A4M36PAH - Plánování a hry

From one to many: Multiagent Planning

Ronen Brafman, Carmel Domshlak, Raz Nissim

Multiagent systems

Overview

- systems consisting of agents
- an agent is a bounded entity
- the entities interact with each other
- generally no limitations on what an agent is (robots, humans, programs, ...)

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For scope of this lecture

- agents $\sim$ intelligent programs
- interaction $\sim$ message passing

Multiagent systems

Technically

- agents $\sim$ a computational thread or process running ideally on its own processor (core)
- interaction $\sim$ inter-process sending of messages (potentially over network)

Constraint Satisfaction Problems (CSPs)

What is a CSP?

- finite set of variables $v_1, v_2, \ldots, v_k$
- non-empty domain of possible values for each variable $D_{v_1}, D_{v_2}, \ldots, D_{v_k}$
- finite set of constraints $C_1, C_2, \ldots C_m$
- each constraint C_i specifies allowable combinations of values for subsets of variables
- a solution is an assignment of values to all variables that satisfies all constraints

Constraint Satisfaction Problems (CSPs)

Example

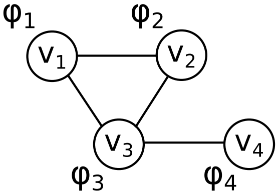
- variables:
  - $v_1 \in \{0, 1, 2\} = D_{v_1}$
  - $v_2 \in \{3, 4\} = D_{v_2}$
  - $v_3 \in \{5, 6\} = D_{v_3}$
  - $v_4 \in \{5, 6\} = D_{v_4}$
- constraints:
  - $C_1 = \{v_1 = 0 \Rightarrow v_2 = 4\}$
  - $C_2 = \{v_1 = 1 \Rightarrow v_2 = 3\}$
  - $C_3 = \{v_2 = 3 \Rightarrow v_3 = 5\}$
  - $C_4 = \{v_3 = 5 \Rightarrow v_1 \neq 0 \wedge v_1 \neq 2\}$
  - $C_5 = \{v_3 = v_4\}$
- solution:
  - ?,+?

Distributed Constraint Satisfaction Problems (DisCSPs)

Distribution of CSP

- each agent $\varphi_i \in \Phi$ is responsible for one variable v_i
- constraints are over more agents according to their variables
- an agent interaction graph of the agents is based on their variables and the constraints

Interaction graph of the previous example:



Detour to Graph theory

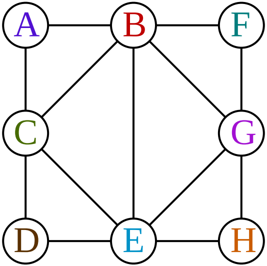
Graph tree-decomposition, width and tree-width

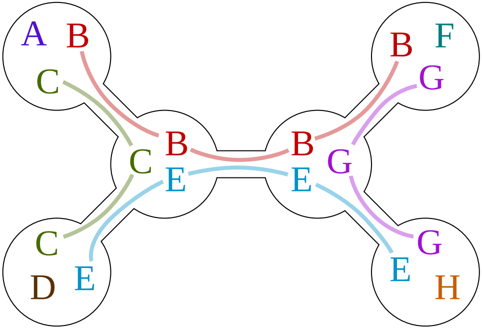
Graph tree-decomposition, width and tree-width

