# Concept Description and Definition Extraction for the ANEMONE System

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**Abstract.** In multi-agent systems a simplifying assumption is that agents represent their expertise using the same language and signature. We relax this assumption and focus on scenarios where agents with overlapping and not necessarily identical signatures seek to communicate. We investigate ways in which agents can restrict and adapt their knowledge with respect to overlap in signatures to ensure that knowledge being shared is understood by their communication partners via the use of *definitions* and *concept descriptions*. We focus on agents that make use of description logic ontologies to represent their expertise.

**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 knowledge 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 potentially increasing the amount of knowledge shared between any given set of agents.

Establishing common knowledge for communicating agents is non-trivial, which 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]. Example approaches may be found in [9,11,12,1].

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.

In this paper, we are interested in agents that use description logics DL(s) to model the expertise in their domain of specialisation. We study knowledge approximation which is useful for communication cases where approximations of a non-common concept exists, and where alignments are non-existent or impossible. Beyond the establishment of common ground, agents still 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 terminology.

We are interested in developing approximation methods for ANEMONE, a system comprising of dynamic communication protocols that agents can use to dynamically establish a common communication vocabulary which they can in turn use to convey concepts to each other. ANEMONE was designed for ontologies with non-standard semantics of DL. ANEMONE proposes communication protocols that account for communication issues that arise with ontology-based communication such as *the symbol grounding problem* [6], *conversational implicature*, and *scalar implicature* [5].

In this paper, we discuss the topic of definitions in agent communication in contrast to conventional and widely accepted notions of definitions in DL. Given two communicating agents, we study approximation techniques that can be used to extract definitions in terms of the common signature of the ontologies of the agents. Furthermore, we introduce *concept descriptions*, a notion alternative to conventional definitions in DL. Our contributions are as follows:

1. A method for extracting definitions in $\mathcal{ALC}$ ontologies.
2. We introduce *concept descriptions*, an alternative to conventional definitions in DL that can be used to characterise concepts and can be used on ontologies built using standard DL(s).
3. A case study of how definition extraction and concept descriptions can enhance ANEMONE for use with expressive DL(s).

The rest of this paper is organised as follows: 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, and finally, Section 7 provides a case study of how the methods presented can be applied to the ANEMONE system.

## 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. $\mathcal{ALC}$-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 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 $\mathcal{ALC}$ concepts as follows:

$\bot^{\mathcal{I}} = \emptyset \quad (\neg C)^{\mathcal{I}}) = \Delta^{\mathcal{I}} \setminus C^{\mathcal{I}} \quad (C \sqcup D)^{\mathcal{I}} = C^{\mathcal{I}} \cup D^{\mathcal{I}}$
$(\forall r.C)^{\mathcal{I}} = \{x \in \Delta^{\mathcal{I}} \mid \forall y.(x, y) \in r^{\mathcal{I}} \rightarrow y \in C^{\mathcal{I}}\}$
$(\exists r.C)^{\mathcal{I}} = \{x \in \Delta^{\mathcal{I}} \mid \exists y.(x, y) \in r^{\mathcal{I}} \wedge y \in C^{\mathcal{I}}\}$

## 3 The ANEMONE System

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

Communication is considered to be 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 the measure of the *quantity* of information exchanged.

The ontology semantics in ANEMONE differs from standard DL semantics which makes its application to real-world OWL ontologies limited. We find that the closest adaptation to a standard DL is $\mathcal{AL}$ without concept intersection, universal restrictions, and limited existential quantification. In addition, a non-standard *overlap* operator $\oplus$ is introduced which is interpreted as follows:

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

The $\oplus$ operator cannot be expressed using the standard DL operators, however, it is not essential to any of the properties of communication discussed. Formal definitions of Sound and Lossless Communication can be found in [19].

The laziness objective of ANEMONE is realised through the communication layers. There are three main 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 still 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. If the $Inform$ performative is used, then the hearer proceeds to check if the concept is *overgeneralised*. If the concept is overgeneralised, then communication switches 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.

The Concept Explication Protocol is underpinned by ensuring the ontologies of the communicating agents are *grounded*, meaning that the domain of discourse contains all 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 the more traditional sense of agent programming, these classifiers can be considered as the sensors of the agent. The use of grounded ontologies in the ANEMONE approach addresses the *symbol grounding problem* [6].

Unlike the Concept Explication and Concept Definition Protocols, the Normal Communication Protocol of ANEMONE does not require any complex mechanisms, as it is the natural means of dialogue for communicating agents. There is an abundance of research on ontology alignment and related approaches to concept explication that 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, and this is where our primary contribution lies. ANEMONE provides a specification of how definitions should be extracted. We have summarised this specification in the next subsection to provide context and as a background upon which we contrast our approaches.

