Ontohub: A semantic repository for heterogeneous ontologies

Mihai Codescu\textsuperscript{1}, Eugen Kuksa\textsuperscript{2}, Oliver Kutz\textsuperscript{1},
Till Mossakowski\textsuperscript{2}, Fabian Neuhaus\textsuperscript{2}

\textsuperscript{1} Free University of Bozen-Bolzano, Italy,
E-mail: \{Mihai.Codescu,Oliver.Kutz\}@unibz.it
\textsuperscript{2} Otto-von-Guericke University of Magdeburg, Germany,
E-mail: \{kuksa,till,fneuhaus\}@iks.cs.ovgu.de

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Abstract

Ontohub is a repository engine for managing distributed heterogeneous ontologies. The distributed nature enables communities to share and exchange their contributions easily. The heterogeneous nature makes it possible to integrate ontologies written in various ontology languages. Ontohub supports a wide range of formal logical and ontology languages, as well as various structuring and modularity constructs and inter-theory (concept) mappings, building on the OMG-standardized DOL language. Ontohub repositories are organised as Git repositories, thus inheriting all features of this popular version control system. Moreover, Ontohub is the first repository engine meeting a substantial amount of the requirements formulated in the context of the Open Ontology Repository (OOR) initiative, including an API for federation as well as support for logical inference and axiom selection.

1 Introduction

Ontologies play a central role for enriching data with a conceptual semantics and hence form an important backbone of the Semantic Web. The number of ontologies that are being built or already in use is steadily growing. This means that facilities for organizing ontologies into repositories, searching, maintenance and so on are becoming more important.

Ontohub’s overall design was conceived to satisfy a substantial subset of the requirements set out in the Open Ontology Repository (OOR) initiative\textsuperscript{1}. OOR is a long-term international effort, which established requirements and designed an overall architecture for ontology repositories. Ontohub is the first implementation of a repository engine meeting a substantial amount of OOR’s requirement, including an API for

\textsuperscript{1}See http://www.oor.net
federation as well as support for logical inference and axiom selection. Moreover, it extends the initial OOR vision by several features suggested by the development of the DOL language. First and foremost, this includes the fundamental abstraction from particular ontology languages, providing a principled logic-based support for heterogeneity in ontology design, based on general model-theoretic semantics.

This paper is an updated and extended version of [17]. Among the new case studies presented here, we include one that appeared in [10]. In the next two subsections, we will give an overview of Ontohub’s features and discuss related work. Section 2 introduces the Distributed Ontology Language (DOL) that is central to Ontohub. Ontohub’s architecture is described in Sect. 3. Section 4 shows Ontohub at use with some ontology alignments, as well as with theorem proving. Section 5 concludes the paper.

1.1 Features of Ontohub

Ontohub is a novel web-based repository engine. Central features are:

multiple repositories ontologies can be organized in multiple repositories, each with its own management of editing and ownership rights,

Git interface version control of ontologies is supported via interfacing the Git version control system,

linked-data compliance one and the same URL is used for referencing an ontology, downloading it (for use with tools), and for user-friendly presentation in the browser.

Ontohub is unique in following OOR’s ambitious goals, in particular,

modular architecture Ontohub is decoupled into different services,

multi-language support ontologies can formalized in various logics like OWL, Common Logic, TPTP and higher-order logic,

logical inference intended consequences of ontologies can be proved.

Finally, Ontohub fully supports modular and distributed ontologies through the Distributed Ontology Language (DOL), a standard approved by Object Management Group (OMG) [14, 21, 15], see also [dol-omg.org]. DOL provides a unified framework for (1) heterogeneous ontologies formalized in more than one logic, (2) modular ontologies, (3) mappings between ontologies (alignments, interpretation of theories, conservative extensions, translation to other ontology languages etc.). All of these features are equipped with a formal semantics.

