**Advances and Challenges in Computational General Relativity**
Barus & Holley Building (Room 190), Brown University, Providence RI, 02912

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**Friday, 20 May 2011**

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08:00-09:00 — Light breakfast and registration, with opening remarks at 8:45

**Morning session.** Chair: J. Hesthaven.

09:00-09:30 — P. Diener (LSU). *The Effective Source Approach to the Self-force Problem.*
Extreme Mass Ratio Inspirals (EMRI's) of compact objects into super massive black holes are expected to be a very important source of gravitational waves for LISA. Traditionally perturbation techniques have been employed to analyze such sources. Here the small compact object is treated as a point particle moving on a perturbed geodesic in an exact black hole spacetime. Gravitational waves are emitted due to the particle motion which are then back scattered off the curvature of the background space-time and interact with the particle itself at a later point in the orbit: The so called self-force problem. In these approaches the field equations have been evolved with a singular delta-source, yielding a singular field at the location of the particle. To calculate the self-force the singular field then has to be carefully subtracted.

Recently a new approach have been proposed where the singularity of the point particle is subtracted from the source before the evolution is done, resulting in a regular field at the particle location from which the self-force can easily be calculated. I will describe the main ideas behind the Effective Source approach, the numerical implementation in the case of a scalar point charge in orbit around a Schwarzschild black hole and give some recent results.

09:30-10:00 — S. Field (Brown). *A Discontinuous Galerkin Method for BSSN-Type Systems.*
A discontinuous method (dG) for evolving the spherically reduced Generalized Baumgarte-Shapiro-Shibata-Nakamura (GBSSN) system is proposed. The system is discretized in its natural first-order in time second-order in space form, and I will discuss in some detail our scheme as well as stable treatment of second-order spatial operators within the dG framework. Our multi-domain method achieves global spectral accuracy and long-time stability on short computational domains. I will conclude by highlighting the benefits and challenges of a 3D dG solver.

10:00-10:30 — M. Tiglio (Maryland). *Reduced Basis in General Relativity: Select, Solve, Represent, Predict.*
I will discuss a reduced basis (RB) approach for modeling, representing and searching for gravitational waves. In essence, RB provides in a precise sense a nearly optimal representation of gravitational waves which converges exponentially with the number of samples by sequentially selecting the most relevant points in parameter space. The method is useful for deciding the most relevant configurations to numerically solve for, as well as for compressing existing catalogs or performing searches. I will discuss results for waveform catalogs of non-spinning compact binary coalescences, for which we find that for accuracies of 99% and 99.999% the method generates a factor of about $10 - 10^5$ fewer templates than standard placement methods. The continuum of gravitational waves is found to be representable by a finite and comparatively compact basis. I will also discuss ongoing work including spin in binary catalogs, as well as two-mode black hole ringdown ones.

10:30-11:00 — Coffee break

**Late morning session.** Chair: A. Buonanno

11:00-11:30 — J. Winicour (Pittsburgh). *The Problem with Treating Boundaries in General Relativity.*
There are no natural boundaries for the gravitational field. The initial-boundary value problem in

general relativity received attention only after recognition of its importance to numerical simulations of the inspiral and merger of binary black holes. I will describe the ensuing complications, successes and failures in dealing with this problem.

11:30-12:00 — M. Holst (San Diego). *The Einstein Constraint Equations, Adaptive Methods for Geometric PDE, and Finite Element Exterior Calculus.*
The Einstein constraint equations have been studied intensively for half a century; our focus in the first part of this lecture is on a thirty-five-year-old open question involving existence of solutions to the constraint equations on space-like hyper-surfaces with arbitrarily prescribed mean extrinsic curvature. Until 2009, all known existence results involved assuming constant (CMC) or nearly-constant (near-CMC) mean extrinsic curvature. We outline a new analysis approach that has allowed for the first existence result without near-CMC assumptions.

In the second part of the lecture, we consider the design of adaptive finite element methods (AFEM) for the nonlinear elliptic systems on Riemannian manifolds. We develop an analysis framework that allows for a proof of convergence of AFEM for the Einstein constraints. We also outline a new analysis approach for surface finite element methods, by first analyzing variational crimes in abstract Hilbert complexes, and then applying this to finite element exterior calculus on hypersurfaces.

