IMPRINTS

21 Celebrating years of Mathematical Synergy

NUS National University of Singapore | IMS Institute for Mathematical Sciences

JULY– DECEMBER 2021 ISSUE 38

NEWSLETTER OF THE INSTITUTE FOR MATHEMATICAL SCIENCES, NATIONAL UNIVERSITY OF SINGAPORE

Celebrating 21 years of IMS

Address by Eng Chye Tan
President, National University of Singapore

Professor Chong Chi Tat, Colleagues, distinguished guests, friends, ladies and gentlemen,

Good morning to everyone!

My heartiest congratulations to the Institute of Mathematical Sciences on its 21st anniversary. I would also like to commend the strong leadership team at IMS, ably helmed by its Director Professor Chong Chi Tat, Management Board Chair Professor Lai Choy Heng, and Scientific Advisory Board Chair Professor Iain Johnstone. They have kept the IMS flag flying.

The Institute for Mathematical Sciences was formally established in July 2000, and opened its doors to its first programme one year later. We were not able to celebrate the institute's official 20th anniversary last year. To us mathematicians, 21 may not be a round number. Nevertheless, it is a significant coming-of-age milestone which we should be happy to commemorate.

Anniversaries are also occasions for reflection and thanksgiving. The IMS website is a well-organized repository, where one can peruse information on the Institute's programmes, workshops and other events since its inception. The Institute's first programme was titled "Coding Theory and Data Integrity", and it ran from July till December 2001. Professor Ling San, the current NTU Provost, was one of the co-organisers. Back then, IMS activities were conducted in seminar rooms in the small IMS colonial buildings, as well as at venues spread across the campus. This auditorium here was only finished two years later, in 2003, and it has now become an integral part of most IMS activities.

Eng Chye Tan

Over the past two decades, IMS has played a significant role in advancing mathematical research, deepening mathematical expertise, and developing talents in mathematical sciences for research and industry.

I must commend IMS for its forward-thinking approach in being inclusive, and recognizing the broader and wider potential of mathematics. As the name "mathematical sciences" suggests,

FEATURED

01 Celebrating 21 years of IMS – Address by Eng Chye Tan

03 21st Anniversary Celebration of Institute for Mathematical Sciences – Address by Chi-Tat Chong

04 21st anniversary – Article by Alexandre Hoang Thiery

05 String and M-Theory: The New Geometry of the 21st Century – II

INTERVIEW

10 Darrell Duffie

20 Ashoke Sen

OTHERS

06 News / Past Activities

08 Outreach

27 Upcoming Activities

28 Lecture Note Series

28 Call for Proposals

Congratulatory message by SAB Chairman Iain Johnstone

the institute does not exclusively host programmes in just mathematics. Instead, the Institute takes on a broader perspective, and recognizes the important role that mathematics plays in science, technology and engineering, and in virtually every field of science.

It is often the combination and interaction between different fields that leads to significant scientific and technological progress. IMS provides this very platform, where interactions are seeded and fostered on a regular basis. The variety of programmes — a total of over 160 of them — that have been organized over the past 21 years, is testimony to the Institute's inclusive approach. The programmes include amongst others, mathematical epidemiology, quantum physics, statistics, string theory, phylogenetics, cryptology, mathematical biology, finance and economic theory. It is heartening to see that the local mathematical community is embracing this diversity and is branching out to take on new and adjacent challenges.

At the same time, mathematics is a discipline on its own right, driven by fundamental human curiosity and the pursuit of knowledge in some of the more abstract and pure areas. The programmes in logic, representation theory, algebraic and complex geometry and algebraic number theory to name a few, reflect the strength and international reputation of our mathematics department in these fields.

Mathematics is foundational - the progress made even in some of these purest areas can lead to surprising and important applications further down the road. Number theory has found applications in cryptography; combinatorics and graph theory have applications in computer science, and are the foundations of the statistical analysis of complex networks; algebraic topology informs the efficiency of algorithms, and the list goes on.

Although mathematics is not usually thought to be fashionable, I sincerely believe that mathematics will always be a fascinating and integral field. There are many scientific questions which ultimately, at their core, must have mathematical answers. As an example, the question on why deep neural networks are so effective at what they are doing is ultimately a mathematical question about families of approximating functions. These are among the types of questions which our colleagues and IMS are working on in their research. Mathematical epidemiology and modelling the dynamics of infectious disease transmission will also see a big uptake over the coming years. The Saw Swee Hock School of Public Health colleagues and other mathematical modellers have become an integral part of the government's efforts to contain and manage the current pandemic.

Another notable success of the IMS is how it has nurtured and built a vibrant research environment in Singapore. IMS activities host more than 700 academic visitors from overseas and Singapore every year, until the pandemic hit. It will be interesting if we can ascertain the proportion of international mathematicians who have passed through the doors of IMS over the past two decades. Many of our colleagues in the mathematics department and statistics departments have mooted new, fruitful collaborations with these friends and visitors; some got to know NUS and the Singapore mathematics community through IMS activities, and even joined NUS subsequently. IMS has thus helped to build a strong community and talent pool at NUS in mathematics and statistical science.

On behalf of NUS, I would like to thank IMS for your contributions to the university, to the research community and to Singapore. Many of you sitting here in the audience have been part of the institute's journey and have helped IMS to achieve the international reputation it holds today. Together, we must keep the IMS going strong. The IMS has had 21 fulfilling years of growth and progress, and I wish the institute every future success. Thank you.

(Left) **Zuowei Shen:** Mathematics Behind Deep Neural Networks

(Right) **Chengbo Zhu:** Orbit Method: From Matrices to Unitary Representations

21st Anniversary Celebration of Institute for Mathematical Sciences

ADDRESS BY CHI-TAT CHONG
IMS Director, National University of Singapore

Professor Tan Eng Chye, President of NUS, Professor Chen Tsuhan, Deputy President for research and technology, colleagues and friends,

Good morning. Welcome to the 21st anniversary celebration of the Institute for Mathematical Sciences (IMS). In the next few minutes, I wish to give you a brief account of its history.

The story of the IMS can be traced back to 1978, the year that I attended the International Congress of Mathematicians in Helsinki and also the international Mathematical Union General Assembly that was held two days prior to the Congress, representing the Singapore Mathematical Society. By chance, I was seated across the table from the great differential geometer Shiing-Shen Chern, 陈省身 of UC Berkeley. He was on the US delegation. We had a good conversation and I took the opportunity to invite him to visit Singapore, which he readily accepted. In June of 1980, he came to Singapore for a two-week visit, during which he gave a public lecture at the Bukit Timah campus in the New Lecture Theater 4 (or NLT 4 as it was then called). The talk was attended by more than 450 people, standing room only. I believe it was by far the biggest mathematical event in Singapore.

In 1986, Professor Peng Tsu Ann, then Head of the Mathematics Department, and I attended the International Congress of Mathematicians in Berkeley. Chern hosted a party at his residence one afternoon and invited Tsu Ann and me to the party. His house was located about half an hour's drive from the Berkeley campus, with a floor-to-ceiling glass window in the living room overlooking the beautiful San Francisco Bay. At the party Chern showed us a nicely made wooden chair with the inscription "Director" on it and told us that it was a gift from the Mathematical Sciences Research Institute (MSRI), which he had served as its founding director. Chern told us many stories about the wonderful things that MSRI was doing and the contributions that the Institute was making to the American mathematical community. As we were leaving the party, we shook hands and Chern smiled at me, and said, “Maybe one day Singapore would have its own mathematical institute too”.

Between 1986 and the late 1990s, the topic of a mathematical Institute in Singapore often came up among the members of the Department of Mathematics over lunch and during meetings. At least two proposals were made to the university on setting up a mathematical institute. But perhaps the time was not right.

Chi-Tat Chong

However, in 1998, an opportunity came up. The Singapore government began to look at new economy for the country in the new century. The term "knowledge economy" was often mentioned. NUS took this opportunity to propose the setting up of a mathematical institute to the Ministry of Education (MOE). And to our great delight, the proposal was accepted.

In the year 2000, IMS was officially launched with Louis Chen as its founding director. A generous start-up funding was provided by MOE for the first five years. Thereafter, NUS took over the responsibility of funding the Institute. The first program that was organized at the IMS was "Coding Theory and Data Integrity". It was a six-month program and Jean-Pierre Serre, perhaps the most eminent living mathematician today, gave the inaugural lecture. Serre just turned 95 recently. Between 2001 and 2021, IMS organized 163 activities. These included thematic programs, workshops, summer schools, winter schools, industry-based undergraduate research program, and public lectures. Overall, more than 15,000 mathematical scientists passed through the doors of IMS, including Fields medalists, members and fellows of national academies, leading figures in various mathematical fields, young mathematicians and mathematical scientists beginning their research career, as well as graduate and undergraduate students.

From the beginning, the mission of the IMS has been to serve as a platform for research collaboration between the local research community and its international counterpart. It also aims to provide research opportunities to young mathematical scientists beginning their careers, as well as to graduate students, for them to have the opportunity to attend workshops, lectures, and tutorials given by leading figures. This mission has remained unchanged over the years. Internationally, IMS has collaborations with a number of institutes. These include the Vietnam Institute for Advanced Study in Mathematics based in Hanoi, the National Institute for Mathematical Sciences in Daejeon, South Korea, the Institute for Pure and Applied Mathematics, which is an NSF funded mathematical institute based in UCLA, with which we have a collaboration called Research in Industry Projects for Students (this year is its third year in running). We also have a collaboration with the Simons Institute for the Theory of Computing based in Berkeley, with which we will have a joint program on machine learning soon.

Looking to the future, we see two important developments. First, the emergence of a number of very well-funded mathematical institutes in the Asia Pacific region, especially those in China. Second, the evolution of the STEM ecosystem in Singapore. For example, the growing importance of data science and artificial intelligence. Both developments will have great impact on the role of IMS, locally and internationally. IMS will continue to strive to maintain its position as a leading mathematical Institute in the new era.

To conclude, let me thank all who have made IMS possible. First, to President Tan Eng Chye, Senior Deputy President and Provost Ho Teck Hua, Deputy President for Research and Technology Chen Tsuhan, for their continued support, encouragement, and generous funding over the years to the Institute. Next, to the Scientific Advisory Board and the Management Board, led respectively by Iain Johnstone of Stanford University and Lai Choy Heng of NUS. We thank them for their advice and guidance on IMS programs and activities. We thank all the colleagues in NUS ranging from the Department of Mathematics, Department of Statistics and Data Science, Department of Biological Sciences, Department of Physics, Department of Economics, Department of Electrical and Computer Engineering, Department of Computer Science, and the Saw Swee Hock School of Public Health, for their involvement and participation in organizing IMS activities. Lastly, I would like to thank all the staff at IMS who, with great dedication and professionalism, ensure that all the activities are given superb administrative and technical support so that every program runs smoothly. It is to their great credit that the Institute has received many compliments from participants and organizers alike. So thanks to all of them. And to all of you for coming today in celebration of the joyous occasion.

IMS 21st Anniversary

BY ALEXANDRE HOANG THIERY
(National University of Singapore)

On the 20th of September 2021, the Institute for Mathematical Sciences (IMS) celebrated its 21th anniversary. The celebration started in the institute's auditorium with a welcome address by the Director, Chong Chi-Tat. In his speech as the guest of honour, the President of NUS, Tan Eng Chye, then delighted the audience with historical perspectives on the institute and highlighted the role of the IMS in the local and international research environment. After the speeches, and as has been a custom during these occasions, the Director presented the President with a token of appreciation – a copy of "The Art and Practice of Mathematics", a volume consisting of interviews published in the IMS newsletter.

The celebration continued with three pre-recorded congratulatory messages by Professor Roger Howe (Yale University) and Professor Siu Yum-Tong (Harvard University), both former chairs of the scientific advisory board of the IMS, as well as by Professor Iain Johnstone (Stanford University), the current chair of the scientific advisory board. The audience was then remotely joined by Professor Andrew Barbour (University of Zurich) and Professor Ted Slaman (University of California, Berkeley) who, during both their live virtual addresses, shared personal anecdotes about the IMS.

As in the official opening of the Institute in 2000 and during its 10th anniversary, a musical performance was offered. On stage, a young cellist, Michelle Zhu interpreted two movements, Sarabande and Gigue, from the Bach Cello Suite No. 3 in C Major.

The anniversary would not have been complete without scientific talks. In the first talk, Professor and Vice Provost Shen Zuowei described the "Mathematics Behind Deep Neural Networks". The day's celebration was concluded by a talk by Professor Zhu Chengbo entitled the "Orbit Method: From Matrices to Unitary Representations".

