Advances and Challenges in Computational General Relativity

Poster presentations will be held on Saturday 20 May 2011 from 10:00 - 11:00 and 15:00 - 16:00 outside room 190, Barus & Holley Building, Brown University, Providence RI, 02912. Only the contact author is listed.

Frank 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.
Philipp Moesta AEI	*The merger of small and large black holes* An unexpected feature has been observed in the simulation of binary black holes following their inspiral and merger. After formation of a common apparent horizon, as the two marginally outer trapped surfaces (MOTS) corresponding to the individual black holes continued to approach, they eventually touch and then penetrated each other. This penetration was surprising because it had not been considered in theoretical discussions and had not been observed in prior simulations of binary black-hole (BBH) mergers. In this project we use an independent numerical evolution code using a harmonic formualtion of the Einstein equations to first confirm that the individual MOTS do penetrate following a BBH merger and then analyze some of the highly interesting features revealed by the simulations. We track the coordinate shapes of the apparent horizons (AH) and illustrate how the detailed penetration process proceeds by using geometrical quantities invariantly measured on the AH surfaces. We illustrate some well-established mathematical theorems about the interaction between two MOTS with numerical simulations and additionally provide some highly interesting predictions on how the final merger between two black-holes might proceed in its very final stages.

Nestor Ortiz Madrigal U. of Mexico at Morelia	*Conformal diagrams for the gravitational collapse of a spherically symmetric dust cloud* We present an algorithm to construct conformal diagrams describing the causal structure in the interior of a relativistic, collapsing matter cloud in spherical symmetry. This algorithm is based on a careful study of the light rays in the vicinity of the singularity and on the numerical integration of radial null geodesics. We apply this technique to the collapse of a spherical dust cloud, and analyze the local and global visibility of the resulting singularity.
Debananda Chakraborty SUNY Buffalo	*A multi-domain hybrid method for head-on collision of black-holes in particle limit* A hybrid method is developed based on spectral and finite-difference methods for solving the inhomogeneous Zerilli equation in time-domain. The developed hybrid method decomposes the domain into the spectral and finitedifference domains. The singular source term is located in the spectral domain while the solution in the region without the singular term is approximated by the higher-order finite-difference method. The spectral domain is also split into multi-domains and the finite-difference domain is placed as the boundary domain. Due to the global nature of the spectral domain, a multi-domain method only composed of the spectral domain does not yield the proper power-law decay unless the range of the computational domain is large. The finite-difference domain helps reduce boundary effects due to the truncation of the computational domain. The multi-domain approach with the finite-difference boundary domain method reduces the computational requirements significantly and also yields the proper power-law decay. Stable and accurate interface conditions between the finite-difference and spectral domains and the spectral and spectral domains are derived. For the singular source term, we use both the Gaussian model with various values of full width at half maximum and a localized discrete delta-function. The discrete delta-function was generalized to adopt the Gauss-Lobatto collocation points of the spectral domain. The gravitational waveforms from black hole ringdown are observed . Numerical results show that the developed hybrid method accurately yields the quasi-normal modes and the power-law decay profile. The numerical results also show that the power-decay profile is less sensitive to the shape of the regularized delta-function for the Gaussian model than expected. The Gaussian model also yields better results than the localized discrete delta-function.

