The International Competition of Distributed and Multiagent Planners (CoDMAP)

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■ *This article reports on the first international Competition of Distributed and Multiagent Planners (CoDMAP). The competition focused on cooperative domain-independent planners compatible with a minimal multiagent extension of the classical planning model. The motivations for the competition were manifold: to standardize the problem description language with a common set of benchmarks, to promote development of multiagent planners both inside and outside of the multiagent research community, and to serve as a prototype for future multiagent planning competitions. The article provides an overview of cooperative multiagent planning, describes a novel variant of standardized input language for encoding mutliagent planning problems, and summarizes the key points of organization, competing planners, and results of the competition.*

Automated planning, as a subfield of artificial intelligence, proposes possibly tractable, heuristic, and algorithmic solutions to computationally hard combinatorial problems of sequential decision making. In the case of domain-independent planning, the input of a planner does not contain only the planning problem instance but also its domain, compactly describing the mechanics of the environment.

The history of competitions of domain-independent automated planning began in 1998, with the first International Planning Competition (IPC)[1] organized by Drew McDermott (chair), Malik Ghallab, Adele Howe, Craig Knoblock, Ashwin Ram, Manuela Veloso, Daniel Weld, and David Wilkins. IPC flourished, and during the next 17 years IPC grew into various tracks comparing a variety of extensions of the classical planning model based on STRIPS (Fikes and Nilsson 1971) and Action Description Language (ADL) (Pednault 1989), using the Planning Domain Description Language (PDDL) (McDermott et al. 1998) as the de facto standard problem-description (input) language. Although IPC focused only on single-agent planning, the competition did add new tracks over the years, beyond the initial deterministic track. For example the probabilistic track, organized by Blai Bonet and Bob Givan, was begun in 2006. Currently this track focuses on planning problems defined as Markov decision processes (MDPs) and partially observable MDPs (POMDPs) suitable for modeling uncertainty in case of single-agent planning, and to some limited extent in case of multiagent planning. For the planning community, IPC became not only a standard way to compare the performance of planners, but also a source of a wide variety of benchmarks motivated by both real-world problems and challenging fundamental features of the planners.

In contrast to multiagent uncertainty planning modeled as POMDPs, Ronen Brafman and Carmel Domshlak (2008) proposed a model for (cooperative) domain-independent multiagent planning for discrete and deterministic environments. A special form of partial observability was defined in terms of privacy, where agents should not know, observe, or use private knowledge of other agents. The motivation was to create a minimal extension of the classical planning model towards multiagent planning. The result was MA-STRIPS — extended STRIPS by partitioning of possible actions according to the particular agents and by defining what facts about the state of the world should be treated as public or private knowledge.

MA-STRIPS planning agents solve one common planning problem, which is partitioned to several subproblems. Partitioning according to agents is related to splitting one large planning problem into smaller parts by factoring, which can radically lower complexity in some cases. MA-STRIPS by its privacy requirements also implies that the private parts of the problem have to be solved by their respective owner planning agents.

The real-world motivation for MA-STRIPS spans over a wide variety of problems (Nissim and Brafman 2014), similarly to classical planning. Be it a consortium of cooperating logistic companies with common transportation tasks, but private know-how about local transport possibilities; or a team of spatially separated gas station inspectors with a common goal to analyze quality of gasoline in the whole country, but with private knowledge about the particular gas stations; or a heterogeneous fleet of satellites and rovers surveying a distant planet, for which keeping local information private is the only feasible way not to overload the communication network. In these motivational cases, MA-STRIPS problem partitioning would be defined over trucks, inspectors, rovers, and satellites. The know-how of mentioned corporations, knowledge of inspectors, and local information of robots would define MA-STRIPS private knowledge and obviate sharing all of the information freely among the agents.

