Efficient Representation and Effective Reasoning for Multi-Agent Systems

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Introduction

In multi-agent systems, interactions between agents are often related to cooperation or competition in such a fashion that they can fulfil their tasks. Successful interactions often require agents to share common and unified knowledge about their working environment. However, autonomous agents observe and judge their surroundings by their own view. Consequently, agents possibly have partial and sometimes conflicting descriptions of the world. In scenarios where they have to coordinate, they are required to identify the shared knowledge in the group and to be able to reason with available information. This problem requires more sophisticated modelling and reasoning methods, which is beyond the classical logics and monotonic reasoning.

We introduce a formal framework based on Defeasible Logic (DL) to describe the knowledge commonly shared by agents, and that obtained from other agents. This enables an agent to efficiently reason about the environment and intentions of other agents given available information. We propose to extend the reasoning mechanism of DL with the *superior knowledge*. This mechanism allows an agent to integrate its mental attitude with a more trustworthy source of information such as the knowledge shared by the majority of other agents.

Literature Review

A well-known and successful approach to model rational agents, the Beliefs, Desires and Intentions (BDI) architecture is inspired by human attitudes towards actions. Beliefs, Desires and Intentions are then the mental components in the architecture (Rao & Georgeff 1991; Kinny, Georgeff, & Rao 1996). This architecture is strongly founded in the philosophical investigation by Bratman on human practical reasoning. BDI model provides an insight view to the decision-making process of an agent. Furthermore, the model facilitates building agent systems thanks to its clear definition of agent functionality.

Generally behaviours of a BDI agent are driven by its own desires. However, as a member of a group, the agent is often required to comply with the group "conventions". The idea of modifying the BDI architecture by introducing deontological properties like laws, norms, and obligations to place constraints on agents' behaviours is supported by several authors (Broersen *et al.* 2001; Castelfranchi 1998; Cavedon & Sonenberg 1998; Dignum, Kinny, & Sonenberg 2002). They strongly support that such concepts are an important factor to "glue" autonomous agents together in a multi-agent system. The deontological properties are considered as external influences on individual's decision making and the commitment to other members. These concepts are very well represented by modal logics but the issue of incomplete and conflicting information is not fully addressed.

DL (Nute 1987; 1994) has been very well developed over the years by (Antoniou *et al.* 2000; 2001; Billington 1993). In the agent research domain, there is a line of works proposes to use DL to model rational agents (Governatori & Rotolo 2004; Governatori, Rotolo, & Padmanabhan 2006; Dastani *et al.* 2005a; 2005b). In general, DL is an elegant and computationally efficient tool (Maher 2001; Maher *et al.* 2001) to tackle with the issue of partial and conflicting knowledge. Also, DL provides a compact representation and an effective way to accommodate new information.

Research Description

Knowledge Representation

In general, each individual agent can take any action driven by the its desires based on knowledge about the environment and its perception of other agents' behaviours. However, as a member of a group, the agent should be aware of mental attitudes commonly held among the group and should avoid actions which can violate desires of the group. By considering individual knowledge and the "collective wisdom" of the group, the individual agent can adjust its behaviours accordingly. Taking this observation into account, we propose a knowledge structure for an agent, which consists of three components named *background*, *other members*, and *internal knowledge* (the agent's own knowledge).

Consider a group of agents, $\mathscr{A} = \{A_1, \ldots, A_{n+1}\}$, and a weight function, $w_A : \{A_1, \ldots, A_{n+1}\} \mapsto \mathbb{R}^+$, representing importance (reliability) of an agent to the group. An individual agent in the group, considering itself as A_{me}, has the knowledge structure represented by a set of defeasible theories

$$\mathscr{T} = \{T_{bg}, T_{me}, \mathscr{T}_{other}\}$$

- T_{bg} is the *background theory* representing the background knowledge. This knowledge is commonly shared by all agents, which motivates general (social) behaviours.
- T_{me} is the *internal theory* representing the internal knowledge. This component is the agent's own knowledge describing its own view about the environment, where the agent acts. This knowledge enables the agent to autonomously and distinctively achieve its goals.
- $\mathscr{T}_{other}$ is the knowledge obtained from other agents in the group. This component is also represented as a set of defeasible theories $\mathscr{T}_{other} = \{T_i : 1 \leq i \leq n+1 \; \& \; i \neq me\}$. T_i represents A_{me}'s perception of agent i. T_i's importance is derived from that of the corresponding agent $w_T(T_i) = w_A(A_i)$. $\mathscr{T}_{other}$ provides a rough understanding of their possible behaviours.

Majority Knowledge

The *majority rule* from (Lin 1996) retrieves a maximal amount of consistent knowledge from a set of agents' knowledge. Conflicting information among agents can be handled by considering not only the number of agents supporting that information but also the importance of the agents. The approach provides a useful and efficient method to discover information largely held by agents. This knowledge can be used either to reinforce the current knowledge of an agent or to introduce new information into the agent's knowledge.

