

# Minimum Spanning Tree

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## *DPHPC*

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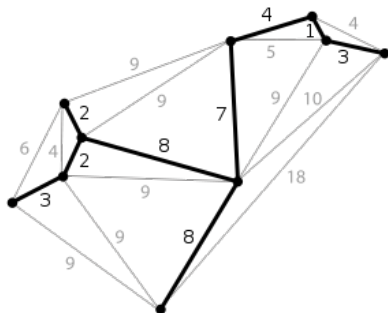


# Problem definition - reminder



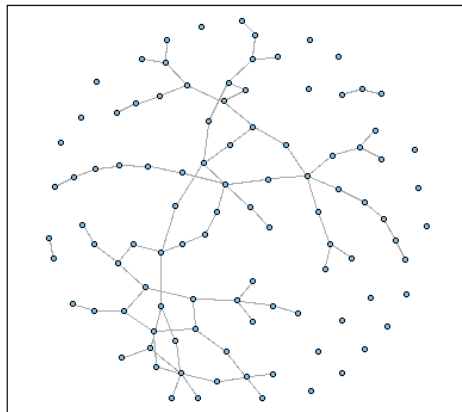
# The MST problem

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.



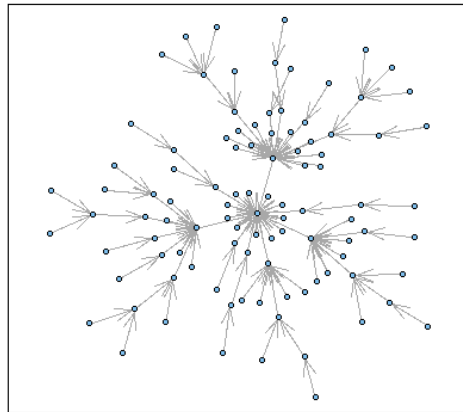
Input sets:  $G(n, p)$

$G(100, 0.02)$



Input sets:  $PA(n, m)$

$PA(100, 1)$



# Input sets: 9<sup>th</sup> DIMACS challenge dataset

## USA Roads

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



# Setup





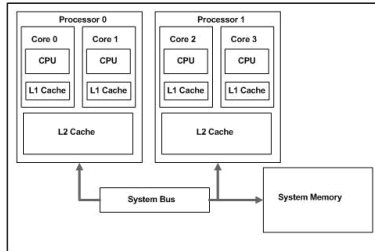
# Software

- OMP
- Intel Threading Building Blocks (TBB)
- Parallel Streaming Transformation Loader Service (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



# 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

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```
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  $A$ 
```

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# Boost implementations

- Boost-Kruskal used as a reference



# Parallel sorting on Kruskal



# 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  $\text{merge}(A_{\leq}, A_{>})$





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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  $E_{\leq}, E_{>}$
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  - Partition function (**Intel Parallel STL**)
- ④  $A_{\leq} = \text{filterKruskal}(E_{\leq})$
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- ⑥  $A_{>} = \text{filterKruskal}(E_{>})$ :  $O\left(T\left(\frac{m}{2}\right)\right)$ 
  - In practice way less than  $\frac{m}{2}$
- ⑦ Return  $\text{merge}(A_{\leq}, A_{>})$



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- 6  $A_{>} = \text{filterKruskal}(E_{>})$ :  $O\left(T\left(\frac{m}{2}\right)\right)$
- 7 Return  $\text{merge}(A_{\leq}, A_{>})$ :  $O(1)$



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



# 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



# 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

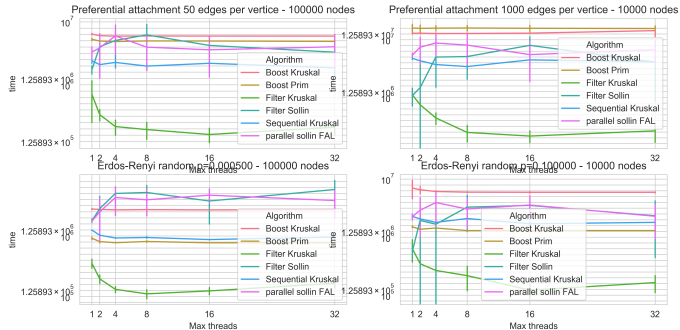


## Results overview



# Runtimes

Runtime per graph





# Speedups

Speedup per graph compared to serial implementation

