Distributed Island-based Query Answering for Expressive Ontologies

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Abstract. Scalability of reasoning systems is one of the main criteria which will determine the success of Semantic Web systems in the future. The focus of recent work is either on (a) systems which rely on in-memory structures or (b) not so expressive ontology languages, which can be dealt with by using database technologies.
In this paper we introduce a method to perform query answering for semi-expressive ontologies without the limit of in-memory structures. Our main idea is to compute small and characteristic representations of the assertional part of the input ontology. Query answering is then more efficiently performed over a reduced set of these small represenations. We show that query answering can be distributed in a network of description logic reasoning systems to scale for reasoning. Our initial results are encouraging.

1 Introduction

As the Semantic Web evolves, scalability of inference techniques becomes increasingly important. While in recent years the focus was on pure terminological reasoning, the interest shifts now more to reasoning with respect to large assertional parts, e.g. in the order of millions or billions of triples. The first steps were done in [FKM+06]. The authors propose to extract a condensed summary graph out of the assertional part of an ontology, and then perform reasoning on that summary. [FKM+06] reports encouraging performance results. However, for avoiding inconsistencies due to merging, the summaries have to be rewritten in expensive *query-dependent* refinement steps. With increasing number of refinement steps necessary, the performance of the aproach degrades [DFK+09]. Moreover, the technical criteria for summarization (creating representative nodes by grouping concept sets), seems arbitrary. In [WM08], a method is proposed to identify the relevant *islands*, i.e. set of assertions/information, required to reason about a given individual. The main motivation is to enable in-memory reasoning over ontologies with a large ABox, for traditional tableau-based reasoning systems.

Given the island of an individual, we will make the idea of summarization more formal. In this paper we present an approach to execute efficient instant retrieval tests on database-oriented ontologies. The main insight of our work is that the islands computed in [WM08] can be checked for similarity and instance

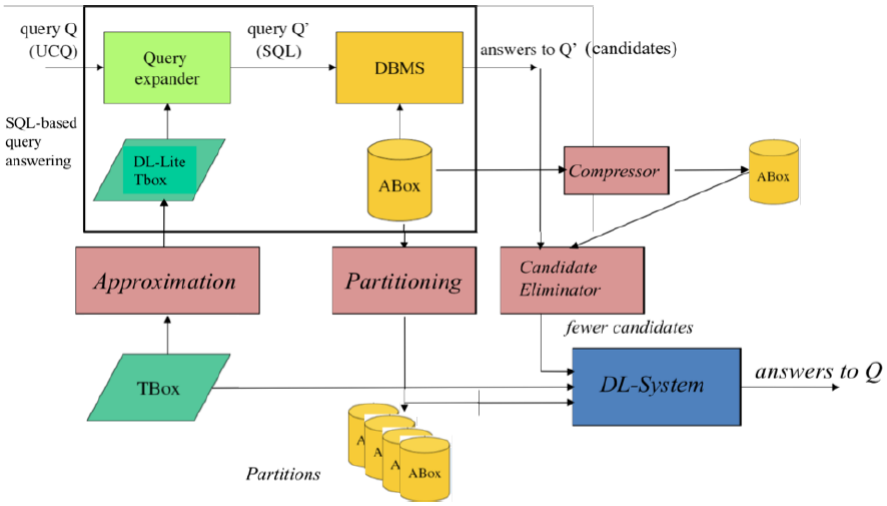

Fig. 1. Efficient query answering for expressive description logics ([KMWW08])

retrieval can then be performed over equivalence classes of similar islands. The query answering algorithm for instance retrieval over similar islands is implemented in a distributed manner. We report interesting scalability results with respect to our test ontology: increasing the number of nodes in the network by the factor of n almost reduces the query answering time to $\frac{1}{n}$. Moreover, we implemented our algorithm in such a way that the input ontology can be loaded in a offline phase and changed afterwards incrementally online.

Figure 1 is taken from [KMWW08] and shows the general structure of a reasoning system for expressive description logics. Our approach is situated in the modules *Partitioning* and *Candidate Eliminator*.

The remaining parts of the paper are structured as follows. Section 2 introduces necessary formal notions and gives an overview over Related Work. The main theoretical contribution of our work is in Section 3, the isomorphism criteria for islands. We show our implementation in Section 4 and provide initial evaluation results in Section 5. The paper is concluded in Section 6.

There is an extended verison of this paper available with proofs and further comments on the implementation and evaluation [WM10].

