Optimizing Breadth-First Search on Modern Multicore CPUs

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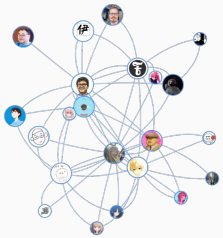

Social network

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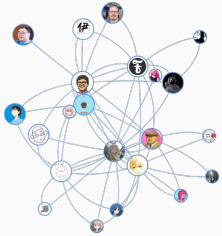

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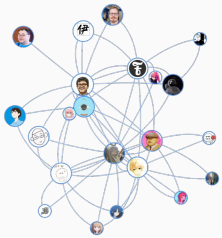

Social network

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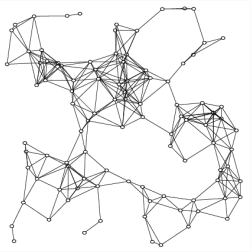
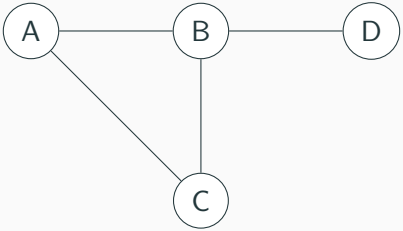


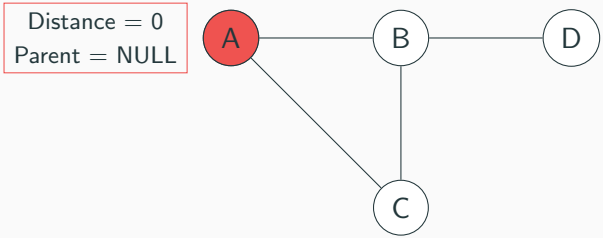
Synthetic graph

Breadth-First Search Example



Source vertex: A

Breadth-First Search Example



Frontier: A

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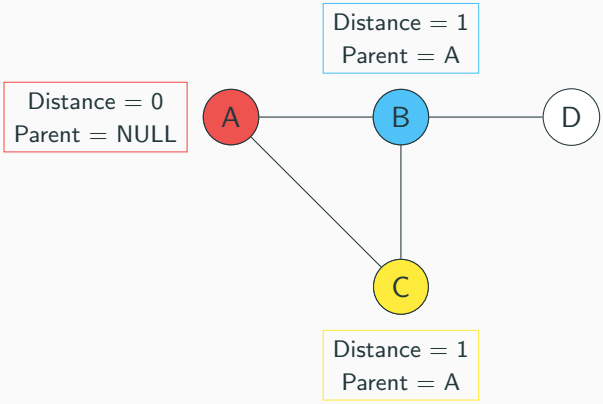
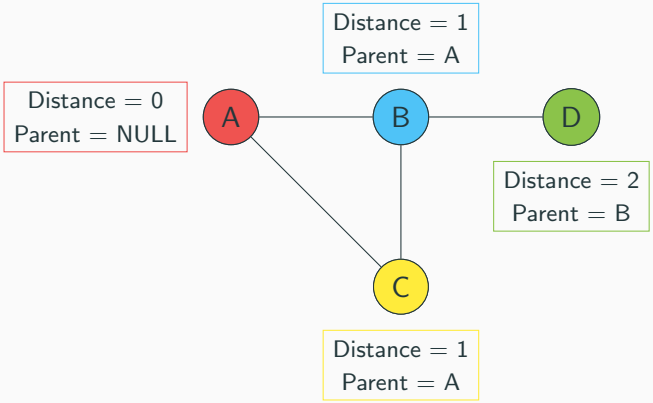


Frontier: B, C

Breadth-First Search Example



Frontier: D

Modern Computer Architectures

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

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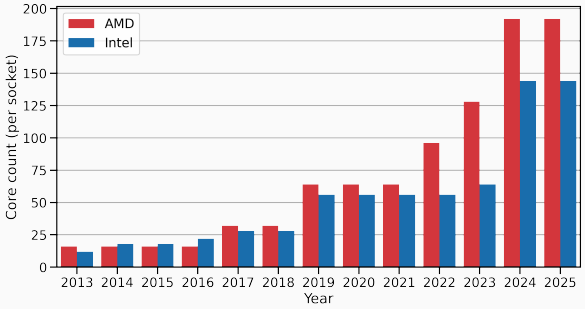
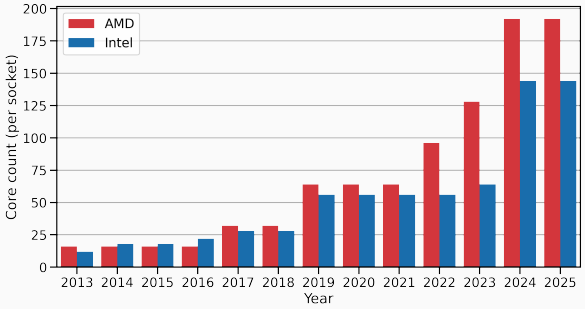


