NEWSLETTER

CMSA

Center of Mathematical Sciences and Applications

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HARVARD UNIVERSITY
CENTER OF MATHEMATICAL
SCIENCES AND APPLICATIONS

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Message From the Director

Dan Freed

Shiing-Shen Chern Professor of Mathematics

Director of the CMSA

It is a pleasure to introduce our first annual CMSA Newsletter. In it you'll find a sample of the many activities at the Center, and you will meet a few of the mathematicians who research here. But let me start at the beginning.

The CMSA was founded by Shing-Tung Yau a decade ago, and he served as its Founding Director until 2022. Horng-Tzer Yau then served as Interim Director until I joined this past July. The Center is an incubator for two-way interactions between Mathematics and Science. One distinguishing feature of CMSA is our nimbleness: we quickly organize programs and workshops to seize opportunities that catalyze interactions among mathematicians and scientists who might not otherwise engage. Our research is driven by interesting problems with no constraint on the techniques used to address them—all branches of mathematics are welcome here. Special named lectures bring in high profile speakers to discuss hot topics. Ongoing seminars explore specific mathematical interactions in detail. We host visitors from around the world. As well, the vibrant mathematical and scientific community at Harvard and in the greater Boston area provides a steady stream of local participants in our activities.

After the difficult years of pandemic, we are delighted to have just completed the first extended program in several years: *Arithmetic Quantum Field Theory*. Less than a year passed from its initial conception to its completion. Despite the short lead time, the excitement of this novel mix of mathematics and physics attracted leading lights in both fields, as well as students and postdocs eager to jump in. You can share the organizers' enthusiasm in the accompanying article. As I write this at the end of April, our spring program on *Mathematical Aspects Of Scattering Amplitudes* has just begun, and a few workshops are planned for the summer.

There were several conferences throughout the year. Highlights include the ninth annual *Big Data Conference*, the fall showcase *Mathematics in Science: Perspectives and Prospects*, and the workshops that accompany our longer programs.

Our special lectures brought in large audiences to hear about cutting edge research on hot topics. This past March, Yann LeCun gave our annual *Ding Shum Lecture* and Josh Tenenbaum gave the annual *Yip Lecture*. Both attracted huge crowds interested in their different approaches to artificial intelligence. Maggie Miller gave the annual *Math Science Lectures* in honor of Raoul Bott. She described new results in the theory of 4-dimensional space. Our *Math-Science Literature Lecture Series* continues as a joint venture with Tsinghua University. We had wonderful lectures both at CMSA and over zoom. I encourage you to sample these, as well as our many weekly seminars, at the CMSA YouTube channel.

As we look to the future, there are stimulating programs and workshops in preparation for the next academic year. Our fall program, *Mathematics and Machine Learning*, is generating huge interest, as is our spring program on *Classical, Quantum, And Probabilistic Integrable Systems*. You will read more about these next year.

Of course, it is the people at the Center that drive our work. Mike Douglas, a Senior Research Scientist at CMSA, is in the third stage of his dynamic career. After many years as a world-class researcher in string theory, he pivoted to applying novel machine learning methods to trading. Realizing that machine learning has great potential for Mathematics and Physics, after several years at Renaissance Technologies he joined CMSA to make that dream a reality. We are fortunate to have Mike here as the driving force behind our research in this direction. Mike Freedman recently joined the Center as a Senior Research Scientist, and he too will have a great impact; Mike will be featured in next year's Newsletter. In these pages we profile two of our many Postdocs in depth, and you'll meet all our Postdocs and Research Associates, as well as the new Postdocs who will join in the fall.

I am energized by the activity at CMSA, and I envision an even more exciting future ahead.

With Best Wishes,

Dan Freed

Arithmetic Quantum Field Theory at CMSA

Program Featured Weekly Seminar Series, Workshops, and a Conference

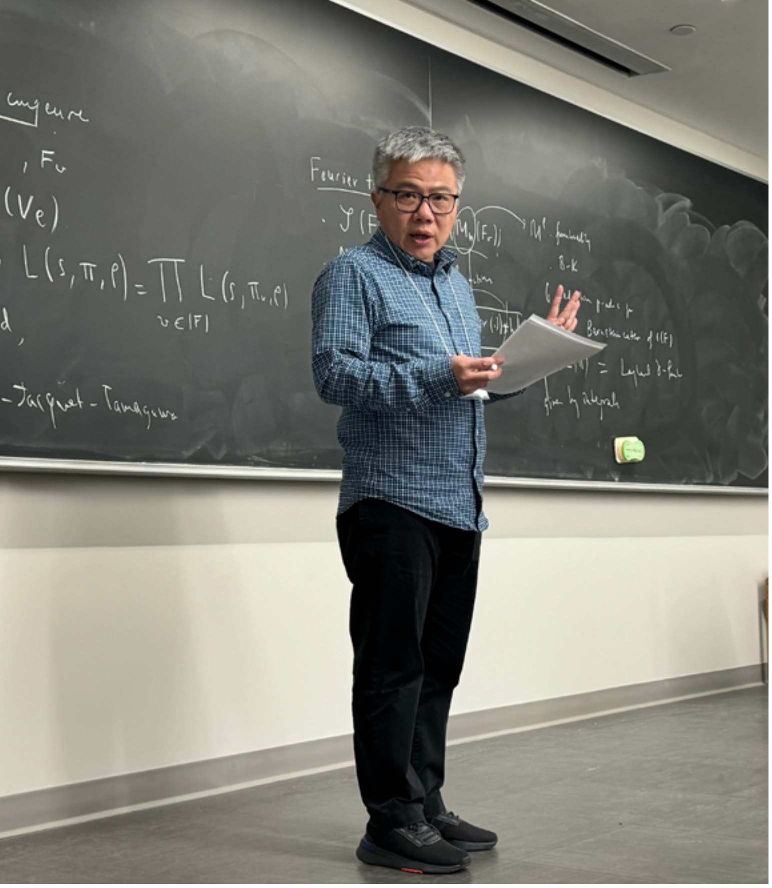
Participants of the Arithmetic Quantum Field Theory program posed for a group photo in front of the CMSA building at 20 Garden Street.

