Award #: 1931280

CSSI Element: A task-based code for multiphysics problems in astrophysics at exascale

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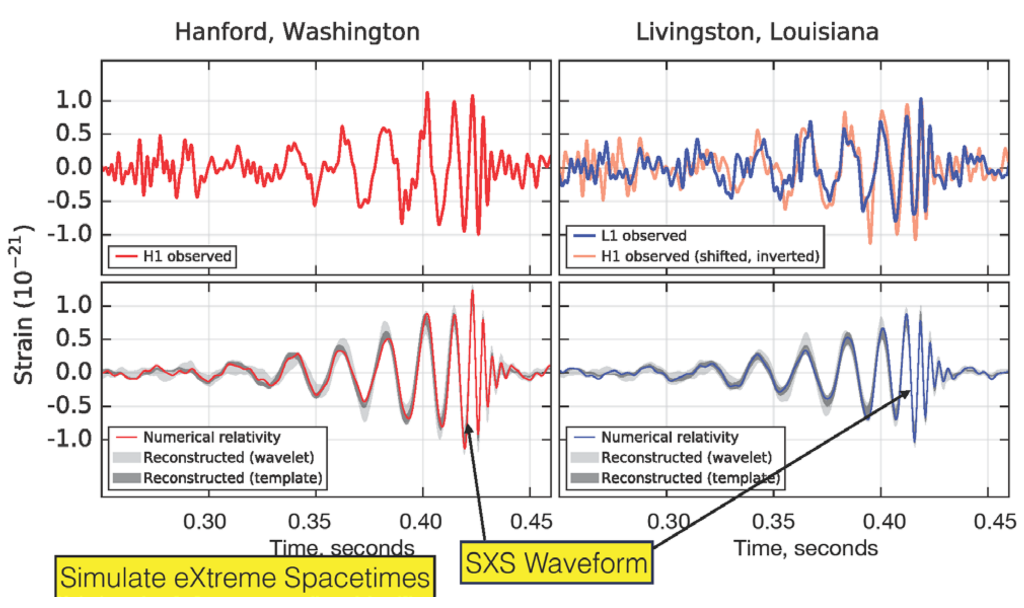
Institutions: Cornell, Caltech

Motivation

- Many astrophysical phenomena now require solving PDEs with quite high accuracy , e.g.
  - LIGO waveforms
  - Core-collapse supernovae
  - Tidal effects in NS-NS mergers
- Detector improvement will require ~ 100 × greater accuracy over next 10 years in some cases
- Existing codes do not scale to millions of cores



Challenges

- Multiple spatial scales in 3-d
- Multiple time scales
- Geometry changes (disruption, merger, black hole formation …)
- Multiphysics (GR, hydro, MHD, neutrinos, EM radiation, nuclear reactions, …)
- Surfaces, shocks: solution is not smooth

Key Innovations of the SpECTRE Code

- Discontinuous Galerkin (DG) for discretization
- Task-based parallelism

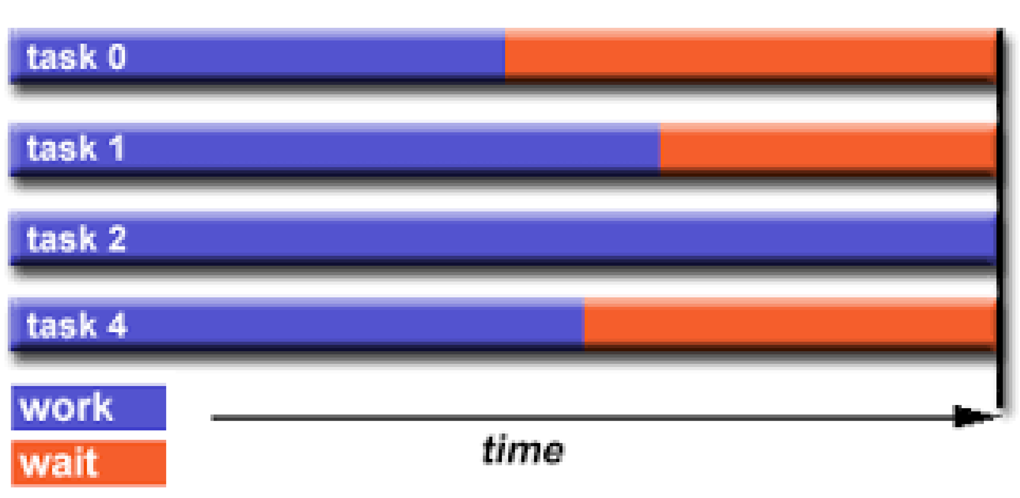
Advantages of DG

- High order (exponential convergence) in smooth regions
- Can handle shocks
- Only nearest-neighbor communication: good scalability
- Local time stepping "easy"
- AMR (hp-refinement) "easy"
- Multiphysics: all equations on same grid

