Nathaniel S. Woodward

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RESEARCH INTERESTS

I am broadly interested in the intersection of machine learning (ML) and high energy theory (HEP-TH) through: (a) developing ML methods for HEP and (b) employing ML as a tool in challenging theoretical calculations.

Specific Interests: ML4HEP, HEP-TH/PH, quantum field theories (QFTs), scattering amplitudes, mathematical & geometric ML, bootstrapping QFTs, ML for symbolic mathematics

EDUCATION

MIT, Cambridge, Massachusetts, USA — Aug 2021 — May 2025
Bachelor of Science: Physics, Mathematics — Cumulative GPA: 4.7/5.00 , Physics GPA: 4.8/5.00

ACADEMIC EXPERIENCE

MIT Undergraduate Researcher: Machine Learning & HEP-PH — MIT, Cambridge
Research Advisor: Professor Phil Harris (MIT) — May 2022 — Present

- Developing novel ML models and methods for high-energy physics
- Building theoretical insights into ML through new architectures and training methods.
- Experience developing a diverse range of models, from compact quantized architectures with thousands of parameters to large-scale, novel transformer-based models with over 10 million parameters
- Self-directed researcher with experience collaborating closely with PhD students, postdoctoral researchers, and faculty
- Software Skills: Python, Pytorch, TensorFlow, Keras, QKeras, Ray Tune, & Data / Model Parallelization

MIT Undergraduate Researcher: HEP-TH — MIT, Cambridge
Research Advisors: Dr. Kyle Lee (MIT) & Professor Ian Moult (Yale) — May 2024 — Present

- Calculating Energy-Energy-Correlators (EECs) in novel QCD scattering processes
- Employ Soft-Collinear Effective Field Theory (SCET) & spin-helicity formalism for QCD amplitude calculations

MIT Physics Mentor — MIT, Cambridge
Physics Mentor — August 2023 — Present

- Weekly mentor for 10+ students in subjects from introductory mechanics to quantum mechanics
- Guide students in reading current physics literature and initiating undergraduate research projects

Undergraduate Representative: Physics Value Committee — MIT, Cambridge
Undergraduate Representative — August 2023 — Present

- Provide recommendations to the MIT Physics Department to improve physics community
- Active member of the Disability and Chronic Illness Working Group

Directed Reading Program: ϕ^4-Theory and the Renormalization Group — MIT, Cambridge
Student under PhD Candidate Jean Du Plessis (MIT) — Jan. 2024 — Feb. 2024

- One month study of QFTs focusing on ϕ^4-theory, the running of the coupling, and the renormalization group

CERN Summer Researcher — CERN, Geneva
Research Advisor: Dr. Jeffery Krupa (SLAC) — May 2023 — August 2023

- Living and working CERN support by MIT and Professor Phil Harris (MIT)
- Develop novel self-supervised learning methods for jet physics
- Collaborated with researchers at MIT, SLAC, & KIT/IC

PROJECTS

Product Manifold Machine Learning for Physics — MIT, Cambridge
Lead author & researcher — July 2023 — Dec. 2024
Contributors: Nathaniel Woodward, Sang Eon Park, Gaia Grosso, Jeffery Krupa, Philip Harris

- Proposed new learnable representations of particle jets in Cartesian products of constant curvature Riemannian manifolds
- Developed product manifold transformer and MLP models as highly generalizable model architectures with data representations in product manifolds

- Demonstrated performance correlation with calculated hierarchical structure through Gromov-δ hyperbolicity
- Achieve classification performance within 0.2% of state-of-the-art transformer models on top tagging datasets while using 66% less parameters
  My Contribution:
  - Project proposer, primary contributor to technical work, and leader author/presenter
  - Created, tuned, and trained all novel ML architectures

$\gamma\gamma \to q\bar{q}$ EEC Factorization in the Back-to-Back Region MIT, Cambridge
Researcher working under Dr. Kyle Lee (MIT) & Professor Ian Moult (Yale) May 2024 — Current
Contributors: Nathaniel Woodward, Kyle Lee, Ian Moult

- Extend EEC factorization theorem [1801.02627] to new hard processes in back-to-back region
- Self-studied scattering amplitudes to perform calculations [1308.1697]
- Weekly meetings with Dr. Kyle Lee (MIT)

Theory Motivated Pre-Training for Foundation Models MIT, Cambridge
Researcher working under Professor Phil Harris (MIT) & Professor Jesse Thaler (MIT) August 2024 — Current
Contributors: Nathaniel Woodward, Phil Harris, Jesse Thaler

- Developed novel self-supervised pre-training methods for ML models studying particle jets
- Leveraged QFT insights such as jet factorization and DGLAP evolution for theoretically sound jet augmentations in contrastive learning

