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Rensselaer

Sandia National Laboratories

Distributed Graph Coloring on Multiple GPUs

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Main contributions and results

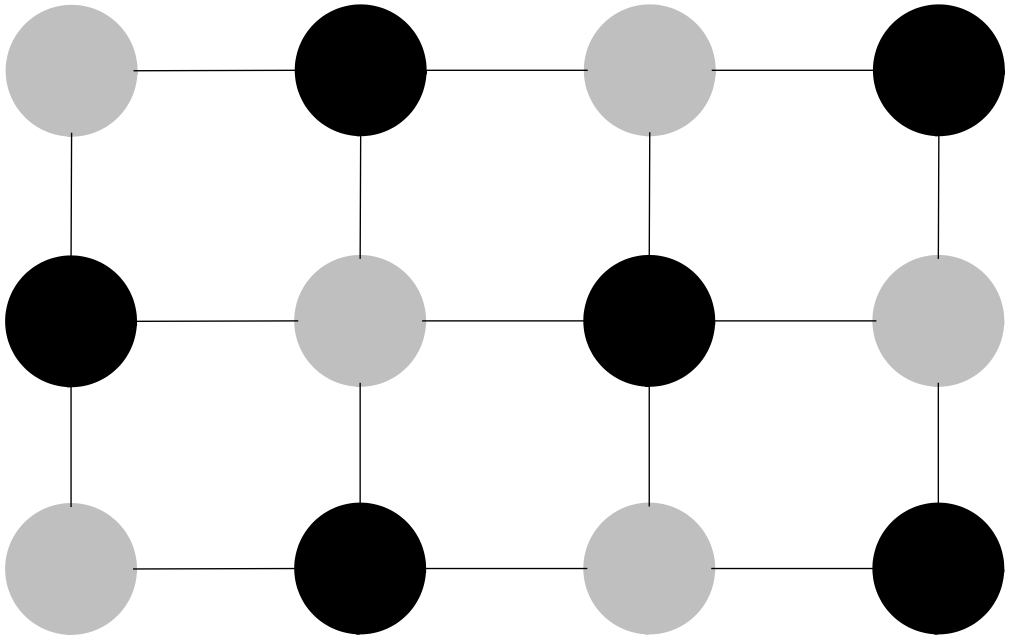
- We present the first distributed memory multi-GPU graph coloring implementation, to our knowledge
- Our distributed distance-1 coloring implementation sees up to a **28x speedup** on 128 GPUs over a single GPU, and **only a 7.5% increase** in colors on average
- Our distributed distance-2 coloring implementation also sees up to a **28x speedup** on 128 GPUs over a single GPU, and a **4.9% increase** in colors in the **worst** case
- Our approach is able to color a 12.8 Billion vertex mesh with **76.7 Billion** edges in **under half a second**
- We also present an approach that reduces the number of collective communications by increasing the cost of each communication.

Graph Coloring is Useful for Finding Concurrency

- Computations with specific data access patterns can be parallelized with colorings
- Compiler parallelization, register allocation
- Preprocessing Jacobian and Hessian matrix computations
- Also useful for finding short-circuits in circuit designs

Distance-1 Graph Coloring

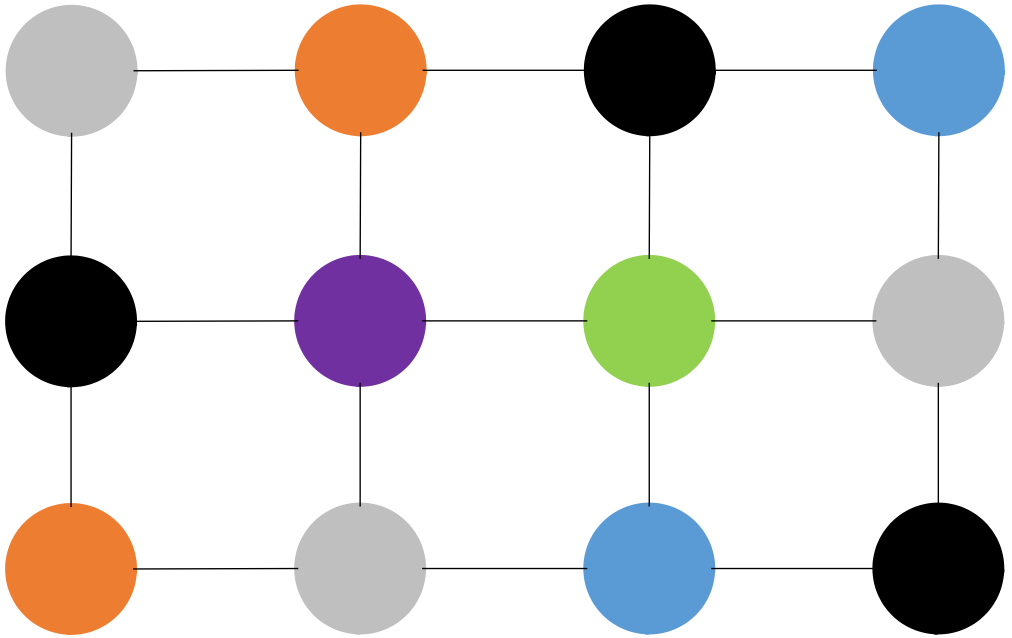
Each vertex ends up with a different color from its neighbors.



Minimizing the number of colors used in the coloring is known to be NP-Hard.

