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ABSTRACT: Though communication is a vital ingredient of Cooperative Problem Solving (CPS) in multiagent systems (MAS), an in-depth analysis of different types of communication has been missing in the MAS literature. This paper presents an investigation into the role that five specific types of dialogue play during consecutive stages of CPS in BDI systems, i.e., *potential recognition*, *team formation*, *plan formation*, and *team action*. The presented approach is based, on the one hand, on our theory of social and collective motivational attitudes in BDI systems, with collective commitment as a central concept. On the other hand, the typology of dialogues given by Krabbe and Walton is exploited. The relevant dialogue types are: *persuasion*, *negotiation*, *inquiry*, *deliberation*, and *information seeking*. The whole process of dialogue among computational agents needs to be transparent. Thus, at each level of CPS the agents' internal attitudes need to be established, and then updated and revised when needed.

1 INTRODUCTION

In multiagent systems (MAS), especially in BDI (Belief, Desire, Intention) systems, teamwork is a crucial notion. An explicit model of teamwork requires that agents' informational attitudes (beliefs) and motivational attitudes (goals, intentions, commitments) are first-class citizens. In this paper, we try to show how these team attitudes can be established by dialogue in the context of a changing, and often unpredictable, environment.

In any form of CPS, vital ingredients are *cooperation*, *coordination*, and *negotiation* in the broad sense. Designers of MAS try to achieve a good balance between communication and reasoning. In recent systems models of communication range from rather inflexible communication protocols to more sophisticated constructions based on speech acts. What is missing is a more in-depth analysis of different types of communication. This sort of discussion may be profitable whenever communication technologies are considered, e.g. in MAS. Our approach to communication is based on the typology of dialogues given by Krabbe and Walton (Walton and Krabbe 1995), working in the strong tradition of argumentation theory and infor-

mal logic. In their framework the dialogue types are: *persuasion*, *negotiation*, *inquiry*, *deliberation*, *information seeking*, and *eristics*. As we consider only cooperative teams, eristics, i.e. verbal fighting between agents, has been left out. In the paper we first give a short characterization of the above dialogue types. Next, we discuss their role during teamwork.

In their dialogue theory, Krabbe and Walton are not interested in informational and motivational attitudes of agents involved in the dialogue, unless these attitudes are communicated explicitly. However, for communication among computational agents, we need to make the whole process transparent. For this reason, at each level of teamwork the agents' internal attitudes need to be established, and then carefully updated and revised. The analysis of teamwork is based on the model by Wooldridge and Jennings (Wooldridge and Jennings 1999), containing the four consecutive stages of *potential recognition*, *team formation*, *plan formation*, and *team action*. Taking into account the unpredictable environment, all four stages have a dynamic character and require methods reflecting this. When defining the levels we abstract from particular methods and algorithms meant to real-

ize level-associated goals, but instead formulate their final results and associate them with appropriate individual, social, and collective motivational attitudes (see (Dunin-Kęplicz and Verbrugge 2000) for extended discussion). In the present paper we show which dialogue types are involved in CPS at different stages.

The theory of collective motivational attitudes focuses on static aspects of CPS. In (Dunin-Kęplicz and Verbrugge 1996; 2002) we have provided a formalization of social and collective motivational attitudes of agents within strictly cooperative groups. Special attention was paid to the strongest attitude: *collective commitment*. We find that commitments are stronger than intentions, in the sense that it is commitments, not intentions, that trigger action execution. Our formal characterization of collective commitments is viewed from the perspective of teamwork, which is reflected in a plan towards achieving a given goal. The collective commitment hinges on pairwise social commitments between the team members to realize the actions resulting from the generated decomposition of the overall goal. The static theory of motivational attitudes in teamwork is formalized in a multi-modal logic framework. In (Dunin-Kęplicz and Verbrugge 2002) we present axioms defining these notions and their semantics. Unfortunately, for lack of space we cannot repeat them here.

