

Institution: Loughborough University

Unit of Assessment: B10 Mathematical Sciences

1. Unit context and structure, research and impact strategy

The Unit is renowned for achievement in Mathematical Analysis, Geometry, Nonlinear Systems, Modelling and Industrial Mathematics. In July 2015, we relocated to a completely refurbished building (£4M investment), vastly improving the quality of our working environment and allowing growth of the Department. Over this REF submission period, we have seen a step-change in research grant income of more than a third on average per year and a threefold increase in the number of postdoctoral researchers working in the Department. More than 70% of our journal outputs have been published with leading international collaborators. We have hosted more than a dozen major international workshops, and obtained our first EPSRC Advanced Research Fellowship and ERC Starting Grant, evidencing a clear upward trajectory in research performance. Moreover, two DMS staff have won prestigious awards for their leadership roles in equality and diversity.

1.1 Research structure

This Unit comprises 36 (headcount) academic staff from the Department of Mathematical Sciences (DMS). DMS is a Department within the School of Science (SSci), which also includes Chemistry, Computer Science, Physics and Mathematics Education. SSci is one of 9 autonomous Schools at Loughborough with its own Research, Enterprise and Senior Management Committees. The DMS is represented on these committees through, respectively, its Research Coordinator, Impact Coordinator and Head of Department. These key staff lead the effort within the Unit and collaborate with their School-level leads (Associate Deans for Research and Enterprise, and Dean of Science).

1.1.1 Research groups

DMS research structure is based on six research groups.

- **Analysis and PDEs:** working on Cauchy and boundary value problems with singularities, and on inverse spectral methods for PDEs.
- **Dynamical Systems:** working on classical and quantum dynamics, including averaging methods, bifurcation theory, ergodic theory and quantum chaos.
- **Geometry and Mathematical Physics:** research ranging from algebraic and differential geometry to integrable systems.
- **Linear and Nonlinear Waves:** developing new analytical and numerical approaches to description of nonlinear waves, instabilities and wave scattering.
- **Mathematical Modelling:** modelling problems in fluid dynamics, medicine, biology, materials and soft matter science.
- **Statistics:** this recently-formed group works on computational, medical and environmental statistics. Its establishment in this REF period was informed by the recommendations from the International Review of UK research in Mathematics.

1.1.2 Interdisciplinary research

In order to facilitate interdisciplinary collaborations and the generation of impact, there are three School Research Centres led from within DMS: the Centre for Geometry and its Applications (CGA, Ferapontov leads); the Interdisciplinary Centre for Mathematical Modelling (ICMM, Ala-Nissila leads); and the Centre for Nonlinear Mathematics and Applications (CNLMA, Neishtadt leads). Additionally, Unit members contribute actively to the Centre for Sensing and Imaging Science (CSIS).

Examples of interdisciplinary activities include:

- CGA's semester-long 'Geometry' programme at Loughborough's Institute of Advanced Studies (IAS), which drives international and interdisciplinary activity. We welcomed

renowned international geometers, including the Fields Medallist Birkar (Cambridge) and Felder (ETH Zurich), for a collaborative programme of four workshops on algebraic geometry and their applications involving 35 invited Visiting IAS Fellows. The programme also included an exhibition of printed 3D shapes (Clebsch cubic, maximal dP2 and DIS quartic), which was a collaborative project involving our School of Design and Creative Arts.

- ICMM's collaboration with Chemical Engineering to develop a model for the deformation and dewetting of liquid films under impinging (plasma) gas jets, relevant to sterilization applications. This work appeared in the *Journal of Fluid Mechanics* 2020.

IAS is a core component of the institutional 'CALIBRE' strategic research framework, which drives interdisciplinary activity across all Schools. We engage with CALIBRE's programmes, particularly the Global Challenges, Beacons, and Adventure programmes. Adventure promotes vitality in research with emphasis on exploring new areas or translation into new application areas; the Unit has been extremely successful in securing funding for 10 Ph.D. studentships across two Centres, one on the Fundamentals of Self-assembly (with Chemistry, Chemical Engineering and Materials) and a second on Geometry in Robotics, Algorithms and Design (with Manufacturing Engineering).

1.2 Review of objectives and research plans in REF 2014

Delivery of the research objectives identified in REF2014 has been guided by the University 'Building Excellence' strategy and its 'CALIBRE' research framework.

Priorities identified in the REF2014 submission were:

- To consolidate and strengthen our research portfolio through attracting outstanding researchers to create groups with the critical mass to operate at the highest levels internationally.
- To continue to energise the Department with new appointments and strive to increase the number of prestigious fellowships.
- To develop young, talented researchers into international leaders.
- Under the University strategic theme 'Raising Standards and Aspirations', to submit an application for Athena SWAN silver award, as part of our longstanding commitment to equality, diversity and inclusion (EDI).

Outcomes of our strategic plans during the assessment period have been:

- The DMS has invested in strengthening its portfolio in Analysis and PDEs, with three new appointments: Cuenin, Discacciati and Eckhardt. The latter was a targeted appointment to strengthen the links between Analysis and PDEs and Mathematical Physics. Indeed, the ability of Eckhardt to create such a link is evident in his outstanding work, including his contribution in *Inventiones Mathematicae* 2016, which provided a full indefinite analogue of a classical result by M. Krein and laid the foundation for establishing the Inverse Scattering Transform for a novel class of completely integrable nonlinear PDEs.

Development of a new DMS research group in Statistics was initiated in this REF period. This strategically important area adds a vital dimension to our approach to a data-driven economy, and realises opportunities for new cross-campus collaborations, such as the work of Zhou and Hunsicker with Computer Science, "Deterministic fibre tracking improved by diffusion tensor similarity", in which an improved tractography algorithm for non-invasive brain imaging is developed. The statistics group now has 4 core members in DMS and others based in other Departments, working on computational, medical and environmental statistics. For example, Shimadzu, *Science* 2014, showed for the first time that there is no systematic loss detected in the mean species biodiversity but systematic changes in species composition, using an extensive set of biodiversity time series data in both marine and terrestrial habitats from the past 150 years.

- During the assessment period, the DMS secured its first EPSRC Established Career

Fellowship (Zhao). Moreover, with the creation of the ICMM in 2018, the DMS secured new appointments through which it received its first ERC Starting Grant (Shendruk).

