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Enabling Tractable Exploration of the Performance of Adaptive Mesh Refinement

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Motivation

- An implementation of AMR in a mini-app to explore issues with AMR on parallel machines
  - added complexity of AMR bookkeeping
  - refinement frequency
  - load balancing strategies (frequency and methods)
  - effects of indirection
  - effects of block size
  - communication strategies
  - OpenMP strategies (future work)
  - task parallel programming models (future work)

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miniAMR

- AMR version of miniGhost – written in C
- Part of the Mantevo Suite (mantevo.org)
- Same finite volume calculation as miniGhost
  - no real physics and little fake physics, but kernel could be easily modified
- Many smaller blocks per processor
- Similar communication strategy to miniGhost
  - May have more communication partners due to the block structure
- Needs load balancing
  - One area may refine while rest does not
- More complicated bookkeeping
  - each block has between 6 and 24 neighbors and parent

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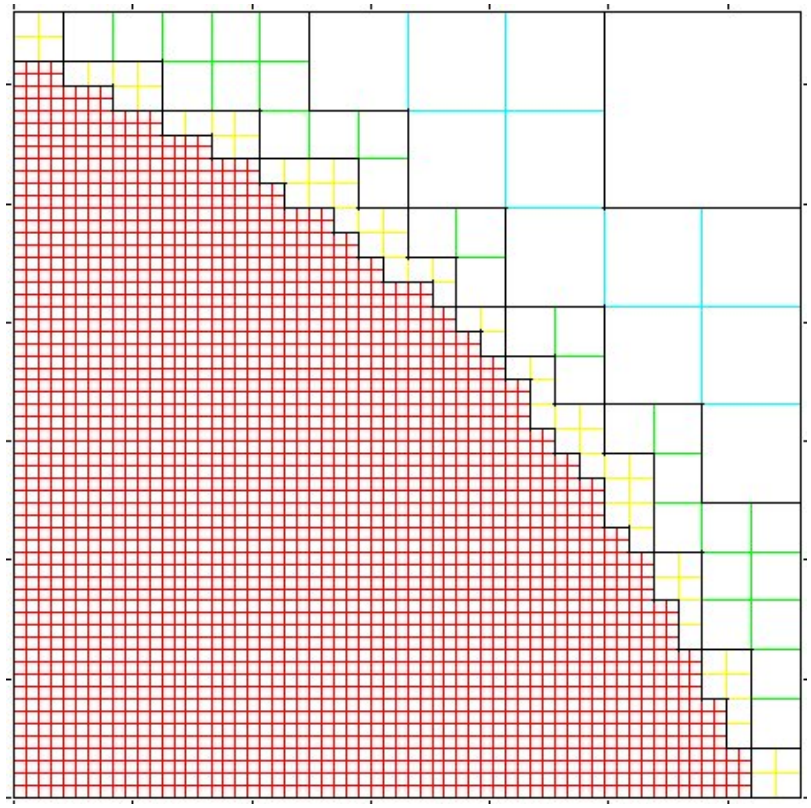
Details of AMR

- All blocks have same number of cells
- Blocks can only have “1 to 1” or “2 to 1” ratio with neighbors
- Area refine determined by moving shapes through mesh

2D slice of 3D mesh with sphere



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AMR Details Continued

- Initial mesh is a unit cube
- Each processor has an initial number of blocks at the lowest refinement level
- Initially the processors are arranged in a npx x npy x npz grid with position determined by an RCB (Recursive Coordinate Bisection) ordering
- Refinement is controlled by objects that move through the mesh and can change size
- Typical problems for AMR applications will have 4 to 7 levels of refinement

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Structure of miniAMR

```
for some number of timesteps {
  for some number of stages {
    communicate ghost values between blocks
    perform stencil calculation on arrays
    if time for checksums
      perform checksum calculations and compare
  }
  if time for refinement
    refine mesh
}
```

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Communication

- For each direction, each rank maintains a list of its block's faces that need to be communicated to adjacent ranks
  - ordered by rank
- Communication step for one direction
  - Post receives
  - Pack messages and do sends
  - Do on-rank communication of faces via memory copy
  - Complete receives and unpack messages

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Refinement

- When a block is refined, it is replaced by 8 blocks (2 x 2 x 2) each being half the physical size in each direction, but with the same number of cells
- The original block's communications in the lists are revised to reflect the new blocks
- A parent block is created to replace the original block
  - Stays on rank where created during load balancing
- Coarsening is done similarly except that all eight blocks need to be on the same rank as the parent before they can be consolidated

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Refinement (continued)

- Marking blocks for refinement is done by levels starting with the most refined blocks
  - Refining a block can cause its neighbors to refine or prevent them from unrefining
- After each level is marked then the results are communicated and then the next level can be marked
- Blocks that are marked to be refined are refined, changes to the mesh are communicated, and then any blocks that need to be consolidated are

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Load Balancing

- After blocks are refined (or unrefined), then load balancing is done
- We use Recursive Coordinate Bisection (RCB) with the directions fixed during initialization
  - This keeps data movement down
- At each step, a group or ranks and associated blocks are divided into some number of sets and then the process is repeated for each set
- Since block locations in a direction are limited, we represent the centers by an integer, and determining the cut can be done by binning the centers

