ML4GW@NL: Dutch Machine Learning for Gravitational Waves Meeting

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Book of Abstracts

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Tuning neural posterior estimation for gravitational waves

Author: Alex Kolmus[1]

Co-authors: Justin Janquart [2]; Tomek Baka [3]

[1] *Radboud University*

[2] *Utrecht University/Nikhef*

[3] *Utrecht University, Nikhef*

Corresponding Authors: j.janquart@uu.nl, alex.kolmus@ru.nl, tbaka@nikhef.nl

Modern simulation-based inference techniques leverage neural networks to solve inverse problems efficiently. One notable strategy is neural posterior estimation (NPE), wherein a neural network parameterizes a distribution to approximate the posterior. This approach is particularly advantageous for tackling low-latency or high-volume inverse problems. However, the accuracy of NPE varies significantly within the learned parameter space. This variability is observed even in seemingly straightforward systems like coupled-harmonic oscillators. This paper emphasizes the critical role of prior selection in ensuring the consistency of NPE outcomes. Our findings indicate a clear relationship between NPE performance across the parameter space and the number of similar samples processed by the model. Thus, the prior should match the sample diversity across the parameter space to promote strong, uniform performance. Furthermore, we introduce a novel procedure specifically designed to swiftly refine NPE predictions for individual events. This method substantially improves sample efficiency, transforming it from nearly zero to double-digit percentages within a matter of minutes. Notably, our research demonstrates its real-world applicability by achieving a significant milestone: we accurately infer posteriors for low-mass binary black hole (BBH) events with NPE.

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Normalizing Flows as an Avenue to Studying Overlapping Gravitational Wave Signals

Authors: Alex Kolmus[1]; Chris Van Den Broeck[None]; Jurriaan Langendorff[2]; Justin Janquart[3]

[1] *Radboud University*

[2] *Utrech University*

[3] *Utrecht University/Nikhef*

Corresponding Authors: vdbroeck@nikhef.nl, j.janquart@uu.nl, alex.kolmus@ru.nl, j.w.langendorff@uu.nl

Because of its speed after training, machine learning is often envisaged as a solution to a manifold of the issues faced in gravitational-wave astronomy. Demonstrations have been given for various applications in gravitational-wave data analysis. In this Letter, we focus on a challenging problem faced by third-generation detectors: parameter inference for overlapping signals. Because of the high detection rate and increased duration of the signals, they will start to overlap, possibly making traditional parameter inference techniques difficult to use. Here, we show a proof-of-concept application of normalizing flows to perform parameter estimation on overlapped binary black hole systems.

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Sequential simulation-based inference for gravitational waves of the current and future era

Author: Uddipta Bhardwaj[1]

Co-authors: Christoph Weniger [2]; James Alvey [2]; Samaya Nissanke

[1] *GRAPPA, University of Amsterdam*

[2] *University of Amsterdam*

Corresponding Authors: u.bhardwaj@uva.nl, j.b.g.alvey@uva.nl, s.nissanke@nikhef.nl, c.weniger@uva.nl

The current and upcoming generations of gravitational wave experiments represent an exciting step forward in terms of detector sensitivity and performance. Key upgrades at the LIGO, Virgo and KAGRA facilities will see the next observing run (O4) probe a spatial volume around four times larger than the previous run (O3), and design implementations for e.g. the Einstein Telescope, Cosmic Explorer and LISA experiments are taking shape to explore a wider frequency range and probe cosmic distances.

In this context, however, a number of imminent data analysis problems face the gravitational wave community. It will be crucial to develop tools and strategies to analyze (amongst other scenarios) signals that arrive coincidentally in detectors, longer signals that are in the presence of non-stationary noise or other shorter transients, as well as noisy, potentially correlated, coherent stochastic backgrounds. With these challenges in mind, we develop PEREGRINE, a new sequential simulation-based inference approach designed to study broad classes of gravitational wave signal.