(Left) Performance by Michelle Zhu

(Right) Welcoming honored guests

String and M-Theory: The New Geometry of the 21st Century – II

From 22 November to 3 December 2021, the Institute hosted a workshop on "String and M-Theory: The New Geometry of the 21st Century – II". The organizers contributed this invited article to Imprints.

BY MENG-CHWAN TAN *(National University of Singapore)*

String/M-theory is the leading candidate for Einstein's dream of a "Theory of Everything", a unified theory of all the four fundamental forces of the universe which underlie every physical and therefore scientific phenomenon in nature. In recent times, it has also inspired new ideas and directions in pure mathematics, and, as such, revived the deep relationship between physics and mathematics first seeded by Isaac Newton who himself formulated the mathematics of calculus through an attempt to understand the physics of motion.

In December 2018, the very first bona fide String/M-theory conference in Southeast Asia was held at the IMS. It was a highly successful 5-day milestone event for the country and the region which saw close to 30 speakers (many of whom were luminaries of the field) acquaint everyone with the cutting-edge of physics and mathematics.

From 22 November to 3 December 2021, the much anticipated sequel to this resoundingly successful event was finally hosted and held online by the IMS. Once again, its aim was to bring together pure and string mathematicians working on the mathematical foundations of string/M-theory and string mathematics, respectively, to further investigate and explore the mathematical underpinnings and implications of string/M-theory, so as to gain a better understanding of the fundamental principles that underlie it. Aside from bringing us closer to obtaining the sought-after "Theory of Everything", the effort would also help advance pure mathematics and theoretical physics in a nontrivial way, as a better understanding of the fundamental principles and therefore "new kind of geometry" that string/M-theory embodies, would mean that new mathematics can be formulated, while current physical models which can be realized within the framework of string/M-theory can also be more deeply understood.

The 2-week program had two parts. As it was held online, a schedule that was compatible with the time zones of all participants had to be sought, whence it was agreed that the event would take place from 8pm to 12am local time each day. The first part, which took place over the first week from 22 to 26 November 2021, consisted of daily lectures by leaders of the field focusing on the following five sub-themes:

1. The mathematics of M-theory
2. The physics of M-branes
3. Higher symmetries in string theory
4. String mathematics
5. Machine learning in string theory

The second part, which took place over the second week from 29 November to 3 December 2021, was the highlight, and it consisted of the conference proper with talks by experts from around the world who brought everyone up to speed on the latest developments in frontier research. There were seven lecturers, 20 speakers and 45 attendees, giving a total of 72 participants, which was more than we had expected. The attendees were a mix of professors, postdoctoral researchers and PhD students.

There were robust and fruitful exchanges between all participants throughout the two weeks of the program, where good progress was made towards understanding the fundamental principles behind string/M-theory and the "new kind of geometry" that it embodies. In particular, there was further understanding of the mathematical structure underlying string/M-theory via algebraic topology and higher groups (Sati, Saemann). There was further understanding of the M-branes in M-theory via an action with a wick-rotated metric (Lambert). There was further understanding of the role that higher symmetries in string theory play via a novel explanation of how gravity emerges from higher-form fields in higher dimensions (Hull). There was further affirmation of string mathematics via a demonstration that the geometric Langlands correspondence could be realized and unified with the theory of knots, integrable systems and quantum algebra in pure mathematics, through string dualities (Tan). Last but not least, there was a novel understanding of how machine learning can help us understand string theory and even pure mathematics (Yang).

As the event was purely online, unlike the flagship program held from 10 to 14 December 2018 which was in-person, there were no local activities for the participants. Nonetheless, on the last day of the first week, there was a virtual discussion cum free-mingling session, which ran as smoothly and spontaneously as an in-person session would.

Overall, the event was once again a success, where many of the participants are already looking forward to a third instalment in which everyone can hopefully interact in person.

NEWS

New Management Board Member

Li Shiuan Peh

The Institute is pleased to welcome Professor Li Shiuan Peh, NUS, as a new member to its management board.

Professor Peh obtained her Ph.D. in Computer Science from Stanford University. She is Provost's Chair Professor of Computer Science and a courtesy faculty member at the Department of Electrical and Computer Engineering at the National University of Singapore. She is an IEEE Fellow (2017) and Alfred P. Sloan Foundation Research Fellow (2006). She received the NRF Returning Singaporean Scientist Award in 2016. Her other accolades include an appointment as an ACM Distinguished Scientist (2011), the MICRO Hall of Fame Award (2011), CRA Anita Borg Early Career Award (2007), and the NSF CAREER award (2003). Her research interests include on-chip networks, parallel architectures, and mobile computing.

Past Activities

Workshop on Data Science

17–19 MAY 2021

This workshop was jointly organized by the Centre for Data Science and Machine Learning, NUS and AI Lab at Sea Limited. There were 11 talks over three days. Speakers were from NUS (Department of Mathematics and Computer Science), A*STAR (Institute for Infocomm Research and Institute of High Performance Computing) and private companies (including SEA and Grab). There were more than 60 participants, which included 16 graduate students.

Hannes Kruppa: When the rubber hits the road

Research in Industrial Projects for Students (RIPS) 2021 – Singapore

30 MAY–30 JULY 2021

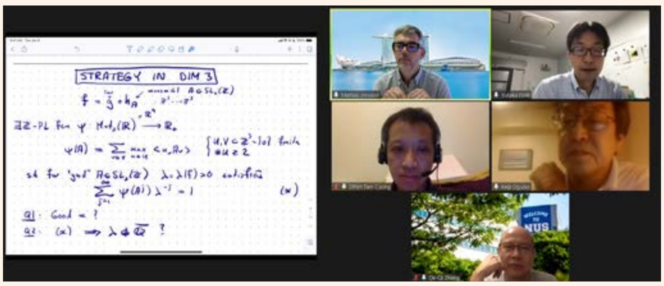
This program was organized in collaboration with the Institute for Pure and Applied Mathematics, University of California, Los Angeles. Due to the international travel restrictions by the COVID-19 situation, 16 undergraduate students (15 from NUS, one from NTU) were selected for the program instead. The industry sponsors were Google, Grab, Procter & Gamble (P&G) Singapore Innovation Center (SgIC) and VNLIFE.

Screenshot of participants interacting via Zoom

Recent Developments in Algebraic Geometry, Arithmetic and Dynamics Part 1

10–18 JUNE 2021

Themes of the program included the classification of higher dimensional algebraic varieties and algebraic dynamical systems, group actions on varieties, holomorphic dynamics in higher dimensions and related topics and number theoretical dynamical systems. There were over 30 talks during the conference from 14–18 June 2021. There were more than 80 participants, which included 22 graduate students.



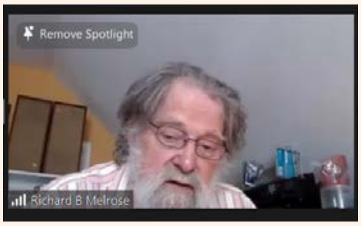
Mattias Jonsson: A birational map with transcendental dynamical degree

Index Theory and Complex Geometry Part 1

16–27 AUGUST 2021

The program started with a Conference on Complex Analysis and Geometry (16–20 August 2021). There were more than 25 invited speakers. The second week continued with another Conference on Index Theory and Related Topics (23–27 August 2021). Jean-Michel Bismut (Université Paris-Saclay, France) and Richard Melrose (Massachusetts Institute of Technology, USA) each gave a talk under the IMS Distinguished Visitor Lecture Series. There were close to 200 participants, of which 48 were graduate students.

Jean-Michel Bismut: Coherent sheaves, Chern character, and RRG

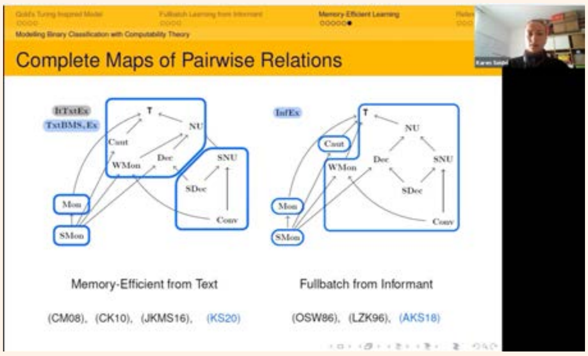


Richard Melrose: The Dirac-Ramond operator

Automata Theory and Applications: Games, Learning and Structures

20–24 SEPTEMBER 2021

This workshop focused on automata theory with some emphasis on three areas: two-person-games played on finite graphs, learning of languages in the setting of automata theory, and structures represented by finite automata. There were more than 15 talks. The organizers also hosted four discussion sessions (90 minutes each). There were more than 50 participants.

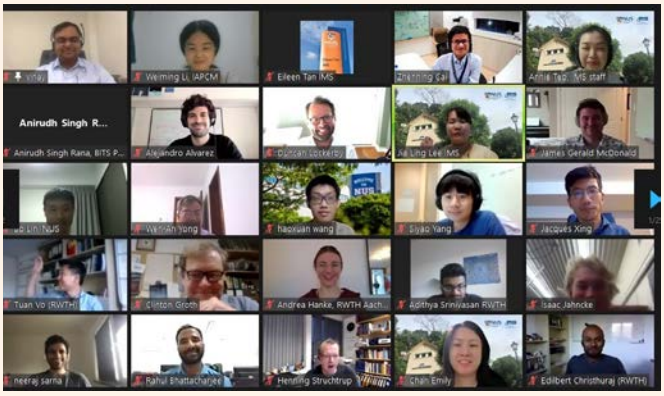


Karen Seidel: Modelling binary classification with computability theory

Modelling and Numerical Simulation of Non-Equilibrium Processes Part 1

27 SEPTEMBER–1 OCTOBER 2021

Due to the COVID-19 situation, the program was split into two parts. There were 16 talks, where speakers covered topics including rarefied gas flows, plasmas, radiative transfer, granular gases, polydisperse flows, evaporations, etc. Part two of the workshop will continue from 17–28 January 2022.



Participants say cheese for group photo!

String and M-Theory: The New Geometry of the 21st Century – II

22 NOVEMBER–3 DECEMBER 2021

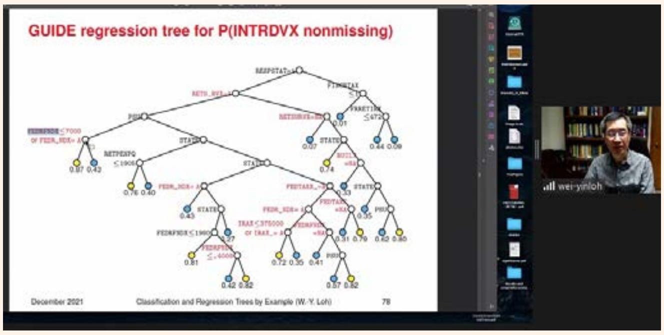
This program is a much anticipated sequel to the conference which was held at the IMS from 10 to 14 December 2018. Notable achievements of the program would be a concrete proposal for a mathematical structure behind String/M-Theory, a concrete proposal for a physical reason behind the emergence of gravity. There were seven lectures (100 minutes each) during the week of 22–26 November 2021. The second week (29 November–3 December 2021) continued with a conference which had 20 talks. There were close to seventy participants.

We have a very young participant in this group photo!

Causal Inference with Big Data

6–23 DECEMBER 2021

The program began with six hours of tutorial lectures titled "Classification and Regression Trees By Example,'' by Professor Wei-Yin Loh (University of Wisconsin-Madison, USA) from 6–15 December 2021. There were 18 one-hour talks planned for the workshop from 17-–23 December 2021. Discussions among participants have led to a bigger picture on the current themes of research on causal inference as well as on potential application areas in biology, economics, finance, healthcare, and social sciences. There were 230 registrants, which included 77 PhD students and 42 Masters students.



Wei-Yin Loh: Tutorial on classification and regression trees by example

Ng Kong Beng Public Lecture Series

Indra's Pearls: A Mathematical Adventure

As part of the two-week workshop Topics at the Interface of Low Dimensional Group Actions and Geometric Structures, which was held completely virtual due to the SARS-CoV-2 pandemic, Professor Caroline Series from Warwick University gave an online public lecture based on her book Indra's Pearls: The Vision of Felix Klein, co-written with David Mumford and David Wright.

