

Minimum Spanning Tree

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DPHPC

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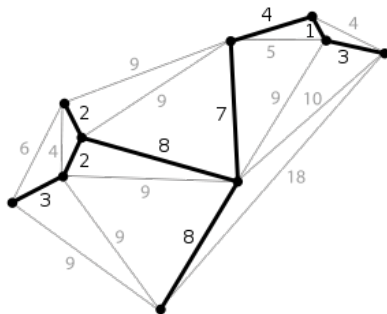


Problem definition - reminder



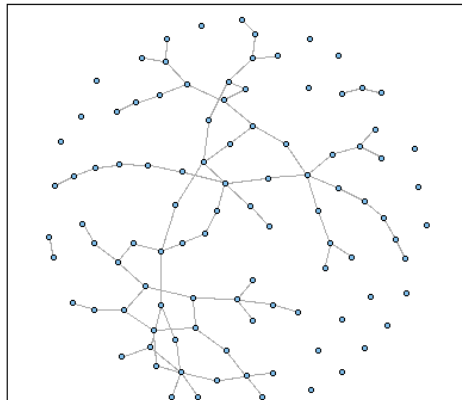
The MST problem

A minimum spanning tree (MST) or minimum weight spanning tree is a subset of the edges of a connected, edge-weighted (un)directed graph that connects all the vertices together, without any cycles and with the minimum possible total edge weight.



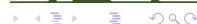
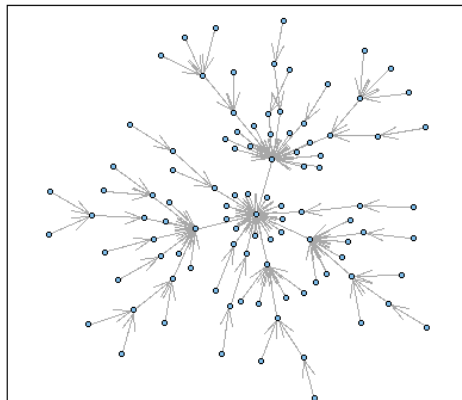
Input sets: $G(n, p)$

$G(100, 0.02)$



Input sets: $PA(n, m)$

$PA(100, 1)$



Input sets: 9th DIMACS challenge dataset

USA Roads

Name	Description	# nodes	# arcs
USA	Full USA	23,947,347	58,333,344
CTR	Central USA	14,081,816	34,292,496
W	Western USA	6,262,104	15,248,146
E	Eastern USA	3,598,623	8,778,114
LKS	Great Lakes	2,758,119	6,885,658
CAL	California and Nevada	1,890,815	4,657,742
NE	Northeast USA	1,524,453	3,897,636
NW	Northwest USA	1,207,945	2,840,208
FLA	Florida	1,070,376	2,712,798
COL	Colorado	435,666	1,057,066
BAY	San Francisco Bay Area	321,270	800,172
NY	New York City	264,346	733,846



Experimental setup



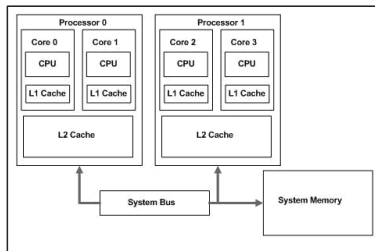
Software

- OMP
- Intel Threading Building Blocks (TBB)
- Intel Parallel Standard Template Library (PSTL)



EULER

- 1 node limitation (OMP)
- 2 sockets filled with 18 cores - up to 3.7Ghz
- Inter-sockets bus speed: 10.4 GT/s



Algorithms and parallel implementations



Baselines

- Boost Kruskal
- Boost Prim



Sollin

- 1 For each connected component, find adjacent edge with minimum weight
- 2 Add edge to mst (each edge add at most twice)
- 3 Merge connected components



Kruskal

```
1:  $A = \emptyset$ 
2: for all  $v \in G.V$  do
3:   MAKE-SET( $v$ )
4: end for
5: Sort (asc.)  $(weight(u, v))_{(u,v) \in G.E}$ 
6: for all  $(u, v)$  in  $G.E$  ordered by weight do
7:   if FIND-SET( $u$ )  $\neq$  FIND-SET( $v$ ) then
8:      $A = A \cup (u, v)$ 
9:     UNION( $u, v$ )
10:  end if
11: end for
12: return  $A$ 
```



Parallel sorting on Kruskal

m is the number of edges, p is the number of cores, $T(m)$ is the runtime with m edges.