This February and March, CMSA hosted a program on Arithmetic Quantum Field Theory, organized by David Ben-Zvi, Sol Friedberg, Natalie Paquette, and Brian Williams. The program was bookended by an introductory week, featuring three survey lecture series, and a research conference featuring twenty-one talks by an international collection of experts. The bulk of the program featured a rotating collection of visitors, a large number of seminars (spilling over to Harvard, MIT, BC, and BU math departments) and, perhaps most importantly, countless blackboard discussions utilizing CMSA's wonderful facilities. The seminars were broadcast live over Zoom allowing for a large number of remote participants, and the recordings are available on the CMSA YouTube playlist where they have already been attracting thousands of views. The conference was partially supported by a grant from the National Science Foundation, which made possible the participation of a large group of graduate students and postdoctoral researchers from around the country. The topic of the program was cutting-edge and rather bold – indeed, we don't actually quite know what an arithmetic quantum field theory is yet! Instead, the program collected an exceptional and eclectic group of mathematicians and physicists to explore some of the diverse phenomena that suggest the existence of this new structure or are expected to be unified under its umbrella. Here we describe some of the main themes of the program (and indicate in the footnotes the recorded talks where these themes are featured). We point out that with the help of the CMSA staff, all lectures from the program (including the culminating conference) were recorded and uploaded to the CMSA YouTube page[1].

Arithmetic Quantum Field Theory

So, what is arithmetic quantum field theory? Most broadly speaking, the topic is the interaction, both direct and ephemeral, between quantum physics and number theory, mediated through representation theory (or the exploitation of symmetry).

The direct aspect arises from the frequent appearance of the special functions of greatest interest to number theory, modular and automorphic forms, as partition functions, scattering amplitudes and other quantities of interest in



Ngô Bảo Châu from the University of Chicago.

quantum field theory and quantum gravity. The study of fundamental questions in quantum gravity (for example the scattering of gravitons and the entropy of black holes) has produced new perspectives on and questions about familiar modular and automorphic functions, as well as producing fascinating new classes of automorphic objects[2]. Thus on the one hand techniques from number theory can be applied to problems in physics, but on the other hand their appearance in physics expands our perspectives on fundamental problems in representation theory, such as the classical problem of classifying unitary representations of Lie groups[3].

The ephemeral aspect arises from a striking dictionary between low-dimensional topology and number theory known as arithmetic topology[4]. This dictionary, first suggested by Barry Mazur in the 1960s, may be viewed as a refinement of André Weil's famous Rosetta Stone relating geometry and arithmetic. It posits a tight parallel between the study of number fields (finite extensions of the rational numbers), for example the study of prime numbers, and the geometry and topology in two and three dimensions, for example the study of knots. This beautiful vision still has the status of analogy or metaphor, but one which has been refined and made significantly more precise thanks to recent progress in arithmetic statistics and geometry[5].

Using this dictionary, we can now ask if we can port over the structures of quantum field theory to the domain of number theory, by replacing the topology of space-time by an arithmetic counterpart. This leads to Minhyong Kim's arithmetic analogs of well-studied topological field theories such as Chern–Simons theory[6], and also has strong resonance with the study of p-adic forms of string theory and quantum field theory[7].

Fleshing out this bold vision requires a deep understanding of the algebraic and topological structures underlying quantum field theory. Such an understanding has thankfully emerged over the past decade, with a central role played by the formulation of observables and correlation functions in quantum field theory provided by the theory of factorization algebras and factorization homology. These structures were explored in depth in many of the talks[8]. The program also featured physicists broadening the scope of mathematics that could be extracted from quantum field theory[9], for example the crucial role of unitarity.

The Langlands Program

A central goal of the CMSA program was highlighting and developing the connections between quantum field theory and one of the pillars of modern number theory, the Langlands program. The Langlands program is a broad vision of number theory filtered through the lens of representation theory. It can be viewed as a vast generalization of Fourier analysis, or the decomposition of functions in terms of simple sine waves. Here modular forms and automorphic functions play the role of the waves while Galois representations (the main tools of algebraic number theory) play the role of wave-lengths. Many of the talks were devoted to different aspects of the Langlands program[10]. A particular area of concentration was the Relative Langlands Program, the relation between period integrals of automorphic forms and L-functions (deep invariants of Galois representations)[11].