### 3.1 Computing Definitions in the ANEMONE system

The Concept Definition Protocol of ANEMONE specifies that a definition for a concept $X$ should be constructed by extracting all the relations $X$ has with the concepts in $\Sigma$ under $O$. Let $X$ be concept-name, $\Sigma$ a signature and $O$ an ontology that conforms to the semantics of those in [19] such that $\Sigma \subseteq sig(O)$, a definition for $X$ following [19] is defined as $\langle\{\langle X, C\rangle \in \sqsubseteq |C \in \Sigma\}\{\langle X, C\rangle \in \equiv |C \in \Sigma\}\rangle$ for axioms in $O$.

*Example 1.* The example is adapted from [19]. In it, we have two agents $Ag_1$ and $Ag_2$ which are both heterogeneous personal news agents that classify news articles according to the ontologies provided below: The agents in the examples are presented in Table 1.

| $A_1$ with ontology $O_1$ | $A_2$ with ontology $O_2$ |
|---|---|
| LawnTennis $\sqsubseteq$ BallAndRacquetGames,<br>Wimbledon $\sqsubseteq$ LawnTennis,<br>UKNews $\sqsubseteq$ RegionalNews,<br>SoftwareAgents $\sqsubseteq$ ComputerScience,<br>ComputerScience $\sqsubseteq$ ScienceNews,<br>BallAndRacquetGames $\sqsubseteq \neg$ RegionalNews,<br>BallAndRacquetGames $\sqsubseteq \neg$ ScienceSubjects,<br>RegionalNews $\sqsubseteq \neg$ ScienceNews | LawnTennis $\equiv$ Tennis<br>Tennis $\sqsubseteq$ RacquetGames,<br>RacquetGames $\sqsubseteq$ BallAndRacquetGames,<br>BallAndRacquetGames $\sqsubseteq$ Sports,<br>EuropeNews $\sqsubseteq$ RegionalNews,<br>SoftwareAgents $\sqsubseteq$ ScienceNews,<br>Sports $\sqsubseteq \neg$ RegionalNews,<br>Sports $\sqsubseteq \neg$ ScienceNews,<br>RegionalNews $\sqsubseteq \neg$ ScienceNews |

**Table 1.** Ontologies of the Agents used throughtout 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 $A_2$

The common signature $\Sigma$ between $O_1$ and $O_2$ is as follows: $\Sigma = \{$LawnTennis, RegionalNews, SoftwareAgents, ScienceSubjects, BallAndRacquetGames$\}$.

Following the Concept Definition Protocol, a definition for $Wimbledon$ w.r.t. $\Sigma$ under $O_1$ would be: $\{$Wimbledon $\sqsubseteq$ BallAndRacquetGames, Wimbledon $\sqsubseteq$ LawnTennis, Wimbledon $\sqsubseteq \neg$ RegionalNews, Wimbledon $\sqsubseteq \neg$ SoftwareAgents, Wimbledon $\sqsubseteq \neg$ ScienceSubjects$\}$. We study this example further in Section 7.

Our motivation is that with standard ontology semantics, agents can convey richer descriptions of concepts in their ontologies in the Normal Communication Protocol, due to the increase in expressivity of their ontologies. This reduces the need to switch to the lower protocols. In the Normal Communication Protocol, agents may only convey concepts that are in their shared vocabulary, however, 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 *definitions* in standard ontology semantics 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 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 $sig(C)$. 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 (formally specified in Definition 1) can also be defined explicitly (formally specified in Definition 2). Languages that are definitorially complete are said to have the *Beth Definability* property.

**Definition 1 (Implicit Definability).** *Let $X$ be an $\mathcal{ALC}$-concept, $O$ an $\mathcal{ALC}$-TBox, and $\Sigma \subseteq sig(X) \cup sig(O)$. $X$ is* implicitly definable *in $O$ using $\Sigma$ if for every two models $\mathcal{I}$ and $\mathcal{J}$ of $O$ satisfying $\Delta^{\mathcal{I}} = \Delta^{\mathcal{J}}$, and for all $C \in \Sigma$, $C^{\mathcal{I}} = C^{\mathcal{J}}$, it holds that $X^{\mathcal{I}} = X^{\mathcal{J}}$.*

