Institution: University of Nottingham

Unit of Assessment: UOA 10 – Mathematical Sciences

a. Overview

Research activity in the School of Mathematical Sciences (SMS) within The University of Nottingham (UoN) is structured across seven Research Groups (RGs): Algebra and Analysis (AA), Industrial and Applied Mathematics (IAM), Mathematical Medicine and Biology (MMB), Mathematical Physics (MP), Number Theory and Geometry (NTG), Scientific Computation (SC) and Statistics and Probability (SP). The Category A staff submitted (names in bold below) comprise 17.25 Professors ([P]), 15 Associate Professors/ Readers ([AP/R]), 20.6 Lecturers ([L]) and two Research Fellows ([RF], one with a tenure-track lectureship); each member of staff has a primary group affiliation, but many are members of more than one, reflecting extensive intradisciplinary working. Since RAE 2008, the School has undergone planned expansion with investment of £7M in new infrastructure and the appointment of 28 new staff (three of whom take up their appointments in January 2014). The value of current research awards to the School is £12M. The REF period has seen numerous strong appointments, high research student numbers and notable grant successes, alongside noteworthy mathematical advances and significant initiatives in applied and stochastic analysis, quantum technologies, systems and synthetic biology and uncertainty quantification.

b. Research strategy

The School reorganised in 2011 into the seven research groupings above - this structure was designed to provide more flexibility than the traditional applied/pure/statistics division and has indeed proved effective in promoting innovative new research directions, in facilitating intradisciplinary activity and in enhancing fundamental research. The School's achievements have led to further significant support from the University, notably in 10 new permanent posts and in the new building in which all SMS members have been housed since 2011: this provides both outstanding facilities and a layout explicitly designed to encourage research interactions, consolidating the benefits of the RG structure. Our research strategy builds on our successes in exceeding goals from RAE 2008.

Achievement of Strategic Aims from RAE 2008 (appointees since 2008 in italics)

- Expertise in SC has been and will be enhanced significantly by the appointments of *Hubbard*, *Iglesias*, ***Tretyakov*** and ***van der Zee***.
- SP has achieved significant success in recruiting talented researchers (*Bolton,* ***Fallaize***, ***Hodge***, ***Kypraios***, ***Preston*** (following his RCUK Fellowship) and ***Wilkinson***).
- Activity in NTG has benefitted from significant external funding over the REF period, underpinning an extensive visitor programme of world-leading researchers.
- Continued investment in systems biology and complex systems has broadened our expertise (notably in agent-based methods, analysis of large data sets, dynamical systems and homogenisation theory) and brought additional new blood (***Avitabile***, *Band*, ***Farcot***, ***O'Dea***, *Scase,* ***Susanto*** and ***Thul***). Two shortlisted CDT bids have recently resulted, one led by MMB with IAM a partner in the other.
- Multidisciplinary research continues to grow in both extent and reach, including involvement in major funding awards in bioenergy (£2.1M BBSRC IPA; two ERASysBio SysMO awards) and synthetic biology (£2.4M BBSRC/EPSRC sLOLA) and in new areas of interaction, for example with Biosciences, Geography and Social Sciences (AHRC-funded) and Psychology (Wellcome-funded).
- Collaborations spanning applied mathematics and statistics continue to blossom, those in MMB leading to significant additional joint funding in root-soil interactions (BBSRC, ERC) and seed germination (ERA-PG), with new areas of synergy including composites manufacture (EPSRC-funded, **Ball**/**Cliffe**/***Tretyakov***), equations of state (UKCCSRC-funded, **Graham**/***Preston***/***Wilkinson***), quantum tomography (**Guta**/***Kypraios***), network analysis (**Hopcraft**/***Preston***) and uncertainty quantification (UQ), including a shortlisted EPSRC Programme Grant bid and the above AHRC grant.

Evolution of Research Strategy since RAE 2008

The University has supported additional developments directed at further enhancing the cohesion and responsiveness of our expertise base.

- AA is the one area of deviation from RAE 2008 plans: following staff departures, strategic decisions were taken to establish a group in applied analysis (nonlinear PDEs and calculus of variations; ***van Gennip***, ***Kurzke***, ***Zhang***) and to strengthen complex analysis (***Nicks***), complementing the developments in SC in powerfully underpinning application-driven work in IAM, MMB, MP and SP.
- Building on established expertise (**Cliffe**, **Dryden**), new appointments (including *Iglesias*, ***Tretyakov***, ***Wilkinson***, ***van der Zee***) and activity seeded by IAM, SC and SP, a major initiative is underway in UQ that will coalesce extensive activity across the University into a Centre of Excellence.
- We have further enhanced the high profile of our work in quantum information (QI), rooted in the influential pioneering research of Belavkin, through the recruitment of ***Adesso*** and ***Fuentes***, targetting quantum technologies and reflected in very highly cited publications. Extensive collaborations with the School of Physics and Astronomy and with the quantum gravity (QG) group (**Louko, *Weinfurtner***) have resulted; new synergies between QI and QG include MP's leading position in relativistic QI, whose applications include to quantum metrology. QG has been correspondingly supported with additional appointments (***Sotiriou***, ***Weinfurtner***).
- Other intradisciplinary MP activity is also being expanded significantly, through interactions with IAM/MMB (e.g. through the identification of complementary expertise in knot dynamics) and, most prominently, with NTG: the latter has resulted in a very well-received EPSRC Programme Grant bid led by NTG and this interface has been supported by the recruitment of ***Bogomolov***, ***Oblezin*** and *Strömberg* to NTG.

Strategic Plans

Our vision, on which the above strategic developments are predicated, has two complementary strands that our active promotion of intradisciplinary research and fine tuning of our skill sets are increasingly interweaving: (I) to make distinctive mathematical contributions to major societal and technological issues and (II) to address fundamental mathematical challenges, in part by interacting with other globally recognised groups. We highlight the following priorities.