Users of Ontohub can upload, browse, search and annotate basic ontologies in various languages via a web frontend, see [https://ontohub.org]. Ontohub is open source under GNU AGPL 3.0 license, the sources are available at the following URL [https://github.com/ontohub/ontohub]. Currently, Ontohub has about 200 registered users, which include ontology researchers, ontology developers as well as master and PhD students.
Ontohub is not a repository, but a semantic repository engine. This means that Ontohub ontologies are organized into repositories. See Fig. 1 for an overview of the currently available repositories. Some of them, e.g. Bioportal or COLORE, are mirrors of repositories hosted elsewhere (as indicated with the mirror icons), while the others are native Ontohub repositories. The organisation into repositories has several advantages:

- Firstly, repositories provide a certain structuring of ontologies, let it be thematically or organisational. Access rights can be given to users or teams of users per repository. Typically, read access is given to everyone, and write access only to a restricted set of users and teams. However, also completely open world-writeable repositories are possible, as well as private repositories visible only to a restricted set of users and teams. Since creation of repositories is done easily with a few clicks, this supports a policy of many but small repositories (which of course does not preclude the existence of very large repositories). Note that also structuring within repositories is possible, since each repository is a complete file system tree.
Secondly, repositories are Git repositories. Git is a popular decentralised version control system. With any Git client, the user can clone a repository to her local hard disk, edit it with any editor, and push the changes back to Ontohub. Alternatively, the web frontend can be used directly to edit ontologies; pushing will then be done automatically in the background. Parallel edits of the same file are synchronized and merged via Git; handling of merge conflicts can be done with Git merge tools.

Thirdly, ontologies can be searched globally in Ontohub, or in specific repositories. Additionally, user-supplied metadata can be used for searching.

Ontohub is linked-data compliant. This means that ontologies are referenced by a unique URL of the form \( \text{https://ontohub.org/name-of-repository/path-within-repository} \). Depending on the MIME type of the request, under this URL, the raw ontology file will be available, but also a HTML version for display in a browser and a JSON version for processing with tools.

1.2 Related Work

Existing ontology resources on the web include search engines like Swoogle, Watson, and Sindice. They concentrate on (full-text and structured) search and querying. Ontology repositories also provide persistent storage and maintenance. TONES [1] is a repository for OWL [9] ontologies that provides some metrics, as well as an OWL sublanguage analysis. BioPortal [20] is a repository that originates in the biomedical domain, but now has instances for various domains. Beyond browsing and searching, it provides means for commenting and aligning ontologies. Besides OWL, also related languages like OBO [24] are supported. The NeOn Toolkit [2] supports searching, selecting, comparing, transforming, aligning and integrating ontologies. It is based on the OWL API and is no longer actively maintained.

The Open Ontology Repository (OOR) initiative aims at “promoting the global use and sharing of ontologies by (i) establishing a hosted registry-repository; (ii) enabling and facilitating open, federated, collaborative ontology repositories, and (iii) establishing best practices for expressing interoperable ontology and taxonomy work in registry-repositories, where an ontology repository is a facility where ontologies and related information artifacts can be stored, retrieved and managed” [22]. One important goal of OOR is the support of ontology languages beyond OWL, for example Common Logic. Another goal is the support of logical inference. Some proposed architecture is shown in Fig. 2. OOR is a long-term initiative, which has not resulted in a complete implementation so far [3], but established requirements and designed an architecture.

\(^2\)In the future, this may change into \( \text{https://ontohub.org/account-name/name-of-repository/path-within-repository} \).

\(^3\)The main implementation used by OOR is (a cosmetically adapted) BioPortal, which however does not follow the OOR principles very much. There are no OOR implementation efforts beyond Ontohub.

\(^4\)See \( \text{http://ontologforum.org/index.php/OpenOntologyRepository_Requirement} \) and \( \text{http://ontolog.cim3.net/wiki/OpenOntologyRepository_Architecture/candidate03.html} \).
2 DOL

Figure 3: ontohub.org portal: overview of logics

The modularity mechanisms of Ontohub are based on those of the Distributed Ontology Language (DOL). DOL aims at providing a unified framework for (1) ontologies formalized in heterogeneous logics, (2) modular ontologies, (3) links between ontologies, and (4) annotation of ontologies.

2.1 Logics

The large variety of logics in use can be captured at an abstract level using the concept of logic syntax, which we introduce below. This allows us to develop results independently of the particularities of a logical system. The main idea is to collect the non-logical symbols of the language in signatures and to assign to each signature the set of sentences that can be formed with its symbols. For each signature, we provide means for extracting the symbols it consists of, together with their kind. Signature morphisms are mappings between signatures. Formally, signatures and their morphisms form a so-called category, which can be understood as a graph together with a composition principle that identifies paths in the graph. Signature morphisms induce a mapping between the sentences of the signatures, usually by replacing the symbols that occur in a sentence with their image through the signature morphism. [15] provides full details of the formal aspects of DOL.
A logic syntax can be complemented with a model theory, which introduces semantics for the language and gives a satisfaction relation between the models and the sentences of a signature. The result is a so-called institution \([6]\). Similarly, we can complement a logic syntax with a proof theory, introducing a derivability relation between sentences, thus obtaining an entailment system \([13]\). In particular, this can be done for all logics in use in Ontohub.

