Optimizing Breadth-First Search on Modern Multicore CPUs

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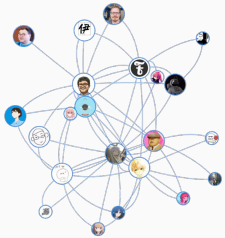
Breadth-First Search

- Breadth-First Search is a fundamental algorithm in graph analysis
- Used in many algorithms: Dijkstra, Maximum Flow, MSP...

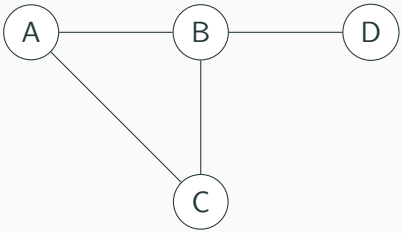


Social network

Road network

Breadth-First Search Example

Vertices are labeled based on the distance from a given *source* vertex



Source vertex: A

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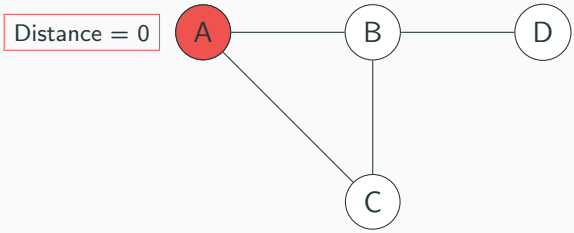

Frontier: A

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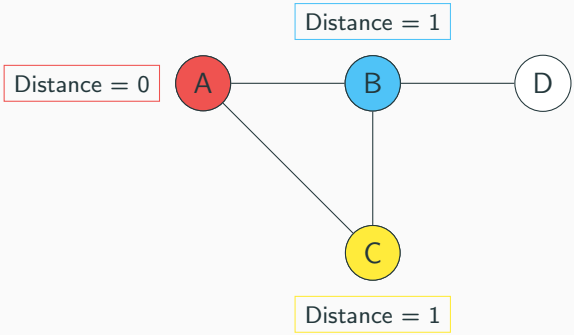

Frontier: B, C

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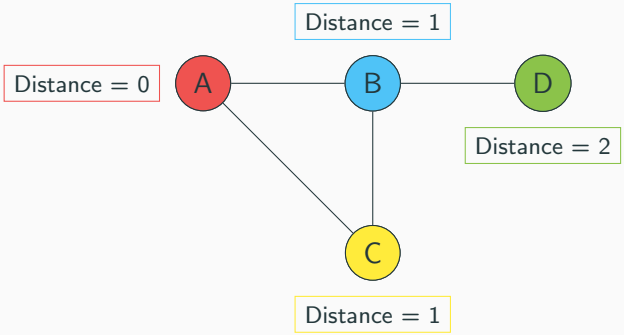

Frontier: D

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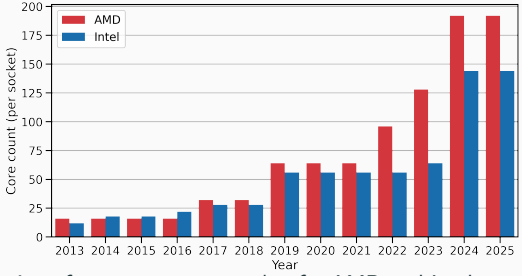
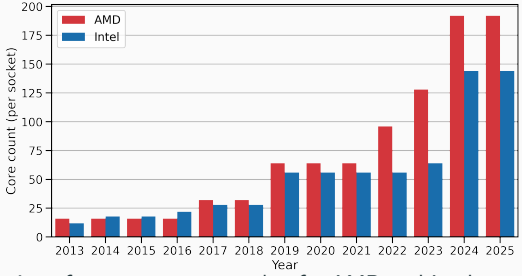


Evolution of core counts per socket for AMD and Intel processors

Modern Computer Architectures

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



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- Propose an improved version of the *MergedCSR* data structure[1]

[1] Ryan Torok. ***Improving Graph Workload Performance by Rearranging the CSR Memory Layout.*** 2020.

