Optimizing Breadth-First Search on Modern Multicore CPUs

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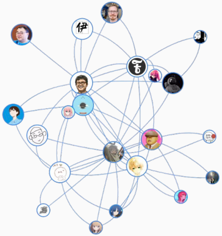
Breadth-First Search

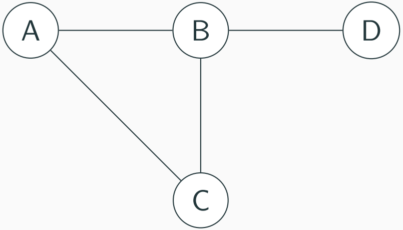
- Breadth-First Search is a fundamental algorithm in graph analysis
- Used in many algorithms: Dijkstra, Maximum Flow, MSP...
- Vertices are labeled based on the distance from a given *source* vertex



Social network

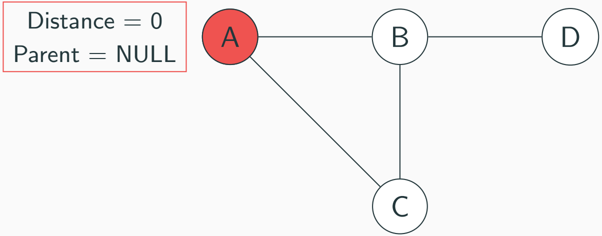
Road network

Breadth-First Search Example



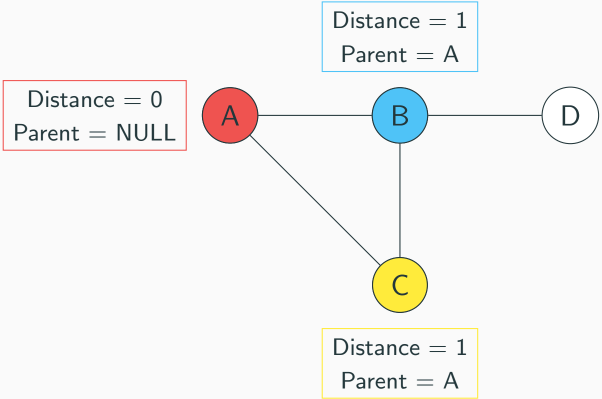
Source vertex: A

Breadth-First Search Example



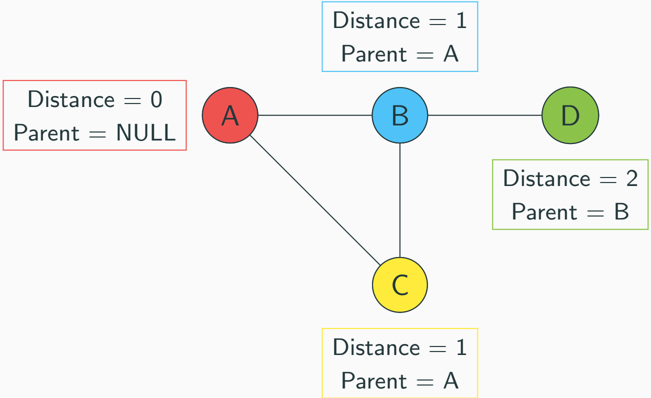
Frontier: A

Breadth-First Search Example



Frontier: B, C

Breadth-First Search Example



Distance = 0
Parent = NULL

Distance = 1
Parent = A

Distance = 2
Parent = B

Distance = 1
Parent = A

Frontier: D

Modern Computer Architectures

- BFS has $\mathcal{O}(V + E)$ time and space complexity (under RAM model)

