Forwarding Credible Information in Multi-agent Systems*

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Abstract. In this work we extend the communication abilities of agents in multi-agent systems by enabling them to reason about the credibility of information to be shared with other agents. We propose a framework in which agents exchange sentences of a logical language enriched by meta-information. We discuss several possible approaches and present an advanced approach overcoming previously shown problems. For this, we make use of a calculation method for the plausibility of information known from approaches to belief dynamics in multi-agent systems. Moreover, we present how this can be implemented in a multi-agent system.

Keywords: Knowledge Representation, Plausibility, Multi-agent System.

1 Introduction

In this work, we focus on enhancing reasoning and communication skills of agents that are part of multi-agent systems (MAS). We consider a group of communicating and collaborating agents that share information and have beliefs about the credibility of their fellow agents. In our proposed framework agents can exchange logical information stored in these beliefs, annotated with meta-information concerning the credibility of this information. Thus, agents can acquire information from multiple sources and incorporate it into their proper beliefs.

In this paper we investigate how an agent can forward information to other agents that could have been acquired from other agents. In particular, we study how to rationally choose meta-information to be sent. At any point in time, each agent has initial beliefs (in form of evidential knowledge) and generic beliefs, as well as knowledge acquired from other agents. The agent has to deal with messages received both from other agents and from the environment itself. Similar to Dragoni [2] and Cantwell [1], in our approach informant agents can have different credibilities. In this article, as in [11], a credibility order among agents is introduced and, based on this order, a comparison criterion among beliefs is

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defined. We propose to attach to each piece of information an agent identifier representing the credibility of the transferred information, as in [7] and [11]. The choice of the agent identifier that is to be sent along with the piece of information is crucial, as it influences the decision of the receiver about whether to accept the transmitted information. Thus, it is in the interest of the sending agent, and in fact in the interest of the whole coalition of agents, to choose this meta-information carefully. We present different ways to select this identifier and give a categorization of possible approaches, to later discuss their advantages and disadvantages. This discussion leads to the definition of a reasoning approach using the credibility of information that selects the most appropriate agent identifier to be sent. Later, we also show how we can adapt multi-source belief revision techniques for this selection operator and present the resulting operator by adapting work from [11]. Moreover, we present an implementation of this operator using answer set programming based on [6], using a common technique for the implementation of the reasoning component of agents in MAS. In this way, we are extending the reasoning component towards the computation of meta-information on the one hand, while improving the communication component by giving reasoning capabilities to it.

The reminder of the paper is organized as follows. In Section 2 we introduce the general framework in which we are working. Section 3 discusses diverse approaches to the forwarding of information in this setting. In Section 4 we introduce a forwarding criterion that uses a method of reasoning about the plausibility of information. Section 5 elaborates the implementation of our proposed approach for MAS and Section 6 concludes our work.

2 Framework

For the presentation of our work we adapt and extend the general communication framework from [7] by combining it with methods from [11]. Hence, our approach can easily be integrated in a complex, implemented multi-agent system like [7] and is compatible with many MAS standards. Agents interact with its fellow agents by means of *messages* (M). In this approach we assume that a message is at least a triple *(S,R,I)* where S is the sender, R is the set of receivers and I is the content of the message. As explained in [7], a message can have other components (as a speech act) but these are out of the scope of this paper.

When interacting, agents incorporate the received messages into their knowledge base in form of *information objects* (I). In this paper we focus on the representation of a knowledge base in form of information objects and on the transmission of information objects, abstracting from the actual communication act. Hence, for simplicity we consider only I from M in the following. For the identification of the individual agents we introduce a finite set of agent identifiers that is denoted as $\mathbb{A} = \{A_1, \ldots, A_n\}$.

Definition 1 (Information object [7]). *An* information object *is a tuple* $I = (\phi, A_i)$*, where* ϕ *is a sentence of some logical language* $\mathcal{L}$ *and* $A_i \in \mathbb{A}$.

In this paper we adopt a propositional language $\mathcal{L}$ with a complete set of Boolean connectives, namely $\{\neg, \wedge, \vee, \rightarrow, \leftrightarrow\}$. Also, we assume the existence of a logical consequence operator Cn which determines the logical closure of the set it is applied to. This operator satisfies *inclusion* ($B \subseteq Cn(B)$), *iteration* ($Cn(B) = Cn(Cn(B))$), and *monotonicity* (if $B \subseteq C$ then $Cn(B) \subseteq Cn(C)$) and includes the classical consequence operator. In general, we write $\phi \in Cn(B)$ as $B \vdash \phi$. The information objects defined above are used to represent an agent's belief base.

