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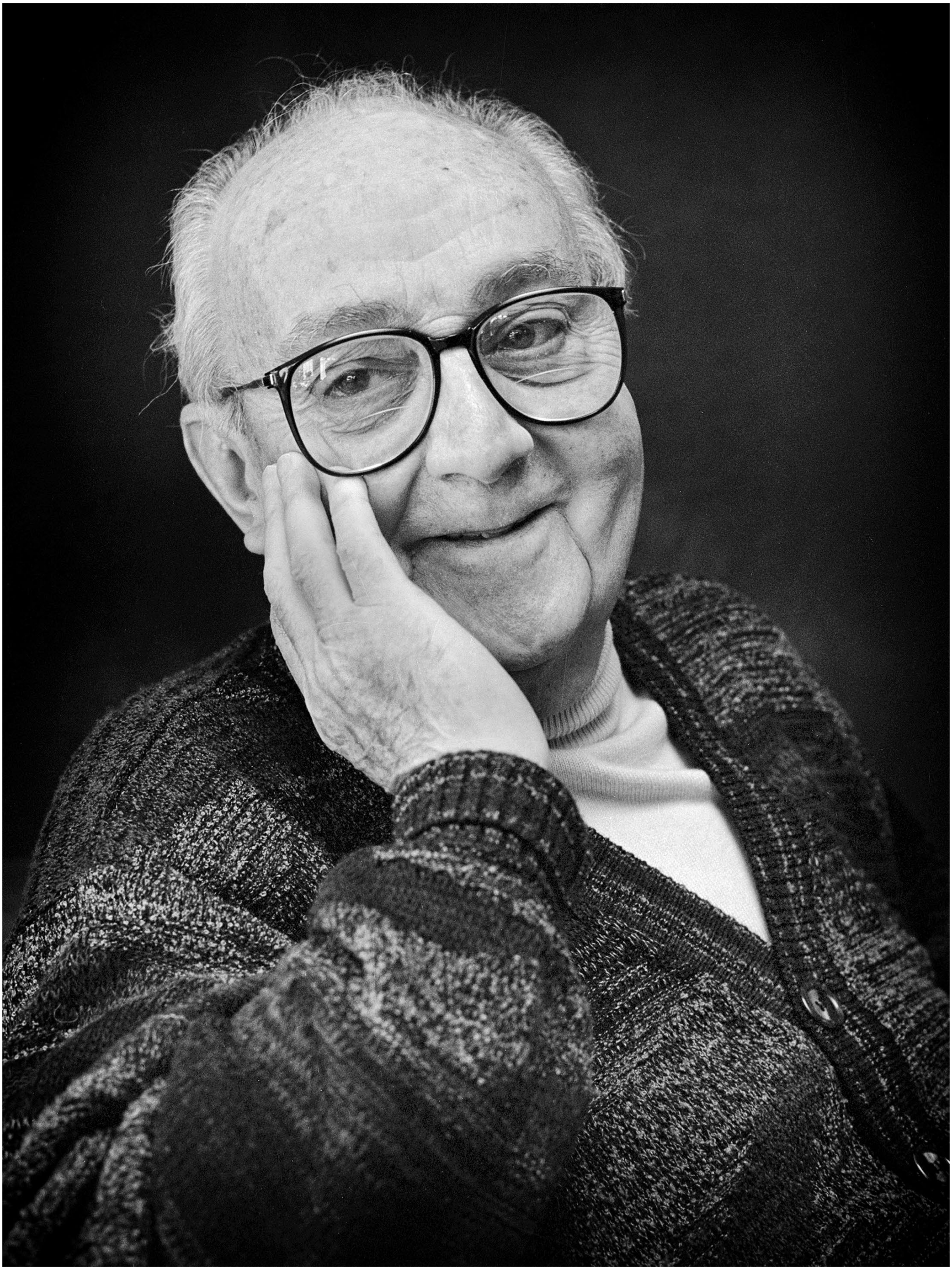

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GEORGE EDWARD PELHAM BOX

10 October 1919 — 28 March 2013

Elected FRS 1985

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George Box was a British industrial and academic statistician who made seminal contributions to theory and practice in the areas of quality control, time-series analysis, the design of experiments, and Bayesian inference, and was the recipient of many awards and honours. He left school at the age of 16 years and, following his early interest in chemistry, found employment as the assistant to the chemist who managed the local sewage treatment plant. While working at the plant, he enrolled for a chemistry degree course with the University of London's External System, but soon after the outbreak of World War II he joined the army and ceased working on the degree. While in the army he was tasked with conducting biochemical experiments relating to the effects of mustard gas but came to realize that the real expertise required was that of a statistician rather than a chemist. After the war he enrolled at University College London and obtained a BSc in mathematics and statistics. From 1948 to 1956 he was employed as an industrial statistician at Imperial Chemical Industries (ICI). While at ICI he took a year's leave of absence in 1953 to serve as a visiting professor at the North Carolina State University at Raleigh. He then returned to ICI but in 1956 accepted a post at Princeton University as director of the university's Statistical Techniques Research Group. In 1959 he left Princeton for the University of Wisconsin–Madison, where in 1960 he founded the University of Wisconsin's Department of Statistics, retiring as an emeritus professor in 1991. He was a man of great personal humour and warmth who cared deeply about his colleagues and was much loved in return by his many students and collaborators.