**Definition 2 (Explicit Definability).** *Let $X$ be an $\mathcal{ALC}$-concept, $O$ an $\mathcal{ALC}$-TBox, and $\Sigma \subseteq sig(X) \cup sig(O)$. $X$ is explicitly definable in $O$ using from $\Sigma$ if there is some $\mathcal{ALC}$-concept $C$ such that $O \models X \equiv C$ and $sig(C) \subseteq \Sigma$. Such a concept $C$ is called an explicit definition of $X$ in $O$ using $\Sigma$.*

The DL $\mathcal{ALC}$ is shown to have the Beth Definability property in [14]. Finding concepts that are defined over a given signature is paramount for agents conversing in the Normal Communication Protocol of ANEMONE as this dictates whether they may have to switch to the lower protocols. A result of [15] 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 $\Sigma$ 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 $\Sigma$ under $O$ iff $O \cup O' \models X \equiv X'$. This can be easily accomplished using a reasoner.

### 4.1 Extracting Definitions for Implicitly and Explicitly defined concepts

After detecting an implicitly definable concept, agents also need to be able to extract a *definition* or concept that is equivalent. Strongest Necessary Conditions (SNC) can be used to compute 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 3 ((Strongest) Necessary Conditions).** *Let $\Sigma$ 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 $\Sigma$ relative to $O$ to be any concept $\alpha$ 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 $\alpha'$ of $X$ over $\Sigma$ relative to $O$ we have that $O \models \alpha \sqsubseteq \alpha'$.*

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 $\Sigma$, and closed theory $O$, the SNC is the uniform interpolant (Definition 4) computed for $O \wedge X(x)$ over $\Sigma$. As such, in DL we can compute the SNC for a concept name $X$ over a signature $\Sigma$ and ontology $O$ by computing the uniform interpolant for $O, X$ over $\Sigma$ 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 $\Sigma$ we compute the uniform interpolant over $O_1, Wimbledon$ w.r.t $\Sigma$ 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 3, However, as can been seen, there are axioms in the result not related to $Wimbledon$, the TBox axiom $SoftwareAgents \sqsubseteq ScienceSubjects$ for example, is not related to $Wimbledon$.

**Definition 4 (Forgetting and Uniform Interpolation).** *Given an ontology $O$, a set of symbols $\Sigma$ such that $\Sigma \subset sig(O)$, a* uniform interpolant *for $O$ over $\Sigma$ is an ontology $\mathcal{V}$ such that $O \models \mathcal{V}$ and $\mathcal{V}$ is a strongest such entailment for $\Sigma$, 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 $\Sigma$. We refer to $\Sigma$ 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 $\psi$ such that $sig(\psi) \subseteq \Sigma$ such that $O \models \psi$, $\mathcal{V} \models \psi$.

Proposition 1 lets us deal with redundant axioms. Let $O$ be an ontology, $\Sigma$ 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 $\Sigma$, we compute a uniform interpolant $\mathcal{V}$ over $\Sigma$ 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 3. This approach is outlined in more detail in Algorithm 1.

**Proposition 1.** *Let $O$ be an ontology, $X$ a concept, $\Sigma \subseteq sig(O)$, and $a$ a fresh individual, such that $a \notin sig(O)$, $sig(X) \not\subseteq \Sigma$. 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 4 that $\mathcal{V} \models C(a)$.

A consequence of Proposition 1 and Definition 4 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 $\Sigma$, 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 $X$.

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

**Step 2:** Add $a$ to $\Sigma$ to get $\Sigma'$ and compute a uniform interpolant denoted $\mathcal{V}$ over $O'$ w.r.t $\Sigma'$. 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 ontology, $\Sigma$ a subset of $sig(O)$, $C$ a concept such that $sig(C) \not\subseteq \Sigma$. 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 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 3 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 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. Given a concept $X$ that is implicitly or explicitly defined under an ontology $O_1$, extracting a DL-definition $\phi$ will enable an agent $A_1$ use the $ExactInform$ performative to convey $\phi$ 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 describe $X$, which are discussed in the next section.

Observe that definitions in the DL sense differ from definitions in the ANEMONE sense as discussed in Section 3.1. To avoid confusion, we will henceforth distinguish between the two, using *ANEMONE-Definitions* to refer to definitions in the sense discussed in Section 3.1, and *DL-Definitions* to refer to definitions in the traditional DL sense discussed in this Section.

## 5 Concept Descriptions

Concept Descriptions 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 $\Sigma$ 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 $\phi$ be a description for $X$ w.r.t. $O$ and $\Sigma$, we say $\phi$ 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 $\phi$ be a description for $X$ w.r.t. $O$ and $\Sigma$, we say $\phi$ 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 $sig(C) \in \Sigma$.

