PETER GAVIN HALL
A BRIEF REMEMBRANCE OF THE MAN AND HIS WORK

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After several extended visits, Peter Hall accepted a permanent appointment for one academic quarter per year as a Distinguished Professor of Statistics at Davis in 2005. It was obvious that we were welcoming to our fold an exceptionally productive scholar, a stimulating and energetic teacher – a colleague with a truly spectacular record of accomplishment. Not everyone knew, at that time, that we were getting much more! One might ask "who would want or expect any more, and what does "more" even mean?" What I and my colleagues quickly discovered about Peter, something that's all the more impressive and surprising because of his obvious dedication, and his attendant time commitment, to an ambitious program of scholarship at the highest level, is that he considered personal interactions to be as important as professional ones. He took a sincere interest in everyday objects like trains, planes and automobiles and in mundane matters like the bee infestation in my garage. It was easy to engage him in conversation, and when a real (non-mathematical) problem arose, he was eager to help in any way he could. He was happy to contribute his thoughtful insights on both personal and professional matters, and he would readily join in when discussions on local or global affairs arose. A few details about his family background might help to understand the person that Peter was.

Peter told me that he felt that he inherited many of his traits and habits from his parents. His mother, Ruby Payne-Scott, obtained a Master of Science degree in Physics in 1936 (the highest qualification then available at any Australian university). She made pioneering contributions toward the use of radar during World War II and was a recognized expert in radio astronomy. Indeed, she was the first female radio astronomer in the world. Her research contributions have been widely recognized and celebrated, and are described in a published biography about her life and work (see Goss and McGee (2010)). Ruby had a good deal to do with Peter's curiosity about science and with his interest in math-

ematics. Ruby was a strong woman with well-formulated and well-articulated views on science, on politics and on life in general, and Peter was encouraged to reflect on a broad array of subjects from an early age. Peter described his father, William (Bill) Hall, as a gentle, easy-going man. Bill Hall started his working life as a French Polisher and carpenter, and later became a telephone technician for the Australian Postmaster General, the government organization that ran the post, telegraph and telephone services. What Peter valued most in his father was his even temperament, his generous nature, his unfailing support of family and friends and his ability to listen sympathetically. It was not hard to tell that he was his father's son.

I will return to some discussion of Peter's personal characteristics, but I will first offer a brief tour of Peter's academic career. Peter was an exceptional undergraduate student at the University of Sydney, completing his Bachelor of Science degree with First-Class Honors and winning the University Medal in Mathematical Statistics in 1974. An additional indication of his "gifted and talented" status was the fact that he read the book *Rank Tests* by Hayek and Sidak in an undergraduate "individual study" course. Those who know the book also know that it is not recommended-reading material for the faint of heart. His next two degrees happened at warp speed. In two years, he completed a Master of Science degree at the Australian National University, writing a thesis on martingale limit theory, and a Doctor of Philosophy degree from Oxford University, writing a thesis on topics in probability theory. Professor Chris Heyde, under whom Peter wrote his Master of Science thesis at ANU, thought highly enough of the work that he proposed to Peter that they collaborate on an expansion of the thesis with a view toward publishing a book on the subject. This important reference book on martingale theory appeared in 1980 as an Academic Press monograph by Hall and Heyde. Academic Press reprinted it in 2014.

Peter had intended to do his doctoral work in Australia, but he changed his mind upon receiving a scholarship offer from one of the Oxford colleges. Peter told me, with a pained smile on his face, that his mother was not pleased with his bolting to the UK. Late in her life, Ruby suffered from Alzheimer's disease. She died in 1981, only faintly aware of the stellar career on which Peter was embarking. It would no doubt have given her great pride to know about Peter's numerous and highly acclaimed professional accomplishments, including an uncommonly distinguished academic career at leading Australian universities. Indeed, Bill and Ruby Hall raised two remarkable children - Peter, who reached the highest echelon, worldwide, among researchers in the mathematical sciences,

and Fiona, whose contributions to the plastic arts (especially, in photography and in sculpture) have garnered for her widespread recognition and high praise both in Australia and internationally.