The Langlands program has a more accessible counterpart, the geometric Langlands program, on the other side of the arithmetic-topology dictionary. While initially introduced as a mere analog, the ideas and techniques developed for the geometric Langlands have recently crossed the divide and transformed several aspects of the original arithmetic program[12]. In particular, ideas from quantum field theory have played a crucial role in the geometric setting (and in particular in the recent

Peng Shan from Tsinghua University.

solution of the Geometric Langlands Conjecture)[13].

Quantum field theory enjoys its own counterpart of the Fourier transform, the electric-magnetic duality symmetry of the theory of light (Maxwell theory), and its own vast generalization, the electric-magnetic duality of supersymmetric gauge theories. Kapustin and Witten showed that the geometric Langlands program can be viewed as an aspect of this duality, opening up a radically new perspective on the subject and bringing in the rich structure of topological field theory as an organizing principle[14]. Recently, this perspective was applied, via the bridge of arithmetic topology, to the Relative Langlands Program, by interpreting both periods and L-functions as partition functions of arithmetic quantum field theories[15]. This provides a new avenue for physics ideas to influence an active field of number theory and new impetus for the further development of arithmetic quantum field theory.

Article courtesy of David Ben-Zvi (University of Texas at Austin), Sol Friedberg (Boston College), Natalie Paquette (University of Washington), and Brian Williams (Boston University)

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[1] youtube.com/@harvardcmsa7486
[2] Kim Klinger-Logan, Axel Kleinschmidt, Alejandra Castro
[3] Stephen Miller
[4] Minhyong Kim
[5] Melanie Matchett Wood, Kobi Kremnitzer
[6] Minhyong Kim, George Pappas
[7] An Huang
[8] Brian Williams, Clark Barwick, John Francis, Natalie Paquette, Ezra Getzler
[9] Fei Yan, Sarah Harrison, Davide Gaiotto
[10] Sol Friedberg, Anne-Marie Aubert, YoungJu Choie, Jayce Getz, Tasho Kaletha, Bao-Chau Ngˆo
[11] Omer Offen, Wei Zhang, Chen Wan, Dihua Jiang, Baiying Liu, Spencer Leslie, Zhiwei Yun
[12] Xinwen Zhu, Charlotte Chan, Roman Bezrukavnikov
[13] Peng Shan, Sasha Braverman, Pavel Etingof, Sam Raskin
[14] David Nadler
[15] David Ben-Zvi

Farzan Vafa

Postdoctoral Fellow

Farzan Vafa received his A.B. in physics and math from Harvard College before completing his graduate studies at the University of California, Santa Barbara. He joined the CMSA as a postdoctoral fellow in 2021.

Discovering Mathematics

Vafa has been interested in physics and math as far back as he can remember. "I wanted to understand the world," he said. "I wanted to know how everything worked and it seemed that physics and math were the natural language in which to answer the questions I had." Vafa's entire family is scientifically- and quantitatively-minded. His father is a physicist, his mother was an engineer, one of his brothers is a postdoctoral fellow studying machine learning and economics as part of the Harvard Data Science Initiative, and the other is a graduate student doing theoretical computer science at MIT.

Vafa followed his desire to understand the world to Harvard as an undergraduate student. He still wasn't sure if he wanted to focus on physics or math, so he took classes in both subjects. "At the time, the sexy thing was high energy theory," he recalled. "It's known as the theory of everything; how the forces work, how many forces there are, how many dimensions we are in, how the universe started. It's easy to sell." However, in college he was exposed to and got interested in other areas of physics. He went into graduate school thinking he wanted to study hard condensed matter physics.

But while he enjoyed what he was studying, Vafa realized that its concepts were too abstract. He wanted the world explained in more concrete terms. Soft matter and biophysics, the areas he studies now, fulfilled that criterion. "One of the questions I'm really interested in is morphogenesis," Vafa said. That would be the biological process that causes a cell, tissue, or organism to develop its shape. Studying morphogenesis involves physics, chemistry, topology, and differential geometry.

About the CMSA

One of Vafa's favorite things about the CMSA is how interdisciplinary it is. "It's not just mathematicians here," he said. "It's people that use math in different ways. There are the high energy theorists, the condensed matter theorists, the economists, the computer scientists, and more. I know that if I have a geometry question, I can just talk to one of the other postdocs and really benefit from the interaction. I talk a lot to Freid Tong and Puskar Mondal because they know a lot about differential geometry and PDEs, so they could very quickly help me get up to speed on what's known and what's not known."

While at the CMSA, Vafa has also collaborated with professors from in and outside of Harvard, experts in the fields of physics, biology, chemistry, and their intersections. Among his varied research interests is analyzing liquid crystals on curved surfaces (in particular cones and hyperbolic cones), exploring topological transitions in biology, as well as examining hidden Markov models on trees and applying what he learns to cell cycle data. Vafa has also been studying the spontaneous self-assembly of swimming embryos into enduring large-scale chiral crystals and the structure of the spindle using ideas from liquid crystal theory.

Aside from his personal research, another scientific highlight for Vafa at the CMSA has been co-organizing the biweekly "Active Matter Seminar." He quickly realized what a great opportunity organizing a seminar could be. If he wanted to learn something, he could invite an expert on the subject to speak. "I've been using my seminar to foster more interactions between physicists, mathematicians, and biologists," Vafa said. He has also enjoyed the chance to teach. He's volunteered to help professors with classes and given guest lectures just to get teaching experience. "Ideally, I'd like to stay in academia," he said. "And a big part of that is teaching."

