On Need-driven Proactive Information Exchanges in Agent Teams

John Yen, Xiaocong Fan
School of Information Sciences and Technology
The Pennsylvania State University
University Park, PA 16802
jyen@ist.psu.edu, zfan@ist.psu.edu

Richard A. Volz
Department of Computer Science
Texas A&M University
College Station, TX 77843
volz@cs.tamu.edu

Abstract

Members of high-performing human teams can often anticipate information needs of teammates and offer relevant information to them proactively. Such capabilities are highly desirable for agent teams to achieve better teamwork processes for supporting information gathering, information fusion, and decision makings of teammates. This paper presents a framework for formally specifying proactive agent behaviors based on the SharedPlan theory. Axioms that specify an agent's anticipations of a teammate's information needs are proposed, which enable the teammate to perform an action or protect the teammate from a threat. We also introduce the semantics of two proactive communicative actions (i.e., proactive inform and third party subscribe) that are driven by information needs of teammates. Based on these semantics, we show that suitable proactive information delivery actions can be derived in the proposed framework. This paper thus establishes a formal foundation for proactive information delivery behavior that not only provides better understanding of the underlying assumptions required to justify the behavior, but also provides a coherent basis for the specification and design of agent teams with proactive information delivery capabilities.

1 Introduction

Psychological studies about human teamwork [10] have shown that members of an effective team can often anticipate needs of other teammates and choose to assist them proactively based on a shared mental model [13]. Anticipating needs of teammates and proactively assisting them regarding their needs are important teamwork behaviors for other types of agent teams, also. For instance, applications for dynamic domains such as Battlespace Infospheres often require a large number of intelligent agents and human agents to form a team to cooperate effectively in information gathering, information fusion, sense-making, information delivering, and group decisions. Such teams require the involved agents to be able to anticipate information needs of teammates and offer relevant information proactively.

Even though several formal theories have been proposed regarding agent teamwork, they do not directly address issues regarding proactive information exchange among agents in a team. There are several potential benefits for developing such a theory. First, it will provide a guide for the specification and design of agent architectures, algorithms, and applications that support proactive information delivery capabilities. For instance, an example of such agent architecture is CAST (Collaborative Agents for Simulating Teamworks)[14]. Second, such a theory can not only be critical for understanding the mental states of the performers involved in proactive communication actions, it can also uncover the assumptions and limitations of proactive information exchanges implemented in a multi-agent system, which might be overlooked otherwise. Finally, the study of proactive information exchanges might offer opportunities for exploiting novel agent communication protocols that support proactive teamwork behaviors.

The rest is organized as follows. In section 2 we prepare some notations, and re-formulate the idea of "performatics-as-attempt" in the SharedPlan framework. In section 3 we identify two types of information needs, and propose axioms for agents to anticipate these two types of information needs for their teammates. In sections 4 and 5, we give the semantics of two proactive performatives based on the speaker's awareness of information needs, and show how agents, driven by information needs of teammates, could potentially commit to these communicative actions to provide help. Section 6 devotes to discussion and conclusion.

2 Preparation

We adopt the SharedPlan theory [5, 6] as the cornerstone of our framework. The modal operators such as DO, $Int.To$, $Int.Th$, CBA, etc., are originally defined in [5]. Actions are represented by $\alpha, \beta, \gamma \cdots$. Appropriate functions are defined to return certain properties associated with an action. In particular, $pre(\alpha)$ and $post(\alpha)$ return a conjunction of propositions that describe the preconditions and effects of α, respectively. By $I \in pre(\alpha)$ we mean I is a conjunct of $pre(\alpha)$. All actions are intended, committed and performed in some specific context [5]. C_α is used to refer to the context in which α is being done, and $Constr(C_\alpha)$ refers to the constraints component of C_α.

An action is either a primitive, or a complex action. Complex actions can be built from primitive actions by using the constructs of dynamic logic: $\alpha;\beta$ for sequential composition, $\alpha|\beta$ for nondeterministic choice, $p?$ for testing (where p is a logical formula), and α^* for repetition. A recipe for a complex action γ is a specification of a group of subsidiary actions at different levels of abstraction, the doing of which under certain constraints constitutes the performance of γ. Thus, a recipe is in *per se* composed of an action expression and a set of constraints on the action expression.