Definition 2 (Belief base [7,11]). *A* belief base *of an agent A_i is a set $K_{A_i} = \{I_0, \ldots, I_m\}$ containing information objects received from other agents and proper initial beliefs represented by information objects (ϕ, A_i). The set $\mathcal{K} = 2^{\mathcal{L} \times \mathbb{A}}$ represents the set of all belief bases.*

Next, two auxiliary functions are introduced in order to obtain the set of sentences and the set of agents that belong to a belief base $K \in \mathcal{K}$.

Definition 3 (Sentence function [11]). *The* sentence function*, $Sen : \mathcal{K} \to 2^{\mathcal{L}}$, is a function s.t. for a given belief base $K \in \mathcal{K}$, $Sen(K) = \{\phi : (\phi, A_i) \in K\}$.*

We call a belief base K consistent if $Cn(Sen(K))$ is consistent.

Definition 4 (Agent identifier function [11]). *The* agent identifier function*, $Ag : \mathcal{K} \to 2^{\mathbb{A}}$, is a function s.t. for a base $K \in \mathcal{K}$, $Ag(K) = \{A_i : (\phi, A_i) \in K\}$.*

As stated above, we investigate how an agent can forward information to other agents. In particular, we study how to rationally choose meta-information to be sent. In our approach agents can obtain information by receiving messages with information objects (I). Therefore, agents can use the agent identifier of I to evaluate the truthfulness of this particular information. For this reason we use an *assessment* function to represent the credibilities each agent gives to other agents known to it. These credibilities are kept in a separate structure to allow for a dynamic change of credibilities within time. According to this, we assume a set of credibility labels $\mathcal{C} = \{c_1, \ldots, c_n\}$ (known to all agents) with a strict order $\prec_c$ on them (*i.e.*, $\prec_c$ satisfies *transitivity* and *totality*).

Definition 5 (Assessment [7]). *An* assessment *c_{A_i} for the agent A_i is a function $c_{A_i} : \mathbb{A} \to \mathcal{C}$ assigning a credibility value from $\mathcal{C}$ to each agent $A_j \in \mathbb{A}$.*

Note, that each agent in the MAS has its own assessment. This means in particular that different agents can have different assessments which can also be dynamic. As informant agents are ranked by their credibilities, a credibility order over the set $\mathbb{A}$ is introduced. This order is total (*i.e.*, satisfies *transitivity*, *totality* and *antisymmetry*) and is based on the assessment of each agent. Hence, each agent has a particular credibility order among agents.

Definition 6 (Credibility order among agents [11]). *A* credibility order among agents *for an agent A_i, denoted by '$\leq_{Co}^{A_i}$', is a total order over $\mathbb{A}$ where $A_1 \leq_{Co}^{A_i} A_2$ means that according to A_i, A_2 is at least as credible than A_1, and holds if $c_{A_i}(A_1) \prec_c c_{A_i}(A_2)$ or $c_{A_i}(A_1) = c_j$ and $c_{A_i}(A_2) = c_j$ with $c_j \in \mathcal{C}$. The strict relation $A_1 <_{Co}^{A_i} A_2$, denoting that A_2 is strictly more credible than A_1, is defined as $A_1 \leq_{Co}^{A_i} A_2$ and $A_2 \not\leq_{Co}^{A_i} A_1$. Moreover, $A_1 =_{Co}^{A_i} A_2$ means that A_1 is as credible as A_2, and it holds when $A_1 \leq_{Co}^{A_i} A_2$ and $A_2 \leq_{Co}^{A_i} A_1$.*

Example 1. Consider the set of agent identifiers $\mathbb{A} = \{A_1, A_2, A_3, A_4\}$ and the set of credibility labels $\mathcal{C} = \{c_1, c_2, c_3\}$, where $c_1 \prec_c c_2 \prec_c c_3$. Suppose that the belief base of the agent A_1 is $K_{A_1} = \{(\phi, A_2), (\phi, A_4), (\psi, A_3), (\psi \rightarrow \phi, A_1)\}$. Observe that K_{A_1} has two tuples with the sentence ϕ. Suppose that according to the assessment of A_1, $c_{A_1}(A_1) = c_1$, $c_{A_1}(A_2) = c_2$, $c_{A_1}(A_3) = c_2$ and $c_{A_1}(A_4) = c_3$. Then, the credibility order, according to A_1, is: $A_1 \leq_{Co}^{A_1} A_2$, $A_1 \leq_{Co}^{A_1} A_3$, $A_1 \leq_{Co}^{A_1} A_4$, $A_2 \leq_{Co}^{A_1} A_3$, $A_3 \leq_{Co}^{A_1} A_2$, $A_2 \leq_{Co}^{A_1} A_4$, and $A_3 \leq_{Co}^{A_1} A_4$. In a straightforward way, this relation implies $A_1 <_{Co}^{A_1} A_2 =_{Co}^{A_1} A_3 <_{Co}^{A_1} A_4$.

