Task Planning and Allocation in Multi-Robot Systems

Dylan A. Shell
Texas A&M University

How do we achieve fluid cooperative behavior in robot teams?

1

The (ancient) history of the ideas

An Early Robot System

W. Grey Walter's Elmer and Elsie (~1950)

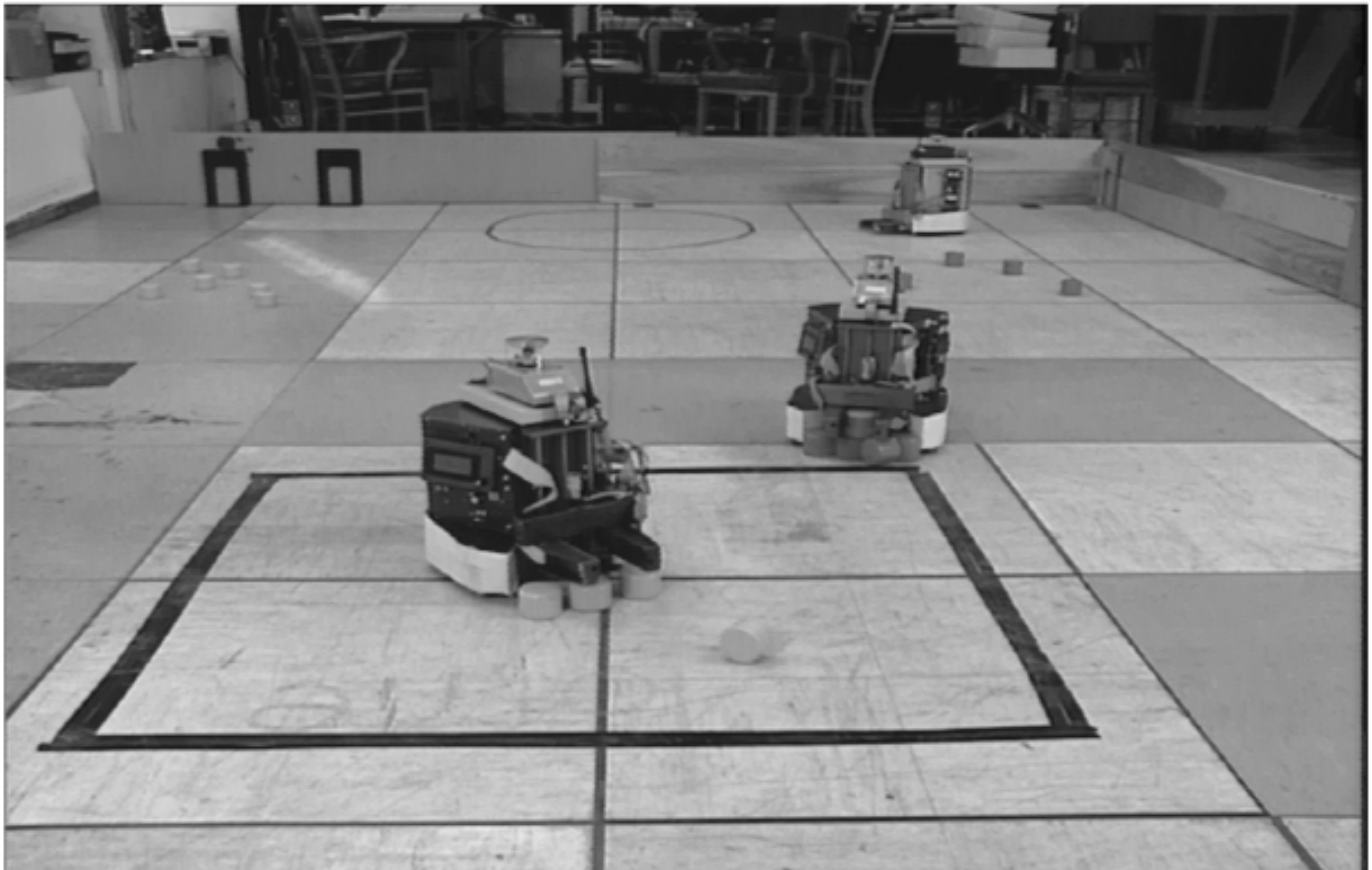
Two Multi-Robot Dissertations

L. E. Parker. **Heterogeneous Multi-Robot Cooperation.** PhD thesis, MIT, January 1994.

M. J. Mataric´. **Interaction and Intelligent Behavior.** PhD thesis, MIT, May 1994.

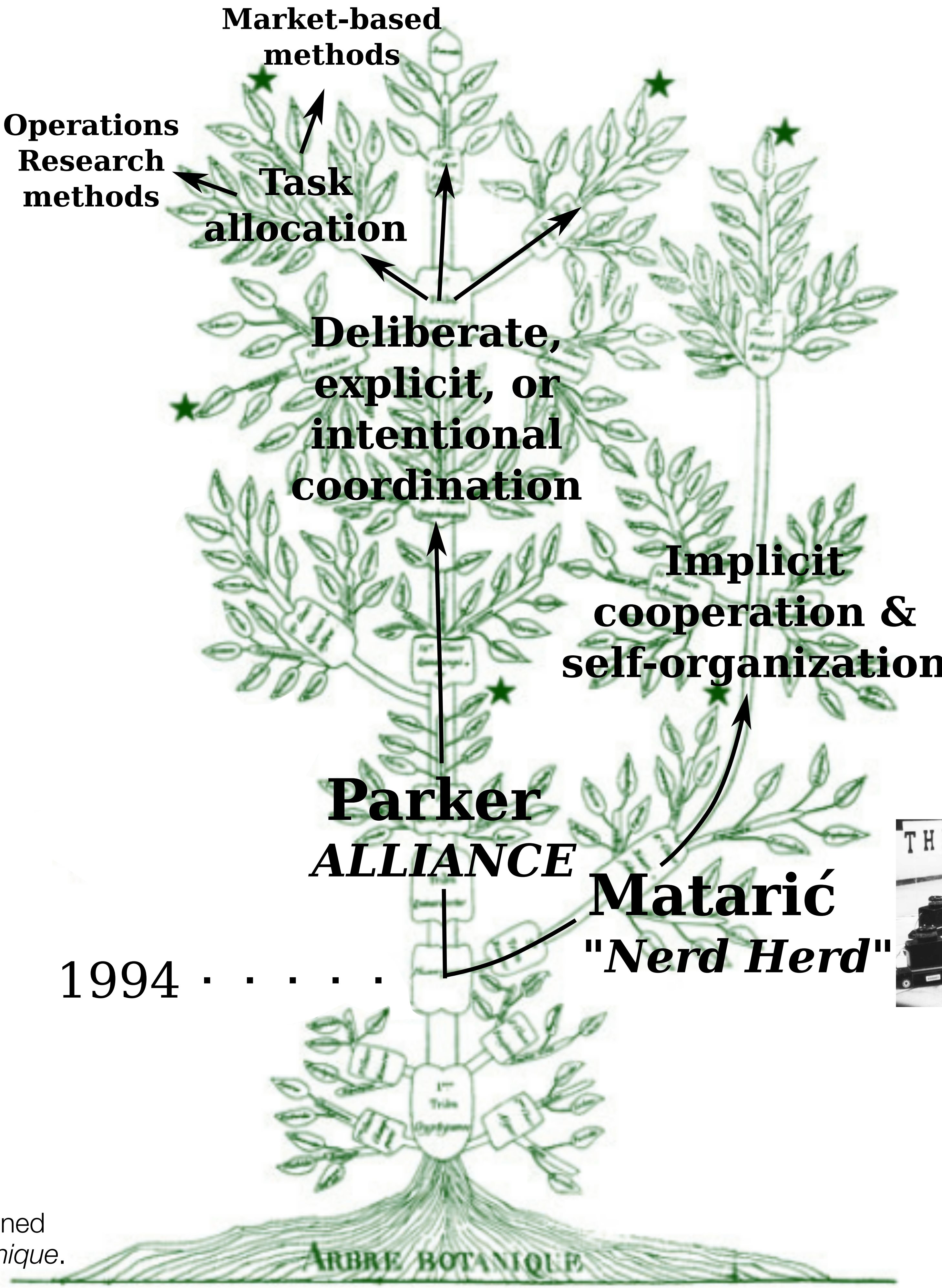
L. E. Parker: Heterogeneous Multi-Robot Cooperation

