Coordination in Distributed Systems

Part I: Introduction. Cooperation

Ulises Cortés
Sergio Álvarez

SID

2019

Knowledge Engineering and Machine Learning Group
UNIVERSITAT POLITÈCNICA DE CATALUNYA

https://www.kemlg.upc.edu

Contents

- **What is coordination?**
  - Coordination Theory
  - Types of coordination
  - Coordination structures
- **What is Cooperation?**
  - Joint Intentions Theory
  - Cooperative Problem Solving Process
  - Teamwork
  - Planning

Agent Interaction Protocols

- Govern the exchange of a series of messages among agents

Case 1: Agents have conflicting goals

Case 2: Agents have similar goals

Message types

- Communication could be active, passive or both (agent is master, slave or peer)
- Two message types: assertions and queries.
- All agents accept information by means of assertions.
- **Passive agent**: accepts queries, sends replies
- **Active agent**: issue queries, make assertions
- **Peer agent**: all of the above.

Agents with conflicting goals

- Conflicting goals or simply self-interested
- Maximize payoff (utility functions)

Agents with similar goals

Objective: maintain globally coherent performance without violating autonomous behavior of agents

- Determine shared goals
- Determine common tasks
- Avoid unnecessary conflicts
- Pool knowledge and evidence

Coordination

- **Coordination** is a desired property in a Multiagent System whose agents should perform complex tasks in a shared environment
- The **degree of coordination** in a Multiagent System depends on:
  - The inability of each individual agent to achieve the whole task(s)
  - The dependency of one agent on others to achieve the tasks
  - The need to reduce/optimize resource usage
  - The need to avoid system halts
  - The need to keep some conditions holding

Coordination

Definitions

- **Coordination** could be defined as the process of ***managing dependencies between activities***. By such process an agent reasons about its local actions and the foreseen actions that other agents may perform, with the aim to make the community to ***behave in a coherent manner.***

- An **activity** is a set of potential operations an **actor** (enhacing a role) can perform, with a given goal or set of goals.

- An **actor** can be an agent or an agent group

- A set of **activities** and an ordering among them is a **procedure**.

Coordination

- Coordination is a must-have functionality in any Multiagent System implementation
- Coordination becomes critical when agents are **heterogeneous** and **autonomous**
- Coordination consists of a set of mechanisms necessary for the effective operation of a MAS in order to get a well-balanced division of labour (***task allocation techniques***) while reducing logical coupling and resource dependencies of agents.