In the rest of this paper we directly use the credibility order among agents for simplicity of representation. The belief base structure is based on information objects, which include meta information and in our case in particular the source of the information. The sources again are connected to the current evaluation of the credibility by means of the assessment of the respective agent. This structure enables epistemic operators to include the credibility of information into the reasoning process. The approach adopted here can deal with a variety of epistemic operators potentially varying among different agents as shown in [7]. A belief operation is a function, that revises (in an abstract manner) the logical belief base of an agent appropriately to a newly given evidence, *i.e.*, a newly received message.

Definition 7 (Belief base operation [7]). *A* belief base operation *is a function $\mathcal{K} \times \mathcal{M} \rightarrow \mathcal{K}$ where $\mathcal{M}$ is the set of all possible messages and $\mathcal{K} = 2^{\mathcal{L} \times \mathbb{A}}$.*

As stated above, an agent A_i can receive an information object $I = (\phi, A_p)$ from other agents through communication. In order to incorporate I to its belief base K_{A_i}, the agent can use a belief base operation that considers its current beliefs (K_{A_i}), the logical sentence that has been received (ϕ) and the agent identifier A_p present in I. For example, the non-prioritized revision operator $\circ$:$\mathcal{K} \times \mathcal{M} \mapsto \mathcal{K}$ defined in [11] can be used. This operator behaves as follows.

If the incoming information I is consistent with K_{A_i} (*i.e.*, $Sen(K_{A_i}) \not\vdash \neg\phi$.)[1], then $K_{A_i} \circ I = K_{A_i} \cup \{I\}$. Hence, a belief base may contain the same belief in multiple tuples but with different agent identifiers (*e.g.*, in Example 1 ϕ is contained in two tuples). Although a sentence ϕ can have several proofs, there is no redundancy because each tuple represents a different informant. The advantage of this is made clear below. Consider for example that $(\phi, A_h) \in K_{A_i}$ and by this operation (ϕ, A_p) is added to K_{A_i}, if A_p if more credible than A_h then the plausibility of ϕ is increased (see Section 4.1 for details).

Since an agent can receive information that is not consistent with its own beliefs, in order to maintain its belief base consistent, it has to decide whether to accept or reject the new information I. For example, the operator "$\circ$" decides whether to accept or reject I considering the *credibility order among agents.* Incoming information can be rejected when the agent has more credible beliefs that contradict the new information. If an agent decides to accept a new belief that is contradictory with its belief base, then it has to select some beliefs from its belief base in order to withdraw them and avoid the contradiction.

[1] In this article, we assume that an agent does not receive contradictions.

3 Forwarding Information

In the following, we describe different criteria for forwarding information that determine which agent identifier is considered by the receiver at the moment of reasoning. That is to say, we analyze different alternatives which determine which agent identifier is to be sent in the information object.

As stated above, when an agent sends information to another agent, it sends information objects. Consider Example 1, if A_1 wants to send ϕ to A_2, it should send the tuple $I = (\phi, Agent)$. As we show below, there are several choices for the identifier "*Agent*" of I: it can be the proper sender (A_1); one of the identifiers stored with ϕ in the sender's base (*e.g.*, A_2, A_4) that can be one of them arbitrarily or the more credible of them; or, in order to decide which identifier to send, a deeper analysis of the whole knowledge base can be performed. In this section, three criteria are introduced and analyzed, and in the following section we propose a more elaborated criterion that takes the plausibility of sentences obtained from agents credibility into consideration.

Sender identifier criterion. As in [2], a simple forwarding criterion can be implemented by sending an information object $I = (\phi, A_i)$ where A_i is always the identifier of the sending agent and ϕ is the belief to be forwarded.

Example 2. Let A_1 and A_2 be two agents and $K_{A_1} = \{(\phi, A_3)\}$. If A_1 wants to send ϕ to A_2 then A_1 forwards to A_2 a message with $I = (\phi, A_1)$.

