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Task Allocation for Cooperative Multi-agent Systems

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Outline

1. Introduction to Cooperative Control
2. Applications
3. Problem of Task Allocation
4. Existing Approaches
5. Future Plan

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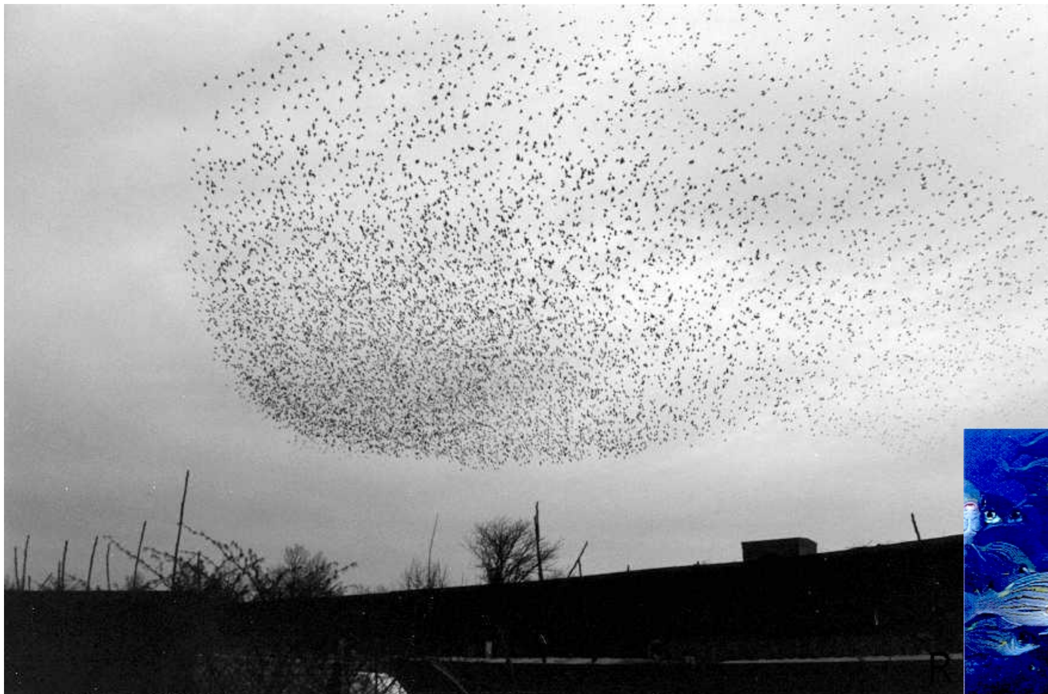
Examples of Cooperation in Nature



Flocking of Birds

Schooling of Fish

Advantage of Cooperative Control

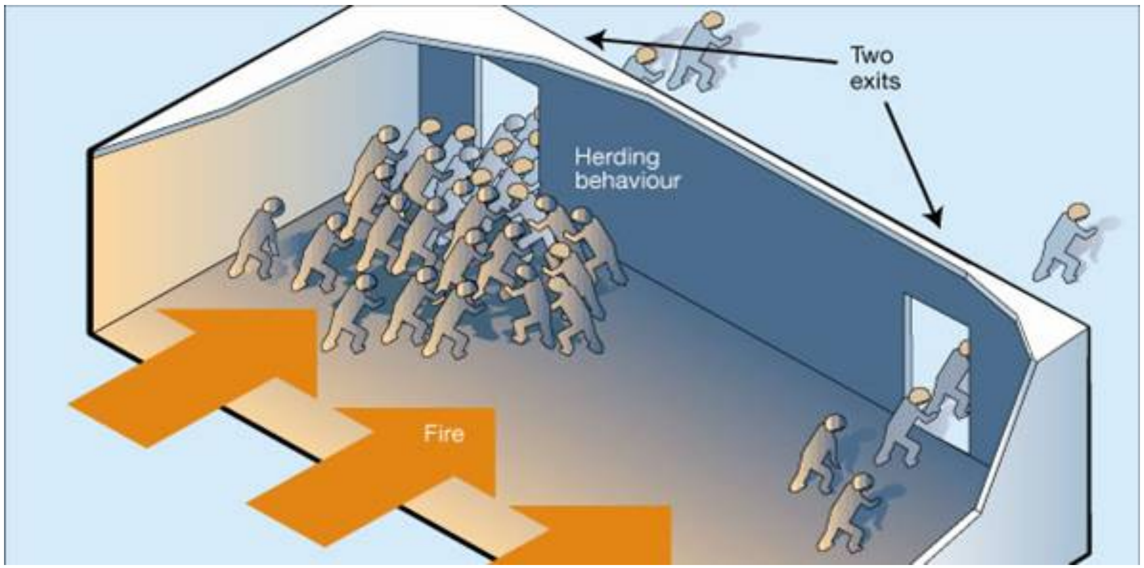
Cooperation is being used to accomplish some common purpose that is greater than the purpose of each individual.

ADVANTAGES

- Faster task completion
- Completion of the task impossible for single agent
- Increased robustness
- More flexible solution