Distance-2 Graph Coloring

A valid distance-2 coloring assigns each vertex a color not used by any vertex at most two edges away



Minimizing the number of colors used in the coloring is known to be NP-Hard.

Related Work

- Coloring heuristics use few enough colors to be useful to applications
- Two main parallelization approaches
  - Jones & Plassmann (1993) uses independent sets to color vertices in parallel
  - “Speculate & Iterate” approaches use heuristics in parallel and fix conflicts
    - Gebremedhin and Manne (2000)
    - More popular approach recently
- Shared Memory & GPU Implementations
  - Catalyurek et al. (2012) and Rokos et al. (2015) present shared-memory implementations
  - Deveci et al. (2016) and Grosset et al. (2011) present coloring implementations on the GPU
- Distributed approaches
  - Bozdăg et al. (2008) adapt the “Speculate & Iterate” approach in distributed memory, subsequent works (2010) include a distance-2 implementation.
  - Sariyüce et al. (2012) presents a hybrid MPI+OpenMP implementation.

We Leverage KokkosKernels to Run on GPUs

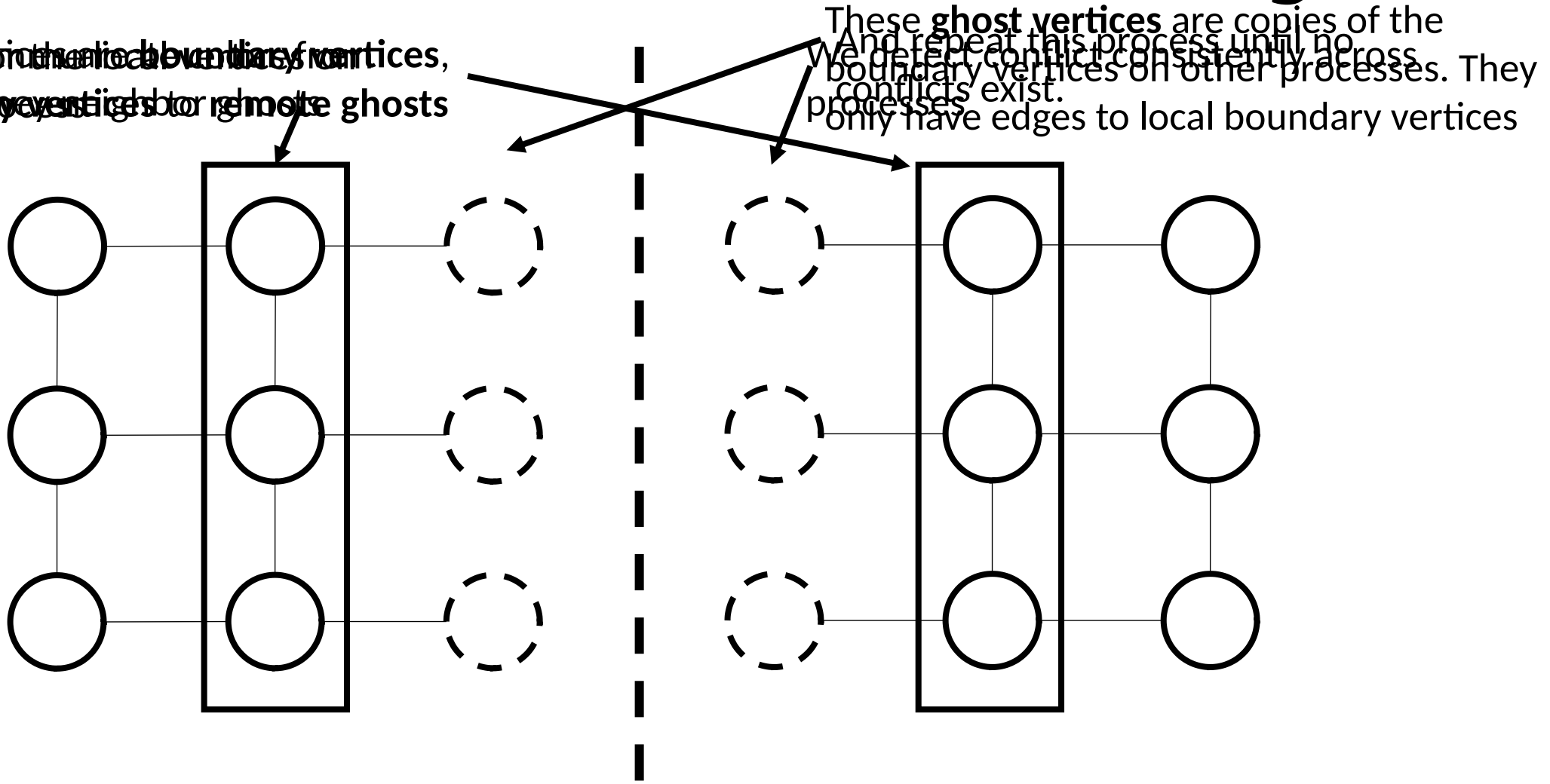
- KokkosKernels is a package that implements various linear algebra and graph operations, using the Kokkos shared-memory parallel programming model
  - https://github.com/kokkos/kokkos-kernels
- The distance-1 graph coloring algorithms we use are described by Deveci et al. (2016)
- The distance-2 graph coloring algorithm in KokkosKernels uses the same Net-Based approach described by Taç et al. (2017)
- We vary the distance-1 algorithms based on how skewed the inputs are.

