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Distributed Computation on Graphs: Shortest Path Algorithms

K. M. Chandy and J. Misra
University of Texas at Austin

We use the paradigm of diffusing computation, introduced by Dijkstra and Scholten, to solve a class of graph problems. We present a detailed solution to the problem of computing shortest paths from a single vertex to all other vertices, in the presence of negative cycles.

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1. Introduction

This paper presents distributed algorithms based on the work of Dijkstra and Scholten [1], for solving graph problems using networks of communicating processes. The solution to one particular graph problem, that of finding shortest paths from a single vertex to all other vertices in a weighted, directed graph, in the presence of negative cycles, is discussed in detail. We then show how this solution may be applied to other graph problems including depth-first search in an undirected graph.

Our model of computation is a network of processes in which processes communicate only by sending and receiving messages; the model is presented in detail in Sec. 2. We describe the classical shortest path problem [2] and the necessary terminology from graph theory in Sec. 3. The distributed algorithm is given in Sec. 4 and its proof in Sec. 5. Applications to other graph problems are discussed in Sec. 6.

2. Model of a Network of Communicating Processes

A process is a sequential program which can communicate with other processes by sending/receiving messages. Two processes P and Q are said to be *neighbors* if they can communicate directly with one another without having messages go through intermediate processes. We assume that communication channels are bidirectional: if P can send messages to Q then Q can send messages to P. A process knows the identities of its neighbors; otherwise it is ignorant of the identities of all other processes and of the general structure of the network.

We assume a very simple protocol for message communication; this protocol is equivalent to the one used by Dijkstra and Scholten [1]. Every process has an input buffer of *unbounded* length. If process P sends a message to a neighbor process Q, then the message gets appended at the end of the input buffer of Q after a finite, arbitrary delay. We assume that (1) messages are not lost or altered during transmission, (2) messages sent from P to Q arrive at Q's input buffer in the order sent, and (3) two messages arriving simultaneously at an input buffer are ordered arbitrarily and appended to the buffer. A process receives a message by removing one from its input buffer.

The assumption of unbounded length buffers is for ease of exposition. We show, in Sec. 6, that for our problem the input buffer length of process Q can be bounded by the number of neighbors of Q.

3. The Shortest Path Problem

$G = (V, E)$ is a directed graph in which V is the set of vertices and E is the set of edges. Edge (v_i, v_j) has an associated length w_{ij}. If edge (v_i, v_j) exists then v_j is said to be a *successor* of v_i and v_i is said to be a *predecessor* of v_j. It is required to determine lengths of the shortest paths from a special vertex v_1 in V to all other vertices in V.[1] Since some w_{ij} may be negative, a cycle of negative total length (called a *negative cycle*) may exist in the graph. If a negative cycle is reachable from v_1 then all vertices reachable from that negative cycle will have a shortest path length of $-\infty$. The *distance* of a vertex v_i is the length of the shortest path from v_1 to v_i and is denoted by L_i.

[1] We assume familiarity with graph theoretic terms such as path, shortest path, etc.

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Authors' Present Address: K. Mani Chandy and J. Misra, Computer Sciences Department, University of Texas, Austin, TX 78712.

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