Applications of Cooperative Control

Crowd Dynamics and Building Egress



Mobile Robot Networks

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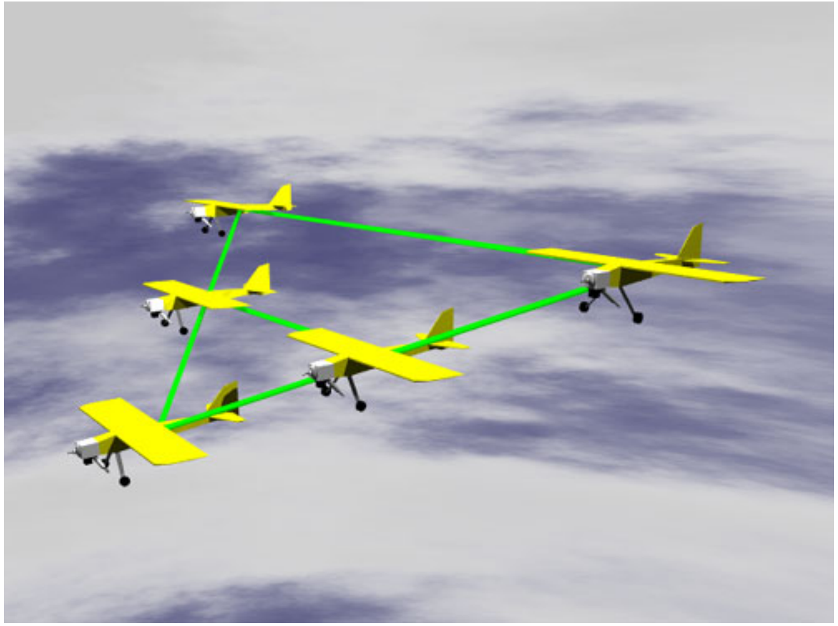
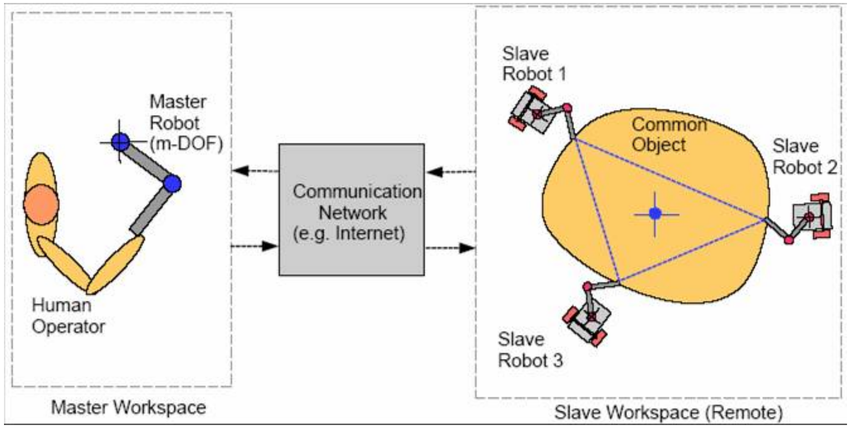
Applications of Cooperative Control

Autonomous Formation Flying and UAV Networks



Multi-Robot Remote Manipulation



Challenges of Cooperative Systems

Challenges

- Dynamic events
- Changing task demands
- Resource failures
- Presence of adversaries
- Limitation in environment (Limited time, energy, computation, communication
- Limitation in individuals capabilities (Limited sensing and mobility)

Issues

- **Formulation, description, decomposition and allocation of tasks**
- Communication languages and protocols
- Coherence, Stability behavior, …

Task allocation

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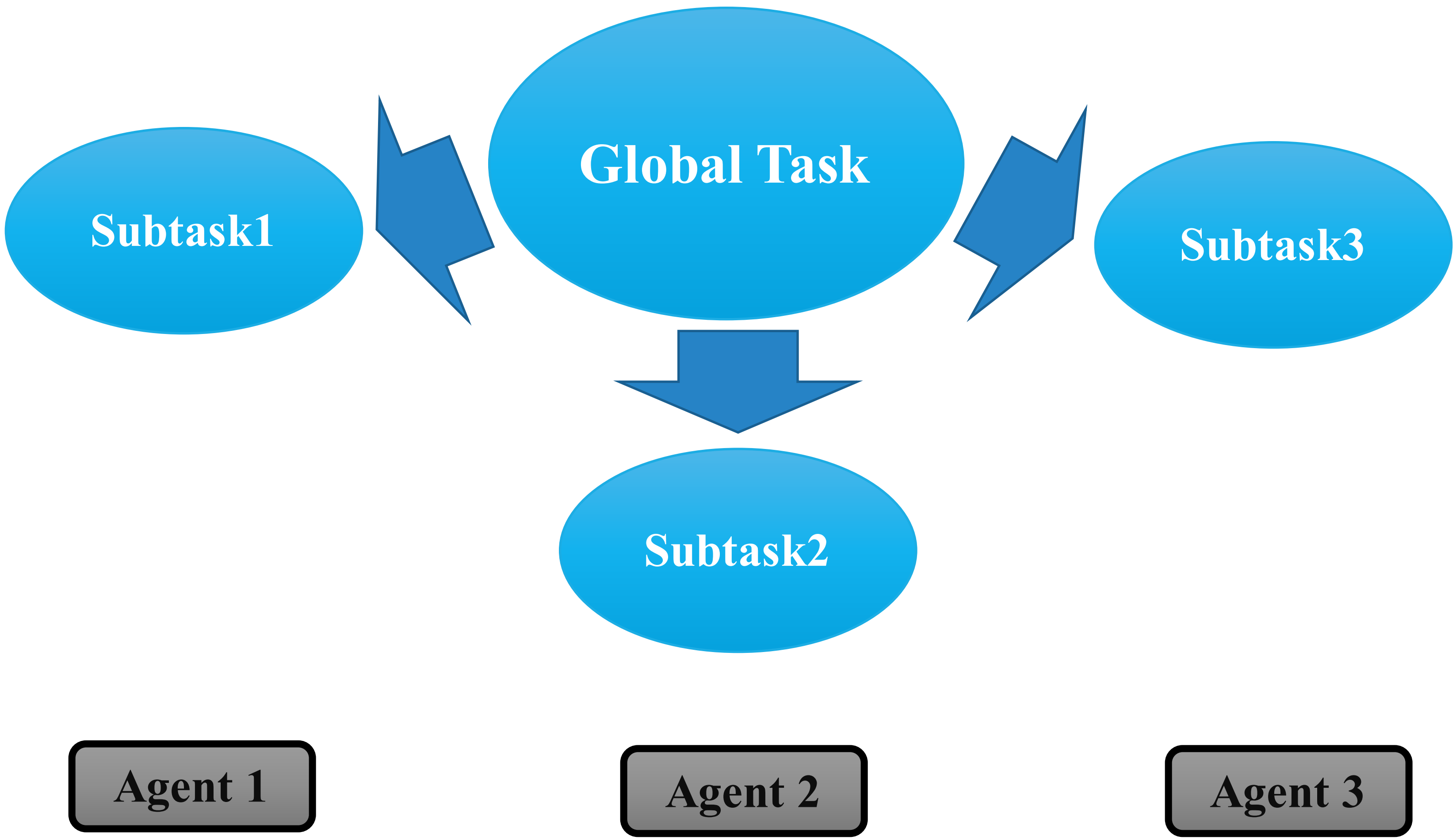
Task Allocation Problem

Which individual should execute which task in order to cooperatively achieve the global goal?