After the MA-STRIPS model was introduced, a substantial number of multiagent planners were proposed. However, the differences in the used input languages and absence of a common set of benchmarks rendered their comparison impractical. In this article, we report on the first competition of distributed and multiagent planners compatible with the MA-STRIPS model. Our goal is to improve the situation by preparing a common language and benchmarks and providing a common ground for comparison. The competing planners were either centralized or distributed, competing in two separate tracks. Each of them performed planning in advance (offline) for cooperative agents with common and publicly known goal(s). The agents acted in a shared deterministic environment, and in the distributed track, they were required to keep parts of their planning problems private, that is, not share it with other agents. All actions were discrete time and nondurative. We have organized the competition as part of the workshop on Distributed and Multiagent Planning at the International Conference on Automated Planning and Scheduling during winter and spring 2015.

Input Language

Following the minimalistic extension of STRIPS to MA-STRIPS by Brafman and Domshlak in 2008, we wanted a simple extension of PDDL toward multiagent planning, also compatible with MA-STRIPS. We chose MA-PDDL (Kovacs 2012) and extended it with a partitioning definition and a definition of privacy of objects and predicates (and thus implicitly of the privacy of actions). The extension allowed defining agents in various ways: as objects, constants, or not explicitly at all. This variability allowed us to reuse many interesting classical planning benchmarks.

The definition of privacy in MA-STRIPS is implicit and follows a simple rule, which says that a fact is public if it is required or modified by two or more actions of different agents. An action is public if it requires or modifies at least one public fact. Based on a review of literature, and a conducted precompetition poll,[2] we found that such a definition could be too rigid, especially for future versions of the competition. We slightly relaxed the MA-STRIPS notion of privacy and declared it explicitly in the MA-PDDL description. Our privacy definition follows MA-STRIPS in the sense that facts and actions can be private to particular agents or public among all agents, however what facts and actions are private and public is determined by a process coined maximally concealing grounding (MCG), which is based on three rules:

(1) A public predicate definition grounded with public objects / constants is a *public fact.*

(2) A public predicate definition grounded with at least one object / constant private to agent α is a *private fact* of agent α (grounding a single predicate definition with objects private to different agents is not allowed).

(3) A private predicate grounds to a *private fact* regardless of privacy of the objects used for grounding.

By convention, a PDDL object representing an agent was private to that given agent. If it was not, other agents of the same PDDL type would be able to ground and use the other agent's actions.

We have defined two ways how to encode[3] multiagent planning problems: either as unfactored MA-PDDL or as factored MA-PDDL. With regard to information, the two representations are equivalent. The difference is in the information separation. As for distributed multiagent planning, it is important to provide the respective agents only with information allowed to them by the privacy requirements. Description of the MA-PDDL variants follows.

Unfactored MA-PDDL

Unfactored MA-PDDL stems naturally from classical PDDL. It uses a pair of files for all agents. One file contains the domain information and the other the specification of a problem instance within that domain.

Unfactored MA-PDDL is defined in terms of two extensions of classical PDDL. The first informs the planner that action definitions are annotated with an additional specification of the agent owning the grounding of the action. Using this extension over all actions unambiguously defines action partitioning. The other extension, with a help of the previously defined MCG rules, unambiguously defines what facts are private and public to given agents and, using the MA-STRIPS definition, what actions are private and public.

Factored MA-PDDL

Factored MA-PDDL results straightforwardly from the distributed nature of multiagent systems. Each separate planning agent uses its own pair of domain and problem description files (denoted as a MA-PDDL factor). Each pair defines information relevant only to that particular agent.

Action partitioning ensues directly from factorization of the input. As each planning agent's factor contains only relevant objects, constants, and actions, there is an unambiguous grounding of them. Objects and constants that were common for more than one agent were by convention bound over the same names. The grounding semantics of privacy using the MCG rules is the same as in the unfactored variant with respect to the partitioning by the MA-PDDL factors.

Competition Tracks

The success of a planning competition is determined to a large extent by the number of contestants. Because there was no historical experience from previous multiagent competitions, we wanted to open the competition to the widest possible audience. A survey of literature on multiagent planners together with the precompetition poll provided enough information to set the rules for the competition so that an ample amount of already existing multiagent planners could compete and still the key motivations of the competition remained satisfied.

