Proactive Communications in Agent Teamwork

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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. To establish a theory about proactive information exchanges, we first introduces the concept of "information-needs", then identify and formally define the intentional semantics of two proactive communicative acts, which highly depend on the speaker's awareness of others' information-needs. It is shown that communications using these proactive performatives can be derived as helping behaviors. Conversation policies involving these proactive performatives are also discussed. The work in this paper may serve as a guide for the specification and design of agent architectures, algorithms, and applications that support proactive communications in agent teamwork.

1 Introduction

Passive communications (i.e., ask/reply) are prevalently used in existing distributed systems. Although the ask/reply approach is useful and necessary in many cases, it exposes several limitations, where proactive approach may come into play. For instance, an information consumer may not realize certain information it has is already out of date. If this agent needs to verify the validity of every piece of information before they are used (e.g., for decision-making), the team can be easily overwhelmed by the amount of communications entailed by these verification messages. Proactive information delivery by the information source agents offers an alternative, and it shifts the burden of updating information from the information consumer to the information provider, who has direct knowledge about the changes of information. In addition, an agent itself may not realize it needs certain information due to its limited knowledge (e.g., distributed expertise). For instance, a piece of information may be obtained only through a chain of inferences (e.g., being fused according to certain domain-related rules). If the agent does not have all the knowledge needed to make such a chain of inferences, it will not be able to know it needs the information, not to mention requesting for it. Proactive information delivery can allow teammates to assist the agent under such a circumstance.

In fact, to overcome the abovementioned limitations of "ask", many human teams incorporate proactive information delivery in their planning. In particular, 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 [1]. We believe this type of approaches developed by human teams provides critical evidence for software agents to be also equipped with proactive information delivery capabilities.

Even though several formal theories on agent teamwork have been proposed, they do not directly address issues regarding proactive information exchange among agents in a team. To do this, "information-needs" should be treated as first-class objects, the intentional semantics of acts used in proactive communications need to be formally defined, and agents should be committed to these acts as helping behaviors under appropriate contexts.

The rest of this paper is organized as follows. 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 section 4 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 in section 5. Section 6 devotes to comparison and section 7 concludes the paper.

2 Preparation

We use $\alpha, \beta, \gamma \cdots$ to refer to actions. An action is either primitive or complex. The execution of a complex action relies on some recipe, i.e., the *know-how* information regarding the action. A recipe is composed of an action expression and a set of constraints on the action expression. Action expressions 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. Thus, a recipe for a complex action γ is actually 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.

Appropriate functions are defined to return certain properties associated with an action. In particular, $pre(\alpha)$ and $post(\alpha)$ return a conjunction of predicates that describe the preconditions and effects of α, respectively. By $I \in pre(\alpha)$ we mean I is a conjunct of $pre(\alpha)$.

We adopt the SharedPlan theory [2, 3] as the cornerstone of our framework. Thus, all actions will be intended, committed and performed in some specific context. By convention, 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.

Bel and MB are standard modal operators for belief and mutual belief, respectively. Three modal operators in the SharedPlan theory are used to relate agents and actions: $Do(G, \alpha, t, \Theta)$ is used to denote that G (a group of agents or a single agent) performs action α at t under constraints Θ; $Commit(A, \alpha, t_1, t_2, C_\alpha)$ represents the commitment of agent A at t_1 to perform the basic-level action α at t_2 under the context C_α; and $Exec(A, \alpha, t, \Theta)$ is used to represent the fact that agent A has the ability to perform basic-level action α at time t under constraints Θ. Four types of intentional attitudes were defined. $Int.To(A, \alpha, t, t_\alpha, C_\alpha)$ means agent A at t intends to do α at t_α in the context C_α; $Int.Th(A, p, t, t', C_p)$ means agent A at t intends that p hold at t' under the context C_p. $Pot.Int.To$ and $Pot.Int.Th$ are used for *potential* intentions. They are similar to normal intentions (i.e., $Int.To$ and $Int.Th$) except that before really adopting them, the agent has to reconcile the potential conflicts that may be introduced by the potential intentions to the existing intentions. Meta-predicate $CBA(A, \alpha, R_\alpha, t_\alpha, \Theta)$ means agent A at t_α can bring about action α by following recipe R_α under constraints Θ.

Grosz and Kraus proposed several axioms for deriving helpful behaviors [2, 3]. The following one simplifies the axiom in [3] without considering the case of multiple-agent actions (we assume communicative acts to be examined are single-agent actions) and the case of action-intention conflicts.

Axiom 1 $\forall A, p, t, \beta, t_\beta, t' > t_\beta, C_p \cdot$
$Int.th(A, p, t, t', C_p) \wedge \neg Bel(A, p, t) \wedge\ lead(A, \beta, p, t, t_\beta, \Theta_\beta) \Rightarrow$
$\quad Pot.Int.To(A, \beta, t, t_\beta, \Theta_\beta \wedge C_p),\ where$
$lead(A, \beta, p, t, t_\beta, \Theta_\beta) \triangleq Bel(A, \exists R_\beta \cdot CBA(A, \beta, R_\beta, t_\beta, \Theta_\beta)), t) \wedge$
$\quad [Bel(A, (Do(A, \beta, t_\beta, \Theta_\beta) \Rightarrow p), t) \vee\ Bel(A, Do(A, \beta, t_\beta, \Theta_\beta) \Rightarrow$
$\quad\quad [\exists B, \alpha, R_\alpha, t_\alpha, t'' \cdot\ (t_\alpha > t_\beta) \wedge (t_\alpha > t'') \wedge CBA(B, \alpha, R_\alpha, t_\alpha, \Theta_\alpha) \wedge$
$\quad\quad\quad Pot.Int.To(B, \alpha, t'', t_\alpha, \Theta_\alpha) \wedge\ (Do(B, \alpha, t_\alpha, \Theta_\alpha) \Rightarrow p)], t)].$

Axiom 1 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 β if it believes the performance of β could contribute to making p true either directly or indirectly through the performance of another action by another agent.