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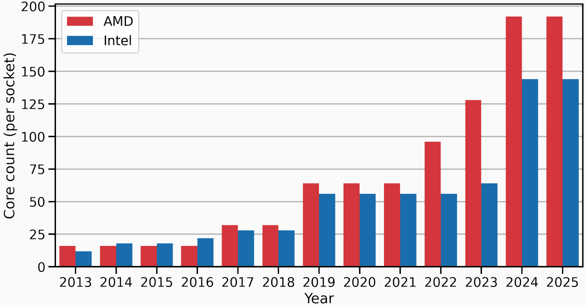
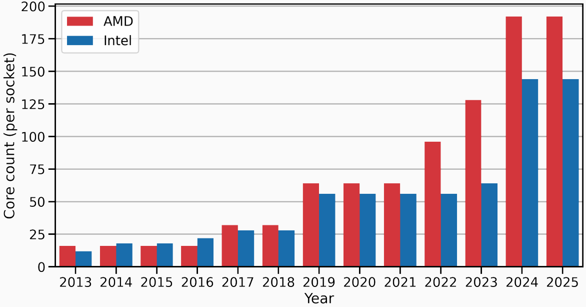


Evolution of core counts per socket for AMD and Intel processors

Modern Computer Architectures

- BFS has $\mathcal{O}(V + E)$ time and space complexity (under RAM model)
- In practice, it is a **memory-bound algorithm**
    - Algorithm exhibits poor cache locality
- CPUs exhibit growing amount of **parallelism**...
- ...and new architectures are coming to the market (ARM, RISC-V)



Evolution of core counts per socket for AMD and Intel processors

Contents

- New *MergedCSR* data structure
- Two optimized parallel implementations (OpenMP and pthreads)

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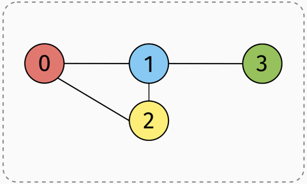
- Two optimized parallel implementations (OpenMP and pthreads)
- Evaluated against GAP Benchmark suite
- Speedups compared on three different architectures (AMD x86, RISC-V, ARM)

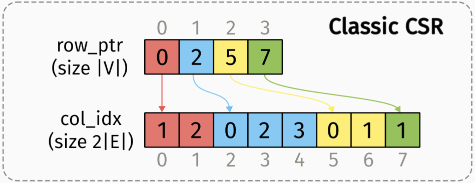
GAP suite logo

Compared architectures

From CSR to MergedCSR

- Graphs are usually stored in the Compressed Sparse Row format (CSR)





	0	1	2	3				
row_ptr (size |V|)	0	2	5	7				
col_idx (size 2|E|)	1	2	0	2	3	0	1	1
	0	1	2	3	4	5	6	7

From CSR to MergedCSR

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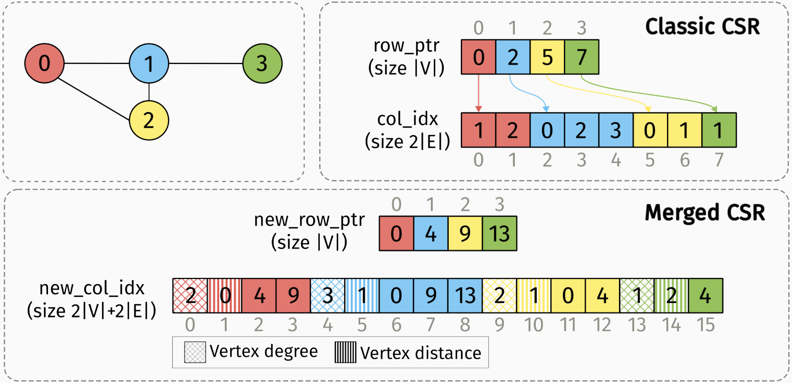
- MergedCSR core idea: access only `row_ptr` array during BFS traversal
  - `row_ptr` array contains also algorithm-specific metadata (ex. distance)



Classic CSR

row_ptr (size |V|)
0 1 2 3
0 2 5 7

col_idx (size 2|E|)
1 2 0 2 3 0 1 1
0 1 2 3 4 5 6 7

Merged CSR

new_row_ptr (size |V|)
0 1 2 3
0 4 9 13

new_col_idx (size 2|V|+2|E|)
2 0 4 9 3 1 0 9 13 2 1 0 4 1 2 4
0 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15