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- Propose an improved version of the *MergedCSR* data structure[1]
- Designed 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

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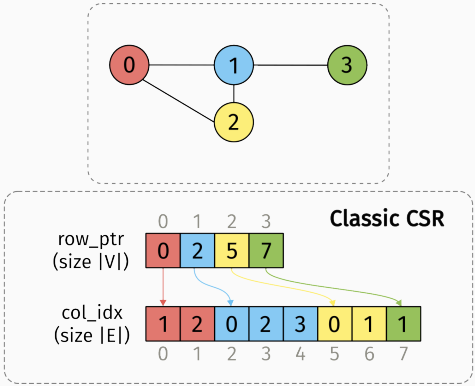

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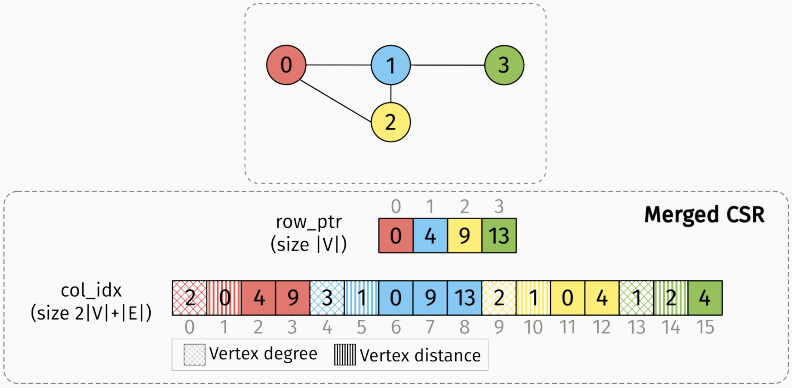
  - `col_idx` array contains also algorithm-specific metadata (ex. distance)



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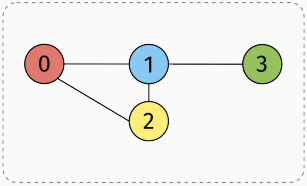

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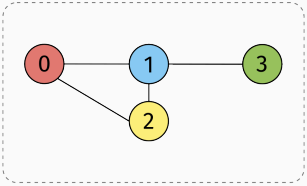
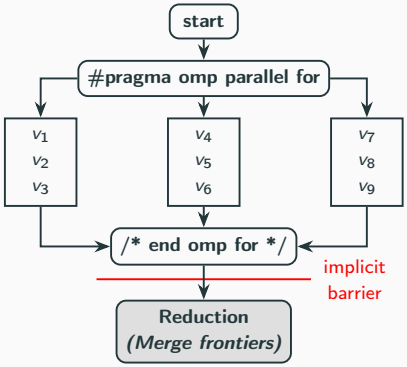


OpenMP implementation

- **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 each BFS run on certain graphs

Pthreads implementation summary

- Pthreads: low-level threading library to create and manage threads in C

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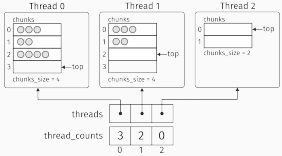

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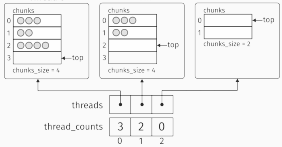

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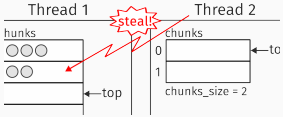

Work-stealing mechanism

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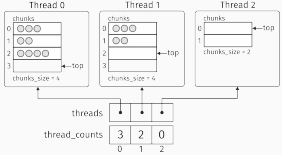

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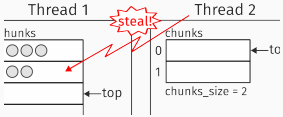

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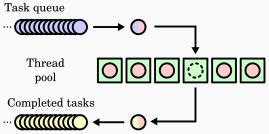

Thread pool

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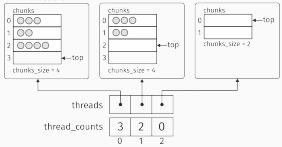

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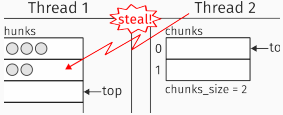

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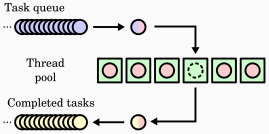

