Concept Description and Definition Extraction for the ANEMONE System

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Abstract. We present algorithms for computing *definitions* and *concept descriptions* that agents can use to restrict and adapt their knowledge with respect to signature shared with other agents. This ensures that knowledge shared is understood by communication partners. We focus on agents that make use of description logic ontologies to represent their expertise. We have implemented and evaluated the performance of the algorithms in the form of a case study example and also empirically on a real-world ontology. Our evaluation suggests that definition extraction can reduce the amount of messages exchanged by agents, thus optimising the communication time and effort of the agents.

Keywords: Agent · Ontologies · Approximation · Definitions.

1 Introduction

One of the appealing characteristics of agents and multi-agent systems MAS(s) is that each agent can provide distinct services and each agent can likewise have a distinct set of facts about the world. This avoids the need for massive upfront coordination and various sorts of integration but introduces fundamental communication challenges including the determination of common knowledge and potential increasing amount of knowledge shared between any set of agents.

Establishing common knowledge for communicating agents is non-trivial, and has been studied in the literature as part of the topics of *agent negotiation* and *ontology alignment* [4]. Ontology alignment rises from the need to find correspondences between related entities of different ontologies and has several applications including agent communication, ontology engineering, and ontology versioning. The correspondences may be one of several semantic relations including *equivalence*, *consequence*, *subsumption*, or *disjointness*, between ontology entities [4]. Beyond the establishment of common ground, agents require the ability to communicate and convey knowledge in their ontologies in terms of common knowledge or established correspondences. Humans have the ability to approximate knowledge naturally, for example, doctors approximate diagnoses into terms patients can understand without using any complex medical terms. Often, either the agent knowledge representations or the messages exchange are expressed entirely in a language restricted to *atomic* predicates (especially monadic predicates aka “classes” or “concepts”). That is, the correspondences are between *terms* and not more complex *expressions* and this can limit the efficiency and efficacy of communication.

We focus on agents that use description logics DL(s) to model the expertise in their domain of specialisation in the context of the ANEMONE framework [21] a framework comprising of dynamic communication protocols that agents can convey concepts to each other depending on varying levels of their common vocabulary. ANEMONE's application to naturally occuring ontologies (such as those found on the BioPortal [22]) is limited because it is designed using a less [1] expressive langauge. The methods we investigate are designed for use on naturally occuring ontologies and intended to be compatible with ANEMONE thus make its application to naturally occuring ontologies more suitable. The implicit hypothesis is that expressive languages such as those found in naturally occuring languages enable rich descriptions of unshared concepts and thus reduce the amount of messages exchanged between the agents.

We study *definitions* in the context of ANEMONE and DL(s) and how they may be extracted and used for conveying meaning and concepts. Definitions in the DL sense (DL-definitions) do not always exist, as such, we introduce and study *concept descriptions* an alternative to conventional definitions in DL that can be used to characterise concepts based on restricted vocabularies. We compare DL-defintions, concept descriptions and definitions in the ANEMONE sense (ANEMONE-definitions) and evaluate their performance on a case study adopted from [21]. We show that DL-definitions are optimal in terms of size and interpretation compared to concept descriptions and ANEMONE-definitions thus making DL-definitions the more suitable candidates for efficient communication. Concept descriptions tend to be bulky in size, and thus suboptimal, as a result, we introduce *minimal concept descriptions* as an alternative to concept descriptions and demonstrate that they smaller in terms of size compared to concept descriptions and ANEMONE-definitions, but larger than DL-definitions (when they exist).

Our contributions are as follows:

1. A method for extracting definitions in $\mathcal{ALC}$ ontologies (We formally define $\mathcal{ALC}$ in Sectin 2).
2. A method for extractinig *concept descriptions*.
3. A case study of how definition extraction and concept descriptions can enhance ANEMONE for use with expressive DL(s).
4. An experimental evaluation of ANEMONE-defintions and DL-definitions on an $\mathcal{ALC}$ ontology.

The rest of this paper is organised as follows: Preliminaries are defined in Section 2, Section 3 discusses the ANEMONE system in detail, Section 4 discusses conventional definitions in DL and our method for extracting definitions in $\mathcal{ALC}$ ontologies, Section 5 discusses concept descriptions, an overview on related work is provided in Section 6, and finally, Section 7.1 provides a case study of how the methods presented can be applied to the ANEMONE sys-

[1] relative to naturally occuring ontologies.

tem. Proofs are in the long version of the paper which is accessible at `https://tinyurl.com/emas2021paper24`

2 Preliminaries

Let N_C be a set of atomic concepts, N_R a set of atomic roles, and N_I a set of individuals (or instances). $\mathcal{ALC}$-concepts have one of these forms: $\top \mid a \mid A \mid \neg C \mid C \sqcup D \mid C \sqcap D \mid \forall r.C \mid \exists r.D$, where $a \in N_I$, $A \in N_C$, $r \in N_R$, C and D arbitrary $\mathcal{ALC}$ concepts. An $\mathcal{ALC}$ ontology consists of axioms which either belong to the TBox or ABox. TBox axioms are of the form $C \sqsubseteq D$ or $C \equiv D$ which can be expressed by two general inclusion axioms $C \sqsubseteq D$ and $D \sqsubseteq C$. ABox axioms are of the form $C(a)$ called *concept assertions* or $r(a, b)$ called *role assertions*.

The language $\mathcal{AL}$ is a restricted form of $\mathcal{ALC}$ that only allows for atomic negation ($\neg A$), concept intersection ($C \sqcap D$), universal restrictions ($\forall r.C$) and limited exisential quantification ($\exists r.D$).

The function $sig()$ returns the set of concepts, roles, and individuals occurring in a given ontology, concept or axiom.

For $\mathcal{ALC}$, an interpretation $\mathcal{I}$ over N_C, N_R, and N_I is a pair $\langle \Delta^{\mathcal{I}}, \cdot^{\mathcal{I}} \rangle$, where $\Delta^{\mathcal{I}}$ is a non-empty set representing an interpretation domain, and $\cdot^{\mathcal{I}}$ is an interpretation function that maps every $A \in N_C$ to a subset $A^{\mathcal{I}}$ of $\Delta^{\mathcal{I}}$; every $r \in N_R$ to a binary relation $r^{\mathcal{I}}$ over $\Delta^{\mathcal{I}}$, to every individual a in N_I to an element $a^{\mathcal{I}} \in \Delta^{\mathcal{I}}$. The interpretation function $.^{\mathcal{I}}$ is extended to concepts as follows:

$\bot^{\mathcal{I}} = \emptyset \quad (\neg C)^{\mathcal{I}}) = \Delta^{\mathcal{I}} \setminus C^{\mathcal{I}} \quad (C \sqcup D)^{\mathcal{I}} = C^{\mathcal{I}} \cup D^{\mathcal{I}} \quad (C \sqcap D)^{\mathcal{I}} = C^{\mathcal{I}} \cap D^{\mathcal{I}}$

$(\forall r.C)^{\mathcal{I}} = \{x \in \Delta^{\mathcal{I}} \mid \forall y.(x, y) \in r^{\mathcal{I}} \rightarrow y \in C^{\mathcal{I}}\}$

$(\exists r.C)^{\mathcal{I}} = \{x \in \Delta^{\mathcal{I}} \mid \exists y.(x, y) \in r^{\mathcal{I}} \wedge y \in C^{\mathcal{I}}\}$ A concept name A is called cyclic if $O \models A \sqsubseteq C$ such that $A \neq C$, and $A \in sig(C)$ [2]. An ontology O is said to be acyclic if it contains no cyclic concept names.