$Hold(p, t)$ is used to represent the fact that p is true at time t. Note that $Hold$ is external to any rational agents. It presupposes an omniscient perspective from which to evaluate p. On the other hand, assume there exists an omniscient agent G, then $Hold(p, t) = Bel(G, p, t)$. $Hold$ will be used only within belief contexts, say $Bel(A, Hold(p, t), t)$, which means agent A believes from the omniscient's perspective p is true. Since omniscient is always trustable, $Bel(A, Hold(p, t), t) \Rightarrow Bel(A, p, t)$, but not vice versa.

We define some abbreviations needed later. Awareness ($aware$)[3], belief contradiction ($CBel$) between two agents (from one agent's point of view), and

[3] We assume belief bases allow three truth values for propositions.

wrong beliefs ($WBel$) are given as:

$$\begin{aligned} aware(A,p,t) &\triangleq Bel(A,p,t) \vee Bel(A,\neg p,t), \\ unaware(A,p,t) &\triangleq \neg aware(A,p,t), \\ CBel(A,B,p,t) &\triangleq (Bel(A,p,t) \wedge Bel(A,Bel(B,\neg p,t),t)) \vee \\ &\quad (Bel(A,\neg p,t) \wedge Bel(A,Bel(B,p,t),t)), \\ WBel(A,p,t) &\triangleq (Hold(p,t) \wedge Bel(A,\neg p,t)) \vee (Hold(\neg p,t) \wedge Bel(A,p,t)). \end{aligned}$$

In the following, let TA be an agent team with finite members. The proposal put forward in the SharedPlans theory is to identify potential choices of action (ultimately represented in terms of a *Pot.Int.To*) as those which would reduce the cost or the resources required to perform actions intended by a teammate. For the purpose of this paper, we will only focus on barriers to actions rooted in lack of information regarding the preconditions of the actions.

2.1 Reformulate Performative-As-Attempt

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, the semantics of $Inform$ and $Request$ are given in terms of attempts, which serves partially to validate our approach of encoding "performative-as-attempt" in the SharedPlan framework.

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

Here, P represents some ultimate goal that may or may not be achieved by the attempt, while Q represents what it takes to make an honest effort. The agent has only a limited commitment (potential intention) to the ultimate goal P, while it has a full-fledged intention to achieve Q. More specifically, if the attempt does not achieve the goal P, the agent may retry the attempt, or try some other strategy or even drop the goal. However, if the attempt does not succeed in achieving the honest effort Q, the agent is committed to retrying (e.g., performing ϵ again) until either it is achieved (A comes to believe P) or it becomes unachievable (t' comes) or irrelevant (the escape condition C_n no longer holds)[4, 6]. Thus, the *Attempt* would actually be an intent to achieve Q by performing ϵ while the underlying intent was to achieve P. Of course, P and Q may refer to the same formula.

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 for A, $MB(\{A,B\},Bel(B,$ $Bel(A,I,t),t'))$ (Q in this case) can be achieved by exchanging appropriate messages with B. In case of communication failure in establishing the mutual belief, A will retry until either the mutual belief is achieved or C_n no longer holds or the deadline t_1 comes. Here ϵ may refer to a sequence of *send*, the act of wrapping the message in a wire language and physically sending it. When communication is reliable and sincerity is assumed, one *send* may suffice.

According to the *speech act* theory [7], every speech act has an utterance event associated with it. For the purpose of this paper, we simply assume all the utterance events are single-agent complex actions, for which each agent has full individual recipes. For instance, when the honest goal of a performative is to establish certain mutual beliefs, the recipe for the corresponding ϵ may involve negotiations, persuasions, failure-handling, etc.

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 [8], 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. $Inform(A, B, \epsilon, p, t, t_a) \triangleq (t < t_a)?; Attempt(A, \epsilon, MB(\{A, B\}, p, t_a),\ \exists t'' \cdot (t \leq t'' < t_a) \wedge MB(\{A, B\}, \psi, t''), C_p, t, t_a)$, *where* $\psi = \exists t_b \cdot (t'' \leq t_b < t_a) \wedge Int.Th(A, Bel(B, Bel(A, p, t), t_b),\ t, t_b, C_p)$, $C_p = Bel(A, p, t) \wedge Bel(A, unaware(B, p, t), t)$.

When communication is reliable and agents trust each other, it's easy to establish the mutual belief about ψ required in the honest goal of $Inform$: agent B believes ψ upon receiving a message with content ψ from agent A; and A knows this, and B knows A knows this, and so on.

A request with respect to action α 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 α [5].

Definition 3. $Request(A, B, \epsilon, \alpha, t, t_a, \Theta_\alpha) \triangleq (t < t_a)?; Attempt(A, \epsilon, Do(B, \alpha, t_a, \Theta_\alpha),\ \exists t'' \cdot (t \leq t'' < t_a) \wedge MB(\{A, B\}, \psi, t''), C_p, t, t_a)$, *where* $\psi = \exists t_b < t_a \cdot Int.Th(A, Int.To(B, \alpha, t_b, t_a, C_p), t, t_b, C_p)$, $C_p = Bel(A, \exists R_\alpha \cdot CBA(B, \alpha, R_\alpha, t_a, \Theta_\alpha), t) \wedge Int.Th(A, Do(B, \alpha, t_a, \Theta_\alpha), t, t_a, \Theta_\alpha)$.