ALLIANCE



M. J. Mataric´: Interaction and Intelligent Behavior

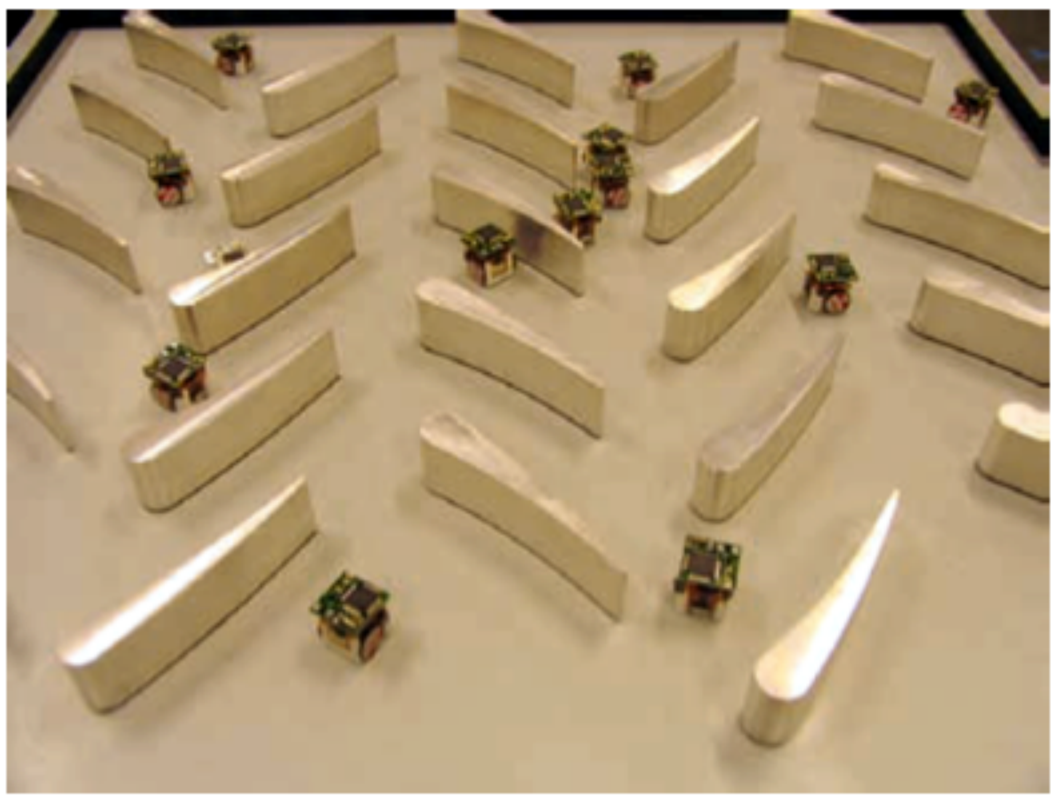
Basic (or Basis) Behaviors



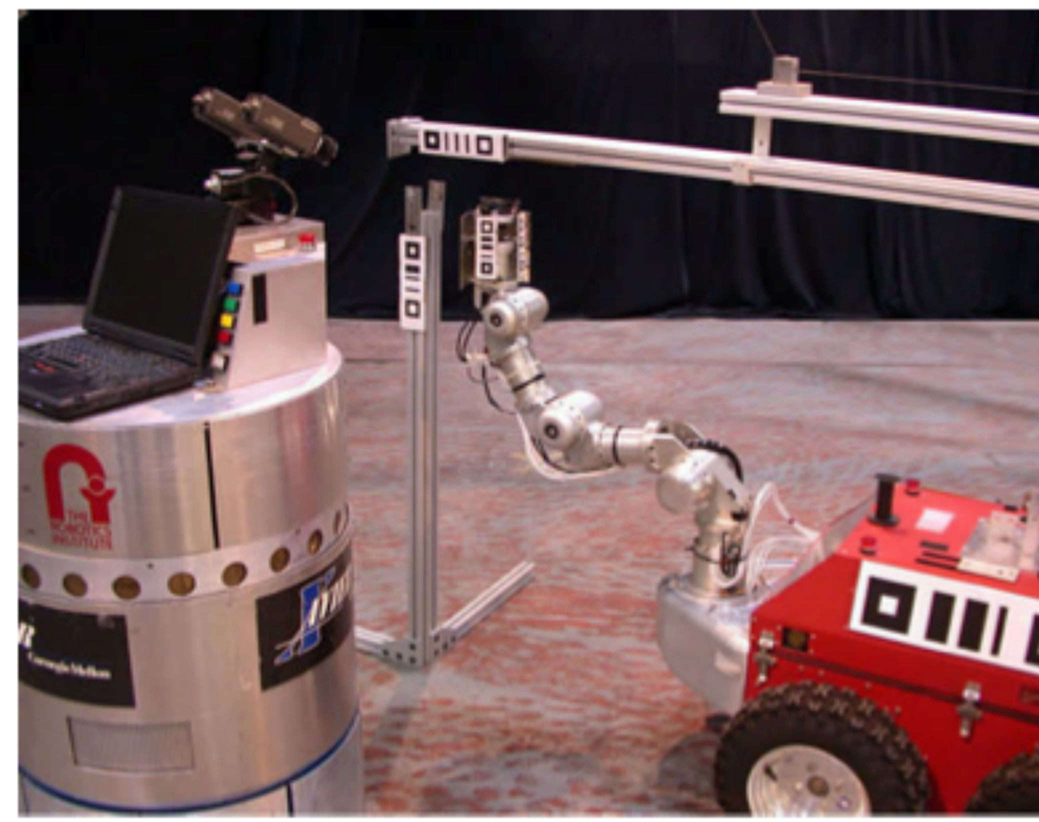
The figure is superimposed on a pruned version of Augier's 1801 *Arbre Botanique*.

