The NSF AI Institute for Artificial Intelligence and Fundamental Interactions

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High Energy Physics Advisory Panel — December 4, 2020
NSF: National AI Research Institutes

5 Inaugural Institutes:
+2 USDA-NIFA Institutes

NSF AI Institute for Research on Trustworthy AI in Weather, Climate, and Coastal Oceanography

NSF AI Institute for Foundations of Machine Learning

NSF AI Institute for Student-AI Teaming

NSF AI Institute for Molecular Discovery, Synthetic Strategy, and Manufacturing

NSF AI Institute for Artificial Intelligence and Fundamental Interactions

8 Themes for Next Round:

- Human-AI Interaction and Collaboration
- AI Institute for Advances in Optimization
- AI and Advanced Cyberinfrastructure
- Advances in AI and Computer and Network Systems
- Al Institute in Dynamic Systems
- Al-Augmented Learning
- Al to Advance Biology
- Al-Driven Innovation in Agriculture and the Food System

[NSF Announcement, August 26, 2020; Call for New Proposals]
The NSF AI Institute for Artificial Intelligence and Fundamental Interactions (IAIFI) "eye-phi"
Advance physics knowledge — from the smallest building blocks of nature to the largest structures in the universe — and galvanize AI research innovation

Training, education & outreach at Physics/Al intersection
Cultivate early-career talent (e.g. IAIFI Fellows)
Foster connections to physics facilities and industry
Build strong multidisciplinary collaborations
Advocacy for shared solutions across subfields

E.g. Analyzing Collision Debris ⇔ Geometric Data Processing

[Harris, Schwartz, JDT, Williams]
[Wang, Sun, Liu, Sarma, Bronstein, Solomon, TOG 2019]
The NSF AI Institute for Artificial Intelligence and Fundamental Interactions (IAIFI) “eye-phi”

Senior Investigators: 20 Physicists + 7 AI Experts + IAIFI Affiliates
Junior Investigators: ≈20 PhD Students, ≈7 IAIFI Fellows in steady state

Boston Area: Critical Mass for Transformative Research in “Ab Initio AI”
Heavy HEP involvement across experiment, phenomenology & theory
Can we teach a machine to “think” like a physicist?

(Have you ever tried to reason with a toddler?)
Deep Learning meets Deep Thinking

Sophisticated networks, increased computational power & large data sets have led to extraordinary advances

Continued progress requires exploiting the structure of physics problems & time-tested strategies of physical reasoning

“Deeper understanding, not just deeper networks”
Extensive Use of ML in HEP

Machine learning is transforming many aspects of society, including fundamental physics research

Off-the-Shelf ML for HEP?

2D Images?
Appropriate for fixed-grid calorimeters, but less ideal for tracking detectors

Natural Language?
Clustering can yield “semantic” structure, but identical particles have no intrinsic ordering

3D Objects?
Much closer to particle physics, though doesn’t capture all symmetries
**Machine learning** that incorporates **first principles**, **best practices**, and **domain knowledge** from **fundamental physics**

Symmetries, conservation laws, scaling relations, limiting behaviors, locality, causality, unitarity, gauge invariance, entropy, least action, factorization, unit tests, exactness, systematic uncertainties, reproducibility, verifiability, …
Convolutional Neural Networks $\Leftrightarrow$ Translational Equivariance
$\Rightarrow$ Momentum Conservation

Energy Flow Networks $\Leftrightarrow$ Identical Particles (QM)
Infrared/Collinear Safety (QFT)

$\text{AI} \times \text{AI} = \text{AI}^2$

Powerful strategy to analyze LHC collisions
Efficient neural network for point clouds
Shared solution across disciplines

[Komiske, Metodiev, JDT, JHEP 2019]

Progress driven by early-career talent with cross-disciplinary expertise:
IAIFI Postdoctoral Fellowships

Recruit and train a talented and diverse group of early-career researchers
Spark interdisciplinary, multi-investigator, multi-subfield collaborations

Physics
Theory

Physics
Experiment

AI Foundations

133 applicants for 2021–2024 IAIFI Fellows

[https://iaifi.org/fellows.html; https://academicjobsonline.org/ajo/jobs/16695]
IAIFI Research Plan

**AI$^2$ for Theoretical Physics**
- Standard Model of Nuclear & Particle Physics
- String Theory & Physical Mathematics
- Astroparticle Physics
- Automated Discovery of Physics Models