Early years

George Edward Pelham Box was born on 18 October 1919 in Gravesend, a town about 25 miles east of London on the River Thames, the son of Harry Box and Helen Martin. George's paternal grandfather, also named George, for a time ran a successful hardware

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business in the town. Harry was the youngest of three brothers. The eldest brother, whom Box knew as ‘Uncle Bertie’, attended private school and took degrees in theology and semitic languages at Oxford. He became a rector and wrote several esoteric and scholarly books but did not maintain contact with the family. In 1892 Pelham, the middle brother, went off to make his fortune in the USA and eventually became a US citizen.

However, the Box family fell on increasingly difficult times and George’s father, who had hoped to go to engineering school, had to stay and find work locally. In his very personal memoir, *An accidental statistician: the life and memories of George E. P. Box* (29)*, George recalls that his father had a far from easy life. When George was growing up, his father worked in a tailor’s shop at Tilbury Docks across the river from Gravesend, and George recalls in his memoir:

> To get to work from our house on Cobham Street he had to walk about a mile to the town pier at the bottom of the High Street, cross on the ferry, walk some more, get on a train that took him to Tilbury Docks and then walk again to get to the shop. In the evening he would face the same journey in reverse, sometimes in the pouring rain. He was poorly paid—two pounds 10 shillings per week was barely a living wage.

Despite the hard life George recalls that his father was a happy man and that with the help of George’s sister Joyce he would frequently organize family picnics and parties:

> We gathered around the piano and sang sentimental Victorian songs; most of these sound pretty silly now. We also played all sorts of party games: musical chairs, hunt the slipper, ‘murders’ and so forth. In addition, we performed plays of our own invention. And there were mysteries when my father demonstrated the power of the magic wand.

George acquired basic skills on the piano and the guitar and this early enthusiasm for creating and participating in musical and other collective entertainment is something that would remain with him throughout his career, as we shall see.

Another important influential strand of George’s early family life was his brother Jack’s interest in science and technology. Jack was three years older and in his early teens he became very interested in amateur radio. He designed and built a transmitter but because he was under age for a radio licence for some years he in effect ran a pirate radio station. The allotments near the Box house proved useful for erecting antenna poles to achieve long-range radio contact, and Jack managed to persuade several allotment holders to allow poles to be erected on their plots so that he had antennas facing in all directions. This obviously ignited a spark in the young George and when he was about 10 years old he came across a book called *The boy electrician*. The apparatus and experiments that the author described could be constructed from components that were readily available and resulted in practical devices; for example, there were instructions on how to make an electric bell, a burglar alarm, a morse telegraph, a wireless telephone and an electric motor. Soon afterwards, George used *The boy electrician* to build himself a crystal set with an antenna looped around the ceiling of his bedroom.

So far as formal education was concerned in the 1920s and 1930s, George recalls:

> In England an elementary education was available to all but you were taught very little—mostly how to read and write and to do simple arithmetic. The classes were very large and you left when you were 14 years old, usually to get a menial job. There was no possibility of escape unless your parents could pay for you to go to a grammar or secondary school, which of course mine couldn’t.

* Numbers in this form refer to the bibliography at the end of the text.

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It was possible to get a scholarship but there weren't very many of these. The class system based on money was heavily entrenched.

Fortunately, the headmaster of the elementary school that George attended recognized some special talent in him and he was found a place at a new secondary school, the County School for Boys, starting in the second form at the age of 10. Together with his brother Jack, he was among the very few scholarship boys in the school. George recalls: 'The second form started immediately with French, Latin, English grammar, English literature, physics and chemistry. We also began mathematics—first algebra and then geometry—and we began calculus in the upper fourth form'. But it was the subject of chemistry that interested him the most and, when the time came to leave school at the age of 16, he got a job as an assistant to a chemist who managed the sewage treatment plan at Gravesend. George recalls: 'I became very interested in the activated sludge process responsible for producing the clean effluent that would not pollute the river; and the first article I ever published was about this topic' (1).

While working at the plant he set himself the goal of getting an external degree in chemistry from London University and was allowed two free afternoons a week to go to Gillingham Technical College to attend the necessary courses. In those days, to get an external degree in science at London University, students had first to pass the intermediate science examination. After that, with a year or two of further study, they could attempt the BSc degree exam itself. George had to go to London to take the intermediate examination, which included a two-day practical examination as well as a week-long written part. His subjects were pure and applied mathematics, physics—including heat, light and sound, electricity and magnetism—and chemistry, both organic and inorganic. He recalls: 'These were the most difficult exams that I ever took but I passed and they helped me get a grounding in science that has been invaluable ever since.'

