furthermore, the concrete syntax allows for identifying missing references and for helping to find errors before code generation.

Model transformations allow for code generation to eventually more than one platform, overcoming the restriction on programming language (RQ5). Additionally, model transformations ease the creation of families of APIs. It enables developers to release a subset of the COMM API for lightweight applications, if required.

12.3.1 Key domain concepts

The *agogo* metamodel extends the TwoUse metamodel and defines the concepts of an ontology API specification and corresponds to the abstract syntax of *agogo* DSL. The definition of the concepts of an ontology API specification in a metamodel raises the abstraction level and allows API developers to work exclusively with relevant constructs. For example, developers handle mappings, patterns and operations without considering implementation issues.

In the following, we describe *agogo* key concepts. Figure 12.3 depicts how these concepts are related in the *agogo* metamodel.

Classes. The construct `Class` defines the associations between platform specific classes and ontology classes. The property `ontoElement` associates classes to patterns or ontology classes.

Patterns. When a platform specific class does not correspond directly to a single ontology class but to an occurrence of an ontology design pattern (OP), the concept of pattern applies. The construct `QueryPattern` describes OPs using SPARQL queries [87]. It is possible to define patterns for classes, properties and operations.

Operations. CRUD operations (Create, Read, Update and Delete) are defined in ontology APIs to enable manipulation of ontology classes. Using SPARQL-like syntax, these operations as well as patterns are defined in a platform independent way.

Imports. Developers may group patterns for classes, properties and operations into packages and make them available or reuse them in another API specification.

The *agogo* metamodel extends the TwoUse metamodel that and reuses existing metamodels for SPARQL, OWL 2 and Ecore.

Metamodel Constraints

Together with the *agogo* metamodel, we define constraints used by the syntax checker to enforce valid ontology API specifications. This functionality allows for identifying errors before generating ontology APIs.

Listing 12.1. Constraints on the *agogo* Metamodel.

```

1 context Operation
  inv inv1: self.ontoElement.SPARQLQuery.whereClause
    .variables.includesAll(self.parameters);

```

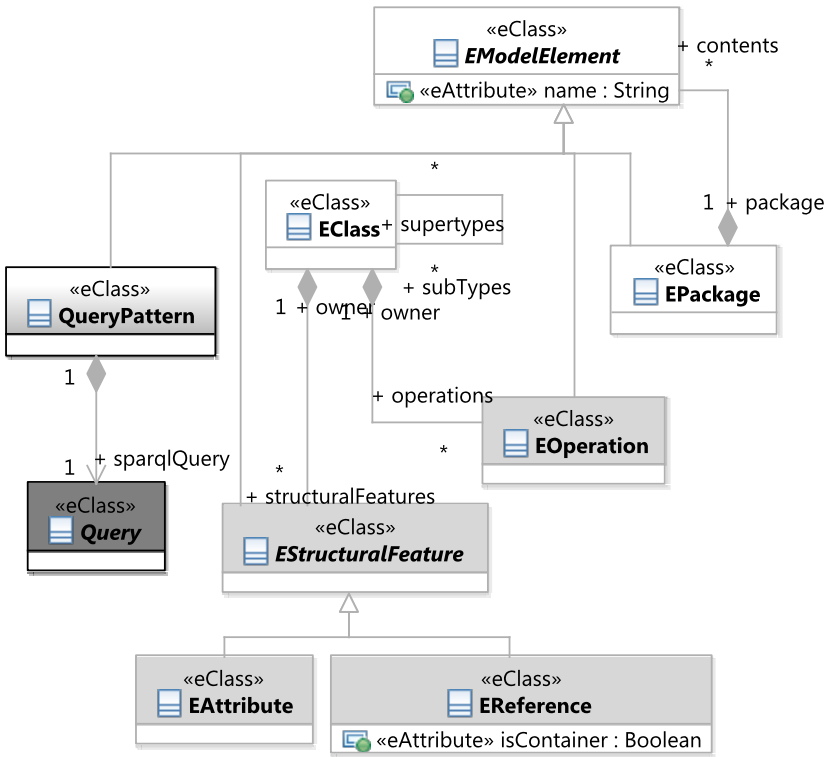



Fig. 12.3. Snippet of the *agogo* Metamodel.

```

5 context Property
  inv inv2: self.ontoElement.SPARQLQuery
    .variables.varname.includes("obj");

```

In Listing 12.1, we exemplify these constraints with two OCL constraints. In the first constraint, we enforce that all variables passed as parameter to an operation are used in the body of the query.

In the second constraint, we enforce that every pattern associated to a property must include the variable `?obj` in the select statement. The predefined variable `?obj` points to the range of a property in the OO representation.

12.3.2 *agogo* Concrete Syntax by Example

In this section, we demonstrate the main components of the *agogo* textual syntax and exemplify them with the running example. In this chapter, we concentrate on how *agogo* supports patterns as first-class citizens, CRUD operations, support for debugging and change management.

To improve user experience, we have based the definition of the *agogo* textual syntax on the SPARQL syntax [87]. For example, for prefix declaration and specification of patterns, we use the SPARQL constructs.

Listing 12.2 presents the basic constructs of the *agogo* syntax like `PACKAGE`, `IMPORT`, `CLASS` and `PROPERTY` in exemplary fashion. We group API specifications into packages, which contain all model elements. The construct `IMPORT` allows for reusing classes and patterns definitions.

The construct `CLASS` specifies the mappings between ontology concepts and OO representations. The reserved word `TO` points to a pattern declaration or directly to a SPARQL query that represents a pattern. The construct `PROPERTY` follows the same rationale. In Listing 12.2, the property `label` is of type `dvl:particular` and points to the pattern `prop_label`, defined in Listing 12.3.

Listing 12.2. An Example of Using *agogo* Basic Constructs.

```

1 PREFIX rdf: <http://www.w3.org/1999/02/22-rdf-syntax-ns#>
PREFIX core: <http://comm/core.owl#>
PREFIX dvl: <http://comm/dolce-very-lite.owl#>
PREFIX edns: <http://comm/extended-dns-very-lite.owl#>
5 PREFIX agogo: <http://uni-koblenz/agogo#>

PACKAGE <http://comm.agogo#> {

    IMPORT <http://comm-lite.agogo#>;

10 CLASS SemanticAnnotation TO core:semantic-annotation{
    PROPERTY label^^dvl:particular TO prop_label;
    ...

```

To detach pattern specifications from class specifications, patterns must be first-class citizens, i.e., their declarations must not be associated to class declarations.

The definition of patterns is an essential point in our approach. To represent a pattern, we need to represent how ontology classes and relations compose this pattern. A user-friendly way of doing it is by using the SPARQL syntax. By using the SPARQL `SELECT` construct, developers describe the pattern structure.

In Listing 12.2, we declare that the OO class `SemanticAnnotation` maps onto the ontology class `core:semantic-annotation` and that the OO class `SemanticAnnotation` has a property of name `label` of type `dvl:particular`. Next, we specify how the values of the property `label` are matched. To have the labels of a semantic annotation, we need to navigate through the structure of the Semantic Annotation Pattern (Figure 12.2).

Listing 12.3 shows the declaration of a query pattern for the property `label`. The pattern is a SPARQL query that describes the structure of the Semantic Annotation Pattern. In the clause `WHERE`, the structure of the pattern is represented. In the clause `WHERE`, we have all classes and relations that need to be created, read, updated and deleted when dealing with the property `label`. The SPARQL query in Listing 12.3 is comparable with the classes and relations composing the pattern in the Figure 12.2.

The definition of patterns includes the usage of two predefined variables: `?subj` and `?obj`. The variable `?subj` identifies the OO class, i.e., in this case, the class

SemanticAnnotation, while the variable ?obj refers to the values or the property label.

For example, this pattern will match the labels associated to the class `semantic-annotation`, e.g., the particular `Carsten` (see Section 12.2). In other words, the domain of the pattern `prop_label` is the ontology class `semantic-annotation` and the range is the class `particular` (see declaration in Listing 12.2).

Listing 12.3. Patterns as First-class Citizens.

```

1 PATTERN prop_label {
  SELECT ?obj
  WHERE
    { ?subj    edns:satisfies ?method .
      ?method  rdf:type        edns:method ;
      edns:defines ?slr ;
      edns:defines ?adr .
      ?slr    rdf:type    core:semantic-label-role .
      ?adr    rdf:type    core:annotated-data-role .
10  ?obj     edns:plays   ?slr .
      ?data   edns:plays   ?adr ;
      rdf:type    core:multimedia-data .
      ?subj    edns:setting-for ?obj ;
      edns:setting-for ?data .
15  }
}
```

Model transformations are responsible for generating automatically CRUD (Create/Read/Update/Delete) operations for each OO property based on the pattern specification. Although CRUD operations are generated automatically, in some cases, developers may want to customize operations. For example, developers may want to customize an insert operation to use existing individuals.

To specify Read operations, we use the standard construct `SELECT` and to specify custom CUD operations, we use SPARQL Update [156] syntax². Listing 12.4 shows the definition of the customized operation `addLabel`. The operation uses an existing instance of the class `method` – `:method1`. For each variable in the `INSERT` clause, one new individual is created in the ontology (except variables `?subj` and `?obj`).

Model transformations take specifications of CUD and generate corresponding programming language code. For example, the usage of variables (Listing 12.4, Lines 4-6) leads to the generation of statements to create a new instance of the class `semantic-annotation-role` (`?slr`).

Listing 12.4. Definition of an Operation Using SPARQL Update Syntax.

```

1 OPERATION addLabel (?obj) {
  INSERT DATA
  {
    :method1    edns:defines   ?slr .
```

² *agogo* does not require a SPARQL Update engine. We use the SPARQL Update syntax only to generate appropriate code.

```

5      ?slr          a core:semantic-label-role .
      ?obj          edns:plays      ?slr .
      ?subj         edns:setting-for ?obj .
    }
    WHERE
10    {
      ?subj         edns:satisfies :method1 .
    }
};

```

Developers may declare patterns anonymously, i.e., developers may associate patterns directly with properties or classes. Listing 12.5 shows the specification of a pattern associated with the property `semantic_annotation`.

Listing 12.5. Mapping a Property onto a Pattern.

```

1 CLASS MultimediaData TO core:multimedia-data {
  PROPERTY semantic_annotation ^^ core:semantic-annotation TO {
    SELECT ?obj
    WHERE
5    {?obj      edns:setting-for ?subj ;
      rdf:type core:semantic-annotation ;
      edns:satisfies ?method .
      ?method  rdf:type          edns:method ;
      edns:defines ?adr .
10   ?adr rdf:type core:annotated-data-role .
      ?subj  edns:plays      ?adr .
    }
  }
};

```

The definition of the SPARQL syntax together with the SPARQL metamodel allows for identifying non well-formed SPARQL statements. Consequently, developers may check for syntax errors at design time. Moreover, by integrating the OWL 2 metamodel into the *agogo* metamodel, *agogo* allows for enforcing the ontology as schema for the specification. If developers mistype names of classes or individuals, the syntax checker identifies that there is no corresponding element in the ontology for that name. This functionally helps to identify typos at design time.

12.3.3 Implementation

agogo consists of a model-driven process composed of model transformations, models and metamodels. Figure 12.4 depicts the *agogo* architecture and the embedded MDA process. Developers use *agogo* textual syntax to specify ontology API specifications. These specifications are injected to platform independent models (PIMs). We use EFMText [157] for defining *agogo* textual syntax and Ecore [22] for defining the *agogo* metamodel.

Model transformations take the PIM and a configuration file as input. The configuration file contains directives for code generation like names of classes and identifiers. Consequently, model transformations produce platform specific models (PSMs) as output, which are then extracted to programming code. To specify model transformations, we use the Atlas Transformation Language (ATL) [35].

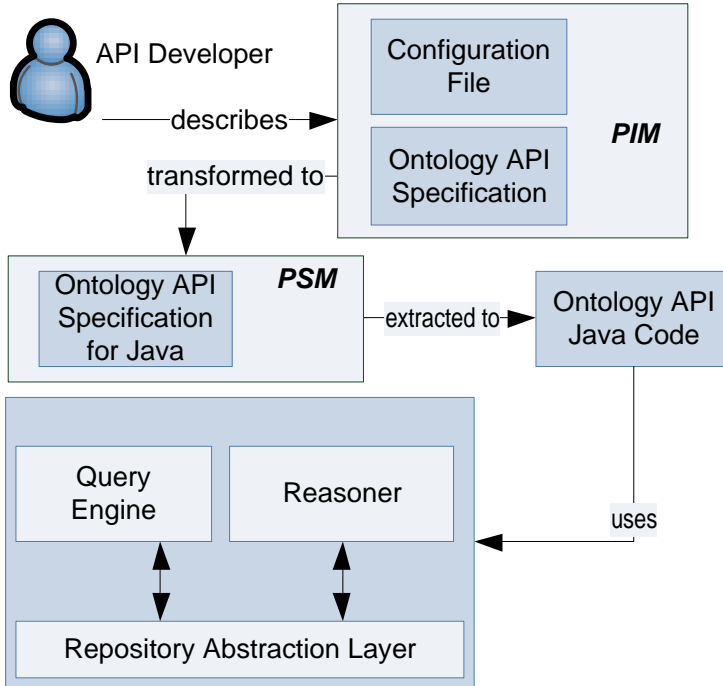


Fig. 12.4. Architecture of the *agogo* Approach.