Coordination

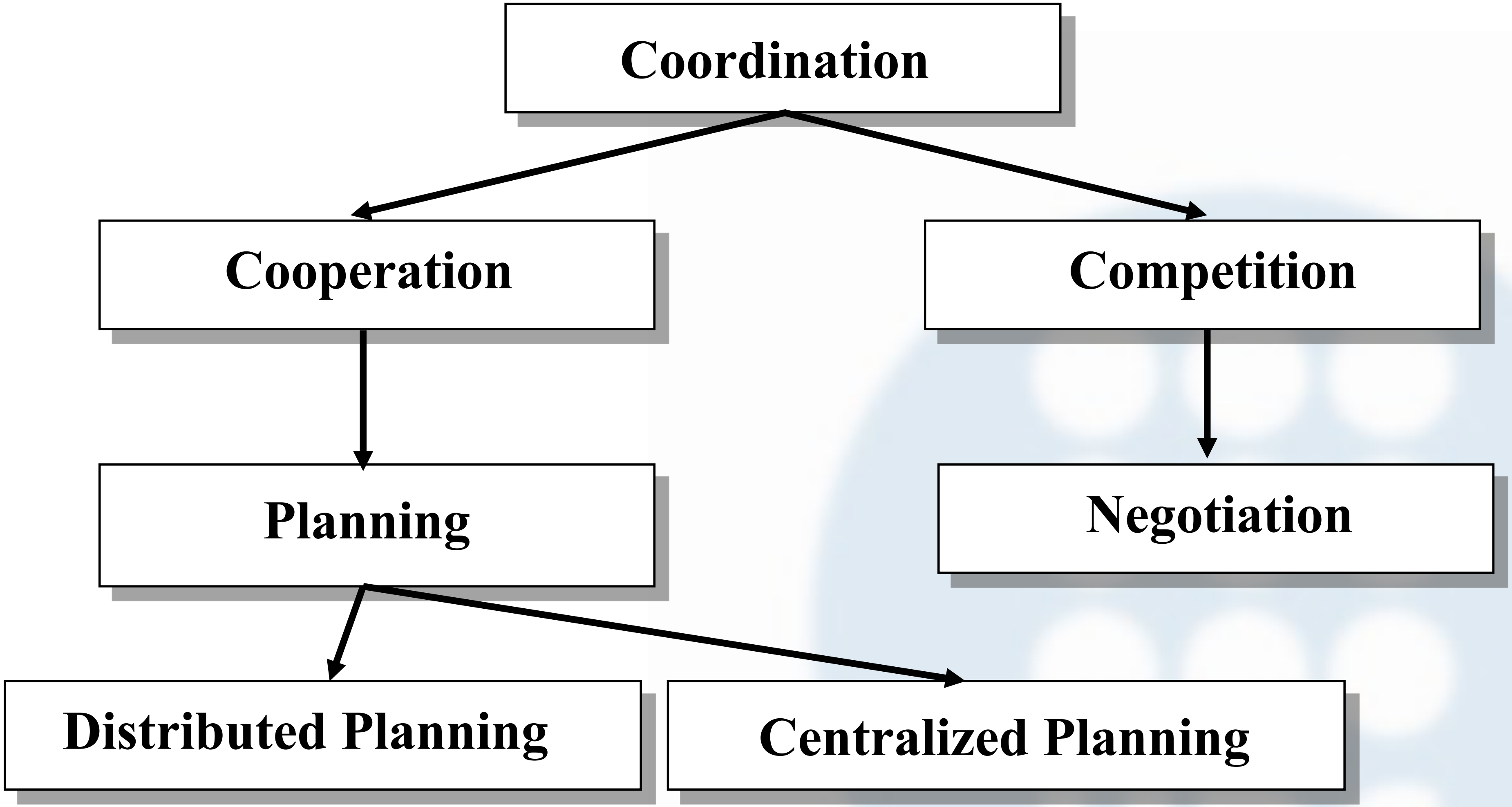
Coordination Theory

- Lots of empirical and theoretical work has been and is currently being done to study coordination, not only for specific domains but in a more generic, domain-independent view.
- Some of this work lead to the creation of coordination theories.
- A **Coordination Theory** can be defined as a set of axioms and the analytical techniques used to create a model of dependency management.
- Examples of coordination theories are
  - *joint-intentions* theory,
  - theories about shared plans
  - domain-independent teamwork models

Some Interaction Protocols

1. Coordination Protocols
2. Cooperation Protocols
3. Contract Net
4. Blackboard Systems
5. Negotiation
6. Multi-Agent Belief Maintenance
7. Market Mechanisms

Coordination
Types of coordination



Types of Coordination
Cooperation and Planning

- **Cooperation** is a kind of coordination between agents that, in principle, are not antagonist.

- The degree of success in cooperation can be measured by
  - the capability of agents to keep their own goals
  - the capability to allow other agents to reach their goals.

- **Planning** is one of the strongest forms of cooperation
  - There are some shared goals and shared plan
  - Agents allocate tasks among them following the plan

Types of Coordination

Competition and Negotiation

- **Competition** is kind of coordination between antagonist agents which compete with each other or that are selfish.

- We will be more interested in **Negotiation**, as it is a kind of competition that involves some higher level of intelligence.

- The degree of success in negotiation (for a given agent) can be measured by
  - The capability of this agent to maximize its own benefit
  - The capability of not taking into account the other agents' benefit or even trying to minimize other agents' benefit.