Distributed “Speculate and Iterate” Coloring

- Based on Gebremedhin and Manne (2000)

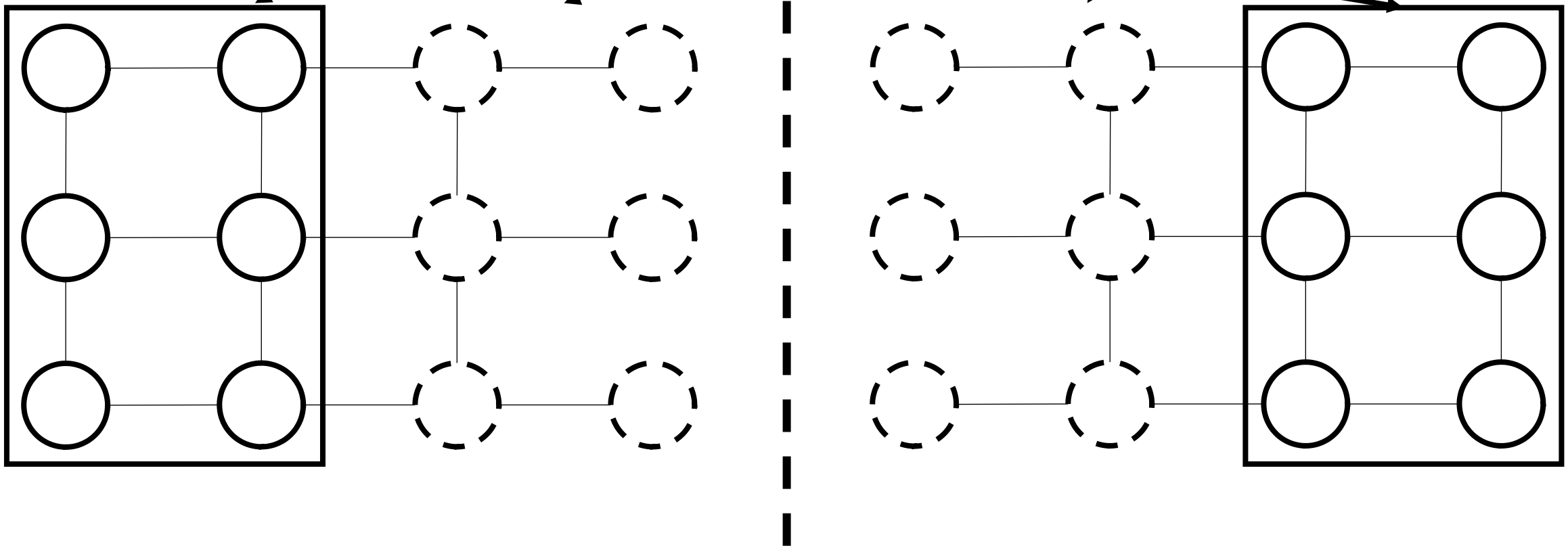
procedure PARALLEL-COLOR(Graph $G = (V, E)$)
    Color all local vertices
    Communicate colors of boundary vertices
    do
        Detect conflicts
        Recolor conflicting vertices
        Communicate updated boundary colors
    while Conflicts exist

Distributed Distance-1 Coloring



Distributed Distance-2 Coloring

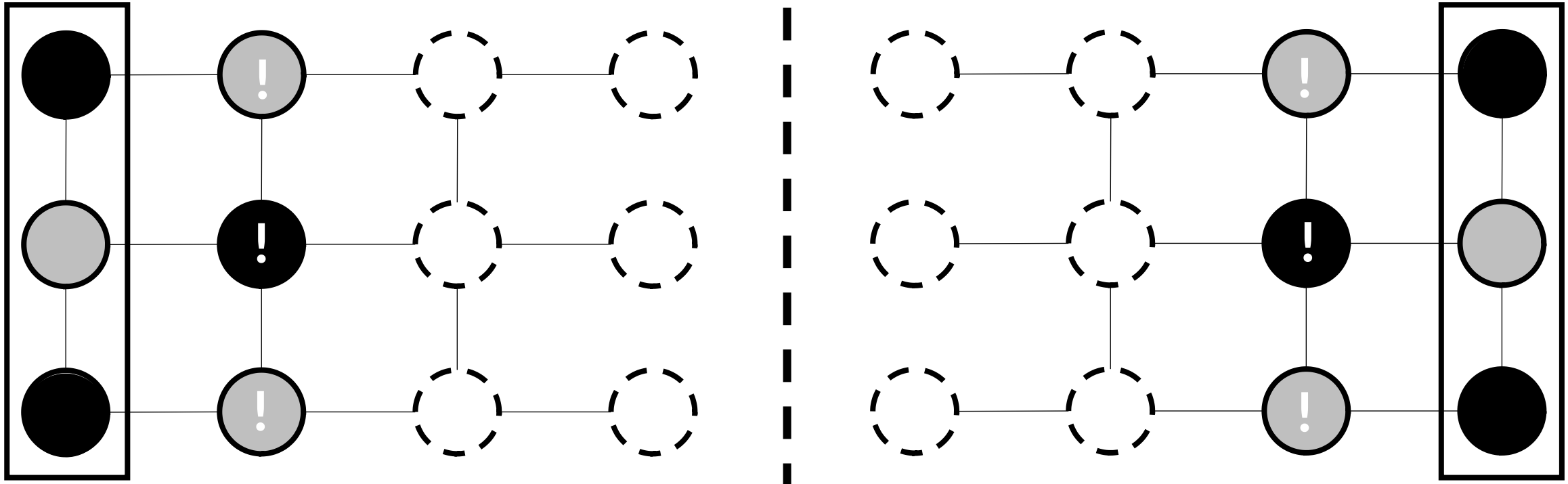
We add another layer of **ghost vertices** by copying the first ghost layer's neighbors. Second layer ghosts only have edges to the first ghost layer