In the following, let TA be a set of agents in the team under concern, and TB be a group of opponent agents, whenever needed. We define abbreviations for awareness, unawareness, contradicting beliefs between two agents, and wrong beliefs:

$aware(A,I,t) \triangleq Bel(A,I,t) \vee Bel(A,\neg I,t)$,
$unaware(A,I,t) \triangleq \neg aware(A,I,t)$,
$CBel(A,B,I,t) \triangleq$
$(Bel(A,I,t) \wedge Bel(A,Bel(B,\neg I,t),t) \vee$
$(Bel(A,\neg I,t) \wedge Bel(A,Bel(B,I,t),t)))$,
$WBel(A,I,t) \triangleq (Hold(I,t) \wedge Bel(A,\neg I,t))$
$\vee(\neg Hold(I,t) \wedge Bel(A,I,t))$.

2.1 Reformulate Performative-as-attempt

Following the idea of "performative-as-attempt" [2, 3], we will model the intentional semantics of proactive performatives as attempts to establish certain mutual beliefs between the speaker and the addressee (or addressees). In order to do that, we first need to reformulate the concept of $Attempt$ within the framework of the SharedPlan theory.

Definition 1 $Attempt(A,\epsilon,P,Q,C_n,t,t_1) \triangleq$
$[\neg Bel(A,P,t) \wedge Int.Th(A,P,t,t_1,\neg Bel(A,P,t) \wedge C_n) \wedge$
$Bel(A,post(\epsilon) \Rightarrow Q,t) \wedge (\exists t_e \cdot (t \leq t_e < t_1) \wedge Int.To(A,$
$\epsilon,t,t_e,Int.Th(A,P,t,t_1,\neg Bel(A,P,t) \wedge C_n)))]?;\epsilon$.

While there is nothing intrinsic in the definition of $Attempt$ that implies a relationship between Q and P, as we will use $Attempt$, Q will be an achievable goal closely related to achieving P (they may have certain causal relations), whereas P itself may be unachievable. As the conditions for making the attempt involve P, not Q, we thus think of the above definition as an attempt to achieve P via achieving Q by performing ϵ. For example, agent A may desire that $Bel(B,I,t)$ under conditions that agent A does not believe that B believes I. While $Bel(B,I,t)$ (P in this case) may be unachievable, $MB(\{A,B\},Bel(B,Bel(A,I,t),t'))$ (Q in this case) can be achieved by sending an appropriate message to B. Hence, the $Attempt$ would actually be an intent to achieve Q by performing ϵ while the underlying intent was to achieve P. Of course, if P can actually be achieved, one can have $P = Q$.

C_n serves as the escape conditions for the $Attempt$. As time goes on, an agent could drop an $Attempt$ and discharge its duty of achieving the ultimate goal when the context C_n no longer holds, or goal P has already been achieved, or it comes to the time limit t_1.

The semantics of elementary performatives are given by choosing appropriate formulas (involving mutual beliefs) to substitute for P and Q in the definition of *Attempt*. As in [4], the semantics of $Inform$ is defined as an attempt of the speaker to establish a mutual belief with the addressee about the speaker's goal to let the addressee know what the speaker knows.

Definition 2 $Inform(A,B,I,t,t_1,t') \triangleq$
$Attempt(A,\epsilon,Bel(B,I,t'),$
$\exists t'' \cdot (t \leq t'' < t_1) \wedge MB(\{A,B\},P,t''),C_p,t,t_1)$, *where*
$P = \exists t_b \cdot (t'' \leq t_b < t_1) \wedge Int.Th(A,Bel(B,Bel(A,I,t'),t_b),$
$t,t_b,C_p)$,
$C_p = Bel(A,I,t) \wedge Bel(A,unaware(B,I,t),t)$.

According to the *speech act* theory [11], every speech act has an utterance events associated with it. For the purpose of this paper, we will simply assume every communicative act can be casted to certain instance of $SEND$–a type of lower-level complex single agent action, and each agent has full individual recipes for performing $SEND$. We also assume by performing the complex action $SEND$, the speaker and the addressee (or addressees) are able to achieve the "honest goal" (i.e., substitute of Q in $Attempt$). When the semantics of a performative is defined in terms of an $Attempt$, the argument ϵ of the $Attempt$ actually refers to an appropriate instance of $SEND$ set up specifically for the instance of communicative act under concern.

