

A Novel Parallel Triangle Counting Algorithm with Reduced Communication

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Abstract—Counting and finding triangles in graphs is often used in real-world analytics for characterizing the cohesiveness and identifying communities in graphs. In this paper, we present novel sequential and parallel triangle counting algorithms based on identifying horizontal-edges in a breadth-first search (BFS) traversal of the graph. The BFS allows our algorithm to drastically reduce the number of edges examined for set intersections. Our new approach is the first communication-optimal parallel algorithm that asymptotically reduces the communication on massive graphs such as from real social networks and synthetic graphs from the Graph500 Benchmark. In our estimate from massive-scale Graph500 graphs, our new algorithm reduces the communication by 21.8x on a scale 36 and by 189x on a scale 42. Because communication is known to be the dominant cost of parallel triangle counting, our new parallel algorithm, to our knowledge, is now the fastest method for counting triangles in large graphs.

Index Terms—Graph Algorithms, Parallel Algorithms, High Performance Data Analytics

I. INTRODUCTION

Let $G = (V, E)$ be an undirected graph with $n = |V|$ vertices and $m = |E|$ edges. A *triangle* in the graph is a set of three vertices $\{v_a, v_b, v_c\} \in V$ such that $\{(v_a, v_b), (v_a, v_c), (v_b, v_c)\} \in E$. *Triangle counting* is defined as finding the number of unique triangles in G and is one of the fundamental problems in graph analytics. In this paper we consider the problem of both counting and finding triangles in G . Triangle counting is used in graph analytics such as clustering coefficients [1], k-truss [2], and triangle centrality [3], and its importance is recognized by its use in high performance computing benchmarks such as Graph500 [4] as well as in future architecture systems design (e.g. IARPA AGILE [5]).

Triangle counting has been studied extensively in the literature for both sequential and parallel algorithms. Latapy [6] provides an extensive literature of sequential triangle counting and finding algorithms. The fastest sequential triangle counting algorithm for sparse graphs due to Itai and Rodeh [7] runs in

$\Theta(m^{\frac{2}{3}})$ time and $\Theta(n^2)$ space, which is cost-prohibitive for practical use on large graphs.

Triangle counting algorithms are often based on techniques such as list intersection, matrix multiplication and subgraph matching [8]. The three main list intersection based triangle counting algorithms are summarized as: the node iterator, the edge iterator and the forward algorithm (detailed in Section III).

Cohen [9] designed a novel map-reduce parallelization of triangle counting that generates open wedges between triples of vertices in the graph, and determines if a closing edge exists that completes a triangle. Most parallel approaches for triangle counting [10], [11] partition the sparse graph data structure across the compute nodes, and follow this strategy of generating open wedges that are sent to other compute nodes to find whether or not a closing edge exists. As such, the running time of parallel triangle counting is often dominated by the communication time for these open wedges.

In fact, most parallel triangle counting algorithms are based on generating open wedges (also known as 2-paths) and checking whether or not a closing edge exists. This approach results in an overabundance of communication because each graph edge is sent repeatedly, the repetition factor being the degree of one of its endpoints. One way to view our new approach is that rather than send all open wedges in the graph, we reverse this and send potential closing edges once, resulting in asymptotically less communication. In this paper, we present novel sequential and parallel triangle counting algorithms. Our contributions include:

- A new sequential triangle counting and finding algorithm that runs in $O(m \cdot d_{\max})$ time and $O(n + m)$ space, where $d_{\max}$ is the maximal degree of a vertex $v \in V$. The algorithm uses breadth-first search to identify horizontal-edges, and uses the intersection of the endpoints of each horizontal-edge to determine triangles.
- A novel communication-optimal parallel algorithm for triangle counting and finding that asymptotically reduces the communication from all prior parallel approaches. The new approach has a total communication volume of $O(m)$ and is the first parallel algorithm to achieve this.

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