Coordination Structures
Centralised Coordination (I)

- One way to tame the complexity of building a MAS is to create a centralized controller, that is, a specific agent that ensures coordination.
- ***Coordinator agents*** are agents which have some kind of control on other agents' goals or, at least, on part of the work assigned to an agent, according to the knowledge about the capabilities of each agent that is under the *Coordinator Agent*'s command.
- From the developer's point of view, this approach reduces complexity in MAS building:
  - the ultimate goal of the system is ensured by the goals of the coordinator, which supersedes the goals of the other agents in the system.

Coordination Structures

Centralised Coordination (II)

- Even though these kind of multi-agent architectures are easier to build, the main disadvantages of this approach come from its *centralized control*:
  - the *Coordinator agent* becomes a ***critical piece*** of the system, which depends on the reliability of a single agent and the communication lines that connect to it.
  - In the worst case scenario when the *Coordinator Agent* collapses (e.g., it receives more requests and messages than it is able to manage in a given time span), the ***system may also completely collapse***.
  - the other agents have a ***severe loss of autonomy***, as the proper behaviour of the systems depends on the agents blindly accepting the commands of the coordinator.

Coordination Structures

Distributed Coordination

- An alternative is to distribute not only the work load but also the control among all the agents in the system (***distributed control***).
- That means to **internalize control** in each agent, which has now to be provided with reasoning and social abilities to make it able to reason about intentions and knowledge of other agents plus the global goal of the society in order to be able to successfully coordinate with others and also resolve conflicts once they arise.
- However, as Moses and Tennenholtz state, in domains where the cost of a conflict is dear, or if conflict resolution is difficult, ***completely independent behaviour becomes unreasonable***.
- Therefore some kind of structure should be defined in order to ease coordination in a *distributed control* scenario.

Cooperation

- Joint Intentions Theory
- Cooperative Problem Solving Process
- Teamwork
- Planning

Cooperation Mechanisms

Cooperating with message exchange

- First defined by Cohen and Levesque, Wooldridge and Jennings
- Agents **communicate with one another** to share:
  - Tasks
  - Task Assignments
  - Information on the State of the World
  - Motivations
  - etc.
- These communications form the basis of forming joint agreement on what to do
- This forms the basis of a “***Cooperative Problem Solving Process***”

Cooperative Problem Solving Process

Four steps to (cooperation) heaven

- **4 Steps (Wooldridge and Jennings):**
  - **Problem identification**: the process begins when one or more agents identify a problem for which cooperation is needed.
  - **Team formation**: the agent (or agents) that recognised the problem solicit assistance and seek others to help with the problem. If this stage is successful a group is formed with a ***joint commitment*** for action.
  - **Plan formation**: the team of agents form an action plan which uses the individual skills in the team. The result of this stage is a series of individual and interdependent commitments to act.
  - **Team action**: during this phase, agents carry out the actions assigned to them.
- Followed by clean up / housekeeping

Joint Intentions

The basis of Joint Action

- First described by Cohen and Levesque:
- Common Characteristics:
  - **Realistic**: agents must believe the state of affairs desired is achievable.
  - **Temporally Stable**: intentions should be persistent in some sense (though not completely inflexible)
- Some argue that Joint Intentions are ***required*** for Joint Action*. i.e.* that if you *happen* to do the right thing but didn't have a joint intention the this ***<u>was not</u>*** Joint Action.
- Jennings et. al. see **Commitments** as instantiations of Joint Intentions

Joint Responsibility

Extending Joint Intentions

- Jennings also introduces Joint responsibility as:
  - A **joint goal** (joint intention).
  - A **recipe** (plan) for achieving that goal.
- This builds on *Joint Intentions* to tie a goal to concrete actions since:
  - If we have the same goal it doesn't mean we are necessarily agreed on the actions to achieve it.
  - Further, when I start to act then I need to be certain you are committed to ***doing your part***.