Enhancing collaboration between RGs Numerous very promising new intradisciplinary directions, implicit in the above and facilitated by the new building, will be pursued; noteworthy among these are collaborations between (i) IAM/MMB/SP, AA and SC in the development, analysis and simulation of novel hybrid (discrete/continuous, deterministic/stochastic) and multiscale formulations for industrial and biological processes and (ii) NTG and MP, exploring connections between geometry, topology, algebra and defects in quantum systems.

Expanding the scope of multidisciplinary research programmes MMB expertise continues to be called upon very frequently by biological researchers; existing programmes will be built upon (particularly in crop science, where multiscale investigations will explore the implications at the organism and field levels of genetic variations, addressing global-food-security concerns) and new areas, notably ones associated with healthy ageing and translational medicine, will be opened up. Ambitious plans to develop Nottingham Centres for Neural Computation and for Translational Cancer Research (both involving MMB together with partner Schools in the Faculties of Science and of Medicine) are well advanced. IAM will broaden its portfolio of industrial collaborations, while maintaining its current partnerships (including its extensive one with Rolls-Royce); its projects with Engineering will focus on manufacturing, energy and sustainability (including carbon capture and storage (CCS)). Support (including a joint appointment) will also be given to the burgeoning collaborations with Physics in both QI and QG, potential topics including quantum sensors and cold atoms. Recent cross-School grant applications are indicative of the scope for entirely new endeavours, including in population dynamics (with Archaeology), network dynamics (with Art History), the quantum vacuum (with Philosophy), neural computation (with Psychology) and evolving networks (with Social Sciences).

Establishing a Centre of Excellence in UQ The central importance of UQ for a host of application areas is increasingly widely recognised and by targetting growth therein we shall support much of the above activity, as well as making distinctive contributions to many of the University's Priority Areas, including global food security, energy and aerospace.

Exploiting opportunities afforded by internationalisation NTG has particularly ambitious goals, developing connections with groups at the Courant Institute, Moscow, Tokyo, Oxford, Paris, Princeton and Yale into long-term research programmes on central challenges in number theory and arithmetic geometry. MMB's participation in funded networks, see **e**, will be drawn upon in further broadening its collaborative activities and maintaining its leading international standing in multicellular modelling; it will host a major (SMB/ESMTB) international conference in 2016.
Pursuing innovative fundamental research The above focus on intra- and inter-disciplinary research will itself drive novel mathematics (e.g. in UQ, in homogenising multicellular models, in epidemic modelling, in the numerical approximation of high-dimensional problems and in addressing the challenges posed by future quantum technologies). Support will also be given to the pursuit of specialist areas of excellence, including algebraic cobordism and A^1-homotopy, complex and quasiregular dynamics, alternatives to string theory in fundamental physics, zeta and L-functions and higher automorphic functions, model theory and algebraic analysis, and shape and object data analysis.

c. People:

i. Staffing strategy and staff development

Appointment of 28 New Academic Staff
Staffing strategy reflects the priorities determined by research strategy, thus facilitating its delivery whilst maintaining high-quality teaching and postgraduate supervision to assure the sustainability of our staffing base. The School had sought to ensure that all groups have an effective blend of experienced leadership and new blood. Since 2008, 19 academic staff have retired (3), died in service (2) or left (14) the School for new challenges, career advancement or to return to their homelands, and we have appointed 28 new academic staff at professorial (AA, NTG, and SC), associate professor/reader (AA, MP, SC) and lectureship (2 AA, 2 IAM, 5 MMB, 2MP, NTG, 2 SC, 5 SP) levels or as research fellows (MP, NTG, SP). We no longer undertake research activity in C* algebras and have exploited the opportunity afforded by the resignations of our two staff in the area in developing the applied analysis group.

The REF period has seen the following staff appointments and promotions (additional significant developments of activity in UQ are currently underway, further posts, including a Chair, having been approved; AP vacancies in IAM and SP are also open).

- AA: ***van Gennip*** **[L]**, ***Kurzke*** **[AP]**, ***Nicks*** **[L]**, ***Zhang*** **[P]**;
- IAM: *Scase* [L], who currently holds an appointment in Engineering at UoN, from January 2014, ***Susanto*** **[L]**; promotions **Graham [AP]**, **Wattis [AP/R]**;
- MMB: ***Avitabile*** **[L]**, *Band* [L], a mathematician who holds a joint appointment between SMS and the School of Biosciences (being submitted to REF by the latter), reflecting the success of the group in cross-disciplinary research, ***Farcot*** **[L]**, ***O'Dea*** **[L]**, ***Thul*** **[L]**; promotion **Owen [P]**;
- MP: ***Adesso*** **[L]**, ***Fuentes*** **[L]**, ***Sotiriou*** **[AP/R]**, ***Weinfurtner*** **[RF]**; promotions **Barrett [P]**, ***Fuentes*** **[AP]**, **Krasnov [P]**;
- NTG: ***Bogomolov*** **[P]**, ***Oblezin*** **[RF]**, *Strömberg* [L], currently in Mathematics at the University of Durham, from January 2014; promotion **Diamantis [AP]**;
- SC: *Hubbard* [AP], currently in Computer Science at the University of Leeds, from January 2014, *Iglesias* [L], ***Tretyakov*** **[P]**, ***van der Zee*** **[L]**;
- SP*: Bolton* [RF], ***Fallaize*** **[L]**, ***Hodge*** **[L]**, ***Kypraios*** **[L]**, ***Preston*** **[L]**, ***Wilkinson*** **[L]**.

Staffing strategy is delivering an excellent balance of age and experience, enabling the sustained successful delivery of our research strategy. *Band*, ***Kypraios***, ***Nicks***, ***O'Dea***, ***Preston*** and ***Thul*** all previously held PGR and/or postdoctoral positions within the School.