While we leave the detailed interface of $SEND$ and how to appropriately set up the instance of $SEND$ for a specific occurrence of a communicative act as implementation issues, we can state two basic requirements related to $SEND$. First, the information content (message) of the $SEND$, say $cont$, must be derivable from the arguments of the performative. Second, it must be shown that $post(SEND(\cdots,cont,\cdots)) \Rightarrow Q$ for the Q in the associated $Attempt$. In the specific case of $Inform$, the $cont$ for the $SEND$ can be extracted from the argument list of the $Inform$. It is also reasonable to assume that if agent B receives an $Inform$ type message from agent A with message content $cont$, it will believe that agent A believes $cont$, and this allows the achievement of the mutual belief goal (Q) of the $Attempt$ implied by the $inform$ goal to be established.

3 Anticipate Information Needs

The most challenging issue in enabling agents to proactively deliver information to teammates is for them to *anticipate* information needs of teammates based on a computable shared mental model. We first introduce a new modal operator $InfoNeed(A, I, t, C_n)$ to denote information needs. It means that agent A needs to know the truth value of information (proposition) I at time t under the context C_n[1]. Like intentional contexts, the context of an information needs is used to record the reason for adopting or anticipating the information needs. In case that an information need is induced from some intention, its context may include the context of that intention. On the other hand, when an agent has anticipated information needs of its teammates, it will adopt appropriate intentions to assist them (refer to Axiom 3). In such case, the contexts of the adopted intentions will be directly constructed from the contexts of information needs. In addition, the context of information needs will be included in need-driven communicative actions. Consequently, an agent can commit to a proactive performative, but only when the context of the information needs remains true. In other words, the context will be used to reason about whether proactive information exchange should be performed or not.

We distinguish two types of information needs. The first type of information need enables an agent to perform certain (complex) actions, which contributes to an agent's individual commitments to the whole team. We call this type of information need *action-performing information need*. Typically, this information need will exhibit itself through appearance of the information item in the precondition of the action. The second type of information need allows an agent to protect a goal from potential conflicts. Knowing such information will help an agent to deal with a threat (conflict) to the goal. Thus, we call this type of information need *goal-protection information need*.

3.1 Action-performing Information Needs

The following axiom states how to anticipate the action-performing information needs. This axiom actually specifies a generic constraint on the mental state of the anticipating agent.

[1]Because information need is defined as a need to know the truth value of the proposition p, $InfoNeed(A, p, t', C_n)$ is equivalent to $InfoNeed(A, \neg p, t', C_n)$. Hence, axiom D of modal logics is inapplicable for $InfoNeed$.

Axiom 1 (Action-performing Information Needs)
$\forall A \in TA, B \in TA, I, t, t_0, t' \cdot (t \leq t_0 < t') \wedge$
$Bel(A, Int.To(B, \alpha, t_0, t', C_\alpha), t) \wedge\ Bel(A, I \in pre(\alpha), t) \wedge$
$[Bel(A, unaware(B, I, t), t) \vee CBel(A, B, I, t)]$
$\Rightarrow Bel(A, InfoNeed(B, I, t', C_n), t)$[2], *where*
$C_n = C_\alpha \wedge Bel(A, I \in pre(\alpha), t) \wedge$
$\quad (Bel(A, unaware(B, I, t), t) \vee CBel(A, B, I, t))$.

Axiom 1 states that agent A believes that agent B will need information I at time t' under the context C_n if A believes that (1) B intends to perform action α at time t', (2) I is a component of the precondition of α, and (3) either A believes that B does not know whether or not I is true, or A believes that B's belief about I is incorrect.

The context C_n of the information need extends the context C_α for B's intention to perform α with A's belief about the fact that I is a piece of the precondition of α, and A's model of B's mental state: B either is unaware of I, or A and B have a conflict on the truth value of I.

When agent A and B in Axiom 1 refer to the same agent, it reduces to say how an agent can anticipate its own action-performing information needs. The proof of this lemma requires the assumption that goals are known, and the idempotence property of Bel.

Lemma 1 $Int.To(A, \alpha, t, t', C_\alpha) \wedge Bel(A, (I \in pre(\alpha)), t) \wedge unaware(A, I, t) \Rightarrow Bel(A, InfoNeed(A, I, t', C_n), t)$, *where* $C_n = C_\alpha \wedge unaware(A, I, t) \wedge Bel(A, (I \in pre(\alpha)), t)$.

Normally, when an agent intends to do some action but lack the pre-requisite information for doing it, the agent can just wait for help from its teammates. The agent will have more choices if it could figure out its own information needs.

3.2 Goal-protection Information Needs

The following axiom states how to anticipate the goal-protection information needs.