Nigel Bishop Rhodes University	*Initial data transients in binary black hole evolutions* It is well known that current practice for the setting of initial data introduces spurious junk radiation into the system, in both the 3+1 and the characteristic approaches. Common practice regards the signal as physical only after it has settled down following the burst arising from the initial data solution, and typically this occurs after less than a light-crossing time of the system. While it is straightforward to handle the junk radiation in this way, a more serious issue is whether the spurious radiation content of the initial data leads to longer-term transients in the wave signal. Characteristic extraction is a method of invariantly measuring the gravitational wave emission of an isolated source by transporting the data to null infinity using a null formulation of the Einstein equations. Initial data is needed on a null cone in the far field region, say $r > 100M$ whereM is the mass of the system. Previous work has taken the simplistic approach of setting the null shear J = 0 everywhere. However, in the generic case a radiating solution has $J \neq 0$, and imposing J = 0 in effect means that the outgoing radiation implied by the boundary data must be matched at the initial time by ingoing radiation. Since the characteristic initial data is needed only in the far field region, linearized theory is a suitable approximation. We construct initial data that, at the linearized level, represents the physical situation of a gravitational field with purely outgoing radiation produced by sources in a central region. We compare the waveforms computed by characteristic extraction using as initial data (a) J = 0, and (b) the linearized solution. We find that a small residual difference is visible between the two approaches, and takes several hundred M to be damped below other effects. Any mis-match between the linearized solution and the actual data is an indication of an ingoing radiation content. Now, on the extraction worldtube, the characteristic metric data is determined entirely by the 3+1 data so that any ingoing radiation can be traced back to the 3+1 initial data. In this way we show that the 3+1 initial data contains a component of ingoing radiation which also results in a transient lasting several hundred M after emission of the junk radiation burst.
Jonathan Thornburg Indiana University	*Computing extreme mass ratio inspiral waveforms with m-mode regularization* A typical extreme mass ratio inspiral (EMRI) accumulates $\sim 10^6$ radians of gravitational-wave (GW) phase in the last year. Phase-coherent modelling of this very long waveform requires highly accurate calculation of the EMRI orbital dynamics. Here I outline the Barack-Golbourn m-mode scheme, which is currently our best candidate for such computations. This scheme poses a number of challenges for numerical implementation, including the efficient evaluation of lengthly series expansions for the puncture function and effective source near the small body (”particle”), the efficient and accurate integration of oscillatory functions, and the numerical solution of PDEs with non-smooth source terms. I outline recent progress in meeting these challenges, with the short-term goal of computing highly accurate self-forces for generic orbits in Kerr spacetime.

Richard Kriske University of Minnesota	*Horizon of the Universe, how well does it work with the Big Bang?* I Would like to present an idea about Horizons, which I find very interesting as it is tangible and often forgetten. Of course the Earth's Horizon is a curved line when viewed at the Ocean on a clear day. Objects at the Horizon of a curved surface not only diminish in size due to perspective geometry, but also tilt back away from the observer so their projective geometry. This effect on a two dimensional surface, with a height can be ignored, and is a matter for artists and navigators, but on a three dimensional surface with time as the height, this diminishment and projective change appears as a force at the horizon and because of a time component generates radiation (the CMBR). Normally people want to talk about the Big Bang, which may also be true and may be just a different way of looking at the same thing (may be mathematically equivalent). At the Horizon itself the Bing Bang is not actually equivalent to my theory in that like a "frozen star" the Horizon can only tilt back so much and then every observor no matter where they are would view a "frozen" condition at the horizon. Another problem is the numerous black holes which (because Horizons in Space Time are Areas) also have Horizons, would have their Horizons add to the over all Large Horizon of the Universe and all observers would see a blotchy, Swiss Cheese Horizon which would change as they move.
Justin McKennon UMass Dartmouth	*Hardware Accelerated Simulations of Extreme Mass Ratio Black Hole Binaries* Due to the complexities that are involved in the modeling of astrophysical phenomena, a novel way to obtain high accuracy results is desirable. Utilizing both the Cell Broadband Engine Architecture for the PS3's Cell Broadband Engine and Compute Unified Device Architecture (CUDA) for NVIDIA GPUs allows one to achieve time saving performance gains of well over an order of magnitude. Harnessing the well known power of massively parallel computational devices such as these provides not only a means for drastically speeding up difficult computations, but also allowing one to model even more complex phenomena in a reasonable amount of time. Implementing the Teukolsky Gravitational Wave Perturbation Equation on both the Cell BE and in CUDA allowed us to obtain enormous high accuracy computational performance gains with respect to performing these calculations on the CPU.

