Toward a Comparison Framework for Interactive Ontology Enrichment Methodologies

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Abstract
The growing demand for well-modeled ontologies in diverse application areas increases the need for intuitive interaction techniques that support human domain experts in ontology modeling and enrichment tasks, such that quality expectations are met. Beyond the correctness of the specified information, the quality of an ontology depends on its (relative) completeness, i.e., whether the ontology contains all the necessary information to draw expected inferences. On an abstract level, the Ontology Enrichment problem consists of identifying and filling the gap between information that can be logically inferred from the ontology and the information expected to be inferable by the user. To this end, numerous approaches have been described in the literature, providing methodologies from the fields of Formal Semantics and Automated Reasoning targeted at eliciting knowledge from human domain experts. These approaches vary greatly in many aspects and their applicability typically depends on the specifics of the concrete modeling scenario at hand. Toward a better understanding of the landscape of methodological possibilities, this position paper proposes a framework consisting of multiple performance dimensions along which existing and future approaches to interactive ontology enrichment can be characterized. We apply our categorization scheme to a selection of methodologies from the literature. In light of this comparison, we address the limitations of the methods and propose directions for future work.

Keywords
Formal Semantics, Ontology Design, Human-Computer Interaction, Knowledge Elicitation

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1. Introduction

In practical knowledge management scenarios, ontologies need to be modified and updated on a regular basis. It is therefore important to aid human domain experts in exploring, understanding, and modifying domain-specific ontologies [1]. Providing human domain experts with intuitive interaction techniques can significantly support comprehension and adaptation of domain representations, ultimately resulting in higher quality ontologies. However, there is no *one-size-fits-all* solution; rather, different use cases demand different interaction techniques to foster user engagement and deliver better performance.

From a general logical perspective, an ontology can fail to meet requirements in two different ways. First, an ontology can contain wrong information (correctness). Second, an ontology can lack information (completeness). In incorrect ontologies, wrong conclusions may be derived, while in incomplete ontologies, valid conclusions may be missed. For example, it was shown that semantically-enabled querying of PubMed[1] using MeSH[2] with one piece of background knowledge removed would lead to a 55% drop in the result [2].

Ontology enrichment addresses the incompleteness problem. We define Ontology Enrichment to be the procedure that enables the addition of novel or missing relations, concepts and rules to an existing ontology [3]. The identified missing information is represented by the set of missing axioms that are correct according to the human and should be added to the ontology. Also, we define the human domain expert to be equivalent to the *limited all-knowing oracle* as defined by Lambrix [2], i.e., the expert knows part of the domain well, however, it may not know the answer to all questions.

In this paper, we focus on designing a comparison framework for interactive ontology enrichment methodologies. In particular, we focus on four different dimensions, namely, expressiveness, comprehensiveness, initiative, and scalability, based on which we can categorize existing interaction techniques. Our aim is to compare the possibilities the fields of Formal Semantics and Automated Reasoning have to offer for the interaction between human domain expert and ontologies. We argue that by involving the user and eliciting their knowledge, we can improve ontologies and expand them to include missing inferences. We demonstrate the usefulness of our comparison framework by evaluating four different ontology enrichment methods that elicit knowledge from human domain experts, and we underline the characteristics of these methods on the proposed dimensions. Addressing these points allows us to outline some of the remaining issues and open questions that implementations of formal methodologies face.

This paper is organized as follows: In Section 2, we define qualitative metrics for comparison of ontology enrichment approaches. In Section 3, we define and explain a selection of existing approaches and their contributions towards ontology enrichment through Formal Semantics. In Section 6, we summarize the characteristics of each of the approaches along the four dimension in a table. Lastly, in Section 7, we discuss the limitations of these approaches and suggest directions for future work.

