

Institution: University of Warwick
Unit of Assessment: B10 Mathematical Sciences
<p>1. Unit context and structure, research and impact strategy</p> <p>1a) Unit Context and Structure</p> <p>The University of Warwick provides an exceptional environment for research in the Mathematical Sciences, hosting a large and extremely active group of researchers belonging to the departments of Mathematics and Statistics covering the whole spectrum of the disciplines. The REF period 2014-2020 has seen dramatic research successes by members of the two departments, including the award of the Fields Medal to Martin Hairer, and very significant investment of resources in mathematical sciences by the university. In particular at the end of 2018 the University opened a brand new Mathematical Sciences Building costing £28M, providing a 40% increase in space for Mathematics, Statistics and Computer Science.</p> <p>The standing of the two departments was recognised by the Queen's Anniversary Prize for research in Mathematics and Statistics in 2015 and the Mathematics Institute appointed to its newly awarded Regius Professorship in mathematics in 2014.</p> <p>Indicators of esteem</p> <p>The excellence of our staff members has been recognised in many ways during the period, in particular:</p> <ul style="list-style-type: none"> ● 3 staff were elected FRS in the period (Hairer, Series, Stuart) ● 6 staff gave ICM lectures and 1 an IMS Medallion lecture ● Presidents of the IMA, LMS and the Bernoulli Society were faculty members ● 5 members of staff won Wolfson Merit Awards ● 12 of our staff held ERC grants ● Staff received 3 Philip Leverhulme Prizes, 13 LMS prizes, a Rollo Davidson Prize, a John Todd Award, an RSS medal, a Bartolozzi prize, a SASTRA Ramanujan prize and a Fields Medal. <p>Funding</p> <p>During the REF period the departments were awarded an average of around £8M per year in research grants from a diverse range of funders. Among them were 6 major Programme Grants with values of around £2.5M each, jointly held with other UK universities and overseas partners. The departments' research successes have also been recognised with the funding of 4 CDTs by EPSRC during the period.</p> <p>Structure</p> <p>Formally the departments of Mathematics and Statistics are separate units within the Faculty of Science, Engineering and Medicine but they occupy the same buildings and cooperate extensively in research, postgraduate training and teaching. A total of 131.5 FTE Category A staff are included in this submission, of whom 87.2 FTE are attached to Mathematics and 44.3</p>

FTE are attached to Statistics. (This compares with 104.1 FTE submitted to REF2014). A further 5 staff attached to the two departments are being submitted to other units.

A major cornerstone in an energetic research environment is the large group of excellent doctoral students. Warwick has proudly (co)hosted four EPSRC funded CDTs based in the unit since 2014, and the CDT model is now fully integrated into the departments' PhD programmes through the funding by the University of an additional Mathematics and Statistics CDT since 2019 (See Section 2). A thriving PhD programme also contributes significantly to our impact strategy (see 1c below).

The departments have an exceptionally vibrant research atmosphere. In addition to the regular colloquia, the departments between them run over a dozen weekly or bi-weekly seminars: Algebra, Algebraic Geometry, Algebraic Topology, Algorithms and Computationally-intensive Inference, Analysis, Applied Mathematics, Combinatorics, Ergodic Theory, Geometric Topology, Number Theory, Probability, Statistical Mechanics, Stochastic Finance and the CRISM seminar series. There are also three graduate student seminars: two in Maths and one in Stats.

The highly collaborative research culture in the departments, enabled by an open structure that encourages intradisciplinary exchange and avoids research group silos, has been augmented by a continuing workshop and visitors programme, bringing world-class experts from across the Mathematical Sciences to Warwick. This is particularly facilitated by four centres within the unit which stimulate and support workshop and visitor activity:

- 1) The **Mathematics Research Centre (MRC)** ran the annual EPSRC Warwick Mathematics Symposium during the period 2014-2019. In the Assessment Period, the MRC hosted 5 year-long symposia, organised 100 workshops and supported over 5,400 individual talks and seminars. The centre hosted approximately 2,450 international visits from 65 countries. An additional 1,950 visits were hosted from other UK institutions and organizations. The symposia were
 - i) Warwick EPSRC Symposium on Statistical Mechanics / Mathematics of Phase Transitions
 - ii) Warwick EPSRC Symposium on Derived Categories and Applications
 - iii) Warwick EPSRC Symposium on Fluctuation-driven phenomena and large deviations
 - iv) Warwick EPSRC Symposium on Partial Differential Equations and their Applications
 - v) Warwick EPSRC Symposium on Geometry, Topology and Dynamics in Low Dimensions
- 2) The **Centre for Research in Statistical Methodology (CRISM)**, funded through the EPSRC's Science and Innovation Awards scheme until 2016 has been highly successful in stimulating innovative research in the methodology of statistics. It has organised 22 workshops within the Assessment Period, and hosted 111 visitors (in addition to workshop participants).
- 3) The **Mathematical Interdisciplinary Research at Warwick (MIR@W)** programme has continued to provide a strong interdisciplinary focus to the unit's work. MIR@W days are half-day workshops intended to stimulate interaction between several departments in the university on topics of an interdisciplinary mathematical nature. During the Assessment Period 41 MIR@W workshops were held. (See Section 4 for some highlights).
- 4) The **Centre for Discrete Mathematics and its Applications (DIMAP)**, based in Mathematics, Computer Science and the Warwick Business School (WBS), also funded

through the EPSRC Science and Innovation Awards scheme, has built on and expanded its strong international reputation in Discrete Mathematics (including Graph Theory) and theoretical computer science. During 2014-2019, some 20 meetings (workshops, conferences, research days) received support from the Centre.

Interdisciplinary research

The two departments jointly or separately host or are strongly affiliated with several interdisciplinary research centres which serve to facilitate interaction with staff from other departments. These include: the Warwick Data Science Institute (WDSI, which is a hub for interaction with the Alan Turing Institute (REF5a-2.12.2); DIMAP (described above), the Complexity Science Centre which involves Computer Science, Maths, Physics and Statistics, and the Warwick Centre for Analytical Science (W-CAS), involving departments from across the Faculty of Science, Engineering and Medicine. Further details are provided in Section 4.

Warwick has one of the country's leading groups in mathematical biology and epidemiology, the Zeeman Institute for Systems Biology and Infectious Disease Epidemiology Research (SBIDER), which is now 4 years old, and has achieved remarkable success over this period publishing major papers for example in Nature Medicine, Nature Communications, Nature Nanotechnology, Nature Sustainability, P.N.A.S., the PLoS journals and the Lancet Global Health, and submitting 50 successful grant applications with a total value exceeding £28M. These include the MathSys CDT (£4.9M), a Health Protection Research Unit in genomics (£4M) and GeMVi (Application of Genomics and Modelling to the Control of Virus Pathogens) (£2M). Its significant role in the national COVID-19 response, its joint leadership of the Juniper modelling consortium that feeds into all the major government scientific groups on COVID-19 and the 4 Impact Case Studies it contributed (ICS1-SBIDER, ICS5-Keeling, ICS7-Rock, ICS9-Tildesley) are described in Sections 1c and 4c.

CRiSM contributes strongly to the unit's interdisciplinary research activity and the **Applied Statistics and Risk Unit (AS&RU)**, based within Statistics, has a specific remit to engage with outside partners. AS&RU encourages and co-ordinates external partnerships which enable the early applications of theoretical, methodological and algorithmic developments. AS&RU has directly contributed to two impact case studies (ICS3-French, ICS4-Hutton) and contributed further significant external impact which has not been recorded in case studies. Details of this and of further interdisciplinary research leading to external impact are given in Section 4c.

One of the key reasons that Warwick's interdisciplinary research is so successful is that we have been able to make joint appointments with other departments. Currently, we have joint appointments with Computer Science, with Engineering, with the School of Life Sciences (SLS) and with the Warwick Manufacturing Group (WMG). These appointments embody direct engagement between the departments involved.

1b) Research Strategy

The University of Warwick aims to be a world leader across a broad spectrum of the Mathematical Sciences, generating research which significantly advances the frontiers of Mathematics and Statistics and engaging in interdisciplinary research partnerships in which the power of mathematical science contributes to advances in other branches of science and in engineering, medicine and the social sciences. Both departments have a long and very strong record of attracting excellent academic staff, postdoctoral researchers, graduate students,

research visitors and research funding and have grown significantly during the relevant submission period. Neither department has a rigid division into research groups, with interest groups forming a close-knit network ranging in an unbroken continuum from pure to applied. This encourages interaction between specialities across the spectrum of the Mathematical Sciences, and much of our best research is produced at the intersection between two or more of these areas. There are additional formal links between the two departments at the PhD training level through the various Warwick CDTs. Research in Operational Research is mainly based in the Operational Research and Management Sciences group (ORMS) in the Warwick Business School (WBS). We have strong connections with this group through the DIMAP centre, as well as many teaching connections, but ORMS staff have been submitted to unit C17.