The proper treatment of collective commitments in a dynamically changing environment entails the maintenance of all individual, social and collective attitudes involved. In other words, a dynamic environment poses the problem that team members may fail to bring their tasks to a good end or new opportunities may appear. This leads to the *reconfiguration problem* which may be treated as the core of plan execution. It has been the main subject of (Dunin-Kęplicz and Verbrugge 2000): in terms of generic levels and their interplay an efficient and flexible *reconfiguration algorithm* has been specified. The algorithm is meant to be generic: a pattern of behavior is described in terms of abstract level-associated procedures, viewed as a sort of black boxes with specified input and output parameters. The next step should be a transformation of *black boxes* into *glass ones*. The investigation into the role that specific types of dialogue play at different stages of CPS is an integral part of this.

The paper is structured in the following manner. Section 2 presents characteristics of dialogue types that appear in CPS. The CPS process can be divided into four stages. On the basis of this structure, in sections 3, 4, 5 and 6 different dialogue types that are involved during consecutive stages are described, with an emphasis on the stages of plan formation and team action. Finally, sections 7 and 8 present a discussion of related work, conclusions, and further research.

Dialogue can be defined as the process of communication among two or more agents. Agents speak in turn, for example asking questions and giving replies, and take into account, at each turn, what has occurred previously. The score of the dialogue is kept by each agent as an *attitude store*, to which propositions may be added or retracted during the dialogue in an orderly way. These propositions represent informational attitudes like individual beliefs ($BEL(a, \varphi)$) or collective beliefs within a group ($C-BEL_G(\varphi)$). In the MAS context they may also represent motivational attitudes like individual goals ($GOAL(a, \varphi)$), individual intentions ($INT(a, \varphi)$), collective intentions ($C-INT_G(\varphi)$), social commitments ($COMM(a, b, \varphi)$), and collective commitments in their strong and weak forms ($SC-COMM_{G,P}(\varphi)$ and $WC-COMM_{G,P}(\varphi)$). See (Dunin-Kęplicz and Verbrugge 2002; 2003) for formal definitions and discussion of these attitudes.

Krabbe and Walton (Walton and Krabbe 1995) provide a typology of dialogue types between two agents, with an emphasis on the persuasion dialogue. For each type of dialogue, they formulate *an initial situation*, *a primary goal*, and *a set of rules*. These constitute a *normative model*, representing the ideal way reasonable, cooperative agents participate in the type of dialogue in question, and not a record of real dialogues. Below, their typology is shortly explained and adapted to the MAS perspective. In the course of communication, there often occurs a shift from one type of dialogue to another. Specifically *embedding* occurs when the second dialogue is functionally related to the first one and improves its quality. For example, a persuasion dialogue about the truth of a proposition may need an information-seeking subphase.

2.1 Persuasion

A persuasion dialogue arises from a conflict of opinions. It may be that one agent believes φ while some others either believe a contrary proposition ψ_i (where $\varphi \wedge \psi_i$ is inconsistent) or just have doubt about φ . The goal of a persuasion dialogue is to resolve the conflict by verbal means, in such a way that a stable agreement results. In the multi-agent context, this would mean that the end result is a collective belief $C-BEL_G(\chi)$, where χ may be the φ of the first agent or one of the ψ_i 's that the other agents started out with, or yet another conclusion that replaces the original belief. Clearly, belief revision takes place here.

Initially, all agents have attitude stores consisting of *theses* and *concessions*. Here, the theses are assertions they are prepared to defend (like φ for the first agent above), while concessions are propositions that are taken for granted for the sake of argument. Krabbe and Walton provide many rules governing the ways that the attitude stores may change during persua-

sion, especially the situations in which concessions and theses may be retracted. In the MAS context we need to define a new kind of persuasion not found in Krabbe and Walton, namely *persuasion with respect to motivational attitudes*. This type of dialogue arises from a conflict of intentions, where one agent intends to achieve φ , while some other agents have a conflicting intention to achieve ψ_i (where φ and ψ_i are inconsistent) or simply lack any positive motivational attitude with respect to φ . The main goal of this type of persuasion is to resolve this conflict in such a way that a stable collective intention results.