The usage of a PIM enables developers to detach the ontology API specification from programming code. Consequently, model transformations for different programming platforms may be specified, allowing code generation for multiple platforms.

We have implemented *agogo* as part of the TwoUse toolkit. Figure 12.5 shows a screen shot of the semantic annotation example design using the *agogo* DSL. By referring to non-existing classes or using misspelled reserve words, the editor raises an error.

12.4 Analysis

In this section, we analyze how *agogo*'s functionalities affect the quality of ontology API specifications. In the following, we consider four quality characteristics of ontology API specification according to ISO 9126 [126].

Q1. Usability. One cognitive dimension of usability analysis is the abstraction level [158]. With *agogo*, developers concentrate on constructs related to the problem domain, e.g., `map` and `pattern`, raising the abstraction level.

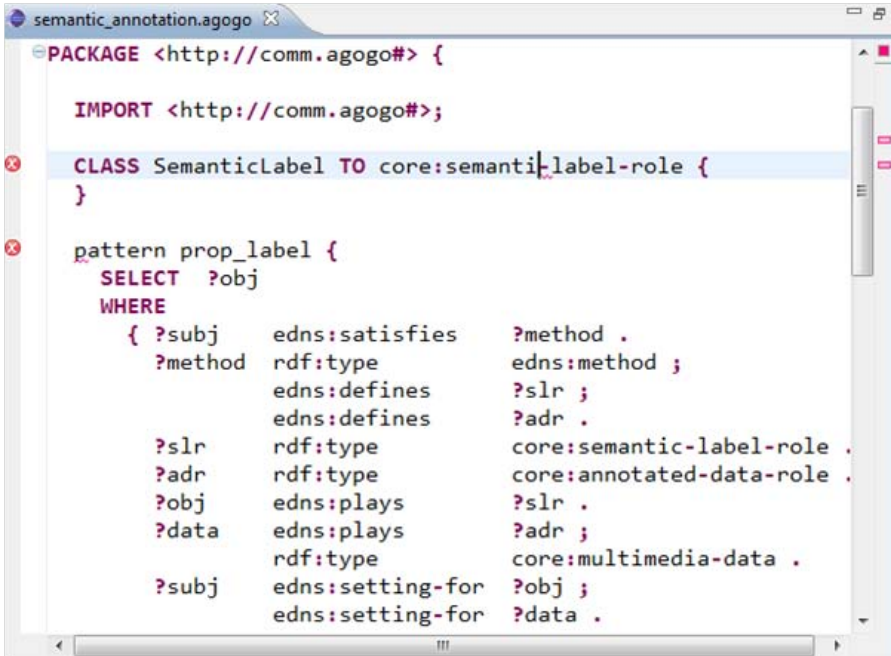


Fig. 12.5. Screenshot of *agogo* Implementation.

Raising the abstraction level influences productivity. To demonstrate this impact, we have conducted an exploratory evaluation of the size of both *agogo* API specifications and Java API specifications of the running example based on the current COMM API.

As metric for size, we consider the number of non-commenting source statements (NCSSs) [159]. Table 12.1 summarizes the comparison of size between *agogo* and the current COMM API in two cases.

In *Case1*, we consider a specification with only two classes: `SemanticAnnotation` and `SemanticLabel`. The current COMM API requires coding 19 Java Classes and more than 400 NCSSs. With *agogo*, developers concentrate on coding 50 NCSSs in two classes.

	<i>agogo</i>		Current COMM API	
	Case1	Case2	Case1	Case2
Packages	1	1	4	15
Classes	2	5	19	101
NCSS	50	70	461	3928

Table 12.1. Comparison of Size between *agogo* and the Current COMM API in Two Cases.

To have an idea of the effort of extending or taking a subset of the COMM API, we consider the addition of the class `MultimediaData` in *Case2*. Although including the class `MultimediaData` implies implementing another OP – the object decomposition –, the size of the ontology API increases drastically to approx. nine times the original size.

Based on this exploratory analysis, even if developers have in *agogo* half of the productivity ratio they have in Java, since the *agogo* specification is smaller than the Java specification, the effort for producing NCSSs in Java is still higher. In other words developers are more productive with *agogo*, with benefits increasing as the API grows due to the possibilities for reuse and improved maintenance.

Q2. Reusability. By defining patterns as first-class citizens, developers may reuse patterns on further mappings. Moreover, complete libraries can be reused to generate derived APIs. For example, API developers may want to have multiple ontology APIs according to the complexity, e.g., COMM lite and COMM full.

Q3. Maintainability. *agogo* defines constructs as metamodel concepts instead of parsing strings of text. Consequently, structured models are easier to maintain than plain text.

When the ontology changes, developers change the ontology API specification and automatically regenerate the ontology API. The syntax checker assists developers with tasks like renaming and raises errors for missing references.

Moreover, constraint validation and syntax checking take place at design time, and not only at runtime as by existing approaches. The developer counts on a syntax checker for pattern specifications.

Q4. Portability. Providing that model transformations are available, it is possible to generate APIs for multiple programming languages. Developers describe ontology APIs once and model transformations use the specification to generate ontology APIs for multiple platforms.

agogo may be seen as an abstraction layer over existing approaches for generating ontology APIs (Section 12.5). As *agogo* does not mandate a specific programming language, developers may specify model transformations for transforming *agogo* API specifications into programming code for the platform of choice.

Nevertheless, developers need to bear in mind the effort of specifying the model transformations. To achieve abstraction from programming code, the model transformations have to handle the gap between the *agogo* API specification and the programming language. The initial effort in developing these model transformations needs to be considered when deciding to provide ontology APIs in a given programming language.

To track how the *agogo* approach addresses the requirements of Section 12.2 and affects ontology API quality characteristics, we present a traceability matrix in Table 12.2. It relates *agogo* requirements, the artifacts that tackle these requirements (metamodel (MM), concrete syntax (CS), and transformations (T)), examples and their relations to quality attributes. As one may notice, by establishing a domain-specific notation for designing ontology APIs, we improve the quality characteristics above, corroborating the literature on domain specific languages [160].

Requirement	Artifact	Example	Quality Attribute
RQ1	MM, CS	Figure 12.3, List. 12.2	Q1
RQ2	MM, CS	List. 12.2, List. 12.3	Q2
RQ3	MM, CS	Figure 12.3, List. 12.1	Q3
RQ4	MM, CS	List. 12.5	Q3
RQ5	T	-	Q4

Table 12.2. Traceability Matrix: Correlating *agogo* Requirements with Quality Attributes.

12.5 Related Work

Ontology Engineers count on a variety of solutions for specifying ontology APIs. In the following, we analyze these approaches according to the abstraction level.

Generic solutions for developing ontology APIs are the Jena API [161] and the Sesame API [162]. However, these approaches are triple-based, i.e., developers have to work with methods such as `getSubject` and `getObject`. Low abstraction level and high complexity are aggravated when dealing with big ontologies.

RDFReactor [163] and [164] are “plain” RDFS - Java/OO mapping approaches. These approaches do not provide support for complex mappings implied by ontology design patterns, i.e., developers have to program one java class for each ontology class. Moreover, when the ontology changes, developers have to manually change ontology API code.

A solution with higher abstraction level is ActiveRDF [165]. ActiveRDF relies on annotations to specify mappings for Ruby programs. As we have seen, annotations are hard to maintain and to debug. Moreover, these applications force API developers to commit to one programming language.

12.6 Conclusion

This chapter presents an application of TwoUse for designing mappings between complex ontology descriptions and object oriented representations – *agogo*. The solution comprises a domain-specific language and model transformations to generate API programming code.

agogo improves productivity on ontology API specification and enables developers with functionalities infeasible until now. Additionally, *agogo* accomplishes improvements on reusability and maintainability.

A Model-Driven Approach for Using Templates in OWL Ontologies

Summary. Integrating model-driven development and semantic web resulted in metamodels and model-driven tools for the semantic web. However, these metamodels or tools do not provide dedicated support for dealing with templates in ontology engineering. Templates are useful for encapsulating knowledge and modeling recurrent sets of axioms. We propose an extension of existing metamodels and tools to support ontology engineers in modeling ontology templates. Our approach allows ontology engineers to keep template specifications as first-class citizens, reducing complexity and increasing reusability in ontology engineering. We demonstrate our approach with templates for ontology design patterns ¹.

13.1 Introduction

As OWL ontologies becomes more complex, approaches that use abstraction to encapsulate complexity emerge. For example, ontology engineers may use macros and annotations to represent ontology design patterns (ODPs) [105], key artifacts for reuse in ontology engineering.

Nevertheless, these approaches do not consider abstraction mechanisms as first-class citizens to encapsulate complexity. For instance, the development of ODPs relies on the usage of macros [167] or annotations [168] to represent the structure of these patterns. Ontology engineers should be able to encapsulate reusable sets of axioms that capture modeling practices in templates. In other words, ontology engineers need declarative specifications of templates and tools to test these specifications and realizations.

The usage of templates is a well-known technique to encapsulate complexity in generative programming, leading OMG to add support for templates in UML [3]. For ontology engineers, the main advantages of using templates are increase in productivity, since ontology engineers rely on well-known reusable pieces to design the ontology; and increase in reliability, since templates comprise reliable sets of axioms developed by domain experts.

¹ This chapter contains work of the paper “A Model-Driven Approach for Supporting Ontology Design Patterns” [166].

Providing declarative specifications of templates and support for template realization enables ontology engineers to handle templates as first-class citizens instead of having template descriptions embedded in ontologies as annotations or using pre-processing macros. Moreover, a dedicated approach for handling templates enables ontology engineers to explore the full expressiveness of template declarations and to analyze template realization scenarios.

Current approaches [167–169] have limited expressiveness and are tool-oriented instead of generic, i.e., they do not allow ontology engineers to choose freely tools and representation notations for templates. Moreover, current ontology metamodels and model-driven tools do not provide those constructs [1, 67, 68].

Templates should be first-class citizens in a higher abstract level than annotations, i.e., in the ontology metamodel. Such an approach allows the following: (1) to extend the usage of templates to other OWL-related languages like SWRL [63], SAIQL [86], or SPARQL-DL [57]; (2) to use different modeling notations, including graphical languages; and (3) to extend the usage of templates beyond individuals, classes and properties to literals and class expressions.

The contribution of this chapter is twofold: (1) we present an approach for modeling ontology templates applicable to different OWL metamodels and extensible to SWRL, SPARQL-DL and SAIQL; (2) we introduce graphical notations containing dedicated constructs to specify templates and to bind them with domain ontologies, enabling ontology engineers to design and test templates as first-class citizens.

We present our approach in this chapter as follows. Section 13.2 gives a scenario motivating template design. We give an example of our approach and describe the graphical notations and the main constructs of our approach in Section 13.3. Section 13.4 presents application scenarios of ontology templates. Section 13.5 presents an analysis of existing approaches and Section 13.6 concludes the chapter.

13.2 Case Study

As running example, we consider an ontology for capturing music records as domain ontology. For this domain ontology, we want to reuse existing knowledge from three resources: ontology design patterns (ODP), SWRL rules and domain closure.

To represent the role of performers, we use the *AgentRole* ontology design pattern [105] from the ontology design pattern collection. The intention of this ODP is to represent agents and their roles. A *Role* is a subclass of the class *Concept*, i.e., a *Role* is a specialization of *Concept*. An *Agent* is a specialization of the class *Object*. The property *hasRole* assigns *Roles* to *Objects*, whereas the inverse property *isRoleOf* assigns *Objects* to *Roles*.

Additionally, we want to propagate the genre of a musical group to a record, i.e., we want to assert that the style of the record is the same as the style of the group. Thus, we reuse a SWRL rule (in this case a description logic rule) to move the property values from one individual to a related individual.

Furthermore, we want to consider the knowledge about genres as complete. In general, OWL models realize the open-world assumption (OWA), i.e., the represented knowledge base is considered as incomplete. However, in certain applications, it is more appropriate to consider a knowledge base as complete. If complete knowledge is assumed, the set of all individuals in the knowledge base must be equivalent to the set of individuals declared.

The following knowledge base (TBox and ABox) describes a simple domain ontology about music records. *Beatles* and *RollingStones* are instances of *Group*. A *Group* has *Performer* as a member. A *Performer* plays a role in a *Group*. The *Group* belongs to a *Genre* and produces *Records*. In our knowledge base, there are only four genres: *Rock*, *Blues*, *Country* and *Samba*.

$$\text{Group} \sqsubseteq \exists \text{hasMember. Performer} \sqcap \exists \text{hasStyle. Genre} \quad \sqcap \exists \text{creatorOf. Record} \quad (13.1)$$

$$\text{Record} \sqsubseteq \exists \text{stylePeriod. Style} \quad (13.2)$$

$$\text{Performer} \sqsubseteq \exists \text{hasRole. Position} \quad (13.3)$$

$$\text{Genre}(\text{Rock}, \text{Blues}, \text{Country}, \text{Samba}), \text{Record}(\text{LetItBleed}) \quad (13.4)$$

$$\text{Group}(\text{RollingStones}), \text{Performer}(\text{Mick}), \text{Position}(\text{Vocalist}) \quad (13.5)$$

$$\text{hasRole}(\text{Mick}, \text{Vocalist}), \text{creatorOf}(\text{RollingStones}, \text{LetItBleed}) \quad (13.6)$$

$$\text{hasMember}(\text{RollingStones}, \text{Mick}) \quad (13.7)$$

$$\text{hasStyle}(\text{RollingStones}, \text{Rock}), \text{Group}(\text{Beatles}) \quad (13.8)$$

$$\text{hasStyle}(\text{Beatles}, \neg \text{Blues}), \text{hasStyle}(\text{Beatles}, \neg \text{Country}) \quad (13.9)$$

$$\text{hasStyle}(\text{Beatles}, \neg \text{Samba}) \quad (13.10)$$

Based on this knowledge base, a user may be looking for all rock bands as described by the following description logic query: $\exists \text{hasStyle.}\{\text{Rock}\}$. If we consider an incomplete knowledge base, the result of this query contains only the individual *RollingStones*. If we assume a complete knowledge base though, the result also includes the group *Beatles*.