In the assessment period, the goals the unit set in 2014 have seen substantial progress:

- 1) *Continue to build on areas of strength and hire internationally leading researchers in these areas at all levels.* Between 2014 and 2020 we have made 48 new permanent hires, and in that period 31 permanent staff left. We have also made 21 appointments to Zeeman and Harrison lectureships (attractive 3 year fixed-term positions for promising ECRs).
- 2) *Emphasis on enhancing applied/numerical analysis.* We have appointed 7 staff with research interests in the area (Evans, Gomes, Grafke, Hudson, Lotz, Sprittles, Wolfram), contributing both theoretically and in applications.
- 3) *Expansion, especially in areas that interface with computer science, machine learning, and the analysis of large datasets and data streams.* In March 2015, the University of Warwick became one of the five founding members of the Alan Turing Institute, the national institute for data science and artificial intelligence (REF5a-2.12.2). Among the 44 researchers from Warwick who are fellows of the Turing, the presence of the Mathematical Science departments is particularly strong: as of October 2020, 16 Turing Fellows are affiliated with the unit. Mijatovic, Vollmer, Kosmidis and Damoulas, all of whom have significant leadership roles within Turing, were hired by Warwick during the assessment period. Four joint appointments were made in the departments in this area during the assessment period (2 with Computer Science and 2 with the Turing).
- 4) *Expand and strengthen the existing interdisciplinary research in Epidemiology (through links with WIDER and its other partners) and Systems Biology.* The Warwick Systems Biology Centre (WSB) and the Warwick Infectious Disease Epidemiology Research Centre (WIDER) were amalgamated in 2016 to become SBIDER and expanded through high-calibre appointments (Didelot, Dyson, Gorsich, Penman, Rock, Tildesley). The outstanding success of SBIDER is detailed at appropriate places throughout this document.
- 5) *Build strategic research programmes around four EPSRC Programme Grants led from Warwick, a Leverhulme Research Leadership award and renewed funding for the Centre of Research in Statistical Methodology (CRiSM).* Three further Programme grants or equivalent large grants led or co-led by Warwick were awarded during the period. These seven programmes were highly successful resulting in a total of more than 54 postdoc years at Warwick. Specific highlights, and the relationship to our ongoing strategy are detailed in Section 3.
- 6) *Make appointments to support activity in the areas covered by CDTs.* We made 6 appointments during the assessment period (Cimpeanu, Dyson, Hudson, Rock, Tildesley, Wolfram) in the area of MathSys and 3 more associated to MathSys II with arrival after the REF census date. The supervisory pool for OxWaSP includes 7 appointments made during the assessment period (Dutta, Herdegen, Jenkins, Koskela, Mijatovic, Tavakoli and Vollmer).

7) *Increased focus on research that connects with research users and other beneficiaries.*

During the assessment period, the former Risk Initiative and Statistical Consultancy Unit expanded its focus to become the Applied Statistics and Risk Unit (AS&RU). The MathSys and OxWaSP CDTs, both with a strong focus on external research users were also established during the assessment period. A comprehensive impact strategy was developed, details of which are given in Section 1c.

To this point, this section has described the implementation of our previous strategy. Our future aspirations are formulated as part of the University's Strategic Renewal process, in which departments make plans for the 5-10 year timescale. The Mathematics Department is currently completing this process, and the Statistics Department is just beginning. The following feature prominently in Strategic Renewal.

- 1) Continue to build on areas of strength, hiring internationally leading researchers and developing highly skilled early career postdoctoral and PhD researchers.
- 2) Focus systematically on engagement and impact through the development of the Centre for Applications of the Mathematical Sciences (CAMS) (a joint venture between Mathematics, Statistics and Computer Science, very much in the spirit of the Bond Review; see Section 1c for further details).
- 3) Expand and strengthen interdisciplinary research. (i) In epidemic modelling this will build on the leading role of SBIDER in the Government COVID-19 response. Our aim is to continue to grow SBIDER, in terms of income, publications and staff and looking to broaden capability in systems biology and more general mathematical/quantitative biology. (ii) In data science this will build on Warwick's active participation in the Alan Turing Institute. (iii) The University's STEM Grand Challenge (REF5a-4.2) will provide opportunities for interdisciplinary engagement between Mathematical Sciences, Physical Sciences and Engineering.
- 4) Continue to develop the CDT model across the range of our PhD provision. Since 2019, Warwick established a university-funded CDT in Mathematics and Statistics. The annual cohort of 12 University-funded students has been expanded using research council and other funding and is the primary route for Warwick PhDs in the Mathematical Sciences. We plan to continue to enhance this CDT, leveraging extra funding and developing the training programme and cohort activities.
- 5) Build the role of Warwick as an outward reaching hub for mathematical excellence.

In addition to continuing our successes in obtaining responsive mode funding from UKRI, we will seek funding from relevant targeted calls. The additional EPSRC funding for the Mathematical Sciences presents an exceptional opportunity. SBIDER's work is in a key position to capitalise on the Global Challenges Research Fund (GCRF).

Programme and other large grants

Our research strategy has been, and continues to be underpinned by a substantial number of major research programmes in key areas, such as those funded by the following EPSRC Programme Grants (or similar large grants), and the Leverhulme Trust Leadership Award (LRLA) for Hairer. Six of these grants are led by Warwick, the other two having a Warwick node (Co-I); they brought in more than 54 Warwick postdoc years between them during the assessment period:

- Roberts and Firth: *Intractable Likelihood: New Challenges from Modern Applications* (£2.4m with Bristol, Lancaster and Oxford, 2013-2017)

- Topping: *Singularities of Geometric PDEs* (£1.6m with Imperial and Cambridge, 2013-2018).
- Cremona and Siksek: *L-functions and Modular Forms* (£2.2m with Bristol and international partners, 2013-2019).
- Stuart and Roberts: EQUIP - *Enabling Quantification of Uncertainty for Large-Scale Inverse Problems* (£2.0m, with Heriot-Watt and UCL, 2013-2018).
- Hairer: *Singular Stochastic Partial Differential Equations* (LRLA, £0.9m, 2013-2018).
- Reid: 3CinG - *Classification, Computation, and Construction - New Methods in Geometry* (£2.7m, with Imperial and Cambridge, 2016-2021).
- Roberts, Johansen, Lee: *CoSiNeS: COmputational Statistical INference for Engineering and Security* (£2.95m with Bristol, Imperial, Lancaster, Oxford, 2018-2023).
- Roberts and Spencer: *Bayes 4 Health* (EPSRC New approaches to Data Science initiative, £3M with Bristol, Cambridge, Oxford and Lancaster, 2018-2023).

Open access and research integrity

The principal mechanism for Open Research in mathematics and statistics is through the use of arXiv, where most researchers place accounts of their research from an early stage. This is supplemented by the University Open Research policy and the institutional repository Warwick Research Archive Portal (WRAP) (REF5a-2.10). Research integrity is embedded in our culture through example, and more formally (REF5a-2.11). The University expects all students and staff involved in research to complete the online Research Integrity training (Epigium) and it is mandatory for those seeking institutional funding. The University manages a comprehensive ethical scrutiny process to ensure that all research involving participants or their data addresses relevant ethical considerations and is subject to appropriate ethical review. The University has created an Ethical Review Decision Making Tool, which can be used by researchers to determine whether a research project requires ethical approval. All research taking place in Mathematics or Statistics that involve human participants or their data either requires NHS Research Ethics Committee approval or Biomedical and Scientific Research Ethics Committee (BSREC) approval before the research can be undertaken. Support for applicants is available at all stages of the process through the centrally managed Research Governance Office.

1c) Impact Strategy

Vision, approach to research impact and areas of impact

At the highest level, our impact strategy seeks to ensure that all benefits of the research we do are realised fully, efficiently and ethically. We group these benefits under the following broad areas:

- 1) Impact on the economy: creation of jobs and new products and services, commercial benefits to existing SMEs and large corporates, improvements to infrastructure.
- 2) Impact on the public sector and policy: improving public services such as healthcare, transportation and education; providing actionable advice to local, national and international policymakers and governments.
- 3) Environmental and social impact: improvements to the quality of life of individuals and communities; contributions to sustainable stewardship of the environment.
- 4) Development of skilled people and leaders: providing researchers with the communication, strategic and ethical skills needed to provide leadership both inside and outside academia.
- 5) Public understanding and appreciation of the mathematical sciences: increasing recognition of the intellectual joy, cultural value and economic impact of the mathematical sciences among the general public.

- 6) Research excellence in the mathematical sciences: providing new research advances and intellectual leadership to benefit the worldwide mathematics and statistics communities.
- 7) Impact on other disciplines: providing new tools and methodologies for use by researchers in science, engineering, medicine, and the socio-economic sciences.

This section focuses on Areas 1 to 5. Areas 6 and 7 are discussed separately in Section 1b (Research strategy) and Section 4c (Interdisciplinary collaborations).

We adopt a bottom-up approach to research impact across the unit: individual academics are encouraged and fully supported in ensuring that their research programmes deliver the appropriate impacts to the appropriate stakeholders on appropriate timescales. This encouragement and support are primarily provided through our disciplinary and interdisciplinary research centres (see Sections 1b and 4c respectively) with AS&RU, SBIDER and WDSI (linking with the Alan Turing Institute) playing central roles. This bottom-up strategy works well due to the combined scale of the departments and the breadth of our underpinning research strengths. It maximises the likelihood of impact activities “feeding back” into our research programmes to stimulate further research. It also avoids focusing responsibility for research impact on the traditional “applied” subdisciplines and ensures that benefits can be realised across the full spectrum of our research capabilities. The primary roles of management and the departmental research impact teams are to tend to the overall health of the impact ecosystem and to ensure that promising opportunities are followed up in a timely manner and are adequately resourced. The effectiveness of this model is illustrated by the fact that the impact case study ICS6-X emerged from abstract mathematical research that might otherwise have been pigeonholed as delivering academic impact only.

Implementation

The translation of our impact strategy into practice encompasses the following:

Institutional support and resources: A designated impact coordinator has been allocated within each department with responsibility for promotion and coordination of impact. These roles are currently held by Barons (Statistics) and Connaughton (Mathematics). As directors of AS&RU and the Centre for Complexity Science respectively, they have broad views of research across both departments. They work closely together to deliver the overall strategy. A full-time research support officer is funded jointly between the two departments and provides help with contracting. The University of Warwick provides additional support with a small team from Research and Impact Services providing strategic and administrative support (REF5a-2.6). The University also makes financial resources available from core funding and from external institutional awards such as the EPSRC Impact Acceleration Account (IAA) (REF5a-2.7), Higher Education Innovation Fund, Industrial Strategy Challenge Fund (ISCF) and Global Challenges Research Fund (GCRF). This includes some ringfenced IAA funding for mathematical sciences which is used in a number of ways. Flexible, project-specific seed funding is available through the EPSRC IAA to defray costs associated with research impact up to a limit of £50K. Larger projects can be funded through internal ISCF and GCRF pump-priming funds.

