Interview with Tony Guttmann

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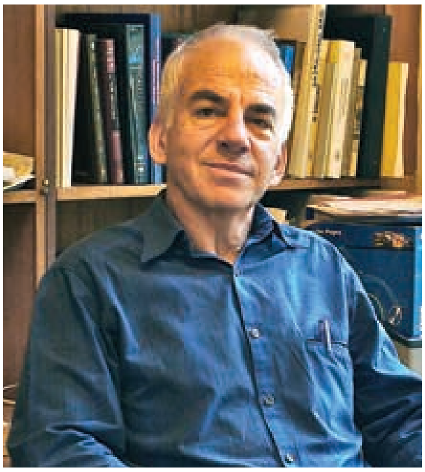
Peter Hall



Tony Guttmann

Introduction: Anthony John Guttmann was born in Melbourne on April 8, 1945, the son of Hungarian immigrants. He studied electrical engineering at the University of Melbourne, before switching to science during his second year. He did his PhD at the University of New South Wales, in Sydney, and went on to postdoctoral work at King's College, London. This training set him on course for a distinguished career in mathematical physics, throughout which a common thread has been his research on the mathematics of critical phenomena.

Early in his career many of Tony's contributions had a strong numerical flavour; he developed ingenious methods for approximating infinite series that converge extremely slowly. In more recent times he has worked on problems that are more typical of the Australian mathematical physics community — for example, research on the Ising model, and more generally on processes defined on lattices and other geometric structures. In 2002, in recognition of his many research achievements, he was elected to the Australian Academy of Science.

However, Tony's contributions to mathematics go well beyond his own research. He has served as the Director of MASCOS (originally the Australian Research Council Centre of Excellence for Mathematics and Statistics of Complex Systems) since its inception in 2003. MASCOS' initial funding from the Australian Research Countil (ARC), about $11 million for five years, was later extended for a second term. In addition to providing substantial leadership and support for excellent research in the mathematical sciences, MASCOS stands out as the only ARC-funded mathematics centre in Australia since Neil Trudinger's Centre for Mathematical Analysis, which operated from 1982 to 1990.

Tony's interest in mathematics is as broad as it is deep. He has made many contributions to school and university syllabuses, and to issues of equity and access.

For almost 30 years he has run a high-level, statewide school mathematics competition in Victoria, often with the support of private industry. The competition has been successful in many ways, primarily by recognising and encouraging mathematical talent.

Peter Hall: Thanks very much, Tony, for agreeing to this interview. If I may I'd like to start not just with your own early life, but with that of your parents. I believe your origins in Australia, like those of number of other Australian mathematicians, owe much to the turmoil in Europe 80 or so years ago.

Anthony Guttmann: Yes, my parents both were Hungarian and Jewish. My father, as a youth, had some particularly unpleasant experiences in World War I which made him apprehensive of German militarism. Thus, with a premonition of difficulties to come, and despite being rather risk averse, he persuaded my mother, whom he had married in 1937, to leave Hungary for Australia. This they did, more or less on the last boat before the outbreak of World War II in 1939. They were bound for Sydney, to a future entirely unknown, but someone on the boat knew someone in Melbourne, and persuaded my parents to disembark there.

PH: Can you tell us a little about your mother and father, and their lives in Australia?

AG: My father was an architect, but had to retrain in Australia as his qualifications weren't recognised here. My mother came from a family of four girls, and her parents did not value education highly, particularly for girls. She was interested in languages, literature and the arts. In Hungary she had worked as a secretary for her uncle, who was at that time Hungary's leading sculptor, Telcs Ede. She spoke excellent German as well as Hungarian and English, and in Melbourne got a job as a secretary with the Dutch Embassy during the war, and quickly learned Dutch. My parents were too uncertain of the future to risk having children until 1945, when I was born. My mother was 35, and that was considered quite elderly for a first child, and so I remained an only child.