There are multiple strategies for closing the domain of a class. In this chapter, we only make the class *Genre* equivalent to the set of existing individuals of the class *Genre*, i.e., *Rock*, *Blues*, *Country*, *Samba*.

Additionally, we want to assert that the genre of a record is the same as the genre of the group:

$$\begin{aligned} \text{Performer}(?a) \wedge \text{Genre}(?s) \wedge \text{Record}(?c) \wedge \text{hasStyle}(?a?s) & \quad (13.11) \\ \wedge \text{creatorOf}(?a, ?c) \rightarrow \text{stylePeriod}(?c, ?s) & \end{aligned}$$

For other ontologies, ontology engineers want to reuse these resources, since these resources represent modeling guidelines and best practices identified by domain experts. Thus, it makes sense to encapsulate these axioms, identifying generic pieces, i.e., to create a *template*. We consider templates as parameterized generic sets of axioms that can be combined with different specifications to produce a variety of artifacts like domain ontologies and queries.

A possibility is to use inheritance to encapsulate reusable axioms and define a super class of *Genre* which is equivalent to a list of existing individuals of this type, and the SWRL rule to propagate the genre to records. However, this super class and rule are reusable for other types of art like poetry, painting, acting and work only for music.

In summary, the usage of a template has the following advantages:

- Templates work as interfaces to encapsulate axioms and expose only the constructs to be used as parameters. Thus, ontology engineers know exactly which concepts and roles are needed for applying the ontology design pattern.
- Ontology engineers can reuse repeatedly templates in other ontologies or in other pieces of the same ontology.
- Ontology engineers bind and unbind templates to exploit different results, e.g., using the open world or closed domain assumption.
- Templates are reliable, since ontology experts derive templates from well-known sets of axioms.
- Templates realize macros when inheritance is not enough.

13.3 Application of the TwoUse Approach

In this section, we describe the application of TwoUse and the main constructs of our metamodel extension and the different notations.

Figure 13.1 depicts the result of applying TwoUse into the running example to add support for templates in OWL ontologies. It uses the UML profile for OWL with package templates. A template `agent-role` represents the agent role ODP. This template has the two parameters – Agent and Role – to be bound in order to adopt this pattern.

A template `closed-domain` defines a class `X` which is equivalent to a list of individuals `{}`. Class `X` and class expression `{}` are template parameters and are bound to the class `Genre` and to the class expression `{Rock Blues Country Samba}` of the ontology music records.

Finally, the third template shows an ontology with a SWRL rule asserting that the genre of an artist is the same as the genre of a record. When realizing these template bindings, the result is set of axioms (1-11) presented in Section 13.2.

13.3.1 Extending the OWL Metamodel with Templates

In this section, we use the TwoUse integration and apply the idea of package templates of UML into OWL and extend it to different OWL-related languages like SWRL [63] and query languages like SPARQL-DL Abstract Syntax [57] and SAIQL [86].

UML [3] allows software developers to design templates of packages and classes. With templates, software developers describe reusable structures with unbound parameters. In order to use these templates, developers have to bind package templates to actual classes or properties to create real structures. By binding template parameters to actual values, developers apply, for example, software design patterns to software model.

While UML package templates allow classes, interfaces and datatypes as parameterable elements, we define ontology templates as templateable elements and allow classes, properties, datatypes, literals and class expressions as parameterable elements.

In the following, we explain each of these metamodel elements as addressed in our solution and present the relationships between them in the Figure 13.2.

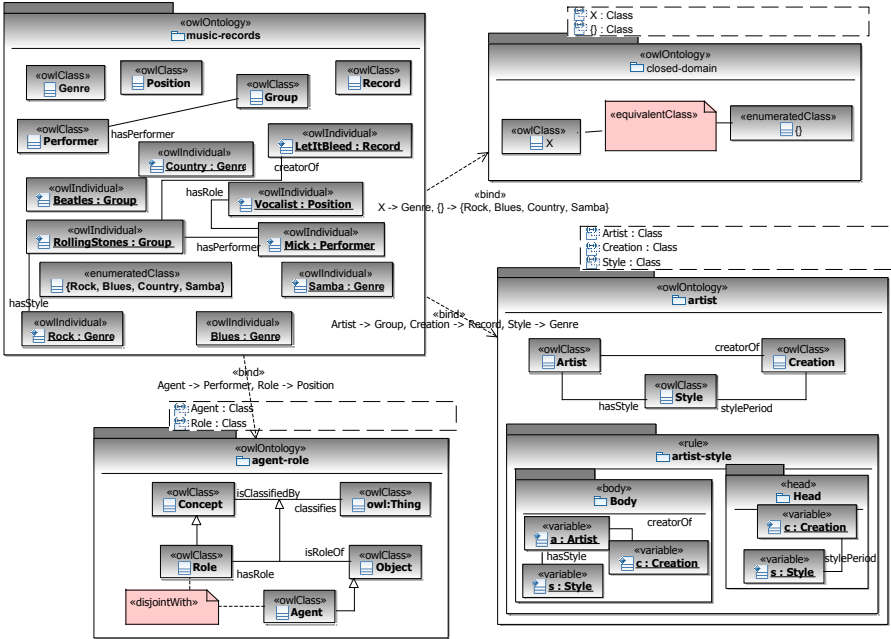


Fig. 13.1. Modeling the Running Example with OMG UML Profile for OWL and UML Profile for SWRL.

- *TemplateableElement*: A templateable element is an element that can optionally be defined as a template. When a template is used, a *template binding* is created describing the replacement of template parameters with actual parameters. Examples of templateable elements are ontologies and queries.
- *Ontology*: The class `Ontology` specializes `TemplateableElement` to specify an ontology template. We apply the same rationale to queries (SPARQL-DL::Query and SAIQL::Query). For example, in Figure 13.1, `closed-domain`, `artist` and `agent-role` are ontology templates.
- *TemplateSignature*: A template signature wraps the set of template parameters for a templateable element. In Figure 13.1, the signature of `closed-domain` is a bundle containing the parameters `X` and `{}`.
- *TemplateParameter*: A template parameter exposes a parameterable element as a template parameter of a template. For example, in the template signature `closed-domain`, `X` and `{}` are representations of the parameterable elements with the same names.
- *ParameterableElement*: A parameterable element is an element that can be exposed as a template parameter for a template or be specified as an actual parameter in a binding of a template. In Figure 13.2, we show only some parameterable elements like `ObjectProperty`, `Class` and `Individual`. Other parameterable elements include `DataProperty`, `ClassExpression` and `Literal`. For Example, in the Figure 13.1, the class `X` and the class expression `{}` are template parameters

while the class `Genre` and the class expression `{Rock Blues Country Samba}` are actual parameters in the template binding.

- *TemplateBinding*: A template binding represents a relationship between a templateable element and template parameters. A template binding specifies the substitutions of actual parameters for the template parameters of the template. In the Figure 13.1, the template binding is represented on top of the ontology music-record ontology by the symbol \rightarrow .
- *TemplateParameterSubstitution*: A template parameter substitution relates the actual parameter(s) to a template parameter as part of a template binding.

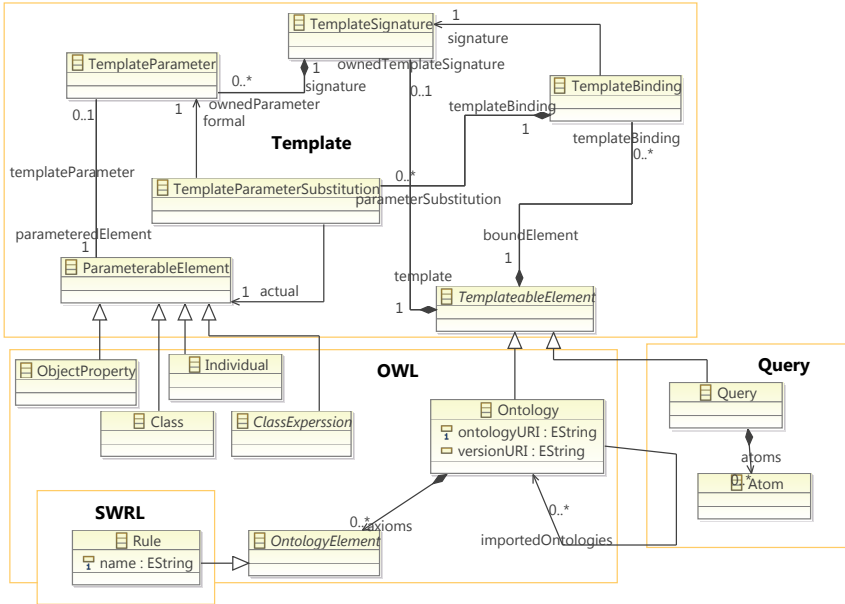


Fig. 13.2. Metamodel for Ontology Templates.

The metamodel for ontology templates depicted in the Figure 13.2 is independent of the ontology metamodel. Although we have considered the OWL 2 metamodel for our implementation, implementers can use any OWL metamodel of choice or other ontology metamodels like RDF. Implementers must then specialize the class `ParameterableElement` with the elements that can be used as parameters, e.g., `RDFClass`.

To write description logic rules, ontology engineers rely on the structure provided by the SWRL metamodel which connects with the OWL metamodel through the class `Rule`.

In order to have query templates, we specialize the class `TemplateableElement` with the class `Query` and the class `ParameterableElement` with variables. Thus, we can specify templates of queries and give variables as parameters. We discuss query templates in Section 13.3.4.

13.3.2 Semantics of Templates

We treat templates as generators, i.e., templates for generating axioms. Thus, reasoners cannot inspect the contents of templates until a transformation *realizes* the template bindings by generating an effective OWL ontology.

One issue when creating templates is to ensure that they are consistent, i.e., that there exists at least one possible valid binding. A mechanism for doing this is to realize the template by automatically generating an ontology and the respective bindings. Thus, the effective OWL ontology can be tested with any standard reasoning for satisfiability and consistency.

The template mechanics do not add to the complexity of the OWL ontology. The complexity of the effective OWL ontology is composed of the complexity of the template and the complexity of the ontology bound to the template. For example, if the template definition has expressivity *SHON* and the ontology bound to the template has expressivity *ALCIQ*, the effective ontology would have expressivity *SHOINQ*.

The outcome of realizing the template bindings is an effective OWL ontology that can be normally checked by reasoners. When realizing template bindings, actual parameters replace template parameters, and the remaining elements are copied. Consequently, the template definition is not part of the effective ontology document (the generated one), but of the implicit ontology document based on our approach. The implicit ontology document contains all axioms defined by the ontology engineers and the template definitions.

The realization of template bindings takes place when transforming the implicit ontology document into an effective ontology document. Figure 13.3 depicts in abstract language the transformation realizing the template bindings of actual parameters of a templateable element (ontology or query) and the template parameters of at least one template.

The recursive algorithm `RecursiveBinding` (Figure 13.3) guarantees that all binds of an eventual template chain take place, since templates can be connected to other templates. The input of the algorithm is a templateable element *E*, e.g., the music record ontology. The second input parameter is the set of all templates that generate the output element (ontology or query). For the templates, the type list is used, since in case of multiple connected templates, the ordering of the binding of the template parameters is significant.

The first case (line 1,2) occurs if no template is given. The second case (line 3,4) is the end of the recursion. In the third case, the binding and generation is realized. The next template (first element of the template list) is bound with the previous (recursive) template bindings and generations, which is templateable element *RecursiveResult*. The binding and generation is in lines 9-14. The template parameters are substituted by the actual parameter of *RecursiveResult* according to the parameter substitution (line 9-11). After the binding, the *RecursiveResult* (ontology or query) is imported or included to the bound template (*Result*). The result, i.e., the effective ontology is a set of axioms, like axioms (1-7) presented in Section 13.2.

```

Algorithm: RecursiveBinding(TemplateableElement E,
List(TemplateableElement) Templates)
Input: A templateable element E (ontology or query) and a set of Template-
ableElements (Templates)
Output: Templateable Element (ontology or query) Result
begin
1: if List == null then
2:   Return E
3: else if List.tail() == null then
4:   Return List.head()
5: else
6:   TemplateableElement RecursiveResult = RecursiveBinding(E, List.tail());
7:   TemplateableElement Result = list.head()
8:   /* Bind the Template (list.head) to RecursiveResult */
9:   for all Param : Result.TemplateBinding do
10:    for all Substitution : Param.parameterSubstitution do
11:      Substitute template parameters in Result by actual parameters of
RecursiveResult
12:    end for
13:  end for
14:  Import RecursiveResult to Result
15:  Return Result
16: end if
end

```

Fig. 13.3. The Template Binding Realization Algorithm.