12:00-12:30 — S. Christiansen (Oslo). *Spectral correctness of linearized Regge calculus.*
We relate linearized Regge calculus to a finite element approximation of the elasticity complex. Drawing on the experience with Maxwell eigenvalue approximations by mixed finite elements (Whitney forms or Nédélec edge elements) we deduce spectral correctness of the method.

12:30-14:00 — Lunch on your own

**Afternoon session.** Chair: G. Lovelace
14:00-14:30 — L. Kidder (Cornell). *The Spectral Einstein Code.*
I will describe the Spectral Einstein Code (SpEC) that has been developed to solve Einstein's equations using a multi-domain pseudo-spectral method. I will describe recent advances that allow SpEC to robustly simulate the merger of a binary black hole spacetime. I will describe the accuracy and efficiency of SpEC for producing gravitational waveforms covering dozens of cycles from the late inspiral, merger, and ringdown of a binary black hole system. I will also describe some of the remaining challenges in improving SpEC.

14:30-15:00 — J. Baker (NASA-Goddard). *Numerical Relativity for Space-Based Gravitational Wave Astronomy.*
In the next decade, gravitational wave instruments in space may provide high-precision measurements of gravitational-wave signals from strong sources, such as black holes. Currently variations on the original Laser Interferometer Space Antenna mission concepts are under study in the hope of reducing costs. Even the observations of a reduced instrument may place strong demands on numerical relativity capabilities. Possible advances in the coming years may fuel a new generation of codes ready to confront these challenges.

15:00-15:30 — A. Buonanno (Maryland). *Modeling the Final Moments of Coalescing Compact Binaries.*
The work at the interface between analytical and numerical relativity has deepened our understanding of the two-body problem in general relativity, revealing an intriguing simplicity, and suggesting a uniform picture along the entire mass-ratio region. I will review those results within the effective-one-body approach, focusing on the most dynamic and non-linear phase of the evolution. I will discuss the implications of those advances in the search for gravitational waves from comparable, small and extreme mass-ratio binary black holes.

15:30-16:00 — Coffee break

**Late afternoon session.** Chair: L. Buchman

16:00-16:30 — B. Szilágyi (Caltech). *Adaptive Mesh Refinement in the Context of a Spectral Evolution Scheme.*
The talk will present our work on an Adaptive Mesh Refinement algorithm applicable to Spectral Methods. We apply this algorithm routinely to our Binary Black Hole evolutions, with visible improvement in our results. I will describe key features of the algorithm and give a snapshot of its successes and limitations.

16:30-17:00 — A. Mroue (CITA). *Eccentricity reduction in precessing binary black holes.*
During the inspiral of an isolated binary, the orbit circularizes via the emission of gravitational waves. As a result, even binaries starting with some eccentricity at the beginning of their stellar evolution are expected to have negligible eccentricity by the time the frequency of the emitted gravitational radiation enters the frequency band of ground based detectors. In this talk, we discuss various aspects of eccentricity in binary black holes simulations: the definition and measurement of the eccentricity, the reduction of eccentricity in simulations of precessing binaries, the evolution of the eccentricity and its secular effects on the orbital phase.

17:30-19:00 — Reception at Faculty Club

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**Saturday, 21 May 2011**

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08:00-09:00 — Light breakfast and registration

**Morning session.** Chair: S. Lau

09:00-09:30 — M. Scheel (Caltech). *Vortex and Tendex Dynamics Around Black Holes.*
Given a timelike vector field, the Weyl curvature tensor can be split into "electric" and "magnetic" parts. The electric part is fully characterized by tidal tendex lines (integral curves of its eigenvectors) and tendicities (eigenvalues); similarly the magnetic part is characterized by frame-drag vortex lines and vorticities. We use these quantities to visualize spacetime curvature for several cases: stationary solutions, linearized gravitational waves, head-on binary black hole mergers, and 'superkick' binary black hole mergers.

09:30-10:00 — L. Buchman (Caltech). *Numerical relativity on conformally compactified CMC hypersurfaces.*
I will discuss recent work completed with the eventual goal of evolving binary black holes on constant mean curvature (CMC) hyperboloidal hypersurfaces which reach future null infinity. Such simulations would allow high-accuracy gravitational radiation modeling, since the Bondi news function, which contains all the gravitational wave information, is well-defined only at future null infinity. Recent work on the initial value problem (including both theoretical and numerical results), as well as a theoretical evolution scheme, will be presented.

