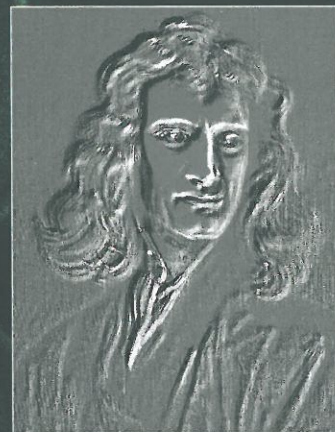


Isaac Newton Institute for  
Mathematical Sciences



*Annual Report*  
1998 ~ 1999

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## APPENDICES

Please note that the following statistical information may be obtained on request from the Institute, or from WWW at

<http://www.newton.cam.ac.uk/reports/9899/appendices.html>

- A Long-Stay Participants
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## Director's Preface



The Director with the Queen's Anniversary Prize Certificate and Medal

The four programmes completed this year have had a distinctly applied flavour: *Biomolecular Function and Evolution in the Context of the Genome Project* ran in parallel with *Nonlinear and Nonstationary Signal Processing* from July to December 1998; then *Turbulence* (January to June 1999) ran in parallel first with *Mathematics and Applications of Fractals* (January to April), then with *Complexity, Computation and the Physics of Information* (May to August) which is in full swing at the date of this report.

The number of participants in programmes of the Institute continues to grow, the total number recorded during the year being in excess of 1500, a slight increase on the previous year which was already a record year. The total UK participation remained at around 40%. This strong level of participation is extremely encouraging.

The Scientific Steering Committee (SSC) met twice during the year (in October and in May) and selected the following programmes:

*Symmetric Functions and Macdonald Polynomials*  
(January to June 2001)

*Nonlinear Partial Differential Equations*  
(January to June 2001)

*Higher Dimensional Complex Geometry*  
(February to July 2002)

*M-Theory*  
(February to July 2002)

In addition, it agreed that two three-week programmes should be run during the summer of 2000: *Free Boundary Problems in Industry*, and *Quantized Vortex Dynamics and Superfluid Turbulence*. Similarly, two short programmes will be run in the summer of 2001, of which one has so far been selected: *Managing Uncertainty - New Analysis Tools for Insurance, Economics and Finance*.

The mixed pattern of six-month, four-month, and short summer programmes has proved popular, and is likely to be continued in 2002 and beyond.

The retiring members of the SSC in December 1998 were Christopher Zeeman, Jean-Michel Bismut, Michael Cates and Simon Donaldson, to all of whom I would like to record my personal thanks. A particular 'Thankyou' to Christopher Zeeman, who has been Chairman of the SSC since the foundation of the Institute, and whose wise guidance during these initial years has helped so much in the stimulation and selection of good scientific programmes, and in the development of our scientific policy.

At the May '99 meeting of the SSC, we welcomed our new members: Robbert Dijkgraaf (Amsterdam), Charlie Elliott (Sussex), Tim Gowers (Cambridge), and Elmer Rees (Edinburgh).

Both Sandu Popescu (Hewlett-Packard Reader in Quantum Mechanics) and Noah Linden (Deputy Director) will retire from their posts on 30 September, to take up appointments at the University of Bristol. Noah has been involved with the Institute since the beginning and has been an enormous support to me over these last three years. Sandu writes separately in this Annual Report about the exciting research that he has accomplished while at the Newton Institute.

Sandu's successor as Hewlett-Packard Senior Research Fellow will be Dr Konstantin Khanin (Heriot-Watt University). He will take up appointment on 1 October, and will continue to promote the strong and vigorous liaison that we enjoy with BRIMS (Hewlett-Packard's Basic Research Institute in the Mathematical Sciences).

On the funding front, the Council of EPSRC agreed in April to earmark an additional tranche of EPSRC funding to extend the current funding period of the Institute (which runs to February 2002) for a further six years, to February 2008. This is subject to triennial review in 2002 and 2005. In association with this most welcome decision, the Institute has agreed to set up a National Advisory Board, which will advise on strategic issues relating to the national role of the

Newton Institute. This Board will be chaired (on the nomination of EPSRC) by Professor Adrian Smith (QMW).

I am glad also to report receipt of a magnificent donation of £1M from the Dill Faulkes Educational Trust, for the construction of the Faulkes Gatehouse which will be strategically placed between the Newton Institute and the new Betty and Gordon Moore Library of physical sciences, mathematics and technology. Both buildings will be completed by June 2001. The Faulkes Gatehouse will permit an invaluable extension of Newton Institute activities, particularly in relation to the hosting of research workshops.

Finally, I am happy to report that a submission of the Newton Institute attracted one of the prestigious Queen's Anniversary Prizes, 1999. The Prize Medal and Certificate were presented by Her Majesty The Queen at a ceremony at Buckingham Palace on 11 February 1999, and are now displayed in the entrance foyer of the Institute.

*Keith Moffatt*

30 June 1999



THE QUEEN'S  
ANNIVERSARY PRIZES  
FOR HIGHER AND FURTHER EDUCATION  
1999

## News in Brief

### Programmes

During the year 1 July to 30 June, a total of 1504 visitors took part in the Institute's programmes and workshops. There were 22 workshops, around 850 seminars were given in the Institute and over 100 papers were produced or are in preparation by participants. (NB This excludes the programme *Complexity, Computation and the Physics of Information* (May-Aug 1999) which will be covered in the 1999/2000 Annual Report).

The programmes that took place in 1998/99 were:

#### **Biomolecular Function and Evolution in the Context of the Genome Project**

July to December 1998

*Organisers: P Donnelly (Oxford); W Fitch (Irvine); N Goldman (Cambridge)*

#### **Nonlinear and Nonstationary Signal Processing**

July to December 1998

*Organisers: WJ Fitzgerald (Cambridge); RL Smith (North Carolina); A Walden (Imperial); PC Young (Lancaster)*

#### **Turbulence**

January to June 1999

*Organisers: GF Hewitt (Imperial); PA Monkewitz (Lausanne); N Sandham (Southampton); JC Vassilicos (Cambridge)*

#### **Mathematics and Applications of Fractals**

January to April 1999

*Organisers: RC Ball (Warwick); KJ Falconer (St Andrew's)*

#### **Complexity, Computation and the Physics of Information (part)**

May to August 1999

*Organisers: A Albrecht (UC Davis); P Knight (Imperial); RM Solovay (Berkeley); W Zurek (LANL)*

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### Queen's Anniversary Prize

The Institute was awarded one of the Queen's Anniversary Prizes for Higher and Further Education for 1999. The awards were announced at a ceremony at St James's Palace on 30 November 1998, and the medals were presented by The Queen at a ceremony at Buckingham Palace on 11 February 1999.

### Special Appointments

The following 'visiting' appointments were made during the year:

- Rothschild Visiting Professors:

Professor AE Perry (Melbourne)  
*Turbulence*

Professor KR Sreenivasan (Yale)  
*Mathematics and Applications of Fractals and Turbulence*

- Gabriella and Paul Rosenbaum Fellows:

Dr RG Baraniuk (Rice)  
*Nonlinear and Nonstationary Signal Processing*

Dr R Goldstein (Michigan)  
*Biomolecular Function and Evolution in the Context of the Genome Project*

Dr B Schumacher (Kenyon)  
*Complexity, Computation and the Physics of Information*

- Institute of Physics Fellow:

Professor I Procaccia (Weizmann Institute)  
*Mathematics and Applications of Fractals*

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### Deputy Director

Dr Noah Linden, who has been a vital member of the Isaac Newton Institute's scientific staff since its opening in 1992, first as Assistant Director but more recently as Deputy Director, is leaving the Institute at the end of September 1999 to take up an appointment at the University of Bristol.

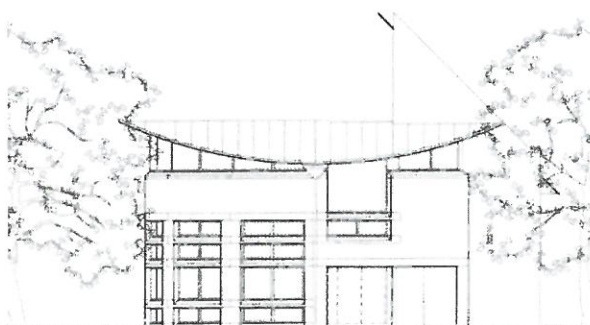


Noah Linden outside the Institute

Findlay Kember



Dr Dill Faulkes



Architects design for the Faulkes Gatehouse

## Faulkes Gatehouse

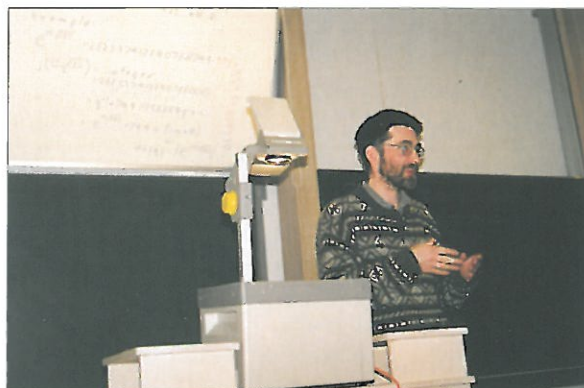
As part of the new Centre for Mathematical Sciences (CMS - see page 7), a gatehouse building will be constructed for the use of the Newton Institute. Funding for this has been generously donated by The Dill Faulkes Educational Trust and it will be known as the Faulkes Gatehouse. The accommodation will consist of three offices at ground-floor level and a purpose-built 50-seat seminar room with reception area at first-floor level. There will also be some basement storage space. The Gatehouse will be built during Phase II of the work on the CMS, which also includes the new Betty and Gordon Moore Library of physical sciences, mathematics and technology, and is expected to be finished in the first half of 2001.

## Institute Seminars

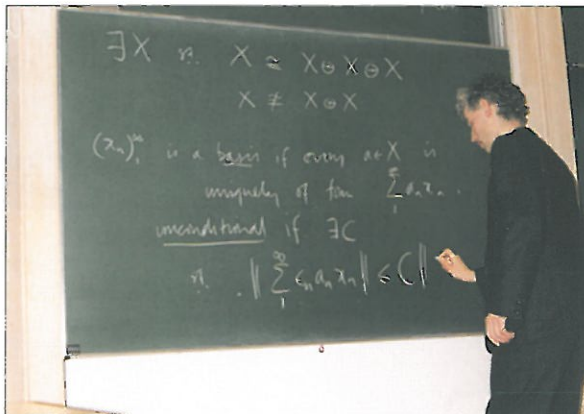
Institute Seminars are held at 5pm on Mondays during term-time. They are intended to be accessible to a general mathematical audience. Institute Seminars given during 1998/99 were as follows:

- 19 October  
W Fitch (UCI)  
*Predicting the future evolution of the human influenza virus*
- 26 October  
D Siegmund (Stanford)  
*Two problems of multiple comparisons in molecular genetics*
- 2 November  
R Smith (North Carolina)  
*Problems and challenges in environmental statistics*
- 9 November  
S Popescu (Newton Institute)  
*Quantum mechanics and non-locality or Why does God play dice?*
- 16 November  
Fisher Memorial Lecture:  
Sir John Kingman (Bristol)  
*Mathematics of genetic diversity before and after DNA*
- 23 November  
P Flandrin (ENS Lyon)  
*Time-frequency/time-scale reassignment*
- 30 November  
G Stormo (Colorado)  
*Experimental and computational approaches to analyse DNA-protein interactions*
- 25 January  
K Sreenivasan (Yale)  
*Turbulence dynamics in polymer solutions*
- 15 February  
B Duplantier (CEA Saclay)  
*Conformal invariance and multifractality*
- 22 February  
M Barlow (British Columbia)  
*Random walks and some fractal graphs*
- 26 April  
IMA Distinguished Lecture:  
H Kreiss (UCLA)  
*Does the large scale determine the small scale in turbulent flows?*

- 10 May  
J Toland (Bath)  
*The point of Stokes' highest wave*
- 17 May  
Hardy Lecture (London Mathematical Society)  
D McDuff (SUNY)  
*Symplectic 4-manifolds*
- 14 June  
P Constantin (Chicago)  
*Mixing, turbulence and rigour*



Dusa McDuff, just before giving her Institute Seminar, with Ben Garling



Fields Medallists Richard Borcherds (above) and Tim Gowers (below) presenting their talks at the Spitalfields Day

### Special Events

A two-day meeting on the Mathematics of Risk Management took place from 2 to 3 October 1998; A list of speakers and titles is given on p57. A volume containing papers based on the presentations at the meeting is in preparation.

A Spitalfields Day was held at the Institute on 6 November 1998 to celebrate the Fields Medals won by Richard Borcherds (DPMMS) and Tim Gowers (DPMMS). Tim Gowers gave a talk on *Fourier analysis and Szemerédi's theorem* and Richard Borcherds gave a talk on *What is moonshine?*

A meeting entitled *Critical Data and Statistical Uncertainties: The Statistics of TSEs* was held from 13 to 14 November 1998. Speakers and titles are listed on p56.

### Other Scientific Events

Regular meetings on Soft Condensed Matter took place on 5 October and 11 January.

During the University of Cambridge's Alumni Weekend, Professor Walter Fitch (an Organiser of the programme *Biomolecular Function and Evolution in the Context of the Genome Project*) gave a lecture at the Institute on 26 September entitled *Getting the flu that gets you: predicting future evolution*.

A peripatetic seminar on *Sheaves and Logic* took place at the Institute on 27 and 28 February 1999.

During SET99 Professor Benoit Mandelbrot, a participant in the programme *Mathematics and Applications of Fractals*, gave a lecture in the Cockcroft Theatre on 16 March entitled *Fractals: for the pleasure of the mind and the eye* and Professor Kenneth Falconer (an Organiser of the same programme) gave a lecture at the Institute on 20 March entitled *Fractals - the new geometry*.



Kenneth Falconer giving his SET99 seminar

The 22nd Conference on Mathematical Geophysics was held at the Institute from 13 to 17 July 1998. (See report, p56)

### *Other Events*

The Institute's Scientific Steering Committee formed a Sub-Committee which met with members of LMS Council to discuss the coverage of the mathematical sciences as reflected by the programmes of the Institute, and to identify particular fields in which new programmes should be stimulated.

The Institute formed a Consultative Group for Symposia Activities in the Mathematical Sciences which included representatives from the Newton Institute, LMS, ICMS, Warwick Research Centre, IMA, Durham Symposia, Royal Statistical Society and IOP. The group met twice during the year (on 17 September 1998 and 4 March 1999).

Hitachi organised a meeting at the Institute on 8 July 1998.

Silicon Graphics organised a demonstration of their computer equipment on 4 February.

ERCOTAC (the European Consortium on Fluid Turbulence and Combustion) held a meeting at the Institute on 30 April during the *Turbulence* programme.

The Institute welcomed Dr Hans Rausing who visited on 26 May. Neil Turok, Jim Mirrlees and Sandu Popescu gave brief presentations.



Left to right: Keith Moffatt, Martin Rees, Robert Nigmatulin, Hans Rausing, Neil Turok, Jim Mirrlees, Sandu Popescu

The 'topping out' ceremony for the first phase of the CMS was held at the site and at the Institute on 12th June.

### *European Post Doctoral Institute*

A meeting of the Scientific Committee of EPDI was held at the Institute on 5 February 1999; five new EPDI fellows were appointed.

### *ERCOM*

ERCOM is a committee under the European Mathematical Society, consisting of Directors of European Institutes. An ERCOM meeting was held at the Newton Institute on 13 March 1999. A parallel meeting for the Administrators of European Institutes also took place on this date.

### *Centre for Mathematical Sciences*

Work began on Phase I of the construction of the new Centre for Mathematical Sciences, adjacent to the Newton Institute, in the summer of 1998. Phase I is due to be completed in February 2000.



## UK Liaison

The Newton Institute has continued to develop its outreach activities during the year. In April 1999 the Institute set up a new National Symposia website, in cooperation with the London Mathematical Society, the International Centre for Mathematical Sciences (Edinburgh), the Mathematics Research Centre (Warwick), the Institute of Mathematics and its Applications and the Royal Statistical Society. This will be a central point for information about UK symposia in the mathematical sciences, including conferences, workshops, instructional courses, one-day meetings and longer research programmes. All UK institutions are invited to contribute information, which is held on a central database and transferred daily to the website at <http://www.newton.cam.ac.uk/symposia.html>

All the Institute's programmes, workshops and seminars are widely advertised. Current information, including lists of long and short-stay visitors which are updated daily, is available on our website at <http://www.newton.cam.ac.uk> Forthcoming events are advertised via regular mailouts to departments and institutions by post and email, and by notices in relevant newsletters and WWW bulletin boards.

Participants in the Institute's programmes are actively encouraged to visit other UK institutions during their time here, and the Institute will pay travel expenses within the UK for such visits. During 1998/99 around 170 seminars were given outside the Institute at institutions including: Birkbeck, Biometrics Society (British Region), Bristol, Cardiff, Edinburgh, Environment Agency, Glasgow, Heriot-Watt, Hewlett-Packard, Leeds, Loughborough, Imperial, LSE, Lancaster, MRC London, Manchester, National Grid Co, Newcastle, Nortel Networks, Oxford, Reading, Rolls Royce, Royal Institution, Royal Statistical Society, Schlumberger, Scottish Power plc, Sheffield, Southampton, Strathclyde, Surrey, UCL, UMIST, UK Met Office, Warwick, Xerox Research.

The Director visited the University of Newcastle-upon-Tyne on 23 October and the University of Sussex on 24 February to talk about the work of the Institute and to receive feedback from members of the UK community. He also visited the BMC meeting (Southampton, March 1999) and the BAMC meeting (Bath, April 1999) for the same purpose.

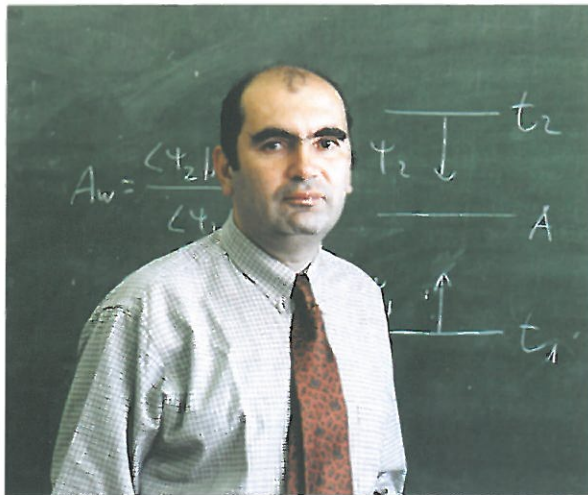
As part of the Institute's response to feedback from discussions with the UK mathematical community, a regular series of lectures, to be given at other institutions by the Rothschild Visiting Professors, has been instigated. The series for the coming year will include lectures at Oxford, Nottingham, Bath, Edinburgh and Imperial.

Starting in 2000 there will be a series of satellite workshops held outside Cambridge in conjunction with Institute programmes. The first of these, *Ergodic Theory and Higher Rank Actions* will be held in April at Warwick University. Others are planned in connection with future programmes, at venues including Liverpool and Edinburgh.

Work has also begun on publishing selected seminars given at the Institute on WWW, in the form of audio files combined with transparencies, thus making them accessible to the wider community.



BRIMS Board meetings took place at the Institute on 3 December 1998 and 30 June 1999. At the latter meeting a new Hewlett-Packard Senior Researcher was appointed to succeed Dr Sandu Popescu, who will leave to take up appointment at Bristol University in October 1999.



Sandu Popescu

### *Report from Sandu Popescu, Hewlett-Packard Reader in Quantum Mechanics, October 1996 - September 1999*

How many times have you wanted to be in two places at the same time? People can't do it. Cats can't do it either. Neither can tables, cars, houses or any other everyday object. But microscopic particles - electrons, atoms or molecules - can. This is a consequence of the strange laws of quantum mechanics, the theory which describes how microscopic particles behave. That microscopic particles behave in such strange ways has been known for more than seven decades. But new exciting implications of this behaviour have only recently emerged. What if one would compute on an abacus with microscopic beads, and a bead could be in two places at the same time? On this abacus a number could simultaneously be both "0" and "1". Could this help us compute better, easier or faster? A drop of "microscopic ink" could look like "a" "b" or "c", all at the same time. Could we then send many messages in a single envelope? Over the last five years these and similar questions have led to the emergence of a new scientific domain at the border of physics, mathematics and computer science - quantum information and computation - with many fascinating results and important potential applications. My work during my three years at the Newton Institute has been largely devoted to these issues.

My research centres on a most important aspect of quantum mechanics which plays an essential role in quantum information processing, namely *non-locality*. Quantum systems which interacted in the past and then moved far from each other, remain, in a certain sense, still connected with one another. In effect quantum systems can *instantaneously* "communicate" with each other (in apparent but not real contradiction with Einstein's relativity). Although the concept of non-locality was first put forward more than thirty years ago, by J Bell's critical analysis of the Einstein-Podolsky-Rosen paradox, the main developments have taken place only very recently. My main results while at the Newton Institute are as follows.

**Teleportation.** Teleportation (invented by C H Bennett and collaborators) is a way of using *non-locality* for communicating quantum information. In this process an unknown quantum state is disassembled into, and then reconstructed from, purely classical information and purely non-classical correlations. I suggested an alternative teleportation scheme, a simplification of the original, which avoids unnecessary experimental complications. This scheme enabled us to perform the first experimental realisation of teleportation [7].

**Thermodynamics of Non-Locality.** Together with D Rohrlich I showed that a "thermodynamic" principle governs non-locality manipulation [4]. This enables one to treat non-locality at a high level of generality, independently of most details of the different specific cases. In particular we proved that among the many proposed quantitative measures of non-locality, only a single one - the equivalent of entropy - has the required properties for a correct measure. Together with H-K Lo I determined the general characteristics of every non-locality manipulation method. Previous work focused on average properties - we were able to go beyond that and describe the fluctuations [19].

**Multi-Particle Non-Locality.** Traditionally, almost all studies of non-local correlations focused on correlations between only two quantum particles. In different collaborations, on different lines of research, I made some of the first steps towards a general understanding of multi-particle non-locality. One of the major difficulties in studying the nature of multi-particle non-locality is that, unlike the case of two particle non-locality, it was not known how to separate the non-local aspects of the states from the irrelevant local ones. Together with N Linden and A Sudbery we solved this problem for all generic (ie "non-degenerate") mixed states. More precisely, we classified the  $n$ -particle quantum states into equivalence classes, all states in an equivalence class having identical non-local properties

but having different local properties [15]. The other research direction (in collaboration with CH Bennett, D Rohrlich, J Smolin and A Thapliyal [23]) is that of manipulating multi-particle non-locality, that is, trying to transform arbitrary states into standard ones. Understanding of these transformations would lead to a quantitative understanding of multi-particle non-locality.

**Quantum Information.** A couple of years ago it was conjectured by A Peres and W Wootters, and later proved by S Massar and myself, that information is stored in quantum systems in a *global* and *non-local* fashion. For example, more can be learned about the state of a number of identically prepared quantum systems by performing a measurement on all the systems together, as a whole, rather than on each of them individually. At present the implications of this nature of quantum information are not yet understood. One of the first such implications - a very paradoxical example - was recently discovered by N Gisin and myself [18]. We view this as a first piece in a much larger puzzle.

**NMR Quantum Computation.** One of the ways which has been suggested for the practical realisation of a quantum computer is based on NMR techniques. The basic idea was that although the states of the molecules in a room-temperature NMR sample are very noisy, the deviation of these states from the maximally mixed one is roughly described by a pure state. Thus, it was claimed, one could in fact focus the attention only on this deviation, and manipulate it in similar ways to the way in which a standard quantum computer is supposed to work. Many results have been reported during the last two years claiming the implementation of simple quantum computation protocols via NMR techniques.

