LESLIE FOX

1918–1992

Oxford University Computing Laboratory

LESLIE FOX

MA, D.Phil, D.Sc.

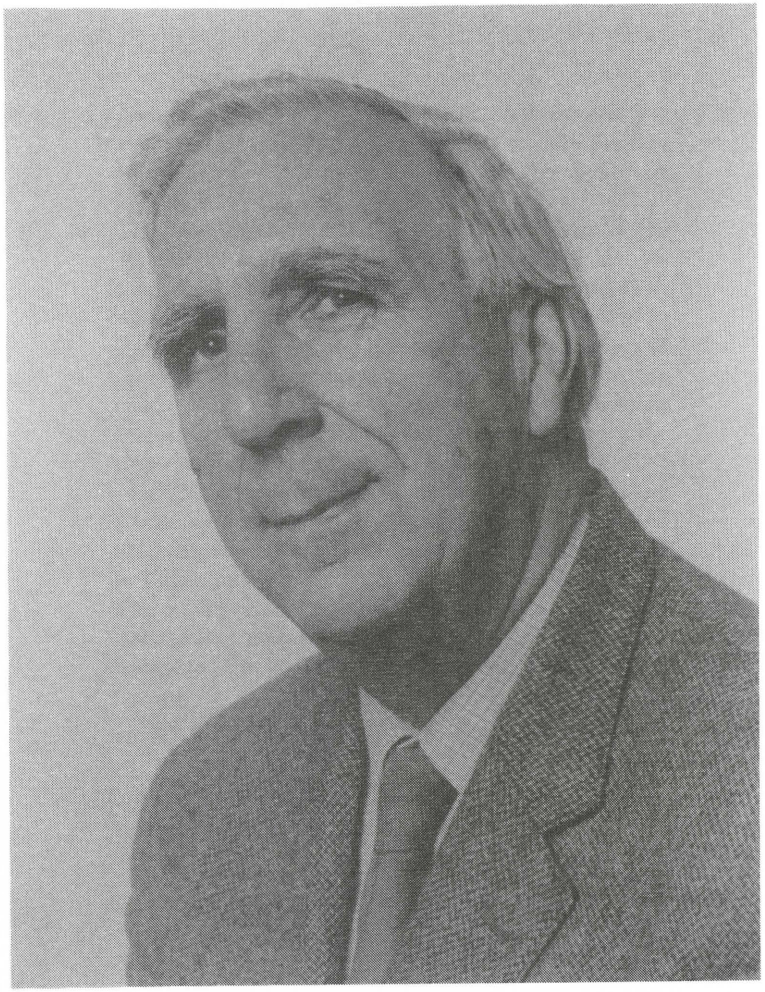
1918–1992

Director, O.U.C.L. 1957–1982

Professor of Numerical Analysis 1963–1983

Fellow of Balliol College 1963–1983

Emeritus Fellow of Balliol College 1983-1992



Foreword

Leslie Fox died on 1st August 1992. A Memorial Service was held in Balliol College Chapel on 30th January 1993. A two-day symposium in his memory took place in Oxford in June 1993.

This booklet includes the two Addresses given at the Memorial Service, by Leslie's brother Roy Fox and his successor as Professor of Numerical Analysis Bill Morton, a brief account of his life and his contribution to Numerical Analysis, and a record of the proceedings of the Memorial Symposium. The biographical section was compiled by David Mayers, and includes contributions from many of Leslie's friends and colleagues; some of the major contributors are acknowledged in the text. Leslie's wife Clemency in particular contributed in several key areas, provided the early photographs, and suggested many improvements to early versions. Bill Morton acted as Editor.

The publication of the booklet coincides with the official opening ceremony by Clemency Fox of the newly designated Fox Room in the Computing Laboratory at Oxford.

Contents

Biography

School

In his Memorial Address, Leslie's brother Roy describes their early life together. This shows how much of Leslie's future success was due to his family. He was also very fortunate in the influence of his school.

The Wheelwright trust was founded in 1724 by a benefaction from John Wheelwright. In its long history there were good and bad times, and a good deal of controversy. The people of Dewsbury always had a passionate interest in the education of their children, and the battles between the Wheelwright Trustees and various local Councils often led to actions in the High Court, the House of Lords, and the Privy Council. The two Wheelwright Grammar Schools opened in Dewsbury in 1888. By 1919 the bitter religious controversies were settled and the schools had grown in size. But the war left them in a serious financial situation when Leslie Sadler was appointed Headmaster of the Boys' School; he remained until 1950.

A double First in Mathematics and Physics from Oxford, he realised that with money so short it was impossible to recruit more staff, so he taught mathematics himself. Over the next thirty years his pupils gained 80 open scholarships to universities, mainly Oxford, Cambridge and Durham. He and the school became so well known that when scholarship candidates arrived at university for interview, they were almost always sent home with instructions to give best wishes to Mr Sadler. At an inspection in 1931 the HMI (His Majesty's Inspector of Schools) said that for its size it was unique in the country. There was another official inspection in 1939; this time the country's Chief Inspector came himself – a most unusual visit, but he wished to see the school for himself, such was its fame.

Leslie was an all rounder at school, in his work as well as at games. When he reached the sixth form he was as successful at Latin and Greek as at mathematics, and he was in some doubt about which way to specialise. On his bookshelves there was always a row of the classic authors, Virgil, Horace, Caesar and the rest; but Sadler promised him that if he took mathematics he would get a scholarship at Oxford. Leslie kept many of the prizes which he won at school. They included some of the well remembered text books on Algebra and Trigonometry, and also as a fifth form prize a copy of the 13th edition of Hardy's Pure Mathematics. It would be interesting to know what the 15-year-old Leslie made of this at the time, but it is an indication of the sort of influence which Sadler had on him. The last prize which he won, the 6th form prize when he left the school, was a copy of Chaundy's Differential Calculus – even more significant, as it was Chaundy who gave him the scholarship to Christ Church, and became his tutor at Oxford.

When he went up to Oxford as a candidate for a scholarship at Christ Church,

he was interviewed at Hertford College (Sadler's old College) as well. Hertford were unable to offer him a scholarship, as the College was still bound by the old statutes, which required all Scholars to be members of the Church of England; it is a curious sidelight on English church history that Christ Church, a bastion of the Establishment, and a cathedral foundation, was able to award a scholarship to a staunch Methodist, while Hertford was not. These statutes have of course been changed since those days. Years later, during an international mathematical meeting in Amsterdam, Leslie went on an excursion round the canals, and discovered that W.L. Ferrar, mathematics tutor at Hertford, was also on the boat. Plucking up his courage, Leslie went up to the great man and introduced himself. "You won't remember me..." he began. "Yes, I do", Ferrar said, "Your name is Fox and you are not a member of the Church of England."

Among the boys at the Wheelwright at about the same time it is no surprise to find other mathematicians and scientists: Tom Kilburn, who was one of the leaders in the design of the early computers, became FRS and Professor at Manchester; Geoff Hayes became a colleague at the NPL, and is now only semi-retired, and Donald Kershaw a few years later became a lecturer in Numerical Analysis at Edinburgh and Lancaster. A bit earlier there was D.H. Sadler (no relation of the Headmaster) who became Superintendent of the Nautical Almanac Office, and another strong influence on Leslie's work.

University

In 1936 Leslie went up to Christ Church, Oxford, where Chaundy was his Tutor for the next three years. He gained a First in both the first and second examinations, Mods and Finals. During this period he certainly played a good deal of sport, but we know very little about his success. A year or two later, when a graduate student, he played football for the University, but this was during the War and the annual match between Oxford and Cambridge did not attract the sort of public attention which it would usually do. At about this time he played for the Oxford City football club; this experience of semi-professional football did not appeal to him. He had a strong dislike of the "professional foul" and turned back to athletics, and, of course, cricket.

After his undergraduate career he joined Professor Southwell's group in the Mathematical Laboratory of the Engineering Department, working for his D.Phil. He took the degree in 1942. His thesis is in the old-fashioned style, rather different from those now being produced. It consists of three published papers, together with a quite short typewritten commentary. The papers appeared in the Philosophical Transactions of the Royal Society, 1941–1943, but in fact they were printed in secret and were not published until some years after the war was over. The preface to his thesis contains the comment that arrangements had been made to give his examiners access to these documents, which were classified as secret.

Since 1935 Southwell and his collaborators had been developing relaxation methods, and had moved on from the simple problems to much more interesting calculations such as those involving free boundaries, and the flow of gas from a nozzle. Leslie was set the task of developing relaxation methods for the biharmonic equation, as it arises in elasticity. The commentary in his thesis still makes interesting reading. The published papers describe the numerical results he obtained, and the successful methods used; in his commentary he fills in more background, with more details about his early unsuccessful attacks on the problem, and an analysis of the reason for their failure. The biharmonic equation is still difficult, as it leads to a system of linear equations which do not have such desirable properties as diagonal dominance.

The Admiralty Computing Service

On leaving Oxford, Leslie joined the Admiralty Computing Service where he stayed for three years. Here he came under the influence of D.H. Sadler (as noted above, another former pupil at the Wheelwright School), and learnt the craft of table-making. The work was varied, but mainly involved tabulating functions and solving differential equations. This experience laid the foundation for his insistence on numerical accuracy – not that numerical results had to be given to large number of figures, but that *all* the figures given should be correct. Scientists and engineers who make use of computed results are often skeptical about their accuracy, and ask for a few more figures than they really need. But the accuracy of the tables produced by the ACS, and later for the Royal Society, is such that all the figures can be relied on without question. As late as 1983, when he had retired, he was corresponding with Alan Curtis of Harwell on some discrepancies between his values and some published elsewhere. Characteristically, Leslie did not just say that his values were correct, but made a careful study of the problem, and showed just why the other values were wrong. The fact that the discrepancies never amounted to more than one unit in the last decimal place tabulated made no difference; for Leslie it was just as important to get the last figure right as it was for all the others.

National Physical Laboratory

In 1945 Leslie and others left the Admiralty Computing Service to join the new Mathematics Division of the National Physical Laboratory at Teddington.

Charles Clenshaw joined the NPL soon after. He writes:

" I first met Leslie in October 1945 when, at the age of 19, I arrived for interview at the new Mathematics Division of the NPL. After an anxious wait on the staircase landing of an old Victorian mansion I was called into a stark

room with the bare essentials of furniture. There I was questioned by two men who were much younger than any who had interviewed me on previous occasions. They appeared very fit and energetic; they were Fox and Goodwin. I was very nervous and overawed by the occasion, but rapidly decided that I would very much like to work there, and that I was completely blowing my chances of doing so.

"I recall only one question put to me by Leslie on that day. He asked me if I knew anything about solving partial differential equations. Deciding that prevarication was the worst policy, I answer with a simple 'No'. This apparently was not too bad, because Leslie said that at least there was nothing that I would have to unlearn if I were to join them. However, I left that day with a heavy heart, and was astonished to receive an offer a few days later. True, the offer was that of a position as Temporary Assistant Grade III, but I knew I wanted to work there, and I duly accepted.

"When I started, I soon found out about Leslie's strange practices with partial differential equations. A large sheet of graph paper would effectively cover his desk top. He would crawl over this paper, pencil in one hand and eraser in the other, making adjustments to numbers written on the paper. To the observer there was no clear method in his choice of the number to be adjusted, nor of the size of the adjustment. Only much later, after the exercise of much patience on Leslie's part, did I begin to understand something of the art of relaxation as he practised it.

" Given an elliptic partial differential equation with its boundary conditions, Leslie would estimate the value of its solution at each internal grid point, and calculate, sometimes mentally, sometimes with the help of a Brunsviga, the value of the local residual. Then the crawling process would begin; the most significant residuals were attacked by altering the values of the estimated solution in their vicinity. 'Most significant' did not necessarily mean largest in magnitude, because a group of moderate residuals with the same sign could be more significant than an isolated larger one. Moreover, the residuals attacked were not necessarily reduced to zero; an intelligent observation of the surrounding picture might cause one to over-relax or under-relax.

"Leslie was a master at this work. In the first place he had made profound contributions to the general approach as it had been suggested by Southwell. Southwell, inspired by the engineering analogy that led him to call the process 'relaxation', believed in the mathematical simplicity that resulted from using a mesh fine enough to render negligible the inevitable truncation errors. Leslie saw the advantages, both theoretical and practical, in relaxing with the coarsest possible mesh, and then adjusting the residuals to take account of the truncation error introduced by this coarse mesh. Then further relaxation could be carried out on the same mesh.

"Secondly, Leslie took pleasure and pride in his ability to carry out the actual relaxation process with speed and accuracy, using a whole armoury of subtle techniques often devised or refined by himself. He was the outstanding theoretician and practitioner of an art that was just beginning to flower when it was killed by advances in electronic computation; some of these advances were inspired by work also going on in the Mathematics Division. But of course the end of the practice of relaxation was not the end of the ideas. Though the art of relaxation was not well-suited to the computer, Leslie's basic philosophy is as relevant today as it was in the 1940's, and his lessons will not be forgotten.

"That relaxation work is my strongest memory of Leslie's early numerical analysis, perhaps because he tried so hard to teach his skills to me, but there was much else, of course. He and his colleagues, Charles Goodwin in particular, covered numerical analysis as it then existed with remarkable facility. There were contributions in matrix algebra, in ordinary differential equations and in integral equations, as well as in table-making; indeed the advances were often inspired by table-making. This subject, which has effectively vanished from the field of study of the numerical analyst, was then a major motivator of research. Leslie's book published in 1956, 'The use and construction of mathematical tables', Volume I of the NPL Mathematical Tables Series, remains as a concise, comprehensive, scholarly account of the subject as it appeared then, just before the computer revolution.

"My memories of Leslie in those early days away from mathematics inevitably involve the sports field. He was an outstanding sportsman at an austere time when sport was an important outlet to many of us. When I first knew him he excelled in athletics, cricket and soccer (in alphabetical order).

"His dominance was most marked in athletics; he used to win all the sprints and the long jump at the NPL Sports, and he performed with distinction at the Civil Service Sports. I remember particularly his remarkable technique in the 440 yards at the NPL Sports, in which he would lope round in long and apparently lazy strides for about 300 yards, at which point he would be some yards adrift of the field, and then he would perform his usual sprint. The dramatic effect was considerable, with Leslie reaching full speed as the others were tiring, and he went past them as if they were standing still.

"I think that soccer could have been his strongest sport. He had all that a modern striker could wish, being very fast, with good control of the ball and a powerful shot. Several times I had the pleasure of playing in the same side, and I saw him score some memorable goals. However, Leslie certainly did not enjoy the increasing ugliness of the professional game in those days, which was also beginning to affect the more competitive amateur leagues, and he soon gave up the game.

"The sport which gave him most pleasure was certainly cricket. At first he was

a good batsman and a very effective seam bowler. Later he started to experiment with leg-breaks, and then soon abandoned seam bowling altogether. The art of the leg spinner delighted him, as he gradually began to master it. I recall how, in his early experiments in inter-Divisional NPL matches, he would be hit all over the place by moderate batsmen. This was galling to the rest of us in the Mathematics team, who had enjoyed many wins when his seam bowling had kept the opposition frustrated. Quite unperturbed, he would smile and tell us to wait a bit. Sure enough, after a season or so the ball began to do what he wanted, and he started to take wickets; indeed he took more wickets now than he had before. He had to admit that he conceded more runs, but he derived great pleasure from this subtle skill."

Oxford

From the beginning of his published work it is very clear that Leslie is doing more than reporting on the work that he has done, in the way of many scientific papers. There is always a strong suggestion that the numerical methods he has used would be useful in a much wider field, and that the reader ought to be using them too. This is of course particularly true of the two major early publications from the NPL days, "The use and construction of mathematical tables", and the important "Numerical Solution of Boundary Value Problems". It was therefore quite natural that when Oxford began to set up a new University Computing Laboratory, Leslie should be invited to be its first Director, and it was not surprising that he accepted. This move from fourteen years in the civil service into academic life was almost inevitable for Leslie, whereas it was not for his close friend Jim Wilkinson. Up to this point their lives had been closely parallel, from what we should now call an underprivileged background to two remarkable schools, one in the south and one in the north, and then to distinguished university careers, Leslie at Oxford, and Jim at Cambridge, coming together at the Mathematics Division of the NPL. But Jim was happy to devote his life to research; firmly based in government service, he held a number of visiting University appointments, but always in research rather than teaching. Leslie, on the other hand, spent what turned out to be the major part of his life in Oxford, where teaching undergraduates and training research students were two of his main tasks.

