Distributed Artificial Intelligence and Intelligent Agents

Agent Coordination

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Agent Coordination

- general models
  - why?
  - how?
  - effective control of distributed search
- common coordination techniques
  - organizational structures
  - meta-level information exchange
  - multi-agent planning
  - explicit analysis and synchronization
  - coordination based on human teamwork
 - commitments and conventions

References - Curriculum

- Wooldridge: "Introduction to MAS",

  – Chapter 8

- Other reading (no curricullum)

  – A. Torreno et al. Cooperative Multi-Agent Planning: A Survey. ACM Computing Surveys, Vol. 50, No. 6, 2017, https://arxiv.org/pdf/1711.09057.pdf

  – Dayong Ye, Minjie Zhang and Athanasios V. Vasilakos. A Survey of Self-organisation Mechanisms in Multi-Agent Systems, 2015https://www.uow.edu.au/~minjie/pub-ps.dir/IEEE-self-organisation-survey2015.pdf

  – A. Khan, B.Rinner, A. Cavallaro. Cooperattive Robots to Observe Moving Targets, IEEE Trans. Cybern. 2018, https://ieeexplore.ieee.org/stamp/stamp.jsp?tp=&arnumber=7763837

  – S. Souissi et al. Distributed Algorithms for Cooperative Mobile Robots: A survey. 2011 Second International Conference on Networking and Computing https://ieeexplore.ieee.org/stamp/stamp.jsp?tp=&arnumber=6131865

Coordination Example

Consider an interaction between two robots, A and B, operating in a warehouse. The robots have been designed by different companies, and they are stacking and unstacking boxes to remove certain goods that have been stored in the building. They need to coordinate their actions to share the work load and to avoid knocking into each other and dropping the boxes.

Another Coordination Problem

• Managing the interdependencies between the activities of agents. e.g.

  – You and I both want to leave the room. We independently walk towards the door, which can only fit one of us. I graciously permit you to leave first.

Cartoon taken from Klein, AAMAS2002.
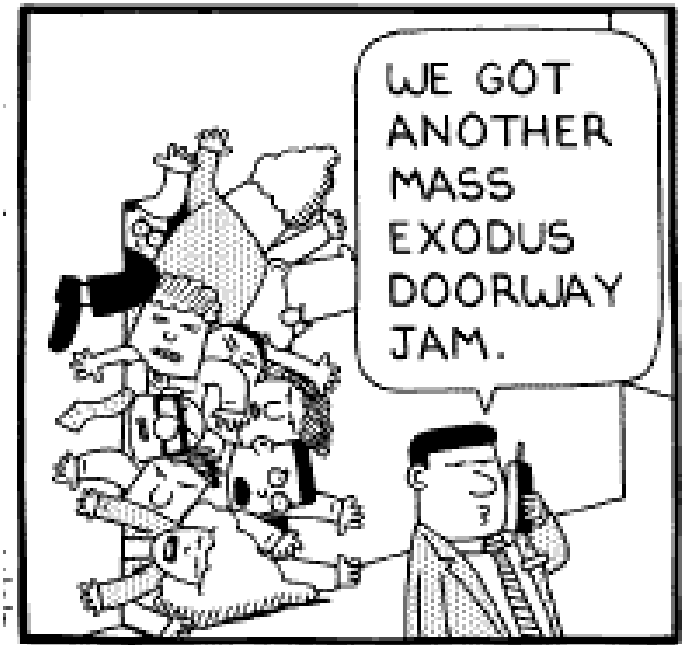
Coordination

"The process by which an agent reasons about its local actions and the (anticipated) actions of others to try and ensure that the community acts in a coherent manner."

Jennings

Coordination

- Preventing anarchy or chaos
- Meeting global constraints
- Distributed expertise, resources or information
- Dependencies between agents' actions
- Efficiency

Coordination

To ensure:
- coverage
- connectivity
- rationality
- capability

Activities:
- supplying timely information to needy agents
- ensuring synchronization
- avoiding redundant problem solving

How to reach coherent behavior?

- complete knowledge
- centralized control
- distributed control

Fundamental coordination processes

- mutual adjustment
- direct supervision
- standardization

Basic steps in coordination problem

- analysis of a perspective for coordination
  - external observation may be not enough
    - coordinated but incoherent
    - coherent but non-coordinated
  - examining an internal goals and motivations is necessary

- applying appropriate coordination model

Control decisions and search

View to coordination as a matter of effective control of distributed search.

What is a control?

- control decisions are decisions about what actions to take next
- control decisions are choices
- control knowledge is any knowledge that informs control decisions
- each control choice is the outcome of an overall control regime which includes knowledge about:
  - what are the control alternatives?
  - what are the decision criteria?
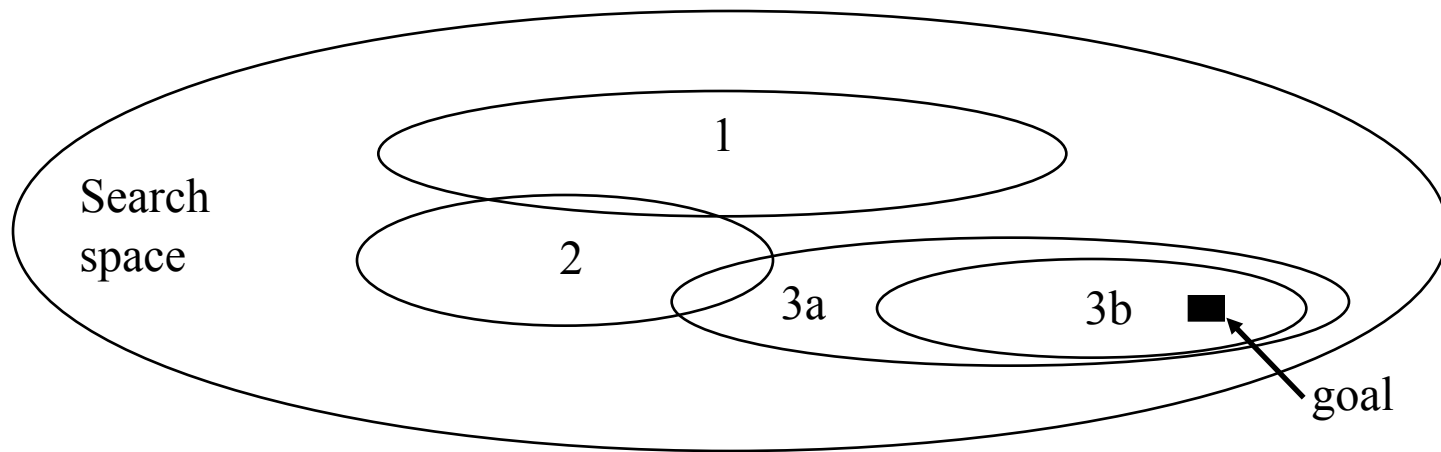 - what is the decision procedure?

Control in cooperative distributed problem solving

Control choice becomes more complicated to the degree that control decisions are more
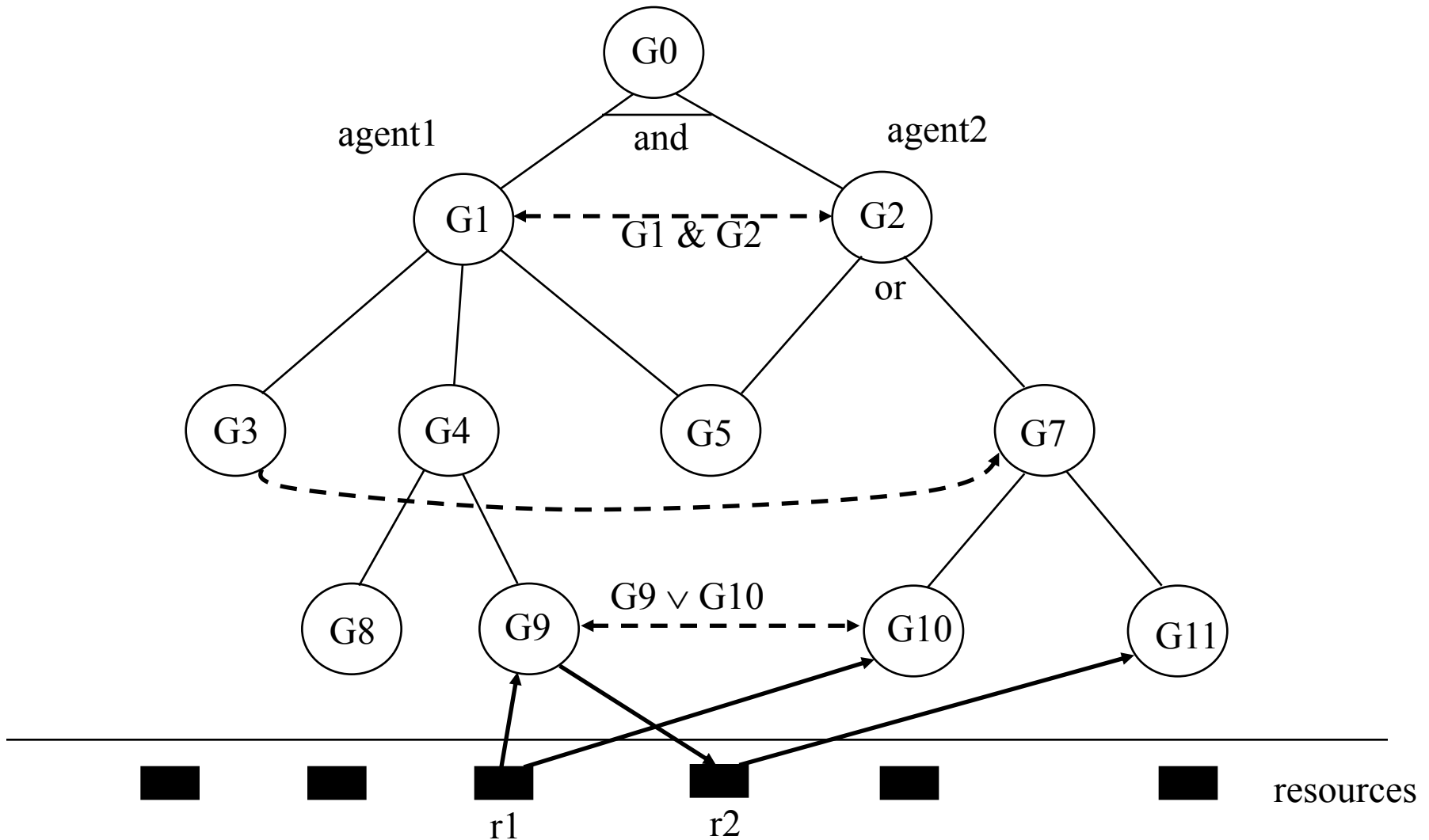
- numerous
- asynchronous
- decentralized

DAI and distributed search

- the space of alternative problem states (goals) can be seen as a large search space investigated by a number of agents

- each agent has to make local control decisions

- these local control decisions have impacts on the overall efforts done by the collection of problem solvers

Search tree (example)

Two kinds of control in DAI

- network control or cooperative control - comprises decision procedures that lead to good overall performance

- local control - refers to decision procedures that lead to good local decisions, and that are based on local information only

Network control

Sets contexts for agent's individual control decisions based on network level information

Network-level information is:

- aggregated from more than one agent or abstracted from data from more than one agent
- information that concerns the relationships among a collection of agents

Network-level information can be utilized to influence:

- set of action alternatives to consider a control decisions
- the decision criteria applied to choose one of them
- the control decision procedure

Network control

One type of coordination based on network control is allocation of search-space regions to agents

