

SOMETHING WITH CONNECTED COMPONENTS

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ABSTRACT

We present an improved parallel implementation of a tree based connected components algorithm originally introduced in 1984 by U. Vishkin. To improve the algorithm's performance the graph's edges are distributed across multiple cores. Each process computes in a lock-free manner a local forest representing the different connected components. The resulting forests are then combined using a reduction. A comparison of our algorithm against a communication avoiding algorithm developed at ETH, on a set of large graphs (5×10^8 Edges with up to 2×10^7 Vertices), is presented. Results where our algorithm uses a mixture of both MPI and OMP are also shown.

1. INTRODUCTION

Motivation. Problems in computer science are often modeled as graphs. Therefore, graph algorithms are ubiquitous. One of these graph problems is finding connected components. It is a well understood problem in graph theory with a variety of applicable domains. Computer vision tasks, such as pattern recognition and image segmentation [1] can make use of connected components [2]. Other fields are medical imaging [3] and image processing [4]. The related problem of strongly connected components will not be discussed in this paper.

Related Work. The first sequential algorithm to solve the connected components problem goes back to [5]. Parallel approaches were presented in [6] and [7]. Recently a communication-avoiding algorithm was published [8]. This algorithm uses asymptotically less communication, but sacrifices some computational efficiency as the root node does most of the work. In this paper we present an algorithm which distributes the work while still avoiding as much communication as possible. This is achieved by distributing the list of edges evenly among different MPI ranks. These then locally compute their corresponding connected components which are represented as a forest. In a next step the algorithm reduces these forests in a binary manner. Two MPI ranks compare and merge their results and then compress

them. This step is repeated until the final result is propagated to the root process.

Connected components.

For an undirected graph $G = (V, E)$, the connected components are the ensemble of connected subgraphs, where connected means that for any two vertices there exists a path along the edges connecting them. A straightforward algorithm to find the connected components is to perform either a breath or depth first search starting from a random vertex in V , and give the same label to all vertices reached. The search is then repeated, starting from an unlabeled vertex. This has a cost in terms of memory accesses of $\Theta(|E| + |V|)$, which turns out to be optimal [5].

2. PROPOSED ALGORITHM

Unfortunately this algorithm does not parallelize in a straightforward way. Instead we first implemented an algorithm proposed by Uzi Vishkin [9] and later described in a class by Pavel Tvrđik [10]. This algorithm casts the problem in terms of the generation of a forest, where the vertices of the same connected component belong to the same tree, and its root can be used as the representative.

We define a star as a tree of height one, a singleton as a tree with a single element, and use the variables $n = |V|$ and $m = |E|$. The algorithm can be summarized as:

Algorithm 1 Pavel Tvrđik's Connected components

```
1: procedure HOOK( $i, j$ )
2:    $p[p[i]] = p[j]$ 
3: end procedure
4: procedure CONNECTEDCOMPONENTS( $n$ , edges)
5:    $p[i] = i \quad \forall i \in \{1, \dots, n\}$ .  $\triangleright$  Initialize a list of
     parents.
6:   while Elements of  $p$  are changed. do
7:     for  $\langle i, j \rangle \in \text{edges}$  do  $\triangleright$  Execute in parallel.
8:       if  $i \geq j$  then HOOK( $i, j$ )
9:       if isSingleton( $i$ ) then HOOK( $i, j$ )
10:    end for
11:    for  $\langle i, j \rangle \in \text{edges}$  do  $\triangleright$  Execute in parallel.
12:      if isStar( $i$ ) and  $i \neq j$  then HOOK( $i, j$ )
13:    end for
14:     $p[i] = \text{root}(i) \quad \forall i \in \{1, \dots, n\}$   $\triangleright$  Compress the
     forest in parallel.
15:   end while
16: end procedure
```

We defer to [10] for a proof of correctness.

After implementing this algorithm we found advantageous to remove the constraint that only singletons and stars can be hooked to another vertex. This allows the algorithm to terminate after a single pass through the edge list. Extra care is then required during parallel execution: as each vertex only has one outgoing connection, we need to avoid the scenario where a thread overwrites a connection that has been formed by another one. Therefore whenever we need to generate a hook from $v1$ to $v2$ we choose the following rules:

1. $\text{index}(v1) > \text{index}(v2)$.
2. $v1$ must be a root.