However, ever since the first announcements of the use of NMR techniques for quantum computation there has been great surprise at the apparent ability to perform quantum computations in room-temperature thermal ensembles. It has always been a puzzle whether such noisy states could really correspond to truly entangled states. Our work solves this puzzle. In collaboration with SL Braunstein, CM Caves, R Jozsa, N Linden, and R Schack, I have shown that all states which have been prepared so far in high-temperature NMR experiments are non-entangled. Thus all the quantum computation NMR experiments to date are not actually quantum computations but only *simulate* quantum computations [17]. Furthermore, together with N Linden I showed that for a very large class of quantum computation protocols (including the famous

Shor protocol for factorising large integers), the noise in the NMR states does not allow *even in principle* to obtain exponential speed-up relative to classical computational protocols [21].

**BRIMS Lectures on Quantum Information and Computation.** Last but not least, together with H-K Lo and T Spiller, I organised at BRIMS Hewlett-Packard Laboratories a series of lectures on quantum computation and information. Based on these lectures we have edited a book, *Introduction to Quantum Computation and Information*, the first pedagogical book on this subject.

During the last three years I have been the Hewlett-Packard Reader in Quantum Mechanics and member of BRIMS, Hewlett-Packard Laboratories, and I have been located at the Newton Institute. My years in Cambridge were very happy indeed, and I would like to thank the Newton Institute and BRIMS for creating very warm and supportive environments for me.

#### Publications 1997-1999

- 1) H Fei, B Jost, S Popescu, B Saleh and M Teich, *Entanglement induced two-photon transparency*, Phys Rev Lett 78, 1679, (1997).
- 2) Y Aharonov, S Nussinov, S Popescu and B Reznik, *Aharonov-Bohm type forces between magnetic fluxons*, Phys Lett A 231, 229, (1997).
- 3) S Popescu and D Rohrlich, *Causality and Nonlocality as axioms for quantum mechanics*, in *Proceedings of the Symposium on Causality and Locality in Modern Physics and Astronomy: Open Questions and Possible Solutions*, York University, Toronto, August 25-29, (1997).
- 4) S Popescu and D Rohrlich, *Thermodynamics and the measure of entanglement*, Phys Rev A 56, Rapid Comm R3319, (1997).
- 5) S Popescu, L Hardy and M Zukowski, *Revisiting Bell's theorem for a class of down-conversion experiments*, Phys Rev A 56, Rapid Comm R4353, (1997).
- 6) N Linden and S Popescu, *On multi-particle entanglement*, Fortschritte Der Physik 46, 567, (1998).
- 7) D Boschi, S Branca, F De Martini, L Hardy and S Popescu, *Experimental realization of teleporting an unknown pure quantum state via dual classical and Einstein-Podolsky-Rosen channels*, Phys Rev Lett 80, 1121, (1998).

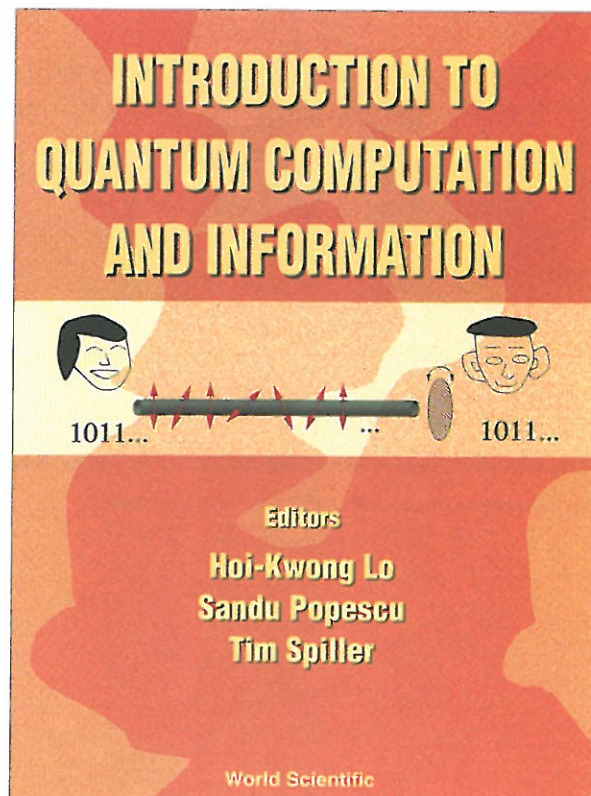
- 8) Y Aharonov, T Kaufherr, S Popescu and B Reznik, *Quantum measurement back-reaction and induced topological phases*, Phys Rev Lett 80, 2023, (1998).
- 9) Y Aharonov, J Oppenheim, S Popescu, B Reznik and WG Unruh, *Measurement of time-of-arrival in Quantum Mechanics*, Phys Rev A 57, 4130, (1998).
- 10) M Muraao, MB Plenio, S Popescu, V Vedral, PL Knight, *Multi-particle entanglement purification protocols*, Phys Rev A 57 Rapid Comm R4075, (1998).
- 11) S Popescu and D Rohrlich, *The joy of entanglement* in *Introduction to Quantum Information and Computation*, H-K Lo, S Popescu and T Spiller eds, World Scientific (1998).
- 12) N Linden, S Massar and S Popescu, *Purifying noisy entanglement requires collective measurements*, Phys Rev Lett, 81, 3279, (1998).
- 13) N Linden and S Popescu, *Bound entanglement and teleportation*, Phys Rev A 52, 137, (1999).
- 14) N Linden and S Popescu, *Multi-particle entanglement*, Found of Phys, to appear.
- 15) N Linden, S Popescu and A Sudbery, *Non-local parameters for multiparticle density matrices*, Phys Rev Lett 83, 243 (1999).
- 16) H-K Lo and S Popescu, *The classical communication cost of entanglement manipulation: Is entanglement an interconvertible resource?*, Phys Rev Lett 83, 1459, (1999)
- 17) SL Braunstein, CM Caves, R Jozsa, N Linden, S Popescu and R Schack, *Separability of very noisy mixed states and implications for NMR quantum computing*, Phys Rev Lett 83, 1054 (1999).
- 18) N Gisin and S Popescu, *Spin flips and quantum information for anti-parallel spins*, Phys Rev Lett 83, 432 (1999).

*Submitted*

- 19) H-K Lo and S Popescu, *Concentrating entanglement by local actions - beyond mean values*, submitted to Phys Rev A.
- 20) N Linden and S Popescu, *The halting problem for quantum computers*, submitted to Phys Rev Lett.
- 21) N Linden and S Popescu, *Good dynamics versus bad kinematics. Is entanglement needed for quantum computation?*, submitted to Phys Rev Lett.
- 22) S Massar and S Popescu, *How much information can be obtained by a quantum measurement?*, submitted to Phys Rev A.
- 23) CH Bennett, S Popescu, D Rohrlich, J Smolin and A Thapliyal, *Exact and asymptotic measures of multipartite pure state entanglement*, submitted to Phys Rev A.

*Book*

H-K Lo, S Popescu and T Spiller, (Eds) *Introduction to Quantum Information and Computation*, World Scientific, (1998).

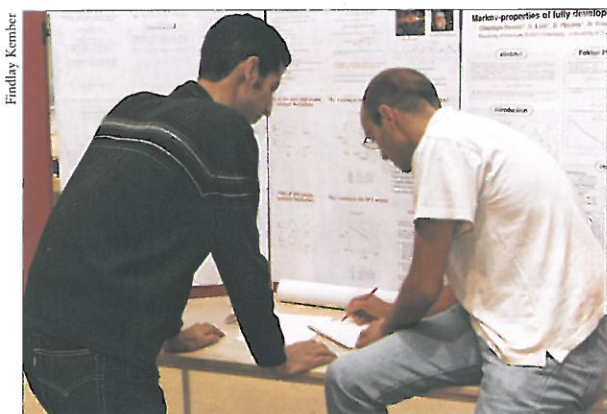


## Young Scientists

### *Junior Membership*

The Junior Membership scheme, introduced in 1997 to help and encourage younger UK researchers to participate in the Institute's scientific activities, continues to be very popular. There are now over 300 Junior Members, with 107 joining during 1998/99.

Home institutions of Junior Members include: Abertay Dundee, Aberystwyth, Anglia Polytechnic, Aston, BT Research Labs, Bath, Belfast, Birkbeck, Bolton Institute, Bradford, Bristol, Brunel, Cambridge, Cardiff, Central Lancashire, Chester, City Business School, Cranfield, De Montfort, Durham, Edinburgh, Essex, Exeter, GEC-Marconi, Heriot-Watt, Goldsmith's, Hertfordshire, Hull, Imperial, KCL, Keele, Kent, Kingston, LSE, Lancaster, Leeds Metropolitan, Leicester, Liverpool, Loughborough, Manchester, Microsoft Research, Napier, Natural History Museum, Newcastle-upon-Tyne, Northumbria, Open University, Oxford, Paisley, Portsmouth, QMW, Reading, Robert Gordon, Royal Holloway, Royal Observatory Edinburgh, Schlumberger Cambridge Research, St Andrews, Sheffield, Southampton, Sowerby Research, Stirling, Strathclyde, Sunderland, Surrey, Swansea, Teeside, UCL, UMIST, Warwick, West Wales Hospital, York.



Participants at an instructional conference for young scientists

### *Instructional Conferences for Young Scientists*

Young scientists are welcome to attend all Institute workshops but some are specifically targeted at them, and special funding is obtained to enable them to attend. Five such workshops were held in 1998/99:

- The *Nonlinear and Nonstationary Signal Processing* programme opened in July with a two-week EC Summer School entitled *Bayesian Methods*.
- The *Biomolecular Function and Evolution in the Context of the Genome Project* programme held a one-week EC Summer School from 10 to 14 August 1998 entitled *Methods for Molecular Phylogenies* which was part lecture course and part practical computing course.
- The same programme also held a NATO ASI entitled *Genes, Fossils and Behaviour: an Integrated Approach to Human Evolution* from 7 to 17 September 1998.
- The *Mathematics and Applications of Fractals* programme opened in January 1999 with an EC Summer School entitled *Multifractals and their Applications*.
- The *Turbulence* programme held an EC Summer School from 15 to 19 March 1999 on *Turbulence Structure and Vortex Dynamics*.

### *Cambridge Philosophical Society Bursary Awards*

The following young scientists were recipients of bursaries from the Cambridge Philosophical Society in 1998/99:

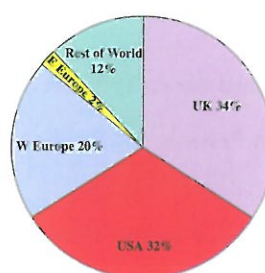
- M Byng (Reading); I Jonassen (Bergen) and J Schneider (Oxford) to attend the *Biomolecular Function and Evolution in the Context of the Genome Project* programme
- A Doucet (ETIS Groupe Signal - ENSEA) to attend the *Nonlinear and Nonstationary Signal Processing* programme
- J Cole (St Andrews) and M Csornyei (Eötvös Lorand, Budapest) to attend the *Mathematics and Applications of Fractals* programme

## Programme Participation

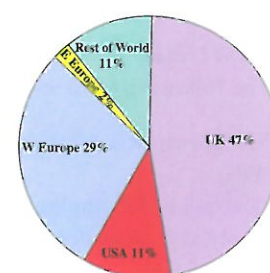
A total of 1504 visitors was recorded for 1998/99. This includes 217 long-stay participants, each staying between two weeks and six months (seven and a half weeks on average) and 474 short-stay participants who stayed for two weeks or less, but excludes participants in the programme *Complexity, Computation and the Physics of Information*, running from May to August 1999. Within the four completed programmes there were 24 workshops in total, which were periods of intense activity on specialised topics, and these attracted an additional 637 visitors to the Institute. In addition, 176 visitors were registered as having taken part in the special events held outside the Institute programmes (see pp6-7 & 56-7). Many others attended occasionally for lectures, workshops or Institute Seminars; the lectures given by Walter Fitch and Kenneth Falconer (p6) for the Alumni Weekend and SET99 both attracted capacity audiences of around 120 each, and the SET99 lecture by Benoit Mandelbrot, held at the Cockcroft Lecture Theatre, attracted a capacity audience of more than 500. Within the programmes, workshops and special events, around 850 seminars were given at the Institute during the year.

In addition to the workshops, which serve to widen UK participation in the programmes, the programme organisers are encouraged to organise more informal special days, short meetings or intensive lecture series which can attract daily or short-term visitors, so further opening the activities of the Institute to the UK mathematical community.

The pie-charts below show the percentages of long-stay and short-stay participants for 1998/99 broken down by country of residence:



Countries of residence of long-stay participants

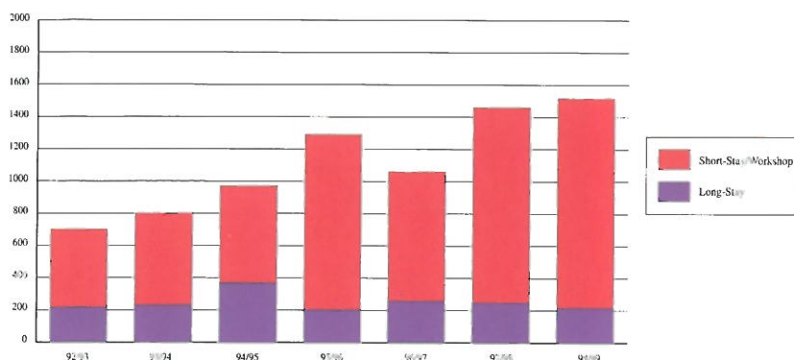


Countries of residence of short-stay participants

The participation statistics for the 1998/99 programmes are summarised in the following table (NB *Mathematics and Applications of Fractals* was the first four month programme to run at the Institute):

Programme	Long-Stay Participants	Average long stay (days)	Short-stay participants	Average short-stay (days)
Nonlinear and Nonstationary Signal Processing	35	59	172	9
Biomolecular Function and Evolution in the Context of the Genome Project	69	51	126	8
Mathematics and Applications of Fractals	42	38	67	8
Turbulence	71	67	109	7

The following chart summarises the total figures for long and short-stay participation since the Institute began its programmes:



The median age for long and short-stay participants combined is 39 years, with an interquartile range 31 - 49 years.

More detailed statistics including visit dates, home institutions and nationalities of long-stay participants, and a complete list of seminars and papers, are given in the Appendices (available separately from the Institute or via WWW).

## Institute Publications

### *Newton Institute Papers and Preprints*

Over 100 papers were produced or in preparation at the Institute during 1998/99 (a complete list is given in *Appendix F*). Many of these are included in the Newton Institute's preprint series, to which participants are encouraged to submit papers. A Web page giving details of Newton Institute preprints is available at <http://www.newton.cam.ac.uk/preprints.html>

### *Books arising from Newton Institute Programmes*

The following titles were published during 1998/99:

MJ Adams, RA Mashelker, JRA Pearson, AR Rennie (Eds)

**Dynamics of Complex Fluids**

Imperial College Press and The Royal Society 1998, viii + 485pp

CM Bishop (Ed)

**Neural Networks and Machine Learning**

NATO ASI series F: Computer and Systems Sciences, Vol 168

Springer-Verlag 1998, 353pp

RW Carter and M Geck (Eds)

**Representations of Reductive Groups**

*Publications of the Newton Institute series*

Cambridge University Press 1998, vii + 191 pp

IEEE Signal Processing Society, IEEE Neural Networks Council

**Neural Networks for Signal Processing**

IEEE Press 1998, 620 pp

IV Lerner, JP Keating, DE Khmel'nitskii (Eds)

**Supersymmetry and Trace Formulae: Chaos and Disorder**

NATO ASI Series B: Physics, Vol 370

Kluwer/Plenum 1999, pp viii + 404

W Maass and CM Bishop (Eds)

**Pulsed Neural Networks**

MIT Press, 1998, 377 pp

DE Olive & P West (Eds)

**Duality and Supersymmetric Theories**

*Publications of the Newton Institute series*

Cambridge University Press 1999, 484 pp

D Saad (Ed)

**On-Line Learning in Neural Networks**

*Publications of the Newton Institute series*

Cambridge University Press, 1998, x + 398pp

JA Sellwood and JJ Goodman

**Astrophysical Discs; An EC Summer School**

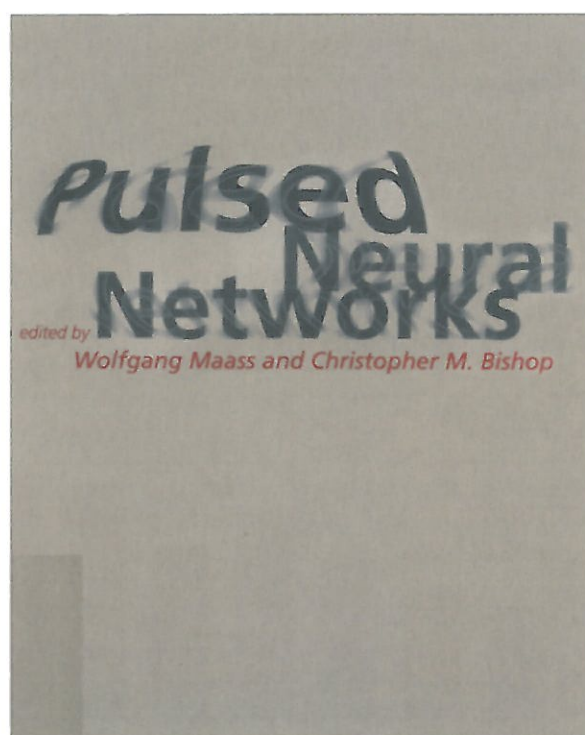
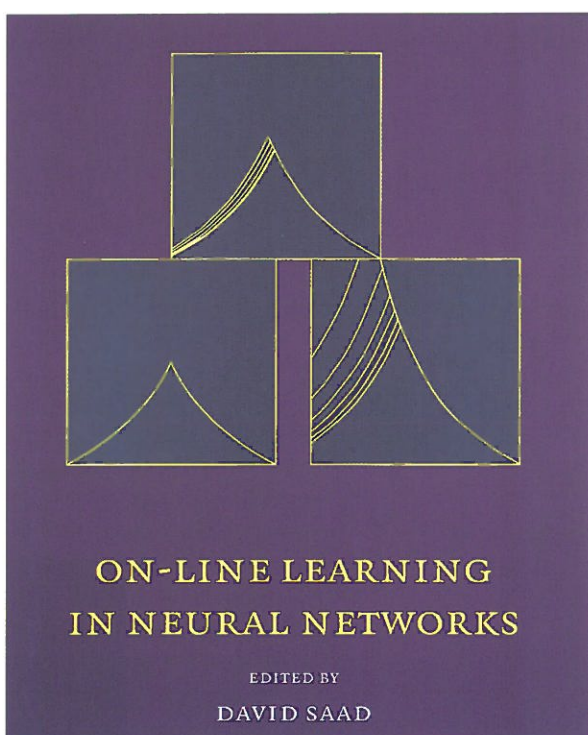
ASP Conference Series Vol 160

Astronomical Society of the Pacific 1999, xxiii + 360pp

A complete list of books published as a result of

Newton Institute programmes is available at

<http://www.newton.cam.ac.uk/inibooks.html>



# Scientific Planning and Future Programmes

## Scientific Steering Committee

The members of the Committee as at 30 June 1999 were:

Professor N Hitchin FRS (Chair)	Oxford
Professor HK Moffatt FRS (Director)	Newton Institute
Professor RM Anderson FRS	Oxford
Professor Sir Michael Berry FRS	Bristol
Professor RH Dijkgraaf	Amsterdam
Professor CM Elliott	Sussex
Professor WT Gowers FRS	DPMMS, Cambridge
Professor A Newell	Warwick
Professor EG Rees	Edinburgh
Professor BD Ripley	Oxford
Professor AFM Smith	Queen Mary and Westfield College
Professor JF Toland FRS	Bath
Professor S White FRS	Max-Planck Inst für Astrophysik, München
Professor D Zagier	Max-Planck Inst für Mathematik, Bonn

During this year Professor Sir Christopher Zeeman FRS retired after being Chair of the Committee since its inception. Professor J-M Bismut and Professor SK Donaldson FRS also retired from the Committee.

The Scientific Steering Committee met twice during 1998/99, on October 26 and May 10. Others who attended included Professor C Frenk (Durham - in place of Professor White, October meeting), Professor D Hand (Imperial - in place of Professor Smith, October meeting) and Professor A Scholl (Durham - in place of Professor Zagier, October meeting).



Members of the Scientific Steering Committee present at the May 1999 meeting. Left to right: Keith Moffatt, Simon White, Brian Ripley, Robbert Dijkgraaf, Elmer Rees, Michael Berry, Charles Elliot, Don Zagier, Alan Newell, John Toland, Nigel Hitchin, Tim Gowers

### New Members

New members of the Committee for 1998/99 are Professor RH Dijkgraaf, Professor CM Elliott, Professor WT Gowers and Professor EG Rees. Professor RM Anderson was co-opted at the March meeting to serve until December 2000.

Robbert Dijkgraaf studied physics and mathematics at the University of Utrecht, where he obtained his PhD in 1989 in theoretical physics (conformal field theory and string theory). He then was a postdoctoral fellow at Princeton University. In 1991 he became a long-term



member of the Institute for Advanced Study, also in Princeton. In 1992 he was appointed professor of mathematical physics at the University of Amsterdam.

His Editorial activities include: Supervisory Editor, Nuclear Physics B (1994); Section Editor, Communication in Mathematical Physics (1992); Editor, Journal of Geometry and Physics (1995); Editor, Advances in Theoretical and Mathematical Physics (1997).

Charles Elliott obtained his DPhil from Oxford and is currently director of the Centre for Mathematical Analysis and Its Applications (CMAIA) at Sussex University. His research is mainly concerned with the modelling, analysis and computation of problems in the physical sciences leading to partial differential equations. In recent years he has worked on models of phase transformations in alloys, vortex motion in Type II superconductors, free boundary problems, numerical analysis of nonlinear partial differential equations and curvature dependent interface motion.

His interests range from rigorous analysis of equations and numerical methods to models and scientific computation. He collaborates with mathematicians and applied scientists throughout Europe and the USA.

Tim Gowers is Rouse Ball Professor of Mathematics at the Department of Pure Mathematics and Mathematical Statistics (DPMMS), Cambridge. He was awarded the prestigious Field Medal this year for his spectacular applications of new combinatorial methods to solve problems in Banach spaces and probabilistic number theory.

His research interests are in problems that are "combinatorial" in the sense that they can be attacked from first principles. He prefers problems that depend on estimates and approximations as opposed to exact formulae. This description applies to certain problems in functional analysis and number theory, as well as to combinatorics as traditionally understood. His most recent result is a new proof of a theorem of Szemerédi on arithmetic progressions.

Elmer Rees has been Professor of Mathematics at the University of Edinburgh since moving there from Oxford in 1979. Previously he was Lecturer at University of Hull and University of Wales, Swansea; PhD Warwick. His main research interests are in Algebraic Topology, particularly in its interaction with other areas of geometry. He was heavily involved in establishing the International Centre for Mathematical Sciences (ICMS), Edinburgh.

He has been visitor at the Institute for Advanced Study (IAS) in Princeton, University of California at Berkeley, University of Sydney, UNAM in Mexico, IHES in Paris and Max Planck Institut in Bonn. He was formerly Vice-President of London Mathematical Society (LMS), and Forder Lecturer of the LMS in 1995 - giving lectures at the Universities in New Zealand.

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## Honours

Sir Michael Berry, a member of the Institute's Scientific Steering Committee, was awarded an honorary degree from the University of Warwick at its summer degree congregation in 1998, as was Andrew Wiles, a past Senior Fellow of the Institute.

Professor John Toland and Professor Tim Gowers, both members of the Institute's Scientific Steering Committee, were elected Fellows of the Royal Society. Professor Peter Knight, organiser of the *Complexity, Computation and Physics of Information* programme, Professor Gary Gibbons, organiser of the *Geometry and Gravity* programme and Professor John Ockendon, organiser of the forthcoming *Free Boundary Problems in Industry* programme were also elected Fellows of the Royal Society, and Professor Ed Witten, who has visited various Institute programmes, was elected a Foreign Member of the Royal Society.

