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A New Approach to Adaptive Control of Multiple Scales in Plasma Simulations

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A new approach to temporal refinement of kinetic (Particle-in-Cell, Vlasov) and fluid (MHD, two-fluid) simulations of plasmas is presented: Discrete-Event Simulation (DES). DES adaptively distributes CPU resources in accordance with local time scales and enables asynchronous integration of inhomogeneous nonlinear systems with multiple time scales on meshes of arbitrary topologies. This removes computational penalties usually incurred in explicit codes due to the global Courant-Friedrich-Levy (CFL) restriction on a time-step size. DES stands apart from multiple time-stepping algorithms in that it requires neither selecting a global synchronization time step nor pre-determining a sequence of time-integration operations for individual parts of the system (local time increments need not bear any integer multiple relations). Instead, elements of a mesh-distributed solution self-adaptively predict and synchronize their temporal trajectories by directly enforcing local causality (accuracy) constraints, which are formulated in terms of incremental changes to the evolving solution. Together with flux-conservative propagation of information, this new paradigm ensures stable and fast asynchronous runs, where idle computation is automatically eliminated. DES is parallelized via a novel Preemptive Event Processing (PEP) technique, which automatically synchronizes elements with similar update rates. In this mode, events with close execution times are projected onto time levels, which are adaptively determined by the program. PEP allows reuse of standard message-passing algorithms on distributed architectures. For optimum accuracy, DES can be combined with adaptive mesh refinement (AMR) techniques for structured and unstructured meshes. Current examples of event-driven models range from electrostatic, hybrid particle-in-cell plasma systems to reactive fluid dynamics simulations. They demonstrate the superior performance of DES in terms of accuracy, speed and robustness.