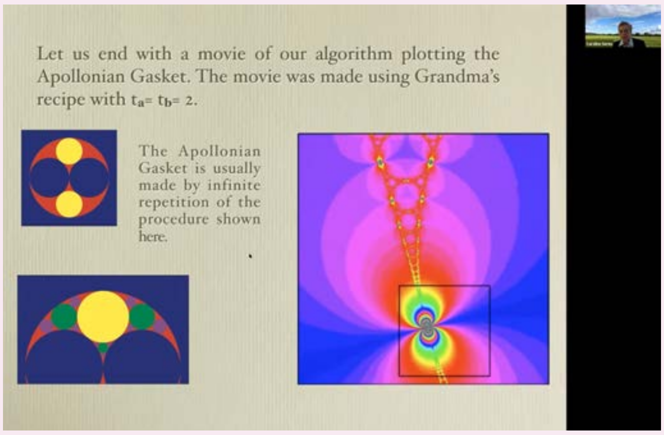
The scientific story starts with a now famous book on automorphic functions, published in 1897 by the German mathematician Felix Klein. It contains intriguing hand-drawn pictures of fractal like structures, and in the 1980s, Mumford and Wright started to program computers to reproduce the pictures in Klein's book. Klein viewed symmetry as shapes that remained unchanged under specific iterative application of specific transformations, and the ones used by Klein are called Möbius maps (linear fractional transformations) on the complex plane. These maps have the property that circles are mapped to circles, albeit rotated, moved to different locations and scaled to different sizes. By combining two Möbius maps and their inverses (generating a so-called Schottky group), it is possible to create intricate patterns of circles inside circles inside circles and so forth, leading to Klein's intricate fractal images and in particular to a limit set, which is unchanged under the respective transformations.

As for which two Möbius maps to choose, Professor Series explained, it turns out that two complex numbers are enough to produce in essence all possible limit sets, subject to the condition that circles touch each other and produce a limit set forming a connected loop. Surprisingly, choosing these two numbers in a way that Mumford and Wright's algorithm, which is able to directly draw the limit set itself, results in a nice (that is fractal) picture turns out to be non-trivial, since many combinations will lead to pictures that are rather chaotic. Even more intriguing, the area that separates pairs of numbers that produce fractal pictures from pairs that produce chaotic pictures is itself fractal in nature, and there is no explicit formula to decide which type of picture a specific pair of number yields.

Professor Series concluded the lecture elaborating on the connection with "Indra's pearls". In Hinduism, Indra is a god, and the myth goes that in the heaven of Indra, there is a vast net made out of shimmering pearls, stretching to infinity, and in each pearl reflected are all the other pearls in the heaven, and in each reflection again are all other reflections, so that through this process, reflections of reflections continue without end. A very befitting metaphor.

Professor Series delivered the public lecture on 28 January 2021. A total of 97 people attended the lecture via Zoom.

Adrian Röllin

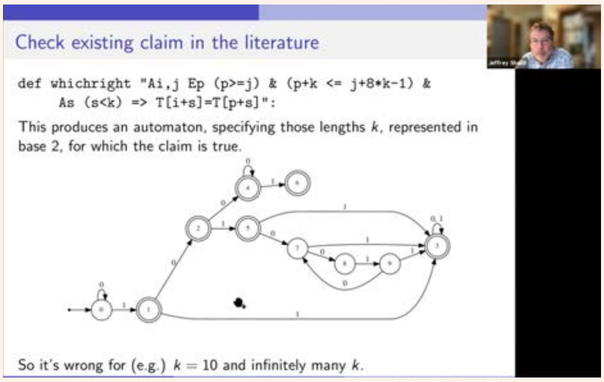


Caroline Series: Indra's pearls: a mathematical adventure

Adventures in Automata with a Theorem-Prover

Professor Jeffrey Shallit of the School of Computer Science at the University of Waterloo, Canada, delivered a public lecture entitled "Adventures in Automata with a Theorem-Prover" at NUS on the 24th of September 2021. In his lecture, Professor Shallit started by describing a new research methodology for mathematics where a computing system can assist mathematicians by automatically evaluating the correctness of conjectures, and even by proposing new ones. Indeed, this is not possible in general, and even when these procedures do exist, the amount of space and compute time can be prohibitive. Nevertheless, Professor Shallit explained that this methodology can be applied for some small domains such as combinatorics on words. After introducing the notion of automata, he then described how this concept plays an important role in the design of a theorem-prover called "Walnut" that he has built with collaborators. With this theorem-prover, dozens of results published results can be reproved in seconds with almost no effort! A total of 62 people attended the lecture.

Alexandre Hoang Thiery



Jeffrey Shallit: Adventures in automata with a theorem-prover

Human Flourishing and Causal Inference

Professor Tyler J. VanderWeele of the Departments of Epidemiology and Biostatistics at Harvard, USA, delivered a public lecture entitled "Human Flourishing and Causal Inference" at NUS on the 16th of December 2021. In his lecture, Professor VanderWeele started by discussing the notion of "human flourishing" and argued that it might be understood as living in a state in which all aspects of a person's life are good including, but not limited to, happiness and life satisfaction, physical and mental health, meaning and purpose, character and virtue, and close social relationships. After spending some time discussing the difficult problem of quantifying and measuring human flourishing, Professor VanderWeele went on to describe approaches to improve flourishing and the use of statistical causal inference, randomized trials, and interventions studies for this purpose. This large body of empirical work suggests major pathways to flourishing such as family, work, education, and religious communities. The session was concluded by a reflection on the policy implications of the study of human flourishing. A total of 79 people attended the lecture.

Alexandre Hoang Thiery

Tyler J. VanderWeele: Human flourishing and causal inference

Watch a recording of our public lectures

Human Flourishing and Causal Inference
Tyler J. VanderWeele, *Harvard University, USA*

Adventures in Automata with a Theorem-Prover
Jeffrey Shallit, *University of Waterloo, Canada*

Indra's Pearls: A Mathematical Adventure
Caroline Series, *University of Warwick, UK*

The Importance of Quantum Mechanics to Saving Our Planet
Kieron Burke, *University of California, Irvine, USA*

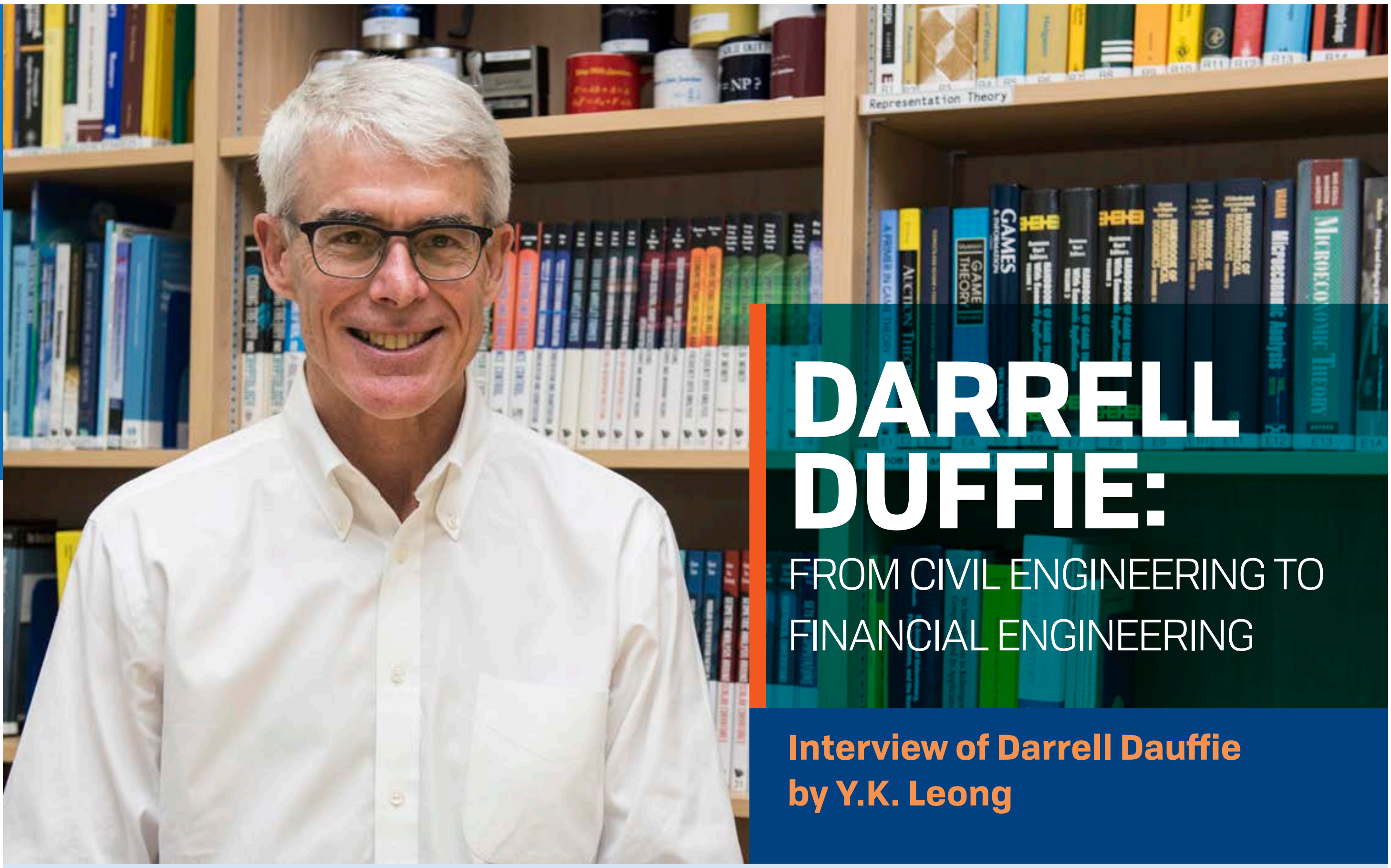
Can Every Mathematical Problem Be Solved?
Menachem Magidor, *The Hebrew University of Jerusalem, Israel*

Mobile Health Intervention Optimization
Susan A. Murphy, *Harvard University, USA*

Mathematics in the Solar System
William A. Casselman, *The University of British Columbia, Canada*

YouTube

Available on our webpage and YouTube channel tinyurl.com/imsnus



DARRELL DUFFIE:

FROM CIVIL ENGINEERING TO FINANCIAL ENGINEERING

Interview of Darrell Dauffie by Y.K. Leong

Darrell Duffie has made significant and influential contributions to the theory of mathematical finance as well as its applications in industry and the real world of international banking.

A Canadian, Darrell Duffie was originally trained as a civil engineer with a B.Sc. in engineering from the University of New Brunswick in Canada. After a short stint at Bell Telephone Company of Canada., he joined the Department of Civil Engineering as an assistant professor. He then took up a scholarship (on leave of absence) to do a Master of Economics (in Economic Statistics) at the University of New England in Australia. This led to his interest in systems theory for which he went to Stanford University to do a PhD (in Engineering Economic Systems) under the supervision of David Gilbert Luenberger. While doing his Ph.D., he worked as a systems engineer at the Systems Control Technology Incorporated at Palo Alto, U.S. for two years, where he did some economic modeling for the U.S. Department of Energy and various industrial clients, including research on futures markets, descriptor variable models; and algorithms for micro-economic and forecasting problems in physical distribution systems. On completion of his PhD in 1984, he stayed on at Stanford, joining the faculty of the Graduate School of Business (GSB), where he found his true calling in financial economics and mathematical finance, and applications to the financial industry, central banking and international finance. He has been called a "deep-level theorist and hands-on plumber [who] marries abstruse theory with solid reality"[1]. He has had a distinguished academic career at Stanford's GSB and is now its Adams Distinguished Professor of Management and Professor of Finance. He also holds, by courtesy, the following positions at Stanford University: Professor in the Department of Economics, Senior Fellow of the Stanford Institute for Economic Policy Institute, and (by courtesy) Senior Fellow of the Hoover Institution.

In his accomplished career, Duffie has received numerous grants to conduct his research work, in particular, at the Mathematical Sciences Research Institute of the University of California, Berkeley, at the *Université de Paris*, Dauphine, and at the Ecole Polytechnique Fédérale de Lausanne. He has authored singly and jointly numerous research papers and articles in leading journals of economics, mathematical finance, econometrics and probability theory such as *Econometrica, Journal of Political Economy* and *Journal of Finance*. He has received the following prestigious awards for his research papers in financial economics: Q Group Research Award, Smith-Breeden Distinguished Paper Prize *(Journal of Finance)*, Graham and Dodd Award *(Financial Analysts Journal)*, NYSE (New York Stock Exchange) Prize for equity research (Western Finance Association), Ross Prize (FARFE, Foundation for the Advancement in Financial Economics) and AQR Insight Award.

[1] https://www.minneapolisfed.org/article/2012/interview-with-darrell-duffie

His recent research work has been influential in international finance and spans a wide range of topics in financial economics ranging from the theoretical to the practical: incomplete security markets; derivative security markets; market and credit risk management of banks and other financial institutions; asset pricing theory; preference theory under uncertainty, financial market innovation and security design; interest-rate modeling and fixed-income security pricing; options and other derivative security markets; credit risk; over-the counter markets, banks and other financial institutions; and most recently, digital currencies and payment systems.