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## Future Programmes

### Structure Formation in the Universe

July to December 1999

Organisers: VA Rubakov (*Institute for Nuclear Research, Moscow*), PJ Steinhardt (*Pennsylvania*), NG Turok (*Cambridge*)

Understanding how structure emerged in the universe provides one of today's great scientific challenges. Huge quantities of new astronomical data, including maps of the cosmic microwave sky fluctuations and of the distribution of galaxies, are providing stringent constraints on possible theories. At the same time, the results of new particle physics experiments are beginning to imply very strong constraints on the possible nature of the dark matter. The two structure formation theories investigated in most detail so far involve quantum fluctuations generated during inflation, and cosmic defects produced at symmetry breaking phase transitions. Both theories involve physics beyond the standard model, and if either is proven correct, there will be important implications for high energy theory.

The programme will begin with discussions of the latest observational data, including the statistical techniques needed to analyse the new data sets, with the aim of fitting the observations together in a coherent framework. Extensions and variants of current theories, as well as entirely novel approaches will then be considered. During the programme, fundamental questions regarding the big bang and inflationary theory will be addressed, as well as connections to string theory and quantum gravity.

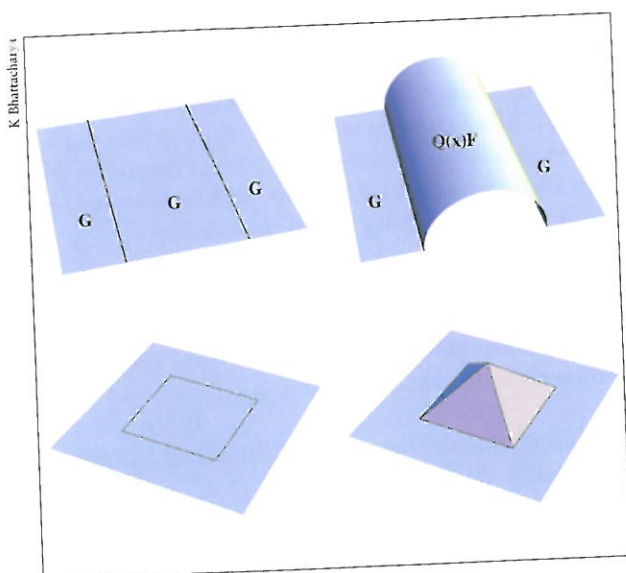
### Mathematical Developments in Solid Mechanics and Materials Science

September to December 1999

Organisers: *K Bhattacharya (Caltech), P Suquet (Marseille), JR Willis (Cambridge)*

There is great current interest in how the microscopic structure of a solid material influences its macroscopic response to stress. Conversely, the application of stress can influence microstructure. Microscopic damage may occur, leading ultimately to the formation of large cracks and structural failure. Phase transformations occur in some materials, creating structures at various length scales which evolve with stress.

The challenge, both for mathematics and physical modelling, is to comprehend relationships between models at different length scales. This has led already to a well-developed theory of "homogenisation" when the scales are widely separated, and has both exploited and stimulated advances in the calculus of variations. When the scales are separated but still comparable, there is a need for a micromechanical rationale for including scale effects in macroscopic



Proposed designs of micropumps/microactuators using shape-memory alloys, that make essential use of recently-acquired understanding of martensite microstructure in thin films

models. The phenomena may be unstable, at least at the microscopic level, and, even if stable, may admit multiple equilibria. Study of the kinetics of the processes is a key requirement, making demands both for modelling and for the analysis of partial differential equations. In particular, the (possibly hierarchical) development of large-scale patterns is an open problem.

The main focus of the programme will be on microstructure formation and evolution, as related to phase transformations, damage development and fracture. Each subject has its own group of specialists (in various mixes, mathematicians, physicists, engineers, materials scientists). There are already overlaps, both between subjects and disciplines, and it is intended that the programme will exploit and extend these, to common advantage.

### Strongly Correlated Electron Systems

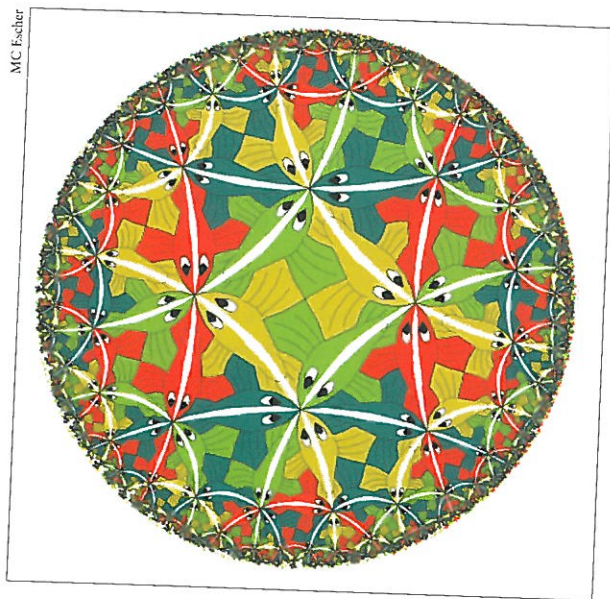
January to June 2000

Organisers: *DM Edwards (Imperial), AC Hewson (Imperial), PB Littlewood (Cambridge), A Tsvetlik (Oxford)*

The effects of strong inter-electron interactions give rise to a remarkable range of anomalous behaviour in condensed matter systems, producing phenomena as varied as metal-insulator transitions, the fractional quantum Hall effect, high temperature superconductivity, and heavy fermion metals, insulators and magnets. The high temperature superconductors may even herald a breakdown of the fundamental Fermi-liquid theory of metals.

Although many theoretical models have been put forward as a basis for understanding these systems, new mathematical techniques are required to provide results in the physically appropriate strong interaction regimes where many-body perturbation techniques are not applicable. In recent years non-perturbative methods have been developed and applied with great success to one-dimensional and impurity models, and these have led to an understanding of the breakdown of Fermi liquid behaviour in one dimension.

The aim of this programme is to develop many-body approaches which can be applied to higher dimensional systems, and to remaining problems in one dimension such as transport, by bringing together experts from a wide range of mathematical approaches. Links with the experimental community in this field will be maintained, particularly through workshops and seminars.



A manifold of negative curvature, whose geometry can be studied by ergodic techniques.

### Ergodic Theory, Geometric Rigidity and Number Theory January to July 2000

Organisers: A Katok (Penn State), G Margulis (Yale),  
M Pollicott (Manchester)

The central scientific theme of this programme is the recent development of applications of ergodic theory to other areas of mathematics. In particular, the connections with geometry, group actions and rigidity, and number theory.

The potential of ergodic theory as a tool in number theory was revealed by Furstenberg's proof of Szemerédi's theorem on arithmetic progressions. Foremost amongst the recent contributions to number theory is the solution of the Oppenheim Conjecture, a problem on quadratic forms which had been open since 1929, and the Baker-Spindzuk conjectures in the metric theory of diophantine approximations. Of equal importance is the role of ergodic theory in geometry and the rigidity of actions. The seminal result in this direction is the Mostow rigidity theorem. In recent years there have been diverse results, including rigidity results for higher rank abelian groups, and results on the classification of geodesic flows on manifolds of non-positive curvature.

This is a quickly evolving area of research. The programme will explore these, and other, emerging applications of ergodic theory. It will bring together both national and international experts in ergodic theory and related disciplines, as well as others from the wider UK mathematical community.

### Free Boundary Problems in Industry 17 July - 4 August 2000

Organisers: N Barton (Sydney), EJ Hinch (Cambridge),  
JR Ockendon (Oxford)

Free Boundary Problems (FBPs) are, as the name suggests, problems that need to be solved in regions whose boundaries are unknown *a priori* and have to be determined as part of the solution. They thus involve the modelling and analysis of both bulk and surface phenomena, where the "surface" may range from that of a block of melting ice to an optimal stopping time. The topic "Free Boundary Problems" would not exist as a distinct mathematical entity without the stimulus it received from industrial research in the 1970s. The industrial demand for better understanding of free boundary problems, especially diffusional ones like Stefan problems, has brought about a startling unification in the mathematical and numerical analysis of models for phenomena such as shock waves, water waves, flame propagation, phase transformations and elastic contact phenomena. In particular it stimulated the search for weak and variational methods with which to prove well-posedness and to suggest robust and efficient algorithms that can be adapted to suit industrial needs.

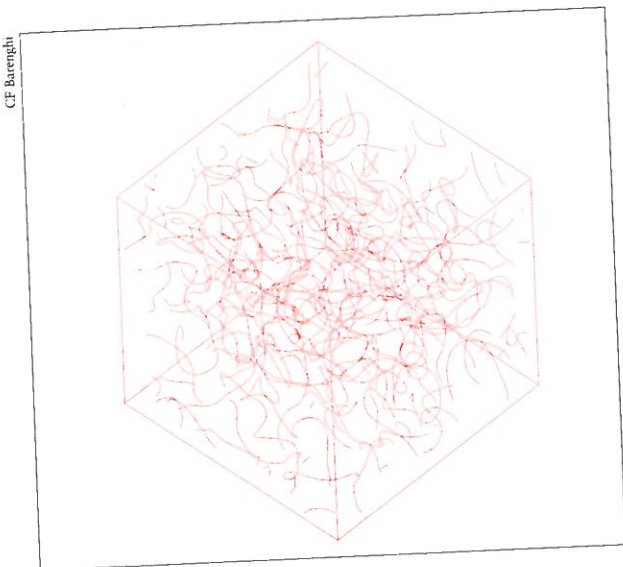
It is very satisfying that recent developments in the mathematical theory of FBPs have given completely new insights into both regularity theories for partial differential equations and into the mathematical modelling of basic phenomena such as phase transitions and pattern formation, as well as equipping the community with off-the-shelf algorithms that answer many of the problems that spawned the subject 30 years ago.

This programme will pivot around workshop-style sessions in which industrial and academic researchers will meet informally to discuss the latest generation of free boundary problems that need to be confronted theoretically. Coherence will be provided by considering problems from the food industry in one week, the glass industry in a second week and the metal industry in a third week. There will also be a small number of expository lectures on the relevant problems and methodologies.

### Quantized Vortex Dynamics and Superfluid Turbulence 7 August to 25 August 2000

Organisers: CF Barenghi (Newcastle), RJ Donnelly  
(Oregon), WF Vinen (Birmingham)

Quantum effects dominate the behaviour of liquid helium and other Bose-Einstein condensed fluids. These



A tangle of vortex lines inside a computational box

effects, which include the existence of discrete quantized vortices and the quantization of hydrodynamic circulation, place severe restrictions on the types of flow that can take place in the superfluid phase. Important aspects of the behaviour of the quantum vortices are still not understood. Turbulent flows in such systems are also of great interest, not only in their own right, but also because, surprisingly, they often appear to share important characteristics with those found in classical fluids. The recent discovery of Bose-Einstein condensation in alkali metal vapours at extremely low temperatures adds to the interest in these types of problem.

The aim of this short programme is to encourage cross-fertilisation by bringing together for intensive cross-disciplinary discussions, physicists and mathematicians with backgrounds ranging from quantum fluids to classical fluid mechanics and magnetohydrodynamics, and from applied mathematics to condensed matter and atomic physics.

Issues that will be surveyed and discussed include the dynamical behaviour of individual quantum vortices, including boundary conditions, frictional forces and reconnections; the use of the non linear Schrödinger equation to describe the flow of helium, including turbulence, at very low temperatures; the effect of a (possibly turbulent) normal fluid; the observed similarity between classical and quantum turbulence; and the possibility that the study of quantum turbulence may be applied to the understanding of conventional flow at very high Reynolds numbers. The emphasis will be on theory and computation, but in close contact with experiment.

### Singularity Theory

July to December 2000

Organisers: VI Arnold (Moscow and Paris IX),  
JW Bruce (Liverpool), V Goryunov (Liverpool),  
D Siersma (Utrecht)

Singularities arise naturally in a huge number of different areas of mathematics and science. As a consequence singularity theory lies at the crossroads of the paths connecting the most important areas of application of mathematics with its most abstract parts. For example, it connects the investigation of optical caustics with simple Lie algebras and regular polyhedra theory, while also relating hyperbolic PDE wavefronts to knot theory and the theory of the shape of solids to commutative algebra.

The main goal in most problems of singularity theory is to understand the dependence of some objects (from analysis, geometry, physics or elsewhere) on parameters. For generic points in the parameter space their exact values influence only the quantitative aspects of the phenomena, their qualitative, topological features remaining stable under small changes of parameter values. However, for certain exceptional values of the parameters these qualitative features may suddenly change under a small variation of the parameter, and these changes must be understood.

In spite of its fundamental character, and the central position it now occupies in mathematics, singularity theory is a surprisingly young subject. Substantial results and exciting new developments within the subject have continued to flow since it first crystallised in its current form in the mid 1960s, while the theory has embodied more and more applications.

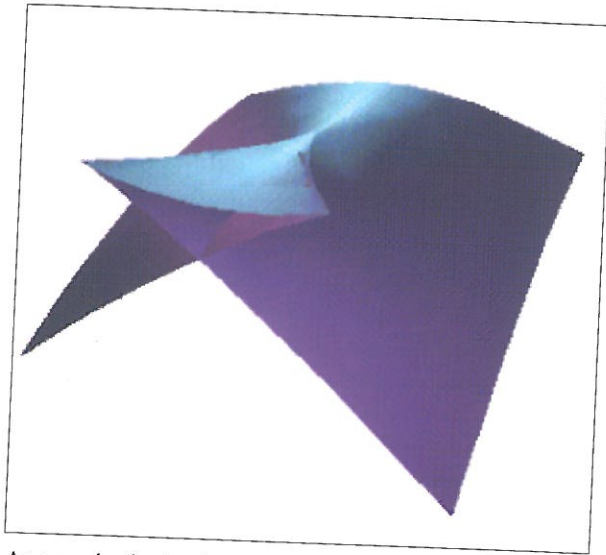
This programme will bring together experts within the field and those from adjacent areas where singularity theory has existing or potential application. Applications of particular interest include those to wave propagation, dynamical systems, quantum field theory, and differential and algebraic geometry, but these should not be deemed prescriptive. It is the programme's aim both to foster exciting new developments within singularity theory, and also to build bridges to other subjects where its tools and philosophy will prove useful.

### Geometry and Topology of Fluid Flows

September to December 2000

Organisers: H Aref (Urbana-Champaign), T Kambe (Tokyo), RB Pelz (Rutgers), RL Ricca (UCL)

The goal of this programme is to bring the disciplines of fluid mechanics and magneto-hydrodynamics (MHD) together with powerful mathematical



An example of a singularity, which arises in duals of smooth surfaces, families of plane wavefronts and caustics in 3-space.

techniques in geometry and topology. Topics will include: Integrals of motion and conservation laws and their relation to the geometrical and topological structure of space; Finite-time singularities in hydrodynamics and MHD; Geometric and group-theoretic approaches to hydrodynamics with applications to stability, mixing and the global structure of complex flows; Topological description of 3D velocity and vorticity fields; Fluid kinematics and chaotic advection.

The geometrical and topological view of fluid mechanics and MHD tends to be more global and based on a Lagrangian representation of the flow, in contrast to the local, coordinate-based, Eulerian representation currently used in most analytical and numerical treatments of fluid mechanical problems.

Because of the potential mutual benefits of connecting the field of fluid dynamics more closely to geometry, topology, dynamical systems, analysis and PDEs, pedagogical workshops and working groups are planned as well as advanced conferences.

Historically, fluid mechanics has both utilised and inspired progress in mathematics. The programme will continue this tradition.

**Symmetric Functions and Macdonald Polynomials**  
January to June 2001  
*Organisers: P Hanlon (Michigan), IG MacDonald (QMW), AO Morris (Aberystwyth)*

The importance of symmetric functions and the representation theory of Hecke algebras and the

symmetric groups derives in part from their applicability in a wide range of scientific and mathematical disciplines. Within the theory of symmetric functions, this programme will focus on a particular topic, the Macdonald polynomials, which have especially wide-ranging mathematical interconnections. The goal of the programme will be to unify the diverse approaches to the study of these polynomials.

In the 1980s, IG Macdonald formulated a series of conjectures which predicted the constant terms of expressions that involve an important new class of symmetric functions called the Macdonald polynomials. Since their introduction, these conjectures and polynomials have been a central topic of study in Algebraic Combinatorics. Of particular note has been the variety of approaches used in efforts to solve the conjectures or to find an algebraic or geometric interpretation for the Macdonald polynomials themselves. Different approaches involve double affine Hecke algebras, homology of nilpotent Lie algebras, generalised traces of Lie algebra representations and diagonal actions of the symmetric group on polynomial rings in two sets of variables. In this programme we will attempt to unify these different approaches to the Macdonald Conjectures in a way that allows for a significant interpretation of the Macdonald polynomials and settles some of the outstanding conjectures that have resulted from this work.

Links with other areas such as algebraic geometry, Lie algebras, non-commutative algebra, mathematical physics and mathematical statistics will be emphasised. Workshops will be arranged in order to foster existing and potential applications in these and other subjects.

**Nonlinear Partial Differential Equations**  
January to June 2001  
*Organisers: H Brezis (Paris), N Dancer (Sydney), J Toland (Bath), NS Trudinger (Australian National)*

Details to be announced

**Managing Uncertainty - New Analysis Tools for Insurance, Economics and Finance**  
23 July to 10 August 2001  
*Organisers: P Embrechts (ETH Zurich), WJ Fitzgerald (Engineering, Cambridge), D Goodman (British Antarctic Survey, Cambridge), RL Smith (North Carolina)*

Details to be announced

### Integrable Systems

July to December 2001

Organisers: JC Eilbeck (Heriot-Watt), AV Mikhailov (Leeds), PM Santini (Rome), VE Zakharov (Moscow)

Details to be announced

### From Individual to Collective Behaviour in Biological Systems

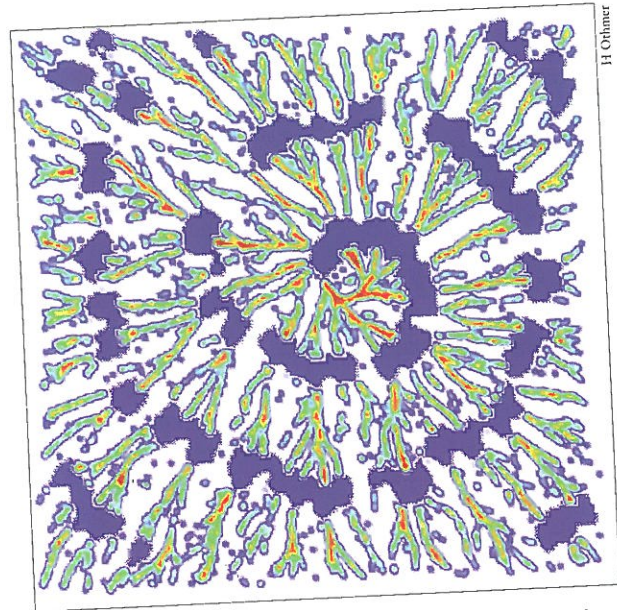
September to December 2001

Organisers: H Othmer (Utah), TJ Pedley (Cambridge), BD Sleeman (Leeds)

In recent years there has been an explosive growth in our knowledge of biological processes, especially at the molecular and cellular level. However, understanding the behaviour of an individual chemical reaction or cell (or organism) in isolation is only a first step in understanding the collective behaviour of a population of such individuals. The situation is complicated by the fact that the individual behaviour is in many cases stochastic, and even if it were intrinsically deterministic, the environment is not. Therefore probabilistic methods are essential in deriving a population-level description from models of individual behaviour, though it is unlikely that the same mathematical approach will be applicable in all systems.

Biology is too broad for one programme to cover all systems susceptible to mathematical analysis. Therefore this programme will concentrate on four biological topics:

- (1) *Physiology*. The emphasis will be on bringing together those who have established detailed descriptions of individual cells and then put them together into a whole organ on a parallel computer, one cell per processor, and those who try to establish average or continuum models, based on the same microscopic data, in advance of computation.
- (2) *Development biology*. This topic covers all aspects of pattern-formation in populations of cells. Given that we know more and more about what chemical and other processes are switched on or off by which genes, it is increasingly desirable to understand how the cells act and interact to produce observed structures.
- (3) *Stochastic spatial ecology*. In this time of unprecedented environmental change it is crucial for scientists to formulate a mechanistic (stochastic) description of the change based on underlying ecological processes: examples include the spatial spread of introduced pests; the shift of species ranges as a result of environmental change (climatic or directly man-made), etc.



Cellular aggregation in response to a spiral wave of cyclic AMP (dark blue) in the cellular slime mould *Dictostelium discoideum*

- (4) *Theoretical immunology*. New techniques have led to an increasing stream of kinetic data on the populations of various types of immune cells. However, proper understanding of the dynamics of these populations will come only in the framework of a formal theoretical model.

The organisers are guided by a leading biologist for each of the above four topics. Each month of the programme will be devoted to one of the topics, beginning with a workshop on both the biological problems and those mathematical approaches which might be expected to be fruitful. While most biological participants will probably wish to stay for only one of the topics, it is hoped that key mathematical scientists will stay for the whole four-month period.

### Higher Dimensional Complex Geometry

February to July 2002

Organisers: AA Corti (Cambridge), M Gross (Warwick), M Reid (Warwick)

Details to be announced

### M-Theory

February to July 2002

Organisers: R Dijkgraaf (Amsterdam), M Douglas (Rutgers), J Gauntlett (QMW), C Hull (QMW)

Details to be announced

# Biomolecular Function and Evolution in the Context of the Genome Project

(July to December 1998)

Report from the Organisers: PJ Donnelly (Oxford); W Fitch (Irvine); N Goldman (Genetics, Cambridge)

## Introduction

There is a long and productive history of interplay between genetics on the one hand and mathematics and statistics on the other. The 'molecular revolution' over the last 15 years, and in particular the impetus of genome projects, has transformed the field into one with an abundance of data and a paucity of relevant mathematical models and techniques. By 1998, the maturation of genome projects had made data on DNA, proteins, gene duplications and gene arrangements on the chromosomes widely available. These data will have a profound impact on the practice of biological research, and, ultimately, medical diagnostics and preventive medicine.

The aim of this programme was to bring together world-leading researchers in molecular biology, biological mathematics and computer science to meet and collaborate for extended periods on bioinformatic problems arising from the analysis of the current flood of molecular genetic sequences and structures. These include topics on subjects such as probabilistic modelling, statistical data analysis, stochastic processes, geometry, computational complexity, neural networks, genetic algorithms and expert systems. These topics were particularly apt for a Newton Institute programme, with the UK being a world-leader in molecular biology, but being generally less well-developed in the application of mathematics to the resulting data analysis problems.

Many challenging biomathematical research topics were raised and, as a consequence of recent advances in computational statistics, vast improvements in the quality of statistical analyses of these data were shown to be possible and various collaborations to that end initiated. Earlier parts of the five-month programme concentrated on explicitly evolutionary topics such as phylogenetic trees and networks, comparative analysis using evolutionary trees, population genetics topics and viral evolution, with conferences on human evolution and viral evolution. The later parts of the programme concentrated on structural, functional and genomic topics, with time devoted to secondary and tertiary structure prediction, fold recognition, motif and pattern recognition, hidden Markov models and gene prediction. Below, we report on the activities of the programme in the order they occurred, generally a week at a time.

## Organisation

The overall organisation was undertaken by Peter Donnelly (Oxford), Walter Fitch (UC Irvine) and Nick Goldman (Cambridge). A semi-formal arrangement had the scientific programme co-ordinated by Walter Fitch in July and August, by Peter Donnelly in September, and by Nick Goldman from October to December. Day-to-day administration of the programme was carried out by Nick Goldman.



