# Proactive Information Exchanges Based on the Awareness of Teammates' Information Needs

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## ABSTRACT

The capabilities for agents in a team to anticipate information needs of teammates and proactively offer relevant information are highly desirable. However, such behaviors have not been fully prescribed by existing agent theories. We attempt to establish a theory about proactive information exchanges based on the SharedPlan framework and Cohen and Levesque's formalization of communicative actions. We first formally specify two types of information needs. A new performative called $ProInform$ is introduced by extending the semantics of $Inform$ to include the speaker's belief about the information needs of the addressee. For agents in a team containing subteams to achieve proactive information exchanges, we define the semantics of "subscribe" through the third party (e.g., a broker agent). We also show that proactive information exchanges using these communicative actions can be derived as assist behaviors from the theory. The framework not only serves 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.

## Categories and Subject Descriptors

I.2.11 [**Artificial Intelligence**]: Distributed Artificial Intelligence—*Multiagent Systems*

## Keywords

Proactive Information Delivery, Information Needs, Shared Mental Model, Teamwork

## 1. INTRODUCTION

Psychological studies about human teamwork 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 [15]. Hence, it is highly desirable for agents in a team to have such similar proactivity. 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.

Agent infrastructures like Grid [11] enable trans architecture teams of agents (a team consisting of subteams of agents with different architectures like TEAMCORE [20], CAST [22], D'Agents [7]) to support joint and coalition activities by providing mechanisms for accessing shared ontologies, and for publishing and subscribing agents' services [11]. However, infrastructures themselves do not deal with the semantics of proactive information delivery among agents.

To enable agents to deliver information proactively, a theory based on reasoning about other teammates' information needs is highly needed. However, 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 can serve as the specification 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 Teamwork)[22]. 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.

In this paper, we attempt to establish a theory about proactive information exchange among team-based agents. In section 2 we make some preparations and define the semantics of elementary performatives 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. Potential conversation policies for ProInform and third-party subscribe are discussed briefly in section 6. Section 7 devotes to comparison and discussion, and section

8 concludes the paper.

## 2. PREPARATION

We adopt the SharedPlan theory [9, 10] as the cornerstone of our framework. 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 $\alpha$, 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 [9]. $C_\alpha$ is used to refer to the context in which $\alpha$ is being done, and $Constr(C_\alpha)$ refers to the constraints component of $C_\alpha$.

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 $\alpha^*$ for repetition. A recipe for a complex action $\gamma$ 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 $\gamma$. Thus, a recipe is in *per se* composed of an action expression and a set of constraints on the action expression.

In the SharedPlan theory, modal operator $Do(G, \alpha, t, \Theta)$ is used to denote that $G$ (a group of agents or a single agent) performs action $\alpha$ at $t$ under constraints $\Theta$. $Commit(A, \alpha, t_1, t_2, C_\alpha)$ represents the commitment of agent $A$ at $t_1$ to perform the basic-level action $\alpha$ at $t_2$ under the context $C_\alpha$. $Exec(A, \alpha, t, \Theta)$ is used to represent the fact that agent $A$ has the ability to perform basic-level action $\alpha$ at time $t$ under constraints $\Theta$. Meta-predicate $CBA(A, \alpha, R_\alpha, t_\alpha, \Theta)$ means agent $A$ at $t_\alpha$ can bring about action $\alpha$ by following recipe $R_\alpha$ under constraints $\Theta$. *Bel* and *MB* are standard modal operators for belief and mutual belief, respectively. There are four kinds of intentional attitudes in the SharedPlan theory. $Int.To(A, \alpha, t, t_\alpha, C_\alpha)$ means $A$ at $t$ intends to do $\alpha$ at $t_\alpha$ in the context $C_\alpha$, where $C_\alpha$ accounts for the reason of doing $\alpha$. $Int.Th(A, p, t, t', C_p)$ means $A$ at $t$ intends that $p$ hold at $t'$ under the intentional context $C_p$. $Pot.Int.To$ ($Pot.Int.Th$) is similar to $Int.To$ ($Int.Th$) except that it could not be evolved into $Int.To$ ($Int.Th$) before being reconciled with the already adopted intentions-to (intentions-that).

The following axiom from SharedPlan theory is used later in the paper. It says that if an agent does not believe $p$ is true now, but has an intention that $p$ be true at some future time, it will consider doing some action $\beta$ if it believes the performance of $\beta$ could contribute (either directly or indirectly) to making $p$ true at some time in the future.