Evolution of core counts per socket for AMD and Intel processors

Modern Computer Architectures

- BFS has $\mathcal{O}(V + E)$ time and space complexity (under RAM model)
- In practice, it is a **memory-bound algorithm**
  - Cache effects must be considered
- 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

- Two implementations with different parallel programming paradigms
  1. OpenMP implementation using the *MergedCSR* data structure
  2. Pthreads implementation using *MergedCSR* + custom synchronization routines

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- Two implementations with different parallel programming paradigms
  1. OpenMP implementation using the *MergedCSR* data structure
  2. Pthreads implementation using *MergedCSR* + custom synchronization routines
- Evaluated against GAP Benchmark suite
- Speedups compared on three different architectures (AMD x86, RISC-V, ARM)

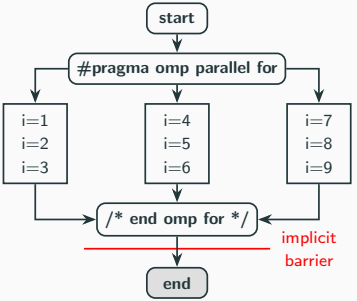
GAP suite logo

Compared architectures

OpenMP implementation

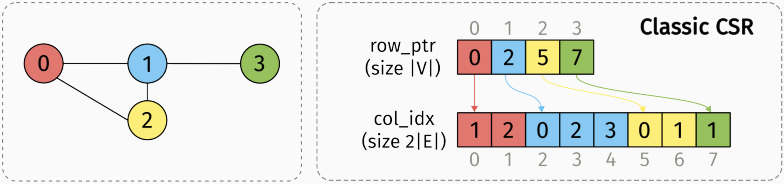
- **OpenMP** is a widely used framework for **parallel programming** in C and C++
- Uses simple compiler directives called pragmas

```
#pragma omp parallel for
for (int i = 1; i <= 9; i++) {
  A[i] = i
}
```



From CSR to MergedCSR

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



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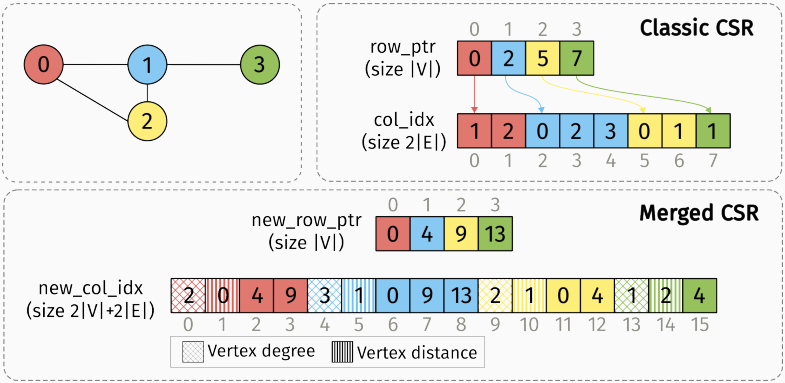
  - `row_ptr` array contains also algorithm-specific metadata (ex. distance)