13.3.3 Notations for Templates in OWL

TwoUse provides an abstraction independent of concrete syntax, i.e., it is possible to provide multiple notations for modeling ontology templates. In the Figure 13.1, we show the running example modeled using the OMG UML Profile for OWL and the UML Profile for SWRL [69]. It relies on package templates natively supported by UML.

Figure 13.4 shows the same example using the OWL 2 graphical notation. We have implemented a graphical notation based on [170] that uses the OWL 2 meta-model as concrete syntax.

A model transformation takes a diagram in one of the supported notations (OWL 2 graphical syntax or UML Profile for OWL/SWRL) and parses it into an implicit ontology document model based on our approach. The realization step takes the output and generates the effective ontology document model, which is later parsed into OWL standard syntax. Figure 13.5 describes these steps.

13.3.4 Query Templates

In this section, we show how ontology engineers can benefit of query templates. Taking the running example, we analyze a simple query about artists belonging to a set of genres.

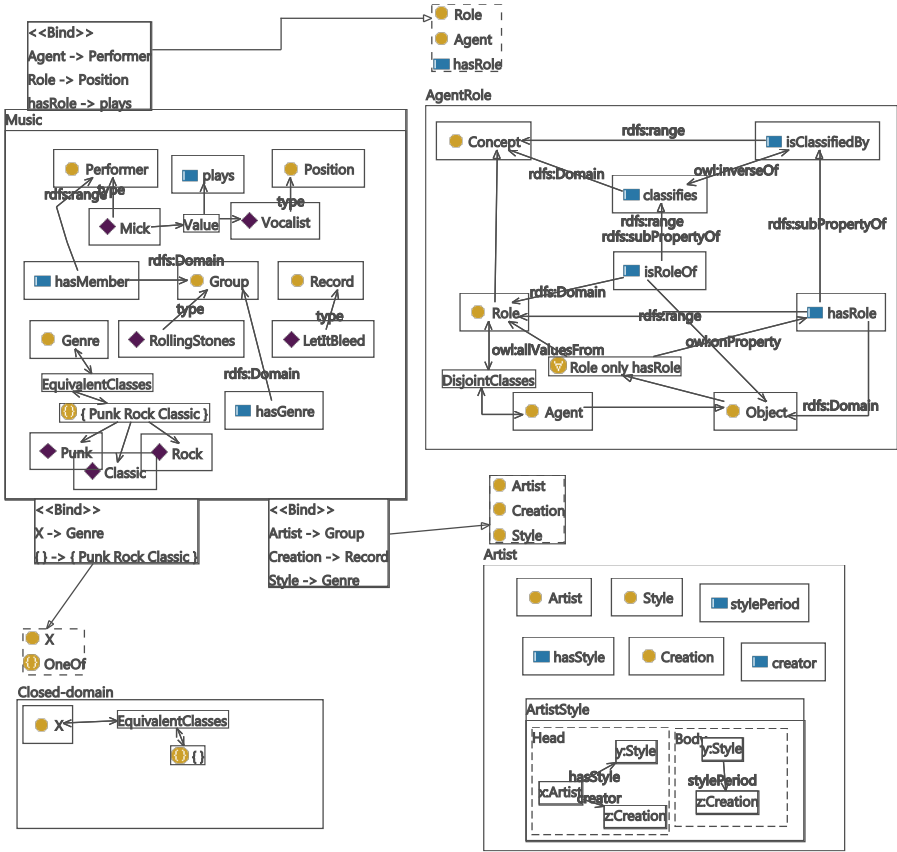


Fig. 13.4. Modeling the Running Example with OWL 2 Graphical Syntax.

Since there exist different types of Artists (musician, painter, actor), it is useful to write the query once and set artist and style as parameters. Listing 13.1 depicts this query using SPARQLAS with templates.

Lines 4-5 of Listing 13.1 show the declaration of two parameters for the query template: ?artist and ?style. Each of these parameters has a specific type associated to it: owl:Class and owl:oneOf (from the default namespace).

Listing 13.1. Artists of a given style.

```

1 Prefix : owl = <http://www.w3.org/2002/07/owl#>
  IRI <http://ArtistsStyle#>
Parameters: ?artist type owl:Class , ?style owl:oneOf
Select ?x
5 Where (
    ?x type (?artist and (hasStyle some ?style))
  )
  
```

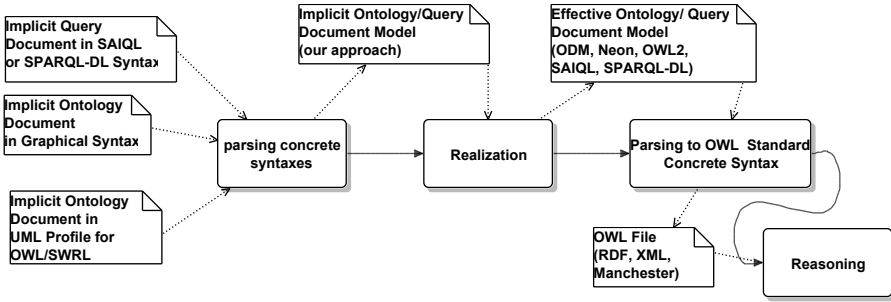


Fig. 13.5. Ontology Development with Templates.

It is possible to reuse this query for search for music groups popular in the USA. Thus, Users need to bind the parameter ?artist to the class Group of ontology Ontology1261152793434 and the parameter ?style to the list {Rock Blues Country}. Listing 13.2 depicts these bindings.

Listing 13.2. Groups and Styles popular in the USA.

```

1 Prefix : = <http://Ontology1261152793434.owl#>
  Prefix : q = <http://ArtistsStyleInUSA#>
  Bind : (q:artist Group) (q:style {Rock Blues Country})

```

Realizing these bindings produce the query presented in Listing 13.3.

Listing 13.3. Effective Query.

```

1 Prefix : = <http://Ontology1261152793434.owl#>
  Select ?x
  Where (
    ?x type (Group and (hasStyle some {Rock Blues Country}))
5 )

```

It is clear here that abstraction plays an important role. Users can reuse knowledge encoded in query templates and combine the results. We apply the same rationale illustrated with SPARQLAS into SAIQL queries [86].

13.4 Analysis

The requirements of using templates in OWL ontologies and SPARQLAS are based in our experience in building core ontologies in the past years [124, 155, 171] and in modeling software artifacts with OWL. In this section, we analyze the application of our approach.

Many versions of ontologies

We can, at the low maintenance cost of a template binding, generate many versions of an ontology. For example, it is possible to have two versions of the artist ontology:

one with the open-world assumption and another with the closed-domain assumption on class `Genre`. In some domains like software engineering, it is usual to assume complete knowledge. We can generate variations of ontologies simply by changing the bindings.

Ontology design patterns

Ontology design patterns (ODPs) are key artifacts for reuse in ontology engineering. Applying templates in ODPs provides demands specialized support for ODP constructs.

We have applied our approach in the development of domain ontologies that use core ontologies: the COMM ontology [124], the Event-Model-F Ontology [155] and the M3O ontology [171]. We are able to model all ODPs of these ontologies (three of COMM, six of Event-Model-F, four of M3O), which pointed at advantages and limitations of our approach.

Introducing templates raises the level of abstraction by allowing ontology engineers to identify the requirements for using a given ODP. For example, in the COMM ontology, the semantic annotation design pattern involves at least 12 concepts and six roles to represent that a multimedia data is annotated with a label. The concepts are grounded by upper level ontologies like DOLCE. In this case, we use templates for creating an *interface* for semantic annotations, i.e., we expose only two classes – label and multimedia-data – as parameters. In comparison with textual templating systems, the main advantage of our approach is portability. Because we handle templates and macros at the platform-independent level, it is possible to develop plug-ins for multiple ontology editors like Protégé or NeOn Toolkit.

13.4.1 Limitations

The usability of the tool is a fact to consider when working with templates. Although we used existing standards for UML profiles for OWL and SWRL created to popularize OWL among software developers, there is limited tool support for those.

Another issue is transparency. Because templates work as generators, their results are not always apparent. Therefore, using templates requires attention about possible unsatisfiability or inconsistency caused by properties or concepts added to the effective ontology.

13.5 Related Work

Relevant works related to this chapter cover mainly the engineering of ontology design patterns from three perspectives: macros, annotations and language dependency.

Multiple works cover the engineering of ontology design patterns [167–169]. Iannone [168] uses a pre-processor language to specify knowledge patterns to allow modeling on a more general pattern level than directly in the OWL ontology. This is a tool-orient application with procedural constructs like ADD and REMOVE. Our approach is declarative and provide support for multiple notations.

Vrandeic analyzes the usage of macros in ontologies in [167]. These macros allow the specification of design patterns for OWL ontologies. In a preprocessing

step, a macro is transformed to a set of axioms in the OWL ontology. However, the authors do not provide a concrete specification language for macros.

In [169] semantic patterns are described in RDF. These semantic patterns are transformed into the target language. The target language is not restricted to a certain language; therefore, the semantic patterns are more general. Although general, this approach does not provide constructs to handle patterns as first-class citizens as our approach does.

Presutti [172] considers the creation of ontology design patterns from existing ontologies. The creation methods that are similar to our approach are the re-engineering from other (conceptual) data models and the extraction method from reference ontologies.

In comparison with related work, we provide an approach that is flexible, since it supports multiple notations (including UML), extensible, as it comprises metamodels for OWL and related languages like SWRL, SPARQL and SAIQL, and platform independent, since templates are tackled at the modeling level and not at the language specific level.

13.6 Conclusion

In this chapter, we present an approach that raises the level of abstraction in the ontology development process by providing platform-independent specifications of templates. The prime benefit of this approach is that it is based on pre-existing metamodels and profiles and therefore, enhances the utility of previous work. Moreover, our approach is generic enough to enable model-driven tools to support metamodels of multiple OWL-related languages.

Conclusion of Part IV

In this part, we investigate the support of generative techniques in ontology engineering services and address the abstraction gap between specification languages and programming languages for ontology engineering tasks (research question IV).

Applying the TwoUse approach raises the abstraction level and consequently, influences productivity. With the TwoUse approach, ontology engineers concentrate on domain problems instead of implementation problems. Moreover, the usage of domain-specific languages enables ontology engineers to handle domain concepts as first-class citizens, improving maintainability (and addressing research questions IV.A and IV.B).

We use the integration between UML class-based modeling and OWL modeling to extend techniques used in model-driven engineering to ontology engineering to declaratively specify artifacts (research question IV.C).

Part V

Finale

Conclusion

This thesis addresses challenges in composing model-driven engineering and OWL technologies. This work comprises multiple facets of this challenge, namely: (1) classification of existing approaches integrating both paradigms; (2) the specification of a coherent framework for integrated usage of both modeling approaches, comprising the benefits of UML class-based modeling and OWL; Applications of the proposed framework to improve (3) model-driven engineering and (4) ontology engineering.

14.1 Thesis Contributions

This work present contributions of different natures. In the following, we summarize the contributions of this thesis.

Classification of Approaches Involving MDE and OWL Ontologies

We outline state-of-the-art research on model-driven engineering and ontology technologies. Then, we describe a domain analysis of both paradigms and identify their commonalities and variations. The contribution is a taxonomy to categorize approaches involving ontology technologies and model-driven engineering.

Integration of UML Class-Based Modeling and OWL Ontologies

We propose an integrated use of both modeling approaches in a coherent framework – TwoUse. We present a framework involving multiple notations for developing integrated models and use a SPARQL-like approach for writing query operations. We validate TwoUse’s applicability with case studies and conclude that TwoUse achieves enhancements of non-functional software requirements like maintainability, reusability and extensibility. The contribution is a method for applying ontology technologies in model-driven engineering and for applying model-driven engineering in ontology engineering.

Ontology-Based Software Design Patterns

We deal with problems in common design patterns and propose ontology-based modeling to overcome drawbacks of the strategy pattern, that are also extensible to the abstract factory pattern and other patterns that deal with variant management. The result is an ontology-based software design pattern to be used with design patterns: the Selector Pattern.

Transformation of Modeling Languages into OWL

In a networked and federated development environment, modeling artifacts need to be linked, adapted and analyzed to meet the information requirements of multiple stakeholders. We present an approach for linking, transforming and querying MOF-compliant modeling languages on the web of data. We use the definition of structural mappings between MOF and OWL and propose the usage of semantic web technologies for linking and querying software models.

Framework for Designing Ontology-Based Domain Specific Languages

In [173], we address major challenges in the field of domain specific languages with OWL ontologies and automated reasoning. We applied the TwoUse approach to enable applications of reasoning to help DSL designers and DSL users through the development and usage of DSLs. DSL designers profit by formal representations, an expressive language and constraint analysis. DSL users profit by progressive verification, debugging support and assisted programming.

A Language for Specifying Ontology Translations

We address the balance between abstraction and expressiveness that causes ontology mapping frameworks to turn to programming languages when built-in constructs fail in specifying complex rules for dataset translation. The contribution is a platform independent language which allows modelers to abstract from implementation details while providing expressiveness to address translation problems at the semantic as well as at the syntactical and lexical layer.