- search space - alternative problem states (goals)
- establishing dependencies between nodes
- search process explores that space by generating a tree of possibilities taking into account dependencies
- since a search process explores a tree of possibilities (and any tree is recursively composed of subtrees) it follows that any region of the search space can be characterized by a set of subtree roots
- allocation of search-space regions to agents takes place by allocating collections of search-subtree roots to agents
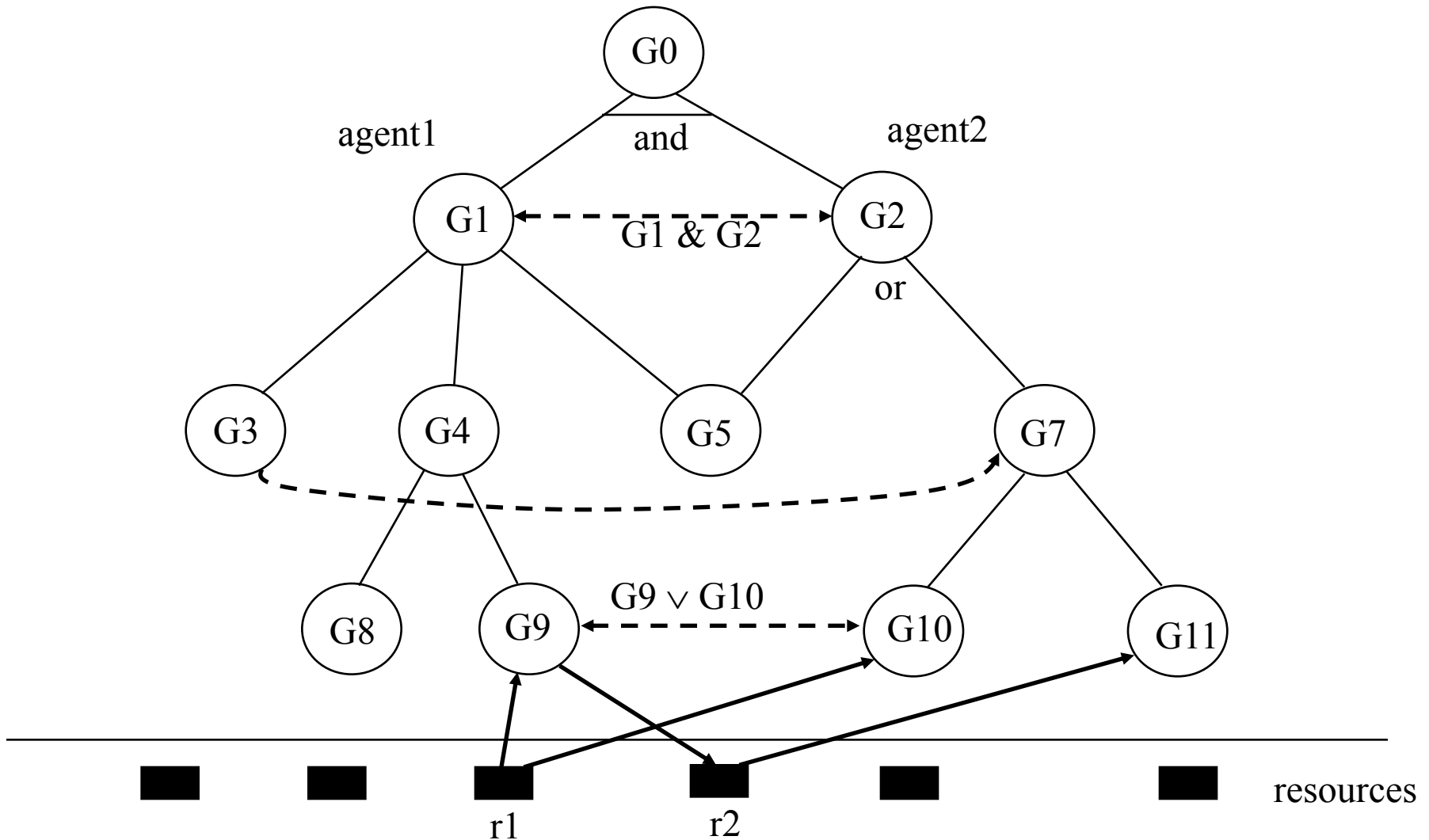- dynamic nature of region allocation

Dependencies analysis

Two kinds of dependencies:
- logical dependencies
- resource dependencies

A very important part of coordination is analysis of interdependencies

Search tree (example)

Joint goals

- team members are mutually responsible to one another
- the team members have a joint commitment to the joint activity
- the team members are committed to be mutually supportive of one another

agent1   G1   G2   agent2

G3   G4   G5

G6   G7
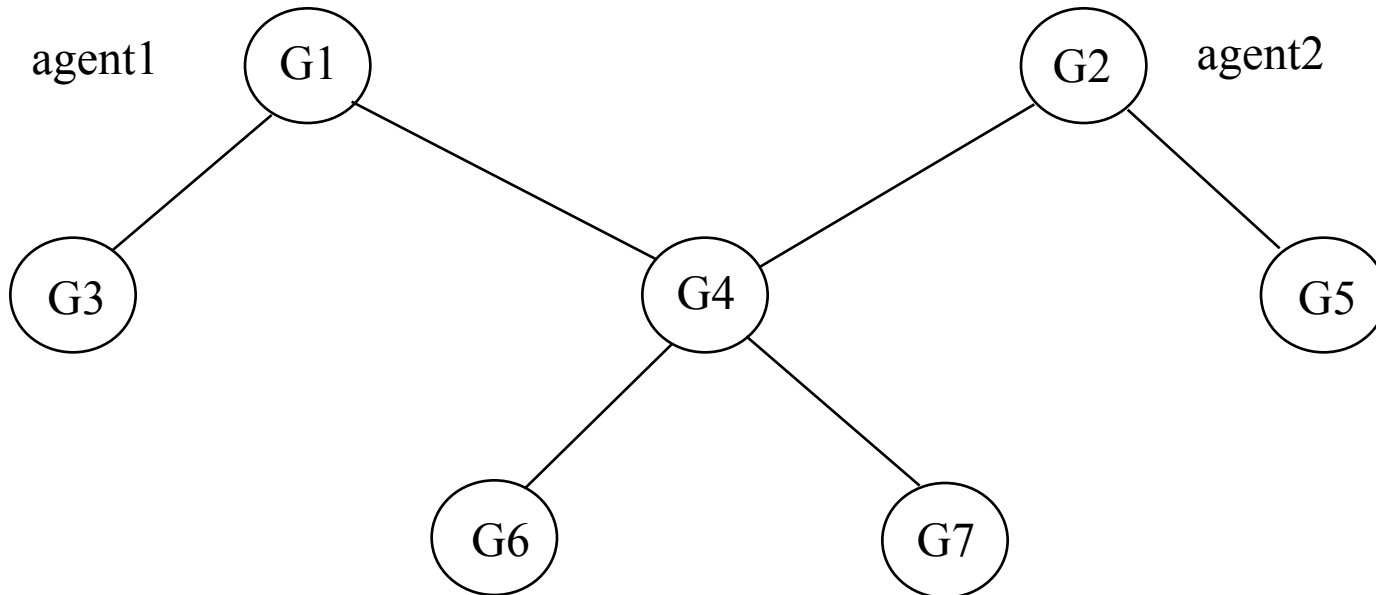
Local control

Concerns the status and process of a single node in its own local environment and its own local search-space region

Interaction with network control:

- network may increase or decrease local control uncertainty

- better local control may more efficiently uncover information that can focus network control decision.

Control uncertainty

Control decision uncertainty - ambiguity in the next action choice (often is characterized as the size of the set of next-states)
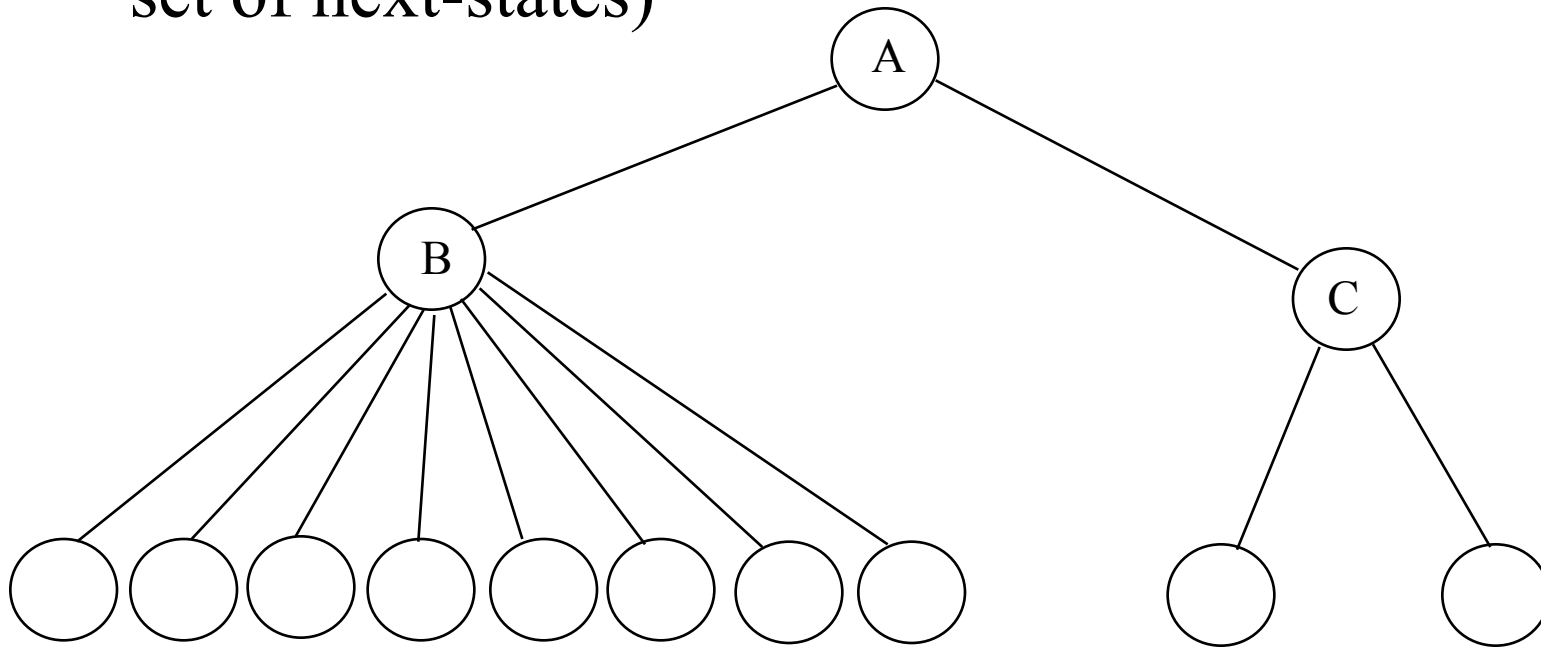
Reducing degree and/or reducing impact of uncertainty
Impact - arbitrariness of control decisions
Impact of control uncertainty can be reduced by reducing common dependencies that agents share