Distance-1 with Two Ghost Layers (D1-2GL)

These ghosts will not conflict with any ghosts

Each process can resolve conflicts independently, without communicating (in this example)

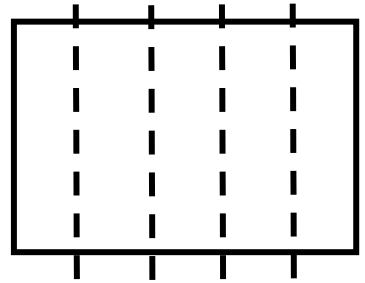


D1-2GL Aims To Reduce the Total Number of Collective Communications

- Second ghost layer vertices can get recolored, in general
- Local colorings need to make the same choices independently
- Each communication costs more
  - Ghosts can be on more than one process
  - Each ghost copy also copies its neighbors
  - Very expensive for dense inputs

Our Results Include Real and Synthetic Inputs

- Our real inputs come from a variety of domains
  - Including: PDEs, social networks, road networks
  - Range in size from 0.9 M vtx, 21 M edges to 30 M vtx, 3.3 B edges
  - Max degrees vary from 13 to 2.9 M
  - Use XtraPuLP graph partitioner developed by Slota et al. (2017)
- Our synthetic inputs are uniform hexahedral meshes
  - Vary only one dimension to keep communication costs constant
  - Partitioned in slabs
  - Range in size from 12.5 M vtx, 75 M edges to 12.8 B vtx, 76.7 B edges



