IMPRINTS

20 Celebrating years of Mathematical Synergy

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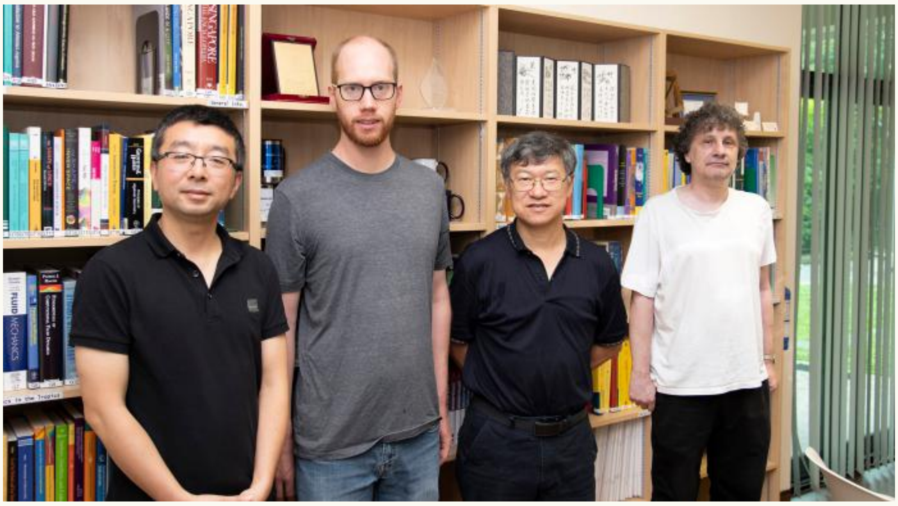
Higher Recursion Theory and Set Theory

From 20 May–14 June 2019, the Institute hosted a program on "Higher Recursion Theory and Set Theory". The program organizers contributed this invited article to Imprints.

BY James Cummings *(Carnegie Mellon University),*
Andrew Marks *(University of California, Los Angeles),*
Yue Yang *(National University of Singapore)* and
Liang Yu *(Nanjing University)*



From left: Liang Yu, Andrew Marks, Yue Yang and James Cummings

"From the paradise, that Cantor created for us, no-one shall be able to expel us."

David Hilbert, from his 1925 lecture "On the infinite".

The famous 1925 quote of David Hilbert, printed above, refers to set theory and the study of cardinality. Almost 100 years later, Cantor's paradise has become even bigger, as more and more "axioms of infinity" have been proposed asserting the existence of various large cardinals. These new axioms of infinity not only enhance our understanding about the set-theoretic universe, but also have more and more applications to other branches of mathematics. These large cardinals can be studied by constructing "inner models" which help us analyse these axioms, and rank them by their mathematical and logical strength. These inner models generalise the constructible universe L introduced by Gödel in

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1938: like L, inner models are closely related to definability and can be studied in great detail using the tools of "fine structure theory" introduced by Jensen.

The focus of this program was twofold. The higher recursion theory part of the program focused on computational aspects of infinity and was more related to fine structure and definability. The set theory part focused on large cardinals, the Axiom of Determinacy (AD), and descriptive inner model theory. Higher recursion theory and the parts of set theory mentioned above have a long history of interaction. In the late 1960s and 1970s, when Sacks and his students began the systematic investigation of alpha recursion theory, they applied many ideas from fine structure theory to study computability on initial segments of L: going in the other direction, Jensen's fine structure theory in some sense can be viewed as recursion theory on L. As another example, the study of the structure of L(R) under AD uses ideas from higher recursion theory, and ideas from this study have influenced the development of descriptive set theory.

The first week (20–24 May 2019) was on Higher Recursion Theory. Antonio Montalban (University of California, Berkeley) gave four sixty minute tutorials on hyperarithmetic theory, with applications to higher recursive model theory. The next two weeks (27 May–7 June 2019) were on Recursion Theory, Set Theory and their interactions. The last week was on Set Theory (10–14 June 2019). Paul Larson (Miami University) gave four ninety minute tutorials on AD+, synthesising a large body of mostly unpublished work by Woodin and others.

Another theme of the workshop was to celebrate the research work of Professors Theodore A. Slaman and W. Hugh Woodin. Beyond being the leading logicians in the area of recursion theory and set theory, they have been dedicated tremendous time and energy to the development of logic in Singapore and in Asia more generally. Since 1997, Professors Slaman and Woodin have come to Singapore every year to supervise graduate students, collaborate with staff members at National University of Singapore, and organize workshops and conferences. Every year since 2006 they have organized the IMS summer school in logic , and during most of these years they have been the main speakers. After more than ten years, this summer school has made a big impact on the younger generations of international logicians. During the workshop, Professors Slaman and Woodin each gave two talks in the IMS Distinguished Visitor Lecture Series. Slaman reported on his joint work with Jan Reimann. Their results built some very interesting connections between higher randomness theory, number theory and set theory. The first lecture by Woodin was on a new basis theorem for Σ^1_3 sets, proved using tools from fine structure theory. In the second lecture he reported on a striking consequence of the V=Ultimate-L axiom, namely that it proves the Ω-conjecture.

There were a number of excellent talks, some of which announced solutions to some long standing open problems in the areas of focus for the program. Benoît Monin (LACL, Créteil University) reported his joint result with Ludovic Patey, separating $SRT^2_2 RT^2_2$ in an ω-model. This solves a major question in the area. Adam Day (Victoria University of Wellington) reported on his joint work with Andrew Marks (University of California, Los Angeles), giving a complete solution to the Decomposability Conjecture under the assumption of Projective Determinacy. Richard Shore (Cornell University) spoke on joint work with Leo Harrington and Ted Slaman, showing that a class which is Σ^1_1 in every Σ^1_1 class is Σ^1_1. This implies many known basis and omitting types theorems. Slawek Solecki (Cornell University) spoke on a promising new approach towards proving the E_1 dichotomy in descriptive set theory, using a new class of Polishable equivalence relations and ideas originating with Hjorth about generalized Scott analyses. John Steel (University of California, Berkeley) reported on substantial progress in descriptive inner model theory, continuing the program of analysing HOD in models of AD+. Ralf Schindler (Universität Münster) reported on a breakthrough result, MM++ implies (*), which connects the two main lines in the search for strong axioms to control $P(\omega_1)$. This solves a long standing problem posed by Hugh Woodin.

During the four weeks there was a high level of communication and strong collaborative activity among the program participants; especially between recursion theorists and set theorists, junior and senior researchers, local researchers and visitors and more generally between logicians based in Asia and other parts of the world.

Finally, Professor Menachem Magidor (The Hebrew University of Jerusalem, Israel) delivered an inspiring Public Lecture entitled *"Can Every Mathematical Problem Be Solved?"* on 13 June 2019. At the end of his lecture Professor Magidor repeated the paradise quote of Hilbert, and he continued: "But in this paradise we face `the ugly monster of independence' (Erdös). The only way to ignore it is a fall from paradise, so we cannot ignore it. It is with us to stay and it is relevant to our mathematical practice… We must tame the monster! We shall tame it!"

In Appreciation

The Institute would like to thank outgoing member, Professor Alice Chang, who joined the SAB in 2017. Her advice and suggestions have added great depth to the programs and activities of the institute.

