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Machine Learning Applied to Analysis of Particle-in-Cell Plasma Simulations

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The particle-in-cell (PIC) algorithm is one of the most common methods for simulating kinetic plasma behavior. Kinetic models of plasma are governed by seven-dimensional system of governing equations (the Vlasov equation and Maxwell's equations), and this high dimensionality leads to both high computational cost and a large amount of information being output from every PIC simulation. Analysis of PIC results is further complicated by the zoo of possible plasma wave modes, complexity in particle motions, and subtle numerical effects that may be conflated with physical behavior. There are some machine learning tools that can aid in interpreting data from PIC simulations. This will ultimately help us learn more from each simulation and have more confidence that the results are physical.

In this presentation, we discuss basic examples of machine learning tools applied to PIC simulations of plasmas. In one example, we show how different classification algorithms can separate plasma particles by their behavior. In a simulation of a two-stream instability, we quantify the number of trapped and streaming particles as the instability grows and saturates. The results are compared to the theoretical nonlinear damping rate, which is proportional to the number of trapped particles. In another example, we show how Bayesian spectral analysis techniques can be used to identify plasma wave modes (e.g., frequency and wavevectors) which can help alleviate problems caused by the uncertainty principle of Fourier transforms in quickly growing instabilities and nonlinear interactions. These ideas are then applied to more complicated systems, such as the electron firehose instability and the velocity ring instability. Beyond mining the abundant data from PIC simulations for more information, we discuss further possibilities for how machine learning tools could be integrated with and enhance the PIC algorithm as it runs in real time. This includes using multiple predictive techniques for the dynamics, which can lower the computational cost of PIC.