Institution: The University of Leeds

Unit of Assessment: B10, Mathematical Sciences

a. Overview The unit consists of members of the School of Mathematics, part of the Faculty of Mathematics and Physical Sciences (MAPS). The unit's key research entities are the following research groups; these have overlapping membership and strong interconnections: 1. Algebra, Geometry, and Integrable Systems (**AGIS**); 2**. Logic**; 3. **Analysis**; 4. Astrophysical and Geophysical Fluid Dynamics (**AGFD**); 5. Applied Nonlinear Dynamics (**AND**); 6. Polymers and Industrial Mathematics (**PIM**); 7. Mathematical Biology and Medicine (**MBM**); 8. Probability, Stochastic Modelling, and Financial Mathematics (**PSMFM**); 9. Statistics (**STATS**).

b. Research strategy

In 2009, the unit re-constituted its research groupings, aligning them to strategic goals and to new funding opportunities. An aim was to ensure that each researcher is in a dynamic research environment, and that artificial boundaries between areas are broken down. Examples of the resulting vitality include (showing funding announced/awarded[†], and received[‡], in the REF period):

- in **AGIS** (research awards totalling over £3.5m[†]), Marsh's EPSRC Leadership Fellowship is developing the multi-faceted field of cluster algebras; among other **AGIS** projects, one investigates links between representation theory, statistical mechanics, and topological quantum information, and another combines integrable systems and model theory;
- **Logic**, which has breadth unique in the UK ranging from model theory to mathematical foundations; in the REF period, 22 PhDs completed and ~£3.1m[†] grants awarded;
- the **AGFD** group, in addition to awards of over £3.3m[‡] PPARC/STFC funding in astrophysical fluid dynamics, has expanded towards geophysical fluid dynamics; supported by a new Chair, this new initiative has already led to current awards of ~£1.1m[†] NERC funding;
- expansion in mathematical biology, with **MBM** coordinating 4 large FP7 and BBSRC networks in mathematical immunology, and securing £568k[†] industrial funding since 2008.
- the new **PIM** group, 5 out of 6 of whose members have industrial consultancies/projects, and whose interdisciplinary expertise and industrial links led to 3 of the unit's 6 impact case studies.

The unit is ensuring a long-term future through a series of permanent appointments (16 in the REF period), through successful undergraduate recruitment and new MSc programmes, and through an increasingly diversified research-funding portfolio. Current research funding (awarded or announced) on 31/7/13 is around £11.74m, on grants with 22 different PIs in the unit. It will participate in two EPSRC Centres for Doctoral Training from 1/4/14: *Fluid Dynamics* (with the Leeds Faculty of Engineering and School of Earth and Environment, and 20 industrial partners, with the unit to contribute to the supervision of the majority of the 50 students); and *Soft Matter and Functional Interfaces* (Universities of Durham, Edinburgh, and 4 Schools in Leeds). From 4/11/13 it will belong to a NERC Leeds-York Doctoral Training Partnership in *Environmental Research*.

The unit is among the largest in mathematics in the UK. Its size enables it to undertake leading research across a wide range of the mathematical sciences, along with broad research-led MSc and undergraduate teaching. Its underlying strategy is to build high-quality research groups, each cohesive but with distinctive contributions from each member, and to encourage links between the groups: the research areas should have potential for long-term impact on other parts of mathematics, other disciplines, or external research users. The groups should be large enough to support stimulating seminar programmes and inspiring postgraduate training, give opportunities for collaboration, and support the research development of junior staff and postdocs. Decisions on which areas to develop are founded both on the pursuit of excellence, and on long-term financial viability. All staff are encouraged to contribute to strategic plans, through suggestions and School and research-group meetings. Plans are developed at a broad level by the unit's Strategy Board, Research Committee, and Management Group, and in more detail among research groups.

In RAE2008, the UoAs 20, 21, 22 (Pure Mathematics, Applied Mathematics, Statistics, respectively) expressed goals to develop interactions between groups, and to expand in the following areas: algebraic geometry (building on shared interests in model theory, algebra, geometry, and integrable systems); analysis; logic; medical mathematics (immunology, statistical bioinformatics); polymers. The unit's reorganisation in 2009 formed **AGIS** from three groups, to promote existing collaborations and joint interests; the resulting combination of representation theory, differential geometry, and mathematical physics is unique to Leeds. Two UOA 21 groups were incorporated into **PIM**, in a strategy to extend polymer research and develop links to industry.

The new **MBM** group crystallises plans from the UOA 21 and UOA 22 RAE2008 statements to develop activity in medical mathematics, especially statistical bioinformatics and mathematical immunology. **PSMFM** is also new and blends financial mathematics with stochastic processes. These changes correspond to deeper enrichments of the activities: several research groups have broadened their scope, and there are strong interactions (collaborations, grants, joint seminars, and PhD students) between groups, and also with other units in the university; also, seminar activity (see **§d**) is greatly expanded, with about 6 invited-speaker seminars per week during term.

Since 2008, we have also developed existing strengths in **AGFD** towards geophysical fluid and ocean dynamics, and in **AND** towards complexity science, giving these groups broader areas of application. There have been expansions in statistics towards applied probability and financial mathematics. In line with RAE2008 strategy the unit has made two appointments in Geophysical Fluid Dynamics, including Bokhove to an Academic Leadership Chair; its other permanent appointments include five in **MBM**, **PSMFM** and **STATS**, three in **AND** (related to complexity science), a transfer from Physics to **PIM**, two in **AGIS** and three in **Logic**. One of the **Logic** appointments (Halupczok) also supports the 2008 plans to develop in algebraic geometry. The RAE2008 goals for expanding certain areas have mostly been achieved. The permanent staff numbers are similar to those of 2008, with substantial increase in PhD and postdoctoral numbers.

