IMOGEN: A Parallel 3D Fluid and MHD Code for GPUs

I. Introduction - Motivation

The ideal magnetohydrodynamic (MHD) equations are a central model in astrophysics where length scales are large enough that individual particle effects and many nonideal effects can often be ignored. They are a hyperbolic system of PDEs, which naturally scales well in parallel. In particular, gridded solution methods are exceedingly well fitted to solution by GPU architectures.

IMOGEN is a fully MPI-parallel code for solving both the fluid dynamic equations and the Ideal MHD equations using nVidia Tesla GPUs. It acheives a large speedup compared to its CPU-based forerunner, and places long-time simulations at billion cell resolutions within reach of a cluster of even a few dozen Tesla processors. The equations Imogen solves are:

$$\partial_t \rho + \nabla_i p_i = 0 \quad (1)$$
$$\partial_t p_i + \nabla_i (p_i p_j + P^{tot}\delta_{ij} - B_i B_j) = F_i \quad (2)$$
$$\partial_t B_i + \nabla_i (v_i B_j - B_i v_j) = 0 \quad (3)$$
$$\partial_t E^{tot} + \nabla_i (v_i (E^{tot} + P^{tot}) - B_i (v_j B_j)) = F_i v_i + \Lambda \quad (4)$$
$$P^{tot} = P^{gas}(\epsilon, \rho) + B^2/2 \quad (5)$$

Where ρ is mass density, p is momentum density, P^{tot} is total pressure, B is magnetic field, F represents the net force density, $E^{tot} = \epsilon + \rho v^2/2 + B^2/2$ is the total (kinetic, thermal and magnetic) energy density and Λ represents any non-conservative energy sources such as radiation.

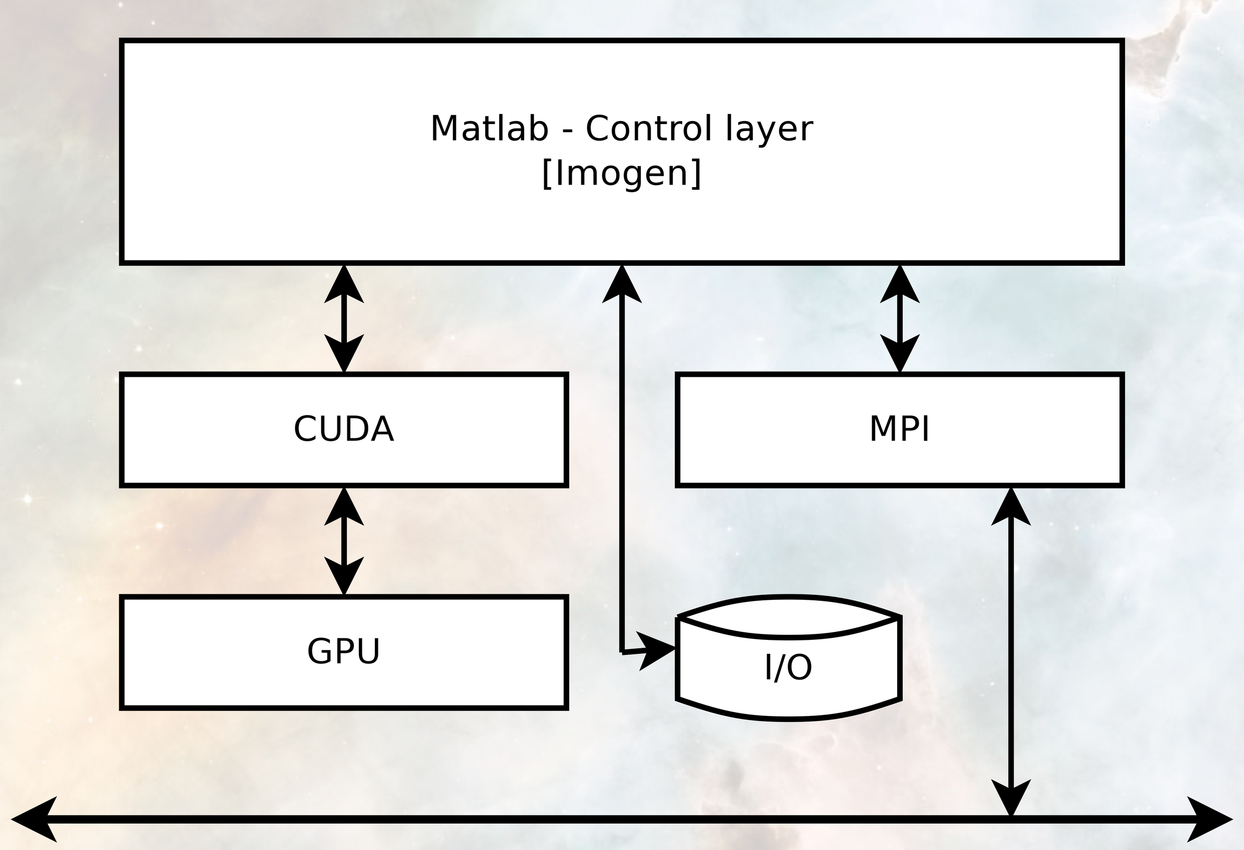
Imogen is a hybrid of both compiled and interpreted languges; its high-level control logic is written in Matlab, while the core fluid routines are compiled in CUDA.