This criterion has as advantage that it is simple, its implementation is easy and as stated by Dragoni in [2] "agents do not communicate the sources of the assumptions, but they present themselves as completely responsible for the knowledge they are passing on". Nevertheless, the original source of the information can be lost. This can lead to a change of the credibility of forwarded information with respect to the sender's belief base. In other words, the credibility of the belief forwarded can be increased or decreased as each agent has its own assessment. For instance, in Example 2 it can be seen that if $A_1 <^{A_1}_{Co} A_3$ then the credibility of ϕ is decreased with respect to the assessment of A_1. In this case, if $(\neg\phi, A_2) \in K_{A_2}$ and $A_1 <^{A_2}_{Co} A_2 <^{A_2}_{Co} A_3$ then A_2 can reject (ϕ, A_1) because $A_1 <^{A_2}_{Co} A_2$ although the original source is A_3 with $A_2 <^{A_2}_{Co} A_3$. Furthermore, if $A_3 <^{A_1}_{Co} A_1$ then the credibility of ϕ is increased. This case can be considered reasonable as the absence of reasons of A_1 against the acceptation of ϕ make this information more credible. Thus, A_1 believes in ϕ and can be considered as another informant for this information. However, this criterion can lead to unnatural settings as we show in the following example.

Example 3. Consider $\{A_1, A_2, A_3, A_4\} \subseteq \mathbb{A}$ where $A_1 <^{A_i}_{Co} A_2 <^{A_i}_{Co} A_3 <^{A_i}_{Co} A_4$ with $1 \leq i \leq 4$. Let $K_{A_1} = \{(\phi, A_1)\}$, $K_{A_2} = \emptyset$, $K_{A_3} = \{(\neg\phi, A_3)\}$ and $K_{A_4} = \emptyset$. Suppose that A_1 sends (ϕ, A_1) to A_4 using the *sender identifier criterion.* Since $K_{A_4} = \emptyset$ then $K_{A_4} = \{(\phi, A_1)\}$. Now A_4 sends (ϕ, A_4) to A_2 and then $K_{A_2} = \{(\phi, A_4)\}$. Then, A_2 has a more credible version of ϕ than its informant ($A_1 <^{A_2}_{Co} A_4$). This does not make sense since if A_3 sends $(\neg\phi, A_3)$ to A_2 and A_4 then, following the revision process proposed above, A_2 rejects $(\neg\phi, A_3)$ ($A_3 <^{A_2}_{Co} A_4$) but A_4 accepts $(\neg\phi, A_3)$ withdrawing (ϕ, A_1) from K_{A_4} ($A_1 <^{A_4}_{Co} A_3$).

Source identifier criterion. Another approach for forwarding information can be implemented by sending an information object $I = (\phi, A_i)$ where A_i is always the identifier of the original informant stored in the belief base of the sender. This criterion has the constraint that the belief ϕ to be sent has to appear explicitly in only one information object in the belief base.

Example 4. Let A_1 and A_2 be two agents and $K_{A_1} = \{(\phi, A_3)\}$. If A_1 wants to send ϕ to A_2 then A_1 forwards to A_2 a message with $I = (\phi, A_3)$.

This criterion, similar to the previous one, has as advantage that it is simple and can be implemented easily, and it also overcomes one disadvantage of the previous criterion. That is, the original informant is maintained such that the credibility of the belief does not change after forwarding with respect to the sender's assessment. For this reason, this criterion does not lead to unnatural settings as showed in Example 3. However, considering Example 4, in the case of $A_3 <^{A_1}_{Co} A_1$ we loose the property of increasing the credibility of non-conflicting information of the former approach. According to this, it would be a good idea to increase the credibility of ϕ and to send it with the agent identifier A_1 as argued in "sender identifier criterion" criterion. That is, in this criterion the sender is not considered as possible information source.

Combined criterion. As stated above, there can be different tuples containing the same sentence. For instance, in Example 1, ϕ can be found in two explicit tuples ((ϕ, A_2) and (ϕ, A_4)). In this case, if A_1 wants to forward ϕ, it should decide which agent identifier appears in the content of the message, A_2 or A_4. We can opt for one of the two policies, we can choose the most credible agent or the least credible one. If we select the least credible agent identifier based on the assessment of the sender agent, we loose the most credible informant of the sender after forwarding. However, this does not occur if we select the most credible agent. But in this case, we are facing similar disadvantages as shown for the "source identifier" criterion. That is, if the sender is more credible than any source of the sentence to be forwarded, it would be a good idea to increase the credibility of the sentence by sending it with the agent identifier of the sender as argued before. This can be resolved performing the calculation of the most credible agent identifier with respect to all agent identifiers which are explicitly represented in the tuples and the sender. For instance, in Example 1 A_1 forwards ϕ with the most credible agent identifier from A_1 (sender identifier), A_2 and A_4. If the sender identifier is forwarded with the belief, then this criterion leads to an unnatural setting as has been shown in Example 3.

A particular case occurs when there exist several tuples with the same belief and different agent identifiers which are considered equally credible by the sender. In this case, we assume that the sender sends one of these agent identifiers according to some policy, although the credibility function of the receiver might assign different credibilities to these agents.