The unit's strategic plans include the following: to reinforce the cohesion of the **AGIS** group, e.g. with appointments in geometric representation theory and global analysis; to build on the strengths of research in analysis, possibly through an appointment in quantum groups; to expand in multi-phase fluid modelling thereby linking **PIM** and **AGFD**, with applications to environmental science (e.g. atmospheric dynamics, particle transport) and strengthening links to Leeds Earth and Environment (rated 2nd in Research Power in RAE2008); to make a senior appointment in complexity science; to develop research that combines biological modelling and statistics, building on existing links with clinicians; to continue expansion in financial mathematics; and to reinforce the unit's capacity for long-term interactions with industry. These plans build on achievements in the REF period and on goals developed among the research groups, summarised below.

1. Algebra, Geometry, and Integrable Systems (AGIS). (Chalykh, Crawley-Boevey, Fordy, Harland, Houston, Marsh, Martin, Mikhailov, Nijhoff, Parker, Ruijsenaars, Speight, Wood, Yu.) This group brings together a cohesive body of research from different mathematical cultures, and extends plans from RAE2008 to develop links between representation theory, statistical mechanics and integrable systems. Research in the group is concentrated on unravelling the rich mathematical structures that are exhibited in representation theory and differential geometry, and their manifestations in exactly solvable and integrable models. These structures often come from, and feed back into, applications in physics. Recent research highlights include: construction of the decomposition matrices of the Brauer algebra over the complex field, using methods inspired by statistical mechanics (a 70-year-old open problem posed by a founding father of modern representation theory); a representation-theoretic interpretation of the Fomin-Zelevinsky quiver mutation rule used to define acyclic cluster algebras, a foundational result subsequently used widely in work on the new representation theory arising from cluster algebras; and the prediction of a new physical regime in multicomponent superconductors, so-called type 1.5 superconductivity, subsequently observed in the laboratory. The group has several strategically significant externally funded collaborations including, for example, an £800k EPSRC grant in the area of topological quantum information (with two Co-Is in the School of Physics), and a £400k EPSRC project in Model Theory, Algebra and Differential Equations which links the group with **Logic**.

2. Logic. (**Cooper, Elwes, Gambino, Halupczok, Macpherson, Rathjen, Schuster, Truss.)** The group, unique among UK logic groups for its breadth, has strengths both on the foundational side of logic (computability theory, proof theory) and in model theory and applications. Plans were expressed in RAE2008 to reinforce these and to develop existing links to other parts of mathematics (e.g. algebra, geometry, combinatorics, integrable systems) and to computer science (CS). Following this strategy, in 2013 Gambino (proof theory) and Halupczok (model theory) joined the group, balancing the departures of Pillay (moved to the USA) and Lewis (moved to LSE). In an EPSRC-funded initiative, the expanded proof theory group is developing proof-theoretic and homotopy-type-theoretic underpinnings of Voevodsky's univalent foundations. Activities in model theory include: around 8 collaborative papers with Hrushovski (Jerusalem) on topics ranging from the model theory of fields with analytic structure to a rich new theory of definable measures; new

connections to CS through a joint project linking model theory, permutation groups, and constraint satisfaction; a new interaction, through a £400k EPSRC grant joint with **AGIS**, on model theory of Painlevé equations; and major joint work of Halupczok (papers to appear), applying model theory and motivic integration to obtain results in prime characteristic on Harish-Chandra characters. The group has coordinated the 11-partner Marie Curie Initial Training Network *MALOA*.

3. Analysis. (**Daws, Kisil, Partington, C.J. Read, Young.)** The group is prominent in many aspects of functional analysis, operator theory, and complex analysis. Two new directions stand out. Daws is leading a new research impetus in quantum groups, viewed as both operator-algebraic and probabilistic models of non-commutative mathematics. Partington is applying his earlier research to inverse problems for PDEs. He is a consultant to INRIA (a French national research institute), where his work has led to new software for solving extremal problems. Other major recent achievements of the group include far-reaching multivariable generalizations of classical results of Löwner and Nevanlinna, and a body of new structural results on non-self-adjoint operator algebras.

4. Astrophysical and Geophysical Fluid Dynamics (AGFD). (Bokhove, Falle, Griffiths, Hollerbach, Hughes, Jones, Kersalé, Komissarov, Rucklidge, Tobias.) The AGFD group is one of the largest in the world, with research interests in the applications of hydrodynamics, magnetohydrodynamics (MHD), and relativistic MHD to a wide range of astrophysical and geophysical phenomena. The most significant strategic decision has been to broaden the group's research in geophysical fluid dynamics. This is reflected in the appointments of Bokhove and Griffiths, providing new analytical and numerical expertise in oceanography, environmental fluid dynamics and climate science. Since 2008, the group has been awarded funding (see above) of over £4m.The underlying goal of the entire group's research, pursued both analytically and numerically, often utilising high-performance computers, is to identify and understand fundamental physical processes. In astrophysical fluid dynamics this has led to significant breakthroughs in the foundations of dynamo theory, with implications for the Sun and the giant planets; in MHD turbulent transport, with particular emphasis on the solar tachocline; in the role of non-ideal MHD effects in star formation; and in the flow dynamics of magnetised relativistic plasma. In geophysics, progress has been made on the geodynamo and the short-term dynamics of the Earth's magnetic field, in the numerical modelling of ocean tides, of waves in hydraulic and multiphase flows (using novel discontinuous Galerkin finite-element methods), and in the understanding of equatorial instabilities and wave mean-flow interactions in planetary atmospheres.

5. Applied Nonlinear Dynamics (AND). (**Azaele, Dean, Lythe, Mobilia, Niesen, Rucklidge, Sturman, Tobias, Ward.)** This group was strengthened by the appointments of Mobilia, Azaele, and Ward in areas that reflect the group's long-term ambition to develop in the field of complexity science; there are plans for a further, senior, appointment in this area. Modern applications, from granular mixing to quasicrystals to collective human behaviour, drive the group's research in core areas such as pattern formation, ergodic theory, stochastic dynamics, evolutionary game theory, network dynamics, and numerical methods for nonlinear dynamics. As well as partnering an interdisciplinary £820k EPSRC grant using complexity science to inform energy decision-making for cities, and developing connections with **MBM** through mathematical ecology, the group is building contacts with research end-users, e.g., the digital-marketing company Bloom Agency.