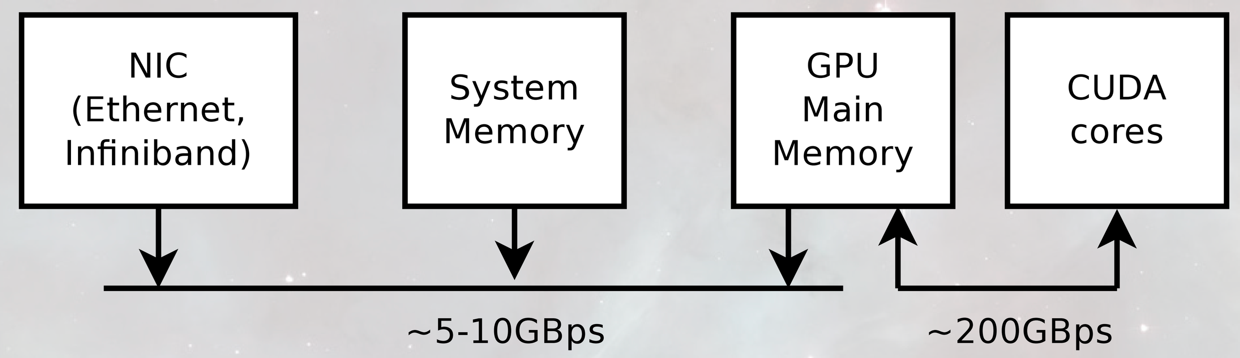
By also presenting the stored GPU arrays as ordinary Matlab arrays, it becomes very easy to experiment on Imogen before committing to the effort of writing good GPU code.

II. Architecture

Imogen runs in Matlab, which controls all of the management functions and runs the outer loops.

The core routines, both ghost cell exchange and GPU access, are compiled Mex files. In most cases the Mex files are fairly minimally written because we wish to keep most of the decisions in Matlab, so that users can easily read and change them.



