

Computational Theories of Collaboration

PH.D. COMPREHENSIVE EXAM

Mohammad Shayganfar - mshayganfar@wpi.edu

May, 26 2015

1 Introduction to Collaboration Theories

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 2.2, collaborators 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 collaboration and their other activities [13].

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 [16].

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 [11, 25].

2 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 [18, 24]. In these theories the discourse analysis is based on search over these tree plans [32].

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

2.1 Theory of Joint Intentions/Teamwork

The Joint Intentions Framework [23] [6] [7] 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.

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 [20]), 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 [5, 23].

2.2 SharedPlans Theory

2.2.1 Communicating Intentions

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

The SharedPlans theory recognises three interrelated levels of discourse structure.

In [18], 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 [18].

2.2.2 Collaboration Vs. Sum of Coordinate Actions

[12]

2.2.3 SharedPlans

Grosz and Sidner [18] Grosz and Kraus [16]

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 [15] [16] [18] aims to provide the theoretical foundations needed for building collaborative robots/agents [12]. 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:

- a) 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.

2.2.4 Intention-to and Intention-that

The notion of *intention to* 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 commits to doing so. In contrast with *intention to*, an *intention that* 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 [16].

2.2.5 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 [30], 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. Grosz and Sidner in their earlier work [18] have considered only simple recipes in which each recipe consisted of only a single act-type relation [26]. 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 they can expand and be modified over time.

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 [13].

Grosz, Sidner and Lochbaum in [18] and [26] 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 specified plan schemas (recipes). These recipes might be underspecified 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.

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 [29, 30] 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 [26]. 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 [16]. Grosz and Kraus in [16], reformulate Pollack’s definition of the individual plans [30], and also revise and expand the SharedPlans to address these shortcomings.

2.3 Hybrid Collaboration Approaches

Tambe’s work on *STEAM teamwork model* [37].

Jennings work in [22]

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 and maintaining Joint Intentions, and uses SharedPlans to formulate the team’s attitudes in complex tasks.

In [37] 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 [21].

3 Relation to Psychology and Sociology

Referring expressions [19]

4 Similarities and Differences

1. None of SharedPlans’ four components (see Section 2.2) 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 emphasizes 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 [16] 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 [35].

5 Application in Human-Computer Collaboration

In [19] 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 [26], Lochbaum and Sidner modify and expand the SharedPlan model of collaborative behavior [18]. 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 [22] 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) [38] [39] 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.

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 [4], or teamwork and its challenges in cognitive and behavioral levels [5, 28, 33, 37]. Some researchers have an overall look at a collaboration concept at the architectural level. In [9] authors present a collaborative architecture, COCHI, to support the concept of emotional awareness. In [8] authors present the integration of emotional competence into a cognitive architecture which runs on a robot, MEXI. In [36] 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 [3, 27, 32] to theories describing collaborative negotiation, and discourse planning and structures [1, 17, 34]. There are other concepts such

as joint actions and commitments [14], dynamics of intentions during collaboration [23], and task-based planning providing more depth in the context of collaboration [2, 31].

The concept of collaboration has also received attention in the industry and in research in robotic laboratories [10].

6 Conclusion

References

- [1] Jerry Andriessen, Koenraad de Smedt, and Michael Zock. Discourse planning: Empirical research and computer models. In Anton Dijkstra and Koenraad de Smedt, editors, *Computational psycholinguistics: AI and connectionist models of human language processing*, pages 247–278. Taylor & Francis, 1996.
- [2] Catherina Burghart, Ralf Mikut, Rainer Stiefelhagen, Tamim Asfour, Hartwig Holzapfel, Peter Steinhaus, and Ruediger Dillmann. A cognitive architecture for a humanoid robot: A first approach. In *5th IEEE-RAS International Conference on Humanoid Robots*, pages 357–362, 2005.
- [3] Aaron B. St. Clair and Maja J. Matarić. Modeling action and intention for the production of coordinating communication in human-robot task collaborations. In *21st IEEE International Symposium on Robot and Human Interactive Communication: Workshop on Robot Feedback in HRI*, Paris, France, 2012.
- [4] William J. Clancey. Roles for agent assistants in field science: Understanding personal projects and collaboration. *IEEE Transactions on Systems, Man and Cybernetics, special issue on Human-Robot Interaction*, 34(2):125–137, 2004.
- [5] Philip Cohen and Hector J. Levesque. *Teamwork*. SRI International, 1991.
- [6] Philip R. Cohen and Hector J. Levesque. Intention is choice with commitment. *Artificial Intelligence*, 42(2-3):213–261, 1990.
- [7] Philip R. Cohen and Hector J. Levesque. Persistence, intention, and commitment. In Philip R. Cohen, Jerry Morgan, and Martha E. Pol-

