A Framework for Specifying Group Decision-Making Mechanisms

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1. INTRODUCTION

Collaborating agents need to make group decisions to establish their initial commitment to a proposed group activity [8] and, once committed, to coordinate the updating of their intentions related to that activity [6]. (We call the first sort *context-free* group decisions and the latter *context-bound*.) In addition, collaborating agents must be able to reason effectively about their participation in group decision-making processes.

To meet these requirements, this paper presents a framework for formally specifying group decision-making mechanisms (GDMMs). This framework, called the GDMM framework, is one component of an integrated agent architecture for a collaboration-capable computer agent [6]. Each GDMM is based on agents making certain declarations, which authorize still other declarations, and so on, until some agent becomes authorized to declare on behalf of the group that they have reached a decision. Using the GDMM framework, a wide variety of mechanisms (e.g., proposal-based or auction-based) can be rigorously specified in a dynamic, deontic, temporal logic that supports both formal analysis by theorists and automated reasoning by participating agents. As an illustration, this paper specifies a sample GDMM and formally analyzes its properties.

2. THE GDMM FRAMEWORK

Agents participate in a GDMM by making declarative speechacts [1]. A GDMM specifies: (1) the allowable *content* of agent declarations (e.g., "a proposal is hereby made"); and (2) the authorization conditions for each type of allowable content (e.g., "an agent is authorized to vote to accept a proposal only if it has not already rejected it"). Finally, it must be possible for some combination of declarations in the GDMM to establish conditions that authorize some agent to declare on behalf of the group that they have reached a decision. Thus, a GDMM is based on the *incremental accumulation of authority*. Once established, a group decision, being a form of agreement, entails certain obligations [9, 5] (e.g., to update one's intentions in accordance with the group decision).

The Logic: DDLTLB. The GDMM framework employs Dynamic Deontic Linear Time Temporal Logic (DDLTLB), developed

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by Dignum and Kuiper [3], to represent speech-acts (in dynamic logic) and social obligations (in deontic logic) within a temporal framework. The main constructs needed by the GDMM framework are: (1) $[A]\phi$, which represents that doing action A would result in proposition ϕ holding; (2) DONE(A), which represents that action A was just done; (3) $\mathcal{P}\phi$, which represents that ϕ held at the previous state; and (4) $\diamond^-\phi$, which represents that ϕ held at some time in the (possibly distant) past. This paper also uses $\diamond^-\phi \equiv \phi \lor \diamond^-\phi$ to represent that ϕ either holds now or held at some point in the past. Finally, $\mathcal{O}(G, GR, X)$, represents that agent G is obliged (to the group of agents GR) to do the action X, where X is a (single-agent) mental action, either to adopt a new intention or to update the contents of an existing intention.

Declarations. Drawing from Dignum and Wiegand [4], the action of agent G declaring to a group GR that proposition ϕ holds is represented by $\delta(G, GR, \phi)$. The speaker is always one of the hearers, but for one-on-one communication we write $\delta(G_1, G_2, \phi)$, not $\delta(G_1, \{G_1, G_2\}, \phi)$.

 $decl(G, GR, \phi)$ represents that G just declared to GR that ϕ holds; it abbreviates $DONE(G, \delta(G, GR, \phi))$. For convenience, we omit certain repeated arguments, writing $\delta(\phi(G, GR, \ldots))$ instead of $\delta(G, GR, \phi(G, GR, \ldots))$ and $decl(\phi(G, GR, \ldots))$ instead of $decl(G, GR, \phi(G, GR, \ldots))$.

Authorization Conditions. The "right circumstances" for making declarations are specified in terms of "authorizing conditions" [4]; however, here, the authorization conditions always include the authorizing party (e.g., the group GR) as an argument. The hearers of a declaration are presumed to be a subset of the authorizing group; and sometimes these two groups will be the same.

 $auth_{\delta}(\phi(G, SG, GR, \ldots))$ represents that G is authorized by the group GR to declare to the subgroup SG that ϕ holds.

AXIOM 1. An authorized declaration establishes the truth of its propositional content: $\models auth_{\delta}(\phi) \Rightarrow [\delta(\phi)]\phi$.

 $authDecl(\phi(G, SG, GR, \ldots))$ represents that G made an authorized declaration that $\phi(G, SG, GR, \ldots)$. It abbreviates $\mathcal{P}auth_{\delta}(\phi(G, SG, GR, \ldots)) \land decl(\phi(G, SG, GR, \ldots))$.

Allowable Content of Declarations. A GDMM specifies the classes of allowable propositional content for agent declarations (e.g., making, accepting or rejecting proposals). Furthermore, such content can *only* be established by authorized declarations.

AXIOM 2. If $\phi(G, SG, GR, ...)$ is allowable content for declarations in a given GDMM, then

 $\models \phi(G, SG, GR, \ldots) \Leftrightarrow authDecl(\phi(G, SG, GR, \ldots)).$

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3. SAMPLE MECHANISM

This section uses the GDMM framework to specify a sample proposal-based mechanism for making context-free group decisions. (The context-bound version is specified in the longer paper [7].) Allowed declarations include making, accepting or rejecting proposals, and announcing group decisions. One agent making a proposal authorizes the others to vote on it. If they all vote to accept it, then the proposer becomes authorized to declare a group decision.