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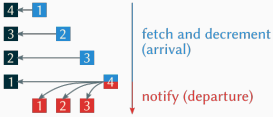
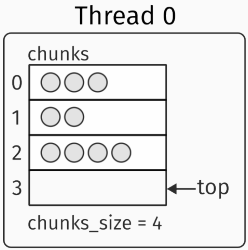


Custom barrier

Frontier implementation



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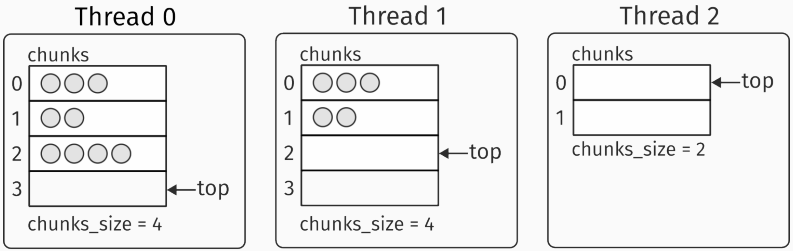

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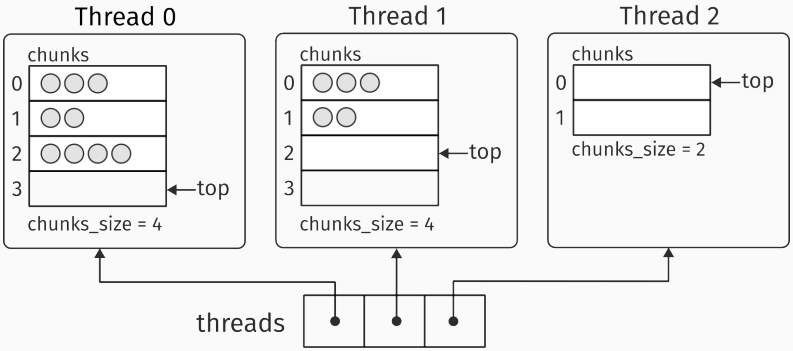

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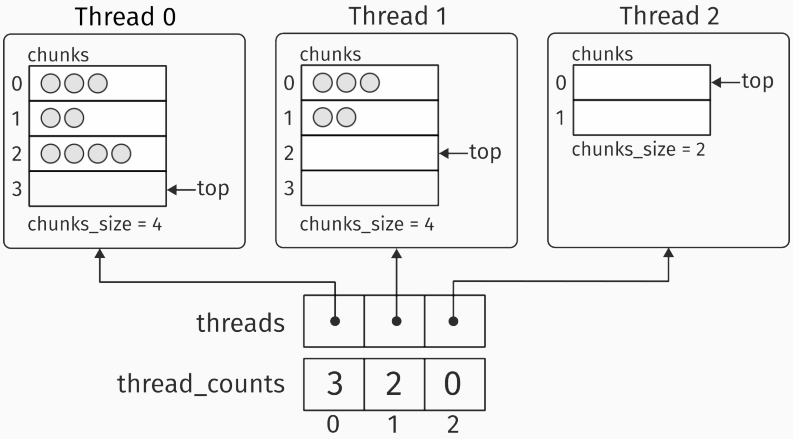
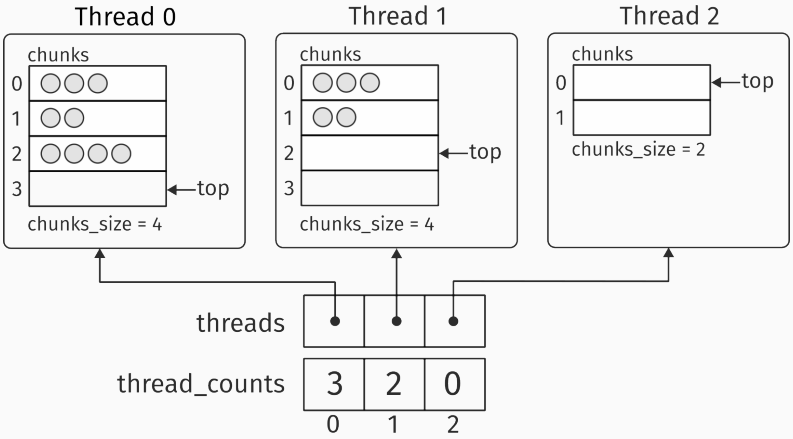