6. Polymers and Industrial Mathematics (PIM). (**Evans, Falle, Harlen, Kelmanson, Lesnic, D.J. Read.) PIM** was formed in 2009 by merging two former groups (Polymers and Computational PDEs), together with Evans from Physics, to form a broader group integrating the development of theoretical and numerical techniques, for solving continuum and molecular-level model processes, with industrial applications. Through jointly funded research projects, **PIM** has forged links (underpinning three Impact Cases) with industrial partners in polymer-melt processing, inkjet printing, fire-safety, ultrasound scattering, health and safety, and tomography. **PIM** has: coordinated the Marie Curie ITN *DYNACOP* (and partners the ITN *SUPOLEN* from October 2013, with Read as training coordinator); provided the mathematical modelling component within a £5m EPSRC Programme Grant on Innovation in Industrial Inkjet Printing; and secured several consultancy projects, e.g. on fire-safety standards and CO_2-transportation hazards. **PIM** actively seeks new collaborative projects, both externally, by hosting Knowledge Transfer Workshops, and internally, through joint grants and co-supervised PhD students with other Schools in Engineering and Physical Sciences.

7. Mathematical Biology and Medicine (MBM). (**Azaele, Barber, Delgado-Eckert, Falle, Gilks, Gusnanto, Kent, Lythe, Mardia, Mobilia, Molina-París, Taylor.)** This group was formed in the REF period to combine expertise from Applied Mathematics and Statistics in a wide range of research at the interface of mathematics, medicine, and biology. Its strategy is to develop current research strengths in: evolutionary dynamics and complex systems in life and the behavioural sciences (reinforced by the appointments since 2008 of Azaele and Mobilia); probabilistic methods for gene expression, next-generation sequence data, and proteomics (e.g. prediction of aspects of protein structure from sequence information); and mathematical immunology, in which Lythe and Molina-París have built research projects with industrial partners Unilever, Astra-Zeneca, and Dstl. It has co-ordinated four multi-partner networks (three FP7, one BBSRC). Two of these (an Initial Training Network on Quantitative T-cell Immunology, *QuanTI*, and an international IRSES network) started in 2013, as did an FP7 Intra-European Fellowship and a three-year Leverhulme project.

8. Probability, Stochastic Modelling, and Financial Mathematics (PSMFM). (Aivaliotis, Bogachev, Gusnanto, Lythe, Mobilia, Molina-París, Palczewski, Rodosthenous, Schenk-Hoppé, Veretennikov, Voss.) This group was formed in 2009 as part of the unit's strategy to build capacity in probability and financial mathematics. The group has an interdisciplinary profile and specialises in: control and stability of stochastic dynamical systems (strengthened by appointment of Aivaliotis and Rodosthenous); and computational statistics, in particular Monte Carlo methods (strengthened by appointment of Voss). The group's expertise in statistics and stochastic modelling has led to projects with industrial partners in finance and economics (e.g. Aon-Hewitt in actuarial mathematics, Yorkshire Bank in statistics/financial mathematics). As organisers of the Trimester "Stochastic dynamics in economics and finance" at Hausdorff Research Institute for Mathematics, University of Bonn (Schenk-Hoppé, 2013) and the ZiF Research Group (Bielefeld) "Stochastic dynamics: mathematical theory and applications" (Bogachev, 2012), the group is a current agenda-setter in the theory of stochastic systems and their applications in biology and social sciences.

9. Statistics (STATS). (**Aykroyd, Barber, Gilks, Gosling, Gusnanto, Kent, Mardia, Taylor, Thwaites.)** The dominant research theme is shape analysis, in which Leeds has long had a strong international reputation. This has major interest in its own right, and has close connections to directional data analysis, image analysis, composite likelihood, and multivariate analysis. There are applications to morphometrics and to molecular shape, both of importance also to the **MBM** group. The group's strategy also involves the development of techniques for the analysis of complex and high-dimensional data, such as sparseness, dimension reduction, kernel methods, causal analysis, and uncertainty and sensitivity analysis of complex computer models; these directions were strengthened by the appointments of Gosling and Thwaites.

c. People, including: i Staffing strategy and staff development

Research strategy, physical infrastructure. New permanent appointments are based on a strategy to sustain excellence across key areas, and to introduce new expertise. To ensure long-term sustainability, many are at a junior level (13 out of 16 in the REF-period were lectureships), and the unit aims for a range of levels of experience in each group. Positions are mostly advertised in specified areas, with likely candidates approached. Those short-listed are invited for interview, to give a talk, and to meet members of the unit. The unit also proactively attracts high-quality postdocs and short- and long-term research visitors, for whom the new Research Visitor Centre (see **§d**) is an invaluable resource. The refurbishment (see **§d**) has enhanced the physical environment for staff and PhD students, with modernised offices and seminar rooms.

Career development

The unit adopts several strands of staff development, summarised as follows; they have differing focus, and address the needs of those at different stages in their careers.

- Probation and research mentoring. Newly-appointed permanent staff generally have reduced teaching loads to allow time to develop their research. Those at a junior level where possible become co-supervisors of research students, and receive support to submit research-grant proposals, or become co-investigators on other proposals. New academic staff undergo a two-year probation period with a probation advisor who, through regular meetings, ensures that a probation plan with clear goals is followed. Each new member of staff is also assigned for the first two years a research mentor. These meet at least twice annually with their mentees and discuss the progress and long-term direction of their mentee's research, as well as publications and grant income. Research mentoring may also be activated for other staff by the staff review process.

- Staff Review. The University's staff review takes two forms. Under the Staff Review and Development Scheme (SRDS), each academic staff member meets annually with an academic reviewer, with an agreed synopsis of the meeting ratified by the Head of School. The scheme aims to help staff achieve their full potential by reviewing work achievements, identifying objectives in the context of wider strategic plans, providing feedback and recognising success, providing support for development, and giving the opportunity to discuss career aspirations. In a separate scheme, each staff member has an 'Annual Academic Review' (AAR) meeting with senior School management. The aim is to ensure good communication and awareness of wider strategies. As examples: junior staff are encouraged through AAR to attend conferences, for which the unit provides funding; AAR reviewers follow up any suggestion that a reviewee's work may have impact beyond the academic sector; and research funding applications are also discussed. AAR gives an opportunity to discuss research-teaching-administration balance, and so can help the unit respond to its research objectives by freeing up time for research.