Duffie's ability in conveying abstract ideas in mathematical finance is well-known and legendary. An embodiment of the versatile scholar and perfect gentleman, he won GSB's Distinguished Teacher Award (Doctoral Program) and the Financial Engineer of the Year Award of the International Association of Financial Engineering. He is a Fellow of the Econometric Society, a Research Fellow of the National Bureau of Economic Research, and a Fellow of the American Academy of Arts and Sciences. He was the 2009 President of the American Finance Association.

He gave the Clarendon Lectures in Finance at Oxford University in 2004 and the Princeton Lectures in Finance in 2007. His influential ideas are expressed in the following books *Security Markets: Stochastic Models*; *Futures Markets* (also translated into Chinese); *Dynamic Asset Pricing Theory* (also translated into French, Japanese and Italian); *Credit Risk: Pricing, Measurement, and Management* (with Kenneth J. Singleton); *How Big Banks Fail — And What to Do About It; Measuring Corporate Default Risk; Dark Markets: Asset Pricing and Information Transmission in Over-the-Counter Markets; and Fragmenting Markets, Post-Crisis Bank Regulations and Financial Market Liquidity.*

Duffie has served on many journal editorial boards including those of: *Mathematics and Financial Economics, American Economic Journal: Microeconomics, International Journal of Central Banking, Stochastic Systems, Econometrica, Review of Finance, Journal of Computational Finance, Advances in Mathematical Economics, Journal of Financial Economics, Journal of Banking and Finance*, and *International Journal of Central Banking.*

Duffie's professional services and activities beyond academia have been phenomenal, from scientific advisory boards to councils and chairs of committees in the international banking community, such as the American Finance Association, the Econometric Society, Pacific Institute of Mathematical Sciences, Society of Financial Econometrics (SoFiE), Banff International Research Station, Moody's Corporation, Bachelier Society, International Association of Financial Engineers, Financial Strategies Group (Graduate School of Internal Business Strategy, Hitotsubashi University, Tokyo), NCCR (Swiss National Center of Competence in Research) FinRisk, and NUS Centre for Financial Engineering. He has been on the Financial Economists Roundtable since 2007 and was on the Financial Advisory Roundtable of the Federal Reserve Bank of New York from 2006 to 2016. He was a non-executive director at Moody's Corporation, which operates one of the largest credit rating agencies in the world, from 2008 to 2018, and has been on the board of iShares Funds and Trusts, San Francisco, from 2008 to 2011. He currently serves as an independent member of the shareholder board of TNB (The Narrow Bank) Inc., Connecticut and of Dimensional Funds, Austin.

In 2009, the G20 countries founded the Financial Stability Board (FSB) which established in 2013 an international committee (Market Participants Group on Reference Rate Reform) to study the possibility of alternative benchmarks for interest rate setting. From 2013 to 2017, Duffie chaired the committee and produced a report in response to the LIBOR manipulation by banks.

In the wake of the Covid pandemic together with the worsening of the trade and political relations between the U.S. and China, the resilience of the U.S. financial system was being tested. Duffie's expertise was sought after by bankers in industry and politicians in government to address the arising issues.

On 27 May 2020, the Hutchins Center at Brookings organized a webinar to discuss the post-COVID effects on the U.S. financial system. Duffie presented a background paper,[2] "Still the World's Safe Haven? – Redesigning the U.S. Treasury Market After the COVID- 19 Crisis," and fielded audience questions. Later, on 4 June 2020, he joined in a discussion of these issues with Itay Goldstein of the University of Pennsylvania, Beth Hammack of Goldman Sachs, and Nellie Liang and Don Kohn of Brookings. Duffie was also a Project Advisor for the G30 report,[3] "U.S. Treasury Markets: Steps Toward Increased Resilience."

In July 2020, the G30 Working Group on Digital Currencies published a report "Digital Coins and Stablecoins: Risks, Opportunities and Challenges Ahead" for which Duffie had served as project advisor. Since early 2021, he has co-directed (with Dr. Elizabeth Economy) the Hoover Institution's Working Group on the Global Implications of China's Central Bank Digital Currency. On 9 June 2021, Duffie gave a testimony during a hearing on "Building a Stronger Financial System: Opportunities of a Central Bank Digital Currency" before the U.S. Senate Committee on "Banking, Housing, and Urban Affairs".

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[2] Hutchins Center Working Paper Number 62, Brookings Institution, May, 2020.

[3] G30 Working Group on Treasury Market Liquidity, Group of 30, Washington, D.C., July, 2021.

INTERVIEW

Duffie has a long association with NUS since 1999 when he was appointed to the International Advisory Board of the then Center for Financial Engineering (renamed in 2006 as the Risk Management Institute). From 30 June to 6 July 2013 he was appointed by NUS as MAS (Monetary Authority of Singapore) Term Professor in Economics and Finance. On 4 July 2013 he gave a public lecture at NUS on "Regulatory Boundaries for the Banking System", jointly organized by NUS's Department of Economics, Center for Quantitative Finance, Institute for Mathematical Sciences (MS) and MAS. On the academic side, he has collaborated with NUS alumnus Lei Qiao and Yeneng Sun, chair of the Department of Economics, NUS[4].

Duffie was invited as IMS Distinguished Visitor to the IMS program "Dynamic Models in Economics" (4 - 22 June 2018 and 2 July - 3 August 2018) and gave two talks on "Redesigning Over the Counter Financial Markets" on 24, 25 July 2018. under the IMS Distinguished Visitor Lecture Series. Because of the exigencies of the COVID-19 pandemic, the Risk Management Institute organized its 14th Annual Risk Management Conference as a virtual event from 26 to 30 July 2021, in which Duffie gave a keynote speech online on "Reforming the Market for U.S. Treasuries" on 28 July 2021.

It was during his 2018 visit that Y.K. Leong interviewed Duffie on 18 June 2018 on behalf of the IMS newsletter *Imprints*. In the interview he spoke about his early beginning as a civil engineer and his quick and successful transition into the world of financial economics. Here, he also gives us a deep and insightful account of some of the recent issues that have plagued international finance, such as the manipulation of credit ratings and interest rates, and some of the perennial issues underlying the trade relations between China and the U.S. Finally, we learned how in 2009 he made one of the earliest attempts in raising the professional opportunities for his female colleagues in a male-dominated world of finance. As a bonus, he briefly gives us his personal views of the differences in political development of China and the West.

Acknowledgement. Y.K. Leong would like to thank Yeneng Sun for providing some background information and new questions for the interview, and Von Bing Yap of the Department of Statistics & Data Science (NUS) for preparing a raw draft of the transcript of the interview.

IMPRINTS I **You received your BSc from University of New Brunswick in Canada, and PhD from Stanford University and MSc from University of New England in Australia. Was there any special reason for you to go to Australia for your MSc?**

DARRELL DUFFIE D Yes, there was a reason. I was a young engineer, just out of school, and I got this opportunity from a scholarship, from the Rotary Foundation. You know, I had a modest family upbringing. We didn't have extra money for me to go to graduate school. At the same time, it had been arranged by another Rotary Club in Australia that I would be invited to go to a city in New South Wales called Armidale, where they had a very good program in economic statistics. This for me was unexpected, not just an honor, but an unexpected opportunity for a very young man, to travel the world and to see another country. And at the same time to go to graduate school, which I was very interested in doing. I immediately accepted the opportunity and that was a huge opportunity because, aside from going to graduate school, I got to see many countries in Asia and Europe on my way around the world, which not many people with my background had the opportunity to do. So, it was a big pleasure.

I **It must be a very long trip halfway around the world.**

D Actually, I remember going to the travel agency and arranging (in those days, paper tickets) many, many pieces of paper tickets because I wanted to visit Japan, Malaysia, Singapore, Australia, Thailand, Nepal, India, Israel, Italy and many countries in Europe. I went all the way around and it took the whole year.

I **So, this is not the first time you are in Singapore.**

D That was my first visit then when I was 21 years old.

I **Did you expect to come back again?**

D I've been in Singapore, maybe every two or three years since I've been an academic and I always love coming here and I will always come back. It's a wonderful country. You're very lucky. It's a country of opportunity for everyone.

[4] Darrell Duffie and Yeneng Sun "The Exact Law of Large Numbers for Independent Random Matching", Working Paper, Graduate School of Business, Stanford University, July 2004;
Darrell Duffie and Yeneng Sun, "The Existence of Independent Random Matching", Annals of Applied Probability, Volume 17 (2007), 386-419;
Darrell Duffie, Lei Qiao and Yeneng Sun, "Continuous Time Random Matching", Working Paper, Graduate School of Business, Stanford University, 2016;
Darrell Duffie, Lei Qiao and Yeneng Sun, "Dynamic Directed Random Matching", Journal of Economic Theory, Volume 174 (2018), 124-183.

I **What made you switch from engineering to financial mathematics?**

D Well, that's an interesting transition. I started my undergraduate in civil engineering. My first job as a practicing engineer was doing economic planning for facilities, meaning new plant and equipment (expensive stuff) for Bell Canada. Bell is the telephone company in Canada. It's analogous to the US Bell. My job, instead of dealing with physical plant and equipment, was the economic planning of it - the cost, when it would be needed. This was all, in those days, called engineering economics. That's why I was quite excited about doing more economics and combining it with engineering. And I very naively just searched all of the graduate programs that combined engineering and economics and of these, there happened to be one department at Stanford University [offering a program] called Engineering Economic Systems. And it seemed perfect for my interests because it had enough mathematics and economics. And so, I applied. In fact, it was the only school to which I applied. I was very naive. I didn't know that you might get rejected. I had nowhere else to go, but they accepted my application. And so, I went to Stanford and it happened that my advisor David Luenberger was very interested in financial mathematics. Before long, I also became very excited about financial mathematics and you know, then the die was cast. I became a financial economist interested in using mathematical methods in finance.

I **It seems that many successful practitioners in econometrics and finance started off as engineers, computer scientists, or physicists. You are a good example. Do you think that a training in engineering does contribute to a suitable mode of thinking in economics?**

D I do. You know, I just came out of a lecture here at the IMS, by Professor Fuhito Kojima, who is doing work in matching markets. The father figure in that area of economics is Alvin [Elliot] Roth, and Roth came from the same engineering school at Stanford that I came from. I think of him as a role model for people that come from math or engineering or physics and move into economics and bring a perspective of solving problems. For example, Al Roth is responsible for developing methods for matching students to schools or doctors to hospitals or organ transplants to recipients, problem solving that I think comes from an engineering perspective. You face possibly a fuzzy set of circumstances that suggest that a solution is needed. You need to formulate a model of whatever the problem is and solve it. And the two of those, I think are very amenable to an engineering approach. Whereas if you come out many straight economics programs, the models that are usually presented to you, you don't have to formulate them. And the solution methods are often in previous work in the literature and you need to make a step beyond. Whereas in engineering, sometimes you're starting from scratch. It's like building an electric power grid, for those in electrical engineering. Or a system of roads and bridges. Or if it's a transportation problem, allocating traffic. You know, there's always some significant application that you're presented with and you have to solve it. So, I think I came with that perspective. A number of other people in financial economics, like Bob Merton, Fischer Black[5] and others have come out of a mathematics background or engineering background.

I **Engineering does help you to think out of the box, isn't it?**

D Yes, it forces you to think out of the box, and to build things much like an engineer would.

I **Credit rating is a highly concentrated industry with Moody's Investors Service and Standard and Poor together controlling 80% of the ratings business in the global market. You served as an independent director of Moody's Corporation for 10 years from 2008 to 2018. Could you tell us something about how this industry works?**

D Sure. Actually, your question is very timely because when I was a director at Moody's Corporation, I felt reticent about speaking about some of the conflicts of interest in the ratings industry, because as a director, you have a conflict of interest, of course. But now I think I can speak more freely about why I think it's natural that credit rating is such a highly concentrated industry, and I think there is a good explanation. First of all, to talk just briefly, what is a credit rating? A firm or a government needs to borrow money, and investors that might lend money need to assess the likelihood that they will lose money from a default. They could do their own due diligence work by examining every lender and every borrower, but that's very costly. So, they hire, in effect, a credit rating agency to do the information work for them, to assess the credit quality. And the credit rating agencies assigns AAA for very high quality, AA, A and so on. And by hiring a professional firm like a rating agency to rate many firms, to rate many borrowers, you have economies of scale. The rating agencies historically were paid by the lenders to do this assessment. However, starting around the 1960s or seventies, it became so simple to share information (for example, photocopying machines and electronic mail and other methods of distributing this information) that it was hard to get investors to pay the rating agencies, because investors

[5] Fisher Sheffey Black (1938-1995)

could simply find the information freely. And so, the rating agencies began to collect the fees from the borrowers instead of the lenders. Now this presents a conflict of interest because you are basically giving a grade for quality to a firm who's paying you to get the grades. If you're a teacher or a professor, you know that it would be a conflict of interest if you give grades to your students and you ask them to pay you. That's a conflict of interest. So, there is a conflict of interest in the ratings industry. And that's why I believe the ratings industry is so highly concentrated to two or three very large ratings firms like Moody's, Standard and Poor, and now a somewhat smaller, but still large, firm called Fitch. And then only a very few smaller firms survive. Why is that the case?