2.2 Negotiation

The initial situation of negotiation is a conflict of interests, together with a need for cooperation. The main goal is to make a deal. Thus, the selling and buying of goods and services, that is often described in the MAS literature, is only one of the many contexts where negotiation plays a role in MAS. Negotiation and persuasion are often not distinguished adequately. One has to keep in mind that the main aim of negotiation is not to convince the others that one's view is right, as it is in persuasion, but to make a deal about a course of action. Also, in general it is not allowed to embed negotiation into persuasion, because bargaining and substituting offers for arguments does not lead to a stable agreement. On the other hand, persuasion may be embedded into negotiation, e.g. when setting up the agenda. The rules governing negotiation include severe restrictions on retracting concessions, which are represented mostly as courses of action. For example, if an agent has conceded that it is prepared to execute some action (e.g. to sell a product for a certain price) it may not generally retract this concession.

2.3 Inquiry

The initial situation of inquiry is one where all agents are ignorant about the solution to some question or open problem. The main goal is the growth of knowledge, leading to agreement about the conclusive answer of the question. This goal is attained by a incremental process of argument which builds on established facts in order to prove conclusions beyond a reasonable doubt. Both information retrieval and reasoning are used in this process. In terms of informational attitudes the end result is at least as strong as $C\text{-BEL}_G(\varphi)$. In some contexts it may even be common knowledge $C\text{-KNOW}_G(\varphi)$. If one agent reaches an intermediate or final conclusion before the others, it needs to convince the others by persuasion. Thus, a persuasion dialogue may be embedded into inquiry. On the other hand, in persuasion sometimes an open problem appears which needs to be settled before the persuasion can continue; in this case, inquiry is embedded into the persuasion dialogue.

2.4 Deliberation

Deliberation is similar to inquiry, and different from both persuasion and negotiation as it starts from an open problem, rather than from a conflict of opinion. The initial situation for deliberation is a need for action performance and is concerned with the future. The goal is to reach a decision on how to act, for the time being.

The kind of reasoning that is central to deliberation, and in general to BDI systems, is *practical reasoning*: goal-directed, knowledge-based reasoning where an agent considers different means of achieving a goal. A typical example of practical inference is means-end analysis, linking a particular goal or intention an agent is committed to with a possibly complex action.

2.5 Information seeking

The initial situation of information seeking occurs when one agent is ignorant about the truth of a certain proposition and seeks information from others to gain more knowledge. In terms of informational attitudes, the end result is a new individual belief $\text{BEL}(a, \varphi)$ of the information seeking agent a .

In contrast to inquiry, the need for proof is not strong in information seeking, and it is not necessary to establish a collective belief. An example of this dialogue type occurs in expert consultation, which is useful if the questioner has no direct access to information.

2.6 Trust in dialogues

Whenever communication between agents appears, the question of trust is inevitably involved. Though this paper is not meant to be yet another voice in the discussion about trust in commonsense reasoning, in order to make communication and reasoning based on it more context-sensitive, it is useful to distinguish different notions or levels of trust.

For example, an agent can trust the other completely: ($\text{TRUST}(j, i)$ for j trusts i), or partially (e.g. $\text{TRUST}_\psi(j, i)$ for j trusts i w.r.t. formula ψ). See (Castelfranchi and Tan 2001) for interesting discussions about trust in MAS.

It seems that in information seeking and inquiry, the speaker's assertions are believed by the hearer (and believed by him to be believed by the speaker) as long as trust is present. Thus, after agent i asserts ψ to agent j in such a context, we have:

$$\text{TRUST}_\psi(j, i) \rightarrow \text{BEL}(j, \psi) \wedge \text{BEL}(j, \text{BEL}(i, \psi))$$

For negotiation and persuasion, this need not hold.

In the next four sections, we will concentrate on the different types of dialogue involved in the realization of level-oriented goals at the four stages of CPS.

The starting point of the CPS process is the overall goal that should be achieved. In this paper, as in (Wooldridge and Jennings 1999), we restrict ourselves to the situation with one fixed goal and one agent that takes the initiative to achieve it. Also, we consider CPS to begin when some agent in a multi-agent environment recognizes the potential for cooperative action to reach the goal φ of the system.