-Promotion. Promotion opportunities are discussed at staff review meetings, and the unit has a MAPS Faculty Promotions Advisor, a senior academic who advises individuals considering an application for promotion. In addition, the unit's *Reward and Recognition Cycle Group* meets annually to discuss possible recommendations of accelerated increments, discretionary increments, and promotion. During the REF period there were 3 internal promotions to Associate Professor or equivalent, and 4 to Professor. The unit has 22 permanent Lecturers, 11 Associate Professors or equivalent, and 32 Professors. Of the 32, 21 were internally promoted to Professor during their employment in Leeds, showing the unit's commitment to career development.

-Training for postdoctoral research assistants and fellows. The support and career development of the unit's postdoctoral researchers is structured around the university's *Next Generation Researcher* scheme, developed in line with the *Concordat to Support the Career Development of Researchers*, and the national *Researcher Development Framework*. Each postdoctoral researcher is assigned a probation advisor and a separate research mentor, both of whom are distinct from their grant holder or line manager. The role of the research mentor is to assist the researcher to focus on their own career and professional development. Following the Roberts review, specialist training courses and workshops for postdoctoral researchers (and PhD students) are provided by a dedicated unit within the Staff and Departmental Development Unit serving the Faculties of Mathematics and Physical Sciences, Engineering, and Environment. These include workshops on applying for research funding, deriving impact from research, and career opportunities beyond academia, along with, for example, courses on team-working and leadership. Postdocs have contributed greatly to the unit's research vibrancy. Of 51 funded through Leeds accounts during the REF5 period, around 24% currently hold permanent academic posts, 56% fixed-term academic posts, the remainder being mostly employed in industry.

-Workload model. The unit operates a workload model (see also REF3a), through which School management can balance staff teaching and administrative loads, as well as commitments on research grants and on external roles, to ensure that staff have sufficient time to develop their research. The unit encourages staff to apply periodically for study leave, and teaching is often compressed into one semester to enable staff to concentrate on research, to travel or to attend research programmes. The majority of staff have had such arrangements since 2008.

Fellowships. The unit strongly encourages staff to apply for externally-funded competitive research fellowships, exemplified as follows: Pillay (Marie Curie Excellence Chair 1/9/05-31/8/08); Marsh (EPSRC Leadership Fellowship 2008-14); Lewis (Royal Society University Research Fellowship 2007-15); Niesen (EPSRC Academic Fellowship 2005-10); Nijhoff held a Royal Society/Leverhulme Trust Senior Research Fellowship for 2011-12, whilst Hughes held such a Fellowship for 2008-09, and in 2009 was appointed as a Visiting Professor at the Institut Henri Poincaré, Paris; Bogachev (Leverhulme Research Fellowship 2009-11); Molina-Paris (BBSRC Research Development Fellow 2009-12). The unit has also attracted postdocs with externally-funded fellowships, e.g.: Gismatullin (2010-12), Benini (2011-12) and Dinh Nho (2011-13), with Delgado-Eckert to start 1/10/2013, all on Marie Curie IEF/IIF Fellowships; Dean (2012-14) on an EPSRC Doctoral Prize Fellowship; and Xenitidis (2009-11) on a Newton International Fellowship.

Internationalism. The unit has a fully international approach to appointments, with new staff from many countries (permanent appointees since 2008 from Germany, Greece, Italy, Netherlands,

Switzerland, UK). Most research staff have a network of international collaborators, and many take short-term fellowships or make extended visits abroad, encouraged through study leave. Likewise, through its Research Visitor Centre, the unit hosts many international visitors (see **§d**).

Equality and Diversity. The unit's commitment to Equality and Diversity, and promotion of women in mathematics, was recognised in 2012 by the Athena SWAN Silver Award to the MAPS Faculty (of which the unit is the biggest member). Only two other UK Mathematics Schools have silver AS-awards or lie in silver-rated Faculties. The award is based on achievements (beyond the University's Bronze level), and on a MAPS Action Plan for 2012-15 which commits the Faculty, *inter alia*, to: ensuring selection policies for key roles are transparent; reviewing workload (ensuring part-time staff are not disadvantaged); requiring Schools to support women returning from periods away from work; ensuring staff recruitment and induction processes are alert to equality issues; ensuring SRDS/AAR meetings consistently focus on promotion and career development; aiming to improve gender parity among staff (where there is still room for improvement), PDRAs, and PhD students (36% female in 2012-13, compared to around 29% nationally). The unit is a Supporter of the London Mathematical Society's *Good Practice Scheme* for women in mathematics.

ii Research students

Quality and Recruitment. The training of PhD students is an essential part of the unit's research activities. The benefits of energetic recruitment, diverse funding, and rigorous supervision and monitoring (all described below) are illustrated by several examples of quality: Fallaize (PhD 2011) obtained a lectureship in statistics in Nottingham immediately after the PhD; Kestner (PhD 2012) and Penazzi (PhD 2011) have permanent lectureships at the University of Central Lancashire, and Boxall (PhD 2009) at Stellenbosch, South Africa; Hoyle (PhD 2011) won the Vernon Harrison award for the most distinguished PhD thesis in rheology in the UK; Atkinson (PhD 2009) and Lobb (PhD 2011) both obtained Australian Research Council Discovery Grant Fellowships in 2011; Sklinos (PhD 2011) took a Lady Davis Fellowship in Jerusalem - his PhD, combining geometric group theory and model theory in original ways, led to papers in Duke Math. J. and elsewhere. The logic thesis of Hendtlass (PhD 2013, post 31/7/13) has led to six publications by him. The unit achieved an 88% 4-year submission rate for students starting Nov 2004-Oct 2007, with a 90% 7-year completion rate for the first of these four cohorts (the most recent statistics available).