[1] https://pubmed.ncbi.nlm.nih.gov/
[2] https://www.nlm.nih.gov/mesh/meshhome.html

2. Comparison Framework

The process of ontology enrichment is essentially a continuous interaction between humans and machines. Therefore, we propose scoping the *repairing* phase as defined by Lambrix [2] to better fit this continuum. First, we argue that the term *expansion* better fits the concept than *repairing*, since *repairing* implies there is something broken; whereas, we are solely focusing on missing information to draw inferences from, rather than correcting incorrect axioms. Furthermore, to draw a line between the different tasks in the enrichment process, and as such, the interaction between human domain expert(s) and the machine (i.e. reasoners), we added the *validation* phase to better follow this interplay. In short, we believe elicitation to consist of the following steps:

1. **Detection**: Identifying which expected inferences are missing;

2. **Expansion**: Updating the existing knowledge base by adding axiom(s);

3. **Validation**: Checking the consistency of the added axiom(s) with the rest of the knowledge base.

A comparative analysis of the different techniques in order to get a better grasp of the pros and cons of each methodology is better enabled with the introduction of specific metrics. For this comparison, we defined the following dimensions:

1. **Expressiveness**: To what extent is the technique able to represent the breadth of the human domain expert's ideas (i.e. what constraint does the technique impose on the human domain expert's comprehensiveness).

2. **Comprehensiveness**: The degree to which the technique is capable of finding all the missing expected inferences (i.e. the expected inferences of the human domain expert) in interaction with the human domain expert.

3. **Initiative**: The degree to which the input requested from the human domain expert is pre-determined (i.e. initiated and put forward by the human domain expert vs. governed by the technique).

4. **Scalability**: What are the possible complexities with regard to scaling the methodology.

3. Formal Semantic Methods

In this section, we compare and contrast different interaction techniques which can be used to elicit knowledge from human domain experts, to enrich existing knowledge bases. Specifically, we examine the methodologies referred to as *Abductive Completion* [4], *Reasoning-Supported Interactive Revision of Knowledge bases* [5], *Advocatus Diaboli* [6] and *Relational Exploration* [7].

The ***Abductive Completion*** method (see Fig. 1) is based on abductive reasoning over ontologies [4]. In this method the domain expert is iteratively prompted to provide inferences that they expect of the ontology. If the inference cannot be entailed from the ontology, the reasoner suggests expansions of the ontology that would entail the desired consequence. The domain expert is then asked to select the most appropriate enrichment according to their domain knowledge and that axiom is added to the ontology. Through this method, the knowledge of the domain expert is elicited both when the domain expert provides the expected inference, as well as when the domain expert selects the most appropriate expansion of the ontology.

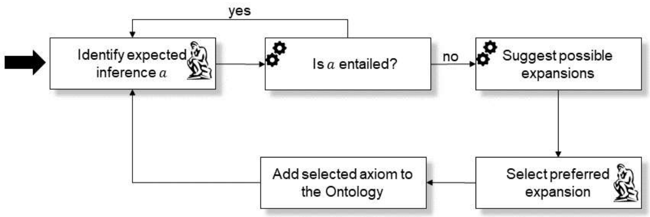

Figure 1: A flowchart of the *Abductive Completion* method. The cog icon denotes involvement of the reasoner and the human figure denotes involvement of the domain expert.

Reasoning-Supported Interactive Revision of Knowledge Bases (RSIR of KB) [5], as seen in Fig. 2, supports ontology revision based on logical criteria. In this approach, a set of candidate axioms are provided, from which the axiom that allows the automatic evaluation of the highest number of unevaluated axioms, i.e., the most *impactful* axiom, is presented to the domain expert. If the expert accepts the axiom, it is added to the knowledge base (i.e. the knowledge base is enriched). Otherwise, the axiom is added to an unintended consequence set.

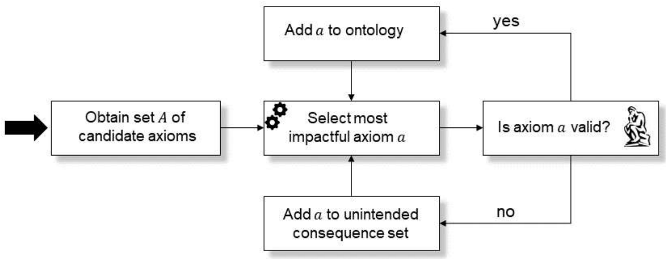

Figure 2: A flowchart of the *Reasoning-Supported Interactive Revision of Knowledge Bases* method. The cog image denotes reasoner involvement and the human figure denotes expert involvement.

