Representing and Executing Protocols as Joint Actions

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ABSTRACT

Families of conversation protocols can be expressed formally as partially ordered landmarks where the landmarks represent the state of affairs that must be brought about during the goal-directed execution of a protocol. Then, concrete protocols represented as joint action expressions can be derived from the partially ordered landmarks and executed directly by joint intention interpreters, thus nearly eliminating the need to implement a separate protocol handling system. This approach also supports (1) flexibility in the actions used to achieve landmarks, (2) shortcutting protocol execution, and (3) application of the joint intention theory to provide automatic exception handling along with a correctness criterion for protocols.

Categories and Subject Descriptors

I.2.11 [**Distributed Artificial Intelligence**]: *Intelligent agents*, *Multiagent systems.*

General Terms

Languages, Theory

1. INTRODUCTION

Conversation protocols are traditionally specified as finite state machines in which the transition arcs specify the communicative actions to be used by the various agents involved in a conversation. Protocols are executed by performing these communicative actions and therefore, the communicative actions have come to be regarded as the central concept around which analyses of protocols are based. However, we believe that it is the states and not the state transitions that are key to the correctness and completeness of a protocol [7, 11]. We propose a landmark-based approach for formal analysis of conversation protocols wherein the most important aspect of a conversation protocol is not the set of communicative actions involved in that protocol but the effects or the states that these actions bring about. The basic idea is that since protocols are used to do certain tasks or to bring about certain state of affairs in the world, one should identify the important landmarks or state of affairs that are brought about by and during the execution of a protocol. Conversation protocols can then be expressed at an abstract level as partially ordered landmarks where each landmark is characterized by the propositions that are true in the state represented by that landmark. The partially ordered landmarks represent a family of protocols. Communicative actions are, then, the tools to realize concrete protocols from a landmark-based representation. Besides contributing to formal analyses of protocol families, the landmark-based representation facilitates dynamically choosing the most appropriate action to use next in a conversation, allows compact handling of protocol exceptions, and in some cases, even allows short-circuiting a protocol *execution* by opportunistically skipping some intermediate landmarks.

There is still a need for a proper formalism for protocols that is suitable for automated reasoning. The very definition of conversation protocols as a pattern of communicative actions suggests such a formalism. We represent concrete protocols along with their precondition and goal as action expressions using dynamic logic constructs. These communicative action expressions involve multiple cooperating agents and henceforth will be called joint action expressions. The motivation for joint action expressions also comes by analogy with natural language wherein dialogues are treated as joint actions [2]. The communicative actions in the joint action expression for a protocol achieve the landmarks of the protocol family of that protocol in the required order. One purpose of this paper is to explore the possibility of applying existing formal theories of dialogue and teamwork, such as joint intention theory [8], to protocols represented as joint action expressions. We present the landmark-based approach for representing and analyzing families of protocols in section 2. In section 3, we introduce the joint action expression based representation for protocols, present a formal analysis of protocol compositions, and apply joint intention theory to protocols. In section 4, we conclude with a discussion of the related and future work in the direction of this paper.

2. LANDMARK EXPRESSIONS

We seek a way of specifying conversation protocols that allows an intelligent agent to choose the best applicable communicative act dynamically in any situation. The proposed representation resembles state machines but instead of specifying the state transitions, it specifies a partially ordered set of states. Several different actions can bring about the same state and therefore, the partially ordered landmarks represent a family of protocols. Each landmark is labeled as either required or optional, and an agent may opportunistically skip only the optional landmarks during protocol execution.

2.1 Representation

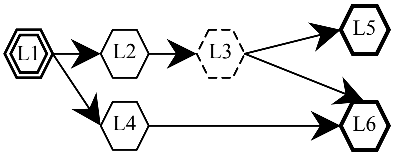

Figure 2.1: Partially Ordered Landmarks

One can visualize a landmark-based representation of protocol families as a directed graph whose nodes represent landmarks and

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whose directed edges represent partial ordering. Figure 2.1 shows a protocol family using partially ordered landmarks. L1 is the initial landmark (the start state) represented by two concentric hexagons, L5 and L6 are final landmarks represented by dark hexagons, L2 and L4 are important intermediate landmarks represented by solid hexagons, and L3 represented by a dotted hexagon is specified as an optional intermediate landmark. The arrows indicate ordering of the landmarks – L1 comes before L2 and L4, L2 comes before L3 and L3 comes before L5 and L6, and so on. We call this ordering partial because there are some landmarks (such as L2 and L4) that do not have a hard ordering relationship between them, and one may insert additional ordered landmarks between any two landmarks. The landmark-based representation specifies the waypoints from the initial landmark to one of the final landmarks. A protocol designer has the option to specify a landmark of a protocol family to be optional. Optional landmarks in any path may be skipped opportunistically during protocol execution but the important landmarks in that path must be followed. Following a path means performing actions in one landmark to reach the next required landmark. The allowed actions to transition from one landmark to the next may be either a single communicative act or a complex action expression consisting of several actions.

Protocol families expressed using landmarks can be represented formally in a suitable logic. Here, we introduce a simple propositional dynamic logic sufficient for our purpose and use it to logically represent the protocol family in figure 2.1. We use temporal operators PRIOR, HAPPENS, and eventually ($\Diamond$), and operators for action sequences ($a;b$) and test action ($p?$), from the logical language of joint intentions (section 2.2), to define the operators for landmark ordering.

Let $\mathbf{L}$ be the domain of landmarks, let $\mathbf{P}$ be the set of atomic propositions, and let $\mathcal{P}$ be a function that gives the *conjunction* of atomic propositions comprising a landmark, i.e.

$$\mathcal{P} : \mathbf{L} \rightarrowtail \{\Lambda s: s \in 2^{\mathbf{P}}\text{-}\emptyset\}$$

where, Λs is the conjunction of elements in set s,
$2^{\mathbf{P}}$ is the power set of $\mathbf{P}$, and $\emptyset$ is the empty set

Let L1, L2, and L3 be three landmarks. We define a partial order operator $\succ$ such that L1$\succ$ L2 means that L1 comes before L2 but not necessarily immediately before L2. Also, two landmarks can be ordered using the partial order operator only if they are different landmarks. The partial order operator is defined inductively as follows.