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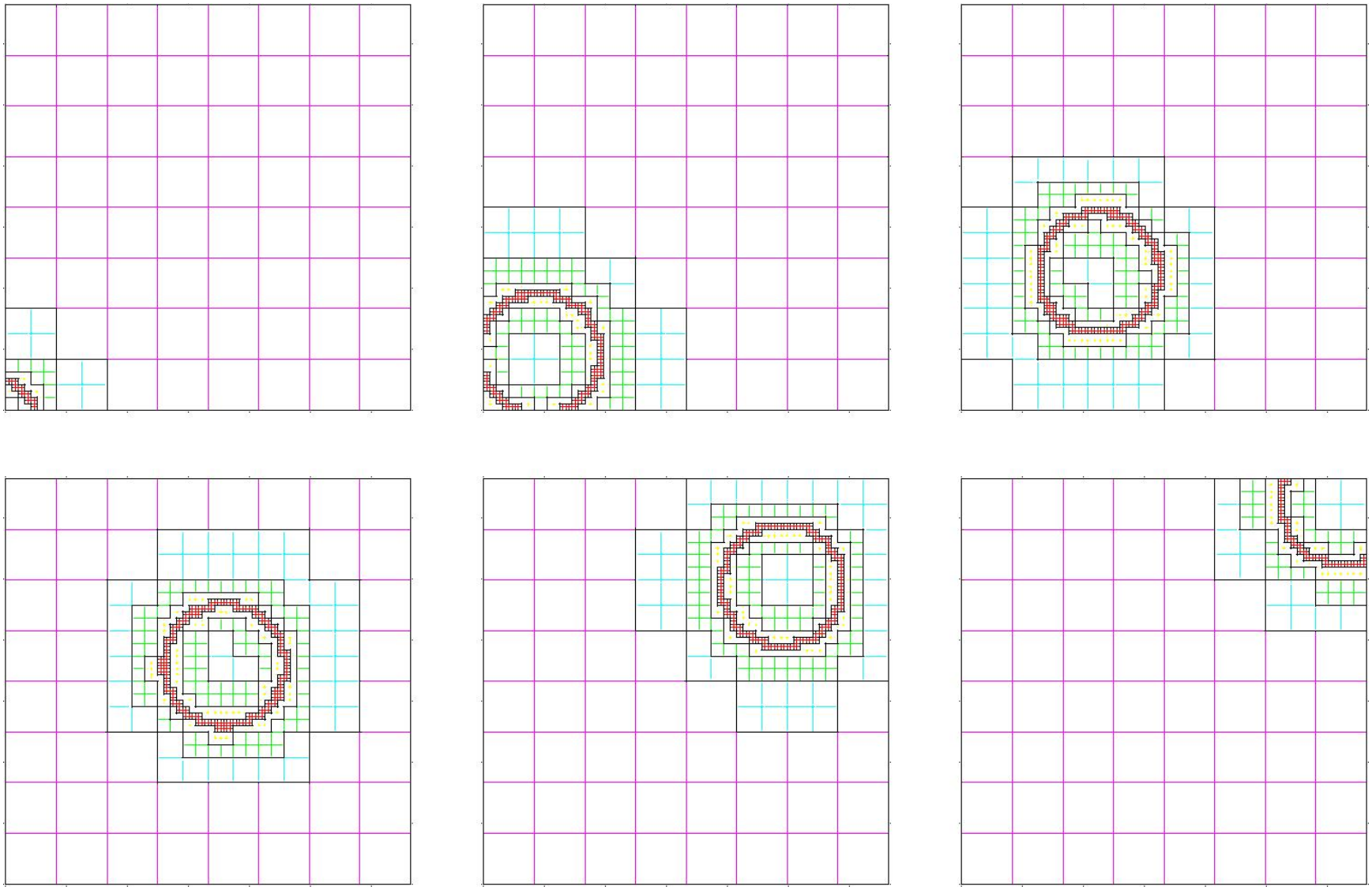
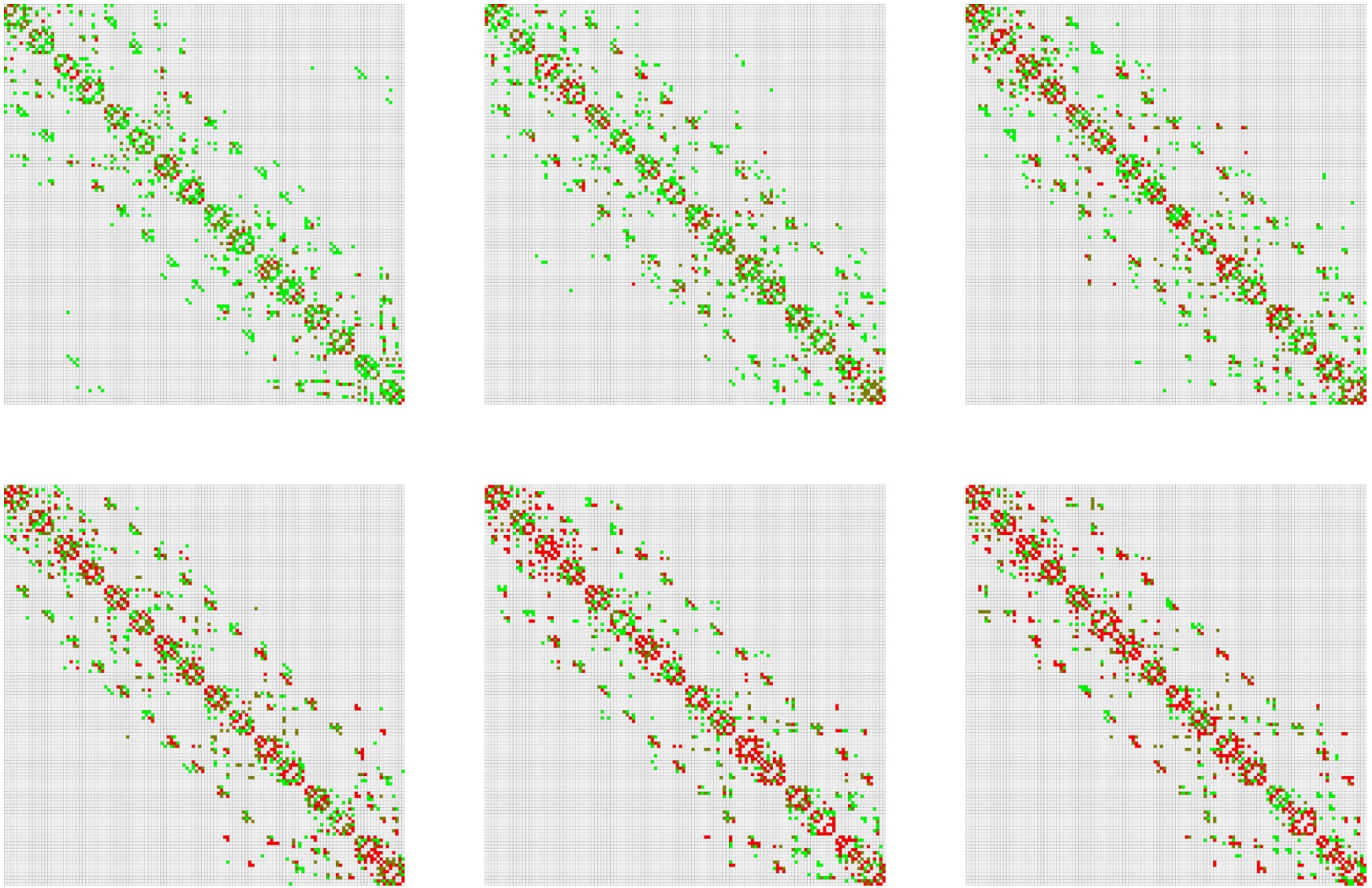
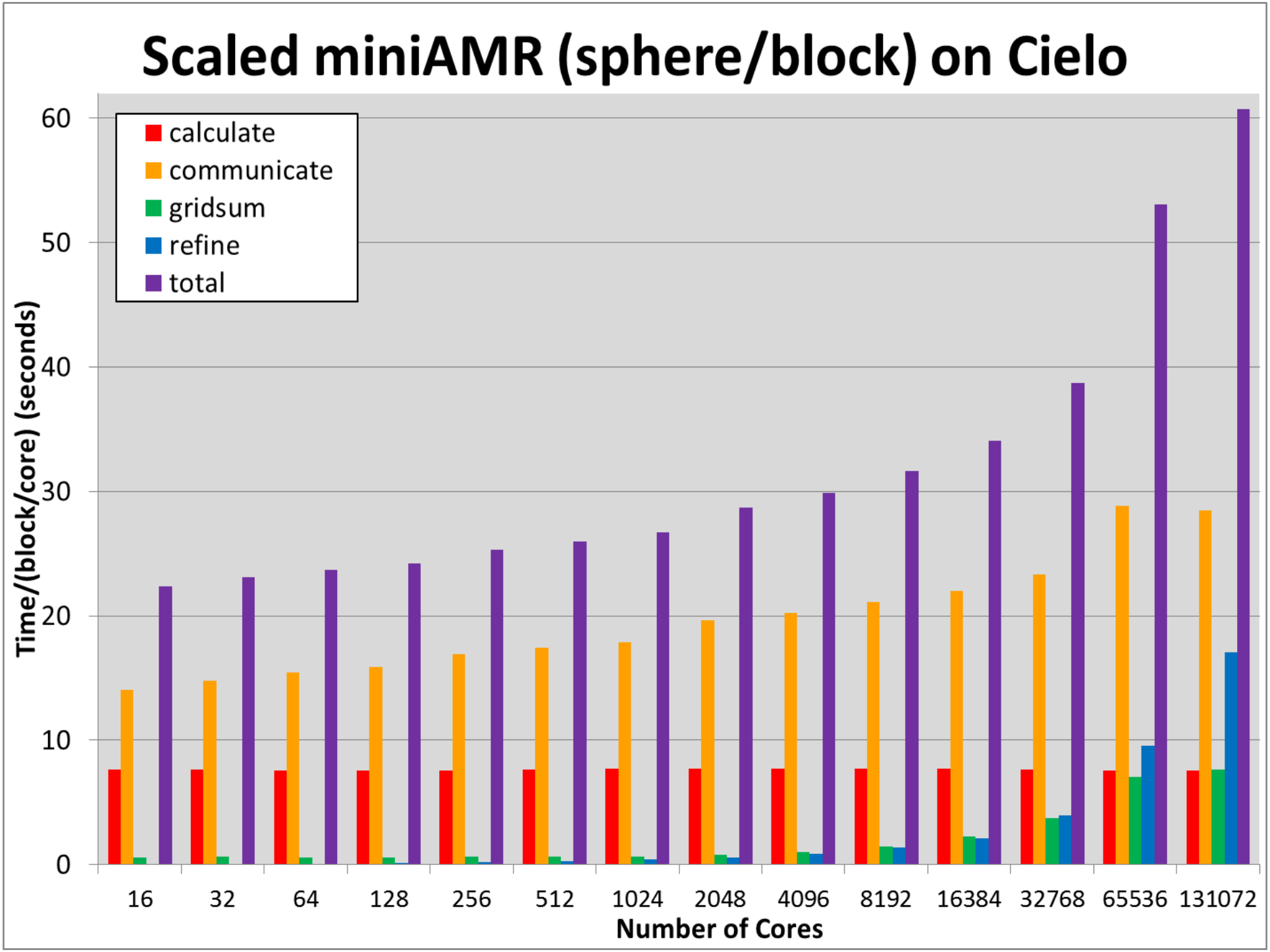
miniAMR – block structure – hollow sphere