**Example 2.1** OWL signatures consist of sets of atomic classes, individuals and properties. OWL signature morphisms map classes to classes, individuals to individuals, and properties to properties. For an OWL signature \(\Sigma\), sentences are subsumption relations between classes, membership assertions of individuals on classes and pairs of individuals in properties. Sentence translation along a signature morphism is simply replacement of non-logical symbols with their image along the morphism. The kinds of symbols are class, individual, object property and data property, respectively, and the set of symbols of a signature is the union of its sets of classes, individuals and properties.

In this framework, an ontology \(O\) over a logic syntax \(L\) is a pair \((\Sigma, E)\) where \(\Sigma\) is a signature and \(E\) is a set of \(\Sigma\)-sentences. Given an ontology \(O\), we denote by \(\text{Sig}(O)\) the signature of the ontology. An ontology morphism \(\sigma : (\Sigma_1, E_1) \rightarrow (\Sigma_2, E_2)\) is a signature morphism \(\sigma : \Sigma_1 \rightarrow \Sigma_2\) such that \(\sigma(E_1)\) is a logical consequence of \(E_2\). Several notions of translations between logics can be introduced. In the case of

![Diagram](image)

**Figure 4:** The part of the DOL ontology concerning mappings

logic syntaxes, the simplest variant of translation from \(L_1\) to \(L_2\) maps \(L_1\)-signatures along \(\Phi\) to \(L_2\)-signatures and \(\Sigma\)-sentences in \(L_1\) to \(\Phi(\Sigma)\)-sentences in \(L_2\), for each \(L_1\)-signature \(\Sigma\), in a compatible way with the sentence translations along morphisms. The complexity of translation increases when a model theory or a proof theory is added to the logic syntax. Fig. 4 shows the inferred class hierarchy below the class *Mapping*.
of the DOL ontology (see Sect. 2.3 below), as computed within PROTEGE. Mappings are split along the following dichotomies:

- **translation versus projection**: a translation embeds or encodes a logic into another one, while a projection is a forgetful operation (e.g. the projection from first-order logic to propositional logic forgets predicates with arity greater than zero). Technically, the distinction is that between institution comorphisms and morphisms [5].

- **plain mapping versus simple theoroidal mapping** [5]: while a plain mapping needs to map signatures to signatures, a simple theoroidal mapping maps signatures to theories. The latter therefore allows for using “infrastructure axioms”: e.g. when mapping OWL to Common Logic, it is convenient to rely on a first-order axiomatization of a transitivity predicate for properties etc.

Mappings can also be classified according to their accuracy, see [16] for details. **Sublogics** are the most accurate mappings: they are just syntactic subsets. **Embeddings** come close to sublogics, like injective functions come close to subsets. A mapping can be **faithful** in the sense that logical consequence (or logical deduction) is preserved and reflected, that is, inference systems and engines for the target logic can be reused for the source logic (along the mapping). (Weak) **exactness** is a technical property that guarantees this faithfulness even in the presence of ontology structuring operations [3].

### 2.2 A Graph of Logic Translations

![Logic Translation Graph](image)

Figure 5: The logic translation graph for DOL-conforming languages
Fig. 5 is a revised and extended version of the graph of logics and translations introduced in [16]. New nodes include UML class diagrams, OWL-Full (i.e. OWL with an RDF semantics instead of description logic semantics), and Common Logic without second-order features (CL−). We have defined the translations between all of these logics in earlier publications [18, 16]. The definitions of the DOL-conformance of some central standard ontology languages and translations among them has been given as annexes to the standard, whereas the majority will be maintained in an open registry (cf. Sec. 2.3).

2.3 A Registry for Ontology Languages and Mappings

The DOL standard is not limited to a fixed set of ontology languages. It will be possible to use any (future) logic or mapping (in the sense of Sect. 2.1) with DOL. This led to the idea of setting up a registry to which the community can contribute descriptions of any logics and mappings. Moreover, logics can support ontology languages (e.g. SROIQ(D) [9] supports OWL), which can in turn have different serializations. All these notions are part of the DOL ontology. This ontology turns Ontohub itself into part of the Semantic Web: it is mostly written in RDF (the data part) and OWL (the concepts), but also contains first-order parts. We use RDF and OWL reasoners in order to derive new facts in the DOL ontology. A full description and discussion of the DOL ontology can be found in [11].