Definition 2.1. *Partial Order Operator*

$$\text{L1} \succ \text{L2} \triangleq (\text{PRIOR } \mathcal{P}(\text{L1})\ \mathcal{P}(\text{L2})) \wedge (\mathcal{P}(\text{L1}) \neq \mathcal{P}(\text{L2}))$$

$$\text{L1} \succ \text{L2} \succ \text{L3} \triangleq (\text{L1} \succ \text{L2}) \wedge (\text{L2} \succ \text{L3}),\ \text{where from [3]}$$

(PRIOR[1] $p\ q$) $\triangleq \forall c\ (\text{HAPPENS } c;q?) \supset \exists a\ (a \leq c) \wedge (\text{HAPPENS } a;p?)$

That is, a proposition p occurs prior to another proposition q if for all event sequences c such that c occurs after which q is true, there exists an *initial subsequence* a of c such that a occurs after which p is true. This definition does not say whether p or q will ever be true. However, if q is ever true then there must be some earlier time when p was true. Formally,

$$\models (\text{PRIOR } p\ q) \wedge \Diamond q \supset \exists\, e\ (\text{HAPPENS } p?;e;q?)$$

Combining this proposition with definition 2.1, we get the following property about landmark ordering.

Proposition 2.1. $\models (\text{L1} \succ \text{L2}) \wedge \Diamond\mathcal{P}(\text{L2}) \supset \exists\, e\ (\text{HAPPENS } \mathcal{P}(\text{L1})?;e;\mathcal{P}(\text{L2})?) \wedge (e \neq nil)$

That is, if landmark L1 comes before landmark L2 and if propositions in landmark L2 will eventually be true, then there exists a non-empty event sequence e of primitive event types such that e occurs after propositions in L1 are true and after e occurs, the propositions in L2 will be true. The empty event sequence *nil* is a subsequence of all event sequences.

From definition 2.1, it follows that the partial order relation is transitive i.e. if landmark L1 comes before landmark L2 and landmark L2 comes before landmark L3 then landmark L1 comes before landmark L3.

Proposition 2.2. $\models (\text{L1} \succ \text{L2} \succ \text{L3}) \supset (\text{L1} \succ \text{L3})$

An OR operator $\perp$ over landmarks is similarly defined in terms of propositions that are true in those landmarks.

Definition 2.2. *OR Operator*

$$\text{L1} \perp \text{L2} \triangleq \mathcal{P}(\text{L1}) \vee \mathcal{P}(\text{L2})$$

This definition says that the current landmark is either L1 or L2 means that the conjunction of propositions in either landmark L1 or landmark L2 is true. A more detail discussion on properties of landmark expressions appears in [7].

Expressing protocol family as a landmark expression. Using the definitions of partial order operator and the OR ($\perp$) operator, the protocol family $\mathcal{F}$ in figure 2.1 can be expressed by the following partial order expressions:

$$\text{L1} \succ (\text{L2} \perp \text{L4})$$

$$\text{L2} \succ \text{L3} \succ (\text{L5} \perp \text{L6})$$

$$\text{L4} \succ \text{L6}$$

Or, more compactly as

$$\mathcal{F} = \text{L1} \succ ((\text{L2} \succ \text{L3} \succ (\text{L5} \perp \text{L6})) \perp (\text{L4} \succ \text{L6}))$$

The landmarks in a landmark expression represent the 'way points' that must be followed to successfully execute the protocols belonging to the protocol family represented by that landmark expression. As such, the landmarks represent constraints on protocol execution. One can *specialize* a protocol family by introducing additional ordered landmarks and thus constraining the landmark-based representation further. Similarly, one may *generalize* a protocol family by removing some of the landmarks and thus relaxing the constraints. The new ordering of landmarks in a specialized as well as a generalized protocol family must still preserve the original ordering of landmarks.

The protocol families represented by landmarks can be reasoned about by intelligent agents and can be used for planning the communicative actions that need to be performed to successfully execute a protocol. But they are not of much use to agents who do not possess reasoning and planning capabilities. The landmarks are used to represent protocol families and not concrete protocols. A concrete protocol is *realized* from a landmark-based representation of a protocol family by specifying action expressions for each landmark transition such that performing the action expressions provably results in the landmark transitions. Even though the resulting concrete protocols look similar to a finite state machine, there are several distinguishing features: (1) the landmarks are

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[1] PRIOR was called BEFORE in [3].

precisely specified using the conjunction of propositions that are true in a landmark, (2) the landmarks are task oriented i.e. they are the waypoints towards achieving the goal associated with a protocol family and that goal must be achieved when the protocol ends properly, and (3) the landmark transitions can be due to arbitrarily complex action expressions. Concrete protocols are represented logically as joint action expressions in section 3. The landmarks as well as the communicative acts involve agent roles such as initiator and participant of a protocol instead of agent instances. These roles must map to an agent or group instance in any actual execution of a conversation protocol.

We want to apply the ideas introduced so far to well-known protocols. In order to do that, we will first introduce the logic needed to formally express the propositions that comprise landmarks and define the communicative actions that realize concrete protocols.

2.2 Logical Preliminaries

We regard multi-agent conversation as a joint action by the participating agents. Joint actions are explained using the joint intention theories of teamwork [8]. We have given a formal semantics to speech acts using joint intention theory and shown that multi-agent conversations based on this semantics result in forming and discharging teams [7, 12]. Here, we review the joint intention theory and the semantics of the communicative acts used in a request protocol.