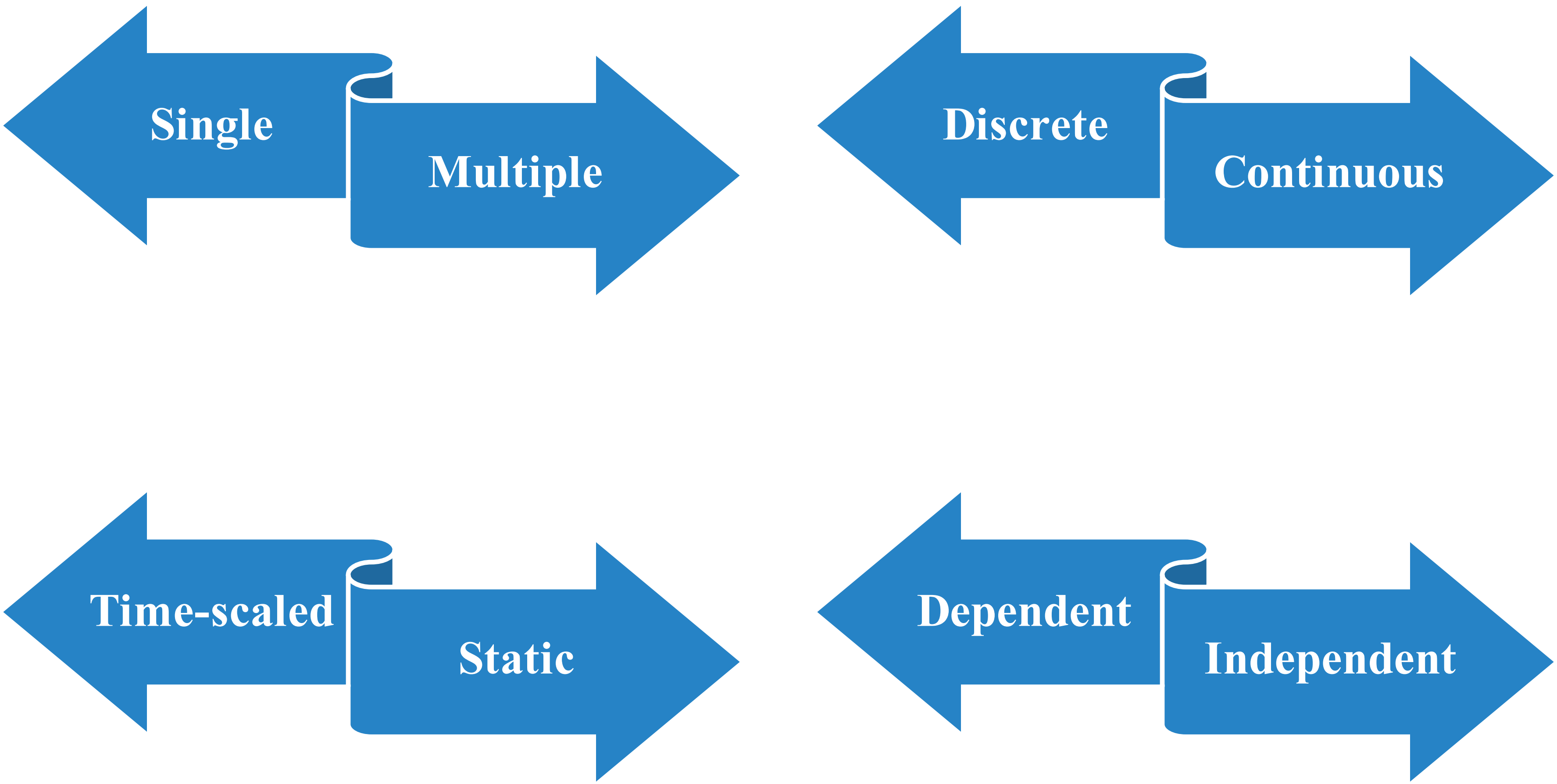
better TA → **more efficient performance**

- Complexity arises with:
  - Larger team sizes
  - Greater heterogeneity of robots and tasks

Task Allocation Problem



Different Types of Tasks



Task Allocation Approaches

- Self-organizing approaches
  - Threshold-based methods
  - Game theoretical methods
- Planning-based approaches
  - Market-based methods
  - DES task-decomposition methods

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Task Allocation Approaches

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Self-organization Approaches

Self-organizing systems rely on group behaviors to emerge from group interactions and individual decision making based on local data.