Figure 6: Top-level classes in the DOL ontology

Fig. 6 shows the top-level classes of the DOL ontology’s OWL module, axiomatizing logics, languages, and mappings to the extent possible in OWL. Object-level classes (that is, classes providing the vocabulary for expressing distributed ontologies) comprise ontologies, their constituents (namely entities, such as classes and object properties, and sentences, such as class subsumptions), as well as links between ontologies.

Mappings are modelled by a hierarchy of properties corresponding to the different types of edges in Fig. 5; see also Fig. 4. The full DOL ontology is available at [http://www.omg.org/spec/DOL/DOL-terms.rdf](http://www.omg.org/spec/DOL/DOL-terms.rdf).

3 Architecture of Ontohub

Fig. 7 depicts the Ontohub architecture. The most challenging part of Ontohub’s implementation is the complex tool integration. The key feature of the OOR architecture is the decoupling into decentralised services, which are ontologically described (thus arriving at Semantic Web services). With Ontohub, we are moving towards this ar-
chitecture, while keeping a running and usable system. We now briefly describe these services.

The services are centrally integrated by the Ontohub integration layer, which is a Ruby on Rails application that also includes the presentation layer, i.e. a front-end providing the web interface, as well as the administration layer, i.e. user rights management and authorisation.

The persistence layer is based on Git (via git-svn, also Subversion repositories can be used) and an SQL database. The database backend is PostgreSQL. For the Git integration into the web application, a custom Git client was implemented in Ruby to be less prone to errors due to changes in new versions of the official Git command line client.

Efficient indexing and searching (the find layer) is done via elasticsearch.

A federation API allows the data exchange among Ontohub and also with BioPortal instances. We therefore have generalised the OWL-based BioPortal API to arbitrary ontology languages, e.g. by abstracting classes and object properties to symbols of various kinds.

Parsing and static analysis is a RESTful service of its own provided by the Heterogeneous Tool Set (Hets [19], available at http://hets.eu). Hets supports a large number of basic ontology languages and logics and is capable of describing the structural outline of an ontology from the perspective of DOL, which is not committed to one particular logic. Hets returns the symbols and sentences of an ontology in XML format. Hets can do this for a large variety of ontology languages, while the OWL API does scale better for very large OWL ontologies. The latter is an example for a service of Ontohub which is provided for a restricted set of ontology languages.

We have integrated OOPS! [23] as an ontology evaluation service (for OWL only), and from the OOPS! API, we have derived a generalised API for use with other evaluation services.

Inference is done by encapsulating standard batch-processing reasoners (Pellet, Fact, SPASS, Vampire etc.) into a RESTful API through Hets (which has been interfaced with 15 different reasoners). Integrating support for logical inference required a substantial extension of Hets’ HTTP interface which returns proof details in JSON format. The prover-independent implementation of the SInE algorithm is a novelty in this field since it has only been used with few provers so far. In Ontohub, it operates independently of the prover and, thus, supports any prover available in Ontohub.

4 Case Studies

4.1 Ontology alignment in Ontohub

The foundational ontology (FO) repository Repository of Ontologies for MULtiple USes (ROMULUS [5] contains alignments between a number of foundational ontologies, expressing semantic relations between the aligned entities. We select three such
ontologies, containing spatial and temporal concepts: DOLCE\(^6\), GFO\(^7\) and BFO\(^8\) and present alignments between them using DOL syntax\(^9\)

```xml
%prefix(  
gfo: <\protect\url{http://www.onto-med.de/ontologies/}>  
dolce: <\protect\url{http://www.loa-cnr.it/ontologies/}>  
bfo: <\protect\url{http://www.ifomis.org/bfo/}>  
)

logic OWL

alignment DolceLite2BFO :
  dolce:DOLCE-Lite.owl to  
  bfo:1.1 =  
  endurant = IndependentContinuant,  
  physical-endurant = MaterialEntity,  
  physical-object = Object,  
  perdurant = Occurrent,  
  process = Process,  
  quality = Quality,  
  spatio-temporal-region = SpatiotemporalRegion,  
  temporal-region = TemporalRegion,  
  space-region = SpatialRegion

alignment DolceLite2GFO :
  dolce:DOLCE-Lite.owl to gfo:gfo.owl =  
  particular = Individual,  
  endurant = Presential,  
  physical-object = Material_object,  
  amount-of-matter = Amount_of_substrate,  
  perdurant = Occurrent,  
  quality = Property,
```