Axiom 2 (Goal-Protection Information Needs)
$\forall A \in TA, B \in TA, I, t, t' \geq t, t'' > t' \cdot$
$Bel(A, Int.Th(B, \phi, t, t'', C_\phi), t) \wedge$
$Bel(A, [unaware(B, I, t') \vee WBel(B, I, t')] \Rightarrow$
$\quad [\exists G \in TB, \alpha, t_1 > t' \cdot Do(G, \alpha, t_1, \Theta_\alpha) \Rightarrow \neg\phi], t) \wedge$
$[Bel(A, unaware(B, I, t), t) \vee CBel(A, B, I, t)]$
$\Rightarrow Bel(A, InfoNeed(B, I, t', C_n), t)$, *where*
$C_n = C_\phi \wedge (Bel(A, unaware(B, I, t), t) \vee CBel(A, B, I, t))$.

Axiom 2 states that agent A believes that agent B will need information I at time t', if (1) A believes that B intends to bring about ϕ at time t'', (2) A believes that, at any

[2]Here as in the SharedPlan theory, we assume intentions persist by default. A might get to know that at some time t_0 before t, B already had an intention $Int.To(B, \alpha, t_0, t', C_\alpha)$. Without any new information, A believes $Int.To(B, \alpha, t, t', C_\alpha)$ still holds at t.

time t' before t'', B's lacking information or holding wrong belief about I will put B in a critical situation: B's goal ϕ would become impossible in case that some agent in an adversary team took some intrusive action α, and (3) A currently happens to believe that B either is unaware of I, or A and B have a conflict on the truth value of I.

The context of the information need consists of the context for agent B's goal, and agent A's model of B's mental state: B either is unaware of I, or A and B have a conflict on the truth value of I. Note that the first occurrence of $CBel$ cannot be replaced with $WBel$. The reason is that the truth value of $Hold(I,t)$ or $\neg Hold(I,t)$ (see definition of $WBel$) is out of the control of any agent. Formulas with any occurrence of $WBel$ can only exist in the context of beliefs. Nor can the $WBel$ be replaced with $CBel$, since the rule for inferring threats has nothing to do with A's belief, but relies on the real state.

It is worthing noting that goal-protection information needs will ultimately reduce to action-performing information needs, as long as the agent DO something to protect its goals. One thing that axiom 1 requires is that the specific ACTION of agent B has to be clear to the anticipator agent A; while in axiom 2, the anticipator agent need not know what action that agent B will choose to respond to the coming threat. In particular, it leaves open the possibility of searching for recipes (plans) to avoid the threat. On the other hand, it offers B the flexibility of choosing one from several possible reactions to deal with the threat.

Also, as far as goal-protection is concerned, a joint persistent goal (JPG) requires all the involved agents take it as an obligation to inform other agents about the achievement or impossibility of the goal and the status of the escape condition. However, the Shared-Plan Theory on which we base our work does not require such *necessary* information delivery behavior. This is actually more flexible, as it leaves open the possibility of reasoning about whether such notification is necessary or useful, and allows us to focus on *helping behavior* related to information delivery.

The above two ways of anticipating others' information needs lay the foundation for developing algorithms (e.g., the DIARG algorithm in the CAST multi-agent architecture [14]) for agents to dynamically reason about information needs of their teammates.

3.3 From Information Needs to Proactive Assist

A critical issue in specifying an agent's help behavior is to relate an agent's belief about information needs of teammates to its own intentions to help. One general approach is to make abstract rather than specific commitments for satisfying the emerging information needs, and postpone the specific commitments (and their reconciliation) to later stages. In this way, the commitment to providing help can be clearly separated from the decisions on how to provide help, which facilitates the implementation of agent teams with multiple kinds of proactive behaviors.

Thus, we introduce the following axiom to first transform an information need of a teammate into certain goal state (i.e., $Int.Th$) the helper intends to establish. Such goals regarding the teammate's belief about the truth value of I can then be translated into potential assist actions the helper can perform. The axiom below states that when agent A realizes that agent B needs information I at t' under context C_n, agent A will adopt appropriate intention-that under the context C_n, in which it chooses "B believes what A believes about I" as a goal.

Axiom 3 (ProAssist) $\forall A, B \in TA, I, t, t' > t \cdot$
$Bel(A, InfoNeed(B, I, t', C_n), t) \Rightarrow$
$[(Bel(A, I, t) \Rightarrow Int.Th(A, Bel(B, I, t'), t, t', C_n)) \vee$
$(Bel(A, \neg I, t) \Rightarrow Int.Th(A, Bel(B, \neg I, t'), t, t', C_n)) \vee$
$(unaware(A, I, t) \Rightarrow Int.Th(A, aware(B, I, t'), t, t', C_n))]$.