Activities in coordination

- defining the goal graph
- assigning regions of search space
- controlling decisions about which areas of the graph to explore
- traversing the goal structure satisfying dependencies
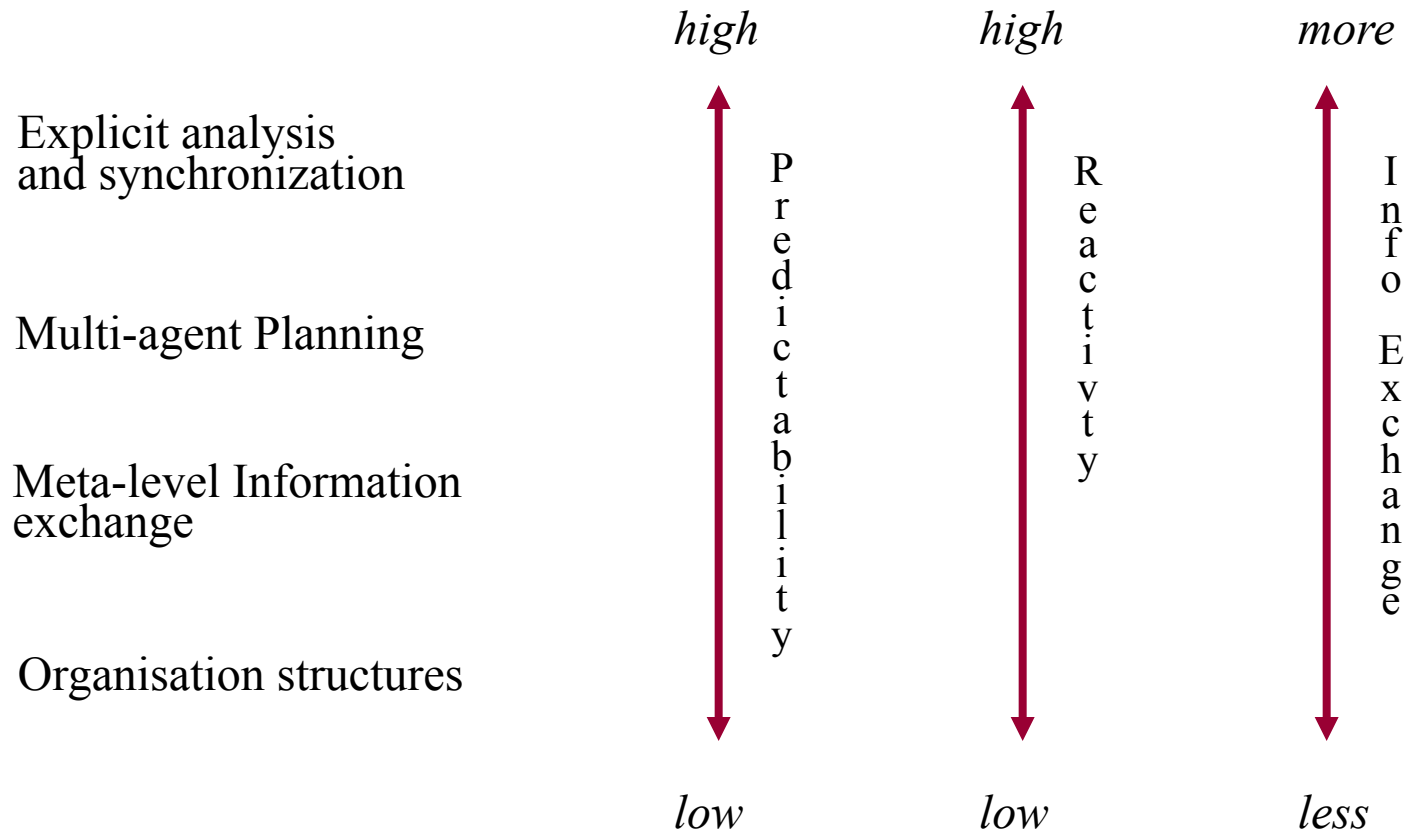- ensuring report of the successful traversal

Determining the approach for each of the phases is a matter of system design and it depends upon:

- the nature of the domain
- the type of agents included into community
- the desired solution characteristics

Coordination Techniques

- Organisational Structures

- Meta-level Information Exchange

  - e.g. Partial Global Planning (PGP), *(Durfee)*

- Multi-agent Planning

- Explicit Analysis and Syncronization

- Norms and social laws

- Coordination Models based on human teamwork:

  - Joint commitments *(Jennings)*

  - Mutual Modelling

Comparing Common Coordination Techniques

Explicit analysis
and synchronization

Multi-agent Planning

Meta-level Information
exchange

Organisation structures

high   *high*   *more*

Predictability   Reactivty   Info Exchange

low   *low*   *less*

Organizational structures

- the simplest coordination approach
- implicit coordination
- provides framework for defining
  - roles
  - communication paths
  - authority relationships
- pre-defined, long-term relations
- specifies the distribution of specializations among agents
- a precise way of dividing the problem space without specifying particular problems
- agents are associated with problem types and problem instances circulate to the agents which are responsible for instances of that type

Organizational Structures

- Organisational structures may be:

  - Functional

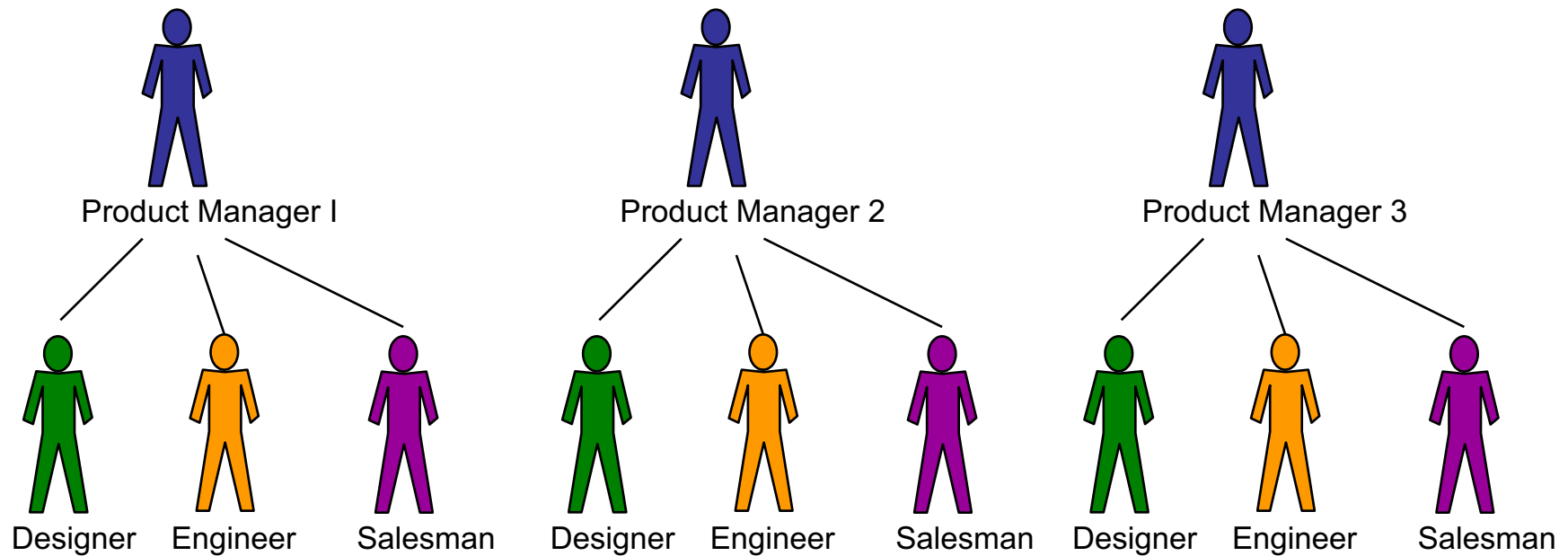 - Spatial

  - Product-Oriented

Organizational Structure Models

- A pattern for decision-making and communication among
  a set of agents who perform tasks in order to achieve goals.
  e.g.

  – Automobile industry

    - Has a set of goals: To produce different lines of cars

    - Has a set of agents to perform the tasks: designers, engineers,
      salesmen

    - Costs considered
      – production costs
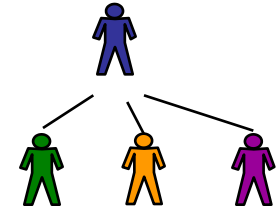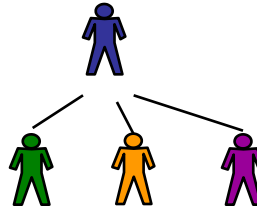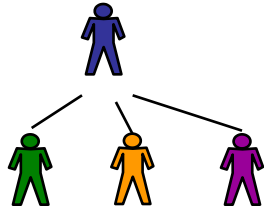   – coordination costs
      – vulnerability costs

Reference: Malone 1987

Alternative Coordination Structures 1
Product Hierarchy

Product Manager I

Designer   Engineer   Salesman

Product Manager 2

Designer   Engineer   Salesman

Product Manager 3

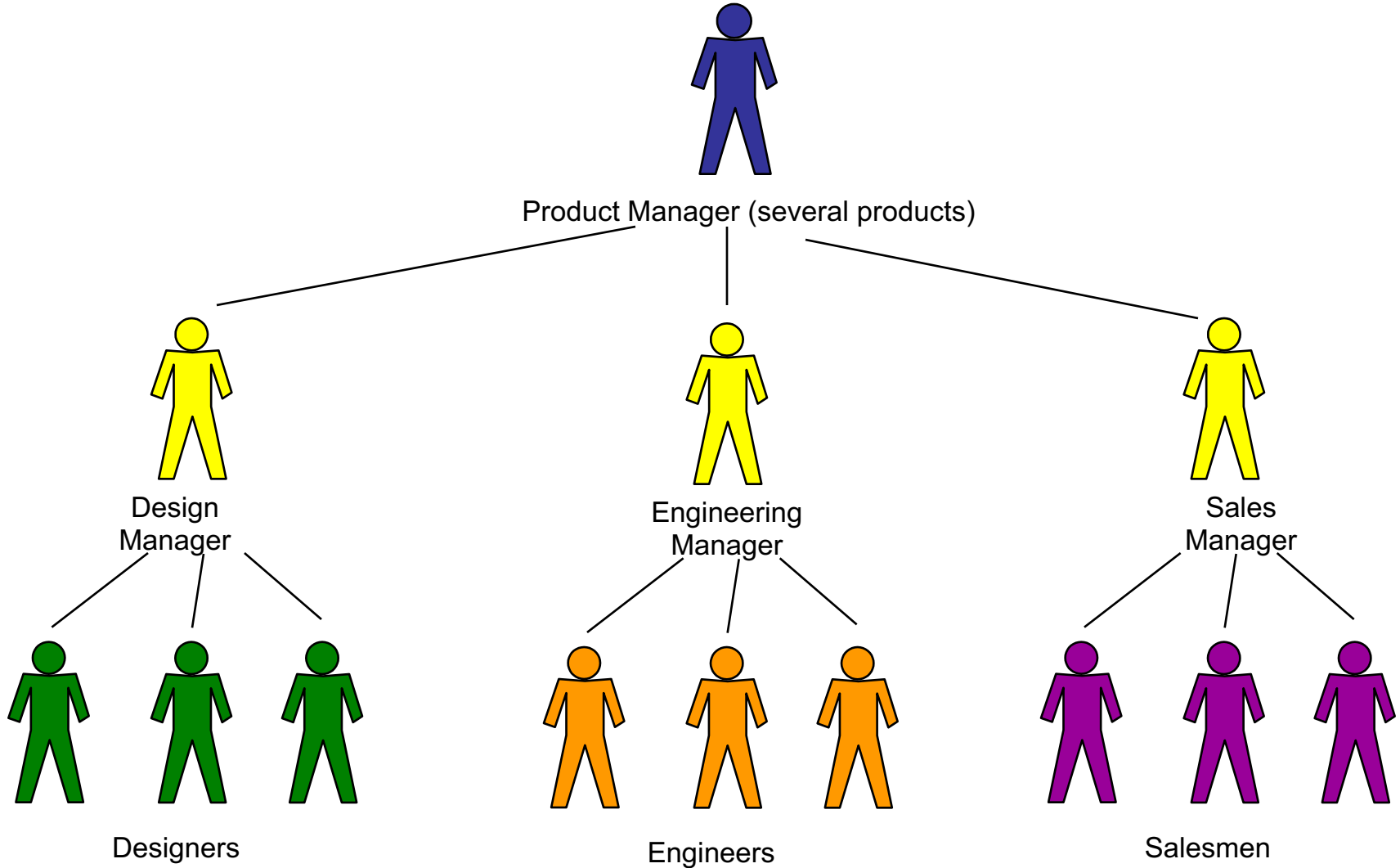Designer   Engineer   Salesman
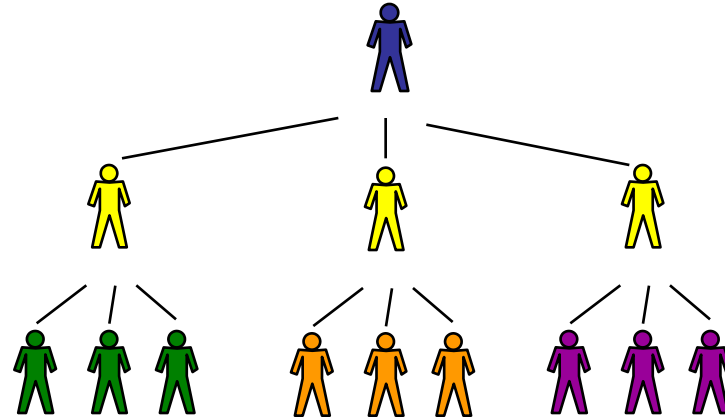
Product hierarchy