After leaving the NPL in 1956 he took a post as Associate Professor at Berkeley, California, for one year. Here as we might expect he made a great many friends, as he did wherever he went. He then came back to Oxford in 1957, and set about building up the Computing Laboratory and a programme of teaching and research.

The first step was to gather the staff together. His secretary, Olive Moon, was there from the beginning. John Rollett joined very soon after, David Mayers

in 1958, followed closely by David Handscomb and Christopher Phelps. It is a remarkable fact that none of the full-time academic staff whom Leslie appointed have ever left. Olive retired after nearly 25 years; she enjoys her retirement to a flat which nearly overlooks the Southfield golf course. When the Computing Service split off as a separate organisation from the Laboratory, Christopher Phelps and Linda Hayes went with it; Christopher retired from his post as Deputy Director in 1990, but retained his teaching post at St Edmund Hall, and is still active as a member of almost every University committee and working party concerned with Information Technology. Linda is still there, as are the rest of us, though retirement is beginning to loom – for John it will mark the end of 38 years. The only small exception would be Sean McKee, who after three years as Atlas Research Fellow and five years as UCINA Coordinator left to become Professor at the University of Strathclyde; but, strictly, Sean's was not a fulltime University appointment.

To account for this stability the high-minded explanation might talk of loyalty, or Leslie's wisdom in picking his staff. Alternatively you might suspect that when any of us thought of moving we found that nobody else would give us a job, or a better job, anyway. Certainly his staff appointments gave no weight to sporting achievements, with the obvious exception of Sean's golf handicap. Oxford has never had extensive inter-departmental sports on NPL lines; if there had been such events Leslie would have had to carry the flag almost single-handed. Among the students there have been a few distinguished athletes and sportsmen, but Leslie's immediate colleagues must have been a great disappointment to him. Perhaps this was an age effect; he reached his 40th birthday quite soon after arriving at Oxford. The day was no celebration, as Leslie at the time regarded it as the end of life as he knew it, though he did manage to go on playing cricket for some years until he finally discovered the joys of golf.

David Mayers writes: "I first met Leslie when I was a research student in the Mathematical Laboratory at Cambridge. At the weekly seminars there would usually be a distinguished contingent of visitors from the NPL, Leslie, Charles Goodwin, Jim Wilkinson, Charles Clenshaw and others. We students were well aware that Leslie was really happier with his Brunsviga than with the developments in computing technology which were going on in the building; he would really sit up and take notice when J.C.P. Miller was talking about difference corrections, or Chebyshev polynomials.

"Some time after I left Cambridge, Hartree told me that Leslie was setting up the new Laboratory in Oxford, and suggested that I might be interested in a job there. He must also have put in a good word, because shortly afterwards I was invited to visit Oxford for an informal meeting. So one afternoon I met him again in his big office in the South Parks Road building, with the big bay window on the first floor overlooking the rose garden. I also met Olive for the

first time, as she produced tea in her willow pattern tea service; this was all very civilised, and rather different from the electronics workshop atmosphere of Cambridge, or the austere security of Aldermaston where I had been working for two years – the computer was not installed until some months later. The meeting was a discussion, rather than a formal confrontation with questions and answers, but it took no more than two minutes for Leslie to convince me that I really didn't have any understanding at all of forward and backward error analysis, and how accurate the numerical solution of a problem really was. This was done in a very friendly way, without any arrogant superiority, as Leslie freely admitted that he did not really understand it either. However, in those days there were very few people about with any qualifications in numerical analysis; shortly afterwards I was summoned to a daunting formal interview by a large appointments committee, where it was clear even to me that Leslie and Professor Charles Coulson had already made the decision in advance. But the earlier discussion sessions continued occasionally for 30 years or so; sometimes Leslie would feel that some of us were getting rather pleased with ourselves, and would set about gently pointing out how very little we really knew or understood."

Teaching

Soon after Leslie arrived the Oxford Mathematics Faculty began a major revision of the undergraduate syllabus; this is a disease which seems to recur about every five or six years. For Leslie it was the chance to force some Numerical Analysis into the syllabus, so in the next year he began to lecture on Numerical Linear Algebra to the first year students. Other topics, such as differential equations, also appeared in the second and third year courses, but for some years he continued to give the first year lectures himself. These lectures developed into the book "Introduction to Numerical Linear Algebra", which first appeared in 1964, with later editions in 1965, 1967 and 1973. Much of the material was quite elementary, but significant parts of it were based on the very recent work of Jim Wilkinson, and of Leslie himself.

The whole undergraduate syllabus has undergone a number of these transformations since that time, but much of Leslie's material is still taught, and in much the same way.

Summer Schools

From the beginning Leslie was determined not to confine the activities of the Laboratory to the narrow field of teaching students. Apart from the research that went on, this was a busy time in running courses to train staff and students from all over the University in programming, mainly in the mysteries of Mercury Autocode, later replaced by Fortran. But Leslie looked further afield, and in 1960

held the first of a series of Summer Schools; the first one was a rather introductory course on Numerical Analysis, and attracted more than eighty participants from government, industry, universities and technical colleges. Following this success came a more specialised Summer School on Differential Equations; this was more ambitious, and the local team were joined by contributors from Aldermaston, Harwell, the CEGB and the Metereological Office, among others. The proceedings of this Summer School were published with remarkable speed and efficiency (for those days, and still setting a good example) and appeared in 1962; for some years the book served as a standard survey of the State of the Art in this area of numerical analysis.

There followed Summer Schools on Computing Methods in Crystallography, organised by John Rollett, and on Approximation Theory run by David Handscomb. In between appeared a rather different one on what was then slightly unusual, and called Advances in Programming and Non-Numerical Computation. This one was somewhat different, since as Leslie explains in his Editor's preface to the published Proceedings, none of the Laboratory staff, including the Editor, had any particular knowledge and certainly no research experience in this field. It arose from some controversial correspondence between Leslie, Stan Gill and Christopher Strachey which appeared in the Computer Journal during 1961. As a result Gill and Strachey accepted Leslie's challenge to present a Summer School to demonstrate that their field was worthy of serious academic study. The success of this venture led directly to Leslie's efforts to obtain funding to enable Christopher Strachey to set up the Programming Research Group in Oxford. At the time this was one of the largest single grants for computing which had been made by the Science Research Council. From its early beginnings as a small group in 45 Banbury Road it has steadily and rapidly expanded until it now forms the larger part of the Computing Laboratory.

The last of this series of Summer Schools led to the publication in 1968 of "Computing Methods for Scientists and Engineers". By this time computers and computation had become widely accepted as a normal part of research, and numerical analysis was becoming a recognised part of many undergraduate mathematics courses, so the demand for expository Summer Schools of this kind was much less.

Leslie's interest in education was not confined to graduates and undergraduates in Universities; he also took a great interest in what was taught in schools. He was an active member of the Oxford and District branch of the Mathematical Association, of which he became president. In 1968 he spoke at the Oxford conference of the Schools Mathematical Project, in collaboration with J.D. Tinsley and A.R. Tammage, who taught mathematics at St Edward's School and Magdalen College School in Oxford. His enthusiasm for introducing computers and numerical analysis into schools occupied him a good deal for some years.

Sometimes the response to his efforts was disappointing. A proposed Summer School on Numerical Analysis in Schools in 1964 was abandoned because of lack of support; in the same year a short course in Manchester, organised jointly with Jim Wilkinson, was cancelled for the same reason. He commented on this in a speech at the NPL, where he mentioned that in his first seven years at Oxford there had been only 15 graduate students in numerical analysis in the U.K., nine of whom came from Oxford. But of course progress took time; after these early students had gone out to other Universities (particularly Manchester) and encouraged their own graduate students the spread of numerical analysis really began.

In his own contribution to the IMA Symposium on "The Contributions of Leslie Fox to Numerical Analysis" in 1983 he took the title "Numerical Analysis in Higher Education". His conclusions were reasonably optimistic at the undergraduate level, but deplored the small overall number of graduate students in the field. He ends with a comment that if we can get school teachers more interested in *good* numerical analysis then their students, who will become our students, may catch their enthusiasm and come to us well prepared in knowledge and motivation.

University and College

In the early years of the Laboratory, Entitlement was a burning issue in Oxford. A substantial number of academic staff in the University, mainly but not entirely in the sciences, held University posts, but with no College connections. In such a collegiate university as Oxford, many of them resented their treatment as second class citizens. Leslie also felt strongly about the justice of the case, though the members of his staff were by no means among the most militant. He was soon appointed one of the Delegates to set about the formation of Linacre, which before long became established as one of the first of the new graduate Colleges. For some years after this he continued to be closely associated with Linacre College, but by this time Balliol had realised what they were missing. In 1963 Leslie became Professor of Numerical Analysis in the University, and was elected to a Fellowship at Balliol.

He was very proud of his new Professorship, not just for his own prestige, but as a recognition of his efforts to make Numerical Analysis a respectable fully fledged branch of mathematics. Now of course a number of Universities have Professors of Numerical Analysis, many of them being Leslie's students. He also immensely enjoyed his membership of Balliol, and made many new friends there. He was elected an Emeritus Fellow on his retirement, and was often to be seen in the College. His last visit was only a few weeks before his death.

Computing Service

The first Oxford computer, a Ferranti Mercury, was financed by a grant from the University Grants Committee. This was one of the first government grants to a University for a computer, and the sum involved was rather large for the administrative machinery to handle. So the UGC followed their usual practice of the time, by making a grant for the capital cost, leaving the university to finance the maintenance and running cost. For a large machine running on thermionic valves the maintenance costs were particularly high, and the University made the new Director of the Computing Laboratory responsible for earning the money required. It took a few years for the various research groups in Oxford to build up the necessary expertise to make full use of the computer facilities now available – except for Chemical Crystallography, of course; John Rollett would have been easily able to saturate the machine on his own. There were only a handful of large computers working in the country at the time, and it was much easier then than it would be now to hire out computer time to various commercial organisations. Even so, it was necessary to do a good deal more than just hold out a hand and wait for the money to fall into it, and Leslie set about marketing the facilities. By 1964 the Annual Report of the Laboratory records that since the delivery of the computer in 1959 the income from this source had reached £250,000, which paid for all maintenance, repaid £15,000 to the UGC, and left £75,000 to contribute to the cost of the KDF9 which would shortly replace the Mercury computer. Allowing for the value of the pound in 1963 this is a very substantial sum of money, and left Leslie with the reputation in the administration of the University as a man who could Get Things Done.

Before long the KDF 9 was being used by a large number of groups and individuals around the University. This pressure on the facilities needed a good deal of organisation. The university decided to split the provision of a computing service off from the teaching and research activities of the Laboratory, and appointed as new Director of the Computing Service, Alan Scott – another former pupil of the Wheelwright Grammar School. With the coming of the ICL 1906 machine the new Computing Service moved into their new premises in the Banbury Road, and the split was complete, with Christopher Phelps and Linda Hayes moving with Alan Scott.

Study groups

This move left some spare space in the Parks Road building, at a time when the Mathematical Institute was very short, so it was arranged that Alan Tayler's group of applied mathematicians would move in. This arrangement, of course, went far beyond just giving these strangers a key to the door, and they were immediately welcomed as part of the Laboratory. The departure of all the ma-

chinery made it possible to use a good sized room for gatherings in the middle of the morning, with Olive Moon providing coffee, etc, from the well equipped bar. Thus began one of the most stimulating periods of the Laboratory. No gathering which included both John Ockendon and Leslie could ever be dull, and the heated arguments ranged over all areas of mathematics, sport, cricket, politics and most other things. The applied mathematicians had already built up a number of contacts outside Oxford, and there was also a continuous stream of visitors.

These visits became slightly more formalised into the first of the series of Study Groups, where a number of research workers from industry brought along a problem to be tackled in all its aspects – modelling, analytical, numerical and computational. The ideal, that at the end of the week there would be a solution, did not happen very often, but many of the problems stimulated new research projects, some of which are still active 20 years later. These meetings lasted a week, with a break on Wednesday afternoon for the Cheltenham Gold Cup. On the first day each of the participants would present their problem, the presentation being followed by heated discussion of the right mathematical model. Leslie usually made an appearance on the second day, hoping that by this time the mathematical problems would be sufficiently decided so that numerical work could begin.

Sometimes these problems were not difficult to solve with a fairly standard numerical method and an amenable research student. Others led to new areas of research in numerical analysis, such as in functional differential equations (the pantograph problem of 1971), and in free and moving boundary problems, leading to the conference of 1973. They were always of enormous benefit to students, bringing them into contact with mathematics in the real world outside universities. They soon learnt that all problems have singularities, all regions have corners, and that a system of differential equations of total order 5 is much more likely to have 4 or 7 boundary conditions than the 5 which a mathematician might expect.

Leslie was particularly in his element when dealing with problems with singularities. In his D.Phil thesis he solved a problem in elasticity which involved a point load on a plate. In this work he uses, with only a casual mention, the idea of subtracting out a singularity which developed into a method of dealing with various types of singularities.

UCINA

In 1978 Bill Morton chaired a sub-panel of the Mathematics Committee of the then SRC which suggested the setting up of consortia throughout the UK to collaborate with industry on problems requiring a numerical solution. Leslie Fox wrote a proposal to the SRC; it was accepted and UCINA was born. Sean

McKee was appointed the first coordinator and spent $6\frac{1}{2}$ interesting years making contacts and friends in industry and academia. The UCINA operation was based on the study group idea, but is concerned with the numerical aspects of the problems, rather than the basic mathematical model. Although the coordinator is based in Oxford, it has remained a consortium, with meetings and workshops being held at the other universities as well.

Sean was, and is, another golfer. After finding himself visiting industrial contacts on two consecutive Friday afternoons he was called into Leslie's office, and was asked "Sean, have you no sense of priority?".

NAG

With the installation of the new KDF 9 computer at the universities of Birmingham, Manchester, Leeds, Nottingham and Oxford, as well as at Culham, the need for a portable library of mathematical subroutines became even more pressing, to avoid needless duplication. Leslie pushed this project along enthusiastically, and was instrumental in getting government funding for the Nottingham Algorithms Group. This group coordinated the efforts of those at the participating universities who turned the latest numerical methods into efficient subroutines.

When the group had to move from Nottingham, Leslie found room for them in a building adjacent to the Computing Service, where they continued to flourish. Now the Numerical Algorithms Group plc, the organisation has the same aims, and serves a vast number of customers worldwide, with a wide range of computers.

The Open University

As part of his constant efforts to spread some understanding of numerical methods to as wide an audience as possible, Leslie showed an early interest in the Open University. In 1970 he obtained leave from Oxford, and held a one-year Visiting Professorship at the OU. In that one year he wrote a large quantity of course material, presented a number of television programmes, and became a familiar figure to those who were keen enough to watch the BBC broadcasts (which were transmitted rather early in the mornings), to learn about Gauss elimination, Chebyshev polynomials, and so on. He also had a good deal of influence in the wider area of the mathematics department of the OU, and continued long after to take a great interest in its development. This long interest was recognised when in 1986 the Open University awarded him an Honorary Doctorate.

During this period he became much more involved in the teaching work of his colleagues in all branches of mathematics than he did in Oxford. An example of this was a stern letter to a distinguished Professor of pure mathematics, a typical outburst on abstract notation: " .. it reaches the limits of pedantic absurdity at

the top of page 63 where it says

$$\underline{x} \text{ is written for the function } x \mapsto x"$$

The television programmes were hard work, and subject to all sorts of technical problems. A note from the BBC producer comments "Golf is obviously what is needed to soothe your fevered brow; I trust all this is not turning your 3 iron rusty."

Outside Oxford

Leslie's travels took him to many parts of the world, making new friends wherever he went. After leaving the NPL and before moving to Oxford he spent a year in California. After a few years spent settling in at Oxford he was soon active in the world outside. In 1962 he gave a series of lectures in North Carolina, and in 1966 he made his first visit to Australia. In 1968 he gave lectures in Czechoslovakia, in 1969 he was at the inauguration of the Scientific Computation Centre in Cairo. In the same year he made a grand tour of Germany, speaking in Karlsruhe, Stuttgart, Heidelberg, Tubingen, Freiburg, and at Oberwolfach. This sort of travelling is quite commonplace nowadays for well-known scientists, but in the 60s it was still something of an adventure. In 1973 he paid a visit to South Africa, at the invitation of Jack de Wet, formerly mathematics tutor at Balliol; he returned profoundly affected by what he had seen of apartheid.

