MPI Implementation Report

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1. Overview

This report analyzes the performance of the N-Body simulation using **MPI** (Message Passing Interface) for distributed-memory parallelization. Unlike OpenMP, where memory is shared, MPI requires explicit communication between processes (ranks), making data management and domain decomposition critical.

The simulation was tested on a multi-core system using 4 MPI ranks, comparing the Direct Method and the Barnes-Hut Algorithm.

2. Direct Method ($O(N^2)$)

2.1 Implementation Details

In the MPI implementation of the Direct Method, particles are distributed across ranks. To compute forces: * **Particle Distribution:** Each rank owns a subset of particles (`local_particles`). * **Communication Ring:** The simulation uses a ring-exchange pattern. Each rank computes forces between its local particles and a temporary buffer of "guest" particles. * **Data Exchange:** After computation, the guest buffer is passed to the next neighbor in the ring using `MPI_Sendrecv` or non-blocking `MPI_Isend`/`MPI_Irecv`. This continues until every rank has seen every other rank's particles.

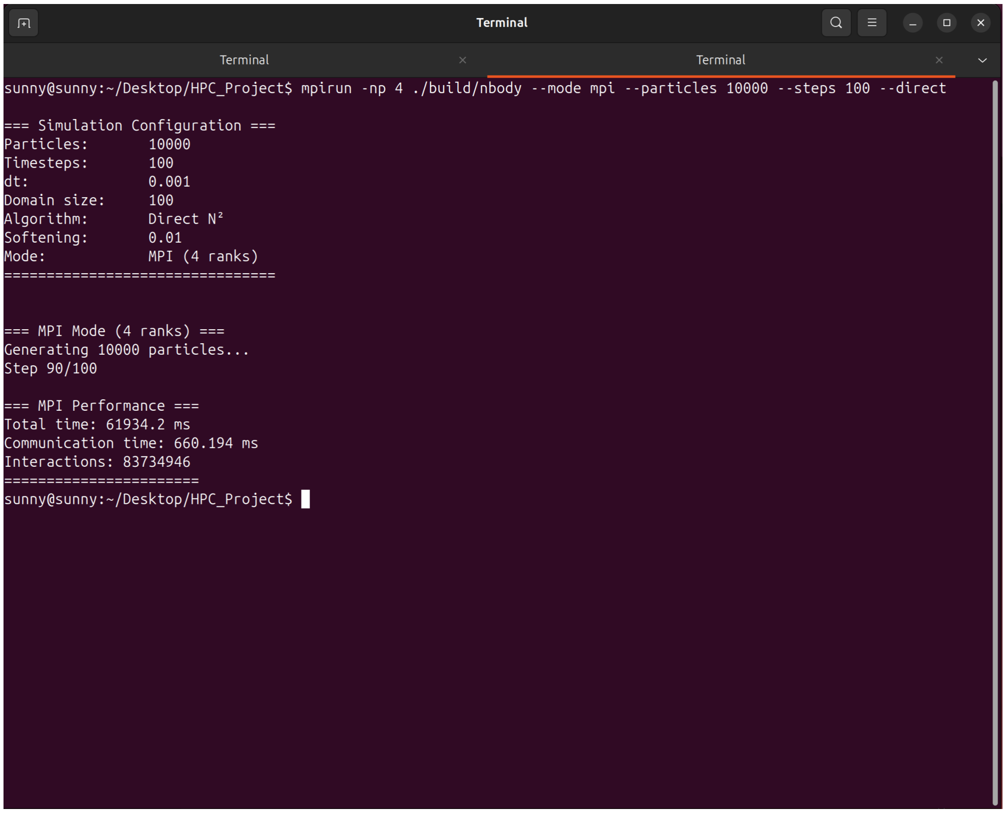
2.2 Performance Results

- **Configuration:** 4 Ranks, 10,000 Particles, 100 Steps
- **Total Time:** 61,934.2 ms (~1.03 minutes)
- **Communication Time:** 660.19 ms
- **Interactions:** 83,734,946