Automatic Generation of Ontology APIs

We address the complex mappings between descriptions of information given by ontologies and object oriented representations of the same information for developing application programming interfaces of ontologies that include instances of ontology design patterns. The contribution is a domain-specific language to tackle these mappings in a platform independent way – *agogo*. Agogo provides improvements on software engineering quality attributes like usability, reusability, maintainability, and portability.

Templates for OWL Ontologies

Metamodels for the semantic web do not provide dedicated support for dealing with templates in ontology engineering. Our contribution is an extension of existing metamodels and tools to support ontology engineers in modeling ontology templates. Our approach allows ontology engineers to keep template specifications as first-class citizens, reducing complexity and increasing reusability in ontology engineering.

The TwoUse Toolkit

The result of implementing the approach is a free open source tool available for use – the TwoUse Toolkit. We address the lack of a framework that allows the integration of multiple W3C and OMG standards at the designing level. The contribution is the implementation of an architecture for designing artifacts using multiple standard languages, turning the focus from code-centric to transformation-centric.

Outlook

This research has been made possible by intensive research work in the last 10 years in the fields of MDE and ontology technologies. There remains a considerable body of research problems that are currently being tackled or that are open for future work.

15.1 Ongoing Research

Integrating Linguistic Metamodeling and Ontological Metamodeling

The integration between OWL modeling and UML class-based modeling covered in this thesis involves the usage of OWL ontologies for linguistic metamodeling [21]. The alignment between UML class-based modeling and OWL in the metamodeling level requires the transformation of elements of the metamodel into OWL classes and properties and the transformation of elements of the model into OWL individuals and assertions.

In this thesis, we do not address the usage of OWL for ontological metamodeling as described by Atkinson and Kühne [21]. An integration of both linguistic metamodeling and ontological metamodeling involves the usage of MOF for metamodeling as a language definition tool (linguistic metamodeling) and the usage of OWL for modeling the relationships between concepts and domain types at the same linguistic modeling level.

Walter investigates such an integration with preliminary results in [174, 175].

Modeling and Querying Patterns for MDE in OWL

In this thesis, we align constructs of UML class-based modeling and OWL modeling and allow the integration of UML class-based modeling and OWL modeling independently of the modeling level, i.e., at the metamodeling level (language bridge) or at the modeling level (model bridge) [131].

Nevertheless, some modeling approaches require a dedicated transformation of model constructs into OWL. For example, the transformation of business process models into OWL handles the mappings of tasks and gateways into OWL

classes [176], whereas the transformation of feature models handles mappings of features and relationships between parent feature and its child features onto OWL classes [90].

Gröner investigates patterns of modeling, querying and reasoning for MDE in OWL in his ongoing research with preliminary results in [177, 178].

Linked Data in Software Engineering

The advent of the Semantic Web has given a new perspective to aspects of software engineering like collaboration, representation and interoperability. For example, existing works present the impact of semantic web technologies like RDF(S) and SPARQL on programmer's assistance [135, 179, 180].

Semantic web technologies and Linked Data principles [129] are paving the way for the Web of Data, a global data space relies on a stack of technologies like URIs, HTTP and RDF to empower information retrieval. In this context, there is a need for investigation on the impact of applying Linked Data principles and techniques for mining, collecting and analyzing software engineering data.

Scalability of ontological reasoning technology

The scalability of ontological reasoning technology has matured over the last 10 years and current implementations point to the assumption that reasoners will scale to higher efficiency by one or several orders of magnitude. Research on techniques for semantic transformations between OWL profiles [181, 182] is in place to benefit from the most appropriate and most efficient technique at each given point in the software development process.

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A

Appendices

A.1 EBNF Definition of the Concrete Syntax for TwoUse

Listing A.1. EBNF Syntax for the concrete syntax

```
1 digit = "0"|"1"|"2"|"3"|"4"|"5"|"6"|"7"|"8"|"9";
  nonnulldigit = "1"|"2"|"3"|"4"|"5"|"6"|"7"|"8"|"9";
  integer = ["-"] nonnulldigit {digit} | "0";
5 nonnegativeinteger = "0" | nonnulldigit {digit};
  name = ( letter | "_" ) { letter | digit | "_" } ;
  letter = "a".."z" | "A".."Z" ;

  EPackage = {EAnnotation} "package" name [EDatatype] ["\"
    EDatatype "\""] "{" {EClass} {EPackage} "}" ;
10 EClass = ["abstract"] ("interface" | "class") ["<" EClass
  {"," EClass} ">"] name ["\" name "\""] ["extends"
  EClass {"," EClass}] {classAnnotation} "{" {EClass |
  EOperation} "}" ;
  EAttribute = {EAnnotation} {"("derived" | "volatile" |
    "unique" | "ordered" | "unsettable" | "changeable" |
    "transient" | "iD")} "attribute" (EClass |
  EGenericType) name ["=" "\" name "\""] ["(" integer
    ".." integer ")"] ";" ;
  EParameter = {EAnnotation} {"("ordered" | "unique")} EClass
    name ["(" integer ".." integer ")"] ;
  EReference =
    {"("containment" | "derived" | "transient" | "volatile" |
      "unique" | "ordered" | "unsettable" | "changeable" |
      "resolveProxies")}
15 {frontReferenceAnnotation} "reference" (EClass |
    EGenericType) name ["=" "\" name "\""] ["(" integer
```

```

    ".." integer ")"] ["opposite" EReference]
    {endReferenceAnnotation} ";" ;
EOperation = {EAnnotation} {"ordered" | "unique"}
    "operation" ("void" | EClass) [{"integer .." integer
    ")"] [{"<" ETypeParameter {"," ETypeParameter} ">"] name
    "(" [EParameter {"," EParameter}] ")" ["throws" EClass
    {"," EClass}] ";" ;
EEnum = {EAnnotation} ["serializable"] "enum" name "\"
    name "\" {" {EEnumLiteral} "}" ;
EEnumLiteral = {EAnnotation} EDataType ":" name "=" "\"
    EEnumLiteral "\" ";" ;
EAnnotation = "(" { "eAnnotations" ":" EAnnotation |
    "source" ":" "\" name "\" | "details" ":" "\" name
    "\" "=" "\" name "\" | "contents" ":" EObject |
    "references" ":" EReference | "eModelElement" ":"
    EObject } ")";
20 EObject = "EObject";
EFactory = "EFactory";
EStringToStringMapEntry = "cardinality" integer;
EDataType = {EAnnotation} ["serializable"] "datatype" name
    "\" name "\"";
ETypeParameter = {EAnnotation} name ;
25 EGenericType = "typed" [{"<" (ETypeParameter | "?"
    "extends" EGenericType | "?" "super" EGenericType) ">"]
    EClass [{"<" (EGenericType | "?" ) {"," (EGenericType |
    "?")} ">"] ;

frontReferenceAnnotation = "(" ("functional" |
    "inversefunctional" | "symmetric" | "asymmetric" |
    "reflexive" | "irreflexive" | "transitive") ")";
endReferenceAnnotation = "(" ("equivalentTo" OPE |
    "subPropertyOf" OPE | "domain" CE | "range" CE |
    "disjointWith" OPE | "inverseOf" name |
    "subPropertyChain" OPE "o" OPE {"o" OPE}) ")";
classAnnotation = "(" (
30     ("equivalentTo" | "disjointWith")
        CE {CE} |
        "subclassOf" CE |
        "disjointUnionOf" CE CE {CE}
    ) ")";

35 CE = "(" ( [{"not"} name |
    "not" CE |
    CE "and" CE { "and" CE } |
    CE "or" CE {"or" CE} |
    OPE ("some" | "only") CE |
40     OPE "Self" |
    OPE ("min" | "max" | "exactly") "cardinality"
        nonnegativeinteger CE )

```

)" ;

OPE = name | "(" "inverse" name ")" ;

A.2 EBNF Grammar of SPARQLAS Functional Syntax

Listing A.2. EBNF Grammar of SPARQLAS Functional Syntax

```

1 cardinality = "a nonempty finite sequence of digits between
  0 and 9";
lexical = "a nonempty finite sequence of alphanumeric
  characters enclosed in a pair of \" (U+22) characters";
variable = "a nonempty finite sequence of alphanumeric
  characters starting with either a ? (U+3F) character or
  a $ (U+24) character";
5 nodeID = "a finite sequence of characters matching the
  BLANK_NODE_LABEL production of SPARQL";
prefix = "a finite sequence of characters matching the
  PNAME_NS production of SPARQL";
fullIRI = "an IRI as defined in RFC3987, enclosed in a pair
  of < (U+3C) and > (U+3E) characters";
abbreviatedIRI = "a finite sequence of characters matching
  the PNAME_LN production of SPARQL";
10 IRI = fullIRI | abbreviatedIRI;

OntologyDocument = [ QueryIRI ] { Import } {
  PrefixDefinition } Query;
QueryIRI = "IRI" "(" fullIRI ")";
Import = "Import" "(" fullIRI ")";
15 PrefixDefinition = "Namespace" "(" [ prefix ] "=" fullIRI
  ")";

Query = SelectQuery | ConstructQuery | AskQuery |
  DescribeQuery;

SelectQuery = "Select" [ variable { variable } | "*" ]
  "Where" "(" { Atom } ")";
20 ConstructQuery = "Construct" "(" { ConstructAtom } ")"
  "Where" "(" { WhereAtom } ")";
AskQuery = "Ask" "Where" "(" { Atom } ")";
DescribeQuery = "Describe" DescribeIRI | "Describe" "Where"
  "(" { Atom } ")";

ConstructAtom = Atom;

```

```

25 WhereAtom = Atom;
   DescribeIRI = fullIRI;

   ClassVariable = variable;
   ObjectPropertyVariable = variable;
30 DataPropertyVariable = variable;
   IndividualVariable = variable;
   LiteralVariable = variable;

   Class = IRI;
35 Datatype = IRI;
   ObjectProperty = IRI;
   DataProperty = IRI;
   NamedIndividual = IRI;
   ConstrainingFacet = IRI;
40 AnonymousIndividual = nodeID;
   NamedLiteral = lexical "^^" Datatype;

   Atom = Assertion | ClassAtom | ObjectPropertyAtom |
         DataPropertyAtom | HasKey | Declaration;

45 Assertion = ClassAssertion | DirectType |
               ObjectPropertyAssertion | DataPropertyAssertion |
               NegativeObjectPropertyAssertion |
               NegativeDataPropertyAssertion | SameIndividual |
               DifferentIndividuals;

   ClassAssertion = ( "ClassAssertion" | "Type" ) "(
       Individual ClassExpression )";
   DirectType = "DirectType" "( Individual ClassExpression
       )";
   ObjectPropertyAssertion = ( "ObjectPropertyAssertion" |
       "PropertyValue" ) "( SourceIndividual
       ObjectPropertyExpression TargetIndividual )";
50 DataPropertyAssertion = ( "DataPropertyAssertion" |
       "PropertyValue" ) "( SourceIndividual
       DataPropertyExpression TargetValue )";
   NegativeObjectPropertyAssertion = (
       "NegativeObjectPropertyAssertion" |
       "NegativePropertyValue" ) "( SourceIndividual
       ObjectPropertyExpression TargetIndividual )";
   NegativeDataPropertyAssertion = (
       "NegativeDataPropertyAssertion" |
       "NegativePropertyValue" ) "( SourceIndividual
       DataPropertyExpression TargetValue )";
   SameIndividual = ( "SameIndividual" | "SameAs" ) "(
       Individual Individual { Individual } )";

```



```

DifferentIndividuals = ( "DifferentIndividuals" |
    "DifferentFrom" ) "(" Individual Individual {
    Individual } ")";
55 SourceIndividual = Individual;
    TargetIndividual = Individual;
    Individual = NamedIndividual | IndividualVariable |
        AnonymousIndividual;
    TargetValue = Literal;
    Literal = LiteralVariable | NamedLiteral;
60
ClassAtom = SubClassOf | DirectSubClassOf |
    StrictSubClassOf | EquivalentClasses | DisjointClasses
    | DisjointUnion;

SubClassOf = "SubClassOf" "(" SubClassExpression
    SuperClassExpression ")";
DirectSubClassOf = "DirectSubClassOf" "("
    SubClassExpression SuperClassExpression ")";
65 StrictSubClassOf = "StrictSubClassOf" "("
    SubClassExpression SuperClassExpression ")";
EquivalentClasses = ( "EquivalentClasses" | "EquivalentTo"
    ) "(" ClassExpression ClassExpression { ClassExpression
    } ")";
DisjointClasses = ( "DisjointClasses" | "DisjointWith" )
    "(" ClassExpression ClassExpression { ClassExpression }
    ")";
DisjointUnion = "DisjointUnion" "(" DisjointClass
    DisjointClassExpression DisjointClassExpression {
    DisjointClassExpression } ")";
SubClassExpression = ClassExpression;
70 SuperClassExpression = ClassExpression;
    DisjointClass = ClassVariable | Class;
    DisjointClassExpression = ClassExpression;

ClassExpression = ClassVariable | Class | ObjectUnionOf |
    ObjectComplementOf | ObjectOneOf | ObjectIntersectionOf
    | ObjectAllValuesFrom | ObjectSomeValuesFrom |
    ObjectHasValue | ObjectMinCardinality |
    ObjectMaxCardinality | ObjectExactCardinality |
    DataAllValuesFrom | DataSomeValuesFrom | DataHasValue |
    DataMinCardinality | DataMaxCardinality |
    DataExactCardinality;
75
ObjectUnionOf = ( "ObjectUnionOf" | "Or" ) "("
    ClassExpression ClassExpression { ClassExpression } ")";
ObjectComplementOf = ( "ObjectComplementOf" | "Not" ) "("
    ClassExpression ")";
ObjectOneOf = ( "ObjectOneOf" | "One" ) "(" Individual {
    Individual } ")";