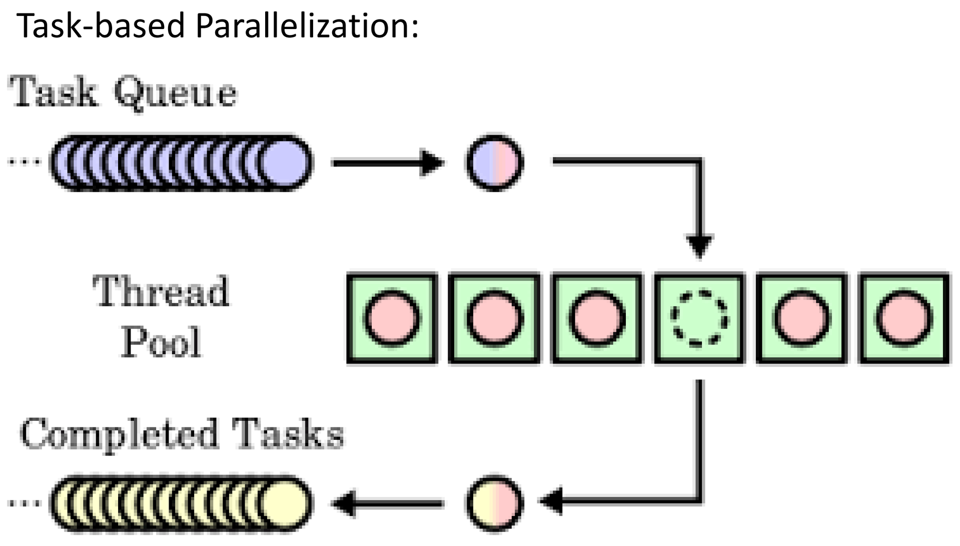
Implementing Task-based Parallelism

- No standard packages
- Charm++ (Parallel Programming Lab, UIUC)
  - Intra-node threading
  - Asynchronous method calls
  - Remote method calls
  - Dynamical load balancing

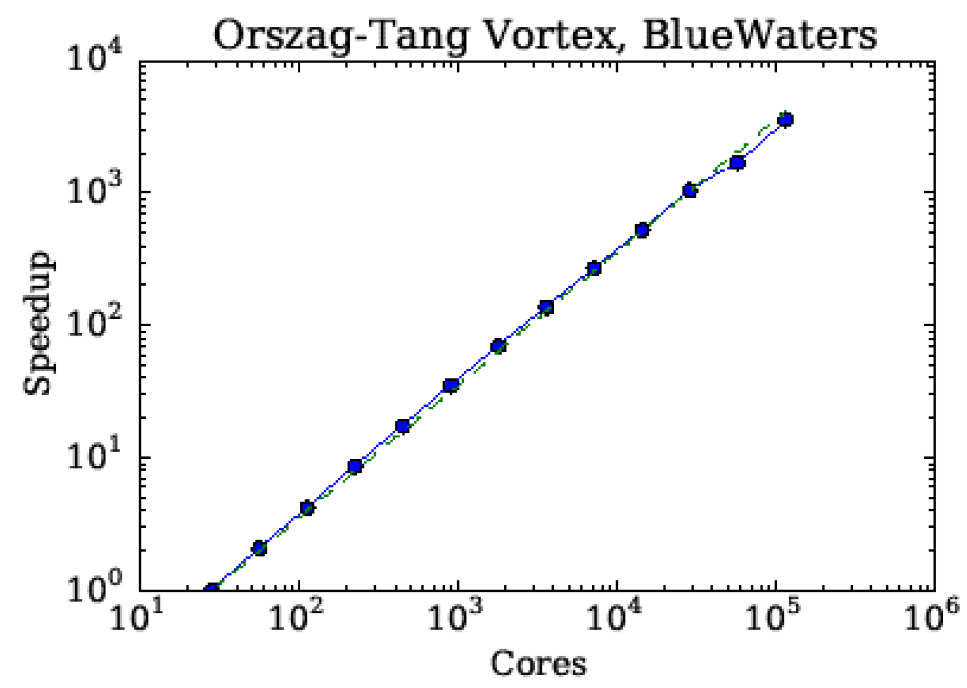
Conventional Parallelization



Task-based Parallelization:

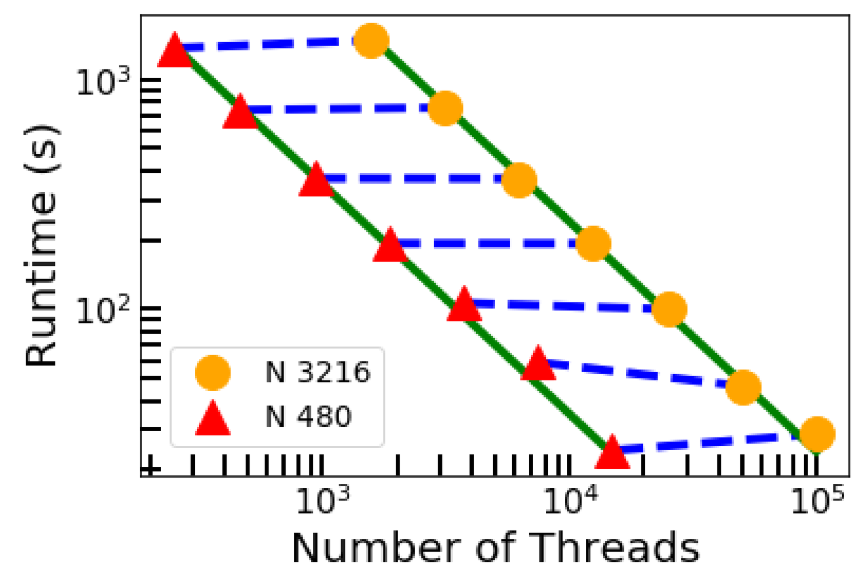


Some SpECTRE Test Cases



$330 \times 330 \times 2$ cells, 2^3 points per cell
Laptop to supercomputer with no hand tuning!

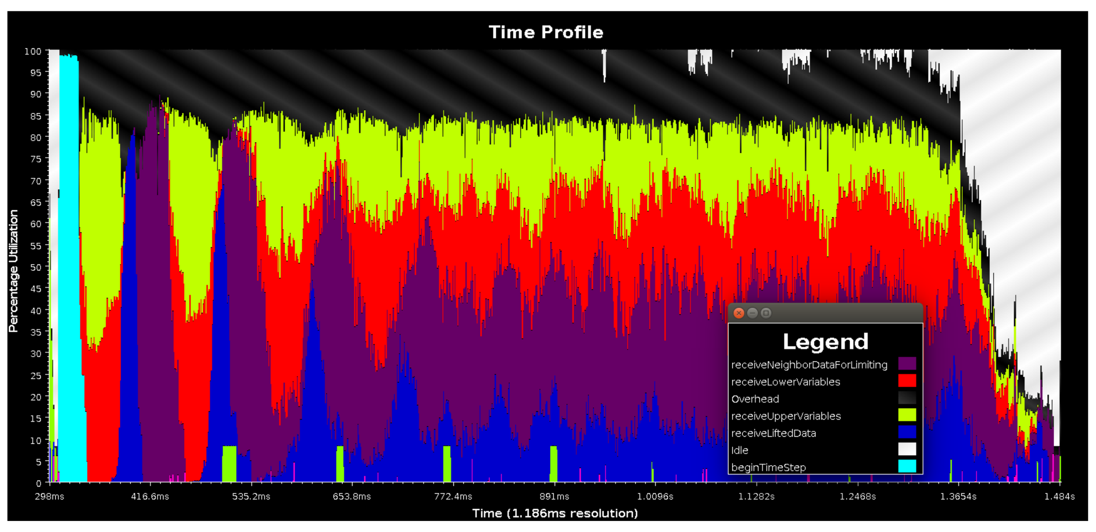
Strong and Weak Scaling on Blue Waters for GR Bondi Accretion



A fixed-size problem with N blocks of 512 DG elements with 5 radial × 4^2 angular basis functons is evolved on an increasing number of threads. Perfect strong scaling: linear speedup if fixed size problem solved with more processors (green lines). Perfect weak scaling: same run time when larger problem solved with proportionally larger number of processors (horizontal dashed lines).