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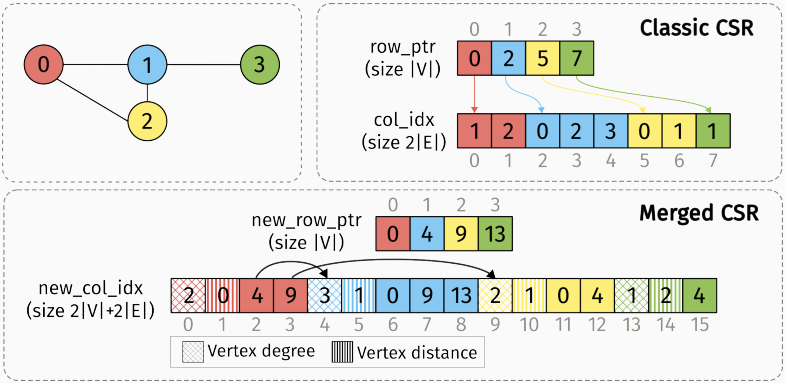
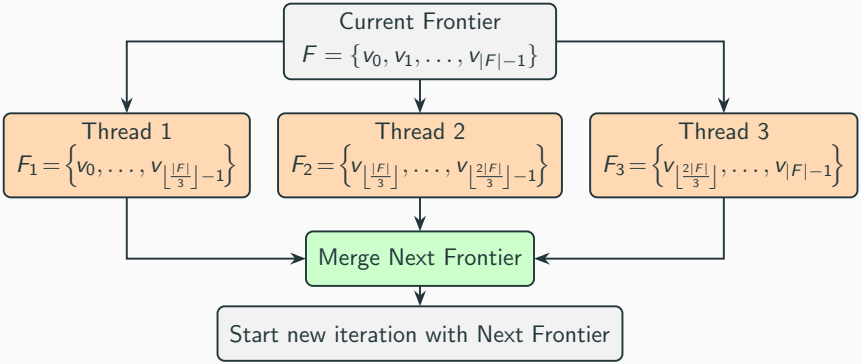


Parallelization strategies

- Different parallelization strategies, depending on the graph type
- Strategy used: Frontier partitioning + Merge step



Implementation

```
#pragma omp declare reduction(vec_add : \
  omp_out.insert(omp_out.end(), omp_in.begin(), omp_in.end()))

#pragma omp parallel for reduction(vec_add : next_frontier)
↪  if(this_frontier.size() > 50)
for (const auto &v : this_frontier) {
  for (vertex i = v + 2; i < end; i++) { // Iterate over neighbors
    vertex neighbor = new_col_idx[i];
    // If neighbor is not visited, add to frontier
    if (DISTANCE(neighbor) == max()) {
    next_frontier.push_back(neighbor);
    DISTANCE(neighbor) = distance; // Set the distance
    }
  }
}
```

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

Pthreads implementation summary

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Pthreads (unofficial)
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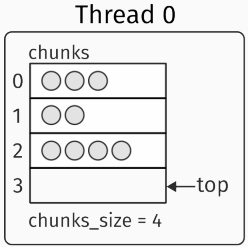
  4. Custom barrier for thread synchronization

Pthreads (unofficial) logo

Frontier implementation



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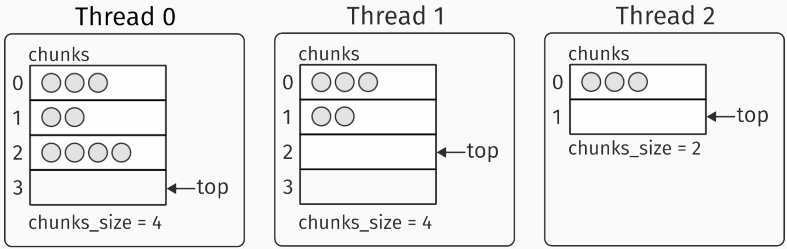

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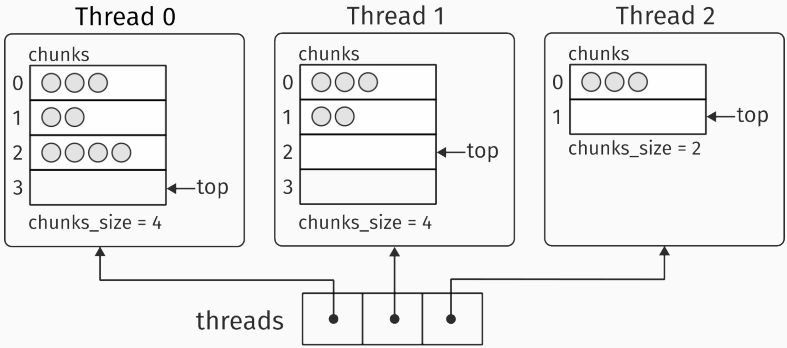

