IMPRINTS
INSTITUTE FOR MATHEMATICAL SCIENCES
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In Turbulent Times >>>

Nobuhide Kasagi: Earth's Simulator

Turbulence was the order of the day for one of the few programs that lasted for six months, from July to December 2004, under the more reassuring title of "Wall-bounded and Free-Surface Turbulence and its Computation". The organizing committee's co-chairs from overseas were eminent researchers from the UK, US and France. The long program attracted 60 foreign participants, many of them leading experts in the field, and a large number of researchers and graduate students from local universities, research institutes and laboratories.

It must have been inspiring for young researchers in the field to listen directly to Brian Launder of the University of Manchester Institute of Science and Technology, who pioneered turbulence modeling in the 1970s and who continues to be actively engaged in research even after his recent "official retirement". He delivered the key-note address "CFD for complex industrial flows: Strategies for turbulence modeling". It was an enriching and stimulating experience for local researchers and graduate students to be in the presence of so many key players in the field and to observe, if not directly partake of, the interaction between theorists and experimentalists. For the new initiates in the field, it might even have been a little awe-inspiring. It is also to the credit of the program organizers that visitors from overseas were pleased with the scientific, social and administrative aspects of the program and that they were happy with the relaxed and conducive atmosphere of the Institute.

The scope of the topics covered required five workshops covering the computation of turbulence, free surface turbulence, control of transition and turbulence, and general developments on the Navier-Stokes equations. There were invited lectures and short seminar papers given at the workshops whose small-group character (and the generous refreshment breaks in the schedules) provided ample opportunities for participants to interact with each other, both scientifically and socially. Local researchers and graduate students found the workshops useful to their work, and the personal interaction with foreign experts a boon and a bonus.

Turbulence prediction: Palm or tea leaves? (From Left) Bijan Mohammadi, Olivier Pironneau, Anthony Leonard, Jean Luc Guermond

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From the Editor >>>

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The phenomenon of chaotic behavior in nature has always captured the imagination and curiosity of philosophers and scientists throughout the ages. It was only barely 100 years ago that what appeared to be qualitatively incomprehensible began to be scientifically studied as a phenomenon termed "turbulence" in fluid dynamics. Considered to be the most important and a highly intractable problem in classical physics, the mystery of turbulence is being gradually unveiled with the aid of fast computers that are now able to deliver the powerful algorithmic punches latent in mathematical models that could, before, only sit at the sidelines.

Turbulence seems to permeate the universe as an inexorable force without which nature would perhaps languish in stagnation, predictably uniform and lifeless. Philosophically, if not physically, man initially needed to understand this force and later to control, if not harness, it. Scientifically, its complexity belies the "simple" set of equations known as the Navier-Stokes equations that encapsulate, among others, the turbulent behavior of fluids. That "elegant" equations can describe "horrendous" flows is itself a wonder. But a complete physical understanding of such equations remains the holy grail of physicists scouring nature at the macroscopic level, in contrast to the microscopic level of quantum physics. Predictable fame and fortune await the discoverer of this grail.

Whether it is about mathematical equations or physical phenomena, the whole paradigm for their understanding seems to be shifting towards a computational realm accessible and exploitable only with the aid of powerful computers. Yet the computer is powerless without the efficient algorithms to fuel the transformation from the mathematical model to the numerical realization in terms of computations and graphics. There is a physical limit, dictated by the laws of nature, to computing power raw and simple, but there is, in principle, no intellectual limit to algorithmic power ingenious and creative. (The logical limit is, of course, another matter which is perhaps not completely resolved.) Thus recent developments in science and technology are giving rise to a new discipline, modestly and broadly referred to as "scientific computation", which demands the intuitive feel for the analytical and the algorithmic skills for the numerical. It is both an art and a science. Its mode is multidisciplinary, its masters and disciples young and revolutionary.

Y.K. Leong

At the Computation Workshop, leading proponents of the computation of turbulence presented the major developments from RANS to DNS, including the hybrid RANS-LES models for realistic simulation of industrial scale problems.

The key concerns of the Free-surface Turbulence Workshop were wave-breaking on ocean surfaces and turbulent transport across air-ocean interface by wave events.

The issues dealt with at the Turbulence Control Workshop were in an area which is highly practical and important, namely the role of stability theory, transition to turbulence in fluid boundary layers, its characteristics and its management, the design of control methods and strategies for fully-developed turbulent wall-bounded shear flows.

The Navier-Stokes Equations Workshop was concerned with a broad range of fundamental and theoretical issues on the analysis, properties, solutions, computation and motional scales of the Navier-Stokes equations – general equations which determine the motion of fluids.

Tutorials have often formed an important pedagogical part of the Institute's workshops. They were given in conjunction with the workshops on turbulence computation and turbulence control. More details are given in a brief report inside this issue of the newsletter.

There were so many exciting results and so much information in the state-of-the-art surveys given during the program that one is resigned to say, "So much progress, so little time." Further details, if only indicative, may be found at *http://www.ims.nus.edu.sg/Programs/wbfst/index.htm.*

Not to miss out on the opportunity of picking the brain of a creative pioneer of a new, fast-developing important scientific field, *Imprints* interviewed Brian Launder on his second visit for the Institute's program. The interview is featured in this issue.

Olivier Pironneau: Paris fashion in turbulence modeling

Anthony Jameson: From Boeings to beings

Annual Visit by Scientific Advisory Board >>>

SAB and the art of listening: (Counter-clockwise) Avner Friedman, Louis Chen, Chi Tat Chong, Keith Moffatt, Hans Föllmer, David Siegmund, Cindy Tok)

It is a ritual that is performed each year at the Institute for Mathematical Sciences for the past five years since 2000. It is a ritual without fanfare and ceremony but it is one which charts the course of the Institute for yet another year, and further, of eventful activities. It bestows scientific blessings to and places confidence on plans and proposals conceived out of passion and love for knowledge. It was most recently performed on 9 and 10 December 2004 by a group of six distinguished scholars and researchers. To them much credit must be given for the fruitful direction taken and high international standing achieved by the Institute. They are known collectively and formally by the name of "Scientific Advisory Board" (or "SAB" in short). If the Institute's management board members are regarded as the oarsmen of the Institute, then the SAB members must surely be regarded as its pathfinders.

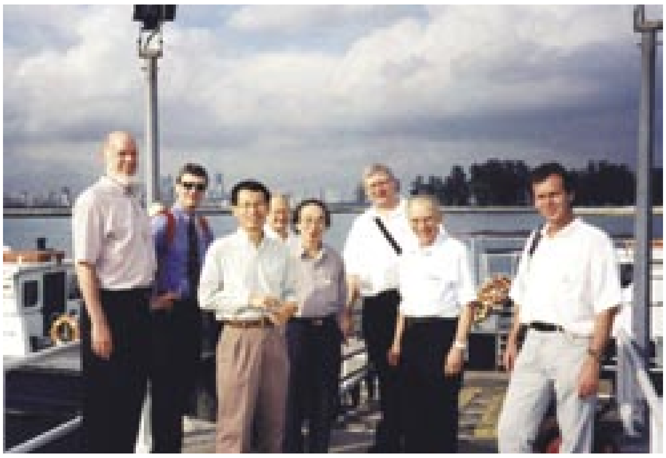
Earlier on, the SAB had studied the pre-proposals and proposals submitted by active local researchers in collaboration with international leaders in their fields. While this preliminary exercise was, in some sense, done in the abstract, the two mornings of 9 and 10 December were close and personal encounters between strategists and protagonists. Four presentations of pre-proposals were made on each morning by their prime movers in what might be described as a battle for the mind of the high command. Just as mathematics does not give any concessions on matters of accuracy and validity, so also the SAB does not mince its words in its evaluation of quality and significance. The presentations are interactive sessions in which the presenters are often enriched by the views and suggestions of the judges. It is an example of the adage that multiple minds (experienced and wise) are better than one (even if it is daring and creative). It also reaffirms, and perhaps even more emphatically so, the important role of personal interaction in the marketplace of abstract intellectual ideas.

As usual, the topics of the presentations reflect the Institute's broad approach to and interdisciplinary emphasis on the mathematical sciences. This time, the topics are in low-dimensional topology, probabilistic combinatorics, mathematical physics, fluid dynamics and computational biology. The coming attractions will offer some hot and current topics in pure and applied areas of the mathematical sciences.

On the afternoon of 10 December 2004, the SAB might also be seen to sit in "judgment" of the Director of the Institute himself when he presented an overview of the Institute's activities during the year under review. Suggestions were given on improving the process of calling for and submitting pre-proposals. It was also the time when the future directions of the Institute were discussed and set for implementation.