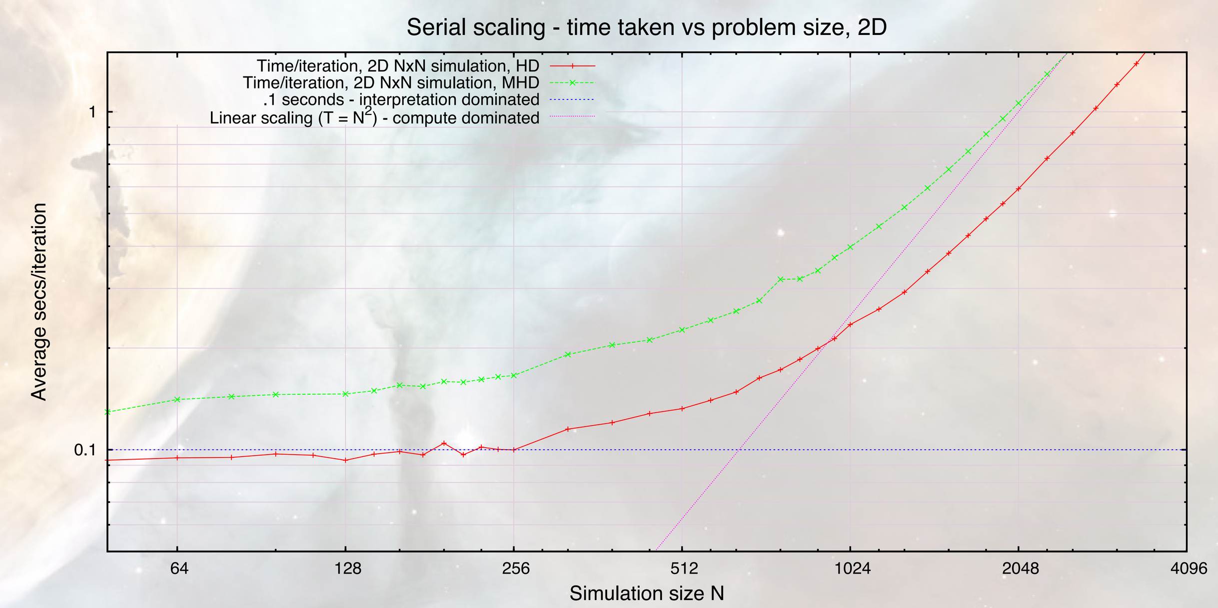


Imogen keeps the entire simulation on the GPU at all times because transferring any significant fraction of it to or from host memory is simply not tractable on a step-by-step basis. Assuming a few hundred timesteps per full data save, the device will read every main array roughly 1000 times before copying it back to host memory.

III. Serial Scaling

- Two clear regimes emerge in testing as expected
- Interpretation- and compute-dominated regimes cross over at roughly 250K cells resolution
- Overhead is minimal — at the few percent level — in normal use, when each GPU is handling 10-30 milion cells

We have observed that the Matlab-level class.set routine is relatively expensive, and the total number of array writes accumulates much quicker than might be imagined.



IV. Parallel scaling

Imogen has been tested at scales up to ~50 GPUs, on the ACISS supercomputer cluster, at the University of Oregon.

Weak Scaling on 1- and 2-Dimensional Grids			
N	secs/iter	M x N	secs/iter
1	1.11706	1x1	0.2676
2	2.13686	2x2	0.6859
3	2.6025	3x3	0.6382
4	2.29682	3x5	0.8141
5	2.73588	5x5	0.8337
6	2.77719	6x9	0.9969
7	2.72253		
8	2.82041		
9	3.22589		
10	2.81778		
30	3.13328		

Strong scaling generally behaves poorly; dividing the problem size down rapidly moves towards the interpretation-dominated regime. Weak scaling, however, behaves well. After the cost of enabling parallel communication is paid, the time per step is essentially flat on one-dimensional topologies, from 3 to 30 GPUs, and is fairly well behaved on 2- and 3-dimensional tests.