Technically, the fundamental discriminator of current multiagent planners is whether they can work distributively on multiple interconnected physical machines or not. Running planners in such a distributed setup is incomparable to running planners centrally on one machine with a shared memory space. To accommodate planners running in either mode, the competition was split into two tracks: centralized and distributed (see figure 1). The following paragraphs describe the requirements and emphasize the differences between them.

Centralized Track

The centralized track aimed at running multiagent planners on one physical multicore machine with one shared memory space that allowed use of any means of communication among its agents (see figure 1, top). This included a setup with only one agent, which is typical for classical planners. It was up to the planner whether it ran on one or more machine cores and which type of communication it used, if any. In contrast to IPC, in the centralized CoDMAP track the planners had to read the input in MA-PDDL, either factored or unfactored. The MA-STRIPS partitioning and privacy definitions were indicated in the input MA-PDDL files, but the planners were allowed to ignore them. The required output was a sound (valid) sequential plan solving the provided planning problem. As a result of the above-described openness, the centralized track allowed comparison of a wide spectrum of multiagent planners. The track was therefore annotated as transitional and highly compatible.

Distributed Track

The distributed track removed the compatibility compromises of the centralized track. All competing multiagent planners had to run in a distributed fashion (as several planning agents) on a cluster of interconnected multicore machines, where each machine was dedicated only for one planning agent (see figure 1, bottom).

The input was limited to factored MA-PDDL and the partitioning matched the physical machines. Privacy followed the factored MA-PDDL definition and the MCG rules. Planning agents could communicate only public information over the TCP/IP network. Competition rules forbid explicitly exchanging any private information among the planning agents. The output was a set of plans: one plan per planning agent using only actions defined by its respective MA-PDDL factor. The soundness of plans was tested after their linearization. Concurrent actions of different agents at any given time did not have to be mutually exclusive. The distributed track was unique and novel in comparison to the IPC tracks.

Competition Domains

The planners were evaluated over a set of 12 benchmark domains. The domains were motivated by important and interesting real-world problems or by problems exposing and testing theoretical features of the planners. We used domains from literature on multiagent planning that are in most cases multiagent variants of the classical IPC domains: BLOCKSWORLD, DEPOT, DRIVERLOG, ELEVATORS08, LOGISTICS00, ROVERS, SATELLITES, SOKOBAN, WOODWORKING, and ZENOTRAVEL. Each domain had 20 problem instances, with varying size, number of objects, constants, agents, and thus

