Institution: University of Oxford

Unit of Assessment: UoA10: Mathematical Sciences

1. Unit context and structure, research, and impact strategy

Context:

The University of Oxford has one of the largest and most diverse cohorts of mathematical scientists in the world. This UoA comprises the Mathematical Institute (MI) and the Department of Statistics, which sit within the Mathematical, Physical, and Life Sciences Division (MPLS), housing 175 Cat A Faculty and Research Fellows, 85 postdoctoral research assistants (PDRAs), and 367 postgraduate research students (PGRs). Our physical infrastructure boasts generous visitor space (almost 1,500 visits of a week or more in period), events facilities (over 25,000 participants in 2019 alone), and carefully configured interaction space, all of which play a key role in attracting researchers at every career stage to come and work in Oxford.

Vision:

Our vision is to be a world-leading centre for mathematical sciences, with a diverse and dynamic research portfolio, generating lasting impact both within and outwith academia. We strive to recruit the very best researchers, regardless of origin or background, and promote an inclusive culture in which they can thrive. The breadth and depth of our research enables an agile response to challenges, and underpins the world-class training delivered to our postgraduate research community.

Since REF 2014, the University has continued to prioritise investment in the mathematical sciences. This includes:

- **Capital investment**: £7.2M to renovate the St Giles Building, a four-minute walk from the MI's Andrew Wiles Building, creating a new home for Statistics enabling co-location of all its researchers for the first time.
- **Investment in people**: Appointment of 16 Statutory and Research Professors and a further 34 permanent appointments, resulting in an increase of 22 'tenured' staff since REF 2014; and a total of 40 Hooke, Titchmarsh, and Florence Nightingale Research Fellows (eight last time), and a five-year Sylvester Fellow.
- **Investment in national infrastructure:** Joining the Alan Turing Institute (**the Turing**) as a founder partner, catalysing new research and accelerating the impact of our burgeoning activities in data science.

Research Groups:

Our research is loosely organised around a set of interconnected groups and centres: Algebra; Combinatorics; Computational Statistics & Machine Learning (CSML); Data Science; Econometrics; Functional Analysis; Geometry; History of Mathematics; Logic; Mathematical & Computational Finance; Mathematical Physics; Number Theory; Numerical Analysis; the Oxford Centre for Industrial & Applied Mathematics (OCIAM); the Oxford Centre for Nonlinear Partial Differential Equations (OxPDE); Oxford Protein Informatics Group (OPIG); Probability; Statistical Genetics & Epidemiology; Stochastic Analysis; Topology; and the Wolfson Centre for Mathematical Biology (WCMB).

Development and implementation of strategy:

Our research committees develop a research vision and a strategy for enacting it. They proactively seek out emerging areas and opportunities within and beyond the discipline. Additional input comes from our External Advisory Panels (EAPs) and the Scientific Boards of our six MScs and the seven CDTs which we lead, or in which we are partners. We believe that interactions beyond academia enrich the mathematical sciences, and that research from right across our portfolio has potential for impact. We aim to maintain breadth, target investment where we see emerging synergies, and maintain the flexibility to respond to the unforeseen developments intrinsic to research. The close working relationship between the two departments

ensures agile and coherent responses to opportunities, as illustrated by developments in Data Science.

1.1. RESEARCH STRATEGY: REF2014 TO REF2021 AND FUTURE PLANS

- *In 2014, we anticipated appointing eight statutory chairs in this period and supporting them through faculty appointments and targeted use of our fellowships.*

We appointed eight statutory chairs: Cont, (Christl) Donnelly CBE FRS FMedSci, Doucet, Holmes (to a new joint Chair with the Nuffield Department of Medicine), Hrushovski FRS, Kirwan DBE FRS, Keating FRS, and Rousseau. We promoted four existing faculty to personal research chairs (Alday, Deane, Reinert, Teh), and appointed four additional research chairs (Brown, Markovic FRS, Maynard, Windmeijer). In 2016 we were awarded a Regius Professorship in Mathematics, to which we appointed Wiles KBE FRS.

Details of other faculty appointments are presented by research theme below.

We expanded the Hooke and Titchmarsh Fellowships programme and created the Florence Nightingale Bicentennial (FN) Fellowships (a total of 40 Fellows in period).

- *We highlighted our commitment to interdisciplinary work, predicting an expansion in energy and with life sciences and the pharmaceutical industry. We anticipated significant growth in big data and new collaborations with Computer Science.*

Interdisciplinary work has burgeoned; 113 researchers in our submission produced an output with a co-author from outside mathematical sciences in the period (64 last time).

Work on **energy** expanded from seven to 14 faculty, and ranges from generation to energy markets. Our battery group plays a key role in the £11.5M Faraday Institution multiscale modelling project (eight academic and 15 non-academic partners).

Collaborations with the **life sciences** are found across the UoA, with 57 of our Cat A staff writing papers at the life sciences interface in the period, and we appointed two software engineers to accelerate the impact of our work in the **pharmaceutical industry**.

Our first steps towards establishing a presence in **data science**, taken in the last REF period, have accelerated massively with mathematical aspects of data science now forming a major part of our activity. This benefits hugely from our involvement in the Turing. Grindrod was on the Board of Trustees, Tanner is Oxford academic lead, Tillmann chaired the Programme Committee, and Holmes is Programme Director for Health and Medical Sciences. Cartis is Theme Lead in Optimisation for Machine Learning (ML), and Cohen for ML in Finance. Cucuringu and Nanda, originally Turing Research Fellows, are now faculty. A further 14 faculty across seven research groups have received support. The Turing funds nine of our PGRs; four more are part of the enrichment programme.

Within Oxford, the Big Data Institute (BDI) opened in 2017; Donnelly and Holmes are affiliates. It hosts the CDT in Health Data Science, in which we are partners.

Investment across the University has transformed the landscape in ML. Seven new permanent faculty in CSML are supported by three FN Fellows. We partner with Oxford Engineering Science and **Computer Science** as a unit of ELLIS, a grassroots ML initiative spanning 14 countries; 12 of our faculty are involved.

In a new collaboration with **Computer Science** and Physics, a £935k EPSRC grant supports a centre for Quantum Mechanics and Computation, and we spun out PQShield, in post-quantum cryptography, which has £5.5M in seed funding and 15 employees.

- *We planned new international alliances* (Section 4.1)*; to further enhance graduate training* (Sections 1.2 and 2.2)*; and to capitalise on our new buildings to extend public engagement with research (PER) and outreach* (Sections 1.2 and 4.4)*, and to exploit the opportunities provided by the move to Oxford of the Clay Mathematics Institute (CMI).*

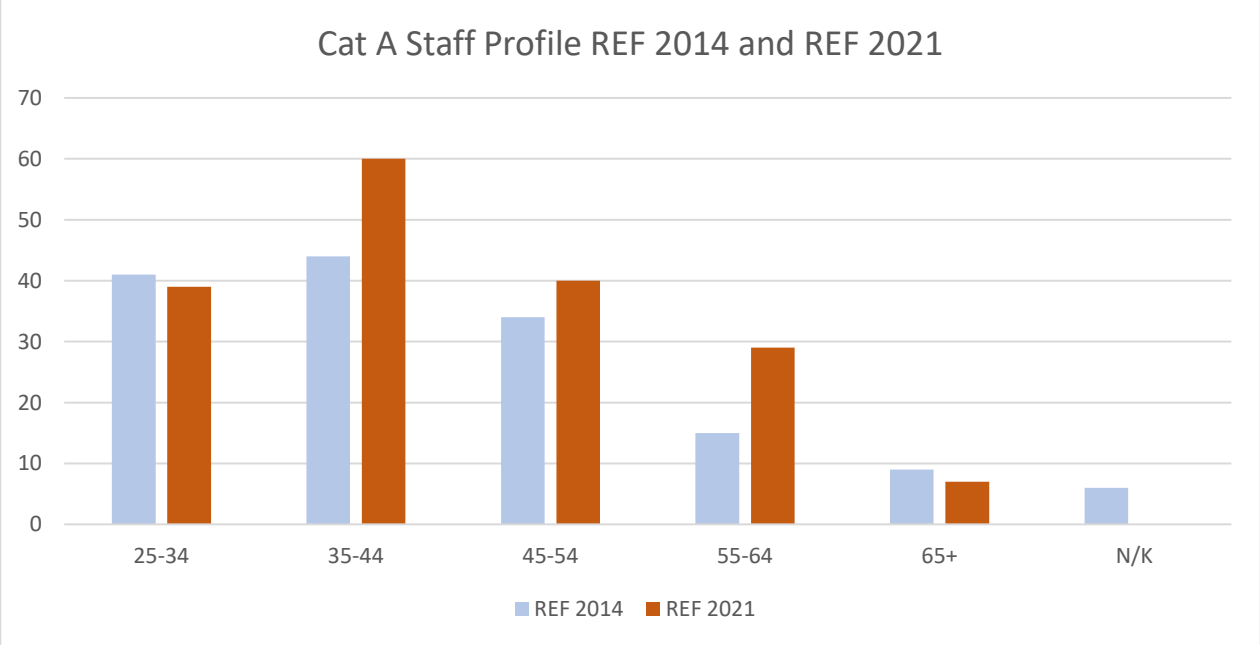
Bridson succeeded N Woodhouse as CMI President. We hosted four CMI-LMS Summer Schools and (throughout the period) the annual Clay Research Conference (six Fields Medallists spoke in 2018 alone). Maynard and Walsh held their Clay Research Fellowships, and Voevodsky his Clay Senior Scholarship, in Oxford.

Future strategy:

Our highest priorities are to foster absolute excellence in research, to recruit and retain the best researchers, and to provide them with an environment in which they can thrive. We will maintain our investment in fundamental research across the spectrum of the mathematical sciences, while driving forward interdisciplinary initiatives, and providing the culture and structures that enable researchers to realise the impact of their work both within and beyond academia.

Appointments to the Rouse Ball Chair in Mathematical Physics (replacing Candelas) and the chair of Pure Mathematics (replacing Heath-Brown) are underway, and we will support them with targeted appointments.

The challenges presented by data science have catalysed exciting new collaborations across our research themes. With significant renewal expected over the next decade (see the graph below) – including the Regius Chair, the Wallis Chair (replacing Lyons), chairs in Mathematical Biology, Numerical Analysis, and Statistical Science, and a planned new chair in Probability Theory – we have a significant opportunity to recruit and support research leaders to drive forwards a strategy for deep fundamental mathematics in symbiosis with applied areas.