It was at Oxford that Peter met the love of his life. Their romance is as engaging as any love story I have heard of or read about. Before arriving at Oxford, Jeannie Jean Chien Lo was a civil servant in Hong Kong. The British colonial government sent her to Oxford, on full salary plus allowances, to study management science and economics. Peter and Jeannie's meeting in the fall of 1974 was unusual – a blend of serendipity and fate. As it happened, a young woman who was studying Mathematics at Oxford with Peter had a bit of a crush on him and invited him to dinner. She asked her friend Jeannie if she could use her drawing room, a rare luxury at the time, to host Peter before dinner, and Jeannie was more than happy to oblige. Her friend then asked Jeannie to join them for dinner. Peter was smitten with Jeannie that fateful night. Shortly thereafter, Peter invited Jeannie to go punting on the river with him. When she told her girlfriend about it, she responded with the exclamation "I'm so jealous". Jeannie insisted that she join them. It is clear that Jeannie and Peter's first date was not a conventional "double date". It was, instead, a date and a half.

Peter proceeded cautiously, seeing Jeannie quite regularly over the next several months, but (my best guess) not wanting to scare her away by getting too serious too fast. Jeannie completed her studies at Oxford in mid-1975, and she left Oxford in July to resume her career in Hong Kong. Although Jeannie and Peter did not really know each other that well when she left Oxford, their relationship would change quite dramatically in the two years that followed. Shortly after Jeannie got home, she received her first letter from Peter. She responded the same day. From that point on, Peter and Jeannie wrote to each other every day, continuing until the day they were married in April 1977. Although they did visit each other both at Oxford and in Hong Kong in the interim, Jeannie credits their intensive correspondence for the growth of their friendship and the blossoming of their love for each other. Jeannie still has all of Peter's letters. They are a lasting gift that she will always be able to savor and enjoy.

I will return to Peter and Jeannie's story, but I will switch gears for a moment and focus on Peter's professional life. Upon reflecting on the latter topic, it occurred to me that Peter's phenomenal research productivity was actually somewhat predictable. We all know that, throughout his career, Peter was the most prolific researcher in our discipline, publishing four books (included here as references) and over six hundred research papers (which have not been refer-

enced here, for obvious reasons). However, when one notes that he wrote several hundred letters to Jeannie over a two-year period, his uncommonly prolific publication record might well have been anticipated. The fellow simply had a lot to say!

People who read Peter's writings can easily tell that he knew a lot of probability theory and that he used it masterfully. However, given the breadth and depth of his statistical work, the fact that Peter's graduate studies concentrated on probability theory rather than on Statistics might pass undetected. How he ventured into Statistics is an interesting story.

It was not easy for a fresh Ph. D. in pure mathematics to get an academic job in the mid-1970s. Peter started his academic career at the University of Melbourne in 1976, but left Melbourne in 1978 for a tenure-track position at the Australian National University. Peter fondly recalled taking a phone call from Chip Heathcote, the department head at ANU, who said, "We'd like to hire you, Peter, but we know that you are a true-blue probability theorist. We will need to have an understanding with you that you will start working on some statistical research." The depth and breadth of Peter's subsequent statistical work made Chip Heathcote's wish a dream come true! In a recent note to Jeannie, Chip mentioned that his proudest achievements at ANU were recruiting Peter to his department and providing the environment and support that enabled Peter to focus on his research and to establish a broad and uncommonly productive research program. I note, quite sadly, that Chip Heathcote also passed away in 2016.

Peter's first research entree into statistical theory was in the 1979 paper entitled "On the 'invariance principle' for U-statistics". In 1980, he published his first papers on problems involving rates of convergence as well as his first papers on density estimation – two areas of research in which he was soon recognized as a leading expert. His expertise in probability theory began to shine through, strikingly and effectively, in his statistical studies. A good example is the paper "Laws of the iterated logarithm for nonparametric density estimators" published in ZW in 1981. It did not take long for his statistical interests to broaden.