2 Preliminaries

For details about syntax and semantics of the description logic $\mathcal{ALCHI}$ we refer to [BCM$^+$07]. Some definitions are appropriate to explain our nomenclature, however. We assume a collection of disjoint sets: a set of *concept names* N_{CN} , a set of *role names* N_{RN} and a set of *individual names* N_I. The *set of roles* N_R

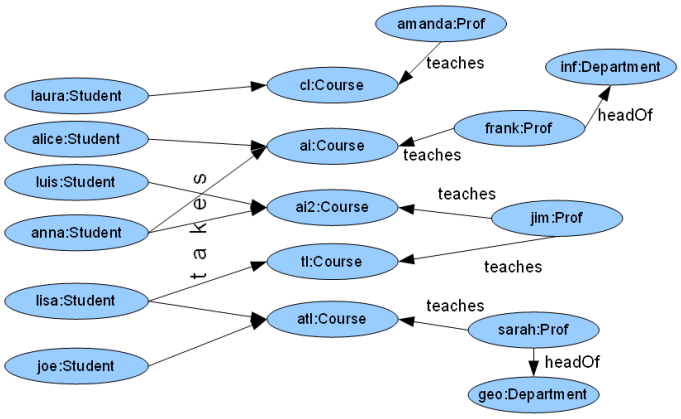

Fig. 2. Example ABox $\mathcal{A}_{EX1}$

is $N_{RN} \cup \{R^- | R \in N_{RN}\}$. We say that a concept description is *atomic*, if it is a concept name or its negation. With $\mathcal{S}_{AC}$ we denote all atomic concepts.

Furthermore we assume the notions of TBoxes ($\mathcal{T}$), RBoxes ($\mathcal{R}$) and ABoxes ($\mathcal{A}$) as in [BCM+07]. A *ontology* $\mathcal{O}$ consists of a 3-tuple $\langle \mathcal{T}, \mathcal{R}, \mathcal{A} \rangle$, where $\mathcal{T}$ is a TBox, $\mathcal{R}$ is a RBox and $\mathcal{A}$ is a ABox. We restrict the concept assertions in $\mathcal{A}$ to only use atomic concepts. This is a common assumption, e.g. in [GH06], when dealing with large assertional datasets stemming from databases. With $Ind(\mathcal{A})$ we denote the set of individuals occurring in $\mathcal{A}$. Throughout the remaining part of the paper we assume the Unique Name Assumption (UNA), i.e. two distinct individual names denote distinct domain objects.

In Example 1 we define an example ontology, used throughout the remaining part of the paper to explain definitions. The example ontology is setting of universities. We evaluate our ideas w.r.t. to "full" LUBM [GPH05] in Section 5. Although this is a synthetic benchmark, several (if not most) papers on scalability of ontological reasoning consider it as a base reference.

Example 1. Let $\mathcal{O}_{EX1} = \langle \mathcal{T}_{EX1}, \mathcal{R}_{EX1}, \mathcal{A}_{EX1} \rangle$, s.t.

$$\begin{aligned}
\mathcal{T}_{EX1} =& \{Chair \equiv \exists headOf.Department \sqcap Person, Prof \sqsubseteq Person, \\
& GraduateCourseTeacher \equiv Prof \sqcap \exists teaches.GraduateCourse\} \\
\mathcal{R}_{EX1} =& \{headOf \sqsubseteq worksFor\} \\
\mathcal{A}_{EX1} =& \texttt{see Figure 2}
\end{aligned}$$

Next we discuss related work relevant to our contribution. In [SP08], the authors discuss a general approach to partition OWL knowledge bases and distribute reasoning over partitions to different processors/nodes. The idea is that the input for their partitioning algorithm is a fixed number of desired partitions, which will be calculated by different means (weighted graphs, hash-based distribution or domain specific partitions). The partitions are not independent from each other.