IMS Distinguished Visitors

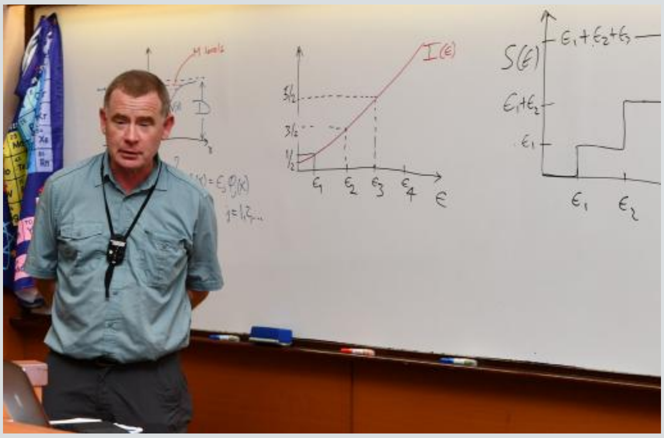
IMS arranges visits to the Institute by distinguished scientists who are prominent leaders in their communities. The program started in 2015. This initiative aims to enhance the diversity of people participating in our research programs, and provide mentoring/ inspire junior researchers and graduate students. Each distinguished visitor spends at least two weeks in Singapore, and participate in a variety of activities, including lecturing about their own research, give public talks, meet with faculty, and interact with program participants.

Under this program, the Institute has enjoyed visits from a stellar array of distinguished scientists. The list of distinguished visitors may be found on our website.

MEL LEVY

Mel Levy is Emeritus Professor at Tulane University. He obtained his PhD at Indiana University and postdoctoral education at Johns Hopkins University. He is one of the founders of the Density Functional Theory (DFT), and his works include the constrained-search formalism, the identification of the derivative discontinuity, the development of DFT perturbation theory, the discovery of many exact conditions on density functionals for the purposes of their approximations, especially those involving coordinate scaling, variational principles for excited states, and many more. He is a member of the International Academy of Quantum Molecular Science and Fellow of the American Physical Society.

***Professor Levy** visited IMS for the program on Density Functionals for Many-Particle Systems: Mathematical Theory and Physical Applications of Effective Equations (2–27 September 2019). He gave two talks on 5 and 10 September 2019.*



KIERON BURKE

Kieron Burke is a Chancellor's Professor of UC Irvine, and he is fellow/member of several scientific societies in both chemistry and physics, in the US and elsewhere. He works on developing all aspects of Density Functional Theory (DFT): formalism, extensions to new areas, new approximations, and simplifications. His work is heavily used in materials science, chemistry, matter under extreme conditions (such as planetary interiors or fusion reactors), magnetic materials, molecular electronics, and other areas. According to Google Scholar, his research papers are now cited more than 15,000 times each year.

***Professor Burke** visited IMS for the program on Density Functionals for Many-Particle Systems: Mathematical Theory and Physical Applications of Effective Equations (2–27 September 2019). He gave two talks on 10 and 13 September 2019.*

Research in Industrial Projects for Students (RIPS) 2019 – Singapore

17 JUNE–9 AUGUST 2019

The Research in Industrial Projects for Students Program in Singapore (RIPS-SG) was run by IMS in collaboration with Institute for Pure and Applied Mathematics at the University of California, Los Angeles.

Sixteen undergraduate students were selected for the program; four from the United States, nine local and three from Vietnam. The students were assigned into four groups, and worked on real-world research projects proposed by sponsors (Google, Grab, Nvidia and Saw Swee Hock School of Public Health). Projects involved mathematics, statistics, data, and computing.

Students take turns to present their work

RIPS 2019 – Singapore

Best shirt affair

Symposium in Memory of Charles Stein [1920 - 2016]

17–28 JUNE 2019

CO-CHAIRS:
Louis Chen | National University of Singapore
Wei-Liem Loh | National University of Singapore

Charles M. Stein (22 March 1920–24 November 2016) was one of the most original statisticians and probabilists of the 20th century. The objective of the symposium was to bring together leading international experts in statistics and probability to pay tribute to Charles Stein, a man whose work has profound and wide-ranging influence on both statistics and probability.

The symposium hosted 34 talks spread over eight days. The topics of the talks included historical perspectives on Charles Stein, his influence on various areas in statistics, in particular shrinkage estimation, and probability theory, in particular Stein's method.

There is a long history of meetings at IMS related to his work, in particular to what is now called Stein's method. What started with a successful and very influential five-week program in 2003, was followed by smaller, but equally important workshops at IMS in 2009, 2010 and

Wei-Liem Loh: Covariance matrix estimation and some memories of Stein

Louis Chen: Stein's concentration inequality for proving the Berry-Esseen theorem

Sums of neighbourhood statistics
(From left: Larry Goldstein, Adrian Röllin and David Siegmund)

2015, and these meetings had a high, measurable impact on the field. While a part of this year's symposium was similar in spirit to these previous meetings, widening the range of topics by including Stein's contributions to statistics and bringing together researchers from otherwise rather separate communities has undoubtedly expanded each community's horizon and will foster new interaction between the fields.

The core participants came from statistics and probability theory, but also from computer science, in particular machine learning. This reflects the broad influence of Charles Stein's work. There were close to 70 participants.

Remembering Charles Stein

IMS Graduate Summer School in Logic

1–19 JULY 2019

Jointly organized with Department of Mathematics, NUS

Theodore A. Slaman (University of California, Berkeley), Angus MacIntyre (Queen Mary University of London) and W. Hugh Woodin (Harvard University) gave 12.5 hours of lectures each, covering topics on "Real numbers and measures for which they are random", "Model theory of fields and local rings" and "Ultimate L". Apart from the lectures, seven participants gave talks during the summer school. The three tutorial speakers also conducted a panel discussion on 10 July 2019. There were more than fifty participants.

Panel discussion

Valued fields and local fields

Statistical Data Integration

5–16 AUG 2019

CO-CHAIRS
Sanjay Chaudhuri |
National University of Singapore

Reliable information about a target population in the form of a representative data-set is indispensable for any statistical analysis. Easy collection and storage of big data-sets, obtained from web based applications, social networks or medical records provide interesting opportunities. Use of big data sources with or without integration with carefully designed survey data would often be beneficial in computing official statistics.

The workshop and the conference generated a lot of discussion on the methods of statistical data integration in many different areas of application. Lectures covered on the applications of such techniques in survey sampling, record linkage and entity resolution which involves computer science, small area estimation, statistical genetics, omics data, econometrics, health statistics, and official statistics.

Integration of multiple sources of data

Big data, opportunities and strategies

The first week was planned with a workshop which had ten talks. A conference on Current Trends in Survey Statistics, which was a satellite conference to the 62nd ISI World Statistics Congress, then continued from from 13 to 16 August 2019. There were 17 invited talks and three contributed sessions.

There was a lot of scientific discussion on data integration in many kinds of data. There were presentations from theoretical statisticians and experts in survey sampling, official statistics, econometric, statistical genetics, Bayesian statisticians, experts in record linkage etc. The activities have also involved researchers in the field of computer science, civil engineering, health statistics and epidemiology, and econometrics. There were more than 100 participants in this two-week event.

Density Functionals for Many-Particle Systems: Mathematical Theory and Physical Applications of Effective Equations

2–27 SEPTEMBER 2019

PROGRAMME COORDINATOR
Berthold-Georg Englert |
National University of Singapore

SECRETARY
Martin-Isbjörn Trappe |
National University of Singapore

CO-CHAIRS
Yuan Ping Feng |
National University of Singapore
Heinz Siedentop |
Ludwig-Maximilians-University of Munich

This program brought together experts on density functionals and effective descriptions of many-particle systems from theoretical physics, theoretical chemistry, mathematical physics, computational materials science, and mathematics.