2.2.1 Joint Intention Theory

The joint intention theory is expressed in a modal language with the usual connectives of a first order logic with equality and operators for propositional attitudes and event sequences. The primitive mental states in this theory are an agent's beliefs and goals, expressed as (BEL x p) and (GOAL x p) respectively, where x is an agent and p is a proposition that follows from x's beliefs or goals. BEL has Kripke's weak S5 semantics and GOAL has system K semantics. Temporal properties are expressed in a linear time temporal logic. $\Diamond p$ says that the proposition p will eventually be true, and $\Box p$ says that p will always be true. (HAPPENS a) and (DONE a) say that a sequence of actions described by the action expression a will happen next or has just happened, respectively. (HAPPENS x a) and (DONE x a) also specify the agent for the action sequence that is going to happen or has just happened. EARLIER, BEFORE[2], AFTER, and UNTIL are defined using HAPPENS and DONE. An action expression is built from variables ranging over sequences of events using constructs of dynamic logic: $a;b$ is action sequence, $a|b$ is non-deterministic choice, $a||b$ represents concurrent actions, $a*$ is indefinite repetition, and $p?$ is a test action. Details of this modal language can be found in [3]. Mutual belief (MB) is defined in terms of unilateral mutual belief (BMB) that is treated as a semantic primitive. Two agents have a mutual goal (MG) that p if they mutually believe that p is a goal of both the agents.

The notion of an agent's commitment to achieving some state in the world is expressed as a persistent goal or PGOAL [3]. An agent x having a persistent goal (PGOAL x p q) is committed to that goal and cannot give up the goal that p is true in the future, at least until it believes that p is accomplished, or is impossible, or is irrelevant (i.e. the relativizing condition q is untrue). An intention (INTEND) is a persistent goal in which the agent is committed to performing an action believing throughout that it is doing the action. This analysis has been extended to multiple agents [8] – an agent team is characterized as having joint commitments and intentions.

Definition 2.3. *Joint Persistent Goal*

$$
\begin{aligned}
&(\mathrm{JPG\ x\ y}\ p\ q) \triangleq (\mathrm{MB\ x\ y}\ \neg p) \wedge (\mathrm{MG\ x\ y}\ p) \wedge \\
&\quad (\mathrm{UNTIL}\ [(\mathrm{MB\ x\ y}\ p) \vee (\mathrm{MB\ x\ y}\ \Box\neg p) \vee (\mathrm{MB\ x\ y}\ \neg q)] \\
&\qquad\qquad (\mathrm{WMG\ x\ y}\ p\ q))
\end{aligned}
$$

Two agents x and y have a joint persistent goal that p with respect to q when precisely the following conditions hold: there is a mutual belief that p is not currently true, it is a mutual goal to bring about p, and p will remain a weak mutual goal until there is a mutual belief that p is either true, or will never be true, or the relativizing condition q is no longer true. A weak mutual goal (WMG) is a mutual belief that each agent has a weak achievement goal (WAG) towards the other agent for achieving p. An agent x has a WAG towards another agent y when the following holds: if agent x believes that p is not currently true then it will have a goal to achieve p, and if it believes p to be either true, or to be impossible, or if it believes the relativizing condition q to be false, then it will have a goal to bring about the corresponding mutual belief with agent y. Joint Intention (JI) between two agents is defined as a joint persistent goal to perform an action believing throughout that the agents are jointly doing the action as a team. These terms are formally defined in [7, 8].

A persistent weak achievement goal (PWAG) is the building block for establishing JPG. The term (PWAG x y p q) states that an agent x has a persistent weak achievement goal with respect to another agent y to achieve p relative to q. PWAG is a longer lasting version of the weak achievement goal used in the definition of JPG and is formally defined in [7]. Mutual belief in each other's PWAG towards the other is sufficient to establish a JPG between two agents provided that the PWAGs are interlocking i.e. if one PWAG is relative to the other [7]. Such a PWAG defines a commitment of one agent towards another and therefore, it represents a *social commitment* provided that it is made public.

We will have occasions when we want to establish mutual belief during a protocol execution. Mutual belief can be established in several different ways by default. A detailed discussion on establishing mutual belief by default appears in [7]. One consequence of the default assumptions in [7] is that it may take only two messages to establish mutual belief in each other's PWAG, and thus create a team due to the interlocking PWAG. We now review the communicative acts that are used in the Request protocol in this paper.

2.2.2 Communicative Acts as Attempts

It has been argued in the philosophy of language that a communicative act succeeds when the hearer successfully recognizes the speaker's intention and it is satisfied when the hearer successfully acts on the speaker's intention. Communicative acts must be characterized as attempts because there is a possibility that the act may not succeed. An attempt (ATTEMPT x e p q t) at time t to achieve p via q is defined [7] as a complex action expression in which the agent x is the actor of event e and just prior to e, the actor chooses that p should eventually become true, and intends that e should produce q relative to that choice. So, 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.

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[2] In this paper, (BEFORE a p) $\triangleq$ (DONE $p?;a$), and

(AFTER a p) $\triangleq$ (HAPPENS $a;p?$)

Compositionality is one of the basic characteristics of speech acts. Accordingly, communicative acts based on the speech-act theory must have a composable semantics. We define two primitive communicative acts, REQUEST and INFORM, and compose all other communicative acts using these basic acts by either specializing their content or by composing them using the action formation operators as in section 3.2. We define our primitive communicative acts as attempts and their definitions that follow are borrowed from [7].