3 The ANEMONE System

The purpose of communication in ANEMONE is mainly to share assertional knowledge. Intuitively speaking, an agent A_1 conveys a concept C to an agent A_2 so that A_2 can share instances of C under its knowledge.

The ontology semantics in ANEMONE differs from those found in naturally occuring ontologies which makes its application to such ontologies limited. We find that the closest adaptation ontology semantics in ANEMONE to OWL2 semantics [13] is $\mathcal{AL}$ without concept intersection, negation, universal restrictions, and limited existential quantification. In addition, a non-standard *overlap* operator $\oplus$ is introduced which is interpreted as follows:

$$C \oplus D \quad \text{iff} \quad C^{\mathcal{I}} \not\subseteq D^{\mathcal{I}}, D^{\mathcal{I}} \not\subseteq C^{\mathcal{I}}, \quad \text{and} \quad C^{\mathcal{I}} \cap D^{\mathcal{I}} \neq \emptyset$$

[2] It is worth noting that this definition of cyclicity is simplified here for brevity. For a more comprehensive description, refer to [7]

The $\oplus$ operator cannot be expressed using the standard DL operators, however, it is inconsequential to sharing instances, thus making it redudant for communication: $C \oplus D$ only tells us that some instances of C are in D and vice versa, the axiom $C \oplus D$ does not influence the interpetation of $C(C^{\mathcal{I}})$ or $D(D^{\mathcal{I}})$.

ANEMONE has three design objectives: (i) Minimal and effective communication, (ii) Laziness, (iii) Decentralised communication. The minimal and effective objective ensures communicated knowledge is not superfluous and can be processed optimally. The laziness objective ensures knowledge sharing only occurs on a *as-need* basis, i.e., knowledge should only be exchanged when strictly necessary. The decentralised objective ensures there is no central control or location of the knowledge.

Communication is considered minimal and effective if it is *sound* and *lossless*. Sound communication dictates that if a speaker agent A_1 wishes to convey a concept X in its ontology to a hearer agent A_2, A_1 must either send X itself as a message or a concept C that is either equivalent to X or is a superconcept of X w.r.t to A_1's ontology. Soundness is a measure of the *quality* of information exchanged. Lossless communication is a measure of the *quantity* of information exchanged.

The laziness objective of ANEMONE is realised through the communication layers. There are three layers of communication: (i) Normal Communication Protocol (ii) Concept Definition Protocol (iii) Concept Explication Protocol. All conversations start by assuming that there are no misunderstandings and occur in the Normal Communication Protocol which is the uppermost layer. If any misunderstanding occurs, the agents switch to the Concept Definition Protocol where they may attempt to resolve the misunderstandings by exchanging definitions of concepts that may have caused the misunderstanding (ideally in terms of concepts that are shared by both agents.). If misunderstandings persist in the Concept Definition Protocol, the agents switch to the Concept Explication Protocol where agents convey the meaning of a concept by exchanging positive and negative examples of the misunderstood concept. The communication protocols help realised the *as-need* requirement of the laziness objective: agents only resort to using complex communication mechanisms only when needed.

To ensure communication is lossless, ANEMONE dictates that any concept X communicated by a speaker agent $A_1(A_2)$ to some hearer agent $A_2(A_1)$ is either X itself or a concept C that is equivalent to X under A_1's ontology. This process is also accompanied by the type of performative used to communicate X to the other agent: if X or an equivalent concept C is communicated to the other agent, the $ExactInform$ performative is used, however, if some other concept is conveyed to the hearer agent, such as a most specific atomic concept C' of X that is not equivalent to X, then the $Inform$ performative is used. The use of these performatives dictates whether the conversation should switch from the Normal Communication Protocol to the Concept Definition Protocol: the use of the $Inform$ performative hints at some loss in communication and often suggests that the agents have to switch to the Concept Definition Protocol. When the agents are communicating in the Concept Definition Protocol (attempting to resolve the meaning for some concept X), they switch to the Concept Explication

Protocol if the definition extracted for X is perceived as inadequate by the hearer agent. A definition is inadequate if the hearer agent can not infer the relation of the definition with every other concept in the hearer agents ontology. Intuitively speaking, the notion of adequacy in ANEMONE is motivated by expecting the hearer agent to be able to place an unshared concept in an exact point in the hierarchy of its ontology, however, as we shall demonstrate, natural occuring ontologies may have multiple hierarchies on concepts which results in this notion of adequacy being moot.

The Concept Explication Protocol is underpinned by ensuring the ontologies of the communicating agents are *grounded*, meaning that the domain of discourse contains all the objects the agent may wish to speak about, e.g. the set of URLs on the internet. The use of grounded ontologies enables agents to realise the intended interpretation of concepts that are used in communication. Grounded knowledge bases, contain *classifiers* (intended to be realised using machine learning techniques) in addition to symbolic descriptions to ensure the agents can classify objects in the domain of discourse. In a more traditional sense, these classifiers can be considered as the sensors of the agent.

Ontology alignment and related approaches to concept explication can be easily adopted into any framework that implements the ANEMONE approach, as such we focus our efforts on the Concept Definition Protocol which can benefit from known knowledge approximation techniques in DL, this is where our primary contribution lies. ANEMONE provides a specification of how ANEMONE-definitions should be extracted.

Computing Definitions in the ANEMONE system ANEMONE specifies that an ANEMONE-definition for a concept X should be constructed by extracting all the relations X has with the concepts in Σ under O. Let X be concept-name, Σ a signature and O an ontology that conforms to the semantics of those in [21] such that $\Sigma \subseteq sig(O)$, a definition for X following [21] is defined as $\{X \sqsubseteq A | O \models X \sqsubseteq A \wedge A \in \Sigma\} \cup \{A \sqsubseteq X | O \models A \sqsubseteq X \wedge A \in \Sigma\} \cup \{A \equiv X | O \models A \equiv X \wedge A \in \Sigma\} \cup \{A \sqcap X \sqsubseteq \bot | O \models A \sqcap X \sqsubseteq \bot \wedge A \in \Sigma\}$.

Example 1. The example is adapted from [21]. In it, we have two agents A_1 and A_2 which are both personal news agents that classify news articles according to the ontologies provided in Table 1.

Let $\Sigma = sig(O_1) \cap sig(O_2) = \{$LawnTennis, RegionalNews, SoftwareAgents, ScienceNews, BallAndRacquetGames$\}$. A definition for $Wimbledon$ w.r.t. Σ under O_1 would be: $\{$Wimbledon $\sqsubseteq$ BallAndRacquetGames, Wimbledon $\sqsubseteq$ LawnTennis, Wimbledon $\sqcap$ RegionalNews $\sqsubseteq \bot$, Wimbledon $\sqcap$ SoftwareAgents $\sqsubseteq \bot$, Wimbledon $\sqcap$ ScienceSubjects $\sqsubseteq \bot$ $\}$.