Tutorial lectures were given by Heinz Siedentop (Ludwig-Maximilians-University of Munich, Germany), Chuck Witt (Princeton University, USA), Sergei Manzhos (Institut National de la Recherche Scientifique, Canada), Peter Pickl (Ludwig-Maximilians-University of Munich, Germany), George Batrouni (NUS), John Dobson (Griffith University, Australia) and Matthieu Lewin (Université Paris Dauphine, France). The lectures of this program were an integral part of the NUS module 'QT5201R: Density Functional for Many-Particle Systems' aimed at graduate students from Centre for Quantum Technologies, physics, mathematics, and chemistry. This program, with support from the Julian Schwinger Foundation, also enabled a considerable number of young scientists at the PhD and postdoctoral level to engage actively in discussions with some of the most distinguished scientific figures in the field.

The need of reconciling the density functional approximations used in practice with systematic derivations based on exactly known relations and constraints emerged as a distinct focus of the program. The workshops contributed to bridging the rigorous mathematical treatment of simple approaches like the Thomas-Fermi approximation and the sophisticated functionals used by practitioners in physics, chemistry, and materials science. Less known alternative many-body methods like density-potential functional theory (DPFT) and collocation with machine learning were introduced to a wider scientific audience,

Quantum many-body systems

Observables of the underlying microsystem providing the community with an enriched set of tools to tackle questions of fundamental and technological relevance. The conceptual relation of DPFT and effective-potential functional theory may yield both fundamental insights and useful computational developments for the wider scientific community.

The programme structure with plenty of time for discussions and dedicated plenary discussion sessions enabled lively exchange of ideas on how to address fundamental questions of density functional theory (DFT). There were 56 talks over the four weeks, and there were more than 80 participants.


Advantageous in full potential calculations


Machine learning optimization


Approximation schemes and their range of validity


Focused on a dynamical description

Ng Kong Beng Public Lecture Series

17 SEPTEMBER 2019

The Importance of Quantum Mechanics to Saving Our Planet

Prof. Burke started his lecture by emphasizing how much our knowledge about climate change has changed over the past 10 years. Parts of the chemistry involved in modelling climate change is still poorly understood, such as the effects of aerosols and clouds on future change of temperature. Simulating chemical systems is therefore of paramount importance, not just in climate research, but in virtually all areas of science. While the laws determining the behaviour of any chemical system is theoretically well-understood by means of quantum mechanics, solving the corresponding equations (the famous Schrödinger equation) for a concrete system is typically very hard, even if, in the context of chemistry, the equations only have to be solved for the electrons involved — roughly speaking, when the number of electrons doubles, the computing costs increase by a factor of 128.

In the 1960s, however, it was proved (the Hohenberg–Kohn theorem) that it is enough to understand the overall electron densities — a much simpler object — in order to understand important functionals, such as the ground state, of the system. Moreover, it was shown that these electron densities were solutions to a fictitious system of non-interacting electrons in an external force field. This method, called Density Functional Theory, was improved over the subsequent decades and is now routinely used even by practical chemists.

Density Functional Theory (DFT) has a wide range of applications, as Prof. Burke continued his talk, in particular new catalyst development, materials design, superconductor development, microchips design etc. According to NVIDIA, a sixth of the world's supercomputing power is spent on DFT calculations alone. So making advancements in the approximations involved in the method can have a huge impact, which is the reason of the continued effort of the research community to improve DFT calculations. In the face of threats like global warming, Prof. Burke says, maybe we not only can, but must try.


Kieron Burke

Prof. Burke of University of California, Irvine, USA delivered the public lecture at NUS on 17 September 2019, which had over 100 attendees.

Adrian Röllin

INTERVIEW

GANG TIAN: FROM KÄHLER GEOMETRY TO QUANTUM COHOMOLOGY

Interview of Gang Tian by Yu Kiang Leong

Gang Tian is well-known for his fundamental contributions to geometric analysis, complex geometry and symplectic geometry.

Born and bred during the tumultuous period of the Great Leap Forward and the Cultural Revolution in China, Gang Tian received his BS from Nanking University and MS from Peking University shortly after China opened up in the early 1980s. He was among the second batch of Chinese students to be selected to go to the United States for graduate studies. He studied for his PhD under the direction of Shing-Tung Yau, first at University of California at San Diego and later at Harvard University.

After a short stint at Princeton University and Stony Brook University, he rapidly rose to the rank of professor at New York University and was the Simons Professor at Massachusetts Institute of Technology. Subsequently he moved to Princeton University where he was a Higgins Professor of Mathematics until 2017 when he returned to China and became a Vice-President of Peking University and an emeritus professor of Princeton University. Before this move, he was already appointed as Distinguished Professor by Peking University and he briefly served as the Dean of the School of Mathematical Sciences. As early as 2005, he also served as the Director of the newly established Beijing International Center for Mathematical Research (BICMR). He has been Visiting Professor at the Institute for Advanced Study at Princeton, Institute des Hautes Études Scientifique and Stanford University.

Tian has actively served on the committees and scientific panels of various international bodies such as the Pacific Institute for Mathematical Sciences, Banff International Station for Mathematics, Pure and Applied Mathematics Institute, International Mathematical Union and Simons Centre for Geometry and Physics, and on the committees of the Centennial Fellowship, Veblen Prize, Steele Prize and Abel Prize. He has also served on the advisory board of the Tianyuan Fund of the National Science Foundation in China and is currently on the advisory board for Special Professorships (Ministry of Education, China) and the scientific council of the Abdus Salam International Center of Theoretical Physics in Trieste.

In addition to being twice invited to give invited and plenary lectures at the International Congress of Mathematicians, Tian has given numerous specialized and public lectures around the world, notably the following: Bergman Memorial Lecture, Courant Lecture, Nachdiplomvorlesung Lectures, Andrejewski Lectures, Ellenberg Lecture, Unni Namboodiri Lectures, Marsten Morse Lecture, Gergen Lecture, University Lecture (University of Wisconsin-Madison), Distinguished Lecture (Instituto de Matemática Pura e Aplicada IMPA), Rainish Lecture, Leonardo de Vinci Lecture, Journée de Rham of Swiss Mathematical Society, Felix Klein Lecture, Joseph D'Atri Memorial Lectures, Aisenstadt Chair Lecture, Takagi Lectures, Landau Lectures and Marker Lectures.

He was awarded the Alan Waterman Award and the Oswald Veblen Prize of the American Mathematical Society for his research contributions. He was elected to the Chinese Academy of Sciences and the American Academy of Arts and Sciences. He was appointed as Special National Expert in the Thousand Talents Program in China.

He has served on the editorial boards of the following journals: *Pacific Journal of Mathematics, Communications in Analysis and Geometry, Pacific Journal of Mathematics, Journal of the American Mathematical Society* and *International Mathematics Research Notices.*

He currently serves on *Acta Mathematica Sinica, Geometry and Topology, Communications in Contemporary Mathematics, Advances in Mathematics, Journal of Geometric Analysis, Annali della Scuola Normale Superiore* and *Annals of Mathematics.*

One of Tian's early contributions to geometric analysis is his work on the existence and obstructions for Kähler-Einstein[1] metrics on compact complex surfaces with positive first Chern[2] class. He found an explicit formula for the Weil-Petersson[3] metric on the moduli space of polarized Calabi-Yau[4] manifolds. He proved the Bogomolov-Tian-Todorov theorem that the moduli space of Calabi-Yau manifolds is smooth. Jointly with Yongbin Ruan, he established a theory of quantum cohomology and Gromov-Witten[5] invariants on semi-positive symplectic manifolds, and that their quantum cohomology ring is associative. He developed a compactness theory for high-dimensional Yang-Mills[6] fields and found a deep connection between high-dimensional gauge fields and calibrated geometry. He introduced the theory of K-stability, which is central in the theory of geometric stability. He and Jian Song initiated an analytical minimal model program (called the AMMP theory) in complex geometry. Tian extended the work of Jeff Cheegar and Tobias Holck Colding in geometric analysis, and independently of Xiuxiong Chen, Song Sun and Simon Donaldson, solved the Yau-Tian-Donaldson conjecture, a central problem in Kähler geometry. He and Jeff Streets discovered new geometric flows that are now central tools in complex geometry.