Definitions

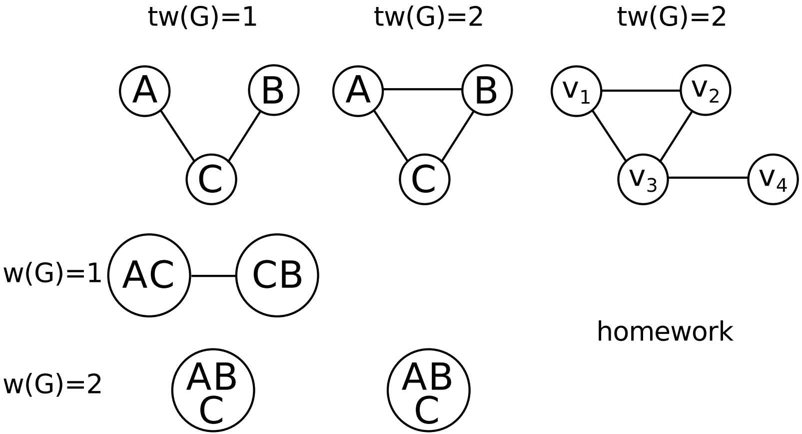
- a tree-decomposition of a graph G is (T, W), where T is a tree and $W = (W_t : t \in V(T))$ satisfies:
  - $\bigcup_{t \in V(T)} W_t = V(G)$ (each graph vertex is associated with at least one tree node)
  - $\forall uv \in E(G) \exists t \in V(T)$ s.t. $u, v \in W_t$ (vertices are adjacent in the graph only when the corresponding subtrees have a node in common)
  - if $t' \in T[t, t'']$, then $W_t \cap W_{t''} \subseteq W_{t'}$(the nodes associated with vertex form a connected subset of T.)
- the width of a graph is $\max(|W_t| - 1 : t \in V(T))$
- the tree-width of G is the minimum width of a tree-decomposition of G

Graph tree-decomposition, width and tree-width





Graph tree-decomposition, width and tree-width



Graph tree-decomposition, width and tree-width

Formally

- $tw(G) < 1 \Leftrightarrow G$ is forest (or tree or a series) graph
- $tw(G) < 2 \Leftrightarrow G$ is series-parallel graph
- $tw(G_n^{k \times k-\mathrm{grid}}) = k = \sqrt{n}$ for a grid graph of n vertices [bigger homework (optional)]
- $tw(K_n) = n - 1$ for a complete graph of n vertices

Informally

- tree-width of a graph determines its "cliquishness" (opposite of linearity or "treeness")
- in the DisCSP problems the tree-width of the interaction graph is related to coupling of the problem

End of the detour

(not end of the lecture, though)

Distributed Constraint Satisfaction Problems (DisCSPs)

Solving (Dis)CSP

- more families of algorithms solving CSP
- *Adaptive Tree Consistency (ATC)* – based on tree-decomposition of the underlying constraint graph, can be described as message passing among the variables (i.e., agents)

Complexity of ATC

- proven that time complexity of ATC is
$$O(kD^{\omega+1})$$
- k corresponds to number of CSP variables and therefore number of agents in DisCSP
- $D = \max_{i=1}^{k} D_i$, i.e., size of the largest domain (because of asymptotic complexity)
- ω is tree-width of the constraint graph (corresponds to the agent interaction graph)

Planning for loosely coupled multiagent systems

[R. Brafman, C. Domshlak: From one to many: Planning for loosely coupled multiagent systems, In *Proceedings of ICAPS*'08, 2008]

Motivation

Logistics planning

Deliver packages using vehicles (trucks, airplanes, ships) operating in/between different countries/regions/cities

- Classical benchmark for "single-agent" planning
- Classic example of a distributed system $\rightsquigarrow$ vehicle $=$ agent

(Informal) Question

Can we exploit the fact that the domain describes a naturally distributed system to make planning more efficient?

(Ultimate) Answer

YES, we can solve distributed components independently

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Basic Motivation/Intuition

k-agents MA Systems (Logistics domain example)

Fully decoupled

Vehicles are a priori responsible for different packages

Same as planning k times for a single agent
$\rightsquigarrow$ linear time-complexity growth
($\exp(k)$ time-complexity reduction)

Fully coupled

Vehicles have to move the same packages and maybe coordinate on loads/unloads

Same as planning for a single "k-times larger" agent
$\rightsquigarrow$ $\exp(k)$ time-complexity growth
(no reduction in time-complexity)

“Loose Coupling” is a Loose Concept

Questions

1. How to measure the coupling level of a MA system?
2. Is there an algorithm that
   1. can handle any “coupling level”, yet
   2. is guaranteed to benefit from lower “coupling level”

Centralized Planning for MA Systems
Problem Statement

Our Focus Here

Input Planning problem for a set of k collaborative agents

Question To what extent is planning for such a MA system harder than solving individual planning problems of each of the agents in isolation?

Approach Theoretical. Try to formulate an algorithm that is tractable under reasonable conditions.