```

```

ObjectIntersectionOf = ( "ObjectIntersectionOf" | "And" )
  "( " ClassExpression ClassExpression { ClassExpression
    } )";
80 ObjectAllValuesFrom = ( "ObjectAllValuesFrom" | "All" ) "( "
  ObjectPropertyExpression ClassExpression )";
ObjectSomeValuesFrom = ( "ObjectSomeValuesFrom" | "Some" )
  "( " ObjectPropertyExpression ClassExpression )";
ObjectHasValue = ( "ObjectHasValue" | "Has" ) "( "
  ObjectPropertyExpression Individual )";
ObjectMinCardinality = ( "ObjectMinCardinality" | "Min" )
  "( " cardinality ObjectPropertyExpression [
    ClassExpression ] )";
ObjectMaxCardinality = ( "ObjectMaxCardinality" | "Max" )
  "( " cardinality ObjectPropertyExpression [
    ClassExpression ] )";
85 ObjectExactCardinality = ( "ObjectExactCardinality" |
  "Exact" ) "( " cardinality ObjectPropertyExpression [
    ClassExpression ] )";
DataAllValuesFrom = ( "DataAllValuesFrom" | "All" ) "( "
  DataPropertyExpression DataRange )";
DataSomeValuesFrom = ( "DataSomeValuesFrom" | "Some" ) "( "
  DataPropertyExpression DataRange )";
DataHasValue = ( "DataHasValue" | "Has" ) "( "
  DataPropertyExpression Literal )";
DataMinCardinality = ( "DataMinCardinality" | "Min" ) "( "
  cardinality DataPropertyExpression [ DataRange ] )";
90 DataMaxCardinality = ( "DataMaxCardinality" | "Max" ) "( "
  cardinality DataPropertyExpression [ DataRange ] )";
DataExactCardinality = ( "DataExactCardinality" | "Exact" )
  "( " cardinality DataPropertyExpression [ DataRange ]
    )";

DataRange = Datatype | DataUnionOf | DataComplementOf |
  DataOneOf | DataIntersectionOf | DatatypeRestriction;
95 DataUnionOf = ( "DataUnionOf" | "Or" ) "( " DataRange
  DataRange { DataRange } )";
DataComplementOf = ( "DataComplementOf" | "Not" ) "( "
  DataRange )";
DataOneOf = ( "DataOneOf" | "One" ) "( " Literal { Literal }
  )";
DataIntersectionOf = ( "DataIntersectionOf" | "And" ) "( "
  DataRange DataRange { DataRange } )";
DatatypeRestriction = "DatatypeRestriction" "( " Datatype
  FacetRestriction { FacetRestriction } )";
100 FacetRestriction = ConstrainingFacet Literal;

ObjectPropertyAtom = SubObjectPropertyOf |
  EquivalentObjectProperties | DisjointObjectProperties |

```

```

ObjectPropertyDomain | ObjectPropertyRange |
InverseObjectPropertyAtom | FunctionalObjectProperty |
InverseFunctionalObjectProperty |
ReflexiveObjectProperty | IrreflexiveObjectProperty |
SymmetricObjectProperty | AsymmetricObjectProperty |
TransitiveObjectProperty ;

```

```

SubObjectPropertyOf = ( "SubObjectPropertyOf" |
  "SubPropertyOf" ) "(" SubObjectPropertyExpression
  SuperObjectPropertyExpression ")";
105 EquivalentObjectProperties = ( "EquivalentObjectProperties"
  | "EquivalentProperty" ) "(" ObjectPropertyExpression
  ObjectPropertyExpression { ObjectPropertyExpression }
  ")";
DisjointObjectProperties = ( "DisjointObjectProperties" |
  "DisjointProperty" ) "(" ObjectPropertyExpression
  ObjectPropertyExpression { ObjectPropertyExpression }
  ")";
ObjectPropertyDomain = ( "ObjectPropertyDomain" | "Domain"
  ) "(" ObjectPropertyExpression ClassExpression ")";
ObjectPropertyRange = ( "ObjectPropertyRange" | "Range" )
  "(" ObjectPropertyExpression ClassExpression ")";
InverseObjectPropertyAtom = ( "InverseObjectProperties" |
  "InverseOf" ) "(" ObjectPropertyExpression
  ObjectPropertyExpression ")";
110 FunctionalObjectProperty = "FunctionalObjectProperty" "("
  ObjectPropertyExpression ")";
InverseFunctionalObjectProperty = (
  "InverseFunctionalObjectProperty" | "InverseFunctional"
  ) "(" ObjectPropertyExpression ")";
ReflexiveObjectProperty = ( "ReflexiveObjectProperty" |
  "Reflexive" ) "(" ObjectPropertyExpression ")";
IrreflexiveObjectProperty = ( "IrreflexiveObjectProperty" |
  "Irreflexive" ) "(" ObjectPropertyExpression ")";
SymmetricObjectProperty = ( "SymmetricObjectProperty" |
  "Symmetric" ) "(" ObjectPropertyExpression ")";
115 AsymmetricObjectProperty = ( "AsymmetricObjectProperty" |
  "Asymmetric" ) "(" ObjectPropertyExpression ")";
TransitiveObjectProperty = ( "TransitiveObjectProperty" |
  "Transitive" ) "(" ObjectPropertyExpression ")";
SubObjectPropertyExpression = ObjectPropertyExpression |
  ObjectPropertyChain ;
SuperObjectPropertyExpression = ObjectPropertyExpression ;
ObjectPropertyChain = ( "ObjectPropertyChain" | "Chain" )
  "(" ObjectPropertyExpression ObjectPropertyExpression {
  ObjectPropertyExpression } ")";
120 ObjectPropertyExpression = ObjectPropertyVariable |
  ObjectProperty | InverseObjectProperty ;

```

```

InverseObjectProperty = ( "ObjectInverseOf" | "InverseOf" )
    "( ObjectPropertyExpression )";

125 DataPropertyAtom = SubDataPropertyOf |
    EquivalentDataProperties | DisjointDataProperties |
    DataPropertyDomain | DataPropertyRange |
    FunctionalDataProperty;

SubDataPropertyOf = ( "SubDataPropertyOf" | "SubPropertyOf"
    ) "( SubDataPropertyExpression
    SuperDataPropertyExpression )";
EquivalentDataProperties = ( "EquivalentDataProperties" |
    "EquivalentProperty" ) "( DataPropertyExpression
    DataPropertyExpression { DataPropertyExpression } )";
DisjointDataProperties = ( "DisjointDataProperties" |
    "DisjointProperty" ) "( DataPropertyExpression
    DataPropertyExpression { DataPropertyExpression } )";
130 DataPropertyDomain = ( "DataPropertyDomain" | "Domain" )
    "( DataPropertyExpression ClassExpression )";
DataPropertyRange = ( "DataPropertyRange" | "Range" ) "(
    DataPropertyExpression DataRange )";
FunctionalDataProperty = "FunctionalDataProperty" "(
    DataPropertyExpression )";
SubDataPropertyExpression = DataPropertyExpression;
SuperDataPropertyExpression = DataPropertyExpression;

135 DataPropertyExpression = DataPropertyVariable |
    DataProperty;

HasKey = "HasKey" "( ClassExpression "( {
    ObjectPropertyExpression } )" "( {
    DataPropertyExpression } )" )";

140 Declaration = ObjectPropertyDeclaration |
    DataPropertyDeclaration | NamedIndividualDeclaration |
    ClassDeclaration;

ObjectPropertyDeclaration = "ObjectProperty" "(
    ObjectProperty | ObjectPropertyVariable )";
DataPropertyDeclaration = "DataProperty" "( DataProperty |
    DataPropertyVariable )";
NamedIndividualDeclaration = "NamedIndividual" "(
    NamedIndividual | IndividualVariable )";
145 ClassDeclaration = "Class" "( Class | ClassVariable )";

```

A.3 EBNF Grammar of SPARQLAS Manchester Syntax

Listing A.3. EBNF Grammar of SPARQLAS Manchester Syntax

```

1 cardinality = "a nonempty finite sequence of digits between
  0 and 9";
lexical = "a nonempty finite sequence of alphanumeric
  characters enclosed in a pair of \" (U+22) characters";
variable = "a nonempty finite sequence of alphanumeric
  characters starting with either a ? (U+3F) character or
  a $ (U+24) character";
5 nodeID = "a finite sequence of characters matching the
  BLANK_NODE_LABEL production of SPARQL";
prefix = "a finite sequence of characters matching the
  PNAME_NS production of SPARQL";
fullIRI = "an IRI as defined in RFC3987, enclosed in a pair
  of < (U+3C) and > (U+3E) characters";
abbreviatedIRI = "a finite sequence of characters matching
  the PNAME_LN production of SPARQL";

10 IRI = fullIRI | abbreviatedIRI;

OntologyDocument = [ QueryIRI ] { Import } {
  PrefixDefinition } Query;
QueryIRI = "IRI" "(" fullIRI ")";
Import = "Import:" fullIRI;
15 PrefixDefinition = "Namespace:" [ prefix ] fullIRI;

Query = SelectQuery | ConstructQuery | AskQuery |
  DescribeQuery;

SelectQuery = "Select" [ variable { variable } | "*" ]
  "Where:" { Atom };
20 ConstructQuery = "Construct:" { ConstructAtom } "Where:" {
  WhereAtom };
AskQuery = "Ask" "Where:" { Atom };
DescribeQuery = "Describe" DescribeIRI | "Describe"
  "Where:" { Atom };

ConstructAtom = Atom;
25 WhereAtom = Atom;
DescribeIRI = fullIRI;

ClassVariable = variable;
ObjectPropertyVariable = variable;
30 DataPropertyVariable = variable;
IndividualVariable = variable;
LiteralVariable = variable;

```

```

Class = IRI;
35 Datatype = IRI;
ObjectProperty = IRI;
DataProperty = IRI;
NamedIndividual = IRI;
ConstrainingFacet = IRI;
40 AnonymousIndividual = nodeID;
NamedLiteral = lexical "^^" Datatype;

Atom = Assertion | ClassAtom | ObjectPropertyAtom |
      DataPropertyAtom | HasKey | Declaration;

45 Assertion = ClassAssertion | DirectType |
              ObjectPropertyAssertion | DataPropertyAssertion |
              NegativeObjectPropertyAssertion |
              NegativeDataPropertyAssertion | SameIndividual |
              DifferentIndividuals;

ClassAssertion = Individual "type" ClassExpression;
DirectType = Individual "directType" ClassExpression;
ObjectPropertyAssertion = SourceIndividual
                        ObjectPropertyExpression TargetIndividual;
50 DataPropertyAssertion = SourceIndividual
                        DataPropertyExpression TargetValue;
NegativeObjectPropertyAssertion = SourceIndividual "not"
                                ObjectPropertyExpression TargetIndividual;
NegativeDataPropertyAssertion = SourceIndividual "not"
                                DataPropertyExpression TargetValue;
SameIndividual = Individual "sameAs" Individual |
                "SameIndividuals" "(" Individual Individual {
                Individual } ")";
DifferentIndividuals = Individual "differentFrom"
                       Individual | "DifferentIndividuals" "(" Individual
                       Individual { Individual } ")";
55 SourceIndividual = Individual;
TargetIndividual = Individual;
Individual = NamedIndividual | IndividualVariable |
            AnonymousIndividual;
TargetValue = Literal;
Literal = LiteralVariable | NamedLiteral;
60 ClassAtom = SubClassOf | DirectSubClassOf |
              StrictSubClassOf | EquivalentClasses | DisjointClasses
              | DisjointUnion;

SubClassOf = SubClassExpression "subClassOf"
            SuperClassExpression;