Combining this Axiom with the *help* Axiom from the SharedPlan theory, information needs are transformed to $Pot.Int.To$ rather than $Int.To$. This enables the framework to specify the situations in which an agent could reflect on its assist behaviors, yet leaving open the agent's commitment on such behaviors. For instance, an agent may be too busy at times to help teammates. When an agent faces multiple assist opportunities, it will not restrict agents to commit to specific assist opportunity. It is worth noting that even if A is unaware of the value of I, it may adopt an intention to help which might lead it to engage other agents in helping.

A and B could refer to the same agent. That means agent A will try to help itself by adopting an intention towards its own awareness of I. Since in such cases "ask" is an action that can lead to the intended mental state, this axiom is also the basis for the agent to request needed information from other agents through ask or $subscribe$, a performative whose semantics will be defined later.

4 Proactively Inform Teammates

As we have mentioned before, members of high performance teams can often proactively offer information to those teammates who need it. To model the semantics of such proactive (information-needs driven) communicative action, we define a new primitive communication action $ProInform$ (Proactive Inform) that extends the semantics of $Inform$ with additional requirements on the speaker's awareness of the addressee's information needs. More specifically, we explicitly include the speaker's belief about the addressee's need of the information as a part of the mental states being communicated. Hence, the meaning of $ProInform$ is an attempt for the speaker to establish a mutual belief (with the addressee) about the speaker's goal to let the addressee know that (1) the speaker knows the information being communicated, and (2) the speaker knows the addressee needs the information. This is formally stated below.

Definition 3 $ProInform(A, B, I, t, t_1, t', C_n) \triangleq$
$Attempt(A, \epsilon, Bel(B, I, t'),$
$\exists t'' \cdot (t \leq t'' \leq t_1) \wedge MB(\{A, B\}, P, t''), C_p, t, t_1)$, *where*
$P = \exists t_b \cdot (t'' \leq t_b \leq t_1) \wedge Int.Th(A, Bel(B, Bel(A, I, t) \wedge$
$\quad Bel(A, InfoNeed(B, I, t', C_n), t), t_b), t, t_b, C_p),$
$C_p = Bel(A, I, t) \wedge [Bel(A, unaware(B, I, t), t) \vee$
$\quad CBel(A, B, I, t)] \wedge Bel(A, InfoNeed(B, I, t', C_n), t).$

Notice that the definition of $ProInform$ includes the context of information needs as an argument. This context serves as the context of the speaker's goal (i.e., intention) to let the addressee know the information. The context is essential to model the mental states relevant to the communicative action. It specifies the behavior of an agent who uses the communicative action. For instance, suppose $ProInform$ is implemented in a multi-agent system using a component that reasons about the information needs of teammates and a communication plan involving sending, receiving confirmation, and resending if confirmation is not received. During the execution of an instance of such a plan, if the agent realizes the context of the addressee's information need is no longer true, the agent can choose to abandon the communication plan. This use of context in the definition of $ProInform$ supports our claim earlier that it is important to include the context of information needs explicitly in the definition of $InfoNeed$.

The semantics of $ProInform$ has direct impacts on the communication policy among team members. By accepting $ProInform$, the addressee attempts to confirm the informing agent that it will accept the information being communicated.
$Accept(B, A, I, t, t_1, t', C_n) \triangleq Attempt(B, e, \phi, \phi, C_n, t, t_1)$,
where $\phi = MB(\{A, B\}, Bel(B, I, t'), t_1)$.

However, the addressee may reject $ProInform$ because (1) it knows something contrary to the information received, or (2) it does not think the information is needed. The first reason for rejection is already modeled in Cohen and Levesque's work as performative $Refuse$. We define a new type of refuse, named $RefuseNeed$, to address the second kind of refusal.
$Refuse(B, A, I, t, t_1, t', C_n) \triangleq$
$\quad Attempt(B, \epsilon, \psi, \psi, C_n, t, t_1)$,
$RefuseNeed(B, A, I, t, t_1, t', C_n) \triangleq$
$\quad Attempt(B, \epsilon, \phi, \phi, C_n, t, t_1)$, where
$\psi = MB(\{A, B\}, Bel(B, \neg I, t'), t_1)$,
$\phi = MB(\{A, B\}, \neg InfoNeed(B, I, t', C_n), t_1)$.