Criticisms of Joint Intentions Approaches

Not applicable to everything

- There are a number of well known criticism of the theories based around Joint Intentions:
  - **Failure to account for Social Structure**: what about coercion? social responsibility?
  - **Focus on internal structures**: who cares what we intended as long as we acted coherently?
  - **Limited Applicability**: the theory does not work for (e.g.) implicit coordination cases.
- However, the theory provides a strong linking point to approaches such as *trust* and *reputation*.

Compromises about actions

- Another way to see it is to create ways that agents establish compromises/commitments about actions
- Compromises bring benefits, constraint (possible) actions and/or future options by modifying other agents' (possible) actions in our own benefit.
- Agents may benefit of being able of limiting its future (possible) actions and perform those that they have compromised.
- An agent (only) gets compromises to perform a future action -- that constraints its future options/incentives – if it receives a larger gain.

Mechanisms to acquire compromises

- To compromise future actions/options is always a difficult decision.
- The law, social rules, *the rules of encounter*, the promises and honour rules do contribute to support agent to compromise.

Advantages of Cooperation

- Complete tasks quicker through shared effort
- By sharing resources, achieve tasks otherwise not possible
- Make use of complementary capabilities
- Avoid harmful interactions

Modes of Cooperation

- **Accidental**: not intended
- **Unilaterally intended**: one agent intentionally helps another
- **Mutual cooperation**: two or more agents intentionally collaborate

Degrees of Cooperation

- **Fully cooperative** (benevolent): Agents always attempt to assist other agents that request or need their help.
- **Antagonistic**: Agents do not cooperate with others and may even try to block their goals.
- **Partly cooperative**: Agents sometimes or to some extent will assist other agents.

Cooperation protocols

- Basic strategy is to decompose and then distribute tasks
- Decomposition done by system designer or by agents
- Distribution mechanisms:
  - Market mechanism: generalized agreements or mutual selection
  - Contract net: announce, bid and award cycles
  - Multiagent planning: planning agents perform task assignment
  - Organizational structure: agents have fixed responsibilities