- several divisions for different product lines
- each division has a product manager
- each division has its own separate departments (agents) for different functions
- product manager assigns tasks to agents in its department
- communication links in product structure
- fails inside department do not affect other products
- one message to assign task and one message to notify result
- also model for set of separate companies

Alternative Coordination Structures 2
Functional Hierarchy

Product Manager (several products)

Design Manager

Engineering Manager

Sales Manager

Designers

Engineers

Salesmen

Functional hierarchy

- a number of agents of similar types are pooled into functional departments
- each department has a functional manager
- reduce duplication of efforts
- executive office - production manager for all products hierarchical task allocation
- 2 messages to assign task and 2 messages to notify about results
- failure of task agent - delay and task reallocation
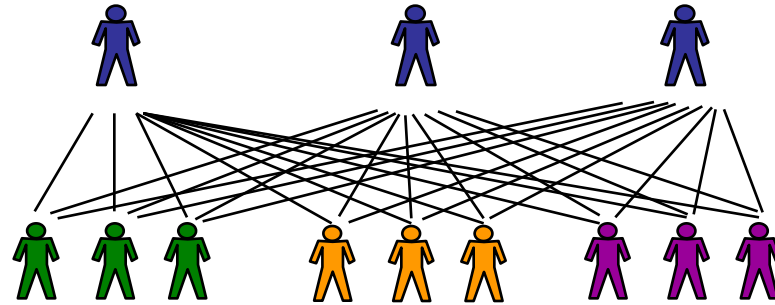- managers are critical

Markets

- not necessary to make all components by itself

- subcontracting

Alternative Coordination Structures 4
Decentralised Market

Product Manager 1   Product Manager 2   Product Manager 3
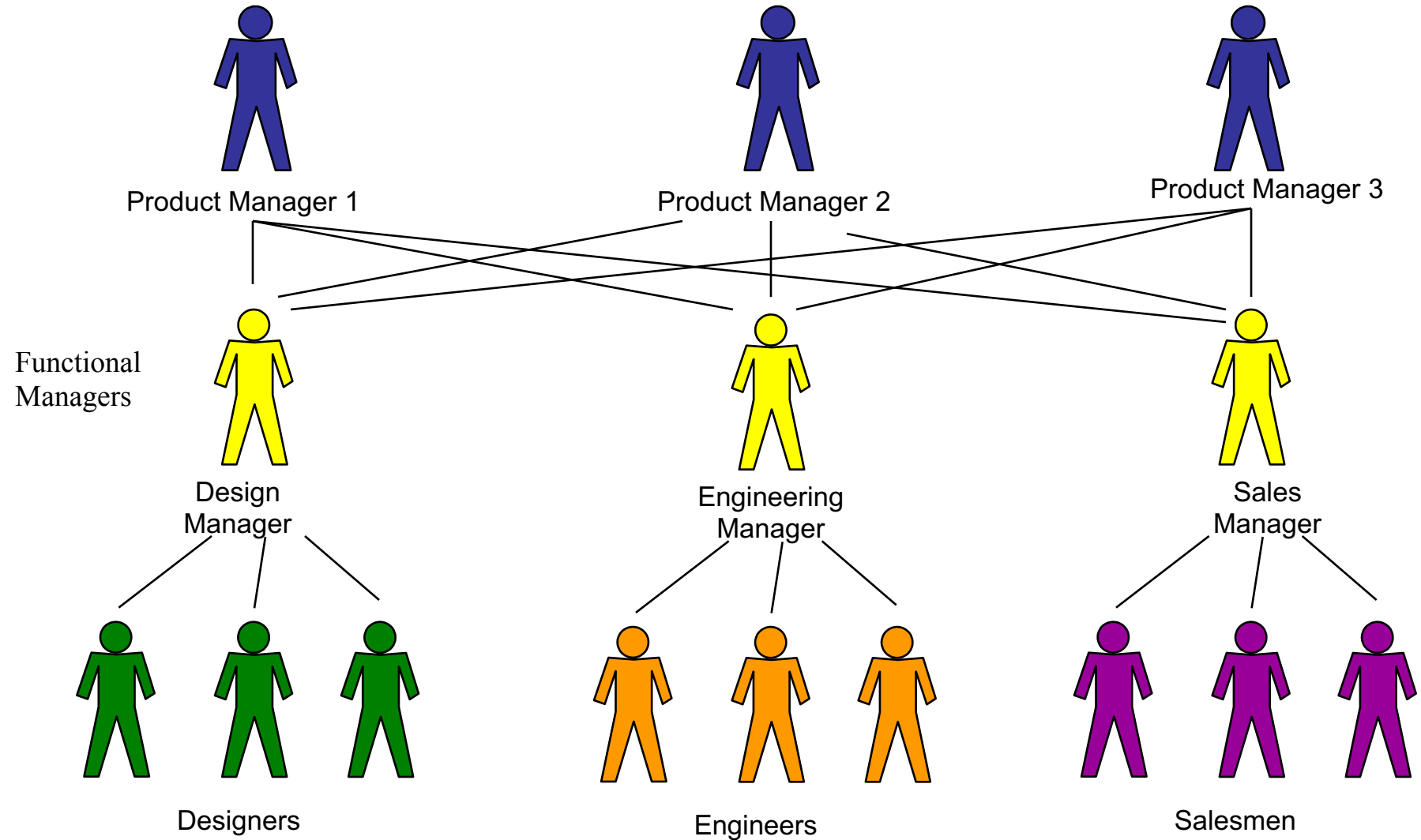
Designers   Engineers   Salesmen
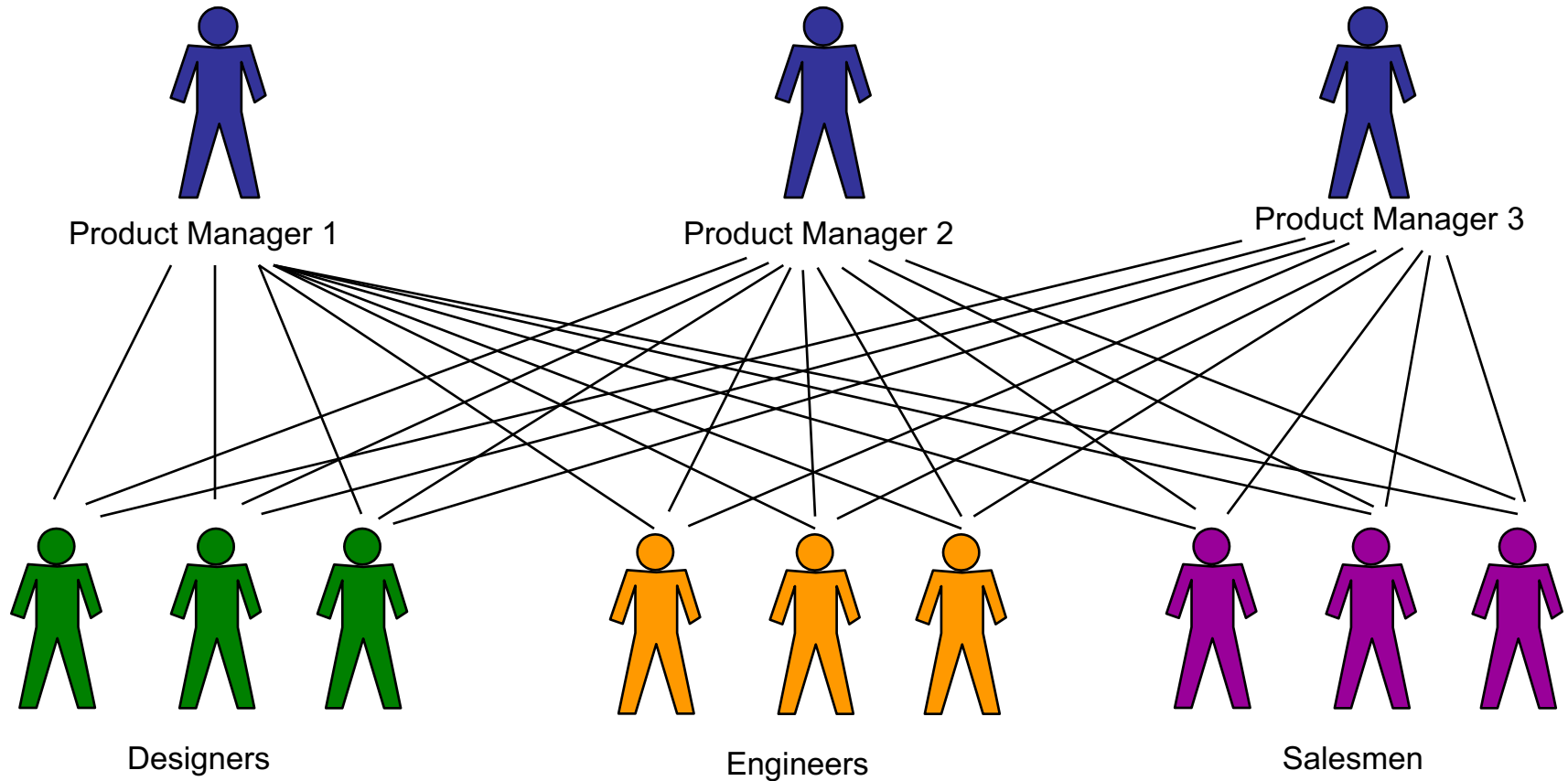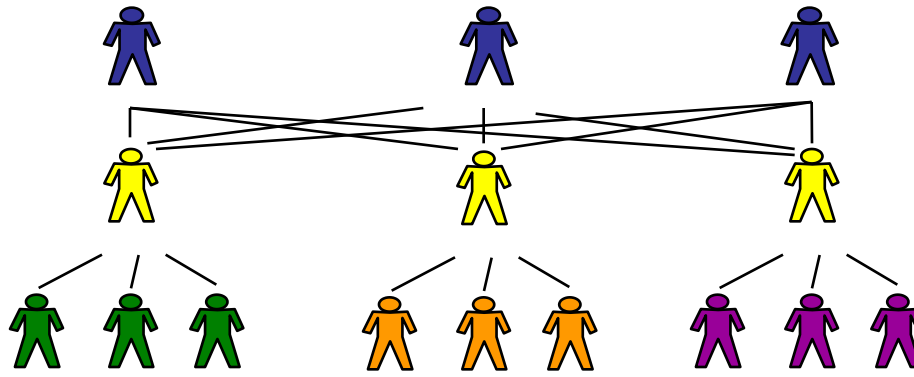
Decentralized market

- all buyers are in contact with all possible suppliers
- buyers play a role of product managers
- each has a communication link with each supplier
- buyers can choose the best supplier
- m suppliers - 2m+2 messages
- processor fails the task is reassigned
- if manager fails – product is failed

Alternative Coordination Structures 3
Centralised Market

Product Manager 1

Product Manager 2

Product Manager 3

Functional
Managers

Design
Manager

Engineering
Manager

Sales
Manager

Designers

Engineers

Salesmen

Centralized market

- brokers are in contact with possible sellers
- fewer connections and communications are required
- brokers play a role of functional managers
- broker chooses the best supplier
- 4 messages
- similar to functional model
- failure of one product manager does not affect others

Summary of organization structures

	Processors shared among products	Messages required to assign task	Result of task processor failure	Result of functional manager failure	Result of product manager failure
Product hierarchy	no	2	1 product disrupted	-	1 prod. disrupted
Decentralised market	yes	2m+2	Task reassigned	-	1 prod. disrupted
Centralised market	yes	4	Task reassigned	All prod. disrupted	1 prod. disrupted
Funtional hierarchy	yes	4	Task reassigned	All prod. disrupted	All prod. disrupted

Comparison of Organization Structures

	Production cost	Coordination cost	Vulnerability cost
Product hierarchy	H	L	H
Functional hierarchy	L	M-	H+
Centralised market	L	M+	H-
Decentralised market	L	H	L

Changes in costs as size of structure increases

	Production cost	Coordination cost	Vulnerability cost
Product hierarchy	+	+	+++
Funtional hierarchy	+	++	+
Centralised market	+	+++	++
Decentralised market	+	++++	++

Organizational Structures - Critique

- Useful when there are master/slave relationships in the MAS.