The ***Advocatus Diaboli*** methodology [6] (see Fig. 3) introduces a system that allows domain experts to enrich an ontology by adding negative constraints, which are often overlooked despite their effectiveness in causing inconsistencies, finding modeling errors [8], repairing the mapping between ontologies [9], and iteratively revising ontologies [10]. The main idea behind the *Advocatus Diaboli* methodology is to allow the domain expert to show that the given ontology is underconstrained by actively constructing class expressions that are satisfiable according to the current ontology[3], but impossible according to the expert's knowledge. Following this process, domain experts can add negative constraints which invalidate the impossible class expressions and thus, make the ontology more complete.

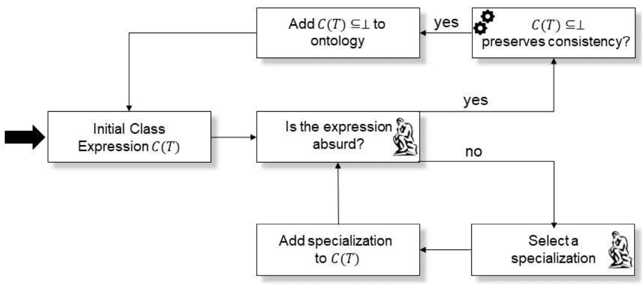

Figure 3: A flowchart of the *Advocatus Diaboli* method. The cog image denotes reasoner involvement and the human figure denotes expert involvement.

The ***Relational Exploration*** approach [7] (see Fig. 4) describes a formal process that aims to produce complete domain specifications by iteratively generating hypotheses which are processed by a reasoner that evaluates if they are entailed or rejected based on the existing ontology. If a generated hypothesis is not entailed or rejected, it is then presented as a question to a domain expert who either accepts or rejects it. This methodology ensures that, upon completion, the resulting domain specification is complete and that the domain expert never has to answer redundant questions, thus, minimizing the burden placed on them. The knowledge elicited from the domain experts results in the enrichment of incomplete ontologies.

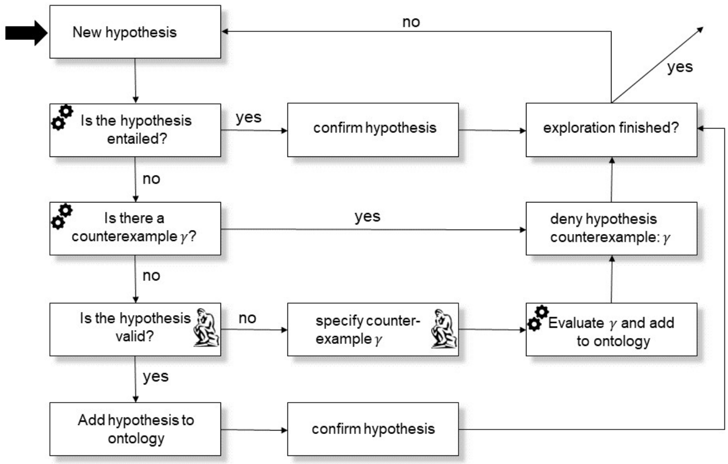

Figure 4: A flowchart of the *Relational Exploration* method. The cog image denotes reasoner involvement and the human figure denotes expert involvement.

[3]Preservation of satisfiability is ensured by the way the class expressions are constructed in a navigation-like process similar to faceted browsing

4. Results

In this section, we utilize our proposed framework for comparison of four ontology enrichment methodologies that elicit domain expert knowledge through structured interaction with a human. The results of this comparison are shown in Table 1.

Table 1
Table comparing the different methods for elicitation of knowledge from human domain experts. Human domain experts are denoted as H, and calls to the reasoner as R.