Definition 2.4. *Request*

$(\text{REQUEST x y } e\ a\ q\ t) \triangleq (\text{ATTEMPT x } e\ \phi\ \psi\ t)$

where $\phi = (\text{DONE y } a) \wedge$
$[\text{PWAG y x (DONE y } a\text{) (PWAG x y (DONE y } a\text{) } q\text{)}\wedge q]$

and $\psi = (\text{BMB y x (BEFORE } e\ [\text{GOAL x (AFTER } e\ (\text{BEL y}$
$[\text{PWAG x y } \phi\ q]))]))$

The goal of a REQUEST is that the requestee y eventually does the action *a* and also have a PWAG with respect to the requester x to do *a*. The requester's PWAG is relative to some higher-level goal *q*. The requestee's PWAG is not only with respect to the requester's PWAG towards her that she does the action *a* but also relative to the requester's higher-level goal *q*. The intention of the request is that the requestee y comes to believe there is a mutual belief between the requestee and the requester that before performing the request, the requester had a goal that after performing the request, the requestee will believe that he (the requester) has a PWAG towards the requestee to achieve the goal ϕ of the request.

Definition 2.5. *Inform*

$(\text{INFORM x y } e\ p\ t) \triangleq (\text{ATTEMPT x } e\ \phi\ \psi\ t)$

where $\phi = [\text{BMB y x } p]$
and $\psi = [\text{BMB y x (BEFORE } e\ [\text{GOAL x (AFTER } e\ [\text{BEL y}$
$(\text{BEFORE } e\ [\text{BEL x } p])])])]$

The goal of an INFORM is that the listening agent y comes to believe that there is mutual belief between him and the informing agent x that the proposition *p* is true. The intention of the INFORM is that the listening agent comes to believe that there is mutual belief between him and the informing agent that before performing the INFORM, the informing agent had the goal that after the INFORM is performed, the listening agent will believe that the informing agent believed *p* before performing the INFORM.

AGREE and REFUSE are composed primitive acts defined as INFORM with specialized content. These communicative acts are used in the Request and the Standing Offer conversation protocols. A REQUEST followed by an appropriate AGREE is sufficient to create the inter-locking PWAGs, and hence the JPG required to form a team [7].

Definition 2.6. *Agree*

$(\text{AGREE x y } e\ a\ q\ t) \triangleq (\text{INFORM x y } e\ \phi\ t)$, where

$\phi = (\text{PWAG x y (DONE x } a\text{) (PWAG y x (DONE x } a\text{) } q\text{)}\wedge q)$

An agreeing agent x informs the listening agent y that he has a PWAG with respect to y to perform action *a* with respect to both y's PWAG that x do *a* relative to *q*, and *q*.

Definition 2.7. *Refuse*

$(\text{REFUSE x y } e\ a\ q\ t) \triangleq (\text{INFORM x y } e\ \phi\ t)$, where

$\phi = \Box\neg(\text{PWAG x y (DONE x } a\text{) (PWAG y x (DONE x } a\text{) } q\text{)}\wedge q)$

A refusing agent informs the listening agent that he will never have the PWAG to perform action *a* with respect *q* and with respect to y's PWAG that x do *a* relative to *q*. The effect of a REFUSE is opposite to that of the AGREE.

Definition 2.8. *Cancel*

$(\text{CANCEL x y } e\ a\ q\ t) \triangleq \eta?;(\text{INFORM x y } e\ \phi\ t)$

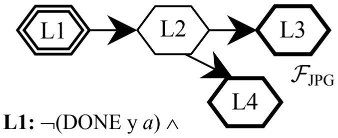
where $\phi = \neg(\text{PWAG x y (DONE y } a\text{) } q)$, and
$\eta = (\text{EARLIER (PWAG x y (DONE y } a\text{) } q))$

A CANCEL communicative act is an INFORM that the initiator does not have a PWAG towards the participant to do *a* relative to *q* in the context of an earlier PWAG (whose cancellation is being informed). The canceling of a request by the initiator (if the initiator was the requester in an earlier interaction) allows the participant to drop his PWAG towards the initiator if the participant's PWAG is relative to the initiator's PWAG. The default assumption of sincere communication [7] requires that the canceling agent x does not have the PWAG towards y that (DONE y *a*) relative to *q* just before performing the inform that ϕ (otherwise the inform is insincere).

Next, we use the information presented so far to represent and analyze two commonly used conversation protocols.

2.3 Example: A Well-known Protocol Family

The request for action protocol and the standing offer protocol are used to get an action done by another agent. Even though these protocols appear to be different from each other, we claim that they belong to the same protocol family – they belong to a family of protocols $\mathcal{F}_{\text{JPG}}$ that is used to get an action done by forming a team between the initiator and the participant. Figure 2.2 shows this protocol family along with the propositions that are true in the various landmarks.



$\mathcal{F}_{\text{JPG}} = \text{L1} \succ \text{L2} \succ (\text{L3} \perp \text{L4})$

L1: $\neg(\text{DONE y } a) \wedge$
$\neg(\text{JPG x y (DONE y } a\text{) (PWAG x y (DONE y } a\text{) } q\text{)}\wedge q)$

L2: $(\text{JPG x y (DONE y } a\text{) (PWAG x y (DONE y } a\text{) } q\text{)}\wedge q)$

L3: $(\text{DONE y } a) \wedge (\text{MB x y (DONE y } a\text{)})$

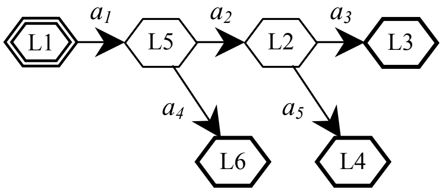
L4: $\neg(\text{DONE y } a) \wedge [(\text{MB x y } \Box\neg(\text{DONE y } a)) \vee (\text{MB x y } \neg q)$
$\vee (\text{MB x y } \neg(\text{PWAG x y (DONE y } a\text{) } q))]$

Figure 2.2: Family of Protocols $\mathcal{F}_{\text{JPG}}$

When a protocol of this family starts, the required action *a* has not been done and the participant and the initiator do not have any joint commitment towards the initiator's persistent weak achievement goal that the participant does the action *a*. These facts characterize the landmark L1. The initiator and the participant have formed a team in landmark L2 – they are jointly committed to the participant's doing *a* relative to both the initiator's PWAG that the participant does the required action, and the initiator's higher level goal *q*. This joint commitment is discharged in both the final landmarks L3 and L4. Landmark L3 is the desired final state in which the participant has done the required action and there is mutual belief between the initiator and the participant about this fact. Landmark L4 provides an escape route for failure of a protocol in this family – the participant has not done the required action and there is mutual belief between the participant and the initiator about impossibility or irrelevance of the required action. This protocol family $\mathcal{F}_{\text{JPG}}$ is formally represented by the landmark expression $L1 \succ L2 \succ (L3 \perp L4)$. A discussion leading to derivation of this protocol family appears in [7].