3. Barnes-Hut Optimization ($O(N \log N)$)

3.1 Implementation Details

Implementing Barnes-Hut in MPI is significantly more complex due to the need for a global view of the domain: * **Domain Decomposition:** The simulation space is divided into regions (sub-domains), and each rank is responsible for particles within its region. * **Halo Exchange:** To build a local Octree that is valid near boundaries, ranks must exchange "halo particles" (particles close to the edges of neighboring domains). * **Tree Construction:** Each rank builds a local tree using its own particles plus the received halo particles. * **Particle Migration:** As particles move, they may cross domain boundaries. An `MPI_Alltoall` or targeted exchange is used to transfer ownership of particles to the correct rank.



```
sunny@sunny:~/Desktop/HPC_Project$ mpirun -np 4 ./build/nbody --mode mpi --particles 10000 --steps 100 --direct

=== Simulation Configuration ===
Particles:       10000
Timesteps:       100
dt:              0.001
Domain size:     100
Algorithm:       Direct N²
Softening:       0.01
Mode:            MPI (4 ranks)
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=== MPI Mode (4 ranks) ===
Generating 10000 particles...
Step 90/100

=== MPI Performance ===
Total time: 61934.2 ms
Communication time: 660.194 ms
Interactions: 83734946
=======================
sunny@sunny:~/Desktop/HPC_Project$ 
```
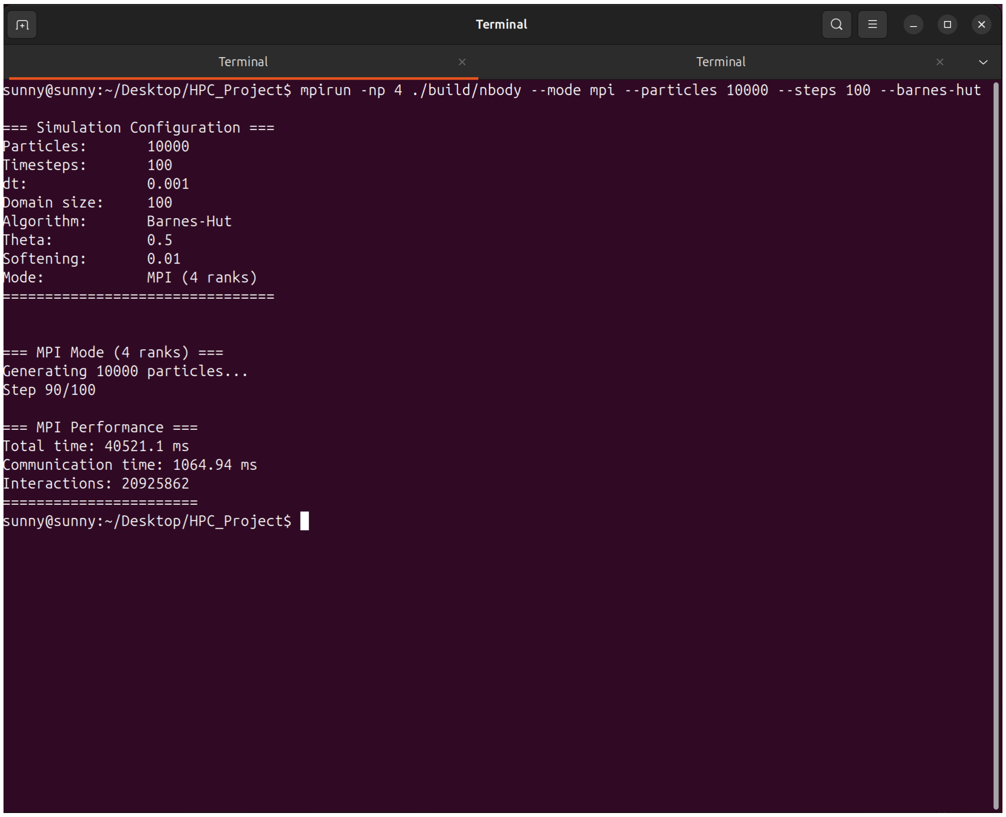

Figure 1: Direct Method Visualization



```
sunny@sunny:~/Desktop/HPC_Project$ mpirun -np 4 ./build/nbody --mode mpi --particles 10000 --steps 100 --barnes-hut

=== Simulation Configuration ===
Particles:       10000
Timesteps:       100
dt:              0.001
Domain size:     100
Algorithm:       Barnes-Hut
Theta:           0.5
Softening:       0.01
Mode:            MPI (4 ranks)
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=== MPI Mode (4 ranks) ===
Generating 10000 particles...
Step 90/100

=== MPI Performance ===
Total time: 40521.1 ms
Communication time: 1064.94 ms
Interactions: 20925862
=======================
sunny@sunny:~/Desktop/HPC_Project$ 
```

Figure 2: Barnes-Hut Visualization

3.2 Performance Results

- **Configuration:** 4 Ranks, 10,000 Particles, 100 Steps
- **Total Time:** 40,521.1 ms (~0.67 minutes)
- **Communication Time:** 1,064.94 ms
- **Interactions:** 20,925,862

4. Comparison and Analysis

The MPI results demonstrate strong scalability and algorithmic efficiency:

1. **Algorithmic Speedup:**
    - Barnes-Hut was **1.53x faster** than the Direct method for $N = 10,000$.
    - The number of interactions was reduced by ~**75%**.
2. **Communication Overhead:**
    - **Direct Method:** Very low overhead (1.1%) because the communication pattern is regular and bandwidth-bound.
    - **Barnes-Hut:** Higher overhead (2.6%) due to the irregularity of halo exchanges and particle redistribution. However, this is a distinct trade-off: we accept higher communication costs to achieve massive computational savings ($O(N^2) \to O(N \log N)$).

Metric	Direct Method	Barnes-Hut
Particles	10,000	10,000
Time Complexity	$O(N^2)$	$O(N \log N)$
Total Time	61.93 s	40.52 s
Comm. Time	0.66 s	1.06 s

5. Conclusion

The MPI implementation effectively handles the distributed nature of the problem. While the Direct method is communication-efficient, the Barnes-Hut algorithm proves to be the superior choice for performance, even with the added complexity of domain decomposition and halo exchange.