Moreover, in some cases, the data is just arbitrarily spread over the different nodes in the networks. This leads to a noticeable amount of communication overhead between the nodes, because partial results have to be passed in between the nodes. The authors discuss rather small data sets, e.g. 1 million triples. These problems can already be solved with state-of-the-art tableau-based reasoning systems. Furthermore, their evaluation only talks about speed-up, without mentioning the actual run-time, or referring to some open/state-of-the art implementation. The work in [UKOvH09] proposes a MapReduce [DG04]-based technique, to compute the closure (set of all implications) over ontologies. Given the underlying MapReduce framework, their approach could scale in theory. The major difference to our work is that we focus on query answering, instead of brute force (bottom-up) generation of all possible implications of a given knowledge base. Moreover we focus on more expressive description logics and it is at least doubtful, whether their approach will work for non-deterministic logics (e.g. allowing for disjunctions). The authors of [BS03] discuss an approach to integrate ontologies from different sources in a distributed setting. They introduce so-called bridge-rules to identify, which parts of the ontologies overlap (and thus need to be communicated between the different reasoning nodes). The main focus of their work is rather on the integration of distributed ontologies, but not on scalable reasoning over large ontologies in general. There is additional work on distributed Datalog implementations (e.g. [ZWC95] and [GST90]) and on non-distributed reasoning optimizations/techniques for description logics, e.g. [GH06].

3 Similarity of Islands

In the following, we discuss how islands can be used for optimized instance retrieval tests and answering conjunctive queries. The main insight is that many of the computed islands are similar to each other. Especially in database-oriented scenarios, ontologies contain a lot of individuals, which follow patterns defined by a schema (i.e. the terminology of the ontology). If it is possible to define a formal notion of similarity for islands, and show that it is sufficient to perform reasoning over one representative island, instead of all these similar islands, then query answering can potentially be increased by several orders of magnitude (depending on the number dissimilar island classes). We consider an example to clarify the idea of island isomorphisms more clear.
In Figure 3 we show the extracted islands of all professors in our example ontology $\mathcal{O}_{EX1}$. While all four graphs are different, they have some similarities in common, which can be used to optimize reasoning over these islands. To define similarities over islands, we introduce formally the notion of an island and define a similarity criterion.

Definition 1. *A* individual-island-graph *IIG is a tuple $\langle N, \phi_n, \phi_e, root \rangle$, such that*

- *N is a set of nodes,*

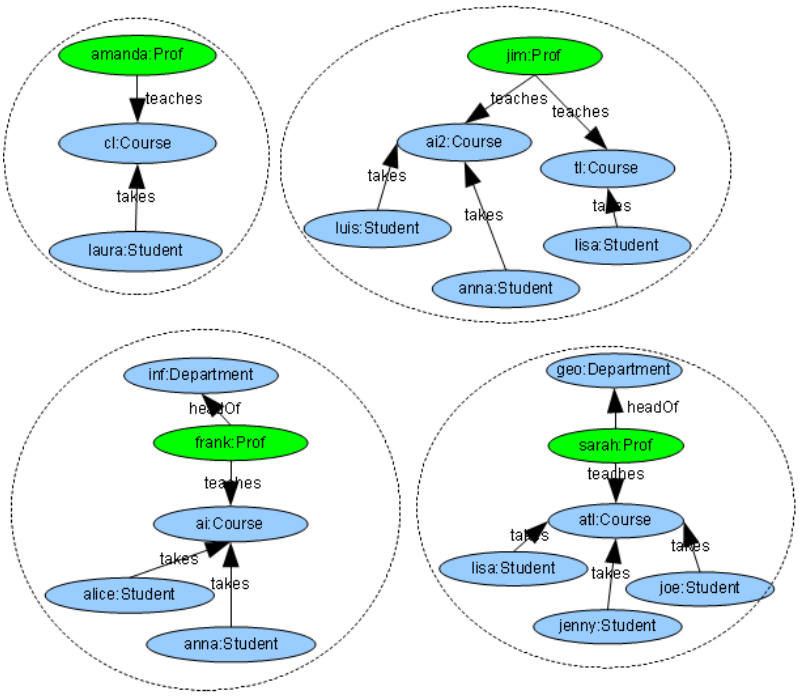

Fig. 3. Example: Islands of the four Professors in $\mathcal{O}_{EX1}$

- $\phi_n : N \rightarrow 2^{\mathcal{S}_{AC}}$ *is a node-labeling function* ($\mathcal{S}_{AC}$ *is the set of atomic concepts),*
- $\phi_e : N \times N \rightarrow 2^{L_e}$ *is a edge-labeling function*
- $root \in N$ *is a distinguished root node.*

If we have $\phi_e(a, b) = \rho$ and $\rho \neq \emptyset$, then we write $a \xrightarrow{\rho}_{IIG} b$. The definition of individual-island-graphs is quite straight-forward. In the following we define a similarity relation over two individual-island-graphs, based on graph bisimulations. Although the term *bisimulation* is usually used in process algebra to define similar processes, we use it here in the context of graphs.

