StreamFEM

A Streaming Language Implementation of the Discontinuous Galerkin Finite Element Method

Timothy Barth (NASA Ames)            Timothy Knight (Stanford CS)

A DG Finite Element Method for Conservation Laws

StreamFEM implements the Discontinuous Galerkin (DG) finite element method for systems of nonlinear conservation laws in divergence form:

\[ u_t + \text{div}(f(u)) = 0 \]

The DG Finite Element Variational Statement

Find \( u \in V_h \), such that \( \forall \phi \in V_h \),

\[ \sum_{\text{elements}} \left( \int_{\Omega} w \, u \, d\Omega - \int_{\Omega} f(u) \cdot \nabla w \, d\Omega + \int_{\partial \Omega} w \cdot \frac{\partial u}{\partial n} \, d\Gamma \right) \]

\[ + \int_{\Omega} r_K(u) \nabla w \cdot \nabla w \, d\Omega = 0 \]

with

\[ r_K(u) = h^\alpha \beta \| u_x + \text{div} f(u) \|_{K} \]

Variable Arithmetic Intensity

StreamFEM includes discontinuous Galerkin models of several representative nonlinear partial differential equation (PDE) systems of increasing complexity:

- Scalar Advection (1 PDE)
- Euler Equations (4 PDEs)
- Magnetohydrodynamics (6 PDEs)

StreamFEM also includes various piecewise polynomial representations with an increasing number of degrees of freedom (dofs) ranging from piecewise constant to piecewise cubic polynomial approximation

- Piecewise constant elements (1 dof / (element-equation))
- Piecewise linear elements (3 dofs / (element-equation))
- Piecewise quadratic elements (6 dofs / (element-equation))
- Piecewise cubic elements (10 dofs / (element-equation))

By increasing the number of PDEs and the number of degrees of freedom per element, it is possible to alter the overall arithmetic intensity of the computation by 8x or more.

StreamFEM Flow Chart

StreamFEM has been implemented in the Brook stream language and later translated into StreamC/KernelC. The current algorithm utilizes a simple Runge-Kutta time stepping algorithm:

For each timestep:

1. Loop over edges:
   - Gather 2 element states
   - Compute flux terms
   - Store fluxes to memory
2. Loop over elements:
   - Gather 3 flux terms
   - Compute interior term and update element
   - Store updated element state

Brook Functional Simulation of Flow Over a Forward Facing Step

M=3

t=0.2

M=3

t=0.8

M=3

t=1.6

SSS Hardware Simulated Performance

Variable Arithmetic Intensity

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Future Directions

- Multiple node performance simulation and optimization
- Implementation in 3D
- Implicit formulation using matrix nested dissection
- Implicit formulation using algebraic multigrid