AXIOM 1 (FROM [9, 10]). $\forall A, p, t, \beta, t_\beta, t' > t_\beta, C_p \cdot$
$Int.Th(A, p, t, t', C_p) \wedge \neg Bel(A, p, t) \wedge$
$LEAD(A, \beta, p, t_\beta, t, \Theta_\beta) \Rightarrow$
$Pot.Int.To(A, \beta, t, t_\beta, \Theta_\beta \wedge C_p)$*, where*
$LEAD(A, \beta, p, t_\beta, t, \Theta_\beta) \triangleq$
$Bel(A, \exists R_\beta \cdot CBA(A, \beta, R_\beta, t_\beta, \Theta_\beta)), t) \wedge$
$[Bel(A, (Do(A, \beta, t_\beta, \Theta_\beta) \Rightarrow p), t) \vee$
$Bel(A, Do(A, \beta, t_\beta, \Theta_\beta) \Rightarrow [\exists B \in TA, \alpha, R_\alpha, t_\alpha, t'' \cdot$
$(t_\alpha > t_\beta) \wedge CBA(B, \alpha, R_\alpha, t_\alpha, \Theta_\alpha) \wedge$
$(Do(B, \alpha, t_\alpha, \Theta_\alpha) \Rightarrow p) \wedge (t'' < t_\alpha) \wedge$
$Pot.Int.To(B, \alpha, t'', t_\alpha, \Theta_\alpha)], t)]$.

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, belief contradiction 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 in the SharedPlan Framework

Following the idea of "performative-as-attempt" [4, 5], 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. Then, as examples, we define the semantics of $Inform$ and *Request* in terms of attempts, which also validates our approach of encoding "performative-as-attempt" in the SharedPlan framework.

*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 $\epsilon$. 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 $\epsilon$ 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 [6], 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
$P = \exists t_b \cdot (t'' \leq t_b < t_1) \wedge Int.Th(A, Bel(B, Bel(A, I, t'), t_b),$

$t, t_b, C_p)$,
$C_p = Bel(A, I, t) \wedge Bel(A, unaware(B, I, t), t)$.

Here, $t$ is the current time. $t_1$ is the time for *Attempt* and is the deadline for establishing the corresponding mutual belief. $t'$ is the time for $B$ to get $I$.

According to the *speech act* theory [17], 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*) [1] . When the semantics of a performative is defined in terms of an *Attempt*, the argument $\epsilon$ 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.

A request with respect to action $\alpha$ is defined as an attempt of the speaker to make both the speaker and the addressee believe that the speaker intends that the addressee commit to performing the action $\alpha$.

*Definition 3.* $Request(A, B, \alpha, t, t_1, t', C_\alpha) \triangleq Attempt(A, \epsilon,$
$Do(B, \alpha, t', Constr(C_\alpha)),$
$\exists t'' \cdot (t \leq t'' \leq t_1) \wedge MB(\{A, B\}, P, t''), C_p, t, t_1)$, where
$P = \exists t_b < t' \cdot Int.Th(A, Commit(B, \alpha, t_b, t', C_p), t, t_b, C_p)$,
$C_p = Bel(A, \exists R_\alpha \cdot CBA(B, \alpha, R_\alpha, t', Constr(C_\alpha)), t) \wedge$
$Int.Th(A, Do(B, \alpha, t', Constr(C_\alpha)), t, t_1, C_\alpha)$.

That is, the *Request* means that agent $A$ at $t$ has an attempt where (1) the ultimate goal is for $B$ to perform $\alpha$ at $t'$, (2) the honest goal is to adopt an intent to $SEND$ a message to agent $B$, and the result of sending the message will establish a mutual belief that agent $A$ has an intention that agent $B$ commit to performing $\alpha$, all of the above being in the appropriate context.

As with $Inform$, determining the argument for a *Request* type $SEND$ is straightforward. The desired action can be determined from the argument list of the *Request*. The semantics associated with the receipt of such a message, however, are a bit more involved. In addition to realizing that the sender wishes the receiver to commit to the action, the receiver can make certain deductions based upon knowledge of the semantics of a *Request*. In particular, the receiver can deduce that the sender believes that there is a recipe the receiver could be following that would lead the receiver to bring about $\alpha$. If the receiver is not directly aware of such a recipe, it could lead the receiver to initiate a search for an appropriate recipe. Also, note that the *Request* does not indicate which recipe the receiver should follow, only that the sender believes there is one that includes the performance of $\alpha$ by the receiver (not even necessarily for the receiver to know the specific recipe in the beginning). This is sufficient, however, to establish the desired mutual belief, though it does not guarantee that the receiver will actually perform $\alpha$.