(iii) To develop young talented researchers, the DMS increased the number of postdoctoral researchers. Indeed, the number of postdocs and research fellows in the Unit has been 10-15 at any given time, compared to no more than 5 at any time during the REF2014 assessment period. This strategy was funded through various grant applications (EPSRC, Leverhulme, Royal Society, AXA), through attracting Visiting Fellows supported by overseas funding schemes and from internal funding. Of the postdoctoral fellows who have now finished their term at Loughborough, all have gone on to prestigious positions. For instance, Ruziboev, mentored by Bahsoun through a Leverhulme Trust grant, jointly published 'Linear response for random dynamical systems', *Advances in Mathematics* 2020, and went on to secure a Senior Lise Meitner Research Fellowship in Austria. While Cléry, mentored by Ferapontov through an EPSRC research grant, jointly published 'Dispersionless Hirota equations and the genus 3 hyperelliptic divisor' *Communications in Mathematical Physics*, 2020, and went on to become a Senior Research Associate at ICERM, Brown University, USA.

(iv) During the assessment period, the DMS jointly with the Mathematics Education Centre received an Athena SWAN silver award. Moreover, as a result of work taken to promote gender equality in Mathematics during the assessment period, two DMS members have been recognised with the prestigious national *Suffrage Science Award*: Hunsicker (2018) and Lombardo (2020).

1.3 Enabling and facilitating the achievement of impact arising from research

The Unit holds regular workshops, training events and forums on impact and enterprise (such as on Knowledge Transfer Partnerships, consultancy, enterprise funding opportunities, intellectual property and commercialisation) delivered by colleagues from the School of Science and the Research and Enterprise Office (REO). REO run regular drop-in sessions for staff to get support. The Unit also has a specific link person in REO who helps with non-disclosure agreements and negotiating contracts. The University's Enterprise Projects Group (EPG) provides competitive funding from the Higher Education Innovation Fund (HEIF) and the EPSRC Impact Acceleration Account (IAA) to support the creation of impact from research. Staff can also receive up to 0.1FTE in the School workload model for impact-creating activity and impact activity can be the basis of submissions for research leave.

Our REF2014 impact strategy identified several strands:

- **Direct engagement with business:** For example, Renzi has collaborated with Ocean Grazer Consortium, a spinoff company of Groningen University, to commercialise scalable eco-friendly energy storage. His visits to Ocean Grazer were funded by EPG.
- **Public engagement:** Janson collaborated with the University of Copenhagen to create an accessible lecture course, pitched at a wide audience, on Dynamical Systems and Synchronisation, available on YouTube, drawing on examples from her research in synchronisation of oscillators and human electrocardiograms.
- **Pathways thinking:** Staff working on fundamental research have been strongly encouraged to think creatively through the pathways leading to impact from their work.

1.3.1 Selected impact case studies (ICS)

The above strategy led directly to the impact case studies submitted for REF2021, as described here.

Direct engagement with business led to Archer and Smith's ICS on modelling the manufacture of surface coatings and structures, which is based on collaboration with the two multinational companies Ashahi Glass Co. and M-Solv Ltd. (part of the CN Innovations group). Archer also had research leave to support his impact work. Our second and third ICSs came out of **pathways thinking**. Neishtadt's ICS on optimising the development of mass spectrometers is

based on pure dynamical systems theory. It has enabled significant economic impact for Thermo Fisher Scientific from the analysis of ion dynamics in their Orbitrap™ mass spectrometer using Hamiltonian perturbation theory. Similarly, Smith's ICS on accelerating new materials design came from developing efficient algorithms to partition charge distributions in materials.

1.4 Research and impact objectives and plans for the next five years

DMS is currently widely recognised in areas of mathematics such as Analysis and PDEs, Dynamical Systems, Geometry and Mathematical Physics, Mathematical Modelling, Statistics and Waves. It is evident from the review of the outcomes of our REF2014 strategy that the Department is on an upward trajectory and this will be maintained over the next five years by:

- (i) creating further headroom to allow a greater proportion of our staff to devote focussed time for research by attracting prestigious research fellowship grants, building upon recent success e.g. EPSRC Established Career Fellowship (2018), ERC starting grant (2019).
- (ii) strengthening research in Geometry to include Arithmetic Geometry. The DMS views this direction of research as top priority to complete the picture in the Geometry and Mathematical Physics group. Currently, our work is focused on Algebraic and Differential Geometry. This new addition will also strengthen our links internally with Computer Science and build on the CALIBRE Adventure funding for Geometry in Robotics, Algorithms and Design.
- (iii) expanding the impact of our research in medical statistics. The statistics group is planning important projects on musculoskeletal diffusion tensor image analysis and on Bayesian modelling and scalable inference of DNA methylation. A major goal of the latter is to develop a novel sequential Monte Carlo algorithm to infer methylation levels for the whole human genome in a matter of hours on a consumer laptop.
- (iv) creating a Centre for Doctoral Training (CDT), ultimately pursuing an EPSRC CDT, within DMS to train the next generation of mathematicians on the interdisciplinary focused research topic of *Nonlinear Systems*. This topic is already established in Loughborough. It includes members from the six research groups with strong connections across the University (particularly physics and engineering) as well as externally.
- (v) continuing to develop the profile of Loughborough Mathematics by bringing prestigious international events to our campus. For example, in 2022 we will host the British Applied Mathematics Colloquium, which typically has ~330 delegates.

1.5 Open research environment

The University has been a pioneer of the 'Open Agenda', actively supporting Repositories for text-based outputs (since 2005) and data (since 2015), working beyond funder (including REF2021) open access requirements. Our landmark Open Research Position Statement committed to depositing the full-text of 100% of our primary research outputs in our now unified (2019) Research Repository (including closed access deposits where unavoidable) from 2020. We have met this target by depositing 100% of our 2020 journal outputs in the Repository.

The position statement of the University, supported by DMS, indicates clearly how open research is a means to enhance further the quality, visibility and impact of our research rather than as an end in itself. As indicators of our long-standing commitment to the 'Open' agenda, DMS's own repository dates from the 1990s, well before the University's first repository, and staff regularly post their outputs on the ArXiv - 391 submitted during the assessment period (from a total of 831 deposited outputs from the Unit).

