New Paradigms for Computational Astrophysics

Lawrence E. Kidder

Cornell Center for Astrophysics and Planetary Science
Cornell University

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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 $\omega_{\text{orb}}, d, v_r$
- 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: $1 \leq q \lesssim 20$ possible
    - $q = 100$ demo; robust for $q \lesssim 6$
  - Spins: $0 \leq \chi \lesssim 0.8$ robust
    - high spin $0.92 \lesssim \chi$ 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 Neighbors

Compute Limit Data

Unlimited Neighbor data

Compute Interface Flux

Compute Volume Term(s)

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
Cyan: setup
Red: interface flux
Black: Charm++
Yellow: slope limiting
White: idle
Time profile (12 cores)

Ten time steps of a relativistic MHD test problem

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