2.3.1 Request For Action Protocol

The request for action protocol restricts the way in which the JPG in landmark L2 in $\mathcal{F}_{\text{JPG}}$ is established. Accordingly, we derive the request for action protocol family by inserting an additional landmark L5 between L1 and L2. The landmark L5 characterizes a state in which the initiator has made a request for action but there is not yet a team between the initiator and the participant. This new protocol family $\mathcal{F}_{\text{Request}}$ is shown in figure 2.3. An additional landmark L6 provides an escape route from landmark L5 when the initiator and the participant fail to establish the joint commitment required in landmark L2.



L5: (GOAL x $\Diamond\varphi$) $\wedge$ (MB x y (PWAG x y φ q))
  φ = (DONE y a) $\wedge$
    [PWAG y x (DONE y a) (PWAG x y (DONE y a) q)$\wedge q$]

L6: $\neg$(DONE y a) $\wedge$
 [(MB x y $\Box\neg$(PWAG y x (DONE y a) (PWAG x y (DONE y a) q)$\wedge q$))
  $\vee$ (MB x y $\neg$(PWAG x y (DONE y a) q))]

Figure 2.3: Protocol Family for Request Protocol

Exceptions may lead to various landmarks with possibly undischarged commitments. However, the exceptions are dealt with by an over-arching joint commitment, as we shall argue in section 3. The following partially ordered landmarks specify completely the protocol family $\mathcal{F}_{\text{Request}}$ of which the request for action conversation protocol is a concrete realization:

$L1 \succ L5 \succ L2 \succ (L3 \perp L4)$
$L5 \succ L6$

Or more compactly by

$\mathcal{F}_{\text{Request}} = L1 \succ L5 \succ (L6 \perp (L2 \succ (L3 \perp L4)))$

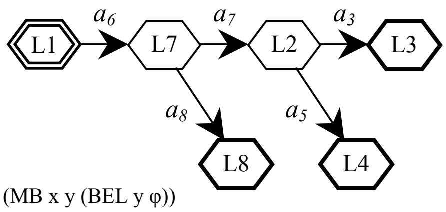
The request for action protocol can be realized from $\mathcal{F}_{\text{Request}}$ by specifying the actions that lead to the landmark transitions. Figure 2.4 shows one such set of actions that lead to the landmark transitions in figure 2.3. The proposition *deadline* is defined as ($t_{\text{current}} > t_{\text{start}}$ + timeout) where t_{start} in this protocol is the time of performing the REQUEST action. The effect of the deadline is assumed to be the same as that of a REFUSE communicative act. It can be shown using the definitions of the communicative acts that the actions in figure 2.4 do in fact result in the landmark transitions in figure 2.3. In particular, it has been shown in [7] that a_1 followed by a_2 establishes the JPG required in landmark L2.

2.3.2 Standing Offer Protocol

The main difference between the standing offer and the request for action protocols is the way in which joint commitment is established. In case of request, the initiator (i.e. the requester) is not the intended actor of the requested action, whereas in standing offer, the initiator is the intended actor of the action being offered. Figure 2.5 shows the standing offer protocol family, and figure 2.6 shows the actions used to realize a standing offer conversation protocol. The protocol family $\mathcal{F}_{\text{Soffer}}$ is obtained by introducing an additional landmark L7 between landmarks L1 and L2 in the protocol family $\mathcal{F}_{\text{JPG}}$ of figure 2.2. In landmark L7, the initiator has made a standing offer but does not yet have a PWAG towards the participant. The required JPG has been established in landmark L2 as required by the protocol family $\mathcal{F}_{\text{JPG}}$. Landmark L8 provides an escape route from L7 upon failure. The protocol family $\mathcal{F}_{\text{Soffer}}$ is specified as,

a_1 = (REQUEST x y e a q t)
a_2 = (AGREE y x e_1 a q t_1)
a_3 = (INFORM y x e_2 (DONE a) t_2);
  (INFORM x y e_3 (BEL x (DONE a)) t_3)
a_4 = (REFUSE y x e_4 a q t_4) | (CANCEL x y e_5 a q t_5) |
  deadline?
a_5 = c_1 | c_2 | c_3 | c_4 | c_5 where,
c_1 = (INFORM y x e_6 $\neg q$ t_6);(INFORM x y e_7 (BEL x $\neg q$) t_7)
c_2 = (INFORM y x e_8 $\Box\neg$(DONE a) t_8);
  (INFORM x y e_9 (BEL x $\Box\neg$(DONE a)) t_9)
c_3 = (CANCEL x y e_{10} a q t_{10})
c_4 = (INFORM x y e_{11} $\neg q$ t_{11});
  (INFORM y x e_{12} (BEL y $\neg q$) t_{12})
c_5 = (INFORM x y e_{13} $\Box\neg$(DONE a) t_{13});
  (INFORM y x e_{14} (BEL y $\Box\neg$(DONE a)) t_{14})

Figure 2.4: Actions for a Request Protocol



L7: (MB x y (BEL y φ))
  φ = $\forall e_1$ (DONE (INFORM x y e_1 (PWAG x y (DONE y a) q))) $\supset$
  (DONE e_1;(PWAG y x (DONE y a) (PWAG x y (DONE y a) q)$\wedge q$)?)