In later years, when he had transformed himself from a chemist to a statistician, he remained firmly of the belief that this basic scientific knowledge was fundamental in enabling him to come up with ideas in the development of statistics. He came to believe in general that it would be helpful if before taking a degree in statistics there was a requirement to pass a preliminary examination in science. He saw it as a serious mistake that statistics had been classified as part of the mathematical sciences rather than as an underpinning of scientific method. In particular he believed it necessary to have experience in running real experiments.

The army: from chemist to statistician

Back in Gravesend, his life, like that of so many of his generation, was about to take a dramatic turn. At 11 a.m. on 3 September 1939 the Prime Minister, Neville Chamberlain, announced on the radio that the UK was at war with Germany. As a teenager in the 1930s, George had been interested in politics and had been particularly angry at the British Government's appeasement of Hitler. Six weeks after the war began, George reached the age required at that time for enlistment into the army. He immediately stopped working on his chemistry degree, went to the nearest enlistment office and joined up. At some stage, someone in the army found out that George had a background in chemistry and he received orders to report to the chemical defence experimental station at Porton Down, near Salisbury in the south of England.

At that time it was expected that the Germans would eventually use poison gas in the war and the purpose of the experimental station was to work out how to react. As part of this project, George was charged with making biochemical measurements in experiments on small animals. However, he found that the results were very variable and he told his superiors that what was needed was a statistician to analyse the data. He was told that none was available and was asked what he knew about the subject. He admitted that he had once tried to read a book by someone called R. A. Fisher but had not understood it. The Officer said that since he had read the book he would have to be the statistician, and so it was that George Box changed his plan to become a chemist and instead became a statistician; as the official statistician at Porton Down, he was provided with appropriate assistance and spent the rest of the war planning, supervising and helping to run experiments both in the laboratory and outside on the range where they simulated warfare.

However, at that time it proved impossible to find a suitable correspondence course in statistics, so he had to try to educate himself on the subject and via the army education corps acquired a number of books on statistics which he carefully studied, including Fisher's *Statistical methods for research workers* (Fisher 1925) and *The design of experiments* (Fisher 1935). He soon realized that the issue was not just a question of statistical analysis but the need to design experiments carefully using statistical principles. He quickly became able to give learned and useful reports on his experiments (2–4). In official circles such individual initiative and contribution often goes unnoticed, but this was not so in the case of Box. The quality and importance of his work was recognized and after the war ended in 1946 he was awarded the British Empire Medal for his wartime contributions.

A very early experiment went as follows: a very small drop of mustard gas liquid was applied to the arm of a volunteer and caused a blister about $\frac{3}{4}$ inch in diameter, similar to that produced by an ordinary burn but more difficult to treat and taking longer to heal. The response measure used was healing time in days. For each experiment there were six volunteers, and six drops of mustard gas were placed at six different places on each arm of each volunteer. There were also six different treatments. Each treatment was tested once on each of the six volunteers and each of the six positions on the arm. So each treatment occurred once with each volunteer and once in each position. Thus differences between the volunteers and differences resulting from positions on the arm could be calculated and eliminated. This experimental arrangement, invented by R. A. (later Sir Ronald) Fisher FRS, is the so-called Latin square design, and it is a testament to Box's extraordinary statistical instincts and insights that he should have been adopting such a sophisticated procedure so soon after having the role of statistician thrust upon him.

This led on to more personal interaction with Fisher. Box recalls that one day at the laboratory he was having trouble with a particular statistical problem and a colleague suggested he write directly to Fisher. He originally thought that Fisher would be much too busy to talk to someone like him, but Fisher replied asking him to come up to Cambridge and see him and bring his data. George recalls:

> When I arrived at Fisher's house it was a beautiful day. He said let's go and sit under that tree in the orchard. I'll look up the probits and you look up the reciprocals and we'll plot the data. In so doing the problem was quickly solved and Fisher was extremely kind and spent the whole day with me.

Building on his early love of family entertainments, involvement in entertainment became another significant aspect of Box's wartime career. During the war, the British army had a division called ENSA (the Entertainments National Service Association), whose task was to entertain the troops; each week they sent troupes of singers, dancers, magicians and so on to

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various army locations. George decided that the official offerings were all rather second-rate and that he could put on better shows himself, which he proceeded to do. Among the female members of the cast was an Auxiliary Territorial Service sergeant, Jessie Ward. They became close companions and were married in 1945.

After the war: University College London, ICI and the USA

Given his wartime role, when Box went back to complete his education after the war ended it was mathematical statistics that he studied rather than chemistry. He obtained a BSc in mathematical statistics from University College London in 1947 and began to undertake research there towards a Master's degree. In the middle of his Master's studies, he accepted a summer placement with ICI, where he was given the task of proof-reading a book that ICI was producing on carrying out experiments. Box's suggestions and corrections were so numerous and of such high quality that he ended up being invited to be a co-author of the book (15), which was hugely influential in promulgating ideas of experimental design.