Local communication

- Limited communication

Group interaction

- Restricted individuals capabilities

Self-interested agents

- Feasible individual decision

No centralized or decentralized control

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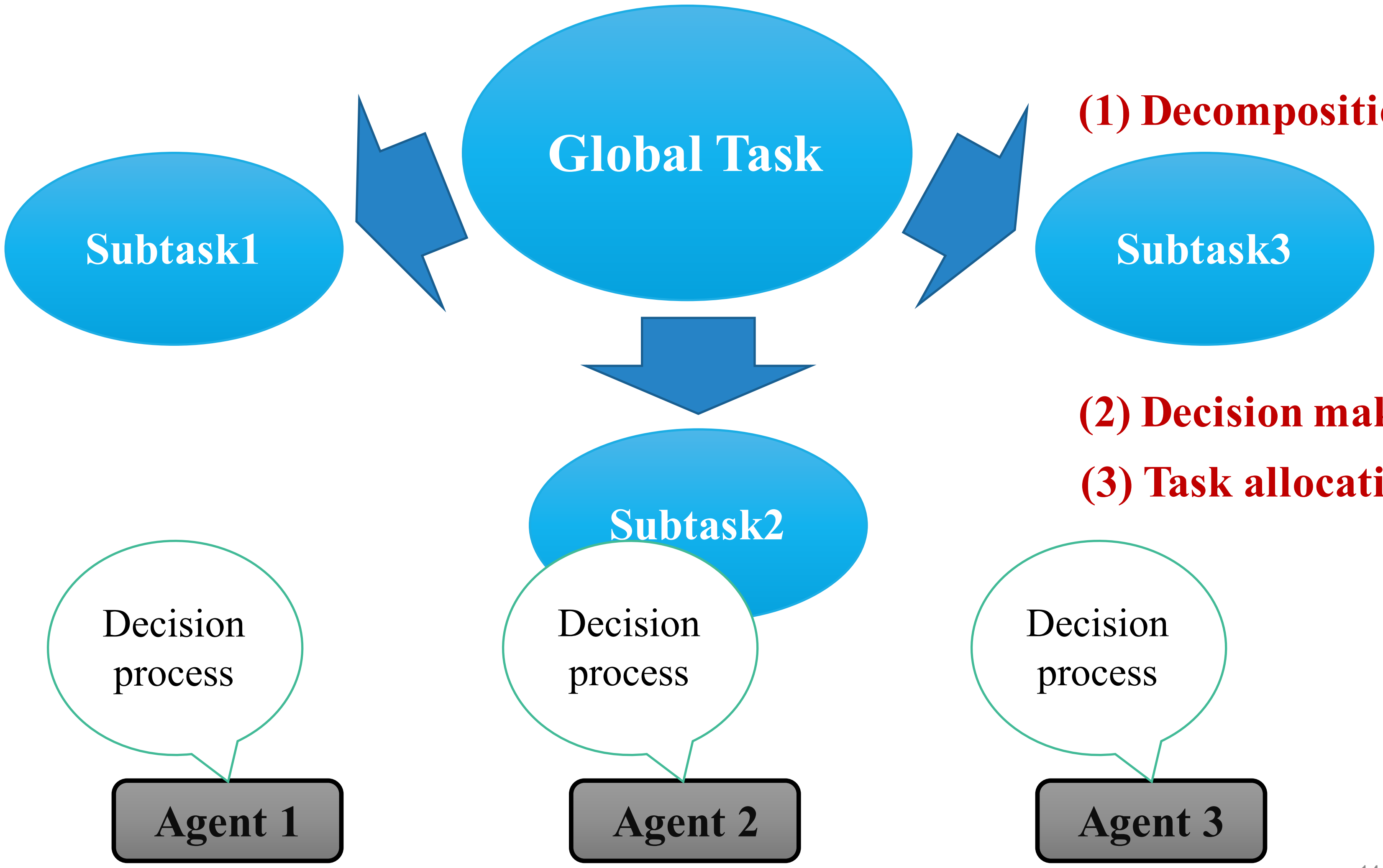
Self-organization Approaches



(1) Decomposition

(2) Decision making

(3) Task allocation

Task Allocation Approaches

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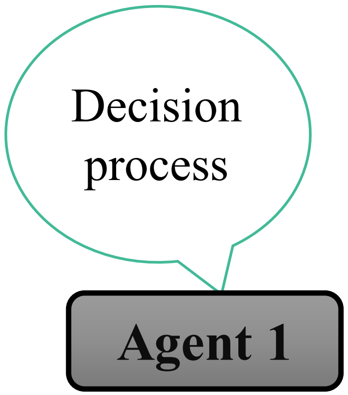
Threshold-based TA Methods



if
decision criteria > threshold
agent picks the task

Decision to select a particular task depends on:

- Individual's perception of a task
- Individual's response threshold for the task:

Threshold types:

- Same fixed response threshold for all agents
- Different fixed response threshold based on individuals capabilities or the configuration of the system
- Adaptive response-threshold models change the thresholds over time

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Problem Formulation

Robotic manufacturing shop-floor scenario:

- **Tasks**:
  - Each task represents a machine capable of producing goods from raw materials.
  - The machines require regular maintenance work.
  - Together the production and maintenance work loads constitute the total workload or task urgency.

- **Individuals**:
  - Represent the robots.
  - The robots repeatedly select tasks and if the robot is outside a fixed task boundary, it navigates towards the task. If the robot is within the task boundary it remains there until the end of the time step when a new (or the same) task is selected.

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Problem Formulation

- At each time step, each machine requires a minimum threshold, μ, number of robots to service the total workload, φ_j. Without this number of robots present the urgency will keep increasing.
- Manufacturing operation split into two phases:
  - the production phase, which includes production and maintenance tasks,
  - the maintenance phase, which contains maintenance tasks only.
- A machine starts out in the production phase with a given production work load, Ω_j. When there is no production work left, it enters the maintenance phase. During both phases, $\Delta\varphi_{INC}$ denotes the amount of maintenance work incurred in a single time-step if an insufficient number of robots serve a task. Correspondingly we denote the decrease in the total workload by $\Delta\varphi_{DEC}$.

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Problem Formulation

- If no robot attends a machine, on each time-step a constant maintenance workload of $\Delta\varphi_{INC}$ will be added to φ_j to increase its task urgency. If t time steps pass without any production work being done, the task urgency at time-step t would have increased as follows:

$$\Phi_{j,t}^{P} = \Phi_{j,\mathrm{INIT}}^{P} + t \times \Delta\phi_{\mathrm{INC}}$$

- If the required number of robots attend a machine, there is no extra maintenance work. Instead, the task urgency of this machine will decrease by $\Delta\varphi_{DEC}$. If v_t robots work on a machine simultaneously at time step t, this decrease will be: $v_t \times \Delta\varphi_{DEC}$. In such cases, task-urgency at time step $t + 1$ is given by the following equation

$$\Phi_{j,t+1} = \Phi_{j,t} - \nu_t \times \Delta\phi_{\mathrm{DEC}}$$

Problem Formulation

- $\boldsymbol{C_j}$: production completion time

For a particular machine j, once $\varphi_{j,t}$ reaches zero, there is no more production work left and this time step t gives us the C_j.