\(^{6}\)See [http://www.loa.istc.cnr.it/DOLCE.html](http://www.loa.istc.cnr.it/DOLCE.html)

\(^{7}\)See [http://www.onto-med.de/ontologies/gfo/](http://www.onto-med.de/ontologies/gfo/)

\(^{8}\)See [http://www.ifomis.org/bfo/](http://www.ifomis.org/bfo/)

\(^{9}\)This and the other examples from this section can be found at: [https://ontohub.org/repositories/ontohubapaperexamples](https://ontohub.org/repositories/ontohubapaperexamples)
We can then combine the ontologies while taking into account the semantic dependencies given by the alignments using DOL combinations:

```plaintext
ontology Space =
   combine BFO2GFO, DolceLite2GFO, DolceLite2BFO
```

Fig. 8 shows the graph of links between ontologies created by Ontohub as a result of analysis of the Space ontology, which appears in the center of the graph. Around it and linking to it there are the aligned ontologies together with the diagrams resulting from the analysis of the alignments.\textsuperscript{10}

\textsuperscript{10}Details on the construction of these diagrams can be found in \cite{4}.
4.2 Ontology Competency Questions with Ontohub and DOL

‘Competency questions’ is the name for a methodology, which supports behavior-driven development of ontologies. The approach can be, somewhat simplified, summarized in the following steps [7]:

1. The use cases for the soon-to-be-developed ontology are captured in form of scenarios. Each scenario describes a possible state of the world and raises a set of competency questions. The answers to these competency questions should follow logically from the scenario – provided the knowledge that is supposed to be represented in the ontology.

2. A scenario and its competency questions are formalized or an existing formalization is refined.

3. The ontology is developed.

4. An automatic theorem prover is used to check whether the competency questions logically follow from the scenario and the ontology.

5. Steps (2-4) are repeated until all competency questions can be proven from the combination of the ontology and their respective scenarios.

Ontohub enables the representation and execution of competency questions with the help of DOL files. For example, let’s assume we are planning to develop an ontology of family relationships called `familyRel.omn`. One way to capture the intended capabilities of the ontology is the following:

The use case is to enable semantically enhanced searches for a database, which contains names of people, their gender, and information about parenthood. Assuming the database contains the following information:

- Amy is female and a parent of Berta and Chris.
- Berta is female.
- Chris is male and a parent of Dora.
- Dora is female.

In this case the system should be able to answer the following questions:

- Is Chris a father of Dora? (expected: yes)
- Is Berta a sister of Chris (expected: yes)
- Is Chris female? (expected: no)
- Is Amy older than Dora? (expected: yes)

These competency questions can be encoded in DOL (see Fig. 4.2). Ontohub analyses the DOL file and recognizes the proof obligations that are derived from the competency questions. These proof obligations can be validated with theorem proving (see section 4.3).
ontology scenario = <https://ontohub.org/appliedontologyontohubpaper/scenario>
ontology genealogy = <https://ontohub.org/appliedontologyontohubpaper/familyRelations>
ontology CQbase = genealogy and scenario end

%% Is Chris a father? (expected: yes)
ontology chrisFather = CQbase then %implies
   { Individual: f1:Chris Types: f1:Father } end

%% Is Dora a child of Chris (expected: yes)
ontology doraChildChris = CQbase then %implies
   { Individual: f1:Dora Facts: f1:child_of f1:Chris } end

%% Is Chris female? (expected: no)
ontology chrisFemale = CQbase then %implies
   { Individual: f1:Chris Types: not f1:Female } end

%% Is Amy older than Dora? (expected: yes)
ontology amyOlderDora = CQbase then %implies
   { Individual: f1:Amy Facts: f1:older_than f1:Dora } end

4.3 Theorem Proving in Ontohub

Ontohub recognises proof obligations in ontologies, like the competency questions above, and allows the user to invoke automated theorem provers to attempt to prove these conjectures. For simplicity, these conjectures are called “theorems” in the web application.

