PROJECT NAME: Parallel Tree Codes and Galaxy-Galaxy Collision Simulations

RESEARCH DIRECTOR: Professor John Boccio

TIME FRAME: Begins Summer 2003

PROJECT DESCRIPTION:

- **Assume each galaxy is an N-body collisionless system**

  A self-gravitating system is collisionless if the granularity of its mass distribution does not influence its evolution. Galaxies, in particular, are expected to evolve collisionlessly even over timescales much longer than a Hubble time.

- **Understand N-body models of collisionless systems**

  Collisional or two-body relaxation is the stellar dynamical equivalent of thermal relaxation in a gas. As a result of the long range nature of the gravitational force and of the non-existence of bounded maximum entropy states for finite isolated self-gravitating systems, the effects of collisional relaxation are rather different in galaxies and galaxy clusters than in a thermalizing gas.

  Because the N-body equations of motion are time-reversible, no information is really lost during the evolution of a stellar system. Effective information loss, however, occurs in two ways. Both violent relaxation and phase mixing can be described using the Vlasov-Boltzmann equation

$$\frac{\partial f}{\partial t} + \vec{v} \cdot \frac{\partial f}{\partial \vec{r}} - \nabla \phi \cdot \frac{\partial f}{\partial \vec{v}} = 0$$

  for the phase space density distribution function $f(\vec{r},\vec{v},t)$. Violent relaxation requires the simultaneous solution of Poisson's equation while phase mixing may not. Since that equation is also time-reversible, all information on the initial distribution function of a collisionless system is contained in the detailed $f(\vec{r},\vec{v},t)$ at later times. Effective information loss occurs because of coarse graining, i.e., in practice, $f(\vec{r},\vec{v},t)$ is only known with limited resolution and evolution transfers much initial information to progressively smaller scales in phase space where it is no longer accessible.

- **Understand tree code algorithm**

  The N-body problem involves advancing the trajectories of N particles according to their time evolving mutual gravitational field. In the simplest algorithm, the force on each particle is determined by direct summation of the contributions from the other $N-1$ particles. In a discrete time integration, the forces at each timestep are then used to advance the particles along their trajectories according to a numerical schemes such as the leapfrog method (Euler-Cromer). Computational costs of direct summation scale as $O(N^2)$, making the algorithm expensive. In collisionless systems like galaxies, however, a simulation can tolerate small errors in the force for improved performance by using techniques which approximate the gravitational field. Tree codes are one class of methods which accomplish this and have the advantage of scaling only as $O(N\ell ogN)$ in computational cost.

  The essence of a tree code is the recognition that the gravitational potential of a distant group of particles can be well-approximated by a low-order multipole expansion. In a tree code, a set of particles is arranged in a hierarchical system of groups that form of a tree structure. The entire set is subdivided into several groups and each of these groups is broken down in succession within the hierarchy until groups contain at most 1 particle. There are many different methods available for efficiently grouping particles hierarchically in this way.

  The evaluation of the potential at a point reduces to a descent through the tree. One sets a minimum distance a point can be from a group to use a multipole expansion. If the point is sufficiently distant from a group, the multipole expansion is used to find the potential from that group (much faster than direct summation methods), while if the point is too close to the group, each of its child subgroups are examined. The procedure continues until all groups are broken down as far as they need be. Some particle that are close to the point will be groups by themselves and for those we still use direct summation. This, however, will be very small in number.

- **Implement single processor tree code algorithm**

  Barnes-Hut(BH) method

  Cell definition

  Cell-opening methods

  Grouping of cells

  Non-Recursive Tree Walks

  Write program codes to simulate "small" galaxies

- **Understand parallel tree code algorithm**
  - Barnes-Hut(BH) method
    - Orthogonal Recursive Bisection (ORB)
      - (1) ORB domain decomposition across processors
      - (2) Construct the local BH tree
      - (3) Exchange tree nodes to construct the locally essential trees
      - (4) Walk through the trees to calculate the forces
      - (5) Move particles along their trajectories using these forces

- **Understand Message Passing Interface (MPI) programming**

- **Understand AppleSeed cluster implementation of MPI**
  - Absoft F95 + Pooch app

- **Implement parallel processor tree code algorithm on AppleSeed cluster**
  - Write program codes
  - Simulate "large" galaxies

- **Investigate several galaxy collision models**
  - Plummer models
    - Head-on collisions
    - Off-axis collisions (net angular momentum)
  - Polytrope models
  - Binary phase-space hierarchies
  - Detonating galaxies