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D. S. Johnson[†]L. A. McGeoch[‡]G. Ostheimer[§]**Abstract**

The choice of data structure for tour representation plays a critical role in the efficiency of local improvement heuristics for the Traveling Salesman Problem. The tour data structure must permit queries about the relative order of cities in the current tour and must allow sections of the tour to be reversed. The traditional array-based representation of a tour permits the relative order of cities to be determined in small constant time, but requires worst-case $\Omega(N)$ time (where N is the number of cities) to implement a reversal, which renders it impractical for large instances. This paper considers alternative tour data structures, examining them from both a theoretical and experimental point of view. The first alternative we consider is a data structure based on splay trees, where all queries and updates take amortized time $O(\log N)$. We show that this is close to the best possible, because in the cell probe model of computation any data structure must take worst-case amortized time $\Omega(\log N / \log \log N)$ per operation. Empirically (for random Euclidean instances), splay trees overcome their large constant-factor overhead and catch up to arrays by $N = 10,000$, pulling ahead by a factor of 4-10 (depending on machine) when $N = 100,000$. Two alternative tree-based data structures do even better in this range, however. Although both are asymptotically inferior to the splay tree representation, the latter does not appear to pull even with them until $N = 1,000,000$.

1. Introduction

In the Traveling Salesman Problem (TSP) we are given a set of cities c_1, c_2, \dots, c_N and for each pair c_i, c_j of distinct cities a distance $d(c_i, c_j)$. Our goal is to find a permutation π of the cities that minimizes the quantity $\sum_{i=1}^{N-1} d(c_{\pi(i)}, c_{\pi(i+1)}) + d(c_{\pi(N)}, c_{\pi(1)})$. This quantity is referred to as the *tour length*, since it is the length of the tour a salesman would make in visiting the cities in the order specified by the permutation, returning at the end to the starting city. The TSP is one of the most widely known NP-hard problems. Lawler et al. [19] give an excellent introduction to the broad range of work on this problem. In this paper, we concentrate on the symmetric TSP, where $d(c_i, c_j) = d(c_j, c_i)$ for $1 \leq i, j \leq N$.

Because the TSP is NP-hard, much research has concentrated on approximation algorithms whose goal is to find near-optimal rather than optimal tours. In practice, the best such algorithms have all been based on the principle of local optimization: One obtains a starting tour using some tour-construction heuristic (such as the Greedy algorithm [9]), and then attempts to repeatedly improve it using local modifications. The most commonly used such modifications are 2- and 3-changes, as illustrated in Figures 1 and 2. By themselves, they give rise to the well-known 2-Opt and 3-Opt algorithms. In more complicated combinations, they give rise to the famous *Lin-Kernighan* algorithm [21] and provide the basic engines for most applications of simulated annealing [5,15,17], genetic algorithms [4,23,24], and tabu search [10] to the TSP.

Two of the authors of the current paper have been involved in an extended study [3,13] of the 2-Opt, 3-Opt, and Lin-Kernighan algorithms [20,21], and how they can be adapted to very large instances. (Many applications give rise to instances with between 10,000 and 100,000 cities, and VLSI applications with as many as 1.2 million cities have been cited [16].) Table 1 shows the current level of performance we have been able to obtain with these algo-

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