The unit aims for high-quality PhD standards, with a 1st-class MMath or BSc+MSc Distinction, or equivalent, as the standard requirement for admission; over 2010-13, 96% of those admitted with UK degrees had 1st MMath or BSc+MSc. Recruitment is assisted by advertising (e.g. FindAPhD.com), professional networks (e.g. allstat), Open Days, and web pages. The unit sends representatives to annual recruitment events, e.g. in Cambridge and Warwick. International recruitment has been assisted by building international links: for example, there have been 6 Mexican PhD students in **Logic** in the REF period, some recommended by a previous Mexican student. The unit has supervised PhD students from 34 countries in the REF period.

Funding for UK and EU students is provided by a combination of Research Councils (RC) (EPSRC including maths CASE, STFC), European Union (Marie Curie), University Research Scholarships (URS) and a School-funded Graduate Teaching Assistantship. The **MBM** group belongs to the White Rose Universities Computational Immunology Partnership, now funding PhD students at Leeds, York and Sheffield. International PhD students are mostly supported either by their governments or the fully-funded University of Leeds International Research Studentships (LIRS).

The unit has also coordinated three FP7 Marie Curie Initial Training Networks during the REF period. The **PIM** group coordinated with Physics the ITN *DYNACOP* (12 partners, 2009-13) and partners *SUPOLEN* from October 2013, the **Logic** group coordinated *MALOA* (11 partners, 2009-13), and the **MBM** group coordinates *QuanTI* (17 partners, May 2013-17).

Among PhD students starting during the REF period, 44 received RC funding, 4 URS and 2 LIRS awards, and 3 students have been funded by the ITNs *DYNACOP* and *MALOA* (above). In order to give time for students to receive broader mathematical training beyond their own research project (as urged in the International Reviews of Mathematical Sciences 2004, 2011), EPSRC studentships are funded for 42 months and, throughout the REF period, the unit has provided when needed an additional 6 months funding for home/EU students on 36-month studentships.

Supervision and monitoring. The unit has three Postgraduate Research Tutors (PGRTs), supported by a Postgraduate Research Secretary (PRS), who are responsible for the admission

and progression of postgraduate students. Each PhD student is supported by a supervisory team consisting of a lead supervisor and at least one additional co-supervisor or advisor. All new supervisors are required to have attended a course on research student supervision. Students typically meet with their supervisors weekly, with formal monthly meetings that are recorded on the online Postgraduate Development Record System (PDRS).

PGRTs monitor the progress of each research student through a system of reports from supervisors, annual meetings with each student at the time of registration, and reports from formal assessment interviews after the first 6 months and the end of each year. Near the end of their first year, research students undergo a formal transfer process from provisional to full PhD status, submitting a report to a review team including an independent assessor, which then holds a formal meeting with the student. All reports are uploaded to the PDRS, which also holds records of training and training plans. These records can be viewed online by the student, their supervisory team, the transfer panel, and the PGRTs, and are monitored by the PRS.

Training. At the beginning of their studies each PhD student agrees an individual training plan with their supervisory team covering both generic skills and broadening of their mathematical knowledge. In keeping with the recommendations of the Roberts review, students are expected to spend at least 30 days on generic/transferable-skills training over 3 years; this is monitored using the PDRS. Most generic-skills training for PhD students is provided by a specialist training unit serving three science-based Faculties. This offers a wide range of workshops and courses on topics including: research presentations, scientific/mathematical writing, time management, career development, as well as public-engagement events.

In order to broaden their mathematical background PhD students also take advanced taught courses (100 hours of which are assessed). These are mostly specialist postgraduate courses from the MAGIC consortium (of which the unit is a founder member) delivered through Access Grid videoconferencing facilities. Leeds is represented on the MAGIC Management and Academic Steering Committees, and the unit has delivered 11 distinct MAGIC courses with around 50-60 hours of lectures p.a.. In addition, the unit annually provides 3-5 internal postgraduate courses, attended also by staff. Students can also attend MSc courses where these are appropriate. First-year **Statistics** students participate in week-long courses of *The Academy for PhD Training in Statistics* (APTS) - a collaboration between major UK statistics research groups.

Students are also encouraged to develop their skills through activities within the school such as seminar, workshop, and conference organisation. For example, **Logic** PhD students in model theory run their own seminar (which led to a paper by one postdoc and four PhD students), and (in 2011) organised in Leeds the 1st British Postgraduate Model Theory conference (4th to be in Leeds in 2014) with participation of non-UK speakers and students. Leeds PhD students hosted the 2nd MAGIC conference in 2009, a 3-day event with over 80 participants, and in **Analysis** hosted in 2008 the first *Young Functional Analysts' Workshop*.

Research seminars (see **§d**) play a key role in PhD training, and students are expected to attend the main seminars of their research group. Some of the more informal seminars (e.g. in **AGFD**, **MBM**, and the three subgroups of **Logic**) are designed around PhD/postdoc training. Every effort is made to ensure that students give several seminars, with feedback provided by the supervisor and other staff. There are regular PG seminars in broad areas (Pure, Applied, Statistics) in which students give talks to their peers and receive feedback from a staff member.