Centralized Planning for MA Systems

Our Focus Here

Input: Planning problem for a set of k collaborative agents

Question: To what extent is planning for such a MA system harder than solving individual planning problems of each of the agents in isolation?

Approach: Theoretical. Try to formulate an algorithm that is tractable under reasonable conditions.

Main Ideas

A New Graphical Model

Potential (positive and negative) interactions between the agents' individual abilities (= actions)

System coupling-level

Define an interaction graph of the system

Nodes = agents

Edges = agents need (to coordination with) each other

Parameter $\omega \rightsquigarrow$ tree-width of interaction graph

Main Ideas

A New Graphical Model

Potential (positive and negative) interactions between the agents' individual abilities (= actions)

System coupling-level

Parameter $\omega \rightsquigarrow$ tree-width of interaction graph

Problem coupling-level

Some problems require more coordination than others!

Parameter $\delta \rightsquigarrow$ minmax number of times a single agent needs some other agent to do something for it

Main Ideas

System coupling-level

Parameter $\omega \leadsto$ tree-width of interaction graph

Problem coupling-level

Parameter $\delta \leadsto$ minmax number of times a single agent needs some other agent to do something for it

Algorithm

- Fix the agents' commitments to each other
  $\leadsto$ *careful selection of language matters!*
- Let each agent independently plan "in-between" commitments
- Use iterative deepening to extend the number of per-agent commitments if needed

Agent Actions

Logistics planning

Deliver packages using vehicles (trucks, airplanes, ships) operating in/between different countries/regions/cities

- Actions $\texttt{move}(v, from, to), \texttt{load}(p, v, at), \texttt{unload}(p, v, at)$
- Agents: vehicles
- Vehicle agent actions:
  moving it, loading into it, unloading from it

From STRIPS to MA-STRIPS

Everything is the same, except that
actions are partitioned between the agents

From STRIPS to MA-STRIPS

Definition

A STRIPS problem is given by a quadruple $\Pi = \langle P, A, I, G \rangle$, where:

- P is a finite set of *atoms*, $I \subseteq P$ is the *initial situation*, and $G \subseteq P$ encodes the *goal* situations,
- Each action $a \in A$ is given by $\langle \mathsf{pre}(a), \mathsf{add}(a), \mathsf{del}(a) \rangle$.

From STRIPS to MA-STRIPS

Definition

An MA-STRIPS problem for a system of agents $\Phi = \{\varphi_i\}_{i=1}^{k}$ is given by a quadruple $\Pi = \langle P, \{A_i\}_{i=1}^{k}, I, G \rangle$, where:

- P is a finite set of *atoms*, $I \subseteq P$ is the *initial situation*, and $G \subseteq P$ encodes the *goal* situations,
- For $1 \leq 1 \leq k$, A_i is the set of actions that the agent φ_i is capable of performing. Each action $a \in A = \bigcup A_i$ is given by $\langle \mathsf{pre}(a), \mathsf{add}(a), \mathsf{del}(a) \rangle$.

Solving MA-STRIPS Problems

Standard Approaches

1. Compile into a single-agent STRIPS problem
   - ☹ Lose all structure and obtain k-times larger "agent"
   - ☹ Worst-case complexity exponential in description size or shortest plan (depending on search strategy)
2. Try to solve as much as possible locally and compose the resulting individual agent plans
   - ☹ What can we say about it?

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A Closer Look at Agent Actions

Private vs. Non-Private

Private affect and depend only on that agent

Non-Private all the rest

Logistic planning

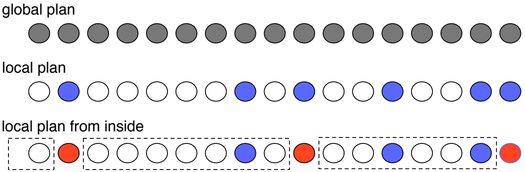
- Move actions are private
  (influence and influenced only by vehicle location)
- Loading into/unloading from a vehicle is non-private
  $\leadsto$ except if the package location is private to the vehicle!