Walter Fitch, Peter Donnelly and Nick Goldman

A number of the programme participants played important roles in the organisation of workshops and theme weeks, and many of these contributions are mentioned below. In addition, the organisers want to note the efforts of David Balding (Reading) as 'social events co-ordinator' throughout the programme. Three seminars in the Newton Institute Seminar Series were presented by programme participants: *Predicting the future evolution of the human influenza virus* (Walter Fitch), *Two problems of multiple comparisons in molecular genetics* (David Siegmund, Stanford) and *Experimental and computational approaches to analysing DNA-protein interactions* (Gary Stormo, Colorado). The programme also hosted the XXI Fisher Memorial Lecture, *Mathematics of genetic diversity before and after DNA*, presented by Prof Sir John Kingman and chaired by Prof Sir Walter Bodmer, and the annual one-day Summer Outing of the British Region of the International Biometric Society, at which Biometric Society members were shown around the Institute and heard three lectures by Institute programme participants, including one contributed by our sister programme.

## Participation

The programme attracted 69 long-term participants (average stay approximately 7 weeks), and 126 short-term participants. A very high proportion of the world's leading researchers was able to attend the

programme at some stage, although the nature of many molecular biologists' laboratory work meant that many were unable to attend for as long as they or we would have liked. Despite this, the organisers worked hard to ensure that participants were at all times drawn from the world's top scientists and not simply from the world's most mobile scientists.

The UK is a world leader in experimental molecular biology, but is less well-developed in the application of mathematics and statistics to analysing and understanding molecular genetic data. At all times, we attempted to co-ordinate the presence of leading researchers from around the world with the attendance of the UK's leading and most promising young researchers. Approximately 65% of the programme's core funding was used to support UK researchers.

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## Scientific Programme

In order to create the maximum possible level of continuity as the programme progressed, we decided to split the programme into 'theme weeks', the scientific content of each of which would be organised by one of the programme organisers and one or two co-opted programme participants (listed below). Theme weeks typically contained from 5 to 10 talks, both prearranged and also impromptu, given by invited speakers and other attendees. The theme weeks were interspersed with workshops, on topics related to the surrounding themes, and a number of free weeks in which participants were entirely at liberty to pursue their own interests. Overall, there was a broad divide into evolutionary topics for the first half of the programme, and genomic topics for the second half.

### Evolution: Phylogenetics

(20 July to 30 August)

One of the first goals in bioinformatics is frequently to discover the historical relations among the sequences one examines. There are several steps in this process, the first of which is to align one's sequences. This is followed by finding the best fitting tree and that by an attempt to understand other biological phenomena in the context of that phylogeny.

#### Alignment (W Fitch; T Smith, Boston)

The study of molecules in an evolutionary context requires one first to have a set of homologous sequences (nucleotide or amino acid), where homologous means that they have a common ancestor. It is then necessary to align these sequences, one under another, so that not only do the sequences possess a common ancestor, but all the nucleotides (amino acids) in a single column have a common ancestral nucleotide (amino acid). As that

ancestor becomes more and more remote in time, it becomes more and more difficult to discern which nucleotide belongs in which column. The first week of the programme, appropriately, was devoted to this primary topic. Topics covered included both optimal global and local alignments and such important details as the effect of different nucleotide frequencies in the sequence and unequal rates of evolution along the sequence. Also considered were approaches that obtain the alignment even while undertaking to obtain the phylogeny at the same time.

#### Phylogeny (W Fitch; D Penny, Massey)

The next step is to use the aligned sequences to obtain a phylogeny, a tree of ancestral relations. The second 'Evolution week' included scheduled presentations including talks about the myths that already inhabit the discipline, the effects on methods which were designed for small numbers of sequences when these numbers are scaled up by several orders of magnitude, the problem of multiple nearly equally good trees and the use of networks rather than trees to represent phylogenetic relations.

#### Workshop: EC Summer School (W Fitch; J Felsenstein, Seattle)

This week was an interruption of the progress on deep problems, and capitalised on the presence of many (indeed, most) leading molecular phylogenetics theorists and public domain software developers to provide a hands-on experience for novices in the use and potential of many of the programs for analysing data. The Summer School, entitled *Methods for Molecular Phylogenies*, was held from 10 to 14 August.

Many methods in molecular phylogenetics were devised in an ad hoc manner by biologists not trained in statistical methods. Consequently the field became controversial, with ill-understood and 'opposing' methodologies being introduced. Only in the past 10 years has a fuller understanding of the statistical properties of phylogenetic inference methods enabled a truly scientific framework for data analysis to be developed. A large proportion of established researchers around the world are still not fully aware of the 'state of the art' in molecular phylogenetics. We felt it was valuable to devise a course to introduce younger scientists to modern ideas on the major methods of data analysis, the mathematical and statistical foundations of these methods, and, in a practical vein, the use of the major computer programs available for performing these analyses.

The course very successfully met these aims, through its daily mixture of lectures (2 to 3 hours each morning)



and computer-based practical classes (afternoons). Computer facilities were kindly provided by the Department of Applied Mathematics and Theoretical Physics, University of Cambridge, and students typically worked with one pair per computer with various opportunities for individual work. The topics covered included the popular methods of parsimony, distance methods and maximum likelihood; optimal searching strategies of tree space; statistical tests in phylogenetics; and advanced uses of phylogenies. The course was attended by 73 official participants, including 51 from 13 EC countries; in addition we were delighted that up to 30 other scientists from Cambridge and elsewhere attended the morning lecture sessions. We had many more wanting to attend than we could admit and the reception was very positive. Our and others' experience leads us to believe that this indicates a great need in Europe for such a course to be given annually.

The Summer School's scientific content was organised by Joe Felsenstein (Seattle), and the computer sessions were co-ordinated by Frank Wright (BioSS, Dundee). Other lecturers were: AWF Edwards (Cambridge), W Fitch, A Rzhetsky (Columbia), J Huelsenbeck (Rochester), M Charleston (Oxford), A von Haeseler (Munich), M Newton (Madison), Z Yang (London), J Hein (Aarhus), W Maddison (Arizona), R Page (Glasgow).

*Beyond Phylogenies* (W Fitch; P Harvey, Oxford)  
Once one has a tree of relationships, what can one do with it? This is what the fourth Evolution week was about. Topics included were correlates of species richness, animal competition, speciation, ecological diversity, estimating ancestral character states, and macroevolution.

## Evolution: Population Genetics

(31 August to 4 October)

Population genetics is concerned with studying the diversity observed at the DNA sequence level between individuals in a population. Part of this, the collection of data, is clearly empirical. The correct interpretation of such data poses challenging mathematical and statistical problems. The data represents an incomplete snapshot, taken at a single point in time, from the evolution of the population. Such data is typically high dimensional, with a complicated correlation structure arising from the extent of shared ancestry between the chromosomal regions sampled. There is a well-developed tradition of mathematical modelling, typically in a stochastic way, of the evolutionary processes. These models provide insight into the ways in which observed patterns of variability depend on both the genetic factors at work (mutation, selection, recombination) and the demographic history of the population. Less well developed are statistical methods for inference from such data.

### *Population Genetics (I)* (P Donnelly; R Harding, Oxford)

The week aimed to set the scene for the focus on population genetics by bringing together leaders from both the experimental and modelling side, with a view to looking forward at the types of data which will be becoming available and the consequent challenges for developing appropriate models and methods of analysis. Both through formal presentations and structured discussions, and informal interactions, it appeared to succeed.

Workshop: NATO ASI: Genes, Fossils and Behaviour  
(P Donnelly; R Foley, Cambridge; S Paabo, Munich;  
A Rogers, Salt Lake City)



Examining human skulls at the NATO ASI

One particular organism of considerable interest is humans. Studies of human history have been seriously undertaken for at least 100 years. The molecular genetic revolution has added a new tool to the existing armoury (fossils, archaeology, language, behaviour, climate), since patterns of extant human genetic diversity have been shaped by the patterns of human demographic history. The ASI aimed to bring together leading researchers from across the range of disciplines involved, to give state-of-the-art lectures to young workers, and to try to integrate much of the existing disparate work. It succeeded beyond even the optimistic hopes of the organisers, in no small part because of the constraints imposed by NATO (limited numbers of 60-minute lectures each of which was followed by 30 minutes of timetabled discussion, a meeting of at least 10 days, a focus on bringing younger workers).

The invited lecturers were Paabo (Munich), Donnelly (Oxford), Foley (Cambridge), Lahr (Sao Paulo), Ward (Oxford), Bertranpetit (Barcelona), Barbujani (Milan), Hublin (Paris), Griffiths (Monash), Takahata (Tokyo), Jorde (Salt Lake City), Stoneking (Penn State).

*Population Genetics (II)* (P Donnelly and S Tavaré, Los Angeles)

The week focused on the specialised area of computationally intensive likelihood-based methods for inference from molecular population genetics data. This represents a new subarea of the field (the first papers are from about 5 years ago) which is extremely promising. Representatives of all the leading groups were present. While the specialisation excluded other programme participants more than for other weeks, there are obvious advantages to having high-level discussions amongst leaders of the field, and those involved were positive about the experience.

**Workshop: Viral Evolution** (N Goldman; E Holmes, Oxford; A Rodrigo, Seattle)

The aim of this workshop, held from 5 to 9 October, was to foster interactions and collaborations among virologists, evolutionary biologists and mathematicians, to discuss how best to analyse the increasing amounts of nucleotide sequence data being obtained from viral genomes, and to address the evolutionary and functional implications of the data already available. This data resource, coupled with the desire to control the spread of viruses through human populations, makes the study of viral genomes one in which an integration of data and theory is very likely to be profitable, both to the medical and biological sciences and also to offer inspiration to theoreticians. The study of viral genomes is an area of biological research that has often witnessed the successful introduction of new methods of data analysis.



Computer artwork of a representation of a spiky virus such as HIV and the Influenza virus. These spikes may change structure, forming a new viral strain and making the immune system less effective.

Within this general framework, a wide variety of topics was covered. Workshop sessions were devoted to Case Studies in Viral Evolution, Rates of Viral Evolution, Within-Host Evolution of HIV, Evolution of Drug Resistance in HIV, Viral Adaptation, Viral Quasispecies and New Uses for Viral Phylogenies. The workshop was deemed to be highly successful by all those who participated (approximately 50 in number). In particular, the meeting whole-heartedly followed the ethos of the Newton Institute in that discussion time was given special emphasis.

The workshop's scientific content was organised by Edward Holmes (Oxford) and Allen Rodrigo (Seattle). Other speakers were: T Gojobori (Mishima), H-U Bernard (Singapore), W Fitch, J Drake (North Carolina), C Bangham (London), P Simmonds (Edinburgh), S Frost (Edinburgh), Y-X Fu (Houston), P Zanutto (Sao Paolo), J Albert (Stockholm), K Crandall (Provo), S Bonhoeffer (Oxford), J Brookfield (Nottingham), L Chao (Maryland), A Sasaki (Kyushu), H Bourhy (Paris), D Smith (Edinburgh), T Leitner (Stockholm), P Sharp (Nottingham), M Pagel (Oxford).

## Genomics: Protein Structure

(19 October to 8 November)

One of the major, and largely unsolved, problems in bioinformatics is the prediction of protein structures from their DNA or amino acid sequences. Sequences are relatively easy and cheap to determine, whereas the experimental determination of the encoded protein's structure, for example by X-ray crystallography, remains difficult, time-consuming and expensive. Yet it is a protein's sequence that determines its structure which, in turn, determines its function and so holds one of the keys to understanding all forms of life. The implications for scientific research, medical applications and commercial exploitation of reliable methods to infer protein structures from their sequences are enormous, and attract continued interest and investment. Three consecutive theme weeks of the programme (19 October to 6 November) were devoted to analysing the current state of affairs in protein structure analysis, concentrating respectively on methods based on sequence analysis, on comparison with known structures, and on the combination of these approaches.

**Sequence Analysis** (N Goldman; G Barton, Hinxton; W Taylor, London)

In some senses, the 'Holy Grail' of protein sequence analysis is the inference of protein function from protein sequence. In practice, this is found to be too difficult even to attempt and the problem is split into simpler pieces, each perceived to be approachable

(although all are hard and as-yet unsolved). Starting with protein sequences, what is considered manageable is the prediction of protein secondary structure. Proteins are almost invariably composed of 'building block' structures which are joined together in specific manners to create the three-dimensional structure of the complete protein. The number of building block structures is very small (around a dozen, of which three predominate). The secondary structure of a protein is the categorisation of its constituent amino acids into these common elements. Although the 3-D structure of proteins (ie the determination of the co-ordinates in space of each of the thousands of atoms of a protein) is not currently estimable from sequence data, it is widely felt that the secondary structure problem is both possible, and would be of great value towards the inference of first 3-D structure and thence function. The first of these three theme weeks was aimed at reviewing the state of the art in protein secondary structure prediction.

*Structural Analysis* (N Goldman, A Lesk, Cambridge, W Taylor, London)

The second 'Protein Structure' theme week was devoted to reviewing the state of the art in our understanding of protein structures. This can be viewed as the other half of the problem outlined above; given what we already know about protein function and the structures that perform those functions, how can we curate our knowledge and find important patterns that might link to the inferences that we can make directly from sequences? One important topic discussed during this week was the relationship between, and strengths and weaknesses of, the various classifications of protein structures that currently exist. A number of participants found this a valuable exercise, particularly since it took place in front of the scientists who had generated the classifications. This very much clarified the situation and showed quite precisely what future steps should be taken both to reconcile the differences and to interpret the results arising from their use. Another recurrent theme was the surprisingly low number of fundamentally different protein structures that have been found to date. Early theoretical studies suggested that the range of protein structures that could in principle be formed by chains of amino acids was huge; in practice, it is found that there is very considerable duplication of structures and that proteins with very different evolutionary histories and functions tend to fall into the same structural 'families' or 'superfamilies'. There were valuable exchanges between those who maintain classifications of protein structures and those currently working on advanced theoretical models of protein structures, who are now beginning to

understand why the number of possible structures that nature has 'chosen to use' is so small.



Arthur Lesk

*Combining Sequence and Structure* (N Goldman; D Jones, Warwick; A Lesk, Cambridge)

The final theme week in this part of the programme aimed to draw together the previous two weeks work and begin to construct a more general programme for future (ie beyond the Newton Institute) research. This was an attempt (albeit not the first) to draw together the approaches based solely on protein sequence and those based on analogy with known protein structures and functions. This is a difficult topic, and it was consequently not easy to make great progress. We feel that nevertheless the week was well spent, as leading researchers in related problems were drawn together and compelled to remind themselves and each other of the 'bigger picture' behind their individual research.

*Workshop: Introducing Mathematicians/Statisticians to Current Problems in Biomolecular Sequence Analysis* (P Donnelly, N Goldman)

It should be clear from the remainder of the report that challenging mathematical and statistical problems abound in modern genetics, and further that the range and importance of these will grow in the "post genome" world. Nonetheless, there is a shortage internationally, and especially in the UK, of suitably qualified mathematicians/statisticians working in the area. We scheduled one structured week in which introductory lectures were aimed at those with a mathematical background - the genetics of the problem was explained simply, with a focus on the mathematical challenges. The week covered all the major areas covered by the programme, and in addition the statistical problems involved in the search for common complex diseases. One afternoon a visit to the Genome Campus at Hinxton was arranged, for further presentations and a chance to look around the laboratories.

We felt the week was helpful, and feedback from those who attended was positive. Nonetheless, the extent of the barrier presented by both the terminology, and the basic science within genetics should not be underestimated. There remains an acute shortage of trained mathematicians/statisticians/computer scientists, at virtually all levels.

## Genomics: Genome Structure

(23 November to 13 December)

Entire-genome sequencing is becoming increasingly feasible. The completion of the first animal genome sequence (that of the nematode worm *Caenorhabditis elegans*) was announced in the penultimate week of the programme, and follows the sequencing of numerous bacterial and viral genomes. The human genome is expected to be completed in 2003, and numerous other animal and plant genome projects are also at advanced stages. These data are now being collected at a faster rate than they can be analysed, and dealing with this explosion of data was a recurrent theme of the entire programme. The three theme weeks between 23 November and 13 December were devoted to some of the most basic problems being generated: how do we even identify and locate organisms' genes, regulatory regions, etc, within their genome sequences? In some complex organisms, these regions of interest may comprise less than 10% of the total genome (the remainder being 'junk' DNA with no known function).

### *Motif and Pattern Discovery*

(N Goldman; G Stormo, Colorado)

A major approach to these problems has been the identification of biologically significant motifs in functionally related sequences. A motif can be as simple as a pattern of five DNA nucleotides, possibly even incorporating some uncertainty, eg ATC[G|C]A, or can be a much longer pattern of amino acids, spread over large genomic regions and incorporating multiple components separated by variable sized gaps. This week of the programme was devoted to discussion of the best ways to represent such motifs, to discover them in novel genome sequences, and to search for further examples. In addition, there was comparison of the different approaches suitable for protein motifs and nucleotide motifs.

### *Hidden Markov Models and Related Probabilistic Methods*

(N Goldman; R Durbin, Hinxton;  
G Mitchison, Cambridge)

During the *Neural Networks and Machine Learning* programme at the Newton Institute (July to December 1997), a workshop was held on *Statistical Analysis of DNA and Protein Sequences*. This was immensely successful, and we were delighted to be able to devote a week of our programme to a similar theme in the

'inverse' context: a programme devoted to statistical analysis of molecular sequences hosting research on probabilistic models. Many of the same participants were able to attend (particularly since this topic is one which is exceptionally well represented in the Cambridge area), and although not formally declared a workshop, a full schedule of talks was arranged throughout the week and was attended by up to 50 people. Speakers gave introductions or updates on explicitly probabilistic modelling approaches to sequence analysis, currently one of the most successful avenues of research in a number of biological problems including gene prediction, evolutionary analysis of genomes, sequence alignment and protein structure prediction.

### *Gene Prediction*

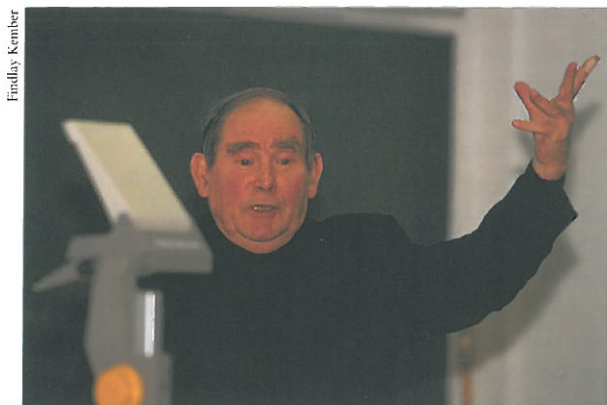
(N Goldman; S Brunak, Lyngby;  
R Durbin, Hinxton)  
Simply to find genes within genomic sequences requires the integration of many different signals: promoter regions, translation start and stop context sequences, reading frame periodicities, polyadenylation signals, and, for eukaryotes, intron splicing signals, compositional contrast between exons and introns, potential differences in nucleosome positioning signals, and sequence determinants of topological domains. It is highly non-trivial to distinguish between sequences that represent true genes and those that do not, and it is clear that additional work is required both to improve detection rates and, particularly, to decrease the level of falsely predicted genes. During this theme week a number of scientists who devise and use these methods presented recent developments and discussed outstanding problems. The main concentration was on probabilistic approaches, which were felt to be the natural way to handle the complexity of the problem of incorporating information from the numerous signals which to a large extent complement each other.

### *Workshop: Bioinformatics, Mathematics and the Genome Project: Future Challenges*

(P Donnelly, W Fitch, N Goldman)

On the final afternoon of the programme we arranged a high profile and widely-advertised meeting, which hoped to:

- i) Give some sense to those who had not been at the programme of its structure, achievements, and importance.
- ii) Look forward, with world leaders (Blundell and Brenner) speculating on future challenges within the genome context.
- iii) Bring to the attention of a wide audience the important role which mathematics and statistics have to play in the field.



Findlay Kember

Sydney Brenner giving his lecture at the *Bioinformatics* Workshop

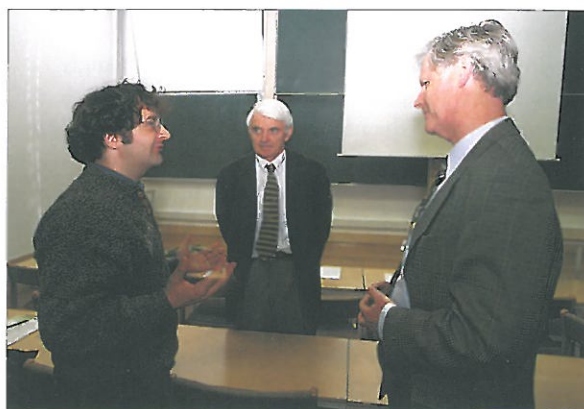
The meeting was oversubscribed. Even with a video link to the upper floor of the Institute, some of those who wished to attend, but applied late, were unable to do so. A concerted (and successful) attempt was made to attract senior individuals from funding bodies and interested commercial organisations, in addition to mainstream scientists. The meeting seemed successful, both in its basic aim of presenting exciting scientific developments, and in the wider aim of making a wider community aware of the (increasing) importance of mathematics and statistics.

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## *Achievements*

It was constantly in the forefront of the organisers' minds that this programme would be of greatest benefit to both UK and other scientists if it were able to bring together molecular biologists and data analysis theoreticians. Bioinformatics and genome-based research are young sciences, and are in need of improved links between the biological problems that must be answered and the data available towards this end on the one hand, and the mathematical, statistical and computational skills which generate the answers from the data (or know the limits of what can be inferred from different data sources) and are themselves often inspired by biological problems on the other. We are delighted, on reading participants' reports on their visits to the Institute, by the very high proportion who specifically mention the inspiration they received from participants with specialities different from their own, and the new cross-disciplinary collaborations that were initiated. Inevitably, as new problems and approaches tended to be the focus of attention, a lot of the achievements of the programme are currently intangible. The success of this programme will be best measured in two to five years time, when the significance of new projects begins to be judged by the wider scientific community. Given the high

hopes and expectations of our participants, themselves experienced scientists, we remain confident that the long-term impact of this programme on the field will be very high. The participating scientists' readiness to collaborate with specialists in very different areas to their own, and the Newton Institute's unequalled ability to facilitate such interactions, consistently exceeded the organisers' expectations throughout the duration of the programme.



Findlay Kember

Richard Goldstein (left), Rosenbaum Fellow, with Walter Fitch and Keith Moffatt

Richard Goldstein (Michigan) was elected as Rosenbaum fellow for the duration of the programme. He was able to contribute expertise on a number of topics relating to protein biochemistry and structure, and made the maximum possible use of the opportunity to interact with statisticians and learn about recent advances in computational statistics. An example of the research he worked on during his time at the Institute is modelling the evolutionary process in proteins and the application of this to the analysis of viral phylogeny. A related project, initiated with Nick Goldman during the Viral Evolution workshop within the programme, was a study which is pursuing an explanation of the surprisingly low effective population size (the number of viruses in a population actually contributing offspring to subsequent generations) of HIV in humans. They believe that this might be simply explained by the recently described finding that HIV is highly compartmentalised within an infected human. These two findings were each the subject of presentations during the Viral Evolution workshop, but had not previously been linked.

A fundamental component of modern bioinformatics is the scanning of exceedingly large sequence databases for potential matches to a newly-determined 'query' sequence. The score assigned to every potential 'query-target' match can be calculated relatively easily, but the statistical assessment of such a very large number of scores, each one itself optimised over the many possible ways of aligning a pair of sequences, is non-trivial.

David Siegmund (Stanford) and Richard Mott (SmithKline Beecham, Harlow) fortuitously discovered that they have been working on an identical problem relating to the estimation of significance levels for these statistical tests. As well as an exchange of their own ideas, they received further useful input from Chip Lawrence (Albany) and Gary Stormo (Colorado) who are interested in related problems.

Grainne McGuire (Reading) has developed her past work on the detection of recombination in phylogenetic data sets. Recombination is the 'horizontal' transfer of genetic information between contemporary individuals in a population, instead of the usual 'vertical' transmission by evolutionary descent. Recombination is not allowed for in most evolutionary analyses, and so can severely compromise evolutionary inferences in some cases. The first step towards ameliorating this situation is to identify sequence regions that have been subject to recombination. Dr McGuire's approach to this problem has been via hidden Markov models (HMMs), which facilitate computations but are, in biological terms, unnecessarily constrained. During her visit to the programme, she was able to discuss with David Balding (Reading), Bob Mau (Madison) and Graeme Mitchison (Cambridge) the relaxation of the HMM formulation by the use of Markov chain Monte Carlo methods. In collaboration with Nick Goldman and Ziheng Yang (London), considerable progress was made on clarifying the analysis of sequence alignments which include 'indels' (insertions or deletions of sequence regions in some of the sequences studied) and/or missing or erroneous data (due to incomplete or

inaccurate laboratory work). A simple theoretical approach has been developed, and lacks only experimental data on sequence accuracy before it can be tested. They are optimistic that these data, which should be increasingly available as genome projects reach completion, can be supplied over the next months by another programme visitor, Chris Burge (MIT).