An intuitive proof of correctness follows: rule 1 means that the graph generated by the hooks is a directed graph without cycles and each vertex has at most one outgoing connection. Therefore, it must be a forest. Rule 2 guarantees that a connection cannot be broken by a different edge. After the algorithm terminates all vertices in a tree belong to the same connected component. The connected component can be canonically represented by the tree's root.

To implement rule 2 in a multi-threaded environment we use an atomic compare and swap. We compare the parent of the hook's origin with its id. If they match it means the vertex is a root, and this status was not modified by another thread. For correctness it does not matter if the destination is a root, but doing so minimizes the tree height. Empirically we found that, using the standard library, weak atomics offer better performance compared to strong atomics.

In pseudocode our algorithm is:

Algorithm 2 Single pass connected component.

```
1: procedure CONNECTEDCOMPONENTS( $n$ , edges)
2:    $p[i] = i \quad \forall i \in \{1, \dots, n\}$ .
3:   for  $\langle i, j \rangle \in \text{edges}$  do  $\triangleright$  Execute in parallel.
4:     while hook is not successful. do
5:       from = max(root( $i$ ), root( $j$ ))
6:       to = mint(root( $i$ ), root( $j$ ))
7:       atomicHook(from, to)
8:     end while
9:     if !isRoot( $i$ ) then  $p[i] = \text{root}(i)$ 
10:    if !isRoot( $j$ ) then  $p[j] = \text{root}(j)$ 
11:  end for
12:   $p[i] = \text{root}(i) \quad \forall i \in \{1, \dots, n\}$   $\triangleright$  Compress the
    forest in parallel.
13: end procedure
```

While step 9 is not necessary for correctness, we found that reusing the already computed vertex's representative leads to a smaller tree height. We avoided using atomic directives for this step and the parallel compression 12 therefore our implementations works only on architectures such as x86, where writes to 32 or 64-bits variables, used to store a vertex's id, are atomic.

We tried implementing the parallel execution of loop 3 with Boost fibers [11] whose execution is scheduled with a work stealing algorithm, and OpenMP with a dynamic scheduler. OpenMP performed better by a large margin and thus was used to acquire the data presented in Section 3.

The overall cost of the algorithm is $\Theta((n + m)\langle H \rangle)$, where $\langle H \rangle$ is the average tree height. Therefore $\langle H \rangle = \Theta(1)$ for a sub-critical random graph, and on average (over the execution order of the loop) $\langle H \rangle = \Theta(\log(n))$ for a supercritical random graph [12].

Multiple compute nodes. Algorithm works only on a single compute node with a shared memory model. Moreover, it is efficient only when the graph is sparse enough that the probability of a collision between two processors trying to update the same parent is low.

We propose to extend our algorithm by distributing the list of edges evenly among each MPI process. Then each one of them computes a forest using only the subset of edges it received. This local computation is followed by a reduction step, where pairs of MPI ranks combine their respective forests. The resulting forest is then compressed before the following reduction step.

Using p processes, the total execution time of this extension scales as $\Theta(\frac{(m+n)}{p} \langle H \rangle + n \log p)$.

On top of allowing to scale past a single compute node, this approach offers better results on dense graphs, where the relative cost of the reduction is small, and multiple threads would have a high probability of collision during the atomic update. Therefore a different mixture of MPI ranks and

OpenMP threads per rank is advised depending on the density of the graph.

Distributed vertices. While the described approach works on generic graphs, it performs poorly on very sparse graphs using a large number of compute nodes. Moreover, the full set of vertex id's must fit in memory, limiting the graph size to 8 billion vertices. If the connectivity of a graph the size of a human brain needs to be studied, we propose to distribute the representation of the vertices as well.

Often, real world graphs are embedded on a space with some metric, and connections occur much more frequently between vertices that are close together. For example the pixel representing features of an image, or the roads connecting cities with a known geographical position.

We represent this type of graph with a very simple model: a two dimensional lattice with random connections between nearest neighbors only. We split the lattice in as many square tiles as there are processes. Then each process applies algorithm 2 to the subset of edges connecting two vertices in its tile. Finally we process edges crossing the boundary between different tiles using MPI one sided communication. The list of the local vertices' parents is stored in an MPI window, so that the representative of a remote vertex can be obtained with `MPI_Get`, while a hook can be created with `MPI_Compare_and_swap`. Therefore only two global synchronization points are necessary: after all edges have been processed, and after the final compression of the forest.