	Multi-robot Swarms	Coordinated Teams
Size:	Envisioned: 10–1,000,000 Demonstrated: 10–300	Envisioned: 2–50 Demonstrated: 2–15
Composition:	Homogeneous	Homogeneous or heterogeneous
Capabilities:	Sensing: local Comm.: none/stigmergic, local	Sensing: local, sometimes global Comm.: local, mesh, or broadcast

Representative examples



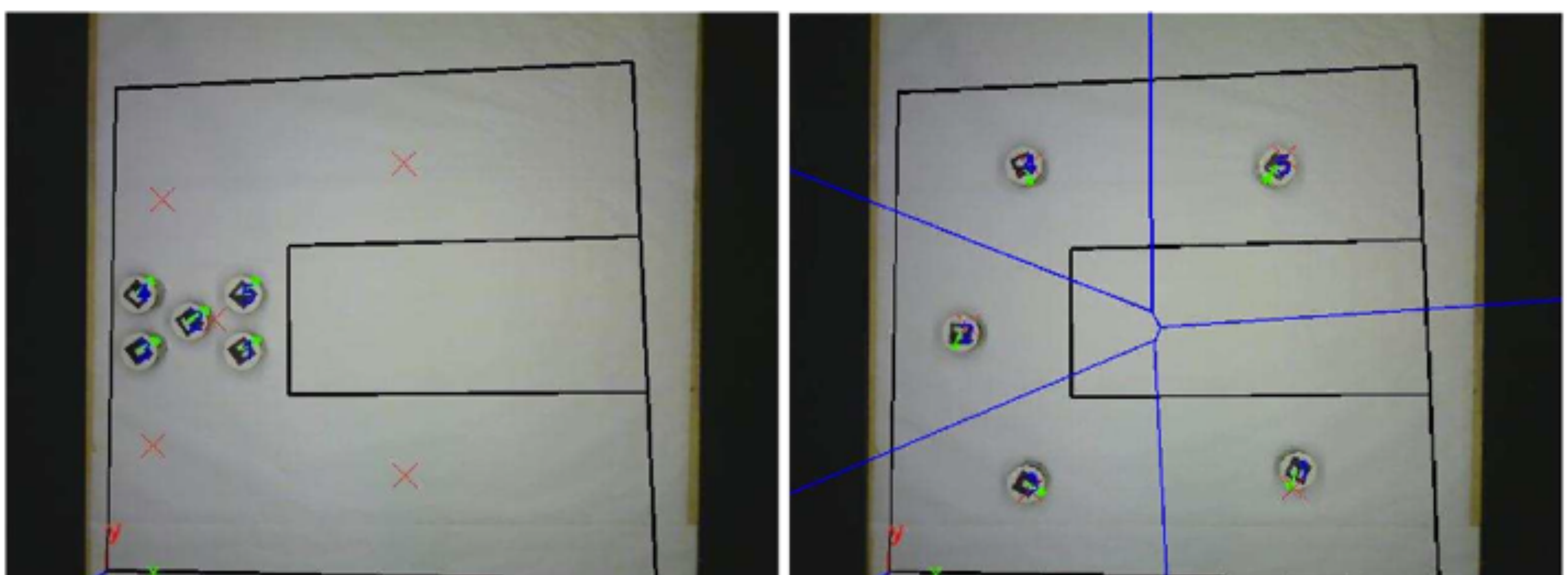
Nikolaus Correll and Alcherio Martinoli. Towards Multi-Robot Inspection of Industrial Machinery. *IEEE Robotics & Automation Magazine*, 16(1):103–112, March 2009.



Brennan Sellner, Frederik W. Heger, Laura M. Hiatt, Reid Simmons, and Sanjiv Singh. Coordinated Multi-Agent Teams and Sliding Autonomy for Large-Scale Assembly. *Proceedings of the IEEE*, 94(7):1425–1444, July 2006.

(Some work falls outside this categorization)

A. Breitenmoser, M. Schwager, J.-C. Metzger, R. Siegwart, and D. Rus. **Voronoi coverage of non-convex environments with a group of networked robots**. In Proceedings of the IEEE International Conference on Robotics and Automation (ICRA'10), pages 4982–4989, Anchorage, Alaska, May 2010.



(Some work falls outside this categorization)

P. Stone, G. A. Kaminka, S. Kraus, and J. S. Rosenschein. Ad Hoc Autonomous Agent Teams: Collaboration with- out Pre-Coordination. In Proceedings of the Conference on Artificial Intelligence (AAAI'10), Atlanta, Georgia, July 2010.

2

What is the underlying organizational principle involved?

"Never be so busy as not to think of others."

— Mother Teresa

At their heart task planning and allocation methods address a combinatorial problem:

- Who should do what?
- What sequence of actions should be performed?

Reviews (early)

Y. U. Cao, A. S. Fukunaga, and A. B. Kahng. Co-operative Mobile Robotics: Antecedents and Directions. Autonomous Robots, 4:226–234, 1997.

G. Dudek, M. Jenkin, E. Milios, and D. Wilkes. A Taxonomy for Multi-Agent Robotics. Autonomous Robots, 3 (4):375–397, 1996.

L. Iocchi, D. Nardi and M. Salerno. Reactivity and Deliberation: A Survey on Multi-Robot Systems. Lecture Notes in Computer Science Volume 2103, 2001, pp 9-3

Reviews (task-allocation)

B. P. Gerkey and M. J. Mataric´. A formal analysis and taxonomy of task allocation in multi-robot systems. International Journal of Robotics Research, 23(9):939– 954, September 2004.

M. B. Dias, R. Zlot, N. Kalra, and A. Stentz. Market-based multirobot coordination: A survey and analysis. Proceedings of the IEEE, 94:1257–1270, 2006.

G. A. Korsah, A. Stentz, and M. B. Dias. A comprehensive taxonomy for multi-robot task allocation. International Journal of Robotics Research, 32(12):1495–1512, 2013.