Our approach to extracting concept descriptions rely on two notions: *most specific superconcept* and *most general subconcept*. We provide formal definitions in Definitions 5 and 6.

**Definition 5 (Most Specific Superconcept).** *Let $O$ be an ontology, $X$ a concept name, $C$ a concept, and $\Sigma$ a subset signature of $O$ such that $X \in sig(O)$, $X \notin sig(O)$, $sig(C) \subseteq \Sigma$ and $\Sigma \subseteq sig(O)$. We call $C$ the most general super concept of $X$ if 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 6 (Most General Subconcept).** *Let $O$ be an ontology, $X$ a concept name, $C$ a concept, and $\Sigma$ a subset signature of $O$ such that $X \in sig(O)$, $X \notin sig(O)$, $sig(C) \subseteq \Sigma$ 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 $\Sigma$, where $\Sigma \subseteq sig(O_B)$, $X \in sig(O_B)$, $X \notin \Sigma$.
**Output:** An ontology $\phi$ 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 consequence 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 consequence 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*.

Given a concept $C$, an ontology $O$ and a signature $\Sigma$ 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 $\Sigma$. Let $\phi$ be a concept description for $X$ w.r.t. $O$ and $\Sigma$, we say $\phi$ 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 $O \models C \sqsubseteq C'$, and $\not\models C \sqsubseteq C'$.
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 $O \models D' \sqsubseteq D$, and $\not\models D' \sqsubseteq D$.
3. If it *description-specific* as discussed above.

**Definition 7 ((Weakest) Sufficient Conditions).** *Let $\Sigma$ 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 sufficient condition of $X$ over $\Sigma$ relative to $O$ to be any concept $\beta$ 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 $\beta'$ of $X$ over $\Sigma$ 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 $\Sigma$, where $\Sigma \subseteq sig(O_B)$, $X \in sig(O_B)$, $X \notin \Sigma$.
**Output:** An ontology $\phi$ 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* [13] implements the *ontology negotiation* framework specified in [16]. 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 [18] 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 [16]: 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 the 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 [17,1]. Similar applications to agent communication include [9,11,12].

## 7 Application to ANEMONE

ANEMONE [19] provides a case study focused on news retrieval using personal agents whose ontologies are grounded using machine learning classifiers and the URL(s) of news articles. In the context of the case study, the domain of interpretation for the ontologies of the agents is the set of all URL(s) on the internet. As a minimal case study, we have adopted all the ANEMONE-definition extraction examples from ANEMONE [19] as Examples 2, 3, and 4. In each example, we present the adopted example and contrast it against the use of concept descriptions as discussed in Section 5. The main observation is that concept descriptions are more comprehensive than ANEMONE-definitions, and that minimal concept descriptions tend to be as effective and less bulky than both ANEMONE-definitions and concept descriptions.

The agents in the examples are as described in Table 1 from Example 1. Each example simulates a conversation occurring in the Concept Definition Protocol where an agent is attempting to describe a concept in its ontology in terms of $\Sigma$.

*Example 2.* $A_1$ attempts to convey $Wimbledon$ to $A_2$. $A_2$ does not understand $Wimbledon$ and $A_1$ cannot find an equivalent concept, thus conversation switches to the Concept Definition Protocol where $A_1$ attempts to define $Wimbledon$. The first column contains the ANEMONE-definition, the second column contains the concept description of $Wimbledon$ as described in Section 5, and the third column contains the minimal concept description of $Wimbledon$ as described in Section 5.

We observe from all columns that all ANEMONE-definitions are adequate because $A_2$ can infer the relation of the $Wimbledon$ with all other concepts in its ontology. With regards to minimality, the minimal concept description computed