As recent migrants from eastern Europe to Australia my parents came under suspicion during the war. For example, my father had arrived with a Leica camera, but was forced to dispose of it here; he had to sell it to the Royal Australian Air Force. And he was forbidden to operate his car.

PH: What was your own schooling like, and were you ostracised as a refugee?

AG: No, I don't recall any prejudice on account of my origins. However, my primary schooling was unremarkable, except that at age six I contracted mumps, which caused permanent nerve deafness in my left ear. I spent six months in Sydney, undergoing a useless course of treatment.

Back in Melbourne I then spent four years at Camberwell Central School, where I recall an excellent French teacher, but little else. The last four years of my schooling were spent at Wesley College. This was not a particularly happy period of my life. Wesley viewed itself as an outpost of an imagined Empire, and attempted to imbue, by osmosis and the cane, values that didn't resonate with me.

However, I liked the science education, and at home set up laboratories for electronics, another for chemistry, a photographic darkroom and a budgerigar aviary. These activities were rather more interesting to me than school. To my current regret I had virtually no interest in sports at that time. I had a brilliant chemistry teacher, Alan Gess, and solid, rather than inspiring, mathematics teachers.

Overall, my education in science was more inspiring than that in mathematics. You might describe me as very "hands-on" as a child. I left school more practically than theoretically minded. This was to determine the directions I took in my early years at university.

When I left school I was rather confused as to what course of study to take at University. I entered Melbourne University in early 1961 at age 16, and, unsurprisingly given my experience at school, enrolled in Electrical Engineering. I loved the freedom of university life, the parties, the fact that most of my friends had cars, and of course there was no querying one's age in pubs in those days. As a result I came very close to failing my first year. This gave me quite a shock. In second year I started taking my studies more seriously, and realised by mid-year that I liked physics and mathematics more than the engineering subjects.

PH: So, in your second year we see your mathematical side, and perhaps even an instinct for abstraction, emerge, despite your experience with mathematics at school.

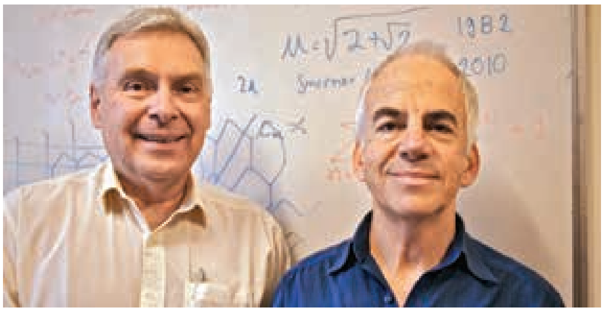
AG: There was little about my experiences at school that could have inspired me to become a mathematician. While studying engineering at university I began to develop an interest in mathematics, but even then it was not deep. But by second year I realised that I was enjoying the mathematics side of my work much more than the experimental side. I was quite adept at experimental work, but not intellectually attracted to it.

In those halcyon days academics controlled the university administration, so I spoke to the person in charge of second year physics, Ken Hines, about my desire to switch to Science. He said that I could switch from engineering mathematics to science mathematics, and make up whatever I'd missed, just by reading the textbooks. Likewise the all-important physics practical work — I could wander into the labs and make up the missed practical work. All this suited me very well.

In third year as an undergraduate I probably learned most of my mathematics from the physics department. I learned about differential equations and, to an extent, group theory by studying quantum mechanics, and complex variable theory and integral transforms through diffraction physics.

PH: So, even though you turned to mathematics at university, it was very much in the context of physics.

AG: Yes, I received a lot of inspiration from John Cowley, who was a brilliant, newly appointed Professor of Physics and built a world class group in diffraction physics. I became interested in the theoretical side. I did my honours project trying to adapt the theory of electron diffraction to neutron diffraction, including an abortive attempt at an experiment at Sydney's Lucas Heights reactor, for which I had to get security clearance. This confirmed to me the advantages of a



Peter Hall and Anthony Guttmann

theoretician's life over an experimentalist's, even though I was probably more inclined to the latter.