Following a trip to India in 1978, visiting Kanpur, Calcutta, Bombay, Bangalore, Madras, Trivandrum, Delhi and Rookee he and Clemency commented that it was hard work and by no means a luxury tour. A second visit to Australia in 1979, as a visiting Professor in the New South Wales Institute of Technology in Sydney, led to his appearance with his Balliol colleague Les Woods as a sort of double act – the "Oxford Professors". Les Woods, a long standing adversary as an applied mathematician, was visiting the department at the same time.

And of course he was much in demand as a speaker at home, and all round Great Britain. He regarded it as a great honour to be invited to give the Rouse Ball lecture in Cambridge in 1969; he spoke on the mathematics of scientific computation. He also became an accomplished after dinner speaker and gave memorable speeches on a variety of occasions, especially at the retirement dinners of his NPL colleagues to whom he stayed very close all his life. By the middle of the 1960s he had perfected his "Meaningless Answers" talk, and gave different versions of it all over the world. For this purpose he collected a range of harmless looking problems for which obvious and standard methods gave a solution which was wrong. Sometimes the numerical result was wrong in a quite startling way, where for example a quantity which *should* be positive was computed to be negative. But Leslie was much more insistent on exposing the more insidious type of error, where the solution to a problem which most people would expect

to be correct to 5 decimal places actually turned out to be wrong in the second place. To him this was a much more serious error, as it is much more difficult to detect.

Relaxation methods

It is often said that a mathematician produces his best and most original work at the beginning of his career. In this respect Leslie was rather unlucky; his first research was on relaxation methods and he published 16 papers in the period up to 1960, all except one of which was on this subject. This line of research then came to a sudden stop, and he did no more in the area, except for one much later paper on the optimum factor in the SOR method. This sudden change was the direct result of the coming of the computer. Relaxation, as practised by Leslie, and the others at that time, was not a systematic process, but succeeded by examining the appearance of patterns of residuals, and recognising situations where particular types of block relaxation would be most effective. The early computers had tiny memories, by modern standards, so that programs had to be quite short; they thrived on the repetition of very simple processes, rather than elaborate schemes of alternative choices. It was realised at a very early stage, for example, that in a large problem there was not sufficient memory to store all the residuals simultaneously; it was therefore quite uneconomic to just find the largest residual, when with almost no additional calculation it was possible to do a complete iterative sweep. For some years after this Leslie would demonstrate to students how easy it was to obtain solutions by relaxation methods, but the students were not much impressed, preferring to write programs for methods which are more systematic and easier to analyse. Perhaps now that Expert Systems are fashionable it may be possible to investigate these older methods, but much of the detailed expertise was lost long ago.

Finite differences and boundary value problems

Leslie's other great interest, in finite difference methods, lives on much more vigorously. This work began in his table-making days at the Admiralty Computing Service, and later in the NPL. His first book, on Boundary Value Problems, was published in 1957, and is one of the very few books on Numerical Analysis of that age which is still in print. It is still often referred to in research literature by scientists who have real problems to solve.

The style of the book is very much Leslie's own, and rather different from current publications. It runs to more than 350 pages, but it contains no Theorems at all. On the other hand, it is far more than just a cookbook of recipes for solving problems. The precision of the solutions is treated at length, and his philosophy is stated very clearly in the Preface: "Throughout I have taken the view that

truncation errors in finite-difference equations should not be tolerated, and have made full use of the *difference-correction* method to eliminate such errors without decreasing the finite-difference interval. I have also discussed in some detail, as an alternative device, the method of *the deferred approach to the limit*" [now often referred to as h^2- extrapolation, or Richardson extrapolation]. Later in the book he says, after referring to an analytical solution of a problem as *exact*, "Our numerical method is also exact. If the difference corrections are properly applied, using an interval which makes the difference-equations meaningful, there need be no significant error from this source." He certainly never published solutions to problems without ensuring, and justifying his assertion, that the solutions were in fact exact to the number of figures given.

Much of the material in that book was his own; the use of high order differences, and the difference correction, in such problems have a longer history, and was developed at the NPL with Charles Clenshaw and Charles Goodwin, among others. These methods and their application to a wide range of numerical problems were described rather concisely in the NPL publication "Modern Computing Methods", 1957 and 1961, which became the working Bible of a very large number of practising numerical mathematicians; Leslie wrote a large part of it, and had a great influence on the rest.

Practical numerical problems

As might be expected, Leslie made significant contributions to most areas of numerical analysis, usually at the practical end. In his work as a research student there is a problem in elasticity which required the subtracting out of the singularity caused by a point load. This technique was applied in a number of different problems, notably in the vibrations of the L-shaped membrane; he never went on to extend the idea to the F-shaped membrane as well. Here the difficulty is caused by the re-entrant corner, and over a period of some years it was used as a test problem for various methods – finite difference, finite element, and a form of spectral method using Chebyshev polynomials, which gave a probably final value of the frequency to high accuracy. This work in particular brought together his continuing interest in the application of Chebyshev polynomials, which he had first met at the Admiralty Computing Service, and singularities.

A study of the problems on which he worked shows how many times his original work stimulated others to carry on the research. He studied integral equations of the first kind, he obtained numerical solutions of the double eigenvalue problem, in which a differential equation with two eigenvalues has three boundary conditions, he obtained numerical methods for calculating singular solutions of implicit differential equations, and as Alan Tayler describes in his talk at the Symposium, he obtained numerical solutions of a novel form of functional differential equation. In all these problems he discussed in detail the accuracy of his

results, and gave convincing reasons for their correctness.

Much of his work with finite differences involved the use of either the difference correction, or the deferred approach to the limit. Both methods require the function to be smooth, with bounded higher derivatives, and he adapted the original method of "Richardson extrapolation" to functions with singularities. He was able to obtain modified forms of asymptotic expansions in the step size when the function had various common types of singularity, showing how accurate results could be obtained with quite a large interval, and with reliable checks on the applicability of the method. Several generations of M.Sc students, in particular, learnt the basics of numerical analysis by calculating accurate values of various singular integrals.

The Institute of Mathematics and its Applications

Leslie was a Fellow of the IMA from the beginning, and served on its Council for some years. He also acted as Editor of the Journal, and when it split into several parts he became Editor of the IMA Journal of Numerical Analysis; he was also involved in organising a number of Conferences under the auspices of the IMA. When he retired the IMA arranged a symposium on "The Contributions of Leslie Fox to Numerical Analysis" held at the Royal Society, London, on September 14th, 1983. A report by John Crank on this event appeared in the IMA Bulletin in 1983. An important outcome of the meeting was the establishment of the Leslie Fox Prize, which Iain Duff writes about in this booklet. Leslie was delighted and very proud to be elected an Honorary Fellow of the IMA in 1989, becoming one of the distinguished group of nine Honorary Fellows.

Marriage

Leslie and Pauline were married in 1945. They slowly drifted apart after the move to Oxford, and then in 1969 came the meeting which changed his life. Clemency tells the story:

" It was almost by chance that I joined *Computer Weekly* as a reporter, as the result of meeting the editor at a lunch. He invited me to come for a month's trial; I stayed four and a half years. I do not now remember how I came to be Computer Weekly's representative reporter round the universities, but I know that it happened very soon after I got there, with no previous journalistic experience and precious little notion of how to write. I remember the editor saying: 'Well, you've had an education, you should be able to write'. So, maybe it was the education (Oxford degree included), which made him think I might also be able to talk to academics.

" In those days computers were always large, or very large, systems; there were no minicomputers or PCs. People in the computing world spent a great

deal of their time politicking, negotiating, debating about how to meet the costs of these systems, and whether a new computer could or should be bought from America, which in practice very often meant IBM, or from Britain, where one of the options was a rather newly formed ICL. Those buyers who were spending their own money were free to go for whatever they wanted. But the universities and other government-funded organisations who were spending taxpayers' money were often constrained, as they thought at the time, to 'buy British', even though for performance reasons, software, reliability and so on, they might have preferred otherwise. For the editorial staff on *Computer Weekly*, therefore, there were sometimes good stories to be found among the wheeling and dealing that was going on for the acquisition of these large systems, costing what seemed (and probably were) huge sums of money.

'And so I found myself visiting university computing departments in different parts of the country, finding out what was going on there, and what their aspirations were for getting a more powerful computer system of the next generation. Sometimes, if I was lucky, I met a somewhat garrulous academic who would spill at least some of the beans about the current state of his (yes, it was usually his!) negotiations, and I would go back to the office and write up what I had heard. At other times I met the kind of academic who was so deeply suspicious of the press that he found it almost impossible to say anything to me at all, in case I got it wrong! Leslie was one of these.

'The day I met Leslie for the first time I had already visited another computing centre, and talked and listened at length to people there. So it was late in the afternoon when I arrived in Oxford, perhaps a little weary. I sat down in his office on the top floor of the building in Parks Road, with its quite splendid view over the Parks, and started trying to interview this professor, Director of Oxford University Computing Laboratory, of whom at that time I knew very little.

"Getting anything out of Leslie, I found, was like trying to chip lumps off a granite rock with a teaspoon. I heard later that he had, not long before this, allowed himself to be interviewed by a local reporter, who apparently knew nothing about numerical mathematics, very little about computing and not much about how to explain the technology to his readers. To Leslie, with his passion for accuracy, the garbled report which subsequently appeared was irredeemably bad. He never recovered a sense of proportion about the press, nor reporters as individuals, and ever afterwards lumped us all together as only capable of misrepresentation of the facts.

"I remember very little, now, about that interview – except one incident. I asked him what seemed, from my standpoint, like a perfectly reasonable question: 'What kind of computer have you got here?' Expecting the answer 'a KDF 9', I was surprised (to say the least) when he looked at me over those dark-rimmed glasses of his and said 'And what will you write, if I tell you the answer to that?'

I don't remember what I replied – what could I have I said? But from that point on I knew that interviewing this professor was a lost cause.

"There *was* a redeeming feature to this episode. When making the arrangements for the visit on the telephone, Leslie had asked me whether I would like to have dinner afterwards. And I, at the time an impecunious reporter who was never averse to accepting a free meal, said yes, thank you. So after this simply ghastly interview, and after being shown round the laboratory and meeting some of his colleagues, he took me to the Lamb and Flag before going on to have dinner.

"It was a whisky – the best I have ever tasted – but there was more. That evening I found that this professor could, after all, talk: about sport and music and books, and life and people and politics, and mathematics (of course) and everything under the sun. I discovered that he was the nicest man I had ever met, and he has remained at the top of my list from that day to this.

"In 1973 we were married. I was Leslie's wife for 19 years and 12 days, the greatest privilege of my life."

After they were married (by another coincidence, a union between two families of Foxes) they moved to Old Marston, to a house right on the edge of Oxford, just opposite the village church. The new home became the hospitable centre of an increasing circle of friends from all parts of the world.

Golf

Clemency writes: "Almost every kind of sport absorbed Leslie's total interest, particularly if he was taking part. It is therefore not surprising that after he decided that he was getting too old for cricket – his reactions were slowing and he felt that he was not seeing the ball well enough – that he should turn to golf. He became more than just reasonably good at it and his enjoyment of playing was enormous, though you might have been forgiven for thinking otherwise if you had heard his grumbles when he had not played well. He managed to keep it going until a few weeks before the end, even though the trouble he had with his eyes meant that he could not see the ball at all well and his balance was not good.

He had his regular golfing arrangements, one of which took place on a Friday afternoon. [For many years no seminars, lectures or meetings took place in the Lab on a Friday afternoon, and it was well known around the University that any committee which involved Leslie could never meet at that time.] In the seventies this was also the day when my work took me regularly to London, so we trained our Labrador dog, Willow, to behave properly on the golf course. Leslie could therefore take the dog with him to golf, and Willow would get his walk. For years, Leslie and dog together were a familiar sight on the course. On one occasion we had another dog (Willow's mother) staying with us. Leslie felt

that he could not manage two dogs at the golf course, so both were left at home that Friday. Leslie never forgot the look of outrage on Willow's face when the dog realised that Leslie was going to the golf course without him.

Leslie's opposite number at Cambridge as Professor of Numerical Analysis, Mike Powell, is also a keen golfer. Whenever they could they played golf together, and the idea emerged of arranging an annual contest between the dons of Oxford and the dons of Cambridge. The golf was to be taken very seriously but was, of course, to be accompanied by conviviality and good food, or as Leslie would have put it, proper eating. Leslie and Mike were to captain their respective sides.

After a few years Mike handed on this task, but Leslie kept the captaincy and organisation of the Oxford team in his own hands from the first match in 1979 right up to the match in 1992, when he was far from well and which was only a few weeks before he died; though for the last two or three years, as his health and therefore his golf deteriorated, he became non-playing captain. When he died, there were flowers from the Academic Golfers of Cambridge University. The card read: " We remember with pleasure your kindness and sportsmanship throughout our annual meetings that you initiated in 1979." After the first match one of the Oxford players, Bill Bald, presented a silver cup for the competition. The Fox-Powell trophy has been the prize for the winning team ever since, and was put on display by Mike Powell at the Memorial Symposium. Among Leslie's papers I found a complete handwritten record of all the matches played, up to and including 1992, with the results."

Retirement

In 1981, soon after the Oxford Gatlinburg meeting, he was taking his usual Friday afternoon on the golf course as a break from the responsibilities as Chairman of the Mathematics Faculty Board, when he was taken suddenly ill, with what was discovered to be a heart attack. After two days in the coronary care unit, and a week in a medical ward at the John Radcliffe Hospital, he was allowed home. By January 1982 he was back at work, slightly chastened, but not much. He accepted the attack philosophically, as one of those things which happens to people of a certain age, but it must have come as an unpleasant shock to a man who had not known what illness, even very minor illness, felt like.

Peter Sleight, his heart consultant (and a fellow golfer), was very insistent that he must give up smoking. Years before, Clemency had accepted his proposal of marriage only on condition that he gave up cigarettes. It took another 18 months before he finally succeeded (up till then he had been a 20 a day man) and changed to a pipe. While he was in hospital after the heart attack Clemency hid even the pipe, and when he came home Leslie never seems to have found it, or missed it.

Sadly, this incident was a foretaste of what was to come. He had already made up his mind to retire in 1983, at the age of 65, rather than go on to 67, but much

of his well-earned retirement was spent battling with illness. There was trouble with a tumour near the pituitary gland, which badly affected his eyesight, so that he could not see the ball properly, and there were more heart problems.

After his retirement Leslie developed a scholarly interest in the history of his subject. He lectured in Britain and the USA on early numerical analysis in the United Kingdom. His last published work was a detailed survey of the numerical work of L.F. Richardson for an edition of his Collected Papers, which was published after Leslie's death.

Conclusion

This memoir has been a combination of records of his sporting interests, and his mathematical work. It is fitting to end with a note from Peter Dickens, who though not a mathematician is one of his oldest friends and cricketing and golfing companions – and a fellow Yorkshireman.

"Leslie was a serious and successful all-round sportsman. He had been inspired by boyhood heroes Huddersfield Town Football Club and Yorkshire Cricket Club, whose recent decline (together with that of the Labour Party) reinforced his pessimistic outlook for the world's future, but did not dent his loyalty to those institutions. As a student he had represented Oxford against Cambridge at Football in war-time, and subsequently played for Oxford City. At the NPL he ran as a sprinter in the Civil Service Championships, was club tennis champion and captain of the cricket team.

On returning to Oxford he became a stalwart member of the Barnacles Cricket Club, a side composed of dons and undergraduates which prospered under the somewhat despotic leadership of the philosopher H.P. Grice and included in its eclectic membership future Vice-Chancellors of Oxford and Cambridge, an Australian Prime Minister and a British Ambassador to the United States – and some good cricketers too. Leslie created havoc in local cricket circles as a remarkably accurate leg-spin bowler who was far more dangerous than at first sight seemed remotely possible, as the Oxford Diocesan Clergy discovered to their cost on one momentous occasion.