10:00-11:00 — Coffee break/Poster session

**Late morning session.** Chair: L. Kidder

11:00-11:30 — P. Laguna (Georgia Tech). *Light-shows from Supermassive Black Hole Mergers.*
Coincident detections of electromagnetic and gravitational wave signatures from supermassive black hole mergers will provide a wealth of opportunities to study gravitational physics, accretion physics, and cosmology. Understanding the conditions under which these electromagnetic and gravitational wave signatures arise requires astrophysical computing addressing general relativity in its strongest manifestation and complex phenomena involving fluids, electromagnetic fields and radiative processes. In this talk, I will review the current status of numerical simulations of supermassive black hole mergers in the presence of hot gaseous environments and circumbinary disks, and I also discuss

future challenges and opportunities.

11:30-12:00 — C. Ott (Caltech). *Recent Advances in the Modeling of General Relativistic Stellar Collapse.*

I summarize the recent progress made by the community in the modeling of stellar collapse in general relativity and present new results from 1.5D (spherical symmetry + rotation) and 3+1 simulations of stellar collapse and black hole formation.

12:00-12:30 — M. Duez (Washington State). *Compact neutron star binary mergers using the Spectral Einstein Code.*

Compact object neutron star binaries (neutron star-neutron star or neutron star-black hole) are important gravitational wave sources and (possibly) gamma ray burst progenitors. Numerical models of the merger and postmerger state must evolve the spacetime metric and the nuclear matter. Impressive simulations of these mergers have been carried out, but there is still a crucial need for simulations with more realistic neutron star physics (including a realistic equation of state, composition evolution, and magnetic and neutrino radiation effects) and, for the black hole-neutron star case, for simulations with higher-mass, spinning black holes. I describe attempts by the Caltech-Cornell-CITA-WSU collaboration to carry out such simulations. Our mixed pseudospectral/finite-difference algorithm is unique in many ways. In this talk, I will focus on our efforts to model moderate ($\sim$5:1) mass ratio black hole-neutron star binaries using nuclear theory-based equations of state.

12:30-14:00 — Lunch on your own

**Afternoon session.** Chair: P. Laguna

14:00-14:30 — G. Lovelace (Cornell). *Simulating merging black holes with spins above the Bowen-York limit.*

The warped spacetime of merging black holes—an important source for gravitational-wave detectors—can only be computed using numerical relativity. Some models of accretion predict black-hole spins that are nearly extremal (nearly 1 in dimensionless units); however, because of the initial data used, typical numerical computations of merging black holes are limited to black-hole spins of 0.93 or lower (the "Bowen-York limit"), which is physically quite far from extremality. Improved initial data can yield binary black holes with spins above this limit, but evolving these data through inspiral, merger, and ringdown is challenging. In this talk, after summarizing the improved initial data and evolution techniques that make them possible, I will discuss recent simulations [obtained with the Spectral Einstein Code (SpEC)] of the inspiral, merger, and ringdown of binary black holes with spins above the Bowen-York limit.

14:30-15:00 D. Brown (Syracuse). *Searching for Compact Binary Coalescence with LIGO and Virgo.*

The coalescence of compact binary systems (including neutron stars and/or black holes) is one of the most likely sources of gravitational-wave signals observable in ground-based detectors. I describe the astrophysical motivation and methods used for joint LIGO-Virgo searches for such signals, and present preliminary results from these searches, including the S6/VSR2,3 Blind Injection Challenge. I also briefly discuss prospects and challenges for improved and future binary coalescence searches.

15:00-16:00 — Coffee break/Poster session

**Late afternoon session.** Chair: P. Diener

16:00-16:30 — M. Hannam (Cardiff). *Solving the binary black hole problem – again and again.*

The widely stated motivation for solving the binary black hole problem was to produce theoretical waveforms for GW astronomy. In practice this means producing waveforms for enough cases to calibrate accurate analytic models, which can in turn be used to generate waveforms at any point in the parameter space, for use in GW searches and in parameter estimation following detections. To do this we will need to produce an extremely large number of simulations much more accurately and efficiently than has been done to date. And there are still issues that need to be resolved before we start. I will discuss a number of these, and a few of the efforts underway to address them.

16:30-17:00 — T. Baumgarte (Bowdoin). *New Approaches to the Initial Data Problem.*
I will discuss new approaches to constructing black hole initial data that render the black holes in a trumpet geometry. I will first review some results in the context of the conformal transverse-traceless (CTT) decomposition, and will then suggest generalizations to the conformal thin-sandwich (CTS) decomposition. I will present results for boosted black holes in the original CTS decomposition, and will speculate on why it does not seem possible to construct such data in the extended CTS decomposition.