The semantics and expressivity of DL(s) used in naturally occuring ontologies agents can convey richer descriptions of concepts in their ontologies in the Normal Communication Protocol, due to the increase in expressivity of their ontologies from the current ontology semantics of ANEMONE. This reduces the need to switch to lower protocols. In the Normal Communication Protocol, agents may only convey concepts that are in their shared vocabulary, however,

A_1 with ontology O_1	A_2 with ontology O_2
LawnTennis $\sqsubseteq$ BallAndRacquetGames, Wimbledon $\sqsubseteq$ LawnTennis, UKNews $\sqsubseteq$ RegionalNews, SoftwareAgents $\sqsubseteq$ ComputerScience, ComputerScience $\sqsubseteq$ ScienceNews, BallAndRacquetGames $\sqcap$ RegionalNews $\sqsubseteq \bot$, BallAndRacquetGames $\sqcap$ ScienceNews $\sqsubseteq \bot$, RegionalNews $\sqcap$ ScienceNews $\sqsubseteq \bot$	LawnTennis $\equiv$ Tennis Tennis $\sqsubseteq$ RacquetGames, RacquetGames $\sqsubseteq$ BallAndRacquetGames, BallAndRacquetGames $\sqsubseteq$ Sports, EuropeNews $\sqsubseteq$ RegionalNews, SoftwareAgents $\sqsubseteq$ ScienceNews, Sports $\sqcap$ RegionalNews $\sqsubseteq \bot$, Sports $\sqcap$ ScienceNews $\sqsubseteq \bot$, RegionalNews $\sqcap$ ScienceNews $\sqcap \sqsubseteq \bot$

Table 1. Ontologies of the Agents used throughout the paper. The first column contains the ontology O_1 for an agent A_1, and the second column contains the ontology O_2 for an agent A_2

if the concept an agent wants to convey is not shared, it uses an equivalent concept that can be expressed using the shared concepts. The next section provides background on DL-definitions which are used characterise *equivalent* concepts in an ontology.

4 Explicit and Implicit Definitions

In DL, concepts are defined using *equivalances*. Following the DL handbook [2], a TBox O defines a concept A if O entails some axiom of the form $A \equiv C$ where the A is the defined concept name [2]. Thus, a DL-definition C for a concept-name A may only exist in one of two forms: (i) *Explicitly* via a syntactic TBox axiom of the form $A \equiv C$ such that $A \notin sig(C)$, or (ii) *Implicitly* via a set of general inclusion axioms O such that for any model of O, the interpretation of A is uniquely determined by the interpretation of the symbols in $sig(C)$. In this section explicit and implicit definitions are to be considered forms of DL-defintions. Intuitively, if a concept is explicitly defined in an ontology, its equivalent concept is obvious and easy to extract, however, if it is implicitly defined, its equivalent concept is not so obvious. Furthermore, a concept may have several equivalent concepts that all have unique signatures in an ontology. Even a concept that is explicitly defined may be implicitly defined over a given signature.

A logical language is said to be definitorially complete if a concept that is defined implicitly can also be defined explicitly (formal definitions can be found in [17]). Languages that are definitorially complete are said to have the *Beth Definability* property, and ensure that the interpretation of a defined concept is equivalent to the interpretation of its DL-definition thus suitable for instance-sharing applications (such as that of ANEMONE). The DL $\mathcal{ALC}$ is shown to have the Beth Definability property in [16] [3]. Finding concepts that are defined over a given signature is paramount for agents conversing in the Normal

[3] Some extensions of $\mathcal{ALC}$ such as all those with role-hierarchies ($\mathcal{H}$) do not possess the Beth Definability property.

Communication Protocol of ANEMONE as this dictates whether they may have to switch to lower protocols. A result of [17] is a test for determining implicit definability for a concept over a given signature and ontology. Let X be a concept, O an ontology, O' a copy of O, and Σ a subset signature of O such that $X \in sig(O)$, $X \notin \Sigma$, $\Sigma \subseteq sig(O)$, and O' is O with every concept-name and role symbol $A \notin \Sigma$ replaced by a copy A', X is implicitly definable from Σ under O iff $O \cup O' \models X \equiv X'$. This can be easily accomplished using a reasoner such as Hermit [5].

4.1 Extracting DL-Definitions for Implicitly and Explicitly defined concepts

After detecting an implicitly definable concept, agents also need to be able to extract a DL-definition or concept that is equivalent. Strongest Necessary Conditions (SNC) can be used to compute DL-definitions for concepts that are implicitly or explicitly defined in an ontology [3]. The primary contribution of this paper is a practical method to compute Strongest Necessary Conditions using uniform interpolation in DL.

Definition 1 ((Strongest) Necessary Conditions). *Let Σ be a set of concept names and role symbols, X a concept, and O an ontology, such that $\Sigma \subseteq sig(O)$, we define a necessary condition of X over Σ relative to O to be any concept α such that $sig(\alpha) \subseteq \Sigma$ and $O \models X \sqsubseteq \alpha$. It is a strongest necessary condition denoted $SNC(X;O;\Sigma)$, if for any other necessary condition α' of X over Σ relative to O we have that $O \models \alpha \sqsubseteq \alpha'$.*

Definition 2 (Forgetting and Uniform Interpolation). *Given an ontology O, a set of symbols Σ such that $\Sigma \subset sig(O)$, a* uniform interpolant *for O over Σ is an ontology $\mathcal{V}$ such that $O \models \mathcal{V}$ and $\mathcal{V}$ is a strongest such entailment for Σ, i.e., for any other entailment $\mathcal{V}'$ of O such that $O \models \mathcal{V}'$ and $sig(\mathcal{V}') \subseteq \Sigma$, then $\mathcal{V} \models \mathcal{V}'$. The ontology $\mathcal{V}$ is called a uniform interpolant for O for signature Σ. We refer to Σ as the uniform interpolation signature. We also call $\mathcal{V}$ the result of forgetting $\bar{\Sigma}$ from O where $\bar{\Sigma}$ denotes $sig(O) \setminus \Sigma$.*

A consequence of this definition is that for every axiom ψ such that $sig(\psi) \subseteq \Sigma$ such that $O \models \psi$, $\mathcal{V} \models \psi$. Algorithms for computing strongest necessary conditions exist in the propositional logic [10, 3] and First Order Logic(FOL)[3]. Since DL is a fragment of FOL, we have adapted the SNC algorithm presented in [3] DL. Following [3], for any first-order formula X, set of relation symbols Σ, and closed theory O, the SNC is the uniform interpolant (Definition 2) computed for $O \wedge X(x)$ over Σ. As such, in DL we can compute the SNC for a concept name X over a signature Σ and ontology O by computing the uniform interpolant for O, X over Σ and there are known practical implementations of the uniform interpolation methods provided in [8]. This method does compute an SNC for X, however, it is not suitable for our application purposes as the result may contain axioms unrelated to X, we call such axioms *redundant*. Consider the ontology O_1 as discussed in Example 1, to compute the SNC for $Wimbledon$ w.r.t O_1 and Σ we compute the uniform interpolant over $O_1, Wimbledon$ w.r.t

Σ which is {LawnTennis $\sqsubseteq$ BallAndRacquetGames, BallAndRacquetGames $\sqsubseteq \neg$ RegionalNews, BallAndRacquetGames $\sqsubseteq \neg$ ScienceSubjects, RegionalNews $\sqsubseteq \neg$ ScienceSubjects, SoftwareAgents $\sqsubseteq$ ScienceSubjects, LawnTennis}. Observe that the result still satisfies Definition 1, however, as can be seen, there are axioms in the result not related to $Wimbledon$, the TBox axiom $SoftwareAgents \sqsubseteq ScienceSubjects$ for example, is not related to *Wimbledon*.

Proposition 1 lets us deal with redundant axioms. Let O be an ontology, Σ a subset signature of O, a a fresh individual such that $a \notin O$ and X a concept name for which we wish to compute an SNC for w.r.t. O and Σ, we compute a uniform interpolant $\mathcal{V}$ over Σ for $O, X(a)$ and solve the issue of redundancies in the result by returning a conjunction of concepts of the form $C(a) \in \mathcal{V}$: it follows from Proposition 1 that all such concepts C are necessary conditions of X, and thus their conjunction would satisfy Definition 1. This approach is outlined in more detail in Algorithm 1.