A Closer Look at Agent Subplans

Private vs. Non-Private

Private affect and depend only on that agent

Non-Private all the rest



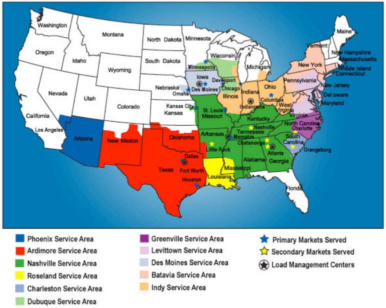
- non-private actions in the plan $\rightsquigarrow$ coordination points
- arbitrarily long sequences of private actions between adjacent non-private actions

Example: Logistics

Logistics

- imagine vehicles moving on a large map
- each vehicle has a service region

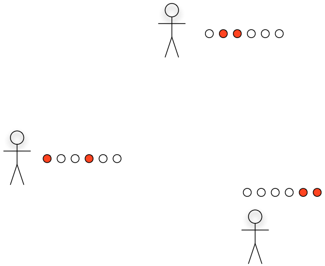
⇝ between each load/unload action, there are multiple `move` actions by the vehicle



Main Idea

"Algorithm"

1. Find a good choice of coordination points
2. Solve k local planning problems over the private actions of the agents only



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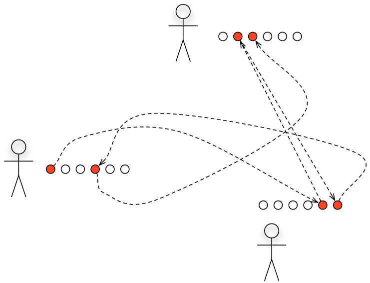

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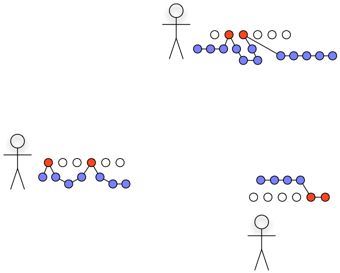
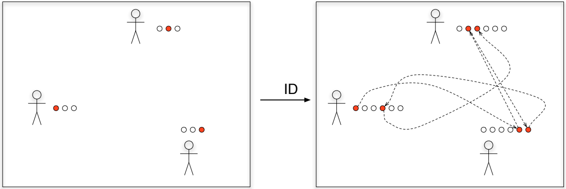


Main Idea

"Algorithm"

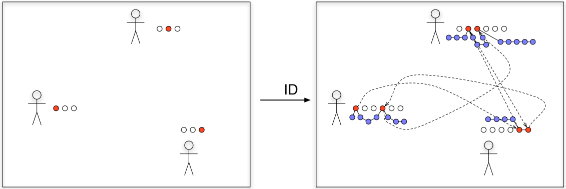
1. Find a good choice of coordination points
   - Iterative deepening on δ — # of coord-points per agent
   - For each choice of δ
     - Define a CSP whose solutions are consistent assignments to the coordination points
2. Solve k local planning problems over the private actions



Main Idea

“Algorithm”

1. Find a good choice of coordination points
2. Solve k local planning problems over the private actions
   - purely independent phase $\rightsquigarrow$ unary constraints
   - can be reduced to regular STRIPS planning



Complexity

The complexity is derived from

- number of agents k in set Φ with public actions A_i^{pub}
- maximal complexity of the local planning $\mathcal{I}$ with a cost function for switching from regular planning $f(\cdot)$
- number of "coordination" CSPs we have to solve (corresponds to δ)
- solving each "coordination" CSP $O(kD^{\omega+1})$
- length of the "coordination" plan $k\delta$

The idea of $k\delta$:

$$\begin{matrix} \alpha : \\ \beta : \end{matrix} \begin{pmatrix} a_1^\alpha & * & a_2^\alpha & * & a_3^\alpha & * \\ * & a_1^\beta & * & a_2^\beta & * & a_3^\beta \end{pmatrix}.$$

Complexity

Size of agent's domain is:

$$|D_i| = \sum_{d=1}^{\delta} \binom{k\delta}{d} \cdot |A_i^{pub}|^d = O((k\delta|A_i^{pub}|)^{\delta+1}).$$

Terms

- $\binom{k\delta}{d}$ represents all possible combinations of d virtual time points for the public actions (e.g., for $d = 2, k\delta = 6$ there are 15 of them $\{(1,2),(1,3),\ldots,(1,6),(2,3),(2,4),\ldots,(5,6)\}$)
- $|A_i^{pub}|^d$ represents all possible public action sequences of length d (e.g, for $d = 2$ and $|A_i^{pub}| = 2$ they are $\{a_1 a_1, a_1 a_2, a_2 a_1, a_2 a_2\}$)
- the summed up result represent the number of all possible coordination sequences for one agent.