Ghost Value Communication Pattern Changes




Scaled miniAMR (sphere/block) on Cielo
calculate
communicate
gridsum
refine
total
Time/(block/core) (seconds)
0
10
20
30
40
50
60
16
32
64
128
256
512
1024
2048
4096
8192
16384
32768
65536
131072
Number of Cores

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Comments on Scaled Speedup Curve

- Communication dominates the time and is increasing gradually
  - Includes time to communicate boundary information on blocks on the same core (30.6% of communication time on 128 cores)
- Calculation time is a consistent amount of time per block
  - If completely refined, then the 128 core problem would have 524288 blocks instead of 18168 and the calculation time would be 218 seconds instead of 7.6 seconds
- The refinement and gridsum times both are increasing gradually
- These reflect tradeoffs that AMR makes to allow problems to be run in less time on fewer nodes

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- Three-dimensional shock hydrodynamics code
- In AMR mode, each processor has a number of smaller blocks and typically sends more smaller messages
  - Communication pattern changes during run
- During each timestep, there are several stages, each of which has a ghost value exchange, and some number of collective operations
  - For problems we are using, there are 17 boundary exchanges and 62 collectives per timestep

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Comparison with CTH

- Run Sphere hits Block problem on 128 cores
- CTH problem is a sphere that hits a block at an oblique angle and produces a shock wave
  - modeled in miniAMR as a deforming spheroid with an expanding hemisphere to represent the shock
- CTH averages 140.9 blocks/core over the run
  - average core has 16.3 messages per communication stage that average 261 KB
- miniAMR averages 141.9 blocks/core over the run
  - average core has 18.4 messages per communication stage that average 224 KB

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Communication Matrices (sphere hits block)

