Computational Theories of Collaboration

Ph.D. Comprehensive Exam

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1 Introduction to Collaboration Theories

The construction of computer systems that are intelligent, collaborative problem-solving partners is an important goal for both the science of AI and its application. There is no question that there is a need to make computer systems better at helping us do what we use them to do. collaboration must be designed into systems from the start; it cannot be patched on. To build collaborative sys- tems, we need to identify the capabilities that must be added to individual agents so that they can work with other agents [13].

Most collaborative situations involve agents who have different beliefs and capabilities. Partial knowledge is the rule, not the exception. As a result, collaborative planning requires an ability to ascribe beliefs and intentions.

Another feature of collaborative activity is collaborative plans are not simply the sum of individual plans.

To be collaborative, partners, e.g., a robot and a human, need to meet the specifications stipulated by some theories that we review in this document. As we discuss in Section 3.2, collborators need to commit to the group activity and to their role in it; they need to divide the task load according to their capabilities so they can carry out the individual plans that constitute the group activity; and they need to commit to the success of others. Collaborators also need to be able to communicate with others effectively, and to interpret others' actions and utterances in the collaboration context. Furthermore, collaborators need to be willing to help others in doing their own tasks, and to reconcile between commitments to existing collabortion and their other activities [14].

Collaboration is a special type of coordinated activity in which the participants work jointly, together performing a task or carrying out the activities needed to satisfy a shared goal [18].

Existing collaboration theories (including SharedPlans) consider the nature of a collaboration to be more than a set of individual acts. These theories argue for an essential distinction between a collaboration and a simple interaction or even a coordination in terms of commitments [12, 30].

2 Teamwork & Collaboration

Bratman's view is that collective intention can be described by referring to individual intention in combination with other mental attitudes. Searle's opposing view is that collective intention cannot be so reduced.

3 Computational Theories of Collaboration

There are prominent collaboration theories that are mostly based on plans and often analysis of the discourse between collaborators revolving around these plans [20, 29]. In these theories the discourse analysis is based on search over these tree plans [40].

The two theories Joint Intentions and SharedPlans have been extensively used to examine and describe teamwork.

Two important theories for modeling teamwork collaboration were derived from the BDI paradigm.

3.1 Theory of Joint Intentions/Teamwork

The Joint Intentions Framework [28] [7] [8] is a theoretical framework founded on BDI logics. The framework focuses on a team's joint mental state, called a joint intention. A team jointly intends a team action if all team members are jointly committed to perform an action while in a specified mental state.

Joint Intentions Theory describes how a team of agents can jointly act together by sharing mental states about their actions. An intention is viewed as a commitment to perform an action while in a mental state. And a joint intention is a shared commitment to perform an action while in a group mental state [7]. Communication is required to establish and maintain mutual beliefs and joint intentions. A team of agents jointly intend to perform an action if and only if the members have a joint persistent goal [6].

In order to enter a joint commitment, the team members have to establish appropriate mutual beliefs and individual commitments. Although the Joint Intentions Theory does not mandate communication and several techniques are available to establish mutual beliefs about actions from observations (see [23]), currently communication seems to be the only feasible way to attain joint commitments. A key aspect of the Joint Intention Theory is the commitment to attain mutual belief about the termination of a team action. This helps to ensure that the team stays updated about the status of the team actions. This behaviour is achieved by enforcing that agents committing to a joint intention also commit to inform their team about any relevant failures or premature terminations. Joint intentions and joint commitments provide a basic framework to reason about coordination required for teamwork as well as guidance for monitoring and maintaining team activities. However, a single joint intention for a high-level team goal is not sufficient to model team behaviour in detail and to ensure coherent teamwork.

There are also some other theories with similarities and contrasts conveying collaboration concepts including Cohen and Levesque's work describing the concept of *joint intentions* in [6, 28].

