

Ontology Engineering: Current State, Challenges, and Future Directions

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Abstract.
In the past decade, we have witnessed a significant adoption of ontologies in a variety of fields including biomedicine, finance, engineering, law, and cultural heritage. The ontology engineering field has been strengthened by the adoption of several standards pertaining to ontologies, by the development or extension of ontology building tools, and by a wider recognition of the importance of standardized vocabularies and formalized semantics. Research into ontology engineering has also produced methods and tools that are used more and more in production settings. Despite all these advancements, ontology engineering is still a difficult process, and many challenges still remain to be solved. This paper gives an overview of how the ontology engineering field has evolved in the last decade and discusses some of the unsolved issues and opportunities for future research.

Keywords: Ontologies, Ontology Engineering, Methods, Standards, Tooling, Patterns, Challenges, Future Research

1. Ontologies Make an Impact

The research on ontologies in computer science started in the early 1990s. Ontologies were proposed as a way to enable people and software agents to seamlessly share information about a domain of interest. An ontology was defined as a conceptual representation of the entities, their properties and relationships in a domain [1]. The ultimate goal of using ontologies was to make the knowledge in a domain computationally useful [2]. The initial research period was followed by a time of great excitement about using ontologies to solve a wide range of problems. However, the enthusiasm dwindled in the early 2000s, as the methods and infrastructures for building and using ontologies were not mature enough at that time. Nonetheless, significant changes have taken place in the last decade: The research and development on ontologies had a big boost, more standardization efforts were on the way, and industry started to buy into semantic technologies. As a result, ontologies are now much more widely adopted in academia, industry and government environments, and are finally making an impact in many domains.

Biomedicine has widely adopted ontologies since their beginnings. The Gene Ontology (GO) [3]—a comprehensive ontology describing the function of genes—is the poster child for a successful ontology development project that has produced a big impact in biomedical research. Indeed, GO is routinely used in the computational analysis of large-scale molecular biology and genetics experiments [4]. Researchers have also used ontologies in biomedicine to standardize terminology in particular domains, to annotate large biomedical datasets, to integrate data, and to aid structured data mining and machine learning [5, 6].

One notable example of the impact ontologies are making in healthcare is the development of the 11th revision of the International Classification of Diseases (ICD-11). ICD—developed by the World Health Organization (WHO)—is the international standard for reporting diseases and health conditions, and is used to identify health trends and statistics on a global scale [7]. ICD-11 is now using OWL to encode the formal representation of diseases, their properties, and relations, as well as mappings to other terminologies [8].

The **financial industry** has embraced the use of ontologies. The most prominent example is the Financial Industry Business Ontology (FIBO)—the industry standard resource for the definitions of business concepts in the financial services industry [9]. FIBO is developed by the Enterprise Data Management Council (EDMC) and it is standardized through the Object Management Group (OMG). FIBO is built as a series of OWL ontologies and is developed using a rigorous and well-defined process, known as the "Build-Test-Deploy-Maintain" methodology.

Engineering is another field that has adopted ontologies from the early 1990s, long before the standardization of the current Semantic Web languages, such as OWL and RDF [10, 11]. In the last decade, we have witnessed significant efforts around using ontologies to cover different aspects of engineering ranging from defining requirements [12], to integrating different engineering models [13], to detecting inconsistencies in models in multidisciplinary engineering projects [14]. Sabou et. al [15] provide a comprehensive overview into how ontologies and Semantic Web technologies can assist in building intelligent engineering applications.

Other fields have also adopted ontologies more widely. Researchers have used ontologies in the **legal domain** to formally represent laws and regulations, to simulate legal actions, or for semantic searching and indexing [16]. In the **cultural heritage field**, the ISO 21127:2014 standard prescribes an ontology that allows the exchange of cultural heritage data between institutions, such as museums, libraries and archives.

The examples we mentioned above are not meant to be comprehensive. They show how ontologies have been embraced by a wide range of fields in the last decade and how they are making an impact.

