Optimizing Breadth-First Search on Modern Multicore CPUs

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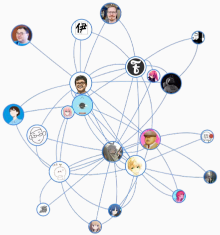

Social network

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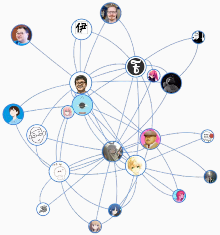

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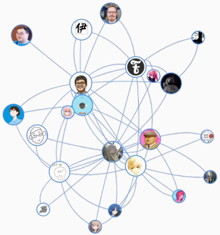

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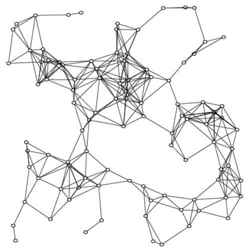
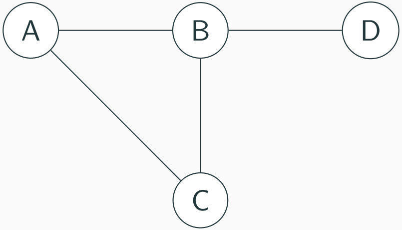


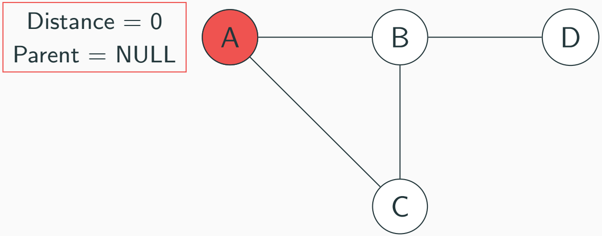
Synthetic graph

Breadth-First Search Example



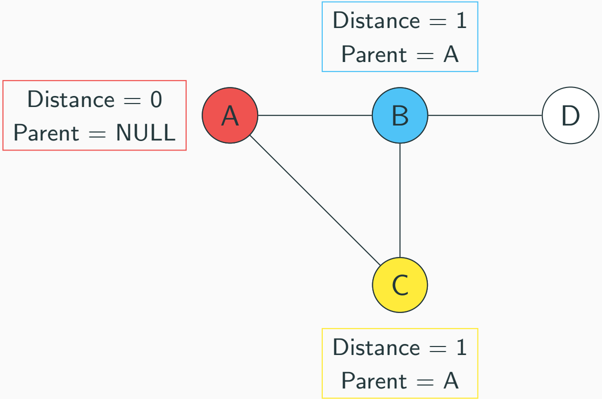
Source vertex: A

Breadth-First Search Example



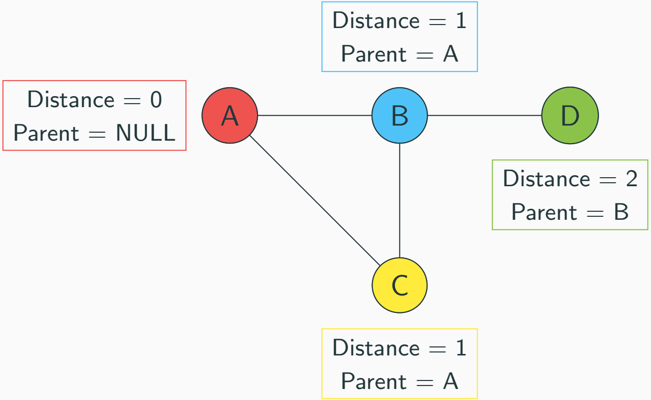
Frontier: A

Breadth-First Search Example



Frontier: B, C

Breadth-First Search Example



Frontier: D

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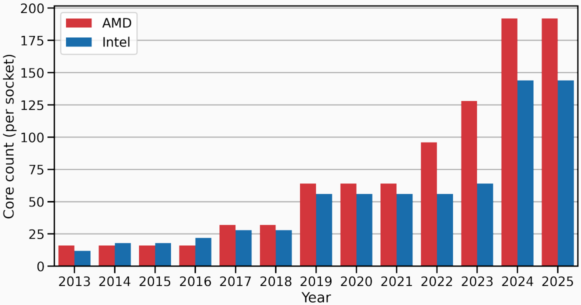