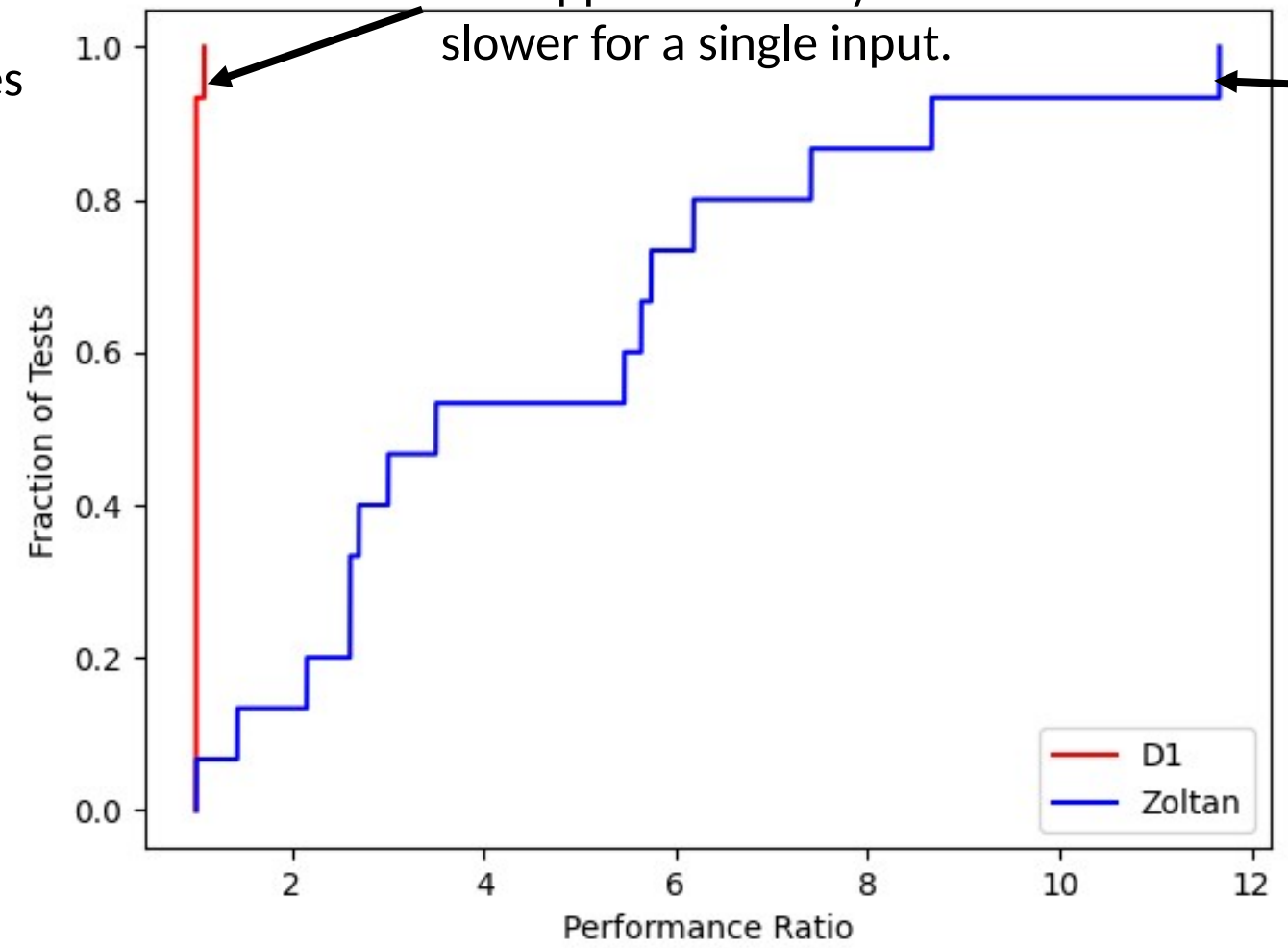
Experimental Setup

- We performed tests on AiMOS, housed at RPI.
  - 268 nodes with 2 IBM Power9 3.15GHz processors
    - 4 NVIDIA Tesla V100 GPUs with 16GB of memory connected with NVLink
  - Infiniband interconnect
  - Compiled with xlC 16.1.1, and Spectrum MPI with GPU-Direct disabled
- We run all experiments with 4 ranks per node
  - On GPU runs each rank gets an exclusive GPU
  - For performance profiles we use 128 ranks, or the largest run for which all approaches completed a run