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**Sunday, 22 May 2011**

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08:00-09:00 — Light breakfast and registration, with opening remarks at 8:45

**Morning session.** Chair: M. Scheel

09:00-09:30 — A. Klöckner (NYU). *Discontinuous Galerkin, Python, and GPUs: the 'hedge' solver package.*
I will be describing the path from a simple, short, stand-alone code implementing an unstructured discontinuous Galerkin scheme in OpenCL and Python to 'hedge', a full-featured and high-level toolkit for solving partial differential equations discretized using discontinuous Galerkin schemes. By a few examples, I will detail the usage of the latter package for hybrid GPU+MPI parallel simulations of phenomena modeled by PDEs such as Maxwell's equations and compressible Navier-Stokes in three dimensions. I will also briefly touch on the advantages of combining GPUs and scripting languages into an environment in which to develop scientific codes.

09:30-10:00 — F. Löffler (LSU). *The Einstein Toolkit.*
The Einstein Toolkit Consortium is developing and supporting open software for relativistic astrophysics. Its aim is to provide the core computational tools that can enable new science, broaden our community, facilitate interdisciplinary research and take advantage of emerging petascale computers and advanced cyberinfrastructure.

The Einstein Toolkit currently consists of an open set of over 100 modules for the Cactus framework, primarily for computational relativity along with associated tools for simulation management and visualization. The toolkit includes a vacuum spacetime solver (McLachlan), a relativistic hydrodynamics solver (GRHydro, an updated and extended version of the public version of the Whisky code), along with modules for initial data, analysis and computational infrastructure. These modules have been developed and improved over many years by many different researchers.

The Einstein Toolkit is supported by a distributed model, combining core support of software, tools, and documentation in its SVN repository with partnerships with other developers who contribute open software and coordinate together on development. It currently has over 60 registered members from over 20 research groups world-wide.

10:00-10:30 — Coffee break

**Late morning session.** Chair: M. Tiglio

10:30-11:00 — C. Sopuerta (CSIC-IEEC). *Modeling of Extreme-Mass-Ratio Inspirals with PseudoSpectral Methods.*
The computation of the gravitational self-force is one of the main challenges in the modeling of extreme-mass-ratio inspirals. It involves the computation and regularization of the metric per-

turbations created by a point mass orbiting a massive black hole. In computational terms, this problem requires adequate techniques to deal with the evolution of wave-type equations sourced by a point-like object in such a way that the solution is obtained with high precision and in an efficient way. In this talk I will describe a program to compute the self-force in the time domain using techniques that avoid the introduction of an artificial scale associated with the particle and its implementation with the use of pseudospectral methods. I will also present results for generic orbits in a simplified model consisting of a scalar charged particle orbiting a non-rotating black hole.

11:00-11:30 — N. Taylor (Caltech). *Progress towards evolving black hole binaries using second-order spectral methods.*
Successful spectral simulations of Einstein's equations currently require using a fully first-order formulation, which has the disadvantage of introducing additional constraints and equations. We have developed a novel pseudo-spectral penalty method for evolving second-order (in space) hyperbolic equations. With this method, the penalties are constructed as functions of Legendre polynomials and are added to the equations of motion everywhere, not only on the boundaries as is typical in first-order formulations. Recently, we have for the first time succeeded in evolving a binary black hole inspiral, merger, and ringdown using this method with Einstein's equations in generalized harmonic form. I will review the second-order penalty approach and discuss the recent results.

11:30-12:00 — S. Lau (New Mexico). *Implicit-explicit (IMEX) evolution of single black-holes using the Spectral Einstein Code.*
We describe single-black-hole evolutions using the generalized harmonic formulation of Einstein's equations and implicit-explicit time-steppers. IMEX time-steppers may enhance performance in BBH simulations, most especially for extreme mass ratio binaries. We address the elliptic-type implicit equation that must be solved to to take a timestep, and present numerical tests. This work is joint with G. Lovelace and H. Pfeiffer, and builds on earlier joint work for scalar fields with H. Pfeiffer and J. Hesthaven. Numerical simulations have been performed with the Spectral Einstein Code <www.black-holes.org/SpEC.html>.

12:00-12:15 — Closing remarks