This paper is meant to give a retrospective overview of how the ontology landscape and ontology engineering have evolved in the last decade, current challenges, and prospects for future research. This paper can hopefully also serve as an introduction for newcomers in the field. We briefly discuss standards relevant to ontology engineering that have been adopted in the last decade (Section 2), highly visible and influential ontologies and knowledge bases that are constructed by large communities (Section 3), trends in ontology engineering from the last ten years (Section 4), and current challenges and opportunities for future research (Section 5).

2. New Standards

The significant standardization efforts on ontologies and Semantic Web languages in the last decade also prove the maturation of the field. Figure 1 shows some of ontology-related standards that the World Wide Web Consortium (W3C) has adopted in the past decade. Several ontologies and vocabularies have become W3C recommendations: The Time Ontology (OWL-Time) [17]—describing the temporal properties of resources; the Semantic Sensors Network Ontology (SSN) [18]—representing sensors and their observations; the Provenance Ontology (PROV-O) [19]—describing provenance information from different systems; or the RDF Data Cube [20]—enabling publishing of multi-dimensional data on the Web.

Ontology and knowledge representation languages have also evolved as proved by the adoption of new versions of the standards: RDF 1.1 was adopted in February 2014, and introduced identifiers as IRIs, RDF datasets, and new serialization formats, such as RDFa[1] and Turtle.[2] OWL 2.0[3] was adopted in December 2012, and introduced several new features, such as support for keys and property chains, richer datatypes and data ranges, qualified cardinality restrictions, and enhanced annotation capabilities.

Another notable W3C recommendation adopted in July 2017 is the Shapes Constraints Language (SHACL)[4] that provides a mechanism for validating constraints against RDF graphs, a feature that was sorely lacking from the current knowledge representation standards. ShEx[5] is an alternative way of validating RDF and OWL and is backed by an active user community. SHACL and ShEx are considered by some as a simpler knowledge representation languages that might provide an alternative to the more complex OWL representation.

3. Large-Scale Community-Driven Creation of Knowledge

Another area of substantial growth in the last decade is the development of community-authored ontologies and knowledge bases. One of the most notable examples is Wikidata,[6]—a free and open knowledge base that serves as the central storage of structured data for several Wikimedia projects, including Wikipedia [21].

[1] https://www.w3.org/TR/rdfa-core/
[2] https://www.w3.org/TR/turtle/
[3] https://www.w3.org/TR/owl2-overview/
[4] https://www.w3.org/TR/shacl/
[5] http://shex.io/
[6] https://www.wikidata.org

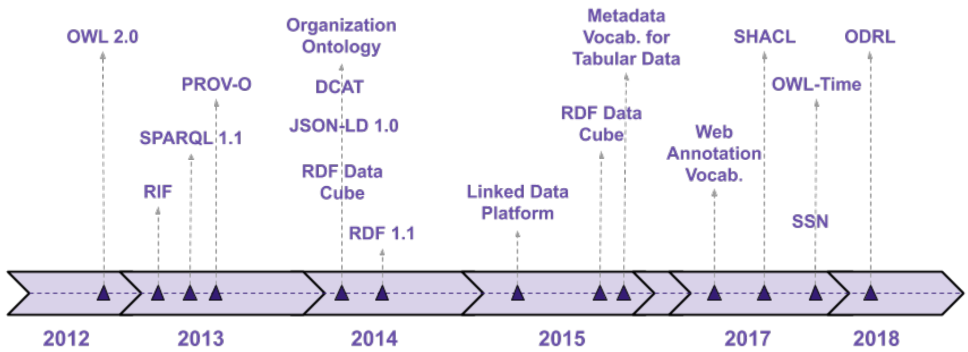

Fig. 1. The timeline of W3C recommendations related to ontologies and vocabularies in the last decade (2010-2019). The years that do not have any recommendations are skipped.