Unfortunately, due to development time constraints each MPI operation is synchronized locally. This leads to good scaling results only on extremely sparse graphs with small connected components.

3. EXPERIMENTAL RESULTS

To evaluate our algorithm's performance a number of experiments were run on both the Euler and the Piz Daint cluster. In the following paragraphs we will first describe both the Euler and the Piz Daint setups. We will then go on to discussing each experiment.

Euler setup. Each node in the Euler V cluster contains two 12-core Intel Xeon Gold 5118 processors and 96 GB of DDR4 memory clocked at 2400 MHz [13]. We were allowed to use up to two nodes, giving us a maximum of 48 cores. The algorithm was compiled and run using gcc 6.2.3 and Open MPI 3.0.0.

Piz Daint setup. Each of the utilized XC40 nodes on Piz Daint contains two Intel Xeon E5-2695, each with 18 hardware threads, and 32 GB of DDR4 memory. We used both gcc and the Cray compiler, and observed marginally faster run times with the latter.

Graph Generation. Our algorithm was evaluated on undirected, unweighted graphs. Multiple edges connecting

the same two vertices and self loops were not allowed. All graphs were generated using [14].

MPI vs OMP vs Communication Avoiding.

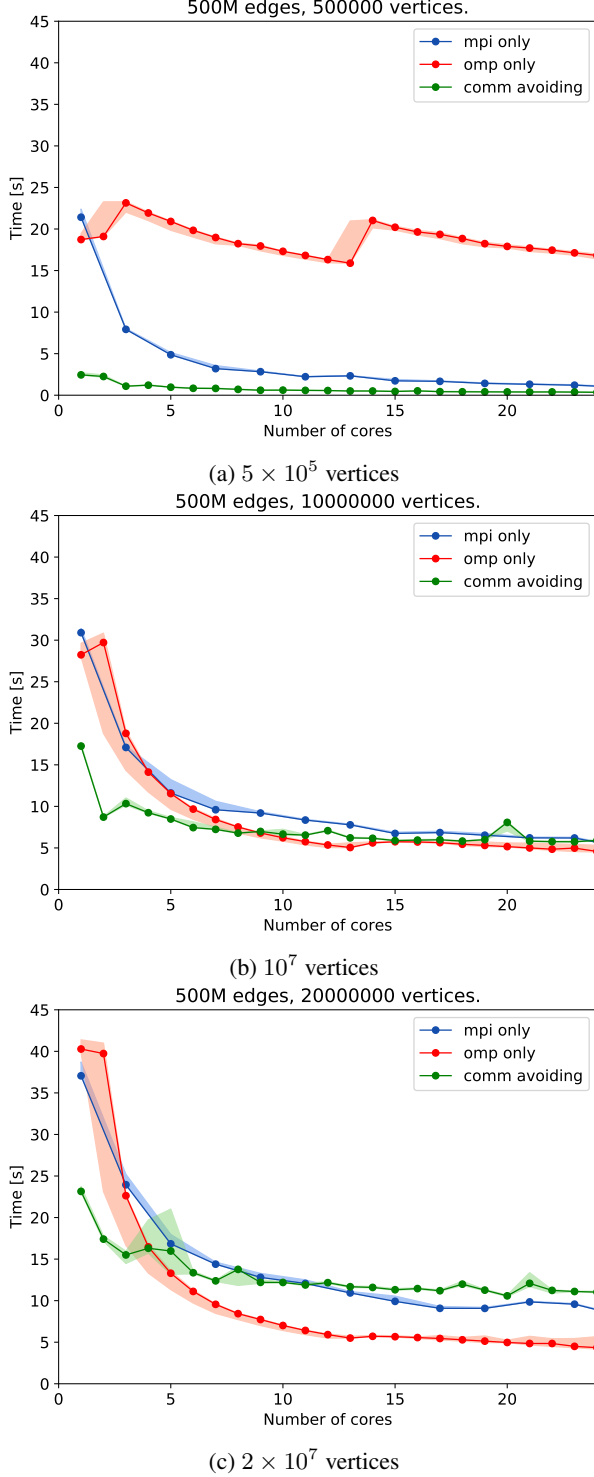


Fig. 1: Comparison of the total runtime of our algorithm with the communication avoiding algorithm [8] over three different graphs each with 5×10^8 edges and 5×10^5 , 1×10^7 , 2×10^7 vertices. The experiment was run on the Euler cluster.