At the turn of the century, when Grigoryi Perelman[7] first put forward his proof of the Poincaré[8] conjecture via William Thurston's[9] geometrization conjecture on the canonical decomposition of closed 3-dimensional manifolds, Tian and John Morgan gave an exposition of this work. His prolific research output is matched by the number (more than 53) of doctoral students he has supervised in at least 11 institutions in the United States, China and Italy.

Tian was at the National University of Singapore from 16–21 January 2017 under the invitation of the Institute for Mathematical Sciences to deliver two lectures on "K-stability and Kähler metrics" in the Distinguished Visitor Lecture Series on 17, 19 January 2017 as part of the Institute's program "Higher dimensional algebraic geometry, holomorphic dynamics and their interactions" (3–28 January 2017). On behalf of *Imprints*, Y.K. Leong interviewed him on 19 January 2017. The following is an edited version of the transcript of the interview in which he talked about his early years, Beijing International Center for Mathematical Research and his first love that is geometry.

IMPRINTS I **When did you first discover your interest in mathematics? Did your teachers in school and Nanking University have any influence in your choice of career as a mathematician?**

GANG TIAN T I first discovered my interest in mathematics when I was pretty young. Actually, my mother was a mathematician. When I was at a very young age, even at elementary school, she gave me some simple mathematical problems.

I **Was she a lecturer in some university?**

T She was an associate professor in Nanking University. While I was in elementary and middle school, China was at that time in a special period. We didn't need to study as hard as today's students. For example, we didn't have so many homework. This is good in some sense. I had more time for myself. My mother was, during that period, most of the time not at home because of this special period in Chinese history.

I **Was that the Cultural Revolution?**

T Yes, the Cultural Revolution. She gave me some books; for example, one book that I spent quite a

[1] Erich Kähler (1906-2000), Albert Einstein (1879-1955)
[2] Shiing-Shern Chern (1911-2004)
[3] André Weil (1906-1998)
[4] Eugenio Calabi, Shing-Tung Yau (Fields Medalist 1982)
[5] Mikhail Leonidovich Gromov (Abel Prize 2009), William Witten (Fields Medalist 1990)
[6] Chen-Ning Yang, Robert Laurence Mills (1927-1999)
[7] Grigoryi Perelman (Fields Medalist 2006)
[8] Henri Poincaré (1854-1912)
[9] William Thurston (1946-2012), Fields Medalist 1982

bit of time on was the book called *The Elements*[10] (on Euclidean geometry). I didn't completely understand what was going on in there, especially the plane geometry problems, but I found that I was quite good and interested in those problems. They gave me a training in logic. That is why when I came to university, somehow I knew in my mind that I wanted to do mathematics. By the time I was in college, I had fixed in my mind that mathematics is to be my career. Of course, I took many classes and my teachers gave me a lot of help. In Nanking University, I learned quite a bit of things and I decided I wanted to do pure mathematics. I had a solid training for my mathematical background.

I **Did your mother have a great influence on you?**

T My mother certainly had a great influence on me from the very beginning. Her influence was not like "you have to finish this homework or that homework" or something like that. Her specialty aroused my interest in mathematics.

I **Can you tell us the name of your mother?**

T Her name is Wang, Ming-Shu. Actually my mother did very good work on Hilbert's 16th Problem. The second part of the problem is about limit cycles. There was a famous Russian mathematician called Petrovskii[11] who claimed in the '50s that he had a proof that for quadratic fields there are at most 3 limit cycles. My mother was one of two groups who found a counterexample[12] to that. She constructed 4 limit cycles. Doing mathematics was not easy for her; a Chinese woman had to take care of the family and also, during that period, she had to travel to other places in China to work.

I **Was the topic of your masters thesis in differential geometry?**

T No, it's related to but not in differential geometry. My masters thesis was in variational methods.

I studied for my masters degree in Peking University. My advisor was K.C. Chang [Chang Kung-Ching]. He organised a lot of seminars in PDE [partial differential equations] and analysis, which would benefit me in my later research in differential geometry.

I **Why did you choose Harvard University for your graduate studies?**

T I didn't actually choose Harvard. I was a masters student at Peking University. I guess I did pretty well and the department wanted to send some students abroad. At the beginning they chose 4 people – two in pure mathematics, two in applied. I was chosen to do geometry and study with Professor [Shing-Tung] Yau. I also applied to other places but my first choice was Professor Yau. At that time he was at University of California at San Diego. I got an offer from UC San Diego and so I declined other places and went to San Diego. Three years later, Yau decided to move to Harvard. So I went with him to Harvard and was there for one year for my degree. Actually, I passed the qualifying exam at San Diego; I wrote a few papers there by 1987, three years after I came to San Diego. I think I could have finished the time there. I already had some results but Professor Yau said it was better to be a student because you would have more time to do research. So then I took his advice and spent one year at Harvard.

I **Your degree was actually from Harvard?**

T Yes, but there was a requirement in Harvard that you need to do something new there. I did prove some new results during my time in Harvard.

I **What about residential requirements?**

T Because it was a special situation, I guess that the residency requirement did not apply to me. Some other students who went with Professor Yau stayed longer, maybe 2 years, but I stayed only for one year.

I **In addition to being professor at Princeton University, you are also the director of the Beijing International Center for Mathematical Research (BICMR). Please tell us something about BICMR – its objectives and setup, and its relation to Peking University.**

T BICMR is a mathematical institute sponsored by the State. It started in 2005. The government provided some money for building the centre. It has a special building. (I can send you some pictures if you want.) It is in the north-west of the campus of Peking University, on the north bank of a lake. This used to be part of Yuan Ming palace and has historical sites. So we cannot build high buildings because of strict regulations to protect historical sites. Of course, I don't want to build high buildings for this centre myself. The mathematical institute is built in the style of classical Chinese architecture – 9 courtyards in the old style and in the right alignment. The buildings are single-storey except one building of two-storey which has a big lecture hall and is situated outside the historical site (of

[10] *Elements* by Euclid (circa 300 BC)

[11] Ivan Georgievich Petrovskii (1901–1973)

[12] Lan Sun Chen and Ming-Shu Wang, The relative position and number of limit cycles of a quadratic differential system, Acta Math. Sinica, vol. 22, pp. 751–758, 1979.

the Yuan Ming Yuan). Eight of the buildings are within the area of Yuan Ming Yuan. For instance, one building I am staying in used to be the palace of the empress of Emperor Jiaqing[13] and the places stayed by the faculty used to be the study of some prince. It is in right alignment and in that sense, it is unique. We do modern mathematics in these ancient classical buildings.