- Control over the slaves actions – mitigates against benefits of DAI such as reliability, concurrency.

- Presumes that atleast one agent has global overview – an unrealistic assumption in MAS.

Comparing Common Coordination Techniques

Explicit analysis
and synchronization

Multi-agent Planning

Meta-level Information
exchange

Organisation structures

high   *high*   *more*

Predictability   Reactivty   Info Exchange

low   *low*   *less*

Meta-level Information Exchange

- Exchange control level information about current priorities and focus.

- Control level information
  - May change
  - Influence the decisions of agents

- Does not specify which goals an agent will or will not consider.

- Imprecise

- Medium term – can only commit to goals for a limited amount of time.

Partial Global Planning (PGP) Durfee

- The basic condition - requirement that several distributed agents work on solution of the same problem
- An agent can observe actions and relations between groups of other agents
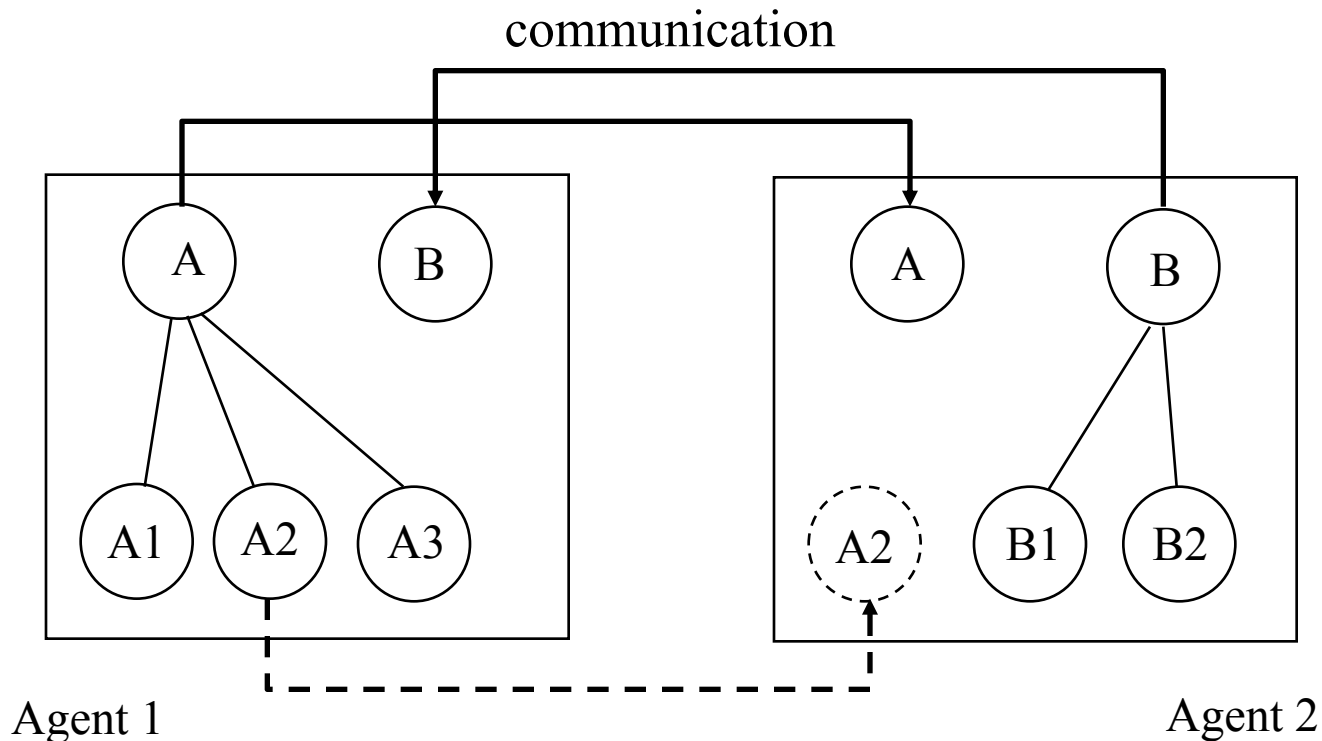
Partial Global Planning (PGP)

- PGP involves 3 iterated stages:

1. Each agent decides what its own goals are and generates short-term plans in order to achieve them.

2. Agents exchange information to determine where plans and goals interact.

3. Agents alter local plans in order to better coordinate their own activities.

Partial Global Planning (PGP)

- Task decomposition
- Local plan formulation
- Local plan abstraction
- Communication of Local plan abstraction
- Partial global goal identification
- PGP construction and modification
- Communication planning
- Acting on PGP
- Ongoing modifications
- Task reallocation

Partial Global Planning (PGP) 1

- A DAI testbed – Distributed Vehicle Monitoring Testbed (DVMT) – to successfully track a number of vehicles that pass within the range of a set of distributed sensors (agents).
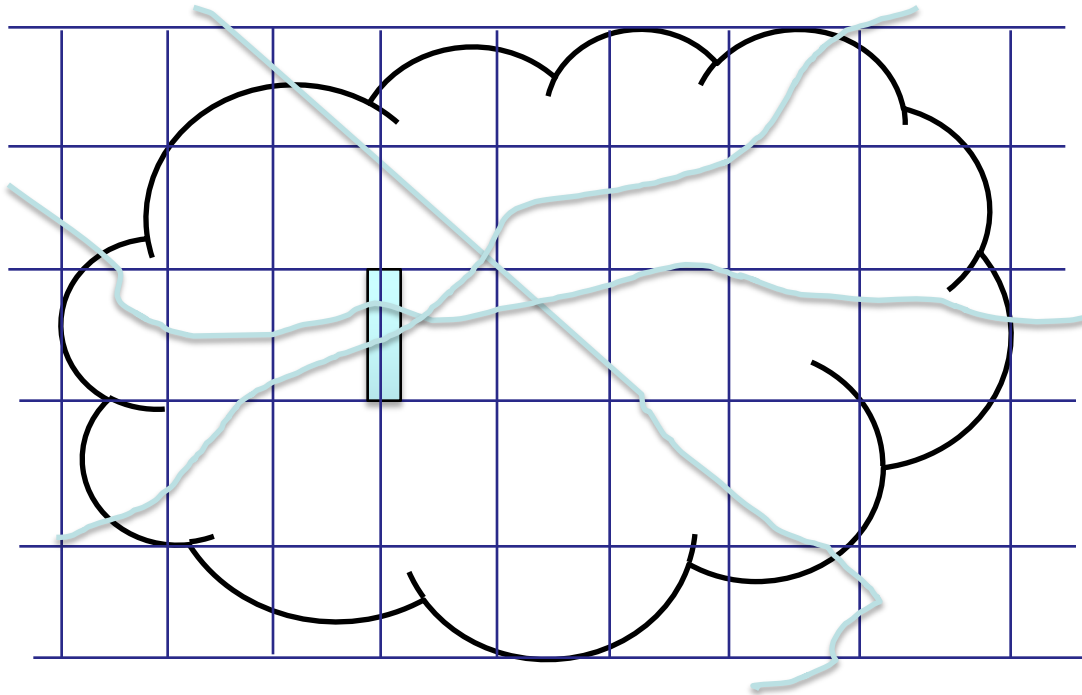
- Geographically distributed agents

- Each agent monitors sensing a portion of the overal area

- Discrete time-interval

- By analyses of sound – type of vehicle and movement map

- Provides information to another agent

- There should be overlapping areas

Partial Global Planning (PGP)

Overlapping areas
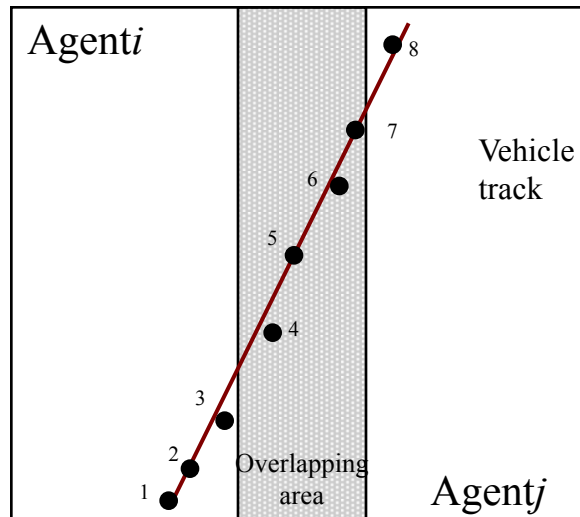
Partial Global Planning (PGP)

- Main principle: cooperating agents exchange information in order to reach common conclusions about the problem solving process.

- Why is planning partial?

  – An agent does not generate a plan for the entire problem.

- Why is planning global?

  – Agents form non-local plans by exchanging local plans and cooperating to achieve a non-local view of problem solving.

Task decomposition (PGP)

- Starts with the premise that tasks are inherently decomposed.

- Assumes that an agent with a task to plan for might be unaware of what tasks other agents might be planning for and how those tasks are related to its own.

- No individual agent might be aware of the global tasks or states.

- Purpose of coordination is to develop sufficient awareness.
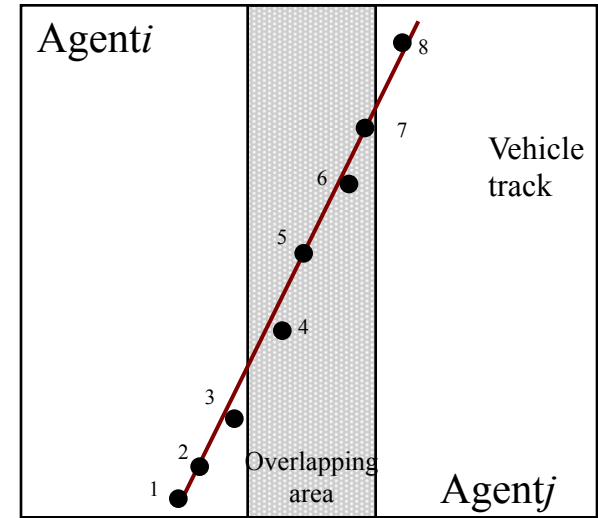
Local plan formulation (PGP)

- before agent communicates with other it must first develop understanding of what goals it is trying to achieve and which actions to perform

- local plans will most often be uncertain, involving branches of alternative actions depending on results of previous actions and changes in environments
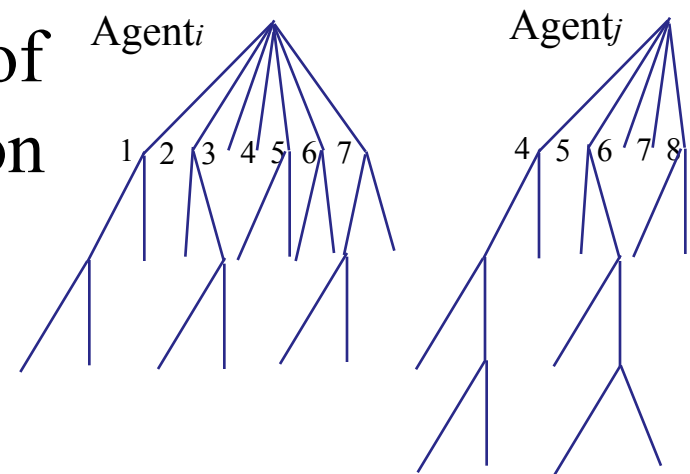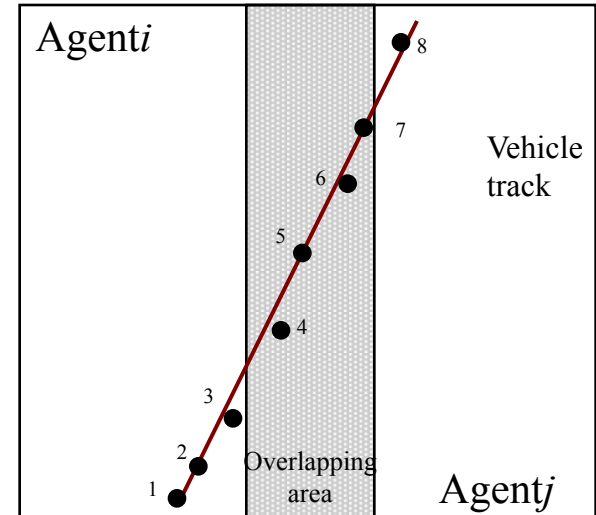
Local plan abstraction (PGP)