PhD students are encouraged to participate and present their work in conferences, and to attend summer schools and external seminars. The unit provides funding for each student to attend at least one overseas conference and several UK events. It has also hosted a number of training workshops including: one-week workshops for the *MALOA* and *DYNACOP* networks; two LMS-EPSRC Short Courses 'Introduction to model theory' and 'Geometry, field theory, and solitons'; the UK Dynamical Systems Graduate Schools in 2008 and 2009; STFC Introductory Summer School in Solar System Physics (2010); and two summer schools (2009, 2010), as part of the **MBM**-run BBSRC Network in Experimental and Theoretical Immunology.

d. Income, infrastructure and facilities

Research Funding. The unit's REF period research income was ~£11.2m, with 28 members being PI of a significant (over £80k) external award. UK research councils provide the dominant

source, primarily EPSRC and PPARC/STFC, but also NERC and BBSRC. The total RCUK+Royal Society income received by the unit in the REF period was approximately £8.7m, including £4.1m (EPSRC), £3.3m (PPARC/STFC), £360k (NERC), £226k (BBSRC), and £690k (Royal Society). There has been significant EU funding (£1.37m received by the unit in the REF period) through Marie Curie FP6 and FP7 projects, with a Marie Curie Chair, four individual fellowships, three Initial Training Networks, and two IRSES research networks, all held/(co)-coordinated by the unit. RCUK funding has fluctuated, partly due to STFC issues with large grants, with a very recent upturn. The overall value to Leeds of grants held/announced on 31 July 2013 with PI in the unit is ~£11.74m (£5.3m EPSRC, £1.88m STFC, £1.15m NERC, £1.5m EU, £1.14m charitable foundations, £712k industry and related). This spread of current awards, with 22 PIs in the unit, gives evidence of the strength of research in the unit, and, in view of the breadth of sources, of financial sustainability.

Industrial Funding. During 1/8/08-31/7/13 the unit has been awarded ~£950k of industry-related grants (**REF3a §b)**. As examples, Molina-París and Lythe (**MBM**) have secured £538k for a 3-year Unilever-funded PDRA to develop stochastic mathematical models of T-cell responses during skin sensitisation (avoiding animal testing), an AstraZeneca CASE studentship (2012-2015), and a six-month project funded by Dstl (MoD) to develop stochastic models of host-pathogen interactions. Unilever is contributing £60k and providing access to data for an NC3Rs-funded project, led by Gosling (**STATS**), also to reduce animal testing (building a framework for replacing it with computer models). In **PIM**, ExxonMobil is providing £115k for a joint Leeds-Durham project, and 8 industrial partners (BASF, Dow, DSM, ICI, Lucite, LyondellBasell, Mitsubshi Chemicals, Ineos) have contributed over £1.1m to the Microscale Polymer Processing project (see Case Study 5); also the inkjet research projects (joint with Cambridge, Durham and Manchester) have been supported by over £1.8m from the industrial partners (Domino, Xaar, Fujifilm Sericol, Inca, Linx, SunChemical, Merck, Fujifilm Electronic Imaging) - the **PIM** outputs from this led to a £556k Technology Strategy Board project with GlaxoSmithKline on printed pharmaceuticals (see Case Study 2). Such sources should expand through new initiatives, such as the recent creation of the External Advisory Board and Impact Advisory Group (see REF3a), and the appointment of a KT Coordinator and Impact Coordinator. The unit on 31/7/13 hosted six CASE students (seven on 1/10/13).

Strategies to generate funding. Grant applications are supported by internal peer review of proposals, and encouraged through staff review. Financial aspects of a proposal are handled by the MAPS finance office. The unit's Research Committee, chaired by the Director of Research, organises annual research Awaydays for academic staff; recent themes include the building of links to industry, PhD recruitment and supervision, and advice on research grant proposals from diverse sources. The University's proactive European Office contributes to the unit's stream of EU grant successes, through advice, workshops, peer review, and dissemination of EU experience.

The unit encourages quality research grant applications by providing grant-holders with additional research funding through 'Incentive Accounts' (~£200k credited since 1/1/08). Payment to the unit by research councils for peer review is added to incentive accounts, and the unit also contributes to the incentive accounts of staff who secure industrial support for CASE studentships, after the student passes the first year. Incentive accounts are flexible, and can be used, for example, for research travel (by the grant-holder or PhD students), equipment, or for research visitors to Leeds.

Consultancies/Professional services. The unit encourages staff, financially and through staff-review, to take consultancies. As examples, Schenk-Hoppé, with LUBS colleagues, participated in a Knowledge Transfer Partnership with Yorkshire Bank that won the ESRC award 'Best Application of Social Science in a KTP in 2011' (see Case Study 4); Falle has held several consultancies (British Gas, the National Grid) in the REF period on transport of liquid CO_2, and of hydrogen in the gas pipeline network; Kelmanson in 2010 acted as consultant for a major international protective-coating manufacturer, with remit to analyse existing European Standards for fire safety by modelling the performance of intumescent paints. Others include: Tobias (consultant for the NASA solar prediction panel for solar cycle 24 - see Case Study 3); Harlen (AkzoNobel - spray paints, Domino - inkjet printing); Lesnic (Oxford Advanced Surfaces Group plc - refraction index of anti-reflection coatings of optical instruments); and Gosling (statistical consultant, Defra, assessing regulatory changes to farm-compliance inspections). Staff are assisted to build links to research institutions: for example, Gilks held a 3-year half-time secondment at Rothamsted Research to promote statistical bioinformatics in agricultural applications.

Infrastructure and Facilities.

-Buildings. The unit is carrying out a major 3-stage refurbishment of its space. Phase 1 (2006-07, £1.556m, with £1.12m from SRIF3 and £436k from HEFCE Learning and Teaching Capital Round 4) provided the new Research Visitor Centre (RVC – see below); it also gave improvements of the seminar room, teaching, and administrative space. Phase 2 (2008-09, £995k, HEFCE, with 10% from the unit) created additional space. Phase 3 (to be completed in 2014, funding £3m from the University + £1m from the unit) will upgrade the remaining office space. This investment has ensured a greatly improved working environment for all members of the unit. Permanent staff have individual offices, whilst fixed-term and postdoctoral staff share offices. PhD students each have desks and storage space in modern shared offices.

-Research Visitor Centre. The RVC has office space for 17 visitors, dedicated administrative support, and seminar-room facilities with Access-Grid video-conferencing equipment. A goal of the unit in 2008 was to ensure that the RVC be fully exploited through hosting visitors to the unit, running research programmes, and providing office space during workshops. Since its opening on 1/6/09 the RVC has been used by over 320 visitors to the unit, on visits ranging from a few days to more than a year. Highlights of RVC support include a 6-week programme on *Banach Algebras*, a 3-week programme in proof theory, and a 3-week programme *Gauge theory and complex geometry*, all of which included conferences (the last with lectures by Atiyah, Donaldson, and Hitchin). It has proved especially valuable for training events (e.g. LMS-EPSRC Short Courses and EU network events), since it can provide office space for lecturers giving courses. The unit encourages staff to apply for funding for extended research schemes for which the RVC is needed, and provides matching funds up to £5000 per year.