Teamwork

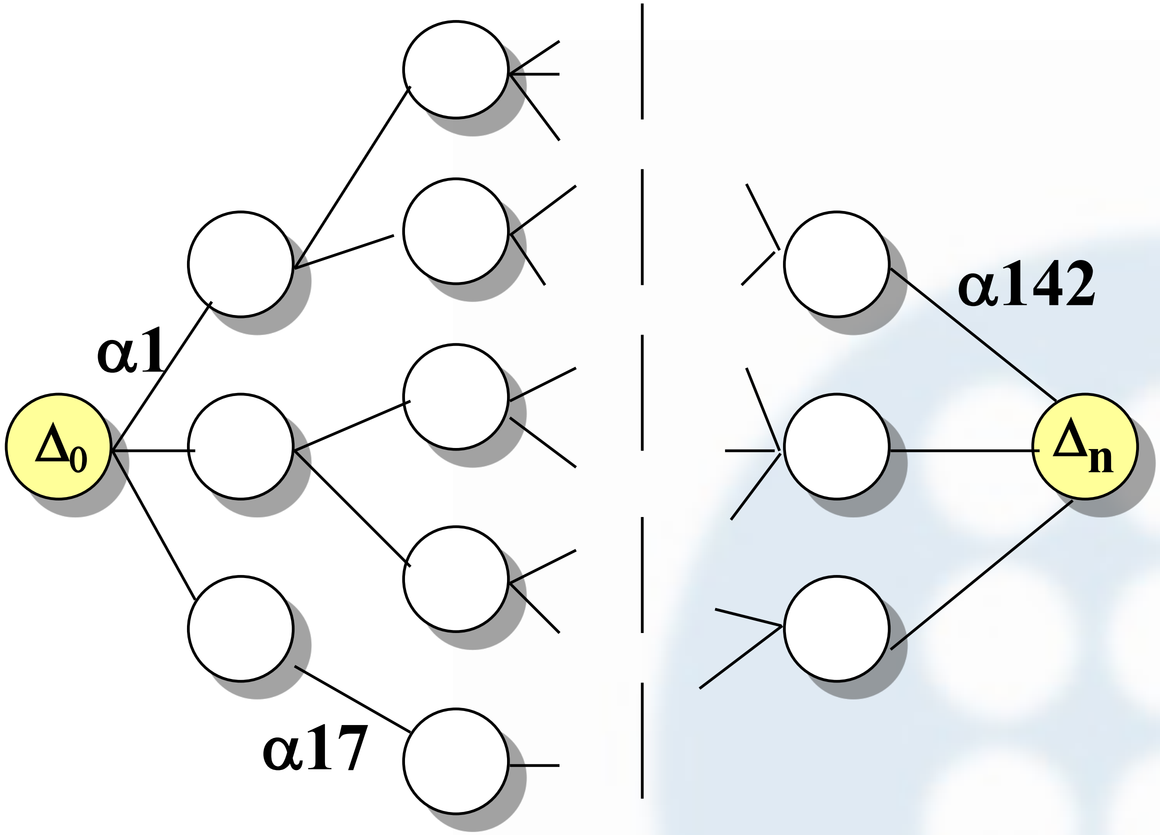
Another view on CPS

- A particular flavour of cooperative problems solving which emphasises the model of the *team* (and attitudes towards the team) rather than individual mental attitudes
- Theory emphasises:
  - **Detecting Interactions**: detecting positive and negative interactions between subplans
  - **Monitoring plan and team progress**: are goals achieved? are team members still reachable etc.
  - **Planning and conflict resolution within the team**: contract net and other mechanisms to resolve conflicts
- Systems include: STEAM, GRATE, COLLAGEN

Cooperation

Planning

Traditional AI Planning



- What is a plan?
  A sequence (list) of actions, with variables replaced by constants.

Traditional AI Planning
Planning Theory (I)

- $Ac = \{\alpha_1, \ldots, \alpha_n\}$: a fixed set of actions.
- $< P_\alpha, D_\alpha, A_\alpha >$ a descriptor for an action $\alpha \in Ac$
  - P_α is a set of formulae of first-order logic that characterise the *precondition* of action α
  - D_α is a set of formulae of first-order logic that characterise those *facts* made false by the performance of α (the delete list)
  - A_α is a set of formulae of first-order that characterise those facts made *true* by the performance of α (the add list)
- A **planning problem** is a triple $<\Delta, O, \gamma>$

Traditional AI Planning

Planning Theory (II)

- $\pi=(\alpha_1, \ldots, \alpha_n)$: a plan with respect to a planning problem <Δ, O, γ> determines a sequence of $n+1$ models:

$$\Delta_0, \Delta_1, \ldots, \Delta_n$$

- where $\Delta_0 = \Delta$ and

$$\Delta_i = (\Delta_{i-1} \setminus D_{\alpha_i}) \cup A_{\alpha_i} \quad \text{for} 1 \leq i \leq n$$

- A plan π is acceptable iff $\Delta_{i-1} \vdash P_{\alpha_i}$,for all $1 \leq i \leq n$
- A plan π is correct iff
  - π is acceptable, and
  - $\Delta_n \vdash \gamma$

Planning

Multiple Agents make planning difficult

- Traditional Artificial Intelligence Planning:
  - Is focused on planning for a single Action (what do “I” do?)
  - Often assumes the agent is the only actor in the world (who locked the door!?!)
  - Planner is omniscient
    - Knows all relevant information about the current state of the world
    - Knows all possible actions that can be applied
  - Actions are deterministic and instantaneous.
  - Goals are fixed and categorical.

  - It is s non-trivial to generalise to multi-agent cases

Planning variations

- There are three key variations:
  - Planning in situations when **several friendly agents** are supposed to work together – who does what and when? However the agents are the only actors in the environment
  - Planning in situations where there are **other (neutral) agent present**.
  - Planning in situations where there are **hostile** other agents present
- Even the *friendly agents* cases is complex and requires:
  - Knowing the capacities of other agents
  - Sharing plan fragments
  - Coordinating individual actions

Distributed Planning

- A combination of traditional AI planning and distributed problem solving.