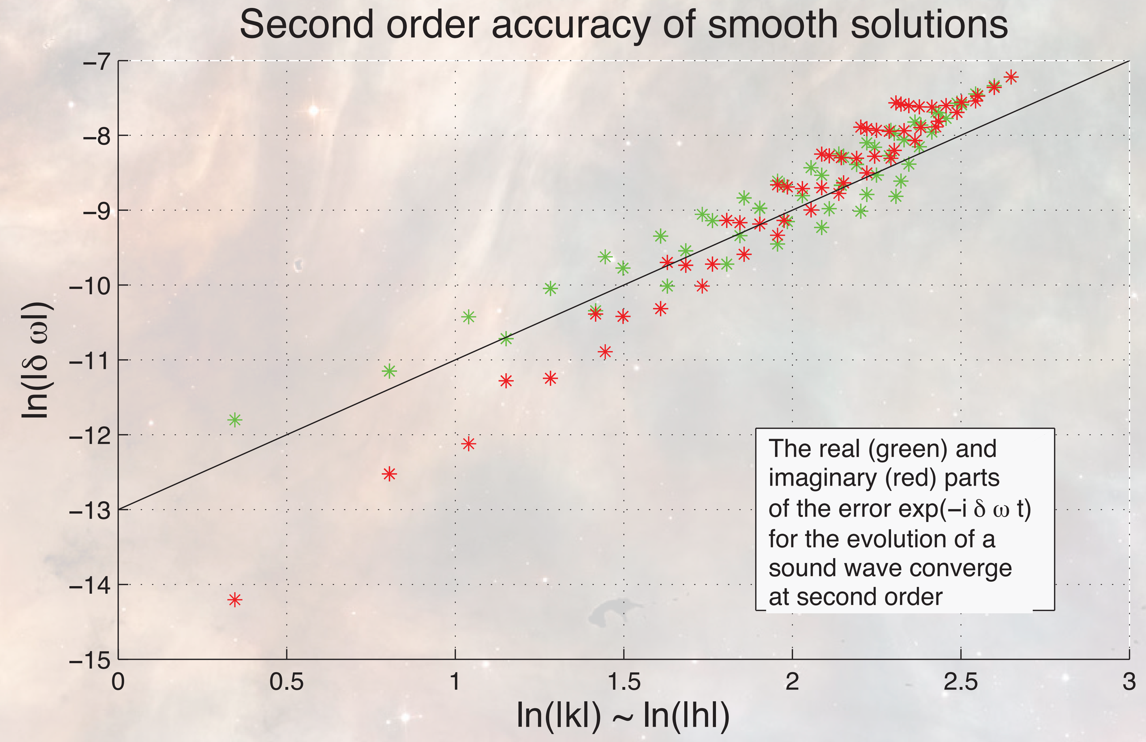
V. Algorithms & Constraints

Imogen implements the TVD fluid algorithm described in [Trac & Pen, 2003] and the divergence-preserving algorithm of [Pen, Arras, Wong 2003] for magnetic field evolution, which conserves the divergence-free condition of the magnetic field to machine precison.

While total energy is conserved, we have observed a potential for problems in the partitioning of its components (thermal, kinetic, magnetic). Observation suggests that when sonic Mach reaches about 100, or when plasma beta reaches about 1/50, Imogen becomes vulnerable to instabilities or errors.

Smooth Solutions

Within this reasonable regime, Imogen is second order accurate in both space and time. Plotted below are the errors in the evolution of a smooth solution (A simple sound wave) - the phase error after one cycle is second order in resolution.

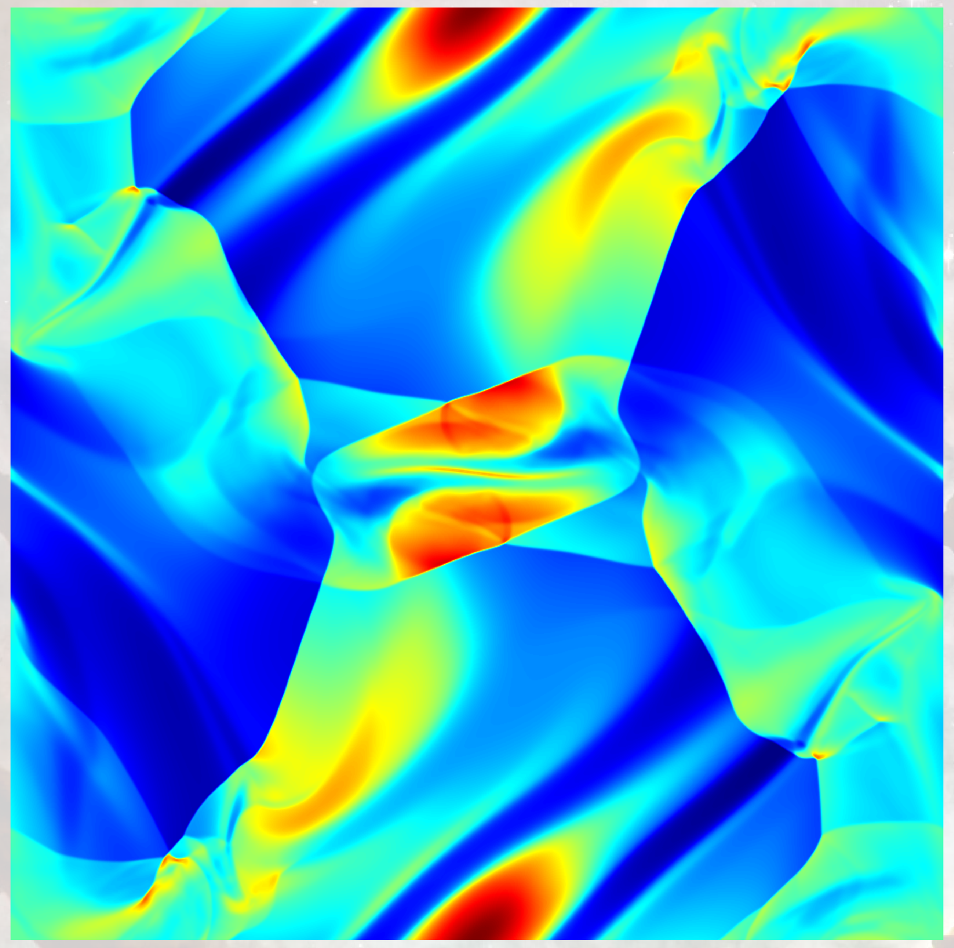


- Errors for waves are ~10^{-5} after one oscillation
- Asymmetry error in propagation is roughly 10^{-9}
- Strang operator splitting is asymmetric at third spatial order

