



Universiteit
Leiden
The Netherlands

The gravitational billion body problem : Het miljard deeltjes probleem
Bédorf, J.

Citation

Bédorf, J. (2014, September 2). *The gravitational billion body problem : Het miljard deeltjes probleem*. Retrieved from <https://hdl.handle.net/1887/28464>

Version: Corrected Publisher's Version

License: [Licence agreement concerning inclusion of doctoral thesis in the Institutional Repository of the University of Leiden](#)

Downloaded from: <https://hdl.handle.net/1887/28464>

Note: To cite this publication please use the final published version (if applicable).

Cover Page



Universiteit Leiden



The handle <http://hdl.handle.net/1887/28464> holds various files of this Leiden University dissertation

Author: Jeroen Bédorf

Title: The gravitational billion body problem / Het miljard deeltjes probleem

Issue Date: 2014-09-02

The Gravitational Billion Body Problem

Het miljard deeltjes probleem

Proefschrift

ter verkrijging van
de graad van Doctor aan de Universiteit Leiden,
op gezag van Rector Magnificus prof. mr. C.J.J.M. Stolker,
volgens besluit van het College voor Promoties
te verdedigen op dinsdag 2 september 2014
klokke 16:15 uur

door

Jeroen Bédorf
geboren te Alkmaar
in 1984

Promotiecommissie

Promotor: Prof. dr. Simon Portegies Zwart

Overige leden: Prof. dr. Steve L.W. McMillan (Drexel University)
Prof. dr. Henk Sips (Technische Universiteit Delft)
Prof. dr. Joost Batenburg (Centrum Wiskunde & Informatica /
Universiteit Leiden)
Prof. dr. Huub Röttgering

Contents

| | | |
|----------|---|-----------|
| 1 | Introduction | 1 |
| 1.1 | Introduction | 3 |
| 1.2 | The very beginning | 5 |
| 1.3 | 1960 - 1986: The Era Of Digital Computers | 5 |
| 1.4 | 1986 - 2000 : Advances in software | 7 |
| 1.5 | 2000 - 2006: The Era Of The GRAPE | 8 |
| 1.5.1 | GRAPE | 8 |
| 1.5.2 | Multi-Core Processors and Vector Instructions | 10 |
| 1.5.3 | Collisionless methods | 11 |
| 1.6 | 2006 - Today: The Era Of Commercial High Performance Processing Units | 11 |
| 1.6.1 | Collisional methods | 11 |
| 1.6.2 | Collisionless methods | 13 |
| 1.7 | Graphics Processing Units | 14 |
| 1.8 | Thesis Overview | 16 |
| 1.8.1 | Chapter 2 - Sapporo2 | 17 |
| 1.8.2 | Chapter 3 - OctGrav | 17 |
| 1.8.3 | Chapter 4 - Bonsai | 18 |
| 1.8.4 | Chapter 5 - Many Minor Mergers | 18 |
| 1.8.5 | Chapter 6 - Parallel Bonsai | 18 |
| 2 | Sapporo2 | 21 |
| 2.1 | Background | 22 |
| 2.2 | Methods | 23 |
| 2.2.1 | Parallelisation method | 23 |
| 2.2.2 | Implementation | 24 |
| 2.3 | Results | 26 |
| 2.3.1 | Thread-block configuration | 27 |
| 2.3.2 | Block-size / active-particles | 28 |
| 2.3.3 | Range of N | 29 |
| 2.3.4 | Double precision vs Double-single precision | 30 |
| 2.3.5 | Sixth order performance | 32 |
| 2.3.6 | Multi-GPU | 32 |