We will omit the discussion about $\epsilon$ and $SEND$ in the rest. However, similar versions of $SEND$ can be easily provided for the definitions of other performatives.

# 3. INFORMATION NEEDS

Proactivity is the ability to take initiatives by exhibiting a goal-directed behavior [21]. Agents with proactivity can not only respond to external stimulus timely, they can also deliberate on actions and pre-act for some expected future knowingly. In this paper we will study the proactiveness of team agents by focusing on how communicative acts are proactively chosen as help behaviors.

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. Hence, a theory about proactive information delivery needs to first formally specify the types of information needs that an agent should reason about. We will propose some axiom schemas for anticipating information needs of teammates, intending that each of the schemas specifies a generic constraint on the mental state of the anticipating agent.

We use modal operator $InfoNeed(A, I, t, C_n)$ to denote information needs[2]. It means that agent $A$ needs to know the truth value of information (proposition) $I$ at time $t'$ under the context $C_n$ [3]. Most of the arguments are necessary for obvious reasons. Our choice to include the context $C_n$ deserves some explanation. There are at least two reasons to make the context of information needs explicit. First, making the context of information needs explicit facilitates the conversion from information needs of teammates to intentions to assist them. Second, explicitly capturing the context of information needs enables the context to be included in need-driven communicative actions. Consequently, an agent can subscribe certain information it needs, but only when the context of the information needs remains true.

## 3.1 Anticipate Info Needs of Teammates

[1] $SEND$ may have a sender, receivers, contents, and the time to perform this action as its arguments, say $SEND(A, B, cont, t)$. When the honest goal of the performative under concern is to establish certain mutual belief, the recipe for $SEND$ may be more complicated to involve negotiations, persuasions, etc. Or to simplify this issue, when sincerity and altruism hold, each agent in the team could assume mutual belief can be established by one round of communication: the listeners know that the speaker is intending them to accept the contents being communicated, the speaker is sure the listeners will accept the contents, and both parties know what the other party is wanting.

[2] Information needs (i.e., needs to know) is different from other types of needs, such as needs for certain resources.

[3] 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 $InfoNeed(A, \neg p, t', C_n)$.

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.* 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.* For instance, suppose fighters are responsible for protecting bombers which have a goal of destroying the enemy base. The locations of approaching enemy aircrafts are action-performing information for fighters, because the fighters have to know where the targets are before they fire. The locations of approaching enemy aircrafts are goal-protection information for bombers, since if the bombers are unaware of the approaching enemies, they might be destroyed by the enemies and their mission might become impossible.

We propose two axiom schemas for anticipating these two types of information needs. Axiom 2 specifies action performing information needs, and Axiom 3 specifies goal protection information needs.

Axiom 2 (Action-performing Information Needs).

$\forall A \in TA, B \in TA, I, t, t' \geq t\cdot$
$Bel(A, Int.To(B, \alpha, t, t', C_\alpha), t) \wedge Bel(A, I \in pre(\alpha), t) \wedge$
$[Bel(A, unaware(B, I, t), t) \vee CBel(A, B, I, t)] \Rightarrow$
$Bel(A, InfoNeed(B, I, t', C_n), t)^4$, *where*
$C_n = C_\alpha \wedge Bel(A, I \in pre(\alpha), t) \wedge$
$[CBel(A, B, I, t) \vee Bel(A, unaware(B, I, t), t)]$.

Axiom 2 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 $\alpha$ at time $t'$, (2) $I$ is a component of the precondition of $\alpha$, 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 $C_\alpha$ for $B$'s intention to perform $\alpha$ with $A$'s belief about the fact that $I$ is a piece of the precondition of $\alpha$, 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 $I$.

Axiom 3 (Goal-Protection Information Needs).

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

Axiom 3 states that $A$ believes that agent $B$ will need information $I$ at time $t'$, if lacking information about $I$ enables some agent in an adversary team to take some actions at a time $t_1$ (later than $t'$) to destroy $B$'s goal. The context of the information need consists of the context for agent $B$'s goal, and agent $A$'s anticipating reason for $B$'s information needs: $B$'s unawareness of $I$, or $B$'s awareness of obsolete information about $I$.

Such way of anticipating others' information needs lays the foundation for developing algorithms (e.g., the DIARG algorithm in the CAST multi-agent architecture [22]) for agents to dynamically reason about information needs of their teammates.