In [6] Cohen and Levesque establish that joint intention cannot be defined simply as individual intention with the team regarded as an individual. This is because after the initial formation of an intention, team members may diverge in their beliefs and hence in their attitudes towards the intention. Instead, Cohen and Levesque generalise their own definition of intention. First they present a definition of individual persistent goal and, in terms of this, individual intention. Both definitions use the notion of individual belief. Next, they define precise analogues of these concepts – joint persistent goal and joint intention – by invoking mutual belief in place of individual belief. The definition of joint persistent goal additionally requires each team member to commit to informing other members – to the extent of the team's mutual belief – if it comes to believe that the common goal has been achieved, becomes impossible or is no longer relevant. The result is that, while a team is not an individual, nevertheless joint intention is similar to individual intention. In Cohen and Levesque's theory, then, a team with a joint intention is a group that shares a common objective and a certain shared mental state. In particular, joint intentions are held by the team as a whole [26].

3.2 SharedPlans Theory

3.2.1 Communicating Intentions

Using discourse plans can help to encode the knowledge about conversation.

The SharedPlans theory recognises three interrelated levels of discourse structure.

In [20], Grosz and Sidner argue that the components of the discourse structure are a trichotomy of linguistic structure, intentions structure and the attention state. In their work, the linguistic structure of a discourse is a sequence of utterances aggregating into discourse segments just as the words in a single sentence form constituent phrases. They also discuss the idea of the discourse purpose as the intention that underlies engagement in the particular discourse. They believe this intention is the reason behind performing a discourse rather than some other actions, and also the reason behind conveying a particular content of the discourse rather than some other contents. They describe mechanisms for plan analysis looking at Discourse Segment Purposes (DSPs). In fact, the DSPs specify how the discourse segments contribute to achieving the overall discourse purpose. Finally, the third component in their theory, the attentional state, provides an abstraction of the agent's focus of attention as the discourse unfolds. The focusing structure contains DSPs and the stacking of focus spaces reflects the relative salience of the entities in each space during the discourse. In short, the focusing structure is the central repository for the contextual content required for processing utterances during the discourse [20].

3.2.2 Collaboration Vs. Sum of Coordinate Actions

[13]

3.2.3 SharedPlans

The SharedPlans formalization distinguishes partial plans and complete plans. A Full SharedPlan (FSP) is a complete plan in which agents have fully determined how they will perform an action. The Partial SharedPlan (PSP) definition provides a specification of the minimal mental-state requirements for collaboration to exist and gives criteria governing the process of completing the plan. Consequently, a full recipe for doing an action A is a set of actions and constraints such that the doing of those actions under those constraints constitutes the doing of action A. A partial recipe is a set of actions and constraints that may be extended to a full recipe [17].

Grosz and Sidner [20] Grosz and Kraus [18]

SharedPlans is a general theory of collaborative planning that requires no notion of joint intentions, accommodates multi-level action decomposition hierarchies and allows the process of expanding and elaborating partial plans into full plans.

SharedPlans is rooted in the observation that collaborative plans are not simply a collection of individual plans, but rather a tight interleaving of mutual beliefs and intentions of different team members.

The SharedPlans model of collaborative action [17] [18] [20] aims to provide the theoretical foundations needed for building collaborative robots/ agents [13]. It specifies four key characteristics for participants in a group activity to be collaborative partners, and thus for their joint activity to be collaborative. The SharedPlans definition states that for a group activity to be collaborative, the collaborators must have:

Look at this carefully!!!

a) individual intentions that the group perform the group activity;

b) mutual belief of a (partial or complete) recipe;

c) individual or group plans for the constituent subactions of the recipe;

d) intentions that their collaborators succeed in doing the constituent subactions.

In other words, to successfully complete a plan the collaborators must mutually believe that they have a common goal and have agreed on a sequence of actions for achieving that goal. They should believe that they are both capable of performing their own actions and intend to perform those actions while they are committed to the success of their plans.

The intentions that this definition specifies constitute different kinds of commitments required of the collaborators.

The idea behind partial shared plans is enabling the agents to modify the shared plan over the course of planning without impairing the achievement of the shared goals.