| | | |
|----------|---|-----------|
| 2.4 | Discussion and CPU support | 34 |
| 2.4.1 | CPU | 34 |
| 2.4.2 | XeonPhi | 35 |
| 2.5 | Conclusion | 36 |
| 3 | Octgrav | 37 |
| 3.1 | Introduction | 38 |
| 3.2 | Implementation | 39 |
| 3.2.1 | Building the octree | 39 |
| 3.2.2 | Construction of an interaction list | 40 |
| 3.2.3 | Calculating accelerations from the interaction list | 41 |
| 3.3 | Results | 42 |
| 3.3.1 | Accuracy of approximation | 43 |
| 3.3.2 | Timing | 44 |
| 3.3.3 | Device utilisation | 45 |
| 3.4 | Discussion and Conclusions | 46 |
| 4 | Bonsai | 49 |
| 4.1 | Introduction | 50 |
| 4.2 | Sparse octrees on GPUs | 52 |
| 4.2.1 | Tree construction | 52 |
| 4.2.2 | Tree traverse | 54 |
| 4.3 | Gravitational Tree-code | 56 |
| 4.3.1 | Time Integration | 56 |
| 4.3.2 | Tree-cell properties | 56 |
| 4.3.3 | Cell opening criterion | 57 |
| 4.4 | Performance and Accuracy | 58 |
| 4.4.1 | Performance | 59 |
| 4.4.2 | Accuracy | 61 |
| 4.5 | Discussion and Conclusions | 64 |
| 4.A | Scan algorithms | 67 |
| 4.A.1 | Stream Compaction | 67 |
| 4.A.2 | Split and Sort | 67 |
| 4.A.3 | Implementation | 68 |
| 4.B | Morton Key generation | 68 |
| 5 | The Effect of Many Minor Mergers | 71 |
| 5.1 | Introduction | 72 |
| 5.2 | Constraining the model parameters | 73 |
| 5.3 | Initializing the galaxy mergers | 77 |
| 5.3.1 | Configuring the major mergers | 77 |
| 5.3.2 | Configuring the minor mergers | 78 |
| 5.4 | Results | 79 |
| 5.4.1 | The growth of the primary due to subsequent mergers | 80 |
| 5.4.2 | The effect on the shape of the galaxies due to subsequent mergers | 82 |

| | | |
|----------|---|------------|
| 5.4.3 | The effect of the virial temperature | 84 |
| 5.5 | Discussion | 87 |
| 5.5.1 | Properties of the merger remnant | 87 |
| 5.6 | Conclusion | 91 |
| 5.A | Resolution effects | 91 |
| 5.B | The effect of child density | 92 |
| 5.B.1 | Circular velocity | 94 |
| 6 | Parallel Bonsai | 97 |
| 6.1 | Introduction | 98 |
| 6.2 | Quantitative discussion of current state of the art | 100 |
| 6.3 | Implementation | 101 |
| 6.3.1 | Tree-walk kernel optimizations | 102 |
| 6.3.2 | Parallelization | 103 |
| 6.4 | Simulating the Milky Way Galaxy | 106 |
| 6.5 | System and environment where performance was measured | 106 |
| 6.6 | Performance results | 108 |
| 6.6.1 | Operation counts | 108 |
| 6.6.2 | Parallel performance | 109 |
| 6.6.3 | Time-to-solution | 111 |
| 6.6.4 | Peak performance | 112 |
| 6.7 | Discussion | 112 |
| 7 | Conclusions | 115 |
| 7.1 | BRIDGE; Combining direct and hierarchical N -body methods | 115 |
| 7.2 | The future | 116 |
| 8 | Samenvatting | 119 |
| 8.1 | De hoofdstukken in dit proefschrift | 120 |
| 8.1.1 | Hoofdstuk 2 | 120 |
| 8.1.2 | Hoofdstuk 3 | 120 |
| 8.1.3 | Hoofdstuk 4 | 121 |
| 8.1.4 | Hoofdstuk 5 | 121 |
| 8.1.5 | Hoofdstuk 6 | 122 |
| | List of publications | 123 |
| | Bibliography | 125 |
| | Curriculum Vitae | 137 |
| | Acknowledgements | 139 |