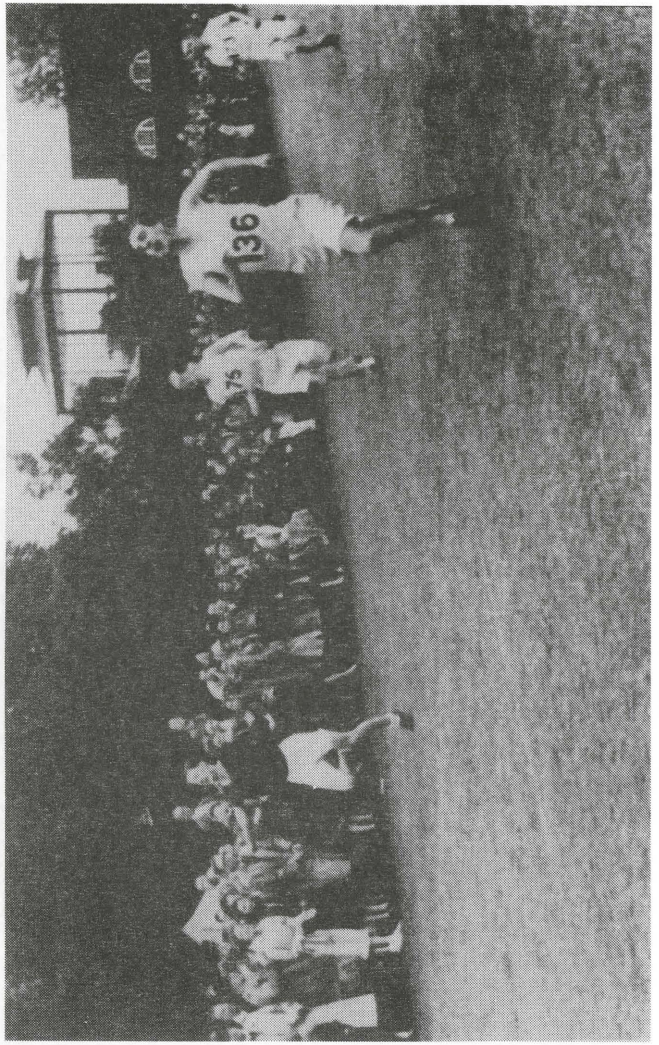
In a reflective moment he once confided to a friend 'I think I've been good or above average at quite a lot of things, but never really outstanding in any one of them'. In this he revealed characteristic modesty but certainly failed to recognise his own world-class capacity to win the friendship, affection and devotion of so many who came into contact with him."

Leslie and Roy with their parents Job and Annie
Holiday portrait 1925

Leslie, aged 8

Elsie Vincent was a younger cousin of Leslie's mother, and was at the same primary school in Chickenley: "I well remember the day our Headmaster put a sum up on the board. We were a class of 12 year old pupils, but none of the class could do it. He said that he could find a boy from the infants' class who could do it, so he came in with this small boy Leslie Fox, 8 year of age. He just looked at it, and did the sum on the blackboard right away."

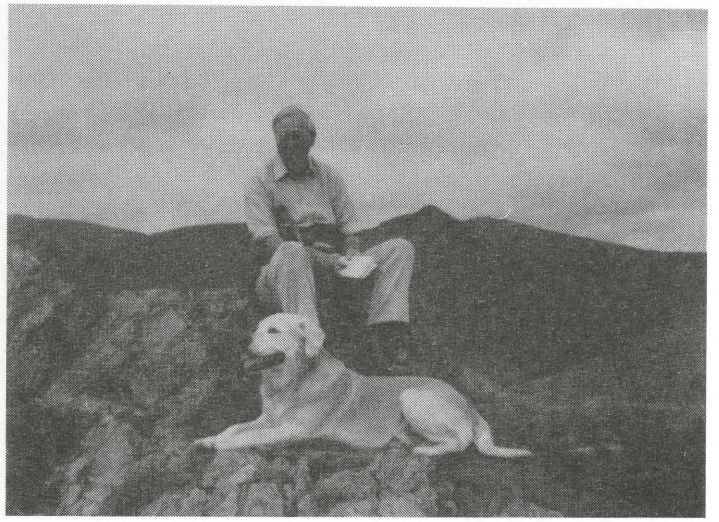
As a research student Leslie spent some time
at Imperial College



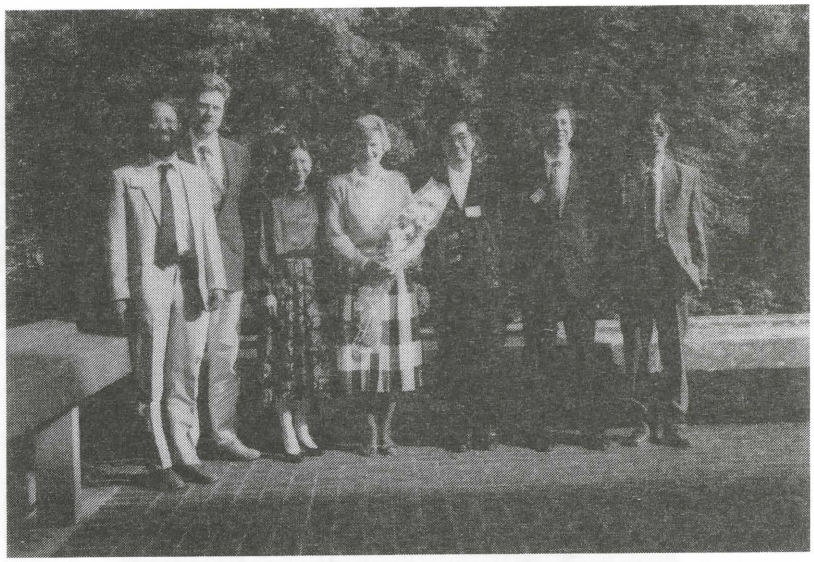
Winning the 440 at an NPL Sports

A proud centurion

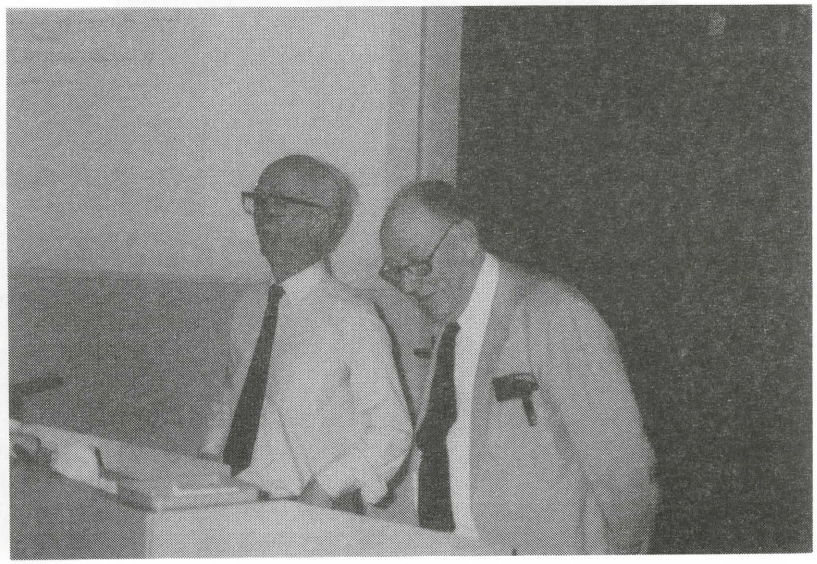
Leslie always looked happy
with a glass in his hand



Leslie and Willow on their way to conquering another peak
in "the most beautiful place in the world" – the Lake District



Clemency with the 1993 Fox Prizewinners



Geoff Hayes and Frank Olver
at the Symposium, June 1993

Memorial Service

At the Memorial Service for Leslie in the Chapel of Balliol College on 30th January 1993 two Addresses were given, the first by his successor to the Professorial Fellowship, Bill Morton, and the second by his brother, Roy Fox, CMG, OBE.

Memorial address by Bill Morton

I count it a great privilege to have the opportunity at this service to pay tribute to the memory and achievements of Leslie Fox. Many of you will have known and loved Leslie, very closely, over many years, and in many different capacities. Some will have been colleagues at work, collaborating with him on books or journal articles; or at this college, where he was a fellow for nearly thirty years; many will have been his students; some of both groups, and many others too, will have been his team-mates or opponents on some field of sport, keeping wicket to his bowling, partnering him at tennis or golf, or engaging with him in his many other sporting activities.

Apart from being his successor here, I have been none of these things. Yet I first met him nearly forty years ago, we planned and carried through many projects together, and he and his work have been a constant reference point in my own career. It was in 1952 or '53 that, as a new graduate starting work at Harwell, I went to see Leslie in his office at the National Physical Laboratory, or NPL. I was engaged in calculating the latent roots (as we then called eigenvalues) of 10×10 matrices on a desk calculator. He was the acknowledged master in matrix computations on desk calculators, and I had eagerly read his paper on escalator methods which had just been published. I still recall the occasion very clearly, and it was my contact with matrix computation that was responsible for my becoming a numerical analyst.

It was at NPL, just after World War II, that Leslie first built his reputation in numerical analysis. This was a new name for a subject which grew rapidly in importance during and after the war, especially with the advent and explosive development of computers. NPL was at the forefront both nationally and internationally. They were exciting times, when the country still had technological ambitions; and Leslie and his group of colleagues – with whom he remained very close throughout his career – laid the foundations for the subject, which they summarised in the widely-read booklet "Modern Computing Methods".

He had started his career at Oxford, getting a first in mathematics at Christ Church and starting his D Phil research under Sir Richard Southwell, in the School of Engineering, at the end of 1939. The aim was to apply Southwell's relaxation methods to the bending and stretching of thin plates. So from the very outset Leslie was engaged in solving practical engineering problems; and

this concern that numerical analysis, and mathematics more generally, should be used to solve practical problems remained strong, and often strongly advocated, throughout his career.

The thesis itself, much of which was published secretly by the Royal Society in 1941, already shows the lucid and elegant style for which Leslie was later noted. It is a lively personal account of the work, including the disagreements between Southwell's intuitive approach, based on mechanical analogies, and Leslie's growing awareness that here was a mathematical technique of much wider applicability.

Leaving Oxford in 1942, Leslie spent the rest of the war at the Admiralty Computing Service before going to NPL. Here he met a very different set of skills and range of problems. L.J. Comrie and D.H. Sadler represented a long tradition of constructing mathematical tables for use in navigation, and their wider use spread with that of computation. Table-making demanded much mathematical ingenuity and great accuracy in calculation. For the latter, punched card equipment was being introduced; but, meanwhile, such as Alan Turing, and Jim Wilkinson were developing programmable electronic computers (the pilot ACE) and new algorithms for them.

Leslie was immensely stimulated by all these people and events, and the result was a very productive fifteen years that led to two influential books, each representing a blend of the new ideas with those of Southwell, in ways which are still the subject of intense research forty years later. I refer specifically to the use of difference corrections and how they should be combined with mesh refinement in the solution of differential equations, and to iterative versus direct methods in numerical linear algebra.

In 1957 Leslie returned to Oxford as the first Director of the newly formed Computing Laboratory. The responsibility was two-fold: to set up a computing service with the university's first computer, a Ferranti Mercury; and to start the teaching of numerical analysis. The former took up a lot of his time and effort, as the early days of running a computing service with unreliable hardware, rudimentary software, and a constant battle for adequate resources, were very demanding ones for all concerned. Eventually the service and academic functions were separated and Leslie and his group in the Computing Laboratory were able to concentrate on research and teaching in numerical analysis.

It was here, over the twenty-five years from '57 to '82, that Leslie made his most lasting contribution to his subject — at Oxford, in the UK, and internationally. It was he above all who took the skills that had largely been developing in government research laboratories and turned them into a key part of the university mathematics curriculum. He gradually introduced them into the Oxford undergraduate syllabus and set up a graduate training programme that produced some 70 D. Phils in numerical analysis at a critical stage in the subject's growth;

these went out and spread the ideas in other universities, where seven are now professors; and it is now in these universities that most of the research is carried out. In the early 1970's on a Saturday morning you could also see him on television teaching Open University courses: before that he organised a series of Summer Schools at Oxford that made a wide impact and initiated the very productive book-writing collaboration with his colleague David Mayers. Through his editorship of journals for the IMA and of books for OUP, he laid the foundations for numerical analysis publication in the U.K.; and he provided a home and support for Brian Ford's Numerical Algorithms Group, at a critical stage of its development into the present flourishing international company NAG.

On a wider front, Leslie argued continually for Oxford mathematics to be more practical; and in 1968 he and Alan Tayler started the Oxford Study Groups with Industry, and gave great support to John Ockendon as this enterprise developed into the highly successful Oxford Centre for Industrial and Applied Mathematics, a development which has been followed now in many countries throughout the world.

But I end with an example of Leslie's initiative which typifies the many occasions where his generous support has sprung from initial vigorous disagreement. In 1961 he published an article entitled "Computing machines for teaching and research" in which he took a very narrow and controversial view of what was involved in "computing" and more specifically in the "programming" of computers. It provoked a very lively and lengthy correspondence indeed from many outraged computer scientists, led by Stanley Gill and Christopher Strachey. The result was a challenge to them from Leslie to present some of this non-numerical computing in a summer school. This was taken up and resulted, first of all, in a highly successful Summer School and a widely read published proceedings for which Leslie acted, in his own words, as "secretary, catalyst, host, editor and student". But even more important, it led to Leslie inviting and finding funds for Christopher Strachey to set up at Oxford what became the Programming Research Group, which now constitutes the major part of our Computing Laboratory. That this should be the outcome of such an initial clash of philosophies, provoked in no small part by Leslie's Yorkshire bluntness, is a typical example of his generosity of spirit and unfailing good humour.

In this brief tribute I have concentrated very much on Leslie's professional achievements, leaving it to his brother Roy to redress the balance. But in all that he did – in mathematics, in his many sporting activities and accomplishments, in his appreciation of music and good wine, in his views on politics and life in general – Leslie was one of those rare individuals who inspire affection and respect in equal measure, from students, colleagues, friends, opponents and all who knew him. We shall and do miss him enormously.

Memorial address by Roy Fox

Leslie decreed about 2 years ago that we would together write the story of our early days. When I came to put together these few paragraphs I realised that he would have liked me to tell you something of his early life, and the village in which we were born.

Leslie Fox began his life in 1918 in a stone middle-terrace house in Princess Street, Chickenley - a village halfway between Dewsbury and Ossett in the middle of the West Riding of Yorkshire. I was born there 2 years later.

At the bottom of the street were fields of wheat and oats. Half a mile away was a pit heap - the last mark of a disused colliery and occasionally, for us, a source of coal. Over to the right was a working colliery - Shaw Cross - and in between were football and cricket pitches and the road to Dewsbury.

At the bottom of Chickenley Lane stood Wilson's mill in the middle of the village. Samuel Lyle's spinning mill was nearby, and a dyers, where we used to play at the edge of the mill pond. Outside the village was a wealth of open space.

The house had one main room, perhaps 6 metres by 5. There was an open fire and oven, a pot boiler for washing clothes and a corner sink. Baths were taken in a large tin bath in front of the fire on Friday evenings; the hot water was boiled in kettles on the fire.

The washed clothes hung on a clothes line which stretched across the street to the wall of number 9 where my mother's mother lived. Leslie was born there, and his first sleeping niche was the bottom drawer extracted from grandma's chest of drawers which stood next to the washing mangle.

Few vehicles used the street, but when they did the clothes prop would be raised like Tower Bridge.

The grandparents were great characters. My grandfather Harry Vincent was a founder member of the Dewsbury Labour Party. He once walked from Hull to Leeds - maybe 25 miles - to get a job. Later he suffered terrible arthritis through working as a navvy in wet trenches. My grandmother had her hands full with a mentally deficient boy who outlived them, something she dreaded all her life.

She encouraged us. " Better yourself lad. You don't want to be like us. There's so much more you can do in this world." Each morning before setting off for school we would call and she would give us one licorice allsort (just one) - the cylindrical one with licorice round white stuff in the middle.

My father's mother lived in Ossett and was married to Jack Fox. He was a gambler and my grandmother would meet him on Fridays to make sure there was money for food. He was a philosopher too. Leslie was one day feeling a little down about something he'd done wrong. "Don't worry about that", he said; "think well of thisen, lad, because if tha' doesn't nobody else will."

There was a cellar in the house, part of which was a coal bunker.

The cellar acted as a 'fridge and did that well even in summer. The lavatory was in the backyard - there was no garden. Toilet paper consisted of squares cut from the Daily Herald and Dewsbury Reporter, through which a piece of string ran and was hooked on the back of the door. Job (dad) and Annie - she was addressed as mother - read the Herald diligently. They thought Churchill was the enemy of mankind and particularly of the workers.

There were two bedrooms upstairs. The smaller one just took a double bed and Leslie and I slept there together. Last year we were recalling the thrill of lying in a warm bed listening to the rain battering against the window.

