Integrating Description Logics and Answer Set Programming for Explainable Decision-Making in Digital Health

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Abstract

This research investigates the integration of logic-based reasoning paradigms for explainable and personalized decision-making in digital health. In particular, it combines Description Logics (DL) and Answer Set Programming (ASP) to bridge structured knowledge representation and constraint-based reasoning. The core objective is to study how these two paradigms can be effectively combined within a unified framework. In this context, ontological knowledge is represented using the Web Ontology Language (OWL), with a focus on large-scale clinical ontologies such as SNOMED CT. From an implementation perspective, the approach investigates the use of ASP systems such as `clingo`, leveraging theory atoms to enable the integration of ontological reasoning within logic programs. The goal is to develop a unified logic-based framework for building explainable and reliable digital health agents.

Keywords

Answer Set Programming, Description Logic, Knowledge Representation and Reasoning, Digital Health

1. Introduction and Problem Description

Artificial Intelligence (AI) is increasingly employed in healthcare to support clinical decision-making, personalized treatment, and patient monitoring [1, 2, 3]. However, many current approaches rely on data-driven and black-box models, which often lack transparency, interpretability, and verifiability [4, 5]. In safety-critical domains such as healthcare, these limitations are particularly critical, since decisions must be auditable, aligned with domain knowledge, and consistent with user-specific constraints.

Healthcare scenarios are inherently complex, as they require the integration of heterogeneous sources of knowledge, including structured medical knowledge, operational constraints, and patient-specific information [6]. Supporting reliable and formally grounded decision-making in such settings remains a significant challenge.

Over the past decades, a significant body of research in the Semantic Web has focused on defining formal languages for representing structured knowledge. This effort led to the standardization of the Web Ontology Language (OWL) [1] in 2004, which has since become a central technology for ontology modeling. OWL is grounded in Description Logics (DLs), a family of knowledge representation formalisms based on fragments of first-order logic, offering a well-understood balance between expressivity and computational properties [7]. Due to these characteristics, OWL has been successfully applied in a wide range of domains, including information integration, knowledge management, and biomedical informatics.

Several reasoning systems have been developed to support inference over OWL ontologies, such as Hermit, FaCT++, Pellet, and ELK [2]. These systems enable tasks such as consistency checking,

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[1]https://www.w3.org/TR/owl2-overview/
[2]A list of reasoners is available at https://www.w3.org/2001/sw/wiki/Category:OWL_Reasoner

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classification, and instance retrieval, and have been widely used both in research prototypes and in emerging real-world applications.

Symbolic approaches based on Knowledge Representation and Reasoning (KRR) offer a promising direction, as they enable explicit modeling of knowledge and logically grounded inference [8]. In particular, DLs and OWL provide formal mechanisms for representing structured domain knowledge, while Answer Set Programming (ASP) supports constraint-based reasoning and decision-making [9, 10, 11, 12, 13].

Despite their complementary strengths, these paradigms are typically used in isolation. DL-based systems focus on inference over structured knowledge, whereas ASP is mainly employed for solving constraint-based problems. Their integration remains limited, especially in domains requiring both rich semantic knowledge and complex constraints.

This research addresses this gap by investigating the integration of DL-based and ASP-based reasoning within a unified framework. The goal is to combine ontological knowledge with constraint-based reasoning to support transparent decision-making in digital health.

2. Background and Overview of the Existing Literature

Knowledge Representation and Reasoning provides formal tools for modeling structured knowledge and supporting logical inference in intelligent systems [14, 15].

Among the most widely used formalisms, Description Logics offer a well-founded framework for representing domain knowledge through concepts, roles, and individuals, while ensuring decidability and effective reasoning capabilities [7]. DL-based systems support inference tasks such as consistency checking, subsumption, and instance retrieval, which are essential for applications requiring formally grounded reasoning.

Ontologies, typically expressed in OWL, provide a standard mechanism for structuring domain knowledge and enabling semantic interoperability [16, 17]. In the biomedical domain, large-scale ontologies such as SNOMED CT [3], the Foundational Model of Anatomy (FMA)[4], and the Gene Ontology (GO) [5] are widely used to represent clinical and biological knowledge.

Recent efforts have focused on integrating ontology engineering within modern AI ecosystems, particularly through Python-based libraries. Frameworks such as OWLAPY [6] provide flexible interfaces for manipulating and reasoning over OWL ontologies, while tools such as Owlready2 [7] and RDFLib [8] support ontology access and RDF-based querying within Python environments.

In parallel, ASP has been extensively used for modeling constraint-based and combinatorial problems [18, 13]. ASP enables declarative problem solving through rules and constraints, supporting transparent reasoning and solution generation.

2.1. Integration of Description Logics and Rules

The integration of ontological reasoning and rule-based systems has been widely studied in the literature. One prominent approach is represented by description logic programs (dl-programs), which combine a DL knowledge base with logic programming rules [19]. In this framework, so-called DL-atoms are used as query interfaces to the ontology, enabling rules to access ontological knowledge while preserving a loose coupling between the two components.