Our aim is to promote mathematical research and education in a first class mathematical institute in the world and to build a platform for scientific exchange among Chinese mathematicians and with mathematicians from abroad. We attract many visitors from overseas each year but we don't want it to be like a conference place. We want it to be more like the Institute for Advanced Study (IAS) in Princeton. We have a small number of faculty and more temporary positions like postdocs. On the other hand, we are also different from IAS because we are within Peking University. Although we get funding from the state, we also get support from elsewhere, elsewhere, especially Peking University, for the centre. We need to have graduate students, we admit about 10 graduate students per year. Right now we are doing quite well. We have hired quite a number of bright people, particularly young people, and built up a very strong faculty.

Within Peking University there is also a School of Mathematical Sciences. We are in a way independent. We have our own students and our own faculty line and staff. Since we are in the same university I fully understand that we cannot be fully independent. So the faculty at the centre also do teaching. If we don't do any teaching, I think it will be a big waste. Peking University has very good students and graduate students. In the first few years, we can offer a reduction in teaching. The new faculty may only do half the teaching load but in the long run they do the normal teaching load of a research professor in Peking University, which is only one course per semester. It's not that much. We have joint teaching and research. Professors from each side can choose students from the other side and also students from one can choose professors from the other. It very much depends on your interest. Students can choose their interests. We encourage students from each side to communicate and have joined activities in mathematics. In total, Peking University, admits about 60 students in mathematics: 50 in mathematical sciences and 10 from the centre. I think it is important to cooperate but we also have our own specialties.

It's very important to have a centre because it provides a new platform for reforms and establishing new systems in order to advance further mathematical research level at Peking University as well as in China. It lures new mathematical talents to Peking University

“OUR AIM IS TO PROMOTE MATHEMATICAL RESEARCH AND EDUCATION IN A FIRST CLASS MATHEMATICAL INSTITUTE IN THE WORLD AND TO BUILD A PLATFORM FOR SCIENTIFIC EXCHANGE AMONG CHINESE MATHEMATICIANS AND WITH MATHEMATICIANS FROM ABROAD.”

and also motivates people to change as needed. The mathematical sciences have a longer history of development in Peking University and have made great achievements. However, at the present time, the State and Peking University expect more and are raising standards. We want to build a first class university in the world, in particular, work hard towards becoming a top mathematical school. It became clear that the School of Mathematical Sciences could not do it alone in the way we used to do. It has its own burdens and needs reforms. For example, its faculty size is big, so it has difficulties to attract new young people of international standards. In the centre, we have fewer people so that we can be more flexible and competitive in attracting younger people. More importantly, any new success at the centre also motivates the school to improve itself, such as hiring at higher standards. Another factor is that most people in the centre are young and came back from abroad. They probably have a similar background and feel more comfortable to be in this place. They need some time to adjust to a local environment. Also we have a very good supporting staff. I think that the centre makes it easier for their new life both in mathematics and other matters. As I said, we can only have a certain number of faculty in the centre; not everyone can stay in the centre forever. We have a very close collaboration with the School. Right now, Peking University made extraordinary efforts to promote our collaboration.

In the past few years, I am the director of the centre and also the dean of the School of Mathematical Sciences. The university does not expect me to function as dean in the normal way and so there is a standing vice-dean to take care of the day-to-day affairs. Technically we are on the same track and as dean I also try hard to introduce new methods and attract the good people to the School. It's a tough job. Since I was a student from Peking University's mathematical sciences, I know many teachers there and get some help from them; so it makes things a bit easier. In general, Peking University is more open-minded. One and a half years ago we had an anniversary celebration for the centre. We had a meeting and many people from within China came and they were impressed.

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[13] Emperor Jiaqing (1760–1820), Qing dynasty

I **China has recently embarked on projects in physics, astronomy and computer technology on a gigantic scale – the largest particle accelerator, the largest radio telescope and the fastest computer. Has mathematics in China caught up with projects on a similar scale or of a similar nature?**

T No, certainly not on that scale. As mathematicians, we don't need that much money. We don't need big equipment. Our financial requirements are much smaller. It's not on the same scale. On the other hand, I feel that we have very good support, especially for bright young people who can get good funding from State. The most important thing for young mathematicians is to have a healthy environment, so that they can concentrate on their research and teaching. To do a first-class research work, money is not the only thing. I think it also applies to all the other sciences. Now that China is richer, the experimental scientists can buy very expensive equipment and have an advantage over people in other countries. But I think it is very important to have young people acting as scientists to think deeply and profoundly. Equipment is not the only thing; good mathematicians and scientists are equally important. China has some of these programs to attract people back, especially young people. To mathematics that is a very good thing.

I **It's the software rather than the hardware.**

T That's right, in mathematics the software (thinking) is more important than the equipment.

I **Methods of algebraic geometry and differential geometry are now part and parcel of the mathematical toolkit for various problems in mathematics and theoretical physics. What are some of the intuitive links between algebraic geometry and differential geometry?**

T Algebraic geometry and differential geometry are closely related. For example, a large class of complex objects like manifolds are also studied by algebraic geometric methods. They have many research problems which overlap and share a large part of common interest. But they approach problems from different angles and use different methods. For me, part of my interest is analytical methods for studying complex algebraic manifolds. Those problems are crucial in algebraic geometry but the algebraic geometers would have studied them differently and the theorems we prove are equally interesting. In the interaction between mathematical physics and enumerative algebraic geometry, differential geometry provides a more analytical approach.

I **In your PhD thesis you solved a hard and important problem. Would you advise a beginning graduate student to try and solve a long standing unsolved problem at the outset?**

G I certainly encourage a graduate student to study a hard problem, an outstanding problem. Of course, sometimes you need some luck to solve the problem. However, for some of these problems you don't really need to solve it before you can get your PhD. For a good student I would encourage him to make a long-range go on a problem of fundamental importance. He may not be able to solve it for a while but it is possible to make some progress which is good enough for his or her thesis.

I **Which piece of your research has given you the greatest sense of achievement?**

T Actually I am doing research on several topics. One of them I feel very proud of (I think I have a very big influence on that) is Kähler goemetry, especially in solving Einstein's equations in the Kähler case. I made some progress on it in my thesis and later research. For this I introduced the notion of K-stability and eventually proved the equivalence between K-stability and solving Einstein's equation in the Kähler case. I'm talking about it in the program here and on certain techniques which can lead to the solution of these things. Some of my papers on these things are widely cited and have good impact; so I'm certainly happy about it.

I **String theory was originally conceived to provide a Theory of Everything for physics. Although its physical reality is not accepted by mainstream physics, it has developed into a sophisticated theory which has attracted not only theoretical physicists but also mathematicians. What is its relevance to mathematics in general and to differential geometry in particular?**

T I think that during these two decades string theory had a deep impact on mathematics especially algebraic geometry and symplectic topology. It has predicted a lot of things and suggested new problems to mathematicians and some of these predictions were not thought of before by math-ematicians. For example, one of my work had a very original contribution in the construction of a mathematical theory of GromovWitten invariants and quantum cohomology. Quantum cohomology was predicted by physicists and relate to very classical things in mathematics. For example, it was studied long ago in enumerative geometry to count the number of solutions of polynomial equations – it has a long history, but somehow mathematicians didn't know there is a deeper universal structure behind it. Quantum cohomology gives one of these structures behind that, for example, the number of solutions of polynomial equations of different degrees are not isolated from each other. Also mirror symmetry predicts some numbers for counting rational curves over Calabi-Yau manifolds.


BICMR auditorium (Courtesy BICMR)

I **The physicists couldn't prove them?**

T The mathematicians could not prove them either but they could check them in many cases. The good thing is that if you assume the hypothesis is true then there are a lot of predictions which are very mysterious to mathematicians. I think the study of string theory by physicists played a crucial role in certain fields of mathematics. In turn, mathematics helps to advance the understanding by physicists of new theories.