It is widely acknowledged that there is currently no satisfactory method for combining and reconciling estimates of phylogenies from different analyses containing overlapping (but possibly not identical) sets of organisms and also potentially containing disagreeing estimates of relationships. Mike Charleston (Oxford), Andy Purvis (Silwood Park) and Mike Steel (Christchurch, New Zealand) made progress with this fundamental problem, clarifying which approaches are or are not likely to achieve all the desirable properties of a successful method. They are optimistic that new methods based on Dr Charleston's 'median network' approach will meet all of their requirements.

Tom Kurtz (Madison), Magnus Nordborg (Lund) and Gesine Reinert (Cambridge) made considerable progress with the problem of incorporating realistic levels of natural selection into coalescent population genetic models. Existing work for the cases of no, or very weak, selection can not be extended to the case of stronger selection. Their new work, including ideas on distributions of genealogies conditioned on various quantities associated with the model, have now put the strong-selection approximation on a firm theoretical footing as a limiting case.

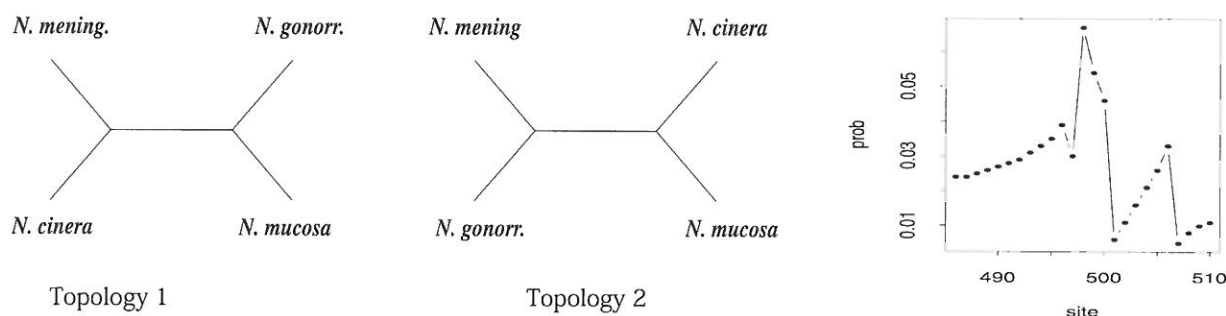


Figure 1: The Hidden Markov model for recombination was applied to an alignment of four *Neisseria* sequences, 787bp long, from the *argF* gene. There is a known recombination event in *N. meningitidis* from the start of the sequence (labelled as 296 bp) to 497 bp. Topology 2 is the non-recombinant topology; the recombination event causes a change in the branching pattern (Topology 1). The right-hand graph shows the probabilities, given the data and the model, that the topology changes from 1 to 2 at sites 486 to 510 along the alignment. It is seen that the estimated changepoint (498 bp) corresponds to the true value.

Adapted from: G McGuire, *A Bayesian model for detecting past recombination events in multiple alignments*

A recurring theme in the programme was the realisation that the results of novel data analysis techniques are increasingly difficult to assess objectively. Computational methods are increasingly complex, due to both advances in statistical methodology and computer hardware, and the data sets to which they are applied are increasing in both size and diversity, due to entire-genome sequencing projects and simply the acceleration of sequence determination methods. The more complicated new methods of data analysis are virtually untestable, as they address new problems with untested algorithms, novel data sets, and using computational resources not available to journals' referees etc. In certain fields, efforts are already being made to monitor these problems. For example, in protein structure prediction there is a biennial 'challenge', the CASP competition, in which novel protein structures are offered for prediction experiments before the true results are publicly released. The 1998 CASP competition was the subject of much discussion during the Protein Structure theme weeks. On two independent occasions during the programme multi-centre collaborative projects were initiated to try to regulate such problems in other areas of research. The first came about during the theme week on Population Genetics (II), and was proposed by Simon Tavare (Los Angeles) and Peter Donnelly. While computationally intensive statistical methods offer great potential for the analysis of molecular genetics data, there are serious issues in the validation of particular implementations. Agreement was reached on the need for a centralised web resource of data sets of various types and the "correct" answers, to relevant inference questions (likelihood surfaces or marginal posterior distributions), and on the types of data which were required. Such a collection will be established in Oxford. Work on this is in its early stages. The other was proposed during the theme week on Gene Prediction, and aims to provide standard 'test cases' for algorithms designed to scan large amounts of genomic sequence to determine the location of genes, regulatory regions, etc. Results of the second of these initiatives may be viewed at: <http://www.hgmp.mrc.ac.uk/Genesafe>

## *Acknowledgements*

The programme benefited from grants from the National Science Foundation of the USA (<http://www.nsf.gov>), the European Community, the Wellcome Trust (<http://www.wellcome.ac.uk>) and NATO, and from sponsorship from Compugen (Israel) (<http://www.compugen.co.il>) and SmithKline Beecham Pharmaceuticals (Bioinformatics Research Group, Harlow, England) (<http://www.skb.com>). We are grateful to all of these for their generosity.

We should like to thank the staff of the Newton Institute for their support throughout this six-month programme.

# Nonlinear and Nonstationary Signal Processing (July to December 1998)

Report from the Organisers: WJ Fitzgerald (Engineering, Cambridge); RJ Smith (North Carolina); A Walden (Imperial College); PC Young (Lancaster)

## Introduction

The classical theory of signal processing is based on models which are stationary, linear and in many cases also Gaussian. Recent advances in time series and the theory of signal processing have drawn attention to many new models and methods. Among these are nonlinear autoregressive and nonlinear state-space models, state-space models with time-varying or state-dependent coefficients as models for nonstationary and nonlinear series, linear non-Gaussian processes which pose some specific problems not encountered with Gaussian processes, methods derived from the theory of dynamical systems, and many others. There has been a parallel growth in the applications of signal processing in many modern areas of modern engineering and into other areas such as financial time series, the environmental sciences, physiology, etc. In many instances, methods have developed in an ad hoc way, being designed for specific applications rather than fitted into a general framework. In particular, very often similar problems have been examined by different groups of workers with minimal contact between the groups. The purpose of this programme was to bring together statisticians, engineers and other researchers who use signal processing methodology to unify existing methods and to identify areas of research where new methodology is required.

The programme was structured around five major themes: Bayesian Statistics, Environmental Science, Dynamical Systems Theory, Econometric and Financial Applications, and Extreme Value Theory.

Each of these themes had a major workshop associated with it and, in addition, several special theme weeks were concerned with mathematical developments in nonstationary signal processing *eg* Gabor analysis and Wavelet Analysis, extreme value statistics and the statistics of transmissible spongiform encephalopathies (TSEs) and how this could possibly explain nvCJD.

The recent advances in numerical approaches to Bayesian inference have enabled complex problems to be solved that were impossible to consider previously and an important area considered in our programme was how these methods could be unified and applied to the field of data analysis. This was a great success and is forming the basis for several future collaborations.

Another important area to come out of the programme was the application of novel statistical methods to



Left to right: Andrew Walden, Bill Fitzgerald, Lenny Smith, Alistair Mees, Ed George, Don Percival, Richard Baraniuk

aspects of *eg* global warming time series analysis and other areas, relevant to the insurance industry where extreme value statistics are appropriate.

## Organisation

The overall planning of the programme was undertaken by Bill Fitzgerald, with the other organisers (as well as some participants) being involved in the arrangement of specific workshops, conferences and seminars.

The programme was the largest international event ever to take place addressing the problems associated with Nonlinear and Nonstationary Signal Processing and was unique in bringing together statisticians, mathematicians, engineers, econometricians and environmental scientists. Many of the world leaders in particular subject areas either spent extended periods of time at the Institute or attended the various workshops.

Weekly seminars were organised throughout the programme and formed a very useful framework which enabled people in different fields to understand the common threads that bind the subject together.

A balance was struck between the number of workshops and seminars and the amount of time that the programme participants could spend on their own research and in discussions with other participants.

The atmosphere was extremely good and very conducive to interactions - so much so that many new collaborations were formed which will be ongoing in the future.

Social events, ranging from cricket matches to receptions were held throughout the programme and these enabled very good interactions to take place between the participants of the programme.





An impromptu seminar over coffee

## Workshops

### Bayesian Signal Processing

The workshop on Bayesian Signal Processing was held in July, and was the start of the six-month programme. This workshop was organised by Bill Fitzgerald.

Bayesian inference is the methodology which underpins most of modern signal processing and data analysis and it was felt that a workshop dedicated to Bayesian methodology would be most appropriate.

In recent years there has been an explosion of interest in Bayesian statistics. The development of new algorithms for Bayesian computation, together with the ready availability of computing resources, have made feasible statistical methods which until the present decade were limited to small data sets and restricted classes of models. This “revolution” in statistical methodology has affected every area where statistics is applied, including medical statistics, the social sciences, analysis of financial data and the modelling of large environmental systems.

Signal processing refers to the class of methodologies available for handling data produced sequentially in time. Most of the methods originated in engineering but are now applied in many other areas as well, *eg* communications, econometrics, geophysics, physiology, image processing. Classical methods of signal processing, such as the Kalman filter, were based on stochastic processes which are linear and Gaussian. One reason for this restriction was that the computations required for such systems are relatively simple and could be readily implemented using the computing resources of the 1960s and 1970s. However such assumptions are inadequate for many modern applications and more flexible models have emerged. Examples include wavelet methods for time-frequency analysis, Kalman filters with time-varying or state-dependent coefficients, new techniques for non-

Gaussian processes, and dynamical systems and chaos as mathematical models for time series. However in many instances the new methodology has developed in an ad hoc way, being designed for specific applications rather than fitted into a unifying framework.

The main focus and thrust of this workshop was the fact that Bayesian methods provide a unifying methodology whereby different kinds of mathematical models may be examined within a common statistical framework. The workshop brought together the statistical and computational expertise of leading statisticians and the modelling expertise of mathematicians and subject matter specialists, with the broad objective of developing new signal processing tools which make efficient use of modern computational resources while combining the most up-to-date research of both groups of specialists.

Specific topics that were covered included:

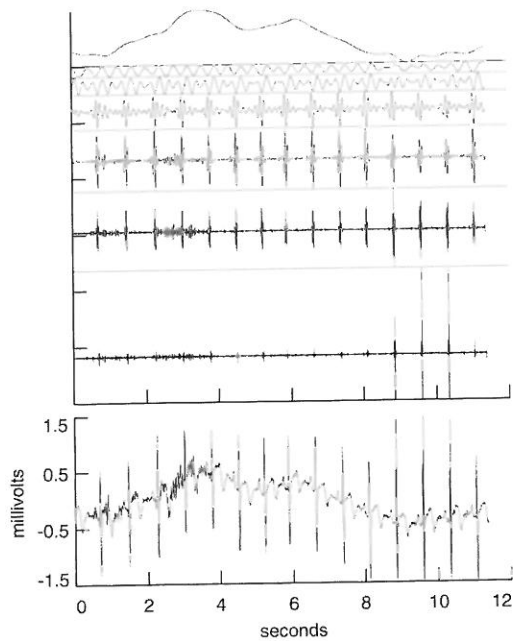
- 1) Bayesian methods in general, and numerical methods in particular,
- 2) Nonlinear and nonstationary time series estimation,
- 3) Forecasting and changepoint modelling,
- 4) Nonlinear signal processing in econometrics and financial time series,
- 5) Dynamical systems and statistics,
- 6) Environmental applications and spatial data analysis.

The workshop had around 100 participants from 18 different countries. Many of the talks were aimed at young research workers and this was combined with more advanced ‘state-of-the-art’ approaches. The younger scientists had the opportunity to show their work during several poster sessions.

The workshop was a huge success and has formed the basis for several collaborations.

### Gabor Analysis workshop

This workshop, which involved around 30 participants, and was held in the first week of August, was organised by Hans Feichtinger and Bill Fitzgerald. For many years the Fourier transform has been one of the main tools in applied mathematics and signal processing. However, due to the large diversity of problems with which science is confronted on a regular basis, it is clear that there does not exist a single universal method which is well adapted to all the problems. In this workshop leading experts in the field



Non-decimated discrete wavelet transform multi-resolution analysis of an ECG time series

of Gabor analysis, which is becoming an accepted area of research which is both theoretically appealing and has had many application successes, were brought together to discuss current new developments. One aim of Gabor analysis is to be able to represent one-dimensional signals in two dimensions, namely time and frequency. One goal is to find simple elements, the *atoms*, of a function space and the assembly rules that allows the reconstruction of all the elements of the function space using these atoms. There are certain similarities between the Gabor approach and the current interest in time-frequency distributions and several talks were aimed at this similarity. The new book, edited by Hans Feichtinger and Thomas Strohmer entitled *Gabor Analysis and Algorithms*, Birkhauser, 1998, discusses many of the areas addressed during the workshop and most of the contributing authors attended the workshop.

#### Environmental Signal Processing

This workshop, which involved around 60 participants, was organised by Richard Smith and Peter Young and took place in the middle of August.

A major area of application of signal processing is in the analysis of environmental data, interpreted here to include areas such as hydrology and oceanography, climatology and studies related to pollution. Characteristic features of such applications include constructing models for dependence and trends, but it is also a common feature that data are collected

spatially. Therefore, a part of our objective here was to extend signal processing techniques to the analysis of spatial data. In this we concentrated on themes closely related to those developed elsewhere in the programme since to consider all aspects of spatial data (eg image analysis) would be going too far from our dominant theme.

A key issue in some environmental applications is the relationship between purely statistical approaches to data analysis and those which use physically motivated models. A general theme developed over many years, by PC Young, is data-based mechanistic (DBM) modelling, in which transfer-function models are fitted to data and then reinterpreted in physical terms. The models fitted are very often nonlinear and/or nonstationary. Specific environmental applications include the "active mixing volume" approach (Young/Lees) to the dispersion of a pollutant in water, and models for rainfall-flow (Young/Beven). Other environmental applications of signal processing include distinguishing between trends and various forms of time series dependence (eg long-memory) in climatic data series, ozone etc, and models based on stochastic time transformations in geological and paleoclimatological problems. There are also a number of researchers looking at climatological problems from a dynamical systems point of view, eg the "singular spectral analysis" approach, and Milan Palus from the Czech Republic gave several presentations on these approaches.

Extensions to spatial-temporal models are important because many of the environmental problems involve spatially collected data. The two main approaches to spatial data are the geostatistical approach, based on Gaussian models with parametrically specified covariance functions, and approaches stemming from the fundamental work of Besag which are based on families of conditional probabilities. Current applications to spatial-temporal data, tend to rely on simple product-form combinations of spatial and temporal operators. Our general approach to nonlinear and nonstationary signal processing suggests many extensions of non-product form, with potential applications including calibration of weather-radar data, modelling of ground-level ozone, spatial-temporal models in climatology, and many others.

#### IEEE Neural Networks workshop

The Eighth IEEE Workshop on Neural Networks for Signal Processing was held at the Isaac Newton Institute and Robinson College, 31 August - 2 September 1998 and formed a very interesting addition

to the programme that was already taking place at the Institute. There was obviously a lot of overlap between the participants and many people who were attending the Newton programme gave papers at the IEEE workshop. Also, many delegates from the IEEE workshop stayed on afterwards to continue interactions with the programme. We also hosted a very successful reception and poster session for workshop delegates and this enabled detailed discussions to take place in a relaxed environment.

The proceedings has already appeared as a published IEEE book (ISBN 0-7803-5060-X).

#### Dynamics and Statistics

This workshop, which involved around 60 participants, was organised by Richard Smith and Alistair Mees and took place in the middle of September.

The “signals” used in signal processing have physical origins, and processing them will be greatly assisted if knowledge about the underlying dynamics is known or can be inferred. During the past 15 years, workers in the dynamical systems community (Eckmann/Ruelle, Farmer/Sidorowich, Casdagli, Mees, Sugihara/May) have developed signal processing from a different point of view. They were often motivated by the desire to identify whether a system is chaotic or noisy but in large measure their work is applicable even in the absence of chaos. There are numerous examples of signals that look random but are not, and cannot be analysed by linear methods. Early successes of these methods encouraged applications which are more controversial, such as deterministic modelling of financial time series.

Initially, statisticians and dynamicists worked almost independently with little exchange of ideas and both groups suffering as a result.



Poster session at the *Dynamics and Statistics* Workshop

There have been comparatively few statisticians working in this field, and much of the best work is being done by L Smith and H Abarbanel who both participated during both the workshop and for longer periods during the programme as a whole. L Smith discussed *surrogate data analysis* which is closely related to bootstrapping; comparisons with the statistical theory of bootstrapping shed much light on the area.

Other areas where statisticians and dynamicists benefited from interaction included: the estimation of fractal dimensions, Lyapunov exponents and other dynamical invariants; the shadowing lemma of dynamical systems theory and its relation with statistical techniques such as extended Kalman filtering; embeddings both as a theoretical property of dynamical systems and the practical estimation of embedding dimension; geometric filtering theory; and the often underestimated question of what happens with all of these techniques when statistical noise is added to a nonlinear dynamical system. In all of these areas, both dynamicists and statisticians have key ideas to contribute and both groups benefited from the interaction.

#### Econometrics and Financial workshop

This workshop, which involved around 60 participants, was organised by Neil Shepard and Ruey Tsay and took place in the middle of October.

Signal processing has played an important role in economics for many years. Classical signal extraction results have influenced recent generations of economists.

Nonlinear signal processing problems come up in tackling many models suggested in various aspects of economics and finance. Leading cases include the stochastic volatility generalisation of the option pricing of the well-known Black-Scholes formula, the nonlinearity in Tobin's  $q$  for optimal investment at the firm level, and the Cox-Ingersol-Ross term structure of interest rates model. These models involve the use of stochastic differential equations with unobserved state variables and must take into consideration nonlinearity and nonstationarity of the underlying signal.

Econometricians have recently turned their attention to developing methods for tackling these types of models. In stochastic volatility studies, many authors have applied numerical methods and Markov Chain Monte Carlo methods to develop nonlinear models capable of describing the observed features such as volatility clusterings and long-range dependence. In addition,

several authors have considered nonlinear diffusions, continuous time models and nonparametric methods in mathematical finance with considerable success.

A different, but closely related, approach to volatility modelling in the econometric literature is to consider duration models which combine point processes with time series analysis to describe the evolution of the underlying signal or information. In financial applications, this approach would consider jointly the transaction events and the associated volumes and prices. This research is also closely related to generalised linear models, and nonlinearity and nonstationarity again play an important role.

Considerable efforts have been devoted to the study of business cycles in economics. For instance, Markov switching models are widely used to study the status of the economy and the transition between recession and expansion. From the signal processing point of view, such studies can be formulated into a nonlinear state-space model and estimated effectively by MCMC methods.

#### Extreme Value Statistics and Insurance

This workshop, which involved around 60 participants, was organised by Richard Smith and Bill Fitzgerald and took place in the middle of August.

*Extreme value theory* is a branch of statistics concerned particularly with the most extreme values (maxima and minima) of a sample of random events. It has applications in many areas where the most extreme values are important, such as strength of materials, structural reliability, extreme values of environmental pollutants such as ozone and sulphur dioxide, and climatological extremes. Its relevance to the subject of insurance stems from the obvious point that a small number of very large claims may have serious consequences for an insurance company. Extreme value theory provides a set of mathematical tools both for characterising probabilities of very large claims and for assessing their consequences for the solvency of a company. During the programme, many data sets were analysed and the results presented at the various workshops. The findings are to be published shortly.

Traditional actuarial theory relies on standard probability distributions such as normal and gamma. Such *short-tailed* distributions have the advantage of being easy to handle statistically, and of leading to a nice mathematical theory of long-term loss probabilities. The trouble is that real data on insurance claims tend to show occasional very large claims which are much more consistent with *long-tailed* distributions such as the Pareto, and which lie

outside the scope of the usual theory. However during the past fifteen years, a new set of statistical and mathematical tools has been developed to handle such distributions. These tools are now at the stage where they are being applied to real data from insurance companies. They are particularly relevant when applied to problems of *reinsurance*, which is where the most critical problems associated with large claims arise.

The application of Bayesian numerical methods to these problems formed a central focus to the analysis of the data during the programme.

Related to concern over the effects of large claims is concern over their causes. The 1990s have seen a series of environmentally related insurance disasters, mostly in the USA, eg Hurricane Andrew, the Northridge earthquake, the Mississippi floods. Although there is no direct evidence to suppose that these are linked with environmental trends such as global warming, nevertheless it is natural to ask whether there is any association. Statistical analyses of climatological data *have* demonstrated a rise in the frequency of extreme events. It was therefore an important research question to establish whether these extreme events have arisen just by chance or can be associated in a causal fashion with known "signals" such as the enhanced greenhouse gas effect. The findings from our analysis are soon to be published in the scientific literature and in the three books that will be published based on the six-month programme.

#### Transmissible Spongiform Encephalopathies (TSEs) and nvCJD

This workshop, which involved around 30 participants, was organised by Noah Linden, Frank Kelly, Bill Fitzgerald and Sheila Gore and took place in November.

This meeting had as its principal purpose to bring together a group of biomathematicians, a group who have been concerned with following the BSE and new variant CJD epidemics and experimental workers in the field of spongiform encephalopathies to assess the present situation with regard to the BSE and CJD epidemics and to explore the possibilities of modelling their progress and predicting their future cause.

An account of the back calculation techniques that have been used to map the BSE epidemic was given.

Estimates of the associated parameters can be obtained from the data that is available on the British bovine herds. The predictions of how the incidence would decline have been fairly closely followed.

The question of under-reporting was discussed and it was pointed out that while there may be some under-reporting its extent has probably been exaggerated in the past.

A session was devoted to the modelling of the new variant CJD epidemic.

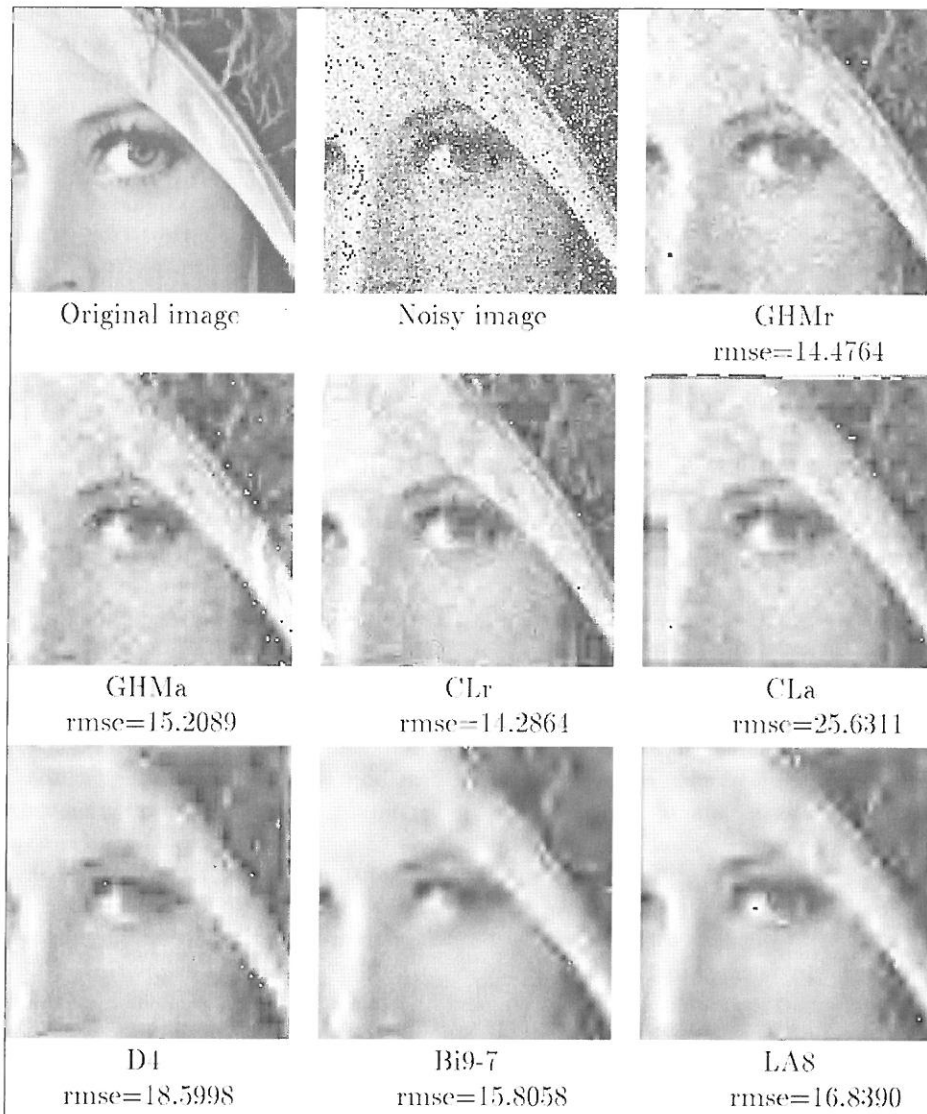
#### Data Analysis

This final workshop of the programme was organised by Andrew Walden and Richard Smith and took place in early December.