Upon receiving the refusal, A might revise its belief about B's future information needs.

Based on the semantics of $ProInform$ and its replies, it is straightforward to get the following property.

Proposition 1 *For any* $t_0 < t_1 < t_2 \leq t_3$,
(1)$ProInform(A, B, I, t_0, t_1, t_3, C_n) \wedge$
$Accept(B, A, I, t_1, t_2, t_3, C_n) \Rightarrow Bel(B, Bel(B, I, t_3), t_2)$.
(2)$ProInform(A, B, I, t_0, t_1, t_3, C_n) \wedge$
$Refuse(B, A, I, t_1, t_2, t_3, C_n) \Rightarrow Bel(A, Bel(B, \neg I, t_3), t_2)$.
(3)$ProInform(A, B, I, t_0, t_1, t_3, C_n) \wedge$
$RefuseNeed(B, A, I, t_1, t_2, t_3, C_n) \Rightarrow$
$\quad Bel(A, \neg InfoNeed(B, I, t_3, C_n), t_2)$.

By Axiom 3 and Proposition 1, we can prove the following theorem. It states that if agent A believes that (1) agent B will need information I at time t' under the context C_n, and (2) A believes I now, it will consider to proactively send information I to B by using $ProInform$. The context of A's potential intention is the context of B's information need augmented with A's belief about I.

Theorem 1 $\forall A, B \in TA, I, C_n, t, t' > t,$
$Bel(A, InfoNeed(B, I, t', C_n), t) \wedge Bel(A, I, t) \wedge$
$\neg Bel(A, Bel(B, I, t'), t) \Rightarrow (\exists t_1, t_2 \cdot Pot.Int.To(A,$
$ProInform(A, B, I, t_1, t_2, t', C_n), t, t_1, C_n \wedge Bel(A, I, t)))$.

5 Subscribe Information

While an agent in a team can anticipate certain information needs of teammates, it may not always be able to predict all of their information needs, especially if the team interacts with a dynamic environment. Under such circumstances, an agent in a team needs to let teammates know about its information needs so that they can provide help. There exists at least two ways to achieve this. An agent might merely inform teammates about its information needs, believing that they will consider helping if possible, but not expecting a firm commitment from them for providing the needed information. Alternatively, the speaker not only wants to inform teammates about its information needs, but also wishes to receive a firm commitment from teammates that they will provide the needed information whenever the information is available. For instance, let us suppose that agent B provides weather forecast information to multiple teams in some areas of a battle space, and agent A is in one of these teams. If agent A needs weather forecast information of a particular area in the battle space for certain time period, A needs to know whether agent B can commit to deliver such information to it. If agent B can not confirm the request, agent A can request another weather information agent or consider alternative means (such as using a broker agent).

An agent's choice between these two kinds of communicative actions obviously depends on many factors including the level of trust between the speaker and the addressee, the criticality and the utility of the information need, the sensing capability of the addressee, and the strength of the cooperative relationship between them. However, we only attempt to capture the semantics of communicative actions without considering such factors, and leave the issue of choosing communication actions to agent designers.

The first kind of communication actions can be modeled as $Inform(A, B, InfoNeed(A, I, t'', C_n), t, t', t'')$. That is, A informs B at time t so that B will know at time t' that "A will need information I at t'' under the context C_n". If agent B's reply to such $Inform$ action is $Accept$, from Theorem 1, agent B will consider (i.e., will have a "potential intention") to proactively deliver the needed information to A when the information is available to B.

The second type of communication actions mentioned above is similar to subscription in the agent literature. In fact, subscription between two agents is a special case of subscription involving a "broker" agent. As the size of a team or the complexity of its task increases, the mental model about information needs of teammates may vary significantly among members of the team. For instance, as the team scales up in size or task complexity, the team is often organized into subteams, which may be further divided into smaller subteams. Because (top-level) team knowledge might be distributed among several sub-teams, agents in one sub-team might not be able to know the team process (the plans, task assignments, etc.) of other subteams, and hence can not anticipate information needs of agents in these subteams. To facilitate proactive information flows between these subteams, an agent in a subteam can be the designated point of contacts with other subteams. These broker agents play a key role in informing agents external to the subteam about information needs of agents in the subteam. Situations such as these motivate us to formally define the semantics of $3PTSubscribe$ (third-party subscribe). Conceptly, $3PTSubscribe$, issued by a broker agent A to information provider C, forwards the information needs "B will need I" to C and requests C to feed I to B whenever possible. When A and B are the same agent, it reduces to "subscribe".