He published his first work on the bootstrap in consecutive papers in a 1986 issue of the _Annals of Statistics_. His interest in this initial foray was the asymptotic validity of confidence statements based on bootstrap samples. In the five years that followed, he published no fewer than a dozen papers further investigating the bootstrap, treating such topics as the behavior of the balanced bootstrap, bootstrap behavior in regression problems, the relative performance of

bootstrap and Edgeworth approximations and new applications of the bootstrap in nonparametric estimation. He also investigated the bootstrap in the treatment of directional data, data from heavy-tailed distributions and robust estimates of location. He clearly elucidated the range and power of this important tool in his influential 1992 monograph entitled *The Bootstrap and Edgeworth Expansion*.

In the decade that followed, Peter published another two dozen papers on the bootstrap, exploring its behavior in a variety of new contexts. During this period, his work included the study of bootstrapping for errors-in-variables models and for samples drawn from finite populations. He also wrote papers on the biased bootstrap, the matched-block bootstrap and the weighted bootstrap. He never did manage to pick himself up by his bootstraps, but some of his friends and colleagues like to say that he did walk on water. Peter himself had a particular fondness for the research he did on the bootstrap. In Peter's recently published interview in Statistical Science (Delaigle and Wand (2016)), Peter mentioned that his interest in the bootstrap began with a conversation he had with Terry Speed upon Terry's return from the Joint Statistical Meetings in the US in 1981. He asked Terry what was new and exciting, and Terry enthusiastically described the surge of interest in Efron's (1979) bootstrap and in resampling methods in general. In the Statistical Science interview, Peter revealed what his work on bootstrapping meant to him, to wit: "My work on the bootstrap is the work which I am proudest of. I made my reputation there. I am particularly proud of the way in which I was able, fortuitously, to bring together my interests and skills in probability theory with my desire to move into mathematical statistics. In the Committee of Presidents of Statistical Societies (COPSS) paper I wrote (in 2014), I said that I feel very privileged to have been able to be active at the time of the development of these computer-intensive methods."

It would not be difficult to include in this discussion a brief review of other of Peter's statistical interests, but the depth and breadth of his overall research accomplishments is well-exemplified by the work that has already been mentioned. Let me simply add that Peter's contributions to several other statistical areas were equally impressive. In addition to his celebrated work on the bootstrap, he made seminal contributions to probability theory, most notably in the areas of martingale theory and varied aspects of the rates of convergence of sequences of random variables. His research contributions in the areas of measurement error models (see Delaigle (2016)), nonparametric function estimation and functional data analysis (see Mueller (2016)) and smoothing parameter selection (see Marron (2016)) are especially well known. He had numerous doctoral students and

statistical collaborators. His 2015 curriculum vitae listed 31 students whose doctoral research he had supervised and 38 postdoctoral researchers who had come to work with him in Australia. His magnetism as a mentor and collaborator was no doubt due to his exceptional breadth and depth as a researcher, his extraordinary problem solving skills and his expansive mathematical toolbox. There is no question that his easy temperament, his innate skill as a mentor and teacher and the joy and enthusiasm that he brought to his work also played prominent roles in attracting both young and established scholars to visit him. Later, his joint academic appointments at the University of Melbourne and the University of California, Davis, permitted him to host visitors both in Australia and in the United States and gave him the opportunity, as well, to visit his collaborators in the US with some regularity. His collaborations with Steve Marron, Ray Carroll and Hans Mueller were especially productive and are widely known and cited.

Peter was, at heart, a mathematician, and he found the open problems he encountered in the fields of probability and mathematical statistics fascinating and compelling. In the interview with Delaigle and Wand published in 2016, Peter characterized his research interests as stemming from his fondness of probability theory and his desire to use probabilistic tools to solve open problems in mathematical statistics. His work on the bootstrap typifies such inclinations. As another example (among many), Peter mentioned explicitly in his Statistical Science interview that he became interested in functional data analysis because of the challenging mathematical problems posed by the development of a comprehensive treatment of statistical inference in this area.