Well, if you think about this conflict of interest, you would say, well, with many, many small rating agencies and only once every 10 or 20 years a major crisis, every small agency would have an incentive to give AAA to everyone because then they could get more business. And that's not a good incentive. You wouldn't want that, but if you have only two or three large rating agencies, then each one will be very cautious about giving triple A's to everyone. Why? Well, because they have a large fraction of the market now. And if when the next crisis comes, they were discovered to have given away too many AAA ratings, they will lose this large franchise value, this profitable ratings business that they have. So, they will be more cautious. If they have a large fraction of the market, they will be more cautious about giving out high ratings to any borrower that asks. They will instead be more discriminating. And I think the equilibrium in the industry is that you have a few rating agencies that give out ratings that are more discriminating between the high quality borrowers and the low quality borrowers. And this is a natural equilibrium in the market. It doesn't suggest that the conflict of interest goes away, but it does suggest that it's controlled in a natural way. I would continue with an additional safeguard on this conflict, which is that since the financial crisis, the ratings agencies have separated the giving of the ratings, the assignment of AAA, AA, A and so on, from the marketing and collection of ratings fees. And so those are separated from each other in a way that reduces the conflict of interest. Before the financial crisis, there was only an informal, but no really rigorous and careful separation of these. And so, for that reason, I think the conflict of interest is much better controlled now than it was before the financial crisis.

Also, just a word or two about what happened in the crisis. The ratings agencies are believed to have conceded too many AAA ratings. That may have been the case for residential mortgage backed securities, like CDOs (collateralized debt obligations), which were famous in the crisis. But it wasn't widespread across the ratings businesses. For example, in ordinary corporate ratings or in government ratings, there's no significant evidence of any conflict of interest problems. And I believe that in the case of the residential ratings, the ratings agencies, like many others in the financial industry, simply didn't understand the severe credit problems associated with these collateralized debt obligations backed by residential mortgages. So, I no longer feel like I need to be an apologist. It is simply my sincere view that firms like the one for which I was a director (Moody's), or at least Moody's in particular, is a very high integrity firm that would not abuse its position to get short term profits from giving away too many high ratings. It just doesn't seem likely that that was the case to me.

I **How is your own research applied in assessing credit risk in theory and in practice?**

D Okay, so it is true that I've done quite a bit of academic research (in fact, that's probably how I got involved with Moody's in the first place) related to assessing the likelihood of default, the likelihood of multiple defaults in the same industrial sector and, also the connection between that and the pricing of credit risk in the bond market. It's basically using advanced statistical methods for judging the likelihood of approaching an insolvency based on all of the available data and also using methods associated with imperfect information, that is, noisy information. I'm sure that we're not going to have time today to go into all the statistical formulas and estimation methods. But I wrote a book[6] about this, published by Oxford University Press. So, if any of your readers want to know more, they can have a look at my book. It involves lots of methods that I developed with many collaborators, not just one or two, but maybe five or six different collaborators, with a focus on understanding the correlation of default risk between different borrowers. That was my main focus.

I **Has AI made any impact on credit risk analysis?**

D Yes, it has. The biggest impact is not by the major rating agencies, but rather by financial information companies. Like in China, there's an affiliate of Alibaba called Ant Financial, that uses hundreds, actually millions of borrower records and AI-like methods to judge the likelihood with which an individual small firm would not pay its debt. And in the United States, one can use similar AI or data science, machine learning kind of methods for analyzing consumer default. These can be used and are being used to give credit scores to consumers or for small municipalities, where there are millions of different borrowers. There are literally millions of different municipal bonds that need to be assigned a credit quality

[6] Darrell Duffie, *Measuring Corporate Default Risk*, (Clarendon Lectures in Finance), Oxford University Press, 2011)

and the common element, everything I've mentioned in using AI or data science or machine learning, is that you need many, many observations. Now, this doesn't apply so well to the larger corporations and governments because you have too few observations to really take full advantage of the data that's available for the case of consumers or small enterprises. And so, I expect that the largest progress in this area will be made at the level of retail, municipalities, or small enterprises. Already there's significant progress in this area.

I **In view of the huge amount of data, is there any danger of getting any fake news?**

D [*Laughs*] Well, that's one of the benefits of huge data sets. It's that one or two individuals might fake, but it's hard to fake an entire population, unless everybody is coordinating, which seems unlikely. I'm not a big believer in fake news. Most of the news that I read is actually realistic.

I **We've seen reports of falsely inflating or deflating the interbank interest rates by major banks across the world. You chaired the Financial Stability Board's Market Participants Group on reference rate reform from 2013 to 2017. In your view, how could such problems be handled by the global financial system?**

D Well, that opens up a lot of issues. And it goes back to your comment about fake news, actually. Leading into the financial crisis, the standard reference rates like Libor and Euribor were manipulated. Really, it was fake news.

First, let me explain briefly how these benchmark interest rates are determined and they're still determined the same way essentially today. What happens is that someone calls all of the large banks every day in London at say, 10 o'clock in the morning, and they ask the bank. If you were to borrow money today, what interest rate do you think you would have to pay? And then they take the reports from each of let's say 20 banks, and then they knock out the top four and they knock out the bottom four, like a diving score in the Olympics, and they average the rest. And that's your score. That's called Libor. That's the average interest rate at which banks lend money in the wholesale credit market. And they publish that number. And then, for literally millions of financial contracts, payments are made based on that announced report called Libor. And so, it's a very important number. You would have to say that Libor is probably the most important financial number published on any given day in the world. It's hugely important. Coming into the financial crisis, however, it became fake news. Why? Because when the financial crisis was causing problems for the banks, they called the banks as usual and asked them at what interest rate do you think you could borrow today? Banks were very worried that news would get out

"THE RATINGS AGENCIES ARE BELIEVED TO HAVE CONCEDED TOO MANY AAA RATINGS. THAT MAY HAVE BEEN THE CASE FOR RESIDENTIAL MORTGAGE BACKED SECURITIES, LIKE CDOS (COLLATERALIZED DEBT OBLIGATIONS), WHICH WERE FAMOUS IN THE CRISIS."

that you were having trouble borrowing money at low interest rates and you were, in fact, borrowing money at high interest rates, indicating a lack of credit quality. And they didn't want this news to get out. They wanted to make the market believe that you were getting low interest rates and therefore were creditworthy. And so they misreported, they faked your true credit quality by reporting that you could borrow at low interest rates. And so, Libor was reported to be much lower than it should have been reported. This caused consternation in London and in New York and the regulators became concerned about the manipulation. And then it was revealed that there was an additional reason of misreporting, which was so that individual traders in the bank could profit on their contracts that were linked to Libor. Some traders on interest rate derivatives would call up to the reporting person at his or her bank and say, "Today, if you don't mind, please report a somewhat higher number because I will profit on my derivatives contract. And if you do that, I will give you a bottle of champagne, or I'll take you to dinner, or you'll be my friend."

Really, this is bad behavior. And the reporting person should not have agreed to this misreporting, but this also generated fake news and Libor was manipulated again. And this came to light. There was litigation. Individual traders, and the banks were found to be criminally liable. The banks paid enormous fines, north of $10 billion in fines. And it's still adding up. And the regulators decided they needed to do something serious. They said, "Well, the main problem is we're just getting the opinion of the bank on its borrowing rate. What we really need to do is to get actual transactions, to get contracts in which we see the interest rate at which they actually borrow."

When they checked to see this, however, they discovered the banks were not actually making very many of these transactions, very few on a given day. A few, and that's not enough to make Libor a good number, even if everyone was reporting honestly. There are just not enough transactions by which the banks are lending money at the relevant maturities to make a good Libor report. Now I'm getting to the key part of the story.

The regulators decided we can't rely on the bank lending costs for the popular maturities related to Libor. We need to go to something where there are a lot of transactions. And so, they decided, in the United States, Switzerland, England and Japan, that they would go to an overnight interest rate, one-day interest rate, for which there were many transactions. They've all made this decision, all of these countries, that they're going to start moving out of Libor, which is like a three-month or six-month interest rate and go to an overnight interest rate. The problem, however, is that we now have very active markets that rely on references to Libor, and we need to get rid of those active markets and make the activity move into new contracts that reference the new one-day benchmarks.

Making this transition is where I got involved with the Financial Stability Board's Market Participants Group, a committee that I chaired, which included participants from Singapore (Standard Chartered), from Australia, from Japan, from all across North America and Europe. We formed a committee; we wrote a 700-page report making recommendations for how to move away from Libor and move into the new overnight reference rates. We did make that recommendation to make this transition with lots of caveats and details, including the legal issues and operational issues. Recently, however, the transition has been accelerated. Why? Well, because in London, the head of the Financial Conduct Authority, who was then Andrew [John] Bailey and who now heads the central bank of the UK, was having difficulty convincing the banks to continue Libor even for another few years. And they wanted out because there is too much litigation risk, too much reputation risk for them to be making these reports where there are no data supporting Libor. The banks wanted out. So, Andrew Bailey has said, "Beyond 2021, we will not support Libor anymore, and it may go away, and you need to make this transition very rapidly now."

And so now we're in the phase in which there's going to be a rapid transition, within a couple of years, if everything goes well. Hundreds of trillions of dollars of contracts that are currently referencing Libor will begin to reference the new overnight benchmark interest rates. That is not an easy transition. I have called this the most challenging financial engineering problem that the world has ever faced.

I Is China part of this?

D China has its own benchmarks, which are called Shibor. Instead of Libor (London interbank offered rate), it is the Shanghai interbank offered rate [Shibor]. In actuality, China is more reliant on the one-week or two-week Repo rate, or repurchase agreement rate, which is a pretty solid benchmark for China. So, I think China will not have a similar problem.

I **In an interview with *Imprints* in May 2004, Lawrence Klein expressed guarded optimism about China's target of quadrupling its GDP between 2000 and 2020. He pointed out that no country has had 40 years of growth of that size in terms of established statistics. China's economic performance has far exceeded the expectation of most people. Its GDP in 2017 is 10 times that of 2000. Could China sustain such high economic growth for another decade or so? In your view, what does China need to do about its financial system in order to meet its long-term target of becoming a developed country?**

D Well, first of all, this is a very insightful question. It's probably the most important question facing the global economic order because China is becoming the world's largest economy. And if it's going to continue to support the global economic growth, it will need to revise its financial system. And the most central point that needs to be revised, in my view, is the corporate debt market because this growth that's been happening for the last 40 years cannot continue at this high rate without a much better corporate debt market. There are several issues here and I want to go through them methodically, because as I said, of all your questions, this is probably the most important one that faces the global economy.

So, first of all, China's financial system is much better than people realize in general, because you couldn't imagine an economy this large that has grown this rapidly without a rather good financial system. So, it's actually quite good. Nevertheless, some problems have arisen with sustaining this kind of growth into the future. One problem is excessive reliance on borrowing by corporations, especially the state-owned corporations. So, in the last 10 years since the financial crisis [of 2008], China's corporate debt has more than doubled. That's almost unheard of in any large economy, for the corporate debt market to grow so rapidly. And one may even say that China has been postponing a financial crisis by borrowing more and more in an unsustainable path of borrowing, to the point at which China's corporations have debt that exceeds 170% of its GDP. As a point of comparison, in the United States, which has a very large debt market, corporate debt is about 70% of GDP. So, China has about two and a half times as much corporate debt to GDP as the United States. Now, it hasn't blown up yet in part because China's government actually has relatively little debt. Compared to the United States, China has less than half of the government debt. So, China has some fiscal capacity to support this huge surge in corporate debt. If the debts of corporations start to fail, the government can step in whenever it likes and bail out those corporations. And it has been doing that historically quite a lot, probably too much. Too much bailout means that the allocation of capital across the economy is not efficient, because lenders will lend to anybody if they think the government will bail it out. So, the first thing the government needs to do and has already begun to do, is to allocate credit more efficiently by allowing some firms to fail instead of bailing them out. In the last year or two, around 20 significant Chinese firms have been allowed to default by the government. Whereas previously the government would have bailed out most of those. And the government is trying to send a message to lenders. "You should be careful to whom you lend money because we will not bail out every firm." Lenders are starting to take that to heart, but still the government supports most of the state-owned enterprises — to the extent that it is not efficient. So, that's one problem. That's one area in which China is improving. It needs to do more, which is to let the private sector allocate credit without so much government bailout.

