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Editorial

AI in Experiments: Present Status and Future Prospects

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Artificial intelligence (AI) has become deeply intertwined with scientific inquiry and experimentation. This Special Issue, "AI in Experiments: Present Status and Future Prospects", provides a timely snapshot of AI's evolving role across diverse experimental domains.

The symbiotic relationship between AI and experiments is reshaping scientific workflows. From physics to biology and materials science, machine learning and statistical models have woven themselves into every facet of research—from hypothesis generation to experimental design, data analysis, and communication of results. Techniques like deep neural networks, reinforcement learning, and generative models are augmenting human capabilities and redefining the boundaries of achievable science.

The integration of AI into experiments has an interesting timeline, beginning in the 1990s, when machine learning methods like neural networks were first applied to analyze physics detector data. In the 2000s, breakthroughs in statistical learning approaches ushered in wider adoption across scientific fields. The 2010s saw rapid advances in deep learning fuel the proliferation of AI techniques. And in the past few years, generative models have opened new frontiers in simulation and data augmentation. As computing power continues to grow exponentially, the future promises more creative and accelerated scientific practices driven by AI.

In physics, AI has emerged as an invaluable tool for analyzing the multi-dimensional data from detectors and telescopes searching for rare events like cosmic rays, photons from distant pulsars, or elusive dark matter. Machine learning models help distinguish signals from overwhelming background noise in these experiments. In particular, dimensionality reduction techniques like principal component analysis and deep neural networks enhance the discrimination power of direct cosmic ray detection [1–3].

Fundamental physics experiments also rely on AI to discern anomalous particle signatures from collider data and pick out gravitational wave signals buried in detector noise. Unsupervised neural networks are gaining traction in both fields by learning from raw data in a self-directed manner without the need for training labels [4–6].

In gamma-ray astronomy, with the advent of sparsely distributed arrays of Imaging Air Cherenkov Telescopes, exemplified by the INAF ASTRI (Astrophysics with Italian Replicating Technology Mirrors) Mini-Array [7,8], AI promises to boost the sensitivity. Sophisticated image processing and classification algorithms help reduce interference from cosmic rays and enhance gamma-ray signals. This entails harnessing the power of artificial intelligence (AI) through advanced image and pattern recognition techniques. The strategic application of AI promises substantial advancements in gamma-ray astronomy, leading to improved instrument sensitivities and further insight into the mysteries of the universe [9,10].

Shifting our attention to the domain of satellite instruments, present AI research embarks on an innovative journey into the realm of cloud masking for satellite images. Departing from conventional techniques used in atmospheric monitoring from space, it explores groundbreaking algorithms designed for binary cloud masking in satellite imagery.

These innovations hold the potential to revolutionize not only weather prediction, climate modeling, and environmental monitoring but also the precision calibration of instruments dedicated to measuring cosmic rays, as exemplified by the JEM-EUSO project [11].

Across experiments, AI has become indispensable for tasks like experimental design, real-time monitoring, simulation, and data analysis. AI-based simulations allow rapid, economical modeling of complex phenomena. Generative models transform noisy, low-resolution data into realistic, high-fidelity outputs. For example, in the ARGO-YBJ cosmic ray experiment, a multiscale AI method was used to help discriminate gamma ray signals from hadronic background events [12,13].

Recent advances demonstrate machine learning's potential to accelerate and augment biomedical experiment analysis in diverse ways. In the realm of histopathology image analysis, innovative techniques can embed images into interpretable representation spaces that cluster similar samples and aid disease diagnosis [14]. Graph neural networks offer a promising new approach for modeling relationships between tissue regions in pathological images. By constructing graphs from histology images, the global structure is maintained to identify relevant patterns across the entire sample [15].

In genetic analysis, deep learning has emerged as a powerful new paradigm for DNA sequence classification, demonstrating advantages over traditional machine learning approaches. Working on tasks like metagenomic classification and chromatin state prediction shows deep network architectures that operate directly on raw DNA and can learn tailored sequence representations [16].

For text analysis, deep neural networks like DeepEva [17] enable automated assessment of complexity in sentences. By processing linguistic annotations, these models learn to classify based on textual features that correlate with readability. Such systems demonstrate superior performance over classical machine learning approaches for binary text classification.

While still evolving, these advances indicate machine learning's immense potential to catalyze discovery and augmentation across biomedical experiments. AI-driven techniques show promise to uncover novel insights from rich sources like images, genetic sequences, and text. With careful integration of human domain expertise, state-of-the-art deep learning could accelerate investigations and provide transparency to build trust. The future is bright for augmented biomedical experimentation powered by artificial intelligence.

However, it is important to acknowledge AI's limitations in scientific reasoning and model building. While machines can search huge datasets for patterns, they struggle to construct abstract explanatory models like humans. Alternative approaches to purely statistical machine learning, including model-based and hybrid AI, may help overcome these constraints [18].

As AI becomes further enmeshed with science, ethical challenges around data privacy, algorithmic transparency, and appropriate use of AI must be addressed. Multidisciplinary teams of scientists, ethicists, and policymakers will be key to charting a responsible path forward [19].

Looking ahead, AI-powered human augmentation and robotics will likely play an increasingly prominent role in reshaping the landscape of scientific experimentation. Exoskeletons and prosthetics infused with AI could enhance researchers' physical capabilities and stamina for conducting lengthy experiments. AI-driven robotic assistants may work alongside scientists to efficiently carry out routine experimental tasks. Additionally, AI-powered microrobots could enable experiments at nanoscales that are far too tiny for direct human manipulation.

As we peer into the future, the prospects for AI in experiments are tantalizing. The ongoing research and development in AI-driven experiments promise to redefine the way we conduct scientific investigations. Machine learning, deep learning, and advanced AI techniques are poised to revolutionize data interpretation, enabling us to unearth hidden patterns, discover new phenomena, and explore the uncharted realms of the universe.

While still an emerging technology, AI is undoubtedly disrupting and enhancing scientific workflows. As scientists increasingly collaborate with AI experts, we can look forward to a future that is driven by augmented intelligence and expand the horizons of discovery.

However, it is imperative to acknowledge the challenges that lie ahead. Ensuring the ethical use of AI in experiments, addressing data privacy concerns, and bridging the gap between traditional scientific methodologies and AI-driven approaches are pivotal steps on this journey. Collaboration between scientists, AI experts, and policymakers will be instrumental in charting a responsible and innovative path forward. The future of experiments is intertwined with the future of AI, and together, they hold the promise of unlocking the mysteries of the universe and reshaping the way we perceive and interact with the world around us.

Conflicts of Interest: The authors declare no conflict of interest.

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