The Institute has also established a tradition in ensuring that the official visit of the SAB should not be "all work and no play". A "mandatory" visit to another organization would also be arranged. But this time there would be no home-work or exercises to be done, only to savor the enjoyable and educational experience of getting a glimpse of local scientific research and development in general.

Convincing the SAB: (From Left) Denny Leung, Avner Friedman, Tieh Yong Koh, Kian Peng Chua



On the waterfront 3.14: (From Left) David Siegmund, Roger Howe, Denny Leung, Hans Föllmer, Louis Chen, Mike Holmes, Avner Friedman, Pavel Tkalich

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Joining the Ranks of International Mathematical Consortiums >>>

This may be the clichéd golden age of mathematics which could be, in part, due to the realization of mathematicians of the need to play a more organizationally and politically active role in promoting their activities and raising the public awareness of their impact on human knowledge. During the past few decades, mathematical institutes have been set up around the world, initially to fulfill national scientific objectives and later on, serendipitously, for plugging into an international network of scientific expertise.

In the early 1990s, a move was made in the west to form an international consortium of research institutes that run thematic large-group programs in the mathematical sciences. The result was the consortium known as the "International Mathematics Science Institutes" with its first meeting being held in 1994 at the International Congress of Mathematicians (ICM) in Zürich. Membership of this consortium is by peer invitation, and the Institute (IMS) was invited to join this 47-member consortium in 2002. The list of members may be found at *http://www.fields.utoronto.ca/aboutus/IMSI.html*.

More recently, in 2004, the international scientific organization Bernoulli Society formed an international consortium of research institutes with a strong focus on the stochastic sciences. It is called the "Bernoulli Society Committee of Stochastic Science Institutes" (BSCSSI). Although the Institute (IMS) runs programs over a large spectrum of both pure and applied mathematics, a significant number of its programs are related to the stochastic sciences. It is therefore an honor for the Institute to be invited to participate in the founding of the BSCSSI.

The component institutes of BSCSSI are Australian Mathematical Sciences Institute (Australia), Erwin Schrödinger International Institute for Mathematical Physics (Austria), EURANDOM (Netherlands), Institut Henri Poincaré (France), Institute for Mathematics and its Applications (USA), Institute for Mathematical Sciences (Singapore), Center for Mathematical Physics and Stochastics (Denmark), Pacific Institute for the Mathematical Sciences (Canada), Statistical and Applied Mathematical Sciences Institute (USA), Stochastic Centre (Sweden), Weierstrass Institute for Applied Analysis and Stochastics (Germany). More information about BSCSSI may be obtained from the website at *http://www.cbs.nl/isi/BS/bshome.htm*.

The Director attended the second meeting of the BSCSSI in April 2005 in Sydney. It was a landmark meeting for the preparation of a strategic document of declaration of partnership of member institutes with a strong focus on the stochastic sciences. In recognizing the increasing importance of the stochastic sciences in human knowledge and the world trend of setting up institutes with a significant emphasis in these fields, the document may be seen as some kind of "manifesto" of intent to collaborate in the organization of scientific activities, to support the training of scientists in fields closely related to the stochastic sciences, and to help individuals in creating or building up new institutes which will contribute to those fields.

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A clammy feeling at TMSI: (From Left) Roger Howe, Konda Reddy, Avner Friedman, Denny Leung (Background), Hans Föllmer

On the afternoon of 9 December 2004, the SAB visited the research station of the Tropical Marine Science Institute (TMSI) on St. John's Island, a twenty-minute ferry ride from the Pasir Panjang ferry terminal and a world apart from the hustle and bustle of the city of Singapore. On hand to serve as a tour-cum-education guide was Dr Michael Holmes, an Associate Director of TMSI. The station conducts research activities mainly on marine biology and marine aquaculture. In addition to research on feeds, the latter activity includes the breeding of both food fishes and ornamental species such as giant clams and sea horses. As Dr Holmes explained, TMSI is a multidisciplinary research institute. Besides marine biology, it has teams working in marine acoustics and physical oceanography. It is indeed a joy to know that members of its physical oceanography team were active participants in parts of the Institute's recently concluded program on wall-bounded and free-surface turbulence.

Imprints pays tribute to the members of the SAB who have contributed to the Institute's success story: Hans Föllmer (Humboldt University, Berlin), Avner Friedman (Ohio State University, USA), Roger Howe (Yale University, USA), Pao Chuen Lui (Ministry of Defense, Singapore), Keith Moffatt (Cambridge University, UK) and David Siegmund (Stanford University, USA).

People in the News >>>

Carl de Boor wins US National Medal of Science
The Institute would like to express its delight at the news of the award of the highest official United States award in science (US National Medal of Science) to Carl de Boor in March 2005. Not only has his work inspired mathematicians at NUS but Carl is also a personal friend of many of us at NUS. He was invited to the Institute for the program on Mathematics and Computation in Imaging Science and Information Processing (July - December 2003 and August 2004) in August 2004 and was featured in an interview published in our newsletter (December 2004). Congratulations, Carl.

Honor for David Siegmund
Congratulations to David Siegmund on a conferment in May 2005 of an honorary Doctor of Science degree by Purdue University. David has served on the Scientific Advisory Board of the Institute since its founding, and is a close friend to all of us at IMS. He will be visiting the Department of Statistics and Applied Probability from August to December 2005 as the first Saw Swee Hock Professor of Statistics.

French Honor for Director
The Director Louis Chen was conferred the title of *Chevalier dans l'Ordre des Palmes Academiques* by the French government on 27 April 2005 for his "contributions made in reinforcing the relations between Singapore and France in the field of science and technology."

A girl for Agnes
The Institute's secretary, Agnes Wu gave birth to a girl on 1 March 2005, quick on the heels of her first child (a son).

At the forefront of turbulence

Program & Activities >>>

Past Programs in Brief

Wall-bounded and Free-Surface Turbulence and its Computation (July – December 2004)

Website: http://www.ims.nus.edu.sg/Programs/wbfst/index.htm

The co-chairs of this six-month program were Mohamed Gad-el-Hak *(Virginia Commonwealth University)*, B. E. Launder *(University of Manchester Institute of Science and Technology)*, Chiang C. Mei *(Massachusetts Institute of Technology)*, Olivier Pironneau *(University of Paris VI (Pierre et Marie Curie))* and Khoon Seng Yeo *(National University of Singapore)*.

The program focused on two important aspects of turbulence, namely turbulence at solid and free surfaces and its computation. A series of five workshops were organized over the six months duration of the programme, covering the computation of turbulence, free-surface turbulence and the control of transition and turbulence. There is also a workshop devoted to general developments in the Navier-Stokes Equations, which underlie the whole subject.

Tutorial sessions took place in the month of July, with three lecturers (Tim Craft (University of Manchester Institute of Science and Technology), Hector Iacovides (University of Manchester Institute of Science and Technology) and Pierre Sagaut (LMM - University of Paris VI (Pierre et Marie Curie)/ (CNRS))) presenting a set of lectures each on his own specialty. Tutorials were complemented by two workshops on "Computation of Turbulence" in the months of July and August. Attendance at tutorial sessions averaged 30; attendance during the two workshops averaged around 55.

A third workshop on "Turbulence at a Free Surface" was organized from 27 – 28 October 2004 and was attended by 45 participants. The two half-day sessions comprised five lectures conducted by Ken Melville (University of California, San Diego), Adrian W.K. Law (Nanyang Technological University) and Vladimir Maderich (Institute of Mathematical Machine and System Problems & Ukrainian Center of Environmental and Water Projects). At the same time, 41 participants attended a tutorial session conducted by Siva Nadarajah (McGill University) from 28 – 29 October.

Turbulence over tea: (From Left) Ivan Marusic, Her Mann Tsai, Joseph Klewicki, Michele Onorato, John Burns, Mohamed Gal-el-Hak

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A fourth workshop on "Transition & Turbulence Control" took place from 8 - 10 December 2004. A total of 56 participants attended the 18 talks conducted by 14 overseas visitors.

The last workshop for this program, "Developments in Navier-Stokes Equations & Turbulence Research" was organized from 13 - 17 December 2004. It was attended by 74 participants. There were 28 talks given by 24 overseas and 3 local speakers.

Some feedback from visitors:

It was a small conference, with plenty of time for formal and informal discussions on the subjects of the lectures. Those meetings are much more productive than bigger ones in which it is only possible to learn outlines of the work being presented.

Meeting and discussing with real experts in their field. We would like to see this kind of excellent events organized regularly throughout the year.

Nanoscale Material Interfaces: Experiment, Theory and Simulation (24 November 2004 – 23 January 2005)

Website: http://www.ims.nus.edu.sg/Programs/nanoscale/

The co-chairs of this program were Weizhu Bao *(National University of Singapore)*, Bo Li *(University of California at San Diego)*, Ping Lin *(National University of Singapore)* and Jian-Guo Liu *(University of Maryland)*.