- There are three flavours:
  - plan creation is centralized but the plan execution can be distributed
  - plan creation is distributed but the plan execution is centralized
  - plan creation is distributed and the plan execution is distributed

Distributed planning
What is needed for agents?

"Autonomous agents in dynamic, multiagent environments also need to be able to manage the plans they generate. They need to determine which planning problems and opportunities to consider in the first place. They need to be able to weigh alternative incomplete plans and decide among competing alternatives. They need to be able to form incomplete plans now, adding detail later, and thus, they need to be able to decide how much detail to include now and when to add more detail. They need to be able to integrate plans with one another and to decide when to treat an existing plan as an inflexible commitment and when, instead, to consider modifications of it. They also need to be able to do this in a way that comports with the inherent bounds on their computational resources."

(Pollack and Horty in [7])

Distributed planning

What is needed for agents?

“Autonomous agents in dynamic, multiagent environments also need to be able to manage the plans they generate. ***They need to determine which planning problems and opportunities to consider in the first place.*** *They need to be able to weigh alternative incomplete plans and decide among competing alternatives. They need to be able to form incomplete plans now, adding detail later, and thus, they need to be able to decide how much detail to include now and when to add more detail. They need to be able to integrate plans with one another and to decide when to treat an existing plan as an inflexible commitment and when, instead, to consider modifications of it. They also need to be able to do this in a way that comports with the inherent bounds on their computational resources.”*

(Pollack and Horty in [7])

Distributed planning

What is needed for agents?

"Autonomous agents in dynamic, multiagent environments also need to be able to manage the plans they generate. They need to determine which planning problems and opportunities to consider in the first place. ***They need to be able to weigh alternative incomplete plans and decide among competing alternatives.*** *They need to be able to form incomplete plans now, adding detail later, and thus, they need to be able to decide how much detail to include now and when to add more detail. They need to be able to integrate plans with one another and to decide when to treat an existing plan as an inflexible commitment and when, instead, to consider modifications of it. They also need to be able to do this in a way that comports with the inherent bounds on their computational resources."*

(Pollack and Horty in [7])

Distributed planning

What is needed for agents?

"Autonomous agents in dynamic, multiagent environments also need to be able to manage the plans they generate. They need to determine which planning problems and opportunities to consider in the first place. They need to be able to weigh alternative incomplete plans and decide among competing alternatives. ***They need to be able to form incomplete plans now, adding detail later, and thus, they need to be able to decide how much detail to include now and when to add more detail.*** *They need to be able to integrate plans with one another and to decide when to treat an existing plan as an inflexible commitment and when, instead, to consider modifications of it. They also need to be able to do this in a way that comports with the inherent bounds on their computational resources."*

(Pollack and Horty in [7])

Distributed planning
What is needed for agents?

"Autonomous agents in dynamic, multiagent environments also need to be able to manage the plans they generate. They need to determine which planning problems and opportunities to consider in the first place. They need to be able to weigh alternative incomplete plans and decide among competing alternatives. They need to be able to form incomplete plans now, adding detail later, and thus, they need to be able to decide how much detail to include now and when to add more detail. ***They need to be able to integrate plans with one another and to decide when to treat an existing plan as an inflexible commitment and when, instead, to consider modifications of it.*** *They also need to be able to do this in a way that comports with the inherent bounds on their computational resources."*

(Pollack and Horty in [7])

Distributed planning

What is needed for agents?

"Autonomous agents in dynamic, multiagent environments also need to be able to manage the plans they generate. They need to determine which planning problems and opportunities to consider in the first place. They need to be able to weigh alternative incomplete plans and decide among competing alternatives. They need to be able to form incomplete plans now, adding detail later, and thus, they need to be able to decide how much detail to include now and when to add more detail. They need to be able to integrate plans with one another and to decide when to treat an existing plan as an inflexible commitment and when, instead, to consider modifications of it. ***They also need to be able to do this in a way that comports with the inherent bounds on their computational resources.****"*

(Pollack and Horty in [7])

Distributed Planning

Partial Global Planning

- **Partial Global Planning** (PGP and GPGP) are the most representative systems in this field.
- Interleaves plan generation, coordination and execution.
  - Agents create plan fragments
  - Share them using a call-for-proposals style protocol
  - Agents modify their behaviour w.r.t. what they believe others are doing.
- Provides a dynamic capability to revise plans in a cost-effective manner.
- Assumes communication over time.