Definition 2. *A* bisimulation *over* $IIG_1 = \langle N_{IIG_1}, \phi_{nIIG_1}, \phi_{eIIG_1}, root_{IIG_1} \rangle$ *and* $IIG_2 = \langle N_{IIG_2}, \phi_{nIIG_2}, \phi_{eIIG_2}, root_{IIG_2} \rangle$ *is a binary relation* $R_{IIG_1,IIG_2} \subseteq N \times N$*, such that*

- $R_{IIG_1,IIG_2}(root_{IIG_1}, root_{IIG_2})$
- *if* $R_{IIG_1,IIG_2}(a, b)$ *then* $\phi_{nIIG_1}(a) = \phi_{nIIG_2}(b)$
- *if* $R_{IIG_1,IIG_2}(a, b)$ *and* $a \xrightarrow{\rho}_{IIG_1} a'$ *then there exists a* $b' \in N_{IIG_2}$ *with* $b \xrightarrow{\rho}_{IIG_2} b'$ *and* $R_{IIG_1,IIG_2}(a', b')$
- *if* $R_{IIG_1,IIG_2}(a, b)$ *and* $b \rightarrow^{\rho}_{IIG_2} b'$ *then there exists a* $a' \in N_{IIG_1}$ *with* $a \xrightarrow{\rho}_{IIG_2} a'$ *and* $R_{IIG_1,IIG_2}(a', b')$

Definition 3. *Two individual-island-graphs IIG_1 and IIG_2 are called* bisimilar*, if there exists a bisimilation R for them.*

Example 2. To make these definitions more clear, we show individual-island-graphs for *amanda*, *jim* and $frank$, plus a possible bisimulation between *amanda* and *jim*:

- $IIG_{amanda} = \langle N_{amanda}, \phi_{n_{amanda}}, \phi_{e_{amanda}}, root_{amanda} \rangle$, s.t.

$$\begin{aligned} N_{amanda} =& \{x_{amanda}, x_{cl}, x_{laura}\} \\ \phi_{n_{amanda}} =& \{x_{amanda} \rightarrow \{Prof\}, x_{cl} \rightarrow \{Course\}, x_{laura} \rightarrow \{Student\}\} \\ \phi_{e_{amanda}} =& \{(x_{amanda}, x_{cl}) \rightarrow \{teaches\}, (x_{laura}, x_{cl}) \rightarrow \{takes\}\} \\ root_{amanda} =& \{x_{amanda}\} \end{aligned}$$

- $IIG_{jim} = \langle N_{jim}, \phi_{n_{jim}}, \phi_{e_{jim}}, root_{jim} \rangle$, s.t.

$$\begin{aligned} N_{jim} =& \{y_{jim}, y_{ai2}, y_{tl}, y_{luis}, y_{anna}, y_{lisa}\} \\ \phi_{n_{jim}} =& \{y_{jim} \rightarrow \{Prof\}, y_{ai2} \rightarrow \{Course\}, y_{tl} \rightarrow \{Course\}, y_{luis} \rightarrow \{Student\}, ...\} \\ \phi_{e_{jim}} =& \{(y_{jim}, y_{ai2}) \rightarrow \{teaches\}, (y_{jim}, y_{tl}) \rightarrow \{teaches\}, (y_{luis}, x_{ai2}) \rightarrow \{takes\}, ...\} \\ root_{jim} =& \{y_{jim}\} \end{aligned}$$

- $IIG_{frank} = \langle N_{frank}, \phi_{n_{frank}}, \phi_{e_{frank}}, root_{frank} \rangle$, s.t.

$$\begin{aligned} N_{frank} =& \{z_{frank}, z_{ai}, z_{inf}, z_{alice}, z_{anna}\} \\ \phi_{n_{frank}} =& \{z_{frank} \rightarrow \{Prof\}, z_{ai} \rightarrow \{Course\}, z_{inf} \rightarrow \{Department\}, \\ & z_{alice} \rightarrow \{Student\}, z_{anna} \rightarrow \{Student\}\} \\ \phi_{e_{frank}} =& \{(z_{frank}, z_{ai}) \rightarrow \{teaches\}, (z_{frank}, z_{inf}) \rightarrow \{headOf\}, \\ & (z_{alice}, z_{ai}) \rightarrow \{takes\}, (z_{anna}, z_{ai}) \rightarrow \{takes\}\} \\ root_{jim} =& \{z_{frank}\} \end{aligned}$$