1.6 A culture of research integrity

Loughborough University Ethics Committee is a joint sub-committee of Senate and Council, attended by the Chief Operating Officer and several senior University managers. DMS member Linton sits on Ethics Committee. Ethics Committee considers all ethical matters arising in the conduct of the University's business. Ethics Committee has specific processes in place for areas such as experiments with human participants, work falling under the Human Tissues Act, philanthropic gifts, and research with military applications. All of these can relate to research in mathematics, particularly (but not limited to) research in statistics and applied mathematics.

Staff and student training is routinely available on ethics issues. While most research in Mathematical Sciences has relatively few ethical implications, research leaders are still accountable for ensuring adherence to the University's formal ethical principles in respect of the nature, conduct, dissemination and foreseeable end-use of research and the behaviour of researchers. Ethical dimensions to Ph.D. projects are likewise considered at the point of inception.

The University Code of Practice for Research is underpinned by the five principles of the UK's Concordat to Support Research Integrity. The DMS supports the mission and goals of the UK Research Integrity Office (UKRIO) of which the University is an active member. Policies and procedures on Research Misconduct and Whistle-Blowing Policy enable staff in DMS and students to report issues of research misconduct without fear of recrimination. No such instances have occurred, a testament to the dedication to research integrity of our staff.

2. People**2.1. Staffing and recruitment policy**

The staff of the Department are our most important resource. Over the assessment period we have recruited 19 permanent academic staff (2 professors, 1 senior lecturer and 15 lecturers) and 20 postdoctoral researchers. The Department aims for all academic staff to contribute to the full range of teaching and research activities over the long term, and we aim to maintain a critical mass in each of our research groups. All appointments, including replacements, need to be justified by strategic planning. Other than occasional need to recruit into specific areas, by preference we have advertised appointments in all areas of research strength. Building a group in Statistics and reinforcing Analysis and PDEs were decisions informed by the recommendations from the International Review of UK research in Mathematics.

All job adverts for staff recruitment within the Unit are checked and approved by the Department Equality and Diversity Coordinator as well as by the School's Director. This ensures the use of inclusive language in job postings. The Department is proactive in approaching excellent candidates such as Postinghel (Algebraic Geometry) who was contacted directly to encourage her to apply.

Since REF2014, the University approach to recruiting excellent staff at all career stages, from postdoctoral and early career researchers (ECRs) through mid-career and senior roles, has radically changed, driven by the University Strategy and the associated People Strategy, which was formally adopted in 2019. Building on the University's 'Excellence100' campaign, recruitment to established posts is now conducted through biannual recruitment rounds, managed centrally but with significant School input, rather than piecemeal replacement hires. These rounds recruit with excellence as the single primary criterion, delivering better international recruitment and improved diversity in hires. We appoint only staff with the potential for, or demonstrable track-record in, high-quality research and impact creation. Since 2014, the majority of our academic appointments have been ECRs at lecturer level, to bring fresh ideas and a younger demographic profile, with hires at senior levels targeted at identified leadership need.

Excellence100 and the School's founding of interdisciplinary Research Centres allowed us to recruit for growth and our success is evidenced generally by the overall growth in numbers between REF2014 and REF2021, and more specifically exemplified by five new appointments to strategically strengthen the ICMM, including the Director position (Ala-Nissila from Aalto, Finland).

In Algebraic Geometry, we strengthened by appointing three lecturers with great promise: Ahmadiyeh, Postinghel and Thompson, who now form, with Prendergast-Smith, a vibrant group within the Department. Indeed, Thompson found a complete, explicit classification for a class of rational surfaces with involution (*Journal of Algebraic Geometry* 2020). This classification is a critical step in the solution of a 40-year-old problem to construct a compactification for the moduli space of $K3$ surfaces of degree 2 that is both geometric and modular.

2.1.1 Succession planning

Strategic emphasis on recruiting and retaining outstanding ECRs means we now have a group of future leaders moving through the grades. Normal practice is to appoint our Head of Department from within the staff of the Department, and the present Head has a deputy who is well-placed to take over in due course. Similarly, the directors of our Research Centres maintain deputies.

Nevertheless, where it is determined that external appointment to a leadership role is desirable, we have done that. During the assessment period, the Unit recruited Lombardo to a Personal Chair, to take up the position of SSci Associate Dean (Teaching), and Ala-Nissila was recruited as the inaugural Director of the ICMM.

Since 2015, all senior leadership roles in SSci and DMS have been filled following an open process inviting interested candidates to apply on an equal basis. This replaced a previous process that staff felt was unsatisfactorily opaque. DMS leaders have proved to be excellent leaders in senior University roles. For example, former Heads of Department Archer and Linton respectively served as Dean of SSci (2018) and Provost (since 2011).

2.1.2 Career pathways for part-time and fixed-term staff

Career pathways for part-time staff are the same as for full-time staff. Two senior DMS academic staff currently work part-time including one appointed to a professorial post on a part-time basis at their request. In promotion applications, appropriate adjustments are made and newly revised processes allow candidates to describe (in writing or to a promotions panel member) how part-time working and associated personal circumstances have affected their work.

Almost all fixed-term staff are postdoctoral researchers. As a consequence of strategic aims around funding and international collaboration, we are proud that the postdoctoral researcher community in this assessment period has been up to three times larger than its maximum at any time in the REF2014 assessment period. Their career development is supported within the Department and by dedicated support from the Careers Network, and our success is evidenced by follow-on appointments in international leading research groups. Within Loughborough, as for all fixed-term appointments, our redeployment register gives them priority for suitable positions at the University in the month leading up to the end of their contract.

2.2. Staff development strategy

All members in the Unit are supported through Loughborough's Organisational Development, which provides a variety of training targeted at staff at all career levels. Courses range from earliest stages ('Welcome to Loughborough') through essential training ('Information security training', 'Unconscious Bias') to training for staff becoming senior managers ('Coaching conversations for managers', 'Recruitment and selection').

Within DMS, staff are supported in a variety of ways: There are funds for international travel and attendance at external training events such as those run by the EPSRC. We view seminars as being crucial to our development. There are 8 seminar series in the Department (Dynamical Systems, Statistics, Stochastic Analysis, Analysis, Applied Mathematics, Geometry and Mathematical Physics and the broad appeal Mathematics Review and termly Colloquia). These now take place only between the core hours 10am-4pm, so that staff with caring responsibilities are not inadvertently excluded from participating.