Complexity

Time complexity of the unary internal-planning constraints:

$$O(f(\mathcal{I}) \cdot k \cdot \max_{i \in \Phi} |D_i|) = O(f(\mathcal{I}) \cdot k(k\delta|A^{pub}|)^{\delta+1}) = O_{ipc},$$

Terms

- $f(\mathcal{I}) \cdot k$ the internal planning has to be run by each agent
- asymptotically (in worst case) $\max_{i \in \Phi} |D_i|$ domains has to be planned by all agents
- asymptotically (in worst case) $|A_i^{pub}|$ for all agents are all public actions $|A^{pub}|$

Complexity

Time complexity of the coordination constraints:

$$O(k \cdot \max_{i \in \Phi} |D_i|^{\omega+1}) = O(k(k\delta|A^{pub}|)^{\delta\omega+\epsilon}) = O_{cc},$$

Terms

- based on ATC algorithm time complexity $O(kD^{\omega+1})$
- $D = \max_{i \in \Phi} |D_i|$
- $\epsilon = \delta + \omega + 1$is dominated by $\delta\omega$
- asymptotically (in worst case) $|A_i^{pub}|$ for all agents are all public actions $|A^{pub}|$

Final Complexity

Time final time complexity bound of the multiagent planning:

$$O_{ipc} + O_{cc} = O(f(\mathcal{I}) \cdot k(k\delta|A^{pub}|)^{\delta+1} + k(k\delta|A^{pub}|)^{\delta\omega+\epsilon}).$$

The exponential bounds can be therefore expressed as:

$$f(\mathcal{I}) \cdot \exp(\delta) + \exp(\delta\omega)$$

Not exponentially dependent on

Algorithm complexity has no direct exponential dependence on the number of agents k, has no direct exponential dependence of the length of the individual plans of the agents and has no direct exponential dependence of the size of the original planning problem.

Exponentially dependent on

Algorithm complexity is exponentially dependent on number of coordination points, i.e., length of the coordination plan and on tree-width of the agent interaction graph.

Multiagent A^*

[R. Nissim, R. Brafman: Multi-Agent A* for Parallel and Distributed Systems, In *Proceedings of HDIP Workshop (ICAPS)*, 2012]

Multiagent Distributed/Parallel A*

Overview

- based on partition of actions from the previous slides
- private/public actions (respecting privacy)
- A* expansion only of agent's own actions
- distributed optimal search
- distributed termination detection
- currently most efficient distributed planning approach

Our approach – optimal forward search

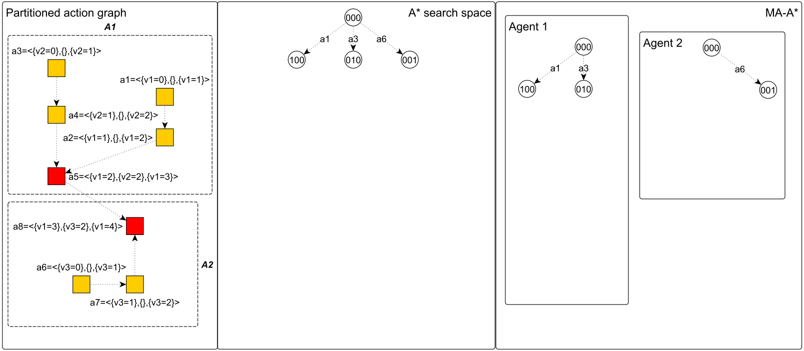
Each agent runs an A*-like search separately, using its own open/closed list. In each iteration, the agent performs:

MA-A*

- Receive messages and insert states into open list.
- Retrieve first node n from open list.
- If n is a solution, perform distributed optimality check.
- Expand n using the agent's own actions only.
- Compute h-value and add to open list all children n'.
- If n' was obtained by applying a public action
  - then send n' to all agents to which n' is relevant.