They are largely independent of problem-domain particularities, allowing one hide details involved in the performance of atomic tasks/actions. This form of abstraction allows:

1. formulation of the coordination problem along with a crisp definition of the assumptions made about low-level robot capabilities;

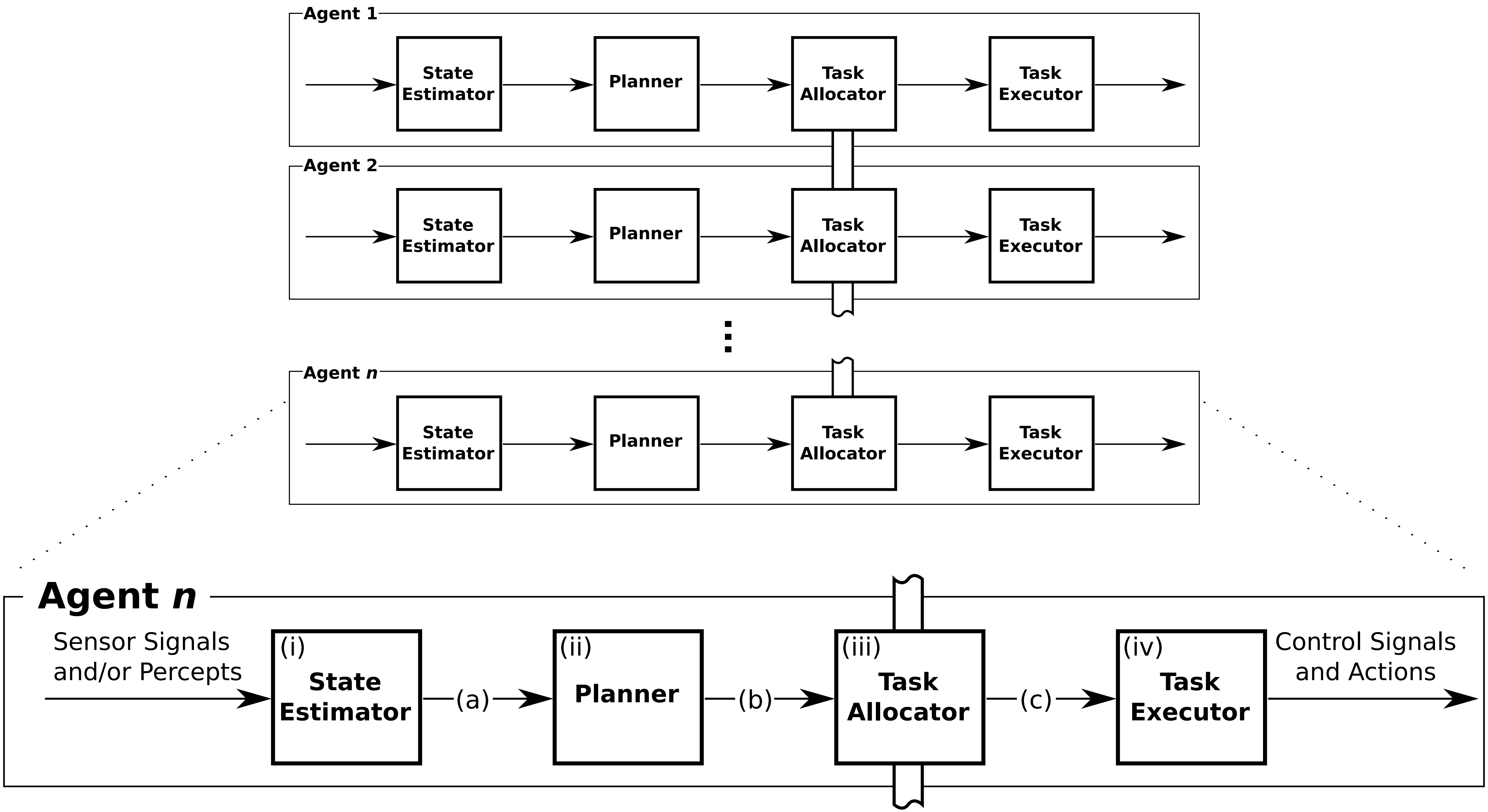
2. description of an algorithm for just the coordination aspect;

3. comparison of different algorithms whilst minimizing robot-specific details that bleed into the comparisons.

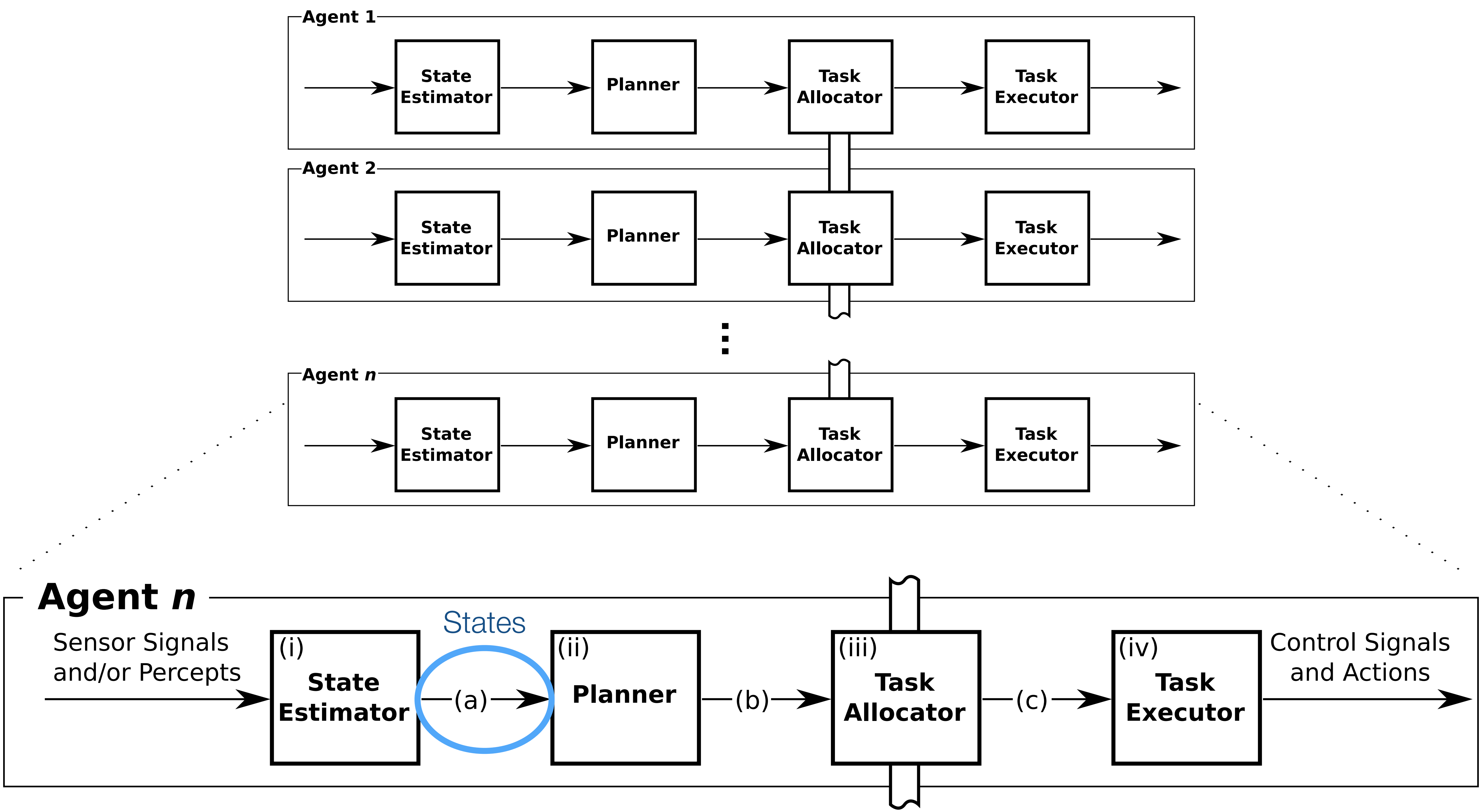
Representative (hypothetical) architecture