Career Development Support
Several schemes are in place to support staff career development. For academic staff, a priority is to balance the demands of teaching, administration and research: to achieve this, we operate a workload allocation model that ensures an equitable distribution of teaching and administration, while taking account of research commitments. SMS revised its long-standing study leave scheme in 2012 and supports a programme of study leave on a 'one for six' basis (i.e. after six teaching semesters), the promise of the proposed activity being the focus of the School's assessment of the

case. Since 2008, 18 academic staff have benefitted from study leave (11 for one semester, the others for more extended periods). Outcomes have included successful grant applications, changes in research directions through participation in international research programmes (such as at SAMSI), outstanding research publications and delivery of impact. The School maintains a cadre of (four) committed teaching officers, protecting the research time of R&T staff.

SMS has a dedicated staff development programme that seeks to identify beneficial changes in School practice, to promote effective use of new technology and to encourage research collaboration, as well as supporting individual staff in their careers. The programme is led by the School's Staff Development Officer, with input from the Head of School, Directors of Teaching and Learning and of Research and Heads of RGs. Specific needs and opportunities are also identified by the SMS Boards and through the annual Personal Development and Performance Review (PDPR) undertaken by all staff, through which advice on training and career development, including promotion, and objective feedback on progress are provided, supplementing the advice and support provided to new staff through our peer-mentoring system (which has recently been enhanced following consultation). UoN's Professional Development Unit (PDU) and Graduate School run a wide range of courses designed in collaboration with the School to foster and enhance skills needed for career development; SMS also runs training events, including an annual exercise allowing draft promotion cases to be considered by senior colleagues and feedback provided. The University Research Board has introduced an annual Research Leadership programme to provide mid-career support, from which **Vishik** has received an award.

Members of academic staff new to lecturing are explicitly given reduced administrative and teaching duties under the School's workload scheme; they attend an induction programme and are further supported through the University's Postgraduate Certificate in Higher Education, which they are expected to complete within three years of appointment. New staff are each assigned an established-staff mentor on joining and are encouraged to disseminate their research within the School's extensive seminar programmes. New lecturers have preferential access to RG travel and equipment budgets to enhance their opportunities to participate in international conferences and to ensure that they have appropriate computational resources. ECRs have representation on the School's Research Board, the strategic group of which all Heads of RGs are also members, where they raise specific issues and provide fresh outlooks on existing activities. All research-grant applicants are supported through the School's formal mentoring and review systems.

Concordat to Support the Career Development of Researchers
The University is committed to embedding the principles of the Concordat in its policies and practices, the School's implementation of the seven key principles of the Concordat being evidenced elsewhere in **b**. UoN's Research-only Staff Group has undertaken benchmarking/gap analysis against the Concordat principles (drawing on data from a review of research staff-related issues, the University's 2009 School-level survey to review implementation of the Concordat, which identified both good practice and gaps, and the Institutional outcomes of the 2009 Careers in Research online Survey) and has established a monitoring process to address the areas that emerged. UoN has gained the European Commission's 'HR excellence in research' badge, incorporating the QAA Code of Practice for Research Degree Programmes and the Concordat, acknowledging alignment with the principles of the European Charter for Researchers and Code of Conduct for their Recruitment, and has twice been shortlisted for the Times Higher Award for Outstanding Support for Early Career Researchers. In the spirit of Concordat, PDPR, in which significant achievements are rewarded by enhanced salary awards, is applied uniformly to research and academic staff, as is the promotions policy.

Fellowships
Suitable PDRAs and PGRs are supported in applying for follow-on funding through research fellowships. Fellowship awards associated with the School and held during the REF period are from a variety of schemes, including Anne McLaren (*Bolton*), Daphne Jackson (**Brook**), EPSRC Career Acceleration/Advanced (***Fuentes***, **Guta**, **Krasnov**), EPSRC Established Career (***Oblezin***), EPSRC Postdoctoral (Cuesta), Leverhulme (Fyodorov, **Houston**, Jensen), Leverhulme Early Career (Ardakov, *Band*, ***Thul***), Marie-Curie (Cherniha, Gelfgat, Meusburger, Taranets), MRC

Bioinformatics (Jabbari), MRC New Investigator (5 year fellowship) (**Brook**), Royal Society URF (***Weinfurtner***), NWO VENI (***van der Zee***) and 1851 (Fairbairn). *Bolton* and ***Weinfurtner*** have each secured UoN Fellowship funds targetted towards outstanding early career female researchers, providing additional funding for research costs (up to £25k p.a.) and, inter alia, additional childcare costs (up to £5k p.a.). Fellows receive the full developmental support provided to other staff.

International Recruitment and Visiting Researchers
The School has a high proportion of internationally-recruited staff and researchers, recently including ***Bogomolov*** (Courant Institute), ***Farcot*** (INRIA), ***van Gennip*** (UCLA), ***Kurzke*** (Bonn), ***Sotiriou*** and ***Weinfurtner*** (both SISSA) and ***van der Zee*** (Eindhoven). Many former SMS members have secured permanent academic appointments overseas (recent ECRs in at least 16 countries over the REF period). UoN provides specific practical advice for overseas applicants, covering visas, finance, accommodation, registering with local facilities, the University system and UK culture. The School has well-equipped dedicated visitor rooms and regularly hosts international visitors (over 90 for a week or more over the REF period from over 20 countries, in addition to the Marie-Curie Fellows noted above) with NTG (c.30 visitors, tinyurl.com/odj4grh) having a particularly extensive and high-profile visitor programme and with a number of long-term visiting PGRs in QI being attracted by MP. Visitors have included Britton (Stockholm), Gaitsgory (Harvard), Kapranov (Yale), Smirnov (Steklov Institute) and Sneyd (Auckland). MMB held a BBSRC USPA with MBI Ohio and participates in further BBSRC Partnering Awards with China and the USA (two), as well as being a partner in a major UKIERI award involving two Indian institutions and leading two Marie-Curie ITNs (see **e** for more on network activities).