Evolution of core counts per socket for AMD and Intel processors

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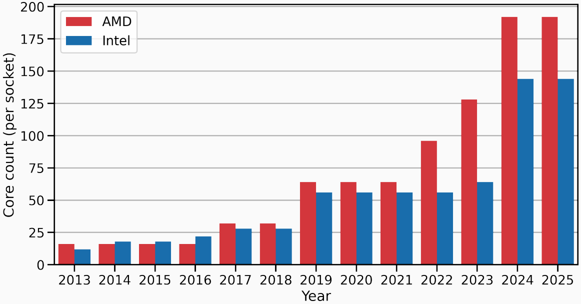
- CPUs exhibit growing amount of **parallelism**...
- ...and new architectures are coming to the market (ARM, RISC-V)



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)

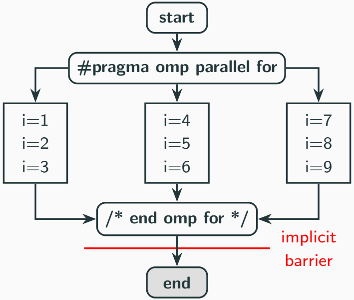
GAP suite logo

Compared architectures

OpenMP implementation

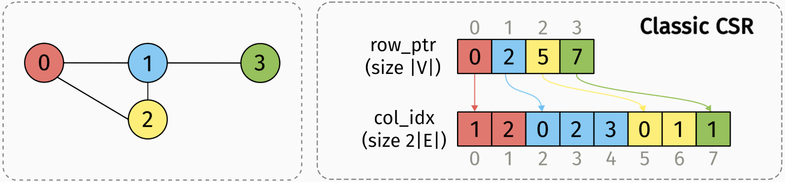
- **OpenMP** is a widely used framework for **parallel programming** in C and C++
- Uses simple compiler directives called pragmas

```