L8: $\neg$(DONE y a) $\wedge$
  [(MB x y $\Box\neg$(PWAG x y (DONE y a) q)) $\vee$ (MB x y (BEL y $\neg\varphi$))]

Figure 2.5: Protocol Family for Standing Offer Protocol

$\mathcal{F}_{\text{SOffer}} = L1 \succ L7 \succ (L8 \perp (L2 \succ (L3 \perp L4)))$

Concrete realizations of the standing offer conversation protocol family in figure 2.5 makes use of an SOFFER communicative act.

Definition 2.7. *Standing Offer Communicative Act*
(SOFFER x y e a q t) $\triangleq$ (INFORM x y e ϕ t), where ϕ is

$\forall e_1$ (DONE (INFORM y x e_1 (PWAG y x (DONE x a) q))) $\supset$
  (DONE e_1;(PWAG x y (DONE x a)
    (PWAG y x (DONE x a) q)$\wedge q$)?)

An SOFFER from x to y to do an action a relative to q is a conditional offer that if ever y informs x that he has a PWAG that x does a relative to q then x will have a PWAG to do a relative to y's PWAG and q. SOFFER extends over time – the offering agent is agreeing to perform the action if the listening agent ever makes it known that he has the appropriate PWAG. An SOFFER does not commit the agent making the SOFFER towards the recipient of the SOFFER. So even if the sender x discovers after making the SOFFER that he is no longer able to honor the SOFFER, he is not required to inform the agent y that the standing offer has been withdrawn. However, acceptance of the SOFFER by agent y does establish mutual belief in interlocking PWAGs towards each other by default, resulting in a joint commitment between the two agents [7]. Once the JPG is established, it is immaterial if agent x withdraws the SOFFER because it is now bound by its PWAG towards agent y.

The actions a_3 and a_5 in figure 2.5 are same as that for the request protocol in figure 2.4 and the other actions are specified in figure 2.6. The effect of a deadline is assumed to be the same as an INFORM from x to y that x will never have the PWAG required by y's SOFFER to establish JPG. A WITHDRAW is a way for the agent who made the SOFFER to get out of the standing offer by saying that the implication in SOFFER no longer holds. It is defined as an INFORM that is performed in the context of an earlier standing offer [7]. One can prove [7] that the action sequence $a_6;a_7$ in figure 2.5 does in fact establish the JPG required in landmark L2 (from figure 2.2) showing thereby that the standing offer conversation protocol belongs to the protocol family $\mathcal{F}_{\mathrm{JPG}}$.

$a_6 = (\mathrm{SOFFER\ y\ x}\ e\ a\ q\ \mathrm{t})$
$a_7 = (\mathrm{INFORM\ x\ y}\ e_1\ (\mathrm{PWAG\ x\ y}\ (\mathrm{DONE\ y}\ a)\ q)\ \mathrm{t}_1)$
$a_8 = (\mathrm{INFORM\ x\ y}\ e_4\ \Box\neg(\mathrm{PWAG\ x\ y}\ (\mathrm{DONE\ y}\ a)\ q)\ \mathrm{t}_4)\ |$
$(\mathrm{WITHDRAW\ y\ x}\ e_5\ a\ q\ \mathrm{t}_5)\ |\ \mathrm{deadline}\ ?$

Figure 2.6: Actions for a Standing Offer Protocol

The protocols discussed so far are directly based on joint commitment. Next we, apply joint intention theory to protocols expressed as joint action expressions.

3. PROTOCOLS AND JI THEORY

We first represent protocols and protocol compositions as action expressions and then discuss the consequences of applying joint intention theory to protocols and protocol compositions.

3.1 Representing Concrete Protocols

Concrete protocols are realized from a landmark-based representation of protocol families using action expressions for landmark transitions. We use the dynamic logic operators for action sequences ($a;b$), concurrent actions ($a||b$), non-deterministic OR ($a|b$), test action (p?), and indefinite repetitions (a*) where a and b are actions and p is a proposition[3].

Conversation protocols are applicable in certain contexts and are used to achieve certain goals. One can think of the starting landmark of the protocol family of a protocol as specifying the precondition and the main final landmark as specifying the goal associated with that protocol. We incorporate the precondition and the goal associated with a conversation protocol in its representation as a joint action expression. Accordingly, we view a joint action expression representation of a protocol as having three components – a test to determine whether the precondition is true, an action expression to achieve the goal associated with the protocol, and a test to find out if that goal is achieved. For example, let p be the precondition, $a;(b|c)$ be the action expression, and let g be the goal associated with a protocol. Further, assume that $a;b$ is the main path in this protocol i.e. the path from the starting landmark to the main final landmark in the landmark-based representation of the protocol family to which this protocol belongs. Then this protocol Π_{example} is specified in terms of joint action expressions as

$$\Pi_{\mathrm{example}} = p?;a;((b;g?)|c)$$

Just as a protocol family can have multiple final landmarks, a protocol may have multiple goals associated with it. For example, if the goals associated with the protocol in this example were $g1$ and $g2$ corresponding to the two actions b and c, then this protocol would be represented as

$$\Pi_{\mathrm{example}} = p?;a;((b;g1?)|(c;g2?))$$

Using this technique, the request for action protocol in figure 2.3 and figure 2.4 can be expressed as:

$$\mathcal{P}(\mathrm{L1})?;\ a_1;[(a_4;\ \mathcal{P}(\mathrm{L6})?)\ |\ (a_2;[(a_5;\ \mathcal{P}(\mathrm{L4})?)\ |\ (a_3;\ \mathcal{P}(\mathrm{L3})?)\ ])]$$

Protocols are action expressions and therefore, protocols can themselves be composed using the same operators used to compose action expressions.

3.2 Protocol Compositions

There are two main issues in composing protocols - what are the possible compositions of protocols and what are the correctness criteria for protocol compositions.