	Expressiveness	Comprehensiveness	Initiative	Scalability
Abduction	• Depending on given set of abducibles	• No completeness guarantee.	• Prio H >R. • H provides required inference.	• R at each step.
RSIR of KB	• class hierarchy and disjointness	• No completeness guarantee.	• Prio R >H • H provides required inference.	• Ranking limits R. • R at initialization. • R after H. • Patronizes H
Advocatus Diaboli	• Negative constraints wrt. cognitively plausible class expressions	• Every reachable situation is possible. • All possible situations are reachable. • Complex quantifiers not possible. • No completeness guarantee.	• Prio on H >R. • H can explore worlds. • H can exclude worlds.	• Expensive for H. • R at initialization. • R at each navigation step.
Relational Exploration	• General class inclusions with respect to a specified logical fragment.	• Terminates after finite steps. • Completeness upon termination. • H can stop it beforehand.	• Prio on R >H. • H if and only if R fails. • H can specify counter-examples. • H can complete assertions.	• R at initialization. • R after H. • Patronizes H • R for counter-examples.

5. Discussion

Of the four methods discussed in this work, the only two that allow situations/hypotheses to be generated dynamically are the *Advocatus Diaboli* and the *Relational Exploration* methods. Because of this, they are the most comprehensive ones and they have the potential to identify the highest number of missing expected inferences through interaction with the human expert. Indeed, the *Relational Exploration* method guarantees the completeness of the knowledge base upon completion. While this guarantee serves to highlight the comprehensiveness of the method, it remains theoretical since it may require the human expert to answer exponentially many questions before completion. As such, in real-world applications, we can expect both methods to perform similarly in terms of comprehensiveness, with the *Advocatus Diaboli* methodology being better at allowing the expert to guide the process toward the situations that are of interest to them, whereas the *Relational Exploration* methodology has the ability to automatically generate new hypotheses that the domain expert may not have thought of.

The interaction techniques use a variety of ways to represent the breadth of the human domain expert's ideas. For example, both *RSIR of KB* and *Advocatus Diaboli* use class expressions to turn axioms unsatisfiable if their consequence is unintended. However, the largest difference between them is on initiative and scalability (see Table 1 above). *Relational Exploration* deals only with conjunction on atomic classes. However, it is possible to leverage ontological background by having complex definitions for named classes [11]. In contrast, Ferré and Rudolph [6] aid the human domain expert in the construction of intuitive satisfiable class expressions, which – if found to be absurd – can be turned unsatisfiable by adding a corresponding negative constraint to the knowledge base.

With respect to initiative, the methods shown in this work are evenly divided with the reasoner leading the process in *Advocatus Diaboli* and *RSIR of KB* and the expert initiating the process in *Abductive Completion* and *Relational Exploration*. An important drawback of the *Abductive Completion* method is that the expected inference must be provided by the domain experts, which places an undue burden on them, since they have to both generate the expected inferences and formulate them in formal logic. Similarly, the *Relational Exploration* method requires the user to input a counterexample for invalid hypotheses which assumes that the domain expert can not only identify the correct counterexample, but also describe it in logical formulae. Given that such familiarity with formal logic cannot be expected in most cases, these methods are prone to inserting wrong information in the ontology and deteriorating its quality. Furthermore, it is important to note that while *Relational Exploration* and *RSIR of KB* are similar in terms of the workflow, the major difference is that in *Relational Exploration* the axioms are not pre-specified but created on the go and therefore, the exploration may require exponentially many human decisions [5].

Heavy reliance on the reasoner at different stages in the elicitation process may negatively affect the scalability of the methodologies, making them unfit for larger knowledge bases. Vice versa, heavy reliance on the human domain expert will greatly reduce the efficiency and could potentially result in the loss of quality in the enrichment of the ontology.

The possible complexities with regard to scaling the methodology are largely intertwined with the number of calls to the reasoner. *RSIR of KB* is the only interaction technique that computes and updates decision spaces to bring down the the number of calls to the reasoner by up to 75% [10]. The axiom's *impact* as defined by Nikitina [10] determines a beneficial order of evaluation that none of the other interaction techniques use.

Naturally, the involvement of a human domain expert is required for the enrichment of ontologies; particularly, in the context of knowledge elicitation, where Formal Semantic methodologies are seldom enough for adequate representations. Yet, often formal reasoning can be leveraged to keep the necessary human interaction at a manageable level.