- $\overline{\boldsymbol{C}}$: the average production completion time of a shop floor
- $\boldsymbol{C_{min}}$: the theoretical minimum number of time steps necessary to finish production works
- $\boldsymbol{\zeta}$: production completion delay

$$\overline{\zeta} = \frac{\overline{C} - C_{\min}}{C_{\min}}$$

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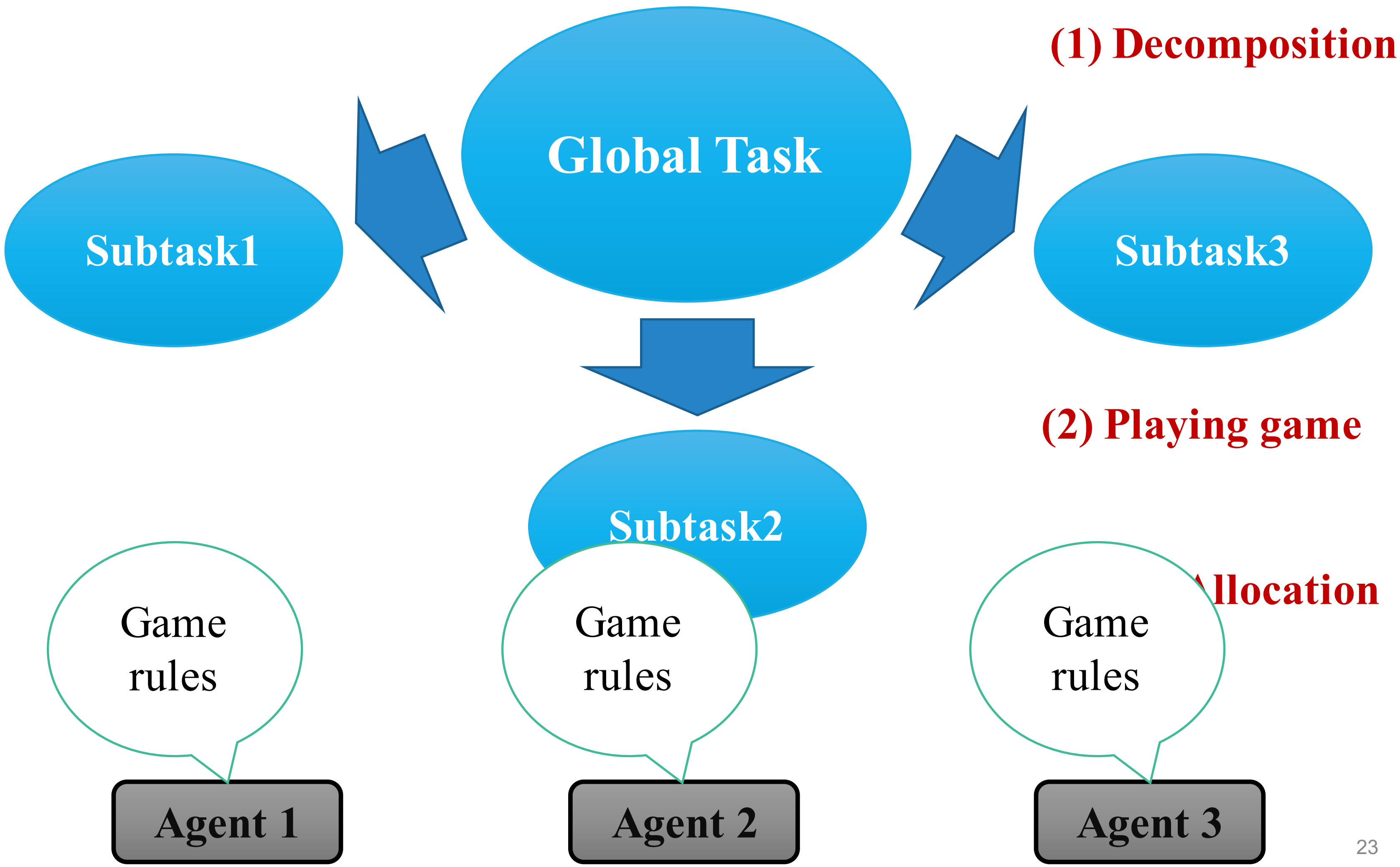
Game Theory Definitions

- **Game:**
  Situation in which players (participants) make strategic decisions that take into account the actions and reactions of the other players
- **Cooperative Game:**
  A game in which players can make binding commitments
- **Non-cooperative Game:**
  A game in which binding commitments are not possible
- **Payoff:**
  Value of an outcome to a player
- **Strategy:**
  Rule or plan of action for playing a game; one player's best response to each action taken by other players

Game Theoretical Approaches



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Problem Formulation

- The problem is modeled as a hedonic coalition formation game between the agents and the tasks that interact in order to form disjoint coalitions.
- A coalition formation game is classified as hedonic, if

1. The payoff of any player depends solely on the members of the coalition to which the player belongs.
2. The coalitions form as a result of the preferences of the players over their possible coalitions' set.

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Coalitions in Hedonic Games

Central concepts:

- N: Finite set of players
- Coalition = non-empty subset of N
- Partition Π divides N into disjoint coalitions
- $\Pi(i)$ denotes coalition in Π containing player $i \in N$
- Every player $i \in N$ ranks all the coalitions containing i via $\leq_i$ and $<_i$
- A coalition S blocks a partition Π, if all players $i \in S$ have $\Pi(i) <_i S$ and hence strictly prefer being in S to being in current coalition $\Pi(i)$
- A partition Π is core stable, if there is no blocking coalition S.

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Coalitions in Hedonic Games

Example:

- Three players a, b, c
- Preferences of player a: $ab > ac > a > abc$
- Preferences of player b: $bc > ab > b > abc$
- Preferences of player c: $ac > bc > c > abc$

- Partition abc not core stable: a blocks
- Partition ab, c not core stable: bc blocks
- Partition ac, b not core stable: ab blocks
- Partition bc, a not core stable: ac blocks
- Partition a, b, c not core stable: ab blocks

This simple cyclic 3-player game does not allow a core stable partition.