Harry Unsworth, Leslie and I with a few others would meet during weekends and evenings either in Harry's house (he played the cello in a local orchestra) or around the gas lamp which stood by Mr Ashcroft's shop at the top of the street. One or two girls sometimes came along and I well remember one occasion when Leslie was ignored by his grandmother because he was talking to one of them.

It was a puritan, chapel existence. There was no alcohol in the house and no visits to the pub. Being pregnant before marriage was shameful. We were not allowed to buy sweets on a Sunday, except wine gums. Chapel was compulsory twice on Sundays, and there was choir practice during the week. All the family sang, and there were many evenings and weekends of singing with Auntie Eva, and later Leslie, at the piano. Relationships between the sexes were frowned upon. No games were allowed on Sundays.

It was not only a chapel world; it was a tough world with tragedy in such villages. One of our earliest experiences of family distress was a visit to a cousin whose back had been broken in an accident at Shaw Cross colliery. There was no breadwinner in the family and there were five kids under nine. The mother clearly could not cope, and wept hysterically. We came away in utter misery - not really comprehending the real measure of the agony involved.

Perhaps the most excruciating part was the lack of educational opportunity.

Leslie was the only boy in a class of 40 in the junior school to win a scholarship at 10 to the Dewsbury Wheelwright Grammar School - as I was two years later. He was permanently affected by the appalling injustice of a system which condemned bright sparks to Council Schools which they would leave at 14 for work in a shop, a mill, or the mines, when they would undoubtedly have done well in due course at the grammar school. This was especially so when he arrived at the grammar school and found a fee-paying boy sitting next to him.

Parents were the key when so few grammar schools were available. We were lucky. Annie was a jewel. She seemed to work from 6 a.m. to midnight and we could see later the magnitude of the task involved in keeping two sporting boys at grammar school when the home had such poor facilities and money was short. She herself had had to leave the grammar school and go to work at the age of 12.

She made it clear that 5 out of 10 for history homework would not do. "Why? Why?" she would say. "Too much football and too little concentration on history. No football for a week." "Don't mess about" she would add. "Your future depends totally on how hard you work now. There are better lives to live - full of interest and opportunity and responsibility. Your father and I didn't have the chance. Don't throw yours away."

This lady was asked years later why she didn't talk much about the apparent success of her boys. She replied that if she did no one would believe her. She died at 91 in Eynsham, and her ashes are in Marston - with Leslie's.

Yet withal it was a happy life for the two Fox children. Grammar school was fascinating and rewarding. Football and cricket dominated free time and there were other games in reserve. Leslie had the patience and sense to work at the piano and later he was to play for outbreaks of singing, on many pianos. He was fit and once won the summer championship for the number of skips done consecutively - with a skipping rope - in the street (871). I remember the sun was beating down and he almost collapsed at the end. My father's income was £3 a week but we still had a week in Blackpool and Yarmouth - playing cricket on the sands of course.

The food was excellent. Home made bread and cakes, including apple pastry the like of which I have never experienced elsewhere. Suet puddings with currants and white sauce, rice pudding, jam tarts and custard; soup made from a ham shank and peas, carrots etc - with dumplings. On Sundays we sometimes had visitors; that meant sandwiches, scones and tinned pears or peaches with cream, cake and apple tarts. No wonder Leslie said he never had a day's illness until he retired.

Sport was in the family; Job had been a good footballer and a near professional cricketer. He augmented his meagre income by getting 50's from time to time. The hat would then be passed round the ground and we would later count the pennies and sixpences, up to perhaps £5, when there was great rejoicing. He usually won the prizes for batting and bowling, or both. Later the three of us played in the same village team and won the Challenge Cup in a thrilling finish at Hanging Heaton.

Leslie took the Grammar School by storm. He went into Form 3A at 10, and took six prizes - all of them except Art and something else. At the same time he excelled in all sports. He was sports champion by virtue of winning the 100 and 200 yards, the long jump and throwing the cricket ball. He played for the cricket and football First XIs. But he wasn't perfect. He went very fast down the right wing, and I remember saying this to the tough, rough diamond captain Norman Jackson. "Yes" replied Norman,"that's true, but I wish he would take the ball with him more often."

He was useful, too, at tennis. I used to try to beat him by running round

my weak backhand, and it was on one of those occasions that he gave me a rare word of advice. "Learn to play *all* the strokes" he said, "so that you can have an all round basis for development. Winning is not all that important at this stage. And don't fret if you can't be world champion at anything. To play a lot of games reasonably well is what matters. But learn them well."

Leslie's success in the first year was kept up throughout his grammar school days. He collared a good proportion of the form prizes and eventually produced 6 distinctions in the Matric. He continued to prosper in the Sixth Form and decided to specialise in Maths, to the delight of the Headmaster, Mr Sadler. There followed the scholarship to Christ Church, a wartime Blue at Soccer with Oxford University, and continued enjoyment of soccer and cricket for a number of teams. He turned to bowling leg breaks and had a fair measure of success. His happiest moments were just after he had bamboozled some aggressive batsman; that delighted smile told it all.

Later a number of us persuaded him to start golf, and it was to nobody's surprise that he became very keen on the game. Towards the end he could not see the ball too well and his stamina ran out, but he still enjoyed the challenge and the company and the atmosphere.

It was not surprising with all the early background that he became a Socialist as soon as he knew about politics. It was, however, a measure of the man that he *remained* a Socialist and regarded me as a turncoat when I pointed out flaws in Socialist policies or personnel. There were self-evident truths to be accepted - that good education and good health treatment *had* to be available to all. He was intolerant of political opposition. He deplored the Thatcher years and their legacy. He was utterly contemptuous of "that wretched woman".

I received a letter recently from a form mate at the Wheelwright. He wrote:

"I am writing to express my sympathy at your loss. Leslie was one of the people I always admired and looked up to. He had that rare quality of prowess at sport and games together with a great intellect, and he was a kind fellow."

We miss his chuckling sense of humour and his ready, full smile. We miss his inability to dissemble and his forthright attitude. Perhaps above all he had no side and cheerfully dismissed those afflicted with pomp and vanity as *brussen* a Yorkshire word for "inordinately cocky". I won the cross country one year when he was home from Christ Church. As I lay writhing in agony on the ground his shoe stirred my ribs. "Well done," he said, "but get up. Don't make an exhibition of yourself."

The Fox Prize

Iain Duff writes: "The Fox Prize Competition owes its origins to a suggestion made by Gene Golub during a visit to Oxford in 1982. When Nancy Nichols and I first heard the idea from Gene we were immediately enthusiastic. The idea of a Prize that was awarded to young researchers seemed a totally appropriate way of commemorating the contribution of Leslie to our field. As this present memorial booklet testifies, Leslie has had a profound and singular influence on the development of numerical analysis as much by his teaching and interaction with and encouragement of young researchers as by his own substantial research output. The plan was then discussed in more detail by many in our community and it was felt that the most appropriate body for administering such a prize was the Editorial Board of the IMA Journal of Numerical Analysis. Mike Powell, then one of the Editors of IMAJNA, drew up a set of rules which, with minor modifications, are still in use. Catherine Richards of the IMA agreed to help in the advertising and collecting of funds and an appeal for support was launched just prior to the first call for entries. Each competition is organized and judged by an Adjudicating Committee appointed by the IMAJNA Editorial Board. It has been normal practice for the chairman to retire and the next most senior member to become chairman for the following year. The chairmen for the six Prize Competitions have been M.J.D. Powell (Cambridge), A.R. Mitchell (Dundee), J.K. Reid (Harwell), K.W. Morton (Oxford), J.C. Mason (Shrivenham), and N.K. Nichols (Reading). C.L. Clenshaw (Lancaster) served as a member of the Adjudicating Committee for the Second Prize Competition.

It had been the original intention to hold the Prize meeting annually and the second meeting was held thirteen months after the first. However, the number of entrants and the effort required to judge them adequately has led to a slightly lower frequency of between 18 months and two years. The first three meetings were held at Imperial College, with local arrangements managed by Mike Bernal. This location had the merit of being easily accessible to many people and the attendance was usually very satisfactory with an audience of from 40 to 60. However, it was felt that it might be better to hold the meeting in conjunction with a major international numerical analysis meeting to attract more overseas attendees, appropriate since many of the Prize finalists were from outside the United Kingdom. This juxtaposition was first tried at the IMA Silver Jubilee Meeting at Cambridge in September 1989 and proved very successful with closer to 100 participants and a wider geographical spread. This formula was repeated with success at the Dundee meeting in 1991 and has now been combined with the Symposium at Oxford this week."

There follows a complete list of prizewinners, and brief reports on former Prize meetings. These are based on full reports which were published in the Bulletin of the IMA or the IMANA Newsletter.

List of prizewinners

First Leslie Fox Prize Meeting—Imperial College—30 August, 1985.

First Prize	*Second Prize*
L.N. Trefethen (MIT)	N.J. Higham (Manchester)
	S.P.J. Matthews (Dundee)
	P.K. Sweby (Reading)
	Y. Yuan (Cambridge)

Second Leslie Fox Prize Meeting—Imperial College—5 September, 1986.

First Prize	*Second Prize*
J.W. Demmel (Courant)	J.L. Barlow (Penn State)
N.I.M. Gould (Harwell)	J. Scott (Oxford)
	A.J. Wathen (Bristol)

Third Leslie Fox Prize Meeting—Imperial College—28 March, 1988.

First Prize	*Second Prize*
N.J. Higham (Manchester)	T. Hagstrom (SUNY, Stony Brook)
	P.T. Harker (Univ of Pennsylvania)
	I.R.H. Jackson (Cambridge)
	T. Tang (Leeds)

Fourth Leslie Fox Prize Meeting—Cambridge—4 September, 1989.

First Prize	*Second Prize*
M. Buhmann (Cambridge)	M. Ainsworth (Durham)
B.R.L. De Moor (Stanford)	R.H. Chan (Hong Kong)
A.M. Stuart (Bath)	A. Edelman (MIT)
	D.J. Higham (Toronto)

FIFTH LESLIE FOX PRIZE MEETING—DUNDEE—24 JUNE, 1991.

First Prize	*Second Prize*
C.J. Budd (Bristol)	J. Levesley (Coventry)
J.F.B.M. Kraaijevanger (Leiden)	P.D. Loach (Bristol)
	B.F. Smith (Argonne)
	H. Zha (Stanford)

SIXTH LESLIE FOX PRIZE MEETING—OXFORD—24 JUNE, 1993.

First Prize	*Second Prize*
Y. Li (Cornell)	A. Edelman (Berkeley)
	D.J Higham (Dundee)
	Z. Jia (Bielefeld)
	P. Lin (Oxford)
	R. Mathias (Minneapolis)

Leslie Fox Prize 1985

The first Leslie Fox Prize meeting was held on August 30th, 1985 at Imperial College, London. As regular readers of the newsletter will know this competition was open to young numerical analysts who were invited to submit a research paper suitable for a 45 minute presentation. The main business of this meeting was the presentation by their authors of the five papers which had reached the final round of the competition.

The meeting was opened by Professor M.J.D. Powell, the Chairman of the adjudicating committee, who congratulated all the entrants, both finalists and non-finalists on the standard of the entries. The chair for the morning session was then taken by David Jacobs who introduced the first three speakers. Peter Sweby of Reading University opened the proceedings with a paper entitled "High resolution schemes using flux limiters for hyperbolic conservation laws". We then moved from nonlinear hyperbolic systems to linear ones with a paper from Nick Trefethen of MIT on "Instability of difference models for hyperbolic initial boundary value problems". This was followed by a complete change of subject with a paper from Ya-Xiang Yuan of Cambridge University on "Conditions for convergence of trust region algorithms for non-smooth optimization".

Nancy Nichols took the chair for the afternoon session and introduced Nick Higham of Manchester University who spoke on "Computing real square roots of a real matrix". The final paper was given by Paul Matthews of Dundee University who spoke on "Stable modification of explicit LU factors for simplex updates".

The content of each of the papers has appeared or will soon appear in the standard literature and so I shall not comment on that here. However I am sure

that when the committee selected these five papers on the basis of their content they could not have anticipated how well they would be presented. The attentive audience, who were mostly ineligible for the prize due to their advanced years, were very impressed by the standard of the presentations given by these relative youngsters.

After a tea-break the committee went away to deliberate while the rest of us enjoyed the final talk given by the man whose career inspired the setting up of the competition — Professor Leslie Fox. It was most appropriate that he should describe some of the work that he had done in his late twenties (the age of the entrants in the competition). This included a live demonstration of relaxation methods which showed that a combination of observation, recognition and speedy mental arithmetic could probably compete very favourably against a modern computer. He then described a problem involving singularities at unknown points which again needed observation and recognition — this time in the behaviour of differences — to solve. His last point should give us all something to think about. In any modern applications in artificial intelligence the computer effectively recognizes situations that it has met before. Could this idea not be used to great advantage in many numerical applications?

The final item of the afternoon's business was the announcement of the winner(s). Mike Powell said that it had been the committee's intention to award one first and at most two second prizes. However after hearing the presentations they had decided that the first prize should go to Nick Trefethen and that each of the other four finalists should receive a second prize. The committee urged those entrants who had been unsuccessful in this year's competition to enter a subsequent one.

Leslie Fox Prize 1986

The finalists for the 1986 Leslie Fox Prize presented their papers at a meeting at Imperial College, London on Friday 5th September, 1986. The five finalists had been chosen from an entry of eighteen, and all gave performances well worthy of that honour. Indeed, one could attend many prestigious meetings before finding two sessions of such high quality.

The speakers in the morning session were Andrew Wathen (Bristol) on "Attainable eigenvalue bounds for the Galerkin mass matrix", Jennifer Scott (Oxford) on "A convergence recipe for discrete methods for generalised Volterra equations", and Jesse Barlow (Penn State) on "On the smallest positive singular value of a singular M matrix with applications to ergodic Markov chains". The more than adequate lunch that followed helped to remove a little of the EEC butter mountain and was enjoyed by all, except perhaps the principals in the afternoon session!

The afternoon session saw Jim Demmel (Courant) expound on "On condition numbers and the distance to the nearest ill-posed problem", followed by Nick Gould (Harwell) on "On the accurate determination of search directions for simple differentiable penalty functions". The jury then retired while a suspenseful tea and biscuits was enjoyed.

On a day when there were deservedly no losers, the adjudicating panel of Mitchell (chairman), Clenshaw, and Reid announced that second prizes would be awarded to Wathen, Scott, and Barlow and that first prizes would be awarded to Jim Demmel and Nick Gould.

Leslie Fox Prize 1988

The third Leslie Fox Prize Meeting was held at Imperial College, London on Monday, March 28th, 1988. Five finalists had been selected to present papers from an entry of seventeen, which included entries from the UK, Europe, China and America. The finalists were chosen by the adjudicating committee for the originality and quality of their papers, together with the suitability of the material for presentation to a general audience of numerical analysts. The five papers chosen for presentation provided a varied programme, covering widely differing areas of numerical analysis.

The meeting was divided into a morning and an afternoon session. The morning session opened with a talk by T. Hagstrom (SUNY) on "Asymptotic boundary conditions for computational studies of wave propagation". This was followed by P.T. Harker (Pennsylvania) speaking on "Accelerating the convergence of the diagonalisation and projection algorithm for finite dimensional variational inequalities", and I.R.H. Jackson (Cambridge) on "An order of convergence for radial basis functions". After lunch T. Tang (Leeds) spoke on "The spline collocation methods for non-standard Volterra integro-differential equations", followed by the final speaker of the day, N. Higham (Manchester) on "Analysis of the Cholesky decomposition of a semi-definite matrix". The adjudicators then met to consider the awarding of prizes.

A first prize deservedly went to N. Higham, the only person to date to have been a finalist at more than one Leslie Fox Prize Meeting. The talk given by N. Higham not only contained new and interesting results but was clearly and carefully presented. Each of the other finalists was presented with a second prize.

Leslie Fox Prize 1989

The Fourth Leslie Fox Prize meeting was held at the University of Cambridge on Monday 4th September immediately preceding the Silver Jubilee meeting of the IMA. We are grateful to Mike Powell for hosting the meeting and to ICI for sponsorship.

I think that I speak for all the 39 attendees at the Meeting when I say that the standard of presentations by all candidates was truly exceptional. The quality both of content and presentation was extremely high and the talks covered many different areas of numerical analysis, some emphasising the theoretical and others the practical aspects of the subject.