```

```

DirectSubClassOf = SubClassExpression "directSubClassOf"
  SuperClassExpression ;
65 StrictSubClassOf = SubClassExpression "strictSubClassOf"
  SuperClassExpression ;
EquivalentClasses = "EquivalentClasses:" ClassExpression
  "," ClassExpression { "," ClassExpression } |
  ClassExpression "equivalentClasses" ClassExpression {
  "," ClassExpression } | ClassExpression "equivalentTo"
  ClassExpression { "," ClassExpression };
DisjointClasses = "DisjointClasses:" ClassExpression ","
  ClassExpression { "," ClassExpression } |
  ClassExpression "disjointClasses" ClassExpression { ","
  ClassExpression } | ClassExpression "disjointWith"
  ClassExpression { "," ClassExpression };
DisjointUnion = DisjointClass "DisjointUnionOf:"
  DisjointClassExpression DisjointClassExpression {
  DisjointClassExpression };
SubClassExpression = ClassExpression ;
70 SuperClassExpression = ClassExpression ;
DisjointClass = ClassVariable | Class ;
DisjointClassExpression = ClassExpression ;

ClassExpression = ClassVariable | Class | ObjectUnionOf |
  ObjectComplementOf | ObjectOneOf | ObjectIntersectionOf
  | ObjectAllValuesFrom | ObjectSomeValuesFrom |
  ObjectHasValue | ObjectMinCardinality |
  ObjectMaxCardinality | ObjectExactCardinality |
  DataAllValuesFrom | DataSomeValuesFrom | DataHasValue |
  DataMinCardinality | DataMaxCardinality |
  DataExactCardinality ;
75 ObjectUnionOf = "(" ClassExpression "or" ClassExpression {
  "or" ClassExpression } ")";
ObjectComplementOf = "not" ClassExpression ;
ObjectOneOf = "{" Individual { "," Individual } "}";
ObjectIntersectionOf = "(" ClassExpression "and"
  ClassExpression { "and" ClassExpression } ")";
80 ObjectAllValuesFrom = ObjectPropertyExpression "only"
  ClassExpression | "(" ObjectPropertyExpression "only"
  ClassExpression ")";
ObjectSomeValuesFrom = ObjectPropertyExpression "some"
  ClassExpression | "(" ObjectPropertyExpression "some"
  ClassExpression ")";
ObjectHasValue = ObjectPropertyExpression "value"
  Individual | "(" ObjectPropertyExpression "vaule"
  Individual ")";
ObjectMinCardinality = ObjectPropertyExpression "min"
  cardinality [ ClassExpression ] | "("

```

```

ObjectPropertyExpression "min" cardinality [
  ClassExpression ] ");
ObjectMaxCardinality = ObjectPropertyExpression "max"
  cardinality [ ClassExpression ] | "("
  ObjectPropertyExpression "max" cardinality [
  ClassExpression ] ");
85 ObjectExactCardinality = ObjectPropertyExpression "exactly"
  cardinality [ ClassExpression ] | "("
  ObjectPropertyExpression "exactly" cardinality [
  ClassExpression ] ");
DataAllValuesFrom = DataPropertyExpression "only" DataRange
  | "(" DataPropertyExpression "only" DataRange ");
DataSomeValuesFrom = DataPropertyExpression "some"
  DataRange | "(" DataPropertyExpression "some" DataRange
  ");
DataHasValue = DataPropertyExpression "value" Literal | "("
  DataPropertyExpression "value" Literal ");
DataMinCardinality = cardinality "min"
  DataPropertyExpression [ DataRange ] | "(" cardinality
  "min" DataPropertyExpression [ DataRange ] ");
90 DataMaxCardinality = cardinality "max"
  DataPropertyExpression [ DataRange ] | "(" cardinality
  "max" DataPropertyExpression [ DataRange ] ");
DataExactCardinality = cardinality "exactly"
  DataPropertyExpression [ DataRange ] | "(" cardinality
  "exactly" DataPropertyExpression [ DataRange ] ");

DataRange = Datatype | DataUnionOf | DataComplementOf |
  DataOneOf | DataIntersectionOf | DatatypeRestriction;

95 DataUnionOf = "(" DataRange "or" DataRange { "or" DataRange
  } ")";
DataComplementOf = "DataComplementOf" DataRange | "not"
  DataRange;
DataOneOf = "{" Literal { Literal } "}";
DataIntersectionOf = "(" DataRange "and" DataRange { "and"
  DataRange } ")";
DatatypeRestriction = Datatype "[" FacetRestriction {
  FacetRestriction } "]" ;
100 FacetRestriction = ConstrainingFacet Literal;

ObjectPropertyAtom = SubObjectPropertyOf |
  EquivalentObjectProperties | DisjointObjectProperties |
  ObjectPropertyDomain | ObjectPropertyRange |
  InverseObjectPropertyAtom | FunctionalObjectProperty |
  InverseFunctionalObjectProperty |
  ReflexiveObjectProperty | IrreflexiveObjectProperty |
  SymmetricObjectProperty | AsymmetricObjectProperty |
  TransitiveObjectProperty;

```



```

SubObjectPropertyOf = SubObjectPropertyExpression (
    "subObjectPropertyOf" | "subPropertyOf" )
    SuperObjectPropertyExpression ;
105 EquivalentObjectProperties = (
    "EquivalentObjectProperties:" | "EquivalentProperties:"
    ) ObjectPropertyExpression "," ObjectPropertyExpression
    { "," ObjectPropertyExpression } |
    ObjectPropertyExpression ( "equivalentObjectProperties"
    | "equivalentTo" ) ObjectPropertyExpression { ","
    ObjectPropertyExpression };
DisjointObjectProperties = ( "DisjointObjectProperties:" |
    "DisjointProperties:" ) ObjectPropertyExpression ","
    ObjectPropertyExpression { "," ObjectPropertyExpression
    } | ObjectPropertyExpression (
    "disjointObjectProperties" | "disjointWith" )
    ObjectPropertyExpression { "," ObjectPropertyExpression
    };
ObjectPropertyDomain = ObjectPropertyExpression (
    "objectPropertyDomain" | "domain" ) ClassExpression ;
ObjectPropertyRange = ObjectPropertyExpression (
    "objectPropertyRange" | "range" ) ClassExpression ;
InverseObjectPropertyAtom = ObjectPropertyExpression (
    "inverseObjectProperties" | "inverseOf" )
    ObjectPropertyExpression ;
110 FunctionalObjectProperty = ( "FunctionalObjectProperty" |
    "Functional" ) ObjectPropertyExpression ;
InverseFunctionalObjectProperty = (
    "InverseFunctionalObjectProperty" | "InverseFunctional"
    ) ObjectPropertyExpression ;
ReflexiveObjectProperty = ( "ReflexiveObjectProperty" |
    "Reflexive" ) ObjectPropertyExpression ;
IrreflexiveObjectProperty = ( "IrreflexiveObjectProperty" |
    "Irreflexive" ) ObjectPropertyExpression ;
SymmetricObjectProperty = ( "SymmetricObjectProperty" |
    "Symmetric" ) ObjectPropertyExpression ;
115 AsymmetricObjectProperty = ( "AsymmetricObjectProperty" |
    "Asymmetric" ) ObjectPropertyExpression ;
TransitiveObjectProperty = ( "TransitiveObjectProperty" |
    "Transitive" ) ObjectPropertyExpression ;
SubObjectPropertyExpression = ObjectPropertyExpression |
    ObjectPropertyChain ;
SuperObjectPropertyExpression = ObjectPropertyExpression ;
ObjectPropertyChain = "SubPropertyChain:"
    ObjectPropertyExpression "o" ObjectPropertyExpression {
    "o" ObjectPropertyExpression };
120 ObjectPropertyExpression = ObjectPropertyVariable |
    ObjectProperty | InverseObjectProperty ;

```

```

InverseObjectProperty = ( "ObjectInverseOf" | "inverseOf" )
    ObjectPropertyExpression;

125 DataPropertyAtom = SubDataPropertyOf |
    EquivalentDataProperties | DisjointDataProperties |
    DataPropertyDomain | DataPropertyRange |
    FunctionalDataProperty;

SubDataPropertyOf = SubDataPropertyExpression (
    "subDataPropertyOf" | "subPropertyOf" )
    SuperDataPropertyExpression;
EquivalentDataProperties = ( "EquivalentDataProperties:" |
    "EquivalentProperties:" ) ObjectPropertyExpression ","
    ObjectPropertyExpression { "," ObjectPropertyExpression
    } | ObjectPropertyExpression (
    "equivalentDataProperties" | "equivalentTo" )
    ObjectPropertyExpression { "," ObjectPropertyExpression
    };
DisjointDataProperties = ( "DisjointDataProperties:" |
    "DisjointProperties:" ) ObjectPropertyExpression ","
    ObjectPropertyExpression { "," ObjectPropertyExpression
    } | ObjectPropertyExpression ( "disjointDataProperties"
    | "disjointWith" ) ObjectPropertyExpression { ","
    ObjectPropertyExpression };
130 DataPropertyDomain = DataPropertyExpression (
    "dataPropertyDomain" | "domain" ) ClassExpression;
DataPropertyRange = DataPropertyExpression (
    "dataPropertyRange:" | "range" ) DataRange;
FunctionalDataProperty = ( "FunctionalDataProperty" |
    "Functional" ) DataPropertyExpression;
SubDataPropertyExpression = DataPropertyExpression;
SuperDataPropertyExpression = DataPropertyExpression;

135 DataPropertyExpression = DataPropertyVariable |
    DataProperty;

HasKey = "HasKey" "(" ClassExpression "(" {
    ObjectPropertyExpression } ")" "(" {
    DataPropertyExpression } ")" "(" )";

140 Declaration = ObjectPropertyDeclaration |
    DataPropertyDeclaration | NamedIndividualDeclaration |
    ClassDeclaration;

ObjectPropertyDeclaration = "ObjectProperty:" "("
    ObjectProperty | ObjectPropertyVariable ")";
DataPropertyDeclaration = "DataProperty:" "(" DataProperty
    | DataPropertyVariable ")";

```

```

NamedIndividualDeclaration = "NamedIndividual:" "("
    NamedIndividual | IndividualVariable ")";
145 ClassDeclaration = "Class:" "(" Class | ClassVariable ")";
    
```

A.4 SPARQLAS Metamodel

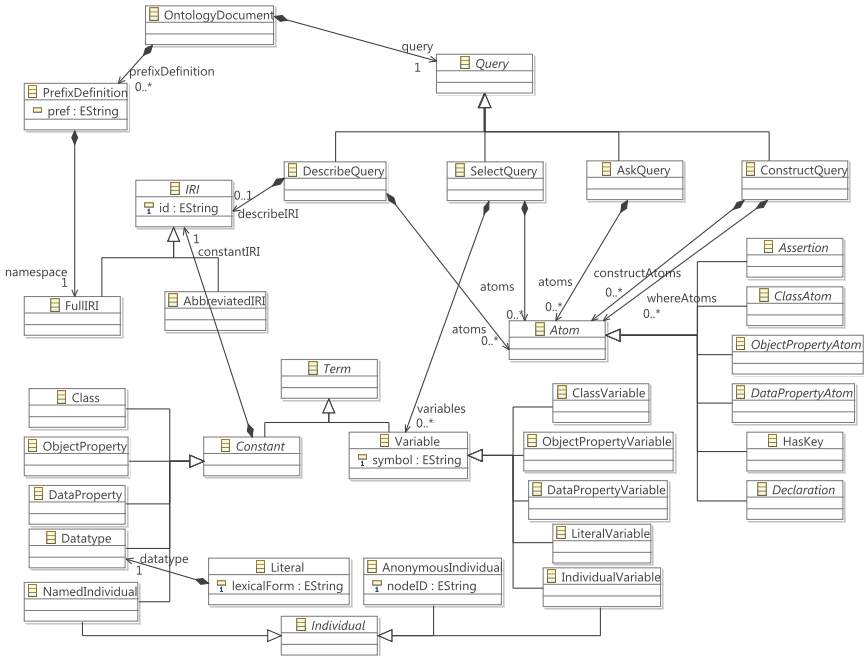


Fig. A.1. SPARQLAS Metamodel

A.5 Ecore to OWL: Translation Rules

In this section, we describe the transformation rule for generating OWL ontologies based on the Ecore metamodel.

OWL::ClassDeclaration(?x) ← Ecore::EClass(?x)

OWL::Class(?x) ← Ecore::EClass(?x)

iri(?x,?y) ← name(?x,?y)

OWL::SubClassOf(?x,?y) \leftarrow Ecore::EClass(?x) \wedge Ecore::EClass(?y) \wedge
superClass(?x,?y)

OWL::Class(?x) \leftarrow Ecore::EClass(?x)

OWL::Class(?y) \leftarrow Ecore::EClass(?y)

iri(?x,?z1) \leftarrow name(?x,?z1)

iri(?y,?z2) \leftarrow name(?y,?z2)

OWL::DataPropertyDeclaration(?y) \leftarrow Ecore::EClass(?x) \wedge Ecore::EAttribute(?y)
 \wedge Ecore::EPrimitiveType(?z) \wedge eAttributes(?x,?y) \wedge eAttributeType(?y,?z)

OWL::DataProperty(?y) \leftarrow Ecore::EAttribute(?y)

iri(?y,?z) \leftarrow name(?y,?z)

OWL::ObjectPropertyDeclaration(?y) \leftarrow Ecore::EClass(?x) \wedge Ecore::EAttribute(?y)
 \wedge Ecore::EEnum(?z) \wedge eAttributes(?x,?y) \wedge eAttributeType(?y,?z)

OWL::ObjectProperty(?y) \leftarrow Ecore::EAttribute(?y)

iri(?y,?z) \leftarrow name(?y,?z)

OWL::ObjectPropertyDeclaration(?y) \leftarrow Ecore::EClass(?x) \wedge Ecore::EReference(?y)
 \wedge Ecore::EClass(?z) \wedge eReferences(?x,?y) \wedge eReferenceType(?y,?z)

OWL::ObjectProperty(?y) \leftarrow Ecore::EReference(?y)

iri(?y,?z) \leftarrow name(?y,?z)

OWL::EquivalentClasses(?v) \leftarrow Ecore::EEnum(?v)

OWL::Class(?w) \leftarrow Ecore::EEnum(?v)

iri(?w,?x) \leftarrow name(?v,?x)

equivalentClass(?v,?w) \leftarrow .