Proposition 1. *Let O be an acyclic ontology, X a concept, $\Sigma \subseteq sig(O)$, and a a fresh individual, such that $a \notin sig(O)$, $sig(X) \nsubseteq \Sigma$. Suppose $O \not\models X(a)$. Let $\mathcal{V}$ be a uniform interpolant for $\Sigma \cup \{a\}$ relative to $O, X(a)$, we have that $\mathcal{V} \models C(a)$ iff $O \models X \sqsubseteq C$ where C is an arbitrary $\mathcal{ALC}$-concept such that $sig(C) \subseteq \Sigma$.*

Proof. If $\mathcal{V} \models C(a)$, then $O \models X \sqsubseteq C$: Since $\mathcal{V}$ is a uniform interpolant for $\Sigma \cup \{a\}$ of $O, X(a)$, $O, X(a) \models \mathcal{V}$. Given that $\mathcal{V} \models C(a)$, we have that $O, X(a) \models C(a)$. This implies $O, X(a), \neg C(a)$ is unsatisfiable and hence $O \models X \sqsubseteq C$, since $O \models X \sqsubseteq C$ iff $O, X(a'), \neg C(a') \models \bot$ for some fresh individual a'.

If $O \models X \sqsubseteq C$, then $\mathcal{V} \models C(a)$: Because $O \models X \sqsubseteq C$, for every interpretation $\mathcal{I}$ such that $\mathcal{I} \models O$, we have that: $x \in X^{\mathcal{I}}$ implies $x \in C^{\mathcal{I}}$ for any individual $x \in \Delta^{\mathcal{I}}$. Therefore, given a fresh individual a not occuring in $sig(O)$, $O, X(a) \models C(a)$. Since $\mathcal{V}$ is a uniform interpolant for $\Sigma \cup \{a\}$ of $O, X(a)$, $\mathcal{V}$ is a strongest entailment for $\Sigma \cup \{a\}$ of O. Since $sig(C(a)) \subseteq \Sigma$, it follows from Definition 2 that $\mathcal{V} \models C(a)$.

A consequence of Proposition 1 and Definition 2 is that $\bigsqcap_{C(a) \in \mathcal{V}} C$ is a strongest necessary of X for $\mathcal{V}$ to be a uniform interpolant.

Algorithm 1: SNC Extraction

Input: An ontology O, a definiendum X, a signature Σ, an individual a where $\Sigma \subseteq sig(O)$, $X \in sig(O)$, $X \notin \Sigma$, $a \notin sig(O)$.
Output: An $\mathcal{ALC}$ concept C which is a SNC of X.

Step 1: Add $X(a)$ to O to get O'.

Step 2: Add a to Σ to get Σ' and compute a uniform interpolant denoted $\mathcal{V}$ over O' w.r.t Σ'. I.e. forget $\overline{\Sigma}'$ from O'.

Step 3: Following Proposition 1, axioms in $\mathcal{V}$ containing a in their signature are necessary conditions of X, as such, return $\bigsqcap_{C(a) \in \mathcal{V}} C$ as $SNC(X; O; \Sigma)$.

Proposition 2. *Let O be an acyclic ontology, Σ a subset of $sig(O)$, C a concept such that $sig(C) \nsubseteq \Sigma$. If there exists a concept D such that $O \models C \equiv D$, and $sig(D) \subseteq \Sigma$, then $O \models C \equiv SNC(C; O; \Sigma)$, and therefore, $SNC(C; O; \Sigma)$ is an explicit DL-definition for C under O.*

Proof. If $O \models C \equiv D$, then it follows that $O \models C \sqsubseteq D$. Since $sig(D) \subseteq \Sigma$, it follows from Definition 1 that $O \models SNC(C; O; \Sigma) \sqsubseteq D$. If $O \models C \equiv D$, then it also follows that $O \models D \sqsubseteq C$, and since $O \models SNC(C; O; \Sigma) \sqsubseteq D$, it follows that $O \models SNC(C; O; \Sigma) \sqsubseteq C$. Thus, $O \models SNC(C; O; \Sigma) \sqsubseteq C, C \sqsubseteq SNC(C; O; \Sigma)$ which means that $O \models C \equiv SNC(C; O; \Sigma)$.

It follows from Proposition 2 that computing Strongest Necessary Conditions can be used to extract DL-definitions for concepts implicitly or explicitly defined.

ANEMONE does not provide any specification for testing whether a concept is implicitly definable, presumably, it is intended to be used with explicit definitions only. This means that not only does a concept have to be explicitly defined, but the signature of its definition must be expressed in the common signature of the agents. ANEMONE can be enhanced using Algorithm 1 to be used by agents with standard DL ontologies. If agent A_1 wants to convey a concept X that is not explicitly defined under the common signature of the agents, it may simply perform an implicit definability check and compute a definition for X using Algorithm 1. It is worth stressing that that if a DL-definition exists for a concept, then communication remains in the normal communication protocol. Given a concept X that is implicitly or explicitly defined under an ontology O_1, extracting an explicit or implicit definition ϕ will enable an agent A_1 use the $ExactInform$ performative to convey ϕ in place of X and thus ensure that conversation stays in the normal communication protocol. If X is neither implicitly or explicitly defined, the agents may attempt to use concept descriptions as an alternative to defintions.

5 Concept Descriptions

Concept Descriptions (CDs) are an alternative to standard definitions in DL that address the ANEMONE objective of stating the relation of a defined concept with other concepts in an ontology under a given subset signature. Let X be a concept name, for the agent communication context of this paper, we say X is described w.r.t. an ontology O if either there is a concept D such that $O \models D \sqsubseteq X$ or a concept C such that $O \models X \sqsubseteq C$ or a concept S such that $O \models X \equiv S$ where C, D, S are concepts and X is an atomic concept.

Given a concept name X, a signature Σ and an ontology O, such that $X \notin \Sigma$ and $\Sigma \subseteq sig(O)$, a mechanism for extracting concept descriptions should satisfy the following requirements.

1. *Comprehensiveness*: Let ϕ be a description for X w.r.t. O and Σ, we say ϕ is *comprehensive* for X if for any concept C such that $O \models X \sqsubseteq C$ and $sig(C) \subseteq \Sigma$, we have that $\phi \models X \sqsubseteq C$ and for any concept D such that $O \models D \sqsubseteq X$ and $sig(D) \subseteq \Sigma$, we have that $\phi \models D \sqsubseteq X$ and for any concept E such that $O \models X \equiv E$ and $sig(E) \subseteq \Sigma$, we have that $\phi \models X \equiv E$.

2. *Description-specificity*: Let ϕ be a description for X w.r.t. O and Σ, we say ϕ is *description-specific* for X if for every axiom $\psi \in \phi$, we have that either $\psi = X \sqsubseteq C$ or $\psi = C \sqsubseteq X$ or $\psi = X \equiv C$ where C is a concept such that $sig(C) \in \Sigma$.

Concept descriptions may be extracted using *most specific superconcept* and *most general subconcept* formally defined in Definitions 3 and 4.

Definition 3 (Most Specific Superconcept). *Let O be an ontology, X a concept name, C a concept, and Σ a subset signature of O such that $X \in sig(O)$, $X \notin \Sigma$, $sig(C) \subseteq \Sigma$ and $\Sigma \subseteq sig(O)$. We call C the most specific super concept of X if $O \models X \sqsubseteq C$ and for any other concept C' such that $O \models X \sqsubseteq C'$ and $sig(C') \subseteq \Sigma$, we have that $\models C \sqsubseteq C'$.*

Definition 4 (Most General Subconcept). *Let O be an ontology, X a concept name, C a concept, and Σ a subset signature of O such that $X \in sig(O)$, $X \notin \Sigma$, $sig(C) \subseteq \Sigma$ and $\Sigma \subseteq sig(O)$. We call C the most general sub concept of X if for any other concept C' such that $O \models C' \sqsubseteq X$ and $sig(C') \subseteq \Sigma$, we have that $\models C' \sqsubseteq C$.*

We denote the most-specific super concept $MSP(X; O; \Sigma)$ and the most general sub concept $MGB(X; O; \Sigma)$.