All colleagues are expected to obtain Fellowship of the Higher Education Academy (HEA). For new lecturers, this is integral to their dedicated development programme. More experienced colleagues are supported through our 'Recognition of Experienced Practitioners' scheme which requires preparation of a dossier of evidence to support their application.

2.2.1 Mentoring

Mentoring for DMS staff is available at all career stages, and is integral for new lecturers. For established staff, mentoring is available to enable the transmission of knowledge, skills and experience in a supportive way. Any member of staff in the School can approach a senior colleague to become a mentor. For example, Linton has acted as mentor for Archer, who in turn has been a mentor for more junior colleagues (Discacciati, Shendruk). For research staff, a dedicated mentoring scheme is in place at institutional level.

2.2.2 New Lecturers' Programme (NLP)

All new lecturers are guided by an experienced and trained academic colleague from the DMS who acts as Adviser. The NLP (formerly academic probation) was substantially revised in 2017 and includes the full spectrum of research and impact activity (publication, funding applications, collaboration, public engagement, non-academic partnerships). New lecturers have a reduced workload in teaching and administration (33, 50 and 67% of Departmental norms in consecutive years), which enables the establishment of a full academic profile in research, teaching and impact at a manageable pace. In addition to an extensive training programme leading to FHEA, the New Lecturer meets four times annually with their Adviser. Minutes of these meetings, as well as overall progress, are monitored in the School and by the University. The School of Science commits to providing a Ph.D. studentship, with support provided by an experienced colleague who acts as a co-supervisor. Supervision is a requirement to pass the programme, alongside a minimum expectation on research output production, and the submission of at least one substantial grant application. Start-up funding of £1k *per annum* is available to all New Lecturers while on the programme.

Of staff members that completed the NLP during the assessment period, Discacciati, Garetto, Prendergast-Smith, Renzi and Sibley all went on to secure promotion to Senior Lecturer. This speaks both to the quality of the appointees, and the effectiveness of the support provided.

2.2.3 Support and integration for research staff

Research staff in the Unit are treated in the same way as other staff of the Department. For example, they are invited to all Departmental and School Staff Meetings and have access to internal travel money. The Loughborough University Research Staff Association is influential in promoting the research staff community and runs the Research Staff Mentoring Programme.

2.2.4 Performance and Development Review (PDR), reward and promotion

All members of post-probationary staff in the Unit have an annual **Performance and Development Review (PDR)**. This has been the case since 2014, and earlier, but the University scheme was totally updated in 2017, with a much stronger focus on development. The PDR is centred on a one-to-one discussion between the reviewee and a trained reviewer. In DMS, the Head of Department and 6 senior staff act as reviewers. Participation is 100% for all eligible DMS staff. The discussion focuses on strengths, ambitions, and areas for development across the full range of activities including CALIBRE-aligned goals for research and impact activity. One result of the new PDR has been an open and transparent way for the institution to recognise

performance exceeding expectations with additional financial **reward**, through one-off lump sum payments, or an additional spinal-point salary increment. The new scheme has particularly benefitted our research staff for whom a rigorous developmental discussion was previously sporadic and consideration for reward a rarity.

Another outcome is much fairer identification of candidates for **promotion**. The University has also revised the criteria for academic promotion (Senior Lecturer and Reader / Professor), to ensure that the research components align with the University Strategy and CALIBRE. Evidence for cases can be based on research, teaching, enterprise (impact) or any combination to encourage balanced portfolios of work. We judge 'Excellence and International Reputation' and 'Academic Leadership and Influence' rather than traditional metrics based on quantity and not quality. This focus allows panels to take into account statements from promotion applicants describing how personal circumstances, such as caring responsibilities, may have affected their profile. The Unit has enjoyed many promotions since 2014: Archer, Brown, Mazzocco and Kenny were promoted to Professor, Bahsoun and Strohmaier to Reader, with Bartsch, Discacciati, Feng, Garetto, Novikov, Prendergast-Smith, Renzi, Shendruk, Sibley, Tseliuko and Zhou to Senior Lecturer.

With an eye on retention of outstanding recently recruited staff, a 'buddy' scheme was recently introduced in the School to support promotion applicants. Applicants are paired with a senior colleague to help them prepare. Four DMS colleagues have volunteered as potential 'buddies' and one successful promotion has already resulted, even though the scheme only began in 2020.

2.2.5 Research and Impact Leave

Two schemes are available to enable staff to take time away from regular duties and dedicate time to a particular activity to support the strategic academic ambitions of the applicant and the University, in research, impact or education. At institutional level, 'University Fellowships' are competitively awarded for up to 12 months, with up to £5k for research expenses. A complementary scheme is run by the School. Ten DMS staff that have benefited from these schemes since 2014: Archer, Bartsch, Brown, El, Ferapontov, Janson, Mazzocco, Strohmaier, Winn and Zhao. For example, Archer had dedicated time to work with M-Solv Ltd to crystallise the impact from his research which led to one of our Impact Case Studies while Zhao prepared his ultimately successful EPSRC Fellowship proposal.

2.3. Research students

Training the next generation of researchers is a key priority of our Department. We treat Ph.D. students as partners in our research and their research contributes to our collective output in an essential way. Important work done in collaboration with our research students includes the work of Bolsinov and (student) Izosimov, "Singularities of bi-Hamiltonian systems", published in *Communications in Mathematical Physics* 2014, in which they developed a conceptually novel approach in the study of qualitative dynamics of bi-Hamiltonian systems. The approach has been thereafter successfully used for stability analysis of equilibria and periodic trajectories of such systems, and the results were presented at an invited talk at the XVIII International Congress of Mathematical Physics, Chile, 2015. While the work of Khusnutdinova and (student) Zhang, "Long ring waves in a stratified fluid over a shear flow", published in *Journal of Fluid Mechanics* 2016, revealed a new linear modal decomposition in the far-field set of Euler equations describing ring waves in a stratified fluid over a parallel shear flow, with applications to oceanic internal waves. This publication formed part of the prestigious LMS Mary Cartwright Lecture given by Khusnutdinova in 2019. The number of Ph.D.s awarded by the Unit has grown to 68.75, 60% growth relative to the 2014 assessment period.

2.3.1 How we fund our research students

Our PhD population is around 35-40 at any given moment, supported by EPSRC DTP funding, research grant funding, industrial funding (e.g. by Ashahi Glass Co.), university and self-funding.