We have argued that protocols, and therefore, composed protocols can be regarded as action expressions. As such, protocols can be composed using the operators of dynamic logic of actions. If Π_1 and Π_2 are two protocols, and p is a proposition then $\Pi_1;\Pi_2$ (sequence), $\Pi_1|\Pi_2$ (non-deterministic OR), $\Pi_1||\Pi_2$ (concurrent execution), Π_1* (repetition), and $p?;\Pi_2$ (conditional execution) and any combination of these is a possible syntactic composition subject to certain semantic constraints. Actions in an action expression may be high-level actions that can be replaced by the equivalent (sub)action expression. This gives another composition operator – for embedding or replacing an action expression in a protocol by another protocol. If Π and π are two protocols then $\Pi[a/\pi]$ represents the protocol obtained by substituting a (sub)action expression a in Π by the action expression for protocol π.

Given the various possible ways to compose protocols, we want to determine which of the compositions are meaningful. One can identify at least the following criteria for correctness and legality of protocol compositions.

Completeness and Ending criteria. In the previous teamwork based analysis of protocols [11, 12], we have argued that a complete conversation should not leave behind any un-discharged commitments. However, this completeness criterion is not applicable to protocols (either individual or composed) that have the goal to bring about certain commitments – for instance, a protocol to form a team is intended to leave behind a joint commitment among the participants. At most, we can say that any complete protocol of which the protocol to form team is a component must have another protocol as its component in a sequence that results in discharging the joint commitment created by the previous (sub)protocol. Therefore, teamwork analysis gives us a *completeness criterion* – a criterion to determine whether a protocol is

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[3] We also introduce a rational choice operator in [7] that is useful for expressing protocols but we will ignore it in this paper.

complete or partial and an *ending criterion* - a criterion to determine the acceptable end-points of a protocol.

Enabling Criteria. Conversation protocols consist of communicative acts that are themselves defined to bring about changes in states. Therefore, it seems intuitive that there must be some relation between the states at the end-point of one protocol and the starting point of another protocol. We call this the *enabling criterion* for composing protocols. For instance, the precondition of the successor protocol must be entailed by the effect of the prior protocol. Also, the commitments at the end point of one protocol and at the starting-point of the next protocol must be related. The enabling criterion is best-expressed using landmarks. Consider for example, two protocols Π_1 and Π_2. Let Lf_1 be the final landmark of the protocol Π_1 and Ls_2 be the starting landmark of the protocol Π_2. The conjunction of propositions in the initial and the final landmarks of Π_1 are represented by $\mathcal{P}(Ls_1)$ and $\mathcal{P}(Lf_1)$ respectively and that of Π_2 by $\mathcal{P}(Ls_2)$ and $\mathcal{P}(Lf_2)$ respectively. A sequential composition $\Pi_1;\Pi_2$ is meaningful if the final landmark of Π_1 entails the starting landmark of Π_2. Formally,

$$\Pi_1;\Pi_2 \text{ is meaningful iff } \vDash \mathcal{P}(Lf_1) \supset \mathcal{P}(Ls_2)$$

Without this entailment relationship, it is difficult to make guarantees about the resulting composition. This same enabling criterion is applicable to substitution (or embedding) composition $\Pi_1[a/\Pi_2]$ at the point of composition. The non-deterministic OR composition $\Pi_1|\Pi_2$ is meaningful if the starting landmarks of Π_1 and Π_2 entail each other. Formally,

$$\Pi_1|\Pi_2 \text{ is meaningful iff } \vDash \mathcal{P}(Ls_1) \equiv \mathcal{P}(Ls_2)$$

In other words, an OR composition of protocols is meaningful if the protocols being composed have the 'same' starting landmark i.e. the protocols being composed should be applicable in the same 'state'. A concurrent composition $\Pi_1||\Pi_2$ is meaningful if the starting and final landmarks of Π_1 are consistent with the starting and final landmarks respectively of Π_2. Formally,

$$\Pi_1||\Pi_2 \text{ is meaningful iff } (\mathcal{P}(Ls_1) \wedge \mathcal{P}(Ls_2)) \text{ and } (\mathcal{P}(Lf_1) \wedge \mathcal{P}(Lf_2)) \text{ are each jointly satisfiable.}$$

Semantically, a concurrent composition of protocols has the same restrictions for the starting landmarks as an OR composition. In addition, when the concurrent protocols end, their end states should be consistent. It is possible to define several other criterions for correctness and legality of protocol compositions [7]. In [7] we also show how to compose the request for action protocol from several (sub)protocols.

3.3 Applying Joint Intention Theory

One can identify several instances where we find ourselves jointly committed to a protocol because of the governing norms [1] of the society, the social institutions, and other institutions that we might be part of. These joint commitments come into effect when a protocol gets instantiated. However, pre-existing societal norms do not cover all conversation protocols; there are also protocols to which we explicitly commit – for instance, two businesses jointly commit to a particular bill-payment protocol when they sign a trade agreement. Whether the joint commitment between the initiator and the participant of a protocol is provided by the governing social norms or by explicit contract, such over-arching joint commitments lead to proper communication, robust protocol execution by handling of exceptional situations, correctness criteria for protocols, and possibly dynamic realization of concrete protocols from protocol families. We express protocol families precisely as landmark expressions in a propositional dynamic logic and therefore, we can apply the joint commitment operator (JPG) directly to protocol families. Similarly, the joint intention operator (JI) can be directly applied to concrete protocols represented as joint action expressions. A number of important properties and behavior can be shown to hold when an overarching joint commitment exists.