#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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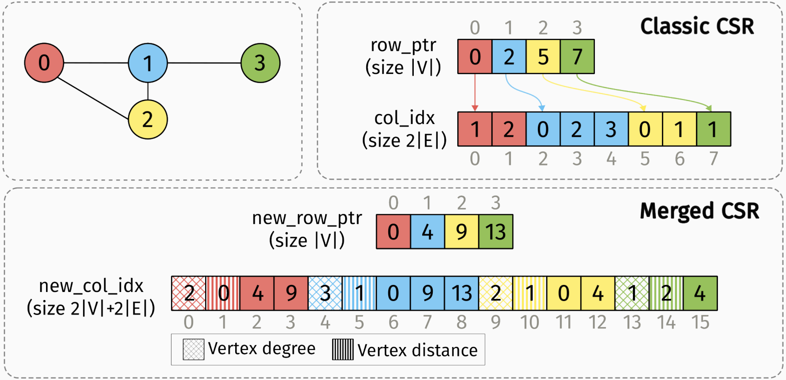

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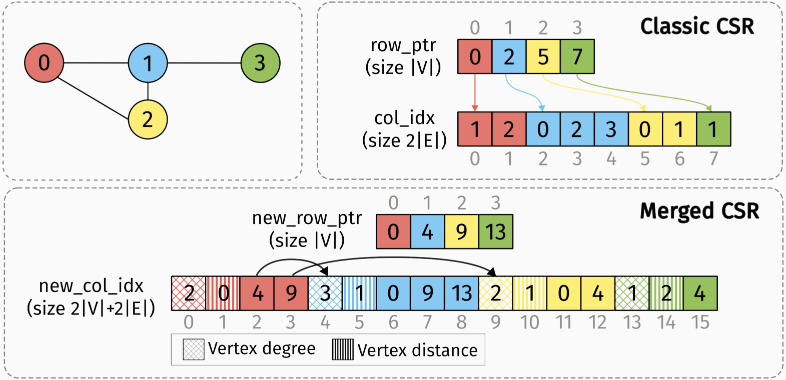
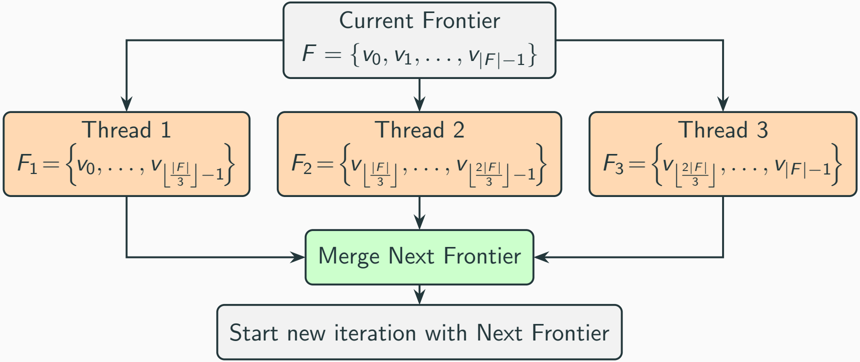


Parallelization strategies

- 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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- Poor cache locality, as vertices are collected and repartitioned among the cores
- For large-diameter graphs, OpenMP enters the `parallel` region more than 10k times for a single BFS runs

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Pthreads (unofficial) logo

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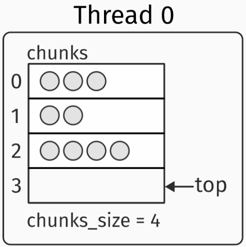