4 Plausibility-Based Criterion

In this section we propose a more elaborated criterion that takes the plausibility of sentences obtained from agents credibility into consideration. Note that in the combined criterion explained above, the agent identifier is obtained through a simple calculation from the set of information objects of the sender's belief base which explicitly contain the belief to be forwarded. However, the combined criterion does not consider that a sentence ϕ can be entailed from a set of information objects. For instance in Example 1, if A_1 wishes to send ϕ then A_1 should consider three proofs: $\{(\phi, A_2)\}$, $\{(\phi, A_4)\}$, $\{(\psi, A_3), (\psi \rightarrow \phi, A_1)\}$.

This criterion proposes to calculate the plausibility of a sentence ϕ based on all its proofs before being forwarded. This calculation should return an agent identifier which is used as the agent identifier of ϕ. In the following subsection we show how this calculation can be formalized.

4.1 Plausible Belief Bases Based on Agent Credibility

In this section we introduce a *plausibility function* as defined in [11] which we intend to use for the determination of the agent identifier of information objects to be forwarded. We use the agent identifiers of the agent's beliefs to compute the plausibility of the beliefs, *i.e.*, each of the agent's beliefs have an associated plausibility that depends on the agent identifier and the *credibility order among agents*. The behavior of this form of plausibility is similar to epistemic entrenchment as defined in [3]. That is, if ϕ and ψ are sentences in $\mathcal{L}$, the notation $\phi \preceq_{K_A} \psi$ means "ψ is at least as plausible as ϕ relative to the belief base K of agent A".

A belief base $K \in \mathcal{K}$ supports explicit and entailed sentences. The explicit sentences are those contained in $Sen(K)$, while the entailed sentences are those that are not in $Sen(K)$ but they are entailed by sentences in $Sen(K)$. In order to obtain the entailed sentences from a base K we use the following function:

Definition 8 (Belief function [11]). *The* belief function*, $Bel : \mathcal{K} \rightarrow 2^{\mathcal{L}}$, is a function s.t. for a belief base $K \in \mathcal{K}$, $Bel(K) = \{\phi : \phi \in \mathcal{L}$ and $Sen(K) \vdash \phi\}$.*

In general, there may be several proofs for ϕ from K. Therefore, to calculate the plausibility of a sentence (ϕ) we must analyze all of its proofs. For doing that, all the minimal subsets of K entailing ϕ are obtained. For this, we adapt the notion of kernel sets [5].

Definition 9 (Kernel). *Let $K \in \mathcal{K}$ and $\phi \in \mathcal{L}$. Then H is a ϕ-kernel of K if and only if* 1) *$H \subseteq K$;* 2) *$Sen(H) \vdash \phi$;* 3) *if $H' \subset H$, then $Sen(H') \nvdash \phi$.*

Thus, a *ϕ-kernel* is a minimal set of tuples from K that entails ϕ. The set of *ϕ-kernels* of K is denoted $K^{\perp\!\!\perp}\phi$ and is called *kernel set*.

We follow a cautious approach of plausibility calculation, that is, from each ϕ-kernel, we want to obtain the least plausible tuples. This gives us the plausibility of each proof. Then, the plausibility of a derived sentence ϕ is the greatest plausibility among those of each ϕ-kernel. In order to define this, two functions are given next.

Definition 10 (Least credible sources function [11]). *The* least credible sources function*, $min : \mathcal{K} \rightarrow 2^{\mathcal{K}}$, is a function s.t. for a given belief base $K_A \in \mathcal{K}$, $min(K_A) = \{(\phi, A_i) : (\phi, A_i) \in K_A$ and for all $(\varphi, A_j) \in K_A$, $A_i \leq^{A}_{Co} A_j\}$.*

Definition 11 (Most credible sources function [11]). *The* most credible sources function*, $max : \mathcal{K} \rightarrow 2^{\mathcal{K}}$, is a function s.t. for a given belief base $K_A \in \mathcal{K}$, $max(K_A) = \{(\phi, A_i) : (\phi, A_i) \in K_A$ and for all $(\varphi, A_j) \in K_A$, $A_j \leq^{A}_{Co} A_i\}$.*

Next, we introduce a function which returns the plausibility of a sentence ϕ that can be explicitly in K or entailed from K. This plausibility is based on a single agent identifier which is used when ϕ is compared to other beliefs. However, as stated above, with respect to the assessment of an agent A_i there may exist two agent identifiers (A_1 and A_2) such that $A_1 =^{A_i}_{Co} A_2$. For this case of a draw, we introduce a function which returns a single agent identifier given a set agent identifiers based on a given policy (for instance, the policy could be based on a lexicographical ordering among agent identifiers - A_1 is lesser than A_2).

