Millions of Bodies, Millions of Cores: the Future of Collisional N-Body Simulations

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Abstract

We discuss the future of collisional N-body simulations on massively-parallel computers.

1. Introduction

Collision-less: "particles" are actually tracers. Do not want them to have the possibility to collide or interact too strongly.

Collisional: interested in two-body relaxation, also three-body and binary interactions around core-collapse, and physical collisions (not original meaning, but implied by collisional: enhanced by triple formation and also gravitational focusing).

- Astrophysics case: what can be done with direct dynamics, that cannot be achieved via other means (MC, FP integrations, etc)?
  - Analyize unusual, small-N populations (requires coupled stellar evolution); particularly when they are (partially) dynamically decoupled (i.e. Spitzer-unstable SMBH's).
  - Many-body events (may be important in core-collapse).
  - Tidal deformations/tails: adds a timescale (potential variation).
  - With stellar-evolution, have another timescale in the problem: SE, orbit, tidal, and cluster evolution; so cannot scale up from $N < N_{\text{physical}}$.
  - IMBH. Adds more timescales: orbital timescale, growth timescale (rate of repopulating loss cone).
- Current practice: only a few (NBODY6, Kira, Gorilla) codes, small-scale distributed, GPU, or GRAPE parallelism ($N \gg N_{\text{core}}$).
- Description of upcoming supercomputers (extrapolate to 5 years). $N_{\text{core}} \sim N$.

GRAPE 6:

$$\frac{N_{\text{core}}}{N} \sim \frac{10^4}{10^5} = 0.1. \tag{1}$$

GRAPE 4:

$$\frac{N_{\text{core}}}{N} \sim \frac{10^4}{3 \times 10^4} \sim 0.3. \tag{2}$$

GPU:

$$\frac{N_{\text{core}}}{N} \sim \frac{10^3}{10^4} \sim 0.1. \tag{3}$$

Cray (Nitadori et al., 2006):

$$\frac{N_{\text{core}}}{N} \sim \frac{4 \times 10^4}{1.6 \times 10^4} \sim 3. \tag{4}$$

K Computer:

$$\frac{N_{\text{core}}}{N} \sim \frac{4 \times 10^6}{10^6} \sim 4. \tag{5}$$

Exa-speed:

$$\frac{N_{\text{core}}}{N} \sim \frac{10^8}{10^{6-7}} \sim 10 \text{ to } 100. \tag{6}$$

'85 vector:

$$\frac{N_{\text{core}}}{N} \sim \frac{10}{1000} \sim 0.01 \tag{7}$$

'90 vector:

$$\frac{N_{\text{core}}}{N} \sim \frac{10}{10^4} \sim 10^{-3} \tag{8}$$

'60's–'70's:

$$\frac{N_{\text{core}}}{N} \sim \frac{1}{100} \sim 0.01 \tag{9}$$

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1960's von Hoerner (1960, 1963)

$$\frac{N_{\rm core}}{N} \sim \frac{1}{10} \sim 0.1 \tag{10}$$

- Time for a new code structure: we are forced to use both hybrid algorithms and hybrid hardware (see Hut et al. (1988)).
  - Adjust or combine algorithms to take advantage of new hardware.
  - Modernize the codebase: ease integration with other codes (stellar evolution, collision hydro, etc). Mention AMUSE.

2. Prior Art

This section:

- Reviews previous work.
- Focuses on parts of algorithms/code that will have to change or are inadequate for the future. We want to make the strong case that we need something *new*, not a small change or extension of older codes.

2.1. Scalar Machines

- The NBODYi series.
- Starlab.

2.2. Vector Machines

FIXME: Steve, could you add references here?

2.3. GPU/GRAPE

- Specialized hardware, still in $N_{\rm core} < N$ regime.
- Architectural choices that can inform work on future hardware (communication architecture, bottlenecks, etc).
- *FIXME: Anyone know about simulations on more esoteric hardware, like CM?* Makino and Hut (1989)

2.4. Parallel Codes

Spurzem, NBODY6++. Also Keigo, NINJA.

2.5. Hybrid/Non-Direct Codes

- The Bridge code.
- Treecodes in general, also for non-collisional systems.
  - Can hybrid codes be used for purely *collisional* dynamics, or do they change the statistics of long-range interaction (i.e. particle noise)?

3. Challenges for the Future

- Cost to core collapse $\sim N^3$.
- Computational power $\sim N_{\rm core}$.
- Moving toward regime where $N_{\rm core} \sim N$, need new algorithms, codes.
- Eventually, will need to figure out how to make $N_{\rm core} \gg N$ work (even ω Cen has $M \sim 5 \times 10^7 M_\odot$; $N_{\rm core}$ should exceed this in *FIXME: XX* years).
- Astrophysical limits to collisionality: if $T_{\rm cc} > T_H$, then don't need collisional simulation. This happens about $N \sim 10^{7-8}$.
- Problems with hardware and cache: hardware hybridization headache.

4. Astrophysical Requirements

4.1. Globular/Open Clusters

4.2. Galactic Center

4.3. Planet Formation

5. Hardware Requirements

5.1. Cache/Memory Hardware

5.2. Cluster Hardware

6. Software

These should probably expand to a section each.

- "Direct:" storage $\sim N$, step cost $\sim N^2$. Replicate state across processes, each processor does one particle update, broadcast.
- "Hybrid:" tree for long-range, direct for short range. How do we take advantage of so many processors? Is the tree force accurate enough? What about RR?

$$T_{\rm RR} \sim \sqrt{N} T_{\rm orb} < T_{\rm NR} \sim \frac{N}{\ln \Lambda} T_{\rm orb} \tag{11}$$

  Also current work from Piet, Jun, others.
- "Hierarchical:" Jun?

6.1. The Promise of High-Level Languages

Cite Koichi: HL can be faster.

7. Conclusion

Acknowledgements

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