Non-Euclidean Anomaly Detection MIT, Cambridge
Researcher alongside Dr. Gaia Grosso (IAIFI) April. 2024 — Current
Contributors: Nathaniel Woodward, Gaia Grosso, Philip Harris

- Explored the use of product manifold embeddings to improve anomaly detection for particle jets at the LHC
- Performed exploratory studies on Higgs rediscovery
- Demonstrated ability to shrink latent dimension while retaining performance with non-Euclidean embeddings

Re-Simulation-based Self-Supervised Learning for Pre-Training Foundation Models CERN, Geneva
Contributing author & researcher May 2023 — Aug. 2023
Contributors: Philip Harris, Michael Kagan, Jeffrey Krupa, Benedikt Maier, Nathaniel Woodward

- New self-supervised learning method for particle jets through resimulating jet shower in several shower software
- Demonstrated resimulation as augmentation for contrastive learning
- Increased performance and reduce systematic uncertainty
  My Contribution:
  - Deployed multi-GPU and multi-node parallelization scheme to reduce training times
  - Trained GNN and transformer based models

Training ML-Based Compression Algorithms for CMS HGCAL Readout at the LHC MIT, Cambridge
Lead author & researcher May 2022 — Dec 2024
Contributors: MIT (Nathaniel Woodward, Simon Rothman, Philip Harris), FNAL (Nhan Tran, Jim Hirschauer, Daniel Noonan), CMU (Erdem Yigit Ertorer, Mariel Peczak, Zachary Baldwin, Matteo Cremonesi)

- Trained HGCAL autoencoder, ML-based compression algorithm, for HGCAL for upcoming High Granularity CALorimeter (HGCAL) to the CMS detector at CERN requires data compression to process detector readout
  My Contribution:
  - Suggested and developed conditional autoencoder (CAE) architecture
  - Lead training and tuning of CAE model to optimize physics performance

PUBLICATIONS

ArXiv Preprints

- Product Manifold Machine Learning for Physics (Full paper). ArXiv: 2412.07033. Woodward, N., Park, S., Grosso, G., Krupa, J., & Harris, P. (Dec. 2024). Product Manifold Machine Learning for Physics.
- Re-Simulation-based Self-Supervised Learning for Pre-Training Foundation Models. ArXiv: 2403.07066. Harris, P., Kagan, M., Krupa, J., Maier, B., & Woodward, N. (Mar. 2024).

Conference Papers

- Product Manifold Machine Learning for Physics (Short-form paper). Conference on Neural Information Processing Systems (NeurIPS) 2024 Machine Learning for the Physics Sciences (ML4PS). Woodward, N., Park, S., Grosso, G., Krupa, J., & Harris, P. (Dec. 2024).

PRESENTATIONS

Poster Presentations

- Product Manifold Machine Learning for Physics. Conference on Neural Information Processing Systems (NeurIPS) 2024 Machine Learning for the Physics Sciences (ML4PS). Woodward, N., Park, S., Grosso, G., Krupa, J., & Harris, P. (Dec. 2024).

Oral Presentations

- Product Manifold Machine Learning for Physics. IAIFI Journal Club. Woodward, N., Park, S., Grosso, G., Krupa, J., & Harris, P. (Dec. 10, 2024)
- Product Manifold Machine Learning for Physics. Bites of Foundation Models for Science - Physics-inspired representations. Woodward, N., Park, S., Grosso, G., Krupa, J., & Harris, P. (Nov. 20, 2024)
- Product Manifold Machine Learning for Physics. IAIFI Thematic Discussion on Representation and Manifold Learning. Woodward, N., Park, S., Grosso, G., Krupa, J., & Harris, P. (Oct. 18, 2024)
- Hyperbolic Machine Learning for Jet Physics. Machine Learning for Jets (ML4Jets). Woodward, N., Park, S., Krupa, J., & Harris, P. (Nov. 2023).

RELEVANT COURSES (ALL AT MIT)

Graduate Courses

- Relativistic Quantum Field Theory I, II, III
- Intro to Stochastic Processes
- Numerical Methods

Undergraduate Courses

- Quantum Physics I, II, &, III
- Experimental Physics Lab
- Statistical Physics
- Introduction to Special Relativity
- Complex Analysis
- Introduction to Machine Learning

FELLOWSHIPS

Institute for Artificial Intelligence and Fundamental Interactions Junior Investigator Fall 2023 — Present, MIT
Paul E. Gray UROP Researcher Fall 2024 — Present, MIT

AWARDS

MIT Outstanding Undergraduate Researcher: School of Science April 2024, MIT, Cambridge

- Recognized as one of six outstanding undergraduate researchers by MIT Undergraduate Research Opportunities Program
- One of two students from the School of Science