Information Flow Perspective

Representative (hypothetical) architecture



Representative (hypothetical) architecture



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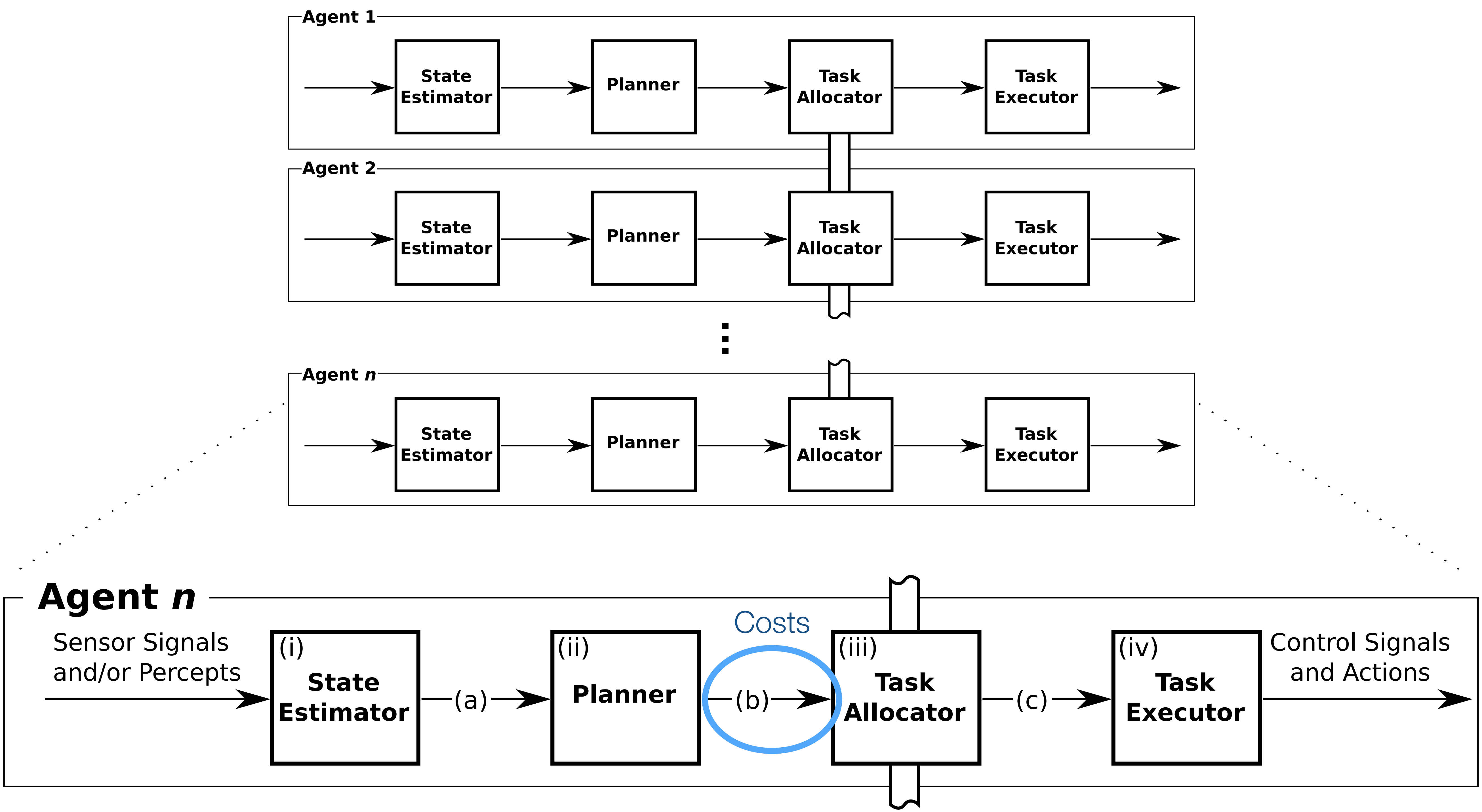
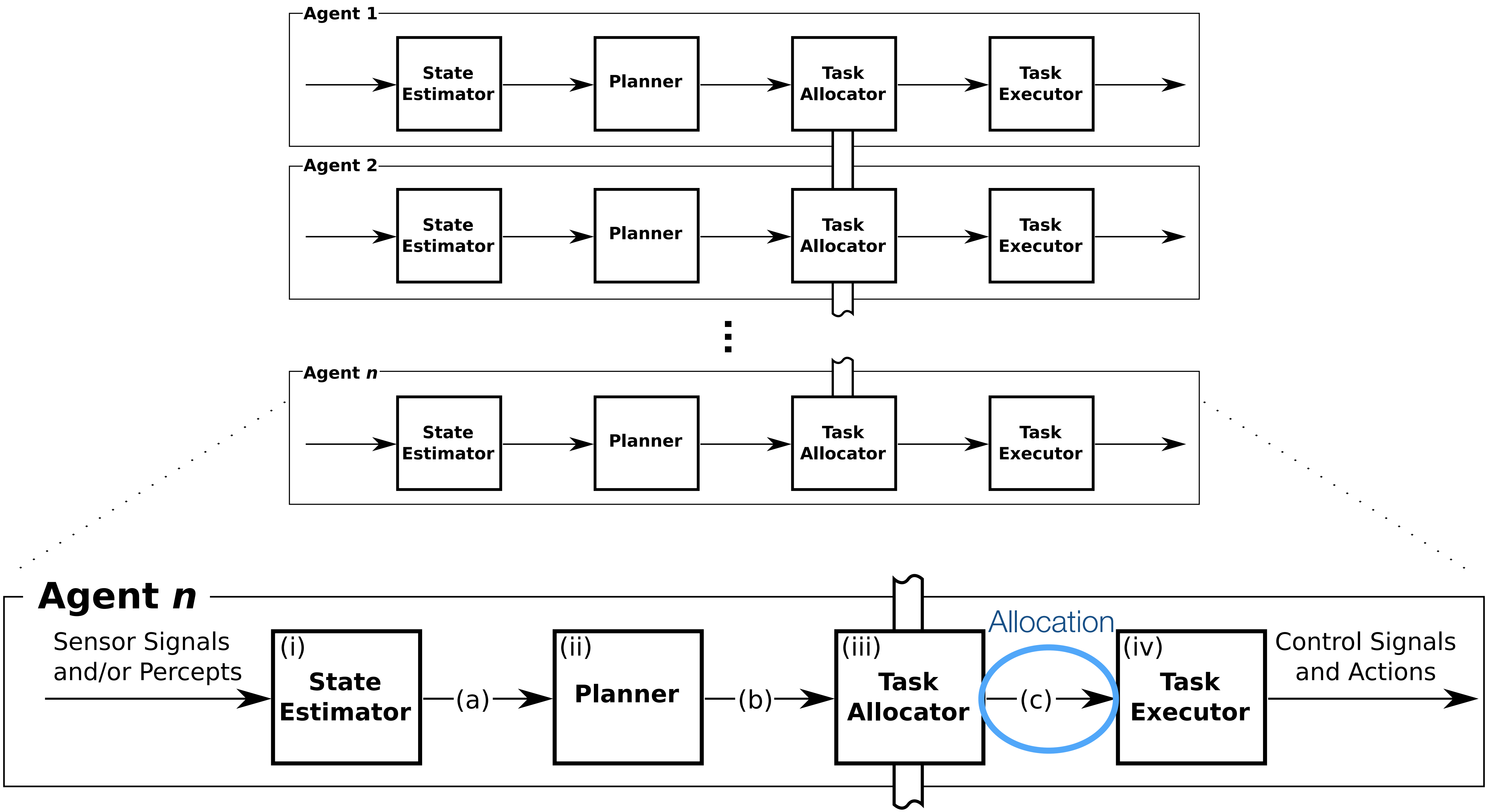
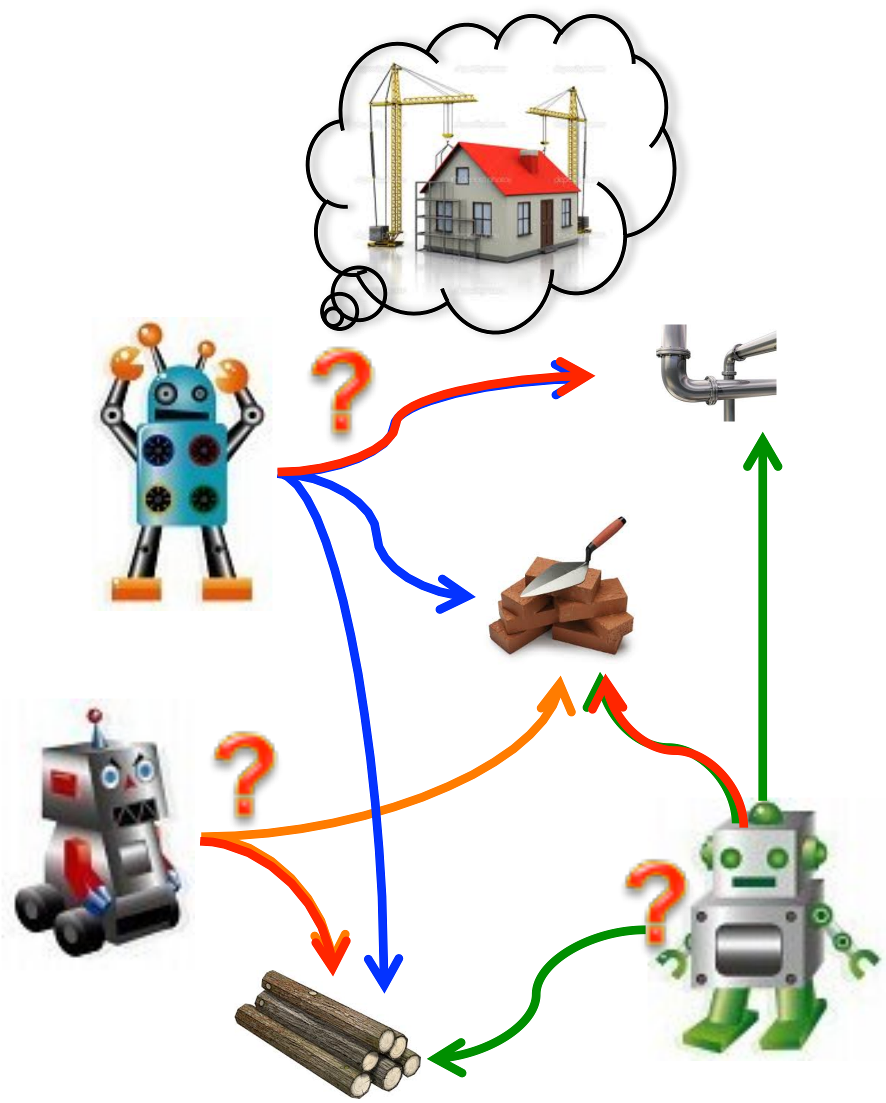