  4. Custom barrier for thread synchronization

Pthreads (unofficial) logo

Frontier implementation



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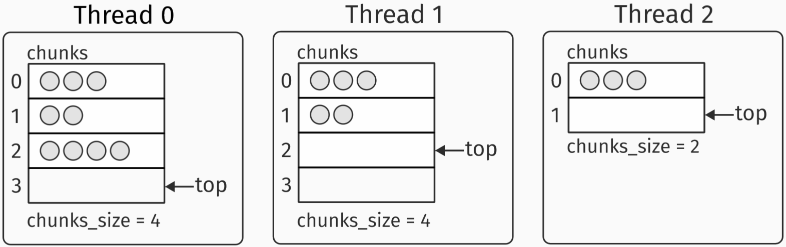

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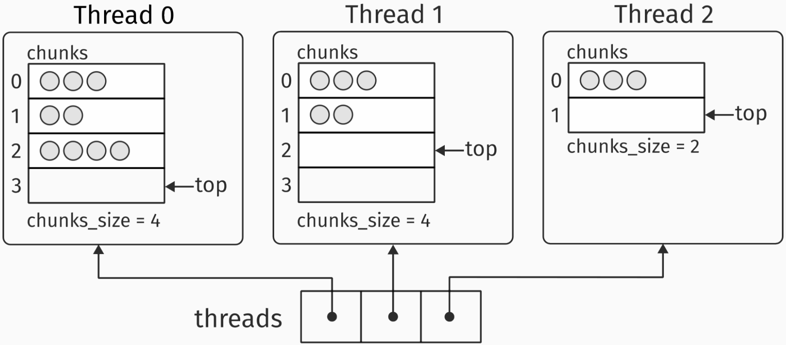

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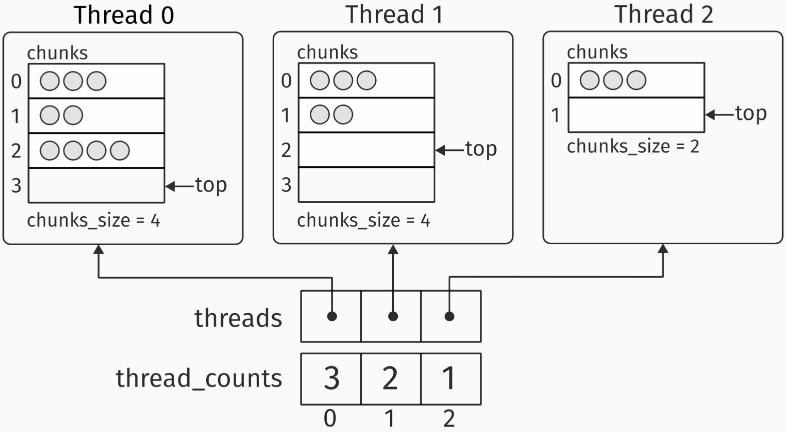
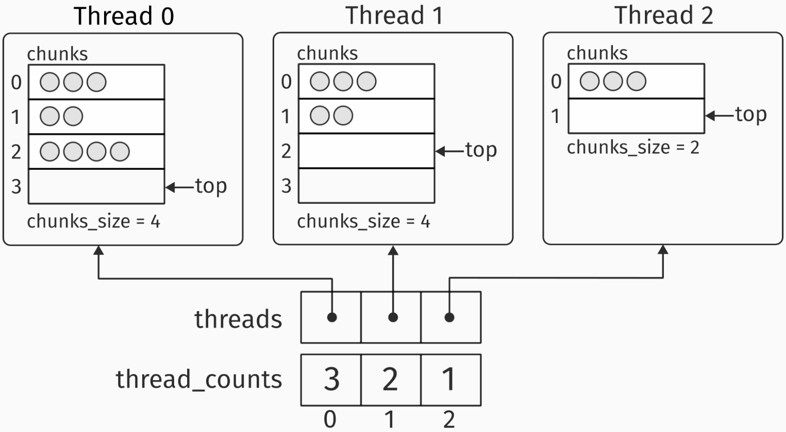


Work-stealing mechanism

Thread 2 processes its vertices...



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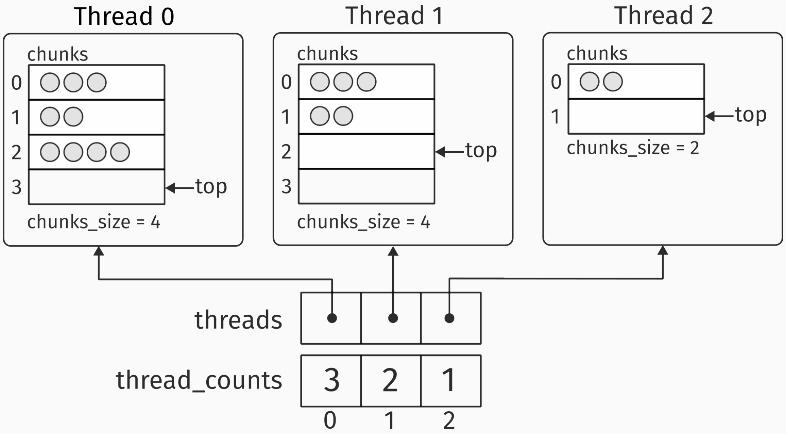

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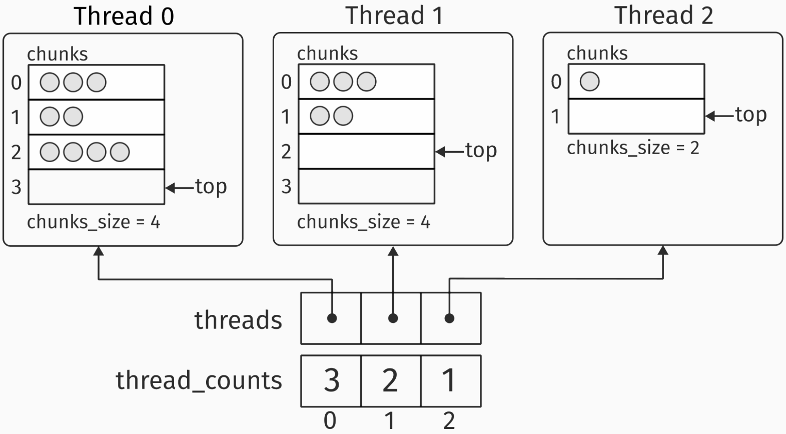