The other area in which more needs to be done is transparency. We spoke about credit ratings a few minutes ago. Currently in China, almost all firms have a credit rating which is either AA or AAA. In global markets and developed markets, AA is an extremely high rating and there's almost no AAA. In China, for every borrower that gets rated, almost everyone is AA or AAA. And, in fact, AA or the lower AA ratings or the high single A ratings are considered junk bonds. They are not very good. You have to have a AAA rating to be a really good credit in China. So, the credit ratings are not that informative in the domestic ratings market, and they need to have more distinction between high ratings and low ratings. One of the reasons the ratings are so high is that the government almost invariably bails out these firms. So, the second area of improvement should be more discriminating domestic credit ratings in China. And I think that it may happen because China is going to allow international rating agencies to go into China and rate the corporate debt. And that may impose some degree of discrimination between the better borrowers and the worse borrowers. That's good because then lenders will know better to whom they should lend money, or at least they will demand a yield, a return on their money that's commensurate with the risk that they're taking. So that's a second area.

The third area that needs to be improved is restructuring firms that are failing and cannot meet their debts. This is very important in China. Not many people realize that China has more corporate debt than any other country in the world by far. I'm not talking per capita, not talking some proportion. I'm saying in total number of dollars of debt, China has more than any other country in the world of corporate debt. And so there needs to be a reliable, standard, homogeneous, uniformly applied bankruptcy law that is predictable, so that if you lend money to a corporation, whether you're a domestic lender, whether you're a foreign lender, whether you're lending to a state-owned firm or a private sector firm, there should be a predictable, reliable method for allocating the remaining assets of the firm when it is unable to meet its debts. So that means a bankruptcy court that is rigid in its application of the law, wise and independent, uninfluenced by selected creditors who might have a relationship with the government, and similar across the entire country. If that were to be developed (it is in the process of being developed now), then lenders would understand what risks they're taking when they lend money to a given firm, because they would understand when it comes time that the firm cannot meet its debts, what will happen to them. It will also be possible for foreign investors to trust that they will have standing in the courts inside China in the same way that a Chinese investor would have standing — that there would be no relationship benefits. And if that were the case, foreign capital would come into China in large volumes and allow Chinese firms to get international sources of debt capital at a much lower cost. It would also allow international investors and Chinese investors to get better diversification of the risks that they take by smoothing their investments across the globe. So, this would be a big improvement.

Another dimension of this is getting your money back out of China. From time to time, China imposes severe capital controls, that limit the ability of foreign investors to get their money back out and for Chinese investors to invest abroad. If these capital controls were more predictable and more open, that is, not necessarily eliminated, but they became more reliably available, that is, you could get your money out in a reliable way, then I think China would see much more foreign investment and that would help its economy continue to grow. Now having said all that, I think China's economy is not going to stop growing. It's going to continue to grow at a rate, which would be viewed as very high in most developed markets. So, more than 4 or 5% for many years. That is not very good by China's historical norms, but it is a very high rate of growth for most countries. Currently China is growing at about six and a half to 6.7%, which is really a very attractive growth rate for the United States, which is growing actually quite well by its standards. Right now, it's only growing at a rate of three to three and a half percent. So, China is growing at roughly double the rate at which the United States is growing. Even if China's growth rate were to step down a bit and become more sustainable, less reliant on debt, it could be sustained at a high rate of growth for years to come and continue to provide prosperity to Chinese citizens. And I think that's the scenario that I have in mind for China. And if some of these measures are taken, I think China will achieve that. But even in the worst case, economically I think China is going to be okay. It's not going to have a major collapse soon because the government can use some of its a large fiscal capacity to support the economy for quite a few years.

I Are you optimistic about China?

D I'm very optimistic for China. When I was a graduate student, I studied Chinese so that I could better follow economic developments in China. I was little bit too optimistic, because the really explosive growth happened much later than in my student years. But I still visit China every year and try to follow what's happening. I teach a course at Stanford on China's financial system, a graduate course, which gives me the opportunity to follow developments in China's financial system. I'm very interested in it because I think its potential continues to be enormous, affecting the lives of so many people, so positively.

I China has quite a long way to go, isn't it?

D But it's come so far. I always see the glass is half full in China. Everything looks quite good to me. Of course, there are momentary changes in the nature of political leadership and freedoms that concern one. But overall, I'm very optimistic, that China will continue to develop and provide prosperity to its people. I think the people of China should be very optimistic. They've accomplished so much.

I What do you think about the trade dispute between US and China?

D That's a very subtle set of issues. You're asking me some of the most challenging questions that anyone could get asked. But it's quite an interesting one. Well, first of all, the headline in the newspapers is that this is about trade flows and about the fact that China exports more to the United States than the United States exports to China. The net trade balance is in favor of China and that's viewed as the central issue. But in fact, it's not the central issue. The central issue for the United States administration is the ability of US firms to get a fair deal in China. Even though I strongly disagree with the rhetoric of the current US [Trump] administration, which strikes me as erratic bullying, unreliable, untrustworthy, its terrible rhetoric. But the driving force behind it, is an issue that needs to be resolved. That's a genuine issue, which is the ability of developed market firms in the United States and Europe and other countries to compete on a level playing field inside China. And China has not allowed that until this point at least, in a number of ways.

Protection of intellectual property, that's one of them. Some firms in China have been taking advantage of intellectual property that's been provided elsewhere. Also, the ability to participate in markets on an equal basis. That's difficult. If you want to participate in China's markets as a US firm, or a European firm or a Canadian firm (I'm a Canadian myself), the norm is that you would be expected to enter into a joint venture and share the benefits of your entrepreneurship with a Chinese firm. And you would be expected to give them access to your intellectual property, on your manufacturing methods and your managerial expertise. Or the alternative would be that while you could perhaps be allowed to compete officially, unofficially you would not get the business. The business would go to firms that had a closer relationship with the Chinese government or cooperated in some other way with the [Chinese] government. Or alternatively, you would be told, "No, we're sorry, we're not going to let you into our markets."

> **"THE NET TRADE BALANCE IS IN FAVOR OF CHINA AND THAT'S VIEWED AS THE CENTRAL ISSUE. BUT IN FACT, IT'S NOT THE CENTRAL ISSUE. THE CENTRAL ISSUE FOR THE UNITED STATES ADMINISTRATION IS THE ABILITY OF US FIRMS TO GET A FAIR DEAL IN CHINA."**

I think this issue of a fair playing field is really what has been motivating this so-called trade war. It's not about trade in the case of China. Now, layered around that is all this rhetoric I mentioned, that the current US [Trump] administration has been throwing around, it needs to get a better deal. It seems counterproductive to me. If the United States really wanted to make progress with China, why would it be attacking all these other countries at the same time? It doesn't make good sense. A more strategic approach would be to work directly on its issues involving China in cooperation with other countries. But instead, the US administration has attacked [its allies] essentially. Recently the president of the United States was asked, who is your greatest adversary? His response: the European Union. I was shocked by that response. He was asked about this during his recent trip in Europe, and one would have thought that if he wanted to make progress with China on trade issues, that he would not pick on the European Union, his ostensible ally. That struck me as quite counterproductive for the US interests.

I Is it possible that he may be speaking for himself?

D Possibly, but I won't even begin to try to understand his own personal approach because I honestly don't understand it.

I **China has always been a closed system historically. So, now we want China to provide a level playing field, it may be a bit difficult.**

D It is a difficult transition, but it's a transition that many countries have made in the past. And I think that China will make that transition because it wants to continue to grow. One of your earlier questions was, what are the conditions for continued growth? China will need to, in my view, become a full participant in global markets. And in order to do that, it will be required, I believe, that it provides access to its own markets on at least a more level basis. Twenty-five years ago, there was a reasonable claim, that China needed to protect its infant industries and needed to give an advantage to local industries, in order to allow it to grow. But now it's reached the point at which those infant industries are among the world's largest producers. And it's not a question only of fair play. It's really a question of real economic game theory. Will China be permitted to continue to participate in global markets without opening up its own markets? I think not, at least not in the sense that it has grown. If it wants to continue to grow at such high rates, it will have to be willing to tolerate domestic competition from foreign firms.

I Now, the last question. You served as president of the American Finance Association in 2009. What is your most memorable experience during your presidency.

D Well, that's another excellent question. Of course, you might think that I would talk about something like my own opportunities as the president of what I could do for myself, but I'd rather not talk about that. I gave a speech, I had the opportunity to present a paper. It was a wonderful experience, but I think the most memorable experience, was the opportunity to develop the meeting agenda for the American Finance Association [AFA] because every year the president of the American Finance Association has a unique opportunity to form the agenda for the annual meeting, which is a very important meeting. It's part of the Allied Social Science [Associations] meeting, which is the largest meeting of economists in the world. There are twenty or thirty thousand economists that come to one place; this coming year [2019], it's going to be in Atlanta. So, the president of the AFA is responsible for selecting the list of sessions, of which there are between 60 and 80, depending on the year. Each session is like a mini conference. So, it's a very big responsibility. And when I faced this responsibility, I decided to try to innovate in a way that would advance the interests of the profession. And I tried something new, which I think is very important, which is to bring women into positions of leadership on the agenda. You can't control whose individual papers will be presented, but you can control who will chair each of these 60 or so sessions or mini conferences. And so, I made a point of selecting half of the session chairs to be women, so that there would be an opportunity for women who are dramatically under-represented in the profession, to play a leadership role. Now it's only one small way to do this, but I think it's one of the ways that's easier for the leadership of the American Finance Association or the other economics associations. To get some movement of women into leadership roles one can appoint women as either program chairs, session chairs, or appoint them to the boards of the academic journals, and to get this process of getting more women into the profession moving along. At most universities, there is a shockingly slow rate of improvement, of advancement of women in the profession, to full professors, for example. It's way too slow – way too slow. And so, that for me was the most memorable part of my experience – leading the American Finance Association that year was that new little impulse that I gave to women in the profession. And I wish there were more opportunities to do things like that. Everyone should try because it needs to be addressed.

I Has there been any resistance [to your efforts]?

D None at all, none at all. People, I think, overestimate how difficult it is to find highly qualified women in large numbers. That on its own is not enough, but there are plenty of opportunities to move women into positions of leadership. And I think it's very unfortunate that this doesn't happen at a higher rate. More could be done.

Post-interview Updates

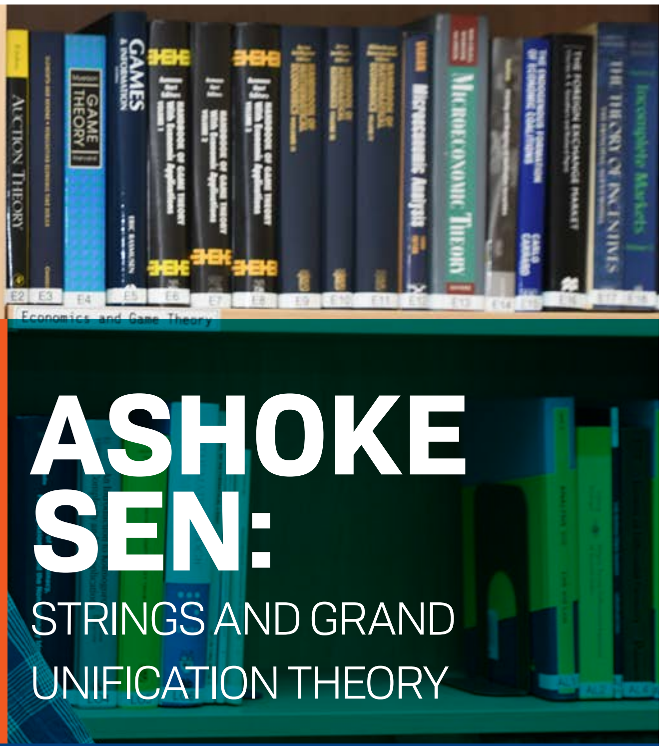
I Do you think the world will develop into a bipolar world on a socioeconomic level with the US and western countries at one end and China and Russia at the other?

D The world does seem to be more divided on those lines. I can see that trend even from how I would have answered one or two of your interview questions a bit differently today than I did a few years ago.

I In retrospect, is it too much for the West to expect a country like China with its long and unique history to accept a western style of economic and political development?

D China has made a clear turn away from a western style of economic and political development. This is discouraging. My own view is that while this may cement in place the leadership and ideology of the party for some additional years, it is not good for the people of China and for the rest of the world.

Disclaimer. *The views expressed in this interview article are purely personal and do not necessarily reflect the views of the Institute for Mathematical Sciences.*



ASHOKE SEN: STRINGS AND GRAND UNIFICATION THEORY

Interview of Ashoke Sen by Y.K. Leong

Ashoke Sen has made important contributions to theoretical physics, especially to the development of superstring theory.