Leveraging postgraduate research: we harness our vibrant PGR community to generate impact from the research they do jointly with their academic supervisors. Students often play central roles in outreach activities and collaborative projects with external partners. PGRs in turn recognise the employability benefits that these activities bring. Our CDTs are central in this aspect of our impact strategy with AS&RU also playing a central role in negotiating student

projects with external partners for the Stats MSc and PhD programmes. In the impact context, the MathSys II, HetSys and Maths and Stats CDTs build on strong foundations laid by the former SysBio, Complexity Science, MASDOC, MathSys I and OxWaSP CDTs. This is evident from the fact that current or former CDT students are co-authors on underpinning research for 3 of our impact case studies (ICS1-SBIDER, ICS5-Keeling & ICS7-Rock). All PhD students are encouraged to involve external partners in their research when appropriate and to undertake a relevant internship, placement or secondment during their studies. For the MathSys I and II CDTs, with their strong focus on impact, these latter two are requirements. Some high-profile organisations that have hosted our students recently include Deepmind, Uber, the World Health Organisation, the Bundestag, the Cabinet Office and Jaguar Land Rover. ICASE awards are used by individual academics to do research with industrial partners where a clear business need is identified. Examples during the assessment period include Thales, JLR and Tata Steel. We also recognise that PhD students bring their research expertise with them into their future careers and provide entrepreneurship training to help maximise this impact. Dr. Steve Hilditch (Thales UK) currently spends one day a week at Warwick as a Royal Society Entrepreneur in Residence. The MathSys CDT has also partnered with London-based tech accelerator Entrepreneur First to run biannual entrepreneurship showcase events to which all science faculty graduate students are invited.

Partnerships and Knowledge Exchange (KE) activities: we recognise the importance of partnerships in generating research impact. We maintain a number of core strategic partnerships with external organisations that play an integrative role in our research and training programmes. These include the Alan Turing Institute (via WDSI, the Turing Fellowship programme, Data Science for Social Good and the PhD enrichment programme), the Heilbronn Institute for Mathematical Research (via its fellowship programme which enabled the underpinning research in ICS6-X) and the Gates Foundation (via the Neglected Tropical Diseases consortium, see ICS7-Rock). In parallel we maintain a much longer list of industrial, governmental and third sector external partners that are engaged in research projects with individual staff. A non-exhaustive list of current or former partners includes Amazon, Deepmind, Department of Health (see ICS5-Keeling), FERA, GlaxoSmithKline, ESTECO, Google, Lubrizol, Illumina, Intelligent Imaging Innovations (3i), Jaguar Land Rover, Julia Computing, Lanner, MAN Investments, Milward Brown, The National Archives, Novartis, Optimor, ONS, Public Health England, Researchfish, Spectra Analytics, Thales, Transport for London, Unilever, US Department of Agriculture (see ICS9-Tildesley), US Centers for Disease Control and Prevention (CDC), West Midlands Combined Authority, World Health Organisation (see ICS7-Rock), Xerox.

Maintaining such a healthy portfolio of appropriate active partnerships requires a much larger pool of relationships to draw from. To achieve this, we engage in regular Knowledge Exchange activities to establish relationships with external organisations thus allowing new partnerships to form as projects end, staff move on or interests diverge. Examples of such activities include the Data Science for Social Good (DSSG) summer programme (piloted in the UK for the first time at Warwick in 2019 in collaboration with the Alan Turing Institute and the University of Chicago), the European Study Group with Industry (hosted at Warwick in 2017), the Uncertainty Quantification and Management Study Group (hosted by the Warwick Centre for Predictive Modelling in 2017), regular Turing Data Study Groups (organised by Vollmer), annual AS&RU partnership days and biannual external partner days organised by the MathSys CDT.

Public engagement activities: the departments work to stimulate public interest and engagement in the mathematical sciences through both collective and individual activities. We have a long history here, beginning with Christopher Zeeman, his Royal Institution Christmas

lectures in 1978 and his mathematics masterclasses which started in 1981. During the Assessment Period, the biannual Warwick Public Lectures in Mathematics and Statistics have regularly attracted up to 200 participants. Staff and students are encouraged to engage in popularising science activities such as authorship of popular science books, appearances on radio and TV (e.g. Stuart, Ezer, Barons), “art-meets-science exhibitions” (e.g. Schleimer: Brilliant Geometry: The Art of Mathematical Projection Through the Magic of 3D Printing, Edinburgh 2017) and participation in science fairs and festivals such as the Big Bang Festival and the British Science Festival (hosted at Warwick in 2019). A full programme of public engagement events organized by Minhyong Kim (in his role as Zeeman Professor of Algebra, Geometry and Public Understanding of Mathematics) originally scheduled for 2020, has been postponed because of COVID-19.

Creation of open-source software: we support academic staff in the creation and maintenance of open-source technical software. In terms of impact, software has a strong multiplier effect when other researchers and organisations use it for their own projects and extend it by adding new functionality. Our staff regularly make important contributions to a diverse range of software projects such as R, MatLab, SAGE (an open-source mathematical software system) and DUNE (a modular C++ library for the solution of partial differential equations using grid-based methods.) Plummer is a member of the R Core Team and co-president of the R Foundation for Statistical Computing. We are also supporting the use and development of Julia (a new high-level programming language designed for high-performance numerical analysis and computational science) with the Julia Computing Company signed up as an external partner of the MathSys CDT. The DSSG summer programme has also produced 7 fully operational open source data-science products to date which have been or are currently being transferred to their respective external users (OfStEd, Paraguay National Directorate of Public Procurement (DNCP), the World Bank, Cochrane, West Midlands Combined Authority, HomelessLink UK).

During the assessment period our impact strategy delivered significant contributions to the economy and society and these are detailed in Section 4b.

Looking to the future, the next stage in the evolution of our impact strategy is to establish a new research centre, the Centre for Applications of the Mathematical Sciences (CAMS), under strategic plans for post-covid recovery. CAMS will bring relevant researchers from the Department of Computer Science and Warwick Business School together with Mathematics and Statistics to create a new shared resource to support impactful research in the Mathematical Sciences and to deliver the resultant impacts in close collaboration with external partners. To start with, it will have three core research themes in industrial applied mathematics, distributed socio-technical systems and applied statistics/data science. CAMS will integrate external partners with core academic activities, public engagement, facilitation of consultancy and incorporate external perspectives into postgraduate training and CDTs.

2. People

Recruitment strategy

Our underlying strategy is to recruit and develop promising ECRs, both our fixed term Warwick Zeeman Lecturers (Mathematics) and Harrison Lecturers (Statistics), which are attractive senior postdoc positions with some teaching duties, and permanent positions at Assistant Professor level. This creates an energetic and forward-looking research environment. These researchers are balanced with more senior appointments as necessary for leadership and development.

This strategy maintains a healthy age profile with one third under 40 and one third in the 40-55 range.

In Mathematics and Statistics we have recruited 48 permanent staff since 2014, 10 of them to Chairs; about half of these have been replacing departing staff FTE, and half constitute expansion. We have also recruited 21 staff to posts as Warwick Zeeman Lecturers or Harrison Assistant Professors. Both departments successfully appointed experienced Heads through an external recruitment process during the assessment period.

Support for career development

The University of Warwick has an enhanced “career-track” probation process where newly appointed staff at Assistant Professor level have a structured progression to promotion to Associate Professor within 5 years (REF5a-3.3). This includes comprehensive annual review with a focus on providing opportunity for career development. Mathematics has an Early Career Committee, designed to support fixed term and probationary staff, representing their interests and offering advice and support on career development and promotion. Statistics has a Welfare and EDI committee, with early career and PDRA representation, part of whose remit is to ensure that career development is supported for early career staff. Active mentoring and annual personal development review is practised at all career stages. In both departments, assistant professors are given lighter teaching and administrative loads during their probation.

During the assessment period the departments made 16 promotions to Chairs, and altogether 36 promotions. The candidates put forward to the University for promotion have had a very high success rate: this reflects the strength of our candidates and the clarity of the criteria. The University promotions process assesses candidates in four areas, including (i) Research and Scholarship and (ii) Impact, Outreach and Engagement, the latter providing explicit recognition of impact-generating research.

The two departments employ 32 support staff who are highly effective at lightening the administrative burden on research staff. The fact that the departments are large by the standards of mathematical sciences also means that administrative loads are lighter because there are considerable economies of scale. Statistics has a comprehensive workload allocation model which is regularly reviewed. The system in Mathematics shares workload within each category. In both departments, an allowance for research time on grants is added to the standard research time that all research-active staff are allocated.

The departments have a “standard” sabbatical policy: staff members can apply for study leave 1 term in 7 with the understanding that such leave will be granted except in unusual circumstances. This allows all research-active staff a regular period of focused time to pursue a particular piece of research, free of teaching and administrative duties. Since 2014 staff have benefited from a total of 168 person terms of study leave.

Staff are entitled and encouraged to apply for “impact leave” when a significant potential impact is identified in their research. This relieves teaching and administrative duties for a designated period of time to deliver the impact. Impact is further incentivised by explicitly recognising the value of research impact in hiring and promotion criteria and workload management.

The departments jointly employ a Research Development Manager (RDM). The RDM alerts staff members to a wide range of opportunities and oversees the process of applying for grants

making it enormously easier and providing detailed advice about how to structure a proposal for a given call. Proposals are read and given feedback by senior researchers and the departments hold mock interviews for shortlisted applicants on fellowship or large grant applications.

The unit has won a large number of prizes and awards (a selection is listed in Section 4e below). We facilitate this by having senior staff members review available prizes, considering staff members who might be suitable nominees given recent research achievements and, where appropriate, soliciting nominations by experts in the appropriate field.

Staff are encouraged to visit collaborators and attend conferences; flexible arrangements are available to cover teaching. Funding arrangements include grant funding, individual discretionary funds (awarded on appointment, and which can be further built up subsequently) and general departmental travel funds available to all academic staff.

Graduate students and CDTs

A major cornerstone in our vibrant research environment is a large group of excellent doctoral students: in the region of 150 research students at any one time, funded from a variety of sources.