Each year the Doctoral College allocates 15, on average, fully funded studentships to SSci, which are then allocated to staff members within the Departments in a competitive process following Prioritisation Principles in the School Strategy. This ensures that, for example, new lecturers have access to studentships to enable them to meet the supervisory requirement of NLP. Prioritisation is also given to members that have made (possibly unsuccessful) applications for external funding to support research students.

Through CALIBRE's *Adventure* Programme, the Unit has been very successful in securing funding for two topical mini-CDTs (cohorts of 5 Ph.D. students). The first is to train research students on understanding the fundamental science of pattern formation and self-assembly, while the second one aims to train research students on geometry in robotics, algorithms and design.

Moreover, the DMS has also accessed, 12 times over the assessment period, the University's full and partial fee scholarships for international applicants from China, Kazakhstan and Turkey. There is also Ph.D. scholarships specifically for elite athletes and DMS has had a student on this scheme.

2.3.2 The approach to recruiting research students

All PGR students are recruited according to the University's admissions policy which explicitly encourages applications from academically able and motivated students of all ages, and from all backgrounds. The process of recruiting and selecting students is designed to be fair and accessible, and applicants with protected characteristics are invited to identify support requirements they may initially have. Decisions on the admission of candidates are based on potential and are taken by two members of staff after an interview, typically held online, has been conducted. PGR students are welcomed at quarterly intake points which helps to foster cohorts of students.

2.3.3 Monitoring and support mechanisms

At least three members of staff are responsible for monitoring the progress of each student: a first and second supervisor and the independent reviewer (IR). The move to having two supervisors by default means all students now have access to a second point of support. The supervisors provide guidance on the academic content of the project, training required and pastoral care. They have regular meetings with the student and monitor their progress closely. These meetings are recorded on a University system to ensure that an agreed minimum level of supervisory support is provided and to ensure UKVI compliance. In practice, in Mathematics, the number of meetings far exceeds the mandated minimum. The IR monitors the overall progress of the student and assists if problems arise.

There is an initial review point at the 6-month stage, at which Ph.D. candidates prepare a report of approximately 5,000 words. A report of approximately 10,000 words is produced at the end of their first year, with a record of seminars and training courses attended. If progress is satisfactory, further reports are required at the end of their second and third year. If not, a meeting between the student, supervisor and IR is held to determine future action.

PGR students enjoy their own high-quality space within the newly refurbished Mathematics building. Students' offices are all in close proximity to each other to help develop their own community. SSci Departments all have an elected PGR student representative, who is the first point of contact regarding any issues that need to be resolved. The PGR representatives participate in the PGR Staff-Student Liaison Committee that offers a direct dialogue between staff and students. As an example of a consequence of this dialogue, the School is currently developing better induction information to help students and supervisors better align their expectations at the start of projects, in line with University expectations.

2.3.4 PGR skills development

An extensive doctoral training programme is delivered by the Doctoral College. This non-discipline-specific training covers specific ('What is a literature review?', Library training) and general skills ('Getting the most out of supervision'), amongst many others. All DMS PGR students are required to broaden their mathematical training by attending and being assessed in courses that are not directly related to their Ph.D. topic, and engagement is monitored through the annual review. The Unit is a member of the MAGIC consortium (Mathematics Access Grid: Instruction and Collaboration) joining 19 UK Universities. These courses cover a wide range of mathematical topics. Courses supplied by Loughborough are: Integrable Systems (Veselov), Lie groups and Lie algebras (Bolsinov), Nonlinear Waves (Khusnutdinova).

Moreover, students compulsorily attend regular weekly seminars and give presentations. Each year the Unit organises a one-day Ph.D. workshop and the best presentation is awarded the Sir David Wallace Prize, named after the former Loughborough Vice-Chancellor who went on to be Director of the Isaac Newton Institute for Mathematical Sciences. Ph.D. students attend conferences and meetings at other institutions to disseminate their research and interact with other researchers. The Unit guarantees that all Ph.D. students are funded to attend such events.

Around 60% of students take the opportunity to gain experience in teaching either by delivering tutorials to undergraduates or by marking coursework. Before undertaking teaching work, students are required to attend a Professional Development course on Teaching Skills designed for Ph.D. students.

2.4. Equality, diversity and inclusion (EDI)

EDI matters have high status and priority at Loughborough and no more so than in SSci. Mathematics received a Silver Athena SWAN award in 2015. The whole of SSci subsequently received a Bronze Award in April 2019.

DMS works with SSci to formulate School-level policies and initiatives. This work is led by a Director for Equality and Diversity (DE&D), who is a member of the School Senior Management Team. The current DE&D (Hunsicker) is from this Unit and she leads a group of five Departmental coordinators. These roles have an associated budget and workload credit. The DE&D monitors activities and outcomes in the School, and works with both a School level Athena Swan Self-Assessment Team (SAT) and a School Equality and Diversity (E&D) Committee, with representation across Departments, job families, levels and diversity characteristics. The DE&D additionally sits on both the University level SAT and the University E&D committee.

There is strong leadership for EDI within SSci, with substantial personal commitment. In particular, the Dean is a woman Professor of Theoretical Physics and a single mother of two children, who herself works flexibly to accommodate her caring responsibilities. Lombardo, one of the Associate Deans, has been involved in EDI activities through her work with the STEM outreach group NUSTEM and on the LMS Women in Mathematics (WIM) Committee. The DE&D (Hunsicker) has had a substantial and long-term involvement at the national level through LMS WIM Committee, of which she is Chair, and through the Athena Forum, of which she is co-chair. She is also involved with the charity Pride in STEM, the group Black Excellence and is a member of the STEMM-Disability Advisory Committee. These works subsequently led to Hunsicker and Lombardo receiving the Suffrage Science award, celebrating achievements of women in STEM disciplines, and Hunsicker became recognised as a Fellow of the Association for Women in Mathematics.

2.4.1 Flexible and/or remote working

Formal flexible working requests may be submitted for approval by HR. These arrangements are available to all members of Unit staff, recognising that enabling each person to optimise their work/home balance is an overall benefit to the Unit. Academic staff within SSci may request up

to one hour each day guaranteed to be free from teaching. This allows staff additional flexibility to accommodate e.g. school runs. Academic staff also have the ability to work flexibly or remotely on an informal basis so long as their responsibilities are fulfilled. For other circumstances, such as caring for a family member in poor health, staff can request compassionate leave for immediate issues or longer-term flexible working for ongoing responsibilities.