Ashoke Sen is the elder son of Anil Kumar Sen, a former professor of physics at the Scottish Church College in Kolkata (Calcutta). He completed his schooling in the Sailendra Sircar Vidyalaya in Kolkata. He went on to obtain his BSc from the then Presidency College (now Presidency University) which was affiliated to the University of Calcutta (Kolkata) and his MSc from the Indian Institute of Technology (IIT) at Kanpur. During his undergraduate studies at Presidency College, he was greatly inspired by the work and teaching of Amal Kumar Raychaudhuri.[7]

Following in the footsteps of many Indian students who sought to further their graduate studies overseas, he applied to New York University at Stony Brook and obtained his PhD under the supervision of George Franklin Sterman. After his PhD, he took up postdoctoral fellowships at the Fermi National Accelerator Laboratory (Fermilab) from 1982 to 1985 and at the Stanford Linear Accelerator Centre (SLAC) from 1985 to 1988.

He met and married Sumathi Rao (also a physicist) in the United States and both returned to India in 1988, he to the Tata Institute of Fundamental Research (TIFR) in Mumbai (Bombay) and she to the Institute of Physics in Bhubaneswar, which is some 1,800 km from Mumbai by train. Then, in 1995, both of them were offered positions by the Harish- Chandra Research Institute (HRI) in Allahabad. So, he moved there where he became a Distinguished Professor. He has been concurrently the Morningstar Visiting Professor at MIT, a distinguished professor at the Korea Institute for Advanced Study and an honorary fellow in the National Institute of Science Education and Research (NISER), Bhubaneswar. In November 2021, he moved to the International Centre for Theoretical Sciences (ICTS) in the city of Bengaluru (Bangalore) in the South Indian state of Karnataka.

Sen has been described as "a shy, reclusive Indian particle physicist working from a non-descript laboratory". From the many interviews he has given, he strikes one as "a simple and down-to-earth person" who will talk to you on any scientific matter that is close to his heart. Yet his unassuming demeanor belies the depth of his scientific contributions and he has shown that working from a third world developing country is no obstacle to reaching one of the highest echelons of scientific excellence. Initially working in high energy physics, he changed his focus to string theory in the run-up to the first superstring revolution (1984-1994). Already in the late 1960s, there were attempts to view the fundamental units of nature as tiny strings instead of point-like particles in the study of the strong nuclear force. This was, however, abandoned

[7] Amal Kumar Raychaudhuri (1923– 2005)

in favor of quantum chromodynamics, but it was soon discovered in the mid-seventies that string theory held some promise as a quantum theory of gravity. Sen's work on the strong-weak coupling duality (S-duality)[8] and his (Sen's) conjecture[9] had a great influence on the developments in the second superstring revolution (1994-2003), and for which he was one of the first (nine) recipients of the Breakthrough Prize in Fundamental Physics in 2012[10].

Sen has singly or jointly written more than 250 research papers in the following scientific journals: *Physical Reviews*, *Nuclear Physics* , *Physics Letters*, *Physical Review Letters*, *International Journal of Modern Physics*, *Modern Physics Letters*, *Communication in Mathematical Physics*, *Advances in Theoretical and Mathematical Physics*, *Journal of High Energy Physics*, *International Journal of Modern Physics*, *Journal of Mathematical Physics*, *Physica Scripta*, *General Relativity and Gravitation*, *Entropy*, *Communications in Number Theory and Physics*, *Classical and Quantum Gravity*. In addition, he has also written a number of review articles on the entropy of black holes and superstring theory. Among his many important contributions are his pioneering study of unstable D-branes (in which he made his famous conjecture about open string tachyon condensation on such branes), the description of rolling tachyons, the entropy function formalism for extremal black holes and its applications to attractors, the precision counting of microstates of black holes, superstring perturbation theory and string field theory.

Sen has received honorary DSc degrees from numerous universities in India and has won practically all the national awards: the S. S. Bhatnagar, B.M. Birla Science Prize, G.D. Birla, R.D. Birla, Padmashri, Kamal Kumari National award, INSA S.N. Bose Award lecture, H.K. Firodia, J. C Bose Fellowship, Infosys Prize, Padma Bhushan and M P Birla award. On the other hand, he has received the following international awards: ICTP (International Centre for Theoretical Physics) Prize in honor of H. Yukawa, Third World Academy of Sciences Prize, Pius IX Gold Medal, Fundamental Physics Prize, Dirac Medal (ICTP). He is a Fellow of the Royal Society, the Indian National Science Academy and the Indian Academy of Sciences and an honorary fellow of the National Institute of Science Education and Research (NISER), Bhubaneswar.

Every year since 1983, Sen has been invited to give invited lectures in major universities, conferences and workshops around the world. In particular, he was invited to the 25th International Conference on High-Energy Physics (ICHEP 90) which was held in Singapore from 2-8 August 1990. In 2018, he was invited as Distinguished Visitor to the IMS (Institute for Mathematical Sciences) program "String and M-Theory: The New Geometry of the 21st Century" held at NUS (National University of Singapore) from 10 - 14 Dec 2018. He gave two lectures under the Distinguished Visitor Lecture Series: "Developments in Superstring Perturbation Theory" (11 Dec 2018) and "Analyticity and Crossing Symmetry in Superstring Theory" (13 Dec 2018). Y.K. Leong took the opportunity of his presence at the program to interview him on 7 December 2018 on behalf of the IMS newsletter Imprints. The following is an edited and vetted transcript of the interview in which he talked about his early beginnings in India and subsequent rise to international fame as one of the first recipients of the Breakthrough in Fundamental Physics Prize. Here, he shares his views on some of the controversial aspects of string theory on multiverses and cosmic strings.

Acknowledgement. Y.K. Leong would like to thank Chee Whye Chin of the Department of Mathematics, NUS for preparing a raw copy of the transcript of the interview.

IMPRINTS I Your father is a physicist; how much influence did he have on your choice of physics as a career?

ASHOKE SEN S I think it's hard to say directly how much influence he had on me, but I certainly learned physics from him. I used to discuss physics with him when I was in school. But perhaps what influenced me most was the atmosphere at that time. Physics used to be considered as the most preferred choice of students who are good.

I **Next to mathematics probably.**

S That's right, yes. But with mathematics, there was a feeling that mathematics is a very good subject, but there were not too many jobs for mathematics then. But as physics goes somewhere in between, it is a good subject and has jobs for it.

[8] Ashoke Sen, "Dyon-monopole bound states, self-dual harmonic forms on the multi-monopole moduli space, and SL(2,Z) invariance in string theory", *Physics Letters* B 329 (1994) 217-221

[9] Ashoke Sen, "Universality of the tachyon potential", *Journal of High Energy Physics* 9912:027, 1999

[10] "Prize citation: "For uncovering striking evidence of strong-weak duality in certain supersymmetric string theories and gauge theories, opening the path to the realization that all string theories are different limits of the same underlying theory."
The Fundamental Physics Prize carries a monetary award of US $3 million and is generously donated by the Russian entrepreneur Yuri Milner.

I **That was in Kolkata [Calcutta]?**

S In Kolkata, that's right.

I **You did your undergraduate at the then University of Calcutta, MSc from Indian Institute of Technology (IIT), and PhD from the State University of New York at Stony Brook. How did you come to take this route?**

S Well, the University of Calcutta was a natural choice because I grew up in Kolkata, and then I joined the Presidency College in Kolkata, which is a popular college for science and the humanities, but mostly for science students. Then from that college, it would have been natural for me to go to Calcutta University for my Master's. But what happened was that there was a lot of political unrest at that time. For example, our final exam got postponed by one year. And then I found out that if I joined there [University of Calcutta] for my master's, then I would lose one more year. Then, I started looking outside [of Kolkata] and several of us in our batch decided that we should try IIT Kanpur. And that's how I ended up in IIT Kanpur.

I **Kanpur is quite far away from Kolkata.**

S Yeah, Kanpur is reasonably far from Kolkata but IIT Kanpur has a very good physics department and has a good reputation for physics. So, I think that was one of the reasons why I went there.

I **From Kanpur, you went to New York.**

S Yeah. From IIT Kanpur, a lot of people used to go abroad, and my friends were all applying for graduate school abroad. So, I decided that I would also apply but my choice was limited because at that time, the application fees [to study in foreign universities] were very high, and I didn't have that much money. So, I looked for universities which didn't have application fees. Stony Book was one of them. I think it was by accident that I ended up in Stony Brook.

I **Six years after postdoctoral training in the United States from 1982 to 1988, you moved to the Tata Institute of Fundamental Research. Was the decision to return to India driven by a nationalistic sentiment?**

S I wouldn't say that it was a nationalistic sentiment, but I somehow like living in India and I never felt at home living outside India. So, I think it was more that I felt more comfortable in India than any nationalistic sentiment that made me come back to India.

I **I think for some people the scientific pull is stronger than the cultural pull.**

S That is true. And it helped that I was in theoretical physics because I felt that it is possible to do theoretical physics in India, even though I have to probably give up some things. But the internet had started coming at that time. There was email at least. Certainly, if I had to make a choice between physics and culture, I would have gone for physics, but it didn't seem that I had to give up physics to come back to India.

I **You were in TIFR (Tata Institute of Fundamental Research) for nine years before moving to the Harish-Chandra Research Institute in Allahabad. Why did you make this move?**

S It was again mostly personal. I got married when I was in Stony Brook, and my wife was also a physicist. She was working in India at a place which was 2000 kilometers away from Bombay. So, we stayed apart for about 12 years, starting from our PhD days. In 1983 we got married.

I **You got married in America?**

S Yes, we got married in US. Then in '95, this place [Harish-Chandra Institute] offered both of us jobs.

I **Same place! That's ideal, isn't it?**

S Yeah. So, I think that was the main reason why we decided to move to this place. It was a new place and I knew the director of the place. He was my former teacher in IIT Kanpur, and he seemed very dynamic. So, I was hopeful that this place would grow.

I **I thought that Tata Institute would be sort of more well known.**

S That is true. I think that is the reason why I went to Tata Institute in the first place. It was the most prominent scientific institute in India.

I **But that was not strong enough to make you remain there.**

S Well, we had to travel by train between Bombay and Bhubaneswar, where my wife was living. It used to take 40 hours. So, we decided that it was getting too much for us.

I **Was your PhD research in some theoretical aspects of high energy physics? And why did you choose to do your postdoctoral work in an experimental environment like Fermilab [Fermi National Accelerator Laboratory] and SLAC [Stanford Linear Accelerator Center] just after your PhD?**

S My PhD research was in QCD (quantum chromodynamics). So, it was theoretical. I didn't have to do any experiments. But in that kind of area that

I was working in, there were very good people in Fermilab, where I first got my postdoctoral position, like Bill Bardeen[11] and Chris Quigg who were in the theory group there. And there were various other people in that group. So that is one of the reasons I decided to go to Fermilab first. And then by the end of my postdoc at Fermilab, I had also started working in string theory. At that time, SLAC used to be a good place for string theory because Michael [Edward] Peskin was doing string theory at SLAC. And then Leonard Susskind was in Stanford. So, I felt that SLAC would be a good place for doing string theory.

I **But I thought that place [SLAC] was mainly experimental?**

S It's mainly experimental, but both places [Fermilab, SLAC] had strong theory groups. I think that in both places now, the emphasis is more on phenomenology. Even the theorists who are there mostly work close to experimental things, but it was not like that at that time [when I was there]. At that time, there was a lot of work in pure theory going on.

I **At that time, the experimentalists and theoretical people have grown more or less apart, isn't it?**

S That's true. Yeah.

I **When did you become interested in string theory?**

S That was during my stay in Fermilab. Because in Fermilab. I once heard a lecture by Edward Witten[12] where he emphasized that the next step to understand grand unification is to understand quantum gravity. And then I found that there was a physics report by John [Henry] Schwarz on string theory, which I started reading and I found it very interesting. So, I started reading string theory, I think, around the beginning of '84 at Fermilab. And then the paper by Michael [Boris] Green and John Schwarz came later in '84, where they showed how to cancel anomalies and make the theory consistent. And that's when I really started working on string theory.

I **That was in the 1970s?**

S No, '70s was the original development in [bosonic] string theory, but in 1984, they actually showed how to cancel anomalies and make the type I superstring theory consistent. That was the first superstring revolution.

I **Now, as a mathematical theory, superstring theory is arguably beautiful and awesome. But as a physical theory, it is still far from being accepted by the physics community. What are the prospects of superstring theory achieving the unification of physics?**

S It's, of course, very hard to predict the future. But I feel that superstring theory is so internally consistent that it's unlikely that it doesn't have anything to do with nature. It incorporates gravity automatically. It also incorporates the other kind of forces. But how to make the connection with nature? Of course, you don't know. That's what we are all working on. And I feel that eventually, even if it turns out that it's not the correct theory of nature, it's important to pursue this and convince ourselves that it is not the correct theory of nature, because unless we try it, we'll never know, right? And, at present, in my opinion, this has the best chance of being the correct theory of nature. It has achieved so much, which is way beyond what other theories have achieved so far.