-Computing. The University has a strong centrally-provided long-term strategy for HPC, with planned capital investments of £1m biennially. This has established a 4500 core facility (45 Tflops), with an expansion of 3000 cores (60 Tflops) being added. Through this support, the University has won the right to host national HPC facilities such as the STFC-funded UK Magnetohydrodynamics Consortium (which won a Royal Astronomical Society Group Achievement Award in 2013), and the £2.6m regional N8 HPC facility of 5312 cores (110 Tflops).

-Seminars. As part of the 2009 reorganisation the unit made a strategic decision to invest in seminar programmes for each research group. All research groups now run a regular seminar programme, many with regular audience participation from outside the unit. In addition, there is a weekly Applied Mathematics seminar, typically with about 40 participants, there are occasional School or Pure Mathematics Colloquia, and the Algebra, Logic, and Algorithms seminar links Mathematics and Computer Science. Vitality is also witnessed by the growing number of informal working seminars and reading groups, with at least 11 such seminars running for at least a semester in the REF period, some running throughout. One example is the Statistical Mechanics Discussion Group combining members from **AGIS**, **Analysis**, **AND**, **PIM**, and the Quantum Information group in Physics. It has stimulated PhD student activities and papers, and led to an £800k EPSRC grant with Martin as PI. Another is the weekly 2010-2013 Differential Algebra Seminar, based on an EPSRC-funded project linking **Logic** and **AGIS**, with regular participation also from other groups; this intra-disciplinary seminar has covered topics linking differential Galois theory, Painlevé equations, and model theory, with notes being developed into a book.

e. Collaboration or contribution to the discipline or research base

Collaborations. In addition to an array of individual international collaborations, the unit is a prominent participant, and often the coordinator, of many research-related networks. These range from regional to national and to international. Regional examples include the following LMS networks: ARTIN, Classical and Quantum Integrability, Yorkshire and Durham Geometry Days, Singularity Days (**AGIS**); NBGGT (**Logic**), PANDA and CoDySy (**AND**), and in **Analysis**, the networks NAG, NBFAS, and Quantum groups, Operators and non-commutative Probability (QOP) with Leeds, Lancaster and IMPAN Warsaw. There are also PhD training networks, from the regional (White Rose) to 3 large multi-partner Marie Curie Initial Training Networks; and major collaborative ventures, such as two FP7 IRSES networks (2008-12, 2013-17) and one BBSRC network (2008-11, 2 summer schools, 11 workshops) led by the **MBM** group. Particularly striking is the **MBM**-coordinated FP7 IRSES network, the *Indo-European Research Network in Mathematics for Health and Disease,* which started in May 2013. This arose from a session of the Royal Society framework 'Frontiers in Science' organised by Lythe in India in 2008, which led to a 2011 conference in Bangalore. This network will run 4 spring schools in India; it aims to develop

mathematical immunology in India through its 5 Indian research partners and 11 partners from the EU, USA, Canada, and Australia. A 15-partner Leeds-run **Logic** IRSES network will start in 2014.

The unit is also central in major industrial collaborations. For example, **PIM** provides mathematical modelling for the £5m EPSRC Programme Grant on Innovation in Industrial Inkjet Printing, and for the £2.6m Microscale Polymer Processing project (both with eight industrial partners); these projects underpin Impact Case Studies 2 and 5 respectively.

The unit supports collaborations in many ways. It provides travel funding through incentive accounts, with support also to staff with no other source. Unpaid study leave is usually available and paid study leave can often be arranged, or teaching compressed, typically into one semester. Incoming visitors find that the RVC (see **§d**), and its associated support, provides an excellent working environment. The workload model takes account of research and network-running activity, and of industrial collaborations. The Leeds EU office assists the running of complex EU networks.

Interdisciplinary research. Many of the above networks involve interdisciplinary research, and the unit also exploits the research breadth of Leeds itself for research collaborations/interactions with, for example: Computer Science (CS), Philosophy, Physics (polymers, quantum computation), Engineering, Earth and Environment, the Business School (LUBS), Biology, and Medicine. As one example, D.J. Read (**PIM**) has collaborations with Physics and CS in Leeds, and with Physics and Chemistry in Durham, along with other collaborations with companies and research institutes. This led to an industrially co-authored publication in *Science* that underpins Case Study 5.

Response to research users. As indicated in **§b**, the research groups were reconstituted in 2009, partly for better alignment with potential research users. This led to the formation of **PIM**, along with **MBM** and **PSMFM**, and to the appointment of 10 permanent staff (of a total of 16 in the REF period) with existing, or the potential for, close interactions with users in industry and health. The research in **MBM** in mathematical immunology, with large research networks and industrial funding, is driven by concerns of pharmaceutical companies. Engagement with the digital-marketing company Bloom Agency (which has a mathematics department) has in part driven **AND**'s choice to develop its research activities in complexity science. Bokhove, Griffiths and Tobias (all **AGFD**) recently initiated a research project with the Met Office, aiming to improve numerical weather prediction through the application of fundamental research on multi-scale processes in fluid models. Industrial questions relevant to whole sectors inform the research direction of **PIM**, one such question being: 'how can one predict flow properties from the molecular structure of polyethylene?' **PIM** contributes answers through its strong links to both the chemical industry (polymer manufacture) and the inkjet printing sectors, and through numerous joint research programmes (for example, *DYNACOP*, the Microscale Polymer Processing project, and the inkjet Programme Grant, each of which involves several companies). Such projects provide an environment in which postdocs and PhD students are regularly exposed to industrial concerns.