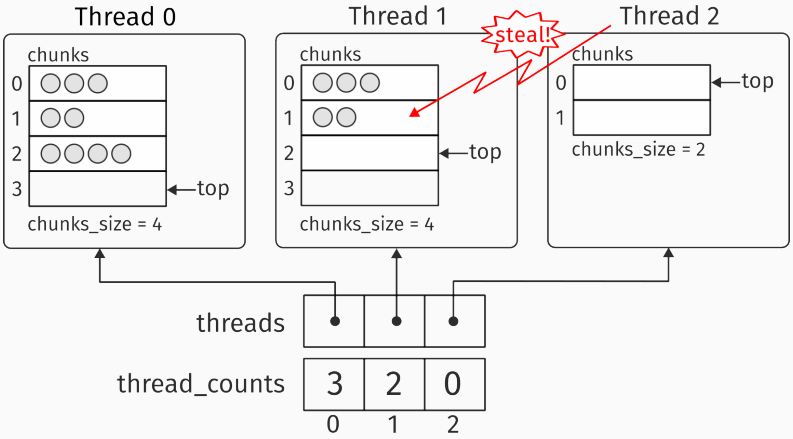
Work-stealing mechanism

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



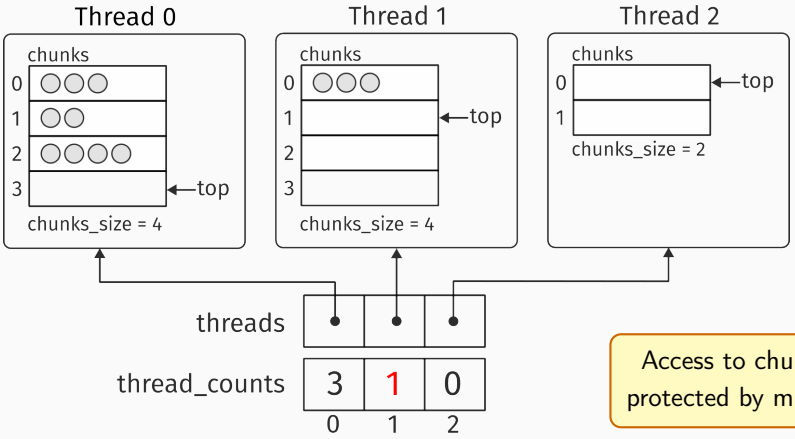
Work-stealing mechanism

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



Work-stealing mechanism

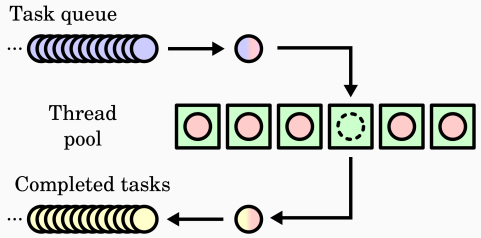
Thread 2 processes the stolen vertices and updates the global count.



Access to chunks is protected by mutexes.

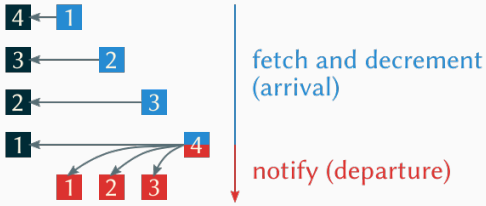
Thread pool

- Optimization to avoid repeated thread creation
- 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. Threads decrease global counter and wait
  2. Last thread resets counter + increments distance
  3. All threads are released together



Experimental setup

- Experiments run on 3 platforms:
  - **x86**: AMD EPYC 7543 CPU @ 2.8 GHz (32 cores)
  - **RISC-V**: Sophon SG2042 CPU @ 2.0 GHz (64 cores)
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[2]Scott Beamer, Krste Asanović, and David Patterson. ***The GAP benchmark suite.*** 2015.