Algorithm 2: Concept Description Extraction

Input: An ontology O, a definiendum X, a signature Σ, where $\Sigma \subseteq sig(O_B)$, $X \in sig(O_B)$, $X \notin \Sigma$.
Output: An ontology ϕ which is a concept description for X

Step 1: Compute $MSP(X; O; \Sigma)$.

Step 2: Compute $MGB(X; O; \Sigma)$.

Step 3: Return $\{X \sqsubseteq MSP(X; O; \Sigma), MGB(X; O; \Sigma) \sqsubseteq X\}$ as a concept description for X.

Our approach to extracting concept descriptions is presented in Algorithm 2. Algorithm 2 satisfies the requirements for *comprehensiveness* and *description-specificity*: any superconcept C of X such that $O \models X \sqsubseteq C$ and $sig(C) \subseteq \Sigma$ would be a superconcept of $MSP(X; O; \Sigma)$, as such, the axiom $X \sqsubseteq MSP(X; O; \Sigma)$ would entail axioms of the form $X \sqsubseteq C$ that follow from O, similarly, $MGB(X; O; \Sigma)$ is a subconcept of any subconcept D of X where $O \models D \sqsubseteq X$ and $sig(D) \subseteq \Sigma$, as such, the axiom $X \sqsubseteq MGB(X; O; \Sigma)$ would entail axioms of the form $D \sqsubseteq X$ that follow from O.

5.1 Minimal Concept Descriptions

Concept descriptions may end up being too large and violate the minimal objective of ANEMONE. To curtail this, we introduce *minimal concept descriptions* (MCDs). Given a concept C, an ontology O and a signature Σ such that $\Sigma \subseteq sig(O)$ and $sig(C) \notin \Sigma$ a minimal concept description for C should capture the closest approximation of C in terms of Σ. Let ϕ be a concept description for X w.r.t. O and Σ, we say ϕ is *minimal* if the following conditions hold:

1. $\phi \models X \sqsubseteq C$ such that $sig(C) \subseteq \Sigma$ and for any other concept C' such that $O \models X \sqsubseteq C'$ and $sig(C') \subseteq \Sigma$, we have that $O \models C \sqsubseteq C'$.
2. $\phi \models D \sqsubseteq X$ such that $sig(D) \subseteq \Sigma$ and for any other concept D' such that $O \models D' \sqsubseteq X$ and $sig(D') \subseteq \Sigma$, we have that $O \models D' \sqsubseteq D$.
3. If it *description-specific* as discussed above.

Definition 5 ((Weakest) Sufficient Conditions). *Let Σ be a set of concept names and role symbols, X a concept, and O an ontology, such that $\Sigma \subsetneq sig(O)$, we define a sufficient condition of X over Σ relative to O to be any concept β such that $sig(\beta) \subseteq \Sigma$ and $O \models \beta \sqsubseteq X$. It is a weakest sufficient condition denoted $WSC(X; O; \Sigma)$, if for any other sufficient condition β' of X over Σ relative to O we have that $O \models \beta' \sqsubseteq \beta$.*

Observe that minimal concept descriptions can be computed using strongest necessary conditions and weakest sufficient conditions. An algorithm to compute a minimal concept description is provided in Algorithm 3.

Algorithm 3: Minimal Concept Description Extraction

Input: An ontology O, a definiendum X, a signature Σ, where $\Sigma \subsetneq sig(O_B)$, $X \in sig(O_B)$, $X \notin \Sigma$.
Output: An ontology ϕ which is a minimal concept description for X

Step 1: Compute $SNC(X; O; \Sigma)$.

Step 2: Compute $WSC(X; O; \Sigma)$.

Step 3: Return $\{X \sqsubseteq SNC(X; O; \Sigma), WSC(X; O; \Sigma) \sqsubseteq X\}$ as a minimal concept description for X.

Weakest sufficient conditions are an inverse of strongest necessary conditions, as such an algorithm for computing strongest necessary conditions can easily be tweaked to compute weakest sufficient conditions. Let O be an ontology, X be a concept name, for any concept C such that $O \models C \sqsubseteq X$, we have that $O \models \neg X \sqsubseteq \neg C$, hence, if we compute the strongest necessary condition for $\neg X$ the result obtained would be a negation of the weakest sufficient conditions for X: in order to compute an weakest sufficient conditions for X, we compute the strongest necessary condition of $\neg X$ and negate the result.

6 Related Work

Terminological negotiation [15] implements the *ontology negotiation* framework specified in [18]. It aims to solve the problem of communication amongst agents with overlapping signatures by generating translations and mappings between symbols in the different ontologies. Our approach differs in the sense that it aims to solve the problem by extracting DL-definitions or descriptions for concept names as opposed to direct one-to-one mappings between concepts. It is possible for both systems to coexist: concepts with mappings can be considered as part of the common signature when extracting DL-definitions or descriptions.

In [20] a framework is provided for agents to learn new concepts based on the assumption that the agents share some minimal common ground. Learning concepts in ontologies is also investigated in [1] from a corporation perspective and uses a similar approach to [18]: both methods utilize positive and negative examples of concepts to find mappings between concepts.

Ontology alignment is also employed in reducing misunderstanding between communicating agents. One approach to constructing alignments is learning mappings through examples. This approach assumes a closed world of agents and relies on the agents exchanging positive and negative examples of concepts they wish to align. This is the employed process in efforts such as [19, 1]. Similar applications to agent communication include [9, 12, 14].

7 Evaluation of Concept Descriptions and Definitions

7.1 Case Study

The data used is that of the agents and ontologies in Table 1. We evaluate ANEMONE-definitions, DL-definitions, concept descriptions, and minimal concept descriptions for the unshared concepts, $Wimbledon$, *RacquetGames*, and $UKNews$. All forms of definitions and concept descriptions are extracted using the methods discussed in the previous sections. The hypotheses we evaluate are as follows: $\mathcal{H}_1$: DL-definitions are the most optimal in terms of axiom size and still convey the same amount of information as ANEMONE-definitions, concept descriptions, and minimal concept descriptions. $\mathcal{H}_2$: (Minimal) Concept descriptions are as effective as ANEMONE-definitions in conveying information about a concept. $\mathcal{H}_3$: Minimal Concept Descriptions are smaller (in terms of axioms) than ANEMONE-definitions and Concept Descriptions. $\mathcal{H}_4$: Expressive languages allow for richer descriptions which reduce the descent into lower communication protocols. Recall from Section 3 that if a DL-definition (or equivalent concept) exists for an unshared concept, communication may remain in the normal communication protocol. For each unshared concept, we list the possible inferences regarding the unshared concept that can be derived from all the methods combined and highlight the specific axioms in the corresponding tables.

Case Wimbledon A_1 attempts to convey $Wimbledon$ to A_2.

1. Wimbledon $\sqsubseteq$ BallAndRacquetGames
2. Wimbledon $\sqsubseteq \neg$ SoftwareAgents
3. Wimbledon $\sqsubseteq \neg$ ScienceNews
4. Wimbledon $\sqsubseteq \neg$ RegionalNews
5. Wimbledon $\sqsubseteq \neg$ EuropeNews
6. Wimbledon $\sqsubseteq$ Sport
7. Wimbledon $\sqsubseteq$ RacquetGames
8. Wimbledon $\sqsubseteq$ Tennis
9. Wimbledon $\sqsubseteq$ LawnTennis

	ANEMONE-D	CD	MCD	DL-definition
axioms	1, 2, 3, 4, 9	1, 2, 3, 4, 9	9	-
inferences	5,6,7,8	5,6,7,8	1,2,3,4,5,6,7,8	-

Table 2. Case *Wimbledon*: Axioms and inferences of definitions and descriptions as computed w.r.t O_1 and O_2. ANEMONE-D stands for 'ANEMONE-definition'. The row labelled 'axioms' displays the axioms that would be in the definition or description from O_1 w.r.t Σ the common vocabulary for the corresponding description or definition method in each column. The row labelled 'inferences' displays the inferences that could be derived from the O_2 w.r.t the description or definition of the corresponding axioms in each column.