Peter was a leader in the field of nonparametric statistical inference. In 2007, he received the American Statistical Association's Gottfried E. Noether Senior Researcher Award for outstanding contributions to nonparametric statistics. By themselves, his extensive research findings on the theory and application of bootstrapping would amply justify this recognition but, of course, Peter made significant contributions to a broad collection of additional topics in nonparametrics. His research in nonparametrics includes substantial published work on cross validation in nonparametric estimation, kernel estimation and multivariate estimation of nonparametric densities, image restoration methods and deconvolution methods. He also made important contributions to the asymptotic theory of statistics. Particularly notable are a varied collection of quite delicate studies on the rate of convergence of selected estimators.

In later years, Peter's focus turned, in large measure, to the treatment of high-dimensional data and to the rapidly developing area of functional data anal-

ysis, investigations which demonstrated, among other things, Peter's proclivity for attacking research problems on the leading edge of statistical inquiry. Peter was truly a pioneer in the development of modern statistical theory and a torchbearer for our discipline in the 21st century.

Peter received countless honors and distinctions. They are too numerous to list them all here, but it seems appropriate to mention some highlights. Peter was appointed an Officer of the Order of Australia (AO), a recognition and honor bestowed upon Australian citizens with the approval of the Queen of Australia in recognition of outstanding achievement. He was an elected Fellow of the Australian Academy of Science, of the Academy of the Social Sciences in Australia, of the Royal Society of London, of the Institute of Mathematical Statistics and of the American Statistical Association. He was a Corresponding Fellow of the Royal Society of Edinburgh and a Foreign Associate of the U.S. National Academy of Sciences. He received honorary doctorates from the Université catholique de Louvain, the Universidad de Cantabria, the University of Glasgow and the University of Sydney. In 1989, he received the COPPS Award, an award given by the Committee of Presidents of Statistical Societies to the outstanding statistical researcher under the age of 40. He received the Guy Medal in Silver from the Royal Statistical Society in 2011 and the Samuel S. Wilks Memorial Medal from the American Statistical Association in 2012. For a more comprehensive accounting of Peter's honors and distinctions, and for an engaging discussion with Peter about his research, see Delaigle and Wand (2016).

I would like to finish with a few anecdotes of a more personal nature. In 2004-05, the Statistics Department at Davis celebrated its 25th anniversary. I was organizing the Department's seminar series that spring. Peter would be visiting that quarter, so I invited him to contribute a seminar and mentioned some possible dates. The first of these was the day that Peter was flying in from Australia. He e-mailed me asking what time the seminar would be, and when I said 4 PM, he wrote back saying that this date would be fine. I asked him when he was actually arriving. He wrote, "My flight gets in at 2 PM." I penciled him in for the following week.

Jane-Ling Wang and Hans Mueller were going to a concert one evening during one of Peter's early stays in Davis, and they invited Peter to join them. He happily accepted the invitation. When Jane-Ling proposed picking him up at his apartment around 7:30, Peter said, "No, actually, I'll be over at the office, so you can pick me up outside the building." She said fine, mentioning that he could bring his brief case and they could drop him off at his apartment after the

concert. He said, "No, actually, I'll be going back to the office after the concert." Peter was always open to social interactions, but he also religiously paid the piper as required by his research agenda.

George Roussas, Jiming Jiang and I served as editors of a Festschrift volume dedicated to our colleague P. K. Bhattacharya on his 80th birthday. We invited our faculty, along with P.K.'s students, former collaborators and professional friends, to contribute a paper to the volume. I invited Peter to join me in writing a careful review of P. K.'s scholarly work. Peter readily agreed. We asked P.K. to give us reprints of twenty-five of his papers that he especially liked. Peter and I looked them over and divided them between us. I mentioned to Peter that we might each try to work up a draft on our discussions of each of our halves of the collection in the next ten to twelve weeks, exchange them and go from there. This was fine with him. The next afternoon, I got an e-mail from Peter with an attachment. You guessed it! It was a ten-page review of his half of the papers. It was a detailed and polished commentary that identified the highlights of the work, what was new, what was important and how the work fit in with the problem area it addressed. In contrast, it took me the full 10 weeks to get my draft to Peter.