Example 1: Definition of *Wimbledon*

| ANEMONE-Definition of *Wimbledon* | Concept Description of *Wimbledon* | Minimal Concept Description of *Wimbledon* |
|---|---|---|
| Wimbledon $\sqsubseteq$ LawnTennis<br>Wimbledon $\sqsubseteq$ BallAndRacquetGames<br>Wimbledon $\sqsubseteq \neg$ RegionalNews | Wimbledon $\sqsubseteq \neg$ ScienceNews<br>Wimbledon $\sqsubseteq \neg$ SoftwareAgents<br>Wimbledon $\sqsubseteq$ Sport<br>Wimbledon $\sqsubseteq$ RacquetGames<br>Wimbledon $\sqsubseteq$ Tennis | Wimbledon $\sqsubseteq$ LawnTennis |
| $A_2$ Inferences from ANEMONE Defintion of *Wimbledon* | $A_2$ Inferences from from Concept Description of *Wimbledon* | $A_2$ Inferences from Minimal Concept Description of *Wimbledon* |
| Wimbledon $\sqsubseteq$ LawnTennis<br>Wimbledon $\sqsubseteq$ BallAndRacquetGames<br>Wimbledon $\sqsubseteq \neg$ RegionalNews<br>Wimbledon $\sqsubseteq \neg$ SoftwareAgents<br>Wimbledon $\sqsubseteq \neg$ ScienceNews | Wimbledon $\sqsubseteq \neg$ EuropeNews<br>Wimbledon $\sqsubseteq$ Sport<br>Wimbledon $\sqsubseteq$ RacquetGames<br>Wimbledon $\sqsubseteq$ Tennis | Wimbledon $\sqsubseteq$ BallAndRacquetGames<br>Wimbledon $\sqsubseteq \neg$ SoftwareAgents<br>Wimbledon $\sqsubseteq \neg$ ScienceNews<br>Wimbledon $\sqsubseteq \neg$ RegionalNews<br>Wimbledon $\sqsubseteq \neg$ EuropeNews<br>Wimbledon $\sqsubseteq$ Sport<br>Wimbledon $\sqsubseteq$ RacquetGames<br>Wimbledon $\sqsubseteq$ Tennis |

Example 2: Definition of *RacquetGames*

| ANEMONE-Definition of *RacquetGames* | Concept Description of *RacquetGames* | Minimal Concept Description *RacquetGames* |
|---|---|---|
| LawnTennis $\sqsubseteq$ RacquetGames<br>RacquetGames $\sqsubseteq$ BallAndRacquetGames<br>RacquetGames $\sqsubseteq \neg$ RegionalNews | LawnTennis $\sqsubseteq$ RacquetGames<br>RacquetGames $\sqsubseteq$ BallAndRacquetGames<br>RacquetGames $\sqsubseteq \neg$ RegionalNews<br>RacquetGames $\sqsubseteq \neg$ ScienceNews<br>RacquetGames $\sqsubseteq$<br>$\neg$ SoftwareAgents | LawnTennis $\sqsubseteq$ RacquetGames<br>RacquetGames $\sqsubseteq$ BallAndRacquetGames |
| $A_1$ Inferences from ANEMONE Defintion of *RacquetGames* | $A_1$ Inferences from from Concept Description of *RacquetGames* | $A_1$ Inferences from Minimal Concept Description of *RacquetGames* |
| RacquetGames $\sqsubseteq \neg$ UKNews<br>RacquetGames $\sqsubseteq \neg$ ComputerScience<br>RacquetGames $\sqsubseteq \neg$ ScienceNews<br>RacquetGames $\sqsubseteq \neg$ SoftwareAgents | RacquetGames $\sqsubseteq \neg$ UKNews<br>RacquetGames $\sqsubseteq \neg$ ComputerScience | RacquetGames $\sqsubseteq \neg$ UKNews<br>RacquetGames $\sqsubseteq \neg$ ComputerScience<br>RacquetGames $\sqsubseteq \neg$ ScienceNews<br>RacquetGames $\sqsubseteq \neg$ SoftwareAgents<br>RacquetGames $\sqsubseteq \neg$ RegionalNews |

Example 3: Definition of *UKNews*

| ANEMONE-Definition of *UKNews* | Concept Description of *UKNews* | Minimal Concept Description of *UKNews* |
|---|---|---|
| UKNews $\sqsubseteq$ RegionalNews<br>UKNews $\sqsubseteq \neg$ BallAndRacquetGames<br>UKNews $\sqsubseteq \neg$ LawnTennis | UKNews $\sqsubseteq$ RegionalNews<br>UKNews $\sqsubseteq \neg$ BallAndRacquetGames<br>UKNews $\sqsubseteq \neg$ LawnTennis<br>UKNews $\sqsubseteq \neg$ ScienceNews<br>UKNews $\sqsubseteq \neg$ SoftwareAgents | UKNews $\sqsubseteq$ RegionalNews |
| $A_2$ Inferences from *UKNews* ANEMONE Defintion | $A_2$ Inferences from *UKNews* Concept Description | $A_2$ Inferences from *UKNews* Minimal Concept Description |
| UKNews $\sqsubseteq \neg$ Sport<br>UKNews $\sqsubseteq \neg$ Tennis<br>UKNews $\sqsubseteq \neg$ RacquetGames<br>UKNews $\sqsubseteq \neg$ ScienceNews<br>UKNews $\sqsubseteq \neg$ SoftwareAgents | UKNews $\sqsubseteq \neg$ Sport<br>UKNews $\sqsubseteq \neg$ Tennis<br>UKNews $\sqsubseteq \neg$ RacquetGames | UKNews $\sqsubseteq \neg$ Sport<br>UKNews $\sqsubseteq \neg$ Tennis<br>UKNews $\sqsubseteq \neg$ RacquetGames<br>UKNews $\sqsubseteq \neg$ ScienceNews<br>UKNews $\sqsubseteq \neg$ SoftwareAgents<br>UKNews $\sqsubseteq \neg$ BallAndRacquetGames<br>UKNews $\sqsubseteq \neg$ LawnTennis |

