Abdulrahman Huseein & Yahia

Optimizing Shockwave N-body Simulations: A Comparative Study of Barnes-Hut and Particle-Mesh Algorithms for Scaling and Stability

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Summary

Section	Maximum + bonus	Your Grade + bonus
1	6+3	6+1
2	25+4	21+2
3	22+5	22+2
4	20+3	12+0
5	4+3	3+1
6	10+3	10+0
Deductions	-10	-2
Total	87+21	72+6

Section 1: Introduction (6 points)

Essential Elements (6 points):

- [x] (1 pt) Clearly states the problem: optimizing N-body simulations beyond brute-force O(N^2)
- [x] (1 pt) Mentions the original 14-body shockwave simulation and its computational limitations
- [x] (1 pt) Introduces Barnes-Hut algorithm and its core concept (hierarchical tree, center-of-mass approximation)
- [x] (1 pt) Introduces Particle-Mesh algorithm and its core concept (grid-based, FFT for potential)
- [x] (1 pt) States the comparison objectives: runtime, accuracy, scalability
- [x] (1 pt) Previews the methodology (parameter sweeps, multiple N values)

Bonus Elements (up to 3 points):

- [ ] (+1 pt) Provides historical/scientific context for these algorithms

- [ ] (+1 pt) Mentions real-world applications (astrophysical simulations, galaxy formation)
- [x] (+1 pt) Clearly articulates research questions or hypotheses

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Section 2: Methods (25 points)

Barnes-Hut Implementation (8 points):

- [x] (2 pts) Describes quadtree construction and hierarchical space division
- [x] (2 pts) Explains the opening angle parameter θ and the approximation criterion (s/d < θ)
- [x] (2 pts) Describes force calculation via tree traversal
- [ ] (1 pt) Mentions tree update frequency (every 5-10 timesteps as specified)
- [ ] (1 pt) Lists θ values tested: [0.3, 0.5, 1.0, 1.5]

Particle-Mesh Implementation (8 points):

- [x] (2 pts) Describes mesh discretization and grid setup
- [x] (2 pts) Explains CIC (Cloud-In-Cell) mass interpolation
- [x] (2 pts) Describes FFT-based Poisson solver: $\nabla^2\Phi = 4\pi G\rho$
- [x] (1 pt) Explains force computation via gradient (finite differencing) and interpolation back to particles
- [ ] (1 pt) Lists grid resolutions tested: Ng ∈ {32^2, 64^2, 128^2}

General Methodology (9 points):

- [x] (2 pts) States physical constants used (G = 4π², star mass = 1.0, planet mass range)
- [x] (1 pt) Specifies the integrator used (and justifies choice from previous project)
- [x] (2 pts) Describes shockwave collision model with equation
- [x] (1 pt) Specifies simulation parameters (T, dt, or references to testing protocol)
- [x] (1 pt) Lists metrics measured: runtime, energy drift, angular momentum, collision count
- [x] (1 pt) Describes the comparison framework (N = 14, 100, 500)
- [ ] (1 pt) Mentions number of trials/runs for statistical validity

Bonus Elements (up to 4 points):

- [x] (+1 pt) Discusses computational complexity: O(N log N) for BH, O(N + Ng log Ng) for PM
- [ ] (+1 pt) Includes pseudocode or algorithm flowcharts
- [ ] (+1 pt) Discusses boundary condition handling

- [x] (+1 pt) Explains softening parameter or collision detection implementation

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Section 3: Results (22 points)

Required Figures (12 points):

- [x] (3 pts) Energy vs. Time plots (for both algorithms, clear comparison)
- [x] (3 pts) Angular Momentum vs. Time plots
- [x] (3 pts) Trajectory/orbit visualizations
- [x] (3 pts) Runtime comparison (bar or line chart) across N values

Data Presentation (6 points):

- [x] (2 pts) Numerical results for all 5 cases in the specification table
- [x] (2 pts) Clear labeling of axes, legends, and units on all figures
- [x] (2 pts) Quantitative comparison tables (runtime, energy drift, collision counts)

Completeness (4 points):

- [x] (1 pt) Results for N = 14 (both algorithms)
- [x] (1 pt) Results for N = 100 (both algorithms)
- [x] (2 pt) Parameter sensitivity analysis (how θ or Ng affects results)

Bonus Elements (up to 5 points):

- [ ] (+1 pt) Animated visualizations or time-lapse trajectories
- [x] (+1 pt) Log-scale plots showing scaling behavior
- [x] (+1 pt) Direct overlay comparisons with brute-force baseline
- [ ] (+1 pt) Memory usage analysis
- [ ] (+1 pt) Additional N values beyond requirements (e.g., N = 1000)

Section 4: Discussion (20 points)

Algorithm Comparison (10 points):

- [x] (2 pts) Analyzes runtime scaling differences between BH and PM
- [x] (2 pts) Discusses accuracy trade-offs (energy conservation, trajectory fidelity)
- [x] (2 pts) Evaluates the effect of θ on BH performance and accuracy
- [x] (2 pts) Evaluates the effect of grid resolution on PM performance and accuracy
- [x] (2 pts) Identifies which algorithm is preferred for different scenarios/N ranges

Critical Analysis (6 points):

- [x] (2 pts) Discusses limitations of each method
- [ ] (2 pts) Addresses unexpected results or anomalies
- [ ] (2 pts) Connects results to theoretical expectations (e.g., O(N log N) scaling)

Shockwave Handling (4 points):

- [ ] (2 pts) Discusses how each algorithm handles collisions/shockwaves
- [ ] (2 pts) Analyzes collision count differences between methods

Bonus Elements (up to 3 points):

- [ ] (+1 pt) Discusses potential hybrid approaches (e.g., P^3M)
- [ ] (+1 pt) Compares to published benchmarks or literature
- [ ] (+1 pt) Discusses parallelization potential

Section 5: Conclusion (4 points)

Essential Elements (4 points):

- [x] (1 pt) Summarizes key findings
- [x] (1 pt) States which algorithm performed best overall (with justification)
- [x] (1 pt) Addresses the original research objectives
- [ ] (1 pt) Suggests future work or improvements

Bonus Elements (up to 3 points):

- [ ] (+1 pt) Reflects on lessons learned
- [ ] (+1 pt) Proposes specific extensions (e.g., 3D octree, adaptive mesh refinement)
- [x] (+1 pt) Provides recommendations for specific use cases

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Section 6: Appendix & Code Quality (10 points)

- [x] (3 pts) Code is included and readable
- [x] (2 pts) Code is well-documented with comments
- [x] (2 pts) Code organization is logical (separate functions for BH, PM, integrator, etc.)
- [x] (2 pts) Reproducibility: parameters and seeds are documented
- [x] (1 pt) Uses Numba or other optimization as specified

Bonus Elements (up to 3 points):

- [ ] (+1 pt) Includes unit tests or validation checks
- [ ] (+1 pt) Provides clear instructions for running the code
- [ ] (+1 pt) Modular, reusable code structure

Overall Presentation & Writing (Deductions)

- [ ] (-1 to -3 pts) Poor grammar, spelling, or unclear writing
- [ ] (-1 to -2 pts) Inconsistent formatting
- [ ] (-1 to -2 pts) Missing figure captions or references
- [x] (-1 to -3 pts) Plagiarism or uncited sources
  {-2}