The *Request* means that agent A at t has an attempt where (1) the ultimate goal is for B to perform α at t_a, and (2) the honest goal is to establish a mutual belief that agent A has an intention that agent B commit to performing α, all of the above being in appropriate contexts.

According to the definition, agent A would be under no obligation to inform B that its request is no longer valid when A discovers that C_n on longer holds. In [9] Smith and Cohen defined another version of *Request* in terms of a $PWAG$ (persistent weak achievement goal) rather than an intention. That means, upon discovering that the goal has been achieved or become impossible, or that C_p is on longer true, agent A will be left with a persistent goal to reach mutual belief with B, which will free B from the commitment towards A regarding α. Rather than introducing a counterpart of $PWAG$ into the SharedPlan framework, we prefer to encode such team-level obligations using an axiomization approach by introducing an axiom stating that any agent intending others to be involved in a team activity should also adopt an intention to release those agents from the obligations whenever the intentional context no longer holds. The axiom is omitted here for space limit.

The semantics associated with the receipt of a *Request* is a bit involved. In addition to realizing that the sender wishes him/her to commit to the action, the receiver can make certain deductions based upon knowledge of the semantics of *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 α. Note that the *Request* does not indicate which recipe the receiver should follow, only that the sender believes there exists one. This is sufficient, though it does not guarantee that the receiver will actually perform α. If the receiver is not directly aware of such a recipe, it could lead the receiver to initiate a search for an appropriate recipe. If the receiver cannot find one as the sender expected, the receiver can discharge himself from the obligation and letting the sender know the reason.

3 Information Needs

For any predicate symbol p with arity n, it will be written in the form $p(\boldsymbol{?x}, \boldsymbol{c})$, where $\boldsymbol{?x}$ is a set of variables, $\boldsymbol{c}$ is a set of constants in appropriate domains, and the sum of the sizes of the two sets is n. We start with the identifying reference expression (IRE), which is used to identify objects in appropriate domain of discourse[10]. IRE is written using one of three referential operators defined in FIPA specification. $(iota\ \boldsymbol{?x}\ p(\boldsymbol{?x}, \boldsymbol{c}))$ refers to "the collection of objects, which maps one-to-one to $\boldsymbol{?x}$ and there is no other solution, such that p is true of the objects"; it is undefined if for any variable in $\boldsymbol{?x}$ no object or more than one object can satisfy p (together with substitutions for other variables). $(all\ \boldsymbol{?x}\ p(\boldsymbol{?x}, \boldsymbol{c}))$ refers to "the collection of sets of all objects that satisfy p, each set (could be an empty set) corresponds one-to-one to a variable in $\boldsymbol{?x}$". $(any\ \boldsymbol{?x}\ p(\boldsymbol{?x}, \boldsymbol{c}))$ refers to "any collection of objects, which maps one-to-one to $\boldsymbol{?x}$, such that p is true of the objects"; it is undefined if for any variable in $\boldsymbol{?x}$ no object can satisfies p (together with substitutions for other variables). We will omit operator *any* if possible. Hence, expressions of form $(any\ \boldsymbol{?x}\ p(\boldsymbol{?x}, \boldsymbol{c}))$ can be simplified as $p(\boldsymbol{?x}, \boldsymbol{c})$.

Information is defined in WordNet Dictionary as a message received and understood that reduces the recipient's uncertainty. We adopt the definition prescribed in the Open Archival Information System (OAIS) [11]: information is "any type of knowledge that can be exchanged, and it is always represented by some type of data". Throughout this paper, we deal with two types of information: factual information and referential information. Factual information is represented as a proposition (predicate with constant arguments), and referential information is represented in terms of a special predicate $Refer(ire, obj)$, where

ire is an identifying reference expression, and obj is the result of the reference expression ire evaluated with respect to a certain theory.

In the following we will use I to represent the information to be communicated: when I refers to a proposition, the sender is informing the receivers that the predicate is true; when I refers to $Refer(ire, obj)$, the sender is informing the receivers that those objects in obj are what satisfy ire evaluated with respect to the sender's belief base.

Now we come to the concept of information-needs. An information-need may state that the agent needs to know the truth value of a proposition. For instance, suppose a person sends a query $Weather(Cloudy, Today)$ to a weather station. The weather station will realize that the person want to know, at least literally, whether today is cloudy [4]. More often than not, an agent wants to know the values of some arguments of a predicate, where the values could trusify the predicate. For example, a person may send a query $Weather(?x, Today)$ to a weather station, this will trigger the weather station, if it's benevolent, to inform the person about the (change of) weather conditions whenever necessary.

Thus, corresponding to information, an expression for information-needs may also be in one of two forms: described either as a proposition, or as a reference expression. In what follows N is used to refer to a (information) need-expression, $pos(N)$ ($ref(N)$) is true if N is a proposition (reference expression). An information-need consists of a need-expression, an information consumer (needer), an expiry time after which the needs is no longer applicable, and a context only under which the needs is valid. To combine them together, we introduce a modal operator $InfoNeed(A, N, t, C_n)$ to denote information-needs. In case that N is a proposition, it means that agent A needs to know the truth value of N by t under the context C_n[5]; in case that N is a reference expression, it means agent A needs to know those objects satisfying the reference expression N. Making the context of information-needs explicit not only facilitates the conversion from information-needs of teammates to intentions to assist them, but also enables the context to be included in need-driven communicative actions. The properties of $InfoNeed$ are omitted here.

The most challenging issue in enabling agents to proactively deliver information to teammates is for them to know the information-needs of teammates. Agents can subscribe their information-needs from other teammates. In this paper however, we will focus on how to *anticipate* potential information-needs based on the SharedPlans theory.