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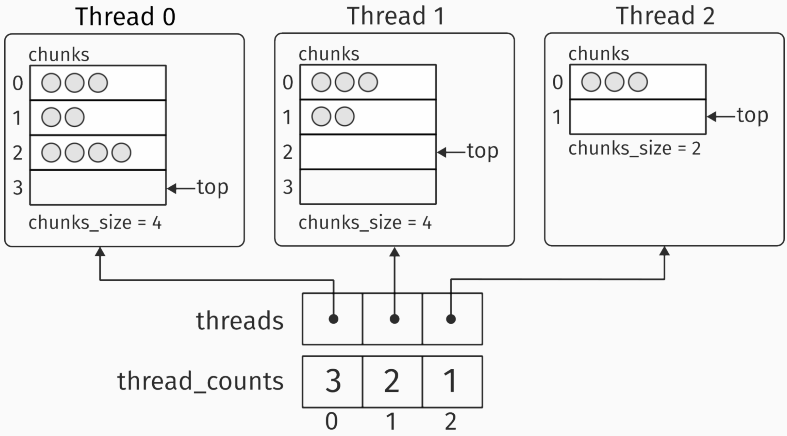
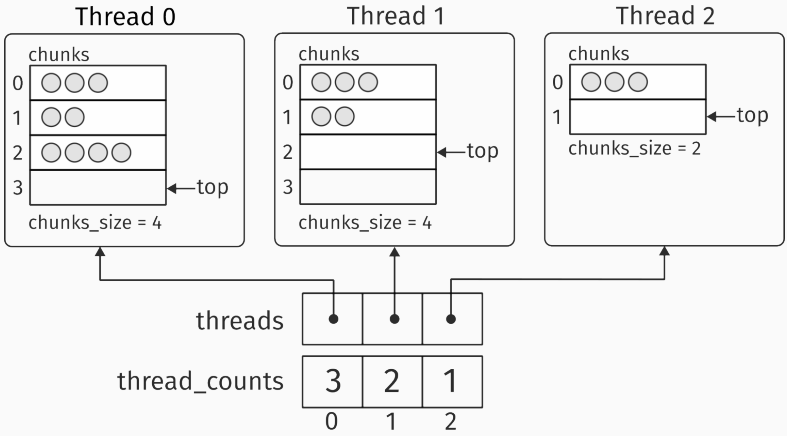


Work-stealing mechanism

Thread 2 processes its vertices...



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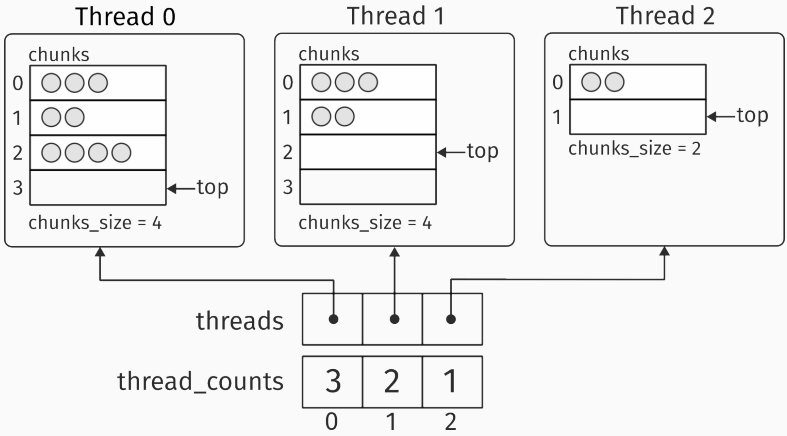

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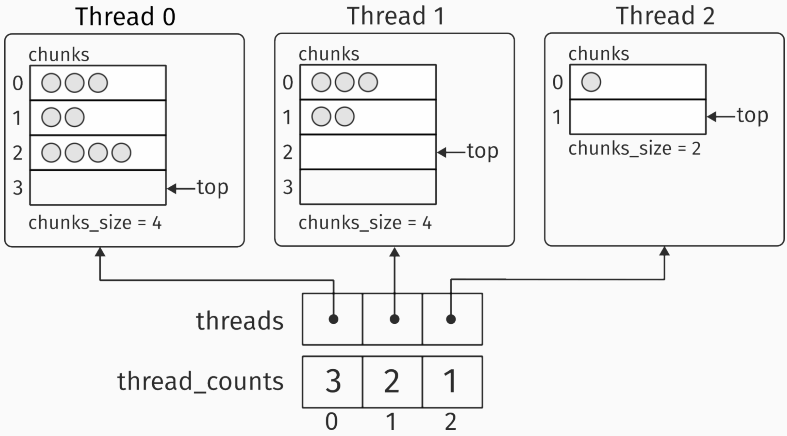
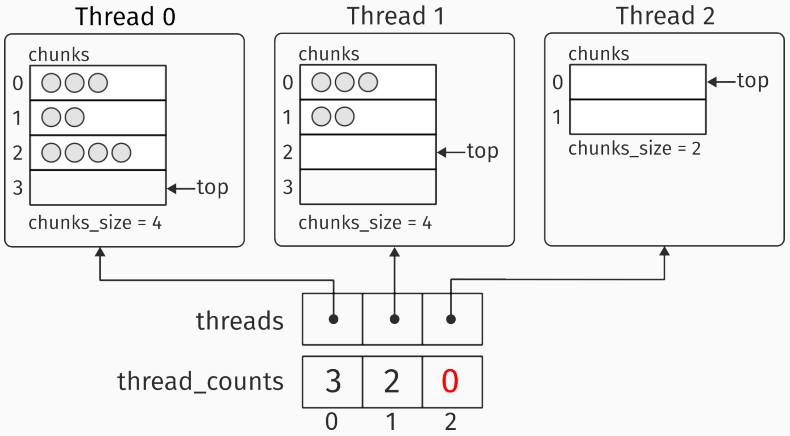