 $\delta(MadeCFP(G_1, GR, GR, I, \alpha))$ is a declaration by G_1 to GR representing a proposal that they commit to doing α , where I is a unique identifier. Any agent is authorized to make such a proposal:

$$= auth_{\delta}(MadeCFP(G_1, GR, GR, I, \alpha)) \Leftrightarrow (G_1 \in GR).$$

 $\delta(AccCFP(G_2, G_1, GR, I, \alpha))$ is a declaration by G_2 to G_1 that G_2 accepts G_1 's proposal. G_2 is authorized to do so if and only if G_1 made the proposal, G_2 has not yet voted on it, and G_1 has not yet announced the group's rejection of it:

 $\models auth_{\delta}(AccCFP(G_2, G_1, GR, I, \alpha)) \Leftrightarrow V_1 \land V_2 \land V_3 \land V_4 \land V_5$

where: $V_1 \equiv \diamond \leftarrow MadeCFP(G_1, GR, GR, I, \alpha)$

$$V_{2} \equiv (G_{2} \neq G_{1})$$

$$V_{3} \equiv \neg \diamond^{\leftarrow} decl(AccCFP(G_{2}, G_{1}, GR, I, \alpha))$$

$$V_{4} \equiv \neg \diamond^{\leftarrow} decl(RejCFP(G_{2}, G_{1}, GR, I, \alpha))$$

$$V_{5} \equiv \neg \diamond^{\leftarrow} decl(GrRejCFP(G_{1}, GR, GR, I, \alpha))$$

Voting to reject a proposal is handled similarly [7].

 $\delta(GrAccCFP(G_1, GR, GR, I, \alpha))$ is a declaration by G_1 that the group GR has decided to commit to doing α together. G_1 is authorized to do this if and only if G_1 made the proposal, G_1 has not yet announced the group's acceptance or rejection of it, and the rest of the agents voted to accept it:

$$\models auth_{\delta}(GrAccCFP(G_1, GR, GR, I, \alpha)) \Leftrightarrow A_1 \land A_2 \land A_3 \land A_4$$

where: $A_1 \equiv \diamond^{\leftarrow} MadeCFP(G_1, GR, GR, I, \alpha)$
 $A_2 \equiv \neg \diamond^{\leftarrow} decl(GrRejCFP(G_1, GR, GR, I, \alpha))$
 $A_3 \equiv \neg \diamond^{\leftarrow} decl(GrAccCFP(G_1, GR, GR, I, \alpha))$
 $A_4 \equiv (\forall G \in GR, G \neq G_1)$
 $\diamond^{\leftarrow} AccCFP(G, G_1, GR, I, \alpha)$

Declaring a group's rejection of a proposal is handled similarly [7].

Entailed Obligations. A context-free group decision obliges each agent to adopt an intention "that GR does α ":

AXIOM 3.
$$\models GrAccCFP(G_1, GR, GR, I, \alpha) \\ \Rightarrow (\forall G \in GR) \mathcal{O}(G, GR, AdoptInt(I, \alpha, GR))$$

It also obliges them to coordinate the subsequent updating of these individually-held intentions by refraining from updating them unless authorized to do so by a group decision [7, 6].

4. ANALYSIS OF SAMPLE GDMM

This section presents theorems that characterize the robustness of the sample GDMM. The analysis presumes a KD45 modal belief operator [2], as well as several axioms concerning agent beliefs. Only glosses of the axioms are given; the formal representations are given in the longer paper [7], as are the proofs. Axioms about Agent Beliefs. First, the hearers of a declaration have correct and complete mutual belief about the occurrence of that declaration. Second, agents only make declarations they believe they are authorized to make. Third, every agent has correct and complete beliefs about agent identity and membership in sets. Fourth, if G believes that ϕ held at some past time, then at some past time G believed that ϕ .

Theorems. Theorem 4 states that agents have sound beliefs about various declarations made during a context-free group decision-making session. Theorem 5 states that an agent will only declare that the group has made a context-free decision if such a declaration is authorized. Theorem 6 states that if an agent believes that another member of the group announced a group decision, then that agent did in fact make such a declaration and it was authorized.

THEOREM 4.
$$\models Bel(G, \Theta) \Rightarrow \Theta$$
, where Θ is any of:
(a) $\Theta \equiv \diamond^{\leftarrow} authDecl(MadeCFP(G_1, GR, GR, I, \alpha))$

(b)
$$\Theta \equiv auth_{\delta}(AccCFP(G, G_1, GR, I, \alpha)), or \\ \Theta \equiv auth_{\delta}(RejCFP(G, G_1, GR, I, \alpha))$$

(c) $\Theta \equiv AccCFP(G, G_1, GR, I, \alpha)$

(d)
$$\Theta \equiv auth_{\delta}(GrAccCFP(G_1, GR, GR, I, \alpha))$$

THEOREM 5.

$$\models decl(GrAccCFP(G_1, GR, GR, I, \alpha)) \\\Rightarrow authDecl(GrAccCFP(G_1, GR, GR, I, \alpha)).$$

THEOREM 6.

$$\models Bel(G, \diamond^{\leftarrow} decl(GrAccCFP(G_1, GR, GR, I, \alpha))) \\ \Rightarrow \diamond^{\leftarrow} authDecl(GrAccCFP(G_1, GR, GR, I, \alpha)).$$

The longer paper [7] extends these theorems to context-bound group decisions. Thus, agents can rely on their beliefs about declared group decisions, whether context-free or context-bound.

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