3.1 Anticipate Information-Needs of Teammates

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

[4] Refer to [12] for indirect speech acts.

[5] In such cases, $InfoNeed(A, p, t, C_n)$ is equivalent to $InfoNeed(A, \neg p, t, C_n)$.

information-need allows an agent to discharge itself from a chosen goal. Knowing such information will help an agent to give up achieving an impossible or irrelevant goal. Thus, we call this type of information-need *goal-escape information-need*. We first define a generated set. For any action α, let $Needs(\alpha)$ be a set of need-expressions generated from $pre(\alpha)$:
1. $p \in Needs(\alpha)$, if $p \in pre(\alpha)$ is a proposition;
2. $(any\ \boldsymbol{?x}\ p(\boldsymbol{?x})) \in Needs(\alpha)$, if $p \in pre(\alpha)$ is of form $p(\boldsymbol{?x})$ [6].

Axiom 2 (Action-performing Information-Need)
$\forall A, B \in TA, \alpha, C_\alpha, t, t' \geq t \forall N \in Needs(\alpha) \cdot$
$Bel(A, Pot.Int.To(B, \alpha, t, t', C_\alpha), t) \Rightarrow Bel(A, InfoNeed(B, N, t', C_n), t)$*, where* $C_n = C_\alpha \wedge Pot.Int.To(B, \alpha, t, t', C_\alpha)$.

Axiom 2 characterizes action performing information-needs, which states that agent A believes that agent B will need information described by N by t' under the context C_n, if A believes that B is potentially intending to perform action α at time t'. The context C_n of the information-need consists of C_α and B's potential intention to perform α.

Lemma 1. $\forall A, B \in TA, \phi, \alpha, C_\phi, \Theta_\alpha, t, t' \geq t, t'' \geq t' \forall N \in Needs(\alpha) \cdot$
$Bel(A, Int.Th(B, \phi, t, t'', C_\phi), t) \wedge$ $Bel(A, \neg Bel(B, \phi, t), t) \wedge$
$Bel(A, Lead(B, \alpha, \phi, t', t, \Theta_\alpha), t) \Rightarrow \exists C_n \cdot Bel(A, InfoNeed(B, N, t', C_n), t)$.

Proof. Follows directly from axiom 1 and 2.

Similarly, let $Needs(C)$ be the generated set of need-expressions from a set C of predicates. Axiom 3 specifies goal-escape information-needs.

Axiom 3 (Goal-escape Information-Need)
$\forall A, B \in TA, \phi, C_\phi, t, t' \geq t \forall N \in Needs(C_\phi) \cdot$
$Bel(A, Int.Th(B, \phi, t, t', C_\phi), t) \Rightarrow Bel(A, InfoNeed(B, N, t', C_n), t)$*, where* $C_n = C_\phi \wedge Int.Th(B, \phi, t, t', C_\phi)$.

Axiom 3 states that if agent A believes that agent B has a goal towards ϕ, it will assume B will need information described by N, which is generated from the context of B's intention. The context of the information-need consists of C_ϕ and B's intention.

By reflection, a rational agent should be able to know its own information-needs when it intends to do some action but lacks the pre-requisite information. In case that A and B in Axiom 2 and 3 refer to the same agent, they state how an agent can anticipate its own information-needs. Being aware of its own information-needs, an agent could subscribe its information-needs from an information provider.

[6] Depending on domains, need-expressions of the form $(iota\ \boldsymbol{?x}\ p(\boldsymbol{?x}))$ or $(all\ \boldsymbol{?x}\ p(\boldsymbol{?x}))$ can also be generated. For instance, if α is a joint action where some doer should be exclusively identified, *iota* expression is preferred. *all* expression is suitable if all objects substitutable for variables in $\boldsymbol{?x}$ will be needed in the performance of α.

3.2 Assist Others' Information Needs

When an agent knows the information-needs of its teammates by being informed or by anticipating, it will consider providing help.

Let B_A be the belief base of agent A, and $\mathsf{B}_A \models p$ means p is a logical consequence of B_A. For any agent A and need-expression N, function $info(A, N)$ returns the information with respect to N evaluated by A:

$$info(A,N) \triangleq \begin{cases} N & \text{if } \mathsf{B}_A \models N, \text{ and } N \text{ is a proposition,} \\ \neg N & \text{if } \mathsf{B}_A \models \neg N, \text{ and } N \text{ is a proposition,} \\ Refer(N,Q) & \text{if } N = (iota\ \boldsymbol{?x}\ p(\boldsymbol{?x})), \\ & Q \in \Sigma = \{\theta \cdot \boldsymbol{?x} : \mathsf{B}_A \models \theta \cdot p, \theta \text{ is most general} \\ & \ \text{substitution (mgs)}\}, \text{ and } \Sigma \text{ is singleton,} \\ Refer(N,Q) & \text{if } N = (any\ \boldsymbol{?x}\ p(\boldsymbol{?x})), \\ & Q \in \Sigma = \{\theta \cdot \boldsymbol{?x} : \mathsf{B}_A \models \theta \cdot p, \theta \text{ is mgs}\} \neq \emptyset, \\ Refer(N,\Sigma) & \text{if } N = (all\ \boldsymbol{?x}\ p(\boldsymbol{?x})), \\ & \Sigma = \{\theta \cdot \boldsymbol{?x} : \mathsf{B}_A \models \theta \cdot p, \theta \text{ is mgs}\}, \end{cases}$$

$info(A, N)$ is undefined in case that N is a proposition, but neither $\mathsf{B}_A \models N$ nor $\mathsf{B}_A \models \neg N$; or in case that $N = (any\ \boldsymbol{?x}\ p(\boldsymbol{?x}))$ but $\Sigma = \emptyset$; or in case that $N = (iota\ \boldsymbol{?x}\ p(\boldsymbol{?x}))$ but Σ is not a singleton. In case that $N = (any\ \boldsymbol{?x}\ p(\boldsymbol{?x}))$ and $|\Sigma| > 1$, a randomly selected element of Σ is returned. We use $defined(info(A, N))$ to denote $info(A, N)$ is defined.

