SatPlan: Planning as Satisfiability

Henry Kautz
Dept. Computer Science & Engr.
University Of Washington
Seattle, WA 98195 USA

Bart Selman
Dept. Computer Science
Cornell University
Ithaca, NY 14853 USA

Jöerg Hoffmann
Max-Planck-Institut für Informatik
Stuhlsatzenhausweg 85
D-66123 Saarbrücken, Germany

SatPlan-2006 is an updated version of the planning as satisfiability approach originally proposed in (Kautz & Selman 1992; 1996) using hand-generated translations, and implemented for PDDL input in the Blackbox system (Kautz & Selman 1999). Like Blackbox, SatPlan-2006 accepts the STRIPS subset of PDDL and finds solutions with minimal parallel length: that is, many (non-interfering) actions may occur in parallel at each time step, and the total number of time steps in guaranteed to be as small as possible. SatPlan-2006 differs from the 2004 version in that (i) mutex propagation is performed on the plan graph but only a subset of the inferred mutexes are encoded a binary clauses, and (ii) an encoding with Boolean variables for both actions and fluents is used, rather than on that only uses actions.

SatPlan works by:

- Constructing a GraphPlan-style (Blum & Furst 1995) style planning graph up to some length k;
- Translating the constraints implied by the graph into a set of clauses, where each specific instance of an action or fact at a point in time is a proposition;
- Using a general SAT solver to try to find a satisfying truth assignment for the formula;
- If the result is unsat or time out, incrementing k and repeating;
- Otherwise, translating the solution to the SAT problem to a solution to the original planning problem;
- Postprocessing the solution to remove (some of the) unnecessary actions.

The final step is useful because the SAT translation of the planning graph does not guarantee that every action proposition that is true in the solution is actually needed in order to achieve the goals of the original plan.

SatPlan-2006 uses a modified form of the SAT encodings described in (Kautz, McAllester, & Selman 1996). The system begins by generating a plan graph up to a level k that contains all the goal literals. During plan graph generation, mutex propagation is performed. It then generates axioms that assert:

1. Goals hold at level k, and the initial state at level 0;
2. If a fluent holds at level k, the disjunction of actions that have that fluent as an effect hold at level $k-1$;
3. Actions at each level imply their preconditions;
4. Actions with (directly) conflicting preconditions or effects are mutually exclusive, encoded as negative binary clauses;
5. Fluents that are inferred to be mutually exclusive are encoded as negative binary clauses.

SatPlan-2006 is written in a modular fashion, so that any SAT solver can be used unchanged: the SAT solvers run as a separate process. In the 2004 and 2006 competitions we used the DPLL-based solve *siege*, that was developed by Lawrence Ryan as part of his research at Simon Fraiser University under the direction of Prof. David Mitchell. Linux binaries of siege can be downloaded from `http://www.cs.sfu.ca/ loryan/personal/`.

The 2004 version of SatPlan did not perform mutex propagation during plan graph generation because on some problems the resulting formulas were so large due to mutex clauses that they were unsolvable due to memory constraints. For 2006, we enabled mutex propagation, but only generated clauses for inferred mutexes for fluents, not for actions. This strategy allowed harder instances to be solved while avoiding the worst memory problems.

References

Blum, A., and Furst, M. 1995. Fast planning through planning graph analysis. In *Proceedings of the 14th International Joint Conference on Artificial Intelligence (IJCAI 95)*, 1636–1642.

Kautz, H., and Selman, B. 1992. Planning as satisfiability. In *Proceedings of the 10th European Conference on Artificial Intelligence*, 359–363. Wiley.

Kautz, H., and Selman, B. 1996. Pushing the envelope: Planning, propositional logic, and stochastic search. In *Proceedings of the 13th National Conference on Artificial Intelligence (AAAI-96)*, 1194–1201. AAAI Press. (Best Paper Award).

Kautz, H., and Selman, B. 1999. Unifying sat-based and graph-based planning. In *Proceedings of the 16th International Joint Conference on Artificial Intelligence (IJCAI-99)*, 318–325. Morgan Kaufmann.

Kautz, H.; McAllester, D.; and Selman, B. 1996. Encoding plans in propositional logic. In *Proceedings of the 4th International Conference on Knowledge Representation and Reasoning (KR-96)*, 374–385. Morgan Kaufmann.