Pros and Cons

Pros

- Better scale-up than planning methods
- Rely less on modeling the environment, tasks and individuals
- Make decision based on local data

Cons

- Difficult to predict the exact behavior of Individuals
- Approaches mainly focus on single global tasks
- Difficult to formally design, analyze and implement

Task Allocation Approaches

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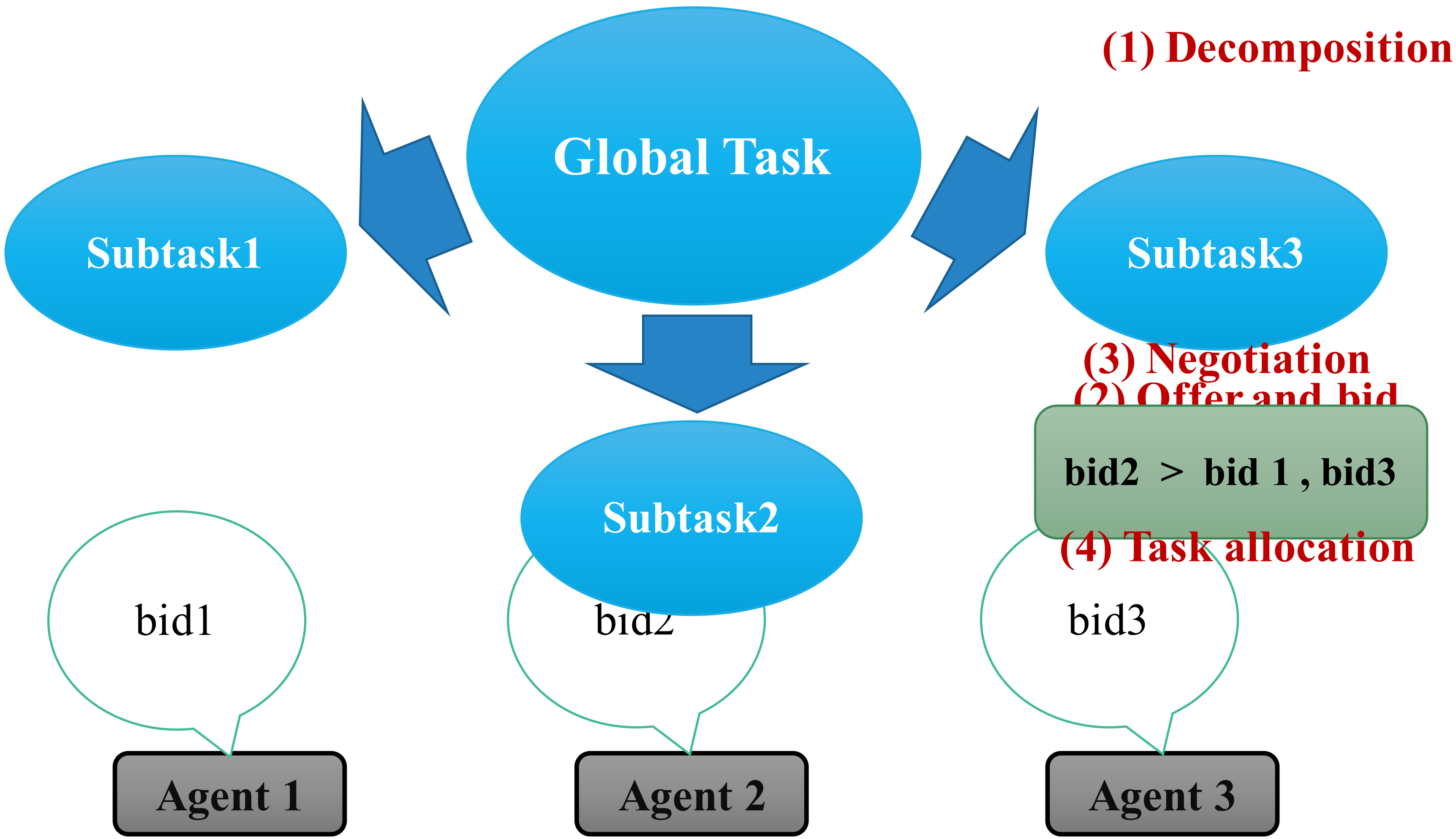
Market-based Approaches



Auction Types

1. Single-item auction:

- only one item is offered
- each participant submits a bid
- auctioneer awards the item to the highest bidder

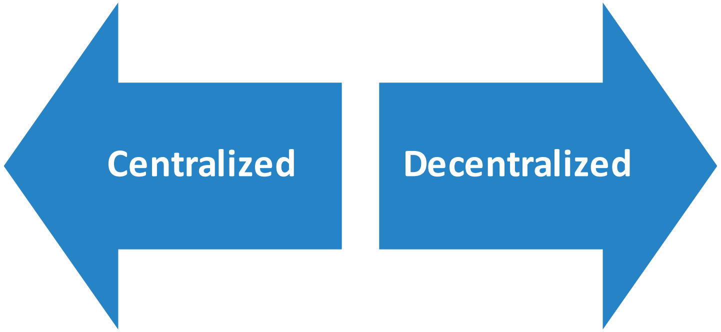
2. Multi-item auction:

- multiple items are offered
- participants can win at most one item apiece

3. Combinatorial auction:

- multiple items are offered
- each participant can bid on any combination of items.

more centralized:
quality of solution



more decentralized:
speed of solution

Pros and Cons

Pros

- Intuitive and straightforward for design and implement
- Tradeoff between speed and quality

Cons

- Performance is reduced if number of agents arises
- Strong communication requirements

Task Allocation Approaches

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Discrete Event System

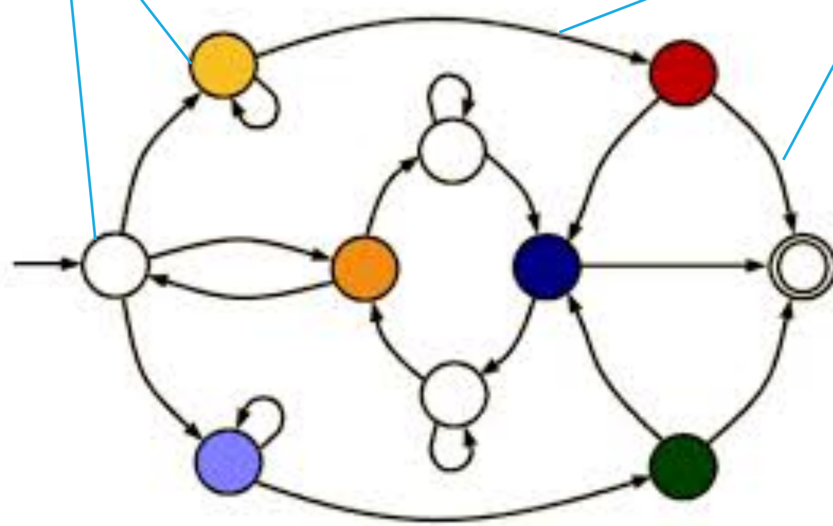
- Mathematically convenient models
- A flexibility to model various levels of detail and complexity
- Allowing the modeling of uncertainty and dynamic (time changing) systems
- Advances and variety in DES software