Our PGRs and Research Fellows are fundamental both to the vitality of our own research and to the health of the discipline. In order to be able to support the very best PGRs, irrespective of nationality, we shall continue to prioritise studentships in our fundraising, while maintaining our investment in fellowships. Building on the success of initiatives started in this period, we will provide a suite of bespoke career development and skills training for our Early Career Researchers (ECRs) and PGRs.

We will continue to play a leading role in the Turing, and plan an expansion of our longstanding relationship with GCHQ/the Heilbronn Institute for Mathematical Research (HIMR). Building on

our approach in statistical genomics, we will explore secondments/joint appointments with Oxford's Medical Sciences Division (MSD) to cement emerging new connections with the medical and life sciences.

We will make strategic investments to support our researchers in securing a diverse portfolio of funding and sustaining engagement with industry.

Inevitably we will need to take stock post-COVID. During lockdown, online tools presented new ways of working. We sustained (and grew) our international networks, and our rapid response to the call for assistance in tackling the pandemic stimulated entirely new research directions. We will endeavour to preserve the positive developments, and to support those researchers now wishing to refocus their research programmes.

As always, we shall be opportunistic, nurturing excellence wherever we find it, and encouraging broad and outward-facing research agendas.

Research themes:

Groups are gathered into seven themes. Cat A staff are only listed against their primary group (new permanent staff in italics; Research Fellows and fixed-term appointments in square brackets). Many staff belong to more than one research group.

Opportunities identified for individual research themes in 2014 are mapped onto our current taxonomy.

Theme 1

Algebra: Ardakov, *Ciubotaru*, du Sautoy, Kremnitzer, McGerty, [Mason-Brown], Nikolov, [Romano], *Rössler*, [Wade]

Geometry: [Bischoff], Dancer, [Gallauer], [Haiden], Joyce, Kirwan, *Lotay*, [Prince], Ritter, Szendrői

Topology: [Barbensi], [Brantner], Bridson, Douglas, Drutu, *Henriques,* [Hume], Juhász, *Kielak*, Lackenby, *Markovic, Nanda*, Papazoglou, Tillmann, [D Woodhouse], [Yazdi]

Mathematical Physics: Alday*, Beem*, Candelas, [Closset], de la Ossa, *Keating*, [Keir], [Kim], Mason, [Panzer], *Schafer-Nameki*, Sparks

We anticipated new collaborations right along the interface with physics, from string theory to discrete random structures.

Ever closer cooperation with Oxford Physics (including a new joint MSc) is reinforced by Beem and Schafer-Nameki, who were central to a successful joint bid to STFC for partial support of nine Faculty (five from the MI) and four postdocs. Keating provides a bridge to number theory and probability.

We undertook to review algebra.

Based on the group's demographic profile, we prioritised appointing outstanding researchers early in their careers. To build links across the theme, we appointed Ciubotaru (algebra), Rössler (arithmetic algebraic geometry) and Kielak (geometric group theory).

Other developments: Led by Tillmann, supported by the appointments of Harrington and Seigal (data science) and Nanda, and with a newly established EPSRC-funded Centre, we have been setting the agenda in topological data analysis (TDA); e.g. one 2017 paper has over 15,000 downloads. Lotay and Markovic bridge geometry, topology, analysis, and OxPDE.

Future plans: Under the successive leadership of Penrose and Candelas our mathematical physics group has had dramatic impact on physics as well as mathematics, and our first priority is to support the new Rouse Ball Chair. We anticipate significant activity in applied algebra, geometry, and topology as our ECRs capitalise on the deep fundamental expertise of our most senior researchers.

Theme 2

Number Theory: *Brown*, [Dogra], Flynn, Green, [Lang], Lauder, *Maynard*, [Pratt], Sanders, [Teravainen], Wiles

Logic: *Hamkins (Department of Philosophy, submitted to UoA10)*, *Hrushovski*, Koenigsmann, Pila

Combinatorics: *Balister,* Keevash, Riordan, Scott

We anticipated new directions to result from filling the Chair of Mathematical Logic.

Hrushovski brings a broad and creative vision in model theory, while strengthening ties with combinatorics.

Other developments: Balister further strengthens combinatorics and probability, while linking to analysis. Hamkins brings expertise in set theory. Brown reinforces links with mathematical physics, and Maynard applies formidable insight and technique in tackling longstanding questions about prime numbers.

Future plans: We anticipate a growth in joint activities across the combinatorics and probability groups. In number theory, we will target recruitment, e.g. seeking expertise in the Langlands programme.

Theme 3

OCIAM: Breward, Chapman, [Dalwadi], Dellar, [Forrow], Fowler, Goriely, *Griffiths*, [Haas], [Hennessy], Hewitt, Howell, Howison, [Moore], Moroz, Münch, Oliver, Please, [Subramanian], Vella, Waters

Numerical Analysis: Cartis, *Farrell*, Giles, Hauser, *Nakatsukasa*, Süli, Trefethen, [Urzua-Torres], Wathen

WCMB: Baker, Byrne, Erban, Gaffney, [Krause], Maini, Moulton, [Thompson]

We aimed to further broaden engagement with industry, build long-term partnerships with large corporations, support our optimisation team in building up a cadre of PDRAs, and expand applications to biology, medicine, and geoscience.

Our step-change in industrial activity, broadened to involve over 90 companies (Section 3), led us to increase capacity by appointing Griffiths. We have developed long-term partnerships with large corporations, including a £5.1M grant with Emirates. The MI optimisation team (led by Cartis and Hauser) is now complemented by Rebeschini in CSML. They co-supervise PGRs/PDRAs with organisations from Culham Centre for Fusion Energy (CCFE) to Adaptix Ltd, medical imaging specialists. The WCMB has broadened its focus to include immunology, integrated data-centric approaches into traditional areas, and developed significant new links with companies ranging from AstraZeneca to Roche. We have grown the International Brain Mechanics and Trauma Lab, a multidisciplinary initiative now involving 27 institutions. In geoscience, Giles' work on groundwater contamination from nuclear waste repositories reflects the substantial increase in stochastic modelling across the theme.

Other developments: Farrell and Nakatsukasa reinforce strengths in numerical solution of PDEs and numerical linear algebra.

Future plans: We aim to maintain our collaborations with industry (by diversifying underpinning funding sources), further develop interdisciplinary activities, enhance connections across the theme (e.g. in homogenisation), and capitalise on synergies arising from appointments in OxPDE and data science.

Theme 4

Functional Analysis: Batty, *White*

OxPDE: *Carrillo,* Chen, [Fehrman], Kristensen, *Mondino*, Nguyen, *Rupflin*, [Sbierski], Q Wang

We identified the opportunity to exploit fresh perspectives brought by our new appointments and broaden OxPDE's national role.

The 64 PGRs in the OxPDE CDT address the pressing need for broadly-trained researchers in PDEs. They have undertaken projects across the UoA, in Oxford Computer Science, Engineering, and Physics; and with 15 academic and non-academic partners outside Oxford.

Other developments: Rupflin brings expertise in geometric analysis. White (operator algebras) and Mondino (optimal transport) create new synergies across our groups in topology, functional analysis, and geometry. To maintain leadership following the retirement of Ball, we appointed Carrillo (formerly a Chair at Imperial), strengthening links to WCMB and numerical analysis.

Future plans: OxPDE will actively seek out new ventures with numerical analysis, stochastic analysis, and WCMB, dovetailing with broader initiatives in the mathematical foundations of data science.

Theme 5

Stochastic Analysis: Belyaev*,* Hambly, Lyons, *Oberhauser*, Qian, [W Xu]

Probability: *Berestycki*, [Caraceni], Etheridge, Goldschmidt, Martin, Reinert, Steinsaltz, Winkel, [Yeo]

Mathematical and Computational Finance: [Ananova], Cartea, Cohen, *Cont*, Jin, Kramkov, Monoyios, Obloj, Reisinger*, Sirignano*, [R Xu]

We anticipated developing novel applications of sophisticated mathematical techniques, e.g. the mathematics of ML via rough path theory.

The success of rough path methods in data science has exceeded all expectations, with Lyons' team driving forward applications of signature methods from mental health to Chinese handwriting recognition. Oberhauser's work connects signature methods with TDA, creating a new bridge to topology.

Other developments: Cont brings expertise in pathwise methods in stochastic analysis, systemic risk, and complex networks, and many external collaborations. Combined with Cucuringu and Windmeijer, this creates a new arc spanning econometrics and data science. Sirignano builds research in data-driven modelling, and Berestycki reinforces links with OxPDE.

Future plans: We will capitalise on Cont's arrival, and the role of stochastic analysis as a portal to data science, to broaden applications and grow our engagement with industry. We will further explore other interfaces, e.g. with the algorithms group in Computer Science.

Theme 6

Statistical Genetics and Epidemiology: *Davies*, *C Donnelly*, Hein, Myers*, Palamara*

OPIG: Deane, *Morris*, [Nissley]

We said we would cement our relationship with the Wellcome Trust Centre for Human Genetics (WTCHG) through (joint) appointments in statistical genomics.

Myers has a 50% secondment to the WTCHG, and new appointees Davies and Palamara are group leaders.

Other developments: The BDI provides an invaluable facility for this theme. Donnelly establishes statistical epidemiology, strengthening links to MSD as theme lead for Emerging Threats in the NIHR-funded Health Protection Research Unit. Protein informatics welcomes Morris (from industry), whose research naturally links to CSML.

Future plans*:* We will support Donnelly in building epidemiology in Oxford, and explore opportunities created by her arrival, for example in genetic epidemiology. We will seek ways to expand OPIG, while ensuring synergies with other groups.

Theme 7

CSML: *Caron*, *Cucuringu*, *Deligiannidis*, Doucet, *Evans*, Holmes, [Mena], Nicholls, [Rainforth], *Rebeschini*, *Rousseau, Sejdinovic,* Teh, [Yang]

Data Science: [Arora], Farmer, Grindrod*, Harrington*, [Lafond]*, Lambiotte*, [Seigal], Tanner, [N Wang]

We expected to grow core research in computational statistics, scalable methods, and statistical ML.