The first task of the *initiator* is to form a partial (abstract) plan for the achievement of the overall goal. On the basis of the (type of) recognized subgoals that it recognizes it will determine which agents might be most suited to form the team. In order to determine this match the initiator tries to find out the properties of agents, being interested in three aspects, namely their *abilities*, *opportunities*, and *willingness* to participate in team formation. The aspect of ability considers whether the agents can perform the right type of tasks. Ability does not depend on the situation, but may be viewed as an inherent property of the agent itself. The aspect of opportunities takes into account the possibilities of task performance in the present situation. It involves resources and possibly other properties. The aspect of willingness concerns a mental attitude towards participating in the team: very capable agents that do not want to do the job are of no use.

3.1 Information seeking for potential recognition

Ultimately, the initiator has to form beliefs about the abilities, opportunities, and willingness of individual agents in order to derive fact that initiator a sees a potential for cooperation with respect to goal φ ($\text{PotC}(a, \varphi)$), as defined in (Dunin-Kępicz and Verbrugge 2000). The initiator can do this by asking every agent about its properties, followed by the agent responding with the requested information about abilities, opportunities and willingness. This information seeking process, including the relevant speech acts and their effects on the agents' mental states, is described in detail in (Dignum et al. 2001).

4 LEVEL 2: TEAM FORMATION

Suppose that agent a sees the potential for cooperation to achieve φ . Somewhat different from (Wooldridge and Jennings 1999), we find that during team formation, agent a attempts to bring it about in some group G that the group has a *collective intention* to make the overall goal φ true. The input of this stage is agent a , a formula φ and sequence of potential groups output by stage 1. The successful outcome of this stage is one group G from the sequence, together with a collective intention $\text{C-INT}_G(\varphi)$ among G to achieve φ .

The main type of dialogue at this stage is *persuasion with respect to motivational attitudes*. This arises from a conflict of intentions, where $\text{INT}(a, \varphi)$ while some other agents in the potential team have a conflicting intention $\text{INT}(i, \psi_i)$ or simply lack any positive motivational attitude with respect to φ . In the case of team formation the persuasion is one-sided so that in the end all agents adopt a 's intention to achieve φ . In contrast to persuasion with respect to informational attitudes, bargaining may be appropriate within a persuasion dialogue with respect to motivational attitudes. For example, during team formation potential team members may be reasonably persuaded using an embedded negotiation about return favors from agent a . In (Dignum et al. 2001), a detailed analysis of the persuasion dialogue during team formation is given, including formal rules in terms of speech acts.

5 LEVEL 3: PLAN GENERATION

The input of this stage is a team G together with its collective intention to achieve a goal φ . The successful outcome is a collective commitment of the group G based on the social plan P . Here we give a short description of strong and weak collective commitments ($\text{SC-COMM}_{G,P}(\varphi)$ and $\text{WC-COMM}_{G,P}(\varphi)$). A wider variety of collective commitments suitable for different types of organizations and environments is presented in (Dunin-Kępicz and Verbrugge 2003).

A collective commitment among a group G based on a social plan P can only be established or maintained if the group has the associated collective intention $\text{C-INT}_G(\varphi)$. Furthermore, the plan should result from the main goal by task division, means-end analysis, and action allocation, as reflected in $\text{constitute}(\varphi, P)$.

In addition, for every one of the actions α that make up plan P , there should be one agent i in the group who is socially committed to at least one (mostly other) agent j in the group to do the action, reflected in social commitments between pairs of agents ($\text{COMM}(i, j, \alpha)$). Moreover, there should be a collective belief in the group that the plan will be entirely realised, i.e. that all actions have been adopted by committed members of the group ($\text{C-BEL}_G(\bigwedge_{\alpha \in P} \bigvee_{i, j \in G} \text{COMM}(i, j, \alpha))$). When the group is planning collectively, so that in the end the plan is completely known to all members ($\text{C-BEL}_G(\text{constitute}(\varphi, P))$) the definition of strong collective commitment is as follows:

$$\begin{aligned} \text{SC-COMM}_{G,P}(\varphi) &\leftrightarrow \text{C-INT}_G(\varphi) \wedge \\ &\text{constitute}(\varphi, P) \wedge \text{C-BEL}_G(\text{constitute}(\varphi, P)) \wedge \\ &\bigwedge_{\alpha \in P} \bigvee_{i, j \in G} \text{COMM}(i, j, \alpha) \wedge \\ \text{C-BEL}_G &(\bigwedge_{\alpha \in P} \bigvee_{i, j \in G} \text{COMM}(i, j, \alpha)) \end{aligned}$$

The definition of weak collective commitment is analogous, except that the conjunct $C-BEL_G(\text{constitute}(\varphi, P))$ is missing: there is no collective awareness that the plan P is correct.