Topics covered included image denoising, teletraffic analysis, car engine diagnostics, analyses of Ulysses spacecraft data and recognition of fax-corrupted

words. Analyses of some common data sets, analysed during the six-month programme, featured in a number of talks. Several methodological themes recurred during the presentations, notably state-space modelling, wavelet analyses, and Polya tree structures. Also the necessity of defining good metrics and loss functions for measuring disparities in trees, images *etc* was considered a rich area for future research.

As evidenced by intriguing and searching questions, a main achievement of the workshop was to make members of the engineering and statistical communities aware of each other's methodological and applied work, in particular in the areas of Polya trees and wavelets, and to help define the interesting and important questions for future research.



Denoising of an image (signal-to-noise ratio of 4) using various multiwavelet methods (GHMr, GHMa, CLr, CLa) and ordinary wavelet methods (D4, Bi9-7 and LA8). The rms error is given in each case. Figure taken from a paper by Strela and Walden presented at the Data Analysis Workshop.

## Achievements

Amongst the many successes of the programme, one of the most notable was the stimulation of new interdisciplinary collaborations between the groups of statisticians, mathematicians and engineers who participated in the programme.

This was apparent at each of the workshops and within the programme as a whole. For example, during the course of the programme various data sets were made available to participants. These data sets represented many and various different aspects of signal and data analysis. For example, some of the data sets were temperature data going back many years and were previously thought, by some people, to show evidence of global warming, other data sets were taken from the insurance industry and are examples of extreme value problems. Various participants analysed these data sets from their own points of view and some of the seminars and workshops were aimed at looking at the different approaches taken by the workers from different backgrounds.

As a direct result of these different approaches many collaborative ventures have started and the results should be very revealing.

For example, Peter Young and Bill Fitzgerald are trying to fuse together the approaches previously taken using Dynamic Harmonic Regression and Bayesian approaches to parameter estimation and Model selection. This will have many interesting applications in time series analysis.

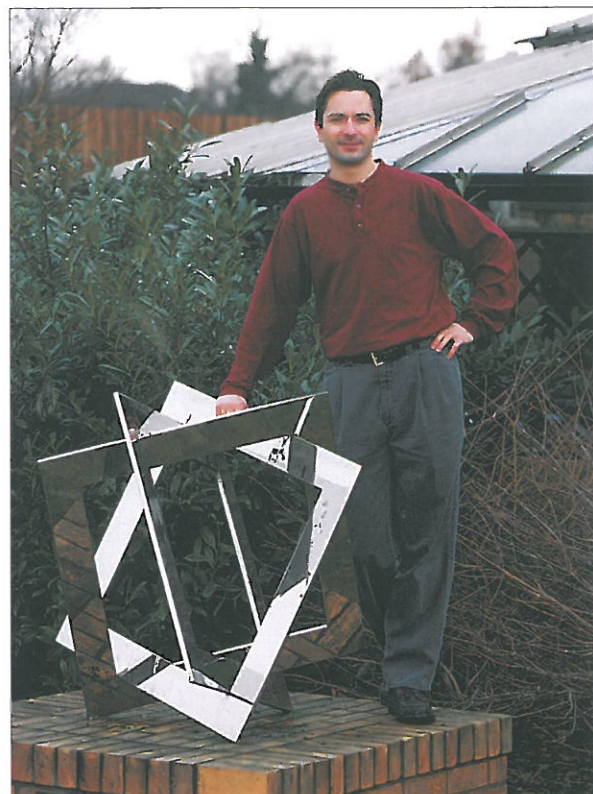
Hans R Kunsch worked on the asymptotics of estimation of mutual information between lagged variables in a time series. This is often used as a diagnostic tool since in contrast to correlations, mutual information captures nonlinear relations between variables. Up until now, no results on the asymptotic properties of this estimator are known. Considerable insight has now been achieved about this estimator.

Hans R Kunsch also presented his work on the so-called particle filter at the Data Analysis Workshop. The particle filter is the basis for the current interest in sequential Markov Chain Monte Carlo Bayesian methods. The work presented by Mike Pitt and Neil Gordon, in this area, formed a very useful opportunity to discuss this very important approach from different perspectives.

Raquel Prado from the University Simon Bolivar, Venezuela, presented her work on latent structure in nonstationary time series and her work on time-varying autoregressions (TVAR) caused much interest since it

forms a very useful potential way of dealing with multivariate environmental and biological time series that are currently being investigated using alternative approaches.

Richard G Baraniuk from Rice University was elected as Rosenbaum Fellow. Amongst the research carried out during his stay, several new areas of research were started: tree-structured lacunary wavelet series, tree-structured optimisations for wavelet-based signal processing, multifractal wavelet series and empirical mode decomposition. Also, interactions with statisticians (EI George and WJ Fitzgerald) showed that many of the new techniques of Markov Chain Monte Carlo have many applications in Time-Frequency analysis which have yet to be fully explored. Several INI technical reports will be forthcoming. Also, a book concerning Time-Frequency representation, together with Doug Jones was started. He wrote papers, during the programme, with Patrick Flandrin and AJEM Janssen. Several seminars were given at various Universities in Europe during the duration of the programme.



Richard Baraniuk, Rosenbaum Fellow

Ed George (Austin) developed, together with AP Dawid, a new approach for putting prior probability distributions over models in Bayesian analyses. The goal was to avoid the problem of putting

too much probability on sets of similar models. The idea was to assign probability to Kullback-Leibler neighborhoods in model space thereby diluting probability across similar models. Work was also undertaken to prove asymptotic consistency of estimators for empirical Bayes methods for variable selection and this showed that such estimators are vastly superior to competing methods.

Work undertaken by Ed George and Bill Fitzgerald concerning model complexity penalisation has shed new light on the problems associated with Bayesian approaches to model selection.

Work was undertaken by Richard Smith, Peter Young and Bill Fitzgerald on certain data sets supplied by the insurance industry and various different approaches were used to very good effect.

These results were presented at the workshop concerning extreme value statistics.

Work undertaken by Don Percival (Washington), who was an EPSRC Senior Visiting Fellow at the Institute, and Andrew Walden, concentrated on wavelet methods applied to time series and half of a CUP book was written on this subject during the programme. Work was undertaken using tree structures and Polya trees in particular, for representing correlation structures arising in wavelet analysis.

David Thomson from Bell Labs visited the programme twice and spoke about multitaper spectral estimation. This formed the basis for a lot of interaction with applications to particular data sets.

Steve McLaughlin (Edinburgh) focused his work on two main areas: Higher order statistics for the detection of quadratic phase coupling in time series and the second was to develop parsimonious models for teletraffic data which exhibits long range dependence.

## *Acknowledgements*

The programme benefited from sponsorship by Schlumberger Cambridge Research, the US office of Naval Research, Barclaycard, BP, the TSUNAMI initiative and the NSF.

We are very grateful to Cambridge Control for supplying us with copies of MATLAB for the full duration of the programme.

This programme would really not have been possible without the super-excellent support of the staff of the Isaac Newton Institute.

detection technique of coherent vorticity using time-scale resolved acoustic spectroscopy, and may have detected something very similar to Lundgren's spiral vortex in jet turbulence. This experimental work was flanked at the Symposium by numerical studies of the structure of small-scale vortex tubes in various turbulent flows (Brasseur, Flohr, Tanahashi).

#### Breakdown to Turbulence (Transition)

Although the principal theme of the programme was the understanding and modelling of fully turbulent flows, it was recognised that the mechanisms by which flows become turbulent, in particular the intermediate "pre-turbulent" flow states, may shed light on the physics of turbulence. The workshop focused on transition of wall-bounded shear flows (boundary layers) which are of the greatest practical importance. In a nutshell the problem faced by the aeronautical and flow machinery industry is the prediction of the transition location in a complex, generally three-dimensional flow, eg a swept wing including its root region or a three-dimensional compressor blade. The state of the art in industry was reviewed by Chris Atkin (DERA) who showed that industrial predictions are still mostly based on N-factors and that only the sophistication with which they are computed has evolved since their invention by AMO Smith. Hence, one of the principal problems of transition prediction remains the integration of receptivity to "free stream disturbances" into the transition prediction methodology which could finally lead to realistic disturbance-dependent predictions.

The different methods of computing disturbance amplification were presented by P Lucchini and J Healey. A lively discussion with S Cowley in particular of the application of parabolised stability equations (PSE) in non-parallel flows clearly revealed its weaknesses relative to the multiple scale method and to "proper" asymptotics based on triple deck theory, which is at the base of J Healey proposal for a non-linear, non-parallel  $e^N$  method. Another serious problem when computing N-factors in three-dimensional flows is the choice of trajectory along which amplification is to be computed. (In the context of PSE, this question is related to the direction in which the equations are to be parabolised). R Lingwood presents a proposal by Brevdo to take a trajectory parallel to the local group velocity vector. It is clear that such computations become very extensive if the maximum N-factor with respect to all the possible instability modes is sought and a superposition of wave packets in the spirit of Huygens may be worth pursuing. This latter point of discussion is related to the possible role of absolute instability in transition prediction. Starting from the unusually good

correspondence between the radius of convective-absolute transition and transition to turbulence in the rotating disc boundary layer, R Lingwood further developed the ideas for the swept wing boundary layer where no true absolute instability (defined by the asymptotic behaviour of the impulse response) has been found. Beyond some chordwise station however, modes with zero group velocity in the chordwise direction exist and lead there to a wave packet edge parallel to the leading edge of the swept wing possibly corresponding to the transition line. While transition predictions based on absolute instability (or "chordwise absolute instability") are in principle independent of the exact nature and magnitude of the initial perturbation, provided there is any, it is still an open question whether this concept alone is sufficient for the swept wing in particular where minute roughness elements on the leading edge create in practice turbulent wedges and a "jagged" transition line. This issue is somewhat related to the non linear development of localised global modes arising from an absolute instability region in a non-parallel flow which has been discussed by S LeDizes.

On the difficult issue of receptivity, X Wu showed how the interaction of convecting gusts with sound can effectively generate Tollmien-Schlichting waves. P Lucchini, on the other hand, discussed the "receptivity" of the boundary layer to low-frequency, spanwise periodic disturbances (streamwise streaks and vortices) and made the connection to the Libby & Fox and Stewartson modes. This direction of research, in which the optimal initial perturbation for maximum amplification over a given streamwise interval is determined by upstream integration of the adjoint stability problem, is attractive as it limits the number of modes that need to be considered in a standard N-factor computation and coupled to free stream disturbances. For high levels of external perturbations, such as provided by passing wakes in multi-stage rotating machinery, H Hodson and W Rodi showed evidence that the standard growth stage of a few instability modes is bypassed and turbulent spots can be formed immediately. An inviscid model for the latter was discussed by F Smith, the internal structure of spots were illustrated by the outstanding experiments of A Perry and the relevance of "shear sheltering" to this transition scenario with strong forcing was discussed by J Hunt.

Advancing further towards turbulence, the secondary instability of streaks and streamwise vortices and their interplay was the subject of talks by F Hussain, N Sandham and D Martinand. From these presentations it is becoming increasingly evident that



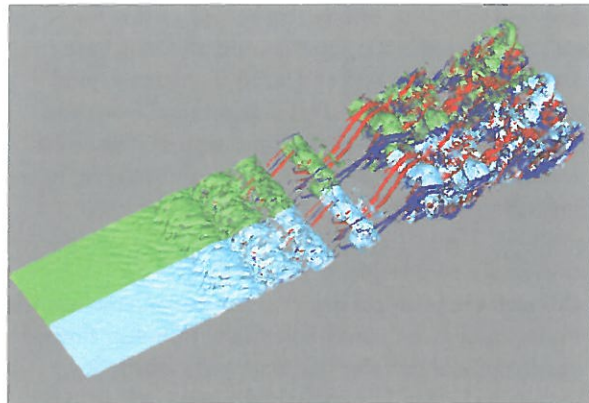
the near-wall dynamics involving non-linear interactions between streamwise streaks, near-streamwise vortices and wave-like secondary instabilities of these structures defines the advancement of transition: after a regime in which these structures appear intermittently, transition is complete when the cycle linking these modes becomes self-sustained, thus constituting the “motor” of turbulence in wall-bounded flows. A transition criterion based on these concepts appears attractive, as the receptivity of the flow must be known for only a few low-frequency modes and, based on 4-mode analytical Waleffe-type models for Couette flow, there is hope that only a rough knowledge of the initial conditions within the basin of attraction of the self-sustained cycle may be necessary. A continuing effort combining DNS simulations, experiments and modelling will be required to assess the potential of these concepts for transition prediction in complex situations, notably strong pressure gradients, three-dimensionality, *etc.*

Finally, issues relating to the control of boundary layers for the purpose of drag reduction or separation avoidance, for instance, have been discussed by B Geurts, P Carpenter and J Morrison. The relationship between optimal control approaches, which generally require very large arrays of sensors and actuators plus considerable real-time computing power, and more practical “*ad hoc*” approaches could be an important area of study in the future.

For the future, the workshop has clearly brought out some of the key problems that need to be addressed in order to arrive at better, more rational transition predictions. Probably the most pressing problem is to quantify the receptivity of a flow to “external” or free stream disturbances with, in practice, a *minimum* knowledge about the nature of the forcing. While the current knowledge base consists mostly of sophisticated analyses of “simple” cases, it may be necessary to explore more probabilistic approaches. Another important problem is the evaluation of disturbance amplification including non-parallel effects, three-dimensionality and nonlinearity, once external perturbations have been converted to modal or non-modal boundary layer structures, and the related definition of more rational transition criteria. It is felt that the workshop has perhaps most contributed in this area through the vigorous exchanges between representatives of different “schools” and the confrontation with the industrial state of the art.

#### Scientific Programme: Modelling and Simulation

Even though a rigorous theory of turbulence is missing, even for the simplest flows, there is a continuing need



Pairings of secondary vortices in a spatially-growing mixing layer in Large-Eddy Simulation (P Comte, Eur J Mech B/Fluids, 17, 615-637, 1998)

to predict properties of turbulent flow for use in the industrial design process. It has long been recognised that the turbulence model is one of the most critical items in the application of computational fluid dynamics (CFD) software packages within industry. Examples of applications where turbulence has a critical influence were presented by industrial participants in the programme. These include prediction of the drag on an aircraft wing, design of a combustion chamber in a jet engine, safety engineering in nuclear reactors’ cooling vessels, turbulent combustion and atmospheric dispersion of pollutants.

Over the last century engineers have developed an array of methods to deal with turbulent flow based on experiments and some limited insight into supposedly universal aspects of turbulent flow, an example of which is the semi-logarithmic law of the wall which approximates the mean flow near a solid surface. Over the last 30 years these semi-empirical methods have been increasingly supplemented with calculations of the time averaged field equations of fluid flow. Due to the averaging, these equations contain more variables than equations and the problem of turbulence closure in this sense is to devise additional model equations that represent the turbulence to some desired level of accuracy.

By far the most popular closures used in CFD codes are the so-called two-equation methods where the required eddy viscosity is represented by two further quantities, for example (in the *k-ε* model) the turbulence kinetic energy and dissipation rate, for which additional transport equations are formed. These methods are numerically robust and have constants that are tuned to predict certain canonical flows. Insight into the applicability of such methods has come from second moment closures where transport equations are written for all the Reynolds stresses. As an example these equations contain pressure-strain rate terms which

amongst other effects need to model the inherent non locality of turbulence. Near a wall these terms contribute a pressure reflection effect. Recent modelling has included the elliptic relaxation method which is one of the first models to include some limited non-locality, and has also been applied in a reduced three-equation model. An alternative simplification of the full second moment closure can be made when the diffusive terms cancel equivalent terms in the turbulence kinetic energy equation. This leads to non linear algebraic equations for the Reynolds stresses, which contain much of the modelling capability of the second moment closure. In devising models, some use may be made of a concept of realisability, which ensures that models may not predict certain kinds of unphysical results, such as negative energy. It is generally accepted that for some problems, such as buoyancy-driven flows, the full second moment treatment is required, whereas for some weakly distorted boundary-layer problems the simpler two-equation models are adequate. Practical experience for model problems is being gathered from collaborative testing programmes. What is not at all clear is how to specify from first principles when a certain model may be expected to work, and when not. This difficulty is being addressed by the development of a guideline document (see *Conclusion* below).

There was lively debate during the programme on the future role of large-eddy simulations (LES) for practical calculations of turbulent flow. Simulations of turbulence are made possible by advances in computer performance. In direct numerical simulations (DNS) all spatial and temporal scales of turbulence are computed and the databases from such simulations effectively provide solutions of the governing equations for use in understanding turbulence and validating models. Model validation proceeds either *a priori*, by testing each term in the model equation against its exact counterpart, or else *a posteriori*, by comparing simulation results with model predictions. The restriction on DNS is that the cost increases dramatically with Reynolds number, putting most practical applications beyond reach for foreseeable developments in computer hardware. LES combines a numerical simulation of the large scales of turbulence with a model for the small scales, a simple rationale being that the small scales may be more universal, and hence possible to model more generally, whereas the large scales will always be problem dependent. If one tries to simulate, rather than model, the small scales of turbulence near a wall, the LES method is also limited by Reynolds number. Nevertheless simulations of flow around bluff bodies at Reynolds numbers comparable to traditional laboratory studies have demonstrated the feasibility of the methods, and there are programmes

under way to compute, for example, the complete flow in a gas turbine combustor using LES. Such progress has led to a view from some quarters that in the not too distant future all predictions of turbulence will be made using LES, whilst others have pointed out that the invention of the car hasn't made the bicycle obsolete, and that traditional methods will continue to have their niche. The feasibility of practical LES calculations has led to detailed study in recent years of the various options for modelling. Most practitioners have by now moved from simple eddy viscosity models to dynamic procedures involving filtering operations on the computed flowfield. A new approach is almost entirely algorithmic, where the simulated scales are extrapolated to provide the prediction of the small scales to be modelled. Various mixed models, combining these approaches are also proposed. The whole area of small-scale modelling in LES is one in which the partial theories of turbulence, developed over the past thirty years may be profitably applied.

#### Intermittency

The issues addressed at the Symposium on Intermittency In Turbulent Flows and Other Dynamical Systems were a good reflection of the concerns and discussions at the INI before and after the Symposium. Intermittency in some form or another is a feature of non-linear ODEs and PDEs. ODEs were effectively the common focus of the studies by Lumley and Mullin. Lumley discussed the intermittent production of turbulence in the turbulent boundary layer's wall region which is dominated by a few large-scale coherent structures that break down intermittently. A Proper Orthogonal Decomposition of the Navier-Stokes equation leads to a system of coupled nonlinear ODEs which can be used to predict breakdown of structures and thereby act to reduce drag on the wall. Mullin's intervention concerned low-dimensional chaos and temporal intermittency found in Taylor-Couette and



Fritz Busse and Tony Leonard at the *Intermittency* Symposium

various other flows and claimed that it is not possible to reduce completely these dynamics to a low-order set of ODEs. The rest of the Symposium was on internal intermittency in PDEs and turbulence experiments.

The main questions asked were:

- How can we relate scaling exponents of structure functions to near-singular flow structure (*eg* vortex tubes but also other straining structures)?
- Is the near-singular flow structure an imprint of finite-time singularities of the Euler equations assuming they exist? If they exist, are they stable (Constantin)?

Ohkitani proved the existence of finite-time singularities in the inviscid Burgers equation without use of the Hopf-Cole solution and applied his method to the Euler equations with a Taylor-Green vortex initial condition to show that if a finite-time singularity exists it cannot be too weak. A condition for the non-existence of finite-time singularities of the Navier-Stokes equation was derived by Doering and Gibbon at the INI during the programme. Other PDEs that have been discussed for their intermittency properties during this Symposium are the advection-diffusion equation for scalar fields (Gawedski, Vassilicos) and the advection-stretching-diffusion equation for magnetic fields (Falkovich). Frisch showed that the probability distribution functions of velocity gradients generated by the Burgers equation has very broad skirts which obey an asymptotic  $-7/2$  power law.

Experiments by Ciliberto, Sreenivasan, Tsinober and Vassilicos generated doubts on whether structure functions have well-defined power-law scalings even using very high Reynolds number experiments in the atmosphere. Mean shear seems to influence structure functions, and measurements of structure functions conditionally on high values of turbulent velocity fluctuations revealed a significant correlation between small and large scales. It may be that longitudinal structure functions, which have focused research interest since the seminal works of Kolmogorov, are not the most appropriate tools to study intermittency and scalings. In particular they are not very instructive as to the spatio-temporal flow structure of the turbulence. It is for this reason that an entire battery of new ideas, concepts and methods were presented and discussed at this Symposium. The oldest of these new approaches are not more than 20 years old, and the most recent date from the second half of the 1990s: they include wavelets, extended self-similarity, numerical vortex tube visualisation techniques, transversal and inverted structure functions, multipoint correlators and geometrical statistics (Constantin, Tsinober).

Arneodo showed how wavelets naturally generalise velocity increments, and by applying his wavelet method to turbulence one-point measurements he was able to conclude that if the turbulence is a multiplicative cascading process (which it may well not be) then this process is not self-similar. The wavelet transform was also applied to energy transfer and spectral properties of the Burgers equation by Brasseur. Van der Water's experimental evidence showed that power-law scalings are better defined for transverse than they are for longitudinal structure functions, and that transverse scaling exponents are smaller than the Kolmogorov predictions. Vulpiani introduced the study of the statistics of separations across which the velocity difference has a certain value. These statistics are called inverted structure functions, and they give improved results for Richardson's turbulent diffusion law. Finally, Pumir and Shraiman studied multipoint correlators and tetrad dynamics: moving from two-point to multi-point statistics seems to be a good way to probe more of the turbulence spatial flow structure.