- $R_{jim,amanda} =$

$$\begin{aligned} & \{(x_{amanda}, y_{jim}), (x_{cl}, y_{ai2}), (x_{cl}, y_{tl}), (x_{laura}, y_{luis}), \\ & (x_{laura}, y_{luis}), (x_{anna}, y_{lisa})\} \end{aligned}$$

It is easy to see, that $R_{jim,amanda}$ is a bisimulation for the islands (graphs) of the individuals *jim* and *amanda*. Furthermore, it is easy to see that there cannot be a bisimulation, for instance, between *jim* and $frank$.

The important insight is that bisimilar islands entail the same concept sets for their root individual, if the underlying description logic is restricted to $ALCHI$. This is shown in the following theorem.

Theorem 1. *Given two individuals a and b, we have $\langle \mathcal{T}, \mathcal{R}, ISLAND(a) \rangle \models C(a) \iff \langle \mathcal{T}, \mathcal{R}, ISLAND(b) \rangle \models C(b)$, if we can find a bisimulation $R_{a,b}$, for $ISLAND(a)$ and $ISLAND(b)$.*

The above theorem can be easily lifted to the case of more than two individuals, i.e. if we have n individuals, and for all of their islands one can find a bisimilarity relation, it is sufficient to perform instance checking on one island. In practice, especially in database-oriented ontologies, this can dramatically speed up the time for instance retrieval. To show this, we need to further introduce some mathematical notions.

Definition 4. *A* individual-island-equivalence $\sim_{ISL}$ *is an equivalence relation over individual islands, such that we have* $\sim_{ISL}$ (ISL, ISL)*, if we can find a bisimulation* $R_{ISL,ISL}$ *between the two islands* ISL *and* ISL*. With* $[\sim_{ISL}]$ *we denote the set of equivalence classes of* $\sim_{ISL}$*.*

The main theoretical result of our work is summarized in the following theorem.

Theorem 2. *Given an ontology* $\langle \mathcal{T}, \mathcal{R}, \mathcal{A} \rangle$*, one can perform grounded instance retrieval for the atomic concept* C *over* $[\sim_{ISL}]$*, instead of all islands.*

Please note that our approach does not work directly for more expressive description logics, e.g. $\mathcal{SHOIQ}$. In the presence of cardinality restrictions we will need more sophisticated bisimulation criteria to identify similar nodes, since the number of related similar individuals matters. Nominals further complicate the bisimulation criteria, since individuals can be forced by the terminological axioms to refer to the same domain object, i.e. one might need to calculate all TBox-implications in the worst calse.

4 Distributed Implementation

We have implemented our proposal for Island Simulations in Java. For ontology access we use the OWLAPI 2.2.0[BVL03]. The general structure of our implementation, a description of each component and performance optimization insights can be found in [WM10]. Here we only give a short overview on the modules.

- (Server) OWL-Converter: converts OWL data to an internal representation
- (Server) Update Handler: determines changed islands in case of ontology updates
- (Server) Island Computor: computes the island for a given an individual and performs similarity computation
- *(Server) Node Scheduler*: determines the responsible node for the island: Round-Robin / capability-based
- (Server) TBox/ABox Storage: terminological/assertional part of the ontology.
- (Client) Query Manager: determines all active islands and uses the DL Reasoner module to find out which islands match the input query.
- (Client) DL Reasoner: implements an interface to a general description logic reasoner (in our case we used Racer [HM01]).

5 Evaluation

Our tests were run with respect to the synthetic benchmark ontology LUBM [GPH05]. Although some people claim that LUBM does not fully represent all the capabilities provided by the complete OWL specification, we think that it fits our constraint of database-oriented ontologies: rather small and simple TBox, but a bulk of assertional information with a realistic distribution with respect to numbers of professors, students, departments, etc. In our evaluation we compare three different measures, to determine the performance of our implementation:

– *Load time*: In Figure 4 we show the size of the assertional part in triples and compare the load time with different number of nodes in our network (1, 2 and 4 nodes). The load time only represents the time spent to traverse the input ontology one time and compute that bisimilarity relation over all islands of all individuals. It can be seen that the load time increases linearly with the number of triples in the assertional part. Please note that our loading algorithm is designed and implemented as an incremental algorithm. Thus, if we add a new assertion, we do not have to recompute all the internal structures, but only update the relevant structures.