states

transitions

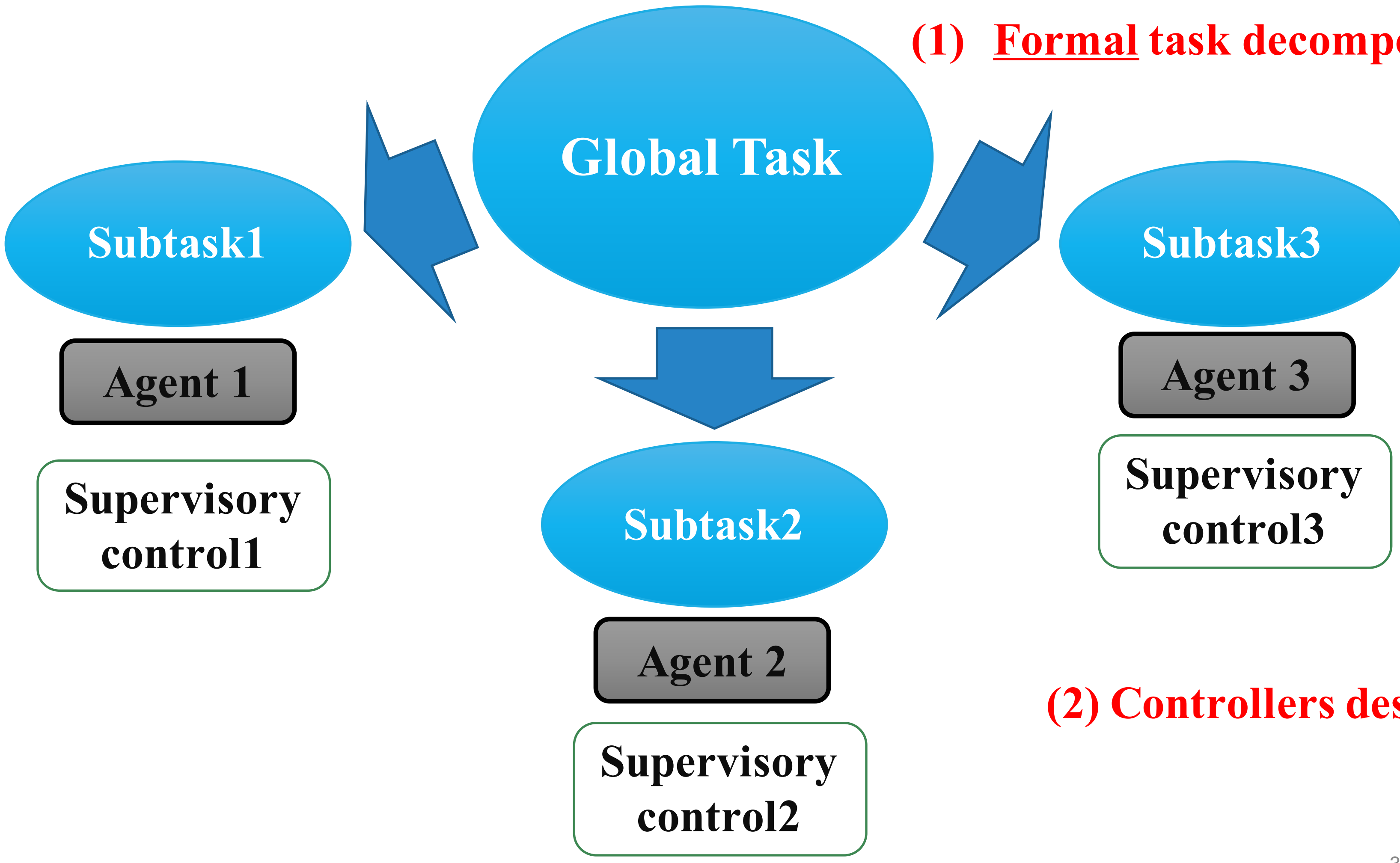
DES model

Complex mathematical model



DES Cooperative Control

(1) <u>Formal</u> task decomposition



(2) Controllers design

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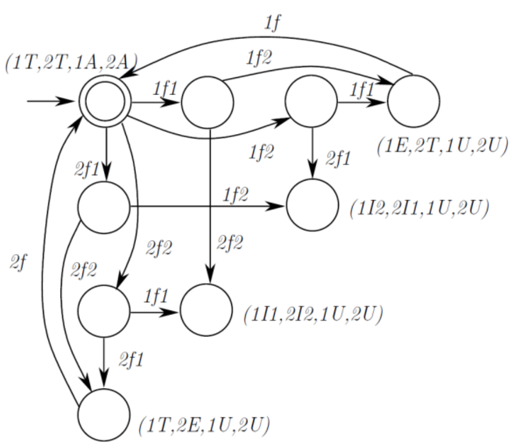
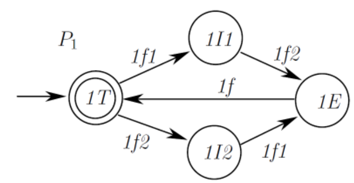
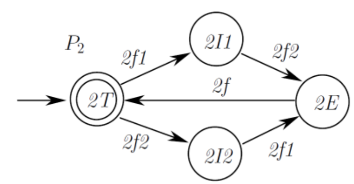
Problem Formulation