3.2.4 Intention-to and Intention-that

In Grosz and Sidner's SharedPlans theory [20], two intentional attitudes are employed: "intending to" (do an action) and "intending that" (a proposition will hold). The notion of *intention to*, as an individual-oriented intention, models the intention of an agent to do any single-agent action while the agent not only believes that it is able to execute that action, but it also committs to doing so. In short, it is an intention to perform an action, similar to Bratmans conception. In contrast with *intention to*, an *intention that*, as the notion of an intention directed toward group activity, does not directly imply an action. In fact, an individual agent's *intention that* is directed towards its collaborator's action or towards a group's joint action. *Intention that* guides an agent to take actions (including the communication), that enable or facilitate other collaborators to perform assigned tasks. This leads an agent to behave in a manner consistent with a collaborative effort. Therefore, agents will adopt intentions to communicate about the plan [18]. There is a significant difference between "Intention that" and

"Intention to". "Intention to" commits an agent to means-end reasoning and acting [2]. In contrast, "Intention that" does not necessarily entail this commitment.

3.2.5 Recipes

The SharedPlans definition of mutual beliefs states that when agents have a shared plan for doing some act, they must hold mutual beliefs about the way in which to perform that act. Following Pollack [36], the term recipe refers to what collaborators know when they know a way of doing something. Recipes are specified at a particular level of detail. Hence, the agents need to have mutual beliefs about acts specified at the particular level of detail of the recipe, and they do not to have mutual beliefs about all levels of acts that each agent will perform. Mutual belief of the recipe essentially means that all the collaborators hold the same beliefs about the way in which the activity will be accomplished. Therefore, the collaborators must agree on how to do the activity. Grosaz and Sidner in their earlier work [20] have considered only simple recipes in which each recipe consisted of only a single act-type relation [31]. Recipes are aggregations of act-types and relations among them. Act-types, rather than actions, are the main elements in recipes. Recipes can be partial, meaning thay can expand and be modified over time.

3.2.6 Plans

Figure 1 shows what we need to add to individual plans in order to have plans for group action, and lists the major components of group plans; to provide a base for comparison, the top of the figure lists the main components for individual plans. First, just as an individual agent must know how to do an action, agents in a group must have knowledge of how theyre going to do an action. In the case of a group plan to do a joint activity, there must be mutual belief of the recipe; agents must agree on how they are going to do the action. Then, just as individual agents must have the ability to perform the constituent actions in an individual plan and must have intentions to perform them, the participants in a group activity must have individual or group plans for each of the constituent actions in their agreed-on recipe [20] [13].

Plans for group actions include two major constituents that do not have correlates in the individual plan. First, the agents must have a commitment to the group activity; they must all intend-that the group will do the ac-

PLANS FOR COLLABORATIVE ACTION

- To have an individual plan for an act, need
  - knowledge of a recipe
  - ability to perform subacts in the recipe
  - intentions to do the subacts
- To have a group plan for an act, need
  - mutual belief of a recipe
  - individual or group plans for the subacts
  - intentions that group perform act
  - intentions that collaborators succeed

Figure 1: Plans for collaborative action [13].

tion. For instance, a robot and an astronaut need to have intentions that they install solar panels. Among other things, these intentions will keep them both working on the panels until the panels are installed. Second, the participants must have some commitment to the other agents being able to do their actions. For example, the robot must have an intention that the astronaut be able to measure the quality of installation. This intention will prevent the robot from interrupting astronaut's measurement action or prevent the robot from using astronaut's measurement tool [20] [13].

3.2.7 Commitment

Bratman in [2] has argued that intentions constrain an agents choice of what else it can intend, and they provide the context for an agents replanning when something goes wrong. The commitment to joint activity leads to a need to communicate.

Finally, the definition of the overall plan in terms of constituent plans of individuals or groups is recursive, with the recursion ending at the level of basic, individual actions [14].

Grosz, Sidner and Lochbaum in [20] and [31] present a model of plans to account for how agents with partial knowledge collaborate in the construction of a domain plan. Agents have a library of partially speci ed plan schemas (recipes). These recipes might be underspeci ed as to how an action is executed or how an action contributes to a goal. Agents then collaborate in constructing a shared plan by uttering statements about their beliefs and intentions about the plan. This collaboration will terminate with each agent mutually believing that each act in the plan can be executed by one of the agents, that that agent intends to perform the act, and that each act in the plan contributes to the goal.

