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Introduction to "Clouds-in-Clouds, Clouds-in-Cells Physics for Many-Body Simulation"

For 30 years, a wide variety of plasma phenomena have been modeled using the method known as cloud-in-cell or particle-in-cell (PIC). Although there have been important elaborations and specializations, the principles are unchanged, and codes such as described by Birdsall and Fuss are still productive. In fact, through simulation, many fundamental discoveries in plasma physics continue to be made, among them parametric instabilities and collisionless shocks.

The method has been adopted for modeling particle accelerators and gravitational systems such as star clusters. It even motivated the development of the vortex-in-cell method by Christiansen, which is reprinted in this issue. The cloud-in-cell model is fully nonlinear and can reproduce subtle kinetic effects such as Landau damping.

Essential features of the model are:

representation of the plasma as a large number of particles having individual positions, momenta, mass and charge;

the use of fields defined on a mesh to mediate the particle interactions, and a low-order time integration with a fixed time step.

The collective phenomena of interest are resolved in space and time, but not the much smaller interparticle scales and the related collisional time scale.

These essential features were already present in work done at Stanford by Oscar Buneman and associates [1], who also originated fast Fourier and cyclic reduction algorithms for rapid accurate solutions of the Poisson equation [2]. Hockney's code used a combination of cyclic reduction and a form of fast Fourier transform (several years before publication of the Cooley and Tukey FFT article). At the 1968 "Numerical Simulation of Plasmas" meeting. Buneman handed out little decks of cards bearing an inscrutable tiny program that solved Poisson's equation by cyclic reduction in two directions. Buneman and co-workers also invented the "capacitance matrix" method for solving Poisson's equation on an irregular domain using noniterative methods.

Much of the discussion in this paper and others that followed concerns the physical interpretation of the particle–grid charge weighting and field interpolation. The Stanford group used the fastest option, nearest grid point (NGP) weighting. (With NGP weighting, one simply counts the particles in a cell to calculate the charge density.) This paper, in part, advocates a smoother weighting, motivated by considering the plasma particles to be diffuse clouds whose charge is shared among several mesh points, and discusses why this greatly improves the modeling. In fact, most of the applications during the last 30 years have used this weighting. (Buneman, who was uninterested in area weighting, became an advocate of even smoother weighting, using parabolic and cubic b-splines.)

Some perspective on the importance of this smoother weighting is given by Morse [3]: "in view of the particulate nature of the model, the question remains, do the simulation particles interact with one another or with the grid in a way that amounts to binary collisions, introducing a prohibitive amount of truncation error in the form of diffusion and field fluctuations. The answer, in general, is no." Birdsall *et al.* [4] confirmed this by computing the scattering collision cross sections for finite-sized particles and showed that collisions decrease significantly with increasing particle size.

It is interesting to note that others discovered the usefulness of finite-sized particles at about the same time [5], but by a different route. Butler *et al.* [6] used a particle–mesh weighting motivated by Harlow's particle-in-cell (PIC) fluid models [7] to model magnetohydrodynamic flow in a plasma focus experiment. The same approach was then used for the plasma kinetics, and described as PIC [5]. In fact, the PIC area-weighting and CIC charge-sharing schemes were numerically the same bilinear weighting! In time, rivalries died away, and now the designation PIC is used for most codes of this type, regardless of the weighting scheme. Reviews of plasma simulation in *Methods in Computational Physics,* (Vol. 3 (1970) written just a short time later measured the rapid development of simulation techniques. Some of the accomplishments of plasma simulation are reviewed by Dawson [8].

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