New Paradigms for Computational Astrophysics

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SIMULATING EXTREME SPACETIMES

Black holes, neutron stars, and beyond...

Payoffs from binary black hole simulations

What do we learn?

- Dynamics of strongly warped spacetime
- Gravitational waveforms

How can they be used?

- Directly compare theory to observations
- Improve analytic waveform models
- Inject into data analysis pipelines
- Construct surrogate models
- Determine remnant black hole properties
- Explore nonlinear behavior of gravity
- Produce visualizations for public outreach

Solving the vacuum Einstein equations on a computer

Goal: determine the spacetime metric describing the inspiral, merger, and ringdown of a binary black hole system

- Solve as an initial-boundary value problem
- Slice spacetime into spatial hypersurfaces
  - Constraint equations
  - Evolution equations
  - Coordinate freedom
- Specify initial conditions that describe a binary black hole system and satisfy the constraint equations
- Choose the computational domain on which to do the evolution
  - deal with singularities inside the black holes
  - introduce artificial outer boundary
- Choose a formulation of the evolution equations
- Choose a numerical algorithm
- Specify coordinate conditions
- Specify boundary conditions
- Decide how to control constraint violations

Running a BBH simulation

- Choose desired physical configuration q, S_1, S_2, e at some initial orbital parameters ω_{orb}, d, v_r
- Iterative initial data solve to get desired parameters
- Evolve for several orbits, measure eccentricity and adjust initial orbit parameters
- Also adjust physical parameters as black holes relax
- Once desired setup is achieved, evolve through merger and ringdown until waves reach extraction surfaces
- Extrapolate/Evolve extracted waves to null infinity
- Depending on parameters and desired accuracy, runs take days to months

What can be simulated?

- Number of orbits before merger
  - Desired orbits for testing analytic models?
  - Desired orbits for parameter estimation?
  - For low mass systems, need to hybridize to cover detector frequency band
  - Routinely do 20-40 orbits, can do hundreds, but ...
- Parameter space
  - Total mass m scales out of the problem
  - Mass ratio: $1 \leq q \lessapprox 20$ possible
    $q = 100$ demo; robust for $q \lessapprox 6$
  - Spins: $0 \leq \chi \lessapprox 0.8$ robust
    high spin $0.92 \lessapprox \chi$ requires improved initial data
  - high spin on small BH is very difficult
  - Precession: no problem
  - Eccentricity: no problem unless $e \approx 1$

LISA Sources that require Numerical Relativity

- Massive Black hole binaries
- EMRIs

- Some signals with SNRs over 1000, maybe 10000
- Expected mass ratios 10 - 100+
- Signals in band for many months

What are requirements for NR BBH Waveforms?

- What is the expected mass and spin distribution?
- How accurate does the waveform need to be?
- How many orbits to test/improve/build analytic models?

Changing landscape of high performance computing

- Processor speed no longer following Moore's Law
- More cores per node
- Problem: specialized languages needed to exploit GPUs
- Problem: Many threads limited by serial chunk size, memory contention, communication between nodes
- Want to hide latency of communication
- Want to avoid global synchronization points

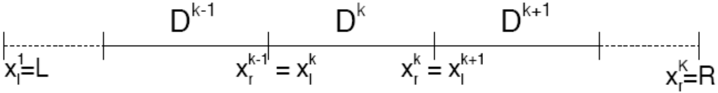
Parallelization strategies

- Domain-based parallelism
- Task-based parallelism

Task-based parallelism

- More natural to divide computation into tasks
- Functions define tasks, parameters define dependencies
- When dependencies are ready, task is put in a ready pool
- Scheduler then selects ready task and it is executed
- When task is finished, check if new tasks can be added to ready pool
- Need to take care of remote dependencies
- Load balancing, task-stealing

Task-based DG



- Cover the physical domain with elements and interfaces
- Method of lines, volume RHS plus fluxes through interfaces
- Limiting to handle shocks, needs info from nearest neighbors

Element:

- Send data to interfaces
- Compute volume RHS
- When fluxes arrive, full RHS
- Send limiting data to neighbors
- When limit data arrive, limit
- Send data to observers