Case Racquet Games A_1 attempts to convey *RacquetGames* to A_2.

1. RacquetGames $\sqsubseteq$ BallAndRacquetGames
2. RacquetGames $\sqsubseteq \neg$ UKNews
3. RacquetGames $\sqsubseteq \neg$ ComputerScience
4. RacquetGames $\sqsubseteq \neg$ ScienceNews
5. RacquetGames $\sqsubseteq \neg$ SoftwareAgents
6. RacquetGames $\sqsubseteq \neg$ RegionalNews
7. LawnTennis $\sqsubseteq$ RacquetGames

	ANEMONE-D	CD	MCD	DL-definition
axioms	1, 4, 5, 6, 7	1, 4, 5, 6, 7	1, 7	-
inferences	2, 3	2, 3	2, 3, 4, 5, 6	-

Table 3. Case *RacquetGames*

Case UKNews A_1 attempts to convey $UKNews$ to A_2.

1. UKNews $\sqsubseteq$ RegionalNews
2. UKNews $\sqsubseteq \neg$ Sport
3. UKNews $\sqsubseteq \neg$ Tennis
4. UKNews $\sqsubseteq \neg$ RacquetGames
5. UKNews $\sqsubseteq \neg$ ScienceNews
6. UKNews $\sqsubseteq \neg$ SoftwareAgents
7. UKNews $\sqsubseteq \neg$ BallAndRacquetGames
8. UKNews $\sqsubseteq \neg$ LawnTennis

	ANEMONE-D	CD	MCD	DL-definition
axioms	1, 5, 6, 7, 8	1, 5, 6, 7, 8	1	-
inferences	2, 3, 4	2, 3, 4	2, 3, 4, 5, 6, 7, 8	-

Table 4. Case $UKNews$

Size evaluation: In all cases, we can see that the minimal concept description is also the smallest in terms of size, which supports $\mathcal{H}_3$ and all inferences follow from the axioms extracted by all methods, thus supporting $\mathcal{H}_2$. We also observe that DL-definitions do not exist in all cases, further highlighting the importance of concept descriptions.

Descent evaluation: None of the cases involve a defined concept, thus the descent evaluation here is focused on switching from the concept definition protocol to the concept explication protocol which is guided by the adequacy of the extracted definition or description. Observe that in the cases for $Wimbledon$ and $RacquetGames$ all definitions and descriptions are adequate in the sense that the hearer agent can relate the unshared concept to all terms in its ontology. However, in the case of $UKNews$, none of the extracted definitions or descriptions are adequate. The ANEMONE notion of adequacy is faulty; in Section 7.3 we demonstrate how this notion of adequacy has no effect on the assertional knowledge exchanged by agents. This means that we can only practically evaluate the descent from the normal communication protocol to the concept description protocol. $Tennis$ is the only unshared defined concept in O_1 and O_2, futhermore, its case is trivial and does not let us test $\mathcal{H}_4$ as a result, we have extended the ontologies with axioms in Table 7.1.

Extensions to O_1	Extensions to O_2
Tournament $\equiv$ KnockoutTournament $\sqcup$ LeagueTournament, Wimbledon $\sqsubseteq$ KnockoutTournament, KnockoutTournament $\sqsubseteq$ EliminationCompetition, LeagueTournament $\sqsubseteq$ GroupCompetition, EliminationCompetition $\sqsubseteq \neg$ GroupCompetition	USOpen $\sqsubseteq$ Tournament, PremierLeague $\sqsubseteq$ GroupCompetition

Table 5. Extensions to the ontologies in Table 1. The first column contains the axioms added to O_1 for agent A_1, and the second column contains the axioms added to O_2 for agent A_2

Now $\Sigma = sig(O_1) \cap sig(O_2) = \{LawnTennis, RegionalNews, SoftwareAgents, ScienceNews, BallAndRacquetGames, KnockoutTournament, GroupCompetition\}$. O_1 now has the disjunctive axiom Tournament $\equiv$ KnockoutTournament $\sqcup$ League-Tournament thus making it an $\mathcal{ALC}$ ontology. The defined concepts in O_1 are now $\{Tournament, KnockoutTournament, LeagueTournament\}$. $KnockoutTournament$ and $LeagueTournament$ are the only defined unshared concepts and we evaluate the definition and description methods on both concepts.

Case League Tournament A_1 attempts to convey $LeagueTournament$ to A_2.

1. LeagueTournament $\equiv$ Tournament $\sqcap$ GroupCompetition
2. LeagueTournament $\sqsubseteq$ Tournament $\sqcap$ GroupCompetition
3. Tournament $\sqcap$ GroupCompetition $\sqsubseteq$ LeagueTournament
4. LeagueTournament $\sqsubseteq$ GroupCompetition
5. LeagueTournament $\sqsubseteq$ Tournament

	ANEMONE-D	CD	MCD	DL-defintion
axioms	4, 5	2, 3	2, 3	1
inferences	2	1, 4, 5	1, 4, 5	2, 3, 4, 5

Table 6. Case $LeagueTournament$

Case KnockoutTournament Possible Inferences of $KnockoutTournament$ w.r.t O_2

1. KnockoutTournament $\equiv$ Tournament $\sqcap \neg$GroupCompetition
2. Tournament $\sqcap \neg$GroupCompetition $\sqsubseteq$ KnockoutTournament
3. KnockoutTournament $\sqsubseteq$ Tournament $\sqcap \neg$GroupCompetition
4. KnockoutTournament $\sqsubseteq$ Tournament
5. KnockoutTournament $\sqsubseteq \neg$GroupCompetition

	ANEMONE-D	CD	MCD	DL-defintion
axioms	4, 5	2, 3	2, 3	1
inferences	3	1, 4, 5	1, 4, 5	2, 3, 4, 5

Table 7. Case $KnockoutTournament$

In both cases, observe that without Algorithm 1, equivalent concepts (DL-definitions) for $KnockoutTournament$ and $LeagueTournament$ can not be extracted and thus conversation will switch to the concept description protocol, which supports $\mathcal{H}_4$. Futhermore observe that $\mathcal{H}_1$ is further supported as the DL-definition (extracted using Algorithm 1) has only one axiom. These cases also highlight a flaw of ANEMONE-definitions: the information conveyed by the ANEMONE-definition is incomplete, however, the information captured by concept descriptions and minimal concept descriptions is complete.

7.2 Experimental Evaluation

Intuitively speaking, the ANEMONE-definition specification requires testing whether an unshared concept is equivalent, disjoint, a subsumer of, or subsumed by concept-names in the common signature of the agents. We implemented this specification using the Hermit reasoner [5] which we will henceforth refer to as *ANEMONE-prototype*. We also implemented the DL-definition extraction algorithm (Algorithm 1) using LETHE [8] and extended it to implement Algorithm 3. All experiments were run on a mac-mini (late 2014) with operating system MacOS Catalina, Dual-Core Intel Core i5 2.6 GHz processor, and eight gigabytes of RAM (1600 MHz DDR3).