In the AI and MAS literature many methods of planning have been proposed. In our perspective, the most interesting one is *planning from first principles*. In MAS, we may assume that this method includes *task division*, *means-end analysis*, and *action allocation*. We will discuss this method now.

During a successful run of plan generation, first, an adequate task division of φ into a sequence of (possibly complex) subtasks $\varphi_1, \dots, \varphi_n$ is constructed. These subgoals are viewed as instrumental to the overall goal and are compared with the individual capabilities and opportunities that the agents are believed to have.

This step is followed by *means-end analysis*, in which actions are associated to the subtasks constructed in task division, and, during *action allocation*, these are given to team members. This results in pairs $\langle \alpha, i \rangle$ of a possibly complex action α that realizes task φ_j and an agent i . For an appropriate allocation of actions to agents, the agents' abilities and resources are taken into account. To make a social plan complete, the temporal structure among the pairs $\langle \alpha, i \rangle$ should be established.

5.1 Deliberation during plan generation

During planning from first principles, *deliberation* is typically the main kind of dialogue. The desired outcome is a collective commitment based on a social plan. It turns out that different kinds of dialogue are phases within this complex stage. We subsequently treat the dialogues during task division, means-end analysis, and action allocation.

5.1.1 Task division

When establishing a collective commitment, the main part of **task division** is discussion of proposals. Krabbe and Walton define this as a subtype of the persuasion dialogue. Thus, *persuasion* is embedded into deliberation. The outcome of this phase should be a sequence of subtasks $\varphi_1, \dots, \varphi_n$ and a collective belief that execution of these subtasks leads to realization of the main goal, reflected in

$$C-BEL_G(\text{realize}(\langle \varphi_1, \dots, \varphi_n \rangle, \varphi)).$$

Information exchange during persuasion

During information exchange, the agents make clear their initial stand with respect to combinations of subtasks that might help to achieve the overall goal. These issues are expressed partly in the form of intentions and beliefs. Other beliefs supporting or related to the above issues might also be exchanged already.

Only when a conflict arises about these issues a persuasion dialogue has to take place. In each persuasion there are two parties or roles; the proponent (P) and the opponent (O). In our case the proponent could be the initiator and the opponent one of the other agents.

The stands the other agents take about the above issues are seen as initial *concessions*. Concessions are beliefs and intentions that an agent takes on for the sake of argument, but need not be prepared to defend. The agents will also have private attitudes that may only become apparent later on during the dialogue. The stand of the initiator is seen as the initial thesis that it is prepared to defend during the dialogue. The initial conflict description consists of a set of O's initial concessions and P's initial thesis.

Rigorous persuasion

During rigorous persuasion the agents exchange arguments to challenge or support a thesis. The following rules can be used to govern these moves adapted from (Walton and Krabbe 1995).

1. Starting with O the two parties move alternately according to the rules of the game.
2. Each move consists of either a challenge, a question, a statement, a challenge or question accompanied by a statement, or a final remark.
3. The game is highly asymmetrical. All P's statements are assertions, and called *theses*, all O's statements are called *concessions*. P is doing the questioning and O the challenging.
4. The initial move by O challenges P's initial thesis. It is P's goal to make O concede the thesis. P can do this by questioning O and thus bridge the gap between the initial concessions of O and the thesis, or by making an assertion to clinch the argument if acceptable.
5. Each move for O is to pertain to P's preceding move. If this move was a question, then O has to answer it. If it was an assertion, then O has to challenge it.
6. Each party may give up. If O's concessions imply P's thesis, then P can end the dialogue by the final remark ("I won"). After this, agent i is obliged to state that it has been persuaded and accepts the thesis ψ , for example that a certain task division is correct. This does not mean that i will actually make this assertion! Just that there is an obligation by the rules of the game.
7. All challenges have to follow logical rules. For example, a thesis $A \wedge B$ can be challenged by challenging one of the two conjuncts.