Shock Capturing

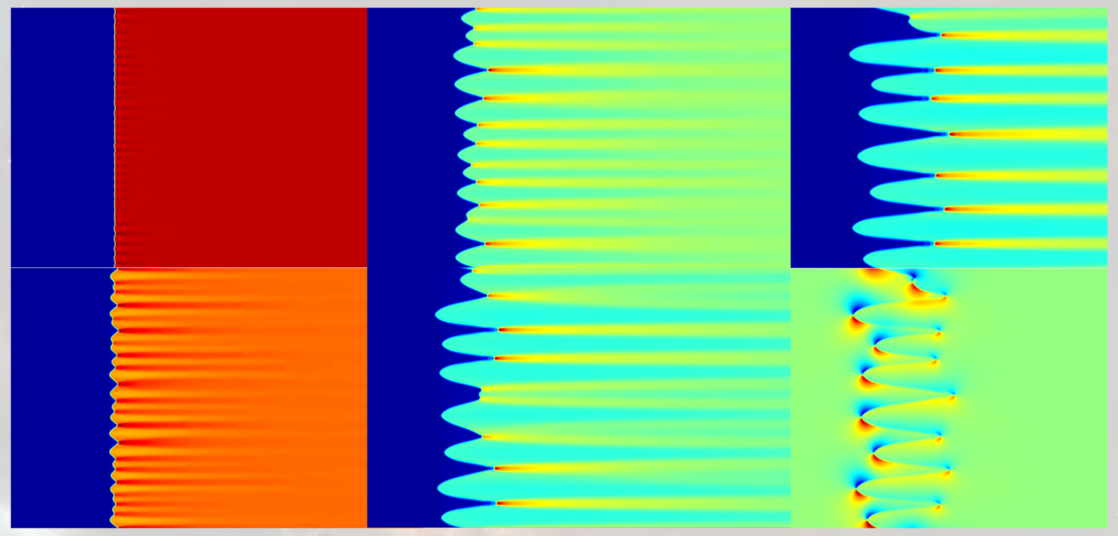
Imogen is fully able to handle strong shocks in MHD situations, as this Orszag-Tang vortex (OTV) shows.

This OTV has a resolution of 1024^2. It ran to completion in only four minutes on a single GPU.



VI. Corrugation Instability

- Slow magnetosonic shocks in ideal MHD are linearly unstable for nearly all flow parameters
- Instability rate proportional to wavenumber implies that front must have zero lifetime in the linear regime
- So what happens in the nonlinear regime?



While linearly it is high modes that are unstable, nonlinearly we observe mode decay. There are three liable final outcomes: saturation at finite amplitude, deformation without limit or disintegration into turbulent flow. 2D simulations evolved for millions of timesteps have continued to deform but have not broken up into turbulent flow.

VII. Acknowledgements & References

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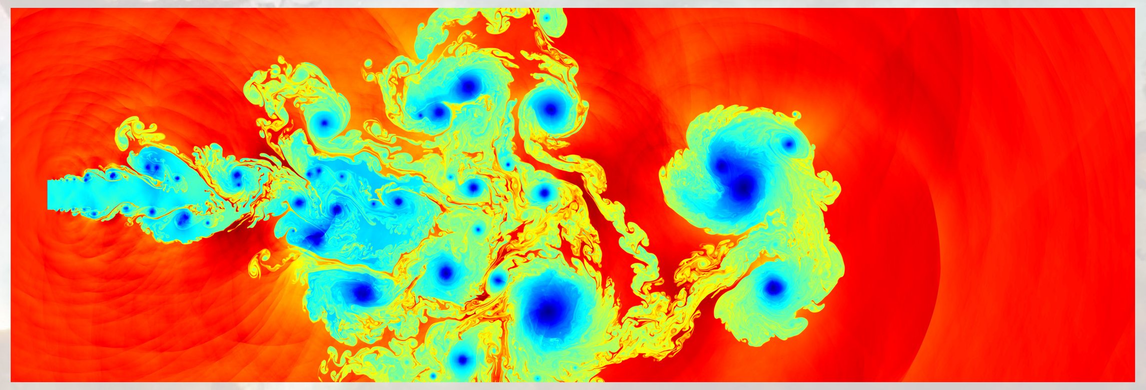
IMOGEN: https://github.com/imogenproject/gpuImogen



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