Remote working is facilitated through the remote working portal, which permits staff to access all online resources remotely, as well as through the choice that academic staff have between a desktop computer or a laptop with docking station and screen for their office.

These policies and supporting infrastructure have eased the transition to effective home working during the COVID-19 pandemic from March 2020.

2.4.2 Conference attendance or travel to support research

Conference attendance and other necessary travel to support research is facilitated for staff and research students with caring responsibilities, ill health etc. through the SSci caring grant scheme, which covers additional costs associated with caring when participating in any career development activity, including conferences and research visits. The SSci DE&D undertakes an annual equality analysis to monitor for unintended bias.

2.4.3 Support for submission of funding applications

The School pays special and increasing attention to equality and diversity in supporting funding opportunities, supported by University data for grant applications and awards analysed by protected characteristic. For example, support for Garetto's and Postinghel's successful EPSRC new investigator awards shows a response to the lower success rates apparent nationally for female academics.

2.4.4 Support for staff and research students returning from periods of leave

For staff returning from extended leave (including parental leave) or ill health, a workload reduction equivalent to teaching one module in the first year and half a module in the second is applied. In addition, they are not expected to pick up substantial administrative positions during this period. This is to support them in their return to research.

For 2014–2019, 9 academic maternity leave returners in SSci remained in post 2 years later (100% retention). In this Unit, Ahmedinezhad, Garetto, Postinghel and Zhou (2 periods of leave) benefitted from maternity or shared parental leave.

2.4.5 Support for staff with protected characteristics

Regarding ill health and long-term illness, these are dealt with through the University's Occupational Health department, which meets with staff and determines accommodations to their work schedule or working environment to allow them to continue in their role. Support for staff with protected characteristics (e.g. disabilities) to enable them to work productively is done through Occupational Health. The University facilitates 10 staff support groups for members to support one another, and raise any concerns, including BAME, LBGT+, and Religion and Belief groups.

2.4.6 Supporting the well-being of staff and research students

There is a variety of support available to staff and research students to support well-being. In 2017, SSci trained 13 Mental Health First Aiders, including a Senior Lecturer in DMS, who are available to talk to colleagues in confidence about any issues causing stress, including bullying, harassment or discrimination. There is also a well-being advisor in the School who supports staff and students with any well-being issues. The University also has a counselling service and the University subscribes to an external service that provides both 24-hour telephone counselling for a variety of well-being issues and counselling sessions for staff with more complex issues. All members of staff received a personal letter from the Vice-Chancellor advertising the availability

of this scheme. Staff who are unwell are supported by their line managers/supervisors during PDR by discussing what adjustments to working conditions or workload can be accommodated. In 2019, all PDR reviewers attended a mandatory, bespoke training: 'The Art of the Inclusive Performance Conversation' which helps reviewers to embed best practice in inclusivity around the PDR discussion.

2.5. Equality and diversity issues in the construction of the REF submission

This submission complied fully with Loughborough's REF Code of Practice (CoP) and supported its commitment to complete equity of treatment of eligible staff with respect to all relevant protected characteristics.

All persons involved in peer-reviewing and preparation of the submission attended a two-hour bespoke REF-specific EDI training course, the details for which are outlined in our CoP. Members of the wider pool of reviewers attended a mandatory online unconscious bias training. We rigorously applied the decision tree set out in the CoP to establish if any of our research staff should be considered as independent researchers to be included in our list of Category A staff.

Outputs have been selected for REF2 on the basis of self-evaluation and peer moderation. Each member of submitted staff was asked to select and assess up to 5 research outputs that constitute their very best work over the submission period. These self-assessments were moderated by reviewers chosen from adjacent subject areas. The reviewers, consisted of the research coordinator, 3 female and 3 male colleagues. At least two reviews were made of each output, with further consideration made in case where reviewers disagreed. These final ratings were used to rank all outputs, from which the top-ranked were selected for return while ensuring the minimum of one of output for all. An extensive programme of Equality Impact Assessments showed no evidence of bias in output selection.

Likewise, the Impact Case Studies (ICS) were chosen following a process, involving members of the Unit submission team, senior University colleagues led by the Pro Vice-Chancellor for Research (PVCR), and external lay reviewers. At all stages, the proposed ICSs were judged solely against the REF criteria of significance and reach.

A confidential University-wide procedure allowed staff to report circumstances that may have affected their ability to research productively throughout the REF period through a secure online form. A group comprising the PVCR, Deputy Director of Human Resources and two Research Policy Managers reviewed the cases and made decisions on whether the circumstances described merited a reduction in expectations according to REF guidance. The reasons behind any reduction in expectation were not shared outside this small group (unless the individual concerned specifically asked for this) but checks were made to ensure adequate support was in place.

3. Income, infrastructure and facilities

3.1 Research funding and strategies for generating research income

One of the goals for the REF2021 assessment period was to achieve growth. The accomplishment of this goal was achieved through remarkable success in obtaining external funding. This includes 14 Standard/New Investigator EPSRC research grants; grants from The Leverhulme Trust: 3 by Bahsoun and 1 by Neishtadt; grants through the Royal Society: 1 by Renzi and 1 by Zhao, a research grant from AXA by Renzi, a network grant from the EU Commission by Bartsch, and finally the major grants of £1M by Zhao (EPSRC Established Career Fellowship) and £1.25M by Shendruk (ERC Fellowship). These grant successes were underpinned by a new internal reviewing process prior to submission of the applications. This

includes a review by an academic from a different scientific discipline and mock interviews where appropriate e.g. Fellowships from EPSRC and ERC.

In addition, several staff have obtained funding as Co-investigators, from different funding bodies, and DMS has hosted research fellows (Casati, Fatighenti, Michele, Scacchi) supported by their individual fellowship grants.

It is inevitable that funding supports high quality research, as reflected in the **high quality outputs produced from funded projects** during the assessment period. For example, the EPSRC grant EP/L026422/1 secured by Garetto on hyperbolic systems with multiplicities led to a publication in the prestigious journal *Mathematische Annalen* and the results of this project are now being used for numerical simulations to model hyperbolic equations with discontinuous coefficients. The EPSRC grant EP/P015689/1, secured by Archer, answered the fundamental question: which wave numbers determine the thermodynamic stability of soft matter quasicrystals? This work was published in the world's premier physics letters journal *Physical Review Letters*.