PH: I imagine that your postgraduate work followed a theoretical course, too.

AG: In early 1965 I commenced an MSc in physics at the University of Melbourne, with my project being to calculate X-ray dispersion corrections — so my thesis topic was distinctly theoretical. I finished this project early, and Norm Frankel got me involved in a calculation of the properties of Bose–Einstein condensates. This was a massive computational project. I was trained to run the university's mainframe computer, and would spend weekends in the machine room running programs for 24–48 hours, with my friends bringing me food from the Genevieve Restaurant. In those days, large scale computing meant boxes of punched cards for input, and storing data on massive tape drives. The area now occupied by the campus post office held the computer at that time.

I shared the prize for the best Masters thesis with Andrew Prentice, and this gave Ken Hines, who'd taken a risk with me, particular pleasure. I was pleased to have justified his faith.

PH: Well done! I believe that in 1964 the university purchased an IBM 7044 machine, and retired CSIRAC II, then the oldest working electronic computer in the world. But we digress. You did your PhD in Sydney, in mathematics; how did you make that transition?

AG:I had heard excellent things of John Blatt, Professor of Applied Mathematics at The University of New South Wales (UNSW), and as my girlfriend, now my wife, lived in Sydney, I applied for (and was accepted as) a PhD student there. This was at the beginning of 1967. Almost immediately there was a Mathematical Physics Summer School at the Australian National University (ANU), with a cast of experts possibly never since matched in Australia. They included C N (Frank) Yang, Freeman Dyson, Bram Pais, Dmitry Shirkov, Joel Lebowitz, John Blatt, Stuart Butler and others. The lectures were mostly at too high a level for me, in my first month of a graduate program, but were inspiring nonetheless. At the end of that year I married Susette, a recent Arts/Social Work graduate.

However, John Blatt was mostly absent, frequently travelling in the US. (He felt he'd been robbed of the Nobel Prize for the discovery of superconductivity.) As a result I did my PhD at UNSW under the joint supervision of Barry Ninham and Colin Thompson. I submitted my thesis in 1969.

PH: At that point, I think, you left Australia to work in London.

AG: Yes, I was offered a postdoctoral position at King's College, London. Susette and I travelled by ship, as I'd won a travelling scholarship to cover those expenses. The Suez Canal was closed, so we went via South Africa, and were able to leave the ship in Durban and drive to Cape Town and reboard. That was the highlight of the trip. The King's College group was a very active one, and I formed life-long friendships with a number of my colleagues there.

PH: You came back to Australia after your postdoc, to the University of Newcastle — established only while you were doing your MSc.

AG: In 1971 we returned to Australia. I'd applied at the ANU, to work in Barry Ninham's department, and also at the University of Newcastle. Newcastle offered me a job first, and we thought that after London there was not much difference between Newcastle and Canberra, so I accepted a lectureship at Newcastle. It was a wonderful time, with typically three or four new appointments each year for a few years, so we were a young, naive but enthusiastic group. Everything seemed possible then.

Newcastle had the first (and probably last) Faculty of Mathematics in Australia. The Foundation Dean was Reyn Keats, a former Rat of Tobruk [the name given to Allied soldiers who held Tobruk, in Libya, against the Afrika Corps in 1941]. He did an outstanding job building the Faculty, and in particular he decided to initiate a postgraduate Diploma in Computer Science. Based on the fact that I knew how to program in Fortran, I was put in charge of this diploma, and asked to lecture in the foundation courses. I had never studied computer science, but read the relevant textbooks, and was at least a week and sometimes two weeks ahead of the students. I wrote a book, *Programming and Algorithms*, based on one of the courses I'd taught!