This program brought together leading international experts and local researchers from various departments at NUS and from A*STAR institutes IMRE and IHPC to conduct interdisciplinary studies involving mathematical perspectives and foundations, computational techniques and experiment progress of material sciences. Fifty leading researchers from overseas were invited to the program. Foreign participants came from places like United States, France, Germany, United Kingdom, Austria, Japan, China, Canada, Italy, Switzerland, Hong Kong and Taiwan.

The program activities consisted of three workshops, four tutorials, one public lecture, two school lectures and a few seminars. The three workshops were held from 25 – 27 November 2004, from 23 – 24 December 2004, and from 10 – 14 January 2005.

One of the three workshops, "First Singapore Workshop on PDE and Scientific Computing" (23 – 24 December 2004), was jointly organized with the Departments of Mathematics and Computational Science.

In addition to the 3 workshops, a total of 22 tutorial lectures were conducted by 4 tutorial speakers: Qiang Du (Pennsylvania State University), Chun Liu (Pennsylvania State University), Robert Pego (Carnegie Mellon University) and Qi Wang (Florida State University).

One public lecture on "The Mathematics of Scientific Computation" (12 January 2005) was given by Eitan Tadmor (University of Maryland).

Ellen Williams: Keeping a straight face at the materials interface.

Qiang Du: How to simulate a Super-Conductor

Nanoscale at the macroscale: (From Left) Lin Ping, Qiang Du, Bao Weizhu

Two school lectures were given:

(i) "Macromolecular 'fluids' and liquid crystals" (12 January 2005) by Qi Wang (Florida State University) at Raffles Girls' School,

(ii) "Can a wire have a memory?" (13 January 2005) by Georg Dolzmann (University of Maryland) at National Junior College.

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Georg Dolzmann: School lecture on wires and memory

Reaching out to math: Junior college students

Current Program

Semi-parametric Methods for Survival and Longitudinal Data (26 February – 24 April 2005)

Website: http://www.ims.nus.edu.sg/Programs/semiparametric/index.htm

Co-chairs:
Zhiliang Ying, *Columbia University*
Yougan Wang, *National University of Singapore*

This program consists of seminars and tutorials on the following subthemes:

- non-proportional hazards regression
- multivariate survival analysis
- semi-parametric models for limited dependent variables in cross-sectional studies and panel data
- longitudinal data analysis
- computer-intensive methods and analysis of large data sets.

A school lecture, entitled "From data to decisions and discoveries", was given at NUS High School on 2 March 2005 by Xuming He (University of Illinois at Urbana-Champaign).

A workshop on R-Computing was conducted by Petra Kuhnert (CSRIO, Australia) from 28 February – 2 March 2005. Tutorial lectures were given by Ming-Hui Chen (University of Connecticut), Wenjiang Fu (Texas A&M University), Jiming Jiang (University of California at Davis), Joel L. Horowitz (Northwestern University) and Zhiliang Ying (Columbia University).

Next Program

Uncertainty and Information in Economics
(9 May - 3 July 2005)

Co-chairs
Robert Anderson, *University of California at Berkeley*
Parkash Chander, *National University of Singapore*
Peter Hammond, *Stanford University*
Yeneng Sun, *National University of Singapore*

Researchers in economic theory have long recognized the importance of uncertainty and information, but major advances have been made during the last two to three decades especially. The program will focus on three areas of microeconomics where uncertainty and information play a key role: game theory, information economics and finance.

Activities:
a) Workshop on Economic Theory, 16 May 2005
b) Tutorial by Sudhir Shah, University of Delhi, 30 – 31 May 2005
c) Tutorial by Parkash Chander, National University of Singapore, 1 – 2 June 2005
d) Tutorial by Felix Kubler, Universitaet Mannheim, 3 June 2005
e) Workshop on Uncertainty and Information in Economics, 6 – 10 June 2005
f) The Tenth Conference on Theoretical Aspects of Rationality and Knowledge, 10 – 12 June 2005 *Jointly organized with the School of Computing, NUS
g) Tutorial by David Parkes, Harvard University, 13 June 2005
h) Tutorial by Nicholas Yannelis & Anne Villamil, University of Illinois at Urbana-Champaign, 14 – 15 June 2005
i) Tutorial by Robert Anderson, University of California at Berkeley, 16 – 17 June 2005

To date, 33 overseas speakers have confirmed their participation.

Programs & Activities in the Pipeline

Workshop on Nonlinear Partial Differential Equations: Analysis, Computation and Applications (3 - 6 May 2005)

Website: http://www.ims.nus.edu.sg/activities/npde/index.htm

Organizers
Weizhu Bao, *National University of Singapore*
Ping Lin, *National University of Singapore*
Jian-Guo Liu, *University of Maryland and National University of Singapore*
Zhouping Xin, *Chinese University of Hong Kong*

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The workshop is jointly organized with the Institute of Mathematical Sciences at The Chinese University of Hong Kong (IMS/CUHK).

Topics will include: conservation laws, fluid mechanics, water waves, numerical methods, transport phenomena, kinetic theory, inverse problems, combustion, semiconductor modeling and simulation, Bose-Einstein condensation, quantum hydrodynamics, nonlinear Schrodinger equations, plasma physics.

Workshop on Data Analysis and Data Mining in Proteomics (9 - 12 May 2005)

Website: http://www.ims.nus.edu.sg/activities/proteomics/index.htm

Co-chairs
Maxey C.M. Chung, *National University of Singapore*
Newman S.K. Sze, *Genome Institute of Singapore*

Confirmed overseas speakers:

- Jacques Colinge (GeneProt Inc., Switzerland)
- David Creasy (Matrix Science, UK)
- Paul Eilers (Leiden University, Netherlands)
- Athula Herath (Nestle Research Center)
- Shahid Khan (Leiden University Medical Centre, Netherlands)
- Neil Kelleher (University of Illinois at Urbana-Champaign)
- Andrew Keller (Institute for Systems Biology, USA)
- Bin Ma (University of Western Ontario)
- Peter Roepstorff (University of Southern Denmark)
- Rovshan G. Sadygov (Thermo Electron Corporation)
- Richard Simpson (Ludwig Institute for Cancer Research, Australia)
- Marc Wilkins (Proteome Systems Ltd., Australia)

A panel of leading international and local experts will review and discuss recent developments and advancements in:

(i) protein science and proteomics
(ii) application of mass spectrometry
(iii) proteomic bioinformatics, and
(iv) high throughput mass spectrometric data analysis

Activities: lectures and discussions.

Computational Prospects of Infinity (20 June – 15 August 2005)

Website: http://www.ims.nus.edu.sg/Programs/infinity/

Organizing Committee :
Chi Tat Chong, *National University of Singapore*
Qi Feng, *Chinese Academy of Sciences, China and National University of Singapore*
Theodore A. Slaman, *University of California at Berkeley*
W. Hugh Woodin, *University of California at Berkeley*
Yue Yang, *National University of Singapore*

This program consists of two parts:
(a) Workshop in Set Theory (20 June to 16 July)
(b) Workshop on Recursion Theory (18 July to 15 August)

The program is sponsored by the Association for Symbolic Logic. Two tutorials will be given in each section. John Steel and Hugh Woodin (University of California at Berkeley) will be the tutorial speakers in set theory, while Theodore A. Slaman (University of California at Berkeley) and Rodney Downey (Victoria University of Wellington) will conduct tutorial lectures in recursion theory. About 20 leading researchers from North America, Europe and Asia in each of these two major areas of contemporary mathematical logic will take part in the workshops. In addition, it is expected that a number of promising young postdocs and graduate students from various parts of the world will also participate.

Asian Mathematical Conference 2005 (20 – 23 July 2005)

Website: http://ww1.math.nus.edu.sg/AMC/index.htm

Chair (International Scientific Committee):
Kenji Ueno, *Kyoto University*
Chair (Steering Committee and Organizing Committee):
Eng Chye Tan, *National University of Singapore*

Jointly organized with Southeast Asian Mathematical Society, Singapore Mathematical Society, Department of Mathematics and Department of Statistics and Applied Probability.

Mathematical Modeling of Infectious Diseases: Dynamics and Control (15 August – 9 October, 2005)

Website: http://www.ims.nus.edu.sg/Programs/infectiousdiseases/index.htm

Chair:
Bryan T. Grenfell, *University of Cambridge, UK*
Co-chairs:
Stefan Ma, *Ministry of Health, Singapore*
Yingcun Xia, *National University of Singapore*

The program will cover five topics in the mathematical modeling of infectious diseases. For each topic, there will be a tutorial presenting background and other introductory materials. There will also be a workshop consisting of seminars on recent developments and future directions. There are also two one-week periods set aside for interaction among the participants. The emphasis will be on dialogue and bridging the gaps between mathematicians, statisticians, epidemiologists, biologists and medical scientists.