When an ontology has been analysed, “Theorems” are shown in its “Contents” area. There, the user can either choose to prove all conjectures at once or only a specific one. Either way, the next step is to configure the proof attempts, as shown in Fig. 10.

Above of the actual configuration options, the selected “theorems” to be proved

Figure 9: Representation of the Competency Questions in Ontohub
are listed with their names and their definitional text. This can be, for example, the competency questions of the previous section.

Multiple provers can be selected which are invoked in parallel for each selected conjecture. If no prover is actively selected by the user, a default prover is used.

A timeout for the automated theorem prover is used to limit the prover’s resources. When the given amount of time is exceeded and no proof or refutation has been found yet, the prover is stopped. Another configuration may lead to a successful proof attempt.

Axiom selection can be used to restrict a proof attempt to only include a subset of the ontology’s axioms for proving. This can reduce proving time and in some cases make proving feasible at all, which is particularly important for large ontologies. Axioms can be selected manually or automatically with a heuristic. The manual method allows the user to select every axiom that may be needed for a proof individually. The automatic heuristic is a prover-independent implementation of the SInE algorithm [8]. It expects three parameters to be set by the user that influence how many axioms are selected. The configured axiom selection is shared between all the proof attempts resulting from this configuration.

When a proof attempt is finished, it is assigned a proof status telling the result in a single word, as displayed in Fig. 11. There, the first conjecture (stating that Chris is a Father) has been evaluated with the resulting status “THM”. Thus, the ontology passes the corresponding competency question. These statuses are defined in the SZS ontology [25]. The most common statuses used by provers are

(i) THM (Theorem): All models of the axioms are models of the conjecture.
(ii) CSA (CounterSatisfiable): Some models of the axioms are models of the conjecture’s negation.

(iii) TMO (Timeout): The prover exceeded the time limit.

Of these statuses, “THM” and “CSA” indicate a successful prover run, while “TMO” shows that the prover did not finish successfully by exceeding the given amount of time. We extended the SZS ontology by a status specifically for proving with reduced axiom sets:

(iv) CSAS (CounterSatisfiableWithSubset): Some models of the selected axioms are models of the conjecture’s negation.

If a refutation of the conjecture is found using a strict subset of the axioms (which means that the prover returns with “CSA”), we do not know whether the conjecture is really false or we have excluded an axiom that is crucial to a potentially existing proof. If the prover returns with “THM”, we know by monotonicity of entailment relations that the found proof is also a proof with the full axiom set.

Details of each proof attempt, including the proof itself if the attempt finished, can be inspected on the proof attempts page. There, the user can see, for example, the configuration with the selected axioms and the actually used axioms.

Figure 11: Overview of the statuses of all theorems.

5 Conclusions and Future Work

Ontohub is on its way from a research prototype to productive use. The FOIS 2014 ontology competition has used Ontohub as platform for uploading ontologies used in submissions, see [https://ontohub.org/fois-ontology-competition](https://ontohub.org/fois-ontology-competition).

Ontologies used in FOIS papers often need expressiveness beyond OWL; here, the

11Our modified SZS ontology can be found on [http://ontohub.org/meta/proof_statuses](http://ontohub.org/meta/proof_statuses)
multi-logic nature of Ontohub is essential. A good example for these novel capabilities is given by the recent FOUST initiative ('FOundational STance'), an effort to build a digital archive hosted on Ontohub to provide authoritative formalized versions of the leading foundational ontologies (including BFO, DOLCE, GFO, GUM, UFO and YAMATO). This will include variants of these ontologies given e.g. in OWL and variants of FOL and HOL, as well as formally establishing their relationships based on theory interpretation or alignment. Another aim of the project is to provide consistency proofs, within Ontohub, by giving interpretations of the ontologies into formalised models.

Future work will improve stability and useability, and include the completion of full DOL support and the integration of ontology evaluation and workflow tools. The integration of interactive provers bears many challenges; a first step is the integration of Isabelle via the web interface Clide [12] developed by colleagues in Bremen, which is currently equipped with an API for this purpose.

Currently, a re-implementation of Ontohub is under way. The idea is to push forward the splitting into different services. Most prominently, we plan to implement the Ontohub frontend completely in ember.js/Javascript, while Ruby on Rails is only used for the JSON API served by the backend. Communication with Hets, which is currently done by the background process manager Sidekiq, will be done in the future through RabbitMQ, which is a fully-fledged service broker. This will ease the distribution of Hets parsing and proving services across server farms.

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