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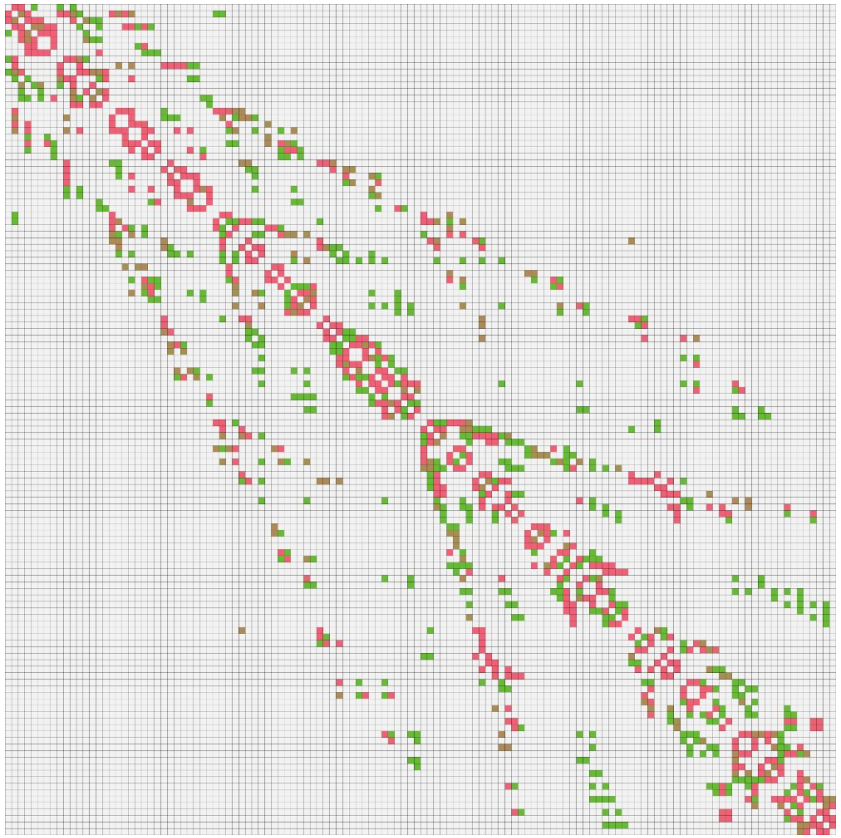
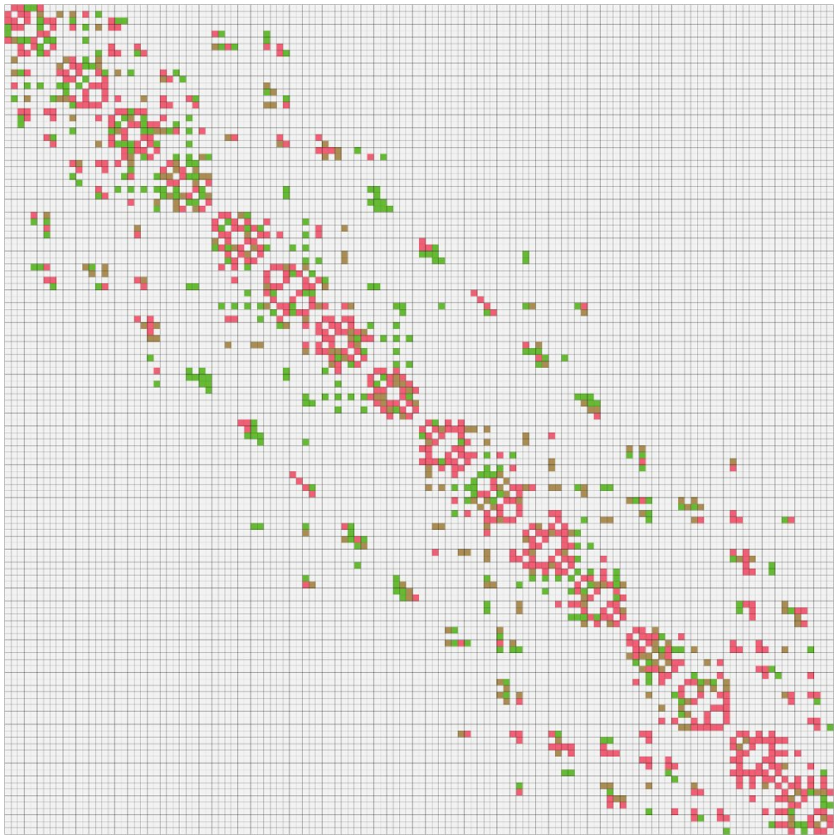
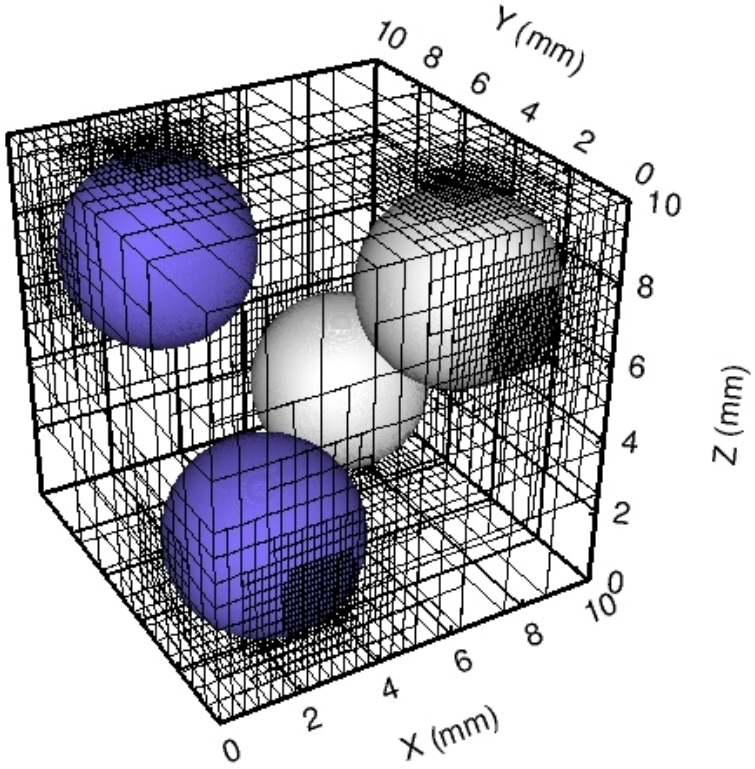


miniAMR



Comparison with CTH (Four Spheres)

- Run on 128 cores
- CTH
  - 685.8 blocks/rank
  - 18.4 messages
  - 503 KB average
- miniAMR
  - 669.3 blocks/rank
  - 17.3 messages
  - 593 KB average