Outside the CMSA

In his free time, Vafa loves exercising. He likes playing squash and running, but a recent passion has been climbing. Vafa sees it as a challenge not only physically—you need strength and good balance—but mentally, as well. "You have to know the correct path up," he said. "It's a puzzle."

Freid Tong
Postdoctoral Fellow

Freid Tong joined the CMSA as a postdoctoral fellow in 2021 after completing his graduate studies at Columbia University. In the fall of 2024, he will take a semester-long postdoctoral position at the Simons Laufer Mathematical Sciences Institute (SLMath), formerly known as the Mathematical Sciences Research Institute (MSRI). After that, he has committed to an assistant professor position at the University of Toronto.

Discovering Mathematics

Growing up in Canada, Tong was drawn to many of the sciences, including math, physics, chemistry, and computer science. “I was pretty good at anything closely related to math,” he recalled. When he attended college at the University of Toronto, Tong was ready to try a bit of everything. He took math and computer science classes his first year—sadly couldn’t fit physics into his schedule—and quickly realized he enjoyed his math classes the most.

“There was a lot of programming and engineering in the computer science classes,” Tong said. “I could spend an hour debugging code and in the end it would turn out to be a minor error like a semicolon instead of a colon. I was frustrated with things like that. In math—at least in the first year honors math classes—I felt like there was more emphasis on the big picture than on the frustrating minutiae.”

One of Tong’s favorite classes as an undergraduate was a course “Analysis II” which, according to him, was really an introduction to differential geometry. He learned about differential forms and Stokes’ theorem, the latter of which he found profoundly beautiful. “There are all these different types of manifestations of Stokes’ theorem that go by different names and share similar features,” Tong said. “In the end, all of these theorems can somehow be summarized into one statement formulated in terms of differential forms. And I thought that was really cool.”

His interest in geometry grew when he completed a summer project in symplectic geometry. That’s the field he intended to study when he started his graduate degree at Columbia, but after his first year, Tong’s interests changed. After attending classes and seminars taught by his eventual advisor, Duong H. Phong, he was drawn to the field of geometric analysis and to applying methods of nonlinear PDEs to geometry.

About Harvard

Tong applied for and received a postdoctoral position at the CMSA for the opportunity to work with Harvard Department of Mathematics Professor Emeritus Shing-Tung Yau. At the time, Yau was also the CMSA director. Tong came to Harvard in 2021, at the height of the pandemic. “The first year there wasn’t too much going on, but it was a very nice environment to work in,” he said. “It was quiet and there were a lot of blackboards.”

Since then, however, things have picked up for Tong. He has taught an introductory calculus course titled “Integration, Series, and Differential Equations” and a graduate course titled “Topics in Geometric PDEs” for the Department of Mathematics. He was also a research mentor at the CMSA in the summer of 2022, where he delivered two lectures on curves and surfaces, and supervised three student projects.

In his time with the CMSA, Tong has worked with Harvard Professor Emeritus Shing-Tung Yau on non-compact Kähler-Einstein metrics. This field was founded by Yau in the ‘80s and ‘90s, and has recently undergone a lot of new developments. “Myself, Yau, and MIT Associate Professor Tristan Collins realized certain natural classes of Monge-Ampere equations are important to the study of these complete Calabi-Yau metrics,” Tong said. “We developed a variational formulation and solved this family of equations. They are quite intriguing and we are still actively studying the regularity for this class of equations. It turns out many parts of the regularity theory are actually closely related to the geometric considerations for the Calabi-Yau metrics.”

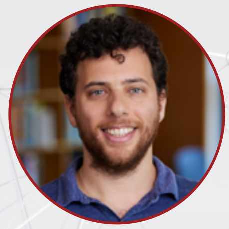
Outside Mathematics

Tong has been a part of the “Geometry and TACoS” online conference for the past several years. The conference encompasses specific themes broadly related to geometry and topology of (almost) complex structures. May 2024 will be his third and final time on the “Geometry and TACoS” organizing committee. Tong spends his free time with friends and family, exploring the Cambridge dining scene. “My wife and I are big foodies,” he shared. “We try out a lot of new restaurants. One of our favorites is “Sugar & Spice,” the Thai place near Porter Square.” Tong also keeps fit by playing squash with CMSA friends and colleagues, and climbing with his wife.

Current CMSA Postdocs

Iacopo Brivio
Mentor: Mihnea Popa

Research Interests
My research interests are in higher dimensional algebraic geometry, especially in positive and mixed characteristic. More precisely, I like to think about the Minimal Model Program and its applications to the moduli theory of varieties of general type. More recently I have become interested in the study of fibrations and sub/super additivity properties of the Kodaira dimension.



Tomer Ezra
Mentor: Yannai Gonczarowski and Scott Kominers

Research Interests
My research interests lie at the intersection of computer science and economics, with a focus on the development of simple mechanisms and algorithms in settings where information is limited.

Samy Jelassi
Mentor: Boaz Barak and Mike Douglas

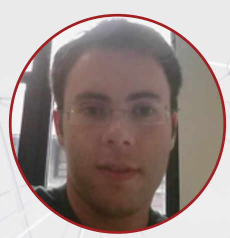
Research Interests
My field of research is deep learning. I am interested in designing large language models that are able to solve multi-step reasoning problems. This framework covers applications ranging from applying a cascade of simple modifications to a string to solving an olympiad-level coding problem.