▨ Vertex degree ▥ Vertex distance

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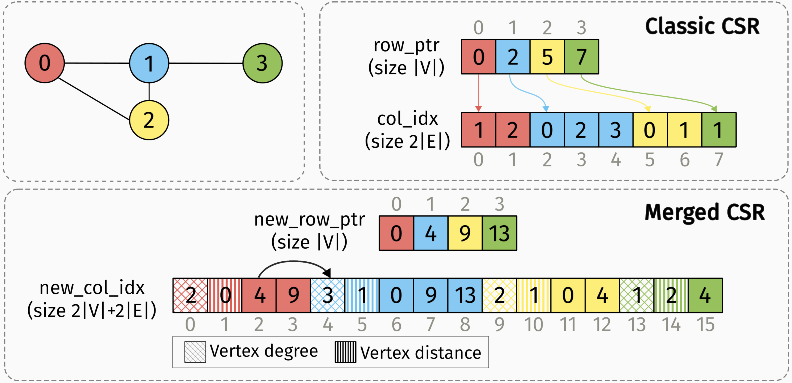

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new_col_idx (size 2|V|+2|E|)	2	0	4	9	3	1	0	9	13	2	1	0	4	1	2	4

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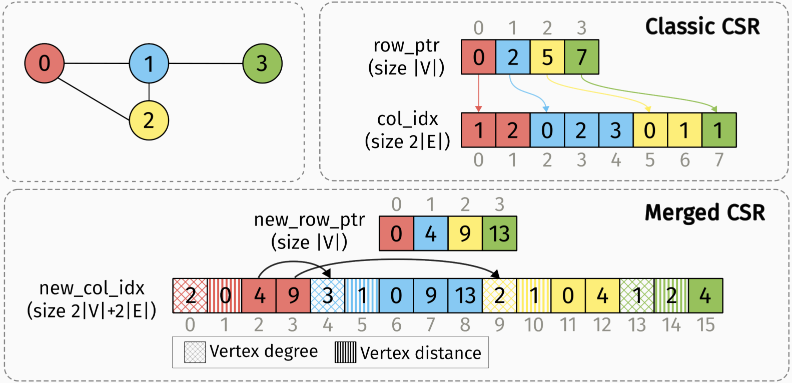

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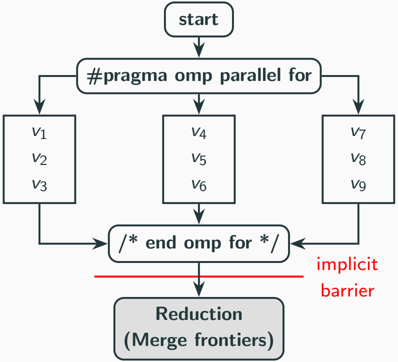
OpenMP implementation

- **OpenMP** is a widely used framework for **parallel programming** in C and C++
- Uses simple compiler directives called pragmas

```
#pragma omp parallel for
↪  reduction(vec_add : next_frontier)
for (const auto &v : this_frontier) {
  // Process vertex v
}
```



Inefficiencies of the OpenMP implementation

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- In graphs with large diameter, OpenMP enters the `parallel for` region more than 10k times for a single BFS runs

Pthreads implementation summary

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Pthreads (unofficial) logo

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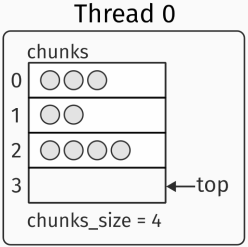
  4. Custom barrier for thread synchronization

Pthreads (unofficial) logo

Frontier implementation



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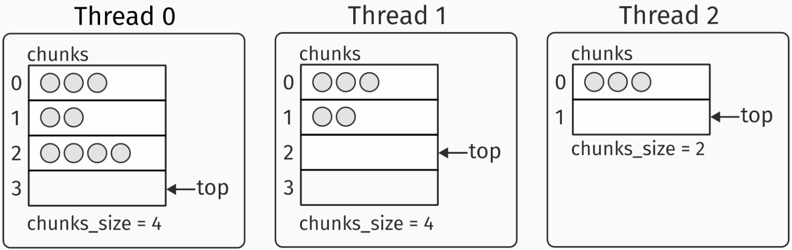

