ChaNGa: from cosmology to a flexible, parallel tree-code framework

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Dark Matter in the Universe

- Cosmic Microwave Background (Gigapc)
- Galaxy Rotation Curves (Kilopc)

Image courtesy ESA/Planck

Begeman, Broels & Sanders, 1991
Fundamental Problem: Dark Matter and Energy: What is it?

- Not baryons
- Gravitates!
- Simulations show: not known neutrinos
- Candidates:
  - Sterile Neutrinos
  - Axions
  - Lightest SUSY Particle (LSP)
Modeling Dark Matter

- Physics is simple: Newton’s Laws
- Computation is challenging: Naively order $N^2$
- Large spacial dynamic range: > 100 Mpc to < 1 kpc
  - Hierarchical, adaptive gravity solver is needed
- Large temporal dynamic range: 10 Gyr to < 1 Myr
  - Multiple timestep algorithm is needed
- Gravity is a long range force
  - Hierarchical information needs to go across processor domains
Basic Gravity algorithm ...

- Newtonian gravity interaction
  - Each particle is influenced by all others: $O(n^2)$ algorithm
- Barnes-Hut approximation: $O(n \log n)$
  - Influence from distant particles combined into center of mass
TreePiece: basic data structure

- A “vertical slice” of the tree, all the way to the root.
- Nodes are either:
  - Internal
  - External
  - Boundary (shared)
Overall treewalk structure
Speedups for 2 billion clustered particles
Light vs. Matter
Smooth Particle Hydrodynamics

- Making testable predictions needs Gastrophysics
  - High Mach number
  - Large density contrasts
- Gridless, Lagrangian method
- Galilean invariant
- Monte-Carlo Method for solving Navier-Stokes equation.
- Natural extension of particle method for gravity.
Charm Nbody GrAvity solver

- Massively parallel SPH
- SNe feedback creating realistic outflows
- SF linked to shielded gas
- SMBHs
- Optimized SF parameters
- AGORA participant

Menon+ 2015, Governato+ 2014
Fundamental Origins

Questions:

How did the Universe begin?
How did stars form?
How did planets form?
How did life begin?
How did intelligent life develop?
Protoplanetary Disks

- Likely result of cloud collapse with conserved angular momentum
- Disks can be gravitationally unstable
- Fragmentation depends on details of gas dynamics
ChaNGa: unprecedented resolution

Resolution comparison: density after 1.89 ORPs

$10^8$ particles  $10^7$ particles  $10^6$ particles

Isaac Backus, Ph. D. Thesis
Terrestrial Planet Formation

- Terrestrial planets are enhanced in refractory elements
- Elements initially condense into grains out of the protoplanetary nebula
- Grains grow (quickly) to ~kilometer size bodies (planetesimals)
- Planetesimals collide to build larger bodies (protoplanets)
- Left over planetesimals remain as small bodies (asteroids, comets, and minor moons)
The simulation model

Planetesimals represented by spherical particles.

Particles gravitationally interact with each other, planets and Sun.

*Heuristic collision model:* particles stick or bounce when they collide.

Particles acquire spin through collisions.

Need a fast collision finder: ChaNGa
The simulation model

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Need a fast collision finder: ChaNGa
Collision scaling: 50M particles
Orders of magnitude better resolution

Spencer Wallace
Moving Mesh Hydrodynamics

- More accurate hydrodynamics requires Riemann solvers
- Galilean invariance: mesh needs to follow the fluid flow
- Mesh needs to have arbitrary geometry
- Need a fast Voronoi mesh generator: ChaNGa (MANGA)
Sedov Test

- **SPH t = 33 min**
- **MM**
- **SPH t = 133 min**
- **MM**
- **t = 233 min**
- **t = 333 min**

**Density (g/cm³)**

-10⁻⁴ to 10⁻⁶
More Physics

- Magnetic fields (with constrained transport)
- Radiative Transfer (Flux limited diffusion and ray tracing)

Phil Chang, UW-Milwaukee
Magnetic fields and outflows

No CRs
Advection
Isotropic Diffusion
Anisotropic Diffusion
Streaming

100 x 100 kpc

Iryna Butsky
Simulations of Star Formation

Norm Murray, 2018
Other Applications

- N-point correlation functions
- Gravitational Lensing maps
- Granular Dynamics
- Cluster finding
- High dimensional classification
- Identification of cytoskeletal structures
- Ray tracing
- Surface reconstruction
Paratreet: parallel framework for tree algorithms
Availability

- ChaNGa: http://github.com/N-bodyShop/changa
  - See the Wiki for a developer's guide
- Paratreet: http://github.com/paratreet
  - Some design discussion and sample code
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- NASA Advanced Supercomputing
CPU Scaling Summary

- Load balancing the big steps is (mostly) solved
- Load balancing/optimizing the small steps is what is needed:
  - Small steps dominate the total time
  - Small steps increase throughput even when not optimal
  - Plenty of opportunity for improvement
GPU Implementation: Gravity Only

- Load (SMP node) local tree/particle data onto the GPU
- Load prefetched remote tree onto the GPU
- CPUs walk tree and pass interaction lists
  - Lists are batched to minimize number of data transfers
- “Missed” treenodes: walk is resumed when data arrives: interaction list plus new tree data sent to the GPU.
Grav/SPH scaling with GPUs

Piz Daint timing for 40M disk

Gravity (+ SPH) time (seconds)

Number of CPU cores

- SMP
- GPU
- SMP with SPH
- GPU with SPH
- SMP GPU with SPH
Tree walking on the GPU