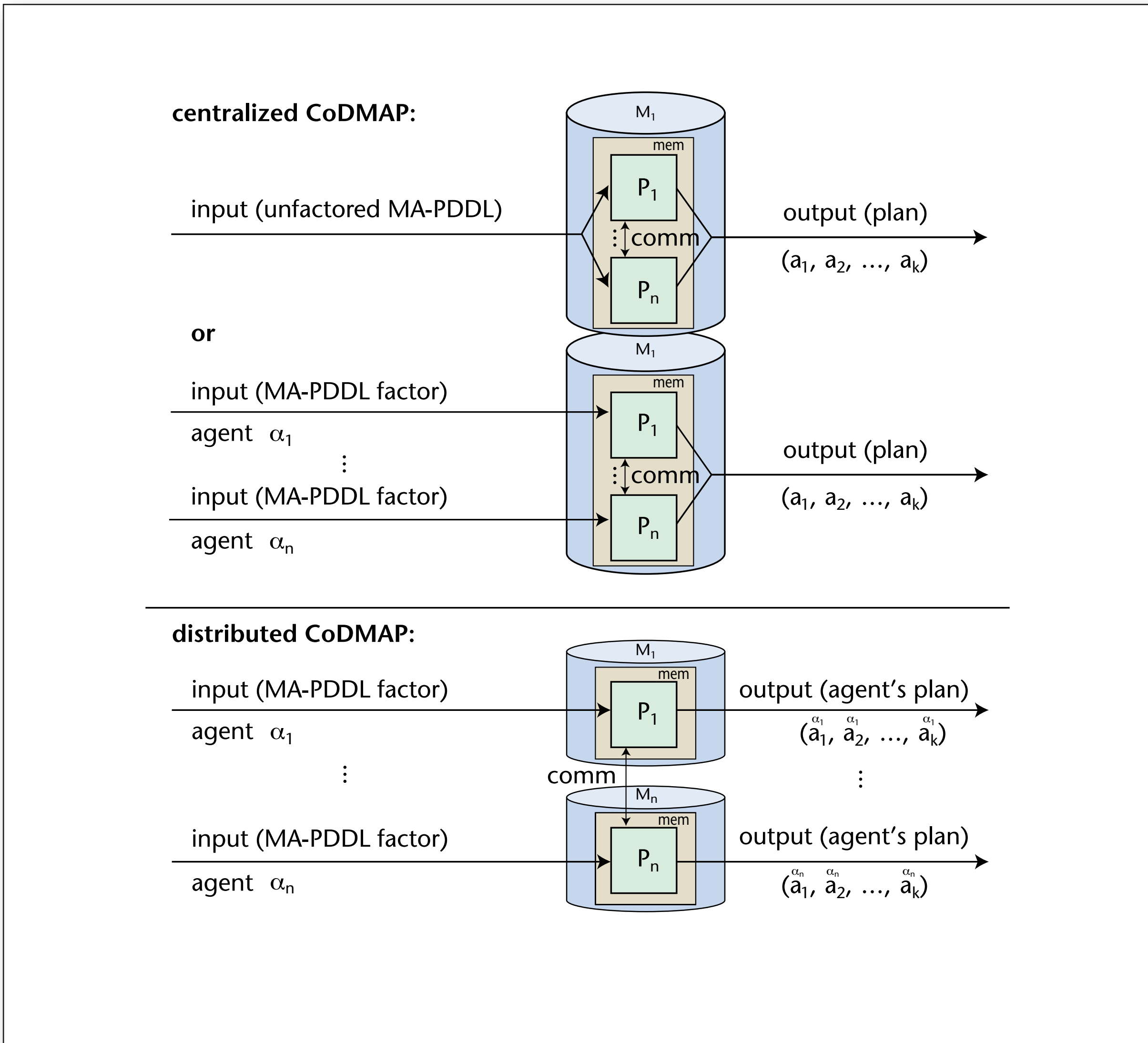

Figure 1. Comparison of IPC and CoDMAP Tracks.

complexity. The biggest problems had 10 agents and about 100 objects/constants. Additionally, we added two novel domains inspired by well-known multiagent problems, not modeled in MA-STRIPS or MA-PDDL previously: TAXI and WIRELESS. The taxi domain can be considered a multiagent variation on the logistic domain, in which monotonous (relaxed) heuristic planning benefits. On the contrary, the wireless domain is modeled such that monotonous planning is deceived by a concept of circulating messages among the sensors causing the relaxation planners to think the communication is free of charge. Description of the novel domains follows.

TAXI

TAXI problems model on-demand transport in a city (see figure 2, left). Two types of agents represent taxis and passengers. Each taxi and passenger is at a particular location. A location can be free of taxis and two locations can be directly connected. Connected locations form a topology of the city. Each taxi can transport only one passenger from the location it stays at and only to a free drop-off location (a location containing no other taxis). A taxi can move only between connected locations.

WIRELESS

WIRELESS problems model distributed gathering of data by a group of smart sensors to a base station (see figure 2, right). The base and sensors are represented by agents, where some of them are neighbors (they are in range of their radios). The neighbor relation defines the topology of an ad hoc radio network among the sensors and the base. Sensor agents have