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Activities:
(a) New development of the SEIR models for the transmission of infectious diseases (15 – 19 August 2005)
(b) Influenza-like diseases (22 – 26 August 2005)
(c) Break for interaction and discussion (29 August – 2 September 2005)
(d) Immunity, vaccination, and other control strategies (5 – 9 September 2005)
(e) Molecular analysis of infectious diseases (12 – 16 September 2005)
(f) Break for interaction and discussion (19 – 23 September 2005)
(g) Clinical and public health applications of mathematical modeling (26 – 30 September 2005)
(h) Break for interaction and discussion (3 – 7 October 2005)

Semi-definite Programming and its Applications (15 December 2005 – 31 January 2006)

Website: http://www.ims.nus.edu.sg/Programs/semidefinite/

Chair:
Michael J. Todd, *Cornell University*

Co-chairs:
Kim-Chuan Toh, *National University of Singapore*
Jie Sun, *National University of Singapore*

Activities:
(a) Tutorial (9 – 10 January 2006)
(b) Workshop (11 – 13 January 2006)

Highlights of other activities

3rd Asia Pacific Workshop on Quantum Information Science (3 – 15 January 2005)

Website: http://www.ims.nus.edu.sg/activities/quantuminfo/index.htm

The Co-chairs of this program were Artur Ekert *(University of Cambridge)*, Choo Hiap Oh *(National University of Singapore)* and Kok Khoo Phua *(SEATPA and National University of Singapore)*.

This workshop was part of an overall effort to develop an interdisciplinary research team in quantum information science with specific emphases on communication theory and quantum algorithm. It had a strong education component. It also aimed at developing new contacts with likely users of quantum information technologies in Singapore and providing them with timely updates and briefings on the progress in the field.

Andrew Yao: Beware the entropy of info scorned

Hans Briegel: Click a quantum leap in information

Quantum states of registration

The invited speakers were: K. Banaszek *(Oxford, UK)*, H.J. Briegel *(Innsbruuck, Austria)*, A. Ekert *(Cambridge, UK)*, J. Eisert *(Potsdam)*, K. Feng *(Tsinghua, China)*, D.M. Greenberger *(CUNY)*, G.J. Milburn *(Queensland, Australia)*, C.P. Soo *(NCKU, Taiwan)*, R.F. Werner *(Braunschweig, Germany)*, K. Vollbrecht *(Max Planck, Germany)*, Andrew Yao *(Tsinghua, China)* W.M. Zhang *(NCKU, Taiwan)*, K. Zyczkowski *(Jagellonian, Poland)*.

The talks focused primarily on quantum coding and cryptography, quantum entanglement, realization of quantum computer using various means, including optical-atom interaction and graphs states, and the foundation of quantum mechanics, including Bell inequalities at various levels ranging from introductory to advanced materials and the workshop provided a possible opportunity for closer collaboration between Singapore and Tsinghua university in China through interactions principally initiated by Prof. Andrew Yao (Tsinghua).

The workshop was dedicated to the memory of Asher Peres (Technion University, Israel). Proceedings of the workshop will form a special issue of the *International Journal of Quantum Information*.

Mathematical Conversations

Brian Launder: Modeling and Harnessing Turbulence >>>

Brian Launder

Interview of Brian Launder by Y.K. Leong

Brian E. Launder made important contributions, both experimental and mathematical, to fluid mechanics and convective heat transfer and pioneered the use of mathematical models to study turbulent flows. He was at the forefront of the development of numerical methods for turbulence models. He has also applied his methods to industrial problems related to turbomachinery and was active in leading research on environmental issues. His influence in engineering is extended through his wide and deep collaboration with his numerous students and other researchers.

He had his university education at Imperial College and MIT. Except for a short teaching stint at University of California at Davis, he taught mainly at Imperial College and from 1980 onwards, at University of Manchester Institute of Technology (UMIST), where he variously headed the department, the Thermo-Fluids Division and the Turbulence Mechanics Research Group. He was Chairman of UMIST's Environmental Strategy Group, Director of the Mason Centre for Environmental Research and Regional Director of the Tyndall Centre for Climatic Change Research.

His scientific contributions were recognized by leading professional and scholarly bodies, and he was elected Fellow of the following professional and scientific bodies: Institute of Mechanical Engineers (IMechE), American Society of Mechanical Engineers (ASME), Royal Aeronautics Society (RAeS), Royal Society and Royal Academy of Engineering. He was Editor-in-Chief of the International Journal of Heat and Fluid Flow, an assessor for leading French institutions and advisor to Stanford University's Center for Turbulence Research. Though recently retired from UMIST, he continues to play a leading role in the Turbulence Mechanics and CFD Research Group.

He took an active part in the Institute's six-month program (July – December 2004) on turbulence. When he came to the Institute for a second time, the Editor (Y.K. Leong) of *Imprints* interviewed him on 16 December 2004. The following is an edited account of an illuminating revelation of his thoughts about a life-long fascination with an awe-inspiring physical phenomenon that is mysterious and gradually beginning to be fathomed and understood, if not harnessed.

Imprints: Do you consider yourself to be an engineer or an applied mathematician? Do you carry out laboratory experiments?

Brian Launder: Yes, I am an engineer but one who always enjoyed mathematics. When I applied to university at the age of 17 or 18, it became a matter of choice whether I became a mathematician or an engineer. I decided that my mathematics was good but not sufficiently brilliant to be a stellar mathematician. I thought, and I think it was a correct choice, that I could contribute much more to engineering at an applied level than by following a mathematics course. On the second question: As an undergraduate, I had a final year project in boiling heat transfer and that was experimental. I was fascinated by that. I wanted to do that for my doctoral study. So I applied to MIT to do my doctoral work and was offered admission to do boiling, but the gas turbine laboratory at MIT offered me a research assistantship which meant that I didn't have to do teaching-assistants' duties to earn my living. I would be paid to do research but, of course, the gas turbine lab would be concerned with gas turbines. From that point on, I forgot about boiling heat transfer and I concerned myself with the types of flow that arise in gas turbines.

I: Would it be correct to say that subsequently you were more theoretical?

L: No, even at MIT my work was experimental. It was certainly related to turbulent flow. So it was there that my interest in turbulent flow arose. But later on, I did move to mathematical modeling of turbulence.

I: Your CV mentions a number of doctorates to your credit, could you tell us a bit more about your graduate training?

L: As I have just mentioned, I decided to go to the USA for my graduate work. I applied to half a dozen institutions there. I had no idea what was a good university and what was a bad university in those days. I got several offers – one from Princeton, I recall, and one from Yale, and then an offer from MIT came through. I was advised by the professor at Imperial College to take the MIT choice. I did my masters and doctorate at MIT and then I came back to join the staff of Imperial College as a lecturer.

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I: It appears that you have more than one doctorate.

L: Ah, yes, let me go on to say that three of the other doctorates I have are what we call higher doctorates. They are awarded on the basis of substantial body of published research - the first of those from the University of London I think I obtained in about 1976 when I was working at the University of California. I have to say that I got it purely to increase my salary. I don't know if they were impressed but I did get a small increase in salary as a result. Of the other two, one was awarded by the University of Manchester and the other by UMIST. In accepting those there was no effect on my salary. Nor did I expect any. I took them to show my commitment to Manchester. I submitted different research for each one and they were submitted at roughly ten-year intervals. It took me about a decade to accumulate enough new research to submit for a possible award of a higher doctorate.

I: Why did you go to MIT and not stay at Imperial College for your graduate work?

L: Well, I was interested in heat transfer and did think of staying at Imperial College, but the head of the Heat Transfer Section Professor Brian Spalding came and gave us a talk when I was in my final undergraduate year. Basically, he said, "Well, don't do your PhD here. The College is being rebuilt, you will lose a year of effort if you try and do your doctorate in this building at the present time." He was very honest and it is characteristic of him. He always says what he believes to be the truth. That stimulated me to look elsewhere. Since I thought Imperial was the best in England, if I wanted to look elsewhere, I naturally looked to America.

I: How did you become interested in turbulence research? Were you interested in turbulence right from your graduate days?