Zi Yang Kang
Mentor: Eric Maskin

Research Interests
I work on market design, mechanism design, and industrial organization. My research applies a theoretical lens to policy design and evaluation.
Future Plans
Assistant Professor at the University of Toronto.

Daniel Kapec
Mentor: Shing-Tung Yau and Andrew Strominger

Research Interests
I am a theoretical physicist. My research interests span a broad range of topics in quantum field theory, general relativity, string theory and quantum gravity. My recent work focuses on classical and quantum mechanical aspects of black hole physics as well as quantum gravity and holography in asymptotically flat spacetimes.



Uri Kol
Mentor: Shing-Tung Yau

Research Interests
My research interests mostly lie within black hole physics and the gauge/gravity holographic correspondence. I borrow concepts from quantum field theory, such as duality and integrability, to study black hole dynamics.

Jue Liu

Mentor: Shing-Tung Yau

Research Interests

My research focuses on geometric analysis and mathematical general relativity. I have investigated the weak cosmic censorship conjecture, one of the fundamental problems in the dynamics of black holes, and proved that the spherical naked singularities are unstable under gravitational perturbations. Lying at the intersection of differential geometry and physics, quasilocal masses and their properties are also of interest to me, especially how to define a suitable quasilocal mass for any domain in space.

Benjamin McKenna

Mentor: Horng-Tzer Yau

Research Interests

I work on probability theory and mathematical physics, especially random matrices.

Future Plans

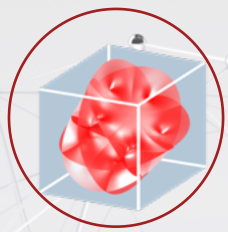
Assistant Professor at Georgia Tech.

Puskar Mondal

Mentor: Shing-Tung Yau

Research Interests

My current research interests include: Nonlinear hyperbolic partial differential equations, mathematical general relativity, geometric analysis. I'm particularly interested in understanding the long time behavior of the solutions of Einstein's equations on manifolds with interesting topology.



Robert Moscrop

Mentor: Michael Hopkins

Research Interests

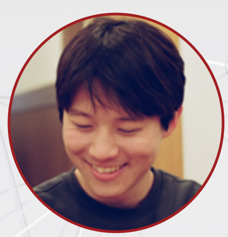
I am interested in the non-perturbative features of superconformal field theories, the classification of such theories and generalized global symmetries.

Matteo Parisi

Mentor: Lauren Williams

Research Interests

My research lies at the intersection of algebraic combinatorics and high-energy physics. My work focuses on a novel combinatorial understanding of scattering amplitudes in quantum field theories - which encode the probability of interaction of fundamental particles - from the (positive) Grassmannian, tropical geometry, cluster algebras and amplituhedra.

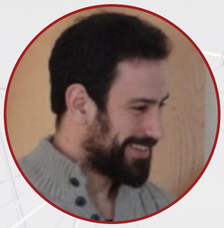


Sunghyuk Park

Mentor: Daniel Freed

Research Interests

I enjoy studying geometric and algebraic structures inspired from physics. My research interests include: topological quantum field theories, topological string theory, complex Chern-Simons theory, quantum groups, categorification.



Alejandro Poveda

Mentor: Hugh Woodin

Research Interests
My research interests lie in set theory and its applications to other areas of pure mathematics, such as Topology, Functional Analysis and Module Theory.

Freid Tong

Mentor: Shing-Tung Yau

Research Interests
My research interest is in complex geometry, geometric analysis, and nonlinear PDEs..

Future Plans
Postdoctoral position at the Simons Laufer Mathematical Sciences Institute (SLMath).

Farzan Vafa

Mentor: David Nelson

Research Interests
I'm interested in soft matter and biophysics, particularly morphogenesis.

Damian van de Heisteeg

Mentor: Cumrun Vafa

Research Interests
My current research focuses on compactifications of string theory, where by using methods from algebraic geometry we try to learn more about the structure of these effective field theories.

Future Plans
Postdoctoral position with the High Energy Theory Group at the Harvard University Department of Physics.

Kai Xu

Mentor: Cumrun Vafa

Research Interests
I am working on algebro-geometric aspects of the string theory, including black hole micro-state counting and categorical structures from brane dynamics.

Future Plans
Postdoctoral Fellow at the Harvard University Department of Physics.

Current CMSA Research Associates

Sergiy Verstyuk
Mentor: Scott Kominers

Research Interests
My research interests are macroeconomics and finance, decision theory, and machine learning.

Juven Wang
Mentor: Shing-Tung Yau

Research Interests
I am a theoretical/mathematical physicist working on quantum many-body systems, condensed matter, and high energy physics. My recent publications include “Ultra Unification,” “Gauge Enhanced Quantum Criticality Beyond the Standard Model,” “Strong CP Problem via Symmetric Mass Solution,” “Noninvertible Categorical Symmetry of the Standard Model via Gravitational Anomaly,” “Family Puzzle or Generation Problem via $c_-=24$ modular invariant”, and an overview on “Symmetric Mass Generation.”