Definition 12 (Selection function). *The* selection function *of an agent A_i, $\mathcal{S}_{A_i} : 2^{\mathbb{A}} \rightarrow \mathbb{A}$, is a function such that for a given set of agent identifiers with equal credibility with respect to the assessment of A_i, it returns a single agent identifier based on a given policy.*

Definition 13 (Plausibility function). *The* plausibility function*, $Pl : \mathcal{L} \times \mathcal{K} \rightarrow \mathbb{A}$, is a function such that for a $\phi \in \mathcal{L}$ and a belief base $K_A \in \mathcal{K}$, $Pl(\phi, K_A) = \mathcal{S}_A(Ag(max(\bigcup_{X \in K_A^{\perp\!\!\perp}\phi} min(X))))$.*

Example 5. Consider a set $\mathbb{A} = \{A_1, A_2, A_3\}$ where the credibility order according to A_1 is $A_3 <^{A_1}_{Co} A_2 <^{A_1}_{Co} A_1$. The belief base of agent A_1 is $K_{A_1} = \{(\psi, A_3), (\phi, A_2), (\phi \rightarrow \psi, A_2), (\phi \rightarrow \psi, A_1), (\omega, A_3), (\omega \rightarrow \psi, A_1), (\varphi \rightarrow \psi, A_3), (\rho, A_1), (\omega \rightarrow \rho, A_2)\}$. Suppose that agent A_1 needs to calculate the plausibility of ψ. In order to do so, A_1 performs the following steps.

- *Step 1.* $K_{A_1}^{\perp\!\!\perp}\psi = \{H_a, H_b, H_c, H_d\}$ where $H_a = \{(\psi, A_3)\}$, $H_b = \{(\phi, A_2), (\phi \rightarrow \psi, A_2)\}$, $H_c = \{(\phi, A_2), (\phi \rightarrow \psi, A_1)\}$, and $H_d = \{(\omega, A_3), (\omega \rightarrow \psi, A_1)\}$.
- *Step 2.* $min(H_a) = \{(\psi, A_3)\}$, $min(H_b) = \{(\phi, A_2), (\phi \rightarrow \psi, A_2)\}$, $min(H_c) = \{(\phi, A_2)\}$, and $min(H_d) = \{(\omega, A_3)\}$.
- *Step 3.* $max(\{(\psi, A_3), (\phi, A_2), (\phi \rightarrow \psi, A_2), (\omega, A_3)\}) = \{(\phi, A_2), (\phi \rightarrow \psi, A_2)\}$.
- *Step 4.* $Ag(\{(\phi, A_2), (\phi \rightarrow \psi, A_2)\}) = \{A_2\}$.

Therefore, $Pl(\psi, K_{A_1}) = A_2$. Hence, when ψ is compared with other beliefs, A_2 is used as the informant of ψ (the plausibility of ψ is given by A_2).

4.2 Forwarding Criterion Using a Plausibility Function

In this section, we define a new criterion in which the agent identifier to be sent is obtained from the calculation of the plausibility of the sentence to be sent. The plausibility function we proposed in the previous subsection fulfills the criteria as laid out before such that it is suitable in order to obtain the agent identifier to be sent.

Plausibility-based criterion. A new forwarding criterion can be implemented by sending an information object $I = (\phi, A_i)$ where A_i is the agent identifier obtained using the plausibility function defined above, *i.e.*, $A_i = Pl(\phi, K_{A_1})$ where A_1 is the sender of the message.

Example 6. Let us consider Example 5 again. If the agent A_1 wishes to send ψ to agent A_4 then, according to the plausibility based criterion, A_1 sends the tuple $(\psi, Pl(\psi, K_{A_1}))$ to A_4. That is, A_1 sends, based on its belief base K_{A_1} and its credibility order "$\leq_{co}^{A_1}$", (ψ, A_2) to A_4.

An important decision we made is to forward an agent identifier with a sentence rather than a credibility label in order to give additional information to the beliefs. One reason for this decision is that we achieve a more dynamic framework since the evaluation of the credibility of the agent identifiers is separated by use of the assessment function. Note that the assessment function may change in time realizing dynamic assessments and learning processes of agents. Hence, the credibility order among agents can be changed without changing the knowledge base or the operator. That is, if the credibility order among agents changes, then the plausibility of all sentences also changes without having to modify the belief base of the agent. Another reason for this decision is that since each agent has its own *assessment* (as stated in Section 2), is more suitable to send agent identifiers as this way the receiver agent can evaluate the received belief based on the credibility it has according to its own assessment. This means that the sending agent expresses that it considers the information it transmits as credible as it considers the agent identifier in the information object. Now it is up to the receiver to assess how credible it considers each agent from its perspective using its own assessment function. We belief, that this represents an advanced way of communication in multi-agent systems.