Due to possible conflicting information within a source, the majority rule cannot be directly applied to our framework. Instead, the majority rule pools joint conclusions derived by the defeasible reasoning. A conclusion c is in the joint knowledge T_{maj} if its weight accumulated from $T_i \in \mathscr{T}_{other}$, which supports c, is greater than half of the total weight W of the group.

Proposition 1 *For any literal q, it is impossible to have both $+\partial q$ and $+\Delta{\sim}q$ in T_{maj}*

Due to the nature of DL proofs, conflicts can arise between strict and defeasible conclusions of a literal and its negation. However, this proposition claims that the outcome of the majority rule is still coherent.

As T_{maj} is derived from what the agent A_{me} knows about the other agents, T_{maj} can conflict with T_{me} (the internal knowledge of A_{me}). In the case that A_{me} joins the majority pool, the greater importance (weight) A_{me} acquires, the greater influence it has on the joint knowledge. If the weight of A_{me} is greater than $W/3$, A_{me}'s support for any conclusion c is tantamount to half of the group's support for c. A_{me} can have two strategies to handle conflicts :

1. *Adaptive strategy* if $w_{me} \leq \max(W/3)$. A_{me} should consider conclusions from the others, since it is unlikely that A_{me} can successfully override conflicts from the joint knowledge. That is T_{maj} can introduce new information to A_{me}.
2. *Collective strategy* otherwise. A_{me} can defeat conflicts from other agents if A_{me} joins the pool. Hence the joint knowledge from the others reinforces the current knowledge of A_{me}. In order to obtain more knowledge, A_{me} should collect all possible consistent knowledge from the others.

In both strategies, *background knowledge* commonly shared by the group is respected; i.e., in case of a conflict between a conclusion from background knowledge and either from the majority or the agent's knowledge, the conclusions, which are supported by the background part prevail.

Defeasible Reasoning with Superior Knowledge

In this section, we propose a simple method to integrate two independent defeasible theories. Note that a defeasible theory has finite sets of facts and rules, and that a derivation from the theory can be computed in linear time (Maher 2001).

Consider two knowledge sources represented by defeasible theories labelled as T_{sp} – the superior theory, and T_{me} – the agent's internal theory. The agent considers that T_{sp} is more important than T_{me}. Thus, conclusions from the internal theory should be withdrawn if they conflict with the superior theory; the agent prefers the superior theory's conclusions to its own.

Owing to the transformations of the superiority relation and defeater rules (Antoniou *et al.* 2001), we can assume that the two theories contain only strict and defeasible rules. To perform the defeasible reasoning, the agent generates a superiority relation over sets of rules as in $R_s^{sp} > R_s^{me}; R_d^{sp} > R_d^{me}$. In this scheme, the subscript denotes the type of rules (s and d for strict and defeasible respectively) while the superscript indicates the type of the theory which contains the rules.

A derivation from the two theories is a finite sequence $P = (P(1), \ldots, P(n))$ of tagged literals satisfying proof conditions (which correspond to inference rules for each of the four kinds of conclusion). $P(1..i)$ denotes the initial part of the sequence P of length i. The definite conclusion, $+\Delta q$, will be derived by performing forward chaining with the strict rules in the superior theory, or in the internal theory if the complementary literals cannot be positively proved by the superior theory.

$+\Delta$: If $P(i+1) = +\Delta q$ then
(1) $q \in F$ or
(2) $\exists r \in R_s^{sp}[q] \; \forall a \in A(r) : +\Delta a \in P(1..i)$ or
(3) $\exists r' \in R_s^{me}[q] \; \forall a \in A(r') : +\Delta a \in P(1..i)$ and
$\forall r \in R_s^{sp}[{\sim}q] \; \exists a \in A(r) : -\Delta a \in P(1..i)$

The conclusions tagged with $-\Delta$ mean that the extended mechanism cannot retrieve a positive proof for the corresponding literals from the strict parts of both theories.

$-\Delta$: If $P(i+1) = -\Delta q$ then
(1) $q \notin F$ and
(2) $\forall r \in R_s^{sp}[q] \cup R_s^{me}[q] \; \exists a \in A(r) : -\Delta a \in P(1..i)$.

The proof for $-\Delta$ implicitly satisfies the principle of strong negation (Antoniou *et al.* 2000). The proof, which strictly complies with that principle, requires an additional condition such that at least one strict rule from the superior theory supports the complementary literals. However, this condition is never met as it violates the coherence property of the strict rules.

A defeasible conclusion $+\partial q$ can either be drawn directly from definite conclusions, or by investigating the defeasible part of the integrated theory. The conclusions tagged with $-\partial$ mean that the extended mechanism cannot retrieve a positive proof for the corresponding literals from the strict and defeasible rules of both theories or these conclusions are rebutted because of "stronger" conclusions. The proof for $+\partial q$ and $-\partial q$ complies with the strong negation principle.