Upcoming CMSA Postdocs

Houcine Ben Dali
Mentor: Lauren Williams

Research Interests
I am interested in algebraic combinatorics. I am currently working on connections between symmetric functions and enumeration of combinatorial maps.

Hugo Cui
Mentor: Mike Freedman

Research Interests
My research lies at the crossroads of machine learning theory, statistical physics and probability. My focus is on reaching a tight theoretical understanding of the workings of machine learning algorithms learning from high-dimensional data.

Ahsan Khan
Mentor: Dan Freed

Research Interests
I am interested in questions related to quantum field theory and its underlying mathematical structure. My work covers a broad range of topics, including algebraic structures emerging from the BPS sector of supersymmetric field theory, quantum field theories with mixed holomorphic-topological properties, and the connection of these topics to quantum groups, vertex algebras and higher category theory. By studying these topics my research aims to uncover ideas that lead to progress in both pure mathematics and theoretical physics.

Vasily Krylov
Mentor: Dan Freed

Research Interests
I am interested in the intersection of representation theory, geometry, and physics. My focus is particularly on symplectic resolutions of singularities, integrable systems, 3D-mirror symmetry, and Coulomb branches.

Han Shao
Mentor: Martin Nowak, Cynthia Dwork, Ariel Procaccia

Research Interests
My primary research centers on machine learning theory, with a specific focus on modeling human strategic and adversarial behaviors within the learning process. I aim to understand how these behaviors affect machine learning systems and develop methods to enhance accuracy/robustness. Additionally, I am interested in gaining a theoretical understanding of empirical observations concerning adversarial robustness.

Bowen Yang
Mentor: Dan Freed

Research Interests
My research area is mathematical physics with a focus on lattice models. My work combines algebra, topology and coding theory to understand phases of matter. I am also curious about field theory, symmetries as well as category theory.

Keyou Zeng
Mentor: Dan Freed

Research Interests
I'm interested in quantum field theory and string theory. I'm currently studying twisted supersymmetric field theory and its duality.

Special Feature: Michael Douglas

Senior Research Scientist

Michael Douglas is best known for the development of matrix models (the first nonperturbative formulations of string theory), for his work on Dirichlet branes (or D-branes) and their relation to derived categories, and for the development of the statistical approach to string phenomenology. He received a bachelor's degree in physics from Harvard in 1983 and a PhD in physics from Caltech in 1988 under John Schwartz, one of the developers and leading researchers in superstring theory. Douglas was a physics professor and director of the New High Energy Theory Center at Rutgers University, and he helped start the Simons Center for Geometry and Physics at Stony Brook University. He was awarded the Sackler Prize in Physical Sciences, and was a Louis Michel Visiting Professor at the Institut des Hautes Études Scientifiques (IHES) and a Clay Mathematical Institute Mathematical Emissary. Douglas is a fellow of the American Mathematical Society and a member of the American Physical Society. After some time at the quantitative hedge fund Renaissance Technologies, he returned to academia and joined the CMSA in 2020.

One of Douglas' most powerful memories growing up in Stony Brook, New York, was being surrounded by books. His father was Ronald G. Douglas, a mathematician specializing in operator algebras. The books he brought home were a big influence on his son and boosted his interest in physics and math. Douglas recalls being particularly affected by "The Rise of the New Physics: Its Mathematical and Physical Theories" by Aram D'Abro. "I remember we were on a vacation and I had appendicitis," he said. "I was in the hospital with my mother for a week and I had all these books. The depth and beauty of physics was something that stuck with me."

Douglas came to Harvard as an undergraduate in 1979, torn between mathematics and physics. "I didn't want to follow in my father's footsteps too closely, so I decided on physics," he recalled. "But I did end up doing a kind of mathematical physics, so in the end I didn't stray too far from his footsteps." At Harvard, his advisor was theoretical physicist Roy Jay Glauber. Douglas learned differential geometry from Raoul Bott and classical mechanics from Arthur Jaffe, and studied under Sidney Coleman, who taught what was widely regarded as the best introduction to quantum field theory. Douglas couldn't have asked for better instructors. "Those were very formative years that gave me a great start in the field," he said.

While applying for graduate school, Douglas visited Caltech and attended a series of courses taught by Richard Feynman, John Hopfield, and Carver Mead about the physics of computation. "Feynman's was the first course on what is a quantum computer," he said. "And Hopfield's course was one of the very first on what is a neural network." Douglas ended up taking those courses when he enrolled at Caltech, but while he found the material fascinating, he realized it might be a while before much could be done with it. "The quantum computer, for example, was just an idea at that point," he said. "Nobody could even imagine how you would do it." Douglas found himself stuck, unsure in which directions to go. He joined Gerald Jay Sussman (on sabbatical from MIT) and helped him build the Digital Orrery—a special-purpose computer for computation in celestial mechanics—but then news broke that changed the trajectory of his academic life.

"It was about the Green-Schwarz anomaly cancellation, and something called superstring theory, which I had never heard of," Douglas said. "There had been lots of doubts about it but now there was this amazing calculation that showed it really made sense." Half of the physics graduate students around him were switching to superstring theory, and so did he. That determined a big part of Douglas' career from that point on. He went on to a postdoc with Daniel Friedan and Stephen Shenker at Chicago, drawn by their imaginative ideas about nonperturbative string theory. In 1989, Douglas followed Friedan, Shenker, and several like-minded physicists to Rutgers University to start the New High Energy Theory Center.