In 2011, Peter accepted my invitation to co-direct the doctoral dissertation of our graduate student Yin (Golden) Jin. Her thesis deals with an interesting problem in Reliability Theory – estimating the common reliability function $\bar{F}$ of system components based on failure time data from m systems of varying design. Peter and I interacted with Golden quite heavily in the spring of 2011, and we managed to identify the asymptotic behavior of two reasonable estimators (the first a mixture of m independent consistent estimators obtained as in Bhattacharya and Samaniego (2010) and the second based on the maximization of an empirical likelihood). We found that, because the problem we were treating was non-standard in various respects, proving the consistency of the likelihood-based estimator involved some unexpected difficulties. Undaunted (as was his custom), Peter constructed a proof of the strong consistency of the estimator in a non-standard fashion, showing that the inconsistency of our estimator would lead to a contradiction in our stated assumptions. Readers who wish to see how he did this can examine Section 4.2 of Hall, Jin and Samaniego (2015).

Before leaving Davis, Peter wrote up some notes summarizing our findings to date and sketching some plans for future work. The notes contained a result that was unanticipated. Peter had sketched an argument for a uniform convergence result when the number of systems tended to infinity at just the right rate. The

idea of allowing the number of systems one samples from to go to infinity had not been on our radar screen. Nevertheless, the result had clear utility as an approximation theorem when m is large. Working with the master of asymptotic arguments and "convergence rate" issues had its benefits!

An interesting surprise awaited us while working on a subsequent paper – an instance in which estimating a nuisance parameter from available data resulted in an estimator of the target parameter that had better performance than one could obtain when the nuisance parameter's value was known with certainty. This circumstance arose in Jin et al.'s (2017) treatment of the problem of estimating the component reliability under the assumption that the tested system was of *unknown design.* That work assumes that the number K of failed components at the time of a system's failure is observable along with the system's lifetime T, making it possible to estimate consistently the system's design (or, more specifically, the system's "signature vector" – see Samaniego (2007)). Jin et al. (2017) showed that the proposed estimator of component reliability $\bar{F}(t)$ was consistent and asymptotically normal. Interestingly, they also proved that the asymptotic variance of the estimator using an estimated signature was uniformly smaller than the asymptotic variance of the NPMLE of $\bar{F}(t)$ under the assumption that the system's signature was known. This uniform domination was rigorously established, and it was explained further through several additional examples of the unexpected phenomenon. I fondly recall Peter's satisfaction with this particular work. Surprises were among his favorite things!

Because Peter's mathematical dexterity was legendary, I often found myself surprised by his many other talents. He was a professional-quality photographer, an extraordinary expert on all aspects of trains and airplanes, a passionate outdoorsman and a great conversationalist. He was someone whose company one would always enjoy, either at work or at play. As enjoyable as my professional interactions with Peter were, the memories that stand out for me now are of a more personal nature. I am pleased to have this opportunity to share a few of these tall (oops, I mean Hall) tales.

Peter and I were leaving a restaurant one recent spring quarter, having just dined with a visiting speaker. I offered to drop Peter off at his place, but he said no, it was a very short walk. (It crossed my mind that he was really going back to the office, but I chose not to bring that up.) As he headed down the sidewalk, I saw that the sole of one of his tennis shoes had become 95% separated from the body of the shoe. He immediately remedied the problem by grabbing the sole and tearing it completely off the shoe. Then he continued walking, with the top

of the shoe still on his foot. I caught up with him and I offered again to drop him off. This time, he accepted. Whether he was going back to the office or not, it clearly would be prudent to go home at this point, if only to change his shoes. The equanimity that he showed on that occasion impressed me. It occurred to me recently that his mild-mannered father's legacy was in play that evening.