**AI$^2$ for Experimental Physics**
- Particle Physics Experiments
- Gravitational Wave Interferometry
- (Multi-Messenger) Astrophysics

**AI$^2$ for Foundational AI**
- Symmetries & Invariance
- Speeding up Control & Inference
- Physics-Informed Architectures
- Neural Networks Theory
AI² for Theoretical Physics

E.g. Lattice Field Theory for Nuclear/Particle Physics

Equations governing the strong nuclear force are known, but precision computations are extremely demanding (>10% of open supercomputing in US)

Industry collaboration to develop custom AI tools

Custom generative models based on normalizing flows achieve 1000-fold acceleration while preserving symmetries & guaranteeing exactness

Tools designed for physics find interdisciplinary applications

[Kanwar, Albergo, Boyda, Cranmer, Hackett, Racanière, Rezende, Shanahan, PRL 2020]
AI$^2$ for Experimental Physics

E.g. Gravitational Wave Interferometry at LIGO

Potential to enhance the physics potential of flagship experiments via improved calibrations, better quantification of uncertainties, enhanced interpretability, and sub-microsecond inference.

Propose using RL for Noise Reduction (Barsotti, Rakhlin)

LHC Fast-ML to speed up multi-messenger astrophysics (Harris)

Autoencoders improve LIGO’s sensitivity by 20% [2005.06534]
AI² for Experimental Physics

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Outgrowth of Sub-Microsecond Inference for LHC Triggering

[Electrical diagram of LHC trigger flow with time points and labels: 40 MHz, L1 trigger, 100 KHz, High-Level trigger, 1 MHz/evt, Offline reconstruction, 1 ns, 1 μs, 100 ms, 1 s.

Knowledge:

LHC Fast-ML to speed up multi-messenger astrophysics (Harris)

Autoencoders improve LIGO’s sensitivity by 20% [2005.06534]

[talk by Ngadiuba, Fast ML Workshop, Nov 30, 2020; Duarte, Han, Harris, Jindariani, Kreinar, Kreis, Ngadiuba, Pierini, Rivera, Tran, Wu, JINST 2018]
\( \text{AI}^2 \) for Foundational AI

E.g. Deconvolution Across Disciplines

The unique features of physics applications and the power of physics principles offer compelling research opportunities to advance the field of AI research itself.

Sparse Coding Networks and Neuronal Source Separation

Event Horizon Telescope and Black Hole Imaging

Highly relevant for HEP tasks ranging from detector unfolding to anomaly detection. Capitalize on physics priors and interpretability for improved robustness.
Artificial Intelligence ⇔ Fundamental Interactions

- Gravitational Waves
- Nuclear Physics
- Astrophysics
- Particle Colliders
- Mathematical Physics
- Dark Matter

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IAIFI Activities & Synergies

Research Engagement
- Regular Internal Meetings
- External Seminar Speakers
- Long-term Visitor Program
- IAIFI Affiliates
- Annual IAIFI Workshop (Summer 2022)

Workforce Development
- IAIFI Postdoctoral Fellowship (Fall 2021)
- Cross-Disciplinary Mentoring
- Interdisciplinary PhD Program
- Annual PhD Summer School (Summer 2022)

Digital Learning
- Online Physics/AI Course Modules
- Expansion of MITx MicroMasters Program

Outreach
- IAIFI Podcasts
- K-12 Engagement
- Festivals & Museums

Broadening Participation
- Early Career & Equity Committee
- Summer Research Program
- MicroFellowship Program

Knowledge Transfer
- Summer Internship Placement
- CSAIL Alliances-like Program
- Joint Research Initiatives

Resources
- Shared Computing Resources
- Building 26 Penthouse Renovations
IAIFI has a compelling vision for the future of Physics and AI research

Fuse “deep learning” revolution with time-tested strategies of “deep thinking” in physics
Gain deeper understanding of our universe and of principles underlying (machine) intelligence

IAIFI will train the next generation of researchers working at the intersection of Physics and AI

Programs like IAIFI Fellowships and Interdisciplinary PhD in Physics, Statistics & Data Science offer unique opportunities for early-career researchers to pursue their interests

IAIFI is part of a growing network of NSF AI Institutes, creating new opportunities for Physics-inspired research

HEP is a unique testbed for AI platforms, given the stringent requirements for verification, calibration, uncertainty handling, reproducibility, and speed
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We look forward to collaborations and synergies with broader Physics + Al community

http://iaifi.org/