He continued to work for ICI while working towards his doctorate at University College, supervised by E. S. (Egon) Pearson (FRS 1966). In 1949 he published his first theoretical statistical paper (5) and, in 1951 with K. D. Wilson, published a path-breaking paper on industrial experimental design (6) based on his work at ICI. In 1953 Box submitted his thesis 'Dependent departures from independence and homoscedastisity in the analysis of variance and related statistical analysis' to the University of London, and was awarded a PhD.

While at ICI, Box had no thoughts of going into academe but in the course of solving practical problems he had come up with several ideas for the development of statistical methods and published them (see, for example, (7–10)). In 1952 he received a letter from North Carolina State University at Raleigh, which had established one of the first departments of Statistics in the USA; it was a letter from Gertrude Cox, who famously ran the Institute of Statistics with departments on both the Raleigh and Chapel Hill campuses. It was an invitation to Box to spend a year at Raleigh as a visiting research professor.

This had come about because J. Stewart Hunter, who had been a graduate student at Raleigh, had worked during the summer vacation at the US Army Research Office (ARO), where he had seen the paper that Box had written at ICI with K. D. Wilson. He showed this to Frank Grubbs, who was in charge of the ARO, and Grubbs proposed to Cox that she use ARO funds to invite Box over. The ICI Board of Directors gave him a year's leave of absence, but made it clear that they expected him to return. Box at that time had not submitted his PhD thesis and although this did not at that time matter much in England, in the USA it was expected that someone taking up a visiting professorship would have a PhD. He had already written the thesis, much of which had appeared in already published papers, so it was arranged for his examination to take place just a few days before he left for the USA on the *Queen Mary*. He recalls that his examiners, E. S. Pearson, H. O. Hartley and M. S. Bartlett (FRS 1961), did not refer to the statistical content of the thesis, but instead chatted to him about the comparative advantages of going to America by air or by sea.

The statistics taught and researched at that time at Raleigh and Chapel Hill was centred on the writings of Fisher and the analysis of variance. In the early 1950s, Box made important contributions to the theory of the latter (12, 13) and his research on response surface methods was a natural extension of Fisher's concepts, applied, however, to technology rather than to agriculture. Word got around that Box had claimed that his response surface methods had superseded those of Fisher. This was not the case, but Box thought he ought to respond to the criticism and wrote an expository paper (11) specifically to make clear what he was doing and that the ideas did not conflict in any way with Fisher's.

Given his wartime experience and his subsequent industrial statistics background, Box believed then, as he did throughout his career, that significant developments in statistics are most likely to arise as an offshoot from work on scientific problems, rather than through purely theoretical speculation. So, while at Raleigh, he with Stuart Hunter focused on working together with applied scientists and engineers, in particular the chemical engineers.

While at the University of North Carolina, Box was invited to give seminars at several other institutions. One of these was Princeton University, where, in 1953, he met John Tukey (ForMemRS 1991), an extremely able mathematician and statistician, who, in addition to his academic work at the university, had an important job at Bell Labs, where he practised and encouraged the use of statistics. Some of Box's early research at ICI, for example (9, 16), had concerned tests of statistical significance. However, in many instances there are several different possible tests of significance to choose from, each of which typically involves assumptions about the form of the probability distribution of the data. Many of the then current tests assumed that this distribution was the normal (Gaussian). Box recognized that, although this is a distribution that can often approximate reality, it is a very strong assumption and although some important statistical tests were insensitive to large departures from this assumption, others were not. One of Box's favourite mantras was 'All models are wrong but some are useful.'

In 1953 Box decided to call tests that are insensitive to a particular assumption 'robust tests'; this became a generally accepted term in statistics. He therefore set about working on how to produce tests that are robust to assumptions. Such procedures, although not necessarily optimal for any particular set of experimental conditions, can be designed to work well in practice over a wide, relevant range of conditions that are likely to be met. Creative statisticians such as Tukey had a flair for coming up with ad hoc statistics that were robust in particular contingencies, but Box was dissatisfied with the ad hoc approach. Box preferred to achieve robustness with a Bayesian approach by introducing a suitable model that allowed flexibility beyond the normal-distribution assumption to cover specific likely contingencies. Early ideas, developed during the 1960s jointly with George Tiao, appeared in (21, 23–25) and culminated in their influential book (28).

When Box returned to England from North Carolina, Tukey contacted him suggesting he leave ICI and come to Princeton to be the Director of the Statistical Techniques Research Group that the university was setting up. In 1956 Box and Jessie agreed to go. During the year that Box spent at Princeton, the group produced a quantity of excellent research; many members of it subsequently went on to be influential statisticians in their own right, including Stuart Hunter, Don Behnken, Colin Mallows, Geoff Watson, Merv Müller (17), Norman Draper, Henry Scheffé and Martin Beale (FRS 1979).