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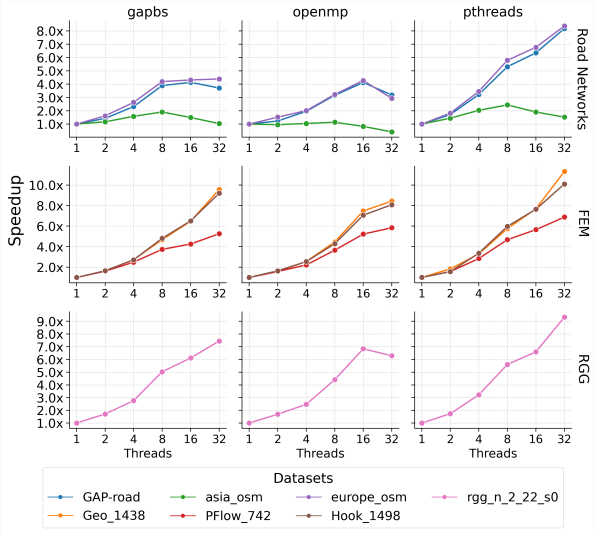
Scalability



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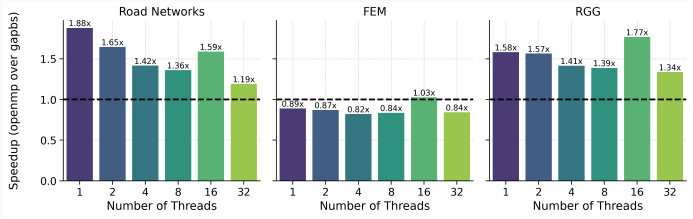
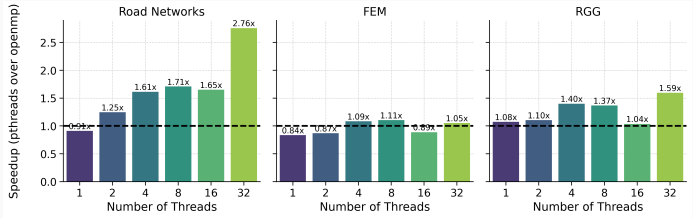
Speedup

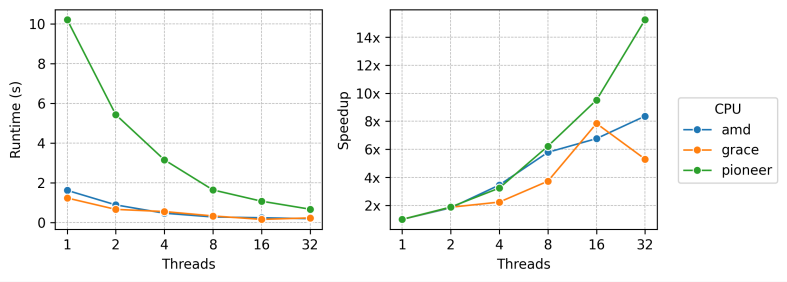


Speedup of the OpenMP implementation compared to the GAPBS implementation



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

- Designed two **multithreaded implementations** using an optimized CSR format and custom components tuned for today's multicore processors
- Compared them 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
- Some of the results presented were developed for the Fastcode Programming Challenge 2025 @ PPoPP'25 ACM conference[3]

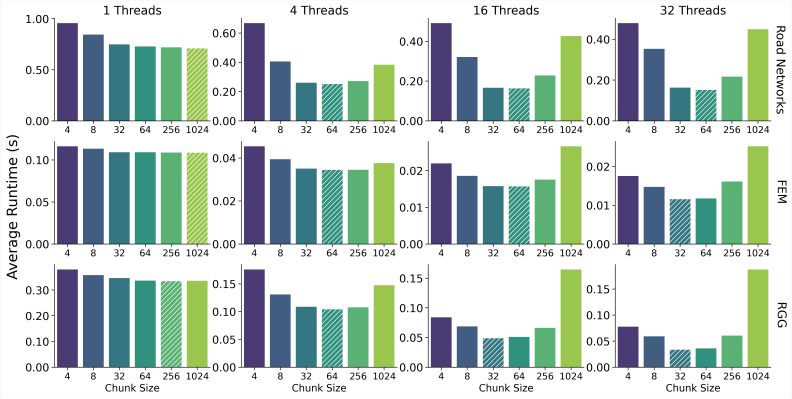
[3] Salvatore Andaloro, Thomas Pasquali, and Flavio Vella. **"Cache-optimized BFS on multi-core CPUs".** In: *Proceedings of the 1st FastCode Programming Challenge*. Association for Computing Machinery, 2025.