In addition to EPSRC DTP-funded students, Warwick has proudly hosted four EPSRC-funded CDTs since 2014, MASDOC (Mathematics and Statistics Doctoral Training Centre), MathSys (Mathematics for Real-World Systems, co-funded by MRC), and the followup CDT MathSys II (awarded in 2018) and OxWaSP (Next Generation Statistical Science, joint with Oxford and also MRC co-funded). Strong connections with two other Warwick CDTs, CUSP (Centre for Urban Science and Progress) and MAS (Molecular Analytical Science), have strengthened interdisciplinary research and PhD training in Mathematics and Statistics. In addition Ortner and Sprittles are Co-Is of the newly EPSRC-funded Heterogeneous Systems CDT (HETSYS), led from Physics.

About 70% of the funding for students in the assessment period comes from EPSRC, mostly in the form of support for the CDTs. The departments/university have funded (or are committed to funding) over £8.5m for scholarships for the seven cohort intakes starting during the REF period, averaging approximately £1.25m per year, or an equivalent of 17.5 full UK-level studentships per year. This excludes any internal financial support for the externally funded CDTs. This additional support allows the departments to recruit excellent international students, creating an exceptional international and multicultural research environment. A further 18 scholarships have been funded by research grants (e.g. ERC fellowship grants) during the REF period.

The departments have embraced the CDT model, with 4-year funded studentships now being the standard model. In recognition of the excellent training environment enabled through cohort based doctoral training, the University started funding an additional combined Mathematics and Statistics CDT in 2019. This comprises 5 cohorts of 12 students each across the two departments.

PhD students in Mathematics benefit from participation in the 5-partner Taught Course Centre (funded by EPSRC to 2016) managed from Oxford with Warwick, Imperial, Bath and Bristol. This TCC delivers 20 PhD-level modules each year by video-conferencing. The national Academy for PhD Training in Statistics (APTS) was set up from Warwick in 2007 (also with EPSRC funding until 2016) and has been continually led by the Statistics Department since. Every year, it runs

four residential training weeks (each containing two modules) aimed at 1st year PhD students in Statistics.

Our PhD graduates show an impressive level of breadth and depth of mathematical training and are highly employable within both academia and industry after graduation. For PhD students in the unit who have completed during the assessment period, approximately 70% continued in academia contributing positively to the academic pipeline. The majority of the rest went into industry or finance, and a small number teach or work in public service. Amongst the academic destinations are Barcelona, Berlin, Bonn, Brown, Cambridge, Carnegie Mellon, Caltech, Chicago, Courant, Duke, Edinburgh, Frankfurt, Geneva, Harvard, Hong Kong, Imperial, Manchester, Michigan, Milan, Moscow, Nice, Oxford, Paris, Rice, Singapore, Turing, UCL, Vienna. Destinations outside academia include Barclays, Citi, Credit Suisse, Goldman Sachs, Lloyds, AWRE, CEH, GCHQ, Ministry of Justice, Amazon, Facebook, Google, IBM.

MathSys I and II (2014-2027, 10 intake cohorts)

Building on Warwick's internationally leading reputation in mathematics and on the successes of the antecedent Complexity Science and Systems Biology DTCs, MathSys was established in 2014, with EPSRC and MRC funding, as a partnership between three strong existing research centres in complexity science, mathematical epidemiology and systems biology. It addressed the 2014 priority areas of "Mathematics for Highly Interconnected Real World Systems" and "New Mathematics for Biology and Medicine". MathSys has since demonstrated its ability to generate impactful, high-quality science through interactions with many world-class partners and received the highest mark in the EPSRC Evaluation Framework.

Student work has been presented to the World Health Organisation policy committees for sleeping sickness, to UK SAGE (Strategic Advisory Group for Emergencies) for Ebola, and United Nations Office for the Coordination of Humanitarian Affairs. Within the UK, students have presented to the Cabinet Office, Highways England and the Bank of England.

MathSys II further strengthens the interaction between students and end-users by continuing to require that all PhD projects have an end-user partner (laboratory, clinical setting, industry or government) and formalising the placement of students within partner organisations at the beginning of their PhDs to understand the context of their problem and constraints on gathering the data they will be modelling.

MathSys II students receive integrated training in a variety of state-of-the-art mathematical and computational techniques. Evidence from past CDT cohorts suggests these are prerequisites for research in modern applied mathematics and are skills that are desired by employers. For MathSys II, the MSc taught component was substantially updated, incorporating feedback from previous cohorts and responding to changes in national and end-user priorities reflected in our two key research themes. MathSys has increased its emphasis on computational modelling for industrial and healthcare applications and is moving closer to the interface between mathematics and data science with emphasis on how the fundamental skill of mechanistic model construction can influence and strengthen modern techniques of data-driven machine-learning model building.

MathSys II has three unique strengths making it ideally placed to deliver a training programme addressing these needs. The first is its cross-disciplinary reach. MathSys was one of the few CDTs to receive joint EPSRC-MRC funding in 2014 and the MathSys II supervisor pool

draws from eleven Warwick departments. A second strength is the set of over 25 outstanding national and international (France, Germany, Italy, USA) organisations lending their strong support (£1.5M in-kind and direct) to the MathSys II agenda as project partners. Through these partners, MathSys II enhances the contributions of mathematical modelling to UK industrial strategy priorities including the Biomedicine/Healthcare (NHS, Dept. of Health, Public Health England, 3i, Philips), Automotive (JLR) and Artificial Intelligence (Alan Turing Institute, Julia Computing) sectors, as well as the "Future of mobility" Grand Challenge (Thales UK, TRL). A third key strength is in bringing the highest level of academic expertise to support the UK government's "Strength in Places" agenda. The West Midlands Combined Authority was selected in 2017 as one of three trailblazer areas to co-design industrial strategies reflecting local strengths and priorities to address the serious geographic imbalances in the UK economy. The University of Warwick is a key partner in this, through its deep partnerships with the automotive and healthcare industries. MathSys II supports this through PhD research and training.

MathSys I represented a step change in the way Mathematical Sciences at Warwick engage with organisations outside academia. Our founding strategic partners were national-scale organisations (JLR, Thales, PHE, Pirbright Institute, BT, National Grid). New partnerships developed since were with typically SMEs (Legion, ESTECO, Julia Computing, Spectra Analytics) and small specialist groups embedded within larger organisations (FSA, Philips Healthcare, Roche, FAO, EU-FMD). MathSys II builds on this trend. Some partnerships work better when mediated by other academic or quasi-academic (e.g. University Hospitals) organisations that are closer to end-users. MathSys II continues to widen its reach by this route through partnerships with Warwick Manufacturing Group, Centre for Mechanochemical Cell Biology and the University Hospital. To date, MathSys has covered 15% of studentship costs from external partner contributions, a number which is on an upward trend as the external-partner base continues to grow.

The CDT has various mechanisms for co-creation with external partners. MSc Research Study Groups, proposed by end-user partners, are obligatory for MSc students and all PhD research projects are formulated in collaboration with and co-supervised by a partner. We also encourage external partners to spend time working within the CDT. At the strategic level, our External Advisory Board always includes representatives of external partners who have provided valuable guidance on course content and research direction from a viewpoint outside academia.

MASDOC (2010-22, 9 intake cohorts)

MASDOC has built up a significant brand reputation, UK and worldwide, for providing an outward-looking training in the applied mathematical sciences, adapted to scientific and technological challenges of the 21st century providing training for around 90 students. It provides an intradisciplinary PhD training in mathematical analysis (for the formulation, approximation and rigorous study of continuum phenomena in science and engineering and computation for the development of numerical analysis), in probability theory (to model complex systems requiring stochastic descriptions to obtain tractable closure) and in statistics (to systematically perform inference using data sets which complement sophisticated deterministic and stochastic models). To complement an initial 4 EPSRC CDT cohorts, the University of Warwick supported 5 further cohorts of students.

The university's investment in the MASDOC CDT has been essential in creating an environment in which the ambitious training programme was achieved. The CDT encourages

both intra- and interdisciplinary research via the innovative Research Study Group component of the first year training. The Research Study Group (RSG) provides introductions to individual and team-based research with the students forming research teams of three to four members to carry out a project. Among other things students learn how to present scientific results professionally in written form, as well as oral and poster presentation.

The CDT promotes national interactions between UK graduate programmes via annual student led meetings involving Cambridge, Oxford, Edinburgh and latterly Bath. An important part of bringing the fundamental topics together is the annual student retreats at which there are student seminars and speakers from industry and talks from MASDOC alumni. MASDOC attracted additional industrial funding through CASE studentships, one with Selex Galileo Ltd and another with EON.

MASDOC supports student travel to domestic and international workshops and conferences as well as to international PhD schools like the bi-annual 4 week long school on probability in Vancouver and the Berlin Mathematical School. Such PhD schools are experiencing increasing demand within the mathematics community, and MASDOC takes an active part in this by organizing its own summer schools such as the MASDOC summer school on 'Topics in renormalisation group theory and regularity structures' with Martin Hairer in May 2015 as well as joint international events such as the International Berlin Mathematical school in September 2014 and the Bilbao summer school 'Probabilistic approaches to Mathematical Physics' in July 2017.

OxWaSP (2014-2022, 5 intake cohorts)

The Oxford Warwick Statistical Programme, jointly run with the University of Oxford, is funded by EPSRC and MRC. The CDT aims to train the brightest graduate statisticians in the theory, methods and applications of Statistical Science for 21st century data-intensive environments and large-scale models. Established in 2014, this was the first centre of its type in the world and was designed to uniquely equip its students to work in an area that is in rapidly growing demand globally.

The CDT provides students with training not only in cutting-edge research methodologies, but also in the development of business and transferable skills – essential elements required by employers in industry and business. The training has been customized to a new type of graduate statistician in statistical methodology and computation which is scalable to big data. Research training focuses on teaching directly from the scientific literature.

All students are based at the University of Oxford in their first year, before either continuing there or moving to the University of Warwick for the final three years. The training in the first year is very intensive, with eight two-week assessed modules, specifically designed for OxWaSP and typically jointly taught by one academic from Warwick and one from Oxford, four residential courses of the Academy for PhD Training in Statistics (APTS), and two mini-projects, designed to lead the students into a PhD project. OxWaSP offered at least 10 funded doctoral studentships per year for Home and EU Students (split equally between Oxford and Warwick) and the universities have typically added 2 studentships per year for international candidates.