The following axiom says that, when an agent comes to know another agent's information needs, it will adopt an attitude of intention-that towards "the other's belief about the needed information".

Axiom 4 (ProAssist) $\forall A, B \in TA, N, C_n, t, t' > t\cdot$
$Bel(A, InfoNeed(B, N, t', C_n), t) \Rightarrow$
$[defined(info(A, N)) \Rightarrow Int.Th(A, Bel(B, info(A, N), t'), t, t', C_n) \vee$
$(\neg defined(info(A, N)) \wedge pos(N)) \Rightarrow Int.Th(A, aware(B, N, t'), t, t', C_n)]$.

We use $Int.Th$ rather than $Int.To$ in the axiom because $Int.To$ requires the agent adopt a specific action to help the needer, while $Int.Th$ offers the agent with the 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. 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 appropriate intentions.

4 Proactive Communication Acts

4.1 Proactive-Inform

$ProInform$ (Proactive Inform) is defined by extending 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.

Definition 4. $ProInform(A, B, \epsilon, I, N, t, t_a, t', C_n) \triangleq [(t_a < t') \wedge (I = info(A, N))]?;$
$Attempt(A, \epsilon, Bel(B, I, t'), \exists t'' \cdot (t \leq t'' < t_a) \wedge MB(\{A, B\}, \psi, t''), C_p, t, t_a)$, *where*
$\psi = \exists t_b \cdot (t'' \leq t_b < t_a) \wedge Int.Th(A, Bel(B, Bel(A, I, t) \wedge$
$Bel(A, InfoNeed(B, N, t', C_n), t), t_b), t, t_b, C_p)$,
$C_p = C_n \wedge Bel(A, I, t) \wedge (I = info(A, N)) \wedge Bel(A, InfoNeed(B, N, t', C_n), t) \wedge$
$[pos(N) \Rightarrow Bel(A, unaware(B, I, t), t) \vee CBel(A, B, I, t)]$.

Notice that $t_a < t'$, which ensures the $ProInform$ is adopted to satisfy other's information needs in the future. Also, the context of information-need is included as an argument of $ProInform$. This context serves in the context (C_p) of the speaker's goal (i.e., intention) to let the addressee know the information. C_p justifies 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 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 choice of explicitly including the context of information-needs in $InfoNeed$.

The semantics of $ProInform$ has direct impacts on the receivers. By accepting $ProInform$, the addressee attempts to confirm the informing agent that it believed the information being communicated at the beginning of the attempt:

$$Accept(B, A, \epsilon, I, N, t, t_a, t', C_n) \triangleq Attempt(B, \epsilon, \psi, \phi, C_n, t, t_a),$$

where $\psi = MB(\{A, B\}, Bel(B, I, t'), t')$, $\phi = MB(\{A, B\}, Bel(B, I, t), t_a)$.

Since the ultimate goal of $ProInform$ is to let the addressee believe I at t', the ultimate goal of *Accept* is also set to establish a mutual belief about I at t'. Neither may be achievable, because I may change between t and t' for both $ProInform$ and *Accept* (In such a case, another $ProInform$ may be adopted). In case that I persists until t', the assumption of persistent beliefs will guarantee the addressee's information-need be satisfied.

The addressee may reject a $ProInform$ because (1) it knows something different from the information received, or (2) it does not think the information is needed. We define the first rejection as $RefuseInfo$, and the second as $RefuseNeed$.

$$RefuseInfo(B, A, \epsilon, I, N, t, t_a, t', C_n) \triangleq Attempt(B, \epsilon, \psi, \psi, C_n, t, t_a),$$
$$RefuseNeed(B, A, \epsilon, I, N, t, t_a, t', C_n) \triangleq Attempt(B, \epsilon, \phi, \phi, C_n, t, t_a),$$ where
$\psi = MB(\{A, B\}, \neg Bel(B, I, t), t_a)$,
$\phi = MB(\{A, B\}, \neg Bel(B, InfoNeed(B, N, t', C_n), t), t_a)$.

Upon receiving $RefuseNeed$, the performer of $ProInform$ might revise its belief about the addressee's information-needs.

The following properties are obvious.

Proposition 1. *For any* t_0, t_1, t_2, t_3, t', *where* $t_0 < t_1 < t'$, $t_0 < t_2 < t_3 < t'$,
(1)$ProInform(A, B, \epsilon, I, N, t_0, t_1, t', C_1) \wedge\ Accept(B, A, \epsilon', I, N, t_2, t_3, t', C_2) \Rightarrow Bel(A, Bel(B, I, t_2), t_3)$.
(2)$ProInform(A, B, \epsilon, I, N, t_0, t_1, t', C_1) \wedge\ RefuseInfo(B, A, \epsilon', I, N, t_2, t_3, t', C_2) \Rightarrow Bel(A, \neg Bel(B, I, t_2), t_3)$.
(3)$ProInform(A, B, \epsilon, I, N, t_0, t_1, t', C_1) \wedge\ RefuseNeed(B, A, \epsilon', I, N, t_2, t_3, t', C_2) \Rightarrow Bel(A, \neg Bel(B, InfoNeed(B, N, t', C_n), t_2), t_3)$.

The following theorem can be proved using Axiom 1, 4 and Proposition 1.