In the completion stage the outcome is made explicit, such that the agents either have a collective belief or they know that they differ in opinion.

Speech acts during persuasion

In contrast to Walton and Krabbe, we need to monitor agent's informational and motivational attitudes during persuasion, as well as during other stages of CPS. In the course of dialogue we are concerned with assertions, challenges, concessions and requests. A detailed discussion and formal implementation of these speech acts is presented in (Dignum et al. 2001).

5.1.2 Means-end analysis

The next phase, **means-end analysis**, may be seen as *inquiry*, resulting in a collective belief that the actions α_i are means that realize the subtasks φ_i , formally: $C-BEL_G(\bigwedge_{i=1}^n \text{means-for}(\alpha_i, \varphi_i))$.

5.1.3 Action allocation

Inquiry and *information seeking* are the types of dialogue usually needed during **action allocation**. During this phase a social plan is devised to realize the sequence of subtasks $\varphi_1, \dots, \varphi_n$. A subphase of this occurs when team members are asked about their abilities, opportunities, etc. as on level 1, but now more seriously. In this case *information seeking* is embedded in inquiry.

Even though agents have established a collective intention $C-INT_G(\varphi)$, being self-interested they usually still have a conflict of interests during action allocation. Thus, the agents may *negotiate* to devise a social plan reflecting the agents' individual interests in a way accepted by all of them. In the end of action allocation for strong collective commitments, $\text{constitute}(\varphi, P)$ is announced by a collectively trusted team member, resulting in a collective belief: $C-BEL_G(\text{constitute}(\varphi, P))$.

During establishment of a weak collective commitment, on the other hand, there are less constraints as to mental states to be achieved during task division, means-end analysis and action allocation: the dialogues generally occur not among the group as a whole, but among subgroups of agents and the initiator. In such a case it suffices if only the initiator believes that task division, means-end analysis, and action allocation have the correct results:

$$BEL(a, \text{realize}(\langle \varphi_1, \dots, \varphi_n \rangle, \varphi)) \text{ and } BEL(a, \bigwedge_{i=1}^n \text{means-for}(\alpha_i, \varphi_i)).$$

For both types of commitments, the end product of action allocation is the same. For each action α in the social plan, we suppose that the individual intention of one agent, say i , to execute it is in place, so $INT(i, \alpha)$; and that there is another agent, say j , who is interested for i to execute this action (for example because he needs the result to carry out his own allocated actions), so $GOAL(j, \text{done}(i, \alpha))$ is in place. Then, by communication between them,

the collective belief about both attitudes is created (similar to *promises* as analyzed in (Searle 1969, Chapter 3)):

$$C-BEL_{\{i,j\}}(INT(i, \alpha) \wedge GOAL(j, \text{done}(i, \alpha))).$$

Altogether, this creates a social commitment $COMM(i, j, \alpha)$ from i to j with respect to α , defined as follows, where $\text{done}(i, \alpha)$ means that agent i has just executed action α :

$$COMM(i, j, \alpha) \leftrightarrow INT(i, \alpha) \wedge GOAL(j, \text{done}(i, \alpha)) \wedge C-BEL_{\{i,j\}}(INT(i, \alpha) \wedge GOAL(j, \text{done}(i, \alpha)))$$

In effect, all interested agents socially commit to carry out their actions, resulting in $\bigwedge_{\alpha \in P} \bigvee_{i,j \in G} COMM(i, j, \alpha)$. Finally, a collective belief $C-BEL_G(\bigwedge_{\alpha \in P} \bigvee_{i,j \in G} COMM(i, j, \alpha))$ about this is created, for example by an announcement from a collectively trusted member (e.g. the initiator). This concludes the collective part of plan generation, by which the collective commitment is established.

5.1.4 Embeddings during plan generation

To sum up, a number of functional embeddings is appropriate in the deliberation dialogue. First, during task division, a persuasion dialogue is embedded into it, which may have inquiry and information seeking as subphases in its turn.

Then, during action allocation, first an inquiry (possibly with its own subphases of information seeking and negotiation) is embedded into deliberation. Then, if necessary, negotiation (possibly with subphases of inquiry and information seeking) is embedded. Finally, in order to establish pairwise social commitments, information seeking is embedded into deliberation.