The Centre provides a focus for coordination and support of international exchange visits. Students are offered the chance to spend three months abroad at some of the world's leading centres in data-intensive statistics; partners included Duke University, National University of

Singapore, ETH Zurich, Columbia University, University of California, Berkeley and University of Washington, Seattle. OxWaSP also has a number of partners in industry, including some of the premier pharmaceutical, consumer, technology, and finance firms (including Amazon, Google, Illumina, Novartis, Unilever, Lubrizol, GSK, the Office of National Statistics, Man Investments, Deepmind, Zurich) who all point to a critical need for statisticians working on methodological techniques. These companies are all important consumers and developers of modern statistical methods and provide a wide range of environments from small machine learning start-ups to multi-national firms. Many of our industrial partners have offered students the opportunity to work on joint PhD projects.

Together with Amazon, we organise an annual advanced training course on topics in statistical machine learning and computing for big-data analysis in their Berlin research centre. Each year we organise a workshop at Warwick for all the CDT students, postdocs and members of the supervisory pool. In addition, at the end of the first year, OxWaSP students attend an annual offsite 2-3 day residential training retreat with a small number of chalk talks each day. The retreat is designed to enhance research independence, foster critical discussion and reflection, and help develop communication skills and small group working.

Warwick Mathematics and Statistics CDT (2019- , 5 intake cohorts initially)

The University of Warwick created a combined Mathematics and Statistics CDT in 2019. To establish the CDT, the University committed to funding 5 cohorts of 12 students each across the two departments. All further EPSRC DTP and departmentally funded students are enrolled in the CDT so that they can benefit from the cohort-building and training opportunities. The first year is based around taught material and cohort building activity, with the formal assignment of supervisors and research projects taking place after a progression hurdle. About 13 broad masters-level modules in Mathematics and Statistics are designed and delivered specifically for PhD students, in addition to a broad range of optional modules from masters and other postgraduate programmes. The training and cohort activities include skills workshops, student-led seminars and a first-year mini-project and have been developed with the benefit of long experience of hosting CDTs in the unit.

Equality, diversity and inclusion

The two departments have closely related approaches to supporting equality and diversity. Both hold Athena SWAN bronze awards. Both departments have a Welfare and ED&I committee which reports directly to their management group. The departments have action plans which are regularly updated: the sections designed to promote gender equality formed part of the Athena SWAN submissions.

Academic careers and promotion are key points for ED&I. Promotion is considered for each eligible staff member each academic year by a departmental promotion committee with bespoke feedback to individuals. This is to ensure that all staff have an equal opportunity to be fairly assessed against the promotion criteria and that applicants are assisted and supported by the department. This arrangement was commended by Athena SWAN assessors. Personal feedback is given by a promotions panel member: it often happens that staff members are encouraged to apply by this feedback. During the past 6 years there have been 3 women promoted to professorships and 7 women promoted at other levels, in both cases the proportion of female academics promoted in the unit exceeding the proportion of males promoted. In both departments the promotion committee is selected to have a diverse membership of senior

academics. The university has implemented a detailed set of promotion criteria that takes into account contributions of staff across the areas of (i) Research and Scholarship, (ii) Impact, Outreach and Engagement, (iii) Teaching, and (iv) Collegiality and Management. This ensures much greater fairness.

The gender ratio is a particular challenge in the unit at Warwick, and so we have special training and oversight to focus on each stage when selecting candidates for academic posts. For example, one of a number of actions that we take is to specifically monitor the gender ratio at each stage. Applications are reviewed to avoid bias in understanding an individual's academic history, their references and research output. All staff engaged on appointment panels are required to complete appropriate EDI training.

Conference participation, external visibility and the hosting of conferences, workshops and external speakers are a crucial part of the research environment at Warwick. The facilities in the Zeeman and Mathematical Sciences buildings are modern, accessible and regularly reviewed in the context of the university's own focus on diversity (which includes disability, gender and trans awareness). In addition to provision at the university level, within the departments we have organised a facility for on-site childcare during conferences and workshops to help visitors and conference organisers alike. There is financial assistance for child-care costs associated with attendance at external conferences funded at the University level and reinforced at the department level.

Both departments have an Equality and Diversity Representative who acts as first point of contact for any colleagues who want advice, especially if they do not wish to approach the management committee directly. Staff in each department are encouraged to sign up to the university's LGBTUA+ Supporters initiative.

The departments' policy towards the REF has always been inclusive; all eligible female academics were submitted in both the previous two assessments. For the current exercise, the unit followed the University processes and practices as described in Sections 3.5-3.7 of the Institutional Environment Statement. Selection of outputs was carried out by two departmental advisory groups, of senior staff with male and female membership, moderated by reference to external expert calibration.

3. Income, infrastructure and facilities

Physical accommodation

In 2018 the University opened a brand new Mathematical Sciences Building (MSB) providing a 40% increase in space for Mathematics and Statistics. For the new MSB, the departments won £2M of funding from the Wolfson Foundation towards the £28M total costs. The MSB is directly connected by multi-level bridges to the Zeeman building (home to the two departments since 2003, and extended in 2008), with its bespoke Mathematics Library, and to the Computer Science Department. It provides a home for the Department of Statistics and hosts key interdisciplinary activities across the two departments and the Department of Computer Science. Prominent amongst these is SBIDER and the Wolfson Data Science Laboratory, a hub for interaction with the Alan Turing Institute.

The MSB has 5 floors and office space for 70 academics and 40 postdoctoral researchers. In addition there is accommodation for around 100 PhD students housed in groups of between 6

and 20; some of the space is specifically designed to accommodate students from CDTs, but the same positive cohort-based training experience is enabled for all our students. Replicating successful features of the Zeeman building, the MSB is designed to foster collaborative research activity, with a large number of seminar rooms and open-plan areas with boards for small group seminars and research discussion, a common room with kitchen facilities for use by all building occupants, and an open plan communal area on the ground floor to provide additional flexible space for collaboration, events, informal meetings and presentations. These spaces act as the central hub for the new building promoting dialogue, debate and interaction between its occupants, acting as a magnet for international visitors. Collaborative and interdisciplinary research is the essence of SBIDER, so bringing all members of this group under one roof in a purpose-built space co-located with Mathematics, Statistics and Computer Science has been especially invigorating and fruitful.

Research Income

The research income across the unit has been strong with total awards on average around £8m in research grants each year (with considerable fluctuation from year to year). This figure is roughly 25% higher than the comparable one for the previous REF period.

The combined research award values for the relevant academic years were as follows:

2013-2014	£ 10.7M
2014-2015	£ 12.9M
2015-2016	£ 4.5M
2016-2017	£ 4.7M
2017-2018	£ 8.9M
2018-2019	£ 8.6M
2019-2020	£5.3M

Included in these figures are 4 EPSRC programme grants, a Leverhulme Trust Leadership Award, 3 ERC Starter Grants, 2 ERC Consolidator Grants, 2 ERC Advanced Grants and 5 Royal Society Research Fellowships. The funding portfolio is very diverse: awards were received from 58 different funding organisations including EPSRC (77 awards totalling £18.3M), BBSRC (14 awards totalling £3.8M), the Royal Society (23 awards totalling £2.6M) and the European Research Council (ERC) (7 awards totalling £7.7M).

The unit has been highly successful securing fellowship awards garnering 75, with the majority of these coming from the Alan Turing Institute (19), the Leverhulme Trust (15 fellowships of which 10 were Early Career Fellowships), EPSRC (10), the European Commission (17 fellowships of which 10 were Marie Curie Fellowships and 7 ERCs) and the Royal Society (7 fellowships, including 5 URFs).

Warwick was a founding member of the Alan Turing Institute, and ongoing collaboration and staff exchange has boosted its research network and world-leading research capability in data science and artificial intelligence. The departments have been central to Warwick's engagement with the Turing. Many staff in the unit were involved in the initial committees and workshops which shaped the Institute's vision. As of October 2020, 16 faculty members from the two

departments are among the selected group of Turing Fellows, part of the vibrant Turing research community at the British Library Location in London. In addition, Damoulas, Johansen, Kosmidis, Mijatovic, Vollmer, Girolami and Lee have all been seconded to significant leadership roles within Turing while at Warwick. Vollmer set up and runs the highly successful Data Study Groups which play a key role in bringing together large numbers of ECRs from all over the country to engage with substantive data science problems from a wide range of companies and industries. He is also Programme Co-Director of Health. Johansen is a Group Leader in the Turing's highly successful Data Centric Engineering Programme; Damoulas is Deputy Director and Mijatovic is the Programme's Strategic Leader for Mathematical Foundations. Kosmidis leads the Theory & Methods Challenge Fortnights in Data Science and Artificial Intelligence initiative. The new annual Data Science for Social Good programme is a joint venture between Warwick and the Turing.

Programme grants and other major projects

CoSnES (£3.2M 2018-23): The CoSnES project builds on many of the methodological themes of *ilike* and Equip together with a strong focus on application in engineering and security. CoSnES is funded by an EPSRC Programme grant (£2.9M) with Turing support (£300K). The project focuses on the development of robust and scalable statistical methodology and associated underpinning theory, with particular focus on applications in Engineering and Security. The overall project PI is Roberts and also includes Johansen and Mijatovic as investigators together with seven other investigators in Bristol, Cambridge, Lancaster and Oxford, and six Research Fellows are currently employed including two based at Warwick. The project partners with three successful Turing programmes: Data-centric Engineering, Defence and Security and the Intel programme. The research spans statistical and associated algorithmic theory and methodology, motivated by and applying directly to the targeted application areas. Early highlights of the project include the development of approximation-free distributed algorithms for Bayesian inference, convergence theory for new non-reversible MCMC methods, and a methodology for statistical finite-element methods for mis-specified models in large scale engineering problems.