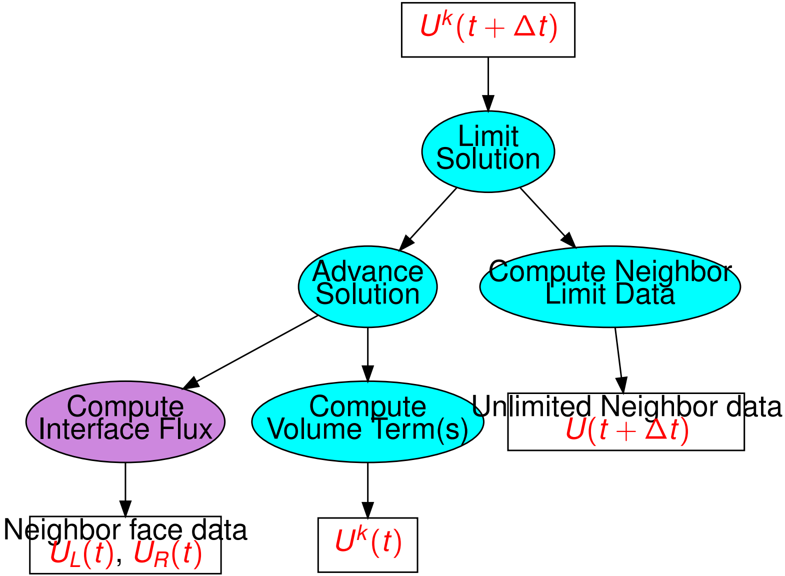
Interfaces:

- When neighbor data arrive, compute fluxes
- Send flux corrections to elements

Observers:

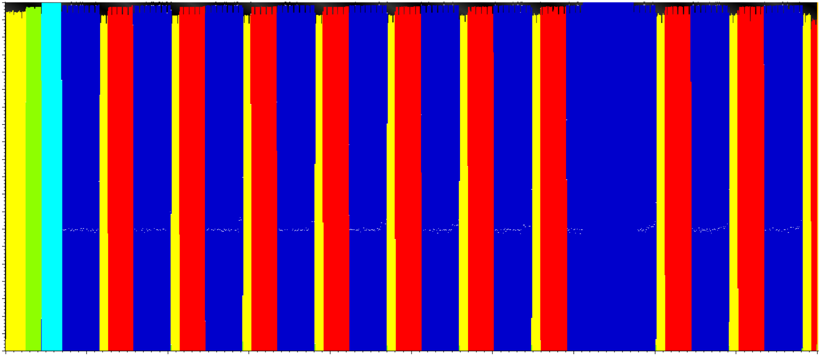
- When data arrives, process
- Write files

Task graph


$U^k(t+\Delta t)$
Limit Solution
Advance Solution
Compute Neighbor Limit Data
Compute Interface Flux
Compute Volume Term(s)
Unlimited Neighbor data
$U(t+\Delta t)$
Neighbor face data
$U_L(t)$, $U_R(t)$
$U^k(t)$

Time profile (1 core)

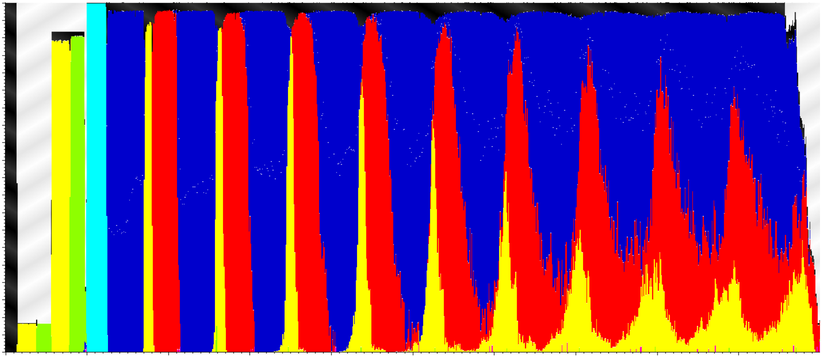
Ten time steps of a relativistic MHD test problem



Blue: volume terms Red: interface flux Yellow: slope limiting
Cyan: setup Black: Charm++ White: idle

Time profile (12 cores)

Ten time steps of a relativistic MHD test problem



Blue: volume terms Red: interface flux Yellow: slope limiting
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Summary

- How accurate do model waveforms need to be?
- How long and accurate do NR waveforms need to be?
- New paradigms needed to meet modeling challenges for LISA
- Do we need a radically new method for high mass-ratio systems?