**Table 2.** A comparison of ANEMONE-definitions, Concept Descriptions, and Minimal Concept Descriptions. Three examples are provided: (i) $A_1$ attempts to describe *Wimbledon* to $A_2$. (ii) $A_2$ attempts to describe *RacquetGames* to $A_1$. (iii) $A_1$ attempts to describe *UKNews* to $A_2$. In each example, the first column contains the ANEMONE-definition and interpretation of the concept (as described in [19]) being conveyed. The second column contains the concept description (as described in Section 5) and interpretation of the concept being conveyed. The third column contains the minimal concept description (as described in Section 5) and interpretation of the concept being conveyed. Note that the set of new statements known by $A_2$ is the same in each case, but the subset which is inferred varies.

is minimal w.r.t the axiom count of the ANEMONE-Definition and the concept description, and still adequate and the reason for this follows from Definition 3, all superconcepts of a concept are also superconcepts of the concepts strongest necessary condition. The minimal concept description is adequate and minimal in terms of axiom count, and therefore is the optimal method that satisfies the minimal and effective objective of ANEMONE. The concept description of $Wimbledon$ is the maximal w.r.t the number of axioms of the ANEMONE-definition and the minimal concept description. Although it is adequate, this method less optimal. However, it is worth noting that although the concept description is less optimal, it reduces the inferences that $A_2$ has to make.

*Example 3.* The misunderstood concept is *RacquetGames* which belongs to $A_2$'s ontology. $A_1$ does not understand *RacquetGames* and $A_2$ cannot find an equivalent concept, thus conversation switches to the Concept Definition Protocol where $A_2$ attempts to define *RacquetGames*. In this example the trend from Example 1 continues, we observe that the minimal concept description is still the most optimal method as all inferences derived from the concept descriptions and the ANEMONE-definition are also derived from the minimal concept description.

*Example 4.* The misunderstood concept is $UKNews$ which belongs to $A_1$'s ontology. Neither the minimal concept description nor the concept description nor the ANEMONE-definition and are adequate because $A_2$ cannot infer any relation between $UKNews$ and *EuropeanNews*, thus communication must descend into the concept explication protocol.

### 7.1 Extending the Concept Definition Protocol for Expressive DLs

Now we consider the agents with more expressive DL(s). Imagine agent $A_1$ has been enhanced with a computer vision classifier that lets it classify famous athletes and politicians given a URL of a photo, and also a text classifier that lets it classify Nordic news. $A_1$'s ontology is extended with the following axioms:

$$\text{NordicNews} \equiv \text{DanishNews} \sqcup \text{SwedishNews} \sqcup \text{FinnishNews} \sqcup \text{NorwegianNews} \sqcup \text{IcelandicNews},$$
$$\exists\ \text{hasThumbnail.Politician} \sqsubseteq \text{PoliticalNews},$$
$$\forall\ \text{hasThumbnail.EliteAthlete} \sqsubseteq \text{CelebrityNews},$$
$$\begin{array}{lll}
\text{EliteAthlete} \sqsubseteq \text{Celebrity}, & \text{DanishNews} \sqsubseteq \neg\ \text{FinnishNews}, & \text{DanishNews} \sqsubseteq \neg\ \text{SwedishNews}, \\
\text{CelebrityNews} \sqsubseteq \neg\ \text{NordicNews}, & \text{DanishNews} \sqsubseteq \neg\ \text{IcelandicNews}, & \text{NorwegianNews} \sqsubseteq \neg\ \text{SwedishNews} \\
\text{IcelandicNews} \sqsubseteq \neg\text{NorwegianNews}, & \text{FinnishNews} \sqsubseteq \neg\ \text{IcelandicNews}, & \\
\text{FinnishNews} \sqsubseteq \neg\ \text{NorwegianNews}, & \text{FinnishNews} \sqsubseteq \neg\ \text{SwedishNews}, & \\
\text{IcelandicNews} \sqsubseteq \neg\ \text{SwedishNews}, & \text{DanishNews} \sqsubseteq \neg\ \text{NorwegianNews}, &
\end{array}$$