EQUIP (£2.0M, 2013-18): The EQUIP programme grant made significant progress on fundamental challenges arising from the need to quantify uncertainty in the solution of inverse problems. The original focus of the applied aspects of the research was geophysical applications but the results were sufficiently general to apply to numerous applications in other scientific and engineering applications, and in the social sciences. Highlights included the first analysis of the convergence properties of ensemble inversion methods, unification of various studies of filtering in high dimensions and a study of approximation of intractable and infinite-dimensional models via unbiased likelihood approximation. The grant supported research leading to 63 publications, many in leading refereed journals in Applied Mathematics and Statistics. Around ten of the publications are in leading geophysical sciences journals. Additionally, the broader impacts of the work were enhanced by three articles in scientific newspapers/newsletters (SIAM News, European Mathematical Society). The grant supported 10 postdocs, 4 of whom are female. 9 have moved on to subsequent academic positions, 7 permanent, 1 has obtained a Leverhulme Trust Fellowship. and 1 a regular postdoctoral position at Cambridge. 1 is employed in industry. The grant also funded 12 workshops and other events at Warwick, further enhancing the outreach of the programme.

ilike (£2.4M, 2013-18): The *ilike* programme grant (Intractable Likelihood) led from Warwick and involving Lancaster Bristol and Oxford, focused on principled statistical methodology for

intractable likelihood inference problems, with a strong focus on Computational Bayesian theory and methodology, and a diverse range of applications including Genetics, Genomics, Infectious Disease Epidemiology and Bibliometrics. Highlights included the construction of novel classes of non-reversible continuous-time Markov chain Monte Carlo algorithms; the development of the most comprehensive underlying theory for approximate Bayesian Computation algorithms; Approximate likelihood methods in the context of model-misspecification; and Bayesian inference for big data. The latter breakthrough led to a JRSS B discussion paper "The Scalable Langevin Exact Algorithm: Bayesian Inference for Big Data" presented at the RSS in June 2020. Overall the project produced 130 papers, many of these appearing in the top Statistics journals. The PDRAs appointed to the project have moved on to excellent academic positions, five of them within leading UK Statistics groups. It organised many workshops drawing in the wider UK Computational Statistics community, and its climax was an Isaac Newton Programme in 2017 featuring a world class participant list and showcasing the grant's achievements.

L-functions and Modular Forms (£2.2M, 2013-19): The programme grant LMF funded a total of 12 person-years of postdoctoral researchers at Warwick, as well as 9 person-years at Bristol. Together with the outputs of the PI and four CIs, the grant has been acknowledged in a total of 85 publications in research journals (as of 2019). Further funding to expand and continue the LMF project has been obtained from the European Commission for an H2020 research infrastructure project, funding the first Research Software Engineers at Warwick, and two Marie-Curie fellowships held at Warwick. As well as journal publications, a significant component of the project's impact is through the L-functions and modular forms database (LMFDB) and website (www.lmfdb.org), which in 2019 received over 400,000 page views from researchers in 159 countries.

Singularities of Geometric PDEs (£1.6M, 2013-19): The project ended up twice the size of the original proposal owing to a large influx of funds from other sources to support our activity, including the governments of China and Brazil, the ERC, Cambridge University, Imperial College and the University of Warwick. Across the different universities involved the grant led to approximately 130 journal publications (including 6 in *Annals of Math*, 5 in *Inventiones*, 10 in *Journal of Differential Geometry* and 1 in *JAMS*). The grant trained 15 postdocs, who have gone on to permanent positions at Johns Hopkins, Paris VI, University of Athens, Leeds University, Tongji-Shanghai, Stanford University, Ecole Polytechnique, Macquarie University, Zhejiang University and IMPA. In addition to the twice-yearly meetings in the UK, the investigators organised conferences in Lisbon 2014, Warwick 2015 and ICMS 2018. The success of the grant can also be gauged by the fact that the PI and both the co-Is all received invitations to speak at the ICM in 2014.

Bayes 4 Health (£3M, 2018-2023): This is funded by EPSRC under their New approaches to Data Science initiative. Roberts and Spencer at Warwick and a Research Fellow collaborate with researchers at Bristol, Cambridge MRC Biostatistics, Oxford and Lancaster (PI). The research aims of the project revolve around scalable Monte Carlo methods, fusing information from disparate sources and robustness in Bayesian analysis, with a focus on applications in the Health Sciences including Epidemiology, Genomics and Phenotyping, and Personalised Medicine. There are 12 investigators on the grant and five funded Research Fellows including one at Warwick. Highlights of the project to date include the work carried out to support the national effort against Coronavirus, which involved the development of new algorithms and models and led to the production weekly reports for for SPI-M, SAGE and the Cabinet Office.

Classification, Computation, and Construction - New Methods in Geometry (£2.2M, 2016-21): 3CinG is an EPSRC-funded Programme Grant joint with Imperial (PI) and Cambridge with £0.75m to fund postdocs at Warwick. The project aims to classify geometric structures, with the main novelty coming from developments in higher dimensional birational geometry and ideas from theoretical physics, especially mirror symmetry. A main component of 3CinG contributed by Warwick is the analysis and construction of algebraic varieties by explicit graded ring methods: Gavin Brown and Al Kasprzyk's graded ring database, <http://www.grdb.co.uk/> lists all possible Hilbert series of Fano 3-folds. 3CinG has run 2 or 3 conferences, workshops and schools each year since 2016 all either in Warwick or co-organized by Warwick postdocs.

Platform grant. The departments also held a £520k Platform Grant during the period. This provided baseline funding to enhance the health and capability of the research base across the departments encouraging interaction with other disciplines and enhancing the visibility and impact of research in the departments. In particular, the grant supported 9 postdocs from Warwick for an average of 3.5 months each. Around half have progressed to full academic positions at Warwick or elsewhere, one took up a 5 year fellowship, whilst the others have taken up research/consultancy positions in industry. Another 4 were hosted from elsewhere for an average of 6 months (3 progressed to permanent academic positions and 1 to a position in industry). The grant was also used to begin a series of lectures which engaged the general public with mathematical research. This has so far brought in around a dozen high-profile speakers including Cédric Villani, Valerie Isham, Alison Etheridge, Hendrik Lenstra, Roy Anderson and Sheila Bird. The grant received applications for funding for around 75 workshops or meetings; largely to fund workshops at Warwick but also to fund short visits abroad. Around half of the applications were successful after internal peer review. Interdisciplinary workshops, especially in new areas for the departments, were given priority.

Computing facilities

The scientific computing strategy of the unit is based on three tiers of computing resource. This provides sufficient local resources to allow staff and PhD students to develop their skills before moving on to more comprehensive high-performance computing (HPC) platforms if required.

- 1) Both departments offer a heterogeneous desktop computing environment with high quality personal Windows, MacOS and Linux desktops and laptops, and a schedule of regular replacement. This is supported both by local departmental and by University IT support services.
- 2) There are local HPC resources in number theory, computational algebra, mathematical biology and statistics. SBIDER have two dedicated clusters with a total of 304 CPU cores and 1.5 TB RAM, soon to be expanded to a total of 600 cores. These are used for bioinformatics, epidemiological modelling and dynamical systems analysis. The statistics cluster "Buster", includes 11 compute nodes with a total of 132 cores, 528GB of memory and 16TB of storage. We also maintain a number of specialized GPU servers as a testbed for users developing general purpose GPU computing applications for deployment on external HPC platforms.
- 3) For users who require a greater capability than local HPC resource provides, or who require distributed memory parallel processing, the centrally resourced Warwick Scientific Computing Research Technology Platform (SC-RTP) provides further resources, detailed below and REF5a-4.3.

Grant applicants for projects with significant computational demands are expected to apply for funding to contribute to the resources provided in Tiers 2 and 3. The continuing development of computationally intensive mathematical and statistical methods and the challenge of analysing large volumes of data imply that demand for HPC in the unit will continue to grow. In future, we plan to replace Buster with state-of-the-art hardware providing expanded facilities for OpenMP and MPI parallel computing. The GPU testbeds will be kept up to date with evolving processor architecture.

Scientific Computing RTP (SC-RTP): The departments played a significant role in establishing the Warwick Centre for Scientific Computing (CSC). Scientific Computing has now developed from a niche activity in mathematical sciences to a mainstream requirement of many disciplines. Consequently, CSC has now become a Warwick Research Technology Platform (RTP) (the Scientific Computing RTP) providing high performance computing access to all staff in the university, including dedicated software engineering support through the team of Research Software Engineers who are available for secondment to projects with advanced software engineering requirements. The SC-RTP facilities are state-of-the-art supercomputers providing many times more computational power than is available from the HPC resource in Mathematics and Statistics. Current facilities provide approximately 250 TFLOPS of double-precision floating point performance. SC-RTP capacity is currently being enhanced within a new data centre space, dedicated to HPC, with high core count (9528 cores) and enhanced number of GPU nodes (16 multi-GPU nodes).

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

4a) Research collaborations, networks and partnerships

There are a huge number of individual research collaborations as evidenced by the large number of submitted outputs with co-authors based elsewhere in the UK and internationally. This is a natural consequence of the international nature of the academic staff, the significance of the work of Warwick staff and our academic hospitality to the many visitors to Warwick.

Our staff travel extensively, to meetings or for research visits, and our very active workshop and visitor programmes bring many existing and potential collaborators to Warwick. Workshops and visitors are facilitated and supported by the MRC and CRiSM infrastructure which provides dedicated administrative support; during the assessment period the two centres have hosted 122 workshops and over 5000 visitors. Additionally, the University provides financial support (both outgoing and incoming) through various international partnership funds and through the Warwick Institute for Advanced Studies (REF5a-2.9.2). Generous arrangements for sabbatical (168 terms during the assessment period) and unpaid leave allow staff to make longer visits where appropriate. There are multiple strong individual links particularly with North America and with many European countries.

Our seven programme or equivalent large grants (see Section 1b), joint with other UK Institutions, are evidence of strong coordinated links across the UK in some of our strongest areas of research. Other grants also have a strong collaborative element, for example an EU grant BREUDS supports visits in both directions with Brazil for researchers in Dynamical Systems. Researchers in the unit have already been successful in three bids under the EPSRC-DMS lead agency agreement with NSF, resulting in total of over £1M from EPSRC and corresponding funding for our US collaborators (at Carnegie Mellon, CUNY and Stanford

respectively) from NSF. Staff lead or participate in numerous LMS subject and regional networks/grants.