- alternative courses of action for achieving the same goal are important for an agent

- however, the detail of alternatives might be unnecessary considering the agent's ability to coordinate with others

- an agent might have to commit to activities at one level of details without committing to activities at more detailed levels

- agents are designed to identify their major plan steps that could be of interest to other agents
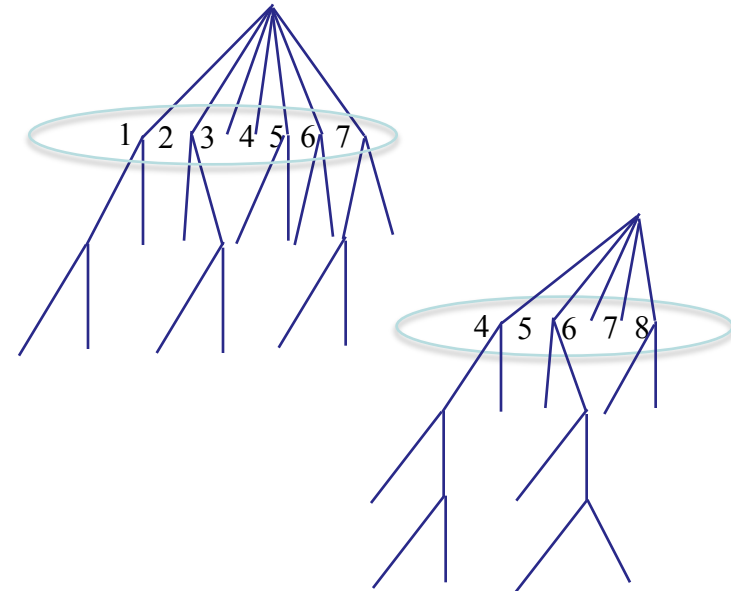
Communication (PGP)

- agents must communicate about abstract local plans in order to build models of joint activity

- in PGP, the knowledge to guide this communication is contained in the meta-level-organization
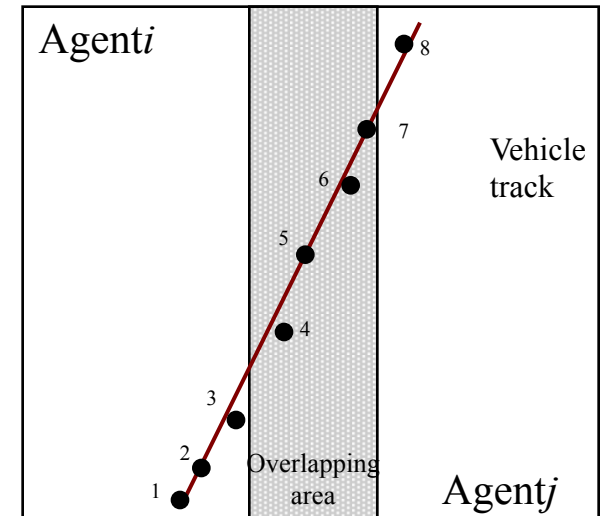
Partial global goal identification (PGP)

- the exchange of local plans gives an opportunity to identify when the goal of one or more agents could be subgoals of a single global goal

- only portions of the global goal might be known to agents

- partial global goal

Agent$i$

8

7

Vehicle track

6

5

4
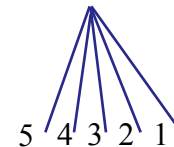
3

2

Overlapping area

1

Agent$j$
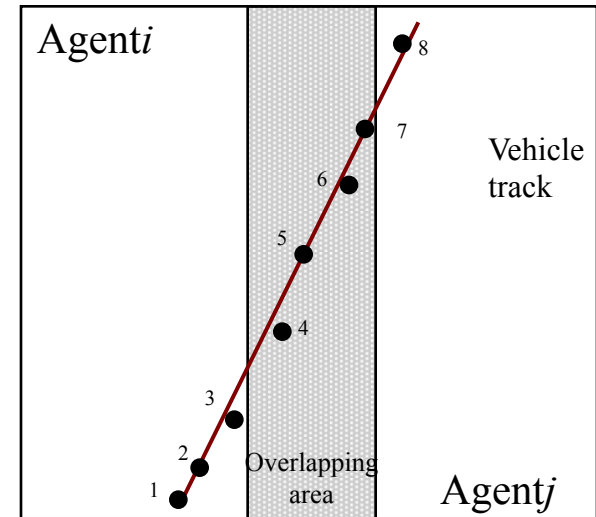
PGP construction and modification

- local plans can be integrated into PGP

- PGP can identify opportunities for improved coordination (performing related tasks earlier, avoiding redundant task achievement)
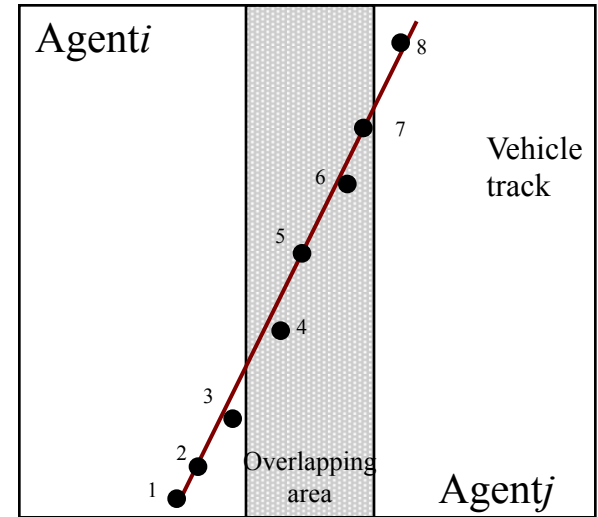
- reordering of actions (usage of action rates)

PGP construction and modification

Rates:

- whether the task is unlikely to have been accomplished already by another agent
- how long it is expected to take
- how useful its results will be to others in performing their tasks

Algorithm
1. For the current ordering, rate the individual actions and sum the ratings
2. For each action, examine the later actions for the same agent and find the most highly-rated one. If it is higher rated, then swap the actions
3. If the new ordering is more highly rated than the current one, then replace the current ordering with the new one and go to step 2.
4. Return the current ordering

Communication planning (PGP)

- agent must next consider what interactions should take place between agents

- interactions in form of communicating the results of tasks are planned

- by examining PGP an agent can determine when a task will be completed by one agent that could be of interest to another agent and can explicitly plan the communication action to transmit the result

Agent*i*

Overlapping area

Agent*j*

Vehicle track
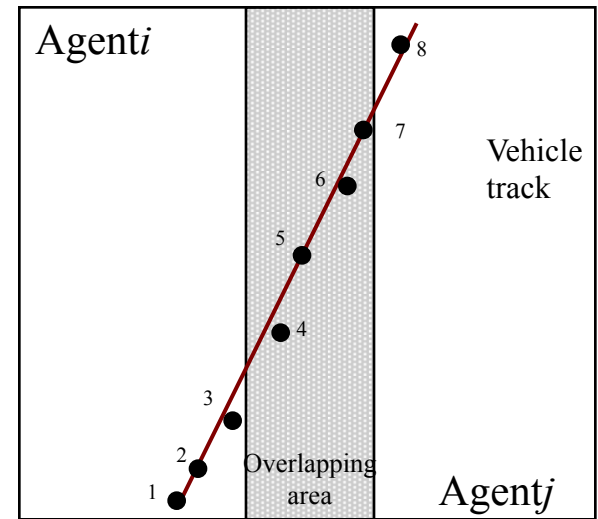
Communication planning (PGP)

1. Initialize the set of partial task results to integrate

2. While the set contains more than one element:

   (a) For each pair of elements: find the earliest time and agent at which they can be combined

   (b) For the pair that can be combined earliest: add a new element to the set of partial results for the combination and remove the two elements that were combined

3. Return the single element in the set
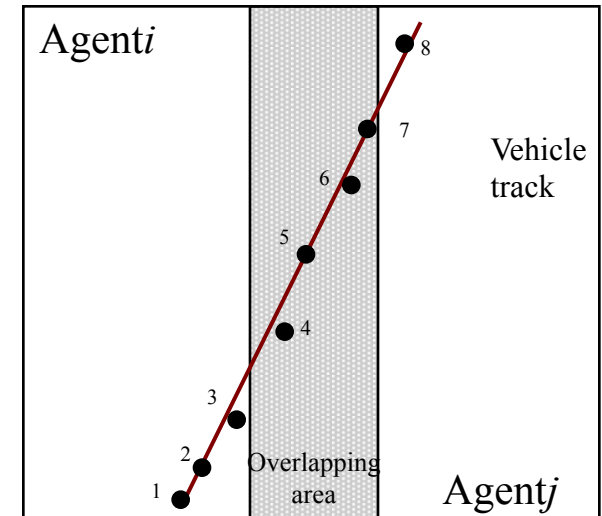
Acting on PGP

- once a PGP has been constructed and the concurrent local and communication actions have been ordered, the collective activities of the agents have been planned

- these activities must be translated back to the local level

- an agent responds to a change in its PGP by modifying the abstract representation of its local plans

- modified representation is used by agent when choosing its next local action
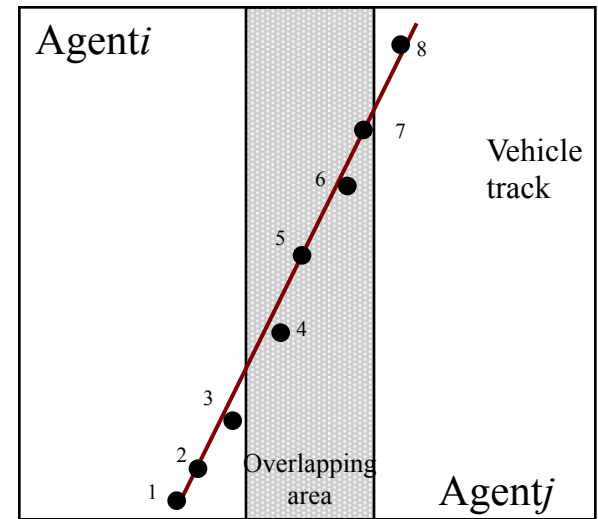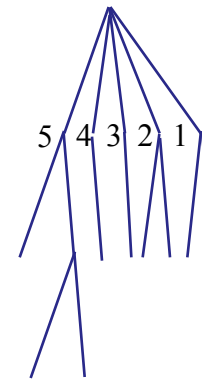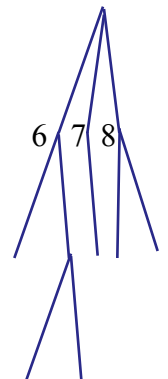
Ongoing modifications (PGP)

- as agents pursue their plans, their actions or events in environment might lead to changes in tasks

- a change in coordination is deciding when the changes in local plans are significant enough

- defining a threshold (significant temporal deviations)
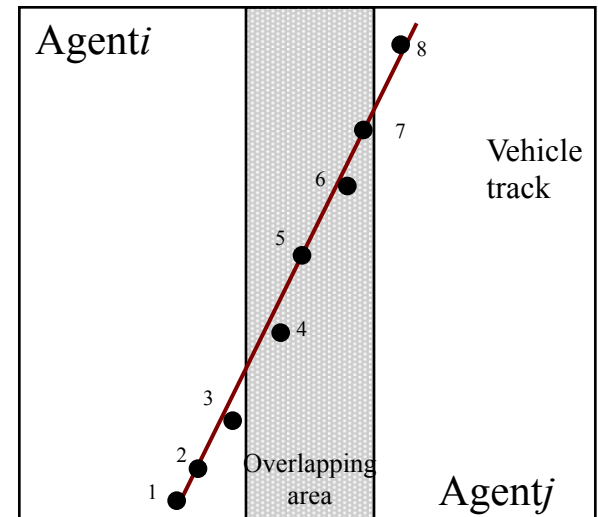
Task reallocation (PGP)

- disproportional task load

- through PGP exchange of abstract models of agent's activities and detection whether they are overburdened

- possible task reallocation
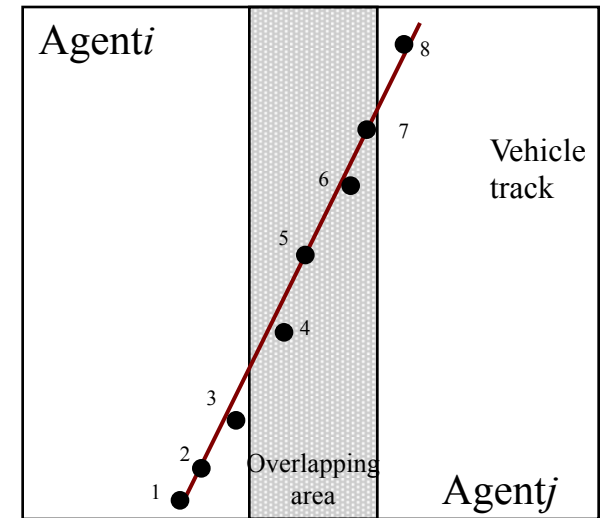
Partial Global Planning (PGP)

- Partial Global Plan: a cooperatively generated datastructure containing the actions and interactions of a group of agents.