OWL::ObjectOneOf(?y) \leftarrow Ecore::EEnum(?v)

OWL::NamedIndividual(?z) \leftarrow Ecore::EEnumLiteral(?z)

oneOfIndividual(?y,?z) \leftarrow eLiterals(?v,?z)

equivalentClass(?v,?y) \leftarrow .

$$\text{OWL::ClassAssertion}(?x,?y) \leftarrow \text{Ecore::EClass}(?x) \wedge \text{Ecore::EObject}(?y) \wedge \text{eClass}(?y,?x)$$

$$\text{OWL::Class}(?x) \leftarrow \text{Ecore::EClass}(?x)$$

$$\text{iri}(?x,?z1) \leftarrow \text{name}(?x,?z1)$$

$$\text{OWL::NamedIndividual}(?y) \leftarrow \text{Ecore::EObject}(?y)$$

$$\text{iri}(?y,?z2) \leftarrow \text{name}(?y,?z2)$$

$$\text{OWL::ObjectPropertyAssertion}(?x,?y,?z) \leftarrow \text{Ecore::EObject}(?s) \wedge \text{Ecore::EObject}(?o) \wedge \text{Ecore::EReference}(?r) \wedge \text{eGet}(?r, ?s,?o)$$

$$\text{OWL:ObjectProperty}(?r) \leftarrow \text{Ecore::EReference}(?r)$$

$$\text{iri}(?r,?n1) \leftarrow \text{name}(?r,?n1)$$

$$\text{OWL::NamedIndividual}(?s) \leftarrow \text{Ecore::EObject}(?s)$$

$$\text{iri}(?s,?n2) \leftarrow \text{name}(?s,?n2)$$

$$\text{OWL::NamedIndividual}(?o) \leftarrow \text{Ecore::EObject}(?o)$$

$$\text{iri}(?o,?n3) \leftarrow \text{name}(?o,?n3)$$

$$\text{OWL::DataPropertyAssertion}(?x,?y,?z) \leftarrow \text{Ecore::EObject}(?s) \wedge \text{Ecore::Literal}(?l) \wedge \text{Ecore::EAttribute}(?r) \wedge \text{eGet}(?a, ?s,?l)$$

$$\text{OWL:ObjectProperty}(?r) \leftarrow \text{Ecore::EAttribute}(?a)$$

$$\text{iri}(?a,?n1) \leftarrow \text{name}(?r,?n1)$$

$$\text{OWL::NamedIndividual}(?s) \leftarrow \text{Ecore::EObject}(?s)$$

$$\text{iri}(?s,?n2) \leftarrow \text{name}(?s,?n2)$$

$$\text{OWL::Literal}(?l) \leftarrow \text{Ecore::Literal}(?l)$$

A.6 Use Cases

In the following subsections we describe the use cases of the TwoUse approach. After describing the use cases, we map these use cases onto the requirements in the traceability matrix presented in Section A.7.

A.6.1 Design Integrated models

Brief Description: This use case covers the creation and visualization of OWL constructs with UML class-based modeling.

Preconditions: None.

Postconditions: An OWL ontology is generated.

Basic Flow:

1. Software Engineer Design Integrated models.
2. Software Engineer saves integrated model.
3. System transforms TwoUse model into OWL.
4. Use case terminates.

Sub flow: abstract Design Integrated models.

A.6.2 Design Integrated UML Class Diagram

Brief Description: This use case covers the creation and visualization of hybrid models using UML as concrete syntax.

Sub flow: Design Integrated models

1. Software Engineer creates a new UML class diagram.
2. Software Engineer use stereotypes of the UML Profile for OWL to annotate UML elements.
3. System transforms the hybrid class diagram into a TwoUse model.

Alternate Flows:

1. Software Engineer imports existing UML class diagram.

A.6.3 Design Integrated Ecore Model

Brief Description: This use case covers the creation and visualization of Ecore models using the textual syntax.

Sub flow: Design Integrated models

1. Software Engineer creates a new Ecore model.
2. Software Engineer creates annotations with OWL axioms to Ecore elements.
3. System transforms Ecore model with annotations for OWL into a TwoUse model.

Alternate Flows:

1. Software Engineer imports existing Ecore model.

A.6.4 Specify SPARQLAS4TwoUse Query Operations

Brief Description: This use case covers the specification of query operations for classes using SPARQLAS4TwoUse for usage of ontology services in UML class-based modeling.

Preconditions: Integrated model exists.

Postconditions: None.

Basic Flow:

1. Software Engineer creates query operations at classes.
2. Software Engineer specifies the body of query operations using SPARQLAS4TwoUse.
3. System transforms the hybrid class diagram into a TwoUse model.
4. System generates an OWL ontology from the TwoUse model.
5. System generates a SPARQL query from the SPARQLAS4TwoUse query.
6. Use case terminates.

Alternate Flows: none

A.6.5 Transform to OWL

Brief Description: This use case covers the transformation of Ecore-based modeling languages. It consists of transforming model and metamodel into individuals and classes in an OWL ontology for usage of ontology services in UML class-based modeling.

Preconditions: A model and its metamodel designed using Ecore technologies exist.

Postconditions: An OWL ontology is generated including elements of the model as individuals and property assertions and the elements of the metamodel as classes and properties.

Basic Flows:

1. Software engineer selects a model for transformation.
2. System creates an OWL ontology.
3. System reads selected model's metamodel and transform it into OWL classes and properties.
4. System reads selected model and transform it into OWL individuals, class assertions and property assertions.
5. Use case terminates.

Alternate Flows: None.

A.6.6 Compute Alignments

Brief Description: This use case covers the computation of alignments between two UML class-based models. It consists of transforming models into OWL and applying matching techniques to identify similarities between two models.

Preconditions: Two models exist.

Postconditions: Results of alignments are displayed.

Basic Flows:

1. Software engineer selects two UML class-based models for comparison.
2. System reads the two corresponding OWL ontologies.
3. System computes the alignment between these ontologies.
4. System displays the result.
5. Use case terminates.

Alternate Flows: None.

A.6.7 Browse

Brief Description: It covers the usage of queries and filters for extrating data.

Preconditions: UML class-based modeling exists.

Postconditions: Results are presented.

Basic Flows:

1. Engineer creates new SPARQLAS query.
2. Engineer saves SPARQLAS query.
3. Engineer executes SPARQLAS query.
4. Engineer Select Model.
5. System transforms UML class-based model into OWL.
6. System transforms SPARQLAS query into SPARQL query.

7. System uses reasoning systems to classify and realize the ontology and to execute the SPARQL query.
8. System shows query results.
9. Use case terminates.

Alternate Flows: Engineer visualizes inferred class hierarchy.

1. System shows the inferred class hierarchy.

A.6.8 Explain Axioms

Brief Description: It covers the usage of explanation services.

Preconditions: OWL exists.

Postconditions: None.

Basic Flows:

1. Engineer selects axioms for explanation.
2. System generates an explanation for the selected axioms.
3. Use case terminates.

Alternate Flows: None.

Sub flow: abstract Select Model.

A.6.9 Query UML class-based models

Brief Description: It covers the usage of queries over UML class-based modeling.

Sub flow: Select Model

1. Software Engineer selects UML class-based model.
2. System transforms UML class-based model into OWL.

A.6.10 Query OWL ontologies

Brief Description: It extends use case Query.

Sub flow: Select Model

1. Software Engineer selects OWL ontology.

A.6.11 Design Ontology Engineering Services

Brief Description: It involves the specification of Ontology Engineering Service.

Preconditions: OWL ontology exists.

Postconditions: None.

Basic Flows:

1. Ontology Engineer Design Services.
2. System Generate Service.
3. Use case terminates.

Alternate Flows: None.

Extension Point: Generate Service.

Sub flow: abstract Design Services.

A.6.12 Design Ontology API

Brief Description: It involves the specification of OWL ontology API.

Sub flow: Design Services.

1. Ontology Engineer creates OWL ontology API specification.
2. Ontology Engineer specifies API using a domain-specific textual language.
3. Ontology Engineer saves OWL Ontology API specification.

Alternate Flows: None.

Preconditions: OWL ontology exists.

Postconditions: None.

A.6.13 Design Ontology Translation

Brief Description: It outlines the design of OWL ontology dataset translations.

Sub flow: Design Services.

1. Ontology Engineer creates OWL ontology dataset translation specification.
2. Ontology Engineer specifies OWL ontology dataset translation using a domain-specific textual language.
3. Ontology Engineer saves OWL ontology dataset translation specification.

Alternate Flows: None.

Preconditions: Source OWL ontology and Target OWL ontology exist.

Postconditions: None.

A.6.14 Design Ontology Template

Brief Description: It covers the usage of templates in OWL ontologies.

Sub flow: Design Services.

1. Ontology Engineer imports domain ontology.
2. Ontology Engineer specifies ontology templates.
3. Ontology Engineer binds templates to domain ontology.

Alternate Flows

1. Ontology Engineer uses UML class diagrams for creating templates.
2. Ontology Engineer uses the OWL 2 graphical notation for creating templates.

Preconditions: Domain ontology exists.

Postconditions: OWL ontology generated.

A.6.15 Generate Service

Brief Description: It covers the transformation of specification into platform specific artifacts.

Extension Flows: Generate Service.

1. System generates platform specific artifacts for the ontology engineering service.

Requirements	OWL Constructs in UML Class-Based Modeling (5.2.1)	Ontology services in UML class-based modeling (5.2.1)	MDE Support for Ontology Modeling (5.2.2)	Domain Modeling for Ontology Engineering Services (5.2.2)
Use Cases				
Design Integrated models (A.6.1)	X			
Design Integrated UML Class Diagram (A.6.2)	X			
Design Integrated Ecore Model (A.6.3)	X			
Specify SPARQLAS4TwoUse Query Operations (A.6.4)		X		
Transform to OWL (A.6.5)		X		
Compute Alignments (A.6.6)		X		
Browse (A.6.7)		X	X	X
Query UML class-based models (A.6.9)		X		
Query OWL ontologies (A.6.10)			X	X
Explain Axioms (A.6.8)		X		
Design Ontology Engineering Services (A.6.11)			X	X
Design Ontology API (A.6.12)				X
Design Ontology Translation (A.6.13)				X
Design Ontology Template (A.6.14)			X	
Generate Service (A.6.15)			X	

Table A.1. Traceability Matrix: Mapping Use Cases and Requirements.

A.7 Connecting Use Cases with Requirements

Having described the use cases in section A.6, we have mapped them onto the requirements presented in Section 5.2 in Table A.1. It depicts a traceability matrix and correlates the requirements with the use cases.

A.8 Connecting Use Cases with the TwoUse Architecture

Each of the components described in Chapter 7 implements one or more use cases specified in Section A.6. Table A.2 shows the traceability matrix connecting components and use cases.

Use Cases Component	A.6.2	A.6.3	A.6.4	A.6.5	A.6.9	A.6.10	A.6.12	A.6.13	A.6.14	A.6.15	A.6.6
SPARQL-DL	X	X	X		X	X					X
OWL 2 Reasoner	X	X	X		X	X					X
SPARQLAS2SPARQL	X	X	X		X	X					
Ecore2OWL2Ecore		X	X	X							X
OntologyTemplate2OWL										X	
UML2OWL2UML	X		X								X
MBOTL2Java+SPARQL										X	
Agogo2Java										X	
SPARQLAS-SPARQL			X		X	X					
Ecore-OWL-Ecore		X		X							X
OntologyTemplate-OWL										X	
UML-OWL-UML	X										X
MBOTL-Java+SPARQL										X	
Agogo-Java										X	
Explanation					X	X					
Onlogy Alignment API											X
TwoUse Modeling	X	X		X							
TwoUse Querying				X		X					
MBOTL											X
Agogo											X
Ontology Templates											X
Ontology Querying						X					
OWL 2 FS									X		
SPARQLAS					X	X					
SPARQL					X	X					
SPARQLAS4Ecore			X								
SPARQLAS4UML			X								
Text Ecore		X									
UML	X								X		
OWL 2 Graphical Editor									X		
Agogo							X				
MBOTL								X			
Class Hierarchy	X	X									
Query Results					X	X					
Explanation					X	X					
Ontology-Based Model Design	X	X	X	X	X						X
Model-Driven Ontology Development						X	X	X	X	X	
Transform to OWL				X							
Execute Query					X	X					
Generate Service										X	
Compute Alignments											X

Table A.2. Traceability Matrix: Mapping TwoUse Components and Use Cases.

Short Biography

Fernando Silva Parreiras was born in Belo Horizonte, Brazil, in 1978. He holds a Bachelor's degree in computer science from the FUMEC University and a Master's degree in information science from the Federal University of Minas Gerais. He held a CAPES/DAAD scholarship during his Ph.D. studies in computer science at the University of Koblenz-Landau.

In Brazil, he has worked for four years at software companies like Unisys as software developer and software architect, developing and designing web applications.

Currently, he is the leader of the Special Interest Group Software Web at the WeST Institute at the University of Koblenz-Landau, Germany. He has worked on the European projects "Marrying Ontologies and Software Technologies" (MOST) and "Network for Enabling Networked Knowledge" (Net2).