Based on Axiom 2, in order for agent $A$ to anticipate agent $B$'s information need regarding information $I$, $A$ needs to know $I$ is a part of the precondition for action $\alpha$ that $B$ intends to do. The question is how to enable an agent to know the preconditions of those actions for which itself is not the doers.

In the SharedPlan theory, it is supposed that a complex action can be decomposed hierarchically. To share a full plan for a complex action $\alpha$ means, all the team members have agreed with each other on some specific full recipe $R_\alpha$ even though each individual might only have a partial view of the full recipe, which means the agents share some information about the recipe like the number of the subactions at the immediate next level, the doer of each subaction, the temporal ordering of those subactions, etc. For instance, suppose a team including agent $A$ and $B$ has achieved a full shared plan for doing action $\alpha$, where agent $B$ commits to subaction $\beta$ in the chosen recipe. $A$ at least has such beliefs: $Bel(A, \exists t', \Theta_\beta \cdot Int.To(B, \beta, t, t', \Theta_\beta), t)$, $Bel(A, \exists R_\beta, \Theta_\beta, t' \cdot CBA(B, \beta, R_\beta, t', \Theta_\beta),\ t)$, and $Bel(A, \exists\rho \cdot \langle\beta, \rho\rangle \in R_\alpha, t)$. However, agent $A$ may not know the detail of the constraints $\Theta_\beta$, which includes the precondition of $\beta$.

This lack of knowledge of preconditions in Shared-Plans is a problem for proactive information exchange. To enable an agent to anticipate action-performing information needs of its teammates, it is critical for other agents as well as the action performers themselves to know the preconditions of actions. Hence, we further assume that upon a team obtaining a full shared plan for a complex action, all the involved agents will know the pre-conditions of all the single agent actions, whether they are the doers or not. This could be done when action bidding is carried out during the phase of parameter identification [9] : to deliver the pre-condition of an action to its teammates when it is bidding for that action.

## 3.2 Anticipate Its Own Information Needs

When agent $A$ and $B$ in Axiom 2 refer to the same agent, it states how an agent can anticipate its own action-performing information needs.

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

When an agent intends to do some action but lack the prerequisite information for doing that action, the agent could wait until some of its teammates helps it out after having anticipated its information needs. Alternatively, an agent may choose to request assistance from teammates proactively. Being aware of its own information needs, an agent may also subscribe its information needs from an information provider.

[4]Here as in the SharedPlan theory, we assume intentions are 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 $t$.

## 3.3 Assist Others' Information Needs

When an agent knows the information needs of its teammates by being informed or by anticipating, it should consider to provide help, and such an attempt should be reflected in its mental state right away.

The following axiom says that, when an agent has realized that another agent might need a certain piece of information, this agent will adopt an attitude of intention-that, in which it chooses "the other's belief about the needed information" as a goal.

AXIOM 4 (PROASSIST). $\forall A, B \in TA, I, t, t' > t \cdot$
$Bel(A, InfoNeed(B, I, t', C_n), t) \Rightarrow$
$[(Bel(A, I, t) \Rightarrow Int.Th(A, Bel(B, I, t'), t, t', C_n))\vee$
$(Bel(A, \neg I, t) \Rightarrow Int.Th(A, Bel(B, \neg I, t'), t, t', C_n))\vee$
$(unaware(A, I, t) \Rightarrow Int.Th(A, aware(B, I, t'), t, t', C_n))]$.

We use $Int.Th$ rather than $Int.To$ in the axiom because $Int.To$ requires the agent to commit to a specific actions to help the needer out, while by adopting an $Int.Th$ towards the needer's awareness of the needed information, the agent has flexibility in choosing whether to help (e.g., when $A$ is too busy), and how to help.

This axiom relates information needs with appropriate intentions-that. Recall that Axiom 1 (the help axiom from the SharedPlan theory) empowers agents to choose appropriate actions to achieve intentions-that. Thus, Axiom 1 and the Axiom 4 together enable an agent to choose appropriate actions to satisfy its own or other's information needs.

Note that $A$ 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 $I$.

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

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.
$Refuse(B, A, I, t, t_1, t', C_n) \triangleq$
$Attempt(B, \epsilon, \psi, \psi, C_n, t, t_1)$,
$RefuseNeed(B, A, I, t, t_1, t', C_n) \triangleq$
$Attempt(B, \epsilon, \phi, \phi, C_n, t, t_1)$, 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)*$ProInform(A, B, I, t_0, t_1, t_3, C_n)\wedge$
$RefuseNeed(B, A, I, t_1, t_2, t_3, C_n) \Rightarrow$
$Bel(A, \neg InfoNeed(B, I, t_3, C_n), t_2)$.