Leadership. The unit encourages staff to undertake major leadership roles nationally and internationally, with contributions recognised in the workload model. Examples include:

- Cooper, aided by study leave, chaired the Advisory Committee for the Turing Centenary Year 2012; its events, in many countries, had over 60 organisations in support; also President till 2015 of Computability in Europe, which promotes interdisciplinary computability-related research.
- Dales (retired 2011), LMS Council member 2004-10; Vice-Chair of the European Mathematics Society Ethics Committee; has also contributed, through lecturing visits part-funded by the unit, to LMS support for the development of mathematics in Africa.
- Rathjen, Scientific Committee of the Oberwolfach Mathematical Research Institute since 2009; Executive Committee of Association of Symbolic Logic (ASL), the main international logic body.
- Partington, on French AERES panel (equivalent to REF), assessing Bordeaux Univ. in 2009.
- Jones, REF2014 subpanel for UOA10.
- Kent, on Royal Statistical Society Council (2005-09) and liaison member of CMS (2008-10).
- Rucklidge, EPSRC Mathematics Strategic Advisory Team 2006-10.
- Harlen was President of the British Society of Rheology from 2009-11.
- D.J. Read, Treasurer of the Complex Fluids group of the Institute of Physics.
- Macpherson, Treasurer (since 2005) of the British Logic Colloquium, the main UK logic body.
- Pillay, prepared logic landscape document for 2011 IRMS, Executive Committee of ASL.
- Lesnic, on Academic Advisory Board of the Knowledge Transfer Network (KTN) for Industrial Mathematics; organises annual Industrial Inverse Problems Sandpits.

- Falle, on EPSRC Technology Watch Panel for High Performance Computing; STFC DiRAC HPC facility project management board; Collaborative Computational Projects Steering Committee.
- Houston (LMS Education Committee), Speight (LMS Research Meetings Committee), from 2013.

Public engagement. The unit promotes wider public understanding of the mathematical sciences. As an example, Elwes has since 2008 published five popular mathematics books and numerous articles, e.g.in *New Scientist, Daily Telegraph*. The unit is committed to communication of advanced mathematics in schools, with over 50 talks in UK schools given by UOA members in the REF period, and others in China, Malaysia, South Korea, often linked to current research. Staff members have presented at both the Leeds Festival of Science and the British Science Festival. Among many outreach activities, Evans writes on developments in theoretical physics/applied mathematics for Sky At Night Magazine, the partner publication to the BBC TV series, with a series of feature articles in 2012-13; he is one of nine official bloggers for the Institute of Physics.

Programme organisation. The unit has contributed centrally to the running of many major research programmes and conferences: Nijhoff and Cooper were organisers of 6-month Newton Institute Programmes ('Discrete Integrable Systems' (2009), 'Syntax and semantics; a legacy of Alan Turing' (2012) respectively); Bogachev was coorganiser of a ZiF Research Group 'Stochastic dynamics: mathematical theory and applications', Bielefeld, May-September 2012. Schenk-Hoppé co-organised in 2013 a 4-month programme at the Hausdorff Research Institute for Mathematics (Bonn) on 'Stochastic dynamics in economics and finance'. Tobias and Jones were the chief organisers of a 4-month programme on Dynamo Theory at the Kavli Institute for Theoretical Physics (KITP) at Santa Barbara in 2008.

Conference organisation. The unit has run the following programmes in Leeds: 'Gauge theory and complex geometry' (4-23/7/11, conference and workshop); 'Banach algebra and operator space techniques in topological group theory' (17/5/10-30/6/10, 2 conferences); 'Leeds Symposium on proof theory and constructivism' (3-16/7/09, 2 conferences). Other events hosted in Leeds include: the 2013 British Applied Mathematics Colloquium (260 participants, the premier UK applied mathematics meeting); the 2010 UK Magnetohydrodynamics Meeting and the 2011 International Taylor-Couette workshop; the Leeds Annual Statistics Research (LASR) workshops, which have run for 25 years and foster interdisciplinary collaborations; 'Variational problems in differential geometry' (2009); a model theory workshop, an LMS regional meeting and workshop on homogeneous structures, and two workshops run jointly by the **Logic** and **AGIS** groups. The unit has had many further central roles running international conferences during the REF period. For example: Pillay was an organiser during the REF period of two meetings in Oberwolfach, two in Luminy, and two in Banff. Partington co-organized workshops at ICMS (2009), Oberwolfach (2010). Rucklidge was on the Scientific Organising Committee of the 2013 SIAM Conference on Applications of Dynamical Systems, with around 700 participants. Hughes and Tobias organised the 2010 CNRS conference `Convection, Magnetoconvection and Dynamo Theory' (Corsica). Nijhoff is Chair of the International Steering Committee of the Symmetries and Integrability of Difference Equations conferences. Veretennikov was a Programme Committee member and section organizer for two major international conferences on Modern Stochastics in the Ukraine.

Editorships. The unit encourages staff to contribute through editorial roles, with over 40 editorial positions (for book series or journals) held by members of the unit over the REF period, some taking on 3-4 editorial commitments. As examples, Kent is an Associate Editor of *Biometrika*, Aykroyd is Editor-in-Chief of the *Journal of Applied Statistics*, Jones is an editor of *Physics of the Earth and Planetary Interiors,* Fordy is Editor of *Physics Letters A,* and Harlen and Kelmanson are Associate Editors of *Journal of Engineering Mathematics*. Macpherson is Managing Editor of the Association of Symbolic Logic's book series *Lecture Notes in Logic*, published by CUP.

Honours. Honours to the unit's members include the following, as well as the Fellowships listed in **§c**: Marsh (2009 LMS Whitehead Prize); Jones (2009 European Geophysical Union Petrus Peregrinus medal); Mardia (2013 Wilks Memorial Award of the American Statistical Association); Cooper (2011 Honorary Doctorate, Sofia University). Crawley-Boevey, Pillay (appointed Fellows of the American Mathematical Society in 2012). As examples of prestigious invited lectures, Pillay gave the Tarski distinguished lecturer series in Berkeley in 2009, Rathjen the Goodstein Lecture in Logic Colloquium 2012, Crawley-Boevey the Maurice Auslander Distinguished Lectures in 2008, and Hughes a keynote lecture in the European Plasma Physics conference (Crete) in 2008.