We argue that our preliminary results show that comparison over the four dimensions allows the identification of the strengths and weaknesses of each methodology. Furthermore, the comparison framework highlights the appropriate application scenario for each of the chosen methods. Additionally, our method facilitates evaluation, hence it helps create a movement toward more effective enrichment processes that allows users more utility using semantic and formal axiom enrichment methods. For example, creating better (i.e., more explainable) user interfaces to make the underlying mechanics more understandable to human domain experts unfamiliar with Formal Semantics.

All the studies reviewed so far, however, suffer from the fact that human domain experts could make mistakes in their assumptions of the domain knowledge, which can cause a loss of quality in the enrichment of the ontology. Likewise, unfamiliarity of the human domain experts with Formal Semantics and logical inferences could result in the enrichment of the ontology with false axioms.

The scope of this study was limited in terms of the compared methods (i.e., selected methods all focus on a subset of enrichment methods). The study does not consider the plethora of "newer" approaches that incorporate external resources through machine- and/ or deep learning (e.g., through recommendations based on natural language processing). However, we argue that the comparison framework as suggested in this study can also be applied to those.

6. Conclusion

In this position paper, we have reviewed a variety of methodologies for ontology enrichment through interaction with human domain experts. We have provided a comparative qualitative analysis on a selection of existing Formal Semantic techniques and their constituent phases (i.e. detection, expansion, and validation) on four dimensions; namely: i) Comprehensiveness, ii) Expressiveness, iii) Initiative, and iv) Scalability.

Involvement of human domain experts in ontology enrichment is required for the maintenance and upkeep of high quality ontologies. However, finding the correct interplay between formal reasoning and human involvement depends on the size of the ontology, the availability of resources, and the requirements of the use case. The task-specific nature of ontologies also forces certain constraints on the human domain experts i.e. the quality of the enrichment is directly intertwined with the domain knowledge of the human domain experts.

We further argue that the provided comparison framework can also help steer the movement towards a more effective enrichment process. Indicating that user interfaces can help improve the explainability of the underlying mechanics, and as such improve the quality of the interaction between the human domain expert and the ontology.

7. Future Work

In this paper, we focused on identification and definition of four dimensions for comparison of ontology enrichment methodologies. A natural progression of this work would be to develop quantitative measures, to increase robustness, for the introduced dimensions. Finally, more work needs to be done to link the Expressiveness, Comprehensiveness, Initiative, and Scalability dimensions to method performance.

In order to increase reliability and confidence in the quality of the ontology, we propose the creation and use of a collaborative framework in which multiple domain experts can communicate and share their understanding of the concepts and agree on conceptual models in the elicitation process. Furthermore, using an intermediate language such as Manchester OWL syntax [12] to translate syntactically challenging logical elements into a simplified version for human domain experts could improve the robustness of the knowledge elicitation process. Another interesting venue would be research into the different combinations of methods for the different steps of the enrichment process, as described in Section 2 of this work. Moreover, research into axiom ranking and axiom choosing strategies, as demonstrated in Nikitina et al. [5], can reduce the amount of manual effort and automated reasoning.

Using the evaluation dimensions described in this work, current and future ontology enrichment methodologies can be evaluated and scored. The scores obtained in each dimension will highlight the strengths and weaknesses of the methodology and, by extension, the scenario that it is best suited for. As such, a web framework can be created where the domain experts can input the ontology that they desire to enrich and specify the importance of each dimension for their enrichment task using appropriate input methods e.g. a slider. The system can then automatically evaluate the ontology based on its entities, relations and other characteristics and suggest the most appropriate enrichment methodology for the task.

In the movement towards a more effective enrichment processes, improvements in the explainability of the underlying mechanics are of imminent importance. Implementations of the examined methodologies rely on keyboard and mouse input which may not be optimal. Therefore, further research in Human-Computer Interaction methodologies needs to be conducted to elucidate which interaction method is best for eliciting the required information from the domain expert while minimizing the burden placed on them.

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