Communication Matrices
Four Spheres

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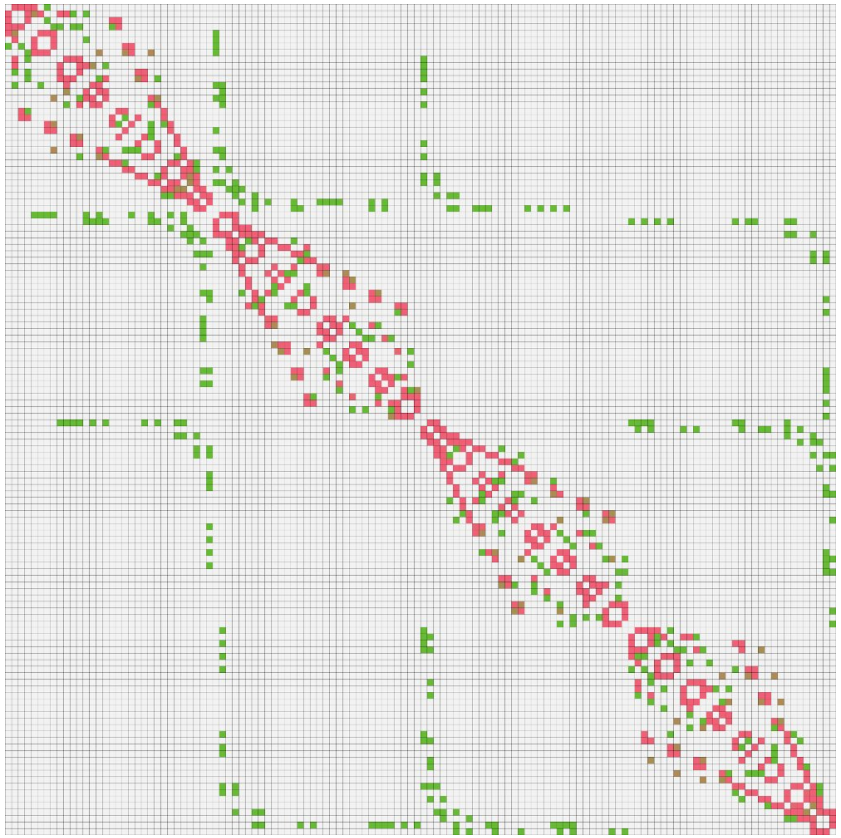
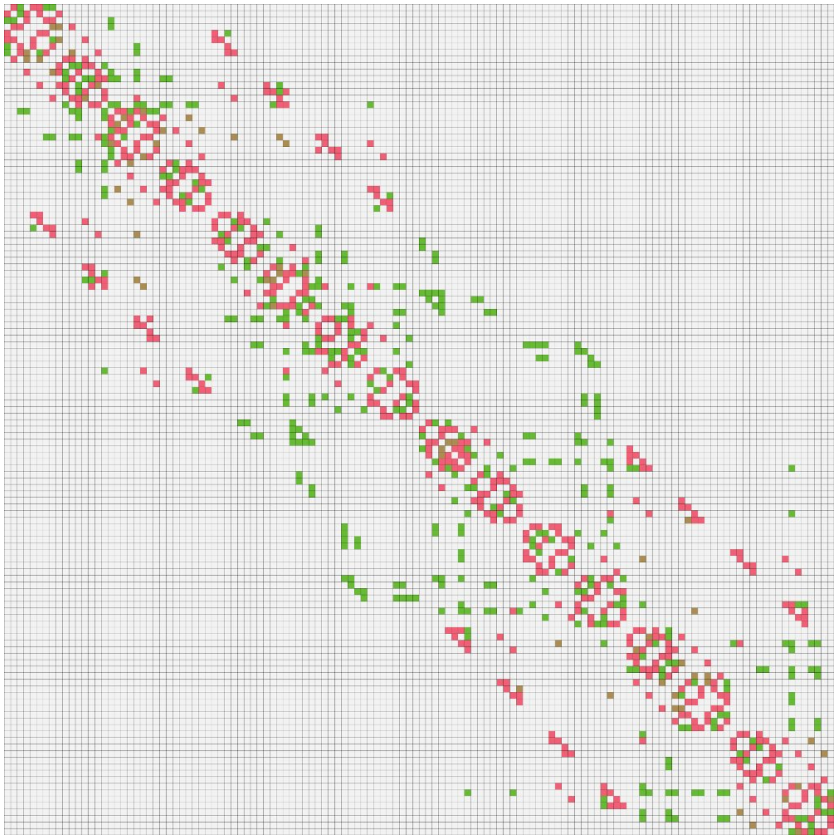


miniAMR



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Communication Differences

- Communication patterns are dependent on the load balancing after refinement
- Three differences between CTH and miniAMR
  - For CTH when a cut is made and there are ties, those blocks are assigned in a random fashion, while miniAMR blocks are assigned based on their position in the cut plane
  - CTH limits the number of blocks that can be moved at any timestep, while miniAMR has no limit
  - CTH allows the cut directions in RCB to be determined when the cuts are made, while these are fixed for miniAMR at initialization

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Modifications to miniAMR load balancing

- Modified miniAMR load balancing to mimic that of CTH
- For Four Spheres problem, the number of blocks moved increased by a factor of 8 and the refinement time tripled
- In addition, the communication time increased by 14% due to the number of messages and size increasing

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Communication Matrices
Sphere hits block

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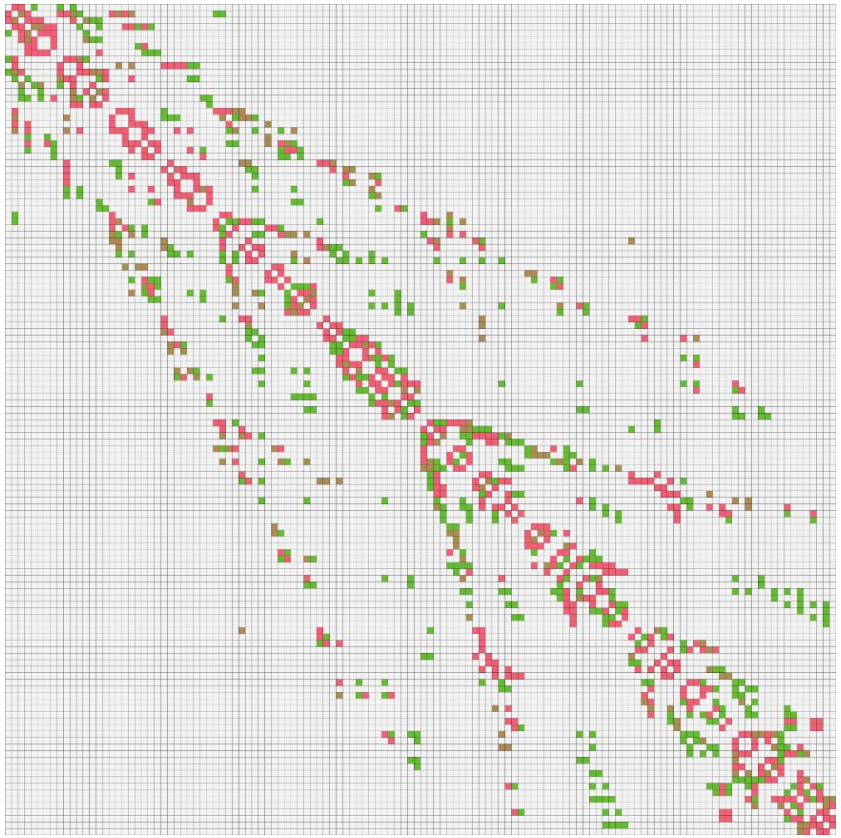
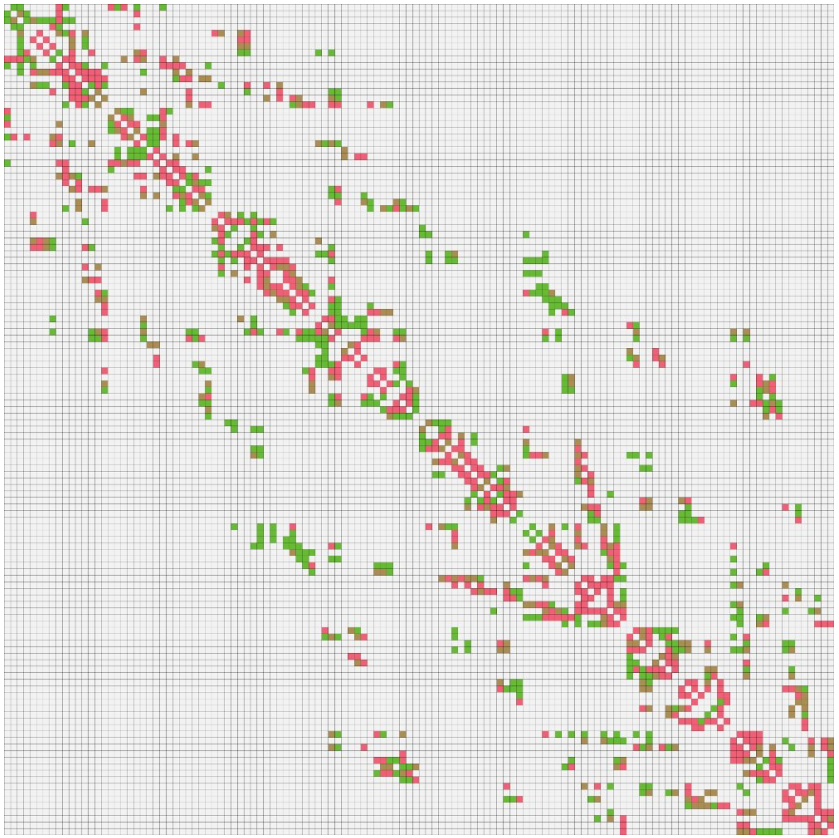