Equality and Diversity
The University is strongly committed to an equal-opportunities policy encompassing gender, race, colour, nationality, ethnic or national origin, age, socio-economic background, disability, religious or political beliefs, trade-union membership, family circumstance and sexual orientation. The effectiveness of its policy has been recognised over the REF period by The Scientist 2009 Best Places to Work in Academia, a Stonewall Diversity Champion award and an Athena SWAN Silver (institutional-wide) award; the School subscribes fully to the University's policies and has additionally received a departmental Athena SWAN Bronze Award for its efforts to recruit and provide for women in mathematics. UoN runs a Women in Science, Engineering and Technology group, of which SMS is a member, to aid career progression for women in STEM subjects and the School Athena SWAN Group seeks to build on SMS's Bronze award. The School has a dedicated Tutor for Women Students and is well represented at events such as the LMS Women in Mathematics days; **Riley** has also contributed to an LMS workshop on Advancing Women in Mathematics. A PGR-instituted group in SMS meets for lunch weekly in term time, allowing female PGRs to benefit from the experience of female staff.

ii. Research students

Recruitment
Our current PGR cohort stands at c.80 FTE. Since 2008 we have on average awarded 22 PhDs p.a., a 57% increase on RAE 2008. The School recruits able, highly qualified candidates through the usual mechanisms of advertising and personal contact. Our annual PhD open day is widely promoted and staff and PGRs frequently represent us at external recruitment events. We recruit strongly from our undergraduate intake, which is one of the best-qualified in the UK, and our extensive summer-internship programme (c. 9 p.a. on average over the REF period; funders include BBSRC, EPSRC, Nuffield Foundation, Rolls-Royce and Wellcome Trust) has paid dividends in identifying and motivating strong candidates – over 15% of male and 20% of female interns have gone on to a PhD here. Furthermore, development funding has been secured to establish the Dr Margaret Jackson Bursary scheme to support future female interns.

Student quality and strategic fit remain the most important criteria in assigning studentships, but other factors considered include support for new staff, leverage of external funding and balancing priority application areas with fundamental research. In addition to EPSRC DTG and internally

funded studentships, the School actively promotes multidisciplinary links, for example through industrially co-funded studentships and participation in the University's BBSRC DTP, as well as with the Digital Economy DTC; moreover, the School has during the REF period benefitted from its own BBSRC DTA and MRC DTG funding, as well as MRC MSc awards (MSc numbers in SMS have grown from fewer than 10 to more than 50 over the REF period). Our extensive network of research collaborations continues to be built upon in pursuing such opportunities, as reflected in leading the recently awarded Marie-Curie ITN NETT. Around 30% of our PGRs are non-HEU.

Training and Support Mechanisms
Guidance on PGR matters is provided in the School's comprehensive online PGR Handbook, which is updated annually. PGRs are assigned at least two supervisors, the Principal Supervisor being responsible for all administrative matters. Detailed working arrangements are established at the first of the weekly supervision meetings, and at least ten further written supervision reports p.a. (agreed by supervisor and student) are required to record progress and suggestions; these are monitored by the School's Postgraduate Student Advisor (SPSA) who, with the Research Secretary, administers all such policies and offers impartial and confidential help and advice. Membership of the Postgraduate Affairs Committee includes the Director of Research, the SPSA and PGR representatives, ensuring effective dialogue. PGRs are provided with dedicated desk space and a computer, sharing Common Room facilities with staff and having further work space and social facilities in the University's new custom-built Engineering and Sciences Learning Centre. Financial support is provided for conference attendance and the School's Research Facilitator advises on funding opportunities. PGRs benefit from extensive internal seminar programmes (each RG runs one or more series, supplemented by involvement in regional activities), study groups (for example, NTG has run 13 semester-long groups since 2008) and workshops. To help new PGRs settle into the School, an informal 'buddy scheme' is operated, pairing a new student with a more established one.

Formal assessed training requirements (which include required broadening training) depend on the length of the PhD programme (usually 3, 3.5 or 4 years), which in turn reflects the incoming student's experience, as well as any multidisciplinary elements of the project. PGRs have access to the advanced modules offered by the School, with many taking additional modules on a non-assessed basis, including from our extensive portfolio of MSc courses, the Graduate School (over 60 courses, such as Research Skills and Techniques, Networking and Employability) and the PDU. Additional training is available through the School's active participation in MAGIC and APTS.

Evidence for the effectiveness of our PhD training includes Prizes and Fellowships awarded (including two LMS Cecil King Travel Scholarships, eight EPSRC PhD+/Doctoral Prizes, a Leverhulme Early Career Fellowship, two on the shortlist for the first IMA Lighthill-Thwaites Prize, a Mathematical-Problems-in-Industry Graduate Fellowship, an MRC Centenary Award, an MRC Fellowship, a Simons Fellowship and a University of Birmingham Fellowship over the REF period to recent SMS PGRs), very active involvement in internship programmes (see **e**) and that the majority of our PGRs go on to postdoctoral research positions. At least 12 recent PGRs have secured permanent appointments in UK universities over the REF period. The initiative and commitment of School PGRs is further illustrated by their running four conferences over the REF period, namely the 3rd European Postgraduate Fluid Dynamics Conference (EUROMECH/IMA/LMS), two in MP (LMS/IMA/IOP) and the 2008 Research Students' Conference in Probability and Statistics (they are also hosting the 2014 meeting). The numerous other conferences and workshops run by the School (see **e**) provide further opportunities for PGR development.