- Zoltan is a package of the Trilinos Library containing distributed combinatorial algorithms, has MPI-only distance-1 and distance-2 implementations
  - http://cs.sandia.gov/zoltan
  - Run with 4 ranks per node, no shared-memory parallelism

Distance-1 Runtime Performance Profile

Performance ratio can be thought of as how many times slower one approach is than the other

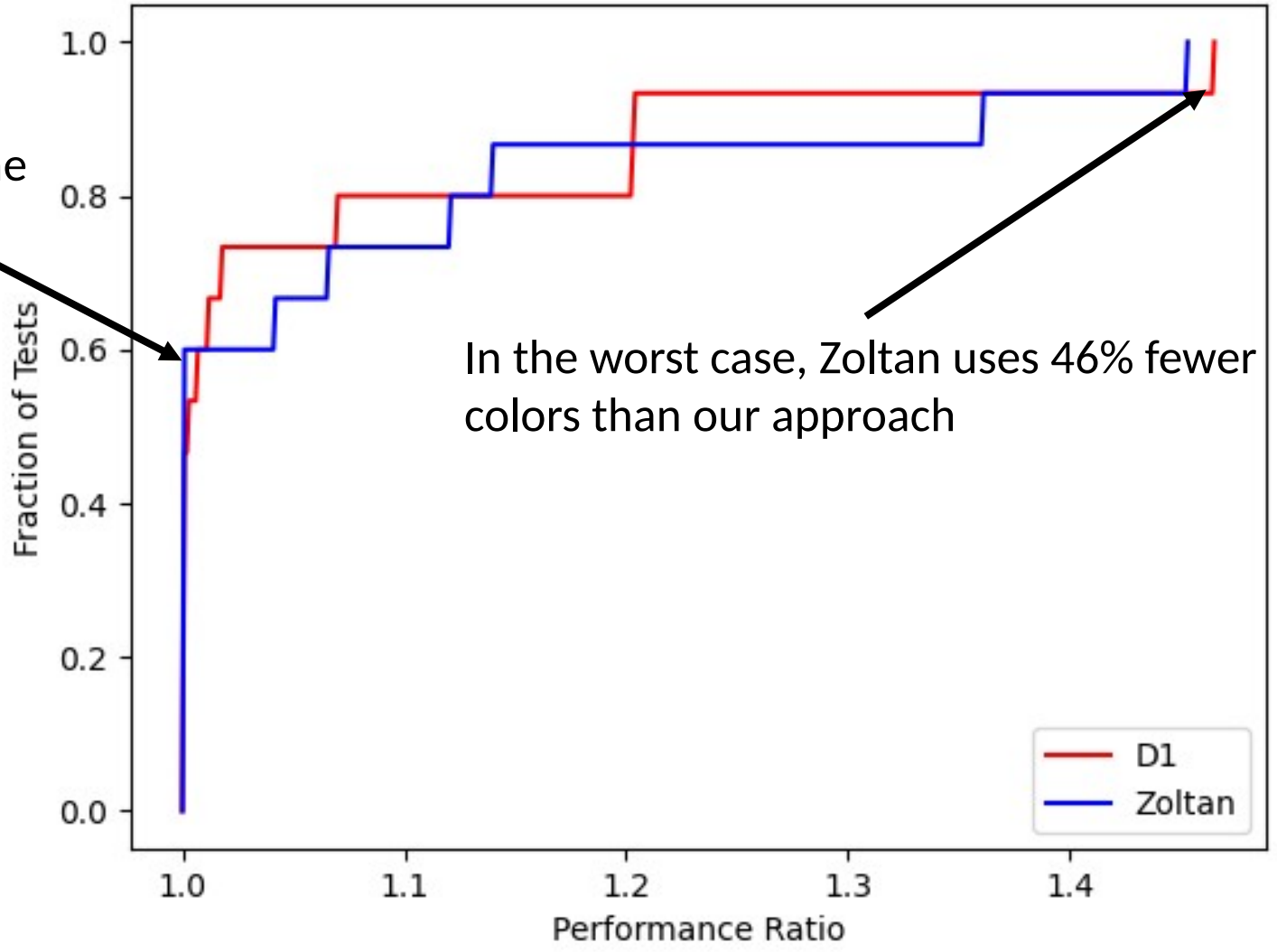
Our approach is only **8%** slower for a single input.