The Wikidata project started in October 2012. Initially, it was conceived as a central place for storing inter-languages links between Wikipedia articles about the same topic in different languages, and nowadays, Wikidata provides the structured data for almost 60% of Wikipedia pages.[7] Wikidata's data model is centered around items with unique identifiers that contain statements—basically, key-value pairs— which can be qualified (e.g., with provenance information). One distinguishing feature of Wikidata is its collaborative authoring model: Both humans and programmable bots can contribute content, with a majority of the edits (about 90%) coming from bots. The project is highly active, containing more than 63 million entities, and over 900 million edits as of April 2019.

Another high-impact project for creating vocabularies for structured data to be used on Web content is Schema.org.[8] Started in 2011 by Google, Microsoft, Yahoo and Yandex, the Schema.org vocabularies enable Web content creators to add structured metadata to their Web pages, so that search engines can better understand the content of the page. The Schema.org vocabularies are developed by an open community process using W3C mailing lists and GitHub.[9] Schema.org also offers an extension mechanism that communities have used to create domain-specific vocabularies, for example, for bibliographic or auto extensions. As of April 2019, these extensions are folded back into the main Schema.org vocabulary.[10]

Freebase [22]—a large-scale knowledge base that aimed to structure general human knowledge—was launched in 2007 by Metaweb. Freebase was built in a collaborative process in which community members submitted wiki entries. In 2010, Google acquired Metaweb, and used the Freebase content as part of the Google Knowledge Graph, which was officially announced in 2012.[11] In 2014, Google announced that they will shut down Freebase, and help to transfer the Freebase content to Wikidata [23].

Certainly, knowledge graphs (KG) are one of the leading topics of the last decade. Even though researchers have built knowledge networks before, the phrase "knowledge graph" started catching on once Google announced their Google KG in May 2012. Since then, we have seen a flourishing of KGs. Indeed, most large companies, including Amazon, Netflix, Pintrest, LinkedIn, Microsoft, Uber, NASA, IBM, and Alibaba are developing their own KGs. Gartner also identified knowledge graphs as an emerging technology trend in their 2018 technology report [24]. Even with this high adoption, there is no single widely adopted definition of a KG. A common denominator is that KGs contain entities that are inter-related, and are usually at the data level. The level of formality varies a lot: While some use RDF and OWL and a schema, others are schema-less and use property graphs.[12] Some KGs are built bottom-up using Machine Learning (ML) and Natural Language Process-

[7] http://wdcm.wmflabs.org/WD_percentUsageDashboard/
[8] https://schema.org/
[9] https://www.w3.org/community/schemaorg/
[10] https://schema.org/docs/extension.html

[11] https://googleblog.blogspot.com/2012/05/introducing-knowledge-graph-things-not.html
[12] A property graph is a graph for which the edges are labeled, and both vertices and edges can have any number of key/value properties associated with them.

ing (NLP) techniques, while others are built top-down. Their uses ranges widely from intelligent search, to analytics, cataloging, data integration, and more.

4. Ontology Engineering

Ontology engineering did not change significantly in the last decade. Even though there has been progress in specific areas, which we will briefly discuss in this section, the work on new ontology engineering methodologies did not seem to progress much. Even to date, the most cited ontology engineering method, according to Google Scholar, is the Ontology 101 guide by Noy and McGuiness [25] from 2001.

The NeOn project (2006-2010) produced the most comprehensive methodology for building networked ontologies [26]. The NeOn methodology describes a set of nine scenarios for building ontologies focusing on reuse of ontological and non-ontological resources, merging, re-engineering, and also accounting for collaboration. In addition, the methodology also publishes a Glossary of Processes and Activities to support collaboration, and methodological guidelines for different processes and activities involved in ontology engineering. Even though the NeOn methodology had modest adoption, the work in the NeOn project produced important research that advanced the field.

In the last decade, researchers have developed other ontology engineering methodologies that have been deployed in specific projects, but are still yet to be widely adopted. For example, the UPON Lite methodology [27] supports the rapid prototyping of trial ontologies, while trying to enhance the role of domain experts and minimize the need for ontology experts. The methodology uses a socially-oriented approach and familiar tools, such as spreadsheets, to make the engineering process more accessible to domain experts.

