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General Comment

Please see attached, from the American Mathematical Society.

Attachments

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Response to the **Request for Information on the Development of a 2025 National Artificial Intelligence (AI) Research and Development (R&D) Strategic Plan** by the Advisory Group on Artificial Intelligence and the Mathematical Community of the American Mathematical Society.

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Preamble

Artificial Intelligence (AI) is posed to play a revolutionary and disruptive role in almost all aspects of our society, on par with the Internet revolution. It is changing how we receive information and make decisions; how we teach children and learn ourselves; how we transact business and how we discover new technologies.

The AI revolution is changing the way we do science, enabling discoveries such as new drugs and new materials on an unprecedented pace. At the same time, AI today is a collection of techniques without a unifying understanding of why and how it works; it is, in the words of one of the AI pioneers Yann LeCun, akin to the process of building steam engines without knowing thermodynamics.

Interdisciplinary work involving mathematics and statistics holds the keys to a deep understanding of how and why AI works, making AI smarter, better, and more applicable. Past NSF and US government support for fundamental research, including mathematics research, made AI possible. A sustained continued investment in fundamental mathematics research must therefore be a key part of the future AI strategy in the United States.

Mathematics and AI

Mathematics as a discipline has a long history of success in enabling scientific and engineering progress by providing the necessary tools and mathematical language. Mathematics is increasingly an interdisciplinary field with a well-established network of collaborations with disciplines such as computer science, engineering, and natural sciences. Through its network of NSF-funded Mathematics Institutes (https://www.nsf.gov/funding/opportunities/mathematical-sciences-research-institutes, https://mathinstitutes.org), the field of mathematics has the necessary infrastructure to enable collaborations with other disciplines that are key to making progress on scientific problems of today. AI is no exception. Successes in development of AI relied, and will continue to rely, on mathematical tools and on interdisciplinary applications of mathematics.

A Theory of AI

The success of modern AI has taken the world by surprise. The idea that a machine can hold conversations with humans, summarize documents, tell stories, paint pictures, and compose music was firmly in the domain of science fiction until just a few years ago. Yet it is fair to say that there is no true understanding of why AI functions so well --- or of when and how it fails. Progress in AI is driven by a combination of heuristic understanding of machine learning coupled with a massive increase in size and complexity of AI models (and the corresponding computer power). A comprehensive explanation of how AI works --- a theory of AI --- is missing.

Mathematics not only provides the common language to express and formalize scientific thought but is also key to unveiling the key concepts and symmetries that underly scientific theories. Mathematical ideas are clearly part of the heuristics of AI and will play a key role in the eventual emergence of a theoretical understanding of AI. For example, early successes in modern AI came from the emergence of Deep Learning and the so-called Convolutional Neural Networks (CNNs). These were heavily influenced by the mathematical theory of translation-invariant transformations (convolutions) in harmonic analysis. Similarly, the emergence of Generative Adversarial Neural Networks (GANNs) was influenced by mathematical game theory. Equivariant Neural Nets arose from the desire to incorporate symmetries into the architecture of a neural net, inspired by (and heavily reliant on machinery from) representation theory. Topics from mathematical physics, harmonic analysis, functional analysis, probability, statistics, data science, numerical analysis, algebra, geometry have all contributed to the development of AI and will continue to do so.

New and existing mathematical methods are needed to describe a future theory of AI, a theory that will explain how to best train AI, to what extent can we rely on AI answers and predictions, and how to make AI models more efficient. Support for fundamental research in mathematics as well as interdisciplinary research between mathematics and other fields is therefore as critical as ever. Continued government and NSF investment in such research is critical for its success and will reap returns that are orders of magnitude beyond such an investment.

Teaching AI to think

AI works because it is trained on large amounts of data. Such training data is a critical part of what makes AI models as successful as they are; in fact, this data is the only information that AI models have about the world. But despite the successes, AI models hallucinate and fail at basic logical tasks. We need to find ways to teach AI how to think logically and mathematically --- just like we teach our children mathematics in school. Making an AI mathematician requires not only progress on the part of AI, but more training data and more mathematical tools to verify and validate AI thought processes. Doing so not only holds the potential of AI-driven discoveries in mathematics, but the emergence of AI models that are able to make reliable decisions accompanied by precise and logical justifications. Again, such progress requires NSF and government funding for fundamental cross-disciplinary research involving a variety of mathematical subjects both at the level of validating AI-generated logical arguments and supplying mathematical questions to AI. Such subjects include logic, number theory, algebra, geometry, analysis, topology, and many others.

AI as a teacher

A new generation of children is growing up with 24/7 access to AI, which holds the promise of giving them undivided attention and becoming a key player in their education, acting as an always-on tutor and information genie. Responsibly leveraging such technology can enable great progress in education, including education in the mathematical sciences. But we need to ensure that AI tutors respect student privacy, not to mention have necessary competency in the subject area. This has to be done well and with the involvement of mathematicians. Government funding is needed to encourage involvement of professional mathematicians in the development of AI-based teaching tools at all educational levels, from kindergarten to college and beyond.

<u>AI as a decision maker</u>

AI is increasingly called upon to make decisions --- such as to approve credit card transactions to combat fraud, make underwriting decisions, evaluate job applicants, identify tumors on medical scans, and so on. Doing so requires training on vast amounts of real-world data requiring privacy protections. Ensuring that the decisions are compliant with laws, regulations, business objectives, and common sense requires AI that can explain its actions and is free of biases inherent in existing datasets. This again requires mathematical and statistical frameworks to evaluate data, pre-trained models, and their output. Government and NSF funding is required to develop new AI training and evaluation tools relying on mathematical approaches such as differential privacy and mathematical theories of fairness.

<u>The Mathematical Workforce</u>

Future developments in AI require a workforce that can leverage AI, make better AI, and promote the use of AI in business and society. This in turn requires a large workforce that is trained in mathematical methods, and who are ready to collaborate with engineers, scientists, and practitioners. Holders of mathematics degrees --- from undergraduate and graduate students to post-graduate researchers --- form a unique talent pool that has the necessary skillset to build the AI of tomorrow. The increasing use of AI in daily life, as well as very real national security implications of development of AI for military applications requires that such a talent pool be nurtured, expanded, and preserved. NSF and government funding of scholarships and fellowships, including the NSF Graduate Fellows and NSF Postdoctoral Fellows programs are thus critically needed, and should be expanded to support more mathematicians.

Conclusion.

The future of US economic and scientific dominance, as well as its national security, rest on continuing leadership in the field of AI. Future developments in AI require further research investment in fundamental science and mathematics. Such investment carries with it the potential of a multifold return, over a 5- to 15-year event horizon. It is precisely the type of research that is unlikely to be undertaken by private industry with its focus on product delivery and shorter event horizons. This makes critical continued and expanded government and NSF investment in fundamental mathematical research that will make AI smarter, better, and more impactful.