In this talk, I discuss the need of the hour for flexible, simulation-efficient, targeted inference tools like PEREGRINE before demonstrating its accuracy and robustness through direct comparison with established likelihood-based methods. Specifically, we show that we are able to fully reconstruct the posterior distributions for every parameter of a spinning, precessing compact binary coalescence using one of the most physically detailed and computationally expensive waveform approximants (SEOBNRv4PHM). Crucially, we are able to do this using only 2% of the waveform evaluations that are required in e.g. nested sampling approaches, highlighting our simulation efficiency as the state-of-the-art when it comes to gravitational waves data analysis.

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Stochastic Gravitational Wave Background Analysis with SBI

Author: James Alvey[1]

Co-authors: Christoph Weniger [1]; Uddipta Bhardwaj [2]

[1] *University of Amsterdam*

[2] *GRAPPA, University of Amsterdam*

Corresponding Authors: u.bhardwaj@uva.nl, c.weniger@uva.nl, j.b.g.alvey@uva.nl

In some sense, the detection of a stochastic gravitational wave background (SGWB) is one of the most subtle GW analysis challenges facing the community in the next-generation detector era. For example, at an experiment such as LISA, to extract the SGWB contributions, we must simultaneously: detect and analyse thousands of highly overlapping sources including massive binary black holes mergers and galactic binaries; constrain and characterise the instrumental noise (which will not be known fully pre-flight and may be non-stationary); and finally separate the SGWB components that might be astrophysical or cosmological in origin. In this brief talk, I will discuss the application of simulation-based inference techniques, implemented in the code saqqara, to this analysis problem, focussing on the ability of SBI to strike a balance between the potentially conflicting goals of precision, scalability, and computational cost.

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cDVGAN: Improved Conditional GANs for Generalized Gravitational Wave Transient Generation

Authors: Daniel Tan[1]; Lyana Curier[1]; Melissa Lopez[None]; Stefano Bromuri[1]; Tom Dooney[1]

[1] *Open Universiteit*

Corresponding Authors: lopezm@nikhef.nl, td1@ou.nl

We present Conditional Derivative GAN (cDVGAN), a novel conditional GAN framework for simulating multiple classes of gravitational wave (GW) transients in the time domain. cDVGAN can also generate generalized hybrid waveforms that span the variation between waveform classes through class-interpolation in the conditioned class vector. cDVGAN transforms the typical 2-player adversarial game of GANs into a 3-player game with an auxiliary critic analyzing the derivatives of time series signals. Our results show that this provides synthetic data that better captures the features of the original waveforms. cDVGAN conditions on three waveform classes, two preprocessed from LIGO *blip* and *tomte* glitch classes from its 3rd observing run (O3), and the third representing binary black hole (BBH) mergers. Our proposed cDVGAN outperforms 4 different baseline GAN models in replicating the features of the three waveform classes. Specifically, our experiments show that training convolutional neural networks (CNNs) with our cDVGAN generated data improves the detection of waveforms embedded in detector noise beyond the synthetic data from other *state-of-the-art* GAN models. Our best synthetic dataset yields as much as a 7% increase in *area-under-the-curve* (AUC) performance compared to the next best synthetic dataset from baseline GANs. Moreover, training the CNN with hybrid waveforms from our cDVGAN outperforms CNNs trained only on the standard waveform classes when identifying real signals embedded in LIGO detector background between SNRs ranging from 1 to 16. Lastly, we illustrate cDVGAN as a viable data augmentation method that can surpass the performance of using a traditional data augmentation approach.

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Ameliorating transient noise bursts in gravitational-wave searches for intermediate-mass black holes

Author: Melissa Lopez[1]

Co-author: Sarah Caudill [2]