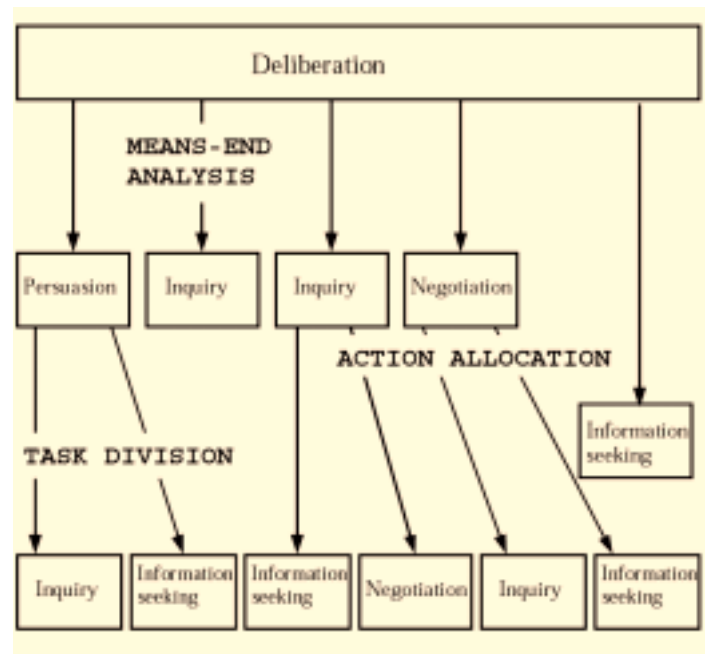


Figure 1: possible dialogue embeddings during different phases of plan generation

Another planning method adopted in MAS uses a *plan library* of more or less instantiated partial plans. Input and output of this level is obviously the same as before. However, the dialogue types involved are less complex here, depending on the degree of plan instantiation. Because we deal with a variety of possibilities, we will not discuss them in detail.

6 LEVEL 4: TEAM ACTION

Even though potential recognition, team formation and plan generation have been extensively discussed in the MAS literature, the phase of team action has received relatively little attention. The requirements of a constantly changing environment lead to the *reconfiguration problem*: when maintaining a collective intention during team action, it is crucial that agents replan properly and efficiently when some members do not fulfill their delegated subtasks or are presented with new opportunities. The solution of this problem leads to the *reconfiguration algorithm* formulated in terms of the abstract levels and their (complex) interplay, see (Dunin-Kępicz and Verbrugge 2000). A forthcoming paper deals with the evolution of collective commitments during reconfiguration.

Team action includes *execution* of agent-specific actions from the collective commitment. Because many different situations may occur, this usually leads to the *reconfiguration procedure*. In terms of motivational attitudes, team action amounts to the maintenance of *social commitments* and associated *individual intentions*. During this process communication, including all types of dialogue, cooperation, and coordination take place.

The successful outcome of team action is that all subtasks making up the social plan P have been carried out by the agents who were socially committed to do them, and by the success of their actions the goal φ of the collective commitment has been achieved. The successful realization of team action finishes the evolution of the team and its motivational attitudes. Before this favorable situation takes place, all aspects of evolution of collective commitment are treated in the reconfiguration process.

6.1 Dialogues during team action

Depending on the application domain and the collective commitment in question, all types of dialogue may occur during *execution of actions* by team members. For example, in scientific collaboration, the whole team action stage may be viewed as *inquiry*. When team members ask the others for intermediate and final results of their individual research, *information seeking* is embedded into inquiry. *Persuasion* also occurs as a subphase of inquiry when one agent has found a result that the others do not know yet. Thus, by information seeking and persuasion, agents' indi-

vidual beliefs are transformed into collective beliefs. In the positive case, the collective commitment is realized according to the original plan. The success of the system is then communicated to the whole team, for example by an announcement from the initiator. The effect on their mental states depends on their level of trust in the initiator.

In the negative case, the *reconfiguration procedure* is followed, leading to an assignment of new social and individual motivational attitudes in order to create a new collective commitment. This may be viewed as *revision* of motivational and informational attitudes. From a pragmatic point of view, proper revision is possible, because it is assumed that agents are obliged to communicate about changes. On the other hand, the presence of social commitments *only* between interested partners ensures that motivational attitudes revision is as efficient as possible.