External **funding has played a major role in delivering impact** including within current impact case studies. In particular, the EPSRC grant EP/C524322/1 secured by Smith led to the case study on Bader charge analysis. In addition, as a result of the follow-on work carried out under this grant, Ashahi Glass Co. has supported Ph.D. studentships whose research underpins part of another impact case study, on modelling thin film coatings.

During the assessment period, **major and prestigious research grants** have included the **£1.25M** ERC grant no. 851196, secured by Shendruk, and a **£1M** EPSRC Established Career Fellowship, EP/S005293/1, secured by Zhao. Shendruk's project aims to simulate fascinating behaviours displayed by biological molecules and microorganisms and to design a new class of man-made materials. Zhao will develop a mathematical framework for periodic stochastic dynamics that is amenable to identify random periodic patterns in the climate system and in financial markets.

3.2 Organisational infrastructure supporting research and impact

In collaboration with Research Development Managers and other professional service staff in the Research and Enterprise Office (REO), SSci has developed and implemented comprehensive support for staff in preparing funding applications by actively supporting the drafting of applications, internal peer-reviewing, setting up mock interviews, negotiation of legal agreements, and by providing post-award financial administration of grants and contracts. For example, to facilitate collaboration towards a future impact case study the Loughborough contracts, finance and marketing team negotiated a contract between Archer and the external company.

In 2019, the Research and Enterprise Offices were merged into one Professional Service under the leadership of a new Director in order to provide comprehensive support for the research and enterprise cycle from research development through to impact generation, partnership development and commercial exploitation of Intellectual Property.

3.3 Operational and scholarly infrastructure supporting research and impact

The University continues to provide facilities and infrastructure to attract and retain the very best academics. In line with this, the University made a £4M capital investment to relocate the Department to a newly refurbished building in 2015, with an increased number of offices to accommodate the strategic expansion in the number of academic and research staff and research visitors. This relocation has significantly improved the accessibility of all parts of the building for disabled and partially-able staff and visitors, and includes non-gender-binary bathrooms.

In addition to routine computational equipment, the University has extensive high performance computing (HPC) facilities available for research use. The HPC service comprises the hydra cluster, a 2460-core 64-bit cluster, and the soon to be introduced Lovelace cluster. There is also access to the HPC Midlands Plus, which is Tier-2 HPC with a focus on Engineering and Physical Sciences, funded by EPSRC. Within the Department, we have a cluster of 24 multi-processor Macintosh computers primarily funded from research grants, that is available to all researchers in the School. For example, the computations underpinning our impact case study on modelling the manufacture of surface coatings and structures were performed using these facilities.

4. Collaboration and contribution to the research base, economy and society

4.1 Research collaborations, networks and partnerships

All DMS staff have actively collaborated with international colleagues during the assessment period, leading in all cases to either joint publications or an ongoing collaboration. These include the collaboration of Ala-Nissila with the Physics Nobel Laureate Kosterlitz (Brown), Ahmadinezhad with Shramov (Steklov Institute), Archer with Knobloch (Berkeley), Bahsoun with Liverani (Rome), Bartsch with de la Llave (Georgia Tech.), Barros with Choi (New Jersey), Bolsinov with Matveev (Jena), Cuenin with Kenig (Chicago), Discacciati with Quarteroni (Milan), Eckhardt with Teschl (Vienna), Ferapontov with Zagier (Bonn), Garetto with Ruzhansky (Ghent), Hunsicker with Banagl (Heidelberg), Janson with Kloeden (Tübingen), Neishtadt with Kuksin (Paris VII) Prendergast-Smith with Coskun (Chicago), Renzi with Dias (Dublin), Sibley with MacDowell (Madrid), Thompson with Alexeev (Georgia), Tseluiko with Stone (Princeton), Veselov with Felder (ETH Zürich), Ward with Chen (Taiwan), Winn with Anantharaman (Strasbourg), among others. For instance, the collaboration with Kosterlitz led to a consistent hydrodynamics for phase field crystals and the work with Coskun led to a publication on the Morrison-Kawamata cone conjecture, one of the major conjectures in birational algebraic geometry, and obtained some of the strongest known results to date in this direction.

Supporting each individual's personal networks, DMS has formal structures in place to facilitate international collaborations. For example, DMS and SSci maintain funds for international travel and to support visitors. Moreover, the DMS organises several well-attended annual networking meetings, such as Annual International ICMM workshop on Mathematical Modelling, Integrable Days, One Day Ergodic Theory Meeting.

4.1.1 Evidence of how staff interacted with, engaged with or developed relationships with key research users, beneficiaries or audiences to develop impact

Our impact strategy elements on 'direct engagement with business' and 'public engagement' have fostered an outward-looking attitude in our staff which has led to several impact generating activities over the REF period. For instance, in August 2016 Jansen was invited to visit Copenhagen University to deliver a series of lectures on applied dynamical systems. These lectures are being used by students of Copenhagen University as a standard learning tool, by research students across Europe collaborating with the Copenhagen group, and also by internet users interested in these topics.

Renzi secured grants that supported the development and distribution of a free, online educational videogame (Storm Force) with the objective of saving lives by teaching children how to identify early warnings of coastal flooding. Renzi partnered with game company 'peek and poke' through which came a relationship with and subsequent endorsement from the United Nations Office for Disaster Risk Reduction, as well as a nomination at the prestigious TIGA Awards (2019). (TIGA is the trade association representing the video games industry.) Off the back of this success, Renzi developed a "Subject in a Box", which is an innovative activity to help schoolteachers offer their class a unique insight into degree-level study whilst providing an engaging, interactive lesson. As of March 2020, the Storm Force Subject in a Box has already been trialled in four schools (two each in London and Leicestershire), involving more than 250 children.