The results in Figure 1 show our algorithm compared with the communication avoiding algorithm [8] on three different graphs with the same number of edges but different densities. Our algorithm was run in MPI and OMP only mode.

Figure 1a shows the MPI only version outperforming the OMP version on the densest graph. This can be explained by the combination of two effects: the first being that a dense graph results in more contention between the OMP threads during the edge contractions, and the second being that the reduction after the contractions scales linearly with the number of vertices. Since the number of vertices is comparatively low in a dense graph the reduction is fast. For the OMP only version we further observe a significant increase in total compute time from one to two cores and from 12 to 13 cores. The first jump can be explained by the initial overhead of doing the computation in parallel. Since a single CPU on Euler has 12 cores the second jump is a result of the cache coherency protocol being slow across multiple CPUs.

The results in Figure 1b and Figure 1c were obtained using sparser graphs compared to Figure 1a. Here, for a large number of cores, the OMP only version is clearly faster than the MPI only version. Figure 1 shows a trend of the OMP only version speeding up as the graph becomes sparser, while the MPI only version slows down. The OMP only version's speed up can be explained by the reduced contention between the OMP threads due to the sparser graph. The MPI only version's slow down is a result of the increased reduction time due to the increasing number of vertices.

The results in Figure 1 show the communication avoiding algorithm scaling badly with the number of cores. This is expected since the edge contractions are computed on a single node in this algorithm. Since our algorithm does to scale with the number of cores up to some point we manage to outperform the communication avoiding algorithm on each graph.

Results on Piz Daint.

In addition to testing our algorithm on the Euler cluster it was also tested on the Piz Daint cluster. The graphs used were the same as in the experiments run on Euler. We will now discuss interesting differences in the results.

Figure 2 shows the results for the densest graph on Piz Daint. The OMP only version behaves differently compared to Euler. We still observe a decrease in performance when going from one to two cores. The decrease is not as severe as on Euler. The performance decrease as we go from one to multiple CPUs is no longer present. This can be explained by Daint's cache coherency protocol being more efficient, especially across multiple CPUs. Figure 3 shows the Piz Daint results for different mixtures of MPI and OMP on the sparsest graph. As on Euler, we do see the OMP only version performing best for a large number of cores. For all ver-

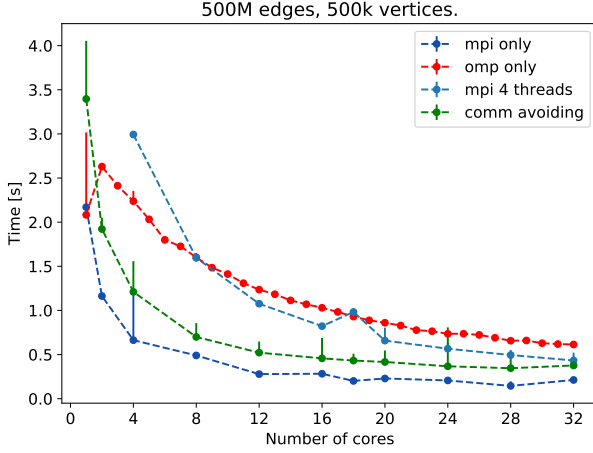


Fig. 2: Piz Daint results on graph with 5×10^8 edges and 5×10^5 vertices.

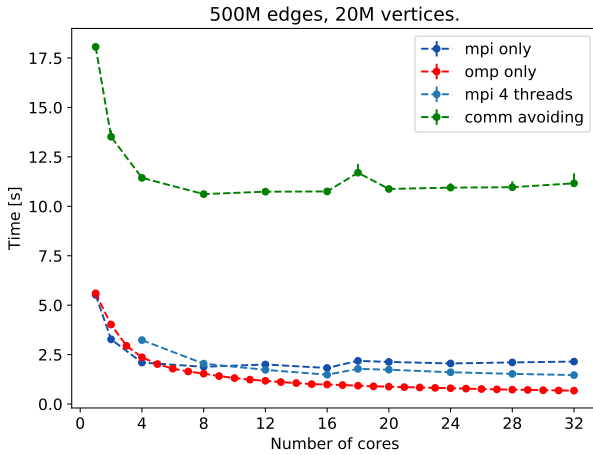
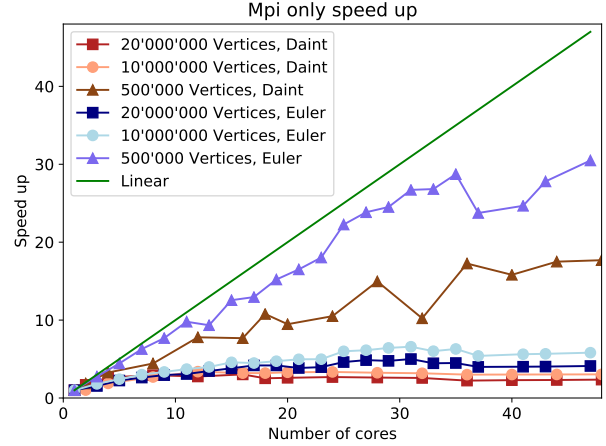