It seems the semantics of $3PTSubscribe$ involves a $Request$, since the speaker expects the addressee to perform the information delivery action to the needer. We might be attempted to model the communicative action as "A requests C to $Inform$ B about information I". However, defined as such, B is demanded to reply based on B's current belief (like a request to a database server). What we want to model is that if B accepts the request, B will commit to deliver information I, whenever it becomes available. Neither can we model it as "A requests C to proactively inform B about information I", because it requires that agent B already know about A's needs of I, which is not the case here. Because we cannot model $3PTSubscribe$ by composing existing communicative actions, we need to define it as a new performative. The performative $3PTSubscribe(A, B, C, I, t_1, t_2, t_3, C_n)$ represents the action that A subscribes information I (as a broker) on behalf of agent B from agent C until time t_3 under the context C_n. The ultimate intent of the action is that A has information I at time t_3. The intermediate effect is to establish a mutual belief between A and C that (1) B needs information I at time t_3 under the context C_n, and (2) whenever C receives new information about I, C intends to proactively inform I to B as long as B still needs it. We formally define the semantics of $3PTSubscribe$ below.

Definition 4 $3PTSubscribe(A, B, C, I, t_1, t_2, t_3, C_n) \triangleq$
$Attempt(A, \epsilon, aware(B, I, t_3),$
$\exists t'' \cdot (t_1 \leq t'' \leq t_2) \wedge MB(\{A, C\}, P, t''), C_p, t_1, t_2)$, *where*
$P = \exists t_b \cdot (t'' \leq t_b \leq t_2) \wedge Int.Th(A,$
$Bel(C, Bel(A, InfoNeed(B, I, t_3, C_n), t_1), t_b) \wedge$
$Int.Th(C, \forall t' \leq t_3 \cdot BChange(C, I, t') \Rightarrow \exists t_a, t_c \cdot Int.To(C,$
$ProInform(C, B, I, t_a, t_c, t_3, C_n), t', t_a, C_n), t_b, t_b, C_n),$
$t_1, t_b, C_n),$

$$BChange(C, I, t) \triangleq (Bel(C, I, t) \wedge Bel(C, \neg I, t-1)) \vee (Bel(C, \neg I, t) \wedge Bel(C, I, t-1)) \vee (aware(C, I, t) \wedge unaware(C, I, t-1)),$$

$$C_p = Bel(A, InfoNeed(B, I, t_3, C_n), t_1) \wedge \neg Bel(A, Bel(C, InfoNeed(B, I, t_3, C_n), t_1), t_1) \wedge unaware(A, I, t_1) \wedge Bel(A, aware(C, I, t_1), t_1).$$

Notice that this definition requires the context of the information need to be known to the addressee (agent C), since it is part of the mutual belief. This enables the information provider (agent C) to avoid delivering unneeded information when the context no longer holds.

A special case of "third-party subscribe" is the case in which the information needer acts as the broker agent to issue a subscription request on behalf of itself to an information service provider. Hence, a two party subscription action $Subscribe(A, C, I, t_1, t_2, t_3, C_n)$ can be defined as $3PTSubscribe(A, A, C, I, t_1, t_2, t_3, C_n)$.

Upon receiving a $3PTSubscribe$ request, the information service agent (agent C in Definition 6) can reply in at least three ways. It can accept the request and commit to proactively deliver the needed information to agent B whenever the information changes. Alternatively, it can reject the request by letting A knows that it has no intention to deliver information to B. Finally, it can accept to believe the information need of B, but choose not to make a strong commitment about proactively inform B. This option still allows agent C to consider (i.e., potentially intend to) $ProInform$ B later based on Theorem 1, yet it gives agent C the flexibility to decide whether to commit to $ProInform$ in a given situation (e.g., based on C's current cognitive load level). We can similarly define these three replies in terms of $Attempt$. Also similar to Theorem 1, an agent could assist its teammates by performing $3PTSubscribe$.

Theorem 2 $\forall A, B, C \in TA, I, C_n, t, t' > t,$
$unaware(A, I, t) \wedge Bel(A, InfoNeed(B, I, t', C_n), t) \wedge$
$Bel(A, aware(C, I, t), t) \wedge \neg Bel(A, aware(B, I, t'), t) \Rightarrow$
$(\exists t_1, t_2 \cdot Pot.Int.To(A,$
$3PTSubscribe(A, B, C, I, t_1, t_2, t', C_n), t, t_1, C_n)).$

6 Concluding Remarks

In this paper we proposed axioms for anticipating the information needs of teammates and defined the intentional semantics of $ProInform$ and $3PTSubscribe$. However, we are not proposing a complete ACL that covers all the categories of communicative acts identified in [12]. Nor are we focusing on the semantics of performatives alone. We are more concerned about information needs and how to enable proactive information flows among teammates by reasoning about information needs. Hence, the semantics of the performatives presented in this paper are motivated by our study about team proactivity driven by information needs, and they rely on the speaker's awareness of information needs.