Imagine agent $A_2$ has been enhanced with a computer vision classifier that lets it classify famous musicians, famous athletes, and maps of countries. $A_2$'s ontology is extended with the following axioms:

$$\begin{aligned}
\text{IcelandicNews} &\sqsubseteq \exists\ \text{hasThumbnail.MapOfIceland} \sqcap \text{NewsArticle},\\
\text{FinnishNews} &\sqsubseteq \exists\ \text{hasThumbnail.MapOfFinland} \sqcap \text{NewsArticle},\\
\text{SwedishNews} &\sqsubseteq \exists\ \text{hasThumbnail.MapOfSweden} \sqcap \text{NewsArticle},\\
\text{DanishNews} &\sqsubseteq \exists\ \text{hasThumbnail.MapOfDenmark} \sqcap \text{NewsArticle},
\end{aligned}$$

$$\begin{aligned}
\text{Musician} &\sqsubseteq \text{FamousPerson} & \text{FinnishNews} &\sqsubseteq \text{NordicNews}, & \text{DanishNews} &\sqsubseteq \text{NordicNews}\\
\text{EliteAthlete} &\sqsubseteq \text{FamousPerson} & \text{SwedishNews} &\sqsubseteq \text{NordicNews}, & &\\
\text{IcelandicNews} &\sqsubseteq \text{NordicNews}, & & & &
\end{aligned}$$

The common signature $\Sigma$ is extended and is now {LawnTennis, RegionalNews, SoftwareAgents, ScienceNews, BallAndRacquetGames, NordicNews, FinnishNews, IcelandicNews, SwedishNews, hasThumbnail, EliteAthlete}.

*Example 5.* Conversation is occuring in the normal communication protocol, $A_1$ attempts request recent instances $NorwegianNews$ from $A_2$, $A_2$ does not understand $NorwegianNews$, $A_1$ then attempts to find a concept equivalent to $NorweigianNews$ in terms of $\Sigma$.

If $A_1$ does not know that $NorweigianNews$ is implicitly definable, it has to switch to the Concept Definition Protocol and extract an ANEMONE-definition or Concept Description. However, $A_1$ can perform an implicit definability test for $NorweigianNews$ following [15]. Upon finding out $NorweigianNews$ is implicitly definable, it proceeds to extract a DL-definition by computing a strongest necessary condition for $NorweigianNews$ as discussed in Section 4 which is as follows:

$$\begin{gathered}
\text{NorweigianNews} \equiv \text{NordicNews} \sqcap\neg\ \text{SwedishNews} \sqcap\neg\ \text{DanishNews} \sqcap\neg\\
\text{IcelandicNews} \sqcap\neg\ \text{FinnishNews}
\end{gathered}$$

Thus, conversation does not descend into the Concept Definition Protocol.

*Example 6.* Conversation is occuring in the normal communication protocol, $A_1$ attempts request recent instances $CelebrityNews$ from $A_2$, $A_2$ does not understand $CelebrityNews$, $A_1$ then attempts to find a concept equivalent to $NorweigianNews$ in terms of $\Sigma$. Since $CelebrityNews$ is neither explicitly or implicitly defined, conversation must descend into the Concept Definition Protocol where $A_1$ may either extract a concept description as follows:

$$\begin{gathered}
\forall\text{hasThumbnail.EliteAthlete} \sqsubseteq \text{CelebrityNews},\\
\text{CelebrityNews} \sqsubseteq \neg\ \text{SwedishNews},\\
\text{CelebrityNews} \sqsubseteq \neg\ \text{IcelandicNews},\\
\text{CelebrityNews} \sqsubseteq \neg\ \text{FinnishNews},\\
\text{CelebrityNews} \sqsubseteq \neg\ \text{NordicNews}
\end{gathered}$$

Or a minimal concept description as follows:

$$\begin{gathered}
\forall\text{hasThumbnail.EliteAthlete} \sqsubseteq \text{CelebrityNews},\\
\text{CelebrityNews} \sqsubseteq \neg\ \text{NordicNews}
\end{gathered}$$

In Examples 2 to 4, all the concept descriptions may be computed using reasoners, however, the case in this example is not trivial. The concept descriptions in this example cannot be easily computed using a reasoner which illustrates one of the consequence-preserving advantage of uniform interpolation.