The Gordon Conferences

In 1953, when at North Carolina, Box attended his first Gordon Research Conference on Statistics. The Gordon Research Conferences on Statistics and Chemistry and Chemical Engineering began in 1951 and continued right through until 2005. They were named after

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Professor Neil Gordon, a chemist at Johns Hopkins University who had become discontented with the habit that big-shot researchers had of presenting their papers at scientific meetings and then disappearing. He felt that the opportunity for informal discussion with colleagues was essential and for many years the conference was held on the campus of the New Hampton School, a private boarding school that was beautifully situated in a small New Hampshire village. The conference lasted five days, and statisticians, chemists and chemical engineers came in from all over the country and were effectively forced to spend all the days interacting together. A celebrated feature of the Gordon Conferences was the last night cabaret, produced and performed by the conference participants. Needless to say, Box was always at the centre of such productions, often contributing his own musical creations, including a lusty rendering of 'There's no theorem like Bayes theorem', to the tune of 'There's no business like show business'.

A close collaborator of Box and a regular attender at the Gordon Conferences was Don Behnken. He had spent two summers working with Box at Princeton on the understanding that he would qualify for his PhD at Raleigh. In 1960 they produced together what came to be called Box–Behnken designs (18, 19), which are experimental designs for response surface methodology.

Technometrics

Another regular attender at the Gordon Conferences was Cuthbert Daniel, a chemical engineer who had never attended a course on statistics but was one of the first to employ factorial experiments in industry. From the 1940s through to the mid 1980s he worked as an industrial statistical consultant for Union Carbide, Procter & Gamble, US Steel, E. R. Squibb and others, and regularly came up with highly original and useful statistical ideas. In the late 1950s, together with Stuart Hunter and Cuthbert Daniel, Box decided that a new journal was needed to meet the needs of those who applied statistics in technology, rather than in agriculture or biomedicine.

Industrial applied statisticians were still a rare breed but with the postwar growth in high-technology industry there was growing interest in the applications of statistics to technology. It was decided that the new journal should be a joint project between the American Society for Quality Control and the American Statistical Association. The first issue came out in 1959 and bore the subtitle *A Journal of Experimentation in the Chemical and other Physical Engineering Sciences*. Stuart Hunter was the first editor, and R. A. Fisher, who suggested the subsequently adopted name *Technometrics* for the journal, contributed a paper.

The Department of Statistics, University of Wisconsin–Madison

Box had enjoyed his time at Princeton and had been planning on staying and taking up a full professorship. However, sadly, in 1959 he went through a divorce, and his wife and son returned to England. In 1960 Box married Joan Fisher, the daughter of R. A. Fisher, and to spare her some of the inevitable gossip that he thought would ensue at Princeton, he decided he needed to leave the university. Henry Scheffé, who was on the faculty of the Statistics Department at Berkeley, became aware that the Mathematics Research Centre at the

University of Wisconsin–Madison had been looking for statisticians as well as mathematicians and suggested that they approach Box. At Madison there was a loosely associated group of about 200 people referred to collectively as the Division of Statistics. The only common feature was that members had some interest in the subject of statistics but the group decided that it wanted to set up a fully fledged statistics department in Madison. The proposal was that Box could begin by being employed part-time at the Mathematics Research Centre and subsequently go on to form the new department, which started at the beginning of the academic year in September 1960.

Box's first duty at Madison was to teach a course entitled 'Advanced theory of statistics'. As a previous student of Egon Pearson, initially he taught Neyman–Pearson theory, which focused on statistical procedures characterized by their long-run sampling properties. However, after he left University College London, partly because of the research he had carried out on what happened when standard assumptions were not true, and partly through what he increasingly saw as common sense, he came to regard the Bayesian approach to statistics as much more convincing. Colleagues who knew them both thought that, given their surnames, it would be amusing for George Box and the distinguished UK statistician David (now Sir David) Cox (FRS 1973) to write a joint paper together. The result, on so-called Box–Cox transformations, appeared in 1964 (22), Cox providing a non-Bayesian and Box a Bayesian perspective.

Box sought to impress on students studying statistics that their subject played a vital role in scientific enquiry. He wanted them to understand that statistics was a catalyst to learning and discovery that had numerous important practical applications in science and engineering. Moreover, he wanted them to take ideas out of the classroom to discuss and to argue them and to meet with industrial statisticians who could explain how they solved problems. Box's initial group of students at Madison included several who went on themselves to become important leaders in statistics, including George Tiao, Bill Hunter and Sam Wu.

The Statistics Department at Madison grew and flourished. By 1968 it had 17 faculty members and attracted several distinguished visitors. Throughout its early period, the department at Madison had what Box regarded as a proper balance between theory and practice. However, by the late 1970s this had begun to change and to worry Box. To recruit respected senior staff, he found they were increasingly from universities such as Berkeley that emphasized theoretical statistics, in his view to the detriment of applied statistics. The result was that those recruited were mostly theoreticians who had a totally different view from Box of what statistics was about.