Subsequent work has further developed this line of research, studying the computational properties and practical implementation of DL-programs, including mechanisms for handling inconsistencies and optimizing reasoning [20]. These approaches highlight the importance of a modular interaction

[3] https://www.snomed.org/
[4] http://si.washington.edu/projects/fma/
[5] https://geneontology.org/
[6] https://dice-group.github.io/owlapy/
[7] https://owlready2.readthedocs.io/en/v0.50/
[8] https://rdflib.readthedocs.io/en/stable/

between rules and ontologies, where information flows between the two layers through well-defined interfaces.

An alternative direction is represented by hybrid semantic frameworks that aim at a tighter integration of Description Logics and rules. For instance, MKNF-based approaches provide a unified semantic foundation by combining open-world reasoning with nonmonotonic rule-based inference [21]. Although these approaches offer a strong theoretical basis, they also introduce additional complexity in terms of semantics and reasoning algorithms.

Despite these efforts, combining DL-based reasoning with ASP in a way that is both expressive and practically scalable remains an open challenge. In particular, the interaction between open-world ontology reasoning and closed-world constraint solving is still not fully understood, especially in the context of large real-world ontologies such as SNOMED CT.

3. Goal of the Research

The main goal of this research is to investigate the integration of logic-based reasoning paradigms for explainable and personalized decision-making in digital health.

The research focuses on combining Description Logics, used for structured knowledge representation in ontologies, with Answer Set Programming, used for constraint-based reasoning and decision-making. The objective is to study how these paradigms can be effectively integrated within a unified framework. The objective is to establish a semantic bridge between ontology-based inference and constraint-based reasoning, enabling the interaction between the open-world semantics of DL and the closed-world reasoning of ASP.

In this context, ontological knowledge is represented using OWL, based on $\mathcal{SROIQ}$ [22], with a particular focus on large-scale clinical ontologies such as SNOMED CT. These ontologies provide rich semantic descriptions that can be exploited during reasoning.

For example, the SNOMED CT concept *Bacterial pneumonia (disorder)* can be defined through an equivalent class axiom involving multiple attributes:

```
EquivalentClasses(
  :BacterialPneumonia
  ObjectIntersectionOf(
    :Disease
    ObjectSomeValuesFrom(:CausativeAgent :Bacteria)
    ObjectSomeValuesFrom(:FindingSite :LungParenchyma)
    ObjectSomeValuesFrom(:PathologicalProcess :InfectiousProcess)
  )
)
```

The corresponding Description Logic representation is:

$$\begin{aligned} \mathsf{BacterialPneumonia} \equiv\ & \mathsf{Disease} \sqcap \\ & \exists\, \mathsf{CausativeAgent.Bacteria} \sqcap \\ & \exists\, \mathsf{FindingSite.LungParenchyma} \sqcap \\ & \exists\, \mathsf{PathologicalProcess.InfectiousProcess} \end{aligned}$$

Such axioms enable a DL reasoner to infer semantic classifications over clinical concepts. The goal of this research is to exploit this inferred knowledge within ASP-based reasoning, for instance by using ontological classifications to constrain and guide decision-making processes.

The expected outcome is a unified framework that integrates ontology-driven inference with ASP-based reasoning, supporting decision processes that are both semantically informed and computationally effective in complex healthcare scenarios.

4. Current Status of the Research

The research conducted so far has focused on the use of ASP for modeling and solving constraint-based decision problems, with particular attention to the representation of heterogeneous requirements and optimization criteria.

An initial line of work explored ASP encoding for constraint-based decision problems in a recommendation setting [23]. In this context, domain knowledge and user-specific constraints are represented as logical facts and rules, allowing the computation of valid solutions through constraint satisfaction. This work provided practical experience in modeling complex interactions between constraints, as well as in the use of aggregates and optimization statements to guide solution selection.

Building on this, the research has progressively moved toward the integration of structured domain knowledge into logic-based reasoning. In particular, current work investigates how knowledge expressed in DL, and encoded in OWL ontologies, can be accessed and exploited within ASP-based workflows. Preliminary experiments have been carried out using Python-based tools to query ontological information, such as concept membership and hierarchical relations.

A central focus of the ongoing research is the integration of DL-based reasoning with ASP. Existing systems, such as DLVHEX [24], provide mechanisms to interface ASP programs with external reasoning components through external atoms. Inspired by these approaches, this work explores integration strategies grounded in the logic of *Here-and-There with constraints*(HT_c) [25], which provides a semantic foundation for hybrid ASP systems, also called ASP modulo theory. The HT_c approach allows the incorporation of theory atoms into the propositional logic of *Here-and-There* (HT) [26] and has been used so far for providing a theoretical semantics to hybrid ASP solvers dealing with numerical constraints [27] such as `clingo[dl]`, `clingcon`, `clingo[LP]` or more recently, `flingo` [28]. In the proposal, we plan to extend the framework with new DL theory atoms. We will also study the possible relation to other approaches that consider the full integration of DL into first order HT [29, 30].