Distributed Planning

Partial Global Planning steps

- Task Decomposition:
  - Assumes tasks are inherently decomposed.
  - Agents may not know when beginning to develop a plan what tasks other agents are doing or plan to do and the relationship to the agent's plan.
  - No individual agent may be aware of the global task or state.
    - Coordination allows them to develop an awareness to complete their task.
- Local Plan Formation:
  - Agent must decide which goal to pursue and what actions it may take to reach the goal.
    - Purely reactive agents cannot use PGP.
- Local Plan Abstraction:
  - Agents commit to an activity on one level of detail without committing to the activity at a more detailed level.

Distributed Planning

Partial Global Planning steps

- Communication:
  - Meta-Level Organization (MLO) indicates the information and control flows between the agents.
    - Who needs to know my plan?
    - Who has authority to override my plan?
- Partial Global Goal Identification:
  - Agents only know parts of the global goal.
  - Is an interpretation problem that attempts to generate an overall global goal that explains the local goals.
- Partial Global Plan Construction and Modification:
  - A goal of PGP is to identify related tasks and avoid redundant task achievement.
  - Integrating local plans that satisfy a partial global goal into a partial global plan.
  - Looks for the best concurrent actions for the partial global plan using hill climbing.

Distributed Planning
Partial Global Planning steps

- Communication Planning:
  - Goal: Communicating the result of an action.
  - Plan for this communication.
  - May be synthesized results that are transformed into a complete result.
- Acting on Partial Global Plans:
  - Agents may first modify the abstract representation of the local plans if the partial global plan requires it.
  - The agent then executes the next local action based upon the modified local plan.

Distributed Planning
Partial Global Planning steps

- Ongoing Modification:
  - Changes in actions or events may cause the agent's abstract plan to be modified thus indicating replanning is required.
  - When do you replan? What sensitivity level?
- Task Reallocation:
  - PGP can identify agents that are over and under-committed through the exchange of abstract action models.
  - Negotiation mechanisms may be then used to manage the reallocation.

Other Cooperation Algorithms

Cooperation by algoritm

- Cooperation by “Algorithm” is somewhat controversial since some approaches do not allow for significant Agent Autonomy in the process.
- Two main approaches:
  - **Distributed Constraint Satisfaction** (DCSP): an extension of CSP solving techniques which capture several variables in each agent. Agents propagate choices for the “edge variables” which affect others.
  - **Hierarchical Authority Algorithms** (Durfee et. al.): mechanisms which enforce authority values on participation and according to these rankings drive plan interchange processes.

References

[1] Jennings, N. & Luck, M.. "Introduction to Autonomous Agents and Multi-Agent Systems" The 5th Int. Conf. On Autonomous Agents. 2001.

[2] Wooldridge, M. "Introduction to Multiagent Systems". John Wiley and Sons, 2002.

[3] Y. Shoham, "An Overview of Agent-Oriented Programming", in J. M. Bradshaw, editor, Software Agents, pages 271–290. AAAI Press / The MIT Press, 1997.

[4] Haddadi, A. "Communication and Cooperation in Agent Systems: A Pragmatic Theory" Lecture Notes in Artificial Intelligence #1056. Springer-Verlag. 1996. ISBN 3-540-61044-8

[5] Weiss, G. "Multiagent Systems: A modern Approach to Distributed Artificial Intelligence". MIT Press. 1999. ISBN 0262-23203

[6] Axelrod, R. "The evolution of Cooperation". Penguin Science. 1991

[7] Pollack and Horty. "There's More to Life Than Making Plans: Plan Management in Dynamic, Multiagent Environments." AI Magazine. Winter 1999 Vol. 20, No.