4.1.2 Engaging with diverse communities and publics

The DMS views broad engagements as crucial to its mission, and encourages and supports staff in doing this. Examples include:

- In a TEDx conference (2016), which is a grassroots initiative created in the spirit of TED's overall mission to research and discover "ideas worth spreading", Janson gave a bold talk entitled "Can We Resolve the Mind-Body Problem with Mathematics?". Aimed at a general audience, she outlined an old philosophical problem about the brain, and explained how modern mathematics, in particular dynamical systems theory, could help resolve this problem scientifically.
- Hunsicker collaborated to produce the film Faces of Women in Mathematics for International Women's Day 2018 featuring cameos by women mathematicians. The video, which attracted almost 4000 views, drew attention to the contributions of women from all around the globe to mathematics.
- A distinctive collaboration with Woolsthorpe Manor (Newton's birthplace) included demonstrations and public lectures on dynamical systems by Neishtadt and Smith. Subsequently (2019), DMS was gifted a direct descendent of Sir Isaac Newton's apple tree at Woolsthorpe by the National Trust in recognition of the work of Neishtadt and Smith. Former Vice-Chancellor Sir David Wallace and celebrated mathematical physicist Sir Michael Berry were welcomed to the tree planting, which was followed by the prestigious Sir David Wallace Lecture given by Richard Keesing, University of York, a renowned expert in the history of Newton's apple tree and the discovery of universal gravitation.

4.2 Evidence of the unit's contribution to the sustainability of the discipline

The Unit organises its traditional annual Christmas lecture and its Sir David Wallace lecture, which are both open to the public. Invited speakers are selected based on their ability to communicate to a general audience and diversity principles. Speakers during this assessment period include Simon Singh (Christmas Lecture), Colva Roney-Dougall (Christmas Lecture) and the **Fields Medallists** Sir Michael Atiyah and Cédric Villani (Sir David Wallace Lecture). The Unit also contributes to events such as the National Science and Engineering Week and provides work experience for school students during the summer holidays.

During this assessment period (2015), DMS hosted the prestigious LMS Undergraduate Summer School. Lecturers introduced modern mathematics to the best UK undergraduates who were not in their final year of study, thus stimulating their interest in higher level mathematics and encouraging them to pursue a Ph.D. in mathematics. The school contained a combination of short lecture courses with problem solving sessions and colloquium style talks from leading mathematicians. Such activities include training on using Maple through a small mathematical project such as 'the PageRank algorithm and the Google search engine'.

4.3 Indicators of wider influence

Members of the Unit have made significant contributions to the wider research base during the assessment period. They are continuously involved in active collaborations with leading institutions around the world and several hold **Visiting Professorships**, including University of Leeds (Archer), Moscow State University (Bolsinov and Veselov), and Shandong University (Zhao).

Our growth strategy has also led to an increase in influence in the Mathematics community. This is demonstrated by the significant increase in **attracting externally funded long-term visitors** such as Prof. Alves, Porto (1 year, funded by The Leverhulme Trust) to collaborate with Bahsoun, Prof. MacDowell, Madrid (6 months, funded by the Spanish Ministerio de Educacion, Cultura y Deporte) to collaborate with Archer and Sibley, Prof. Liu, Xi'an Jiaotong University (1 year funded by Royal Society) to collaborate with Zhao. In addition, several research fellows were attracted to DMS: Dr Casati (1.5 years funded by Marie Curie Fellowship) to collaborate with Ferapontov, Dr. Fatighenti (2 years funded through the EPSRC Doctoral Prize) to

collaborate with Ahmadinezhad, Michelle (3 years, funded by the Royal Society to collaborate with Renzi, and Scacchi (1.5 years funded by the Swiss Research Council SNSF) to collaborate with Archer.

During the assessment period, Unit members have served in **key positions with learned societies, funders and professional bodies**. For example, Linton was President of the IMA for two years, while Hunsicker became the LMS Women in Mathematics Committee chair and the Athena Forum deputy chair. Moreover, while Linton served as a Member of the EPSRC Strategic Advisory Network (2013-2019), during the assessment period new key EPSRC roles were taken by Lombardo, who was selected to join the EPSRC Mathematical Sciences Strategic Advisory Team, Hunsicker, who was selected to join the EPSRC Advisory Board for Reimagining Recruitment and Ahmadinezhad served on the EPSRC early career forum 2017-2020. Smith and Zhao have continued to serve on the EPSRC Peer Review College, and there has been a significant increase in new memberships to the College during this assessment period (Ahmadinezhad, Ala-Nissila, Archer and Bahsoun).

Editorships: Ala-Nissila, Bahsoun, Bolsinov, Ferapontov, Khusnutdinova, Linton, Lombardo, Neishtadt, Shimadzu, Veselov have all served on editorial boards of peer reviewed journals during the assessment period. In particular, Neishtadt was **Co-Editor-in-Chief** of the prominent journal **Nonlinearity** until the end of 2014, and also served on the editorial board of **Chaos** (2001-2018), Lombardo became an Editorial Board Member of the **Proceedings A of the Royal Society** (2017-) and Khusnutdinova became an Editorial Board Member of **Nonlinearity** in 2020. In line with our REF2014 aim to support diversity, we are proud to see this recognition, in the latter two cases, of female colleagues.

During the assessment period, members of the DMS significantly contributed to the **organisation of major events and conferences** including programmes at leading international research institutions such as: EFPL, Lausanne (Ala-Nissila), Isaac Newton Institute, Cambridge (Lorinczi), Max Planck Institute, Dresden (Smith), Institute Henri Poincaré, Paris (Bahsoun), ICMS, Edinburgh (Archer, Ferapontov, Novikov, Thompson), CSF ETH Zürich (Bolsinov, Veselov).

The DMS views organising research and impact conferences and workshops as being essential to the national and international mathematics community. Since 2014, we have organised over 20 international conferences and workshops, attracting the participation of world leading mathematicians to Loughborough. This includes:

- LMS-CMI School, Statistical Properties of Dynamical Systems, including 5 lectures by **Carlangelo Liverani (Rome)**, and an invited lecture by **Mark Pollicott (Warwick)**, 2015.
- LMS Invited Lectures: including 10 lectures by **Edgar Knobloch (Berkeley)**, 2016.
- Kodaira workshop in Algebraic Geometry, including a talk by the **Fields Medallist Caucher Birkar (Cambridge)**, 2019.

A highlight was our hosting of “Dynamics Days Europe 2018”, a major international conference that attracted 400 delegates to Loughborough and had an impressive list of plenary speakers including **Mark Ablowitz (Colorado)**, **Viviane Baladi (Sorbonne)**, **Sylvie Benzoni-Gavage (Lyon)** and the **Fields Medallist Martin Hairer (Imperial)**.

These outstanding meetings and the research activities from which they arose showcase well the vibrant and remarkable research environment of the DMS.