By Axiom 1, Axiom 4 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. $\forall A, B \in TA, I, C_n, t, t' > t,$
$Bel(A, InfoNeed(B, I, t', C_n), t)\wedge Bel(A, I, t)\wedge$
$\neg Bel(A, Bel(B, I, t'), t) \Rightarrow (\exists t_1, t_2 \cdot Pot.Int.To(A,$
$ProInform(A, B, I, t_1, t_2, t', C_n),\ t, t_1, C_n \wedge Bel(A, I, t)))$.

As we explained earlier, without being informed, $A$ could get to know $B$'s information needs by reasoning about $B$'s mental state according to their current shared team plans.

For instance, suppose in a battle-field domain, all the fighters and scouts share the same team recipe *destroy_enemy base*, where the scouts keep searching for the location of the enemy base, and the fighters will move towards the enemy base as soon as they know the location of the enemy base. In this scenario, the scouts could get to know fighters' information needs by checking their shared team recipe and the current status of the fighters in the recipe, and then consider to $ProInform$ the fighters about the enemy base information when it is detected.

# 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 5.* $3PTSubscribe(A, B, C, I, t_1, t_2, t_3, C_n) \triangleq$

$$
\begin{aligned}
&Attempt(A, \epsilon, aware(B, I, t_3),\\
&\exists t'' \cdot (t_1 \le t'' \le t_2) \wedge MB(\{A, C\}, P, t''), C_p, t_1, t_2), \text{ where}\\
&P = \exists t_b \cdot (t'' \le t_b \le t_2) \wedge Int.Th(A,\\
&\quad Bel(C, Bel(A, InfoNeed(B, I, t_3, C_n), t_1), t_b) \wedge\\
&\quad Int.Th(C, \forall t' \le t_3 \cdot BChange(C, I, t') \Rightarrow \exists t_a, t_c \cdot Int.To(C,\\
&\quad ProInform(C, B, I, t_a, t_c, t_3, C_n), t', t_a, C_n), t_b, t_b, C_n), t_1, t_b, C_n),\\
&BChange(C, I, t) \triangleq (Bel(C, I, t) \wedge Bel(C, \neg I, t-1)) \vee\\
&\qquad\qquad (Bel(C, \neg I, t) \wedge Bel(C, I, t-1)) \vee\\
&\qquad\qquad (aware(C, I, t) \wedge unaware(C, I, t-1)),\\
&C_p = Bel(A, InfoNeed(B, I, t_3, C_n), t_1) \wedge\\
&\qquad \neg Bel(A, Bel(C, InfoNeed(B, I, t_3, C_n), t_1), t_1) \wedge\\
&\qquad unaware(A, I, t_1) \wedge Bel(A, aware(C, I, t_1), t_1).
\end{aligned}
$$

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 call these three replies $AcceptSub$, $RejectSub$, and $WeakAcceptSub$ respectively. They are formally defined below.

Let $Q = (\forall t' \leq t_3 \cdot BChange(C, I, t') \Rightarrow \exists t_a, t_c \cdot Int.To(C, ProInform(C, B, I, t_a, t_c, t_3, C_n), t', t_a, C_n))$.

$AcceptSub(C, B, A, I, t_1, t_2, t_3, C_n) \triangleq$
$\quad Attempt(C, \epsilon, \psi, \psi, C_n, t_1, t_2)$, where
$\psi = MB(\{A, C\}, Bel(C, InfoNeed(B, I, t_3, C_n), t_2) \wedge$
$\quad Bel(C, Q, t_2), t_2)$,

$RejectSub(C, B, A, I, t_1, t_2, t_3, C_n) \triangleq$
$\quad Attempt(C, \epsilon, \phi, \phi, C_n, t_1, t_2)$, where
$\phi = MB(\{A, C\}, \neg Bel(C, Q, t_2), t_2)$,

$WeakAcceptSub(C, B, A, I, t_1, t_2, t_3, C_n) \triangleq$
$\quad Attempt(C, \epsilon, \rho, \rho, C_n, t_1, t_2)$, where
$\rho = MB(\{A, C\}, Bel(C, InfoNeed(B, I, t_3, C_n), t_2), t_2)$.

Similar to Theorem 1, An agent could assist its teammates by performing $3PTSubscribe$.

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

The proof is based on the indirect effect of $3PTSubscribe$, which can LEAD to $aware(B,\ I, t')$.