Grosz, Sidner and Lochbaum in [20] and [31] are interested in the type of plans that underlie discourse in which the agents are collaborating in order to achieve a shared goal. They propose that agents are building a shared plan in which participants have a collection of beliefs and intentions about the actions in the plan.

Grosz, Sidner and Lochbaum in [20] and [31] model how several agents with partial knowledge collaborate on constructing a shared domain plan . Each agent communicates their beliefs and intentions by making utterances about what actions they can contribute to the shared plan. Collaboration is again modelled by the agents establishing a mutual belief that each action in the shared plan contributes to the goal of the plan, and that each action can and will be performed by one of the agents.

Shared plan is another essential concept in the collaboration context. The definition of the shared plan is derived from the definition of plans Pollack introduced in [35, 36] since it rests on a detailed treatment of the relations among actions and it distinguishes the intentions and beliefs of an agent about those actions. However, since Pollack's plan model is just a simple plan of a single agent, Grosz and Sidner extended that to plans of two or more collaborative agents. The concept of the shared plan provides a framework in which to further evaluate and explore the roles that particular beliefs and intentions play in collaborative activity [31]. However, this formulation of shared plans (a) could only deal with activities that directly decomposed into single-agent actions, (b) did not address the requirement for the commitment of the agents to their joint activities, and (c) did not adequately deal with agents having partial recipes [18]. Grosz and Kraus in [18], reformulate Pollack's definition of the individual plans [36], and also revise and expand the SharedPlans to address these shortcomings.

3.2.8 Coordinated Cultivation of SharedPlans

Grosz and Hunsberger [15] claim to reconcile the two approaches. They provide the "Coordinated Cultivation of SharedPlans" (CCSP) model, which, while relying solely on individual intention, captures the essential properties argued for in accounts that require group-oriented intention. CCSP also provides a general architecture for collaboration-capable agents.

3.3 Hybrid Collaboration Approaches

Tambe's work on *STEAM teamwork model* [46].

Jennings work in [27]

STEAM (Shell for Teamwork) builds on both Joint Intention Theory and Shared Plan Theory and tries to overcome their shortcomings. Based on joint intentions, STEAM builds up hierarchical structures that parallel the Shared Plan Theory as described in the previous chapter. Hence, STEAM formalises commitments by building an maintaining Joint Intentions, and uses SharedPlans to formulate the team's attitudes in complex tasks.

In [46] Tambe presents STEAM, an implemented model of teamwork based primarily on Cohen et al.'s theory of Joint Intentions, but informed by key concepts from SharedPlans. Following Cohen et al., a team initially adopts a joint intention for a high-level team goal that includes commitments to maintain the goal until it is deemed already achieved, unachievable or irrelevant. The agents then construct a hierarchy of individual and joint intentions analogous to partial SharedPlans. Tambe notes that as the hierarchy evolves, if a step involves only a subteam then that subteam must form a joint intention to perform that step, and the remaining team members need only track the subteam's joint intention, requiring that they be able to infer whether or not the subteam intends to, or is able to, execute that step [24].

4 Relation to Psychology and Sociology

Referring expressions [21]

5 Similarities and Differences

1. None of SharedPlans' four components (see Section 3.2) has the notion of a joint intention. This is a significant difference between SharedPlans and Joint Intentions theories, since the notion of joint intention is an integral part of Cohen and Levesque's theory. In particular, SharedPLans theories emphesizes on the agents individually intending that the joint action be done successfully as well as the agents individually intending the success of their collaborators' actions which is introduced in [18] by Grosz and Kraus as the notion of *intention-that.*

2. Communication requirements are derived from any intention that's, as opposed to being "hard-wired" in Joint Intentions.

3. In contrast to Joint Intentions, the SharedPlans Theory employs hierarchical structures over intentions, thus overcoming the shortcoming of a single Joint Intention for complex team tasks. The Shared Plans Theory is not based on a joint mental attitude but on an intentional attitude called intending that, which is very similar to an agents normal intention to perform an action.

4. Another main difference between the Joint Intentions Theory and the SharedPlans Theory is that the Shared Plans Theory describes the way to achieve a common goal through the hierarchy of plans, whereas the Joint Intentions Theory describes only this common goal [44].