He believed that statistics was about solving real-life problems in engineering, chemistry, biology and agriculture, and he had spent his life employing statistics precisely for this purpose. In response to his fear that the department might becoming over-theoretical in its teaching of students, Box set up the famous Monday night 'beer session', which met every Monday evening in the basement of his house. It was far removed from a formal university course; there were no grades or credits, and students and faculty from any department were welcome to attend. In these Monday night sessions, Box tried to simulate the experience he had gained in industry by letting students experience the catalyst of discovery that occurred from discussing practical problems. People who had brought a problem and received some help would return to let everyone know in subsequent sessions how the project was getting on. Several discoveries and publications came about as a result.

Despite divisions between the theoretical and applied wings of the Statistics Department, Box ensured that the whole department came together for parties and celebrations—most

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notably the festivities that surrounded the 50th anniversary of the department in 2010. One form of festivity was the annual Christmas party that took place at Box's house with the tradition that students and staff presented skits to each other. Box always held the view that if you could write a first-class skit you could also write a first-class thesis, and that originality and wit were very closely related. At those Christmas parties, 'There's no theorem like Bayes theorem' would inevitably be sung (several times!).

Main areas of research

Experimental design

From his earliest army experience with the Latin square design to test treatments for mustard gas, Box was throughout his career involved in developments in experimental design. The key problem is to understand how outputs from a system or process—agricultural, medical, industrial—are related to inputs, the outputs only being observable in the presence of some kind of measurement noise. Typically, the inputs involve some factors that are necessarily present but not of intrinsic interest and other (treatment or intervention) input factors whose effect on the response or output is the issue of primary interest. In most experimental circumstances, there are practical constraints on the number and range of combinations of input factors that can be studied. The statistical experimental design problem is to choose from the available input factor settings the ones that enable the most precise understanding of the effects on outputs of the key input factors of interest. The pioneering ideas in the field, based mainly on applications to agricultural experiments, were published by R. A. Fisher, particularly in his influential book *The design of experiments* (Fisher 1935).

Typically, in many agricultural experiments the input factors are binary—such as the presence or absence of a fertilizer at a specific level of application—and the questions asked are about whether certain combinations of treatments have a statistically significant effect. However, problems at ICI, and more generally in the chemical engineering industries, were rather different. Input factors to a chemical process are typically continuous variables—for example temperature, pressure, concentrations of input chemicals—with the output of the system, for example the quality of the chemical product, forming a response surface—perhaps a quadratic arising as a function of the input variables. In many contexts, the commercial need for continuity of production and the expense of shutdowns for experimentation pose the problem of how, with minimal perturbation of the production process, one can nevertheless systematically learn about the optimum input conditions. In those other contexts in which controlled experimentation is possible, the design problem becomes that of selecting combinations of levels of the input variable to yield the best estimate of the response surface. Box made seminal contributions to both problems.

In 1957 Box published a paper on what he called 'evolutionary operation' (14). The idea is that information on how to improve a production process is generated from a simple local experimental design, while the process is still running. To avoid significant perturbation of the production process, and therefore the output, only small incremental changes are made to levels of input factors, but sufficient to be able to learn in what directions to move input variables to improve the output, thus evolving towards the optimal output (the maximum of the response surface). This led to a considerable body of related work, brought together in 1969 in an important book, written jointly with Draper (26). In 1960 two papers with Donald Behnken

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(18, 19), adapting earlier Fisher design approaches to this industrial context, introduced what have come to be called Box–Behnken designs and to be adopted as the standard approach to these kinds of response surface design problems.

Time series

Box had been exposed to a course on time series when studying statistics at University College. At that time he found it all very theoretical and did not understand where it had practical use. However, much later at ICI, while he was working mainly on experimental design, he interacted with a group from the Intelligence Department that forecasted monthly sales. He was intrigued to find that when 'retrospectively' he compared their forecasts with what actually occurred, the errors were not just white noise but had variation that could itself be partly estimated from past data. He began to experiment with moving-average models, but soon afterwards he left ICI and did not follow this up.

While in Princeton he discovered that related situations arose in problems of feedback control in chemical engineering, but he was unable to find someone locally to collaborate with. However, Gwilym Jenkins, a time-series expert, was at that time visiting Stanford but was not happy there; his thesis supervisor, George Barnard, who was aware of Box's growing interest in forecasting problems, suggested to Box that he invite Jenkins to Princeton. They met and subsequently began collaboration in Wisconsin in 1959. They came to realize that the problems they were working on were essentially those of the modelling, analysing and forecasting of non-stationary time series; a first joint paper appeared in 1962 (20), beginning a close collaboration that would span the next decade and culminate in 1970 in their celebrated joint book (27).