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## Output and Achievements

The Research Programme was greatly beneficial to the participants, both those in residence and those who attended the seminars, symposia and workshops. People were given an opportunity of working closely with each other through the medium of the Research Programme and many future collaborations were initiated as a result of this process. Although it is always difficult to identify specific scientific and technical achievements, it is important to try to do so in order that the more detailed benefits of the Research Programme can be assessed. Such specific examples of achievements are as follows:

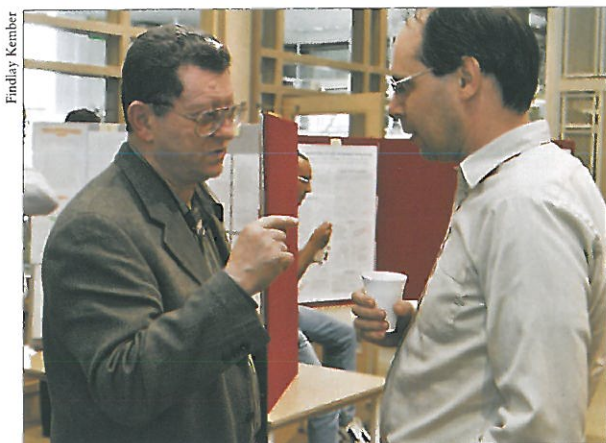
S Tanveer reported that Kolmogorov's celebrated  $-4/5$  law can be obtained without Kolmogorov's assumption of local isotropy. In fact, it is important to note that a significant shift from studies of homogeneous isotropic turbulence to studies of non-homogeneous and/or non-isotropic turbulence by theoreticians and mathematicians was evidenced during the Programme.

During the programme, K Ohkitani and J Gibbon carried out pseudo-spectral computations of an Euler flow starting from a simple smooth initial condition and leading to what may be a breakdown in finite time. Moreover, they found that this apparent singularity persists in the Navier-Stokes case.

In response to discussions during the programme D McComb modified his Renormalization Group

Theory approach to drop the assumption that probability density functions of velocity differences have a symmetric shape about their mean.

A Tsinober produced a significant advance in the relationship between statistics and structure in turbulence.



Arkady Tsinober and Neil Sandham

A number of interesting developments in large-eddy simulation were considered by participants in the programme. S Sarkar provided a rationale for mixed models that have been found previously to give good performance in several practical calculations. D McComb worked on an operational method for controlling the behaviour of high-wavenumbers in numerical simulation. B Geurts and A Leonard wrote a paper on the issue of whether LES was ready for practical calculations yet. The paper debates many of the issues discussed during the programme, including filtering, commutation errors, de-convolution methods and mixed models, and concludes with a set of guidelines for use of current methods. These recognise the fundamental limitations of current techniques and should provide a useful validation strategy for users of the methods. D Thomson and R Kerr provided a cross reference between engineering applications of LES and meteorological applications.

C Doering and J Gibbon collaborated in identifying a condition for the non-existence of finite-time singularities of the Navier-Stokes equations.

G Eyink produced a new analysis of the relationship between singularities and the  $-5/3$  spectrum.

C Thompson and G Eyink wrote a joint paper on late-stage turbulence decay.

T Lundgren found a new asymptotic solution to the Navier-Stokes equation which has a  $-5/3$  energy spectrum without time averaging.

As a direct result of interactions in the Research Programme, one of the companies made major changes in its strategy for the prediction of natural convection systems.

Useful progress was being made on mathematical analysis of turbulence models, and analysis leading to new models. R Maneau presented new work carried out with P Durbin's idea of elliptic relaxation. B Launder and T Craft showed practical benefits of introducing concepts based on realisability into second-moment closures by ensuring that a two-component limit of turbulence anisotropy was satisfied. T Gatski showed the way models could be more rigorously constructed by starting with homogeneous turbulence and adding complexity, with continuous validation against DNS and experiment.

J Ferguson of Schlumberger made a presentation on what is believed to be the first applications of LES to two-phase dispersed flows.

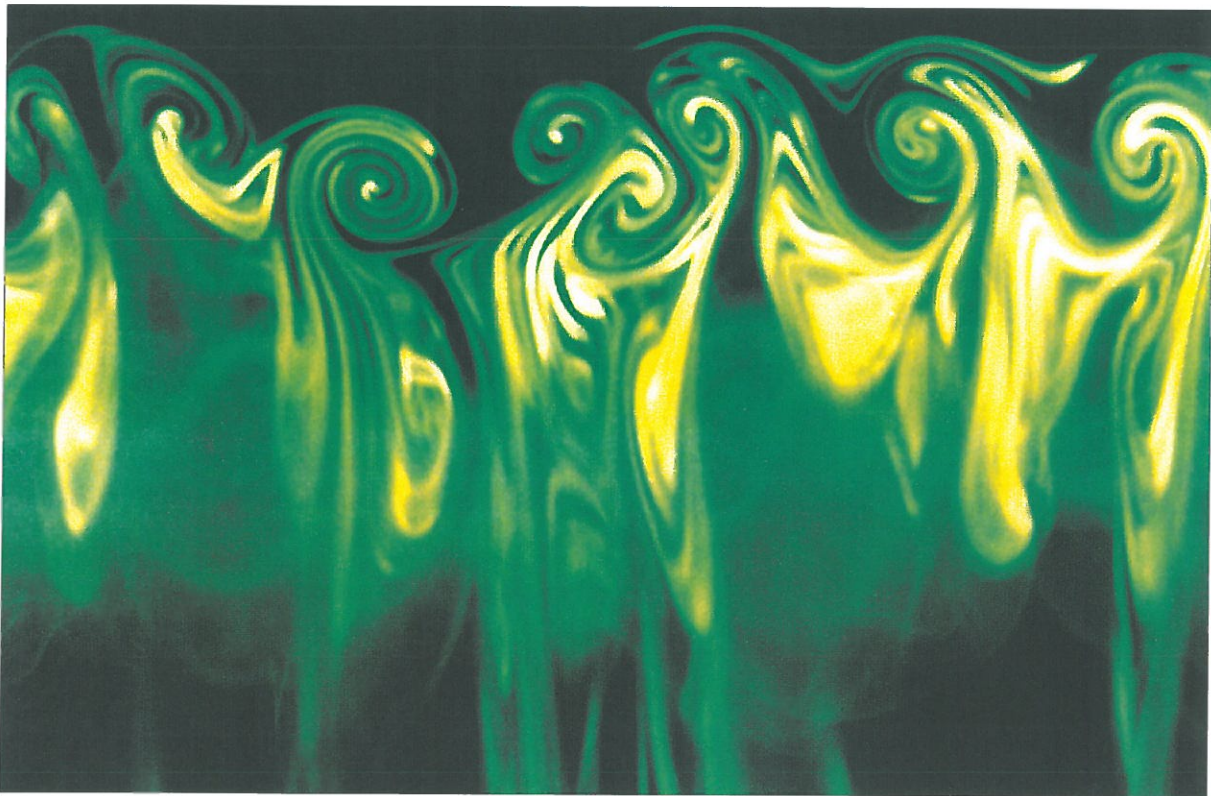
The lagrangian view of turbulence was studied by A Pumir using a new method of tetrad dynamics. Collections of four points are followed in time and a tensor of velocity differences is formed. Preliminary results show some departures from expected scalings.

C Barenghi had useful interactions with B Geurts on the knottiness of the vortex tangle in superfluid turbulence. It appears that previous work on polymers can be carried over to this problem.

D McComb and M Oberlack began a collaboration to write a paper on the application of Galilean invariance principles in turbulence.

Core dynamics, an instability of vortex tubes that can lead to transition in the mixing layer without vortex pairing, was put forward as a cascade mechanism by F Hussain. S Le Dizès demonstrated that core dynamics could be considered as one example of a wider range of problems of elliptic instability and C Cambon noted the connections with rapid distortion theory of homogeneous turbulence. CHK Williamson was able to illustrate the phenomena with beautiful photographs from experiments (see opposite).

Vortex structure identification remains a complex issue but progress towards a common definition is being made using analysis based on the pressure Hessian.



From Leweke, T and Williamson, CHK *Cooperative elliptic instability of a vortex pair*, Journal of Fluid Mechanics 360, 85-119

F Hussain proposed a threshold amplitude of the second eigenvalue of an approximation to the pressure Hessian, including only the strain and rotation rate tensors. S Kida prefers a method with no arbitrary choice of threshold, based on choosing a plane perpendicular to the axis of a vortex and then checking a discriminant in that plane. The resulting vortex 'skeleton' can then be analysed.

The problem of mean velocity profile near a solid wall has certainly not been solved to any general satisfaction but an achievement of the programme has been to bring the different approaches to a much wider audience, with the ideas subjected to extensive discussion. W George presented similarity approaches which give a semi-logarithmic law for boundary layers and an algebraic law for boundary layers. K Sreenivasan investigated multiple layers, leading to two semi-logarithmic laws with the possibility of a critical layer in-between. M Oberlack showed how the possible forms of mean profile are related to the successive breaking of symmetries in near-wall turbulence. S Nazarenko worked on a new derivation of the semi-logarithmic law based on a feedback loop using rapid distortion theory.

There was some detailed work on turbulence mechanisms near a solid boundary. D Martinand and

P Monkewitz presented a new dynamical system model of near-wall turbulence that provided a realistic model of the interplay between streaks, rolls, instability and mean flow modification. N Sandham verified streak stability calculations with F Hussain and J Jimenez, and in a new collaboration with F Hussain developed a streak-education algorithm to determine typical streak amplitudes from numerical simulation. A new collaboration between N Sandham and A Tsinober was begun to analyse enstrophy and strain rate budgets.

A new view on the structure of turbulent boundary layer at high Reynolds number was developed during the programme by J Hunt and J Morrison. They consider the dynamics to be controlled by outer-layer motions impinging on the wall. By contrast J Jimenez presented work in which all outer-layer motions had been filtered out by means of numerical experiments, yet the inner-layer still exhibited turbulent behaviour. Whether the two mechanisms can exist side by side at high Reynolds number is a question for future research.

Flow control applications of research on structures were stressed by F Hussain and J Morrison. The utility of minimal channel simulations to test control theories is now in some doubt after simulation results presented by J Lumley. As the number of active modes increased the flow became less amenable to control.

There was much support during the programme for new experiments, especially to clarify turbulence behaviour at high Reynolds number. A Tsinober presented new results from measurements of the atmospheric boundary layer using advanced instrumentation whereas P Tabeling was using a stirred tank of liquid helium to study scalings over a wide range of Reynolds number. A Perry described the features of boundary-layer turbulence that were Reynolds number dependent and how wall structural similarity methods could be applied. F Nieuwstadt presented plans for a new pressurised facility to study high Reynolds number boundary layers and address some of the issues. Given the increasing capabilities of numerical simulation at lower Reynolds numbers, it was agreed in discussion that the most useful experiments in the future would be those that could address the largest ranges of Reynolds numbers, and similarly for other non-dimensional parameters.

### *Outcome in Books and Documents*

It is important, of course, to maintain records of the outcome and achievements of the Research Programme. The following books are being published, based on the various Workshops and Symposia:

**Turbulence Structure and Vortex Dynamics** (Edited by JCR Hunt and JC Vassilicos). Being published by Cambridge University Press in the Autumn of 1999.

**Closure Strategies** (Edited by BE Launder and ND Sandham). Being published by Cambridge University Press in early 2000.

**Direct Numerical Simulation (DNS) and Large Eddy Simulation (LES)** (Edited by P Voke, L Kleiser and ND Sandham). Being published by Kluwer in late 1999.

**Intermittency** (Edited by JC Vassilicos). Being published by Cambridge University Press in early 2000.

In addition to these more formal publications, it is noted that:

- Regular seminars and discussion sessions were held throughout the duration of the Research Programme. Copies of the transparencies etc produced for these presentations have been deposited in the Isaac Newton Institute Library.
- The material presented at the Workshop on Future Strategies (29th-30th June 1999) contains a wealth of information about the latest status in various areas and about industrial requirements. Copies of the presentations at this Workshop have been produced in bound form by the Institute and distributed to all participants. They are also available for reference in the INI Library.

### *Conclusion*

The Research Programme on Turbulence provided a unique opportunity to review and examine this field. A wealth of new information was presented and discussed. Future strategies for development in the area were reviewed and agreed and two major reports are being prepared as follows:

- A paper for the Journal of Fluid Mechanics co-authored by the Chairman of the Scientific Advisory Committee and the Organisers where a broad review on current turbulence research is given on the basis of the six-month programme.
- A guidance document on closure models is being prepared by JCR Hunt which will provide a "road map" for users of such closure models. The choice of an appropriate closure model is strongly connected to the particular application. There are no universal models!
- A report is in preparation which will deal with the main areas of industrial and environmental applications, digesting all the material arising from the Research Programme, giving a state of the art description and recommendations based on current knowledge. Gaps will be identified and strategies for addressing them discussed. This report will be financed from the funding from the industrial participants and it will be completed by around the end of 1999.

All in all, it can be claimed that the Research Programme on Turbulence allowed a realistic view to be taken on the current state of the field. Central to many of the developments is the critical assessment of universality; quantitative aspects of scalings appear non-universal and other qualitative aspects relating to flow structure and geometrical statistics may well be universal. Much effort is focused on the relation between spatio-temporal flow structure and turbulence statistics and on new kinematics for the description of turbulent flows. Although DNS is making important contributions to fundamental understanding, it seems very likely that it will be many years yet before even LES can be realistically applied to the high Reynolds number, complex geometry situations found in industry. Thus, there is a need to use and develop new modelling approaches and also perhaps new closures which necessarily have to be based on new experiments. The need for good and innovative experiments motivated by existing and new turbulence concepts and theory, and the need for new modelling approaches taking full account of new findings from experiments and from numerical simulations (DNS and LES) are still paramount for the immediate future.

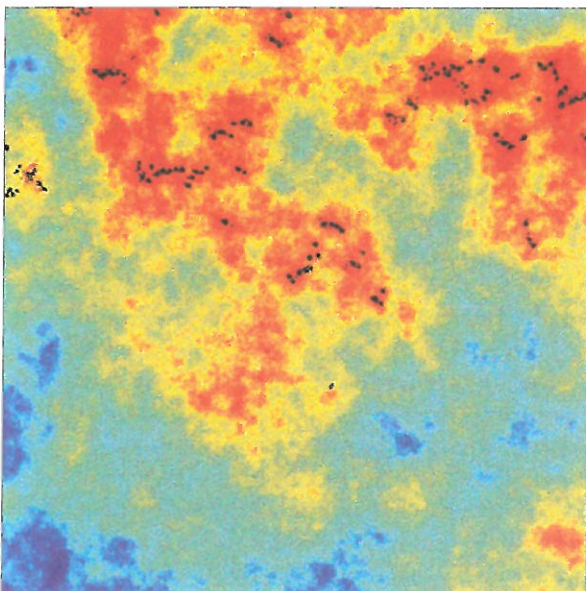
# Mathematics and Applications of Fractals (January to April 1999)

Report from the Organisers: RC Ball (Warwick);  
KJ Falconer (St Andrews)

## *Scientific Background and Objectives*

Throughout this century mathematicians have studied the sets that are now known as 'Fractals'. An enormous body of theory, 'Geometric measure theory', was developed to analyse geometric properties of sets and measures of a very general form, though at the time these were thought of as mathematical curiosities in their own right, rather than with a view to modelling natural phenomena. In the 1970s, partly as a result of the advent of fast computation, it was realised that such sets could provide realistic representations of physical phenomena and that this body of mathematical theory ought to have useful applications. Moreover scientists came to appreciate how some very rich structures (and subsequently processes upon them) could be described semi-quantitatively in terms of statistical scale invariance. This suggested self-organisation in the mechanisms which created the structures, an idea familiar from the theory of critical phenomena, which thereby became applicable to a very wide range of problems, notably in systems far from equilibrium. In the process fractal ideas not only provided the basis for understanding 'new' problems like aggregation and growth, but have also led to 'old' phenomena such as Brownian motion and intermittency being reinterpreted

This led to an explosion of activity in developing the mathematics of fractals and in applying them across



Contour plot of a Brownian surface used in studying how the fractality of a surface is reflected in the fractality of its horizon. The highest points of north-south sections are marked.

science and beyond. Nevertheless, on the mathematical side, activity was concentrated where rigorous work was tractable, in particular on 'static' problems such as the calculation of dimensions in idealised instances. On the scientific side much of the work was merely 'fractal-spotting' which did not deserve to impress the mathematical community, proceeding too rapidly for contributions concerned with mathematical rigour to have much impact.

About 10 years ago a further concept came to the fore, namely that of multifractal measures, which gave a model for different moments scaling with non-trivially different powers. The development of multifractals has also been marked by a gulf between the mathematics and the physical applications.

In the last few years developments have ranged across the whole spectrum of mathematics and science. For example, mathematicians have started to address problems of a more 'dynamic' nature relating to physical problems, (albeit in idealised models), such as diffusions, PDEs and harmonic measures on fractals and on domains with fractal boundary. New mathematical techniques have recently been introduced into the study of fractals and multifractals, for example tangent measures and renewal theory methods. Multifractal theory has started to be placed on a formal mathematical (*ie* measure theoretic) basis, and progress is being made towards a rigorous explanation of observed phenomena such as 'negative dimension'. Measures of fractality other than dimension are being introduced, such as new generalisations of lacunarity. Scaling terms with complex exponents have been observed in applications such as stress analysis for scale invariant structures; such exponents have also been noticed in some mathematical descriptions. Quite rich but certainly non-rigorous arguments have been developed by physicists for the self-consistency of multifractal growth, and the apparent variation in dimension across aggregation clusters is being addressed. The distribution of galaxies in space and its time development has progressed from a confrontation between fractal speculation and uniform density assumptions to a more serious discussion of cross-over length scales in increasingly rich data sets; this is helped by recent data which reaches much further out in distance.

A major aim of the Programme was to bring together mathematicians and physicists, so as to increase awareness by mathematicians of applications requiring mathematical development and by scientists of what mathematics is available. A number of areas were identified as particularly appropriate and timely for development.

These included the mathematical development of useful 'dynamic' fractal and multifractal models. In particular the general theory of differential equations on fractal domains or domains with fractal boundaries, aggregation models, *etc* needed to be advanced with an eye to the requirements of applications. The definition of differential operators such as the Laplacian on fractals should be extended to a more all-embracing definition that might improve our appreciation of relations between exponents such as the walk dimension, spectral dimension and the resistivity-distance exponent.

The characterisation and measurement of fractal structures (and their interpretation) needed to be developed. Dimension alone is inadequate for quantifying fractals, and generalisations of lacunarity, and classification of fractals under Liouville equivalence are needed. In particular, descriptions that might relate to the mechanism by which the fractal object or measure was generated are highly desirable.

Multifractal analysis has recently developed in many directions, with diverse applications and a bulk of mathematical theory available. The various strands of the subject should be brought together and awareness of the different facets of the subject increased.

Geometric measure theory has provided the mathematical foundation of the subject for many years, and the techniques available should be reviewed.

Mathematically based protocols are needed to identify that a structure is fractal, as is an analysis of the extent to which the geometry of fractals defined 'in the limit' carry over to a finite range of scales. Similarly, the information that can be usefully measured from a single realisation of a statistical fractal should be addressed.

The inheritance from critical phenomena and the Renormalisation Group could be ripe for pursuing. Although a major part of the historical background to fractals in physics, they have not been much developed mathematically in the fractal context.

The distribution of galaxies in space and how it developed over time has, with the rapid increase of available data, reached the stage of facing reconciliation or developing into extraordinary controversy.

The theory of growth processes and in particular DLA (Diffusion Limited Aggregation) has not advanced significantly for some years. It may be time to overcome some of the sticking points in this area.



Benoit Mandelbrot, Kenneth Falconer and Robin Ball

## Organisation

The overall planning was undertaken by Robin Ball and Kenneth Falconer, with planning help from Martin Barlow and assistance with seminar organisation from Jacques Levy-Vehel and Ben Hambly.

Apart from the main workshops, the Programme generally revolved around two formal seminars each Tuesday afternoon, and an informal discussion, generally led by two participants, on Thursday mornings. In addition, a variety of talks were contributed at other times, and open working discussions on particular topics were arranged on an ad hoc basis.

Two seminars in the Newton Institute Seminar series were presented by programme members: B Duplantier, *Conformal invariance and multifractality* and M Barlow, *Random walks and some fractal graphs*, and B Mandelbrot and K Falconer gave public lectures to packed houses during the national Science, Engineering and Technology Week.

The staff of the Isaac Newton Institute provided tremendous help to organisers and participants in many different ways, and were praised by many participants for their professional but friendly support.

## Participation

Altogether the Programme involved about 40 long-term participants, 70 short-term participants, 8 affiliated members with many others taking part in the workshops. Several talks attracted mathematicians from elsewhere in Cambridge and Britain and from the parallel *Turbulence* Programme. Conversely, many Programme members visited other Cambridge departments and British universities to give talks and take part in discussions. Feedback suggests that the



Programme succeeded in stimulating interaction and collaborations between participants, including between those with widely-differing scientific backgrounds.

## Workshops

### EC Summer School: Multifractals - Mathematics and Applications

Organisers: KJ Falconer (St Andrews), RC Ball (Warwick), L Olsen (St Andrews)

This School was held at the beginning of the Programme, from 4-8 January 1999. The 70 participants had backgrounds from pure and applied mathematics, physics, engineering and computer science and came mainly from EU countries.

The School brought together mathematicians and physicists interested in multifractals and their applications and stimulated exchanges of ideas between participants with differing backgrounds. The week began with some introductory presentations on multifractal theory and then the main lectures typically consisted of a general exposition of a topic leading to ideas at the frontiers of research. Topics covered included geometric theory; negative dimensions; calculation and interpretation of multifractal spectra in specific cases such as conformal systems, self-affine sets and Brownian-type processes; multifractal properties of signal processes and wavelet applications; multifractal time; growth models, especially DLA (diffusion limited aggregation); pattern forming systems; multifractal properties of harmonic measures on percolation clusters, Brownian boundaries, *etc*; conformal methods.

A book of survey papers on multifractals, based on some of the presentations, is in preparation. The main lecturers were: R Ball (Warwick), B Duplantier (Saclay/Inst H Poincare), K Falconer (St Andrews), TC Halsey (Exxon), M Hastings (MIT), S Jaffard (Paris), J Levy-Vehel (INRIA), B Mandelbrot (Yale), R Mauldin (North Texas), L Olsen (St Andrews), N Patzschke (Jena), I Procaccia (Weizmann Inst), R Riedi (Rice), SJ Taylor (Sussex), C Tricot (Clermont II).

### EU Fractals Network Meeting

Organisers: R Ball (Warwick), L Pietronero (Rome)

This two-day meeting, held on 12-13 February 1999, was organised as part of the EU Network on Fractals that is running from October 1997 to September 2000, with the lectures open to all. The meeting consisted of short talks by members of the 12 Network teams from institutions across Europe on work in progress and open problems.

The emphasis of the meeting was on physical aspects of fractals and their applications. Topics covered included lacunarity; galaxy distributions; fractal growth; self organisation; fracture; earthquakes and landscapes; granular; dynamics; economics and time series.

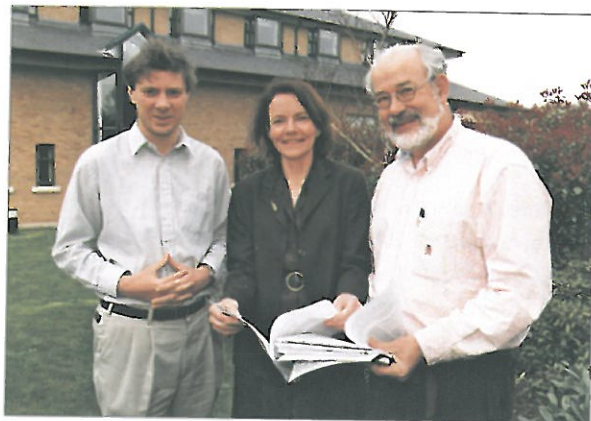
The meeting attracted about 45 participants.

### Spitalfields Day on Geometric Measure Theory

Organiser: K Falconer

This one-day meeting on 5 March 1999 was organised as a 'Spitalfields Day' supported by the London Mathematical Society. The 50 participants included many research students, particularly from UK.

The four lectures were given by G David (Orsay), J Harrison (Berkeley), P Mattila (Jyvaskyla) and D Preiss (University College London) and covered topics including rectifiability, Lipschitz maps, singular integrals, quasi-minimal sets and bounded currents.



Martin Barlow, Jenny Harrison and Jens Feder

### Workshop on Differential Equations and Physics on Fractals

Organisers: M Barlow (Vancouver), R Ball (Warwick), H Herrmann (Paris)

This week-long meeting was held on 22-26 March 1999 and attracted about 70 participants from all parts of the world.