There were more finalists than in any previous year and the adjudicating committee of Bill Morton (Chairman), John Mason, and Nancy Nichols had great difficulty in selecting this short-list from an entry of 17 papers from six countries, such was the overall standard of this year's entry.

The quality was such that they almost overshadowed the numerical analysis minisymposia at the IMA Silver Jubilee Meeting the following day. Nearly all the more "senior" speakers at that meeting used vital minutes from their precious thirty to pay tribute to the speakers at the Fox Meeting whom they regarded with some awe and a great deal of respect.

The cast of this outstanding performance were (in order of appearance) ...
A.Edelman (MIT)— Eigenvalues and condition numbers of random matrices
M.Buhmann (Cambridge)— Multivariable cardinal interpolation with radial basis functions
B.L.R.De Moor (Stanford)— The restricted singular value decomposition: properties and applications
D.J.Higham (Toronto)— Highly-continuous Runge-Kutta interpolants
R.H.Chan (Hong Kong)— Circulant preconditioners for Hermitian Toeplitz systems
A.M.Stuart (Bath)— Linear instability implies spurious periodic solutions
M.Ainsworth (Durham)— An asymptotically exact a-posteriori error estimator for the finite element approximation of problems with singular solutions

Unfortunately, because of a family bereavement, Nancy Nichols had been unable to come to the meeting. The remaining adjudicators, after one is sure much agonizing, awarded three first prizes to Martin Buhmann, Bart De Moor, and Andrew Stuart and second prizes to Mark Ainsworth, Ray Chan, Alan Edelman, and Des Higham. Leslie Fox presented the prizes.

Leslie Fox Prize 1991

The Fifth Leslie Fox Prize meeting was held at the University of Dundee on Monday 24th June immediately preceding the Dundee Biennial Conference in Numerical Analysis. We are very grateful to to the Conference organizers, Alistair Watson and David Griffiths, for extending the accommodation arrangements to include the Meeting, for assisting with the registration, for arranging the excellent lunch, and for providing tea and coffee at zero cost.

This was the first time that the Fox Prize Meeting had been coupled with a Dundee meeting and, from the viewpoint of audience size and diversity this

coupling was a distinct success. Even more gratifying was that among the 75 or so attendees, there were many "famous" numerical analysts in addition to many previous Fox Prize winners, not that there is any implication of exclusivity between these two classes.

Indeed the number of finalists equalled the record of the last meeting, in part indicating the difficulties that the adjudicating committee of John Mason(Chairman), Nancy Nichols, and Charlie Elliott had in selecting this short-list.

The resulting cast list in order of appearance was:

C J Budd (University of Bristol)— Convergent and spurious solutions of nonlinear elliptic equations.

H Zha (Stanford University)— The restricted SVD and its numerical problems.

J Levesley (Coventry Polytechnic)— A Chebyshev collocation method for solving Symm's integral equation for conformal mapping: a partial error analysis.

J F B M Kraaijevanger (University of Leiden)— Contractivity of Runge-Kutta methods.

B F Smith (Argonne National Laboratory)— A domain decomposition algorithm for elliptic problems in three dimensions.

P D Loach (University of Bristol)— On best l_2 continuous piecewise polynomial approximation.

John Mason then announced the prize winners, maintaining suitable suspense by announcing the second prize winners first, in a different random order. First prizes were awarded to Chris Budd and Hans Kraaijevanger, and second prizes to Hongyuan Zha, Jeremy Levesley, Barry Smith, and Paul Loach.

Gene Golub, who initially suggested the idea of establishing the Prize, chaired one of the sessions and echoed the feelings of the audience in a warm tribute to Leslie, whom we were delighted had made the long journey north to attend the Meeting and to present the prizes.

SIXTH LESLIE FOX PRIZE COMPETITION
and
SYMPOSIUM IN HONOUR OF LESLIE FOX

24/25 June 1993

Nuclear Physics Lecture Theatre, 1 Keble Road, Oxford
24 June, 1993

(i) Leslie Fox Prize Competition

10:00 **Nancy Nichols**
Opening Remarks

Chairman: Iain Duff

10:15 – 11:00 **D.J. Higham**
The dynamics of variable stepsize Runge-Kutta algorithms

11:00 – 11:45 **Z. Jia**
Generalized block Lanczos methods for large unsymmetric eigenproblems

11:45 – 12:30 **R. Mathias**
The stability of parallel prefix matrix multiplication with applications to tridiagonal matrices

12:30 – 13:45 **Lunch — Balliol College**

13:45 Opening of afternoon session

Chairman: John Reid

14:00 – 14:45 **A. Edelman**
Eigenvalue roulette and random test matrices

14:45 – 15:30 **P. Lin**
Characteristic Galerkin schemes for scalar conservation laws in two space dimensions

15:30 – 16:15 **Y. Li**
On the convergence of reflective Newton methods for large-scale nonlinear minimization subject to bounds

16:15 – 16:45 **Tea**

16:45 – 17:05 **PRIZE AWARDS — Clemency Fox**

(ii) Leslie Fox Symposium

Chairman: Mike Powell

17:15 – 18:15 **Gene Golub**
More on modified eigenvalue problems

19:15 **Sherry Reception — Balliol College**

20:00 **Dinner — Balliol College — Speaker: Charles Goodwin**

SYMPOSIUM IN HONOUR OF LESLIE FOX

25 June 1993

Nuclear Physics Lecture Theatre, 1 Keble Road, Oxford

08.30	**Registration**
09.00	**Bill Morton** Opening remarks
Chairman:	**Geoff Hayes**
09.15 – 09.40	**Donald Kershaw** Leslie Fox, Linda Hayes and Wronski
09.40 – 10.30	**Frank Olver** Superasymptotics
10.30 – 10.55	**Joan Walsh** Leslie Fox and the teaching of numerical analysis
10.55 – 11.20	**Coffee (and continuation of registration)**
Chairman:	**Sean McKee**
11.20 – 11.45	**Alan Tayler** Study Groups
11.45 – 12.35	**Nick Gould** Linear algebraic issues in large-scale optimization
12.40 – 14.00	**Lunch**
Chairman:	**Charles Clenshaw**
14.00 – 14.40	**Andrew Stuart** Analysis and computations for a model of phase transitions
14.40 – 15.20	**Hans Stetter** Defect correction from Gauss to the present day
15.20 – 16.00	**David Mayers** Relaxation
16.00	**John Mason** Closing remarks
	Tea

The meeting organisers gratefully acknowledge generous sponsorship from Chapman & Hall, ICL, NAG Limited, Nuclear Electric and OUP.

Fox Prize Day Proceedings

Opening remarks – Nancy Nichols, University of Reading

It is a pleasure to welcome you all here and to open this meeting in honour of Leslie Fox, combining the Sixth Leslie Fox Prize Competition with a special Symposium in recognition of Leslie's many contributions to education, research and teaching.

I should like to begin by thanking various sponsors of this meeting. First of all, our gratitute should go to all the contributors to the Fox Prize Fund who have made possible the foundation and the success of the Prize. Secondly, the following (in alphabetical order) should receive our thanks for their support for this meeting: Chapman and Hall, ICL, IMA, NAG and OUP, all of which were closely associated with Leslie. Chapman and Hall and OUP were both publishers of Leslie's books. ICL provided support for the Oxford Computing Laboratory (including machines and grants for research) during Leslie's tenure as director. Leslie was involved in the development of the original NAG — then known as the Nottingham Algorithms Group, and helped in their transfer to their current home in Oxford. Finally Leslie was active as a Fellow of the IMA from its inception and was elected to one of twelve honorary Fellowships of the Institute in 1989.

Our thanks should go to the Nuclear Physics Department for providing us the facilities for this meeting, and the staff of the Oxford Computing Laboratory for all their help in arranging the Symposium.

Amongst the many honours Leslie received, he particularly valued the foundation of the Leslie Fox Prize. Leslie devoted much of his life to education in numerical analysis. He wrote eight expository books describing both the theory and the practicalities of numerical computation, in addition to eighty-seven research papers. As the first Professor of Numerical Analysis at Oxford he brought computational mathematics into the regular undergraduate syllabus and he introduced numerical analysis as an option in the Diploma/MSc course. He also brought his subject to a wider audience through the Open University courses which he developed — you could say he brought NA to TV. As Director of the Oxford Computing Laboratory he opened the laboratory to school pupils, providing computational experience at an influential time in the development of the school mathematics curriculum.

Leslie was especially encouraging to research students. As a supervisor, I found that he had two particularly important qualities. The first was an ability to anticipate new topics which would in the future become significant areas of research. This facility he brought also to his other activities. For example, Leslie had the foresight to pick green as his favourite colour long before it became 'politically correct'. (Of course, Leslie's political ideas were always correct, at

least according to Leslie!)

The second valuable quality Leslie displayed was the ability to ask precisely the right question — the question that went right to the heart of a problem. This also was a talent that he developed early in life. As an example, when as a young pupil at Wheelwright Grammar School he was told by his teacher that the answer to his question was not 'ten', Leslie responded quick as a flash, "Is there a question to which 'ten' is the answer?" This anecdote also illustrates Leslie's interest in inverse problems, which later became a major topic of his research with various colleagues and students.

Leslie was clearly fond of numbers, and a little numerical data seems appropriate here to demonstrate Leslie's far-reaching influence. During his tenure at the Oxford Computing Laboratory, 70 students form the laboratory were awarded the degree of Doctor of Philosophy in numerical analysis and 43 additional students received the Master of Science (or equivalent Diploma in Advanced Mathematics). These students are now working and teaching in some 21 different countries. Of these Leslie supervised, himself or jointly, 24 successful doctoral candidates plus 12 masters students. Many of these now have had students of their own, who are supervising further students. (Leslie's 'grand-children' and 'great-grand-children'!)

The aim of the Fox Prize is to continue Leslie's encouragement and support for young numerical analysts. I have no doubt of the delight he would have felt in the prize candidates now enriching the field by their contributions. In this year after his death, it is particularly pleasing to have such excellent entries to choose from. Unfortunately, only six finalists could be chosen from the 19 submissions. The choice was as usual very difficult, but the adjudicating committee is certain that the audience has some interesting presentations to look forward to.

I shall now hand over to Iain Duff to introduce the first session of the Leslie Fox Prize Competition.

Introduction to morning session – Iain Duff, Atlas Centre, RAL, Didcot

The meeting today is the Sixth time that the Leslie Fox Prize Competition has been held and is the first one since Leslie's death. I think it is appropriate at this point to think a little about the history of the Prize Competition and reflect on the outstanding quality of the past prizewinners.

From the beginning, Leslie was delighted with the idea of the Prize and enthusiastically supported it. He presented the prizes at all the previous meetings including the 1989 Meeting in distant Dundee. We are delighted that his enthusiasm is shared by his wife, Clemency, and that she is present today and will present the Prizes at the end of the day's proceedings.

If there ever has been any embarrassment it has been that the quality has been too high! It certainly has made judging difficult and one's heart must go

out to those extremely worthy candidates who just failed to get a First Prize. I think it is important to recognize, in advance of today's talks, that all finalists have come to this tie-breaker as winners over a very strong field of nineteen original submissions. This is a similar pattern to earlier competitions and has led occasionally to thoughts of reducing the age limit. However, such considerations are outweighed by the continuing quality of the meetings and the knowledge that younger people who might not quite receive the supreme accolade can have another try. It is hard to compromise excellence. In fact, it was the original intention to boost the meetings with a talk from an eminent "senior" numerical analyst and Leslie himself spoke at the first meeting. However, since then it has not been felt at all necessary to provide this boost although, I should add that we are delighted that the first talk in the Symposium will take place ere this day has ended.

As a postscript, a call for entries for the Seventh Leslie Fox Prize Competition will shortly be made. It will be held in conjunction with an International meeting in June/July 1995. The Adjudicating Committee are: C.M. Elliott, chairman (Sussex), C.T.H. Baker (Manchester), and I.S. Duff (RAL).

Introduction to afternoon session – John Reid, Atlas Centre, RAL, Didcot

A student's view of Leslie Fox as a supervisor: I was Leslie's second D. Phil. student, immediately following Joan Walsh, with whom I did not overlap, and studied in South Parks Road from 1961 to 1964. The Computing Laboratory was a conversion of a typical North Oxford family house, now demolished for the Zoology Building. Leslie himself has said that a doctorate is really a test of the supervisor and I am pleased to relate that Leslie passed.

Leslie was always kind-hearted and my experience on the day of my examination was characteristic. I was given a well-deserved grilling during my viva by Jim Wilkinson and was invited to join Jim and Leslie (who was not an examiner) for dinner. It was not conventional to tell the student the result until later, but as I left to go back to Sussex, Leslie said "Goodbye, Dr Reid". The immediate response from Jim, with a totally straight face, was "but that is not my opinion"! [I should say that he apologized to me a few years later.]

Working with computers at that time was very different from today. We had a Mercury with a memory of 1k words of 40 bits (large compared with my previous experience as a vacation student) and 32k words on drum. The only input-output was by paper tape. I remember sometimes finding at a weekend that John Rollett had been particularly successful and so had paper tapes leading up and down the stairs to all the teletype printers in the building. We learned to be expert in making manual changes to paper tapes and to be patient with the breakdowns associated with a valve machine. Despite its unreliability by modern standards, Mercury was able to do some very significant calculations and it was

the fascination of being able to control such a big computation that attracted me.

Leslie preferred to work with a hand calculator, but taught me not to do so. One day, we had a discussion about the conditioning of a matrix problem and decided that the issue could be settled by solving a 4x4 set of linear equations. He told me to solve this by hand. I found it totally excruciating. I kept making mistakes and it took me all evening. In fact, the only way I could ensure that I had the correct solution was to write a Mercury program the next morning. I was convinced of the merits of computers.

I must thank Leslie overall for his encouragement, particularly in a typical period of student blues in the middle of my first year. He made me go and talk to several people with problems to solve and I saw the opportunities there were. He insisted on high standards of writing and of accuracy. His linear algebra book was published at this time and he offered a shilling (at least a pound in modern money) for every error, but I found none. He was critical of my first draft thesis chapters, but in a constructive way and the rewritten versions were much better.

The Computing Laboratory in those days provided a comfortable and friendly environment in which a great deal of work was done. This even included my girl friend of the time, now my wife, who came in to do her History essays because her digs were so cold. She wondered what Leslie would say if she met him on the stairs - he just encouraged her, too.

The Adjudicating Committee for the Fox Prize comprised Nancy Nichols (chairman from Reading), Charlie Elliott (Sussex), and Christopher Baker (Manchester). They had the difficult task, first of selecting finalists from nineteen very high quality entrants, then the even more unenviable task of choosing prizewinners from the finalists.

The full list of speakers and the titles of their papers is given in the Programme on page 47.

After a break for tea, and deliberation by the adjudicators, the meeting recovened for the presentation of the prizes.

The standard was so high that the Committee decided to award all finalists a prize with a First Prize being awarded to Yuying Li from Cornell University and Second Prizes to Alan Edelman, Des Higham, Zhongxiao Jia, Peixiong Lin, and Roy Mathias. Clemency Fox, who attended all the sessions of the meeting, presented the prizes which included book donations from IMA, OUP, and Chapman and Hall in addition to a monetary prize.

Symposium in Honour of Leslie Fox

The Symposium followed on from the presentation of the Fox Prizes, and began with a talk by Gene Golub, introduced by Mike Powell as Chairman. Mike gave an entertaining description of sporting exchanges between the Cambridge and Oxford dons golf teams using the actual trophy as a visual aid. The speaker for the session was Gene Golub which was doubly appropriate because not only was he a friend and visitor to Oxford but he was also a prime instigator in the foundation of the Leslie Fox Prize. Gene spoke on modified eigenvalue problems with reference to a very early paper by Leslie on the computation of latent roots, prompting a lively debate on nomenclature. The tone of the whole meeting was well set by the excellent atmosphere established by Mike and Gene in this first session of the Symposium.

The setting of the Fellows Garden at Balliol for the aperitifs was a marvellous prelude to a memorable dinner at Balliol which I am sure would have been greatly enjoyed by Leslie himself. Indeed several speakers remarked that Leslie would have very much enjoyed the proceedings although he might have found the alternative fixture of the visiting Australian cricket team at the Parks a little tempting. The dinner, made even more memorable by the quality of the wine sponsored by NAG Ltd, was a time for more reminiscing led by entertaining and informative speeches by Bill Morton who introduced Brian Ford who then, after some remarks of his own, introduced Charles (E.T.) Goodwin the after dinner speaker. Charles spoke mainly about Leslie's pre-Oxford days at the National Physical Laboratory. The banter and comraderie continued well into the evening in the Senior Common Room and, after what for some seemed a rather short night, at breakfast on the Friday morning.