Following the reconfiguration algorithm, if an obstacle appears, the problems are solved by moving up in the hierarchy of levels, but as little as possible: to the nearest point up where a different choice is possible. If such a point does not exist anymore, the reconfiguration algorithm fails. In technical terms, depth-first search is used. This means that exactly those dialogue types play a role that correspond to the stages up in the hierarchy which need to be revisited in order to make a new collective commitment.

Let us trace the evolution of the system during realization of the reconfiguration algorithm. We will focus on the points where failure of the four main stages of the process takes place. In all the following situations, all mental attitudes related to the current level are revised, and information exchange between interested agents is realized when needed.

The failure of potential recognition, meaning that agent a does not see any potential for cooperation with respect to the goal φ , leads to total failure of the system and ends up its evolution. The initiator announces this failure to all relevant agents, leading to their individual or collective belief in this, depending on their level of trust in a .

The failure of team formation, meaning that the collective intention cannot be established among any of the teams, requires a return to potential recognition to construct a new sequence of potential teams. Mostly *information seeking* is involved here.

The failure of task division requires a return to team formation in order to establish a collective intention in the chosen new team. This may be viewed as the evolution of the team together with the evolution of motivational attitudes on the level of collective intention and respective individual attitudes. In this case *persuasion* is the main type of dialogue involved.

The failure of action allocation (assumed here to start with means-end analysis as a technical prepro-

cessing substage), requires return to task division in order to create a new sequence of tasks. This may be viewed as the evolution of the first part of a social plan P to realize the goal φ . Here, *deliberation* with all other embedded dialogue types takes place.

Finally, during team action, after the failure of some actions together constituting the social plan, the reasons of failure have to be recognized. Depending on the outcome, either the system fails, or returns to task division, means-end analysis or action allocation. Then again, different types of dialogue take place, as treated in section 5.

7 DISCUSSION OF RELATED WORK

Our approach is based on the typology of dialogues given by Krabbe and Walton, which has also inspired (Reed 1998). In that paper, Reed gives a formal definition of dialogue frames and functional embeddings, together with some simple examples of dialogues formulated in his formal language. However, he does not explain how these dialogues actually play a role in CPS, nor does he associate them to the construction of individual, social, and collective informational and motivational attitudes, as we do.

Related work can be found in (Parsons et al. 1998), that also presents an agent architecture and a representation for agent communication. In the discussion they note that their own “negotiation” in fact covers a number of Walton and Krabbe’s different dialogue types. We find the more fine-grained typology to be very useful when designing agents for teamwork: one can use specific sets of rules governing each type of dialogue as well as the possible embeddings between the different types. Thus desired kinds of communication are allowed and harmful ones prevented, without completely fixing any protocol. Also (Parsons et al. 1998) use multi-context logic whereas we stick to (multi-)modal logic.

8 CONCLUSIONS AND FURTHER RESEARCH

In our previous work (Dunin-Keplicz and Verbrugge 2000) it was shown how CPS can be divided into four stages, each of them resulting in specific motivational attitudes that are formally described. In the present paper the stages are related to specific types of dialogue. It is also shown for each stage which dialogue types may be appropriately embedded into the other.

In (Dignum et al. 2001), the analysis of the present paper is taken a step further, down to the level of speech acts. It is shown for the first stages of potential recognition and team formation which rules govern the dialogues and how the moves within these dialogues can be expressed by formally represented speech acts. The complete formal description of the dialogues has thus been made possible. This way, it will be possible to prove that in given circumstances

the dialogue results in a certain outcome. This is of prime importance when constructing a MAS for automated CPS. Also, the theory is illustrated by a running example of dialogues and their effects during the first two stages of teamwork in a travel agency domain.

The first issue for further research is to complete the formal normative model of CPS related dialogues. Thus, one needs to construct a complete set of formal rules for all the types of dialogue and indicate how these are implemented through formal speech acts. In particular, formal rules should be formulated for negotiation, deliberation, and inquiry. This would make it possible to extend the analysis initiated in (Dignum et al. 2001) to plan formation and execution.

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