Example Time Profile

10 steps of relativistic MHD test

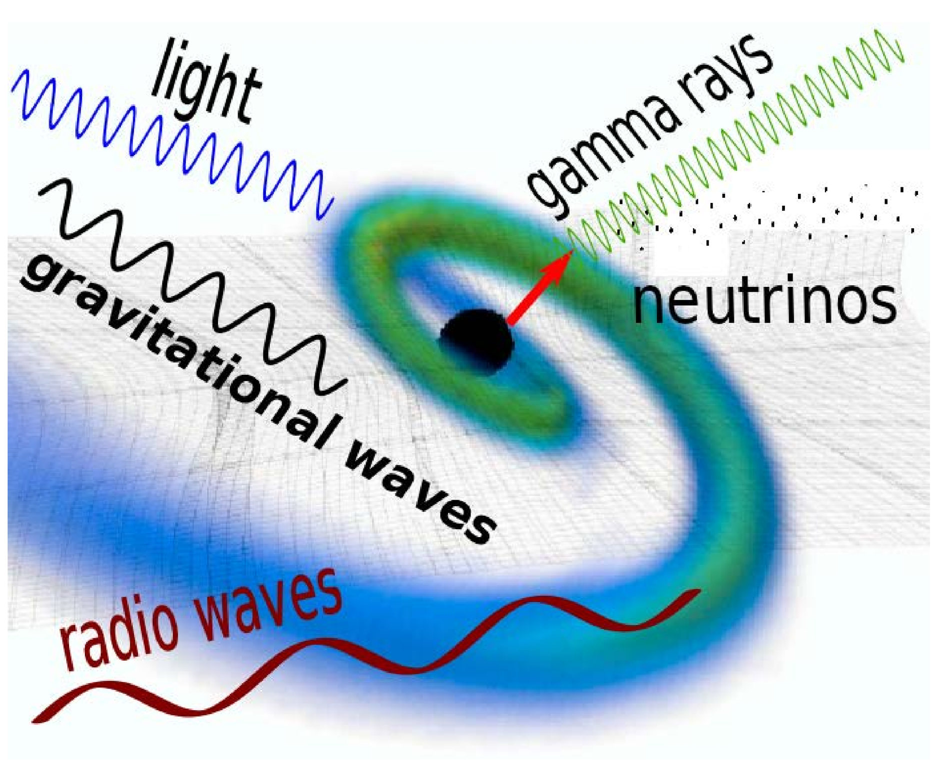


Red/Yellow: Data to interfaces (hides rhs volume computation)
Blue: Fluxes to elements
Cyan: Setup
Purple: Slope limiitng
Black: Charm++
White: Idle

Software Engineering

- SpECTRE is open source: `https://github.com/sxs-collaboration/spectre`
- C++14 with Brigand for tempate metaprogramming (e.g. tensors)
- CMake, TravisCI
- Code review before merging includes documentation and tests

Multimessenger Astronomy



Local Time Stepping

- AMR leads to a large range of Courant conditions
- Advance each element with its own timestep (bad scaling unless task-based parallelism!)
- We have developed a new algorithm that is high-oder and conservative

How to Fool a Computer Allocation Committee:

Advance all elements in lockstep! Perfect scaling, but only 10% of machine is doing useful work.

"It's becoming more and more human -- using only 10% of its brainpower."

Cross-disciplinary Applications

- Any field that requires large-scale time evolution of PDEs:
  - Fluid dynamics, plasma physics, geoscience, …

Summary

- After 60 years of finite differencing, it's time to move on if we want to tackle complex problems
- Algorithms like DG are high-order, robust for shocks, and local (good scaling)
- Task-based parallelism will enable exascale computing

"It says it's sick of doing things like inventories and payrolls, and it wants to make some break-throughs in astrophysics."