Messages contain the full state n', its g and h-values, and its creating action.

Running example



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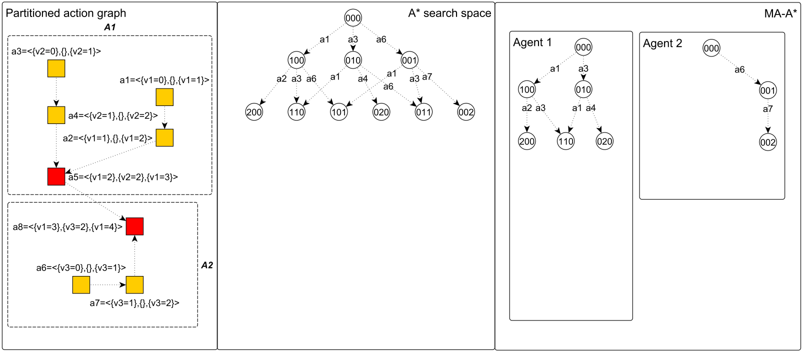

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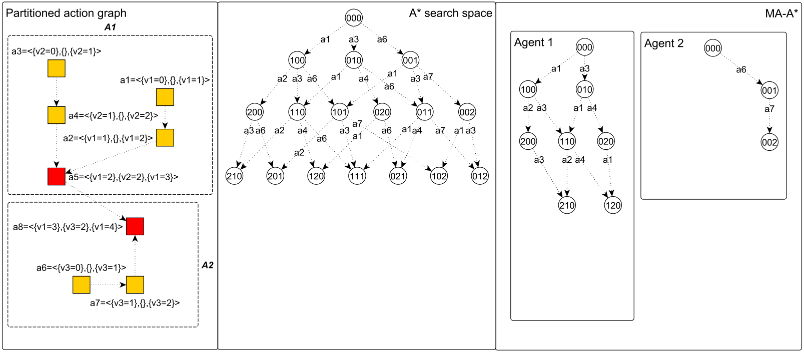

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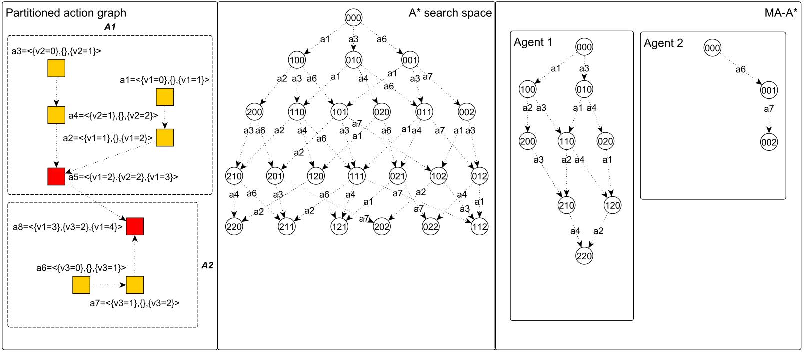

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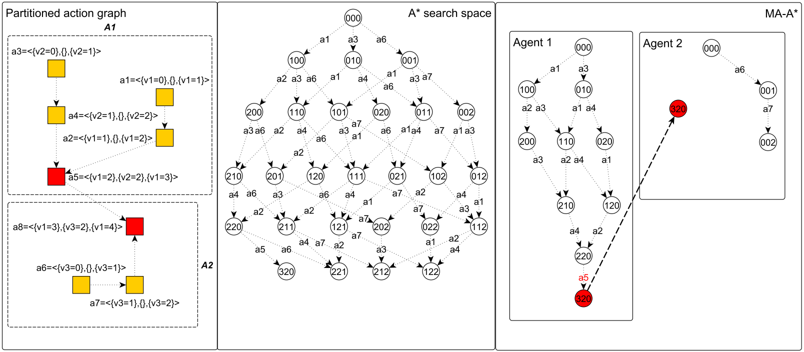