- Sequential: $O(m \ln(m) + m)$
- Parallel sort (**Intel TBB**): $O\left(\frac{m \ln(m)}{p} + m\right)$



Filter Kruskal

E : set of edges, $m = |E|$, p is the number of cores, $T(m)$ is the runtime with m edges.

- 1 If $m \leq \text{threshold}$ then solve with Kruskal
- 2 Find pivot for edges (weight)
- 3 Partition E into $E_{\leq}, E_{>}$
- 4 $A_{\leq} = \text{filterKruskal}(E_{\leq})$
- 5 $E_{>} = \text{filter}(E_{>})$
- 6 $A_{>} = \text{filterKruskal}(E_{>})$
- 7 Return $\text{merge}(A_{\leq}, A_{>})$



Filter Kruskal

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- ① If $m \leq \text{threshold}$ then solve with Kruskal
- ② Find pivot for edges (weight): $O(1)$
 - Concurrently sample 256 elements from the list (**OpenMP**)
 - Sort the list and return the median (**TBB**)
- ③ Partition E into $E_{\leq}, E_{>}$
- ④ $A_{\leq} = \text{filterKruskal}(E_{\leq})$
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- ❷ Find pivot for edges (weight): $O(1)$
- ❸ Partition E into $E_{\leq}, E_{>}$: $O\left(\frac{m}{p}\right)$
 - Partition function (**Intel Parallel STL**)
- ❹ $A_{\leq} = \text{filterKruskal}(E_{\leq})$
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- ⑤ $E_{>} = \text{filter}(E_{>})$: $O\left(\frac{m}{p}\right)$
- ⑥ $A_{>} = \text{filterKruskal}(E_{>})$: $O\left(T\left(\frac{m}{2}\right)\right)$
 - In practice way less than $\frac{m}{2}$
- ⑦ Return $\text{merge}(A_{\leq}, A_{>})$



Filter Kruskal

E : set of edges, $m = |E|$, p is the number of cores, $T(m)$ is the runtime with m edges.

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- 3 Partition E into $E_{\leq}, E_{>}$: $O\left(\frac{m}{p}\right)$
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Filter Kruskal: Complexity analysis

- Worst case: $T(m) \leq O\left(\frac{m}{p}\right) + 2T\left(\frac{m}{2}\right)$
- Best case: $T(m) \leq O\left(\frac{m}{p}\right) + T\left(\frac{m}{2}\right)$



Filter Kruskal: Complexity analysis

- Worst case: $T(m) \leq O\left(\frac{m}{p}\right) + 2T\left(\frac{m}{2}\right)$
$$T(m) = O\left(\frac{m \ln(m)}{p} + m\right)$$
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$$T(m) = O\left(\frac{m}{p} + m\right) = O(m)$$



Filter Kruskal: Complexity analysis

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- Best case: $T(m) \leq O\left(\frac{m}{p}\right) + T\left(\frac{m}{2}\right)$
$$T(m) = O\left(\frac{m}{p} + m\right) = O(m)$$
- $O(m) \leq T(m) \leq O\left(\frac{m \ln(m)}{p} + m\right)$



Kruskal vs Sollin

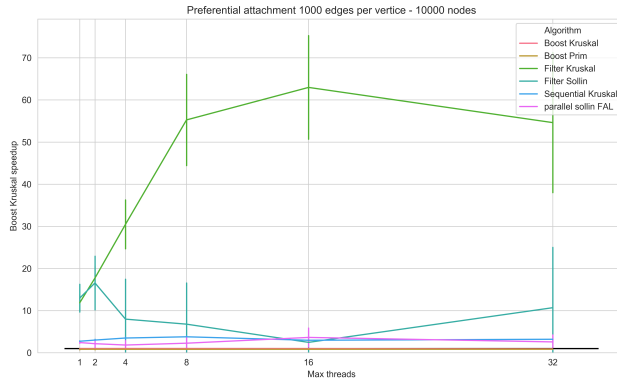
- Same complexity, but Sollin computing steps are more fine-grained
- Sollin is entirely paralelizable
- Filter Kruskal can be adapted to Filter Sollin