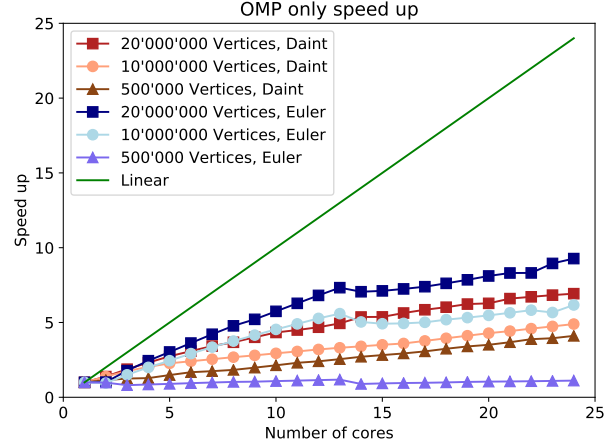
Fig. 3: Piz Daint results on graph with 5×10^8 edges and 2×10^7 vertices.

sions, except the OMP only version, we can clearly see the effect the number of reduction steps has on the runtime. It is most noticeable as we go from 16 to 18 cores. Here each version has to perform an additional reduction step which results in the increased runtime.

Speedups.



(a) MPI only



(b) OMP only

Fig. 4: Speedup of MPI only and OMP only version on three different graphs each with 5×10^8 edges.

Figure 4 shows the measured speed up of the MPI only and OMP only version. As one would expect from the results discussed previously the MPI only version achieves better scaling on dense graphs while the OMP only version scales better on sparse graphs.

We can also see that our algorithm achieves better scaling on Euler for the MPI only version. The reason our algorithm scales better on Euler is that the single core performance is lower on Euler compared to Daint. This means that the edge contractions dominate the runtime for longer before the reduction step starts to be an issue.

For the OMP only version the differences in speed ups can

be explained by the differences in the shared memory architecture.

4. CONCLUSIONS

The proposed algorithm manages to take advantage of the parallelism available within shared memory units while avoiding excessive communication between them. By choosing the right number of OMP threads per MPI rank the algorithm achieves good scaling across a variety of graphs. While on dense graphs the Communication Avoiding algorithm [8] yields better results, it is outperformed by our algorithm on sparser graphs.

5. FUTURE WORK

The main drawback of our algorithm is the reduction step's runtime of $O(n \cdot \log(p))$, where p is the number of MPI ranks and n is the number of vertices. For a large number of MPI ranks the $\log(p)$ factor becomes an issue.

Limiting the reduction "height" addresses this problem. In our algorithm this is done by using a mixture of OMP and MPI which reduces the number of MPI ranks.

~~Since OMP does not scale well once the number of OMP threads exceeds the number of cores per CPU this approach is only viable up to a limited number of cores.~~

~~Another approach would be reducing the work n done in each reduction step. Due to time constraints we were unable to investigate this approach. One could imagine a more efficient hook tree representation solving this problem.~~

Another drawback of our algorithm is that in order to achieve satisfying performance one needs to find the right mixture of MPI and OMP. While we analysed the behaviour of different mixtures on graphs with varying density we did not come up with an a priori scheme to determine the right mixture. A good heuristic or even a scheme to find the optimal mixture would be worth exploring.

Finally we expect that large improvements can be made in the distributed vertices algorithm described in section 2 by batching several MPI one sided reads before synchronization. Further data should be gathered to validate the algorithm with different components sizes, while comparing different MPI implementation such as foMPI [15].

6. REFERENCES

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