In addition to $3PTSubscribe$, there are at least two other ways a third-party agent ($A$) can assist a team member ($B$) with its information needs: (1) *Ask-ProInform*: agent $A$ asks agent $C$, then pro-informs agent $B$ upon receiving $I$ from $C$, (2) *request-inform*: agent $A$ requests agent $C$ to $Inform$ $I$ to agent $B$ directly (by composing *request* and $inform$ together).

In the *ask-ProInform* approach, agent $A$ needs to perform two communicative actions. The benefit is that $A$ can also obtain information $I$ during the process. While in the second approach, agent $A$ only needs to perform one communicative action. The drawback is that agent $A$ cannot obtain the information $I$.

An agent's choice between these two approaches and the acts mentioned earlier (i.e., *Inform-InfoNeed* and *3PTSubscribe*) could depend on the nature of the needed information. For instance, if the information needed is static, *request-inform* is better than $3PTSubscribe$, because the former relieves the information providing agent ($C$) from monitoring $I$ for detecting changes.

# 6. CONVERSATION POLICIES

Intentional semantics of performatives is desirable because human's choice of commitments to communicative acts really involves reasoning about the beliefs, intentions, and abilities of other agents. However, reliable logical reasoning about the private beliefs and goals of others is technically extremely difficult, and in practice, agent systems typically employ various assumptions to simply this issue [8].

One promising approach is to characterize the semantics of performatives in terms of protocols or conversation policies. Conversation policies are publicly shared, abstract, combinatorial, and normative constraints on the potentially unbounded universe of semantically coherent message sequences [8]. Conversation policies make it easier for the agents involved in a conversation to model and reason about each other, and restrict agents' attention to a smaller (otherwise maybe larger) set of possible responses.

Since intentional semantics is not enough, one important issue is how to design protocols or policies with regard to *proactive* performatives based on their intentional semantics. Ideally, the conversation policies should be able to enhance team intelligence concerning about others' information needs by considering the flow of information needs as well as information itself.

We first consider $ProInform$. Suppose agent $A$ initiates $ProInform$ to agent $B$ about information $I$ that $A$ believes $B$ will need. The policy shown in Figure 1 (represented as Petri-Net) covers the possible conversation sessions between agents $A$ and $B$.

For instance, the following is a possible conversation between $A$ and $B$:

A: ProInform I to B
B: RefuseNeed to A
A: Query B about whether B knows some knowledge K that links I to B's needs (A may infer that K is a consequence of I, but B cannot for lack of information or reasoning capability).
B: Replies No
A: ProInform K to B
...

We now consider third-party subscribe, where an agent helps an information needer by subscribing services from a potential information provider. Figure 2 is a possible reification of the conversation policy involving $3PTSubscribe$. For instance, according to the policy, a conversation may looks like :

A: choose an addressee C
(A knows C is a potential provider)
A: Subscribe I from C on behalf of B
(A expects C to satisfy B as much as possible)
C: RejectSub to A
A: Revise info about C
(C made no commitment to help B)
A: Query C about whether C could acquire I
C: Reply Yes
A: Revise info about B's needs (B does not need I)

Typically, conversation policies and computational models of communication behavior are separated so that agents using different computational models (e.g., DFA, CPN, entailment based models, etc.) could cooperate with each other, as long as they have common policies governing their conversation [8]. One benefit of using transition net models, such