From an implementation perspective, current efforts concentrate on extending ASP systems, in particular `clingo`, to interact with ontological knowledge through theory atoms and external interfaces. The goal is to enable logic programs to query ontological predicates during solving, while preserving the declarative nature of ASP.

Overall, the research is evolving from application-driven ASP modeling toward the design of hybrid reasoning systems, where constraint-based logic programming is combined with ontology-based knowledge representation in a unified framework.

5. Preliminary Results Accomplished

The work carried out so far has focused on building the foundations for integrating ontology-based reasoning with logic programming, starting from the acquisition and analysis of real-world clinical knowledge sources.

A first step consisted in obtaining the complete SNOMED CT ontology, which is distributed as a structured release containing concepts, descriptions, and relationships. In particular, SNOMED CT organizes clinical knowledge through unique concept identifiers, lexical descriptions (including synonyms), and typed relationships that define hierarchical and semantic connections between concepts. This structure enables the representation of complex medical knowledge, including diseases, procedures, substances, and clinical findings.

Following this, the structure of SNOMED CT has been analyzed in order to understand how clinical concepts are modeled and interconnected. Concepts are organized in a hierarchical taxonomy through *is-a* relationships, while additional attributes (such as causative agents, finding sites, and pathological processes) provide richer semantic definitions. These characteristics make SNOMED CT particularly suitable for ontology-based reasoning.

To enable formal reasoning, SNOMED CT data have been converted into OWL format using the

SNOMED OWL Toolkit.[9] This step is necessary because the native SNOMED distribution is not directly usable by standard DL reasoners. The OWL representation allows the ontology to be processed using Description Logic reasoning tools, enabling tasks such as classification, subsumption, and instance checking.

Once the ontology was available in OWL format, different reasoning approaches have been explored within Python environments. Several libraries for ontology manipulation and reasoning have been evaluated, and the final choice has been OWLAPY [31], due to its flexibility and ease of integration with external systems. This enables programmatic access to ontological knowledge, including concept hierarchies and semantic relationships.

To move toward integration with ASP, a preliminary interface between ontology-based reasoning and logic programming has been investigated.

From an implementation perspective, this interaction can be modeled in `clingo` through theory atoms. In `clingo`, a theory is defined by specifying its syntax via the `#theory` directive:

```
#theory T {D1 ;. . .;Dn }.
```

where each D_i defines a component of the theory syntax. A theory atom can then be used within a `clingo` program according to the following general form:

```
&name { terms } : condition.
```

In the context of this research, theory atoms are used as an interface between the ASP solver and an external ontological reasoning component. This allows logic programs to query semantic information derived from OWL ontologies during the solving process. For instance, an ASP program may select a candidate drug and then query the ontology to verify whether the corresponding concept belongs to a given class, such as an antibacterial drug, thus integrating ontological inference into constraint-based decision-making.

This component is intended to act as a bridge between the ontology layer and the ASP reasoning layer: `clingo` is used for constraint solving and decision-making, while the Python-based ontology component performs DL reasoning and returns results to the ASP program.

6. Open Issues and Expected Achievements

The proposed research builds upon several previous works developed during the PhD. In particular, earlier work has shown the effectiveness of ASP for modeling constraint-based decision problems in personalized nutrition scenarios, where complex user requirements are encoded and solved through logical rules [23]. Additional work has explored the use of ASP in scheduling and optimization problems, demonstrating its suitability to handle combinatorial decision-making tasks [32].

More recently, a hybrid framework that combines ASP with epistemic logic has been proposed to move from static constraint-based systems to cognitively enriched agents capable of reasoning about beliefs, preferences, and actions [33]. In this approach, ASP is used for optimization, while epistemic reasoning enables adaptive and explainable decision-making.

These previous works provide a foundation for the current research, which aims to extend such approaches by incorporating structured ontological knowledge. In particular, integration with OWL ontologies allows moving from purely data-driven constraints to semantically enriched reasoning, where domain knowledge (e.g., diseases, drugs, and clinical relations) is explicitly modeled and exploited.

The next phase of the research will therefore focus on combining these existing ASP-based modeling techniques with ontology-driven reasoning, enabling applications such as disease classification combined with treatment selection. In this setting, ontological inference can be used to derive semantic information, while ASP can enforce constraints and guide decision-making.

The expected outcome is a unified logic-based framework that integrates ontology-driven knowledge representation with constraint-based reasoning. The implementation based on SNOMED CT will be

[9] https://github.com/IHTSDO/snomed-owl-toolkit

evaluated in collaboration with healthcare professionals, with the aim of assessing its accuracy, usability, and alignment with clinical practice. This evaluation will provide feedback to refine the proposed approach and validate its applicability in real-world scenarios.

Declaration on Generative AI

During the preparation of this work, the authors used Grammarly and ChatGPT (OpenAI) to assist with grammar and spelling checks, as well as paraphrasing and rewording of certain sentences. After using these tools, the authors carefully reviewed and edited the content to ensure accuracy, coherence, and compliance with academic standards. The authors take full responsibility for the content of this publication.

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