Progress Monitoring
A student's status as a PhD candidate is probationary during the first year of registration: each is subject to a Confirmation Review by the end of that year, followed by Progression Reviews in subsequent years. These involve a written report and research plan that are assessed in an oral exam by two independent assessors (typically including the eventual internal examiner), who also monitor successful completion of training requirements. Further reviews can be held at any time should concerns be raised, for example through the regular supervision reports. Progress monitoring seeks to ensure thesis submission within (or, at the latest, shortly after for 3 and 3.5

programmes) the period of registered study.

d. Income, infrastructure and facilities

Infrastructure

The School's new building houses all UK-based staff, PDRAs and PGRs (other than a number on multidisciplinary projects) and has facilitated a wide variety of new research interactions, in part through the Common Room and eight rooms dedicated to small group discussions, all of which are heavily used. It also includes an AccessGrid room used in particular for advanced courses delivered by the EPSRC-funded MAGIC consortium. SMS has first-class computer facilities (including seven dedicated Linux multi-core servers) and its researchers also make good use (e.g. >100K CPU hours in the first half of 2013) of UoN's High Performance Computing Facility: this has received sustained institutional investment, the most recent (£1.2M) refresh delivering a 2656-compute core facility with a peak performance of 46 teraflops (12 GPGPU accelerators each providing approximately an extra teraflop compute power); UoN is in addition a partner in the EPSRC-funded MidPlus regional HPC centre. SMS has an in-house IT support team comprising three computer officers, who maintain the servers, PCs and laptops, as well as providing support for software and liaising with the University's Information Services team. The School's support team also includes a full-time (mathematically trained) Research Facilitator who assists staff and ECRs in identifying and applying to relevant funding schemes, as well as liaising with other Schools and with the central research support teams. The University's campuses in Malaysia and China both deliver mathematics teaching programmes and offer growing opportunities for research collaboration and internationalisation, for example through the 'Crops for the Future' initiative in Malaysia. Its new building will allow SMS to absorb planned increases in staff numbers and growing cohorts of PGRs and PDRAs and the School's Resources Committee will ensure provision of computing hardware and software facilities remain at the high level required to support our developing research portfolio. The well-resourced George Green Library, which is undergoing a £19M upgrade during 2014, is adjacent to the School.

Funding Portfolio and Future Plans

Research income to the School averages £2M p.a. over the REF period. The funding of the associated grant portfolio of value £14.4M comprises 47% EPSRC, 30% EC, 12% BBSRC, with the remainder from a wide range of other sources including industry, MRC, STFC and the Wellcome Trust; SMS currently has over 40 major research awards worth around £80M in total value (£12M to the School). Over the REF period, SMS has been a partner in numerous major projects; since many of these involve multidisciplinary (and/or multi-institutional) collaborations, these are far from being fully reflected in its income data – significant such awards include (only SMS members being listed among coIs): the Horizon Digital Economy Hub (EPSRC, £12.6M; PI McAuley, Computer Science; coI **King** with involvement of **Hopcraft**, ***Hodge*** and ***Preston***); Centre for Plant Integrative Biology (CPIB) (BBSRC/EPSRC, £9.2M: PI Hodgman, Biosciences; Modelling Director and coI **King**, coIs Byrne, **Dryden**, Jensen, **Owen**, **Wood**); Second Generation Sustainable Bacterial Biofuels (BBSRC, £2.1M; PI Minton, Molecular Medical Sciences; coI **King**); Physics of the Early Universe, Cosmology of the Early and Late Universe (STFC, £1.3M, with follow-on funding awarded subject to confirmation; PI Copeland, Physics; coIs **Barrett**, **Krasnov**, **Louko**); Mathematics of Regenerative Medicine (BBSRC/EPSRC, £1.2M; PI **King**; coIs Byrne, Jensen, **Owen**); MMBNOTT (FP6 single-site ITN, €1.7M; PI Jensen; coIs **Ball**, Byrne, **Coombes**, **Dryden**, **King**, **O'Neill**, **Owen**, Richardson, **Wattis**, **Wood**); BBSRC Professorial Fellowship and ERC Advanced Grant (Root systems biology; PI Bennett, Biosciences, c. £4M; collaborators/team members **King**, **Owen**, **Wood**). Major multi-institutional awards include NETT (Neural Engineering Transformative Technologies FP7 ITN, €5.3M; PI **Coombes**); COSMIC and COSMIC2 (Systems biology of *Clostridium acetobutylicum*, SysMO, £1.3M to UoN; group leader **King**); vSEED (Virtual seed, ERA-NET Plant Genomics, €1.7M; coIs **King**, **Wood**); Virtual Physiological Human (VPH) Network of Excellence (FP7, €8M; group leader **King**); AirPROM (Airway disease outcome prediction, FP7 VPH, €11.7M; group leader **Brook**); ADIGMA (Variational methods for aerodynamic applications, FP6, €3.2M; group leader **Houston**). This multidisciplinary funding complements support from, for example, the EPSRC Mathematics Programme (new awards over the REF period exceeding £4M, including a recent award on statistical analysis of manifold-valued data (PI **Wood;** coIs **Dryden, Le, *Preston***)) and the ERC (MP having secured Starting Grants to

Krasnov (€1.2M) and ***Sotiriou*** (€1.4M)).