- Contains:

  – Objective – the larger goal of the system.

  – Activity map – what agents are actually doing and the results generated by the activities.

  – Solution construction graph – a representation of how the agents ought to interact in order to successfully generate a solution.

Summary (PGP)

- PGP focuses on dynamically revising plans in cost-effective ways given an uncertain world

- PGP particularly suited to applications where some uncoordinated activity can be tolerated and overcome

- PGP works well for many tasks, but could be inappropriate for domains such as air-traffic control where guarantees about coordination must be made prior to any execution

Comparing Common Coordination Techniques

Explicit analysis
and synchronization

Multi-agent Planning

Meta-level Information
exchange

Organisation structures

high   *high*   *more*

Predictability   Reactivty   Info Exchange

low   *low*   *less*
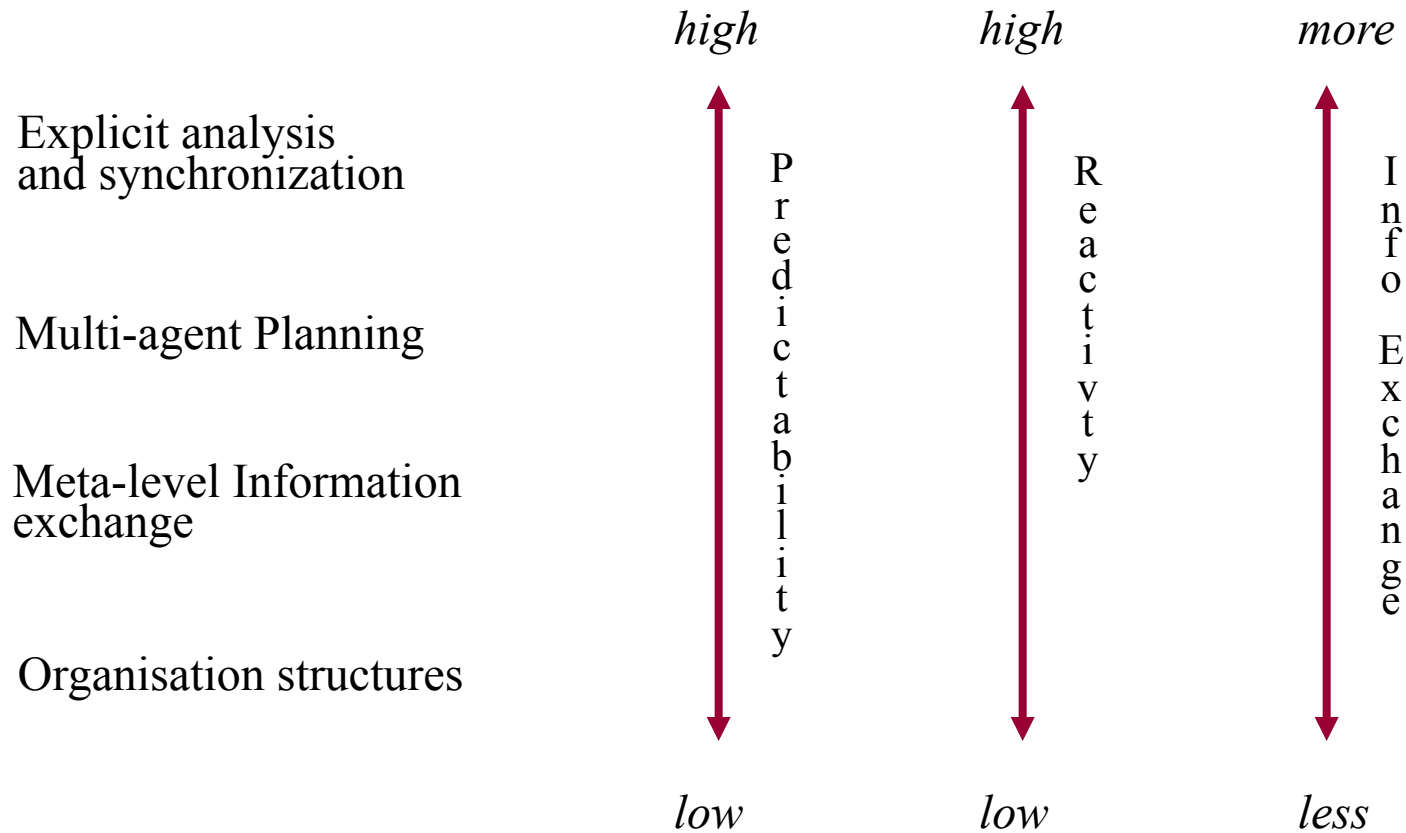
Multi-agent Planning

- Agents generate, exchange and synchronize explicit plans of actions to coordinate their joint activity.

- They arrange apriori precisely which tasks each agent will take on.

- Plans specify a sequence of actions for each agent.

- Consideration of uncertainty is moved to the planning activity

- More specific than organizational structures or PGP and shorter time-horizon

Multi-agent Planning

- Two basic approaches:

1. Centralised – a central coordinator develops, decomposes and allocates plans to individual agents.

2. Distributed – a group of agents cooperate to form:

    1. Centralised plan

    2. Distributed plan

Multi-agent Planning

Centralized planning for distributed plans

- Given a goal description, a set of operators and an initial state description, generate a plan
- Decompose the plan into subproblems such that ordering relationships between steps tend to be minimized across subproblems
- Insert synchronization actions into subplans
- Allocate subplans to agents using task-passing mechanisms
- Initiate plan execution and optionally monitor progress

Multi-agent Planning

- Distributed Planning for centralised plans:
  - e.g. Air traffic control domain (Cammarata)
    - Aim: Enable each aircraft to maintain a flight plan that will maintain a safe distance with all aircrafts in its vicinity.
    - Each aircraft sends a central coordinator information about its intended actions. The coordinator builds a plan which specifies all of the agents' actions including the ones that they should take to avoid collision.
  - e.g. A general technological process (manufacturing)
    - Plan is centralized but each step can be planned in parallel
    - Disitrbuted expertize but control is centralized

Multi-agent Planning

- Distributed Planning for distributed plans:

  – Individual plans of agents, coordinated dynamically.

  – No individual with a complete view of all the agents' actions.

  – More difficult to detect and resolve undesirable interactions.

Centralized multi-agent plans (plan coordination) - an example (Georgeff)

- robots world
- actions - sequences of states
- each action has pre- and post-conditions
- plans are generated separately

This approach has several steps
- interaction analysis
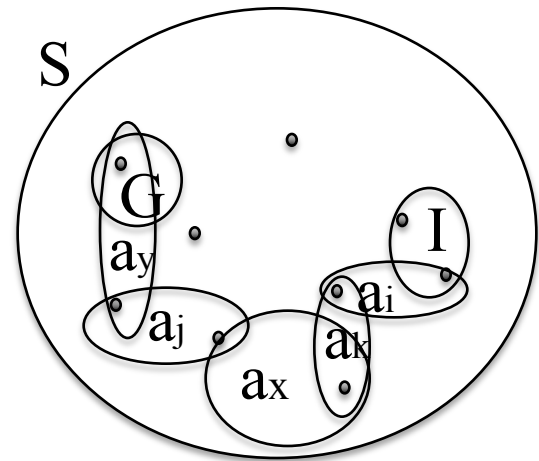- safety analysis
- interaction resolution

Centralized multi-agent plans

An action a is a sequence of states p :

a = {p_1, ... , p_i, ... , p_n}, where p_1 is action's initial state, p_n is action's final state and p_2,…, p_{n-1} are intermediate states

A planning problem consists of
- set of states S
- a designated set of initial states I
- a set of actions A
- a set of goal states G

A single-agent plan P is a description of sequence of actions a_1, a_2, ... , an from A such that:
- a_1 is applicable to all initial states (a_1 initial state is in I)
- for all i, 1 < i ≤ n, the action a_i is applicable to all states in the range of a_{i-1}
- an achieves the goal G (final state of an is in G)

Interaction analysis

- establishing incompatible situations
- <p, q> - the situation where both p and q hold (it can be unsatisfiable if contradictory)
- possible alternatives for safe action execution
  - actions can be executed in parallel (actions said to be commuted)
  - suspending one of the action
- precedence may exist of one over another (post-condition of one is a pre-condition for another)
  - both actions may have precedence over each other
  - neither actions may have precedence
- plans are generated separately

Safety analysis

Determining unsafe situations for each pair of actions in two plans

- if a_i and b_j do not commute, then $\langle \text{begin}(a_i), \text{begin}(b_j) \rangle$ is unsafe

- if a_i doesn't have precedence over b_j, then $\langle \text{begin}(a_i), \text{end}(b_{j-1}) \rangle$ is unsafe

The set of all such unsafe situations is called interaction set

Rules for safety governing

- if s=<begin(a_i),begin(b_j)>, then s is unsafe if either of its successor situations are unsafe
- if s=<begin(a_i),end(b_j)>, then s is unsafe if <end(a_i),end(b_j)> is unsafe
- if s=<end(a_i),end(b_j)>, then s is unsafe if both successor situations are unsafe
- together with those situations occurring in the interaction set, these are all the unsafe situations

Interaction resolution

The set of unsafe situations is next analyzed to identify contiguous sequences of unsafe situations

Handling synchronization

- critical regions
- communication commands
  - P!s - send s to process P
  - P?s - receive s from P

Centralized multi-agent plans (plan coordination)

- drop commuting actions
- exponential search of interleavings
- introducing synchronization

Example - 2 robots

The actions are informally as follows:

- a1m: agent 1 moves to the lathe
- a2m: agent 2 moves to the lathe
- a1p: agent 1 places metal stock in lathe
- a2p: agent 2 places metal stock in lathe
- a1b: agent 1 makes a bolt
- a2n: agent 2 makes a nut
- a1f: agent 1 moves to end
- a2f: agent 2 moves to end

Preconditions for a1b and a2n - the lathe must be in possession of the appropriate agent, as well as postconditions for a1p and a2p

Example (cont.)

Assume the simple planner produces the following single-agent plans:

a1m -> a1p -> a1b -> a1f
a2m -> a2p -> a2n -> a2f

The following properties can be established
- actions a1b and a2n conflict with one another
- actions a1p and a2p each have precedence over each other but do not commute
- action a1b has precedence over a2p, but not vice versa
- action a2n has precedence over a1p, but not vice versa

Example (cont.)

Interaction set is determined to be:
  <begin(a1b),begin(a2n)>, <begin(a1b),end(a2p)>,

  <end(a1p),begin(a2n)>, <begin(a1p),begin(a2p)>,

  <begin(a1b),begin(a2p)>, <end(a1p),begin(a2p)>,

  <begin(a1p),begin(a2n)>, <begin(a1p),end(a2p)>

We next form the simplified solutions:
  begin(a1p) -> end(a1p) -> begin(a1b) -> end(a1b)

  begin(a2p) -> end(a2p) -> begin(a2n) -> end(a2n)

Example (cont.)

