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Numerical Relativity's Contributions to Theoretical Astrophysics, and Its Path Forward

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In the extreme violence of merger and mass accretion, compact objects like black holes, neutron stars, and white dwarfs are thought to launch some of the most luminous outbursts of electromagnetic, neutrino, and gravitational wave energy in the Universe. Modeling these systems realistically remains a central problem in theoretical astrophysics, due to two key challenges. First, the emission mechanisms often stem from magnetized flows and dynamical gravitational fields spanning many orders of magnitude in lengthscale and timescale, from the strong-field region near compact objects, to the often magnetically-dominated, weak-field regions far away. Second, the equations governing the dynamics are highly complex and nonlinear, including the full general relativistic field equations as coupled to the equations of radiation general relativistic magnetohydrodynamics. I will review some of the current progress in developing numerical relativity codes that robustly and efficiently solve these equations (or some subset thereof) on non-uniform numerical grids to capture the multi-scale nature of compact object merger and mass accretion. Some key results from such codes will also be explored, providing examples of how numerical relativity has advanced theoretical astrophysics. Though these results are highly interesting, they often rely on extremely computationally expensive simulations that lack the accuracy and physical realism required for complete theoretical models. Thus, although numerical relativity simulations have begun to address key astrophysical questions, large gaps in our understanding remain. Bridging these gaps will require a continued focus on adding more physics to our simulations, as well as development of more computationally-efficient formulations of the equations and the algorithms for solving them.