Research Abstract: Planning Under Uncertainty via Stochastic Satisfiability

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Our research has successfully extended the planning-as-satisfiability paradigm to support contingent planning under uncertainty (uncertain initial conditions, probabilistic effects of actions, uncertain state estimation). *Stochastic satisfiability* (SSAT), a type of Boolean satisfiability problem in which some of the variables have probabilities attached to them, forms the basis of this extension. We have developed an SSAT framework, explored the behavior of randomly generated SSAT problems, and developed algorithms for solving SSAT problems (Littman, Majercik, & Pitassi 2000). We have also shown that stochastic satisfiability can model compactly represented artificial intelligence planning domains, an insight that led to the development of ZANDER, an implemented framework for contingent planning under uncertainty using stochastic satisfiability (Majercik 2000).

ZANDER solves probabilistic propositional planning problems: states are represented as an assignment to a set of Boolean state variables and actions map states to states probabilistically. Problems are expressed using a dynamic-belief-network representation. A subset of the state variables is declared *observable*, meaning that any action can be made contingent on any of these variables. This scheme is sufficiently expressive to allow a domain designer to make a domain fully observable, unobservable, or to have observations depend on actions and states in probabilistic ways. ZANDER operates by solving an SSAT encoding of the planning problem; the solution to this SSAT problem yields a plan that has the highest probability of succeeding. ZANDER can solve arbitrary finite-horizon partially observable Markov decision processes and solves planning problems drawn from the literature at state-of-the-art speeds (Majercik 2000).

The general motivation for our planning research was to explore the potential for deriving performance gains in probabilistic domains similar to those provided by SATPLAN (Kautz & Selman 1996) in deterministic domains. There are a number of advantages to encoding planning problems as satisfiability problems. First, the expressivity of Boolean satisfiability allows us to construct a very general planning framework. Another advantage echoes the intuition behind reduced instruction set computers; we wish to translate planning problems into satisfiability problems for which we can develop highly optimized solution techniques using a small number of extremely efficient operations. Supporting this goal is the fact that satisfiability is a fundamental problem in computer science and, as such, has been studied intensively. Numerous techniques have been developed to solve satisfiability problems as efficiently as possible. Stochastic satisfiability is less well-studied but many satisfiability techniques carry over to stochastic satisfiability nearly intact (Littman, Majercik, & Pitassi 2000).

There are disadvantages to this approach. Problems that can be compactly expressed in representations used by other planning techniques often suffer a significant blowup in size when encoded as Boolean satisfiability problems, degrading the planner's performance. Automatically producing maximally efficient plan encodings is a difficult problem. This problem has been addressed for deterministic planning domains (Kautz, McAllester, & Selman 1996; Ernst, Millstein, & Weld 1997), but remains unsolved. We are currently exploring the impact of alternative SSAT encodings on ZANDER's efficiency. In addition, translating the planning problem into a satisfiability problem obscures the structure of the problem, making it difficult to use our knowledge of and intuition about the planning process to develop search control heuristics or prune plans. This issue has also been addressed for deterministic domains; Kautz & Selman (1998), for example, report impressive performance gains resulting from the incorporation of domain-specific heuristic axioms in the SAT encodings of deterministic planning problems.

Our current research focuses on three areas, briefly described below: 1) an improved action representation for probailistic planning problems, 2) developing

and assessing alternate SSAT encodings of probabilistic planning problems, and 3) developing an approximation technique for solving SSAT-encoded planning problems that will allow us to scale up to larger domains.

First, we are developing $\mathcal{PAR}$, a high-level action language that is an extension of the action language $\mathcal{AR}$ developed by Giunchiglia, Kartha, and Lifschitz (Giunchiglia, Kartha, & Lifschitz 1997). $\mathcal{PAR}$ allows the user to express probabilistic planning problems in a natural, flexible, and compact format. In particular, $\mathcal{PAR}$ gives the user the opportunity (but does not require them) to easily express domain invariants and action preconditions—information that can greatly decrease the time required to find a solution. The $\mathcal{PAR}$ representation is then automatically converted to an SSAT representation for solution by ZANDER.

Second, we are developing and assessing alternate SSAT encodings of planning problems. Our current encodings are similar to the linear encodings with classical frame axioms described by Kautz, McAllester, and Selman (Kautz, McAllester, & Selman 1996) for deterministic planning problems. Two other possibilities are analogous to linear encodings with explanatory frame axioms, and GRAPHPLAN-style encodings (Kautz, McAllester, & Selman 1996). A further interesting possibility is to construct hybrid encodings. Although it is not always true that more constraints (clauses) is better, adding clauses that make implicit information explicit (in the manner of caching lemmas in a theorem prover) or restate information in a different form can frequently guide the solver to a solution more efficiently. In one domain, this approach reduced the solution time from 9300 CPU seconds (linear encoding with classical frame axioms) to less than a second (linear encoding with explanatory frame axioms *augmented* with GRAPHPLAN-style axioms).

Finally, we are developing an approximation technique for solving SSAT encodings of planning problems. The uncertainty in a probabilistic planning problem is encoded in *chance* variables. A chance variable is a Boolean variable that has an independent probability associated with it indicating the probability that that variable will be `True`. In our approximation technique the possible assignments to these chance variables are enumerated in decreasing order of probability (consider what is most likely to happen first). For each assignment, the solver finds all the settings of the action variables that are consistent with this assignment. At any point, the the enumeration can be stopped and an approximation of the optimal plan constructed. Of course, if all chance variable assignments are considered, the optimal plan is discovered. Tests so far, however, indicate that frequently only a relatively small fraction of the assignments needs to be considered in order to construct an optimal or near-optimal plan.

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