L: As I indicated, I got shifted into gas-turbine problems - problems of aerodynamics. I was given a free choice for my PhD project and I looked through maybe 150 alternative topics that the laboratory offered. The one that I chose I thought was very interesting. As an undergraduate, I learned a little bit about the transition of laminar flow to turbulent flow. I had always assumed what all the textbooks said: that was a one-way process; that is, once you get into turbulent flow, you never go back to laminar flow. But one of the projects that was put forward at MIT reported that the Russians had done some experiments suggesting that you could go from turbulent flow back to laminar flow if you accelerated the flow sufficiently quickly. This seemed a fascinating question to me. So I decided to look at it in more detail. The Russian paper had been complicated because the flow was supersonic and effectively they were looking at the flow around a projectile where there was a Prandtl-Meyer expansion wave, and effectively, in passing through the expansion wave, the turbulent boundary layer got peeled off and the laminar boundary layer grew up beneath. I was asked to look whether in subsonic flow one could get such a phenomenon. That was what I did for my master's and my doctoral theses.

I: Did it ever occur to you to become an aerospace engineer?

L: It did occur to me. Indeed, I did make some exploratory enquiries, when I was getting near the completion of my doctorate, about the possible positions. I didn't pursue that for two reasons. Firstly, I was a holder of a Fulbright grant and if you hold that grant, you have to leave the USA for two years after completing your doctorate. I did think of going to Canada, but mainly I wanted to get back to England because my grandfather at that time had terminal cancer and I wanted to see him before he died. So having been offered a position by Imperial College, that seemed the best possible choice.

I: The Clay Mathematics Institute in the United States is offering a million U.S. dollars for the understanding of the Navier-Stokes equations in fluid mechanics. Do these equations apply to all forms of hydrodynamic motion?

L: If one has a fluid that one calls Newtonian, that is to say there is a linear relationship between stress and strain, the Navier-Stokes equations apply to a large part of such flows. Of course, if one is in special regimes like free-molecule flows, then they aren't applicable. What makes them especially difficult to solve, however, is the non-linear convective transport term in those equations coupled with the viscous term. Those two together are very challenging. Also, if the convective term becomes more dominant, then steady solutions, that is to say, solutions independent of time, no longer become stable. You get a transition to a phenomenon that they call turbulence. Occasionally, over a limited range, you can have periodic solutions, but the more usual form is this chaotic motion that is called turbulence.

I: Are the solutions analytically obtainable in principle?

L: Not by formal mathematics. Nowadays, computers are large enough that for a limited range of Reynolds number, one can with the computer solve the Navier-Stokes equations numerically. Of course, there are some analytical solutions for laminar flow.

I: Is turbulence a matter of boundary conditions?

L: No, even if you have perfectly calm inlet conditions, if

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the Reynolds number is high enough (high Reynolds number means that you have only got very weak damping by viscous forces), in that event you will find that small perturbations will grow and you will rapidly end up with turbulent flow even if you have a laminar flow coming in.

I: It's not that it is asymptotically so?

L: No, it is certainly not asymptotic. If you have a high Reynolds number flow (the Reynolds number is a measure of how strong the convection terms are compared with the viscous terms) and you have a laminar flow entering the domain, the smallest perturbation will trigger a transition almost immediately to a turbulent agitated motion. It's not asymptotic, it occurs almost instantaneously.

I: Is it also due to an initial condition, like a high Reynolds number?

L: No, it's simply the ratio between how fast the flow is going, what is the size of the range you are looking at, and what is the viscosity of the fluid. One is looking at things which are not related to boundary conditions.

I: In the real world, the phenomenon of "turbulence" seems to be the rule rather than the exception, and the human mind seems to be able to survive, if not thrive, under conditions of "turbulence". Why is turbulence scientifically so intractable?

L: (*Laughs*) I'm not sure how far I can answer this question. To start with your beginning question, turbulence is the rule rather than the exception in the world we live in. Why is that? It's because the two most important fluids to us (air and water) are, on the scale of fluid viscosity very small in value. If we lived in a world of castor oil, we would find that most of the fluid motions that concerned us would be laminar rather than turbulent. Above a certain Reynolds number, the flow does become chaotic. Unless one is going to make a major numerical solution of unsteady three-dimensional turbulent flow, one is forced to look at the averaged equations and, because of the non-linearity of the equations, one finds extra terms (what are known as Reynolds stresses). So, one is forced to adopt modeling to determine those unknowns.

I: Is there a fair amount of modeling for turbulence?

L: It depends at what level one works. I mentioned that one can, over a limited range of Reynolds number, solve the turbulence equations. If one wishes to do what I call "light modeling" of the equations, one can adopt what we call a "large-eddy simulation". This is in some way like a direct numerical simulation except that one recognizes that turbulence has fluctuations on a scale smaller than the numerical grid one is using and one has to include a model to represent that subgrid scale fluctuations. At that level, a simple turbulence model is the usual choice. Most of the effort is in the numerical solution. The model is just a small part of the numerical scheme that ensures that turbulence is destroyed at the required rate. If one goes to the level of modeling that I work at, however, (this is called Reynolds-averaged modeling), then there is a huge amount of input into the turbulence model because all of the statistical fluctuations are contained in the model of turbulence, whereas at the level of large-eddy simulation, most of the transport associated with turbulent flow comes from the simulation itself and it is only a small amount associated with the model.

I: Are the models you mentioned verified by experiments?

L: Indeed, one verifies them either by experiment or increasingly nowadays, by referring to large eddy simulations or direct numerical simulations. There are models that inevitably don't cover all turbulent flows. They will have a range of applicability. Modelers try to make the range of applicability as wide as possible. A one-flow turbulent model is of no good to anyone.

I: Feynman once said that turbulence is the most important unsolved problem of classical physics, and Heisenberg was reputed to have said that he had only two questions to ask God: "Why relativity?" and "Why turbulence?" How much nearer are we to a clear understanding of turbulence?

L: I'm not sure I can respond to this question in a meaningful way. I think that "understanding" is such a personal state, it's almost like religion. For myself, I feel remarkably assured when I am in tune with direct numerical simulation. If we can numerically solve the Navier-Stokes equations, it's very nice to see that the flow that comes out is what we see when we do a careful experiment for identical conditions. Now, at the level of modeling that I do, I find understanding in looking at the relevant equations (the Reynolds stress transport equations) and gaining insight from the different roles taken by certain terms under particular force fields or strain fields which explain why turbulence behaves the way it does. For example, why is it that, when we have a rotating flow, due to the resultant Coriolis force one initially gets some augmented turbulent mixing on the high-pressure side of the flow and diminished turbulence on the opposite (low pressure) side? One can see this directly just by looking at the equations ... qualitatively at any rate. One can also understand qualitatively why, on the high-pressure side there is a cut-off level beyond which further increased mixing does not occur whereas on the low-pressure side mixing is continuously reduced until the flow becomes quasi-laminar. Yes, I find great insight and understanding of turbulence by looking at those equations. Of course these

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insights are usually not precise enough to give quantitative answers. One needs to provide a model for the unknown terms, to complete the mathematical specification of the equations and then, by solving them, one can get, hopefully, accurate results.

I: So you think that understanding of turbulence has increased tremendously over the last fifty years?

L: Undoubtedly so. I don't say there are no unresolved problems but there has been tremendous progress. Of course, as in many fields in the mathematical sciences, with the coming of the computer and the development of techniques to exploit the ability of the computer, it is inevitable that one sees many changes.

I: Is there a master plan or program conducted by researchers around the world to solve the turbulence problem like what the physicists are doing for, say, a theory of everything in string theory?

L: Turbulent flow covers so many fields from blood flow motion in the human body to atmospheric turbulence. You've got such a large range of scale. People's own interests don't span that range. I said atmospheric turbulence; gosh, stellar turbulence also has a large group working in it. So some areas may have this "grand plan"; it may seem grand but it is relatively focused and limited compared to the range of turbulence. No, there is no "theory of everything" in turbulence. Nor will there ever be, I suspect.

I: Will an understanding of turbulence provide the answers to problems in meteorology?

L: Of course, at one level. We are dealing with air which is a Newtonian fluid and it gives rise to turbulent motion. It is, in principle, described by the Navier-Stokes equations. No matter at what level we attack the problem, whether it is direct numerical simulation, large eddy simulation or the sort of Reynolds average modeling I do, what is so different is the scale. One is looking at thousands of kilometers; yet the smallest motion of turbulence is still as small as they are in the experiments I get involved with – they are fractions of a millimeter. There is really no way one can adopt the same approaches. So while people working in atmospheric turbulence do make some use of the approaches that we adopt, they are almost like a special large eddy simulation. A special feature of the atmosphere is that its horizontal extent is very much greater than its vertical extent, for example.

I: Recently I read in the *Scientific American* that some experiments done by a group at the Delft University of Technology in the Netherlands detected some kind of small eddies or currents that are supposed to be "building blocks" of turbulence. What do you think of that discovery?