What I know about Peter and Jeannie's life together paints a sharp portrait of two lives well lived and two people, each well loved by the other. Jeannie and Peter would joke that they lived the most boring of lives. When travel and nonnegotiable commitments didn't get in their way, they liked to spend their time hunkered down together in their home, enjoying each other's company and avoiding "intrusions" as much as possible. Even eating out was a rarity for them when they were at home together. Peter and Jeannie also protected each other from real or prospective harm, just what one would expect from best friends.

Jeannie greatly admired Peter's humility. As Jeannie mentioned in her talk at the Hall Memorial Conference at UC Davis in the fall of 2016, Peter never dwelled on any of the honors or awards he received. He never displayed any of them, either at home or in his office. The cupboard where Jeannie would put away 'things' he brought home got so crammed that she would eventually find herself saying: 'no, not another one!' Most of us recognized Peter as the premier researcher in our discipline. Jeannie came to understand the full extent of his contributions and the respect and love that he engendered in others only after his passing, as research workers around the world sent her their condolences and expressed their deep admiration for his work and its influence. Jeannie says she was especially proud of Peter's kindness, his generosity of spirit and his integrity. Further, his complete lack of ego and his disregard for status were both surprising and admirable. He would engage in conversation with a taxi driver just as he would interact with an esteemed colleague, with genuine interest and an open mind.

Peter had a lovely sense of humor and a particular fondness for the ridiculous. One summer, Jeannie and Peter went shopping for a rubber mallet that Peter needed for a project at home. At the hardware store, Jeannie told the shop assistant that they were looking for a rubber mullet. Peter nearly fell over laughing. From then on, he created an ongoing story about the adventures of a 'rubber mullet' and he would extend the story whenever frivolity was needed.

I recall that when Peter was hospitalized in Davis early in the spring of 2014, I visited him there and we talked about the various theories doctors had about what was ailing him. Peter said to me "I'm not too worried. Jeannie

is coming and she'll make sure I get the care I need." Peter was right. When Jeannie arrived, she immediately uplifted Peter's spirits and took on the job of overlooking his care. Her goal was to help him regain the strength he would need to fly home with her to Melbourne and reconnect with his doctors there. She did this successfully, even though the medical challenges that Peter was facing were revealing themselves in real time and becoming increasingly complex. Through this difficult period, Peter did his best to retain his natural optimism and Jeannie, through her love for him and her determination to help him, steered a well-conceived course for his medical care. Tragically, the challenges that Peter faced were too great for Jeannie's love and modern medical science to overcome.

In the fall of 2015, I wrote to Peter about a research paper on which we were collaborating. I had made several changes in response to the reviewers' suggestions. I knew that it would be difficult for Peter to spend much time on the paper, but I did not want to proceed without his OK. Mary and I were leaving for Europe in a week for a long-anticipated cruise down the Danube. Peter was prompt and gracious in responding, saying that he agreed with the latest changes in the paper, and ending his note of October 11, 2015, with the remark "Have an excellent cruise!" Perhaps I was in denial, but it did not occur to me then that Peter might well be on his own final cruise. These notes were, in fact, our last exchange. Looking back on this exchange and the many notes and interactions that preceded it, I cannot recall even one that was anything but positive, sympathetic and helpful. Peter was a genuinely nice person, the best possible version of the "much more" that I alluded to in my first paragraph.

Those in our profession who had the privilege of personally interacting with Peter richly appreciated him for his amazing professional skills and for his uncommon kindness and unfailing equanimity. His friends, colleagues and collaborators in the field of Probability and Statistics are now feeling deeply the void left by his passing. Peter's influence on their personal and professional lives was immeasurable. I hope that Jeannie will find some comfort in the fact that Peter remains with us. We will always cherish our memories of him. The effects of his contributions to the advancement of statistical science will outlive us all.

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