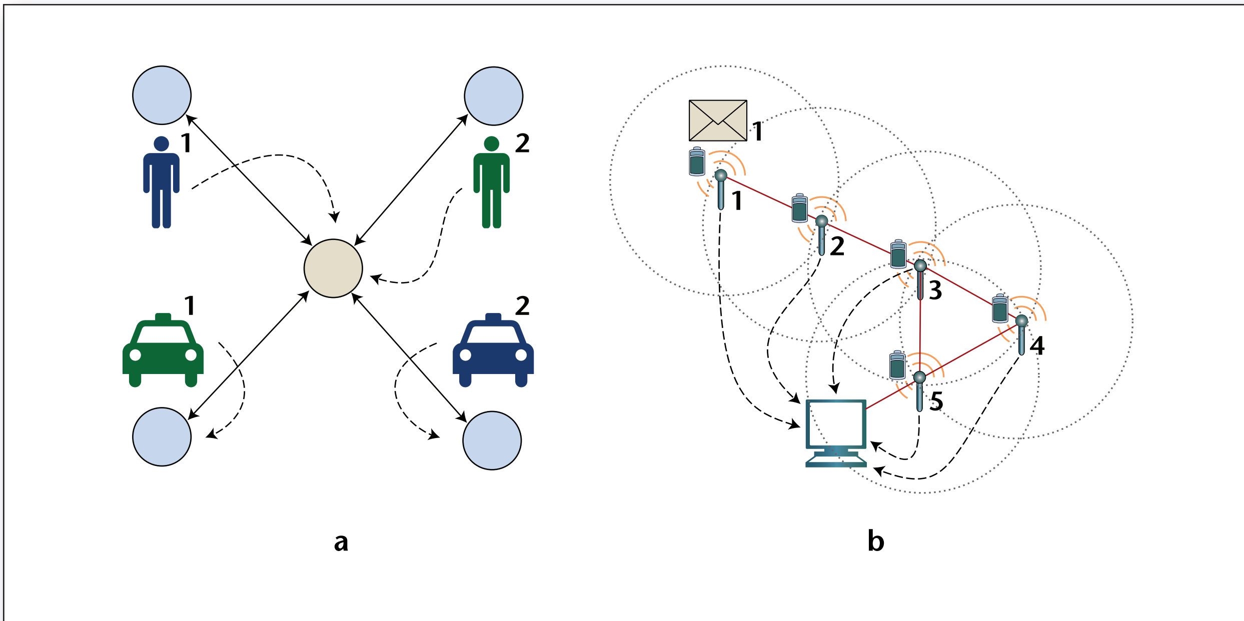

Figure 2. Example Problem Instances of the Two Novel CoDMAP Domains.

TAXI (left). WIRELESS (right). The figures represent initial states of the easiest instances of the domains. Dashed arrows show the goals of individual agents. In the TAXI problem, both passengers want to be transported to the central location and the taxi drivers want to end at the same locations they started from (the garage). In the WIRELESS problem, all five sensor nodes are initially at normal battery level, and there is only one allowed message in the system represented by an envelope initially at sensor 1. Data from all sensors has to be gathered by the base station represented by a computer.

four possible private energy levels. A sensor with more than zero energy can do its measurement and generate measurement data, which decreases its energy by one level. A sensor can add measurement data (possibly of other sensors) to a message if it has the data and the message is in its memory. A sensor with more then zero energy can send a message to a neighboring sensor or base, which decreases its energy by one level. Receiving a message as well as extracting measurement data from a message does not change the energy level. The number of messages usable in parallel is limited; however, they can be reused sequentially. The goal is to gather the measurement data of selected sensors at the base station.

Validation and Evaluation

Each run of a planner in the competition was restricted to 30 minutes and 8 gigabytes of RAM per physical machine (in the centralized track per problem, while in the distributed track per one agent, that is, a factor of a problem) on quad-core machines at 3.9 GHz. The machines were for the distributed track interconnected into an IP subnet with one 10 Gbps switch and 1 Gbps Ethernet cards.

The metrics used to compare the planners were coverage (number) of solved problems, IPC score over the plan quality (ratio to the optimal solution), and IPC score over the planning time (ratio to the fastest solution). In the distributed track, the plan quality was evaluated both in terms of total cost (sum of costs of all used actions) and makespan (the maximum time step of the plan if executed in parallel). The validity and quality of plans was evaluated using the VAL tool,[4] which can handle parallel plans and also performs checks of mutually exclusive actions.

The intentionally weak rules of the centralized track attracted a number of (classical) planners adapted to process multiagent input in MA-PDDL. This resulted in a wide spectrum of planners in terms of the way of partitioning and privacy preservation. To fairly compare the efficiency of these planners, competition rules required submission of a short paper for each submitted planner with a list of required items, which can be used by the community to select only those results that are relevant for their research. The tighter rules of the distributed track allowed a much easier comparison of competing planners.