Safety analysis - we get 2 critical regions

    begin(a1p) -> end(a1b)

    begin(a2p) -> end(a2n)

Next we insert synchronization commands into initial plans:

    a1m -> S!begin(a1p) -> a1p -> a1b -> S!end(a1b) -> a1f

    a2m -> S!begin(a2p) -> a2p -> a2n -> S!end(a2n) -> a2f

Synchronizer (very generally):

    N, M := false

    not N; P?begin(a1p) -> M := true

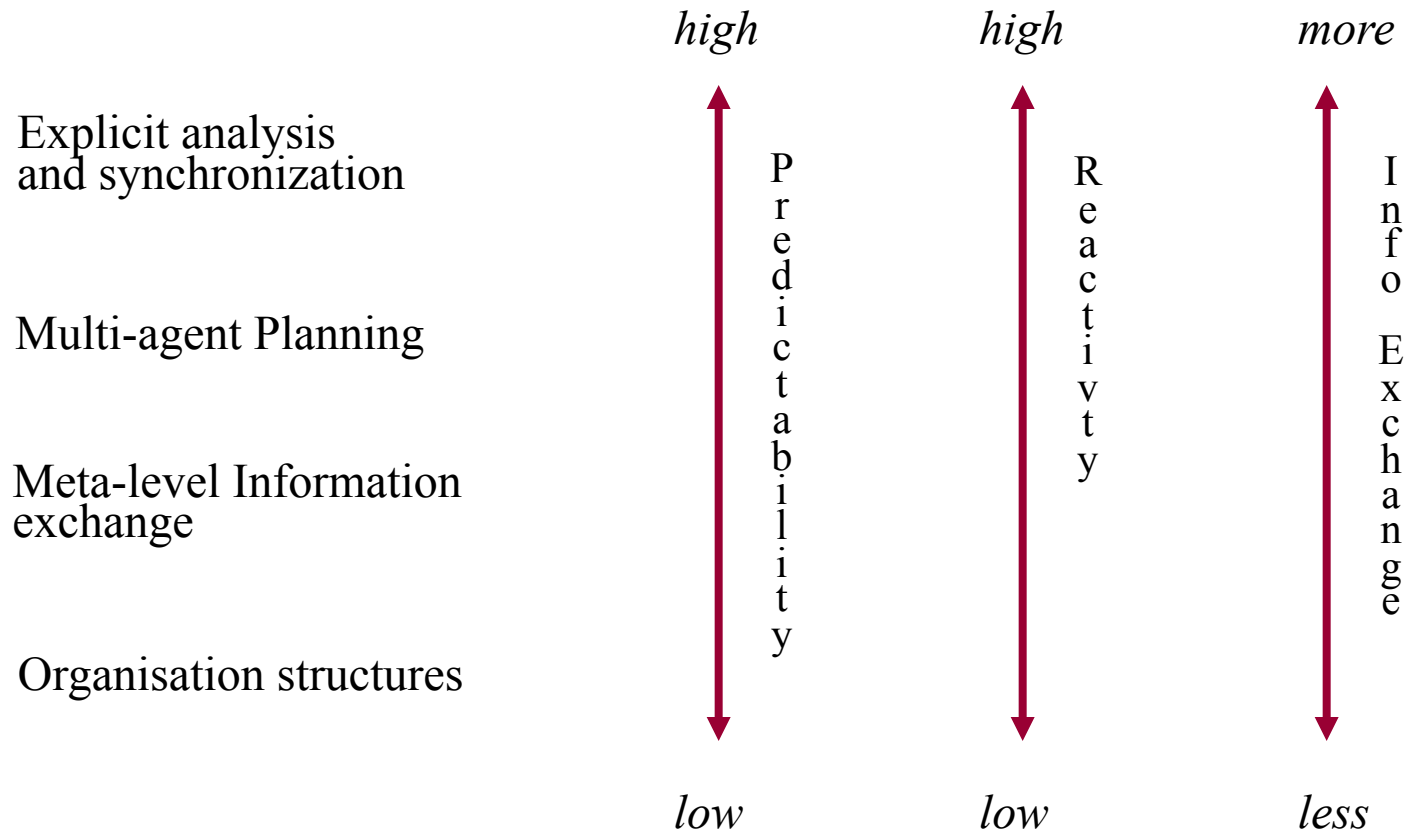   not M; Q?begin(a2p) -> N := true

    true; P?end(a1b) -> M := false

    true; Q?end(a2n) -> N := false

Multi-agent Planning

- Critique:

    - Agents share and process a huge amount of information.

    - Requires more computing and communication resources.

- Difference between multi-agent planning and PGP:

    - PGP does not require agents to reach mutual agreements before they start acting.

Comparing Common Coordination Techniques

Explicit analysis
and synchronization

Multi-agent Planning

Meta-level Information
exchange

Organisation structures

high   *high*   *more*

Predictability   Reactivty   Info Exchange

low   *low*   *less*

Explicit analysis and synchronization

- analysis of a situation in each decision-making step (possible-next-action-set)
- interacting with other agents
  - exchange among all interdependent agents
  - locks action
  - uses reply information to prune its next-action set
  - send synchronization unlocking messages
- a lot of time for communication during planning
- if the level of dependency is low and the granularity of actions is high - can provide useful coordination
- short time-horizon

Coordination Techniques

- Organisational Structures

- Meta-level Information Exchange

  - e.g. Partial Global Planning (PGP), *(Durfee)*

- Multi-agent Planning

➢ Norms and social laws

- Coordination Models based on human teamwork:

  - Mutual Modelling

  - Joint commitments

Social Norms and Laws

- **Norm**: an established, expected pattern of behaviour.

  - e.g. To queue when waiting for the bus

- **Social laws**: similar to Norms, but carry some authority.

  - e.g. Traffic rules.

- Social laws in an agent system can be defined as a set of constraints:

  - Constraint $\Rightarrow \langle E', \alpha \rangle$,

    - $E' \subseteq E$ is a set of environment states

    - $\alpha \in Ac$ is an action, (Ac is the finite set of actions possible for an agent)

  - if the environment is in some state $e \in E'$, then the action α is forbidden.

    An agent (or plan) is said to be legal wrt a social law if it never attempts to perform an action that is forbidden by some constraint in the social law

Coordination Techniques

- Organisational Structures

- Meta-level Information Exchange

  - e.g. Partial Global Planning (PGP), *(Durfee)*

- Multi-agent Planning

- Norms and social laws

➢ Coordination Models based on human teamwork:

  - Mutual Modelling

  - Joint commitments

Mutual Modelling

- Build a model of the other agents – their beliefs and intentions.

    ➢ *Put ourselves in the place of the other*

- Coordinate own activities based on this model

- Cooperation without communication

# Coordination without cooperation

- Can we have coherent behaviour without cooperation?

    ”A group of people are sitting in a park. As a result of a sudden downpour, all of them run to a tree in the middle of the park because it is the only source of shelter.”

Coordination with cooperation

A group of dancers converge to a common point when called by the choreographer – this is a cooperative action because they each have the aim of meeting at a central point.

Teamwork
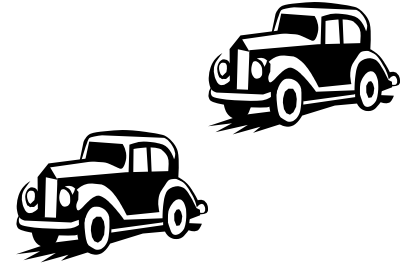
Two vehicles travelling in a convoy:

Consider two agents Bob and Alice. Bobs wants to drive home, but does not know his way. He knows that Alice is going near there and that she does know the way. Bob talks to Alice and they both agree that he follows her through traffic and that they drive *together*.

Ref: Cohen & Levesque, 1991

Teamwork

- Distinction:
  - Coherent behaviour that is not cooperative, e.g
    - Individual drivers in traffic following traffic rules – maximizing own utility
  - Coordinated cooperative action, e.g
    - Maximizing system utility like in the dancers example
  - Teamwork action, e.g
    - Convoy- combining individual efforts –sharing a common goal

Teamwork Definition

- American Heritage Dictionary

  – *Cooperative effort* by the members of a team to achieve a *common goal*.

Teamwork

- How does an individual intention towards a particular goal differ from being a part of a team with a collective intention towards a goal?

  - **Responsibility** towards the other members of the team.

    - e.g. You and I are lifting a heavy object

  - Agents i, j and k are a **team** and have a common goal G.
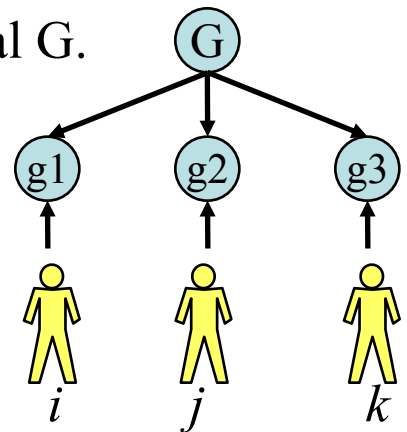
Joint Intentions model

- Based on human teamwork models

    ”When a group of agents are engaged in a cooperative activity, they must have a joint commitment to the overall aim as well as their individual commitments.”

Commitments

- Commitment – a pledge or promise (e.g. to lift the heavy object).

  - Commitment persists – if an agent adopts a commitment, it is not dropped until for some reason it becomes redundant.

  - Commitments may change over time, e.g. due to a change in the environment

  - Main problem with joint commitment:

    - Hard to be aware of each others states at all times

Conventions

- Convention – means of monitoring a commitment

  - e.g. specifies under what circumstances a commitment can be abandoned.

- Need <u>conventions</u> to describe when to change a commitment:

  1. When to keep a commitment (retain)

  2. When to revise a commitment (rectify)

  3. When to remove a commitment (abandon)

Convention - Example

- Reasons for terminating a Commitment:
  - Commitment Satisfied
  - Commitment Unattainable
  - Motivation for commitment no longer present

- Rule R1:

```
If Commitment Satisfied OR
    Commitment Unattainable OR
    Motivation for Commitment no longer present
then
    terminate Commitment.
```
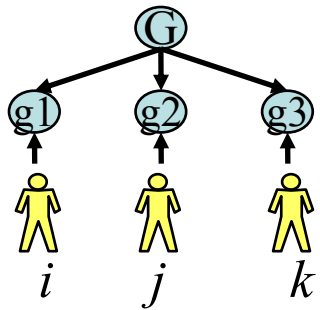
Joint Commitments

- Joint action by a team involves more than just the union of simultaneous individual actions.

   - When a group of agents are engaged in a cooperative activity, they must have:

        - **Joint commitment** to the overall activity

        - **Individual commitment** to the specific task that they have been assigned to

Social Conventions

- Individual Conventions describe how an agent should monitor its commitments, but not how it should behave towards other agents.

- For inter-dependent goals:
  - Need *social* **conventions**
    - Specify how to behave with respect to the other members of the **team**.

Social Conventions

- Team members must be aware of the convention that govern their interactions. e.g.
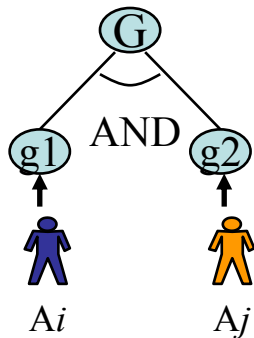
- Both Ai and Aj must fulfill their commitments to achieve G.
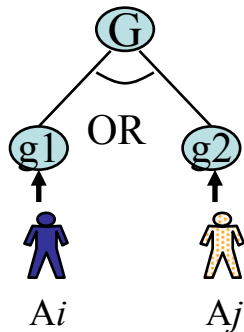
- Either Ai or Aj must fulfill their commitment.

➢ *There is a need for all agents in a team to inform other members of the status of their commitments!*

Coordination Summary

- Coordination – ensuring coherent behaviour.

- Can be considered as a control over distributed search

- Coordination Techniques:

  – Organisational structures

  – Meta-level information exchange

  – Multi-agent Planning

  – Social norms and laws

  – Mutual Modelling

  – Joint Intentions