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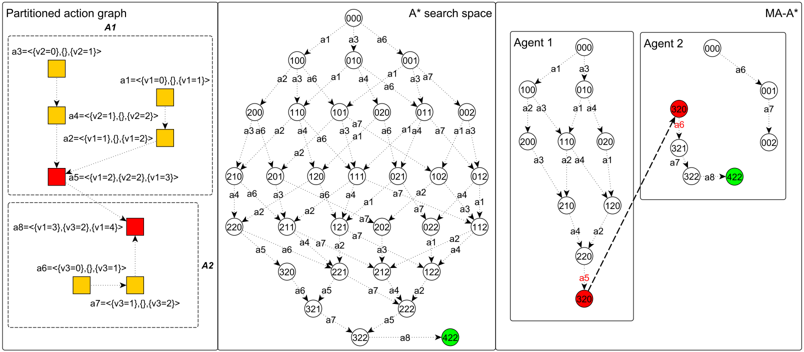

Relevancy of messages

- A state *s* is relevant to an agent if it has a public action for which all public preconditions hold in *s*.
- When some agent performs a private action, other agents' view of the system relevant to them has not changed!
- Sending only states for which the creating action is public, maintains optimality.
- This effectively prunes many equivalent parts of the search space $\Longrightarrow$ may result in fewer expansions than centralized A^*.

Experimental results

Problem	#	LM-cut heuristic					Merge&Shrink heuristic					Planning First	
		A*		MAP-A*			A*		MAD-A*				
(# of processors)	agents	time	expands	time	expands	eff.	time	init-h	time	init-h	eff.	time	δ
logistics7-1(4)	4	55.3	155289	27	504102	0.51	0	44	57	36	0	–	N/A
logistics8-1(4)	4	24.1	43665	13	168545	0.46	0.1	44	49.5	37	0	–	N/A
logistics10-0(4)	5	203	193846	66.6	627314	0.76	81.7	43	–	36	0	–	N/A
Rovers3(2)	2	0	50	0	90	1.00	0	9	0	6.5	1.00	0.3	2
Rovers4(2)	2	0	9	0.04	68	0	0	8	0	6	1.00	0.2	1
Rovers5(2)	2	8.8	37397	1.8	18975	2.44	11.7	20	4	10.5	1.46	9.3	3
Rovers6(2)	2	–	–	236	2255393	∞	–	27	325	17.5	∞	–	N/A
Rovers7(3)	3	6.7	18315	1	12929	2.23	55.9	14	7.2	9	2.59	38.5	3
Rovers8(4)	4	–	–	154	1271971	∞	–	15	–	10	N/A	–	N/A
Rovers12(4)	4	12.1	15222	0.9	10704	3.36	119	16	22.2	8.25	1.34	–	N/A
Rovers14(4)	4	–	–	598	5311741	∞	–	17	–	11	N/A	–	N/A
satellites5(3)	3	1.3	1174	0.1	793	4.33	7	13	3.8	8	0.61	52.3	2
satellites6(3)	3	3.5	2976	0.2	1650	5.83	23.5	18	9.2	9.3	0.85	457	3
satellites7(4)	4	94.5	36652	12.4	53465	1.91	–	14	343	9.5	∞	–	N/A
satellites8(4)	4	–	–	94.8	345667	∞	–	15	–	10	N/A	–	N/A
satellites9(4)	5	–	–	105	2132756	∞	–	18	–	11	N/A	–	N/A
satellites10(4)	5	–	–	61.8	95192	∞	–	17	–	10	N/A	–	N/A
zenotravel9(3)	3	72.1	15408	20	29321	1.20	56.7	19	370	14	0.05	–	N/A
zenotravel10(3)	3	16.1	1587	4.3	3453	1.25	26.7	22	–	17	0	–	N/A
zenotravel12(3)	3	458	41311	57	41819	2.68	–	–	–	–	N/A	–	N/A
zenotravel13(3)	3	–	–	382	185827	∞	–	–	–	–	N/A	–	N/A

Experimental results: Comparison of centralized A*, MA-A* in its parallel (MAP-A*) and distributed (MAD-A*) settings, and Planning First. Runtime (in sec.), number of expanded nodes and efficiency values (speedup/# of processors) are shown.