- lack, editors, *Intentions in Communication*, pages 33–69. MIT Press, Cambridge, MA, 1990.
- [8] Natascha Esau, Lisa Kleinjohann, and Bernd Kleinjohann. Integrating emotional competence into man-machine collaboration. In *Biologically-Inspired Collaborative Computing, September 8-9, Milano, Italy*, pages 187–198, 2008.
 - [9] Octavio García, Jesús Favela, Guillermo Licea, and Roberto Machorro. Extending a collaborative architecture to support emotional awareness. In *Emotion Based Agent Architectures (ebaa99)*, pages 46–52, 1999.
 - [10] Scott A. Green, Mark Billingham, XiaoQi Chen, and J. Geoffrey Chase. Human-robot collaboration: A literature review and augmented reality approach in design. *International Journal of Advanced Robotic Systems*, 5(1):1–18, 2008.
 - [11] Barbara Grosz and Sarit Kraus. The evolution of shared plans. In *Foundations and Theories of Rational Agency*, pages 227–262, 1998.
 - [12] Barbara J. Grosz. AAAI-94 presidential address: Collaborative systems. *AI Magazine*, 17(2):67–85, 1996.
 - [13] Barbara J. Grosz. Beyond mice and menus. *Proceedings of the American Philosophical Society*, 149(4):523–543, 2005.
 - [14] Barbara J. Grosz and Luke Hunsberger. The dynamics of intention in collaborative activity. *Cognitive Systems Research*, 7(2-3):259–272, 2007.
 - [15] Barbara J. Grosz, Luke Hunsberger, and Sarit Kraus. Planning and acting together. *AI Magazine*, 20(4):23–34, 1999.
 - [16] Barbara J. Grosz and Sarit Kraus. Collaborative plans for complex group action. *Artificial Intelligence*, 86(2):269–357, 1996.
 - [17] Barbara J. Grosz and Candace L. Sidner. Attention, intentions, and the structure of discourse. *Computational Linguistics*, 12(3):175–204, July 1986.
 - [18] Barbara J. Grosz and Candace L. Sidner. Plans for discourse. In P. R. Cohen, J. Morgan, and M. E. Pollack, editors, *Intentions in Communication*, pages 417–444. MIT Press, Cambridge, MA, 1990.