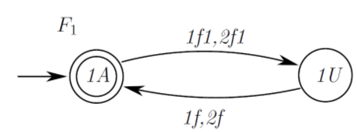
Global task

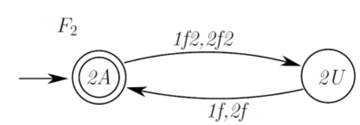


Subtasks









Individuals

Agent 1

Agent 2

Agent 3

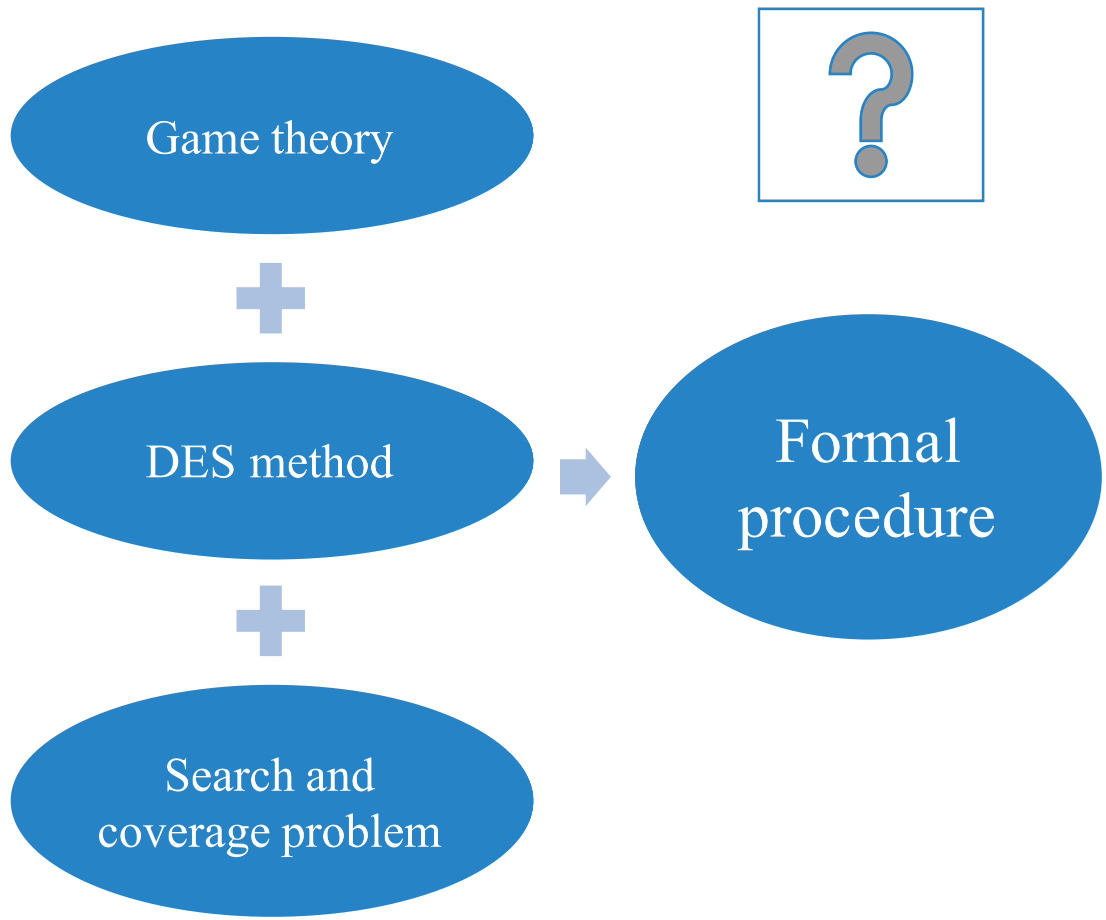
Agent 4

Problem: Given a deterministic task automaton A_S with event set $E = \bigcup_{i=1}^{n} E_i$ and local event sets E_i, $i = 1, \ldots, n$, what are the necessary and sufficient conditions that A_S is decomposable with respect to parallel composition and natural projections P_i, , $i = 1, \ldots, n$, such that $||_{i=1}^{n} P_i(A_S) \cong A_S$?

Future Plan

Objective:

Obtain a **decentralized**, **near-optimal** and **formal** method for task allocation in search and coverage problems by combining task decomposition methods, DES models and game theory



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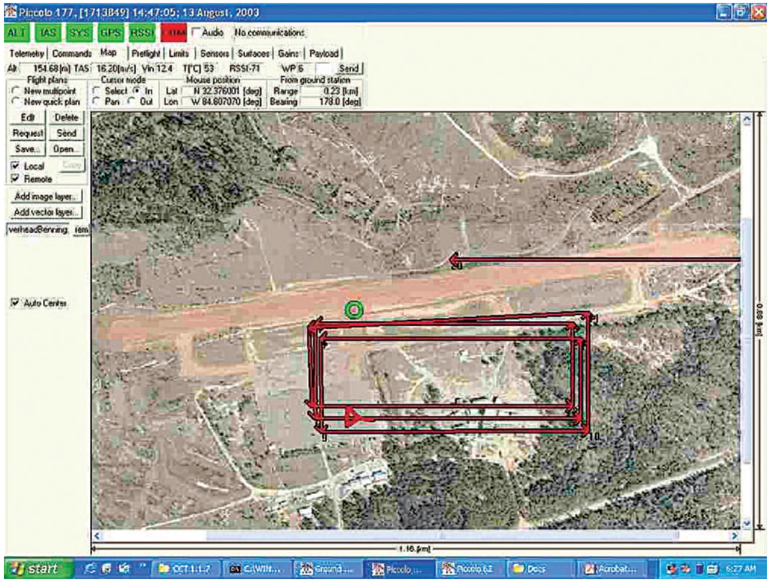
Why Search and Coverage Problem?

- The use of robots in surveillance and exploration with minimal human supervision or intervention is gaining prominence.
- As the number of vehicles increases it becomes increasingly difficult and even impossible for direct human supervision.
- Typical applications include air- and ground-based mapping of predetermined areas for tasks such as surveillance, target detection, tracking, and search and rescue operations.
- The use of multiple collaborative robots is ideally suited for such tasks.



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Why DES?

- Rapid evolution of computing, communication, and sensor technologies has brought about the proliferation of new dynamic highly complex systems (Example: computer and communication networks; automated manufacturing systems; air traffic control systems; advanced monitoring and control systems in automobiles or large buildings; intelligent transportation systems; distributed software systems, etc.)
- DES has emerged to provide a formal treatment of such man-made systems
- The challenge is to develop new modeling, analysis and design techniques, and systematic control and optimization procedures for this new generation of systems
- Discrete event systems is a growing field that utilizes many interesting mathematical models and techniques.

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Why Game Theory?

- To jointly satisfy all three of the requirements of agility and robustness, timeliness and high-quality solutions for search and coverage problems
- negotiation protocol allows to spread the computational burden of solving the problem across the agents in the system, which adds to the control mechanism's robustness and the timeliness of its solutions
- Better scale-up than other methods
- Rely less on modeling the environment, tasks and individuals
- Make decision based on local data

Thank you

Any Question?

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