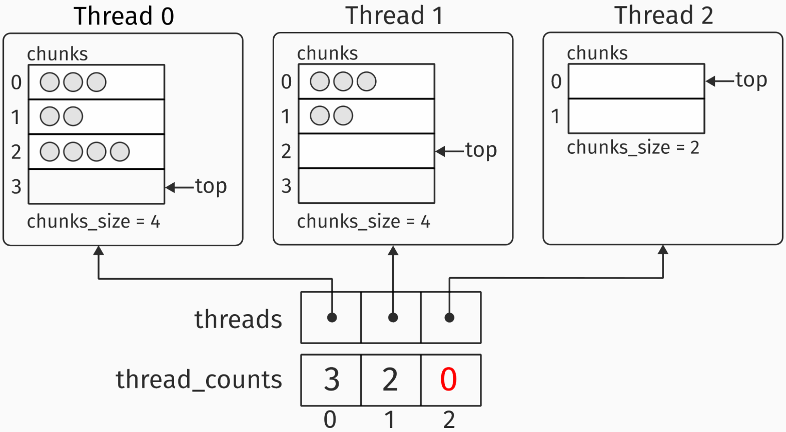


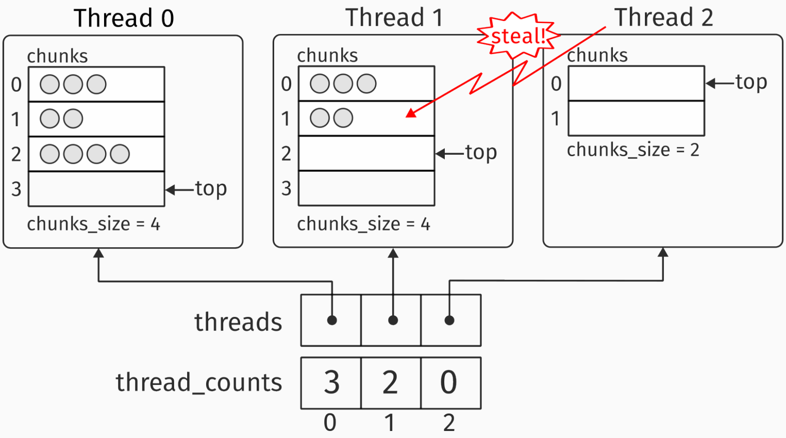
Work-stealing mechanism

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



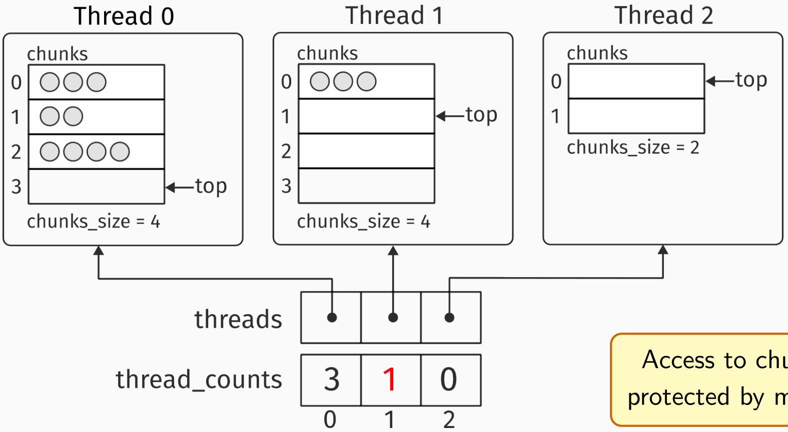
Work-stealing mechanism

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



Work-stealing mechanism

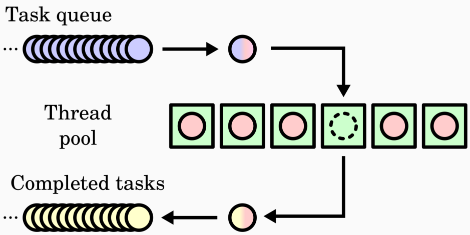
Thread 2 processes the stolen vertices and updates the global count.



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

- Central counter tracks arriving threads
- Last thread resets counter + toggles global sense
- Others wait until global = local sense
- All released together, barrier reusable