modified miniAMR



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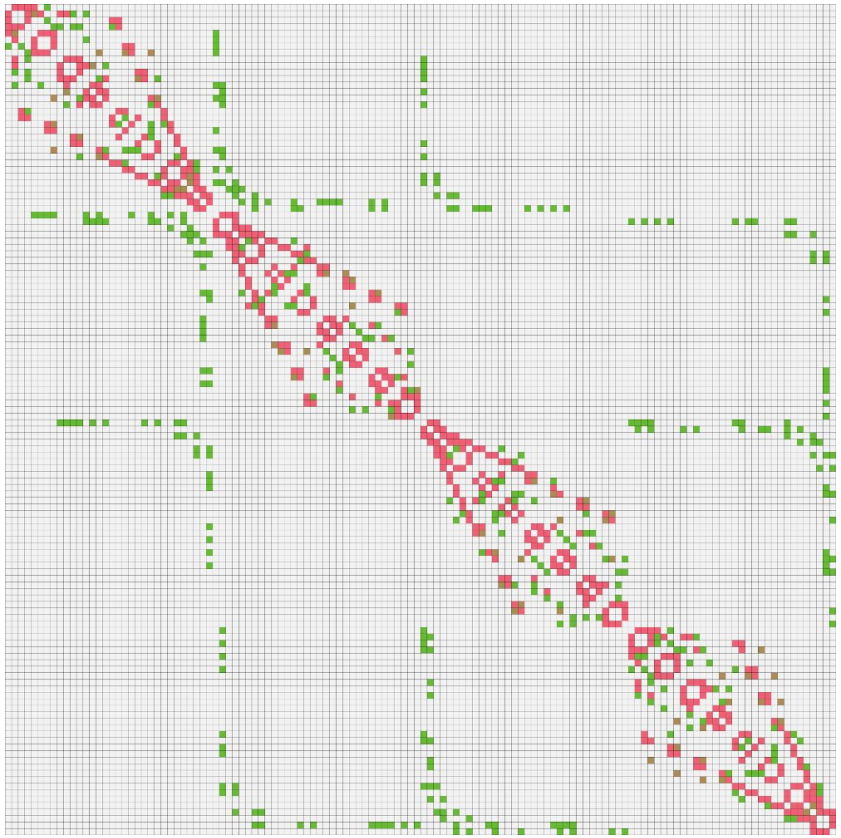
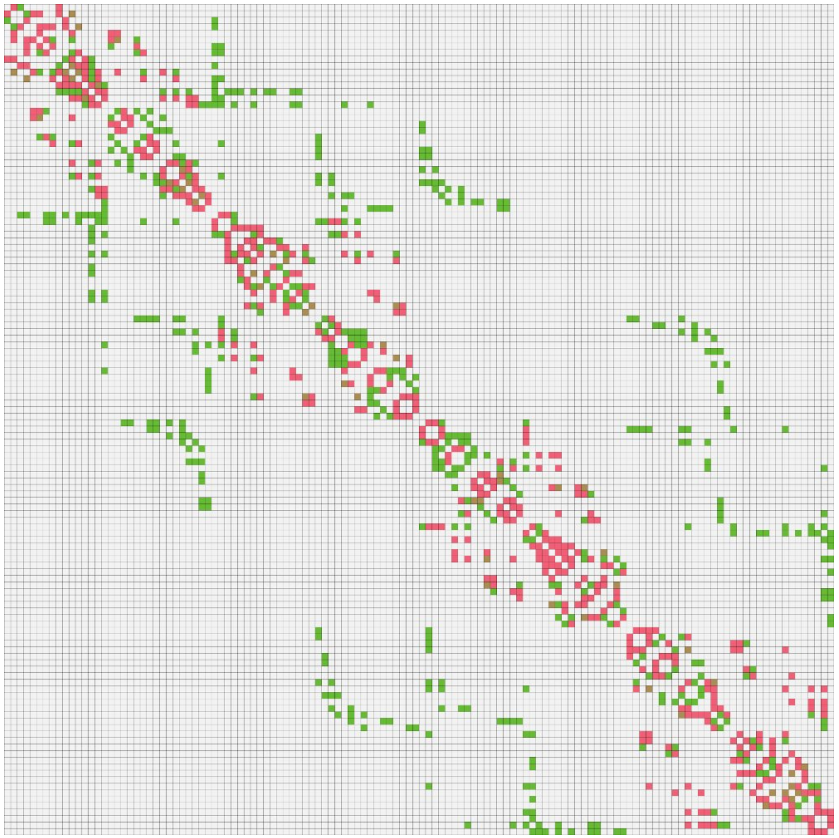
Communication Matrices
Four Spheres

CTH



modified miniAMR



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Communication for Refinement Step
Sphere hits Block