Zhoujian Cao Academy of Mathematics	*Effects of the third body on binary black hole* Binary black hole systems are usually located in the gravitational potential well formed by a massive black hole, which are mostly located in the center of a galaxy. In most past studies, binary black hole systems have been treated as isolated systems, ignoring the effects of the background. The validity of the approximation is based on the belief that the background gravitational field provided by the other sources is extremely weak compared with the strong gravitational field produced by the binary black hole itself during the evolution, and can be neglected in gravitational wave detection. However, it is still interesting to check how valid this approximation is. In this work, instead of a heavy numerical calculation of the evolution of the three black hole problem with a full relativistic treatment, we propose a perturbational scheme to investigate the effects of the background gravitational potential on the evolution of a binary black hole, especially on the waveform of gravitational radiation. The existence of the background gravitational potential accelerates or decelerates the plunge process depending on binarys detail configuration. Consequently, the gravitational wave form is affected, including higher mode excitation, red shift, amplitude changing and phase shift effects. These effects may provide opportunity to detect the third body around some binary through gravitational wave detection, but also gives more confusion for data analysis.
Larne Pekowsky Syracuse University	*The NINJA-2 project* Two important advances have occurred in recent years which have brought us closer to the goal of observing and interpreting gravitational waves from coalescing compact objects: the successful construction and operation of a world-wide network of ground-based gravitational-wave detectors and the impressive success of numerical relativity in simulating the merger phase of Binary Black Hole (BBH) coalescence. The aim of the NINJA project is to study the sensitivity of gravitational-wave analysis pipelines to numerical simulations of waveforms and foster close collaboration between numerical relativists and data analysts. NINJA-1 was a huge success, over 75 numerical relativists and data analysts participated in the contribution of a simulated data set containing numerical waveforms, analysis of this data and interpreting the results of this analysis. We present the status and some preliminary results of the followup project, NINJA-2, which is currently ongoing.
Gerhard Zumbusch University of Jena	*Galerkin schemes in general relativity* Numerical schemes for Einstein's vacuum equation of general relativity are developed. The equation in harmonic gauge is discretized in space-time by Galerkin methods. A split into space and time leads to time-stepping schemes for second order wave equations. Finite Element and Discontinuous Galerkin are covered along with local mesh refinement in space-time.

Shawn Walker LSU	*Mesh Generation With Large Deformations and Topological Changes* We present a method for generating 2-D unstructured triangular meshes that undergo large deformations and topological changes in an automatic way, and we discuss how to extend this idea to 3-D. We employ a method for detecting when topological changes are imminent via distance functions and shape skeletons. When a change occurs, we use a level set method to guide the change of topology of the domain mesh. This is followed by an optimization procedure, using a variational formulation of active contours, that seeks to improve boundary mesh conformity to the zero level contour of the level set function. Our method is advantageous for Arbitrary-LagrangianEulerian (ALE) type methods and directly allows for using a variational formulation of the physics being modeled and simulated, including the ability to account for important geometric information in the model (such as for surface tension driven flow). The meshing procedure is not required at every time-step of a simulation and the level set update is only needed during a topological change. Hence, our method does not significantly affect computational cost. Lastly, this method may be useful for accurate reconstructions of event horizons in black-hole simulation data.
Sarah Caudill LSU	*Status of the search for gravitational wave ringdowns from perturbed black holes* We report on the status of the search for gravitational wave ringdowns from perturbed black holes with masses between 25-100 $M_{\rm sun}$ in LIGO's fifth science run. This mass range is the first regime explored as part of the ringdown search's participation in the Inspiral-Merger-Ringdown (IMR) project, a joint effort between LIGO's Burst group and Compact Binary Coalescence group to study the efficiency with which we detect high mass binary black holes with masses between 25-500 $M_{\rm sun}$. We also review the recent changes made to the ringdown analysis pipeline for LIGO's fifth science run. These changes include the implementation of a new 3D coincidence test to compute the distance between pipeline triggers in frequency, quality, and time space as well as a number of improvements to increase efficiency and automation in the pipeline.
Michael Puerrer University of Vienna	*A new method for reducing orbital eccentricity of binary black-hole initial data* We present a new iteration method for reducing orbital eccentricity of binary black hole initial data. Given reasonably low eccentricity starting momenta for puncture initial data we evolve these data numerically for a couple of orbits and construct improved initial parameters by comparing NR with post-Newtonian quantities using either the starting momenta or perturbed momenta. We can reach eccentricities below 10^{-3} in one or two iteration steps.
Alex Benedict U. of New Mexico	*Fast Waveform Extraction from Blackhole Perturbations* We present a scheme for extraction of asymptotic waveforms from simulations of gravitational perturbations on "short domains". Although in its initial phase, our investigation suggests that such "waveforms at infinity" can be extracted with arbitrary accuracy, with relevant physical phenomena (ringing and tails) faithfully captured. We present several numerical experiments.