The years that followed were not easy, but the group was convinced that nonperturbative string theory was the future. A series of discoveries in ‘93 and ‘94 now known as string duality, initiated by Ashoke Sen, proved them right. “We realized this was the way to do nonperturbative string theory,” Douglas said. “For that period in the mid-’90s we were arguably the best, and certainly one of the best groups on string theory in the world.” By 1996, Douglas had hit his stride. The main accomplishment that allowed him to do so was his work on D-branes, a key ingredient in string duality and in nonperturbative string theory.

It was an incredible time in the world of physics but by the late ‘90s, the success of the center meant that many of its top people were offered more prestigious positions. Douglas stayed and became its director. He started hiring mathematical string theorists such as Greg Moore and phenomenologists such as Scott Thomas, whose work was attempting to predict what would happen when the Large Hadron Collider (LHC) at CERN was turned on. But stimulated by a famous collaboration with Alain Connes and Albert Schwarz on noncommutative geometry in string theory, and by annual visits to the IHES, Douglas' own interests gradually became more mathematical. In 2008, he left Rutgers for Stony Brook University as a founding member of the Simons Center for Geometry and Physics, and initiated many of its programs.

In 2012, having gotten the Simons Center off to a strong start, Douglas joined Renaissance Technologies. He had been aware of the hedge fund and its work for decades. In its early days, founder James H. Simons frequently invited Stony Brook University math department faculty members—including Douglas' father—to consult. Douglas spent eight years at Renaissance Technologies, developing sophisticated trading models based on machine learning. He had followed machine learning since his days at Caltech, but this was the first chance he'd gotten to do serious work in it. And 2012 was in retrospect a banner year for machine learning, with the famous AlexNet deep learning system which could recognize natural images. Then came DeepMind's Go software AlphaGo, followed by AlphaGo Zero, a version of AlphaGo created without using data from human games, far stronger than any human player. “We could see that something big was happening,” Douglas said. “It was revolutionary.”

By 2018, Douglas had switched to work at Renaissance Technologies half-time and was touring various departments and AI labs, looking for an opportunity to study how AI could help scientists do math and physics. He came to the CMSA in February of 2020. “I knew Shing-Tung Yau [the then director of the CMSA] and his response was by far the most positive and enthusiastic one I'd gotten,” Douglas said. Not long after came Covid and lockdown. Douglas took a visiting position at the CMSA and, eventually, became a long-term senior research scientist.

During his time here, Douglas has been focused on the intersection of AI and science. One project has involved applying machine learning tools to geometry by calculating Calabi-Yau metrics on a computer. He had worked on this in the mid-2000s, but computers at the time were not powerful enough to get results for anything other than a very symmetric, particular Calabi-Yau. Using modern machine learning, Douglas “killed that problem.”

Another field of research has been interactive theorem proving. “This is trying to make a language and a system where you can write out a mathematical proof in such a precise way that the computer can just check it and say, “yes, correct,” or “there's a gap in your proof here,”” Douglas explained. “That's existed at various levels of sophistication for many decades now, but it's always been too hard to use.” Over the past decade or so, however, the technology has steadily improved. While still not easy, the process has gotten easier; there are still mistakes and so-called “AI hallucinations”—incorrect or misleading results that AI models generate—but research is moving in the right direction.

Douglas is keeping his future interests open-ended. According to him, Cambridge and the Boston area are at the heart of a lot of work in math, AI, and science. “Just in terms of having opportunities to find out what's going on and bring people together, that's already very satisfying,” he said. He expects that in the next five years there will be computers powerful enough to combine language models and theorem proving that could be turned on math and physics problems. “Maybe we'll prove great things,” Douglas said.

Past CMSA Events

Big Data Conference 2023

Conference
August 31–September 1, 2023
The ninth annual Conference on Big Data featured speakers from the Harvard community as well as scholars from across the globe, with talks focusing on computer science, statistics, math and physics, and economics.
Organizers: Michael Douglas (CMSA, Harvard), Yannai Gonczarowski (Harvard), Lucas Janson (Harvard), Tracy Ke (Harvard), Horng-Tzer Yau (CMSA, Harvard), Yue Lu (Harvard)

Mathematics In Science: Perspectives and Prospects

Conference
October 27–28, 2023
A showcase of mathematics in interaction with physics, computer science, biology, and beyond.
Organizers: Michael R. Douglas (CMSA), Dan Freed (CMSA, Harvard), Mike Hopkins (Harvard), Cumrun Vafa (Harvard), Horng-Tzer Yau (Harvard)

60 Years of Matching: from Gale and Shapley to Trading Networks

CMSA/Tsinghua Math-Science Literature Lecture Series
November 20, 2023
Speaker: Scott Kominers (Harvard Business School)

Arithmetic Quantum Field Theory Program

Program
February 5–March 29, 2024
A program meant to develop and disseminate exciting new connections emerging between quantum field theory and algebraic number theory, and in particular between the fundamental invariants of each: partition functions and L-functions.
Organizers: David Ben-Zvi (University of Texas Austin), Solomon Friedberg (Boston College), Natalie Paquette (University of Washington Seattle), Brian Williams (Boston University)
bit.ly/4awLPus