Suitably refreshed, we reconvened in the Nuclear Physics Lecture Theatre for a wide range of contributions from speakers, chairmen, and floor. The mathematical range was testimony to the great breadth and influence that Leslie brought to Numerical Analysis and the range in mode of presentation reflected the admiration and esteem in which all participants held him. After some opening remarks by Bill Morton, Geoff Hayes took the chair. Geoff shares a distinction with the first speaker, Donald Kershaw, of having been to the same school as Leslie in Yorkshire. Donald spoke about some work of Leslie Fox with Linda Hayes at Oxford related to work of Wronski that has generated recent interest in the numerical linear algebra community. Frank Olver then gave a highly entertaining and informative talk on "Superasymptotics". The second morning session was chaired by Sean McKee, the first UCINA coordinator and golfing colleague of Leslie, and included talks by Alan Tayler on differential equations arising from the Study Groups with Industry and by an ex-Oxford student Nick Gould on linear algebra issues in optimization.

After a most pleasant lunch in Balliol, the Symposium reconvened with a talk by Andrew Stuart, another ex-Oxford student and possibly the last to be directly influenced by Leslie. He talked about "Analysis and computations for a model of phase transitions". The chairman of the session was Charles Clenshaw who was a colleague of Leslie's at the National Physical Laboratory. Hans Stetter, who had visited Oxford several times as a guest of Leslie gave the second talk on "Defect correction from Gauss to the present day" and was followed by Leslie's Oxford colleague and co-author David Mayers on the subject of "Relaxation" .. an appropriate title for the last talk and a topic on which Leslie had been involved since his early work with Southwell. The meeting was brought to a close with characteristically witty remarks by John Mason who irreverently reviewed the talks at the Symposium as if they were contenders for a senior citizen's Leslie Fox Prize.

At the end of the meeting, presentations were made to the ladies from the Oxford Computing Laboratory who had worked hard to ensure the smooth running of both the meeting and the arrangement with Balliol College. At the final afternoon tea, a very lively conversation amongst all participants, friends of Leslie and thence friends together, concluded a most successful and enjoyable event and one which did much to uphold the memory of our dear friend and colleague.

Although registration costs were kept low, the generosity of several sponsors (Chapman and Hall, ICL, IMA, NAG Limited, Nuclear Electric, and OUP) enabled a healthy surplus to be donated to the Leslie Fox Prize Fund which will be used to support further Leslie Fox Prize Competitions.

There follows a record of the welcoming remarks by Bill Morton, and abstracts of the talks.

Opening remarks – Bill Morton, Oxford University Computing Laboratory

First of all let me welcome you all here for the second day of this meeting. The suggestion for this two-day meeting, combining the Prize Competition yesterday and the Symposium in Leslie's honour today, was made independently by several people last autumn. It was quickly followed by suggestions that the theme of today's meeting should reflect the whole of Leslie's career, roughly in chronological order. So we on the organising committee (Iain Duff, Sven Hammerling, David Mayers, Nancy Nicholls and myself) have had a relatively easy time, and are grateful to all the speakers for readily accepting this suggested format. We have had one unfortunate late withdrawal: Professor Joan Walsh who was Leslie's first student here is unable to speak at the meeting due to a throat infection; but I am confident the remaining speakers will have plenty of material to fill the gap.

I had the opportunity and privilege in January, at the Balliol Memorial Service, to honour Leslie on behalf of all the numerical analysis community and to give thanks for his immense service to us and our subject. (Incidentally, the paper on escalator methods that I referred to there as having led to our first meeting was exactly the paper referred to by Gene Golub in his lecture last night.) So I shall say little now; but I would like to emphasise something that struck me very forcibly when I read through all his early papers — that the concerns he had then are often still very active issues today. To give just two examples: the differing views that he and Southwell took regarding the relative advantage of refining the mesh or using higher order differences in order to get higher accuracy continue today in the arguments over h-refinement and p-refinement; and the choice between relaxation methods and direct methods for solving linear systems continues to be as lively an issue as ever.

Both of these topics and many others that Leslie made key contributions to will be taken up by our main speakers today.

Leslie Fox, Linda Hayes and Wronski

Donald Kershaw, University of Lancaster, Fylde College, Lancaster

In 1968 L.Fox and L.Hayes published in The Journal of Linear Algebra and its Applications a method for factorizing a polynomial P as the product of two polynomials. This was based on the LU factorization of a band matrix associated with P. An analysis of the convergence was given when P was a quartic, and it was shown that there was a close connection with the Q-D algorithm. Later, in 1987, I gave an analysis of the method with rather more general assumptions, and showed that the method essentially constructed Hankel polynomials. Last century Wronski (1778-1853) gave an algorithm for finding polynomial factors of a polynomial based on polynomial division. It will be shown that the two methods are essentially the same, and a simpler and more direct proof of convergence will be given. Although the methods are equivalent it will be shown that the method of Fox and Hayes is more flexible, and less likely to fail.

Superasymptotics

F.W.J. Olver, Maryland

Leslie Fox's extensive researches in applied mathematics did not include asymptotic analysis *per se*, nevertheless he exerted a considerable indirect influence on

my own work on this area. It is to him, more than anyone, that I owe my training as a practical numerical analyst. As a consequence of this training I have constantly been aware of the need for asymptotic analysis to be an effective numerical tool. One result has been the development of a theory of realistic error bounds. Another is a frequent desire to squeeze ever-higher accuracy from asymptotic expansions by appropriate forms of re-expansion. My lecture in this symposium is on the latter topic. It describes some very recent, and elegant, re-expansions of remainder terms in the asymptotic solutions of linear differential equations in the neighbourhood of an irregular singularity. I dedicate this lecture most gratefully to the memory of Leslie, a true pioneer of scientific computing in this century.

Leslie Fox and the teaching of Numerical Analysis

Joan Walsh, University of Manchester

Leslie Fox's influence on a whole generation of numerical analysts had three strands: the rapid development of a "Graduate School" in Oxford from 1958, which provided staff in due course for many other universities, a series of practical and readable text-books from 1964 onwards, as well as the proceedings of the Oxford Summer Schools, and the encouragement of algorithm development at the highest level to make the results of research widely available. A theme particularly associated with him is the vital importance of using computers intelligently, with error checks and estimates of accuracy regarded as part of the calculation. He promoted these ideas in the early days of the Numerical Algorithms Group library, which owes a lot to his support, and he saw the basic difference correction technique developed into mathematical software by workers in Germany and the U.S.A. The common thread of all his teaching, which spanned many areas, was always the soundness and practicality of computational methods.

Asymptotic and numerical analysis — some examples

A.B. Tayler, Oxford

I first met Leslie soon after his arrival in South Parks Road and asked his advice about my use of relaxation methods on my transonic flow equations. He

quickly convinced me that it would be a difficult task to estimate the errors in my procedures and after much heart-searching I wisely decided to look for new applications of mathematics. We regularly took lunch together in Halifax House before colleges welcomed us, and mixed mathematical arguments with mean table tennis. Out of these informal discussions the idea of the Study Groups with Industry arose and Leslie committed himself to the project despite his other responsibilities. We worked together on problems as competitive partners—modelling and asymptotics v numerical analysis and computation.

The second Study Group in 1969 was very successful and out of six problems, three still have developments of current mathematical and physical interest. In my talk I will describe one of them, which concerns the overhead collection of current for an electric locomotive. After considerable simplification of the real problem we are reduced to solving the functional differential equation

$$\frac{dy(t)}{dt} = ay(\lambda t) + by(t), y(0) = 1,\ 0 < \lambda < 1. \tag{0.1}$$

Little analytical information was available about such equations and for practical values of a, b and λ Leslie easily obtained sensible numerical solutions using finite differences. However the mathematician is interested in all values of the parameters and for $\lambda = 1- \ll 1$ numerical difficulties arise. My colleague John Ockendon was able to construct an asymptotic solution for small ϵ valid for all time t and all values of the parameters a and b. With $a > 0$, $a + b < 0$, the solution decays for times of order $1/\epsilon$, then oscillates with small amplitude for times of order $\epsilon^{-1/3}$ before growing exponentially. The challenge to confirm numerically the number of oscillations suggested by the asymptotic analysis was a great stimulus to Leslie, and he enlisted David Mayers and Linda Hayes to help him. References to the problem are:

Ockendon and Tayler, 1971. Proc. Roy. Soc. A **322** 447-468.

Fox, Mayers, Ockendon and Tayler, 1971. J. Inst. Maths. Applics. **8** 271-307.

This problem illustrates the value of the group approach to real world problems and there are many more examples. The success of the Study Groups led Leslie to found UCINA and play a central role in the development of the MSc in Mathematical Modelling and Numerical Analysis.

Leslie was a mathematician who enjoyed basic problems—indeed his favourite lecture was 'How to obtain meaningless answers in scientific computation'. He was an excellent communicator who wrote well and was well read. His advice was always well considered and his enthusiasm for problem-solving was a great stimulus to all of us.

Linear algebraic issues in large-scale optimization

Nick Gould, CERFACS, Toulouse, France

Considerable progress has been made in recent years in designing efficient algorithms for solving large-scale nonlinear optimization problems. At the heart of most methods lies a system of linear equations. In this talk, we survey the types of equations which typically arise in optimization applications; we give examples from unconstrained optimization, linear and nonlinear least-squares, linearly constrained optimization and penalty function methods for general constrained optimization. The unifying feature is that all these applications give rise to systems of symmetric equations of the form

$$\begin{pmatrix} H & A^T \\ A & G \end{pmatrix} \begin{pmatrix} x \\ \lambda \end{pmatrix} = - \begin{pmatrix} g \\ b \end{pmatrix},$$

where $x \in \Re^n$, $y \in \Re^m$ and, ideally, the inertia of the coefficient matrix is $(n, m, 0)$.

We consider how this structure may be exploited in direct and iterative methods for unconstrained and linearly constrained optimization. In particular, this leads us to consider modifications to the conjugate gradient method, which result in globally convergent methods for the unconstrained problem, and in suitable pivot selection rules for the factorization of the above coefficient matrix. We are particularly concerned with the case when the number of variables and/or constraints is large. Encouraging numerical results are given.

This work is fully described in [1].

References

[1] M. Arioli, T. F. Chan, I. S. Duff, N. I. M. Gould, and J. K. Reid. *Computing a search direction for large-scale linearly constrained nonlinear optimization calculations.* Technical Report TR/PA/93, CERFACS, Toulouse, France, 1993.

The viscous Cahn-Hilliard equation

Andrew Stuart, Stanford University

In this talk we study the *Viscous Cahn-Hilliard equation:*

$$(1 - \alpha)u_t = \Delta\theta, \quad x \in \Omega$$

$$\alpha u_t = \gamma\Delta u + f(u) + \theta, \quad x \in \Omega.$$

This equation was derived as a model of phase transitions and can also be obtained as a singular limit of the Phase-Field model. For simplicity we use Dirichlet boundary conditions:

$$u = \theta = 0, \quad x \in \partial\Omega$$

and the simplest example of a nonlinearity to which our analysis applies is

$$f(u) = u - u^3.$$

This equation contains two interesting limits: at $\alpha = 1$ we have *the Cahn-Allen Equation* (a model for grain-boundary migration):

$$u_t = \gamma\Delta u + f(u), \quad x \in \Omega$$

$$u = 0, \quad x \in \partial\Omega;$$

this equation is well-understood mathematically. On the other hand, at $\alpha = 0$ we obtain *the Cahn-Hilliard Equation* (a model for spinodal decomposition):

$$u_t = -\Delta\{\gamma\Delta u + f(u)\}, \quad x \in \Omega,$$

$$u = 0, \quad \gamma\Delta u + f(u) = 0, \quad x \in \Omega.$$

This qualitative model was introduced by Cahn and Hillard.

Mathematical and physical interest in the problem is focussed on the long-time behaviour of the solutions.

In the talk we study numerical methods for computing solutions of the viscous Cahn-Hilliard equations as α varies in [0,1]. The computations indicate extreme insensitivity of the global attractor to the parameter α and this observation is backed-up by a mathematical analysis of the properties of the global attractor as α varies.

This is joint work with Fengshan Bai, Alastair Spence and Charles Elliott.

Defect correction from Gauss to this day

Hans J. Stetter, Vienna

The term "defect correction" was introduced in the mid '70s to denote a variety of algorithmic techniques with a common principle. For an approximate solution, a "correction" is computed from its (accurate or approximate) defect. In the talk, we trace the development of this fundamental idea in computational mathematics.

After a long tradition in linear algebra, the use of defect correction in analytic problems was initiated by Leslie Fox in 1947 through his "difference corrections". This technique was further refined in "deferred corrections" algorithms by Pereyra and others. An outwardly very different use of defects was proposed by Zadunaisky; his surprising results led to an elaboration of the general principle in the discretization context in Vienna (Stetter, Frank et al.) and elsewhere (Skeel etc.). After a formal presentation of the two possible modes of defect correction (in the nonlinear case), we interpret some well-known algorithmic techniques from the point of view of defect correction (e.g. multigrid) and we sketch some techniques which have been designed as defect correction methods. Historical remarks and references to L. Fox have been woven into the presentation.

Relaxation

David Mayers, Oxford

After a brief view of the Pantograph problem described by Alan Tayler, but from a different angle, comes another example of Leslie's contribution to a Study Group problem. This involved a fairly simple elliptic equation on a rectangular region, with boundary conditions which seemed to indicate a mild singularity in the corner. John Ockendon alleged that (i) there was no singularity, and (ii) even if there was it wouldn't matter. Joyce Aitchison went off that night to compute some numerical values. Next day Leslie, who had not taken any part in the discussions on the previous day, asked to look at the numbers. After making some notes in the margin for a few seconds he said that there was a singularity like $r \log r$ in the corner. And he was right, of course - but more important, he made this deduction just by looking at the numbers, without any information about the equation which they came from.

Leslie spent the first years of his career in developing Relaxation methods, which died out (at least in their original form) very soon after the advent of the computer. The immediate reason for this rapid decline was that the early computers had a very small memory, and were only well adapted to the repetition of short loops of instructions. Any search for patterns of numbers, and decisions on different strategies, would rather quickly exhaust the storage available. Perhaps now is a good time to look again, to see if some of those ideas can now prove useful, when the problems are much more complicated and the machines are much more powerful.