Plant-and-crop systems biology continues to provide an exceptional opportunity: following the successes of CPIB and of subsequent BBSRC and ERC funding (other grants involving SMS include ones on hormone signalling, tomato ripening, plant fertility and photosynthesis), the area has received significant further UoN investment. Collaborative papers in high impact journals (e.g. Interface, Nature Cell Biology, Plant Cell, PNAS) are raising MMB's already high profile in this fast developing field: alongside MMB's more established expertise in cancer, neuroscience, regenerative medicine and VPH, we are in an outstanding position to pursue multiscale modelling opportunities associated with initiatives in the Digital Organism, as well as contributing to the strategic areas of bioenergy and global food security. More generally, much of our funding relates to the development and application of new mathematics to priority areas that will be of long-lasting significance, including advanced materials, agri-science, big data, energy, healthy ageing and sustainability. The long-standing strategy of promoting collaborations between applied mathematics and statistics, as exemplified by MMBNOTT in which all 10 students had a supervisor from each (as well as a biological supervisor), is also continuing to pay off (cf. **b**). In addition, numerous seeding activities have taken place in the last few years, such as internal pump priming and bridging the gaps awards, designed to prepare junior staff for external applications and to initiate relationships with partners in industry and other disciplines: continued growth is expected from this, building on initial successes such as BBSRC funding to ***Kypraios***, FQXi to ***Adesso*** and Leverhulme to ***Thul***. Plans for future funding are implicit in the strategy outlined in **b**: in particular, major funding bids are being developed at the MP/NTG interface and in MMB; QI is particularly active in attracting Fellowship applicants, as well as pursuing other funding opportunities; SP will both expand existing interdisciplinary activities (in biomedical imaging, bioinformatics and the digital economy) and build on the enhanced breadth achieved through its recent strategic appointments to extend these further (e.g. in business management and climate science and with the School of Veterinary Medicine and Science), *Bolton's* Fellowship on pandemic influenza representing a further timely development; the expansion in both applied analysis and SC will similarly generate further synergies, both between them (especially on PDE analysis) and on applications to multiscale problems in biology, engineering and physics; very recent discussions with Unilever, which focussed on potential projects on customer behaviour and molecular analysis, illustrate the considerable further potential of IAM's industrial collaborations; and we shall seek to realise the potential for novel interactions with the Social Sciences (e.g. through Horizon or via an MSc programme under development with Economics), amongst others. In summary, we believe our established expertise and our strategy-led appointments outlined in **b**, **c** combine to place us in an outstanding position to secure funding both to address major intradisciplinary challenges within mathematics and to contribute significantly and distinctively to multidisciplinary programmes associated with many key international priorities.

Consultancy and Professional Services

Formal consultancies have included those with AMEC (**Cliffe**), Element Six (**Cliffe**, **Houston**), the Institute for Crystal Growth, Berlin (**Cliffe**), Garrad Hassan (***Preston***, ***Wilkinson***), legal consulting (**Wood**), Mars Petfood (**Wattis**) and Unilever (**King**). **Cliffe** (Rolls-Royce) and **Tanner** (inuTech) have been part-funded by industry and extensive interactions also occur through other mechanisms, including internships and CASE awards (see **e**) and Mathematics-in-Industry and other Study Groups (both UK and overseas), with the Mathematics-in-Medicine, Mathematics-in-the-Plant Sciences and VPH Study Groups all being initiated at Nottingham and all featuring extensive end-user participation. ***Zhang*** is in discussion with a company over its use of an image-processing approach for which he has a patent application submitted.

e. Collaboration or contribution to the discipline or research base

Research Collaborations

The School is engaged in research collaborations of exceptional number and scope, including an enormous variety of highly productive multidisciplinary projects (cf. grants noted in **d**): these range from highly focussed ones (such as that of **Cox** on class-D amplifiers with co-workers in Singapore) to very wide-ranging ones in NTG, plant systems biology and QI, for instance.

Externally funded network activities over the REF period include: BBSRC: Mathematical Tools for Systems Biology networks: SIGNET (cell signalling; PI **Owen**, coIs **Coombes**, Monk); STEMN (spatiotemporal plant modelling; PI Bangham, UEA; coI **King**). Partnering awards: China – integrative approaches to understanding and improving nutrient uptake efficiency in crops (PI Hodgman, Biosciences; coI **King**); USA – systems approaches to study hormone regulated root growth (PI Bennett, Biosciences; coIs **King**, **Owen**); USA – CMMB/MBI partnership on multiscale mathematical modelling (PI **Owen**); USA – regulatory networks for asymmetric cell division (PI de Smet, Biosciences; coI **Owen**); EPSRC: ANGIONET (angiogenesis; PI **Owen**); Mathematical Neuroscience Network (PI **Coombes**); Bridging the Gaps between Mathematics, ICT and Engineering at Nottingham (PI Benford, Computer Science; coI **Cliffe**); Analysis on Graphs (PI Brown, Cardiff; Nottingham members **Gnutzmann**, **Tanner**); ESF: Quantum Geometry and Quantum Gravity (PI **Barrett**).

Both these and the very many more *ad hoc* networks of collaborations in which we engage have led to a considerable number of research outputs and funding opportunities and hold out immense promise for further development. The School's extensive hosting of research meetings, ranging in scale from the British Applied Mathematics Colloquium in 2009 to focussed one-day meetings, has further enhanced the range of our research interactions, as well as providing outstanding opportunities for both ECRs and established staff to learn from leaders in their fields. Many of these meetings (notably the various Study Groups) were explicitly designed to initiate and promote cross-disciplinary investigations and have borne considerable fruit in terms of follow-on funding and publications. Conferences, short courses and other research meetings hosted at Nottingham, in addition to the PGR ones noted in **c**, include (in almost all cases those listed were (co-)chairs): (AA) Quadratic Forms, Algebraic Groups and Algebraic Cobordism, 2008 (Hoffmann, **Vishik**; EPSRC, LMS); (IAM) BAMC 2009 (Jensen, **King**), Bifurcations and Instabilities in Fluid Dynamics, 2009 (**Cliffe**), CO_2 Transportation for CCS, 2009 (**Graham**), Free Boundary Problems in Fluid Mechanics, 2012 (**King**, **Riley**; ESF, LMS), Innovations in Wave Modelling, 2012 (**Tanner**), PANDA meetings in 2008, 2010, 2011, 2013 (**Matthews**; LMS); (MMB) Biological Modelling Summer Schools, 2008-13 (**Owen**), MMBNOTT/MRM Summer Workshops, 2008-11 (Jensen, ***Thul***), Mathematics-in-the-Plant Sciences Study Groups, 2008-13 (CPIB; *Band*, **King**), Calcium Dynamics, 2008 (***Thul***), Angiogenesis in Tissue Engineering, 2008 (**Owen**), 1st VPH Study Group, 2009 (**Brook**, **King**), Non-local Neuronal Connectivity, Wave Control and Migraine Modelling, 2009 (**Coombes**), Systems Biology of GPCR Signalling, 2010 (**King**, **Owen**), Multicellular Modelling, 2011 (**Owen**), Multiscale Modelling, 2012 (**Owen**), NETT Workshop and Summer School, 2013 (**Coombes**); (MP) Quantum Geometry and Quantum Gravity, 2008 (**Barrett**; ESF, IOP), Quantum Chaos, 2009 (**Gnutzmann**, **Tanner**; LMS/EPSRC), Disordered Systems, 2009 (**Ossipov**; LMS), Waves in Cavities, 2011 (**Creagh**; LMS), Relativistic Quantum Information, 2011, 2013 (***Adesso***, ***Fuentes***, **Louko**), Signatures of Quantumness in Complex Systems, 2011 (***Adesso***; ESF), Quantum Correlations and Information Flow, 2012 (***Adesso***), Mathematical Techniques for Quantum Physics, 2012 (***Adesso*;** LMS), New Directions in Quantum Statistics, 2012 (**Guta**), Quantum Probability, Statistics and Control, in memory of Belavkin, 2013 (**Guta**); (NTG) Nottingham-Poznan Arithmetic Geometry, 2008 (**Fesenko**), Nottingham-UCD Number Theory, 2009 (**Fesenko**); (SP) RSS Conference, 2008 (**O'Neill**), APTS meetings, 2012, 2013 (**Brignell**).

