State-Space Search

While State-Space Search was not new to planning in the 1990's, it became a practical tool when Bonet and Geffner released the Heuristic Search Planner (HSP), a planner that searches from the initial state of a problem to the goal state, using a heuristic function to estimate the distance from a given state to the goal (Bonet and Geffner, 2001; Russell and Norvig, 2009). When HSP competed against other planners, it solved the most problems, at 91 out of 165, but was the slowest. Moreover, HSP was not guaranteed to be optimal, although its solutions were either optimal or within 10% of optimality (Bonet and Geffner, 2001). The Fast Forward (FF) planner came out a year later, based on the HSP approach (Hoffman and Nebel, 2001), and outperformed all planners at the 2000 International Conference on Artificial Intelligence Planning and Scheduling (AIPS) competition, gaining nomination as the Group A Distinguished Performance Planning System. The key difference between HSP and FF is the heuristic used. While both use a relaxed version of the problem as a heuristic, HSP uses a variation of the "ignore-delete-list" heuristic, wherein actions are assumed to be independent, FF uses a heuristic based on a planning graph, which was put forth previously as the GRAPHPLAN system (Blum and Furst, 1995; Hoffman and Nebel, 2001).

By 2008, the FF planner was still the state of the art, and heuristic-based searches continued to be the primary basis for solving classical or sequential satisficing planning problems (Richter and Westphal, 2008). LAMA won the 2008 International Planning Competition by extending HSP, FF, and Fast Downward (Richter and Westphal, 2008). LAMA improved upon Fast Downward in three major ways: It used landmarks, or steps that are included in all plans that satisfy the goal, originally introduced by Porteous, Sebastian, and Hoffmann (2003); LAMA considers estimated action costs together with estimated goal distance, in contrast to FF, which uses action cost only in its heuristic; and LAMA uses the whole search space, or all of its time until interruption, restarting each time it finds an improved solution.

In 2012, another planner that used the FF planner's forward search technique was developed, titled COLIN, which was used to add two new types of problem-handling to the field of AI planning: 1) continuous linear change, and 2) duration-dependent effects combined with duration inequalities (Coles, Coles, Fox, and Long, 2012). Continuous linear change, as used in the COLIN paper, is the continuous change of a state variable depending on the time at which the a process may have been initiated previously in the given plan. An example given is the amount of sand in a truck, while sand is being poured in. Duration-dependent effects are effects that vary based on the amount of time an action is performed (Coles, Coles, Fox, and Long, 2012). For example, in the sand-and-truck example, the amount of sand will be different for a 5-second sand pour and a 10-second sand pour.

To address the problem of admissibility in heuristics used in the FF planner, which can lead to suboptimal plans, a technique of using Pattern Databases (PDBs) for admissible heuristics was developed (Edelkamp, 2001). The PDB is automatically generated by using a general abstraction scheme, resulting in a domain-independent memory-based heuristic that can be accessed at constant time (Edelkamp, 2014). The PDB heuristics were found to be comparable in quality to that of the FF planner, although the heuristics should be pre-calculated. Overall it seems that state-space search has remained the state of the art for autonomous planning, with recent developments coming in the form of heuristic improvements.

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