L: Well, I'm not sure what words they used. Workers in turbulence, as in other fields, are always wishing to promote what they are doing by making it sound very general. Terms like "building blocks" are frequently ones that come to mind as an attempt to make a very complicated subject understandable by people without any specialized knowledge in the field. At Delft, there are some very strong people in turbulence. One is my first ever PhD student Professor Hanjalic. He has been doing some fine work there, particularly on Rayleigh-Benard convection, in which one takes a pair of horizontal plates at some fixed distance apart. If one then heats the lower plate natural convection is started – that's what we term Rayleigh-Benard convection. You get something like that in the atmosphere. I mention Hanjalic because you asked me about the applicability of our model to atmospheric phenomena. He is originally Yugoslav and lived in Sarajevo that has a long valley. It's a city that suffers desperately from pollution. He has done a CFD study of the Sarajevo valley to help local authorities decide whether they should put a chemical plant with potential emission in one position rather than another. Clearly one wants the effluent gas from the plant to be carried far away. On the atmospheric micro-scale, one is using just the same methods that we were using in engineering.

I: The designs of airplanes and ships are presumably related to the study of turbulent flows in air and water. Yet nature has provided its own designs in the form of creatures that fly and live under the oceans. Has there been any attempt to look for possible answers in the designs of nature?

L: That's an interesting question. The answer is yes, we have. Let me cite a couple of examples. In the late 1970s and early 1980s, we (the community, not just myself) empirically discovered, principally from research funded by NASA, that by putting small longitudinal ridges in the surface you can actually reduce the drag to levels below what you would get on a smooth plate. (This seemed remarkable and it has been established and understood now.) Then people said to themselves, "Okay, we have gone this far. Can we do better?" because they were getting drag reduction of the order of ten percent. Somebody called Bieter Bechert, who was a professor in Berlin and is retired now, looked at the performance of sharks. The great white shark seems to have an ability to swim at speeds faster than what people feel it should be able to, given its size and power and so forth. Bechert's idea then was that the shark must have some drag-reducing feature on its skin. He then took some shark's skin and examined it in detail and discovered that the shark had something like riblets - these devices that had been discovered empirically. But, of course, what the shark had weren't shaped exactly like those that have been evolved empirically. So Bechert launched a major research effort mimicking the shark's skin. Alas, I have to say that Bechert came to retirement before those experiments reached any firm conclusion.

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I: Could he do better than Nature?

L: Looking at the results that he published, I don't think he did better than Nature. Looking at it another way, one can say that Nature had the same idea. I said I would quote two examples. So, as a second example, an area where it is certainly the case that one is looking at Nature is in the development of what I call "micro-sized vehicles". There is a lot of interest, partly from the point of view of surveillance but not only from that point of view, in building flying machines that are really the size of just my fist. Obviously, they will not contain anything except sensors: a small camera, sound recording equipment, or whatever. If you go down to that sort of size, you can't have a fixed wing. It is just not feasible. So various designs of flapping wing devices are being explored. Naturally, one looks extensively at the various solutions that Nature has come up with over the millennia in order to get good ideas.

I: But then birds are not the same as inanimate objects. Birds are "dynamic" but aeroplanes are not.

L: Well, there is a lot of research in this field (it's not an area where I do research), in bringing in basically dynamic response capability into inanimate objects. Certainly it is the intention that smart devices should be embedded in, say, the wings or some other part so that if things are not exactly ideal, this can be sensed perhaps as a perturbation in pressure and there can then be feedback control to change it. However, what man creates in his instruments will be inferior to what Nature, even in a bird or an insect, has evolved over millions of years. Nonetheless, there is movement in that very direction.

I: Do you work on any projects in industry?

L: Well, I have done a wide range of industrially-driven problems sponsored by industry. Let me just mention a few. One has provided research, both experimental and computational, for at least ten years - it's on blade cooling. It may not be generally known that the jet engine becomes more efficient the higher the temperature one makes the air flow coming out of the combustion chamber. The problem is that when it meets the turbine blades, the blades will melt at that sort of temperatures they want to use. So, one puts cooling passages in the inside of the blades. Because turbine blades are very small it is pretty challenging to develop effective cooling systems inside them.

I: Is the cooling done by coolant or by air itself?

L: It is done by air that has been compressed in going through the compressors and is then taken off before it goes into the combustion chamber. The air is heated up by the sheer compression but it's heated even more in the combustion chamber. This high pressure cool air is, I'm guessing here, around 600 degrees Centigrade; that's a high temperature, but it is much cooler than the temperature on the outside of the blades. So that's what protects the turbine blades. So that's one area.

I'm also looking at the trailing vortices that are being created behind an aircraft wing. These are created at the tip of the wing as the aircraft flies through the air, and as you know, it can be dangerous for following aircraft to get caught up in these vortices. We are looking at ways to cause the vortices to die out faster. Finally, I mention research that I'm doing on nuclear reactors where one is trying to work with the people designing the next generation of nuclear reactors to improve better ways of cooling.

I: Has your research resulted in any patents or immediate applications in technology and industry?

L: Although I've been talking about my industrial work, I actually operate at a fairly fundamental level. So it isn't that I discover something that can be patented. So there's no patenting of my modeling work but there is a lot of industrial take up of it. My colleagues and I have advanced mathematical modeling so that it is used in industry. The turbulence model (not just my own work but work of modelers around the world) has altered what has gone into the computer programs that industry use. Much of the industrial computing actually makes use of what are known as the industrial codes. There are now three, perhaps four, major CFD computational fluid dynamics vendors. Certainly the vendors have imported my group's models into their codes. That is sometimes a terrible struggle, I have to say. Some code vendors have got models I produced thirty years ago and they're still using them. They complain that they don't work and I've been producing new models over the last thirty years. It's hard to get them to throw away what's in their codes and put in the new models.

I: It's very surprising to me that, given that engineers are well-known for going for patents generally, you are approaching your work from a more intellectual point of view.

L: It's probably what I'm best at and certainly what I enjoy. You will find people in the field who are more financially driven. I mentioned at the beginning the professor at the time when I was an undergraduate. He was probably the first person to get a serious CFD industrial program (that is to say, commercial); he was a commercially concerned scientist. Another colleague from my early days now has one of the most successful current CFD companies. These people just have different interests and different skills. They are more into the numerical discretization of the equations. I'm more into the physics. Like most academics I suppose, turbulence modelers are much more interested in our subject and the

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associated ideas than turning ideas into money.

I: The work you did on blade cooling must surely be patentable and could have been sold to aircraft companies.

L: Yes, but what we produced then is a software for computing a particular arrangement. What one could devise is an entirely different type of cooling arrangement - that would, I believe, be patentable. But that isn't what we were directed at. We were simply showing industry that we can compute this type of flow because we do both experiments and the CFD work. That enables the industry to say, "We'll use your computer code with its modeling and use that to design for ourselves a more efficient cooling system."

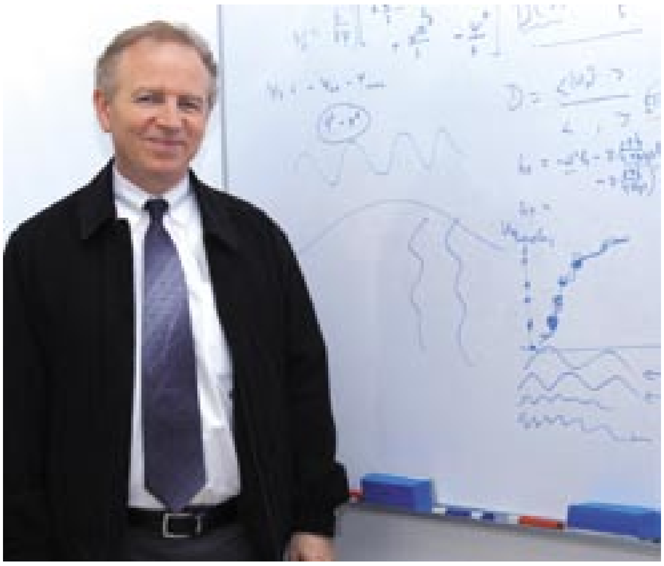
I: Do you have any PhD students?

L: I don't have any at the moment, and the reason is that I'm 65 and until a few months ago, I was going to retire when I reached that age. But my university has offered me an extension of my contract for two years. However, it seems to me irresponsible to take on PhD students at an age when I won't be there to supervise them over the final eighteen months of their doctoral research.

I: What about in the past?

L: Oh, I've had over 40. Yes, that's the biblical number to signify 'quite a lot'. I still have some post-docs working with me - three post-docs at the moment. I also interact with academic colleagues helping them in preparing research proposals and offering advice when it's sought. I'm also under contract to write a book for Cambridge University Press. So, if I can get rid of all the administrative work that clogs up my days (and evenings and weekends!) I hope to make some further contributions to the modeling of turbulent flows. In that respect, the opportunity to contribute to the turbulence program here in Singapore has been a real pleasure.