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

It states that if agent A believes I, which agent B will need by t', it will consider proactively sending I to B by $ProInform$.

4.2 Proactive-Subscribe

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, here we focus on capturing 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 $Inform(A, B, \epsilon, InfoNeed(A, N, t'', C_n), t, t')$. That is, A informs B at time t so that B will know at time t' that "A will need information described by N by t'' under the context C_n". If agent B's reply to such an $Inform$ action is *Accept*, B will consider (i.e., have a "potential intention") to proactively deliver the needed information to A when relevant 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 third-party subscribe (called $3PTSubscribe$). Conceptually, $3PTSubscribe$, issued by a broker agent A to information provider C, forwards the information-needs of B to C and requests C to meet B's needs 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 regarding B's information need". However, defined as such, C is demanded to reply based on C's current belief (like a request to a database server). What we want to model is that if C accepts the request, C will commit to deliver relevant information whenever it becomes available. Neither can we model it as "A requests C to proactively inform B regarding B's information need", because it requires that agent C already know about B's needs, which is not the case here.

Failed to capture the semantics of $3PTSubscribe$ in our mind by composing existing communicative actions, we introduce it as a new performative. Thus, by $3PTSubscribe(A, B, C, \epsilon, N, t_1, t_2, t_3, C_n)$ we mean the action that A subscribes information-need N (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 could hold the information relevant to N at time t_3. The intermediate effect is to establish a mutual belief between A and C that (1) B has an information-need N by t_3 under the context C_n, and (2) whenever C acquires new information about N,

C intends to inform the information proactively to B as long as B still needs it. We formally define the semantics of $3PTSubscribe$ below.

Definition 5. $3PTSubscribe(A, B, C, \epsilon, N, t_1, t_2, t_3, C_n) \triangleq (t_1 < t_2 < t_3)?; Attempt(A, \epsilon, Bel(B, info(B, N), t_3), \exists t'' \cdot (t_1 \leq t'' < t_2) \wedge MB(\{A, C\}, \rho, t''), C_p, t_1, t_2)$, *where*
$\rho = \exists t_b \cdot (t'' \leq t_b < t_2) \wedge Int.Th(A, \psi \wedge \phi, t_1, t_b, C_n)$,
$\psi = Bel(C, Bel(A, InfoNeed(B, N, t_3, C_n), t_1), t_b)$,
$\phi = Int.Th(C, [\forall t' \leq t_3 \cdot BChange(C, N, t') \Rightarrow \exists t_a, t_c \cdot Int.To(C, ProInform(C, B, \epsilon', info(C, N), N, t_a, t_c, t_3, C_n), t', t_a, C_n)], t_b, t_b, C_n)$,
$BChange(C, N, t) \triangleq info_t(C, N) \neq info_{t-1}(C, N)$ [7],
$C_p = Bel(A, InfoNeed(B, N, t_3, C_n), t_1) \wedge Bel(A, defined(info(C, N)), t_1) \wedge \neg defined(info_{t_1}(A, N)) \wedge \neg Bel(A, Bel(C, InfoNeed(B, N, t_3, C_n), t_1), t_1)$.

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 can be modeled as $3PTSubscribe(A, A, C, \epsilon, N, t_1, t_2, t_3, C_n)$.

Upon receiving a $3PTSubscribe$ request, the service provider (agent C in Definition 5) can reply in at least three ways. It can accept the request and commit to proactively delivering the needed information to agent B whenever the information changes. Alternatively, it can reject the request by letting A know 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 to proactively informing B. This option still allows agent C to consider (i.e., potentially intend to) to $ProInform$ B later based on Theorem 1, yet it gives agent C the flexibility to decide whether to commit to $ProInform$ based on the current situation (e.g., take into account of C's current cognitive load level). We call these three replies $AcceptSub$, $RejectSub$, and $WeakAcceptSub$ respectively. They are formally defined below.
Let $Q = (\forall t' \leq t_3 \cdot BChange(C, N, t') \Rightarrow \exists t_a, t_c \cdot Int.To(C, ProInform(C, B, \epsilon', info(C, N), N, t_a, t_c, t_3, C_n), t', t_a, C_n))$.

$AcceptSub(C, B, A, \epsilon, N, t_1, t_2, t_3, C_n) \triangleq Attempt(C, \epsilon, \psi, \psi, C_n, t_1, t_2)$,
$RejectSub(C, B, A, \epsilon, N, t_1, t_2, t_3, C_n) \triangleq Attempt(C, \epsilon, \phi, \phi, C_n, t_1, t_2)$,
$WeakAcceptSub(C, B, A, \epsilon, N, t_1, t_2, t_3, C_n) \triangleq Attempt(C, \epsilon, \rho, \rho, C_n, t_1, t_2)$, where
$\psi = MB(\{A, C\}, Bel(C, InfoNeed(B, N, t_3, C_n), t_2) \wedge Bel(C, Q, t_2), t_2)$,
$\phi = MB(\{A, C\}, \neg Bel(C, Q, t_2), t_2)$,
$\rho = MB(\{A, C\}, Bel(C, InfoNeed(B, N, t_3, C_n), t_2), t_2)$.

Similar to Theorem 1, an agent could assist its teammates by performing $3PTSubscribe$. The proof is based on the indirect effect of $3PTSubscribe$, which can LEAD to $Bel(B, info(B, N), t')$.

[7] $info_t(C, N)$ means C evaluates N at t.

Theorem 2. $\forall A, B, C \in TA, N, C_n, t, t' > t$,
$Bel(A, InfoNeed(B, N, t', C_n), t) \wedge \neg defined(info_t(A, N)) \wedge$
$Bel(A, defined(info(C, N)), t) \wedge \neg Bel(A, Bel(B, info(B, N), t'), t) \Rightarrow$
$(\exists t_1, t_2, C_p \cdot Pot.Int.To(A, 3PTSubscribe(A, B, C, \epsilon, N, t_1, t_2, t', C_n), t, t_1, C_p))$.