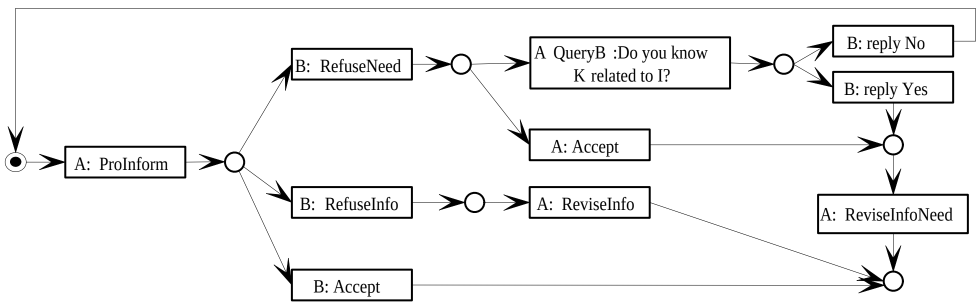


**Figure 1: A conversation policy involving $ProInform$ regarding information $I$**

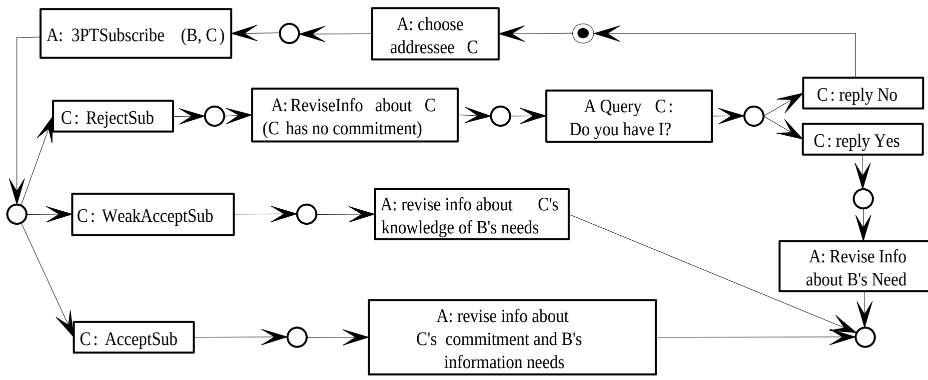


**Figure 2: A conversation policy involving $3PTSubscribe$**

as the Petri-nets model used here, is that agents with the same transition-net representations of conversation policies could track each other's progress in a conversation session.

# 7. COMPARISON AND DISCUSSION

## 7.1 Comparison

As mentioned earlier, we are not proposing a complete ACL that covers the seven categories of communicative acts (assertives, directives, commissives, permissives, prohibitives, declaratives, expressives) [18]. 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. Even though the motivations are different, the way of defining semantics for performatives in this paper shares the same origin with the other approaches in literature.

We can trace the origin of speech acts to the work of Austin [1], which was extended by Searle in [16]. In [5], Cohen and Levesque modeled speech acts as actions of rational agents in their framework of intentions. Henceforward, several agent communication languages were proposed, such as Arcol [3], KQML [13], and FIPA's ACL (<http://www.fipa.org/>). The formal semantics of the performatives in these languages are all framed in terms of mental attitudes. More recently, social agency is more emphasized than mental agency due to the fact that communication is inherently public, and depends on agents' social context. Society-based [18] or protocol (conversation)-based [14, 12] approaches were proposed as a complement to mental agency.

A common element of the approaches mentioned above and the approach adopted in this paper is the strictly declarative semantics of performatives. For example, Arcol uses performance conditions to specify the semantics of communicative acts. KQML adopts a more operational approach by using preconditions, postconditions and completion conditions. FIPA ACL is heavily influenced by Arcol. The semantics of performatives in FIPA ACL are specified by feasibility preconditions and rational effect, both of which are formulas of a semantic language SL. Similarly, the semantics of proactive performatives proposed in this paper also draws heavily on Cohen's work.

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. In Arcol, if agent $A$ is informed that agent $B$ needs some information, $A$ would supply that information as if $B$ had requested it by reducing the explicit $inform$ to implicit $request$. While this is achieved in our approach by first reasoning about the relevant information needs, and then choosing appropriate help behaviors.

Our definition of $ProInform$ (proactive inform) is comparable with *tell* in KQML, although they are not equivalent *per se*. Both *tell* and $ProInform$ require that an agent cannot offer unsolicited information to another agent. The modal operator $WANT$ in KQML, which stands for the psychological states of desire, plays the same role as $InfoNeed$. The semantics of $WANT$ is left open for generality, while $InfoNeed$ is proposed to explicitly express information needs under certain context.

Both $3PTSubscribe$ and *broker_one* in KQML involve three parties (they have different semantics, though). However, $3PTSubscribe$ is initiated by a broker agent, while *broker_one* is not. Consequently, the speaker of *3PTSubscribe* needs to know the other two parties, while the speaker of *broker_one* only needs to know the broker agent. Such difference results from the fact that we are focusing on proactive information delivery by anticipating information needs of teammates, while KQML is more concerned about achieving a complete ACL. In our approach, if an agent does not know any information provider of information $I$, it could wait until some potential provider has anticipated its needs. Acting more proactively by itself, the needer could alternatively $publish$ (not included here for space limit) its needs to certain facilitator in its team. The facilitator then could initiate a $request$ (involving three parties) to some known provider. Hence, the semantics of $broker\_one(A, B, ask\_if$ $(A, -, X))$ [13] can be simulated by $publish$ and $request$. However, the semantics of $3PTSubscribe$ cannot be easily simulated in KQML.