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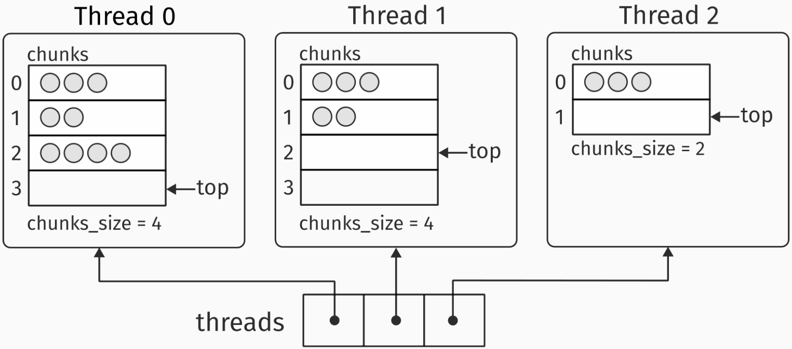

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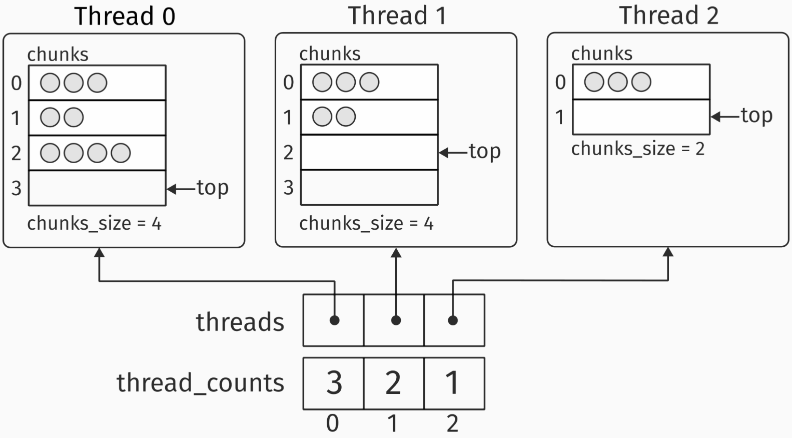
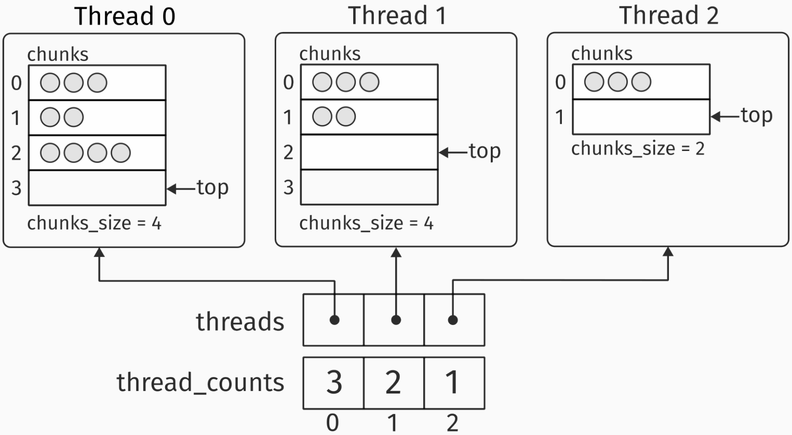


Work-stealing mechanism

Thread 2 processes its vertices...



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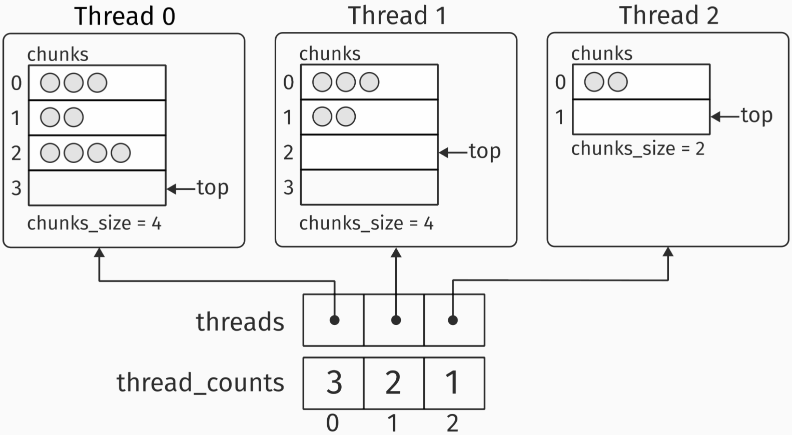