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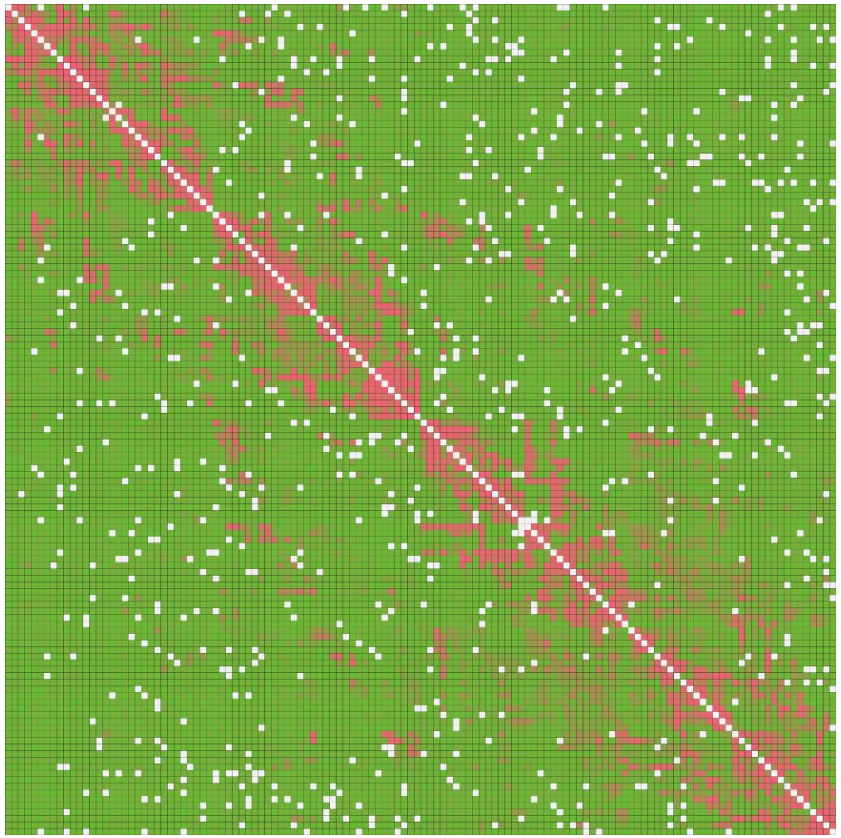
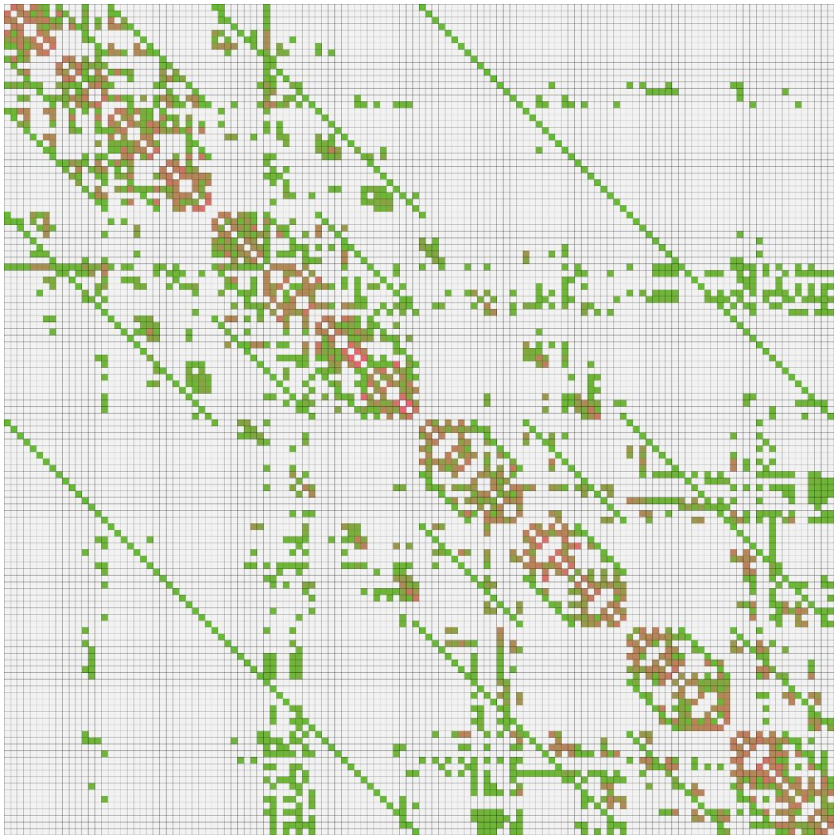
CTH



miniAMR



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Refinement Step Differences

- Refinement step communication has the regular communication pattern embedded in it since information about what blocks are being refined has to be passed to neighboring blocks
- Diagonal lines in miniAMR matrix is communication for load balancing
- Large amount of communication for CTH is communication with parent blocks since CTH load balances those parent blocks
- CTH uses 34 times as many messages and communicates 54 times as much information for refinement than does miniAMR