- [19] Peter Anthony Heeman. *A Computational Model of Collaboration on Referring Expressions*. PhD thesis, University of Toronto, 1991.
- [20] Marcus Huber and Edmund H. Durfee. On acting together: Without communication. In *In Working Notes of the AAAI Spring Symposium on Representing Mental States and Mechanisms*, pages 60–71, 1995.
- [21] Luke Hunsberger. Making Shared Plans More Concise and Easier to Reason About. In *Proceedings of the 5th International Workshop on Intelligent Agents V : Agent Theories, Architectures, and Languages (ATAL-98)*, volume 1555, pages 81–98. Springer-Verlag: Heidelberg, Germany, 1999.
- [22] Nicholas R. Jennings. Controlling cooperative problem solving in industrial multi-agent systems using joint intentions. *Artificial Intelligence*, 75(2):195–240, 1995.
- [23] Hector J. Levesque, Philip R. Cohen, and Jos H. T. Nunes. On acting together. In *AAAI*, pages 94–99. AAAI Press / The MIT Press, 1990.
- [24] D. J. Litman and J. F. Allen. Discourse processing and commonsense plans. In P. R. Cohen, J. Morgan, and M. E. Pollack, editors, *Intentions in Communication*, pages 365–388. MIT Press, Cambridge, MA, 1990.
- [25] Karen E Lochbaum. A collaborative planning model of intentional structure. *Computational Linguistics*, 24(4):525–572, 1998.
- [26] Karen E. Lochbaum, Barbara J. Grosz, and Candace L. Sidner. Models of plans to support communication: An initial report. In *Proceedings of the Eighth National Conference on Artificial Intelligence*, pages 485–490. AAAI Press, 1990.
- [27] Laetitia Matignon, Abir Beatrice Karami, and Abdel-Ilah Mouaddib. A model for verbal and non-verbal human-robot collaboration. In *AAAI Fall Symposium Series*, pages 62–67, 2010.
- [28] Stefanos Nikolaidis, Przemyslaw A. Lasota, Gregory F. Rossano, Carlos Martinez, Thomas A. Fuhlbrigge, and Julie A. Shah. Human-robot collaboration in manufacturing: Quantitative evaluation of predictable, convergent joint action. In *ISR*, pages 1–6, 2013.
- [29] Martha E. Pollack. A model of plan inference that distinguishes between the beliefs of actors and observers. In *Proceedings of the 24th Annual*

- Meeting on Association for Computational Linguistics*, pages 207–214. Association for Computational Linguistics, 1986.
- [30] Martha E. Pollack. Plans as complex mental attitudes. In *Intentions in Communication*, pages 77–103. MIT Press, 1990.
 - [31] Charles Rich. Building task-based user interfaces with ANSI/CEA-2018. *IEEE Computer*, 42(8):20–27, July 2009.
 - [32] Charles Rich, Candace L. Sidner, and Neal Lesh. COLLAGEN: Applying collaborative discourse theory to human-computer interaction. *AI Magazine*, 22(4):15–26, 2001.
 - [33] Paul Scerri, David Pynadath, Lewis Johnson, Paul Rosenbloom, Mei Si, Nathan Schurr, and Milind Tambe. A prototype infrastructure for distributed robot-agent-person teams. In *Proceedings of the Second International Joint Conference on Autonomous Agents and Multiagent Systems*, AAMAS ’03, pages 433–440, New York, NY, USA, 2003. ACM.
 - [34] Candace Sidner. An artificial discourse language for collaborative negotiation. In *In Proceedings of the Twelfth National Conference on Artificial Intelligence*, pages 814–819. MIT Press, 1994.
 - [35] Hendrik Skubch. *Modelling and Controlling of Behaviour for Autonomous Mobile Robots*. Springer Science Business Media, 2012.
 - [36] Donald Sofge, Magdalena D. Bugajska, J. Gregory Trafton, Dennis Perzanowski, Scott Thomas, Marjorie Skubic, Samuel Blisard, Nicholas Cassimatis, Derek P. Brock, William Adams, and Alan C. Schultz. Collaborating with humanoid robots in space. *International Journal of Humanoid Robotics*, 2(2):181–201, 2005.
 - [37] Milind Tambe. Towards flexible teamwork. *Journal of Artificial Intelligence Research*, 7:83–124, 1997.
 - [38] John Yen, Jianwen Yin, Thomas R. Ioerger, Michael S. Miller, Dianxiang Xu, and Richard A. Volz. Cast: Collaborative agents for simulating teamwork. In *In Proceedings of IJCAI2001*, pages 1135–1142, 2001.
 - [39] Jianwen Yin, Michael S. Miller, Thomas R. Ioerger, John Yen, and Richard A. Volz. A knowledge-based approach for designing intelligent team training systems. In *Proceedings of the Fourth International Conference on Autonomous Agents*, pages 427–434. ACM, 2000.