Our approach is around **12x** faster than Zoltan in the best case

Distance-1 Color Usage Performance Profile

Zoltan uses fewer colors in 60% of the inputs

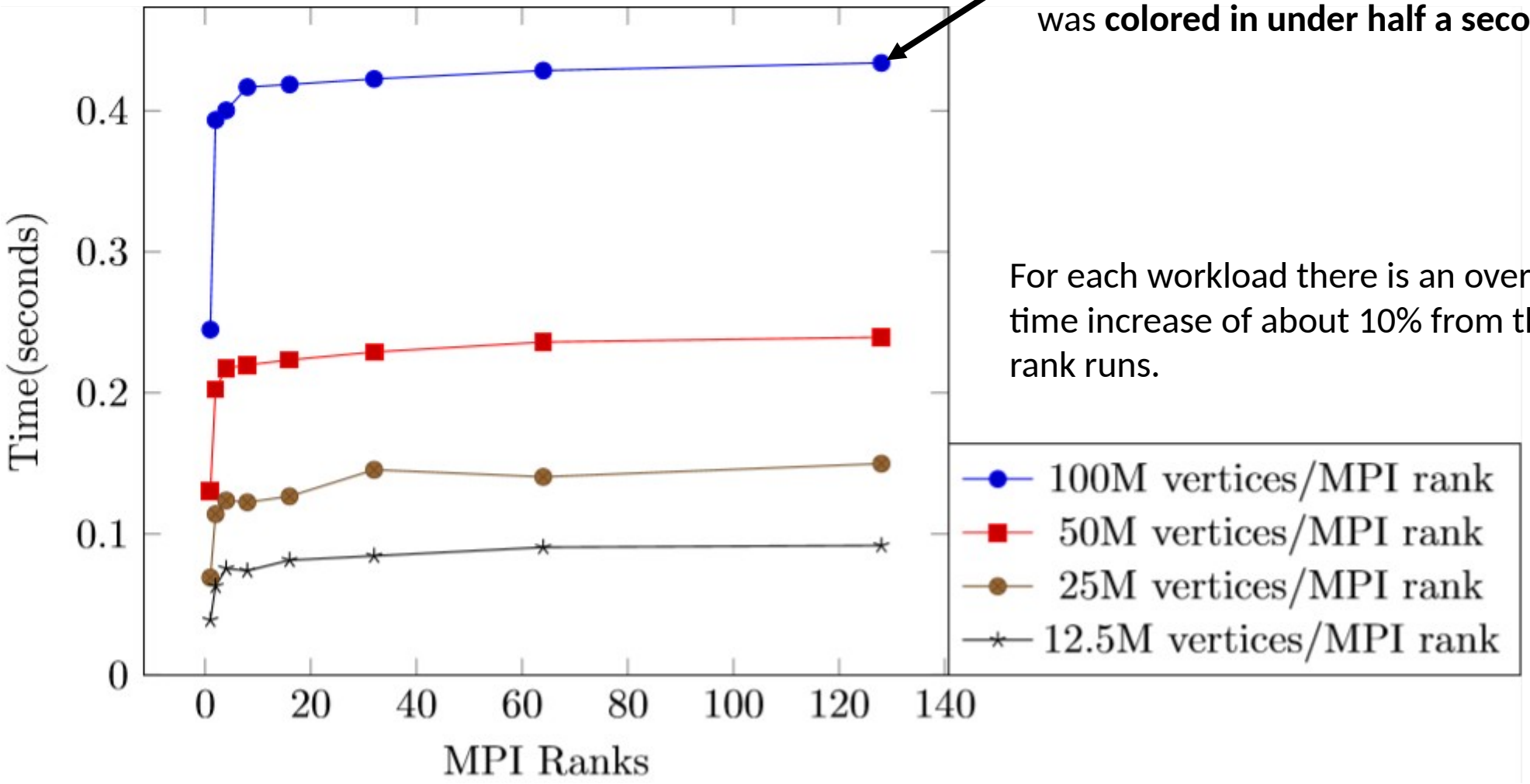


In the worst case, Zoltan uses 46% fewer colors than our approach

On average we use **6.8% more colors** than Zoltan

Distance-1 Weak Scaling

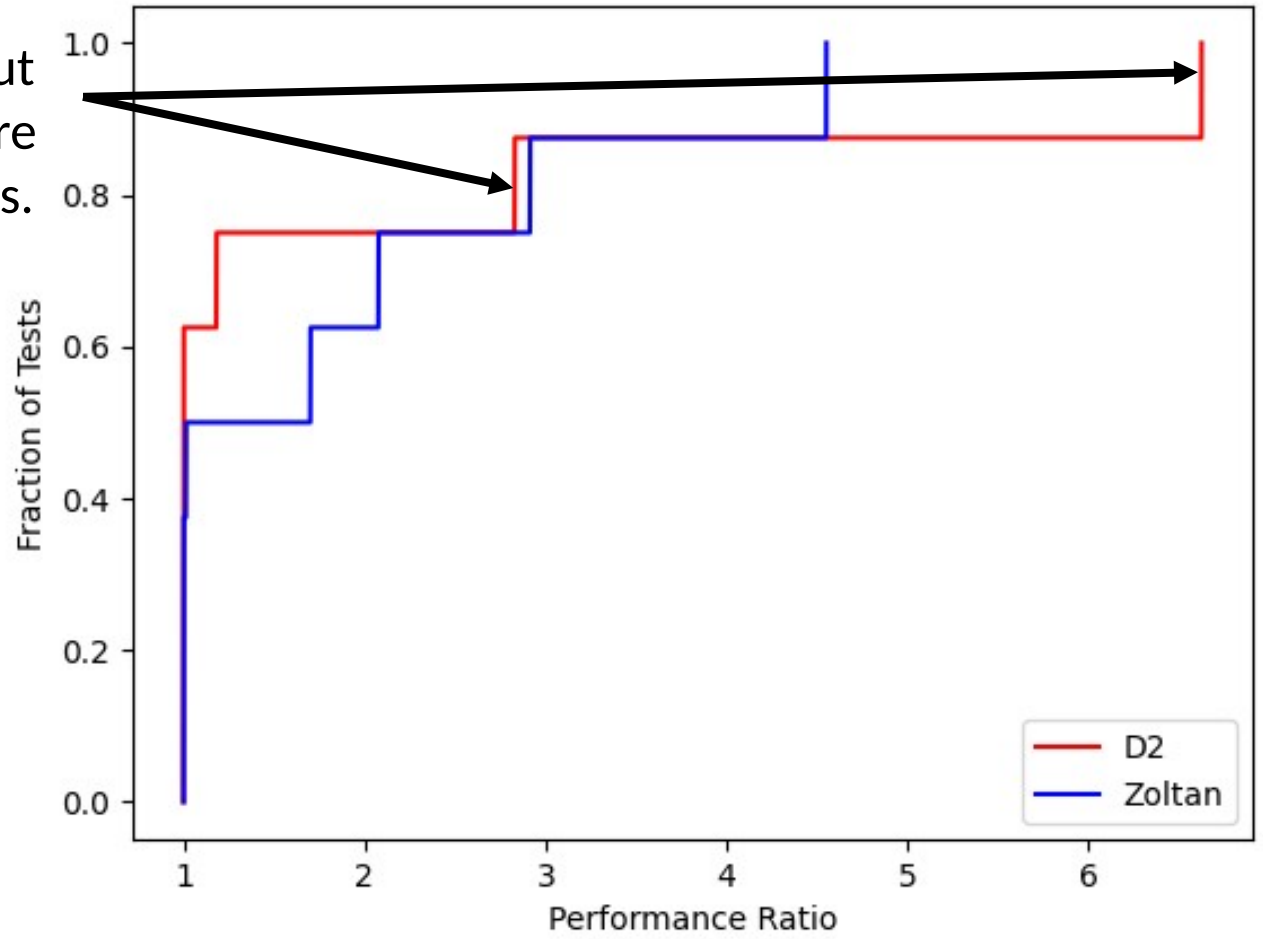
The largest input we ran has **12.8 Billion vertices** and **76.7 Billion edges**, which was **colored in under half a second**.



For each workload there is an overall time increase of about 10% from the 2 rank runs.

Distance-2 Runtime Performance Profile

We are competitive with Zoltan for all but two inputs, which are highly skewed inputs.