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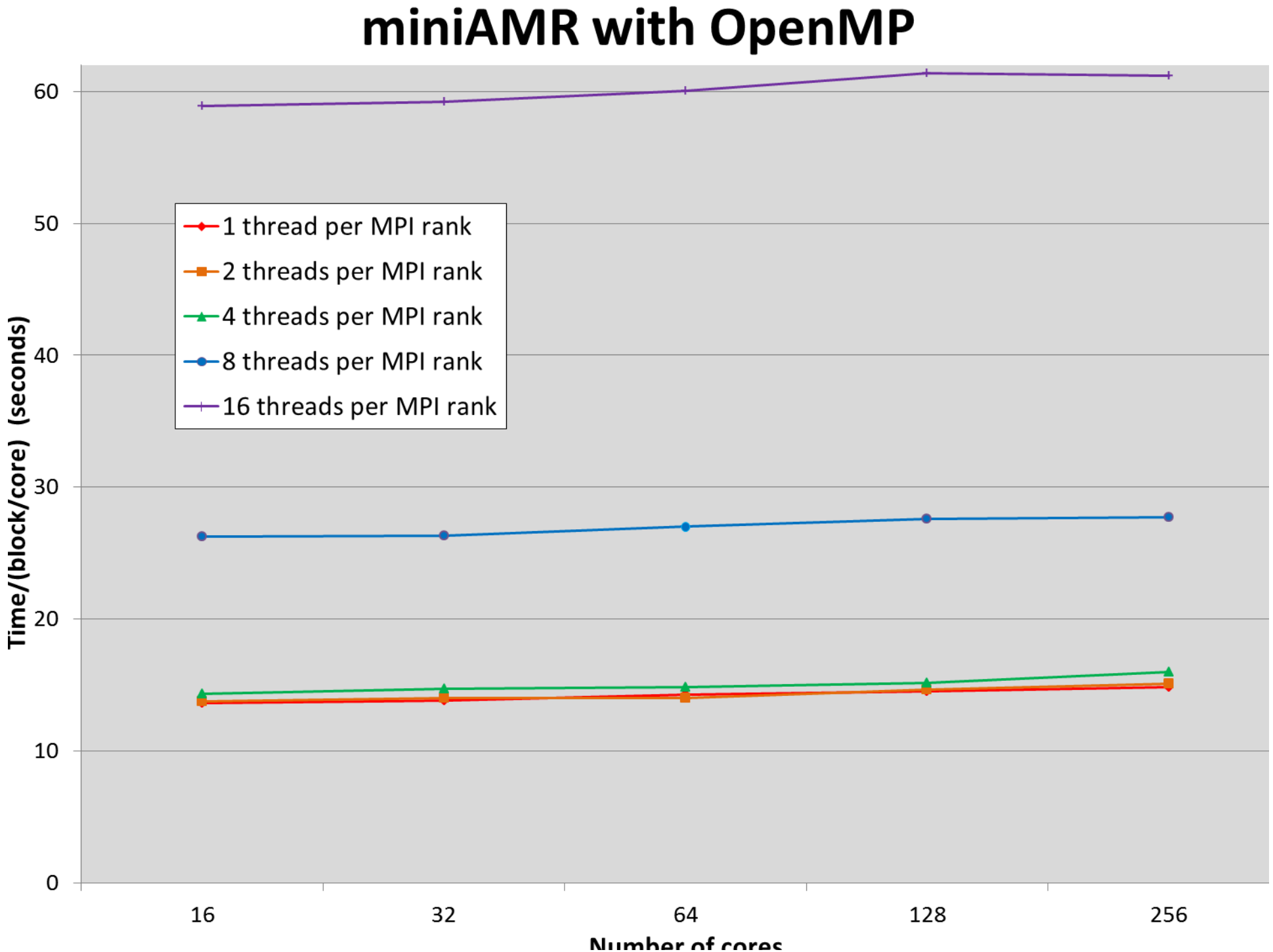
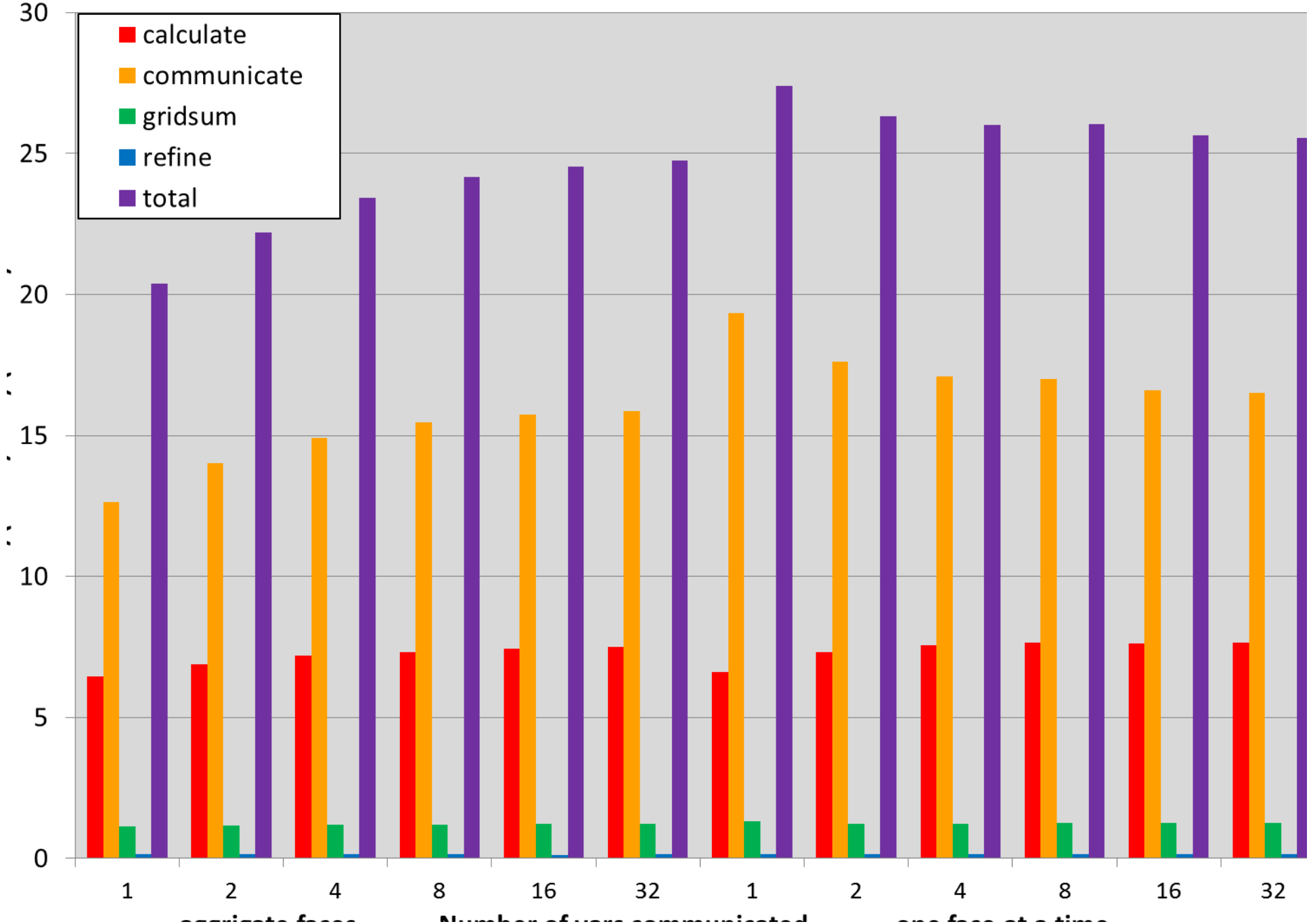

miniAMR with OpenMP
60
50
40
30
20
10
0
Time/(block/core) (seconds)
1 thread per MPI rank
2 threads per MPI rank
4 threads per MPI rank
8 threads per MPI rank
16 threads per MPI rank
16
32
64
128
256
Number of cores

miniAMR Sphere/Block Problem on 128 cores



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Conclusions and Future Directions

- miniAMR can be fairly representative of the communication portion of CTH in AMR mode
  - We have explained the differences in the codes
- We are planning to use what we have learned from miniAMR to improve CTH
- We are planning to improve the OpenMP implementation of miniAMR
- We are working on a task-parallel version of miniAMR
- We are working on other changes to miniAMR to look at varying workloads among blocks

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