The experiments evaluate extracting ANEMONE-definitions, DL-definitions, concept descriptions, and minimal concept descriptions on varying restricted signatures [4]. The experiments were performed on the Cancer Care Treatment Outcome Ontology [11] (CCTOO). CCTOO is an $\mathcal{ALC}$ ontology consisting of 4,494

[4] these may be considered to be the common vocabulary of the agents

axioms, 1,133 concept-names, and six roles. To simulate the common vocabularies, random subsets varying from 10 to 70% of the $sig(CCTOO)$ were selected. We repeated this process three times, resulting in three samples for each subset signature. Using the implicit definability test discussed in Section 4 (which we also implemented using Hermit and the OWL-api [6]) we could determine which concepts were defined for any signature. For each sample signature we iterated over each concept that was not in the sample signature which we call the *unshared concept*. For each iteration, we check if the unshared concept is defined w.r.t the sample signature. A DL-definition extraction is deemed successful if the signature is a subset of the sample signature and if and the ontology entails that the unshared concpet is equivalent to the definition.

For the ANEMONE-prototype, we iterate over the concept names in the sample signature and use Hermit to check if it is equivalent to the unshared concept. We use Algorithm 3 to extract a minimal concept description, if either the strongest necessary condition or weakest sufficient condition is equivalent to the unshared concept, and either of the conditions is a subset of the sample signature, we deem the minimal concept description successful in extracting a DL-definition. The results are in Table 7.2, and it is obvious that Algorithm 1 fails in some cases, this may be due to the signature of the extracted definition not being a subset of the sample signature. This hints at the unshared concept being cyclic as defined in Section 2 because LETHE introduces *definer symbols*[5] to represent cyclic concept-names that need to be eliminated. An interesting observation from Table 7.2 is that minimal concept descriptions are more succesful than strongest necessary conditions in extracting DL-defintions, this is probably due to the weakest sufficient condition satisfying the requirements as opposed to the strongest necessary condition. Observe that for all samples, minimal concept descriptions and strongest necessary conditions extract more definitions than the ANEMONE prototype, further supporting $\mathcal{H}_2$. When the unshared concept is not definable, we only extract an ANEMONE-definition and a minimal concept description. The extraction is deemed successful if it extracts a description or ANEMONE-definition that is non trivial (i.e., not $\top$ or $\bot$) and whose signature is a subset of the sample signature. The results are in Table 7.2 and we observe that in overall, the minimal concept description is more successful than the ANEMONE-prototype, further supporting $\mathcal{H}_2$.

The axiom sizes of the extracted descriptions for definable concepts are displayed in Table 7.2. Due to the page limit, we can only display the results for the first sample of unshared concepts that were not DL-definable. Observe that the ANEMONE-defintions are larger than the minimal concept descriptions overall further supporting $\mathcal{H}_3$.

7.3 Limitations of ANEMONE

Over-reliance on assertional knowledge Given agent A_1 requesting for instances of B, a shared concept-name, from agent A_2, all that is expected is that

[5] symbols not in the signature of the ontology.

	10 %	20 %	30 %	40 %	50 %	60 %	70 %
Sample 1							
DL-def concepts	0	1	4	8	6	4	5
ANEMONE	0	0	1	1	2	1	0
Algorithm 3(MCD)	0	0	1	2	4	2	2
Algorithm 1(SNC)	0	0	0	2	0	2	2
DL-undef concepts	1133	1132	1129	1125	1127	1129	1128
ANEMONE	106	891	760	678	541	455	342
Algorithm 3(MCD)	987	896	768	678	546	449	342
Sample 2							
DL-def concepts	0	0	3	6	2	2	2
ANEMONE	0	0	2	2	0	1	0
Algorithm 3(MCD)	0	0	3	6	2	2	2
Algorithm 1(SNC)	0	0	3	0	2	0	2
DL-undef concepts	1133	1133	1130	1127	1131	1131	1131
ANEMONE	1020	891	790	573	554	443	342
Algorithm 3(MCD)	1020	900	790	668	564	445	342
Sample 3							
DL-def concepts	0	0	1	2	1	2	3
ANEMONE	0	0	1	0	0	1	1
Algorithm 3(MCD)	0	0	1	2	1	2	3
Algorithm 1(SNC)	0	0	0	2	1	2	3
DL-undef concepts	1133	1133	1132	1131	1132	1131	1130
ANEMONE	102	797	760	671	565	456	341
Algorithm 3(MCD)	997	893	772	677	565	456	341

Table 8. Successful Definitions and Descriptions extracted for signature samples of CCTOO. Each column (apart from the first) displays the percentage of the CCTOO signature that forms the simulated common vocabulary. For each sample, the implicit definability test was run on all concept-names in CCTOO, and the number of concepts that were definable under that sample are displayed on the 'DL-def concepts' row. The 'ANEMONE' row displays the definitions successfully extracted using the reasoner implementation of ANEMONE. The 'MCD' row displays the definitions successfully extracted using Algorithm 3. The 'SNC' row displays the definitions successfully extracted using Algorithm 1. A similar pattern is repeated for the non-defined concepts (in row 'DL-undef concepts' but only for ANEMONE and MCD, as undefined concepts have no definitions.

	10 %	20 %	30 %	40 %	50 %	60 %	70 %
ANEMONE Q1	0.0	3.0	2.0	3.0	3.0	2.0	5.0
ANEMONE Q2	0.0	3.0	2.0	3.0	4.0	3.0	7.0
ANEMONE Q3	0.0	3.0	3.0	4.0	4.0	3.0	8.0
ANEMONE Q4	228.0	446.0	678.0	795.0	1136.0	1285.0	1244.0
MCD Q1	3.0	4.0	4.0	5.0	4.0	4.0	4.0
MCD Q2	3.0	4.0	5.0	6.0	4.0	5.0	4.0
MCD Q3	3.0	4.0	5.0	7.0	4.0	6.0	4.0
MCD Q4	114.0	81.0	288.0	390.0	112.0	505.0	188.0

Table 9. Axiom sizes of ANEMONE-definitions and minimal concept descriptions. All results are shown in quartiles 'Q1' stands for the first quartile, and similarly 'Q2', 'Q3', and 'Q4'.

A_2 returns instances of B w.r.t O_2. This is problematic because O_1 may interpret B differently than O_2 w.r.t. the TBox, it is not difficult to imagine a case where B is interpreted differently. This implies that the queries results returned by the agents can be potentially irrelevant and faulty making some interactions of the agents ineffective and useless. Let O_2 be $\{A \sqsubseteq B, A(a), B(c), B(d)\}$ and O_1 be $\{B \sqsubseteq \neg D, D(a)\}$, then A_2 would return a as an instance of B to A_1, and this information clearly contradicts A_1's knowledge. In the current framework, this condraction is can not be handled and is not discussed. Observe that this can be easily mitigated by imposing constraint stating that all shared concepts must be query inseparable over all common instances, or at the very least that one of the agents ontology should be a conservative extension of the other over the common signature.

Faulty Notion of Adequacy for Definitions ANEMONE specifies a description as adequate if every symbol in the hearers ontology has a relation to the description. This is not practical in DL ontologies as not all concepts in DL have relations to one another. Furthermore, given that the speaker agent will utilise the information returned to the hearer agent, the speaker agent has to also evaluate the adequacy of a description it generates for an unshared concept. Adequacy should be measured relative the communication objective which is to exchange assertional knowledge, with DL ontologies, with DL ontologies, stating the relation of an unkown concept to other concepts has little to no effect on the assertional knowledge that may be associated with the unkown concept. Consider agent A_1 with ontology $\{A \sqsubseteq D, F \sqsubseteq \neg A, F(a), A(d)\}$ and agent A_2 with ontology $\{E \sqsubseteq B, B \sqsubseteq F, F(b), E(c)\}$. Consider the description $\{F \sqsubseteq \neg A\}$ which relates A to every concept in A_2's ontology, this description although deemed *adequate* gives A_2 no information on how find assertions of A in its ontology thus making it irrelevant for communication.