Representative (hypothetical) architecture



Assignment Problem

Assign every robot to do a unique task, and optimize the overall team performance.



	t_1	t_2	t_3
r_1	7	4	3
r_2	6	8	5
r_3	9	4	4

Cost matrix

	t_1	t_2	t_3
r_1	7	4	3
r_2	6	8	5
r_3	9	4	4

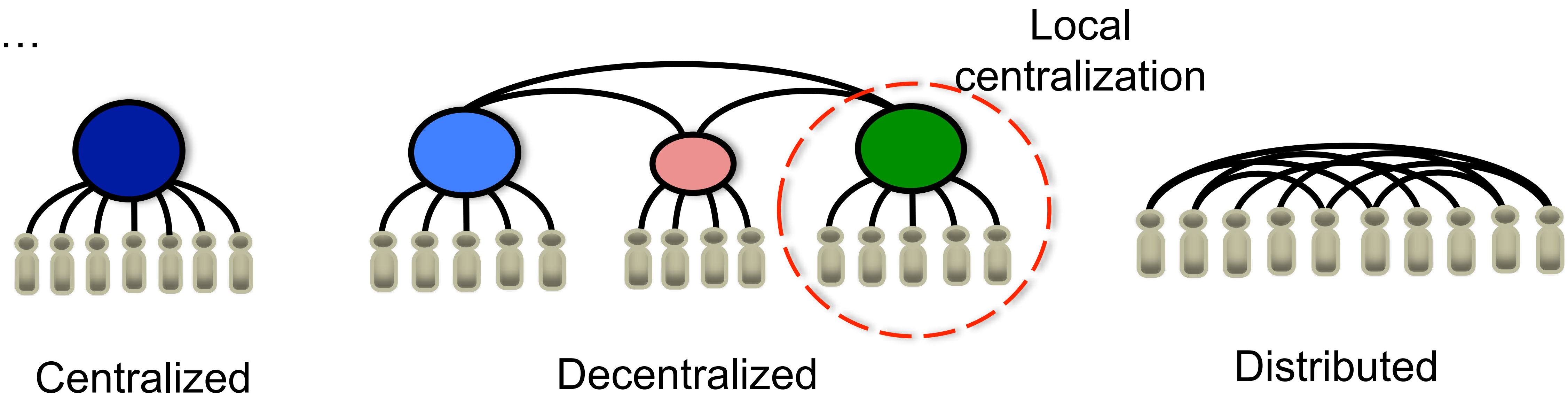
Solution with minimized cost

Optimal solution: $r_1 \rightarrow t_3$, $r_2 \rightarrow t_1$, $r_3 \rightarrow t_2$

Optimal value: 3+6+4 = 13

Challenges in robotics:

- Real time systems: low running time
- Possible failures: decentralization
- Costly communication: minimal communication
- Dynamics involved: adaptive ability
- Timeliness: flexibility
- Uncertain costs: risk-aversion
- …



Optimal Assignment:
- Fast, optimal solution;
- **Not robust** against failures;
- e.g., LP, Hungarian, pseudo-flow

Centralized

Robotic Task Allocation:
- Heuristic, intuitive methods;
- **Not optimal** for solutions;
- e.g., market/auction, task swap

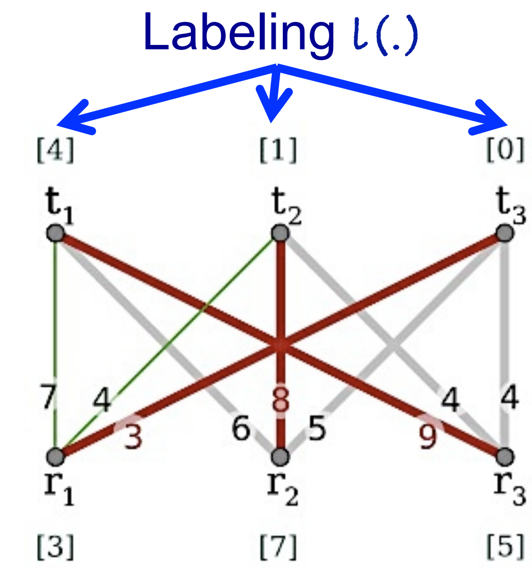
Decentralized / Distributed

	t_1	t_2	t_3
r_1	7	4	3
r_2	6	8	5
r_3	9	4	4

Utility u_{ij} **maximization**

Bigraph: 2 sets of nodes, 3 types of edges

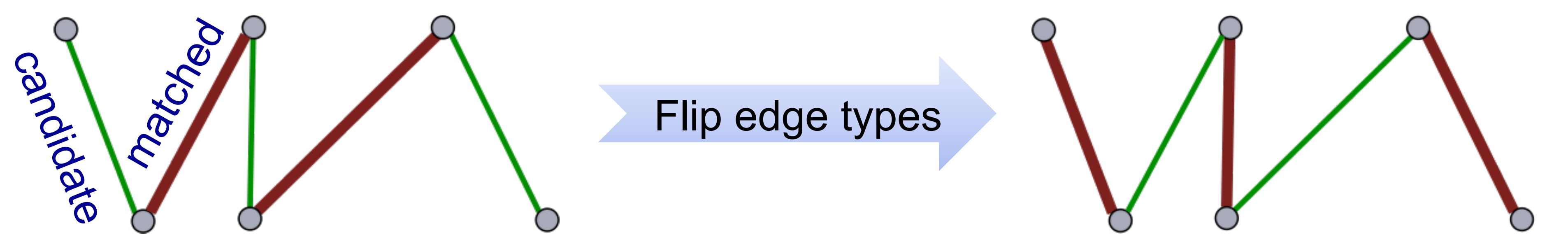
- Matched (assigned): $l(r_i) + l(t_j) = u_{ij}$
- Unmatched (unassigned): $l(r_i) + l(t_j) > u_{ij}$
- Candidate (unassigned): $l(r_i) + l(t_j) = u_{ij}$

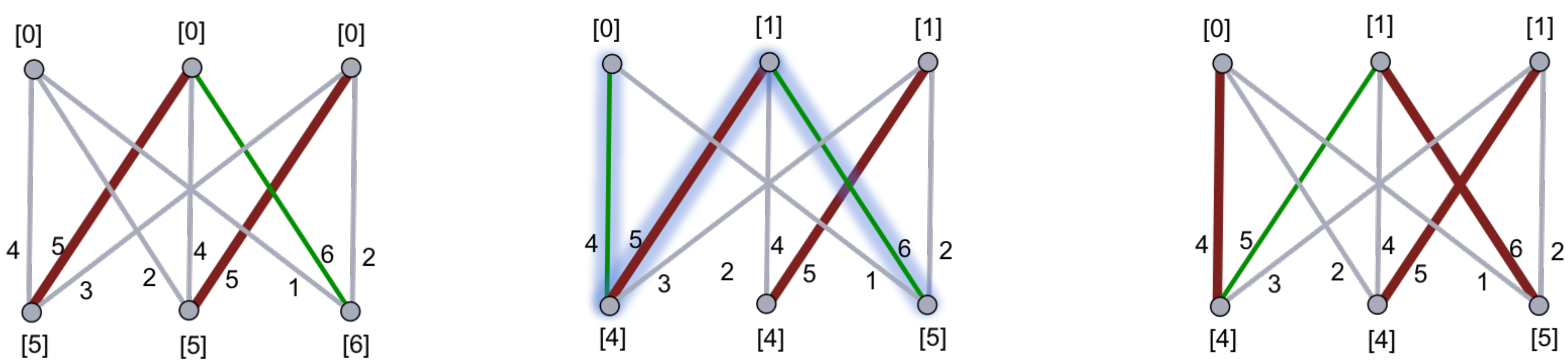


perfect matching as optimal solution

The Hungarian Method:

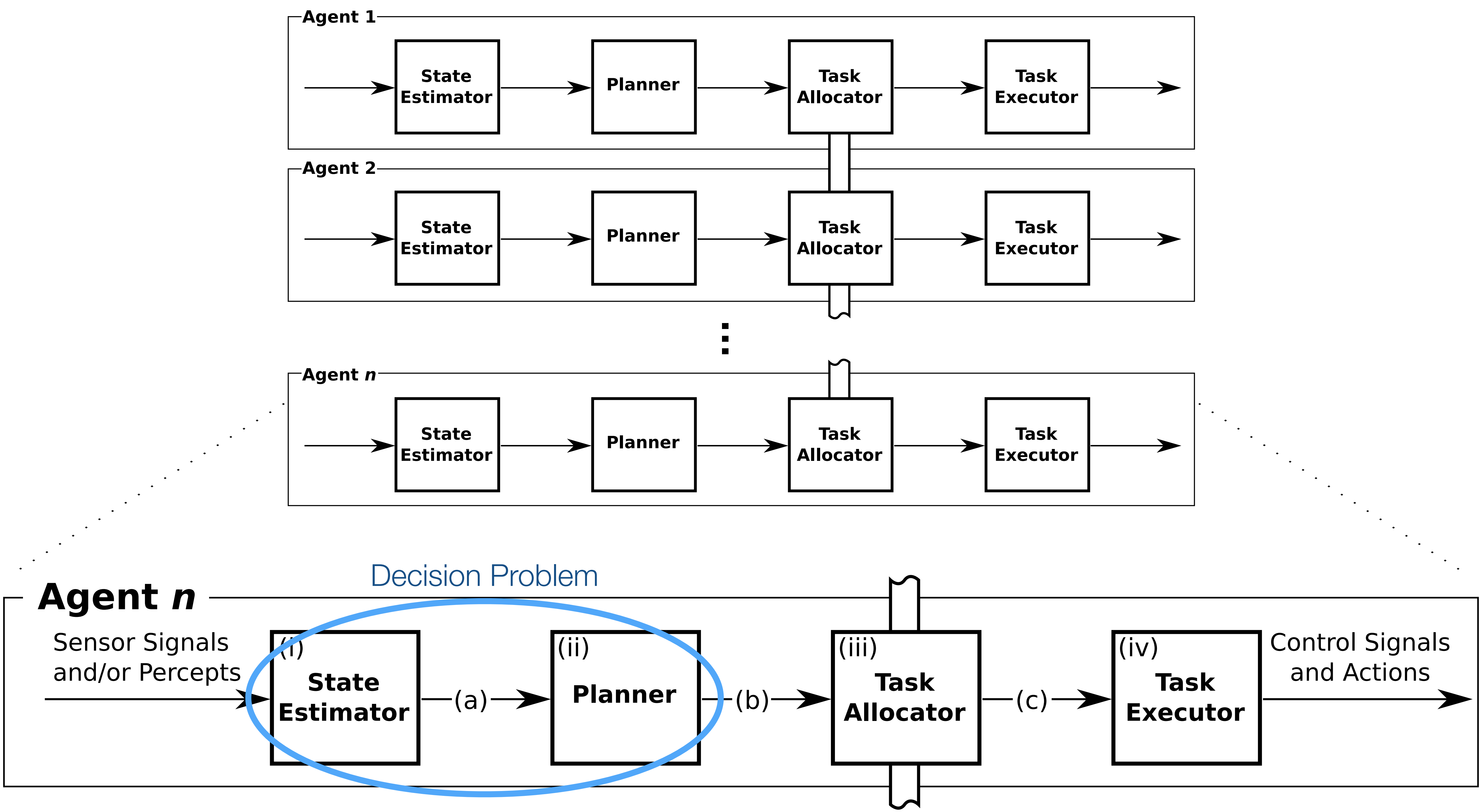
- Treats $n \times n$ assignment as a bigraph (weighted by utilities);
- Goal: find a maximally weighted perfect matching;
- Technique: search for augmenting paths to augment No. of matched edges.





Each augmenting path requires $O(n^2)$, at most n paths, so total time complexity is $O(n^3)$.

Representative (hypothetical) architecture



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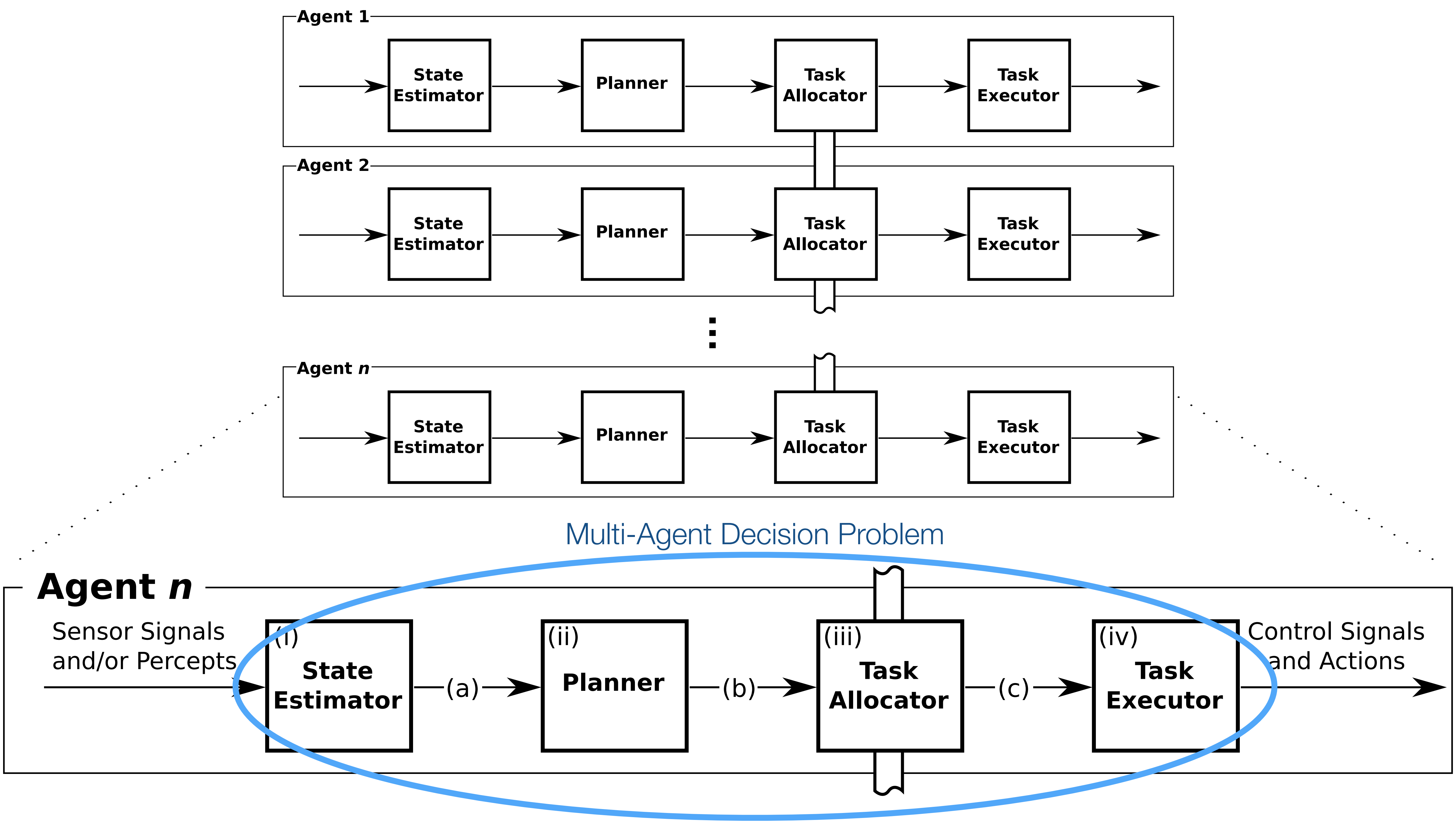

2 What is the underlying organizational principle involved?

The traditional engineering methodology of top-down decomposition into sub-systems

- Does well in managing design complexity
- Overall optimality unclear

3

What are the research problems and topics we expect for the coming years?

Heterogeneity

How do we cope with highly heterogeneous systems?

Elements of interrelatedness become much more important in heterogeneous robot systems involving robots with diverse capabilities.

Ex. ASYMTRE line of work by Zhang and Parker

Utility Estimates

How do we compare utility estimates to realized task performance? How do we use this?

There is a little work on learning algorithms, otherwise this aspect is largely ignored.

Coordination vs. Competition

How do gain a deeper understanding of cooperative vs. competitive points of view?

Auctions and market-based methods involve a competitive, self-interested point of view. Is this really appropriate?

Connecting methods

How do we establish connections between the existing methods?

Many methods exist as islands…

Questions