Growth from five to 11 faculty in CSML underlines the importance of ML to our strategy. The appointments of Rousseau, Caron (previously Marie-Curie Fellow), Cucuringu, Deligiannidis and Evans (both previously on temporary contracts), Rebeschini, and Sejdinovic reinforce our strength in both theoretical underpinnings and developing applications.

Other developments: The MI data science group, formally constituted in 2018 to help develop a coherent strategy across the UoA, incorporates 20 faculty with research interests including foundations of algorithms (including deep learning), optimisation, networks, and TDA, with applications from medical imaging to finance. Lambiotte renews interdisciplinary work on complex networks.

Future plans: We will build on recent growth by expanding our cadre of Fellows. Information Sciences is a strategic priority for the University, with exciting plans for a new building. Working with colleagues across the University, we will expand research and training, and grow further relationships with industry.

Other groups

In **History of Mathematics**, *Hollings'* research on Ada Lovelace underpins a Case Study. *Windmeijer* seeds a group in **Econometrics**, with interests in causal inference (dovetailing with Evans and Holmes) and reaching into ML and epidemiology. We will support him in forging new connections with the Social Sciences Division.

1.2. IMPACT STRATEGY

Impact stems from research spanning our entire portfolio and maintaining research strength right across the mathematical sciences is central to our strategy. Our approach is to (i) cultivate an environment conducive to realising impact, (ii) develop relationships with external organisations, and (iii) stimulate an ambitious programme of PER activities. We encourage serendipitous interactions and, above all, we remain flexible and responsive to opportunities.

We are supported by the MPLS Industrial Research Partnerships Team (IRPT), and, where appropriate, we commercialise our research with the help of Oxford University Innovation (OUI).

(i) Cultivating an environment conducive to realising impact

Impact is particularly championed by Breward, Deane, Griffiths (OUI Innovation Champion), Grindrod, Morris, Please, and Sejdinovic, but 63 submitted staff have written an output with a non-academic co-author in period (31 last time). Staff are supported as they gain experience (Section 2.1). The dramatic growth in our industrial activity (Section 3) has also been supported by our Industry Facilitator (appointed in 2014), our Research Software Engineers (appointed 2016, 2018, and 2020), and our Industry Ambassador (appointed from industry in 2019). Interaction with external users is integral to our day-to-day activities, from developing and delivering training to fortnightly industrial and interdisciplinary workshops.

All seven CDTs in which we are closely involved have non-academic partners who contribute to course design and delivery and provide research challenges. The renewal of the Systems Approaches to Biomedical Sciences (SABS) CDT (in 2014, and in 2019 as SABS:R^3), and the establishment of the Industrially Focused Mathematical Modelling (InFoMM) CDT in 2014 and the Random Systems and StatML CDTs (in 2019) have been particularly important. For example, InFoMM's company partners have delivered 153 training days. Each student (68 in period) undertakes two 10-week projects on focused company challenges; for at least one they are embedded at a company premises for at least 80% of the time. For 14 established faculty and 13 ECRs, InFoMM has provided their first experience of supervising a project with a company, so this has created an entirely new cohort of academics with experience of working with industry. Significant industrial funds and local resource have been invested to recruit an additional cohort of InFoMM students. The SABS CDT (46 students in UoA in period, each with an industrial co-supervisor), operates under its pioneering open innovation model: a signed agreement guarantees that students, academics, and industrialists talk openly to one another about their work in the CDT, even permitting students to work for more than one partner.

(ii) Developing and maintaining relationships with external organisations

Engagements with policymakers reflect both targeted approaches and our extensive networks. In 2017, we sought advice from the MI EAP (including representatives from the Home Office and GCHQ) on developing channels to Government for seeking, offering, and receiving advice. In 2020, Claire Craig, formerly Director of the Government Office for Science, joined the Statistics EAP. Government agencies (e.g. CCFE, NPL) are strategic partners in our CDTs. Faculty serve on Science Advisory Councils for Government departments and repeatedly interact with Government Chief Scientific Advisors, MPs, and Peers through their work for research councils and learned societies. We use our influence to shape wider appreciation of mathematics and its use in industry, society, and government.

Relationships with external organisations often begin with personal or institutional contacts, referral by colleagues or partners (e.g. Iontas introduced us to Agenus Bio and Teva Biologics), or through Oxford University Statistical Consulting (OUSC). We hold industrial events in Oxford and at local Science Parks. Potential industrial collaborators are invited to scoping workshops (93 events in period). Whatever the pathway (e.g. consultancy or sponsorship of MSc, doctoral, or PDRA projects), we seek to sustain and broaden relationships. For example, OPIG's relationship with UCB developed from an initial collaborative discussion around membrane proteins to a large body of work in immunoinformatics, linked to multiple company groups. UCB

has sponsored or co-sponsored 16 PGRs and had linked projects with four PDRAs in period. Three OPIG members have gone on to work at UCB. The company provides financial support, access to datasets, experimental validation of work, and inspiration for new research ideas.

Strategic single-company investments funding large multi-year projects can take research from inception to impact. For example, building on a relationship initiated through the OxWaSP CDT, jointly with the BDI, Statistics has entered into a five-year project with Novartis (c.$3M per annum to Oxford). Drawing on clinical expertise within Novartis, our researchers will develop innovative IT and AI technology to combine anonymised imaging, genomic, and biological data from approximately five million patients with anonymised data from Novartis clinical trials, to predict patient response to existing and new medicines.

Maintaining relationships with (multiple) companies requires significant effort, so academics are supported. For example, our Industry Facilitator has been fundamental to sustaining InFoMM's partnerships.

The EPSRC Impact Acceleration Account (IAA) is a valuable tool, with ten projects in period totalling £357k (and two analogous awards from ESRC and Wellcome). In 2016, IAA funding pump-primed a new mechanism through which 17 companies (from major players like Roche to start-ups like Tikcro) have engaged our Research Software Engineers to support deployment, maintenance, and integration of OPIG's software to in-house systems, and its development to meet company needs.

(iii) Stimulating public engagement with research

Catalysed by our new buildings, PER activities have been taken to a new level. We have raised their profile within the Departments, increased support to remove barriers to participation, and embraced social media to extend the reach of our activities.

Initiatives have been championed by Goriely (Director of External Relations and PER), Cohen (PER Champion), and du Sautoy (Professor of the Public Understanding of Science), and supported by an External Relations Manager, PER leader, Outreach Events Coordinator, and Events Officer. The Whitehead Lecturership was established in 2014 to expand academic leadership in outreach and establish the CMI PROMYS Europe Summer Schools. We use the interplay between mathematical research and music and art to draw in broader audiences. The Oxford Mathematics YouTube Channel (210,000 subscribers) features a mix of Public Lectures, research films, and undergraduate lectures. Twitter and Facebook channels (21,000 and 10,000 followers) are complemented by an Instagram page. We also engage with University initiatives; e.g. creating an "Oxford Sparks" animation explaining ML, and developing a virtual reality exhibit for the Ashmolean Museum. Crucially, our PER showcases the full breadth of our research. For example, when Keevash's work on combinatorial designs resolved a 150-year-old mathematical conundrum, it featured in Wired.com and Quanta magazine. (Also see Section 4.4).

Our strategy of using social media meant that we were well placed when, in March 2020, we moved all PER activities online. We chose to balance presenting work at the forefront of understanding and modelling the crisis, with a clear message that all our work is important (and continues). The audience for our first online Public Lecture topped 80,000.

Relationship to case studies

Our Rolls-Royce, Adjoints, Glass, and classified cases reflect our commitment to sustained relationships with research users. The Filtration case demonstrates our use of personal networks, scoping workshops. and study groups; and, through Griffiths, the pathway from PDRA to impact champion. The Chinese handwriting recognition case reflects our 2014 research strategy and engagement with the Turing. The reach and significance of our Antibodies case is supported by our Research Software Engineers, and our Ada Lovelace case reflects our ambition in reaching diverse audiences. Billmonitor, which arose from a serendipitous interaction in the last REF period, has turned its sights to new markets in this one, and our COVID case illustrates our researchers' agile response.

Future strategy

The central importance of mathematical sciences, combined with the Government's "2.4% agenda", will lead to an unprecedented demand for postgraduate students trained to tackle industrial and societal challenges. We will work with non-academic partners to design and deliver a broad menu of collaborative training, from traditional industrial mathematics to emerging areas like applied algebra and geometry, producing a pipeline of students and supervisors comfortable moving between academic and non-academic environments.

Building on the successful approaches of InFoMM, we will make strategic investments to maintain our current levels of engagement with industry.

We will exploit our involvement in the Turing, the Faraday Institution, and other networks to develop impact in areas such as energy, emerging infectious disease, and health data science.

Recognising the value of embedding staff within companies, we anticipate further part-time appointments/secondments. Equally, we will host more non-academic visitors in Oxford.

In an age of information and misinformation, we see PER as crucially important. Learning from our experiences during the pandemic, we will enrich our online offering with more interactive content, even as we look forward to welcoming the public back into our buildings.

1.3. INTERDISCIPLINARITY

The vitality of research across the UoA is sustained by interactions with disciplines spanning physical, biological and social science, medicine, and the humanities. During the period our submitted researchers have collaborated with 30 other departments within Oxford alone; 65% have a co-author in another academic area, and around 30% of our PGRs had a co-supervisor outside the mathematical sciences. Interdisciplinary work is often intertwined with impact: 55% of our researchers with a co-author outside mathematical sciences had a co-author outside academia.

Our strategy is to (i) harness opportunities from participation in both national initiatives and multidisciplinary centres in Oxford, (ii) create local networks, and (iii) support and scale up successful interdisciplinary collaborations.

Within Oxford we are involved in numerous multidisciplinary initiatives including the BDI, the WTCHG, the Oxford Martin School, and the Oxford Networks for the Environment. Oxford colleges are intrinsically multidisciplinary and serendipitous mealtime conversations have grown into numerous projects from historical linguistics to using plant radionucleotide analysis to understand prehistoric farming methods.

Networks bring lasting benefits. For example, Morris' *Comp Chem Kitchen* brings together 'molecular geeks and hackers' to listen to industrial speakers, and share best practice, code snippets, and software tools. Internal seed-funding has catalysed the newly-established *Probability for Machine Learning* and *Oxford Materials Design* networks.