Thank You!

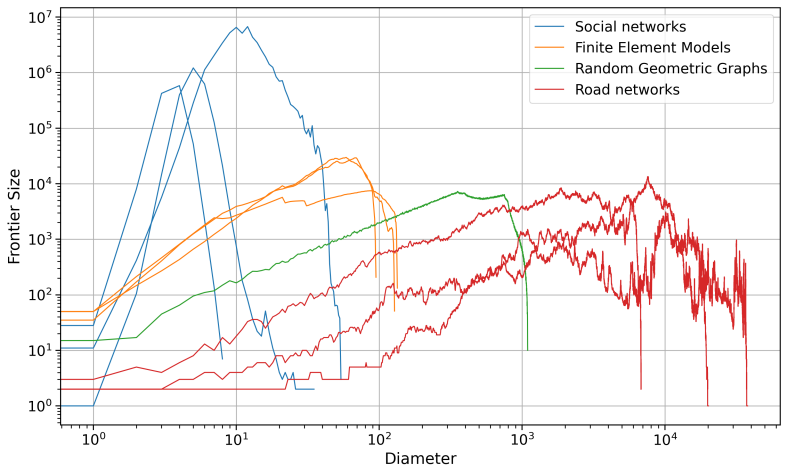
Questions?

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



Frontier sizes for different datasets



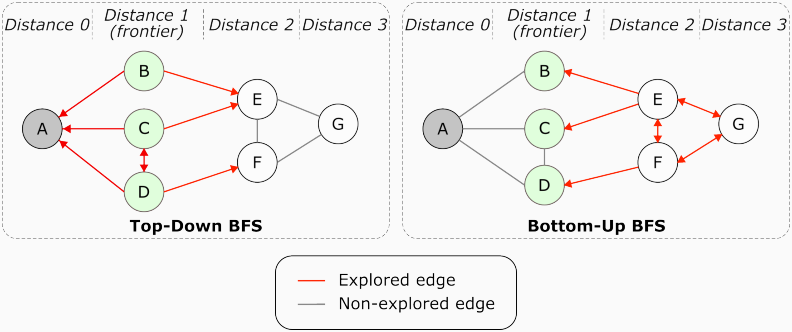
The evolution of BFS frontier size for different graphs, colored by their graph class.

Datasets used

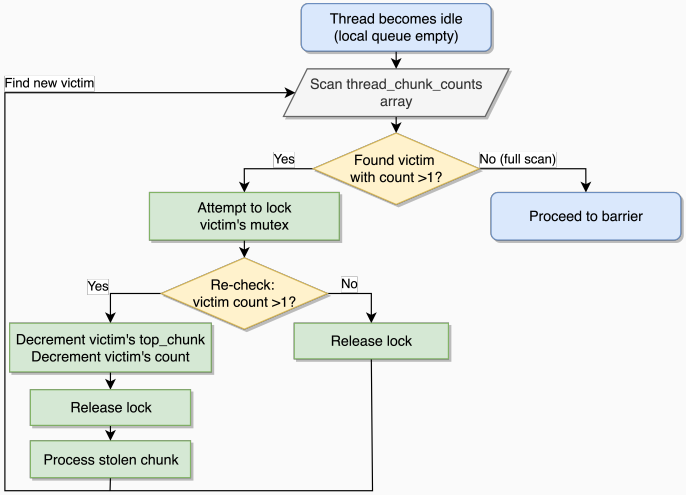
Name	Graph class	Vertices	Edges	Notes
GAP-Road	Road Network	23.9M	57.7M	Road network of the USA.
europe_osm	Road Network	50.9M	108M	Road network of Europe.
asia_osm	Road Network	11.9M	25.4M	Road network of Asia.
Geo_1438	FEM	1.4M	60.2M	Geomechanical model of Earth's crust.
Hook_1498	FEM	1.4M	59.4M	3D model of a steel hook.
PFlow_742	FEM	0.7M	37.1M	3D pressure-temp in porous media.
rgg_n_2_22_s0	RGG	4.2M	60.7M	Random Geometric Graph.

Datasets used in the evaluation.

Top-Down and Bottom-Up approaches



Work-Stealing protocol



Thread pool implementation