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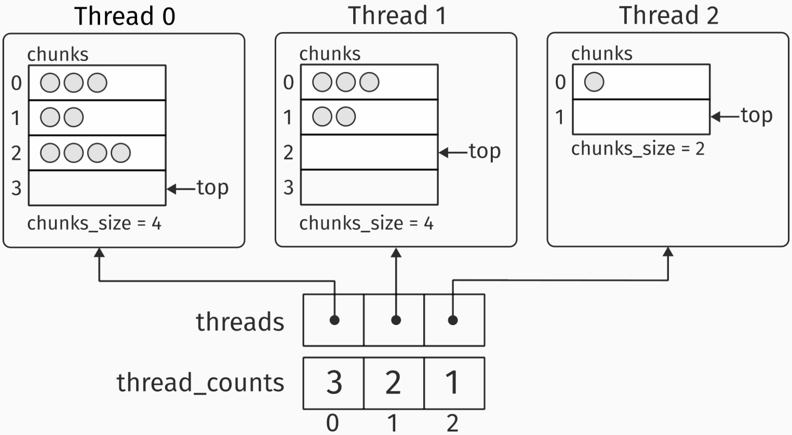
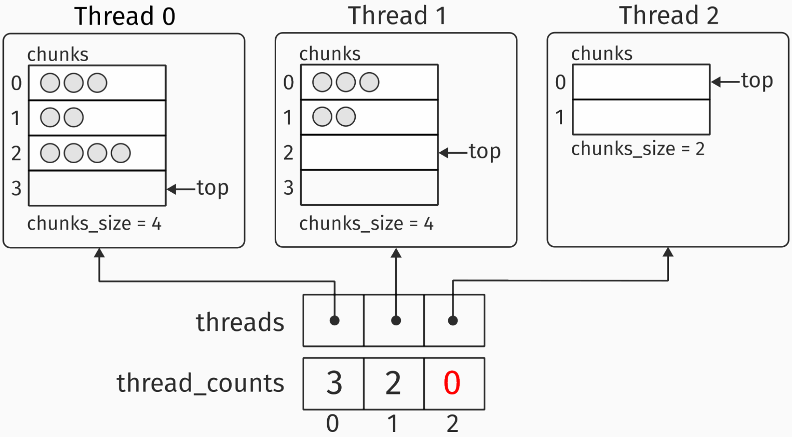


Work-stealing mechanism

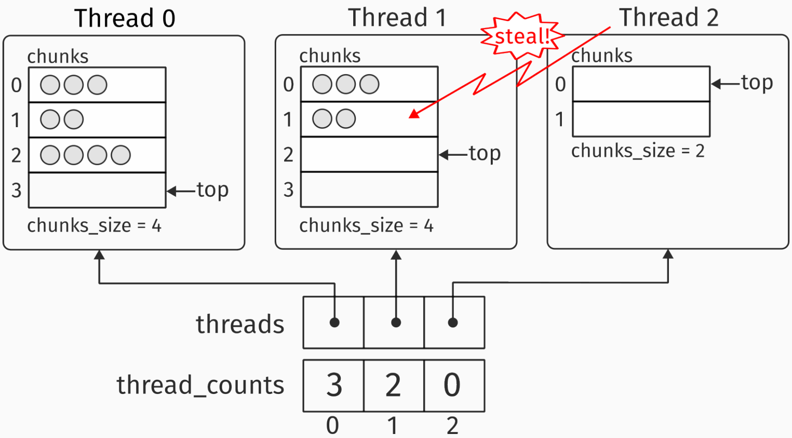
Thread 2 is out of work, will attempt a steal soon...