There are several existing agent communication languages such as Arcol [1], KQML [8], and FIPA's ACL (<http://www.fipa.org/>). The formal semantics of the performatives in these languages and the approach adopted in this paper are all framed in terms of mental attitudes, which originates from the seminal work of [3], where Cohen and Levesque modeled speech acts as actions of rational agents in their framework of intentions.

However, the semantics defined in this paper distinguish from other approaches in two aspects. First, the semantics of $ProInform$ and $3PTSubscribe$ rely on the awareness of information needs. Secondly, the semantics of $ProInform$ and $3PTSubscribe$ adopt a richer notion of context than those offered by existing approaches. As noted in [12], mental agency alone cannot provide the normative basis for an ACL semantics. An ideal ACL would take a public perspective, emphasize conventional meaning, and consider context. The context of $ProInform$ and $3PTSubscribe$ includes the context of the information need under concern. Consequently, an information providing agent could terminate the information delivery service once the context is no longer valid. Also, appropriate conversation policy [12, 9, 7] and other relevant social constraints could be included in the context of proactive performatives. This will enable agents to consider the corresponding social context while intending to perform a communicative act. In such a sense, as well as the private (sender's or/and receiver's) perspectives, our approach is also able to take public perspective (e.g., team goals) into consideration.

The framework in this paper not only can serve as a formal specification for designing agent architectures, algorithms, and applications that support proactive information exchanges among agents in a team, but also offers opportunities for extending existing agent communication protocols to support proactive teamwork, and for further studying proactive information delivery among teams involving both human and software agents.

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References

[1] P. Breiter and M. Sadek. A rational agent as a kernel of a cooperative dialogue system: Implementing a logical theory of interaction. In *Proceedings of ECAI-96 workshop on Agent Theories, architectures, and Languages*, pages 261–276. Springer-Verlag, Berlin, 1996.

[2] P. R. Cohen and H. J. Levesque. Performatives in a rationally based speech act theory. In *Proc. of the 28th Annual Meeting of the Association for Computational Linguistics*, pages 79–88, 1990.

[3] P. R. Cohen and H. J. Levesque. Rational interaction as a basis for communication. *Intentions in Communication*, pages 221–255, 1990.

[4] P. R. Cohen and H. J. Levesque. Communicative actions for artificial agents. In *Proceedings of the International Conference on Multi-Agent Systems*. AAAI Press, June 1995.

[5] B. Grosz and S. Kraus. Collaborative plans for complex group actions. *Artificial Intelligence*, 86:269–358, 1996.

[6] B. Grosz and S. Kraus. The evolution of sharedplans. *Found. and Theories of Rational Agencies*, pages 227–262, 1999.

[7] Y. Labrou. Standardizing agent communication.

[8] Y. Labrou and T. Finin. Semantics and conversations for an agent communication language. In M. Huhns and M. Singh, editors, *Readings in Agents*, pages 235–242. Morgan Kaufmann, San Mateo, Calif., 1998.

[9] J. Pitt and A. Mamdani. A protocol-based semantics for an agent communication language. In *Proceedings of IJCAI-99*, pages 486–491, 1999.

[10] W. Rouse, J. Cannon-Bowers, and E. Salas. The role of mental models in team performance in complex systems. *IEEE Trans. on Sys., man, and Cyber*, 22(6):1296–1308, 1992.

[11] J. R. Searle. How performatives work. *Linguistics and Philosophy*, 12:535–558, 1989.

[12] M. P. Singh. Agent communication languages: Rethinking the principles. *IEEE Computer*, 31(12):40–47, 1998.

[13] K. Sycara and M. Lewis. Forming shared mental models. In *Proc. of the 13th Annual Meeting of the Cognitive Science Society*, pages 400–405, 1991.

[14] J. Yen, J. Yin, T. Ioerger, M. Miller, D. Xu, and R. Volz. Cast: Collaborative agents for simulating teamworks. In *Proceedings of IJCAI'2001*, pages 1135–1142, 2001.