List of participants

Dr. J.M. Aitchison	RMCS (Cranfield)
Dr. S. Amini	Salford University
Mr. I.J. Anderson	RMCS (Cranfield)
Prof C.T.H. Baker	University of Manchester
Dr. T.M. Bromilow	The Open University
Dr. H. Brunner	Memorial University of Newfoundland
Dr. C. Budd	University of Bristol
Prof C.W. Clenshaw	
Dr. J.A. Coleman	University of Durham
Prof T.F. Coleman	Cornell University
Dr. C. Cryer	Inst. for Numerical Analysis (Muenster)
Mr. A.R. Curtis	ARC Scientific Ltd
Dr. P. Davies	
Prof A.R. Davies	University of Wales
Dr. J.S. de Wet	Balliol College
Mr. S. Doole	O.C.I.A.M.
Prof. A.S. Douglas	Buxton-Douglas Ltd
Dr. J. Du Croz	Numerical Algorithms Group Ltd
Prof. I. Duff	Rutherford Appleton Laboratory
Dr. A. Edelman	University of California (Fox Finalist)
Dr. G.H. Elliott	University of Portsmouth
Prof. C. Elliott	University of Sussex
Dr. R. England	The Open University
Dr. B. Ford	NAG Limited
Mrs. C. Fox	
Prof. G. Golub	University of Stanford

Dr. E.T. Goodwin	
Dr. N.I.M. Gould	CERFACS
Dr. S. Hammarling	NAG Limited
Dr. D.C. Handscomb	Oxford University Computing Lab
Mr. S. Harbour	RMCS, (Cranfield)
Mrs L. Hayes	Oxford University Computing Service
Prof. J.G. Hayes	
Dr. G. Hedayat	University of Manchester
Dr. D. Higham	University of Dundee (Fox Finalist)
Dr. J. Howlett	
Mr. A. Humphries	University of Bristol
Mr. Z. Jia	Bielfeld University (Fox Finalist)
Dr. D. Kershaw	University of Lancaster
Prof. D. P. Laurie	P.U. for C.H.E. Vaal Triangle Campus
Dr. Y. Li	Cornell University (Fox Finalist)
Dr. P. Lin	Oxford University Computing Lab(Fox Finalist)
Dr. K. Lord	BAe SEMA
Dr. J. Lyness	Argonne National Laboratory
Prof. J. Mason	RMCS (Cranfield)
Dr. R. Mathias	University of Minneapolis (Fox Finalist)
Dr. H. Matthies	
Dr. D.F. Mayers	Oxford University Computing Lab
Prof. S. McKee	University of Strathclyde
Dr. D. Modi	University of Cambridge
Prof. P. Monk	University of Delaware
Prof. K.W. Morton	Oxford University Computing Lab
Dr. N. Nichols	University of Reading

Prof. F.W.J Olver	IPST University of Maryland
Dr. I. Parker	ICI
Dr. A.K. Parrott	Oxford University Computing Lab
Mr. A. Paul	Queens University
Dr. D.H. Peirson	AEA
Dr. T.N. Phillips	University of Wales
Dr. P. Plechac	University of Bath
Prof. M. Powell	University of Cambridge
Dr. J. Pryce	RMCS Shrivenham
Dr. T. Ratnanather	Johns Hopkins University School of Medicine
Prof. J. Reid	Rutherford Appleton Laboratory
Dr. S. Salvini	Numerical Algorithms Group Ltd
Dr. J. Scott	Rutherford Appleton Laboratory
Dr. G. Shaw	Numerical Algorithms Group Ltd
Prof. D. Spence	Imperial College
Prof. H. Stetter	Tech. Univ. Vienna
Prof. G. Strang	M.I.T.
Dr. A. Stuart	Stanford University
Dr. A.B. Tayler	University of Oxford
Dr. P. Vickers	W.H.O. Devavesm Palace
Prof. J. Walsh	University of Manchester
Dr. A. Wathen	University of Bristol
Mr. A. Watkinson	Chapman and Hall
Prof. J.R. Whiteman	Brunel University
Prof. L.C. Woods	University of Oxford
Dr. S.J. Wright	Argonne National Laboratory

Curriculum Vitae

In July 1992 Leslie was asked to provide a c.v. as background information for an article in the IEEE Annals of the History of Computing. He had done a complete bibliography of his books and papers, but he realised that he had never before needed a c.v., so he set to work and completed it; Clemency typed it the next day. Leslie died three days later. These follow just as he wrote them.

Born:	September 30th, 1918, in Dewsbury, Yorkshire
School:	Wheelwright Grammar School, Dewsbury
University:	Scholarship to Christ Church, Oxford, 1936 B.A. with First Class Honours in Mathematics 1939 Research Student, supervised by Professor Sir Richard Southwell, 1939–42 D.Phil 1942, Thesis entitled "Relaxation methods applied to problems of plane stress and strain" M.A. 1946 D.Sc 1956
Professional Experience:	Admiralty Computing Service, 1943–45 Mathematics Division, National Physical Laboratory, 1945–56 Associate Professor, University of California, Berkeley, 1956–57 Director , Oxford University Computing Laboratory, 1957–82 Professor of Numerical Analysis, Oxford University, 1963–83 Research Professor, University of Illinois, 1963–4 Commonwealth Universities Interchange Scheme, Australia, 1968 Visiting Professor, the Open University, 1970–1 Visiting Professor, University of Ljubliana, Yugoslavia, 1972 Visiting Professor, Indian Institute of Technology, Kampur, 1978 Visiting Professor, New South Wales Institute of Technology, 1979
Honours:	Professorial Fellow of Balliol College, Oxford, 1963–83 Emeritus Professorial Fellow of Balliol College, 1983–1992 Rouse Ball Lecturer, Cambridge University, 1967 Chairman, Numerical Analysis Panel, International Congress of Mathematicians, Vancouver, 1974 President, Mathematics and Physics Section of the British Association for the Advancement of Science, Guildford 1975

	IMA Symposium: "The contributions of Leslie Fox to numerical analysis" at the Royal Society, London, 1983 Honorary Chairman, 10th Canadian Congress of Applied Mechanics, 1985 The Leslie Fox Prize, first awarded 1985 Issue of the "IMA Journal of Numerical Analysis" dedicated to L.Fox on his 70th birthday Honorary Doctorate, the Open University, 1986 Honorary Fellow, Institute of Mathematics and its Applications, 1989.
Editorships:	Co-editor, Monographs in Numerical Analysis, Oxford University Press, 1957–91 Associate Editor, SIAM Journal (Applied Mathematics), 1961–68 Associate Editor, SIAM Journal (Numerical Analysis), 1968–75 Member of Editorial Advisory Board, USSR Computational Mathematics and Mathematical Physics, 1961–90 Co-editor and Editor, Journal of the IMA, 1970–1980 Associate Editor, IMA Journal of Applied Mathematics, 1981–89 Associate Editor, IMA Journal of Numerical Analysis, 1981–89.

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The proper use of recurrence relations. (1964 Presidential address to Oxford and District branch of the Mathematical Association), Mathematical Gazette, 49, 371-387, 1965.

Chapter 1(General Survey) and Chapter 12, Part III (Further comments on Uni-

versity work), (with J.E. Walsh) from "Numerical Analysis, an introduction" (edited J.E. Walsh), Academic Press, 1966.

Approximations and bounds for eigenvalues of elliptic operators, (with P. Henrici and C. Moler), SIAM J. Num. An, 4, 89-102, 1967.

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Mathematical and physical polynomials. From "Constructive aspects of the fundamental theorem of algebra." (edited B. Dejon and P. Henrici), 63-68, Wiley, 1967.

Polynomial factorisation and the QD algorithm (with Linda Hayes), Linear Algebra and Applications, 1, 445-463, 1968.

Comments on singularities in numerical integration and the solution of differential equations. From 3 - Numerical Methods, Colloquia Math Soc. Janos Bolyai, 61-91, Tihany, Hungary, 1968.

Generalized consistent ordering and the optimum successive over-relaxation factor (with Nancy K. Nichols), Num. Math., 13, 425-433, 1969.

Boundary singularities in linear elliptic differential equations (with R. Sankar), J.I.M.A., 5, 340-350, 1969.

On the definite integration of singular integrands (with Linda Hayes), Siam Review, 12, 449-457, 1970.

Chapter 1, Introduction, to "Numerical approximation to functions and data", (edited J.G. Hayes), IMA and Athlone Press, London University, 1970.

Some experiments with singularities in linear elliptic partial differential equations. Proc. Roy. Soc. A, 323, 179-190, 1971.

How to get meaningless answers in scientific computation (and what to do about it). Bulletin IMA, 7, 296-302, 1971.

On a functional differential equation, (with D.F. Mayers, J.R. Ockendon and A.B. Tayler), J.I.M.A. 8, 271-307, 1971.

The double eigenvalue problem, (with Linda Hayes and D.F. Mayers), Conference on Topics in Numerical Analysis (edited J.J.H. Miller), 93-112, Dublin, 1972.

The teaching of numerical analysis. Bulletin IMA, 8, 255-258, 1972.

The Regula-falsi method for free-boundary problems, (with R. Sankar), J.I.M.A. 12, 49-54, 1973.

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Computation of the lemniscate constants, (with Linda Hayes), Bulletin IMA 10, 425-426, 1974.

What are the best numerical methods? from "Moving boundary problems in heat flow and diffusion" (edited J.R. Ockendon and W.R. Hodgkins), 210-241, Oxford 1975.

A further helping of π, (with Linda Hayes), Mathematical Gazette, 49, 38-40, 1975.

Foreword to the Numerical Algorithms Group Library Manual (with J.H. Wilkinson), 1975.

Introductory Numerical Analysis. From "Computational methods and problems in aeronautical fluid dynamics", (edited B.L. Hewitt et al). Proceedings of IMA Conference, 1974, 15-52, Academic Press, 1976.

Numerical analysis, computers and problem solving. Interdisciplinary Sc. Rev., 1, 167-175, 1976.

Finite difference methods for elliptic boundary value problems. Chapter 7 of "State of the art in Numerical Analysis" (edited D.H. Jacobs), 799-881, Academic Press, 1976.

An inverse eigenvalue problem. Bulletin IMA 13, 162-163, 1977.

All about Jim Wilkinson, with a commemorative snippet on backward error analysis. From "The contribution of J.H. Wilkinson to numerical analysis", IMA Symp. Proc. No. 19, 1-20, 1978.

Finite differences and singularities in elliptic problems. Chapter 3 of "A survey of numerical methods for partial differential equations" (edited I.Gladwell and R.Wait), 42-69, Clarendon Press, Oxford, 1979.

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Some experiments with interval methods for two-point boundary value problems in ordinary differential equations, (with M.R. Valencia) B.I.T., 20, 67-82.

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On the numerical solution of implicit ordinary differential equations, (with D.F. Mayers), IMA J. Num. Anal., 377-401, 1981.

Computers still have a lot to learn about good numerical analysis and numerical algorithms, (N.A.G. AGM Lecture 1983). NAG newsletter 2/83, 5-15, 1983.

Numerical analysis in higher education. (Presented at Symposium on "The contribution of Leslie Fox to numerical analysis"). Bulletin IMA, 20, 103-108, 1984.

Mathematical and numerical modelling. Chairman's address for Proc. Tenth Canadian Congress of Applied Mechanics, W. Ontario, 1-10, 1985.

The beginnings of numerical analysis, lecture to British Society for the History of Mathematics, King's College, London, 1985.

James Hardy Wilkinson, 1919-1986. Biographical Memoirs of Fellows of the Royal Society, 33, 671-708, 1987.

Early numerical analysis in the United Kingdom. From "A history of scientific computing" (Edited Stephen G. Nash), 283-300, ACM Press history series, 1990.

Numerical Analysis in "Collected papers of Lewis Fry Richardson" (Edited by P.G. Drazin), CUP 1993.

Numerical analysis D Phil students during Leslie Fox's era (dates are years of graduation)

1960		
Walsh, Joan	Numerical solution of partial differential equations using a high speed computer	L. Fox
1962		
Phelps, Christopher	Applications of high speed computers to the solution of differential equations	L. Fox
1964		
Baker, Christopher	The numerical solution of integral equations	D.F. Mayers
Reid, John	Computational problems in linear algebra	L. Fox
1965		
Mason, John	Some new approximations for the solution of differential equations	D.F. Mayers
1967		
Sankar, R.	Numerical solution of differential equations	L. Fox
1968		
Campbell, Nigel	Stability theory of finite difference schemes	L.Fox & K.W. Morton
El-Tom, Mohammad	Numerical approximations of functions of one or more variables	L. Fox & D.C. Handscomb
Ford, G.C.	Computing problems in crystal structure analysis	J.S. Rollett
Stonebridge, Brian	Minimization methods in crystallography	J.S. Rollett
Williams, Jack	Some numerical problems in theoretical physics	D.F. Mayers
1969		
Nichols, Nancy	Numerical solution of elliptic differential equations	L. Fox

1970

Hartshorn, Timothy	Numerical solutions of differential equations	D.F. Mayers

1971

Aitchison, Joyce (nee Taylor)	Solution of differential equations	L. Fox & D.F. Mayers
Buttigieg, Alfred	Numerical solution of differential equations	L. Fox
Ganado, A.L.	Some numerical problems in integral equations	L. Fox
Redman, Geoffrey	Some numerical problems in Quantum theory	D.F. Mayers

1972

Arthur, Derek	Numerical approximation in one or more dimensions	D.C. Handscomb
Duff, Iain	Analysis of sparse systems	L. Fox R.P. Tewarson & J. Reid
Ris, Frederic	Interval analysis and applications to linear algebra	L. Fox

1973

Davies, Arthur Russell	Some problems in the analysis of resolution	J.S. Rollett
Ellison, David	Numerical solution of radiative transfer problems	I.P. Grant
Shanks, John	Numerical multiple integration of functions which have singularities	J.D.P. Donnelly
Thomas, Kenneth	The numerical solution of integral equations	B. Noble

1974

Hazelwood, Leslie	New applications of finite differences	D.F. Mayers
Ruloff, Volker	Problems in approximation theory	D.C. Handscomb
Spence, Alastair	Numerical solution of the integral equation eigenvalue problem	B. Noble
Wilton, David	Numerical solution of some exterior boundary value problems of mathematical physics	D.F. Mayers

1976

Elliott, Charles	Some applications of the finite element method in numerical analysis	J.D.P. Donnelly
Gaffney Patrick	Optimal interpolation	L. Fox & M. Powell
Quinney, Douglas	The numerical solution of initial value problems in partial differential equations	D.F. Mayers
Townsend, Stephen	Some methods of crystallographic phase determination	J.S. Rollett

1977

Ward, Pauline	Numerical analysis of Stefan problems	L. Fox

1978

Bromilow, Michael	Applications of spline functions	L. Fox & J.D.P. Donnelly
Dearing, Andrew	Computer studies of molecular structure and function	J.S. Rollett
Jackson, Michael	Optimization	D.C. Handscomb
Valenca, Maria	Interval methods for ordinary differential equations	L. Fox
Wong, Yau Shu	Iterative methods for problems in numerical analysis	J.S. Rollett

1979

Fernandes, Edite	Investigations of the convergence of optimization procedures	J.S. Rollett

1980

Allen, Keith	The numerical solution of delay-differential equations	D.F. Mayers
Dahmardah, Habib-Olah	Some problems in numerical integration	L. Fox & D.F. Mayers
Grayston, Alan	Some numerical problems in differential equations	D.F. Mayers
Harbottle, Philip	Numerical Methods with particular reference to non-linear problemsncOpe SrrsHD.C. Handscomb	

Pitcher, Neil	An analysis of discretisation methods for ordinary differential equations	S. McKee
Williams, Helen	Variable step-size predictor-corrector schemes for second kind Volterra integral equations	S. McKee

1981

Cameron, Ronald F.	Direct solution of applicable volterra integral equations	S. McKee
Peeling, Nicholas	Numerical solution of differential equations	D.F. Mayers
Tomlin, Janette	The conjugate gradient method in computer modelling of substrate complexes of hen human and tortoise lysozyme	J.S. Rollett

1982

Gould, Nicholas I.M.	Numerical methods for linear and quadratic programming	J.S. Rollett & W. Murray (Stanford)
Jacques, Ian	Predictor corrector methods for differential equations of parabolic type	J.M. Aitchison
Li, Chin-Hsien	Applications of the finite element method to numerical solution of Stefan problems	L. Fox & J.D.P. Donnelly
Meek, Peter	The solution of nonlinear parabolic equations using finite difference schemes	J. Norbury
Nicholas, Michael	Numerical solution of forward-backward heat equations	L.Fox
Phillips, Timothy	The numerical solution of elliptic partial differential equations	D.F. Mayers
Saxelby, Colin	The solution of partial differential equations by the finite element method	J.M. Aitchison
Turner, David	Some numerical problems in atomic physics	D.F. Mayers
Ypma, Thalling	Numerical solution of systems of nonlinear algebraic equations	D.C. Handscomb

1984

Baldwin, Dean	Pattern Formation in reacting and diffusing systems (with applications to morphogenesis)	S. McKee

Karageorghis, Andreas	The finite element method in then solution of free boundary problems	J.M. Aitchison
Lawson, Duncan	Combustion in a Porous Media	J. Norbury
Scott, Jennifer (nee Dixon)	A unified analysis of discretisation methods	S. McKee
Sivaloganathan, S.	Iterative methods for large sparse systems of equations	J.S. Rollett

1986

Hamilton, Stuart	The boundary element method for flow around submerged bodies	J.S. Rollett
Paisley, Martin	Finite volume methods for the steady Euler equations	K.W. Morton
Priestley, Andrew	Lagrange and characteristic Galerkin methods for evolutionary problems	K.W. Morton
Stuart, Andrew	The mathematics of porous medium combustion	J. Norbury
Trickett, Sarah	The numerical solution of elliptic problems	D.F. Mayers

1987

Burgess, Neill	Stable boundary conditions for the shallow water equations	K.W. Morton
Cuminato, J.A.	Numerical solutions of Cauchy integral equations and applications	S. McKee
Meneguette, Messias	Multistep multiderivative methods and related topics	S. McKee
Wu, Wei	Petrov-Galerkin methods for parabolic convection-diffusion problems	E. Suli