We adopted the plausibility function of an approach [11] of multi-source belief revision [9] for the means of improving the communication in MASs. As our proposed setting and framework is one of multi-source belief revision the proposed forwarding criterion blends in perfectly into a system equipped with the corresponding belief operator. This leads to a consistent strategy of belief operations as well as communication and can improve the overall agent performance. Furthermore, the general idea of using a plausibility function in this way can be adopted to other operators. In the following section we demonstrate that our presented extensions of the multi-agent framework can be easily implemented and integrated in existing systems and thus are ready to be used.

5 Implementation in Logic Programming

For the implementation we show how our approach to forwarding can be implemented within an advanced MAS blending in with the belief operations. For this we adapt credibility logic programs [6,7] and sketch how this can be used to implement our proposed approach. We assume here, that our language for knowledge representation is the one of logic programming. In particular, an information object consists of an agent identifier and a logic program $I = (P, A)$ and the agents store sets of these as there knowledge base. We are working with extended logic programs under the answer set semantics [4]. A rule r is written as $H(r) \leftarrow \mathcal{B}(r)$ where the head of the rule $H(r)$ is either empty or consists of a literal L and the body $\mathcal{B}(r)$ is a set of literals $\{L_0, \ldots, L_m, \mathsf{not}\ L_{m+1}, \ldots, \mathsf{not}\ L_n\}$. The body consists of a set of literals $\mathcal{B}(r)^+ = \{L_0, \ldots, L_m\}$ and a set of default negated literals denoted by $\mathcal{B}(r)^- = \{\mathsf{not}\ L_{m+1}, \ldots, \mathsf{not}\ L_n\}$. Credibility logic programs work on a set of extended logic programs [4] and a total preference relation on this set. This can be seen as a sequence of programs $\mathcal{P} = (P_1, \ldots, P_n)$ whose order reflects the preference order on the programs which enables the assignment of priorities to programs. This sequence of programs can be extracted from our belief base by taking the program part of each tuple, ordering them using the corresponding agent identifiers in combination with the agent assessment function. The knowledge base of an agent A can be seen as $K = \{(P_1, A_1), \ldots, (P_n, A_n)\}$. For the logic program representation of the knowledge base we overload the agent function defined above as $Ag(P) = A$ iff $(P, A) \in K$. Given this, we construct the sequence of logic programs $\mathcal{P} = (P_1, \ldots, P_n)$ with $Ag(P_i) \leq_{Co}^{A_p} Ag(P_{i+1})$, $1 \leq i < n$. Note that in this representation the program identifiers are unique even though they might have the same content.

In credibility logic programs the credibility of a head literal is determined given the inferred credibilities of the body literals. For the propagation of credibilities a cautious approach in which the minimum of the credibilities of the body literals is used to prioritize the head literal is used. When the credibility of a literal L is to be used for propagation purposes the maximal credibility of the existent prioritized literals for L is used. This way, we achieve an implementation of the plausibility criterion presented above using exclusively the language of extended logic programming. The original alphabet $\mathcal{G}$ of $\mathcal{P}$ is extended to the alphabet $\mathcal{G}'$ by adding several new predicates and atoms revealing the inferred credibility, *i.e.*, plausibility, of each literal. For each literal $L(\boldsymbol{x}_L)$ occurring in $\mathcal{P}$ a prioritized version $\hat{L}(\boldsymbol{x}_L, \mu)$ is added. Let $\mathcal{H}(\mathcal{P})$ denote the set of literals occurring in the head of a rule r in $\mathcal{P}$. The achieved implementation is independent of any specific answer set solver like smodels [10] or DLV [8]. For DLV, however, there exists an implementation of credibility logic programs as a front-end. Next, we state the construction of the a program for the generation of the plausibilities for each literal of an answer set which is an adaption of the construction seen in [6].

Definition 14 (Credibility propagation program). *The following rules are generated from a sequence $\mathcal{P} = (P_1, \ldots, P_n)$ of programs. For each program $P_i \in \mathcal{P}$ with an agent identifier μ_i and each rule $r_j \in P_i : H \leftarrow \mathcal{B}(r_j)$:*

$$\hat{H}(\mu) \leftarrow \mathcal{B}(r_j), minr_j(\mu), \mathsf{not}\ exLowerMinr_j(\mu).$$
$$exLowerMinr_j(\mu) \leftarrow minr_j(\mu), minr_j(\mu'), Prec(\mu', \mu).$$
$$minr_j(\mu_i) \leftarrow .$$

For each $L \in \mathcal{B}(r_j)$: $minr_j(\mu) \leftarrow \mathcal{B}(r_j), \hat{L}(\mu), \mathsf{not}\ exHigherL(\mu).$