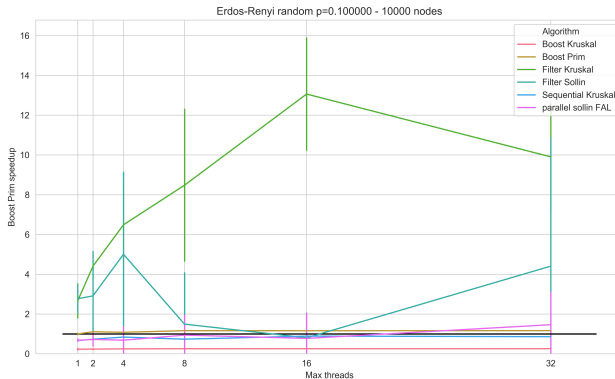
Results overview



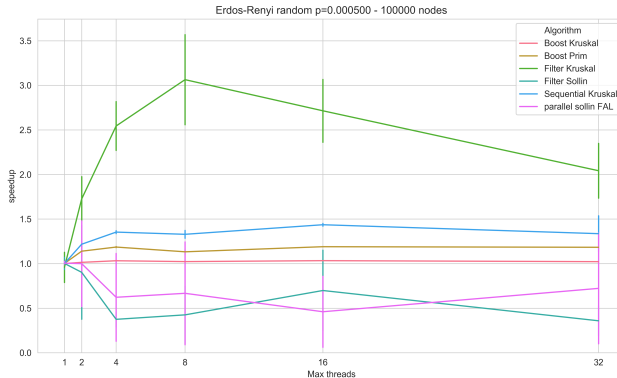
Speedup compared to Boost Kruskal



Speedup compared to Boost Prim



Speedups



Amdahl's law

S_p is the speedup with p cores, f is the part of the program that is sequential.

$$S_p = \frac{1}{\frac{1-f}{p} + f}$$

$$f = \frac{\frac{p}{S_p} - 1}{p - 1}$$



Amdahl's law: Kruskal

Graph: Erdos-Renyi (100,000 nodes, $p = 0.0005$)

Cores	Median speed-up	Standard deviation	f
1	1	0.0129805395	-
2	1.1881513396	0.0400305172	0.6832872491
4	1.3340592415	0.0130798641	0.6661225318
8	1.3134515984	0.01048841	0.7272602975
16	1.4399618642	0.0088220116	0.6740936918
32	1.3877640643	0.0442081933	0.7115701488






Amdahl's law: Filter Kruskal

Graph: Preferential attachment (10,000 nodes, 1,000 edges per vertex)

Cores	Median speed-up	Standard deviation	f
1	1	0.174182691	-
2	1.6268639022	0.2472258016	0.2293591353
4	2.669168898	0.5213238241	0.1661979381
8	5.3584384444	0.9757941767	0.0704246098
16	5.7447285937	1.108109986	0.1190108026
32	5.6322979489	1.497976882	0.1510166972



References

-  Bader, D. A. and G. Cong (2006). “Fast shared-memory algorithms for computing the minimum spanning forest of sparse graphs”. In: *Journal of Parallel and Distributed Computing* 66.11, pp. 1366–1378.
-  Chung, S. and A. Condon (1996). “Parallel Implementation of Boruvka”. In: *ipps*. IEEE, p. 302.
-  Osipov, V., P. Sanders, and J. Singler (2009). “The Filter-Kruskal Minimum Spanning Tree Algorithm”. In: *Proceedings of the Meeting on Algorithm Engineering & Experiments*. New York, New York: Society for Industrial and Applied Mathematics, pp. 52–61.