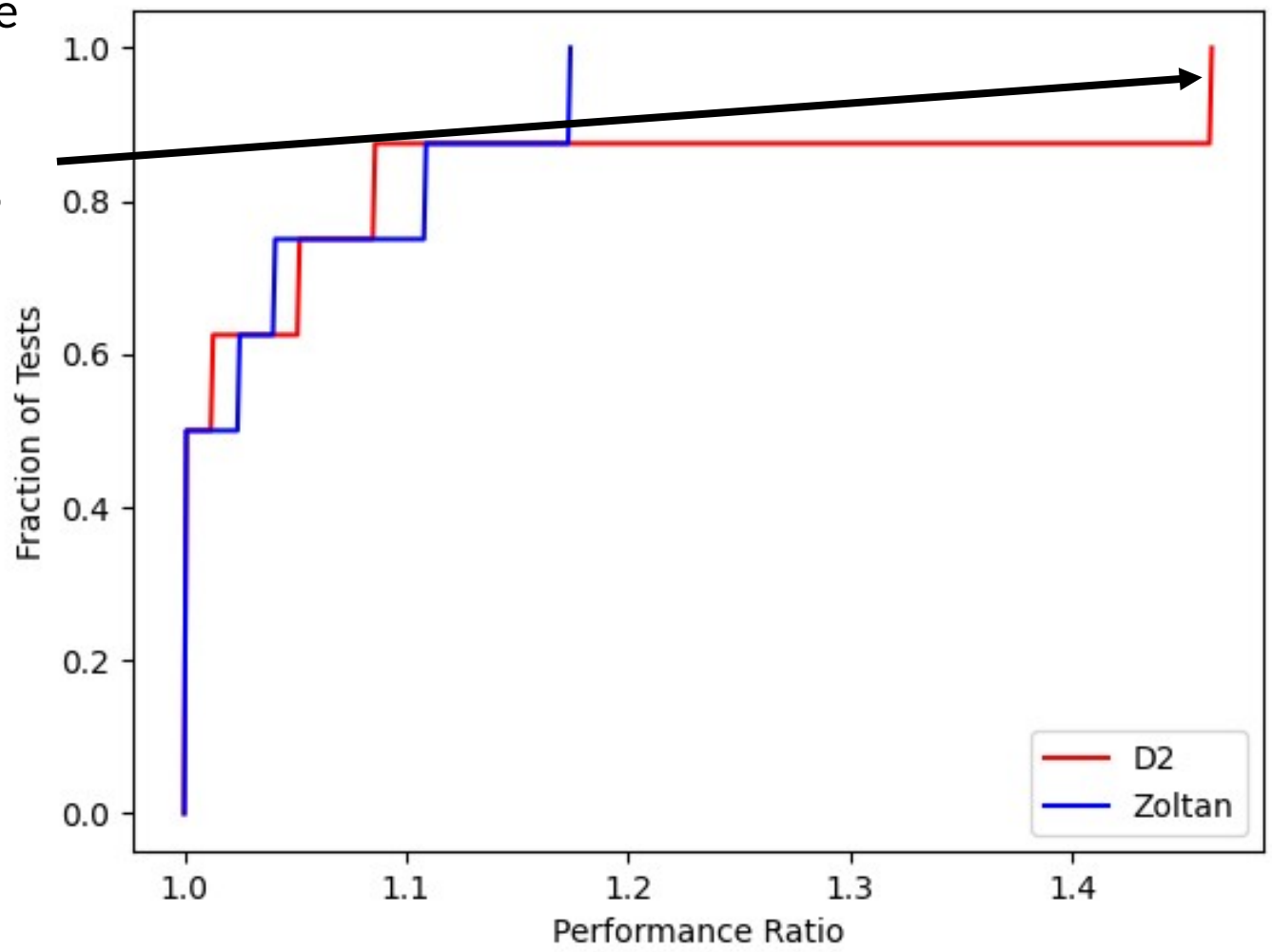


We use a smaller set of inputs for these profiles

Our approach sees at most a **4.5x speedup** relative to Zoltan

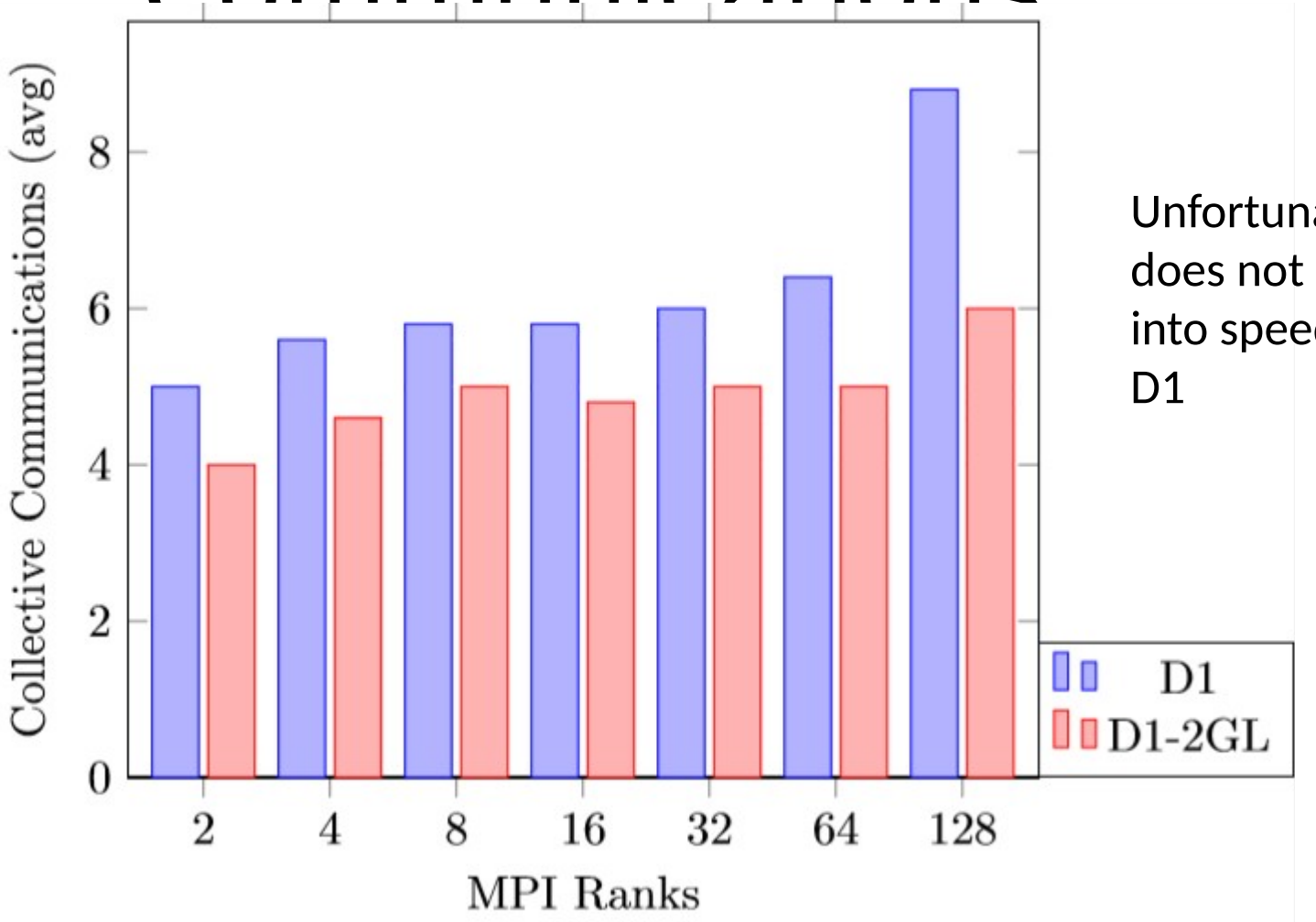
Distance-2 Color Usage Performance Profile

We are competitive with Zoltan on all but one input, where we use 46% more colors than Zoltan.



Our approach uses at most 10% more colors than Zoltan in all but one case

Two Ghost Layers Reduce the Number of Collective Communications



Unfortunately, this does not translate into speedup over D1

Future Work

- Optimizing distance-2 communication
- Extending our approach to solve different coloring problems
- Exploring optimizations to D1-2GL communication

Main contributions and results

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