For each $L \in \mathcal{H}(\mathcal{P})$:

$$exHigherL(\mu) \leftarrow \hat{L}(\mu), \hat{L}(\mu'), Prec(\mu, \mu').$$
$$sendL(\mu) \leftarrow \hat{L}(\mu), \mathsf{not}\ exHigherL(\mu).$$

Furthermore the preference predicate is defined by the following rules: For each program $P_i \in \mathcal{P}$: $Prec(\mu_{P_i}, \mu_{P_{i+1}}) \leftarrow .$ And rules for transitivity:

$$Prec(x, z) \leftarrow Prec(x, y), Prec(y, z).$$

For each rule r_j the credibilities of all body literals are represented by the $minr_j$ predicates which are inferred by the maximal of the respective literals credibilities. Additionally, one $minr_j$ representing the rule credibility is generated. The minimal of the credibility values for the body $\mathcal{B}(r_j)$, which are given by all $minr_j$ predicates is unified with the credibility argument of the head literal of rule r_j. The *max* and *min* functions are realized by the introduction of the predicates $exLowerMinr_j$ for each rule $r_j \in \mathcal{P}$ and $exHigherL$ for each literal occurring in the head a rule in $\mathcal{P}$; for more details cf. [6]. The answer set of the constructed credibility propagation program now contains for each literal the encoded credibility as an argument and for each literal a predicate $sendL(\mu)$ expressing the agent identifier to be send for the literal L. This enables the agent to infer the plausibility of each literal and to determine the agent which represents this plausibility from the answer set. Hence, we showed here that there is an implementation of our here proposed approach at hand which can be used in current implementations of multi-agent systems.

6 Conclusion and Related Work

In this paper we introduced a framework which enhances the communication skills of an agent in MAS by combining them with its reasoning abilities to allow the propagation of credible information. We assumed a collaborative MAS where deliberative agents can receive new information from others through communication and in which they have beliefs about the credibilities of their fellow agents. Similar to Dragoni [2] and Cantwell [1], in our approach, informant agents can have different levels of credibility. However, in [1] a relation of *trustworthiness* is introduced over sets of sources and not between single sources, whereas we used an assessment function in order to represent the credibilities each agent gives to other agents known to it. In [2] their tuples contain 5 elements: <Identifier, Sentence, OS, Source, Credibility>, where Origin Set (OS) records the assumption nodes upon which it really ultimately depends (as derived by the theorem prover). In contrast to them, in our model a tuple only stores a sentence and a source, but a tuple does not store the credibility. That is, in our model the plausibility of a sentence is not explicitly stored with it, as [2] does. Thus, when the plausibility of some sentence is needed the *plausibility function* (Definition 13) is applied. As is shown in Example 5, given a sentence ϕ its plausibility depend on its proofs (ϕ-*kernels*). Therefore, if one of the sentences of these proof changes, then the plausibility of ϕ may change.

We proposed to send an agent identifier with a piece of information which represents the credibility of the transferred information as in [7] and [11]. Based on this setting, we investigated how an agent can forward information to other agents that, in turn, could have been acquired from other agents. In particular, we studied how to rationally choose the meta-information to be forwarded. The choice of the agent identifier that is to be sent along with the piece of information is crucial, as it influences the decision of the receiver about whether to accept the transmitted information. Here, we presented different ways to select this identifier and gave a categorization of possible approaches, to later discussed their advantages and disadvantages. This discussion led to the definition of a criterion that uses a plausibility function which determines the plausibility of a sentence based on all its proofs according to a given base. In [2] the agents do not communicate the sources of the assumptions, but they present themselves as completely responsible for the knowledge they are passing on; receiving agents consider the sending ones as the sources of all the assumptions they are receiving from them.

An important decision we made is to forward an agent identifier with a sentence rather than a credibility label in order to give additional information to the beliefs. One reason for this decision is that since each agent has its own *assessment*, is more suitable to send agent identifiers as this way the receiver agent can evaluate the belief received based on the credibility it has according to its own assessment. Another reason is that we achieve a more dynamic framework since the evaluation of the credibility of the agent identifiers is separated by use of the assessment function. That is, if the credibility order among agents changes, then the plausibility of all sentences also changes without having to modify the belief base of the agent.

In addition to this, we presented an implementation of this operator using answer set programming adapting methods of [6], and thus using a common technique for the implementation of the reasoning component of agents in MASs. To sum up, we extended the reasoning component towards the computation of meta-information and additionally improved the communication component by giving reasoning capabilities to it.

One of the limitations of our communication framework is that a total order among agent is considered for each agent. As future work, we want to relax this assumption and to consider a partial order among agents. We also plan to expand the framework towards the incorporation of temporal information into the information objects.

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