Differentiable Waveforms - CASPEN Program Exit Report

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Date of Visit: 13th April - 26th April, 2022

1 Introduction

The observations of gravitational waves (GWs) from merging compact objects has revolutionized our understanding of both astrophysics and fundamental physics. Future observing runs of current generation detectors, as well as next generation detectors, promise to unveil much more. Analyzing the data from these detectors is an arduous task involving many stages from searching for true astrophysical signals to correctly calculating the posterior distribution for the physical parameters of each observed system.

Theoretical predictions of GW waveforms have come along way over the last few decades with state-of-the-art techniques able to predict the inspiral, merger, and ringdown (e.g. the effective one body (EOB) formalism [1] and IMRPhenom [2]). Each family of waveforms uses a variety of analytic techniques, calibrated on numerical relativity simulations, to produce accurate waveforms across large fractions of the parameter space.

Automatic differentiation has emerged as a fundamental tool for machine learning. Moreover, simple but efficient implementations, such as `JAX` [3], have enabled its use in scientific programming. By constructing a set of differential GW waveforms, we hope to drastically accelerate both parameter estimation and searches.

2 Work and Activities During the Visit

During my visit to the Flatiron Institute Center for Computational Astrophysics (CCA) I made significant progress towards the implementation of differentiable waveforms. I started to develop a fully self-contained python package called `ripple` (https://github.com/tedwards2412/ripple) built upeon `JAX`. In particular, I implemented the aligned spin model IMRPhenomD [2] and performed a full comparison with lalsuite, the gold standard for GW analysis. This involved verifying that both the amplitude and phase implemented in `ripple` agree with lalsuite to within $\mathcal{O}(0.01)\%$. In addition, I verified that the *match* (a measure of the similarity between two waveforms) is equal to one across the entire parameter space. I also worked with Adam Coogan to develop `ripple` into an installable package format for easy use by the GW community.

Together with Daniel Foreman-Mackey and Kaze Wong we began working on parameter estimation using an efficient sampling method called Hamiltonian Monte Carlo (HMC). Importantly, HMC uses derivatives of the likelihood to be more efficient that traditional sampling methods. We therefore worked on interfacing `ripple` with Kaze's existing detector projection code which is also built around `JAX`. We successfully integrated the two code bases and have now started preliminary tests using HMC for parameter estimation. Maximiliano Isi, in addition to Will Farr, also provided valuable feedback and help throughout this work.

In addition to this work, I participated in both the "Astro Data Group" and "GW Group" regular weekly meetings. In both, I gave a short introduction to automatic-differentiation and the idea of differentiable waveforms, as well as a progress update the following week. These meetings helped to structure the code into a format that would be maximally useful for the target community as well as direct suggestions for future directions.

The long term goal of the project is to further develop the `ripple` codebase to include more complicated and realistic waveforms. In particular, I will initially target precessing models with higher order modes [4]. In addition, it maybe be useful to expand beyond fourier-domain waveform models and also develop time-domain waveform models. I expect at least one paper to come out within the next year although the scope of the paper is yet to be finalised.

3 Update – June 2023

After finishing the CASPEN program I have continued to work on differentiable waveforms. It has now turned into a dedicated research program with an ongoing collaboration primarily involving me, Max Isi, and Kaze Wong. We have currently written two papers [5, 6] with plans for several more in the future. Our headline result is that we were able to bring parameter estimation times down to 1 minute for binary neutron stars, over a factor of a 1000 times faster than standard methods.

The CASPEN program allowed me to explore a new research direction in a field which, at the time, I was not very familiar. CASPEN was therefore fundamental to the development of a research program that I believe will contribute significantly to the field of gravitational wave data analysis over the next few years.

4 Acknowledgments

This work was supported by collaborative visits funded by the Cosmology and Astroparticle Student and Postdoc Exchange Network (CASPEN).

References

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