I **In addition to your permanent position at Princeton University, you also serve as director and advisor in many organisations outside the United States. To what extent does this affect your research work?**

T It certainly takes up a lot of my time. Not only that; when you are in a certain senior position, you need to write a lot of reference letters and reports. That reduces your time to do research. But you feel that it is your responsibility to do some of these things as a kind of service to the community. Sometimes you have to organize, you cannot spend all your time on these things, you need to keep some time for your own research. Also when you are more senior, you are more experienced and that can help to get things done.

I **In your contacts with students in China and the United States, do you see any differences between their attitudes towards learning and research?**

T Indeed, I have many students in China and US. One difference I see is that students in United States tend to be more confident. They are more simple-minded. I think that is good for research. This is true on the average; not every but many Chinese students are less confident. I don't know why, but the first thing I do is to train a student to be more confident. I tell them, don't think complicated, focus on your research and studies and don't worry too much on non-examinable things.

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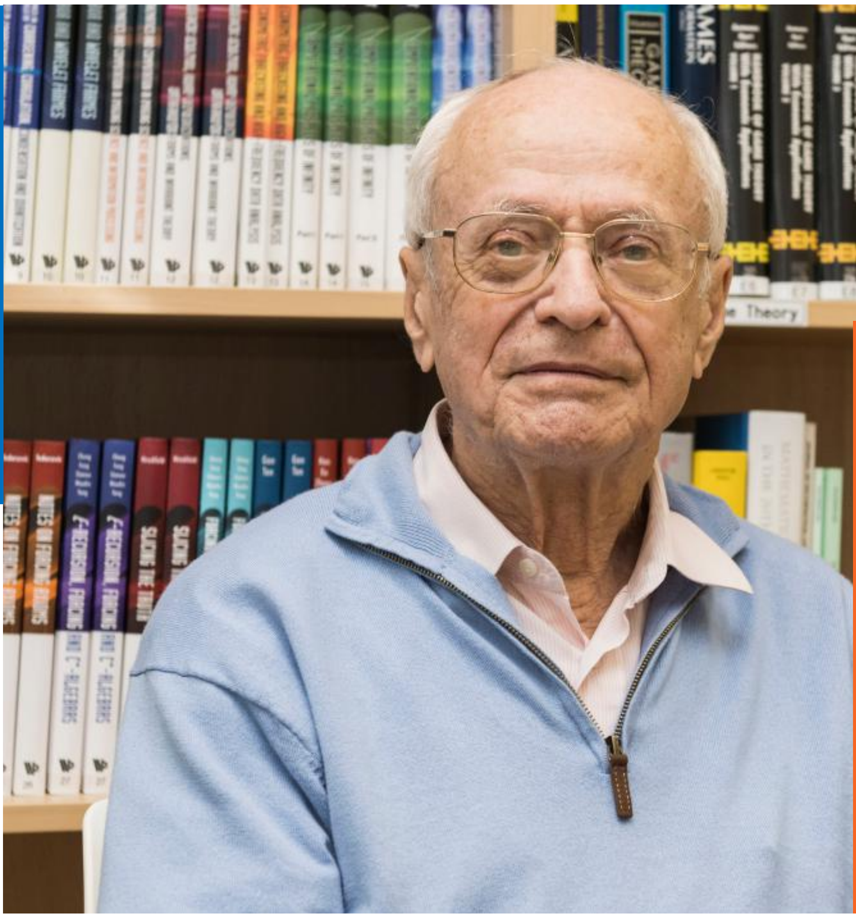

JEAN-PIERRE SERRE

Interview of Jean-Pierre Serre by Chi Tat Chong and Yu Kiang Leong

Acknowledgements

We wish to thank Wee Teck Gan and Chee Whye Chin for their participation in the interview and for their comments on the draft.

Jean-Pierre Serre has made fundamental and ground-breaking discoveries in algebraic topology, number theory and algebraic geometry.

Serre was educated at the *École Normale Supérieure* in Paris and the Sorbonne, from which he obtained his PhD in 1951 under the supervision of Henri Cartan (1904-2008). His thesis (1951) made a breakthrough in algebraic topology with his use of fiber spaces and loop spaces for the computation of homotopy groups of spheres. For this breakthrough and his pioneering use of sheaves in the theory of complex variables, he was awarded the Fields Medal in 1954, becoming the youngest recipient of the Fields Medal at the age of 27 (a record that has not been broken thus far).

Serre's two papers in the following years *Faisceaux Algébriques Cohérents* (FAC) (1955)[1] and *Géométrie Algébrique et Géométrie Analytique* (GAGA) (1956)[2] further opened up a new pathway into the then *terra incognita* of algebraic geometry partially revealed by the landmark conjectures of André Weil[3] in 1949. This subsequently led to the creation of étale cohomology in 1960 by the two-years younger Alexandre Grothendieck[4] that eventually led to the solution of the hardest of the three Weil conjectures by Pierre Deligne in 1974.

In addition to several French scientific prizes such as the *Prix Peccot-Vimont, Prix Francoeur, Prix Gaston Julia, Médaille Émile Picard,* and *CNRS Gold Medal* (1987), Serre has also been awarded the Prix Balzan (1986), the Steele Prize (1995), the Wolf Prize (2000) and the inaugural Abel Prize (2003). He has received honorary degrees from institutions and was elected to memberships in the national academies of many countries such as Canada, China, France, Greece, Hungary, Norway, Russia, Spain, Sweden, United Kingdom and United States.

Serre's career spans seven decades. He was elected as professor in Collège de France at the age of 30 and retired as professor emeritus in 1998, and continues to be active in research at the present age of 93. His total devotion to his craft and willingness to share his

[1] Jean-Pierre Serre, Faisceaux Algébriques Cohérents, *Annals of Mathematics,* **61 (1955), 197–278.**
[2] Jean-Pierre Serre, Géométrie Algébrique et Géométrie Analytique, Annales de l'institut Fourier, **6 (1956), 1–42.**
[3] André Weil (1906–1998)
[4] Alexandre Grothendieck (1928-2014), Fields Medalist 1966
[5] C.T. Chong and Y.K Leong, An interview with Jean-Pierre Serre, Mathematical Medley **13**(1) (1985), 11-19
[6] Mathematical Intelligencer **8** (4) (1986), 8-13

passion and knowledge are legendary. His lectures and books are well-known for their clarity of exposition. He is equally well-known for his skills in table tennis, skiing and rock climbing. His favourite hobbies are reading, chess and movies.

NUS (National University of Singapore) has maintained a long association with Serre, beginning in 1985 when he first visited NUS under the French Academic Exchange Program. It was during that visit that he was interviewed (published in *Mathematical Medley*, Singapore Mathematical Society[5], and reprinted in the *Mathematical Intelligencer*[6].) Thirty three years later, Serre was back in NUS on his fifth visit—this time to deliver the 2018 Oppenheim Lecture (22 June 2018) and as invited speaker for the Pan Asia Number Theory Conference (25–29 June 2018), organized by NUS's Institute for Mathematical Sciences (IMS) and Department of Mathematics, where he delivered two lectures *The number of points modulo p as p goes to infinity* and *Logarithmic capacity and equidistribution of algebraic integers* respectively).

During this visit, IMS arranged for Serre to be interviewed by Chi Tat Chong, Wee Teck Gan, Chee Whye Chin and Yu Kiang Leong on 28 June 2018. The interview turned out to be a long session in which Serre reminisced about his early years and, true to form, talked with gusto about the mathematics that lies closest to his heart. Follow-ups took place through email between Serre and Chong and Leong. The following is an attempt to convey, if only inadequately, some of the excitement of an era of modern mathematics through the experiences of one of its greatest exponents and protagonists.