[1] *Utrecht University*

[2] *University of Massachusetts Dartmouth*

Corresponding Authors: scaudill@umassd.edu, lopezm@nikhef.nl

The formation mechanism of supermassive black holes is yet unknown, despite their presence in nearly every galaxy, including the Milky Way. As stellar evolution predicts that stars cannot collapse to black holes
$gtrsim50 - 130M_{\odot}$ due to pair-instability, plausible formation mechanisms include the hierarchical mergers of intermediate-mass black holes (IMBHs). The direct observation of IMBH populations would not only strengthen the possible evolutionary link between stellar and supermassive black holes, but unveil the details of the pair-instability mechanism and elucidate their influence in galaxy formation. Conclusive observation of IMBHs remained elusive until the detection of gravitational-wave signal GW190521, which lies with high confidence in the mass gap predicted by the pair-instability mechanism.
Despite falling in the sensitivity band of current detectors, IMBH searches are challenging due to their similarity to transient bursts of detector noise, known as glitches. In this work, we optimize a matched filtering algorithm, the state-of-the-art for searches, using Machine Learning. In particular, we employ a multi-layer perceptron network that targets IMBHs, distinguishing them from glitches in real single-detector data. Our algorithm successfully recovers over 90% of simulated IMBH signals. Furthermore, we detect GW190521 with high confidence.

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Accelerating gravitational wave parameter estimation with normalizing flows

Author: Thibeau Wouters[1]

Co-author: Tsun Ho Pang

[1] *Utrecht University*

Corresponding Authors: twouters@nikhef.nl, t.h.pang@nikhef.nl

After identifying a gravitational wave, the goal of parameter estimation pipelines is to infer the parameters of the source that generated the signal. Current methods rely on computationally expensive numerical approaches, such as Markov chain Monte Carlo (MCMC) samplers. For longer signals with a high-dimensional parameter space, such as gravitational waves generated by binary neutron star mergers, parameter estimation runs can take hours to weeks to complete. We present our ongoing efforts to improve existing pipelines by combining likelihood heterodyning, automatically-differentiable tidal waveforms, and gradient-based MCMC sampling enhanced by normalizing flows.

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Machine Learning Gravitational Waves from Binary Black Hole Mergers with Higher Order Modes

Author: Stefano Schmidt[None]

Corresponding Author: sschmidt@nikhef.nl

We develop a machine learning model to fast and accurately predict the time domain gravitational wave emission non-precessing binary black hole system. Our model incorporates the effect of higher order modes of the multipole expansion of the waveform.
Building on our previous work we decompose each mode by amplitude and phase and we reduce the dimensionality with Principal Component Analysis. We train an ensemble of Artificial Neural Networks to learn the relation between orbital parameters and the low dimensional representation of each mode.
We train our model, called mlgw-NN, on ˜ 10ˆ5 signals generated with the state-of-the-art approximant SEOBNRv4PHM and we find that mlgw-NN achieves a median faithfulness of 10ˆ{-4}, averaged across the parameter space.
We show that our model generates a single waveform two orders of magnitude faster than the training model, with the speed up increasing when waveforms are generated in batches.
Our framework is fully general and can be applied to any other time domain approximant.

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Introduction to the discussion panel

Corresponding Author: j.b.g.alvey@uva.nl

PANELISTS:

- **Dr. Samaya Nissanke** [MMA, PE]
- **Dr. Tanja Hinderer** [Waveform modelling, Testing GR]

- **Dr. Christoph Weniger** [ML methods, SBI]
- **Melissa Lopez** [Glitches, Detector characterisation, ML]
- **Dr. Peter T.H. Pang** [Extreme matter, Testing GR]

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Quantum Support Vector Machine for Gravitational Wave Detection

Author: Jeremie Gobeil[1]

Co-authors: Stefan Verhoeven [2]; Daniel Blatman [1]; Domenica Dibenedetto ; Ivano Tavernelli [3]

[1] *Maastricht University*

[2] *Fontys*

[3] *IBM Zurich*

Corresponding Authors: jgobeil@nikhef.nl, d.dibenedetto@nikhef.nl

We present an initial approach to applying a quantum support vector machine (QSVM) to the detection of gravitational waves. We explore the effect of the variation of the hyperparameters associated with quantum computing on the detection rate and compare the results with a classical support vector machine (SVM). The training and testing dataset is generated by injecting simulated events into noise samples from the detector L1. To reduce the dimension of the training samples, we generate features from the time series and use auto machine learning (AutoML) and permutation feature importance (PFI) to obtain a subset of the most significant features. Using this approach, we created a reduced set of features without sacrificing much of the accuracy of the SVM and allowed this use in the QSVM. Our experiments indicate that the method can achieve high detection rates and that the QSVM can achieve better accuracy than an optimized SVM algorithm when submitted to the same dataset.