Newcastle was meritocratic, and it was possible to advance quickly. I became a Senior Lecturer after a year, and Associate Professor a couple of years later. A few years after that I was Professor and Dean.

PH: Those were heady times, and must have contrasted with your experience at King's College. However, the administrative load must have been considerable.

AG: Yes, the University of Newcastle was unconstrained by tradition, unlike King's. Keats always tried to appoint the very best people he could. However, the distribution of students' preparation was much broader than at Melbourne.

After about a year of being Dean, and still in my 30s, I decided I really didn't care for the amount of administration that the job entailed. I took a six month sabbatical at Melbourne University, and was offered a Readership at the end of that time. I accepted this (which did not go down well at Newcastle) and was appointed to a Personal Chair a year later. Colin Thompson had started the Statistical Mechanics Group, and I was fortunate enough to be there at a time when the opportunity was available to build the group into a large and highly successful one.

PH: This must have been quite a contrast to your time at Newcastle.

AG: In my 15 years at Newcastle I'd had one PhD student and one postdoctoral colleague, but at Melbourne the opportunities were much better, and I had a steady stream of very good to outstanding students, as well as very many first-class postdoctoral colleagues. Only one student failed to complete — he'd done more than enough for a thesis, but was seduced by Google before he finished writing up, and never bothered to do so, to my regret. I've also been able to help out with some exceptional school students, and undergraduates.

At the University of Newcastle I met Nick Wormald, whom I think you know from your school days in Sydney. He is a strikingly strong discrete mathematician, and, was one of the mathematicians I persuaded to move to Melbourne. These days he is at the University of Waterloo, where he has a Canada Research Chair, although I'm particularly pleased to see that he will return shortly to Australia, to a position at Monash University.

PH: Perhaps we can turn now to your work developing and leading research institutes in Australia. It has been highly successful, and particularly influential.

AG: It began in 2002 when Jan Thomas and I wrote a successful proposal to the Victorian Government for a mathematical sciences institute. Thus the Australian Mathematical Sciences Institute (AMSI) was born. I was the first Director. Melbourne University was very supportive and provided premises and other facilities. A year later I participated in a bid for an ARC funded Centre of Excellence. This was successful, and thus MASCOS, the ARC Centre of Excellence for Mathematics and Statistics of Complex Systems, was born. I became, and still am, the Director of MASCOS, so I had to resign from the Directorship of AMSI, though MASCOS and AMSI have continued to cooperate on various activities, to our joint benefit.

PH: Your efforts have been remarkable — Australia has had so little by way of research institute activities in the mathematical sciences, and you have been behind the two most recent successful ones. Do you have in mind any model for the type of research institute that might suit Australia best?

AG: I think there are two conventional models, both working successfully abroad. The first is for an institute that runs programs, typically weeks or months long, in which both young and experienced visitors participate. The second type focuses more on younger people, for example students or postdocs, and there the period of residency may be (but is not necessarily) relatively long. The first type is more common, and includes, for example, Berkeley's Mathematical Sciences Research Institute (MSRI), Oberwolfach, and the Isaac Newton Institute.

I think the most appropriate type for Australia is probably a mixture of these two. I've recently spent periods at both MSRI and the Mittag-Leffler Institute in Stockholm, which focuses on the training of young mathematicians, especially students. It runs both long and short programs. Canada arguably has the greatest variety of mathematics research institutes, at least in terms of the ways in which they operate, and we could learn a great deal from the Canadian experience.

My preference is for an institute that is a reasonable distance from major institutions, such as universities. I'd favour a stand-alone facility, away from a major metropolitan centre. If it is attached to a university, the local people tend to go home in the evenings and much of the life of the institute is drained away.

PH: Perhaps you could give us your view of the state of mathematics in Australia.

AG: Australia, like most English speaking countries, has a good rather than a great history of mathematics education at the school level. Given our comparative wealth, I feel we should all be doing a great deal better. There have been enough credible reports into the mathematical sciences in Australia that I don't need to repeat the outcomes and recommendations here.