The opening page of the book details the five major objectives of what came to be called the Box–Jenkins methodology: (i) the forecasting of future values of the time series; (ii) the determination of how the output is dynamically related to the input for a system subject to inertia; (iii) determining the effect of intervening events on the behaviour of the time series; (iv) the representation of relationships among several time series; and (v) the design of control schemes for compensating deviations from a desired target.

Box–Jenkins models are built from combinations of autoregressive and moving average terms, and they are implemented using an iterative three-stage approach. The model identification and selection step first uses differencing, if necessary, to remove seasonality and achieve stationarity; it then uses plots of the autocorrelation and partial autocorrelation functions to decide on the orders of the autoregressive (AR) and moving-average (MA) components. The second stage then estimates the AR and MA parameters, typically using maximum-likelihood or nonlinear least-squares procedures. Finally, there is a model-checking stage, testing whether the estimated model has the properties of a stationary process, for example with independent residuals and constant mean and variance over time.

Bayesian statistics

George Tiao received his MBA from New York University in 1958 and came to Madison, Wisconsin, with the intention of getting a PhD in international finance. Eventually he pursued econometrics; he was one of the first students of Box, in the first course he taught. He was very interested in Bayesian ideas, and while still a student wrote with Box their first article about Bayesian methods for the journal *Biometrika* (21).

In 1963 a new university had been set up in Essex and in 1966 George Barnard had left Imperial College to become chair of the Mathematics Department at Essex. In 1970–71 he

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invited Box to come to Essex for the academic year. Tiao decided to go to Essex as well for that year and they began the collaboration that was to lead in 1973 to the publication of their joint book (28).

Until the 1960s, the Bayesian approach to statistics had been regarded unfavourably by many of the leaders of the profession. Individual statisticians such as L. J. Savage in the USA and D. V. Lindley in the UK had argued the cause, but theirs was very much a minority viewpoint. Much of the criticism levied against the supporters of the Bayesian viewpoint was that although there was no disputing some of the logic of their arguments, the approach did not lend itself to practical applications. The impact of the Box–Tiao book was therefore considerable, as no one could possibly accuse Box of not being a practical statistician. The preface states: ‘The object of this book is to explore the use and relevance of Bayes’ theorem to problems such as arise in scientific investigation in which inferences must be made concerning parameter values about which little is known a priori.’

The book brings together Box’s interests in both Bayesian statistics and robustness. Most standard statistical theory and practice relating to estimates and tests was at that time based on the assumption that the distributions governing errors of measurement can be modelled by the normal (Gaussian) distribution. This leads to inferences about means and variances being based on averages, and averages of sums of squares, of observations. But if the actual error distribution departs from the normal—either heavier-tailed or lighter-tailed—averaging, which gives equal weight to each observation, is not the appropriate procedure. If the distribution were heavier-tailed, outlying observations should be somewhat down-weighted, and conversely if the distribution were lighter-tailed. Ad hoc procedures of this kind had characterized much of the non-Bayesian work on what Box himself had christened the problem of robustness.

The major innovation in much of the analysis presented by Box and Tiao was to model the data explicitly as having been generated by a flexible family of distributions—the exponential power family—that generalized the normal. The mathematical form of the normal is characterized by the exponential of the negative quadratic difference between an observation and its theoretical mean. Box and Tiao replaced the quadratic by the absolute difference raised to the reciprocal of a further parameter, taking values between zero and one. In the mid-range, at the value one-half, this reproduces the normal, but as the parameter goes towards zero or one, respectively, it generates a class of lighter-tailed and heavier-tailed distributions. By including this parameter as a further unknown to be learnt about from the data, Box and Tiao effectively replaced the conventional analysis of mean-variance models by a fully Bayesian robust alternative.

Retirement years

George Box retired from Madison in 1991, but he continued to take a keen interest in industrial statistics, in particular the so-called Quality Movement, and often worked informally with colleagues at home long after his retirement. He and his wife, Claire Quist, whom he had married in 1985 after the breakdown of his marriage with Joan Fisher, travelled a lot, in particular spending extended periods in Spain. His 80th birthday was celebrated in Chicago, and his 90th at Madison. As always, there was much merriment, with George at its centre.

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Honours and awards

1946 British Empire Medal
1955 Elected Fellow of the Institute of Mathematical Statistics
Elected Fellow of the American Statistical Association
1964 Royal Statistical Society Guy Medal in Silver
1968 Shewhart Medal of the American Society for Quality Control
1972 Wilks award of the American Statistical Association
1974 Elected Member of the American Academy of Arts and Sciences
1975 DSc, University of Rochester
1978 Elected President of the American Statistical Association
1979 Elected President of the Institute of Mathematical Statistics
1985 Elected Fellow of the Royal Society
1989 DSc, Carnegie Mellon University
1993 Royal Statistical Society Guy Medal in Gold
Elected Honorary Fellow of the Royal Statistical Society
1995 DSc, Don Carlos III University, Madrid
2000 DSc, Conservatoire National des Arts et Métiers (CNAM), Paris
DSc, University of Waterloo

Acknowledgements

Much of the chronological material and insights into Box's history and development are derived from his autobiographical memoir, *An accidental statistician: the life and memories of George E. P. Box* (29). Further useful material is contained in 'A conversation with George Box' conducted by Morris H. DeGroot and published in *Statistical Science* **2**, 239–258 (1987).