Stretching and Shrinking: 85 Years of the Hopf Argument for Ergodicity

CMSA/Tsinghua Math-Science Literature Lecture Series
February 7, 2024
Speaker: Amie Wilkinson (University of Chicago)

Fibered Ribbon Knots and the Poincaré Conjecture & Fibered Knots and the Slice-Ribbon Conjecture

Math Science Lectures in Honor of Raoul Bott
February 20 & 22, 20204
Speaker: Maggie Miller (University of Texas at Austin)

How to Grow a Mind from a Brain: From Guessing and Betting to Thinking and Talking

Yip Lecture
February 29, 2024
The fourth annual Yip Lecture.
Speaker: Josh Tenenbaum (MIT)

The Unknotting Number of a Knot

CMSA/Tsinghua Math-Science Literature Lecture Series
March 20, 2024
Speaker: Cameron Gordon (University of Texas at Austin)

Arithmetic Quantum Field Theory Conference

Conference
March 25–March 29, 2024
A conference bringing together a wide range of mathematicians and physicists working on adjacent areas to explore the emerging notion of arithmetic quantum field theory as a tool to bring quantum physics to bear on questions of interest for the theory of automorphic forms, representation theory, harmonic analysis and L-functions
Organizers: David Ben-Zvi (University of Texas Austin), Solomon Friedberg (Boston College), Natalie Paquette (University of Washington Seattle), Brian Williams (Boston University)
bit.ly/3UpONeN

Objective-Driven AI: Towards AI Systems that Can Learn, Remember, Reason, and Plan

Ding Shum Lecture
March 28, 2024
Speaker: Yann Lecun (New York University & META)

Upcoming CMSA Events

Mathematical Aspects of Scattering Amplitudes Program

Program

April 15–May 24, 2024

A program bringing together and fostering interaction between theoretical physicists and mathematicians working on various topics connected to recent developments in our understanding of scattering amplitudes in quantum field theory.

Organizers: Nima Arkani-Hamed (Institute for Advanced Study), Marcus Spradlin (Brown University), Andrew Strominger (Harvard), Anastasia Volovich (Brown University), Lauren Williams (Harvard)

Amplituhedra, Cluster Algebras, and Positive Geometry

Conference

May 29–May 31, 2024

The conference will center on the amplituhedron—the first and major example of a positive geometry. Featuring: Introductory Lectures, an Open Problems Forum, Emerging Scholars Talks, and talks by experts in the fields. The conference aims to actively engage and empower junior researchers and women, ensuring their integral presence and impactful contributions.

Organizers: Matteo Parisi (CMSA), Lauren Williams (Harvard)

Fibration and Degeneration in Calabi-Yau Geometry

Workshop

June 24–June 26, 2024

Details TBA

Organizers: Chuck Doran (CMSA)

Advances In Probability Theory And Interacting Particle Systems

Conference

August 26–28, 2024

A Conference in Honor of S. R. Srinivasa Varadhan.

Organizers: Paul Bourgade (New York University, Courant Institute) and Horng-Tzer Yau (Harvard)

Mathematics and Machine Learning Program

Program

September 3–November 1, 2024

Machine learning and AI are increasingly important tools in all fields of research. Recent milestones in machine learning for mathematics include data-driven discovery of theorems in knot theory and representation theory, the discovery and proof of new singular solutions of the Euler equations, new counterexamples and lower bounds in graph theory, and more. Rigorous numerical methods and interactive theorem proving are playing an important part in obtaining these results. Conversely, much of the spectacular progress in AI has a surprising simplicity at its core. Surely there are remarkable mathematical structures behind this, yet to be elucidated. The program will begin and end with two week-long workshops, and will feature weekly seminars.

Organizers: Francois Charton (Meta AI), Michael R. Douglas (CMSA), Michael Freedman (CMSA, Harvard), Fabian Ruehle (Northeastern), Geordie Williamson (University of Sydney)

Big Data Conference 2024

Conference

September 6–7, 2024

The tenth annual Big Data Conference featuring speakers from the Harvard community as well as scholars from across the globe, with talks focusing on computer science, statistics, math and physics, and economics.

Organizers: Rediet Adebe (Berkeley Institute for Data Science), Morgane Austern (Harvard), Michael R. Douglas (CMSA), Yannai Gonczarowski (Harvard), Sam Kou (Harvard)

Titles TBA

Math Science Lectures in Honor of Raoul Bott

October 16 & 17, 2024

Speaker: Andy Neitzke (Yale University)

Program on Classical, quantum, and probabilistic integrable systems – novel interactions and applications

Program

March 24–May 24, 2025

The program will explore and developing a recent wave of the influence of exactly solvable models in stochastic models together with accompanying combinatorial, classical, and quantum integrable systems.

Organizers: Amol Aggarwal (Columbia University & Clay Mathematics Institute), Guillaume Barraquand (École Normale Supérieure, Paris), Alexei Borodin (MIT), Ivan Corwin (Columbia University), Pierre Le Doussal, (École Normale Supérieure, Paris), Michael Wheeler (University of Melbourne)

QFT and Topological Phases via Homotopy Theory and Operator Algebras

Workshop

June 30–July 11, 2025

A CMSA/Max Planck QFT workshop.

Organizers: Dan Freed (Harvard, CMSA), Owen Gwilliam (UMass Amherst), Andre Henriques (Oxford), Anton Kapustin (Caltech)

Credits

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