Initiatives that begin in Oxford are nurtured from their inception. For example, £20k seed funding to Baker, Byrne, and Waters launched the QBIOX (Quantitative Biology Oxford) network. A series of colloquia and sandpits established strong academic and non-academic collaborations and links to the BBSRC/EPSRC/MRC UK Regenerative Medicine Platform. Through an EPSRC Discipline Hopping award, Waters spent time embedded in the cell and tissue engineering group of El Haj (now Birmingham). The activities resulted in a position paper, joint PGRs between MPLS and MSD, and interdisciplinary grants, including Waters' Oxford-led £609k MRC grant with El Haj's lab.

1.4. OPEN RESEARCH AND RESPONSIBLE RESEARCH AND INNOVATION

In our UoA, open research has three main elements: publications, data, and software.

Publications: All authors must deposit author accepted manuscripts in the Oxford Research Archive (ORA); a software tool monitors academics' publications and issues monthly alerts if they have failed to do so. We make extensive use of preprint repositories, with 80% of our submitted outputs on ArXiv alone.

Data: We believe strongly in making our research data available so that others can compare their findings with our own. Researchers are encouraged to upload data to ORA alongside publications. Where possible, a permanent DOI is used. Although biomedical data that we use is (necessarily) largely confidential, we make extensive use of the open access UK Biobank, and actively help others to interpret analyses; e.g. the website http://big.stats.ox.ac.uk supports interpretation of genome-wide association studies results for brain imaging phenotypes.

Software: Our sustained commitment to open-source software is exemplified by Ripley's contribution to the R-project (from 2014-19, as measured by subversion commits, he was the biggest contributor). Much of our research software is open source, including Farrell's dolfin-adjoint for adjoint PDE calculations, which won the 2015 *J.H. Wilkinson Prize*; Trefethen's chebfun, a MATLAB package for extremely accurate computations in 1D and 2D; and Davies' genotype imputation software, STITCH (over 7,700 downloads since 2016).

Our OPIG software engineers are pioneering a model which simultaneously achieves the ideal of fully open software while sustaining a revenue stream that directly benefits University research.

Research integrity, and responsible research and innovation

Explicit consideration of responsible research and innovation is integral to our practices. For PGRs, the University's compulsory online research integrity training is supplemented by training tailored to each programme; e.g. a session on industrial ethics for InFoMM. The 'R^3' in SABS:R^3 stands for Responsible and Reproducible Research; best practice in sustainable and reproducible research is woven into all the training, and *Ethics in Statistics* is explicitly addressed.

More widely, Grindrod established a corporate network, *Professionalising Data Science*, which meets quarterly, and produces white papers and discussion papers. The 19 corporate members range from BT to Unilever.

2. People

Our greatest asset is the people who study and work in the UoA. We promote a supportive and inclusive culture in which everyone can thrive, irrespective of their origin or background. We recognise and reward contributions to all aspects of our mission, without giving the impression that everyone will, or is expected to, excel at everything. This was especially important in 2020 when we wished to celebrate our researchers' work on COVID-19, without compounding any feelings of guilt of those unable to contribute to that research effort.

Alongside our independent Fellows, we employed 300 PDRAs over the period (with 85 in post in July 2020, compared to 53 in Autumn 2013), and we enthusiastically embrace the Concordat to support the career development of researchers. We supplement MPLS/University activities in support of its implementation, as described across the sections below.

2.1. STAFF

Staffing and recruitment

We aim to recruit, motivate, and retain academics who will contribute at the highest level. Our staffing strategy dovetails with our research strategy. Before making appointments, we consider the demographic profile and succession planning in our research themes.

Of our 50 faculty appointments, 16 came directly from institutions overseas, including Harvard and Yale. Nine progressed from early-career positions in Oxford, and we support those making this transition; e.g. Cohen, a College Research Fellow when he arrived from Australia, was a Department Lecturer (DL), mentored by Howison, before becoming an Associate Professor in 2016. Of the 28 permanent academics who left in period (including three who came and left), 13 retired, 12 took up senior academic posts elsewhere (including named Chairs in Columbia and Yale), and three moved to industry.

To ensure a thriving community of Research Fellows, expanding our Hooke and Titchmarsh Fellowship scheme has been a strategic priority. Competition is intense (e.g. 274 applicants for two Titchmarsh Fellowships in November 2019). One ex-Fellow is a mathematical consultant; all others are pursuing academic careers, from Assistant Professors in Warwick and Milan to a Royal Society URF (in Oxford). The scheme is mirrored by the FN Fellowships, and supplemented by MPLS Glasstone Fellowships (four hosted in period), College Research Fellowships (24 in period), and our (five-year) Sylvester Fellowship.

To address specific needs created by research buyouts and workload relief, we appoint fixed-term DLs, career development positions with a reduced teaching load and the opportunity to co-supervise PGRs. DLs in period have gone on to tenure-track positions in Australia, Germany, Switzerland, and the UK.

Staff development strategy

Our overarching aim is to nurture and support all staff, regardless of career stage. All new staff have mentors, offering confidential guidance and support. As a minimum, regular (informal) meetings are held throughout probation (throughout the appointment if fixed term). A comprehensive induction programme covers teaching, research, and applying for grants. Faculty have a five-year probation. A mandatory review after two years is supplemented with annual progress reviews with the Head of Department (HoD). During probation, staff have reduced teaching, examining, and administrative loads.

Beyond probation, uptake of appraisals was historically very low. In 2016, Statistics rebranded the annual meeting and uptake is now around 80%. The meeting provides an opportunity for reflection, and discussion of how the department can support work/life balance (especially important for those with extensive commitments outside the department). The MI's previous scheme is being replaced with biennial career development discussions.

Extensive training is available through the University's Centre for Teaching and Learning. Locally, we run sessions (compulsory for ECRs/PGRs) tailored to class teaching in the mathematical sciences. During the COVID pandemic, we developed training to demonstrate a variety of technical solutions and approaches to online presentations and discussions.

As part of succession planning, seven senior faculty have undertaken the University's Heads of Department Development Programme, and faculty have benefitted from Oxford's Academic Leadership Development programme. We also commission bespoke, in-person sessions (e.g. *Bystander Training* and *Supporting Postgraduate Students*) to encourage informal discussion. When taking on new roles, staff are reminded of training, good practice, and where to get help.

Key to researcher development is building professional networks. All staff have travel funds, averaging around £2.5k per annum. Research incentive schemes provide additional funds to be

spent for the benefit of research groups; e.g. in Statistics, personal research accounts are annually credited £600 per PGR and £1k per PDRA supervised. New faculty receive start-up funds (£3k for our Fellows). In order to ensure inability to travel doesn't impact on collaborations, a further fund supports visits to Oxford. Competitively awarded Visiting Professorships support longer visits; for example, McCullagh (Chicago) was 2015/16 George Eastman Professor, and Gabai (Princeton) was Senior Research Visitor at Keble (Autumn 2019).

Policy for leave

Academic staff (including fixed-term or part-time) are entitled to (and encouraged to take) one fully-funded term of sabbatical leave for every six terms worked. In this period, 79 faculty members have collectively taken 170 terms of leave (with similar levels of uptake for men and women).

We are responsive to changing needs as staff progress through their careers, alerting and supporting them when opportunities arise. Additional workload relief, to offset particularly heavy commitments elsewhere, is at the discretion of the HoD. For example, Etheridge has been relieved of teaching while she serves on EPSRC Council.

Supporting and integrating those at the beginning of their careers

Recognising the continuum of experience between PGRs and established academics, activities for PGRs and ECRs are open to all, including those on external fellowships (e.g. NSF postdocs, Section 3.1), who also receive support from our ECR advisors.

Our ECRs, including 45 independent Research Fellows and 85 PDRAs in July 2020, are central to the vitality of the UoA. ECR representatives sit on almost all department committees and 'Voice Reps' represent the UoA at the Oxford Research Staff Society.

The newly-established Associate Head for Career Development manages Hooke and Titchmarsh Fellows; the HoD manages FN Fellows. All ECRs have mentors. Three senior academics are ECR Advisors: reporting to our Equality, Diversity and Inclusion (ED&I) committees, they ensure that we fulfil our responsibilities under the Concordat. Each ECR meets an Advisor on arrival, who checks they have good academic contacts and are aware of support, helps identify a mentor, and explains annual career development reviews. Researchers are signposted to the huge range of development opportunities.

The PI (for grant-funded positions) or another senior academic supports those on fixed-term contracts through probation, helping set, monitor, and review objectives at the beginning, middle, and end of the period.

Numerous events are organised by ECRs for ECRs. Bi-termly colloquia, each with two ECR speakers, are part of the Fridays@4 project (Section 2.2), and Statistics ECRs run 'the Network'; e.g. in Autumn 2019 arranging sessions: *The Advanced Research Computer* (by a FN Fellow), *Grants and Fellowships* (Research Facilitator), and *Implementation of the New Concordat* (MPLS Researcher Training and Development Manager).

To broaden their experience, PDRAs give undergraduate classes and present at reading groups and seminars, whereas Research Fellows might deliver a lecture course and co-supervise PGRs.

ECRs are encouraged to write fellowship and grant applications. Research Facilitation teams and senior colleagues support project planning, review the proposal and response to referees, and organise mock interviews. Applying to the University's John Fell Fund (JFF) develops grant writing and management skills: nine ECRs won JFF grants totalling £218k in this period.

Support from the Careers Service is supplemented by a local programme of practice interviews for academic and non-academic jobs, and annual careers events with alumni panels leading discussion. A panellist from the 2020 online event praised us as 'trailblazers'.

COVID brought considerable challenges for our ECRs. We offered flexible end-dates to five in-post Hooke and Titchmarsh Fellows facing uncertainty and significant delays in moving to new academic positions abroad.

Stimulating and facilitating exchange with business, industry, and third sector bodies

We have three mechanisms for embedding those with experience outside academia in our departments: (i) faculty recruitment (20 current faculty, ten appointed in period, have spent part of their career outside academia); (ii) part-time appointments, enabling faculty to spend part of their time in industry (e.g. Doucet and Teh at DeepMind), and industrial colleagues to work part-time with us (e.g. through Royal Society Industrial Fellowships); (iii) visiting lecturerships/ fellowships for industrial partners making substantial contributions to our activities (around 20 in post in 2020). The Chief Technical Officer of the mathematical consultancy the Smith Institute is a member of the MI.

All academic and research staff may undertake up to 30 days paid consultancy work. In addition to those arranged independently by staff, OUI has supported 118 consultancy agreements for our staff in period (54 last time), not including those for OUSC or our software engineers.