At the level of PhD training, Warwick collaborates with Oxford, Imperial, Bath and Bristol on the Taught Course Centre (TCC) in mathematics and the national Academy for PhD Training in Statistics (APTS) is led from and run by Warwick (see also Section 2). APTS continues to be highly successful currently with 26 member institutions who commit to using the APTS courses for their first year PhD training. In total 56 institutions have used APTS and courses typically have between 100 and 150 registered students. Since the end of the initial round of EPSRC funding in 2011, 15 "underwriting institutions" have entered into a collaboration agreement and shared the financial risk associated with running an operation of this size. Warwick has now been commissioned to continue running APTS until 2027.

MRC and CRiSM run graduate schools and vacation schools, and staff also frequently lecture in such schools organised elsewhere (both in the UK and overseas). Warwick hosted the Young Researchers in Mathematics (YRM) Conference in 2014, repeating a successful conference hosted in 2011. In 2018 Warwick hosted BAYSM, the Bayesian Young Statisticians an official conference of the International Society for Bayesian Analysis (ISBA).

4b) Engagement with key research users, beneficiaries and audiences

Throughout the assessment period we have engaged with a wide range of key research users, beneficiaries and audiences. We categorise the diverse impacts according to the strategic objectives described in 1c above. This includes wider contributions to the economy and society, impact of research that is not captured in the impact case studies and our public engagement activities.

- 1) Economy: Savage's work on machine learning has led to the creation of a spin-out company to commercialise an innovative new blood test for cancer. Complexity Science PhD students Ong and Sprague set up the data analytics company, Spectra Analytics, in 2014. Spectra has since grown to employ 8 people and has joined the MathSys II CDT as an external partner. Kennedy's work on mathematical finance has been adopted by some leading financial institutions to improve their pricing models. Tildesley's work of animal disease epidemiology has been used to develop a mathematical model of foot and mouth (FMD) disease for the US Department of Agriculture which has recently been approved for use in scenario planning to guide the response of the US farming industry to future FMD outbreaks [ICS9-Tildesley]. Stallard's statistical research was vital to the adoption of new OECD test guideline for acute inhalation, which has reduced the number of animals required for animal testing (ICS8-Stallard).
- 2) Public sector and policy: Since the start of 2020, rapid response epidemiological modelling work done by SBIDER has contributed in multiple ways to the formulation of UK government policy in response to the Covid-19 crisis via SPI-M, JCVI and SAGE (ICS1-SBIDER). Prior to that, Keeling's work on epidemiological modelling and membership of the UK Department of Health Joint Committee on Vaccination and Immunisation (JCVI) led to the July 2018 JCVI recommendation for gender neutral vaccination against HPV (ICS5-Keeling). Implementation began in 2019 and over the next 50 years is expected to lead to 13,000 fewer cancers, 25,000 fewer cases of Cervical intraepithelial neoplasia and 230,000 fewer cases of genital warts. Beyond the UK, SBIDER's mathematical epidemiology work, particularly that of Rock, Hollingsworth and Keeling has informed WHO guidelines for efforts to eliminate several infections which thrive mainly among the poorest populations of the world. This has been

done via the Gates Foundation funded Neglected Tropical Diseases Modelling Consortium of which Warwick is a member (ICS7-Rock). Our pure mathematicians, in collaboration with the Heilbronn Institute for Mathematical Research, have done fundamental work with significant national security implications (the sensitive nature of this work means that the details are classified (ICS6-X)).

- 3) Environmental and social: Damoulas work on spatio-temporal inference has led to improved estimates of air quality in London. Barons's work on food security with Warwickshire County Council has had significant local impact by helping to inform policy on food banks. French's deep knowledge and experience of expert elicitation and risk has led to improvements in the IAEA nuclear safety guidelines in response to the Fukushima disaster (ICS3-French). Hutton's consultancy and expert witness work has led to improved outcomes for legal cases involving healthcare and life expectancy (ICS4-Hutton). In summer 2019, Vollmer and Connaughton teamed up with colleagues from Computer Science and Warwick Business School to run a UK pilot of the DSSG summer fellowship programme in collaboration with the Alan Turing Institute and the University of Chicago. Drawn from a pool of almost 800 applications from all over the world, 19 DSSG fellows spent the summer at Warwick. Working in 5 teams under the supervision of 2 professional project managers and 2 technical mentors, they delivered data-driven solutions to problems with high social value brought by medical charity Cochrane, homelessness charity HomelessLink, OFSTED, the government of Paraguay and the West Midlands Combined Authority. A smaller scale online DSSG programme in 2020 delivered two additional projects, a second one with OfStEd and an anti-corruption tool with the World Bank.
- 4) People: Barons is a leading figure in the implementation of the Bond Review of Knowledge Exchange in the Mathematical Sciences as a member of the working group. Plummer is a member of the R Core Team and co-president of the R Foundation for Statistical Computing. Universities UK and the UCU have drawn heavily on Jacka's statistical expertise as a member of the Joint Expert Panel tasked with resolving the USS pensions dispute. The two departments contribute significantly to the leadership of the Alan Turing Institute, as described in Section 3.
- 5) Public engagement: Stewart has continued to delight and entertain readers around the world with his popular science and science fiction writing. Recent titles include "Do Dice Play God?: The Mathematics of Uncertainty"(2019), "Significant Figures: Lives and Works of Trailblazing Mathematicians" (2017) and "Calculating the Cosmos: How Mathematics Unveils the Universe" (2016). At the interface of art and mathematics, Schleimer's 2017 exhibition, "Brilliant Geometry: The Art of Mathematical Projection Through the Magic of 3D Printing", in collaboration with Peter Reid and Henry Segerman at Edinburgh's Summerhall Gallery attracted hundreds of visitors and widespread media coverage. The Warwick Public Lectures in Mathematics and Statistics series has regularly seen well-attended talks by leading figures including Alison Etheridge, Bernard Silverman, Sheila Bird, Cédric Villani, David Spiegelhalter. Barons exhibited at the Big Bang Fair and several staff from the unit engage with activities such as 'Pint of Science' and Café Scientifique. Firth's statistical work on election exit-poll design is used by all major broadcasters, producing forecasts which are widely trusted by the watching public. Tildesley's 400 appearances on radio and TV to give expert commentary on the COVID-19 pandemic have been a reassuring source of factual information.

4c) Key relationships with non-academic research users

Our mathematical and statistical collaborations with non-academic research users including industry, government and policy makers have been accelerated by the establishment of SBIDER

and of AS&RU, our involvement in the Alan Turing Institute and the focus on real-world interactions for our CDT students.

SBIDER has been heavily involved in advising the government on infectious disease control during the ongoing COVID-19 pandemic. Keeling, Tildesley, Dyson and Hill (PDRA) are all serving on the Scientific Pandemic Influenza Modelling Group (SPI-M), a subgroup of the Scientific Advisory Group for Emergencies (SAGE). The Warwick group have contributed significantly to SPI-M since January 2020 - their real-time forecasting model is one of the models that contributes to the calculation of the weekly R number published every Friday during the pandemic. In addition, they have developed a suite of models that informed several key government decisions including re-opening of schools, return of students to universities, the need for an autumn "circuit breaker" lockdown and optimal strategies for the ongoing vaccination campaign. Warwick jointly leads the Juniper modelling consortium of 7 universities, that feed into all the major government scientific groups on COVID-19.

AS&RU has established a number of key non-academic partnerships, including BEIS (assessment of the risk of a UK-wide electricity blackout to inform the number and location of backup generators for resilience planning), Transport Research Laboratory (interventions to reduce accidents among young drivers), SPD Ltd trading as Clearblue (pregnancy test reliability improvement) and DEFRA (decision support for pollinator abundance). Two particularly significant collaborations have been:

Digital Risk decision support with The National Archive (TNA). The centre helped TNA to identify risks to items they have preserved which were born digital or have been digitised. Digital resources have additional risks in preservation coming from technological obsolescence, carrier deterioration, bit flipping and deliberate corruption. Born digital resources, such as the videos of the London Olympics have huge societal importance and government records, emails and bespoke software outputs also must, by law, be preserved for accountability. This work has already led to a large financial settlement for TNA to enhance its capability to preserve the nation's digital heritage.

Analysis under Uncertainty for Decision Makers network. This network is joint with Imperial. Research coming from that and the Alan Turing Institute around decision analysis and visualising uncertainty has led to the publication of two catalogues which are being used widely, including by the Defence Science and Technology Laboratory.

Staff and students in the applied mathematics group, the MathSys and OXWaSP CDTs and interdisciplinary research centres like Complexity Science and SBIDER have relationships with many external partners from business, industry, policy-making and third sector organisations. These include NHS, University Hospitals Birmingham, University Hospitals Coventry and Warwickshire, 3i Microscopy, Inscopix, DEFRA, EuFMD, the Food and Agriculture Organisation (FAO), the US Department of Agriculture (USDA), the World Organisation for Animal Health (OIE) and the World Health Organisation, Thales, Network Rail, Highways England, Legion Ltd, Greater London Authority, BT, Sciteb, National Grid, Cadent, JLR, Warwick Manufacturing Group, Tata Steel, ESTECO, Waters Corporation, Bell Labs. OxWaSP partners and collaborators include Amazon, Deepmind, FERA, GlaxoSmithKline, Google, Lubrizol, Illumuna, MAN Investments, Millward Brown, Novartis, Optimor, the Office of National Statistics, Unilever and Xerox, The West Midlands Combined Authority, The National Institute for Health and Care Excellence (NICE), the Home Office, Julia Computing, Digital Catapult, Office of National Statistics (ONS), the Center for Data Science and Public Policy (DSaPP) at the University of

Chicago, Turing Defense and Security Programme, Institute for Apprenticeships, Feeding Britain, Transport Research Laboratory, FERA, Barnardos, as well as FaceBook.

We also collaborate with external organisations through internships and placements for students. MathSys and Complexity CDT students have undertaken or are currently undertaking internships with WHO, Legion Ltd, Public Health England, Alan Turing institute, Capp Ltd., Google Deepmind and Barclays. In addition, the Centre for Complexity Science ran annual one-day External Partner days for its CDT, continued by MathSys CDT. MathSys has run annual MSc Group Project Presentation days by external partners since its inception. We also host Dr S Hilditch (Thales) under the Royal Society Entrepreneur in Residence Scheme.