IMPRINTS I **It was more than 30 years ago, in 1985, that you had so kindly given an interview in Singapore. We are very pleased to have the opportunity to talk to you again today, to cover topics that were not in our last interview. First of all, could you tell us something about your early years as a student in École Normale Supérieure (ENS)?**

JEAN-PIERRE SERRE S There were three years (1945-1948). The first year was about passing exams at the Sorbonne (including exams in physics, and mechanics). I managed them well enough (too well, since I was first on several of these exams, including the physics one, which was completely undeserved).

The second year was the best: I was free to learn what I wanted, and also to enjoy sports. That was when I began reading more advanced books, such as van der Waerden[7] (in German), Chevalley[8] (on Lie groups—in English) and Banach (in French, even though Banach[9] used to publish in German); all three were splendid books.

The third year was half good and half bad. The bad part was the preparation—all year long—of a competition called *Agrégation*. A very scholarly exam—and very tiring (4 problems, 7 hours each). You were supposed to know about conics and cosmography, but not about groups, fields, matrices or linear algebra. A nightmare. At the oral exam, I was asked to give a one-hour lecture on prime numbers; an interesting subject, except that I managed to give a stupid definition of them (which one ? I do not remember—maybe it was that an integer is prime if it is not divisible by itself nor by 1?). Fortunately, the rest of the lecture was good enough, so that I did pass. Enough for the bad part. The good part was that Henri Cartan gave us some lectures, and also organized a seminar around harmonic analysis on abelian locally compact groups, and such. It was miraculous! A complete change from the stale mathematics I had learned at the Sorbonne.

I **How did you choose to do your doctoral thesis under the supervision of Henri Cartan?**

S As I just said, he had been my professor at ENS, and he had made a strong impression on me. Besides, it was clear that he was the most active of the Paris mathematicians at the time (1948), except for Leray[10] who was doing deep things but was very hard to understand. It is only later that other good active mathematicians came, such as Lichnerowicz[11], Schwartz[12], Godement[13], Choquet[14], Chevalley.

I **One of your first discoveries was in topology but you later moved to algebraic geometry. Could you elaborate a bit on what led to the move?**

[7] Bartel Leender van der Waerden (1903-1996)
[8] Claude Chevalley (1909-1984)
[9] Stefan Banach (1892-1945)
[10] Jean Leray (1906-1998)
[11] André Lichnerowicz (1915-1008)
[12] Laurent Schwartz (1915-2002)
[13] Roger Godement (1921-2016)
[14] Gustave Choquet (1915-2006)

S I have already answered this in my 1985 interview: "it was a continuous path, not a discrete change". The path was: topology → sheaves → complex analytic geometry → algebraic geometry. And the next step was: algebraic geometry → number theory.

I How and when did you get into the inner circle of the Bourbaki group?

S In 1948, Bourbaki had a meeting in Paris, not for the seminar, but for the writing of the *Éléments*[15] .

It took place in a small lecture room at École Normale. I happened to pass by, I entered, and I was very interested. I learned that the next meeting would be in Nancy, a few months later. At that date, I was in Auxerre, rather far from Nancy. Without asking for the permission of anybody, I took a train, I boarded in a hotel in Nancy, and I went to the Bourbaki meeting, which was in a lecture room at Nancy University. I listened, but I also made comments. The meeting was about a week long. At the end of it, Bourbaki invited me to the next meeting. I went there, I collaborated, and at the end of that meeting (Spring 1949), Bourbaki took me as a regular member—even though I was then a graduate student, without any publication. My thesis came about two years later.

I Is the Bourbaki project still being continued?

S Yes. In two ways. The most active one is the Bourbaki seminar, which is a big success. The publication of the books has slowed down; the recent ones are: new revised edition of *Algebra, Chap. VIII (Semisimple rings and modules)*, and four elementary chapters on coverings (under the ambitious title *Algebraic Topology*).

I When did you first meet André Weil?

S In 1948, when I was a third year student at ENS. He gave a series of lectures on his recent proof of the analogue of the Riemann conjecture for algebraic curves over finite fields (a result which had been conjectured by E. Artin[16] , and proved in genus 1 by Hasse[17]. That was when I heard for the first time about abelian varieties—and recent algebraic geometry.

I When you heard about Robert Langlands'[18] ideas in the late 1960s, were you convinced or sceptical about them? Did you correspond with Langlands?

S I was immediately convinced, because the "Langlands program" fitted so well with several other things that I knew, such as the theory of motives, and the Taniyama-Weil conjecture[19]. And, yes, I corresponded with Langlands; in fact he has put on the web some of his letters to me (but none of my own letters. An oversight?).

I Although you did not write any paper with Alexandre Grothendieck, both of you had shared many ideas with each other. Could you tell us more about this unique collaboration?

S That would be too long. You should look instead at our published correspondence (bilingual edition by AMS + SMF, 2004)[20] .

I When did you first meet Pierre Deligne? Did you think he would solve the Weil conjectures some years later?

S When did I first meet him? I don't remember but I had heard a lot about him, especially from Jacques Tits. As for the Weil conjectures, I was delighted that he could prove them—and I especially liked the way he did it, with the help of a slightly different part of mathematics, namely analytic number theory.

I Could you tell us something about your collaboration with Armand Borel (1923-2003)?

S That was a long collaboration, which started when I was a beginner, around 1950, and continued until at least the '90s. The most important part of it was between 1950 and 1980; the topics ranged from topology to Lie groups—not much number theory. We had a long and interesting correspondence, which I have carefully kept (there is a copy of it at Geneva University); maybe it will be published a few years from now.

I There was a paper[21] which you wrote with John Tate[22]. How did that take place?

S We had discussed these things together, and I thought it would make a nice expository paper. I started writing it, and Tate contributed a few sections.

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[15] *Éléments de mathématique* [Note that *mathématique* is written deliberately in the singular as the Bourbaki group believes that the contents of their volumes form a unity, in contrast to the normal use of the word.]
[16] Emil Artin (1898-1952)
[17] Helmut Hasse (1898-1979)
[18] Robert Langlands (Abel Prize 2018)
[19] Also called (wrongly in Serre's opinion) the Taniyama-Shimura conjecture, now known as the modularity theorem.
[20] *Grothendieck-Serre Correspondence* (Bilingual Edition) American Mathematical Society, Société Mathématique de France, 2004, 600 pp
[21] Jean-Pierre Serre and John Tate, Good reduction of abelian varieties, Annals of Mathematics, **88 (1968), 492–517**
[22] John Tate (1925–2019)

In his *Collected Papers* (Vol. I, p. 402), he says that the whole paper was written by me; that's not completely right.

I **You have mentioned before that the lectures of Emil Artin were very impressive. How was he as a speaker?**

S Extremely clear. He was a bit of a showman. When you listened to him, you had the impression that it was not possible to improve on his exposition – except by doing it in a completely different way.

I **Did you ever try Fermat's Last Theorem? What was your first reaction when you heard that Andrew Wiles had solved it?**

S I do not try to prove things unless I feel that I have some little idea that others have missed. Hence I never thought about proving Fermat's theorem. As a matter of fact, my interest in it was only when it became clear that it would be a consequence of the Taniyama-Weil conjecture. As for Wiles' proof, it was not made available to me before its publication - just as if it were a *secret d'état*! Then I heard that there was a mistake. What I could read later was the corrected version which appeared in the *Annals*; Joseph Oesterlé and I made a report on it at the Bourbaki seminar.