Primary and secondary school teachers here tend to be undertrained in the mathematical sciences, with some notable exceptions, and so are unable to provide as rich an education as they can in other areas. As a result, too many school children are indifferent or hostile to mathematics. There is a strong case for making school teaching a better paid profession, with more highly trained teachers, as is the case in some European countries.

Our universities are also doing as good a job as is possible in current circumstances, but are significantly under-resourced. This is due to a combination of increasing government imposition of rules and regulations, and a tendency by Vice Chancellors and Councils to run universities as corporations, so that the administration and support side is generally bloated, and the academic side — which is the heart of the university — is comparatively starved. Australia will never have a university, or mathematics department, in the top 25 until Vice Chancellors realise that they need to spend money on world class academics, rather than on yet another Deputy/Associate/Assistant Vice Chancellor, and the associated entourage.

It is still a source of considerable regret that Australia has no research institute of the type we've discussed. While I am delighted at the sporting success produced by various state and federal Institutes of Sport, it should be a source of national shame that we have no corresponding institute for the mathematical sciences. It is telling that the Australian Olympic team bound for London is larger than the Chinese one, yet China has several mathematics institutes; we have none.

PH: We haven't yet spent much time discussing your own research. Let's turn to that topic now.

AG: My PhD topic was a blend of combinatorics and numerical analysis. At that time mathematical models of phase transitions were something of a mystery. The Onsager solution of the two-dimensional Ising model free-energy was a singular exception. This was before the days of the renormalisation group, before the Yang–Baxter equation and concepts of integrability were utilised, before the theory of universality, and before Monte Carlo was a useful technique.

The idea at the time — and still a powerful technique — is that to determine the asymptotic behaviour of some property of, say, the Ising model, one expanded it in a power series expansion. My thesis topic was to develop numerical techniques to determine the asymptotics, and, to a lesser extent, to compute the terms more efficiently. As an indication of how far we have come, the susceptibility of the two-dimensional Ising model was then, and remains, a seminal problem. At the time of my PhD studies we had some 20 terms in the series, and we could predict the dominant asymptotic behaviour. We currently have 10,000 terms, and have about 100 terms in the asymptotic expansion, including subtle powers of logarithms.

During my time as a postdoc at King's College I developed, with my colleague Geoff Joyce, the best method at the time for analysing power series expansions, called the method of differential approximants. Some 40 years later it is still the best method. Again with Joyce, and a Canadian visitor Donald Betts, we developed a generalised law of corresponding states, a modern version of van der Waal's work, and a complement to the then burgeoning ideas of scaling and the renormalisation group.

Two years after I left King's in late 1971, Ian Enting arrived at King's from Monash, and together with Tom de Neef developed a powerful method for generating series expansions, called the Finite Lattice Method. It is still an incredibly powerful method, and Ian and I formed a partnership using his series expansion techniques and my analysis techniques to reshape what was considered possible in that area. Melbourne University is still the world centre of these ideas, due to further developments by Ian Enting, Iwan Jensen, and very recently Nathan Clisby.

Later, after joining Melbourne University, Ian Enting and I realised that we could use numerical techniques to explain why some lattice statistical problems were solvable, and others were not. This was a totally different, semi-numerical approach, which didn't give a solution, but gave a strong hint of the presence or absence of solvability, which in favourable circumstances could be refined into a formal proof — as first demonstrated by my PhD student, Andrew Rechnitzer. It was quite different from the powerful analytic work than being done by Rodney Baxter and his colleagues at the ANU, and the connection with integrability remains obscure. I am still studying lattice models, but now from a more algebraic viewpoint, and using techniques from number theory, and more modern ideas like discrete holomorphicity to derive solutions, or sometimes proofs of conjectures.

