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Monitoring and control of anytime algorithms: A dynamic programming approach

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Abstract

Anytime algorithms offer a tradeoff between solution quality and computation time that has proved useful in solving time-critical problems such as planning and scheduling, belief network evaluation, and information gathering. To exploit this tradeoff, a system must be able to decide when to stop deliberation and act on the currently available solution. This paper analyzes the characteristics of existing techniques for meta-level control of anytime algorithms and develops a new framework for monitoring and control. The new framework handles effectively the uncertainty associated with the algorithm's performance profile, the uncertainty associated with the domain of operation, and the cost of monitoring progress. The result is an efficient non-myopic solution to the meta-level control problem for anytime algorithms.

Keywords: Anytime algorithms; Flexible computation; Meta-level control; Monitoring; Resource-bounded reasoning; Real-time deliberation

1. Introduction

From its early days, the field of artificial intelligence (AI) has searched for useful techniques for coping with the computational complexity of decision making. An early advocate of the view that decision makers (both human and artificial) should forgo perfect rationality in favor of limited, economical reasoning was Herbert Simon. In 1958, he claimed that "the global optimization problem is to find the least-cost or best-return decision, net of computational costs" [32]. The statistician I.J. Good advocated a similar approach to decision making that takes deliberation costs into account [9].

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By the mid 1980s, AI researchers began to formalize these ideas and produce effective models for trading off computational resources for quality of results (e.g., [19]). At the forefront of these efforts were two, essentially identical, models called "anytime algorithms" (developed by Dean and Boddy [2,4]) and "flexible computation" (developed by Horvitz [13,15,17]). We adopt the phrase "anytime algorithm" in this paper, although our work is equally influenced by both models.

The defining property of an anytime algorithm is that it can be stopped at any time to provide a solution, and the quality of the solution increases with computation time. This property allows a tradeoff between computation time and solution quality, making it possible to compute approximate solutions to complex problems under time constraints. Anytime algorithms are being used increasingly in a range of practical domains that include planning and scheduling [2,38], belief network and influence diagram evaluation [12,16, 36], database query processing [31,33], and information gathering [10]. By itself, however, an anytime algorithm does not provide a complete solution to Simon's challenge to make the best-return decision, net of computational costs. To achieve this, a meta-level control procedure in needed that determines how long to run the anytime algorithm, and when to stop and act on the currently available solution.

Horvitz developed an approach to meta-level control of computation based on the *expected value of computation* (EVC) [17]. The expected value of computation is defined as the expected improvement in decision quality that results from performing a computation, taking into account computational costs. (The concept of the expected value of computation is related to the concept of the expected value of information, although the two are not identical [22].) The meta-level control problem for anytime algorithms is the problem of determining the stopping time for an anytime algorithm that optimizes the expected value of computation.

Meta-level control of an anytime algorithm can be approached in two different ways. One approach is to allocate the algorithm's running time before it starts [2,13]. If there is little or no uncertainty about the rate of improvement of solution quality, or about how the urgency for a solution might change after the start of the algorithm, then this approach works well. Very often, however, there is uncertainty about one or both. For AI problem-solving in particular, variance in the rate at which solution quality improves is common [24]. Because the best stopping time will vary with fluctuations in the algorithm's performance (and/or the state of the environment), a second approach to meta-level control is to monitor the progress of the algorithm (and/or the state of the environment) and determine at run-time when to stop deliberation and act on the currently available solution [3,17,37].

The optimal time allocation for an anytime algorithm depends on several factors: the quality of the available solution, the prospect for further improvement in solution quality, the current time, the cost of delay in action, the current state of the environment, and the prospect for further change in the environment. In this paper, we develop a framework for run-time monitoring and control of anytime algorithms that takes into account these various factors. The solution differs from previously developed approaches to this problem that rely on a myopic estimate of the value of computation. We formalize the meta-level control problem as a sequential decision problem that can be solved by dynamic programming, in order to construct a non-myopic solution. Dynamic programming has been used