$+\partial$: If $P(i+1) = +\partial q$ then either
(1) $+\Delta q \in P(1..i)$ or
    (2.1) $\exists r \in R_{sd}^{sp}[q] \cup R_{sd}^{in}[q]\ \forall a \in A(r) : +\partial a \in P(1..i)$ and
    (2.2) $-\Delta{\sim}q \in P(1..i)$ and
    (2.3) $\forall s \in R_{sd}^{sp}[{\sim}q] \cup R_{sd}^{me}[{\sim}q]$ either
        (2.3.1) $\exists a \in A(s) : -\partial a \in P(1..i)$ or
        (2.3.2) $\exists t \in R_{sd}^{sp}[q] \cup R_{sd}^{me}[q]$ such that $t > s$ and $\forall a \in A(t) : +\partial a \in P(1..i)$

The extended defeasible reasoning with the superior knowledge has the properties[1]

1. If $T_{sp} \vdash +\Delta q$ then $T_{sp} + T_{me} \not\vdash +\Delta{\sim}q$ and $T_{sp} + T_{me} \not\vdash +\partial{\sim}q$. If a strict conclusion is derived from the superior theory, the extended mechanism does not provide any proof for its negation.
2. If $T_{sp} \vdash {\sim}\Delta{\sim}q$ and $T_{me} \vdash +\Delta q$ then $T_{sp} + T_{me} \vdash +\partial q$. The conclusions from the extended mechanism can violate defeasible conclusions obtained from the superior theory if the agent has a strong evidence of the contradiction in its internal knowledge.
3. The extended reasoning mechanism is coherent and consistent.

The extended mechanism computes a consistent set of conclusions with respect to the superior theory. The mechanism goes beyond the standard defeasible reasoning since it extends the superiority relation of rules to that of theories. This increases the size of theory to be investigated. Hence the complexity class of the reasoning algorithm (Maher 2001) remains unchanged.

Reasoning Engine

The reasoning mechanism operates in two steps. The first step is to identify the majority knowledge from the other agents. In the next step, the agent performs either adaptive or collective reasoning depending on its weight.

1. Determining the majority knowledge from other agents:
   (a) *Draw defeasible conclusions from the others with respect to background knowledge*.
   $$T_{bg} + T_i \vdash C_i : 1 \leq i \leq n$$
   (b) *Establish the majority knowledge T_{maj}*. The extended defeasible reasoning already guarantees that conflicts are removed from the final conclusions. Hence the majority knowledge can be determined by applying the *majority rule* (Lin 1996) over the sets of defeasible conclusions, $\{C_i : 1 \leq i \leq n\}$, from the previous step. The conclusions with support from the majority will be projected to the joint knowledge.
2. Reasoning strategies. Depending on the weight, an individual agent can either follow the majority knowledge or collect all possible information. The two strategies are implemented by the defeasible reasoning with the superior knowledge.
   (a) *Adaptive reasoning*. At this stage, the set of knowledge sources is reduced to the background, the majority, and the agent's own knowledge. As shown in Figure **??**, it takes two steps to derive the final conclusions. First, the agent combines the background and its own knowledge by considering these two as the superior knowledge and the internal knowledge respectively. Next, the joint knowledge from the other agents is used to adjust the derivation from the first step. That is, the agent withdraws conclusions which violate the joint knowledge.
   $$T_{maj} + (T_{bg} + T_{me}) \vdash C'_{me}$$
   (b) *Collective reasoning*. Owing to its importance, the individual agent considers itself as dominant over the other agents. Instead of reinforcing its current knowledge, the agent derives new knowledge by accumulating all possible consistent knowledge from the others. This is achieved by performing the sequence of inference processes with the superior theory The sequence starts with the theory having the minimum weight and takes the next theory in the order of weight as the superior theory. The sequence ends with the background theory, which implicitly has the maximum weight. This reasoning strategy requires a total order over the weights of agents in the group.

Proposition 2 *The complexity of the proposed mechanism is in the $O(n)$ class.*

This property is due to the linear complexity of defeasible reasoning and *majority rule*.

Furture Work

In our framework, the information about the weight (reputation) of an agent is initiated by designers. We are developing a reputation model to update this special knowledge. Generally, behaviours of our agents are driven by three types of knowledge including the internal knowledge, knowledge shared by the group and knowledge from other agents. Knowledge commonly shared or largely recognised by individuals enables agents to "discover" common values in the group. Hence agents can justify behaviours of others. Behaviours for/against the values of the group can increase/decrease the reputation of the owners. Thanks to knowledge from others, an agent can reason about intended actions of other agents. The agent can balance between actual and intended actions to update the reputation of other agents. That is by tracking the commitment of individuals to the group, we can build up a social reputation model for our agents. The approach provide more quantitative evidences than interaction rating model proposed by (Sabater & Sierra 2001) or on-line auction systems like eBay.

(Boella *et al.* 2007) a mechanism for exchanging rule-based information using FIPA communicative acts. The semantics of communicative acts do not only depend on the

[1]The proof for these properties is omitted due to the space limit

private knowledge of an agent but also on mental attitudes publicly known by agents. We are investigating to extend this mechanism in the way that agents can recognise mental attitudes largely shared by agents. These attitudes should be considered as an important source for the assertion of coming information.

We are investigating a computer-based tool to simulate emergency situations where rescue teams are well equipped with comprehensive emergency procedures but the information is incomplete and conflicting. The simulation tool facilitates studying behaviours of individual members and the whole team, and the effectiveness of the rescue procedures.

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