Nathan Johnson-McDaniel Penn State	*Constructing more astrophysically realistic binary black hole initial data* As numerical simulations of black hole binaries continue to mature, the construction of astrophysically realistic initial data for these simulations remains an important challenge. In particular, such initial data will likely be needed for the simulations that will supply advanced detectors with templates for parameter estimation, since current binary black hole initial data clearly do not correspond to a timeslice of an astrophysical black hole binary: All sets lead to an initial burst of spurious ("junk") radiation when evolved, and all but two of the sets lack the outgoing radiation from the binary's past inspiral. We discuss various methods of constructing more astrophysically realistic initial data, and, in particular, describe the data we have generated by matching the post-Newtonian metric to two perturbed Schwarzschild metrics. These data include the binary's outgoing radiation, in addition to the expected tidal deformations on the holes (whose absence in standard initial data is thought to be the cause of the high-frequency component of the junk radiation). Our matched data are currently being evolved in two different implementations, and we discuss ways of improving the construction. We also investigate how much the spurious radiation (and lack of initial outgoing radiation) in simulations affects the binary's subsequent evolution through post-Newtonian tail effects.
Nick Tacik CITA	*A parameter space investigation of junk radiation in binary black hole simulations* We investigate the parameter space (spin and initial separation) dependence of junk radiation in simulations of equal-mass, equal-spin, non-precessing binary black holes. We look at six different spins (from 0 to 0.5), and five differential initial separation (from 12M to 30M). Results are quantified using three different parameters: The energy carried away from the system by junk radiation, the fractional mass change of a black hole due to junk radiation, and the fractional spin decrease of a black hole due to junk radiation. We then compare the results when using conformally flat initial data, and when using superposed-Kerr-Schild initial data.
Patricia Schmidt Cardiff	*Tracking the precession of a black-hole-binary systems* We have developed a simple method to track the precession of a black-hole-binary system, using only information from the gravitational-wave (GW) signal. Our method, applied to numerical waveforms, consists of locating the frame from which the magnitude of the (2,2)-modes is maximized. We find that our method locates the direction of the orbital angular momentum L of the binary (which differs in general from the normal of the orbital plane), and reproduces higher-mode amplitudes similar to a comparable non-spinning binary. The simple form of this quadrupole-aligned waveform will be useful in attempts to analytically model the inspiral-merger-ringdown (IMR) signal of precessing binaries.