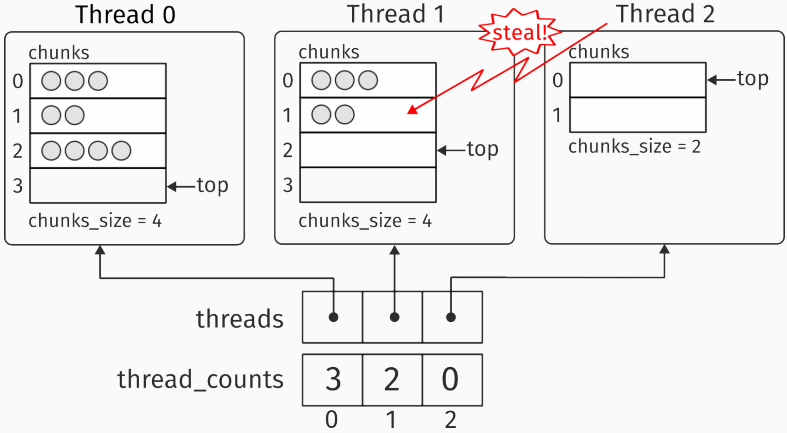
Work-stealing mechanism

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



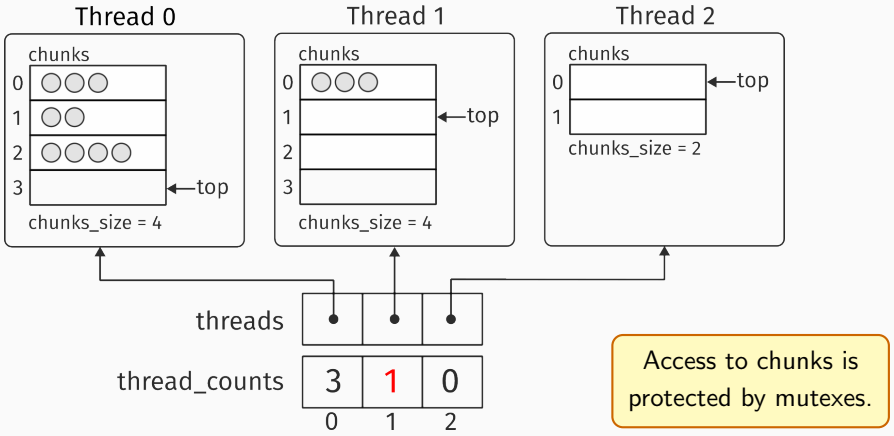
Work-stealing mechanism

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



Work-stealing mechanism

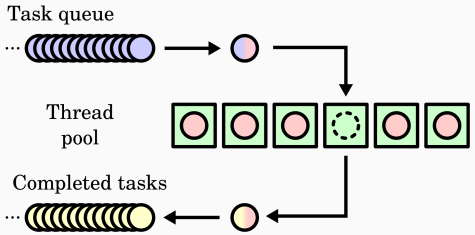
Thread 2 processes the stolen vertices and updates the global count.



Access to chunks is protected by mutexes.