Secondly, the semantics of $ProInform$ and $3PTSubscribe$ adopt a richer notion of context than those offered by existing approaches. As noted in [18], 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 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.

There are many other works related to communications in teamwork settings. Tambe adopted a hybrid approach in implementing the communication mechanisms for STEAM [20]. In STEAM, Communication is mainly raised (implicitly) from the prescriptions of joint intentions, while additional communication is generated by checking the explicit declaration of information-dependency relationships among domain actions. Our work in this paper, however, is focusing on the semantics of the communicative acts related to proactive assistance for teammates' information needs.

In [19], a communication paradigm was proposed for periodic team synchronization (PTS) domains with a single, unreliable, low-bandwidth communication channel for agents that might belong to adversary teams. They are more concerned about dynamic team formation in a class of PTS domains. In this paper, we assume that communication is reliable, and focus on the semantics of communication acts, and how they are adopted as help behaviors in supporting team activities. The treatment of communication acts as help behaviors is useful in dynamic team formations.

## 7.2 Discussion

It is now widely recognized within the agent community that there are fundamental limitations on only using mental attitudes to formalize the semantics of performatives, and thus protocol (conversation)-based [14, 8, 12] or society-based [18] approaches were proposed as a complement. The limitations of mental agency have three-fold. (1) It's questionable that agents should be understood primarily in terms of mental concepts. Lots of agents are modeled and implemented without any notions of beliefs and intentions. It's hard to build heterogeneous agent teams, since mental agency supposes that agents can read each other's minds [18]. (2) It's unlikely that a single set of axioms will cover all eventualities because communication is inherently context-dependent [14]. (3) The formalism using mental agency must deal with the revision or updating of mental state, which is intractable in general [2].

However, pointing out the drawbacks of mental agency, Singh did admit that explicit representation of mental state is necessary, but more emphasizing on social agency (protocols), where communicative acts are taken as part of an ongoing social interaction rather than individual actions [18]. The formalism in this paper is based on the SharedPlan theory, but it's not purely in terms of intentions and beliefs. The semantics help to lay foundations of communication protocols to support proactive teamwork. The protocols based on the semantics of proactive performatives are useful in analyzing and understanding the proactive information flows at different abstract levels in teamwork settings.

The semantics of performatives is not purely in terms of mental attitudes, either. Since a communicative act will ultimately be performed in certain conversation session or social context, a special parameter ($C_n$ or $C_\alpha$) is hooked up to the semantics of *Attempt* and performatives. Such contexts could be composed of other conversation-related social constraints , as well as those mental attitudes explicitly specified in the currently definitions.

As for the second limitation, we are not attempting to give a complete set of axioms to cover all eventualities. Our modest intention is to extend the SharedPlan theory with communication-related axioms. This is an important step to facilitate the establishment of mutual beliefs and intentions-that [9], and in the future, to fully understand how need-driven communications impact team performance.

In practical teamwork settings, an agent usually can infer what another agent does not know based on its prior beliefs about that agent's observability. Hence, the third issue could be simplified by allowing an agent to infer its teammates' belief from their sensing abilities.

It may be argued that in many if not all practical real-life settings, the agents are not so much interested in convincing the other party but in conveying the necessary information to the other party. Surely, it's not necessary to convince the other party if what that agent needs is just static information. This could be avoided by distinguishing information types. However, oftentimes, information needs has long term value, especially when the relevant information is changing dynamically. To be convinced that another agent has a piece of information needs, an agent will have a persistent commitment to that agent. Actually, one of the key features of the proposed performatives is that they not only initiate information flows, but also enable the flow of information needs.

# 8. CONCLUDING REMARKS

Based on overlapping shared mental models, members of an effective human team can often anticipate information needs of teammates and offer relevant information proactively. Agents empowered with such shared mental models can be used to better simulate, train, or support human teams in their information fusion and decision making.

In this paper we proposed axioms for anticipating the information needs of teammates based on shared team knowledge such as shared team process and joint goals, and defined the semantics of $ProInform$ and $3PTSubscribe$ based on the speaker's awareness of the information needs of teammates. $3PTSubscribe$ formally specifies the semantics of "subscribe" action through a broker agent, which plays an important role in agent infrastructure such as Grid [11], developed under DARPA's CoABS program. However, instead of focusing on the semantics of performatives, we are more concerned about information needs and how to enable proactive information flows among teammates by reasoning about information needs. One of our ongoing work is to understand how need-driven communications impact team performance.

The framework in this paper not only serves 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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