Competing Planners and Selected Results

Some of the competing planners were submitted in several configurations. For the centralized track, we received 12 planners in 17 configurations prepared by 8 teams. For the distributed track 6 configurations of 3 planners by 3 teams were received. All teams

Centralized track			Distributed track		
1.–2.	ADP	222	1.	PSM	180
3.	MAP-LAPKT	216	2.	MAPlan	174
4.	CMAP	210	3.	MH-FMAP	107

Table 1. Best Performing Planners in the Metrics of Solved Problems (Coverage) Out of Overall 240 Benchmarks.

were from the research community of automated planning and multiagent systems. A selection of the results is listed in table 1. Complete, detailed, and interactive results can be found on the official CoDMAP webpage.[5] In the following paragraphs we summarize the key principles of the best performing planners.

The winner of the centralized track, ADP, by Crosby, Rovatsos, and Petrick (2013), was based on the idea of automatic decomposition of a planning problem to agents (however, it ignored the partitioning and the privacy predefined in MA-PDDL) using a graph of causal dependencies among actions. The planning process itself interleaved the subgoal calculation phase and the search phase by the FastDownward planner (Helmert 2006). A similar principle was used in the CMAP planner by Borrajo (2013), where the planner did not plan for subgoals but adapted and merged partial plans of different agents. Additionally, the subproblems were obfuscated such that privacy was preserved. The MAP-LAPKT planner by Muise, Lipovetzky, and Ramirez (2015) compiled the multiagent planning problems to classical problems respecting the predefined partitioning and emulating the partial observability resulting from the privacy.

The winner of the distributed track represented sets of possible local plans of the agents as finite state machines. The structures, coined *planning state machines,* giving the planner name PSM (Tozicka, Jakubuv, and Komenda 2014), were projected to a public part of the problem and merged. Provided that a merger of all public projections of agents' PSMs was nonempty, a coordination plan was found and was extended to the global solution. The PSM planner preserved privacy as the PSMs were kept local and the merging process communicated only the public projections. MAPlan by Fišer, Štolba, and Komenda (2015) and MH-FMAP by Torreño, Onaindia, and Sapena (2014) were distributed multiheuristic forward-chaining search planners, in the former case, in the space of states and in the latter, in the space of partial-ordered plans by a distributed variant of the best first search algorithm. MAPlan and MAP-LAPKT were the only optionally optimal planners in the competition.

Conclusions and Future Directions

The first international Competition of Distributed and Multiagent Planners became a thorough and nearly complete comparison of existing multiagent planning systems compatible with the MA-STRIPS model. It served as a successful proof-of-concept prototype of a multiagent competition showing good direction and viability similarly to first IPC 17 years ago. We are highly confident that a new track on multiagent planning can become a valuable addition to the next International Planning Competition.

Future directions for the competition can take advantage of the extensibility of the MA-PDDL language. An obvious direction is to use the looser privacy definition allowed by MA-PDDL and MCG and propose planning problems with complex privacy requirements like private goals. A partitioning related extension is to allow joint actions, which have to be performed by two or more agents at the same time.

Acknowledgments

This work was partially supported by the Czech Science Foundation (grant no. 15-20433Y), Israel Science Foundation, and the International Conference on Automated Planning & Scheduling 2015. We thank the ICAPS 2015 conference chairs Ronen Brafman and Carmel Domshlak for valuable initial input about the competition and Peter Benda from Czech Technical University in Prague for IT support. We would like to thank all participants in the competition; without their interest and hard work, the competition would be impossible.

Notes

1. See ipc98.icaps-conference.org/.
2. See the precompetition poll, bit.ly/1IsNoqY.
3. The extended BNF of MA-PDDL can be found at agents.fel.cvut.cz/ codmap/MA-PDDL-BNF.pdf.
4. See www.inf.kcl.ac.uk/research/groups/ planning.
5. See agents.fel.cvut.cz/codmap.

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