In addition to $3PTSubscribe$, there are at least two other ways a third-party agent can assist a team member with its information-needs: (1) *Ask-ProInform*: agent A asks agent C, then pro-informs agent B upon receiving replies from C, (2) *request-inform*: agent A requests agent C to $Inform$ agent B directly (by composing *request* and $inform$ together) [8].

In the *Ask-ProInform* approach, agent A needs to perform two communicative actions. The benefit is that A can also obtain the information as a by-product 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.

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 information-needs. For instance, if the information needed is static, *request-inform* is better than $3PTSubscribe$, because the former relieves the information providing agent from monitoring a need for detecting changes.

5 Conversation Policies with Proactiveness

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 difficult. Practical agent systems typically employ various assumptions to simply this issue. One promising approach is to frame the semantics of performatives using protocols or conversation policies. As publicly shared, abstract, combinatorial, and normative constraints on the potentially unbounded universe of semantically coherent message sequences [14], 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.

Conversation protocols are traditionally specified as finite state machines [6, 15]. Enhanced Dooley graphs[16], Colored Petri Nets [17], and Landmark-based representation [18] were proposed to specify richer semantics of protocols. For instance, in Landmark-based representation, a protocol (family) is specified as a sequence of waypoints (landmarks) that must be followed in order to accomplish the goal associated with that protocol, while concrete protocols are realized by specifying action expressions for each landmark transition such that performing the action expressions provably results in the landmark transitions [18]. Here we

[8] It's different from PROXY with INFORM as the embedded act [13], which, like *forward*, requires the originating agent A already believes the information to be delivered.

only consider concrete protocols, which are viewed as patterns of communicative acts, and their semantics tie to those of the involved individual acts.

One of our design criteria for conversation protocols is that it should be able to enhance team intelligence concerning about others' information-needs by considering the flow of information-needs as well as information itself. Figure 1 shows the Petri-Net representation of a conversation protocol regarding $ProInform$, where the applicable contexts and goal (let B know I) are encoded as predicates and kept in the *start* node and main *end* node (i.e., $e1$), respectively. The protocol covers all the acceptable end points possibly occurring in conversations between agents A and B: terminate when B accepts, B keeps silent or refuses the pro-informed information, or when A accepts B's refusal of information needs.

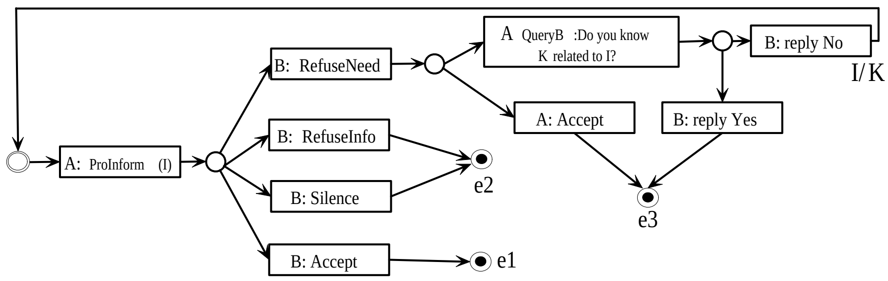

Fig. 1. A conversation policy involving $ProInform$ regarding information I

One case is a bit involved, wherein agent A keeps trying to help B figure out his related information needs derived from I and appropriate inference knowledge. Suppose agent A initiates $ProInform$ to agent B about information I that A believes B will need, but B responds with $RefuseNeed$. A has two choices at this point: either accepts B's refusal and revises his beliefs regarding B's information needs; or assuming B could not recognize her own information needs regarding I (e.g., due to lack of inference knowledge), A will take K as B's information-need that is closer than I to B's purpose (e.g., action performing), and adopts another instance of $ProInform$ with K this time instead of I. Such recursive process may end when A chooses to accept B's refusal, or B clarifies to A that her refusal is not due to lack of certain inference knowledge (e.g., B regards A's anticipation of her needs as wrong).

It's easy to show that the protocol is complete in the sense that no undischarged commitments are left behind [18]. The protocol is also correct in the sense that successful execution of the protocol can achieve the goal of the protocol (refer to Property 1).

Conforming to the abovementioned criterion, we also designed a protocol involving communicative act $3PTSubscribe$ as shown in Figure 2. There are three end points: either agent C accepts agent A's subscription regarding agent B's information needs, or C weakly accepts agent A's subscription (i.e., C comes to believe B's information needs, but not makes an commitment) and agent A chooses to end this helping behavior by keeping silent, or C rejects A's subscription, and A comes to take C's view regarding B's needs [9] after being informed by C that C does not believe B will need I.

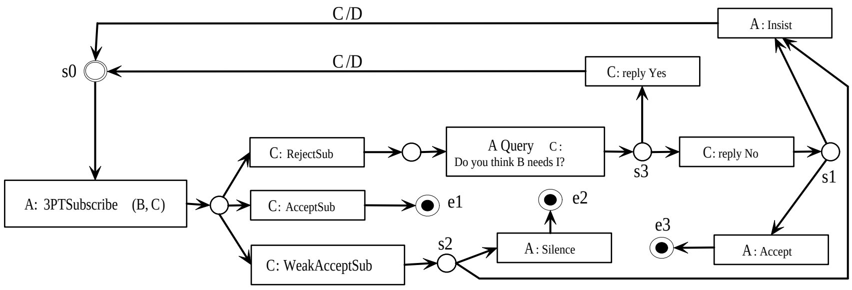

Fig. 2. A conversation policy involving $3PTSubscribe$

Likewise, this protocol allows recursive invocations (with different third-party service providers): (1) at state $s2$ agent A chooses to continue helping B (Insist) by finding another potential information provider (D) and attempting to subscribe B's needs from D; (2) at state $s3$ agent C replies "Yes" to A's query (i.e., C rejects A's subscription under the situation that C himself is already aware of B's needs [10]); (3) at state $s1$, instead of accepting C's view on B's needs, agent A insists on his/her own viewpoint of B's needs and attempts to subscribe B's needs from another known teammates.