It is not difficult to imagine how the number of axioms in the ontologies of these agents can explode to a few hundred or even thousands of axioms upon the addition or improvements to the classifiers of the agents. Extracting minimal concept descriptions would be useful and important for communication in such cases. In order to do this, agents may leverage the approach in s to ensure that conversation is still minimal and effective.

### 7.2 Using Concept Descriptions to detect differences in understanding

Observe that in the evolved ontologies of the agents, the notion of $NordicNews$ is different in both of the agents ontologies: $A_1$ understands $NordicNews$ to be *equivalent* to a disjunction of $SwedishNews$, $DanishNews$, $FinnishNew$, $IcelandicNews$, and $NorweigianNews$ which is in contrast to $A_2$ which understands $NordicNews$ an *umbrella* term for $SwedishNews$, $DanishNews$, $FinnishNew$, $IcelandicNews$, and $NorweigianNews$. This may lead to misunderstandings further down the line of conversation. In such cases, a useful tool is for agents to extract all their knowledge about $NordicNews$ in terms of $\Sigma$ for comparison which may be accomplished using concept descriptions. Such comparisons may result in the agents retricting their common signature further or expanding it, depending on the outcome. For example, the agents may not reach a consensus on the meaning of $NordicNews$ and decide to exclude $NordicNews$ from the signature in order to make conversation simpler, however, this means that the agents must revise all concepts in the common signature that rely on $NordicNews$ such as $NorwegianNews$.

### 7.3 Prototype Evaluation

The goal of the evaluation was to measure the *completeness* (i.e., how often does the prototype extract a DL-definition for a defined concept?) and *performance* (i.e., (i) how long does it take a prototype to extract a DL-definition? (ii) How big is the DL-definition?). Since we have no implementation of concept descriptions, our evaluation was restricted to concepts that were either implicitly or explicitly defined, which means that the completeness measure is also an evaluation of the laziness objective of ANEMONE: a DL-definition that could not be extracted for an implicitly or explicitly defined concept signified a potential an unnecessary descent into the Concept Definition Protocol.

We implemented a reasoner-prototype searched for equivalent concepts for a misunderstood concept $X$ under a simulated common signature $\Sigma$ to simulate communication in the Normal Communication Protocol. All searches were implemented using the ELK reasoner [7]. We evaluated the reasoner-prototype against our prototype of the DL-definition extraction algorithm (Algorithm 1) which was implemented using LETHE [8]

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).

Both prototypes were evaluated on the Parkinson's disease ontology [20] (PDON). PDON is an $\mathcal{EL}$ ontology consisting of 4068 axioms, 632 concept-names, and 12 roles. We used the implicit definability test discussed in Section 4, to find concepts that were implicitly defined. To simulate the common signature of the agents, we extracted a random signature of the ontology consisting of 185 terms (29% of the ontology's signature). There were 630 implicitly defined concepts under the selected signature, and only 69 (11%) of the 630 had been explicitly defined under the selected signature. The reasoner-prototype extracted DL-definitions for 507 concepts, while the Algorithm 1 prototype extracted DL-definitions for 630 concepts. The average number of axioms of the DL-definition extracted by the reasoner-prototype was 9.91, while that of the Algorithm 1 prototype was 1.78. The average time taken by the reasoner-prototype was 108.48 milliseconds while that of the Algorithm 1 prototype was 5,647.77 milliseconds.

From the results, we observe that the reasoner-prototype performed better in terms of speed, however, the Algorithm 1 prototype was optimal (more compact) in terms of number of axioms. The Algorithm 1 prototype extracted DL-definitions for all 630 concepts further confirms its completeness, however, the reasoner-prototype did not extract DL-definitions for 183 of the concepts that were implicitly definable, and in all such instances, communication would have to switch to lower protocols. Furthermore, without the use of standard ontology semantics, the use of reasoners and the Algorithm 1 prototype would not be possible, only 69 of the 630 defined concepts could be conveyed in the Normal communication protocol and conveying the remaining 561 concepts would have required switching to lower protocols.

Both prototypes manage to extract DL-Definitions within a matter of seconds, suggesting that Algorithm 1 is also feasible in terms of *latency* for agent communication.

## 8 Conclusion

The DL-definition extraction and concept descriptions presented in this paper can enable ANEMONE to be applied to standard DL(s) world ontologies by ensuring that DL-definitions are extracted in cases where a misunderstood concept implicitly or explicitly defined. For concepts that are neither explicitly nor implicitly defined, we propose that concept descriptions can be used to compute ANEMONE-definitions.

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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