8 Conclusion

We have demonstrated methods for extracting DL-definitions and concept descriptions. Our results suggest that the definition extraction methods presented can potentially reduce the amount of descension into lower communication protocols, thus reducing the amount of messages exchanged between agents. We have also proposed *Concept Descriptions* as an alternative to describe concepts that are not defined. Computing concept descriptions relies on computing most specific super concepts and most general subconcepts as discussed in Section 5. Future work will focus on leveraging uniform interpolation to compute most specific super concepts and most general subconcepts.

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9 Appendix

10 Corrections

Notes from Reviewer 2:

1. **Note:** *What is an ALC ontology? This cannot be given as "commonly known", and the missing explanation of it makes the understand of the initial problem and starting point completely unclear.*
   Remedy: Section 2 now contains an explanation on $\mathcal{ALC}$ ontologies.
2. **Note:** *Please check the definition of C+D (before Definition 1): it seems to have a repeated part, the usage of C "elevated to" I is not explained, and it is not clear why this operator is introduce if then it is never used.*
   Remedy: This should be made clearer by the addition of Section 2 (Preliminaries). It is a reference to the interpretation of the "overlap" operator of the ANEMONE ontology, it is added to provide a full context of the ANEMONE framework and how it differs from $\mathcal{ALC}$ ontologies.

3. **Note:** *Definition 1: are all the parts between "()" meaning "respectively"? if yes, please clarify it.*
   Remedy: The referenced definition has now been removed and a more natural-language explanation has been put in place.
4. **Note:** "under O. a specification for computing definitions. Let X" please check this sentence
   Remedy: This should be clearer with the introduction of Section 2 (Preliminaries).
5. **Note:** *"a definition for X following [17] is defined" please explain that formula, it seems a sequence of symbols with no sense. . . .*
   Remedy: The formula is now written in standard set notation, and should be clearer with the inclusion of Section 2 (Preliminaries).
6. **Note:** *"not only does a concept have to be" please check this sentence.*
   Remedy: Sentence has been removed.
7. **Note:** *"Given a concept X that is implicitly or explicitly defined under an ontology O1, extracting a DL -definition o will enable an agent" (end of page 8). I do not really understand how you move from what you were saying to DL. . . if it was described in the previous part, it was completely unclear, could you please try to explain it better?.*
   Remedy: This was a reference to explicit or implicit definitions (as discussed earlier in the Section) and has now been corrected.
8. **Note:** *Definition 8: how can X belong and not belong to sig(o). . . ?.*
   Remedy: This was a typo and has now been corrected.
9. **Note:** *Section 4.1, point 3 seems missing some term.*
   Remedy: Point 3 is referring to *Description-Specificity* as described in the second paragraph of Section 5.
10. **Note:** *Section 5, Table1 seems wrong: o1 and o2 are the same. . . and they also contain wimbledon! so, example1 seems completely wrong, but also all the remaining make few sense, since it is not clear the content of the ontologies.*
    Remedy: This table has now been corrected and can now be referenced in Section 3
11. **Note:** *"Example 2. The misunderstood concept is RacquetGames which belongs to A2's ontology." This again is not reflected in the ontologies in table1.*
    Remedy: Table 1 has been corrected
12. **Note:** *Table2, example1, first column: how do you deduce "Wimbledon ¡ not(SoftwareAgents)" from A2O? I would suggest, for une of these examples, to explain the steps to get the results (or maybe, correcting the ontologies, it will become clearer).*
    Remedy: Ontologies have been corrected, and example should be clearer.
13. **Note:** *The very last sentence of the paper misses something to be correct.*
    Remedy: There was a typo that has now been corrected.

Notes from Reviewer 3

1. **Note:** *No related work section is included in the paper, that is a limitation of this work..*
   Remedy: A related work section (Section 6) has now been added.

2. **Note:** *a distinct set of knowledge about the world: is "set of knowledge" correct? I would understand "set of facts", "set of beliefs". Not sure about "set of knowledge".*
   Remedy: Has been corrected to "set of facts"
3. **Note:** *potentially increasing the ammount of knowledge: please check the sentence, either "potentially increases" or "potential increasing". Ammount is wrongly spelled.*
   Remedy: Typos have been addressed.
4. **Note:** *Establishing common knowledge for communicating agents is non-trivial, which has been studied: is the use of "which" correct? What does it refer to?.*
   Remedy: This was a typo that has now been addressed.
5. **Note:** *Often, either the agent knowledge represetations: mispelled "represetations" word.*
   Remedy: Fixed typo.
6. **Note:** *esp monadic predicates: what does "esp" mean?.*
   Remedy: Typo has now been corrected to "especially"
7. **Note:** *A method for extracting definitions in ALC ontologies: ALC is not introduced/referenced.*
   Remedy: Section 2 now introduces $\mathcal{ALC}$
8. **Note:** *Do not add the bibliographic reference any time you mention ANEMONE: once in the Introduction is enough.*
   Remedy: Formatting issue has been addressed.
9. **Note:** *(i) Minimal and effective communication. (ii). Laziness (iii) Decentralised communication.: please check the use of full stops.*
   Remedy: Formatting issue has been addressed.
10. **Note:** *The ontology semantics in ANEMONE differ: differs.*
    Remedy: Typo has been corrected.
11. **Note:** *to a standard DL is AL: AL is not introduced/referenced.*
    Remedy: *AL* has been defined in Section 2
12. **Note:** *In the definition of the overlap operator, the not inclusion condition is repeated twice.*
    Remedy: Typo has now been corrected.
13. **Note:** *Section 2.1: you should not use a colon at the end of a title.*
    Remedy: Formatting issue has been addressed.
14. **Note:** *X has with the concepts in Σ under O. a specification for computing definitions.: please check this sentence.*
    Remedy: Issue has been addressed with a clearer sentence.
15. **Note:** *You repeat the structure of the paper at the end of Section 2.1, this is not customary.*
    Remedy: Repetition has been removed.
16. **Note:** *This means that a concept not only does a concept have to be explicitly defined: please check.*
    Remedy: Typos have now been addressed.
17. **Note:** *but the signature of its definition must also be a subset of the common signature of the communicating agents but can be achieved using Algorithm*

1: please shorten and split, the sentence is long and not very clear.
Remedy: Sentenced has been shortened.

18. **Note:** *The title "Applying these ideas to the ANEMONE case" does not clearly convey the message on the section's contents, "these ideas" is very vague.*
Remedy: Title has been changed.
19. **Note:** *Table 1 caption, "Ontologies of the Agents used throughtout Examples 1,2 and 3" should be "Ontologies of the Agents used throughtout Examples 1, 2 and 3".*
Remedy: Table 1 has been changed and the caption is clearer.
20. **Note:** *With regards to minimality, the minimal concept description in computed is minimal w.r.t the axiom: what does "in computed" means?.*
Remedy: This was a typo and has been addressed.
21. **Note:** *it is the optimal method in with regard: please check.*
Remedy: Typo has been addressed.
22. **Note:** *and maps of countries A2's ontology is extended with the following axioms: please check.*
Remedy: Sentence has been split into two (a period was missing).
23. **Note:** *Thus, conversation does not decend into the concept definition protocol: decend should be descend.*
Remedy: Spelling has been fixed.
24. **Note:** *our prototype of the a of the DL-definition extraction algorithm.*
Remedy: Typo has been fixed.
25. **Note:** *was optimal in minimal in terms of size: please check.*
Remedy: Typo has been addressed.
26. **Note:** *Bibliography: Many uppercase letters in the papers' title appear as lowercase, for example in.*
Remedy: Formatting issue has been addressed.