6 Comparison

The reasoning of speech acts can be traced to the work of Austin [19], which was extended by Searle in [20]. 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 [21], KQML [22], 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.

The way of defining semantics for performatives in this paper shares the same origin with those adopted in the abovementioned languages. A common element

[9] That is, at state $S1$, agent A believes that agent C does not think B has a need regarding I. At the end state $e3$, A will revise his mental model about B's needs.

[10] Most likely, C cannot help B with B's needs because C is not an information provider of I. In such a case, C's reply is actually an indirect speech act, from which A can infer that C does not have (the observability regarding) I. However, there may exist other reasons, say, C is simply too busy. But anyway, at state $s0$ agent A needs to revise his/her model of C appropriately.

lies in 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, wherein the semantics of performatives are specified by feasibility preconditions and rational effect, both of which are formulas of a semantic language SL. The semantics of proactive performatives defined in this paper draws heavily on Cohen's work on performative-as-attempt.

The main difference is not in the way of defining semantics, but in the requirement of proactive performatives that prior to delivering information to an agent, the speaker needs to know (either by anticipating or being informed) that agent's information-needs, which guarantees the information delivered is relevant to what the receiver should hold in order to participate team activities smoothly. To fully support such proactive communications, we also established a framework for reasoning other's information needs. Needs-driven communication is also allowed partially in Arcol. For instance, 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 $request$. However, in essence, agent A acts in a reactive rather than a proactive way, because Arcol lacks a mechanism for anticipating information needs as presented in this paper.

$ProInform$ (proactive inform) defined in this paper 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 $InfoNeed$. However, the semantics of $WANT$ is left open for generality. $InfoNeed$ can be viewed as an explicit way to expressing 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 does not. In our approach, if an agent does not know any information provider of information I, it could choose not to offer help. Of course, the needer itself could alternatively $publish$ its needs to certain facilitator agent in its team, who then might initiate a $request$ (involving three parties) to some known provider. In such a sense, $broker\_one(A, B, ask\_if\ (A, -, X))$ [22] can be simulated by $publish$ and $request$. However, $3PTSubscribe$ cannot be easily simulated in KQML.

Proxy is defined in FIPA [10] as an Inform between the originating agent and the middle agent, which captures rather weaker third-party semantics. Stronger third-party semantics as we have introduced in this paper has independently defined for PROXY and PROXY-WEAK in [13]. Both PROXY and PROXY-WEAK are based on REQUEST. PROXY imposes significant commitments upon the intermediate agent, while PROXY-WEAK reduces the burden placed upon the intermediate agent. "PROXY of an INFORM" and "PROXY-WEAK of an INFORM" are different from $3PTSubscribe$. PROXY of an INFORM requires the middle agent believe the information that the speaker wants him/her to forward to the target agent. Even though PROXY-WEAK of an INFORM loosens this requirement, both still require the speaker already hold the information to be delivered. $3PTSubscribe$, focusing on information-needs, applies to situations when the speaker does not have the information needed by others.

To fully understand the ties between the semantics of communicative acts and patterns of these acts, conversation policies or protocols have been studied heavily in ACL field [23, 24, 6, 18, 25, 26]. The protocols proposed in this paper are rather simple, but they are helpful in understanding proactive communications enabled by proactive communicative acts and how information-needs flow.

More recently, social agency is emphasized as a complement to mental agency due to the fact that communication is inherently public [27], which requires the social construction of communication be treated as a first-class notion rather than as a derivative of the mentalist concepts. For instance, in [15] speech acts are defined as social commitments, which are obligations relativized to both the beneficiary agent and the whole team as the social context. Kumar [18] argued that joint commitments may simulate social commitments, because PWAG entails a social commitment provided that it is made public. We agree on this point. In our definition, the context argument of $ProInform$ and $3PTSubscribe$ includes the context of the information-need under concern. Thus, an information providing agent could terminate the information delivery service once the context is no longer valid. The contexts can be enriched to include protocols in force, as suggested in [6], and even social relations.

To summarize, we are not proposing a complete ACL that covers various categories of communicative acts (assertives, directives, commissives, permissives, prohibitives, declaratives, expressives) [27], 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. 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.

7 Concluding Remarks

In this paper we established a theory about proactive information exchanges by introducing the concept of "information-needs", providing axioms for anticipating the information-needs of teammates based on shared team knowledge such as shared team process and joint goals, and defining the semantics of $ProInform$ and $3PTSubscribe$ based on the speaker's awareness of the information-needs of teammates. It is shown that communications using these proactive performatives can be derived as helping behaviors. Conversation policies involving these proactive performatives are also discussed.

Agent infrastructures like Grid [28] aim to enable trans-architecture teams of agents (a team consisting of subteams of agents with different architectures like TEAMCORE [29], D'Agents [30], CAST [31]) to support joint activities by providing mechanisms for accessing shared ontologies, and for publishing and subscribing agents' services. $3PTSubscribe$ plays an important role in sharing information among hierarchical teams, but there is still a long way to go to fully support proactive communications among teams with heterogeneous agents.

The work 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, it 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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