Almost a quarter of the 614 PGRs in period have worked with a company as a formal part of their training. We also support those wishing to pause their studies for internships (41 in period). We use the IAA to co-fund secondments to user organisations; e.g. embedding a PDRA in dunnhumby to apply her work on community detection to their business.

We encourage careers straddling academia and industry. For example, Gyurko (a PGR and then Research Fellow, now at Citi) is an Alan Tayler Visiting Lecturer, regularly teaching for our MSc in Mathematical and Computational Finance. Davies, previously a PGR at the BDI, worked for Genomics PLC and the Toronto Hospital for Sick Children before joining Statistics.

Recognising, rewarding, and supporting staff in achieving research and impact

The main route to promotion in Oxford is through Recognition of Distinction (RoD), an annual gathered-field exercise through which faculty apply for the title of full professor. Those with the title can apply for Professorial Merit Awards in a biennial University-wide gathered-field. Personal research chairs provide the mechanism for opportunistic recruitment/retention of research leaders.

The MPLS review and reappointment procedures are explicit: *'Research' is to be understood as original investigation undertaken to gain knowledge and understanding, including work of direct relevance to the needs of commerce and industry, as well as to the public and voluntary sectors.* We include impactful activities in workload considerations and dedicated support relieves administrative burdens such as contractual issues. Our OUI Innovation Champions provide initial advice (including identifying OUI contacts) and experienced faculty mentors ensure that those new to impact activities are not overwhelmed.

External Relations and Outreach teams have largely removed barriers to undertaking PER; in period, 59 submitted researchers have been involved, 16 in delivering our Public Lectures. We celebrate impact with news stories on our websites and in weekly bulletins and we are proactive in nominating staff (including ECRs and professional services staff (PSS)) for MPLS Impact Awards: Griffiths, Krawczyk (software engineer), and O'Kiely (PDRA) won awards for non-commercial and commercial impact; Grady (PSS), Martin (Emeritus), and Rogers (now at PHASTAR) for Outreach and PER. Griffiths received a Vice-Chancellor's Innovation Award for his work on mitigating arsenic mass poisoning.

2.2. POSTGRADUATE RESEARCH STUDENTS

We admitted 614 students (249 home, 183 EEA, 182 non-EEA) in period, including 82 who transferred in (after Year 1) from interdisciplinary programmes (mostly CDTs) administered elsewhere in Oxford.

Approach to recruitment

We aim to recruit those PGRs with the greatest potential for research, irrespective of origin or background. We advertise widely, using social media to broaden our reach. Applications per place have risen from six in 2013 to ten in 2019. We try to ensure that no offer-holder is prevented from accepting by financial considerations. In 2013, 43 of the 76 PGRs joining us (54%) were fully funded by Oxford-administered funds (including UKRI/industry funds awarded to Oxford); by 2019 this had risen to 79 of 92 (86%).

Oxford's highly-competitive Rhodes Scholarships (12 in period, including scholars from West Africa, Zambia, and Hong Kong) and Clarendon Scholarships (46) are supplemented by department-funded scholarships. In 2019, Oxford funds supported 23 full and seven partial studentships (up from nine full and four partial awards in 2013). Students not in receipt of Oxford-administered funds often receive bursaries from overseas governments or charities (e.g. from Canada, China, Norway, Spain, and Switzerland in 2019). Graduate bursaries remain our top fundraising priority.

Research placements help undergraduates make informed decisions about postgraduate study. Since 2015, we have hosted an average of over 25 students each summer, funded by EPSRC, the LMS, Wellcome, industry, and Oxford sources. Additionally, the UNIQ+ Programme, originally an initiative of SABS:R^3, enables UK undergraduates from areas and groups that traditionally have low progression into postgraduate study to experience six weeks as a research student (with free accommodation and a £2,500 stipend). Before attending UNIQ+, 64% of the 2019 cohort (33 students) were considering postgraduate study, 36% were not. After attending, 89% planned to apply, 11% were undecided. Of the eight 2019 students hosted in the UoA, three are now postgraduate students in Oxford.

Studentships from major funding bodies

The quality of our graduate training is reflected in the external funds that we attract to support our PGRs. There are five CDTs within the UoA: InFoMM, OxWaSP (with Warwick), and OxPDE started in 2014; Random Systems and StatML (both with Imperial) started in 2019. This represents UKRI investment in Oxford of £17.4M plus substantial direct industrial support (e.g. over £3M secured by InFoMM). We are partners in the SABS(:R^3) and Health Data Science CDTs. Over 40% of PGRs in period have come through a CDT.

Of the 484 fully-funded PGRs in period, 245 were fully and 51 partially funded by EPSRC DTP and CDTs. A further 45 were primarily funded by industry. There were three BBSRC, one CRUK, two NERC, and two UKRI NPIF doctoral training awards; seven EPSRC, two BBSRC, and one MRC iCASE. Nine PGRs were supported by Turing studentships, and 12 received ERC funding.

Integration, supervision, monitoring, and support

Once the offer is accepted, each PGR is assigned a current PGR 'buddy' as a point of contact for practical questions. In 2020, groups wrapped offer-holders into online activities, from virtual board games and pizza nights to reading groups and 'watching groups' for online lectures.

Induction days outline events, facilities, support, and opportunities to contribute, including speaking at Open Days and organising social events. All PGRs have a second supervisor and a College Advisor. Concerns can also be raised with the Directors of Graduate Studies. Graduate liaison committees discuss postgraduate provision and PGR representatives sit on most other department committees.

PGRs are embedded within research groups in dedicated offices next door to faculty. Co-location of researchers at all levels, an open door policy, daily coffee, and weekly social events ensure that they are integrated both academically and socially.

Alongside quarterly written self-evaluations and supervisor reports (evaluated by Directors of Graduate Studies, CDT Directors (where appropriate), and College Advisors), a series of milestones mark progression through the doctorate. At the outset, PGRs and their supervisors agree a programme of broadening training. After at most four terms of research PGRs must *transfer status*. They submit a dissertation (25-50 pages) and a record of training. An oral examination with two academics (neither being the supervisor) comprises a presentation by the student and discussion of skills training, the dissertation, and future research. Before the end of year three, PGRs *confirm status*. Another oral examination discusses submitted material (thesis table of contents, sample chapters, and a timetable for completion) and training/support needs, paving the way for successful submission.

Training, skills development, and preparation for future careers

A broad appreciation of the mathematical sciences (and beyond) is a central (and mandatory) part of our PGR training. In addition to the training that is integrated into the first year of our CDTs, there are well over 100 Masters-level and 40 third-year undergraduate lecture courses available – complemented by around 20 courses in the Taught Course Centre (TCC) with Bath, Bristol, Imperial, and Warwick; and four week-long residential courses from the Academy for Postgraduate Training in Statistics (APTS). An average of 777 seminars per year across the UoA is supplemented by graduate lectures, reading groups, and PGR/ECR seminars. Travel funds are available to support attendance at residential graduate schools and conferences.

Of the PGRs enrolled in July 2020, 37 (including 22 SABS students) joined us after a year of broad interdisciplinary training on programmes ranging from the EPSRC Cyber Security CDT to the NERC Environmental Research DTP.

All PGRs undertake mentored teaching to hone skills in organising and presenting information, and in gauging an audience. Starting with marking, and presentation of material under the guidance of an experienced tutor, this builds to leading classes of 10-12 students.

The MPLS Graduate School offers comprehensive training starting with *Making the most of Oxford* and *Managing your Supervisor*, through *Time Management* and *Scientific Writing*, to *Viva Preparation*. Popular courses include *Public Engagement* and *Making an Impact*. The *Enterprising Women* lunchtime talk attracted 20 participants from the UoA in 2018/19.

Our CDTs provide bespoke skills training. For example, InFoMM's training day *Asking the Right Questions*, delivered by Tessella, precedes the UK graduate modelling camp,

We support and encourage PGR participation in activities like *STEM for Britain*, *3 Minute Thesis*, and *Soapbox Science*. In 2016, we launched *Oxford Maths Ambassadors*, providing training and regular PER and outreach opportunities. Volunteers assist with activities from writing blogs to the *Oxford Mathematics Escape Room* (delivered by 15 PGRs).

Weekly Fridays@4 events – designed to help integrate PGRs, develop study skills, and enhance long-term career development – began in 2015. Past events include *Careers beyond academia, Applying for EPSRC Fellowships* (with an EPSRC Mathematical Sciences portfolio manager), and *Dealing with journals.* In the 2018 MI survey, 69% of PGRs reported attending many or all of these events. This initiative resulted in MPLS Teaching Awards for Cohen, Griffiths, and Kirwan.

Whilst 92% of PGRs who began their courses in 2010-13 successfully graduated, only 72% completed within four years. With closer monitoring, and initiatives like Fridays@4, 86% of those starting in 2014-15 completed within four years.

The quality of our training is reflected in the success of our PGRs. They go on to varied careers, the most popular being academia (55%) or the technology (13%) and finance (12%) sectors. Notable prizes include: IMA Lighthill-Thwaites Prize (O'Kiely 2017, Butler 2019); Gold Award in Mathematical Sciences at *STEM for Britain* (Grogan 2017, Kiradjiev 2019); IMA Leslie Fox Prize (Smears, Townsend 2015); Bar-Ilan Young Researcher Prize in Financial Mathematics (Sojmark 2018); G-Research 1st Prize (Mariapragassam 2017, Wechsung 2018); Lee Segel Prize (Taylor-King 2017); and the Gioacchine Lapichinio Prize of the Italian National Academy (de Filippos 2020).

2.3. EQUALITY, DIVERSITY, INCLUSION AND WELLBEING

Our pursuit of excellence is underpinned by commitment to equality of opportunity. Of our 175 Cat A researchers, 55% are non-UK nationals, representing 34 different nationalities; 17% are women (14% last time), rising to 23% of ECRs. We have seven female Statutory and Research Professors (two in 2014); four are FRS, with two elected in the period. In July 2020, 22% of PDRAs (15% in 2013) and 23% of PGRs are female. 12% of Cat A researchers identify as BAME (68% white, 20% undeclared). These numbers are too crude a way to measure inequality, and we are very aware that there are further inequalities, particularly within the BAME categorisation. Global events in June 2020 challenged us to recognise and address the disadvantages and systemic racism faced by minority members of our own community, and we created Race Equality Action Plans which will define our response in the next period.