The main lecturers were: A Aharony (Oslo), M Barlow (Vancouver), R Ball (Warwick), R Bass (Connecticut), M van den Berg (Bristol), C Vassilicos (Cambridge), B Derrida (ENS Paris), K Falconer (St Andrews), J Harrison (Berkeley), H Herrmann (ESPCI Paris), R Hilfer (Stuttgart), J Kigami (Kyoto), S Kusuoka (Tokyo), B Mandelbrot (Yale), U Mosco (Rome), L Sander (Michigan), B Sapoval (EP Paris),

R Stinchcombe (Oxford), R Strichartz (Cornell),  
D Vassiliev (Sussex), T Vicsek (Eotvos).

Topics covered included: Laplacian and heat equation on domains with fractal boundary; definition and properties of the Laplacian and other operators on fractal domains; diffusions, heat and wave equations, eigenvalue problems and nonlinear PDEs on fractals; physical processes on fractals; DLA and conformal maps; variational fractals.

## Achievements

The Programme undoubtedly achieved its aim of bringing together scientists from a wide variety of backgrounds and has stimulated many new collaborations. It was satisfying to see a great deal of interaction between those with very different approaches to fractals and their applications. From the reports of participants a great deal of research was done at the Institute, much of which is ongoing. Many papers are already being written, but many more are likely to result from ideas developed during the Programme. Whilst the benefits cannot be judged so soon after the end of the Programme, the following paragraphs outline some areas of activity, of course such a selection is inevitably highly selective.

### Multifractal theory

The Programme started with an EC Summer School on Multifractals and this stimulated discussion and research in the following weeks. A continuing aim is to calculate the multifractal spectrum of classes of measures and functions and look for new features. In this direction, J Barral, B Mandelbrot, J Peyriere and R Riedi analysed ‘multifractal pulses’ and other measures constructed using products which do not depend on a fixed scaling ratio. In particular B Mandelbrot presented recent results on products of

harmonics of periodic functions. A Manning developed a neat approach to give the existence of the generalised dimensions in a way that has computational applications.

On the stochastic side, SJ Taylor, N-R Shieh and Y Peres obtained new results on the multifractal structure of Galton-Watson trees, and SJ Taylor and X Hu gave a multifractal analysis of a general subordinator, that is a monotone increasing process with stationary independent increments. SJ Taylor and N-R Shieh showed that the multifractal formalism breaks down for occupation measures associated with Brownian motion and super-Brownian motion. L Olsen suggested a functional version of the multifractal formalism to restore this breakdown.

Multifractal theory of functions was also advanced. S Jaffard developed a two-parameter approach to detect ‘chirps’ (ie intense local oscillations) as well as Holder exponents; this approach is closely related to wavelet theory. He also progressed his work on lacunary wavelet series. J Levy-Vehel worked on multifractal analysis of time-series, and in particular introduced a definition of dimension of a curve that is computationally tractable.

Considerable interest was shown in multifractal time, which has been used, for example, in modelling fractal time series that occur in finance. A mathematical theory of this was presented by B Mandelbrot and R Riedi.

Multifractal aspects of harmonic measure on percolation clusters and Brownian perimeters were also discussed intensively, see below.

### Geometric measure theory

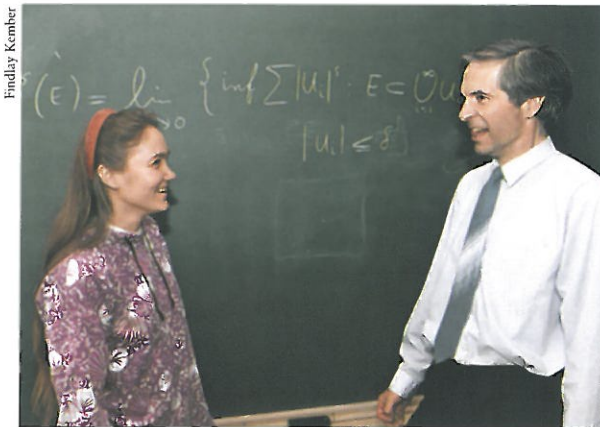
Many look to geometric theory to provide the rigorous foundation of fractal geometry in a general context, going back to the work of A Besicovitch on density, regularity, rectifiability and projections. Thus it was natural for a core of Programme members to concentrate on such topics, particularly around the Spitalfields Day on Geometric Measure theory. J Harrison presented a new approach to geometric aspects of currents which attracted considerable interest. This allows the classical theorems of Stokes, Green, etc to be formulated in a consistent way on fractal objects. This work was developed and extended at the INI and some progress is being made towards unifying this approach with the definitions of the Laplacian on fractals in common use. J Harrison also showed how these techniques could be applied to problems in vision.



Benoit Mandelbrot

Findlay Kember

M Csornyei revived interest in problems on projections of sets from points by obtaining elegant new results in an area that had been dormant since the 1970s.



Mariana Csornyei with Kenneth Falconer

D Preiss presented new results, obtained with B Kircheim and M Chlebik, that answered several long open problems on the existence of Lipschitz functions with finitely many gradients.

The problem of quantifying lacunarity was addressed in various ways. R Ball presented a definition involving 3-point correlations. E Jarvenpaa and M Jarvenpaa considered the notion of porosity of sets and extended the definition to measures.

Further progress was made on understanding the geometry of packing measures, which is markedly less well-behaved than that of Hausdorff measures, the covering analogue. K Falconer, M Jarvenpaa and P Mattila constructed examples demonstrating the lack of stability of the packing measure of sections of sets. K Falconer and C Tricot made progress on the structure of packing measures defined by convolution kernels which occur in certain geometric questions.

M Lapidus stimulated interest in complex dimensions of fractals, embarking on studies of complex dimensions of random fractal strings and Brownian excursions with B Hambly, and on complex dimensions of multifractals with S Jaffard.

K Falconer continued his investigation of the 'horizon problem' - that is the relationship between the fractality of a (random) surface and its horizon. He obtained a complete solution for the case of an isotropic Brownian surface, and the solution for fractional Brownian surfaces assuming a natural property of the maximum of the corresponding (1-dimensional) fractional Brownian function.

### Partial Differential Equations on Fractals

A workshop on PDEs on Fractals was held at the end of March, and this brought together world experts in the field, many of who stayed on as Programme participants. This area is still young and there are many outstanding problems, but progress was made in several directions at the INI.

M Barlow and T Kumagai studied the short time asymptotic behaviour of the heat equation for a multifractal measure, obtaining surprising results for the spectral behaviour. With B Hambly they realised that their pointwise results fit into the context of multifractal analysis.

M Barlow and R Bass considered divergence operators on fractal domains with large scale structure resembling the Sierpinski carpet, obtaining versions of Moser's elliptic Harnack inequality, which provided an interesting contrast to the parabolic Harnack inequalities.



Ben Hambly and Andrew Laurent

Random recursive fractals are a source of challenging problems. B Hambly and T Kumagai were able to construct a Laplacian and locally regular Dirichlet forms for a large class of such fractals using Schauder's fixed point theorem. B Hambly, Y Peres, J Taylor and Q Liu used ideas from branching processes to obtain a type of multifractal spectrum for the local spectral dimension of such random fractals.

J Kigami and M Lapidus wrote a paper on the volume measure associated with self-similar sets, leading to an expression for the spectral volume of a self-similar set with respect to a trace of some power of the Laplacian.

In discussion with others, J Kigami made considerable progress on properties of heat kernels on self-similar sets, including on the Nash inequality, the continuity

and positivity of the kernel and the continuity of the solution.

A Gangal and K Kolwankar introduced a new kind of differential equation on fractals involving fractional derivatives, generalising the Fokker-Planck equation and diffusion equations.

#### Harmonic measure on fractals

B Duplantier announced some remarkable results on the multifractal spectrum of harmonic measure on planar sets such as percolation clusters, polymers and the external boundary of Brownian paths. Using techniques involving conformal invariance and quantum gravity he obtained an exact formula for the multifractal spectra of such harmonic measures, thus answering many long-standing problems. Whilst at the INI he extended his ideas to Potts clusters and other models. With R Ball and T Halsey he uncovered a symmetry of multifractal spectra corresponding to an invariance under the exchange of interior and exterior domains with respect to certain random fractal frontiers. Numerical work by A Aharony and B Mandelbrot has corroborated these predictions.

#### Growth models and DLA

DLA (Diffusion Limited Aggregation) is a growth model for pattern-forming systems such as viscous fingering, colloidal aggregation and electrodeposition. The Programme revived interest in DLA theory which had developed little in the previous 15 years.

B Davidovitch announced numerical results showing that the fluctuations in the radius of a DLA cluster are anomalously small compared to the typical fluctuations of fractal and multifractal properties of DLA. During the programme R Ball, B Davidovitch, L Sander and T Halsey developed theoretical arguments to explain this phenomenon. R Ball, M Hastings and T Halsey worked on theoretical approaches based on a fugacity expansion on tip-splitting events which will allow better computation of certain DLA properties.

C Bandt presented recent work on the Bak-Sneppen model of self-organised criticality, and his discussions at INI led to rigorous derivations of geometrical properties of the model.

R Stinchcombe made progress on scaling collective particle systems with stochastic dynamics via their quantum spin representation.

#### Other physical models

J Feder, with input from A Aharony and R Stinchcombe, made steady progress on fractal models for friction, an area which is still not fully understood.



Raphael Blumenfeld, Bernard Sapoval and Marcel Filoche

M Filoche and B Sapoval continued work on the question of linear transfer across irregular or fractal interfaces when they are random or deterministic, a question that is important to the understanding of porous electrodes in batteries.

#### Galaxies

R Ball, G Caldarelli, B Mandelbrot and L Pietronero discussed the question of galaxy distribution in the light of recently available data. In particular progress was made in the relationship of lacunarity to galaxy distribution.

## Special Events: Further details

### *Colloquium of Mathematical Geophysics 1998 'The Dynamic Earth'*

12–17 July 1998

Report from the Organiser, HE Huppert (DAMTP)

This meeting was one of a series which have been organised every two years since the early 1960s on mathematical aspects of geophysics. The meeting has traditionally attracted research workers from all over the world and has been viewed as an important occasion for the dissemination of the latest research in mathematical geophysics. The 1998 Colloquium, which was held at the Isaac Newton Institute for Mathematical Sciences in Cambridge from 12 to 17 July, was no exception.

Ninety-five participants, both academics and scientific researchers, came from numerous different countries to attend. The lectures and posters were grouped in eight themes: *Geophysical Inverse Theory and Image Reconstruction; Atmospheric Dynamics and Secular Variations; Small Scale Processes in the Mantle; Large Scale Mantle Convection; Ocean Circulation, Global Climate, Heat Transfer and Turbulence; Modern Numerical Investigations; Magnetic Field Generation and Core Dynamics; Crustal Processes: Deformation, Friction and Rupture.*

Each theme was considered in a special session which commenced with an overall review lecture by an eminent worker in the field. There then followed four or five shorter contributions of latest research findings. A very successful dinner attended by the delegates, in addition to a number of Heads of Departments and the scientific leaders at Schlumberger Cambridge Research, was held on the Thursday evening. Many of the attendants expressed their delight at the conference, and a number, who had attended the conferences for many years, suggested that the splitting up of the sessions and the facilities of the Isaac Newton Institute made it one of the best conferences of the series.

HE Huppert

### *Critical Data and Statistical Uncertainties: The Statistics of TSEs, 13–14 November 1998*

Speakers and titles were as follows:

- P Lachmann  
*Introduction and Overview*
- C Donnelly  
*BSE backcalculation estimates as a basis for vCJD risk assessment*
- J Kent  
*Under-reporting - evidence and estimates*
- C Bostock  
*Titration curves and incubation periods for the estimation of infectious dose*
- J Huillard  
*Incubation period of iatrogenic Creutzfeld-Jakob in French human growth hormone recipients*
- J Collinge  
*What kuru and animal experiments tell us with relevance to incubation period for TSEs in man*
- P Farrington  
*Current trends in nvCJD incidence*
- S Cousens  
*How occupational exposure is being monitored: risks and precautions*
- S Gore  
*How is maternal transition being monitored  
Critical data on dietary consumption*
- A Aguzzi  
*Neuroimmunology of prion diseases*
- P Comer  
*The risk from vCJD infectivity in blood and blood products*
- J Cooper  
*Calendar year uncertainty in dietary exposure incidence to bovine ID50s: by gender and age*
- S Cousens  
*Uncertainty in vCJD projections - nature revisited*
- J Collinge  
*Tonsil screening to establish vCJD prevalence*
- A Ghani  
*When can we come off the fence - with and without anonymous testing*

## *Mathematics of Risk Management,* 2–3 October 1998

Speakers and titles were as follows:

- RN Gormo (Barclays Corporate Banking)  
*Financial engineering: The architecture and pricing of structured derivative products;*
- P Embrechts (Zürich)  
*Measuring well beyond VaR;*
- M Dempster (Judge Institute, Cambridge)  
*Dynamic risk management of optioned portfolios;*
- P Kupiec (FreddieMac)  
*Stress testing in a value-at-risk framework;*
- R Smith (North Carolina)  
*Extreme values in insurance and finance;*
- E Picoult (Citibank, New York)  
*Issues in the quantification of risks of trading;*
- W Perraudin (Bank of England and Birkbeck College, London)  
*Back testing credit risk models;*
- S Srivastava (Carnegie Mellon)  
*Value-at-risk analysis of a leveraged swap*

## Financial and Fundraising

### *Fundraising*

The Institute was successful in fund-raising in 1998/99 from the following organisations:

**ESPRC:** The EPSRC reviewed the Institute's position and decided, at a meeting of Council on 21 April 1999, to renew funding in principle for a further six-year period, *ie* to the end of February 2008, subject to triennial review.

ESPRC also awarded a grant of £20,000 to the Institute for the purpose of displaying posters with a mathematical theme in the trains of the London Underground to mark World Mathematical Year 2000.

**Hewlett-Packard:** HP confirmed funding to the Institute for a further five years from August 1999, at a rate of £115,000 *pa*.

**Newton Trust:** The Trust confirmed the conversion of the loan for £1,000,000 to permanent endowment. In addition, it granted the Institute a further £50,000 *pa* for the next five years, subject to matching funding being raised from other sources.

**LMS:** LMS agreed to extend its funding for a further five years from July 1999, at an increased level of £20,000 *pa*.

**NSF:** Both the *Biomolecular Function and Evolution in the Context of the Genome Project* and the *Nonlinear and Nonstationary Signal Processing* programmes were successful in obtaining funding from the National Science Foundation in the US.

**NATO:** NATO funded an Advanced Study Institute entitled *Genes, Fossils and Behaviour: An Integrated Approach to Human Evolution* from 7 to 17 September 1998 as part of the *Biomolecular Function and Evolution in the Context of the Genome Project* programme.

**EC:** The EC funded four Summer Schools during 1998/99. These were entitled *Bayesian Methods* (within the *Nonlinear and Nonstationary Signal Processing* programme), *Methods for Molecular Phylogenies* (within the *Biomolecular Function and Evolution in the Context of the Genome Project* programme), *Multifractals - Mathematics and Applications* (within the *Mathematics and Applications of Fractals* programme) and *Turbulence Structure and Vortex Dynamics* (within the *Turbulence* programme).

**Programme Funding:** The *Nonlinear and Nonstationary Signal Processing* programme obtained funding from TSUNAMI, BP, Schlumberger, the Bank of England, Barclaycard and the US Navy. In addition, permission was granted for the programme to use 10 copies of S Plus free of the usual licence charge. The *Biomolecular Function and Evolution in the Context of the Genome Project* programme obtained additional funding from the Wellcome Trust, Compugen and Smith Kline Beecham. The *Turbulence* programme, with the active involvement of the Royal Academy of Engineering, obtained additional funding from British Aerospace, British Gas, DERA, Magnox Electric, the Met Office, Rolls Royce, Ove Arup, JRC Ispra and Schlumberger.

**1, 1, 2, 3, 5, 8, 13, 21, 34, 55, 89, ...**  
**Can you spot the pattern?**

**maths counts**

**WORLD MATHEMATICAL YEAR 2000**  
Posters in the London Underground  
Supported by **EPSRC**

**Mathematics of Nature**  
The sequence of numbers on the left is attributed to Leonardo Fibonacci, who used it in the 12th century as a model for the growth of a population of rabbits. It has since been the key to understanding an astonishing array of natural phenomena, including the spiral patterns of sunflower seeds and pine cones.

**The sequence of fractions**  
 $1/2, 2/3, 3/5, 5/8, 8/13, 13/21, 21/34, \dots$  approaches the Golden Ratio, a special number in mathematics, which also plays an important role in art and architecture.

**Nature of Mathematics**  
Isaac Newton Institute for Mathematical Sciences  
<http://www.newton.cam.ac.uk/>  
University of Cambridge, UK  
The Isaac Newton Institute exists to promote Mathematics

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For the Isaac Newton Institute, Cambridge. A. D. Burbanks & S. Moffatt  
Software: John J. Mullan. Text: B. K. Jennings, Ulrike Bruning & A. D. Burbanks

The first in the series of 'Maths in the Underground' posters for WMY2000.

*Financial Report for 1998/99*

Accounts for July 1998 to June 1999 (Year 7)

	Year 6	Year 7
<b>Income</b>		
Grant Income - Revenue	1,382,437	1,325,782
Grant Income - Workshop	217,845	179,280
Donations - Revenue	366	3,526
Donations - Capital	0	340
General Income	48,261	46,999
Housing	7,295	6,231
<b>Total</b>	<b>1,656,204</b>	<b>1,562,158</b>
<b>Expenditure</b>		
Scientific Salaries	322,539	279,388
Scientific Travel and Subsistence	412,831	436,938
Scientific Workshop Expenditure	182,065	139,533
Other Scientific Costs	13,462	20,610
Staff Costs	264,210	293,296
Computing Costs	65,172	36,548
Library Costs	19,785	28,326
Audio-Visual	3,727	1,566
Building - Capital	13,870	1,906
Building - Rent	184,000	190,000
Building - Repair and Maintenance	10,907	12,879
University Overheads	35,564	27,826
Consumables	53,271	49,989
Equipment - Capital	1,232	29,139
Equipment - Repair and Maintenance	5,174	5,360
Publicity	10,389	9,091
Recruitment Costs	1,402	11,125
Miscellaneous	3,324	(113)
Reprovision	80,000	85,000
<b>Total</b>	<b>1,682,924</b>	<b>1,658,407</b>
<b>Income Less Expenditure</b>	<b>(26,720)</b>	<b>(96,249)</b>



## Notes to Accounts

### 1. Grant Income - Revenue

This breaks down as follows:

	Year 6	Year 7
EPSRC/PPARC Salaries	375,113	276,656
EPSRC/PPARC Travel and Subsistence	272,627	246,665
Newton Trust	108,267	62,886
Hewlett-Packard	98,000	98,000
Rothschild	–	20,714
CNRS	38,589	40,549
Rosenbaum	47,269	27,504
Leverhulme	76,231	56,899
Marie Curie	15,002	–
Royal Society	8,444	6,339
LMS	15,000	15,000
Institute of Physics	10,000	7,500
Jesus College	5,000	–
CPS	2,000	2,000
UofC Director's Fund	40,000	40,000
UofC/DAMTP (Staff)	55,947	57,272
UofC Rent	184,000	190,000
BP	–	5,000
Wellcome Trust	–	5,000
British Antarctic Survey	–	40,000
Bank of England	–	2,500
Barclaycard	–	1,500
Schlumberger	–	5,000
US Navy	–	2,960
Compugen	–	4,000
Smith Kline Beecham	–	2,000
RAE	–	95,999
CMG	–	10,040
ERCOFTAC	–	3,800
Met Office	6,500	–
Rolls Royce	5,000	–
British Aerospace	5,000	–
British Airways	5,000	–
Gonville and Caius	1,000	–
Thriplow Trust	6,000	–
ConwayFest	300	–
EU Network Meeting	2,149	–
<b>Total</b>	<b>1,382,438</b>	<b>1,325,782</b>

Only half of the Rosenbaum grant was spent on salary for this year. The remainder has been carried over to Year 8.

### 2. Grant Income - Workshop

This is slightly less than last year's figure because the Institute has only received funding for one NATO conference this year as opposed to two last year.

**3. Donations - Capital**

The Institute has also received a donation of £1,000,000 from the Dill Faulkes Educational Trust for the Gatehouse to the Centre for Mathematical Sciences which is not included in the present figures.

**4. Scientific Salaries**

These are lower than the previous year and will be lower than next year because there were no EPDI attendees at this year's programmes

**5. Other Scientific Costs**

These include costs for the Conference on Mathematical Geophysics, held in July 1998, and costs for meetings on Risk Management and TSEs.

**6. Staff Costs**

These were higher than expected because several members of staff left the Institute in the course of the year and agency staff were used whilst they were being replaced.

**7. Computing Costs**

These are lower than expected because of a loan of equipment by Silicon Graphics.

**8. Library Costs**

These are higher than in previous years because of additional journal subscriptions to replace previous donations, and greater use of the British Library copying facility.

**9. Building - Capital**

Phase II of the Library Gallery was built during this year with money donated in previous years and put aside for building purposes. The cost of the gallery is not therefore included in these figures.

**10. Equipment - Capital**

These costs include the purchase of new colour photocopier, a new staff photocopier and new blinds throughout the building.

**11. Recruitment Costs**

These are high due to several members of staff leaving during this year and also because of the costs of advertising the Hewlett-Packard Senior Research Fellowship.

*Financial Donations (cumulative totals)*

SERC/EPSRC/PPARC	£5803k over 10 years
Isaac Newton Trust*	£2300k over 12 years
NM Rothschild and Sons	£2083k over 10 years
Hewlett-Packard	£1065k over 10 years
Dill Faulkes Educational Trust	£1000k
St John's College	£750k over 5 years
NATO	£529k over 7 years
Cambridge University	£512k over 9 years
Le Centre Nationale de la Recherche Scientifique	£435k over 10 years
European Union	£425k over 8 years
Leverhulme Trust	£375k over 6 years
Rosenbaum Foundation	£330k over 7 years
London Mathematical Society	£217k over 12 years
Gonville and Caius College	£100k
Prudential Corporation plc	£100k over 4 years
Institute of Physics	£68k over 7 years
British Meteorological Office	£64k
Nuffield Foundation	£57k
TSUNAMI	£40k
AFCU (Hamish Maxwell) \$50,000	£32k
AFCU (Anonymous Donation) \$50,000	£32k
Emmanuel College	£30k
Jesus College	£30k over 6 years
Daiwa Anglo-Japanese Foundation	£26k over 2 years
British Aerospace	£25k
Rolls Royce	£25k
Corporate Members (FIN programme)	£22k
British Gas	£20k
DERA	£20k
Magnox Electric	£20k
Rolls Royce	£20k
Thriplow Trust	£18k
Cambridge Philosophical Society	£15k over 10 years
Bank of England	£15k
Applied Probability Trust	£10k over 3 years
Trinity College	£10k
National Environment Research Council	£10k
Unilever	£10k
Schlumberger UK	£12k
Wellcome Trust	£12k
DSM (Netherlands)	£6k
GLOBEC	£6k
BP	£5k
British Airways	£5k
Christ's College	£5k
Harlequin Software	£5k
Compugen	£4k
British Society of Rheology	£3k
JRC Ispra	£3k
Ove Arup	£3k
Agricultural and Food Research Council	£2k
Smith Kline Beecham	£2k

\* The Isaac Newton Trust donated £1,050,000 to the Institute over the first five years of its operation and has now given an endowment of £1,000,000 and a promise of a further £250,000, subject to matching funding being obtained.

### *Donations in Kind*

Computer equipment has been donated by Hewlett-Packard, Sun Microsystems (who have also sold equipment to the Institute at a very substantial discount) and Apple UK. Silicon Graphics have provided equipment on a 'rolling loan' basis. Software has been donated by NAG, Claris and Wolfram Research.

Over 4,000 books and journals have been donated by a large number of publishers and individual members of the mathematical community



Front cover: Short wavelength instability of a vortex pair,  
T Leweke and CHK Williamson (*Turbulence* programme)

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