After a sabbatical in Oxford in 1992, and visits to the University of Bordeaux both then and again in 1996, my interests changed to include a lot more algebraic combinatorics. As these interests grew, I was asked to edit a special issue of *Annals of Combinatorics* highlighting the connections between statistical mechanics and algebraic combinatorics. I was subsequently asked to organise the annual Formal Power Series and Algebraic Combinatorics Conference in Melbourne — I think the only time that that conference has been in the southern hemisphere.

PH: Against this background, perhaps we could take a look at how your areas of research have changed during your career.

AG: Mathematical physics and mathematics have definitely grown closer. Mathematical physicists really need a broad armoury of techniques these days, across many areas of mathematics and probability. Mathematicians have brought into the mainstream the outlandish ideas usually first developed by physicists. The theory of generalised functions is an early example with which I became familiar. In physics, areas like conformal field theory make predictions that are eventually made rigorous by mathematicians. Traditional concepts of mathematics, like analyticity, have been extended to the discrete case. The resulting concept of discrete holomorphicity is responsible for several important recent advances. Similar ideas, plus applications of stochastic ODEs leading to Schramm–Loewner Evolution and probability theory, have led to advances recognised by the award of several recent Fields Medals.

To be more specific, one problem that spans both algebraic combinatorics and statistical mechanics that I've been involved with all my professional life is studying the properties of self-avoiding walks on a lattice. Let c_n denote the number of SAW on a lattice (periodic graph) equivalent up to translation. Some 60 years ago, John Hammersley proved, by simple concatenation arguments, that $\mu := \lim_{n\to\infty} c_n^{1/n} = \inf_n c_n^{1/n}$ exists, and is greater than zero. A few years later he refined this to establish that $c_n \sim \mathrm{const.}\, \mu^n\, n^{O(\sqrt{n})}$. Numerical studies, and comparison with exactly solvable models, leads us to believe that $c_n \sim \mathrm{const.}\, \mu^n n^g$, where it is known that μ depends on the choice of lattice, and it is believed that the exponent g depends only on the dimensionality of the lattice. For two- and three-dimensional lattices, to this day we do not even have a proof of the existence of the exponent g; though it is universally believed that $g = 11/32$ for two-dimensional lattices, and a somewhat smaller value, estimated to several decimal places but not believed to be rational, for three-dimensional lattices.

The value of μ was conjectured for precisely one lattice, the hexagonal lattice, 40 years ago by B Nienhuis. It was not until 2010 that S Smirnov and H Duminil-Copin proved this conjecture, using ideas from discrete holomorphicity, notably the identification of a so-called parafermionic operator. For SAW originating in a surface, there is a second exponential growth constant associated with the number of steps of the walk that lie in the surface. Above a certain critical value of attraction, a macroscopic fraction of the steps of the walk lie in the surface. Following Nienhuis, M Batchelor and C Yung conjectured the exact value, again in the case of the honeycomb lattice in 1995. This was finally proved by my colleagues and I in 2012. You will be pleased to hear that one aspect of the proof relied heavily on probabilistic arguments.

As for critical exponents, if one could prove that the scaling limit of SAW was describable by $\mathrm{SLE}_{8/3}$; for which abundant evidence exists, but no proof, then not only would the existence of the exponent g be proved, but so would its value. A lot of effort is going into attempts to achieve this proof.

Changes in technology include the development of algebraic packages like Maple, Mathematica and Matlab, as well as more specialised systems. These free us from some of the drudgery of routine calculations — and at least in my case lowers the error rate significantly. Using computers to provide proofs, through certification of identities, is now commonplace. Also, increases in computer speed and reduction in memory costs permit calculations of formerly inconceivable scope to be made.

PH: How have your own students done? You have had more than ten, which in mathematical physics in Australia is large. Some of them have been remarkably young, like Yao-ban Chan, who was a postdoc with me for several years.