	0	1	2
thread_counts	3	2	0

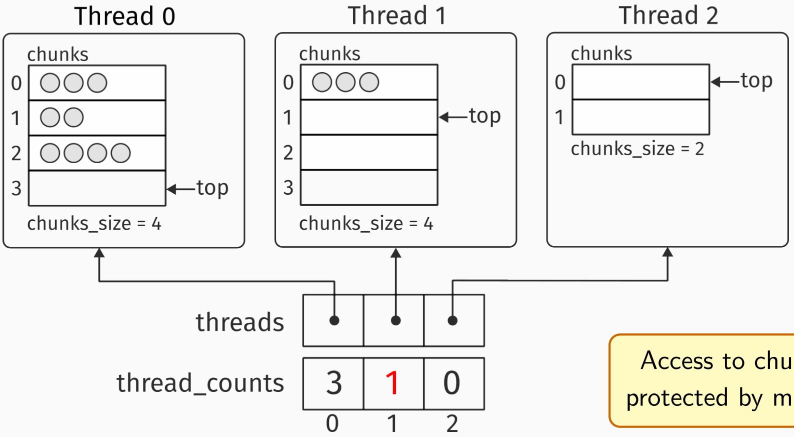
Work-stealing mechanism

Thread 2 steals a chunk of work from Thread 1...



Work-stealing mechanism

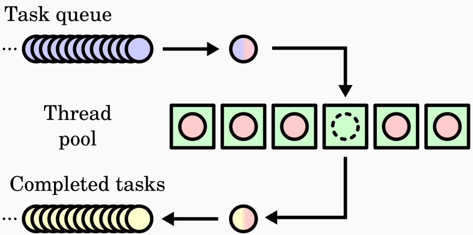
Thread 2 processes the stolen vertices and updates the global count.



Access to chunks is protected by mutexes.

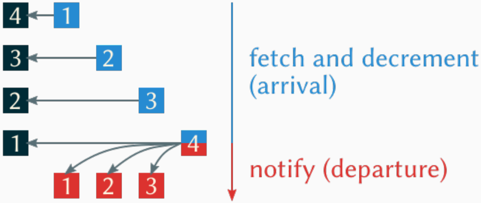
Thread pool

- When the program is run, a group of threads is spawned
- At the beginning of each BFS run, the threads are awaken
  1. Process own chunks
  2. Steal work from other threads



Sense-Reversal Centralized Barrier

- Barrier: point that threads must reach before any can proceed
- Procedure:
    1. Central counter tracks arriving threads
    2. Last thread resets counter + increment distance
    3. Others threads spin wait until distance changes
    4. All threads are released together



Experimental setup

- Experiments run on 3 platforms:
  - AMD EPYC 7543 CPU @ 2.8 GHz (32 cores)
  - Sophon SG2042 RISC-V CPU @ 2.0 GHz (64 cores)
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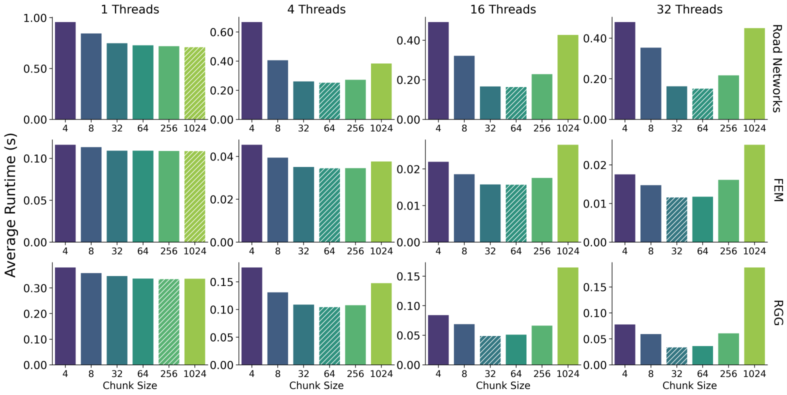
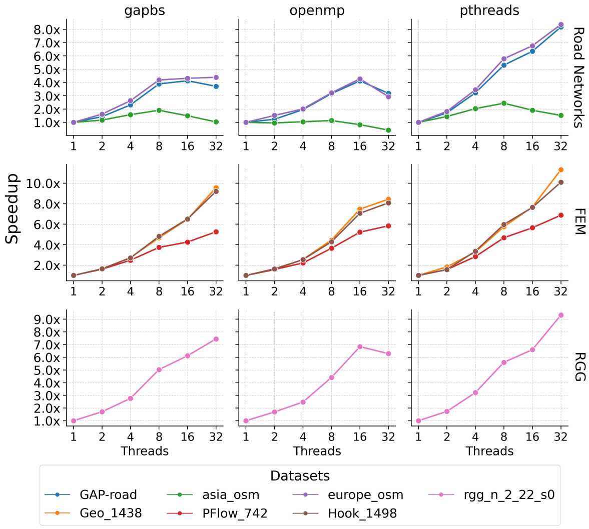
- Compared against the GAP benchmark suite