The Gene Ontology (GO)—arguably, the most visible and successful ontology project—has generated several ontology engineering methods and tools that are generic, reusable, and that have already been validated in several large-scale ontology development projects [28, 29]. The OBO Foundry defines many of the principles[13] by which OBO Foundry ontologies, including the GO, should abide, such as versioning, naming conventions, defining relations, locus of authority, documentation, collaboration process, orthogonality of ontologies, and reuse [30]. The OBO Foundry is a good example of how a community can develop ontologies for a specific domain. Motivated by the need to manage ontologies that are becoming more modular and inter-dependent, the GO project developed a continuous integration process using Jenkins and Hudson for building ontologies that became a model for the development of other ontologies [31]. ROBOT[14] is a generic command-line tool and Java library for performing common ontology tasks, such as, computing differences between ontology versions, merging, extracting ontology modules, reasoning, explanation, materializing inferences, etc. The commands in ROBOT can be chained together to create a powerful, repeatable workflow. Another generic tool that was developed as part of the GO project is TermGenie [32], a Web-based class submission form that can generate new classes, once the submission passes a suite of logical, lexical and structural checks. TermGenie is generic and customizable and has been deployed in the development of several biomedical ontologies.

The adoption of ontologies into mainstream is also proven by the recent publication of several books focusing on ontology engineering, such as, “Demystifying OWL for the Enterprise” in 2018 by Uschold [33], the “Ontology Engineering” in 2019 by Kendall and McGuiness [34], and the "An Introduction to Ontology Engineering" in 2018 by Keet [35].

4.1. Patterns, Templating, and Automation

As ontology engineering became more broadly used, knowledge engineers needed ways to optimize and accelerate parts of the ontology development process. One of the approaches was employing ontology design patterns—small, modular, and reusable solutions to recurrent modeling problems—and templates based on these patterns or other representation regularities in the ontology. Another approach was to use automation, such as bulk imports, or scripts to accelerate ontology population.

The initial work on ontology design patterns (ODP) dates back to 2005 [36]. The research on ODPs has only intensified in the last decade. The Workshop on Ontology Design Patterns (WOP) that attracts researchers working on ODPs, as well as users trying to apply them, is already in its 10th edition.[15] In their

[13]http://www.obofoundry.org/principles/fp-000-summary.html

[14]http://robot.obolibrary.org/

[15]http://ontologydesignpatterns.org/wiki/WOP:2019

book, "Ontology engineering with ontology design patterns: Foundations and applications", Hitzler and colleagues [37] provide a current assessment of the research and application of ontology patterns. Some of the new work on ODPs include the definition of a language for the representation of ontology patterns and of their relationships [38].

Several biomedical projects adopted the Dead Simple OWL Design Patterns (DOS-DPs)[16]—a lightweight, YAML[17]-based syntax for specifying design patterns [39]. DOS-DPs support the generation of OWL axioms and user-facing documentation using a simple format that can be parsed using out-of-the-box parsers. With DOS-DP, users can quickly generate new classes, or change existing ones when a design pattern changes.

Other mechanisms for specifying patterns and generating axioms are the Ontology PreProcessing Language (OPPL) [40] and the Tawny OWL [41]. OPPL is a macro language based on the Manchester OWL Syntax [42] that contains instructions for adding or removing entities and axioms to an OWL ontology. Tawny OWL, which is built in Clojure[18] and backed by the OWL API [43], provides a programmatic way to build ontologies. Tawny OWL allows ontology engineers to use a wide range of tools available for software development, including versioning, distributed development, building, testing and continuous integration.

Another approach that adopts widely-used technologies from software engineering to ontology development is OntoMaven [44]. OntoMaven adapts the Maven development process to ontology engineering in distributed ontology repositories. It supports the modular reuse of ontologies, versioning, the life cycle and dependency management.

