Solving Navier–Stokes-like problems with discontinuous features via information geometric regularization

Spencer H. Bryngelson

Georgia Institute of Technology
shb@gatech.edu

Co-Authors: Anand Radhakrishnan, Benjamin Wilfong

High-fidelity prediction of hypersonic, shock-laden flows requires capturing sharp discontinuities and their interaction with turbulence and acoustics without sacrificing fine-scale physics. We present a simulation method based on *information geometric regularization* (IGR) for the compressible flow equations that produces grid-smooth shock profiles. This well-conditioned formulation enables efficient high-order finite-volume schemes to operate without artificial viscosity or limiters, preserving the small-scale content needed to assess base heating and plume–plume interactions in multi-engine spacecraft and to inform hypersonic aeronautics and propulsion simulation.

A performance-focused implementation combines IGR with unified CPU–GPU memory and mixed precision (FP32 compute, FP16 storage), allowing zero-copy access and substantially reduced footprint. The result is the first compressible CFD campaigns exceeding 200 trillion grid cells and roughly 10^{15} degrees of freedom, about 20× beyond previous records, while improving simulation wall-time over optimized shock-capturing baselines. On OLCF Frontier, LLNL El Capitan, and CSCS Alps we observe ideal weak scaling to the full system size. Representative simulations of Mach 14 engine arrays resolve intricate shock–shock interactions, shear-layer instabilities, and location-dependent back heating; notably, configurations that destabilize baseline WENO reconstructions remain stable with IGR.

Beyond scale, the approach directly advances *fidelity*. By lowering memory and numerical overhead, the method frees headroom to incorporate additional physics that *increase the per-cell state dimension*: multi-species transport and nonequilibrium chemistry introduce $\mathcal{O}(10\text{–}100)$ reactive scalars per cell, enabling realistic modeling of hypersonic dissociation, ignition, and shock–acoustic coupling. The demonstrated stability, accuracy, and scalability potentially enable shock-resolved, chemistry-aware design exploration for high-speed flight and propulsion on flagship exascale systems.