Eitan Tadmor: Zen of Computational Attraction >>>



Eitan Tadmor

Interview of Eitan Tadmor by Y.K. Leong

Eitan Tadmor has made fundamental contributions to numerical analysis, the general theory of applied partial differential equations and scientific computation. His influence on applied mathematics is as deep as it is wide-ranging and as mathematical as it is organizational. His prolific research output, both personal and collaborative, must surely rank him as one of the top leading figures in his field. His direct influence may be glimpsed from an article written on the occasion of his 50th birthday and published in *Computational Methods in Applied Mathematics,* Vol. 4, No. 3 in 2004.

Tadmor's contributions span a spectrum varying from research to administration and institutional organization. He has given plenary lectures at many major scientific meetings, including an invited address at the International Congress of Mathematicians in Beijing in 2002. He was a founding co-director of the National Science Foundation (NSF) Institute for Pure and Applied Mathematics (IPAM) at the University of California, Los Angeles and is currently the Director of the Center for Scientific Computation and Mathematical Modeling (CSCAMM) of the University of Maryland, College Park. In addition to his being a professor concurrently in the Department of Mathematics, CSCAMM and the Institute for Physical Science and Technology at Maryland, he also holds the university's title of Distinguished University Professor. The list of his professional services, whether on worldwide scientific committees or editorial boards of numerous leading journals in applied mathematics is vast, and clearly shows breadth and personal commitment rarely found in a single scholar.

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When Tadmor visited the Institute as an invited speaker of the program on nanoscale material interfaces, he was interviewed by the Editor (Y.K. Leong) of *Imprints* on 11 January 2005. The following is an edited and enhanced transcript of the interview, in which he reveals his unusually early, if not precocious, fascination with mathematical analysis, both pure and numerical, and a Zen-like attraction to things computational and algorithmic. It also gives an insight into his consuming passion for research and total commitment to the scientific community.

Imprints: Could you tell us something about your graduate training and how you became attracted to your present research interests?

Eitan Tadmor: I was attracted to mathematics during the early years of my elementary school in Tel-Aviv. At age 13 I joined a local math club which was run by a Tel-Aviv University Professor, Gideon Zwas. He had a lively personality and a great ability to make very appealing presentations of mathematical ideas. I attended Zwas' π-club throughout my early years of high-school. It was there that I first became interested in applied and numerical analysis. Zwas became my first mentor as I had begun taking courses at the university while still in high-school. Back then, in 1970, it was the first administrative arrangement of its kind. Later on, I was pleased to see how it paved the way for more established channels of bright students who wish to study an academic curriculum during their high-school years.

In 1973, I continued with my graduate studies in applied mathematics at Tel-Aviv University. Tel-Aviv had an outstanding group of numerical analysts. Those were formative years for me, with teachers and students who later became colleagues and who helped shape my interest in applied and numerical analysis. I felt very comfortable with analysis and was caught up by the interplay between the analytical and computational aspects of numerical algorithms.

Later, I continued with my post-doctorate studies at CalTech which was home to one of the top rated groups in applied and computational mathematics. It was then that I met Professor Heinz-Otto Kreiss, who later became my mentor. I was greatly influenced by his work. Fifteen years later we ended up as colleagues at UCLA and have remained close friends over the years.

I: Is the π-club still in existence?

T: No, unfortunately. It lived through the 70s and it was very successful in attracting many bright young mathematicians, led first by Professor Zwas and later by Professor Moshe Goldberg. The topics covered in those weekly meetings were a cross section of analysis and computation. I know that the memory of the π-club remains very vivid in the minds of those who attended it; I know it is in mine.

I: You were attracted to numerical analysis right from the beginning?

T: Yes. My interest grew out of my education. There were the analytical tools that one learns about at the early stages. I mentioned my early years at the π-club and at Tel-Aviv University. At the same time, there were the numerical algorithms that one could implement and one would like to know if they work; more important, why they do not work. The analysis part of the numerical analysis plays an important role in clarifying these "if" and "why" parts. Often, these questions cannot be addressed within the numerical universe per se: they cannot be divorced from the underlying mathematical model they are trying to simulate. I have always liked the interface between mathematics and numerics. I still do. Back then, mathematics was used to design more efficient numerical algorithms. Today, there is a feedback loop, when numerical algorithms impact the kind of mathematical questions being asked.

I: Do you actually use the computer to create the patterns and algorithms?

T: Well, the computer cannot replace the creative process. So the answer is "No". If you would like to create or analyze a numerical algorithm you are on your own. But this is only part of the answer. The computer is the test bed which enables your ideas to be tested. It is the new experimental laboratory, so you are not alone but you go back and forth. At the same time the answer is "Yes"; the computer, or more precisely its output, does produce patterns. These could be just spurious numerical artifacts; but they could also reveal new phenomenon that was not observed before and drives a new mathematical inquiry. It is a partnership. Numerical algorithms are an asset of this partnership.

I: Do you actually devise the algorithms?

T: Yes. I devised, for example, algorithms for solving certain nonlinear partial differential equations. Other algorithms were constructed which enable me to "manipulate" various representation of discrete data. You often read that the computer "solves" a problem. The computer does not solve anything. It implements different algorithms to solve different problems. In my case, I am interested in developing and analyzing numerical algorithms which produce accurate solutions for differential equations, or process voice and image data.

I: Am I right to say that you are not interested in the algorithms per se but that you are interested in algorithms to solve partial differential equations and so on?

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T: You are right. I am more interested in the mathematical aspects of such algorithms. Having said that - numerical algorithms are not just a thought experiment; computers enable us to actually implement the algorithms we devise. This is the partnership I was talking about and the various aspects of implementation, therefore, become an integral part of the overall computational task.

I: Computer scientists study algorithms too. Are you interested in computer science?

T: The various aspects of implementation I was talking about are traditionally a main focus of computer science. But computer science can be viewed as the totality of what computer scientists are interested in, and there are many who study the algorithmic aspects combined with the mathematical aspects. There is no clear borderline. It is more a question of different emphasis. My emphasis is more on the mathematical aspects and less with the algorithm per se.

I: Do you consider yourself to be more of an applied mathematician than a pure mathematician?

T: I am an applied mathematician. But considering my work on the theoretical aspects of partial differential equations and their counterpart in numerical algorithms, some applied mathematicians would classify me on the pure side. It is difficult to decide where pure mathematics ends and where applied mathematics begins. The branches of mathematics I am involved with are primarily analysis and scientific computation, which, in the great vague divide of classifying pure and applied math, is categorized on the applied side.

I: Do you use the algorithms to actually solve the differential equations?

T: I develop algorithms for accurate solution of differential equations and I test them on a host of model problems. These then become tools that are applied to solve a host of problems in various fields. In some cases, the problems and the methodology for solving them could be very specific. For other cases, we developed a family of "black box" solvers which are portable enough to solve differential equations from a great variety of different applications.

I: What about the Navier-Stokes equations?

T: The set of Navier-Stokes equations governs the dynamics of flows at the human scale. That is, everything from air flow around airplane wings to the water flow in your bath tub. One might be surprised, maybe even worried, that just one simple set of equations is sufficient (or supposed) to describe so many different phenomena. Well, the Navier-Stokes equations are essentially one set of equations, worked out by the giants of the past. But they are not as simple as they appear to be. It is not totally surprising, therefore, that our mathematical understanding of these equations is incomplete. Indeed, there is a $1M [one-million-dollar] Clay [Institute] prize for successfully clarifying part of the puzzle surrounding the mathematical quantities governed by these equations: what properties do they have? But even without the full understanding of their mathematical properties, we are developing numerical algorithms for the approximate solution of these equations. Practitioners compute the numerical solutions without necessarily waiting for their full mathematical understanding. At the same time, it excites a lot of research, a lot of ingenuity, and a lot of numerical experiments which try to complement each other in gaining insight into the mathematical properties of the Navier-Stokes solutions. A large component of the weather system, for example, is also governed by the Navier-Stokes equations. Here, interactions occur across several scales which are still human scales, say, larger than atomic scales and smaller than cosmological scales. The enormous complexity cannot be contained between the purely analytical walls, but it requires modeling and numerical simulations.

I: Can we say that in some sense, numerical analysis depends on the ability to design more and more powerful computers?

T: This depends on what your meaning of the word "depends" is (excuse the cliché). The mathematical models we are trying to simulate are independent of computers and to a large extent, so are the numerical algorithms which perform these simulations. The numerical analysis of such algorithms is intimately connected with the properties of the underlying model. In this sense, numerical analysis is independent of the computer running these algorithms.