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References to other author

Fisher, R. A. 1925 *Statistical methods for research workers*. Edinburgh: Oliver & Boyd.
Fisher, R. A. 1935 *The design of experiments*. Edinburgh: Oliver & Boyd.

Bibliography

The following publications are those referred to directly in the text. A full bibliography is available as electronic supplementary material at http://dx.doi.org/10.1098/rsbm.2015.0015 or via http://rsbm.royalsocietypublishing.org.

(1) 1939 (With R. Hicks) Rate of solution of air and rate transfer for sewage treatment by activated sludge. *Sewage Purif. Land Drain. Wat. River Engng* (June), 271–278.
(2) 1946 (With H. Cullumbine) Sodium salt solutions for Lewisite shock. *Br. Med. J.* **1**, 607–608.
(3) 1947 (With H. Cullumbine) The relationship between survival time and dosage with certain toxic agents. *Br. J. Pharmacol. Chemother.* **2**, 27–37.
(4) (With H. Cullumbine) The effect of exposure to sub-lethal doses of phosgene on the subsequent L(*Ct*)50 for rats and mice. *Br. J. Pharmacol. Chemother.* **2**, 38–55.

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(5) 1949 A general distribution theory for a class of likelihood criteria. *Biometrika* **34**, 317–346.

(6) 1951 (With K. B. Wilson) On the experimental attainment of optimum conditions. *J. R. Statist. Soc.* B **13**, 1–45.

(7) 1952 Multifactorial designs of first order. *Biometrika* **39**, 49–57.

(8) Statistical design in the study of analytical methods. *Analyst* **77**, 879–891.

(9) 1953 Non-normality and tests on variances. *Biometrika* **40**, 318–335.

(10) A note on regions for tests of kurtosis. *Biometrika* **40**, 465–466.

(11) 1954 The exploration and exploitation of response surfaces: some general considerations and examples. *Biometrics* **10**, 16–60.

(12) Some theorems on quadratic forms applied in the study of analysis of variance problems. I. Effect of inequality of variance in the one way classification. *Ann. Math. Stats* **25**, 290–302.

(13) Some theorems on quadratic forms applied in the study of analysis of variance problems. II. Effects of inequality of variance and of correlation between errors in the two way classification. *Ann. Math. Stats* **25**, 484–498.

(14) *Evolutionary Operation—a proposed technique for process development*. ICI.

(15) (With L. R. Connor, W. R. Cousins, O. L. Davies, F. R. Himsworth & G. P. Sillitto) *Design and analysis of industrial experiments* (ed. O. L. Davies). London: Oliver & Boyd.

(16) 1955 (With S. L. Andersen) Permutation theory in the derivation of robust criteria and the study of departures from assumption. *J. R. Statist. Soc.* B **17**, 1–34.

(17) 1958 (With M. E. Müller) A note on the generation of random normal deviates. *Ann. Math. Stats* **29**, 610–613.

(18) 1960 (With D. W. Behnken) Some new three level designs for the study of quantitative variables. *Technometrics* **2**, 455–475.

(19) (With D. W. Behnken) Simplex-sum designs: a class of second order rotatable designs derivable from those of first order. *Ann. Math. Stats* **31**, 838–864.

(20) 1962 (With G. M. Jenkins) Some statistical aspects of adaptive optimization and control. *J. R. Statist. Soc.* B **24**, 297–343.

(21) (With G. C. Tiao) A further look at robustness via Bayes's theorem. *Biometrika* **49**, 419–432.

(22) 1964 (With D. R. Cox) An analysis of transformations. *J. R. Statist. Soc.* B **26**, 211–252.

(23) (With G. C. Tiao) A note on criterion robustness and inference robustness. *Biometrika* **51**, 169–173.

(24) (With G. C. Tiao) A Bayesian approach to the importance of assumptions applied to the comparison of variables. *Biometrika* **51**, 153–167.

(25) 1968 (With G. C. Tiao) A Bayesian approach to some outlier problems. *Biometrika* **55**, 119–130.

(26) 1969 (With N. R. Draper) *Evolutionary Operation—a statistical method for process improvement*. New York: Wiley.

(27) 1970 (With G. M. Jenkins) *Time series analysis: forecasting and control*. San Francisco: Holden-Day.

(28) 1973 (With G. C. Tiao) *Bayesian inference in statistical analysis*. Reading, MA: Addison-Wesley.

(29) 2013 *An accidental statistician: the life and memories of George E. P. Box*. John Wiley & Sons. (Includes a George Box timeline, available at http://onlinelibrary.wiley.com/doi/10.1002/9781118514948.oth1/pdf.)

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