Milton Ruiz University of the Balearic Islands	*Constraint preserving boundary conditions for the Z4c formulation of general relativity* We discuss high order absorbing constraint preserving boundary conditions for the conformal decompostion of the Z4 formulation of general relativity coupled to the moving puncture family of gauges. Using a Kreiss-Winicour technique based on an appropriate pseudo-differential reduction to a first order system, we prove well-posedness of the initial boundary value problem with a particular choice of the puncture gauge in the frozen coefficient approximation. Numerical evidence for the efficacy of the first and second order boundary conditions in constraint preservation and absorption is compared with the standard sommerfeld conditions in the evolution of flat, spherical black-hole and neutron star spacetimes.
Christian Reisswig Caltech	*Gravitational wave extraction in simulations of rotating stellar core collapse* We use curvature-based methods for extracting gravitational waves in fully general relativistic simulations of rotating stellar core collapse. Due to the rather weak signals emitted in core collapse, it is inherently difficult to reliably extract gravitational waves using curvature-based methods. Thus, previous studies were almost exclusively limited to wave extraction using the quadrupole approximation. Here, we succeed in computing the gravitational strain from curvature-based methods. For three representative rotating core collapse models, we compare waveforms extracted via the Regge-Wheeler-Zerilli-Moncrief formalism as well as waveforms computed from the Weyl component Psi4. Most notably, we also apply the method of Cauchy-characteristic extraction, allowing to compute the waveforms where they are unambiguously defined, that is, at future null infinity scri+. We quantify the various sources of error and find that the simple quadrupole approximation yields waveforms that are in very good agreement with more sophisticated methods.
Curran Muhlberger Cornell University	*Basis functions for neutron star interiors* The Spectral Einstein Code has been a valuable tool for studying the mergers of black holes and neutron stars whose efficiency relies on choosing basis functions well-adapted to regional spacetime dynamics. We recently improved its treatment of neutron star interiors by implementing a basis for functions over B3 (filled spheres) using one-sided Jacobi polynomials in the radial direction. Here we describe in detail the steps needed to use such a basis in a pseudospectral code and provide intuitive explanations for some of the restrictions encountered. We also discuss recommendations for filtering high-order modes and examine performance on both test problems and astrophysical systems.

Garav Khanna UMass Dartmouth	*High-accuracy simulations of extreme-mass-ratio black hole binaries in the time-domain* We present high-accuracy EMRI simulations using Kerr black hole perturbation theory (Teukolsky equation with particle-source-term) in the time-domain. High accuracy is achieved using a combination of techniques, including improved representation of the particle-source on a finite-difference grid, multiple extrapolations and brute-force acceleration of the computations using advanced HPC hardware (such as GPUs). We are able to generate long waveforms (several 100,000M) with relative-errors less than one-part in 10,000 in just a few hours of run time.
Satya Mohapatra UMass Amherst	*Observing the orbital hang-up effect in a binary black hole merger through a gravitational wave burst search* Spins of binary black holes greatly affect the energy/amplitude of gravitational wave emitted during their mergers. The phenomenon of orbital hang-up [1], described by binary black holes with higher aligned-spins taking longer time to merge, has been shown in a wide range of numerical relativity simulations. In this poster we present orbital hang up effect of the merger of non-precessing spinning binary black holes [2] signal injected to simulated LIGO noise and as detected in Omega burst search [3] algorithm. This allows us to conclude the effect of spins on the detectability of binary black hole mergers in a burst search. We further discuss how this influences the characteristic time and frequency of a binary black hole merger signal observed in this burst search.
James van Meter NASA Goddard	*Computing the spin of a black hole in numerical relativity* Computing the spin of a numerically simulated black hole is nontrivial as, not only will its direction generally precess during a binary inspiral, but its magnitude may not necessarily be known precisely due to uncertainties in the initial data and other factors. Post-merger, it is also useful to compute the spin of the remnant black hole in order to verify conservation of angular momentum. I present a new method to compute black hole spin based on a complex invariant constructed from the Weyl tensor called the Coulomb scalar, as evaluated on the apparent horizon. For Kerr spacetimes of known spin the method presented here is found to be more accurate than other leading methods, such as that using an approximate Killing vector field.
Daniel Hemberger Cornell University	*Control systems in binary black hole evolutions* Over the past several years, aspects of Operations Research and control theory have been integrated into the Spectral Einstein Code (SpEC) as part of the dual frames approach to solving the moving excision problem. Today, we control not just the trajectory of the black holes, but also the size and shape of their apparent horizons. Robustness of the size control during the initial relaxation and the merger is achieved by monitoring the characteristic speeds on the excision boundary. This new strategy has enabled collaborators to successfully evolve binary black hole systems with spins above the Bowen-York limit. I discuss the details of our control system and describe how it is implemented in SpEC.