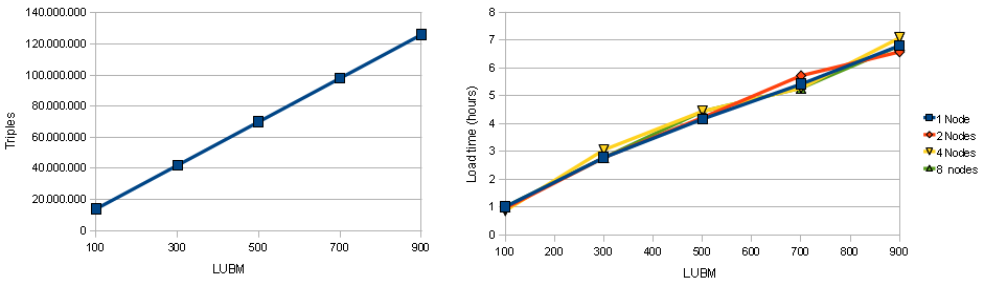

Fig. 4. Input size and load time

– *Preparation time*: This measure indicates an initial preparation time after the ontology is fully loaded. Please note that this preprocessing step is query independent and only performed one time after the ontology was updated. The idea is that we can perform incremental bulk loading (measured in *load time*), without updating the (expensive) internal structures of the DL reasoner all the time.
In the left part of Figure 5, we show the query preparation time for different numbers of universities and different numbers of nodes in the network. The number of nodes indeed affects the query preparation time. If we use 8 nodes, the preparation time is almost $\frac{1}{8}$ of the time needed for one node.
In the right part of Figure 5 we compare the necessary number of islands to perform instance retrieval with the original work in [WM08]. It can be

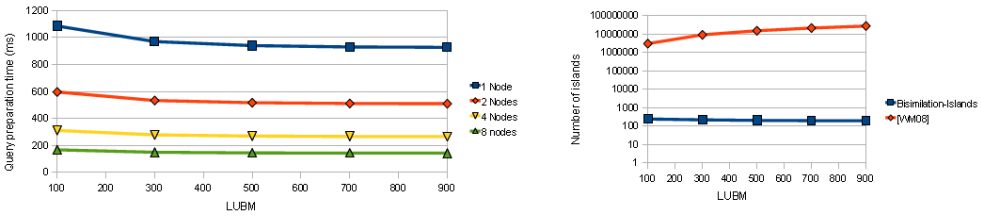

Fig. 5. Query preparation time and island count

seen, that the number of islands increases linearly with the size of the input ontology for [WM08] (please note the logarithmic scale). Using bisimulation, the number of islands is almost constant for all input ontologies, since most of the newly introduced individual-islands are bisimilar to each other, e.g. professors who teach particular students in particular kinds of courses.

– *Query answering time*: The third measure indicates how long the actual query answering takes. In Figure 6, the query answering time (for instance retrieval) for the concepts *Chair*) are shown. This is the actual description-logic-hard task.

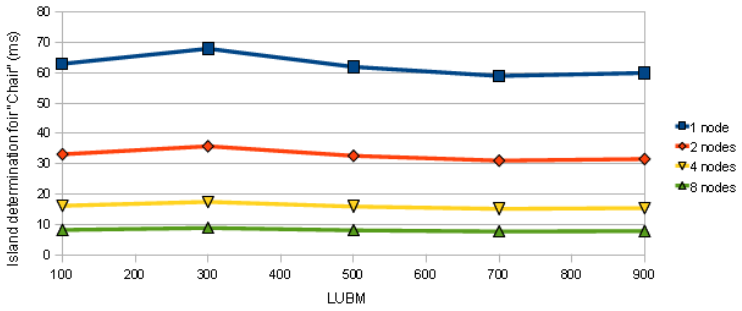

Fig. 6. Query answering time

6 Conclusions

We have proposed a method for instance retrieval over ontologies in a distributed system of DL reasoners. To the best of our knowledge, we are the first to propose instance retrieval reasoning based on similarity of individual-islands. The results are encouraging so far. We emphasize that our approach especially works for ontologies with a rather simple or average size terminological part. For future

work, it will be important to investigate more ontologies and check the performance of our proposal. Furthermore, we want to extend our proposal to more expressive description logics, e.g. SHIQ or even SHOIQ.

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