An Overview of the Numerical Relativity Code *openGR*

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Introduction

openGR is designed to treat large scale simulations (e.g., binary black hole mergers) and is well suited to treat a wide range of problems in general relativity.

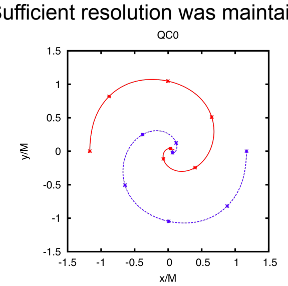
•*SAMRAI:* *openGR* is based on SAMRAI (Structured Adaptive Mesh Refinement Application Infrastructure), which provides its mesh refinement capabilities and largely dictates its scaling performance.

•*Evolution scheme:* Unlike Berger-Oliger method, the Adams-Bashforth Adams-Moulton predictor-corrector evolution scheme that *openGR* uses requires the timestep to be the same across all levels throughout the domain regardless of spatial resolution (the magnitude of the timestep is determined and adjusted by the predictor-corrector method). The tradeoffs are that *openGR* evolves slower than comparative finite difference codes while having the potential for improved accuracy.

•*Modular design:* The modularity of *openGR* allows others in the numerical relativity community to easily make changes to the physical problem under consideration while retaining its AMR capabilities and scaling performance benefits. It is straightforward to change the equations being solved, the formulation to something other than BSSN, and the number of variables being evolved.

QC0

We conducted the a simulation of QC0, the standard test case of binary black holes merging after completing one full orbit. The simulation was on a domain of +/-160 M with 9 levels of mesh refinement. The two finest levels were moving boxes that track the black holes with the finest resolution of M/64 and the coarsest resolution being 4 M. Sufficient resolution was maintained to satisfactorily extract the gravitational waves.



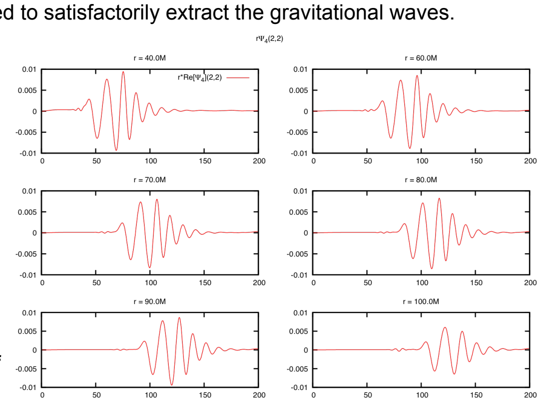


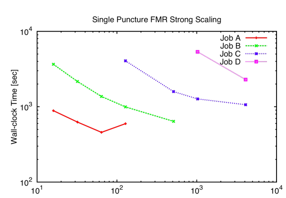
Figure 1. Results of *openGR* simulating QC0. Above: The points on the curve represent the positions of the black holes at time intervals of 5 M. Right: The real part of Ψ_4 (l = 2, m = 2) (scaled by extraction radius) for various extraction radii.

Scaling

openGR scales well, which allows for simulations to be run in parallel on thousands of processors. We conducted scaling runs for a single puncture at rest with 9 levels of factor-of-2 mesh refinement.

•*Strong scaling:* The simulation remains the same as the number of processors increases. On a log-log plot, the ideal slope is -1. For *openGR*, the average slope is -.59.

•*Weak scaling:* The size of the job per processor remains the same (same number of points is being evolved on each processor) as the number of processors increases. The ideal case is a slope of 0. For *openGR*, the average slope is .13.



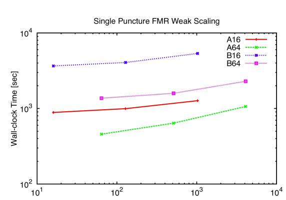
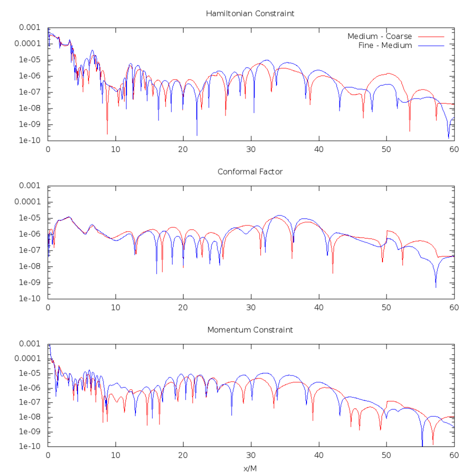


Figure 2. Strong (top right) and weak scaling (middle right) of *openGR* for a single puncture with nine levels of mesh refinement. Aspects of the different jobs are listed in the table (bottom right).

Job	A	B	C	D
Points / Level	40^3	80^3	160^3	320^3
Refinement Levels	9	9	9	9
Domain	$\pm 100M$	$\pm 200M$	$\pm 400M$	$\pm 800M$
Coarse Resolution	$5M$	$5M$	$5M$	$5M$
Fine Resolution	$\frac{5M}{256}$	$\frac{5M}{256}$	$\frac{5M}{256}$	$\frac{5M}{256}$

Convergence

openGR uses 6th order interpolation and 4th order finite difference stencils. By conducting tests of a single stationary black hole, we observe the expected convergence at 4th order accuracy across the 8 levels of mesh refinement. The Medium – Coarse curves (red curves in figure below) have been rescaled by a factor appropriate with 4th order finite differentiation.



	Coarse	Medium	Fine
Points / Level	40^3	60^3	80^3
Refinement Levels	8	8	8
Domain	$\pm 100M$	$\pm 100M$	$\pm 100M$
Outer Boundary Resolution	$5M$	$\frac{10M}{3}$	$\frac{5M}{2}$
Puncture Resolution	$\frac{5M}{128}$	$\frac{5M}{192}$	$\frac{5M}{256}$

Figure 3. openGR convergence tests (top above) of the Hamiltonian constraint (top), conformal factor (middle), and momentum constraint (bottom). The table (bottom above) outlines the simulations of a single puncture at rest.

Future Work

Our initial data solver (KINSOL) has recently been modified to be multigrid, and we are in the process of testing this upgrade. We are also further conducting convergence tests to ensure the expected behavior and accuracy of the code *openGR*.

References

Anderson, M., *Constrained Evolution in Numerical Relativity*, PhD Dissertation, University of Texas at Austin, 2004

Walter, P., *Using openGR for Numerical Relativity*, PhD Dissertation, University of Texas at Austin, 2009

McIvor, G., *Computing Binary Black Hole Merger Waveforms Using openGR*, PhD Dissertation, University of Texas at Austin, 2012