Appropriate Communication. JPG specifies that a jointly committed goal will persist until there is mutual belief among the agents involved about its achievement, impossibility or irrelevance. If an agent privately comes to believe that the jointly committed goal has been achieved or is impossible or irrelevant then it will have an individual commitment to bring mutual belief about the privately discovered fact. Establishing mutual belief requires communication of some sort – either by exchanging explicit messages or by mutually understood signaling or by some other means. Therefore, joint commitment towards a protocol family predicts that there will be appropriate communication to establish the required mutual beliefs among the agents involved in any protocol that realizes a protocol family. The initiator and the participant will eventually mutually believe that the protocol execution has been successfully achieved or was impossible or irrelevant. The initiator and the participant of a protocol get jointly committed to that protocol by (1) a mutual belief that there is an over-arching joint commitment towards the protocol family of which the protocol at hand is an instance, and (2) a mutual belief that these agents instantiate the roles involved in the protocol.

Automatic Exception-Handling. Joint commitment characterizes teamwork and agents bound together by joint commitment form a robust team that can handle exceptions, failures, and adverse situations. The persistence of the jointly committed goal and the requirement to establish mutual belief ensures that agents can depend on each other. If something goes wrong the agents will attempt to resolve it by communicating to establish mutual belief. For instance, if an agent does not understand a message, it will communicate this fact to the sender of the message because of the joint commitment. As such, performatives such as "not understood" and "re-transmit" that tend to clutter traditional protocol diagrams are taken care of as a consequence of jointly committing to a protocol. Therefore, such exceptions related to execution of a protocol need not be specified as part of the protocol.

Correctness Criterion. (1) Landmarks are the waypoints towards achieving the goal that a protocol or protocol family is meant for. Therefore, the main correctness criterion for any protocol is whether or not successful execution of that protocol achieves the goal associated with that protocol. The goal associated with a protocol is specified as a proposition that is true only in the final landmark. If there are multiple final landmarks, the goal is true in the 'main' final landmark that represents the successful execution of all protocols in that protocol family. (2) A protocol family specified using landmarks might be used by an intelligent agent with reasoning and planning capabilities to figure out the communicative acts required to achieve the goal associated with that protocol family. However, most agents that lack these capabilities do not care about the landmarks – they need to know the complete communicative action expression that can achieve the required goal. These two cases represent the two possible extremes – on one hand we have landmarks that may consist of mental states internal to an agent and on the other hand we have observable and executable communicative actions. One can think of landmark-based representation as a protocol design specification and a concrete protocol as a protocol implementation. Given a concrete protocol that is completely specified using communicative actions, the assumption of joint commitment towards a protocol family gives another criterion to determine whether or not the protocol is correct – a joint intention towards the action expression representation of a protocol must satisfy the joint commitment towards the landmark expression for that protocol.

Direct Execution. The most practical advantage of applying the joint intention theory to protocols is that joint intention interpreters can then directly execute protocols. We are currently working on implementing a joint intention interpreter for declaratively programming teamwork [6] that is designed to execute team specifications in terms of joint intentions and joint commitments. The direct execution framework is part of an effort to design and implement a multi-agent programming language called STAPLE (*Social and Team Agents Programming Language*) that is formally connected with a logical theory of agency. It is still a work in progress though the interpreter currently executes (with some limitations) fully specified protocols represented as a joint action expression by jointly intending that action expression, thereby nearly eliminating the need to implement a separate protocol handling system.

Next, we discuss some of the related work, and conclude with a summary and direction for future work.

4. DISCUSSION

The present paper extends the work started by Smith and colleagues [11, 12] towards formally integrating protocols and individual communicative acts. A central theme of the current work has been to formally treat conversation protocols as joint actions by representing them as joint action expressions and applying joint intention theory to those expressions. Grosz and Sidner [5] also treat conversations as joint actions but whereas we consider joint actions as actions that parties perform while in the state of having a joint intention, for these researchers, joint actions are actions performed while executing a shared plan. Vongkasem and Chaib-draa have argued in [4] that a conversation in the context of an agent communication language is a joint activity that can be realized as sequences of smaller actions and they propose to view conversation protocols as a joint commitment. The informal ideas presented by Vonkasem and Chaib-draa is to some extent similar to our formal analysis in this paper. Another key idea in the present paper is that protocols are meant to do certain tasks, that is, they have associated goals. Both the landmark based representation for protocol families as well as action expression representation for protocols presented in the current work makes the goal or the purpose of a protocol explicit. Work by Pitt and others [9] explicitly links "successful outcomes" (ostensibly, goals) to conversation protocols but does so by annotating a syntactic framework with semantic summary expressions in such a manner that the two are not directly connected. In [4], Elio and Haddadi informally discuss conversations for joint tasks and jointly maintaining global coherence in a conversation. Dignum and colleagues have analyzed the process of team formation in [4] using structured dialogue in a modal logic different from the one presented here. Pitt and Mamdani [10] and Yolum and Singh [13] have also attempted to address the issue of integrating protocols and individual communicative acts using different approach than ours. Pitt and Mamdani differ from most researchers in taking conversation protocols as the starting point for inter-agent communication, in which the semantics of single utterances are defined within the context of a syntactic protocol definition with some semantic attachments. Similar to the prior work by Smith and Cohen [11], Yolum and Singh explore the idea that states in a conversation protocol are more important than the communicative acts. They propose a way of executing protocols by compiling them into "commitment machines" obtained by constraining finite state machines in certain ways but they do not integrate independently motivated speech acts into their framework.

To conclude, we have presented an approach for formally representing and executing protocols within the framework of joint intention theory. We treat conversation protocols as having associated goals that they are meant to achieve and we proposed a formalism for protocol families using partially ordered landmarks that must be accomplished in order to achieve the goal associated with a protocol of that protocol family. We treat conversation protocols as joint action expressions, define composition of protocols using action expression operators, and give criterion for meaningful compositions. We discussed the consequences of jointly intending protocols and argued that one can gainfully apply the joint intention theory to protocols and their compositions. Future work in the direction of this research includes incorporating groups into protocols. Completing the direct execution interpreter for protocols is another objective of this research.

5. ACKNOWLEDGMENTS

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