I **But in terms of experimental verification, it has not been achieved.**

S No, it hasn't achieved anything so far, except that it has explained gravity. No other quantum theory has been able to incorporate gravity in this consistent way.

I **You mentioned consistent – mathematically consistent?**

S Exactly. It's a mathematically consistent way of incorporating gravity, which no other theory has been able to do. And it's certainly known that any theory of nature that is complete must incorporate gravity, right? So, in that sense, string theory is the unique theory which has done that so far. To directly test this in experiments seems very far in the future, because the kind of energies that one needs, we cannot achieve very soon. But it may be possible that there are indirect consequences. That's what people are looking for – some possible signatures of string theory, perhaps in cosmology. But so far, there is no direct experimental evidence for string theory.

I **You mention evidence in cosmology. Maybe they have to trace back to the origin of the Big Bang?**

S Yes. So many people are trying to understand whether, by looking at the cosmological data [cosmic microwave background], we can find some evidence for string theory.

I **Is there anybody that has achieved some success in detecting strings in the early universe?**

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[11] William Allan Bardeen, son of John Bardeen (1908-1991) who was awarded the Nobel Prize in physics twice
[12] Fields medalist 1990

S Not yet, so far, but that's one of the things that people are trying to do. And then there are also other expectations that maybe there are some relic strings, which people call cosmic strings (some very long strings which stretch across the cosmos) that have their own signatures. There are people who are looking for possible signatures of that kind.

I What do you think is the success of such an approach?

S Again, I think if we're lucky, we will find one. But it's very hard to say what will be the chances of success. because the problem is that we don't understand our universe that way. If people could understand the full evolution of the early universe, then they would also know what is the probability of finding such a string. But because you don't know the early universe that well, we don't know what is the probability of finding such objects.

I It took them a long time to find a way to detect gravitational waves, for example.

S That's true. It took them almost a hundred years to detect gravitational waves.

I But I think one particular difficulty about string theory is that it involves extra dimensions.

S I think that is not a serious problem, because while it has extra dimensions, we also know how to make that consistent with the current universe. String theory says that there are extra dimensions, but it doesn't require that those extra dimensions are large. They can be as small as a string. So, it's perfectly consistent with today's universe, where you see three large dimensions, provided there are six extra dimensions, which are small and compact[13].

I It's so small that we cannot see and cannot detect it at all.

S Well, not in an absolute sense. I mean, if we can actually go to an energy scale where you start seeing the strings, then you'll also start seeing the extra dimensions, because we know that the size of the extra dimensions cannot be smaller than the string size. In that sense, they are not totally invisible. I mean, we'll see them at the same scale where we start seeing the strings.

I Mathematically, there's also a lot of connections with number theory.

S Exactly. I think mathematically, string theory certainly has achieved a lot. There are so many ways it could have become inconsistent, but it hasn't. People calculate numbers in string theory in different ways, and if they didn't agree, then we would know that the whole structure of string theory will break down. And strangely, string theory has passed all the tests so far. There is no inconsistency. It's not that string theory is consistent by definition. Some of these tests could have certainly failed by giving different results for the same quantity in two different ways of doing the computation. And we always get the same result. The only explanation of this is the internal consistency of string theory.

I It's too beautiful to be true. I think another problem is philosophical because string theory introduces what they call multiverses. [See previous footnote.] That seems to be a bit philosophically not acceptable to many people.

S See, it introduces multiverses which can exist in different parts of the universe in different ways. But because the theory is dynamical, it also tells us that in our universe, if we can pump in sufficient amount of energy into one small region, we can see all these other phases. It's like, suppose you are living inside water. And water, we know, has other phases, like ice and steam. There may be other creatures who are living in ice, and there are other creatures living in steam. And we are all different from each other. But even those who are living in water, if they can put in sufficient amount of energy into one region, you can create small pockets of steam. Or if you can cool it sufficiently, then you can create small pockets of ice inside.

So, while we are living in one particular phase, we can create these other phases in our own universe, even though you may not be able to see the other people who are living inside ice or who are living inside steam. And so, in that sense, I would say, it's not philosophically that unsatisfactory. It's not that we can never explore those phases. We can see them in our own universe, and we can explore them.

I Do you believe in them [multiverses]?

S Well, as I said, I would like it not to be true. I'd like a better answer, but so far, I think this seems to be the most promising way that our universe realizes itself. But I would say that this is something that is not as concrete as many of the other things in string theory. I mean, the idea of multiverse is still not as mathematically rigorous in a way that many other aspects of string theory are. So, I think that's why there is still a lot of debate going on whether this is the right picture or not.

I Can I mention something about your conjecture? You are known for your conjecture

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[13] This process of compactification can be done in many (of the order of 10^{500}) ways and hence allow the existence of a large number of different universes.

on the tachyon condensation in string theory. I understand that tachyons are supposed to be particles that move faster than light. How does this fit into the scheme of general relativity, where nothing can move faster than light?

S Actually there is some misunderstanding about tachyons. While originally tachyons were described as particles which move faster than light, now we know that they actually represent some kind of instability in the theory. Suppose you have a potential, which is described like the potential near the top of a hill and suppose you have a particle moving under the influence of that potential. You put the particle on the top of the hill and you try to describe the motion of the particle down the top by perturbation theory. You assume that the particle has only moved a little bit away from the top, and describe the motion of the particle under that approximation. But clearly this is not a good approximation since as time progresses the particle moves further and further away from the top and the approximation becomes worse. Similar situation may arise in quantum field theory. If you try to take a quantum field, which has a potential with a maximum, and you try to describe the small fluctuations of the quantum field around the maximum using perturbation theory, then you'll find that there are apparently particles which move faster than light. But, of course, we know that it's not possible to describe the motion of a particle near the top of a hill by using perturbation theory, because if you give it a small push, it is not going to remain near the top. Eventually it'll roll down. And a similar thing happens in quantum field theory, that when you take a quantum field, which is near the top of a potential, and if you give it a small push, then it will eventually roll down and settle down to its minimum. So, if you don't take into account the fact that the actual correct vacuum of the theory is near the minimum and not near the maximum, then you'll discover that there are particles which move faster than light.

I **These are not real particles. They are fictitious?**

S They are fictitious particles. If you follow the usual rules of quantum field theory, but instead of quantizing the theory around the minimum, you quantize the theory around the maximum, you find particles which move faster than light. But you know that that's not the correct perturbative step. You should try to describe its motion around the minimum. And once you describe the motion of the field around the minimum, then you'll find that they are regular particles that do not move faster than light. And, in fact, this is not very esoteric. Our standard model of particle physics is like that, because if you take the Higgs field, the potential of the Higgs field has a maximum near the origin (near zero) and it has a minimum. If you try to describe the quantum field theory of the Higgs field around the maximum, even in the standard model, you'll find tachyons. But the correct way to describe it is not by looking near the maximum, but near the minimum.

So, in string theory what happens is that people found that there are tachyons, that there are apparently particles which move faster than light. String theory, of course, is not formulated as a field theory, but it was formulated in a slightly different way. And so, what my work does is to show that these apparent tachyons have exactly the same origin as in quantum field theory; that is, instead of describing the motion of a field near the maximum of the potential, the correct thing to do is to do it near the minimum. So, what I showed is that once you start describing the motion around the minimum of the potential, which is called tachyon condensation, that is, you don't work near the maximum, but you condense the field to go to a minimum, then there is no tachyon. Then there is no particle which is moving faster than light and everything is perfectly consistent.

I **What is the latest development in your conjecture?**

S Well, I think at that time, it was a conjecture, but now it has been proved in many contexts. People, beginning with the pioneering paper[14] by Martin Schnabl, actually proved it.

I **Is it in general? A general proof?**

S No, I'm not saying a general proof. What has been proved so far has been in the context of bosonic open string theory, but people believe that it should also be true in superstring theory. An explicit proof has been given in bosonic string theory.

I When you say an explicit proof, do you mean mathematically?

S Yeah. The idea is that in string theory, you know that there is a maximum, that we are studying the theory around the maximum, and the tachyon conjecture says that there should be a minimum. And around the minimum the theory should have certain properties. And now people have actually constructed that. They have found the classical solution of the theory which is a minimum.

I **Exact solution?**

[14] Martin Schnabl, "Analytic solution for tachyon condensation in open string field theory", *Advances in Mathematical and Theoretical Physics* Vol 10, No 4 (2006), 433-501

S Exact solution. And then they showed that when you actually quantize the theory around the minimum, you get sensible results. There are no tachyons around the minimum.

I **In 2012, you were one of the first recipients of the Breakthrough Prize in Fundamental Physics worth about 3 million US dollars. How has this influenced your research and maybe even your life?**

S Well, I don't think it has influenced my research as such, or my life very much. I mean, I can say financially I'm more secure today, but probably its main impact has been that it has influenced many students in India, at least. Now I keep getting letters from students asking for advice and so on. So, I think that has been the main influence of [the Prize, at least inside India, that many people have now become interested in physics and science. And as I said, I keep getting letters from people asking for advice and what to do, how to proceed, to become scientists and so on.

I **Talking about advice, what advice would you give to a student who wants to do research in string theory?**

S Well, I'd give the advice that right now develop your basics very well because to do string theory, you have to understand the basics of physics very well. So when they're in college, I don't suggest that they read advanced material but just try to develop the basic concepts very well. Then once you go to graduate school, then, of course, you have to learn quantum field theory and general relativity very well, and also statistical mechanics to some extent, before you can start doing string theory.

I **Would you advise students to go to string theory?**

S Well, I wouldn't advise them to go to string theory, but what I would say is that if you are interested in doing string theory, don't get discouraged and you should go for it. But it should be your own choice. Certainly, things are tough here in string theory; problems are hard, you don't know when the progress will come or how the progress will come. But if one can make progress, it's very rewarding. That's what I would say.

I **Will there be any new revolution in string theory?**

S Well, I hope so, but certainly, it's not something that I can predict.

21st Anniversary Volume

The Art and Practice of Mathematics

This book constitutes the second volume of interviews with prominent mathematicians and mathematical scientists who visited the Institute for Mathematical Sciences, National University of Singapore. First published in the Institute's newsletter Imprints during the period 2010–2020, they offer glimpses of an esoteric universe as viewed and experienced by some of the leading and creative practitioners of the craft of mathematics.

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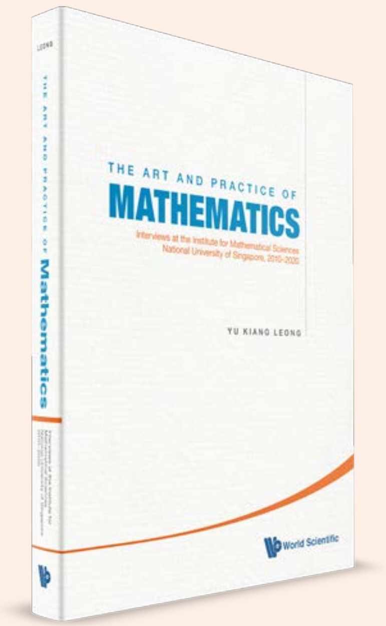

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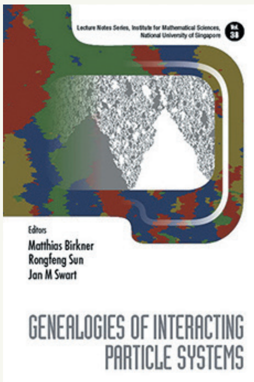

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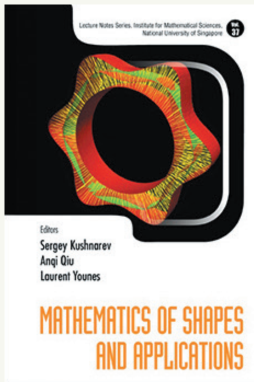

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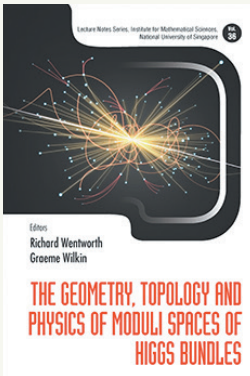

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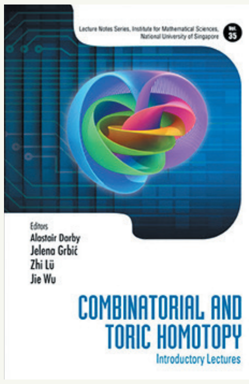

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