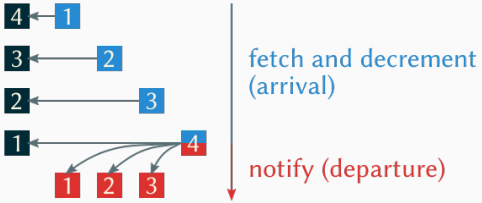
Thread pool

- When the program is run, a group of threads is spawned
- At the beginning of each BFS run, the threads are awaken and the starting vertex is assigned to the 0^{th} thread



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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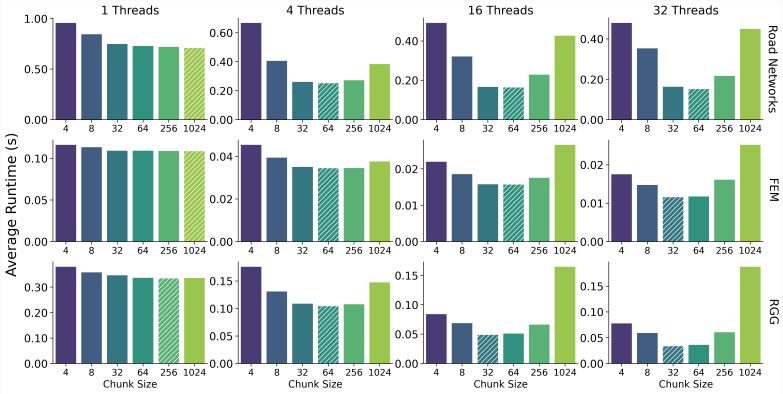
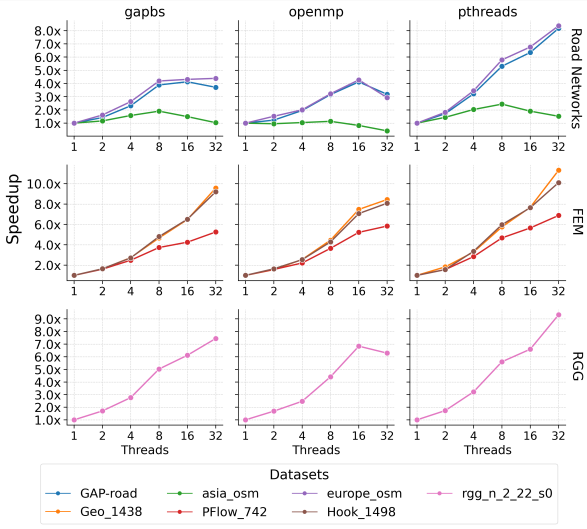
- Compared against the GAP benchmark suite

Chunk size impact on performance

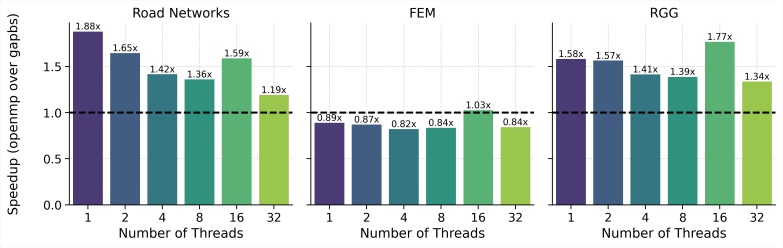
- Chunk size determines the number of vertices in a chunk
- Chunk sizes of 32 and 64 are optimal for most datasets in multithreaded environments



Scalability

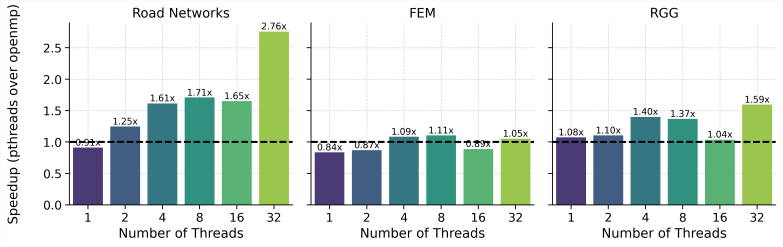


Speedup - OpenMP



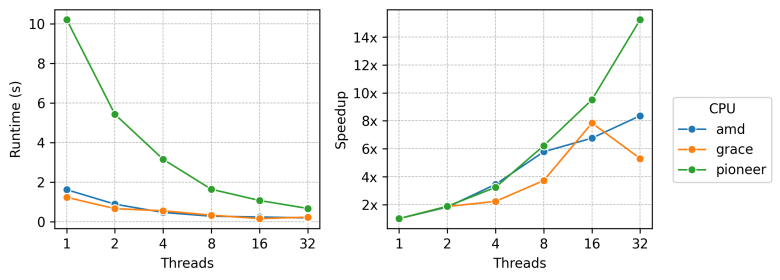
Speedup of the OpenMP implementation compared to the GAPBS implementation

Speedup - Pthreads



Speedup of the pthreads implementation compared to the OpenMP implementation

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?