In 2017, the departments hosted a European Study Group for Industry (led by MacKay) 2017. This was the annual UK edition of the series. Participants from over the UK and beyond tackled seven problems, presented by DSTL (2), Resonate, Syngenta, MoD, CAST and ARC.

Notable direct funding by non-academic partners include: a Zeeman lectureship for 3 years, Icardi, co-funded 50% by AVL, a National Grid funded postdoc for 2 years, and ICase studentships including JLR, Selex, Tata Steel and Thales. The MathSys CDT has brought in £373K of direct studentship support from external partners during the assessment period.

4d) Interdisciplinary collaborations

Support for and examples of interdisciplinary research within and beyond Warwick include the affiliation of our staff (and joint appointments where appropriate) with Warwick interdisciplinary centres and their internal and external research collaborations and activities. The support provided by CRiSM, and MRC described above includes interdisciplinary workshops and collaborations, across local, national and international communities. The physical co-location of the two departments encourages intradisciplinary, cross-departmental research at the interfaces between the mathematical sciences and other disciplines.

At a University level, Warwick has organised elements of its collective research activities through a series of Global Research Priorities (GRPs; REF5a-2.9.1) that promote interdisciplinarity, encourage critical mass, and focus on major research challenges. The departments have particular involvement in the GRPs in Behaviour, Brain and Society (Henderson is one of the leaders), Energy, Food (Barons is one of the leaders), Health, and Innovative Manufacturing and Future Materials.

MIR@W brings together researchers in the unit with departments in science, engineering, business and social sciences to promote and coordinate interdisciplinary research involving the mathematical sciences. One key MIR@W activity is the MathSys Group project topics meeting, held annually since Feb 2015, specifically to expose the MSc students in the MathSys CDT to real-world problems posed by non-academic externals, but also playing a wider role in fostering interactions between Mathematics and Statistics and other departments (notably the Business School, Physics, Engineering, Life Sciences, the Warwick Manufacturing Group and Computer Science). Highlights of other MIR@W activities over the assessment period include:

Detection of modes of oscillation (2020). This meeting revealed that faculty members in Economics and Mathematics have developed very similar methods, also related to those in use by structural engineers. A colleague in Physics has used analysis of modes of oscillation

to reveal features of the structure of the sun. One upshot is a plan to employ a similar approach to understanding fluctuations in the power grid.

Modelling and calibration of pedestrian dynamics (2019). This meeting led to two distinct interdisciplinary and multi-institutional collaborations involving parameter identification (involving Bristol) and on parameter estimation for models of crowd dynamics (involving Nottingham and Oxford).

Circadian and sleep-wake cycle (2018). This meeting established a network in the UK of researchers on this topic, combining models with data. In particular it resulted in a strong collaboration between Warwick Maths/Stats/Medical School at Warwick and partners in Surrey.

Predictive modelling at Warwick (2017). This meeting served as the relaunch of the Warwick Centre for Predictive Modelling (WCPM), founded in Engineering but expanded after a change in management to benefit from interest in Mathematics and Statistics. It is now highly active, running regular study groups on externally posed problems, for example. This is just the latest example of MIR@W incubating significant activities which go on to be successfully established in their own right, previous examples being the Complexity Science Centre and Systems Biology.

DIMAP is based in Mathematics, Computer Science and WBS, and facilitates research in discrete mathematics, theoretical computer science and the interface. At least 9 academic staff from the unit are directly involved, as well as a number of PDRAs and PhD students. The centre runs a weekly seminar (in addition to the more specialised Combinatorics and Computer Science Seminars) that cover topics of broad interest across the three departments, and is instrumental in organising scientific meetings.

SBIDER is a highly interdisciplinary centre specialising in bringing sophisticated mathematical modelling and statistical inference techniques to challenges in biological systems, spanning from fundamental life sciences to practical policy advice, and across scales from the genome to the population (REF5a-2.9.4). Hosted in the new mathematical sciences building, the centre hosts 20 staff with affiliations in Mathematics, Statistics, Computer Science, Life Sciences and Medicine and generates substantial research income from NIHR and the Bill & Melinda Gates Foundation amongst others.

Warwick Data. The Warwick Data Science Institute (WDSI) was established in 2014, to build upon the significant power and range of Warwick's research expertise in novel mathematical, statistical and computational approaches to the acquisition, management and analysis of big data. WDSI has been a highly effective vehicle for promotion of innovative research collaborations across its three departments (Computer Science, Mathematics and Statistics) and for national and international engagement through the extensive WDSI programme of research workshops and visitors. Most significantly, in 2014-15 WDSI organised five workshops, each with leading national and international speakers as part of the *WDSI Year of Big Data*. Since the establishment of the Alan Turing Institute in 2015 with Warwick as one of the five founding University partners, there has been a natural shift of activity from WDSI towards the Alan Turing Institute. That, in conjunction with an expansion in Turing involvement from across the institution (there are a total of 35 current Turing fellows with Warwick affiliation) has resulted in the evolution (in progress) of WDSI to *Warwick Data*. The long term aims of Warwick Data are very

similar to WDSI, but with a pan-institutional focus and providing a natural hub for Warwick interaction with the Turing.

The long standing **Complexity Science Centre** is deeply embedded in the unit. Staff from the two departments and from Physics and Computer Science, are engaged in interdisciplinary research. It plays a major role in the training of PhD students through the MathSys CDT. It will become the starting point for one of the major themes in the Centre for Applications of the Mathematical Sciences (CAMS) currently being planned (see Section 1c).

4e) Wider Influence, Contributions to and Recognition by the Research Base

The importance of the departments' contributions to the community and the sustainability of the discipline is attested to by the awards of numerous prizes, fellowships, distinguished lectureships, panel memberships and prestigious grants to members during the period. These include:

Prizes and Fellowships:

Fields Medal: **Hairer**

Elected FRS in the period: **Hairer, Series, Stuart**

(The departments are also home to six previously elected FRS, **Ball, MacKay, Roberts, Preiss, Epstein**, and **Reid**, one FRSE **Ball** and one FBA **Firth**.)

Elected Fellow of the Learned Society of Wales: **Roberts**

IMS Medallion Lecture: **Girolami**

SIAM Fellows: **Barkley, Elliott**

IMS Fellow: **Leng, Roberts**

Philip Leverhulme Prizes: **Weber, Kral, Loeffler**

LMS Froehlich Prize: **Hairer**

LMS Polya Prize: **Reid, Vogtmann**

LMS Senior Whitehead Prize: **Mackay**

LMS Shephard Prize: **Ball**

LMS Senior Anne Bennett Prize: **Series**

LMS Hirst Prize: **Gray**

LMS Whitehead Prize: **Harper, Loeffler, Mathe, Mondino, Ortner, Rindler**

Otto Negebauer Prize: **Gray**

Rollo Davidson Prize: **Weber**

John Todd Award (Oberwolfach Foundation): **Ortner**

SASTRA Ramanujan prize: **Harper**

Ockendon Prize: **Wolfram**

RSS Ramsay Medal: **French**

Bartolozzi Prize: **Mondino**

Wolfson Research Merit Awards: **Elliott, Hutton, Roberts, Smillie, Vogtmann**

Humboldt Research Award and Clay Senior Scholarship: **Vogtmann**

RISE Fellowships: **MacKay, Roberts**

Honorary doctorate Copenhagen: **Vogtmann**

Member of Academia Europaea: **Vogtmann**

Learned Societies and Service

President of Bernoulli Society: **Kendall**

President IMA: **MacKay**, Vice President: **Barons**

President LMS: **Series**, Vice President: **Greenlees**

RSS Vice-President: **Forster**, Council: **Roberts**, Section Committee: **Leng** (chair) and Honours Committee: **Firth, Roberts**

Joint Committee on Vaccination and Immunization (JCVI): **Keeling**

Scientific Pandemic Influenza Group on Modelling (SPI-M): **Dyson, Keeling, Tildesley**

R Foundation for Statistical Computing co-President: **Plummer**

Big Mathematics Initiative Implementation Group: **Barons**

EPSRC Mathematics Advisory Group: **Topping**

EPSRC Mathematics SAT: **Girolami, Grafke, Robinson**

EPSRC Early Career Forum: **Grafke**

REF2014 panel: **Series, Stuart**

REF2021 panel: **Greenlees, Mijatovic**

Isaac Newton Institute: Scientific Steering committee: **Ball, Kendall** and **Jacka**; Management Committee: **Greenlees**

ICMS Programme Committee: **Greenlees**

Heilbronn Inst. External Board: **Ball, Sparrow**.

Royal Society Sectional committees: **Ball** (chair), **MacKay, Roberts**, Governing council: **Ball** and Grants panel: **Ball, Roberts**.

Significant invited lectures

Plenary address ECM 2016: **Vogtmann**

ICM speaker in 2014: **Hairer, Malchiodi, Pollicott, Stuart, Topping**

ICM speaker in 2018: **Mathe**

IMS Blackwell Lecture: **Roberts**

INFORMS Markov Lecture: **Roberts**

De Rham Lecture: **Kendall**

Journal editorships

During the assessment period, the unit has provided main editors for the following journals: BMC Veterinary Research (Tildesley), Ergodic Theory and Dynamical Systems (Melbourne, Sharp), Transactions of the LMS (Ball, Rodrigo), LMFDB (Cremona), Transactions in Mathematics and its Applications (Mackay), Proceedings of the Edinburgh Math Soc (Robinson), IMA Journal of Numerical Analysis (Elliott), EMS Interfaces and free boundaries (Elliott), SIAM J Discrete Mathematics (Kral), Advances in Combinatorics (Kral), Zeitschrift fuer Angewandte Mathematik und Physik (Wolfram), J Graph Theory (Georgakopoulos), Biometrika (Robert), Stochastics (Jacka).

In addition the unit has provided 90 members of Editorial Boards or Associate Editors and 5 of book series.