5. Joint Intentions theory assumes that knowledge about the team-mates is always available.

6 Application in Human-Computer Collaboration

COLLAGEN [39, 40] is the first implemented system based on the SharedPlans theory. It incorporates certain algorithms for discourse generation and interpretation, and is able to maintain a segmented interaction history, which facilitates the discourse between human user and the intelligent agent. The model includes two main parts: (1) a representation of discourse state and (2) a discourse interpretation algorithm utterances of the user and agent [41].

In [21] Heeman presents a computational model of how a conversational participant collaborates in order to make a referring action successful. The model is based on the view of language as goal-directed behaviour, and in his work, he refers to SharedPlans as part of the planning and conversation literature.

In [31], Lochbaum and Sidner modify and expand the SharedPlan model of collaborative behavior [20]. They present an algorithm for updating an agents beliefs about a partial SharedPlan and describe an initial implementation of this algorithm in the domain of network management.

The system GRATE* by Jennings [27] is based on the Joint Intention Theory. GRATE* provides a rule-based modelling approach to cooperation using the notion of Joint Responsibilities, which in turn is based on Join Intentions. GRATE* is geared towards industrial settings in which both agents and the communication between them can be considered to be reliable.

CAST (Collaborative Agents for Simulating Teamwork) [47] [48] is a teamwork framework based on the SharedPlans Theory. CAST focuses on flexibility in dynamic environments and on proactive information exchange enabled by anticipating what information team members will need. Petri Nets are used to represent both the team structure and the teamwork process, i.e., the plans to be executed.

Researchers in [22] discuss developing an ontology of microsocial concepts for use in an instructional system for teaching cross-cultural communication. They believe being acquainted with one another is not a strong enough relationship to create a society from. Hence, there is a need for commitment and shared plans (as the basis of social life) to achieve a shared goal. In this work, Gorsz and Sidner's SharedPlans theory [20] is used to explain the concept of shared plans within the interpersonal relationships of societies in an industrial environment.

In [25] Hunsberger and Grosz discuss the idea of whether the rational, utility-maximizing agents should determine commiting to a group activity when there is an opportunity to collaborate. They call this problem as the "initial-commitment decision problem" (ICDP) and provide a mechanism that agents can use to dolve the ICDP. They use the representation of action, act-types and recepies in the SharedPlans theory.

In [49] an integrated agent-based model for Group Decision Support Systems is proposed and discussed. The decisional model that authors outline in this paper is based on the SharedPlans theory.

Rauenbusch and Grosz in [37] formally define a search problem with search operators that correspond to the team planning decisions. They provide an algorithm for making the three types of interrelated decisions by recasting the problem as a search problem. Their model respects the constraints on mental states specified by the SharedPlans theory of collaboration.

In [32] authors provide their in RoboCup (robotics soccer testbed) in which their focus is on teamwork and learning challenges. Their research investigationin RobotCup is based on ISI Synthetic, a team of synthetic soccer-players. They also investigate the use of STEAM as their model of teamwork which is influenced by the Joint Intentions and SharedPlans theories.

There are many research focusing on different aspects of collaboration each of which are different than my own work. In my thesis, I focus on emotion functions and how they impact collaboration's structure and processes, and how the dynamics of the collaboration structure influences emotion-regulated processes. Some of the other works focus on the concepts of robot assistants [5], or teamwork and its challenges in cognitive and behavioral levels [6, 34, 42, 46]. Some researchers have an overall look at a collaboration concept at the architectural level. In [10] authors present a collaborative architecture, COCHI, to support the concept of emotional awareness. In [9] authors present the integration of emotional competence into a cognitive architecture which runs on a robot, MEXI. In [45] authors discuss the challenges of integrating natural language, gesture understanding and spatial reasoning of a collaborative humanoid robot situated in the space. The importance of communication during collaboration has been considered by some researchers from human-computer interaction and human-robot collaboration [4, 33, 40] to theories describing collaborative negotiation, and discourse planning and structures [1, 19, 43]. There are other concepts such as joint actions and commitments [16], dynamics of intentions during collaboration [28], and task-based planning providing more depth in the context of collaboration [3, 38].

The concept of collaboration has also received attention in the industry and in research in robotic laboratories [11].

7 Conclusion

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