At the same time, more powerful computers alter the kind of questions we may ask about our numerical algorithms, and lead to different notions of what optimal algorithms are. If in the past, it took 48-72 hours to simulate tomorrow's weather, then naturally, numerical analysis turned its focus on developing much faster algorithms. Over the years, the speed-up in computer power accelerated by Moore's law, doubling itself every 18 months. Everyone is familiar with it from his or her PC, but this doubling factor also applies to the new and improved numerical algorithms that were developed over the years. So nowadays, when it is feasible to compute tomorrow's weather in less than 24 hours, the demand arises to include more realistic models, or to develop new algorithms to include much better visualization. In this sense, numerical analysis depends on more powerful computers. Moreover, if computers become powerful enough, they can run different algorithms that communicate across different scales, and thus, instead of using mathematics to model the ensemble of small scales we

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can think of numerical algorithms performing the modeling "on the fly". Clearly, this requires the development of new numerical algorithms which are byproducts of more powerful computers. A more powerful computer will enable us to reach new territories that have not been reached before. Still, you need the creative process of developing and analyzing new numerics to conquer these territories, and this is independent of how powerful the computers are.

I: Have the powerful computers raised any new issues and brought about new developments in numerical analysis?

T: Absolutely. The canonical example is parallel computers. Parallel computers completely changed the scope of what algorithms can do. What might be impractical or even impossible to do with computers based on a single processor becomes possible to do in parallel processing. Quantum computing could be the next and perhaps ultimate leap.

I: So the limit exists?

T: I think it does. One might say that if we just have powerful enough computers, many times more powerful than what we are having today, then we will be able to solve *everything*, to simulate a complete dynamical ensemble, perhaps even from quantum scales all the way up to the human scales. I do not know about the technological barriers here. But I will argue that even if the technological difficulties will be resolved, say in the next hundred years, still the smaller it gets, the slower the clock gets. That is, one needs to sacrifice a certain level of detailed information for having a computational algorithm to run at a finite time, that is, finite in human scales. And as powerful as computers can get by miniaturization in space, they will slow down in time. In this sense limits exist and there is room for developing numerical algorithms for mathematical models which will bridge this gap of space and time.

I: Could you give us some examples of successful numerical algorithms?

T: The Gauss elimination method for solving N linear equations with N unknowns is perhaps the most ubiquitous numerical algorithm of all. It was always out there. But the Fast Fourier Transform was not and its discovery in the mid-sixties has had a lasting impact. It computes the periodic building blocks of general waves based on N samples and it reduces the computational work by order N. This is Huge. If N has the reasonable size, say, of ten thousands, then this is equivalent, by Moore's law, to ten years of hardware speedup. These are exact algorithms. Their success is based on clever rearrangement of the computed quantities to achieve the final result in a fraction of the time it requires for a straightforward computation. In other cases, only approximate solutions are sought. This is the case with the solution for a host of partial differential equations drawn from various branches of science; the equations are just too complicated to be solved exactly. Approximate solutions are satisfactory. Here, there is a trade-off between how accurate the computed solution is versus how fast it can be computed. Many modern numerical algorithms are successful in making this trade-off. These numerical algorithms are successful in being very efficient.

I: There is an old perception that a mathematician's job is done once the model is formulated and that the rest is the job of the mathematical technician. How much has the role of the mathematician in modeling changed over the years?

T: On the contrary, the job of a mathematician just starts when the model is formulated. The modeling I am referring to is not necessarily mathematical modeling. Before the genome there was the double helix and it was more descriptive than quantitative. Before Kepler's laws, you had Copernicus and his concept was not as quantitative but has had much more impact than Kepler's. Mathematics seems to be the most successful language to translate our qualitative concepts about the physical world around us into a set of quantitative statements. Today, more than ever before, there is a large effort to duplicate this success with quantitative biology. Still, the mathematical modeling is not left to mathematicians but to the interaction between scientists from different disciplines with mathematics. Once a model having its roots in biology, nano-science, chemistry or astronomy has been quantified, mathematicians study the interconnections, trying to fit the mathematical model as part of a greater puzzle. Often, modeling is a much more laborious and less glamorous task than the formulation of "$E=mc^2$". It involves experiments, measurements, statistical evidence and numerical experiments. More than before, pure and applied mathematicians are involved in all those aspects. This is particularly true with regard to the computational aspects. In the past, there was one critical reality check for a scientific theory, namely, that its predictions can be proved or disproved by experiment. Nowadays, computations provide another reality check for developing theories. This is the interplay I was talking about before, of numerical algorithms simulating mathematical models from different scientific disciplines. This is the intersection called "scientific computation".

I: Is there a coherent theory of scientific computation or is scientific computation nothing more than a collection of ad hoc methods and clever techniques?

T: Yes, there is a coherent theory of scientific computation. There are the fundamental concepts, technical tools, hierarchy of knowledge. But like every other area in mathematics, there are many isolated islands. Scientific computation, more than most of the other areas in mathematics (statistics

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might be the exception), is at the forefront of interaction with the other sciences and therefore, it has a constant flood of new input from the "outside". It absorbs clever new tricks, ingenious mathematical techniques and algorithms we do not always understand why they work so well. But over time, some coherence emerges. Sometimes there are ad hoc methods pulling the theory forward. Other times, the theory identifies the danger zones where the numerics will not work, or even worse, will work out the wrong solution. There is a healthy tension between the hierarchy of knowledge and the collection of ad hoc methods. Over time they merge into a coherent theory of scientific computation. It is a relatively young area of twentieth century mathematics and it is a very lively one.

I: Do you consider mathematical modeling a science or an art? Is there some quality beyond mathematical expertise that one need to possess in order to be successful in mathematical modeling?

T: Mathematical modeling is an art, expressing itself in a quantitative language. Well, there is no recipe of how to make a mathematical model. It requires creativity, curiosity, ingenuity, imagination in addition to understanding the science behind the model.

Let me mention the example of modeling images. Images are all around us and nowadays our world is going digital. Digital images are collections of many pixels. My digital camera has five mega pixels. And each pixel has its own, very local grayscale (or color scale). We do not see these individual pixels, but instead, we see their collection as an image. In the last decades, many models were developed in order to manipulate the collection of pixels as images so that we can transmit, compress and in general, manipulate digital images. There are many mathematical models but there is still no final word about the one way that we should interpret a collection of pixels as an image.

I: Is the model independent of what goes on in the brain? Are the images not affected by the processes in the brain?

T: This is the reason I mentioned this example of image processing. Modeling digital images lives outside the mathematical universe. There is the mechanical part of the human eye. There is the conceptual part of the brain which puts together an ensemble of small pixels and gives them sense of what we understand to be an image. Once again, mathematical modeling seeks to match the world we see around us on the human scale, to a world made up from basic elements on a much smaller scale.

I: What is the greatest satisfaction you have had in your research career?

T: There are the moments you understand the answer to a mathematical question that bothered you for a long time. You know when you unlock the puzzle. These moments are very rewarding. It is a peak of a creative process. Another rewarding aspect is the development of numerical algorithms. It is rewarding to see a numerical algorithm that you have thought about, realized on the computer. And there is a great satisfaction in learning new ideas that are born into mathematics. There is a constant process of renewal, a generation of new ideas. There is still part of me which remains as excited about mathematics as I was during my days in the π-club. This is very satisfying. I feel blessed.

I: I believe that our Institute (IMS) is modeled in part on your Center for Scientific Computation and Mathematical Modeling. While IMS spreads its programs over diverse fields, your Center is extremely focused. Could you tell us something about your Center?

T: The director of IMS, Louis Chen visited us in 2001 when I was the director of the NSF Institute of Pure and Applied Mathematics (IPAM) at UCLA. This visit took place just before the IMS was launched. Certain aspects of the IMS, like its scope, covering a wide spectrum of mathematical areas, are modeled after the national NSF institutes such as IPAM, MSRI and IMA. In this sense, the IMS serves the purpose of appealing to a wider spectrum of the pure to the applied crowds. In 2002 I was recruited by the University of Maryland to serve as a director of its Center for Scientific Computation and Mathematical Modeling (CSCAMM). Our center is not a national center. It is a major initiative which is completely funded by university, devoted primarily to scientific computation and mathematical modeling and their interaction with other scientific disciplines. I elaborated before on my views as to the role of mathematics in this critical junction. A main part of our visitors' program centers around CSCAMM workshops. We organize several workshops each year and they have already achieved a considerable success in increasing the visibility of the outstanding faculty and activities in Maryland. Our center is an independent arm of the College of Physical Sciences in Maryland, with the mission of increasing the interaction between the different units through their common interface of scientific computation. Thus, the flavor of CSCAMM is somewhat different from the national institutes and it has a different strategic direction, as it is trying to lower the barriers between faculty inside and outside the university through the more focused platform of scientific computation and mathematical modeling.

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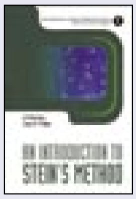

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