The School's global influence is further sustained by the organisation of international conferences at research centres elsewhere, extensive overseas lecturing and numerous overseas collaborations and visits. Amongst the first of these we highlight membership of the organising committees of the following meetings (mainly as (co-)chairs; we have served as such for over 30 meetings outside Nottingham, and on the scientific or organising committees of very many others): ICMS: Multiple Dirichlet Series, 2008 (**Diamantis**, **Fesenko**), Uncertainty Quantification, 2010 (**Cliffe**, **Houston**), Mathematical Neuroscience, 2008-2011 (**Coombes**), Nonlinear Waves and Solitons in Lattices, 2011 (**Wattis**), Neurodynamics, 2012 (**Coombes**), Scale Transitions in Chemistry and Biology, 2012 (**King**), Complex Analysis and Complex Dynamics, 2013 (**Langley**); ICTP: Effective Gravity in Fluids and Superfluids, 2012 (***Weinfurtner***); MBI: Workshop for Young Researchers, 2008 (**Coombes**, **Owen**), Recent Advances in Statistical Inference for Mathematical Biology, 2012 (***Kypraios***, ***Preston***), Statistics, Geometry and Combinatorics on Stratified Spaces arising from Biological Problems, 2012 (**Le**); MFO: Design and Analysis of Infectious Disease

Studies, 2009, 2013 (**O'Neill**); MSRI: p-adic L-functions and Modular Symbols, 2010 (**Wuthrich**), Free Boundary Problems, Theory and Applications, 2011 (**King**); Kavli Royal Society International Centre: Complex Patterns in Wave Functions, 2012 (**Gnutzmann**); SAMSI: Analysis of Object Data, 2010-11 (**Dryden**).

Interdisciplinary Research (see also **d**)
Much of the School's exceptionally strong interdisciplinary ethos stems from the close relationships between IAM and Engineering and between MMB and Biosciences, Life Sciences, Medicine and Health Sciences and Pharmacy, the former built on a long history of collaboration of work in theoretical mechanics, with the formation of the Spencer Institute in 2007 helping to create a focal point for joint work on continuum mechanics and on CCS. Recent PGR co-supervision has involved at least 14 other Schools across UoN. Work with Engineering and the Rolls-Royce University Technology Centre in Gas Turbine Transmission systems has continued to grow, with PGRs and PDRAs co-funded by Rolls-Royce and with joint grants including the EC programme ELUBSYS (**Cliffe**, €4.5M). Other extensive collaborations with Engineering include further EC grants on CCS, such as MUSTANG (**Cliffe**, €8.0M) and PANACEA (**Cliffe**, €3.7M). **Tanner** won a Marie-Curie IAPP grant in 2009 (MIDEA) with inuTech, also involving partners Bosch, ISVR (Southampton) and ViF (Austria). Collaborative work by MMB has expanded its reach considerably over the REF period and includes significant international and industrial components. For example, the €5.3M Marie-Curie ITN NETT (**Coombes**) involves a cross-disciplinary team across Europe of mathematicians, engineers and biologists, with support from 12 industrial partners, providing outstanding multidisciplinary training for PGRs and strong engagement with industry. Connectivity of MMB with VPH activities remains strong, for example through **Brooks**' AirPROM grant that builds on the success of her Fellowships and through Peter Hunter FRS (Auckland) serving as Visiting Professor in SMS. SP additionally collaborates with Physics (MRI) and with Computer Science (on multiple areas, for example through Horizon), while members of MP work in close collaboration with Physics, holding joint EPSRC and STFC grants.

Industrial Engagement (see also Impact Template)
Engagement with industry, and with other disciplines, has for many years shaped much of the School's research activity, topics arising from Study Groups and other such interactions routinely raising distinctive and novel mathematical questions and thereby initiating new research directions. We remain highly responsive to such new challenges. Many of our funded projects are in association with industrial partners who have contributed significant funding, including BBSRC IPA grants with Syngenta, with Lanzatech and with TMO renewables, while at least eight EPSRC grants involve industrial partners (including two in Maths for Manufacturing, further support for which has been secured through significant involvement in an Engineering-led ITN). **Owen**'s BBSRC Modular Training for Industry award on Mathematical Modelling for Life Scientists has further enhanced the delivery of our research expertise into industry. CASE awards number nine over the REF period, five in biomedical applications (with an additional student joint with the HPA) and four in engineering applications (alongside five other studentships associated with Rolls-Royce). Long-term relationships with industry have been encouraged through mechanisms such as EPSRC Knowledge Transfer Secondments (Utev, Network Rail and **Tanner**, Jaguar Land Rover) and student internships (sKTP) through the Industrial Mathematics KTN (five, including with Airbus (**Billingham**), Russell Group Ltd (**Wood**) and Unilever (**King**)). Keith Winters, Chair of the Industrial Advisory Board of the Industrial Mathematics KTN, is a Visiting Professor in the School who shares his insight from many years' work in industry to enhance our interactions further.