4.2. Better Tooling Is Available

The tooling for building ontologies has also evolved considerably in the last decade. The open-source Protégé ontology editor [45] has grown its active large community to more than 300,000 registered users. WebProtégé [46] is a Web-based editor for OWL 2.0 with a simplified user interface [47] that supports collaboration. WebProtégé also supports tagging, multilinguality, querying and visualization. The Stanford-hosted WebProtégé server (https://webprotege.stanford.edu) hosts more than 60,000 ontology projects that users have created or uploaded to the server.

The OnToology [48]—an open-source project that automates part of the collaborative ontology development process—will generate different types of resources for a GitHub ontology, such as documentation using Widoco [49]; class and taxonomy diagrams using the AR2DTool[19]; and an evaluation report for common pitfalls using the OOPS! framework [50]. VocBench [51] is another open-source Web-based SKOS editor that focuses on collaboration.

Commercial ontology engineering tools have also proliferated and gained wide adoption in the last decade. Some of the commercial offerings include the TopQuadrant's tool suite[20] for vocabulary and metadata management, the PoolParty Semantic Suite,[21] or Mondeca's Intelligent Topic Manager (ITM),[22] just to name a few. Gra.fo[23] is the most recent addition of commercial ontology tools that was launched in late 2018. Gra.fo is a visual, collaborative, and real-time ontology and knowledge graph schema editor that supports both OWL/RDF and property graphs. Several other commercial ontology tools have morphed recently into knowledge graph solutions.

5. Challenges and Opportunities for Future Research

Despite of the broader adoption of ontologies and of the advancements in ontology engineering in the last decade, we cannot declare victory just yet. Potential ontology adopters are facing not only years-old challenges, such as a steep learning curve and the difficulty of modeling, but also the conundrum of choosing between ontologies and competing technologies, such as knowledge graphs and property graphs. The current challenges in the ontology engineering field present also several opportunities for future research and development, as we detail below.

Steep entry for newcomers and usability of ontology tools. Semantic Web languages, and especially OWL, have a steep learning curve [52, 53] and require a change of perspective, especially for people coming from software engineering, object-oriented program-

[16]https://github.com/INCATools/dead_simple_owl_design_patterns
[17]https://yaml.org/
[18]https://clojure.org/
[19]https://github.com/idafensp/ar2dtool
[20]https://www.topquadrant.com
[21]https://www.poolparty.biz/
[22]https://mondeca.com/itm/
[23]https://gra.fo

ming, or relational database backgrounds. Newcomers are faced not only with the daunting task of creating a new type of model for their problem or domain, but also trying to find the right tool—ontology editor, visualization, reasoner, etc.— and workflow/development process to help them solve their problem. Currently, there is no central resource (e.g., a Web page) that can point a newcomer to options for tooling, documentation or development processes. Ideally, such a Web page should be hosted by a central authority, like the W3C, and be updated regularly.

There are several opportunities in terms of research. User studies on **usability of ontology tools** and on different aspects of ontology engineering are scarce [53]. As a consequence, ontology tools are not informed by the actual needs of users, and are often difficult to use. We need more high-quality user studies to understand what the roadblocks are, and what works and what doesn't work for users while authoring ontologies. We also need more research into supporting the initial phases of building ontologies. Ontology authors usually have to combine data from a variety of sources, such as spreadsheets, databases, lists, UML diagrams, and mind-maps to bootstrap their ontology. Developing methods and tools that support such **import and integration of data from different sources** is essential.

At the same time, we also need **friendlier user interfaces** and UI interactions for ontology authoring to enable domain experts to contribute content. Although there has been some initial research into using templates and Web forms for ontology authoring [54–57], none of these approaches have become mainstream. More research is needed into creating knowledge acquisition (KA) forms for modern knowledge representation languages. Another area of research is the (semi-)automatic generation of KA forms for an ontology. An early example is the forms generation of the Protégé Frame ontology editor [58] that created class-based forms based on the constraints of the slots attached to a class. The Protégé forms mechanism was widely used to create knowledge-based applications in different domains [45]. However, the Protégé forms mechanism worked with a Frames representation; new research and approaches are needed to generate forms for OWL ontologies.