AG: I have had twelve PhD students for whom I was the primary supervisor. Six of these have gone on to academic careers. Eva Swierczak, Andrew Rogers and Will James are working in the finance industry, Debbie Bennett-Wood became a school teacher and is now raising horses, John Dethridge works for Google, and Andrew Conway started in academia, then built up his own software company in Silicon Valley, and now pursues private and family interests. Of the six currently pursuing academic careers, Albert Nymeyer is at UNSW, Andrew Rechnitzer is at the University of British Columbia, Yao-ban Chan is at the University of

Vienna, Nick Beaton is at Université Paris 13, Henry Wong moved to psychology at Melbourne University, and Markus Vöge was until recently at the Swiss Federal Laboratories near Zurich. Two of these, first Andrew Conway and then Yao-ban Chan, were the youngest PhD students in the history of the University of Melbourne.

PH: You've had an outstanding and varied career. Against this experience, do you have any advice for young men and women starting out in mathematics today?

AG: My generation has been extraordinarily fortunate. We have largely escaped wars — though I was drafted during the Vietnam war, but was medically rejected — and an academic life was very rewarding. Now there are ever-increasing burdens placed on academics. It is not enough to be an excellent researcher and a decent educator. One needs to be an educator loved by students, a successful earner of research grants, a supervisor of numerous graduate students, to be heavily involved in administration, to be chair of numerous committees, to respond to numerous on-line training courses, to fill out regular bizarre questionnaires, use incredibly expensive user-hostile software to perform what should be trivial tasks, and respond to reporting requirements of an invasive and time consuming nature. As a result it is increasingly difficult to find sufficient stretches of uninterrupted time that is needed to undertake high quality research.

On the other hand, there are far more opportunities for mathematics graduates these days. Indeed, I can think of few professions where having a mathematics degree would not be a great advantage, by virtue of both the obvious skills one possesses, and also for the analytic way of thinking with which a mathematical sciences degree equips one. I should also mention that it's not just mathematics that has changed. To be a virtuoso violinist it used to be sufficient to play like an angel. Now it seems necessary, especially if you are female, to look like one as well.

PH: Discussing your academic descendants reminds me that we have not yet considered your family.

AG: I have two children, Jacki, who is an Arts Administrator with Melbourne Museums and has two children of her own, who are a delight to my wife and me. My son Laurence is a school teacher, initially trained as an English as a Second Language teacher, but who subsequently did a Masters degree in mathematics education, and is increasingly teaching mathematics. Both my children did their final year's of schooling at Wesley College, which has greatly changed for the better since my day — not least by becoming co-educational — and both attended Melbourne University for their undergraduate and graduate programs. My wife has worked as a Social Worker or Manager for much of our life together.

PH: Do you have any parting comments?

AG: Well, in my mid-30s my first PhD student, Albert Nymeyer, got me interested in running, and I have been running ever since, for example in marathons and triathlons. I could wax lyrical about the benefits of running — it was enormously helpful to me when I was appointed Head of Department in my early-mid 30s, with no training or experience; it helped me cope with stress.

I have also found running extremely useful when doing mathematics. Whenever I get stuck on a problem, I try to go for a run. I usually come up with a new angle or direction to tackle the problem. It doesn't always work of course, but it is an alternative to a dead end. Running also provides a pleasant and beneficial way to stay in close touch with younger colleagues, and colleagues from different disciplines, not to mention one's children and grandchildren.

PH: Thanks very much, Tony. This has been a particularly enjoyable experience, not least since our careers have much in common, meeting even in technical terms in the area of percolation. I wish you the very best for the future.

Peter Hall
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Peter Hall was born in Sydney, Australia, and received his BSc degree from the University of Sydney in 1974. His MSc and DPhil degrees are from the Australian National University and the University of Oxford, both in 1976. He taught at the University of Melbourne before taking, in 1978, a position at the Australian National University. In November 2006 he moved back to the University of Melbourne. His research interests range across several topics in statistics and probability theory.