I **Were the developments in number theory and algebraic geometry after 1970 as exciting as those before 1970?**

S I would say that number theory was even more exciting after 1970 than before, especially because of the Langlands program. As for algebraic geometry, I don't know; it is a topic I do not work on; it is something that I use when needed.

I **There has been some recent progress on the Riemann hypothesis by Ken Ono and his colleagues[23] based on some earlier ideas of George Pòlya. What do you think of the prospects of proving the Riemann hypothesis in the near future?**

S I did not know about the paper you quoted. As a US president famously said: it is difficult to make predictions, especially about the future.

I **The way mathematical research is now developing seems to be changing on a global scale. There are personal and public internet blogs that discuss unsolved problems and produce some partial results and even their solutions. A public blog called the Polymath blog has been successful in settling some hard problems through such collaboration. What do you think of such massively collaborative mathematical research programs?**

S I like it very much. I have learned a lot myself by looking at internet blogs, or just putting a few well-chosen mathematical words on Google.

I **Do you work on more than one hard problem during a specific period of time?**

S Yes and no; quite often different looking questions turn out to be related.

I **You have been active physically in sports like skiing, rock climbing and table tennis. Have you ever had any epiphany moment in research during one of your favourite physical activities?**

S No. When I skied, my mind was on skiing, not on mathematics. As for table-tennis, there was one occasion where I did do maths – on a very elementary level! I was training at my club, and my opponent suddenly told me: "Serre, I hear that you are a mathematician. How does one show that there are infinitely many primes?" Then (without stopping the game) I started explaining to him Euclid's proof in down-to-earth terms: "Suppose you know that 2, 3, 5 are prime and you want a new one. What do you do? You look at 1 + 2 . 3 . 5. Either it is prime and you win. Or you take a prime factor, and you also win.'' A nice souvenir.

I **Do you think that the reason why some people developed a negative view of mathematics is the way that they have learned or were taught mathematics?**

S I am not competent to answer that. What seems clear is that most people have a very definite feeling about mathematics: they love it or they hate it. (Of course, I am a bit exaggerating.)

I **What are you now working on?**

S Two things. One of them is the revision (for publication) on my 1985 Harvard notes on number of points on curves over finite fields; I have been spending about a year and half on this; I hope to finish it soon. Another one is a long-standing project on cohomological invariants of Weyl groups. The theorems are proved, but writing them down will take time. All I have published yet is a three-page abstract *Cohomological invariants mod 2 of Weyl groups*[24] in the Oberwolfach reports.

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[23] https://www.pnas.org/content/116/23/11103 , PNAS June 4, 2019 116 (23) 11103-11110
[24] https://arxiv.org/abs/1805.07172

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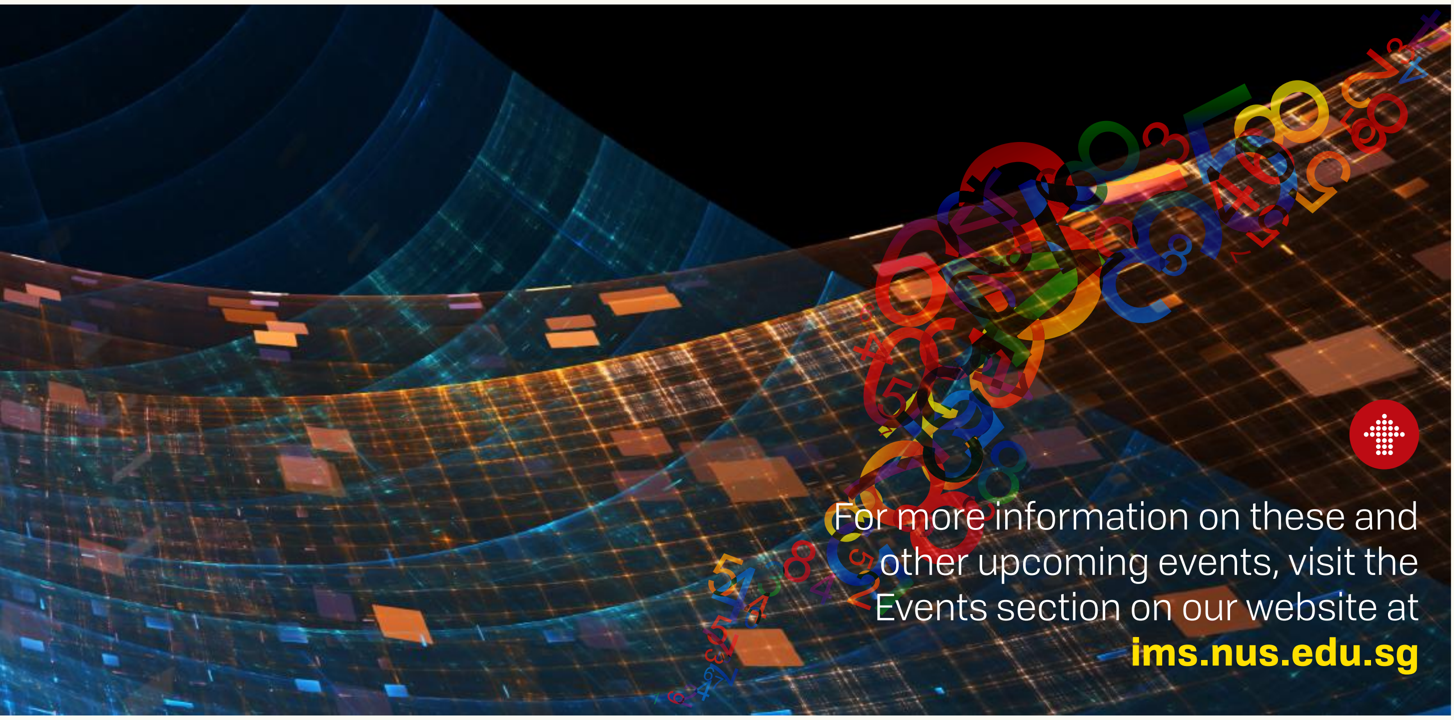

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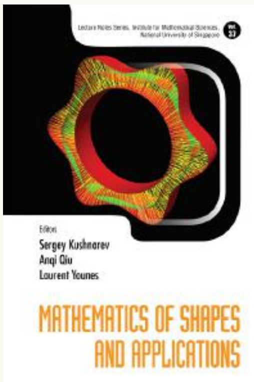

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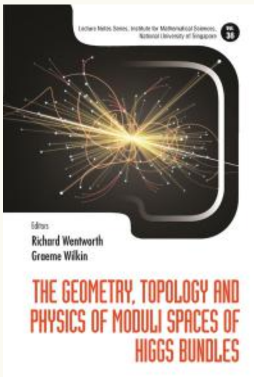

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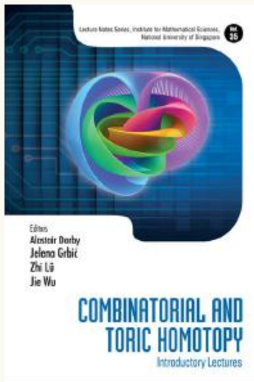

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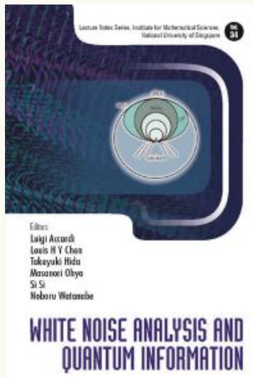

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