Academic Leadership (posts held by former staff were while members of SMS)
International advisory board memberships include: AERES advisory panel (**Coombes**); APS member-at-large (***Fuentes***); ESF Forward Look Programme: Complex quantum systems working group co-chair (***Adesso***); Steering committee memberships of ESF networks on Harmonic and complex analysis and its applications (**King**), Global and geometric aspects of nonlinear PDEs (**King**), Quantum geometry and quantum gravity (**Barrett**, chair); EUROMECH Council (Jensen); IRCSET Postdoctoral Fellowships (**Barrett**); ISGRG committee (**Louko**); MITACS review panel (**Coombes**); Netherlands Computational Life Sciences advisory panel (**Coombes**); Relativistic Quantum Information International Society Committee (***Fuentes***, secretary, **Louko**); St Petersburg

Mathematical Society Council (**Fesenko**); VPH Network of Excellence Steering Committee (**King**).

Research Council roles include: EPSRC: College – ***Adesso***, **Barrett**, **Cliffe**, **Diamantis**, **Dryden**, ***Fuentes***, **Guta**, **Hopcraft**, **Houston**, **King**, **Matthews**, **Owen**, **Wood**; Panels – ***Adesso***, **Diamantis**, ***Fuentes***, **Hopcraft**, **Houston**, **Matthews** (chair), **Owen**; Sandpit Directors – Jensen (Maths of Life), **King** (Predictive Modelling of Healthcare Technologies through Maths). BBSRC: Panels – Byrne, **Coombes**, **King**; Integrative and Systems Biology Strategy Panel – Byrne; Digital Organisms Expert Working Group – **King**; Core Panel Member – **King**; Pool of Experts – **Coombes**, Jensen. MRC: Panels – **Coombes** (Biomedical Informatics, Strategic Skills), **King** (Systems Immunology). NERC: Panel – ***Wilkinson*** (Earth System Modelling Strategy).

Learned society/professional body roles include: COPS: Member of Executive (**Wood**); IMA: Journals Board of Management (**King**), Research Group (Jensen); Industrial Mathematics KTN: Scientific Committee (**Billingham**, **King**); LMS: Prizes Committee (**King**), Research Policy Committee (**Riley**), Women in Mathematics Committee (Byrne); Royal Society: Grants Scheme Physical Sciences Board (**Coombes**), Newton International Fellowships Assessment Panels (Jensen, **King**); RSS: Chair of Research Committee (**Dryden**), Chair of East Midlands Group (**Wood**).

The many hundreds of invited talks at international conferences include at Algebraic Geometry, K-Theory and Motives (**Vishik**, St Petersburg, 2010), Algebraic K-theory and Arithmetic (**Fesenko**, 6th ECM Satellite Conference Będlewo, 2012), Foundations of Computational Mathematics (**Houston**, Hong Kong, 2013), Frontiers in Applied and Computational Mathematics (***O'Dea***, NJIT, 2013), Loops 13 (**Krasnov**, Perimeter Institute, 2013), SIAM Annual Meetings (**Coombes**, Denver, 2009; **King**, Pittsburgh, 2010), STAMM 2010 (**Parry**, Berlin, 2010) and World Statistics Congresses (**Dryden**, Durban, 2009; **Ball**, Dublin, 2011; **Le**, Hong Kong, 2013).

Current Editorial Board memberships include: ***Adesso***: PLOS ONE; **Ball**: Mathematical Medicine and Biology; Mathematical Biosciences; Scandinavian Journal of Statistics; ***Bogomolov***: Central European Journal of Mathematics (editor-in-chief); Geometrical and Functional Analysis; **Billingham**: QJMAM; **Coombes**: Bulletin of Mathematical Biology; DCDS Series S; Physica D; Journal of Mathematical Neuroscience (editor-in-chief); **Dryden**: Methodology and Computing in Applied Probability; England: QJMAM; ***van Gennip***: Nieuw Archief voor Wiskunde; **Hopcraft**: Waves in Random and Complex Media; **Houston**: International Journal of Numerical Analysis and Modeling; Numerical Mathematics: Theory, Methods and Applications; Numerical Methods for PDEs; **King**: European Journal of Applied Mathematics; Frontiers in Plant Systems Biology; Mathematical Medicine and Biology (co-editor in chief); Mathematics in Industry Case Studies; QJMAM (chair of trustees); SIAM Journal on Applied Mathematics; **Krasnov**, **Louko**: Classical and Quantum Gravity (Advisory panel); ***Kypraios***: Statistics and Computing; **O'Neill**: Statistical Communications in Infectious Diseases; **Owen**: Computational and Mathematical Methods in Medicine; ***Preston***: International Journal of Corpus Linguistics; **Soldatos**: Mechanics of Advanced Materials and Structures; Journal of Engineering Mathematics; ***Tretyakov***: SIAM Journal on Scientific Computing; **Wood**: Biometrika (screening editor); ***Zhang***: Communications in Mathematical Research (deputy editor-in-chief); Frontiers of Mathematics in China.

Prizes and awards in addition to the Fellowships in **c** include: Humboldt Fellowships: ***Fuentes*** (2008), **Krasnov** (2011); Fellowship of the Institute of Mathematical Statistics: **Dryden** (2012); LMS Whitehead Prize: **Owen** (2009); Waters' (2012) prize cited work initiated while a member of CMMB; Leverhulme Study Abroad Fellowship: ***Tretyakov*** (2012); Max Planck Society Research Scholarship: **Diamantis** (2011); MSRI Visiting Research Professorship: **King** (2011); Pierre Deligne Award: ***Oblezin*** (2009); Royal Society Wolfson Research Merit Awards: **Dryden** (2012), **King** (2008); SIAM Julian Cole Lectureship: **King** (2010); Society of Rheology Metzner Award: **Graham** (2011).