For each permanent post a search panel explicitly considers diversity. All three female Statutory Professors appointed in period applied after being approached by search panels. Combined with two new female Research Professors (via promotions), this has transformed the gender profile of our most senior faculty.

We advertise vacancies across a wide range of networks and media, highlighting options for part-time/flexible working, and monitor how applicants hear of posts. The European Women in Mathematics network seems especially effective. Unconscious bias training is recommended for all members of selection panels (mandatory for panel chairs). A new dedicated Recruitment Co-ordinator focuses on the quality of information provided to applicants and engages with them throughout.

We are proactive in reaching out to underrepresented regions. For example, Szendrői's work on research development in Africa led to the recruitment of our first sub-Saharan African PGR and visits (from a few days to a month) by eight African scientists in period.

Many of our retired faculty remain actively engaged in academic activities and they have office space, access to facilities, secretarial support, and small research allowances.

Our ED&I Committees (membership includes faculty, ECRs, PGRs, and PSS) meet twice termly. One member from each sits on the MPLS ED&I steering group. They drive our Athena SWAN agenda (MI Silver Award 2016; Statistics Bronze 2014, 2017) and ED&I and wellbeing activities, with particular emphasis on career development of underrepresented groups. Their budgets contributed almost £100k to initiatives this period, including weekly *Mathematrix* events (discussing challenges in academic life and being a minority in the mathematical sciences community), and Mirzakhani Society events (providing a focus for women and non-binary students). Senior female faculty have a twice-termly catch-up.

Diverse role models for staff with protected characteristics are highly visible in everyday life in the UoA. For example, in 2016, Kirwan received the Suffrage Science award, and Bruna (now Cambridge) won the *Women of the Future* Science Award and a *L'Oréal UK and Ireland Fellowship for Women in Science*; the prize money funded flexible childcare and a workshop. Female faculty host a welcome lunch for new ECRs/PGRs. Both departments have active LGBT+ role models (trained through Stonewall) and publicity material and displays are vetted for unintended messages. Seminar/event organisers are asked to consider diversity. The

percentage of female seminar speakers rose from 13% in 2013 to 23% in the first half of 2020. A Distinguished Speaker Seminar is being named to create an annual event in honour of an African-American statistician; it will coincide with Black History Month. We hosted the 2016 BAMC (over 375 participants) with 3/8 female plenary speakers.

Our new buildings invite ambitious events. During the LMS 150th Anniversary celebrations, an expanded version of the Society's Women in Mathematics Day brought 230 mathematical scientists and 430 school students and teachers to Oxford; this is now the annual event *It All Adds Up.* In 2020, the annual Florence Nightingale lecture was to be replaced by a major three-day event celebrating the bicentenary of her birth but was postponed due to the pandemic.

We have been recognised in the MPLS Equality and Diversity Awards each year since 2017 with lifetime achievement awards (Kirwan); best initiative for *It All Adds Up;* and a Student Choice Award to Vella for "*creating and fostering a diverse and inclusive research group, with people from many different countries, socio-economic and educational backgrounds, and varying ethnic, gender and age profile".*

Flexible and/or remote working

We encourage staff to adapt their working patterns (formally or informally) as their caring and other responsibilities change. Nine faculty have moved to part-time contracts (not including secondments) during this period, either for personal reasons or to take advantage of external opportunities. Meetings and seminars take place in core hours, and we take childcare and other constraints into account when scheduling teaching.

In March 2020, we provided (and delivered) specialised IT equipment and office furniture for home workspaces, particularly for PGRs/ECRs. Since reopening our buildings, we have ensured that nobody is disadvantaged by being unable to come in. Many staff and students wish to maintain a mixture of office-based/home working for the foreseeable future.

Career pathways for part-time and fixed-term staff

Our part-time staff are predominantly late-career or exploring opportunities with industry; their needs are considered on a case-by-case basis.

All our fixed-term staff are ECRs, the vast majority being PDRAs or Research Fellows. A typical path is another postdoc, possibly a fixed-term lectureship, then a tenure track position. PDRA career development benefits from broader experience, often in other institutions. For example, Style went from PDRA in Oxford to postdoc in Yale, before returning to Oxford as a DL; he is now a group leader at ETH Zürich. Farrell took a different route: joining us as a Research Fellow after a PDRA in Imperial, with support from Research Facilitation he secured an EPSRC Early Career Fellowship, from which he progressed to Associate Professor.

Supporting those with caring responsibilities or ill health

With guidance from the University's Disability Advisory Service, Occupational Health, or Counselling Service, we support those with serious or long-term health concerns through adjusted working hours and practices, specialist equipment, and teaching relief. For example, we provided a PGR with a voice recognition system and enabled a PDRA to bring their support dog to work.

During the period, eight Cat A staff, two PDRAs, and two PGRs took maternity leave, and one male academic shared parental leave. There is teaching relief in the first term after family leave, and the University's Returning Carers Fund (five awards totalling £22k) can be used to support the cost (including additional childcare) of academic activities. The MI offers up to £500 towards additional costs of care to support conference organisation/attendance (eight awards in the period). One PGR reported being "*able to catch up on… crucial developments in the field that had happened in my absence*", attributing a key chapter in her thesis to attendance at this

meeting. We are proactive in offering assistance; additional support is at the discretion of departmental leadership teams.

Promotion, funding, and research leadership roles

In this period 28 faculty (six female) have gained the title of full professor. For each RoD round, we identify senior academics (at least one of each gender) who can be approached for confidential advice and guidance. HoDs proactively encourage individuals to apply; for example, a female member of Statistics was encouraged to apply and mentored through the process by a senior (female) colleague.

Data on the gender of applicants for research funding is monitored and analysed. During the period, the percentage of applications for funding from women has risen from 12.7% to 30.9%; the percentage of awards to women rose from 13.3% to 31.4%. We assist with extra costs (such as childcare) arising from attending interviews. For other protected characteristics, the numbers are too small to report; but all members of the UoA, including emeriti, have access to research support.

We actively promote diversity in leadership roles. Three of our female faculty have been Associate Heads of MPLS (leading on Finance, Research and Innovation, and Equality & Diversity), and two of these served as Deputy Head of Division. Two have been HoDs, one deputy HoD, and three Associate HoDs. One Associate HoD is BAME. Beyond the University, female faculty take on myriad leadership roles (Section 4.6).

Leadership is explicitly discussed in professional/career development reviews and staff have engaged in University-wide courses. Staff are supported as they build experience. For faculty this might begin with membership of departmental committees/working groups, followed by appointment committees or MPLS committees, and chairing committees; while in parallel mentoring students and postdocs, then managing grants/groups, and taking on professional activities. Experienced female and BAME faculty mentors are available to those developing their leadership skills.

Initiatives extend externally. For example, as part of an EPSRC-funded project with Oxford Brookes, Byrne is developing practical solutions for institutions to create inclusive opportunities and overcome the barriers for women following the entrepreneurial pathway from research to leading a spinout.

Supporting wellbeing of staff and PGRs

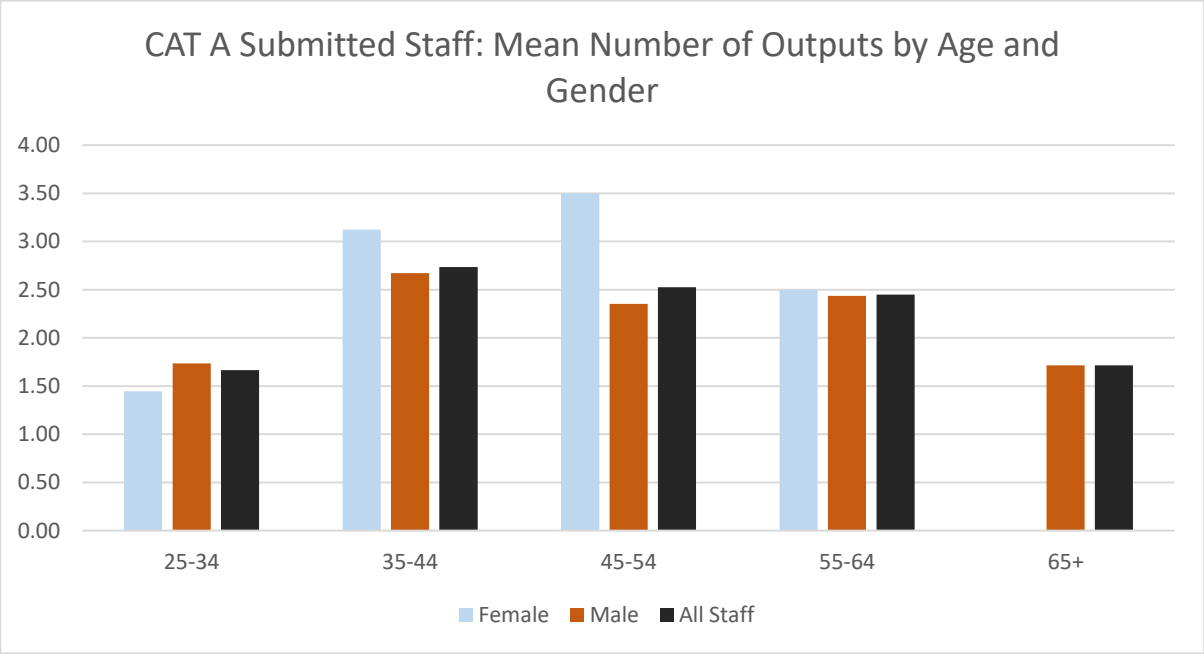
We combine specific, targeted initiatives with fostering an inclusive, welcoming culture, in which staff and students across all levels have informal opportunities to meet.

Support and networking opportunities across Oxford are collated on department web pages. In the 2019 Statistics graduate student survey, 89% reported being aware of support available from the University Counselling Service, compared to 45% in 2018. In the MI, trained peer supporters hold drop-in sessions four times a term. We hold events such as *Life in the Department*, in which PGRs share things they wish they'd known on arrival. We encourage discussion: e.g. at the 2019 Statistics Away Day the Head of the University Counselling Services led *Thriving and Surviving: A conversation about stress, mental health, and resilience at University*. We also provide access to confidential support, e.g. through an external Employee Assistance Programme.