Modeling challenges Ontological modeling is cognitively hard, and requires extensive training. One of the main ways to make ontology engineering more manageable is to use ontology design patterns (ODPs), as we discussed in Section 4.1. Blomqvist et. al [59] discuss the current barriers in using ODPs that range from the availability of relevant patterns, to challenges related to evaluating them, and to lacking tool support.

Another recommendation in ontology engineering is **ontology and term reuse**. While all ontology building methodologies are encouraging reuse, enacting reuse in practice is difficult. Several published studies have shown that the level of ontological reuse is low [60–62]. For example, in a recent study, Kamdar et. al [61] show that the term reuse is only <9% in biomedical ontologies, even though the term overlap is between 25–31%, with most ontologies reusing fewer than 5% of their terms from a small set of popular ontologies. There are many opportunities for further research into reuse of ontologies: Investigating better methods and building better tools to help users find the appropriate ontology or set of terms in an ontology to reuse; identifying "trustworthy" ontologies for a particular task—building a measure for the "trustworthiness" of an ontology based on different aspects (e.g., authority, development status, evaluation tests, etc.); identifying potential overlap between a source ontology and other ontologies to reuse; extracting the right type of subset or module to reuse for a particular task; investigating methods to handle the evolution of the extracted subset to reuse when the source ontology has also evolved.

Synergies with other fields Ontology engineering has evolved over many years, and as we have discussed, there are already established standards for representation and querying languages, development methodologies, and tooling. While many of these methods and tools are specific for ontologies, there are many aspects of the ontology engineering process that can benefit from the maturity and experience from established fields, and vice versa—other fields may benefit from the research and resources available in ontology engineering and the Semantic Web domain. For example, Machine Learning (ML) has been long employed for ontology learning, or for populating knowledge bases or linking data, while ML algorithms can be improved by applying ontological knowledge. Similarly, ontology engineering has already adopted some of the methods used in Software Engineering, for example the design patterns, the development process and continuous integration. While these are certainly encouraging initiatives, much more can be gained by taking a closer look at how ontology engineering can benefit from other fields, and vice versa.

Last, but not least, **knowledge graphs** are gaining in popularity, and they will likely become even more widespread in the next five to ten years, as Gartner hype report from 2018 predicts. Knowledge graphs and ontologies have a lot in common: They deal with representing entities and their relationships, and using these representations to solve different computational problems. Several of the ontology engineering methods have already been applied to knowledge graphs. We expect that many synergies will be uncovered or will be newly developed between these two fields, and both domains can benefit from them. For example, KGs can benefit from the abundance of research on knowledge representation, querying, and development methodologies that have been established in ontology engineering for a long time; while, ontology engineering can benefit from methods for automatic building of KGs that are commonly using Machine Learning or Natural Language Processing, or adopt some of the methods and tools that deal with large amounts of data and that scale well.

6. Conclusions

The goal of the paper is to give an overview of how the field of ontology engineering has evolved in the last decade. Due to space limitations, we could only cover some of the main topics in ontology engineering. We hope that the paper can serve as an entry point for a newcomer in the ontology field, and as a quick reference for the more knowledgeable researchers. As a result of the research and development efforts in the last ten years, ontologies are now adopted in wide range of domains, from biomedicine to engineering and finance. The infrastructures for storing, finding and building ontologies have also evolved significantly. Several standards pertaining to ontology engineering have been adopted in the last decade, and highly-visible efforts to build large-scale ontologies and knowledge bases are well underway. Even though the ontology engineering field still faces several challenges—many of them long-standing—we have also identified many opportunities for future research and development, and exciting new opportunities from synergies with other domains that can drive the ontology engineering field even further.

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