Chunk size impact on performance

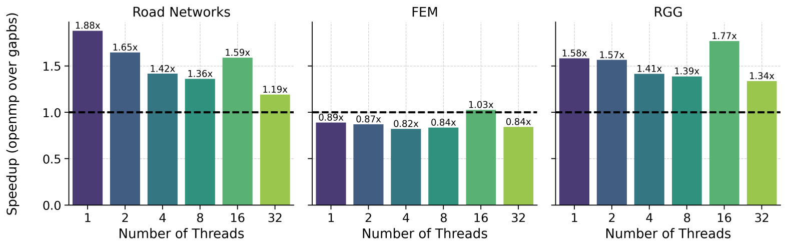
- Chunk size determines the number of vertices in a chunk
- Chunk sizes of 32 and 64 are optimal for most datasets in multithreaded environments



Scalability



Speedup - OpenMP



Speedup of the OpenMP implementation compared to the GAPBS implementation

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Introduction

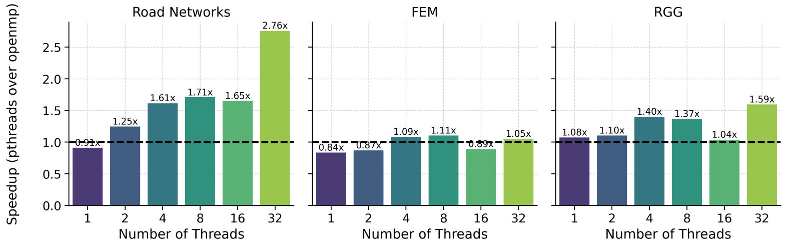
OpenMP

Pthreads

Results

Conclusions

Speedup - Pthreads



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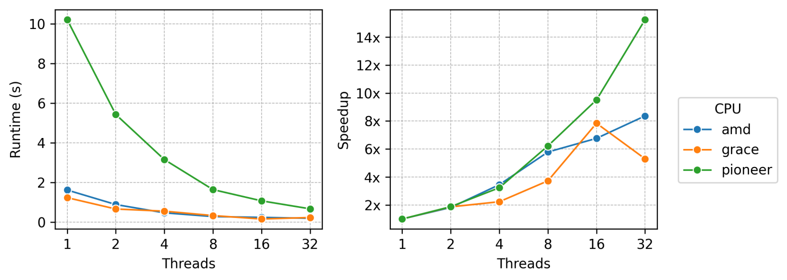
Comparison on different architectures



Execution time and speedup on different architectures for the Europe road network dataset

Conclusions

- Presented a multithreaded implementation of the BFS algorithm using OpenMP and Pthreads
- Compared it on different architectures (x86, RISC-V, ARM) and different datasets
- Achieved $\approx 1.5x$ geomean speedup for OpenMP and $\approx 2x$ speedup for Pthreads compared to the GAP benchmark suite
- Future work: explore other graph algorithms, optimize for more graph types, use different barrier or synchronization primitives

Thank You!

Questions?