Wellbeing is a particular challenge during the pandemic. Surveys monitor how our community is coping, and regular updates include easily-accessible links to available support. Supervisors hold at least weekly video calls with PDRAs/PGRs (even if just for a chat). PGRs and those on probation have been granted (automatic) extensions. When we reopened our buildings, we prioritised PGRs facing mental health challenges for return to on-site working.

ED&I in construction of the REF submission

The University Code of Practice provided a clear and comprehensive framework within which we have operated throughout. All local decisions have been checked and, where necessary, challenged in MPLS, with careful checks of contracts validating eligibility decisions. Our researchers had informal meetings with the HoD and/or UoA coordinator to explain the REF and discuss research and impact. Eligible staff nominated up to six outputs for consideration, which were read and scored by two independent reviewers. Out of 175 Cat A staff, there are 29 women and 40 ECRs. The mean number of outputs submitted is 2.36 for all Cat A staff, 2.55 for women, 2.32 for men, and 1.48 for ECRs. The breakdown by gender and age is shown in the graph below. Interim figures from the University indicate an average of 2.19 for BAME staff (who are more concentrated in earlier career stages). The research underpinning three of our ten Impact Case Studies was led by women.



3. Income, infrastructure and facilities

3.1. RESEARCH FUNDING

Research grants started in the period total £81.6M in value[1]: £37.9M from UKRI, £4.6M from UK charities, £23.8M from the EC, £9M from industry, and £6.3M from other sources. These numbers exclude studentships. A further £11.8M has been secured (not yet started). In addition, donation income totalled £10.4M, including three donations of £1M or more, and a further four of £500k or more.

As planned in 2014, a priority in this period has been to create a sustainable portfolio of funding to replace our KAUST grant. Our strategy has been to (i) support faculty in securing longer, larger ERC and UKRI grants and fellowships, (ii) increase involvement in multi-disciplinary / multi-institution awards, (iii) actively engage small and medium-sized enterprises (SMEs), (iv) nurture long-term industrial partnerships to complement the explosion of CASE-like studentship contracts fuelled by our CDTs, and (v) pursue philanthropic funds to support our research.

During the period, faculty have held/been awarded 25 ERC grants: eight Advanced, five Consolidator, and 12 Starter (compared to three, zero, six last time). 16 UKRI grants, totalling over £20M, each brought over £500k into the UoA. Reflecting the expansion in interdisciplinary

[1] Total research income recognised in period (REF 4b) = £80.5M.

research, we are Co-Is on projects led by 25 other Oxford departments. Grants are often held as part of larger consortia; e.g. a £495k EPSRC grant to Douglas, to build theoretical and practical tools for higher-dimensional algebraic computations in geometry and quantum information science, is part of a £1M consortium with Birmingham and Cambridge computer scientists. Similarly, a £534k EPSRC grant to Doucet is part of a Multidisciplinary University Research Initiative led by the US Department of Defense, with a total EPSRC contribution of £3.2M.

The significant scientific impact of larger grants is illustrated by Teh's EUR1.9M Consolidator grant, *BigBayes.* Outputs ranged from theoretical underpinnings of Bayesian non-parametrics to applications in natural language processing and genetics. Crucially, it crystallised a large group around Teh, and provided vital support as he shifted his research focus to reflect the rise of deep learning and related methods in ML.

Central to our strategy is supporting researchers at every career stage in pursuing opportunities to develop transformational research programmes. They have held four EPSRC Early Career Fellowships, two EPSRC Established Career Fellowships, eight Royal Society URFs (with a further two secured, not yet started, and four secured but transferred elsewhere), a Dorothy Hodgkin Fellowship, and six Leverhulme Trust Research/Senior Research Fellowships. In addition to around 80 locally-funded independent Research/Visiting Fellowships, we have hosted around 140 independent personal fellowships funded from external sources including: five Royal Society Newton Fellows, 13 EC Marie Curie Fellows, three NSF Postdoctoral Fellows, nine SNSF Mobility Fellows, with the remainder supported by 39 funders from six continents.

There has been a step-change in our engagement with industry, with over 300 industry-funded projects within the UoA compared with 63 in the last REF period. Around one third are ten-week InFoMM student projects, with the remainder dominated by other PGR/PDRA projects. The effectiveness of short projects is reflected in companies' repeated engagement; 18 have funded three or more projects. In order to build engagements with SMEs, we made a direct University investment of £387k towards studentship costs. 24 SMEs have been InFoMM partners, collectively funding 35 ten-week and 17 three-year research projects (total direct commitment: £523k).

We have developed and nurtured long-term partnerships, producing a pipeline of PGRs/PDRAs comfortable working with industry, vital for the sustainability of the discipline and for enabling impact. For example, our blossoming six-year (so far) engagement with Elkem has involved ten staff, supervising nine short projects and six thesis projects, and raised £286k for direct student support and £238k in-kind.

The current five-year research programme of Farmer (Baillie Gifford Professor of Mathematics) is supported by generous philanthropic funding from Baillie Gifford, and through the Institute for New Economic Thinking (INET). Farmer is Director of Complexity Economics for INET-Oxford. His research on financial instability in the wake of the 2008 global financial crisis has been particularly influential, with Farmer providing advice to both the European Central Bank and the Bank of England.

3.2. ORGANISATIONAL INFRASTRUCTURE SUPPORTING LARGE-SCALE PROJECTS

As illustrated below, the infrastructure supporting large projects comes from a variety of sources: (i) our involvement and investment in the Turing, (ii) our own strategic investments within Oxford, (iii) business and research council investment in our research clusters, and (iv) the support underpinning our interdisciplinary research programmes.

(i) The convening power of the Turing is invaluable in stimulating significant new collaborations. For example, the Centre for Topological Data Analysis arose from a 2015 Turing-funded workshop on TDA (organised by Grindrod, Harrington, Tillmann, and Wolfe, (UCL)). A £2.85M Oxford-led EPSRC grant leveraged internal funding to create a permanent post (Nanda) and five

postdocs (two in Oxford) across Oxford, Swansea, and Liverpool. There are currently nine PGRs in the Oxford centre; three more have graduated with theses in computational topology.

(ii) Strategic use of our own resources creates critical mass to support large collaborations. For example, the targeted appointment of Grindrod in data science in 2013 made possible the £5.1M Oxford-Emirates Data Science Lab, with which we supported ten postdoctoral researchers, spanning data science, cryptography, and numerical analysis, who worked half-time on collaborative Emirates' proof-of-concept and translational data science projects and half-time on their own research programmes. Emirates embedded employees in Oxford; one stayed for three years, giving lectures and hosting workshops. The Oxford lab addressed Emirates requirements from developing seat-pricing algorithms to social media analytics for assessing young peoples' views on flying. Building on this investment, we recruited a researcher at the interface with the United Nations Sustainable Development aims, following which we secured GCRF funds for two further researchers.

(iii) Synergistic development of multiple facets of research problems can underpin substantial portfolios of business/research council investments. For example, our fundamental filtration research has been developed to deliver substantial humanitarian and business impact. Funding for filtration and separation science over this period totalled £2.26M, through business sponsorship (£474k: Beko, Dyson, Gore, Pall Corporation, Smart Separations) and others (£1.79M: UKRI, Royal Society, KAUST GRP). This has supported one research fellow, ten PDRAs, three PGRs, five short projects (by PGRs), a workshop, and two web developers. Outputs include novel generalisations of homogenisation theory, with direct application to modelling Dyson's dust filters, and Gore's Mercury Control System (which works to prevent acid rain). The relationship with Dyson illustrates the value of IAA pump-priming support: the original £34k project established a connection with Dyson, laying the groundwork for understanding their filters; the collaboration has continued for over five years, described by Gareth Morris, Research Manager, Dyson Technology Ltd, as *"a shining example of how an industrial/academic relationship should be undertaken to make it as relevant and impactful as possible".*

(iv) Our formal collaborative arrangements support seamless access to specialist infrastructure elsewhere in Oxford. For example, Myers and collaborators revealed the importance of the gene PRDM9 in recombination (a mechanism through which chromosomes pair and swap DNA during reproduction). Errors in recombination are responsible for a wide range of human diseases. In addition to two computational PDRAs, Myers' £1.58M 2018 Wellcome Trust Investigator award supports an experimental PDRA and research assistant, working in specialist laboratories in MSD, to perform experiments to understand how chromosome pairing succeeds/fails depending on how PRDM9 binds. In an early success, this combination of statistics and experiment has revealed the essential role of the protein ZCWPW1 in meiotic double strand break repair, pointing to a possible role in fertility.

3.3. OPERATIONAL AND SCHOLARLY INFRASTRUCTURE SUPPORTING RESEARCH AND IMPACT

Our physical estate, Oxford's exceptional library holdings, and access to outstanding computing facilities provide an exceptional backdrop for research. The new Statistics building has been transformational, especially for PGRs. Cognate groups are accommodated in adjacent offices, clustered around interaction areas, resulting in seamless peer-to-peer learning. The scale and ambition of our PER activities is also underpinned by our new buildings; the Andrew Wiles Building incorporates extensive purpose-built facilities, including a 360-seat lecture theatre and adjacent breakout and exhibition space.

Support staff and events teams look after practical arrangements for incoming/outgoing visits (Section 2.1) as well as the numerous seminars, conferences, workshops, and other events in the buildings. Dedicated administrative support underpins CDT partnerships.

Research Facilitation teams (5 FTE) proactively seek out and promote opportunities for funding, discuss proposals, help respond to reviewers, and organise mock interviews. Proposals over £50k typically undergo internal peer review. Since 2014, we have appointed a dedicated Research Facilitator in Statistics and an additional MI post has deepened support for ECRs. A new MI Research Grants Manager and dedicated resource in Statistics strengthen post-award support for large grants. The University Research Services Office (RSO) provides specialist support for ERC grants. As part of their induction, new researchers meet with research facilitators. Since 2013, there has been a dramatic increase in the numbers of awards to women (Section 2.3); our target now is to increase the value of those awards.

Research and confidentiality contracts are negotiated through the RSO; they have negotiated 77 collaborative contracts (68 with industry) and a further 23 contracts for full research project funding (11 from industry) in period. They have also completed over 200 individual studentship contracts with external organisations.

OUI has supported members of the UoA with 38 new IP disclosures, filed 28 patent applications, and issued 26 commercial licences in period.

A world-class, up-to-date computing environment is essential to much of the research in the UoA. To support the growth in ML research, including two impact case studies, local resources in July 2020 included 11 GPU servers comprising 31 of NVIDIA's latest-generation GPUs and 40 previous-generation GPUs. These are supplemented by over 50 CPU compute servers, all with high-bandwidth links to large filestores. A comprehensive range of software packages is available, including COMSOL Multiphysics, Magma, Maple, Mathematica, Matlab, Python and R, and the GPU systems have the latest ML packages such as TensorFlow, PyTorch, Theano and Caffe. Departmental resources are managed by a team of 11 FTE specialist IT staff.

We also make extensive use of computational facilities across Oxford – at the BDI and WTCHG, and the Advanced Research Computing Facility (ARC; Morris chairs the advisory board) – and commercial cloud providers like AWS. In July 2020, our researchers had over 100 projects running on the ARC, accounting for about 10% of the total. Uses range from a computer-aided drug discovery project to numerical investigation of rank 2 attractor points on Calabi-Yau manifolds.

The Mathematical Observatory is a small experimental facility within the Andrew Wiles Building that supports and challenges modelling work through simple proof-of-concept experiments. For example, experiments on cutting and wrinkling of thin elastic solids showed them changing their 'apparent' Gaussian curvature and supported the development of new mathematical models of wrinkling.

Collaborative use of major facilities

Our researchers make extensive use of UK Biobank, and we benefit from other cross-HEI infrastructure such as the Diamond Light Source (DLS), which is a partner in SABS:R^3. Two OPIG students were funded and co-supervised by the DLS: one used DLS compute servers in developing software that accelerates early-stage drug discovery; the other developed software to perform automated chemical synthesis using robots at DLS. Lyons' group uses the national supercomputer JADE.

Benefits-in-kind and sponsorship

A very significant benefit-in-kind is the access to facilities, data, specialist software, training, and supervision provided to our graduate students, almost a quarter of whom have an industrial supervisor. For example, 86 partners have contributed over £4.9M of in-kind investment to the InFoMM CDT, whilst the £4.69M of in-kind investment committed by 62 partners in the Imperial/Oxford StatML CDT includes annual training camps at Amazon's European Research Headquarters.

Data access agreements are crucial benefits-in-kind. For example, proprietary tick-by-tick market data, data management expertise, and analysis hardware, storage, and licences from LMAX underpins Cartea's research on FX microstructure. Similarly, companies (currently including AstraZeneca, Kymab and Alchemab) share multiple datasets and use of in-house compute resources with OPIG.

Generous sponsorship from XTX Markets supports our Public Lectures and major events like the Florence Nightingale Bicentennial celebrations.

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

4.1. COLLABORATIONS

The vast majority of our activity is collaborative, spanning institutional and/or disciplinary boundaries: 96% of Cat A researchers have an international co-author (from a total of 85 countries) in period. They have presented their research in around 70 countries. We provide support for incoming/outgoing visits (Section 2.1) and Research Facilitation (Section 3.3) supports applications for larger scale networks/collaborations.

Visiting researchers at every career stage hugely enrich our research environment. Some visit groups (e.g. Strang, MIT, visits our numerical analysts annually); others come for intensive collaboration with individuals; e.g. annual visits of Seymour (Princeton) to work with Scott resulted in 36 joint papers in period, and resolved well-known conjectures on graph colouring from the 1980s.

In 2014, we planned further international alliances, building on the successful Oxford-Princeton mathematical finance network. New partnerships include Oxford-ETH, funded by the Swiss Science Foundation (postdoctoral exchanges and joint meetings); the CNRS-funded International Network, ALEA; the Horizon 2020 funded COSTNET collaboration in Statistics of Network Data Science; and we are an organising node of the new Horizon 2020-funded European Network of AI Excellence Centres (ELISE).

Significant advances in mathematical sciences often result from large international networks combining to offer insights from disparate parts of the field. For example, the 14-PI Simons collaboration *Special Holonomy in Geometry, Analysis, and Physics,* led by Bryant (Duke), capitalises on recent breakthroughs related to geometric structures associated with exceptional holonomy spaces, while making use of powerful new tools for analysing singular spaces. The two-stage project brings £1.3M to Oxford. For stage two (funding five postdocs and two students in Oxford), Lotay and Schafer-Nameki join Joyce as PIs.

University initiatives provide the legal and financial structures required to operate at scale with overseas partners. As part of OSCAR (Oxford Suzhou Centre for Advanced Research, the University's first overseas centre for physical sciences research), the OSCAR Institute for Mathematical Modelling and Data Analytics, with initial funding of approximately £2M to support 12 PDRAs and research costs, serves as an umbrella for collaboration with Chinese partners including the Chinese Academy of Science, Fudan University, Shandong University, and the Shanghai Futures Exchange.

Networks – like the UK-wide Applied Algebra and Geometry Research Network, initiated by Harrington in 2017 – link researchers in emerging areas. Members secured a £170k EPSRC GCRF grant (PI Szendrői), out of which grew the Abram Gannibal project, establishing collaborations between UK mathematicians and emerging Sub-Saharan African scientists. This dovetails with AfOx, a cross-University platform for collaborations between Oxford and African researchers. Kremnitzer hosted inaugural AfOx visiting scholar Ssevviiri (coordinator of the Eastern Africa Universities Mathematics Programme). In collaboration with Elsevier, our researchers have demonstrated the value of research collaborations to developing economies.

The Turing has catalysed numerous multi-institution/multi-disciplinary collaborations. For example, when Lyons' ideas around applying rough paths to data science were very tentative, the Turing facilitated an intensive workshop to test the viability of the methods, creating an entirely new research direction. After just four years, Lyons' team won the worldwide Physionet 2019 competition to predict sepsis in intensive care patients, and in July 2020 has five postdocs and two software engineers funded through Turing projects in Data-centric Engineering, Defence and Security, Finance, and Mental Health. In 2019, they secured a £4.1M EPSRC programme grant (Oxford-led, Imperial, UCL) to fund six further postdocs and a software engineer, to create tools to merge this new mathematics with existing data science and apply them to exemplar challenges.

4.2. ENGAGEMENT WITH KEY RESEARCH USERS

More than 25 academics have helped inform government decision making and public policy formulation through engagements with the Home Office, DCMS, BEIS, the Biometrics Commissioner, DEFRA, the Bank of England, MoD, DSTL, GCHQ, and National Security organisations. For example, C Donnelly co-authored a 2019 assessment of the impact of badger culls on levels of tuberculosis in cattle for DEFRA; Windmeijer is on the Technical Advisory Group to the Department of Health; and Farmer advised the Financial Conduct Authority and sat on the expert panel for the 2015 Blackett review *Fin Tech Futures.* In the wake of the Salisbury Novichok incident, we worked with DEFRA on modelling the treatment of chemical spills, requiring us to develop novel theory for the motion of the sharp reactive interface between chemical agent and cleanser.

Further afield, we have advised the World Health Organisation, and the governments of Bermuda, Chile, Sweden, and Tanzania. Our decontamination work has also been presented to government representatives from Canada, Norway, and the USA.

Our submitted researchers have written 166 journal papers with 76 corporate entities in period. Company challenges often call for novel theory; and theory developed in completely different contexts can have unexpected applications. For example, with Siemens Healthcare, Tanner developed new variable density message passing algorithms to make compressed sensing applicable to 3D dynamic multi-coil MRI scans with real time reconstructions, leading the way to reduced patient scan times and on-the-fly rescanning, reducing the need for further appointments. Conversely, motivated by the challenges of coarse-graining models of biological cell motion, Chapman developed new techniques for the homogenisation of dynamical processes on networks, which have since found applications in models of calciner furnaces (with NORCE), and are being extended for oil recovery (with BP).

4.3. WIDER CONTRIBUTIONS TO THE ECONOMY AND SOCIETY

We present a small sample of contributions not highlighted in our impact case studies.

Myers and co-authors developed new approaches to analysing genetic differences between individuals from different geographical locations at extraordinarily fine scales, which they applied to data from the *People of the British Isles* project, revealing many stories about our shared past. The work featured in the eight-month exhibition *Settlers* at Oxford's Museum of Natural History (with over 150,000 in-person and online visitors), a specially-produced animation, an interactive website, and in two bestselling popular science books. Christine Kenneally, author of *The Invisible History of the Human Race*, wrote "*…the work is truly one of the most extraordinary studies I've had the privilege to write about.*"

In healthcare, Holmes is working with researchers in Edinburgh and Durham to deliver a new ML-enabled risk prediction algorithm to GP practices in Scotland. More broadly, he serves on the AI Expert Evaluation Panel for the Accelerating Access Collaborative, established with £140M under the NHS-X AI Lab to deliver technological innovation into the NHS.

P Donnelly (now emeritus) was among the co-founders of Genomics plc, a 2014 spin-out, whose vision is to use genomic insights to transform drug discovery and deployment. It employs over 100 people across three offices.

Since arrival in Oxford, with collaborators at the European Systemic Risk Board and the International Monetary Fund (IMF), Cont has developed new approaches for monitoring and quantifying systemic risk, which the IMF has applied in stress-testing financial institutions in the USA and Switzerland. Most prominently, the methodology has been applied during the COVID-19 crisis to quantify interconnections between various European investors in corporate bonds, and to assess the second round effects if bonds were downgraded by rating companies.

DNA evidence typically comprises a mixture of DNA from multiple individuals. Theoretical work of Lauritzen (now emeritus), and the accompanying software DNAmixtures, allows interpretation of DNA evidence based on complex mixture traces. It has been used to successfully prosecute cases in Denmark and the UK, including four UK murder cases.

Rogers was commissioned by BBC Consumer Affairs programme *Watchdog* to investigate Ryanair's seating algorithm. Her work demonstrated that the 'random' seat allocation for those who had not paid a surcharge to pre-book a seat was biased towards separating groups that booked together. It was instrumental in persuading the CAA to develop a new framework for assessing whether airlines were complying with legal and best practice.

An initiative led by Szendrői, in collaboration with a Kenyan NGO, incorporated a corruption risk methodology into *R-Instat* to empower young African mathematicians to uncover evidence of corruption in big datasets (e.g. procurement data). Workshops were held in Tanzania (2017), Ghana (2018), and Uganda (2018). After the Ghana event, the UK Foreign Office reported "*In some countries this is adding considerably to states' capacity to identify and reduce corruption risks*." The Ghanaian media framed the event as part of a campaign for a 'Right to information' bill.

Amongst our ECRs, IAA funds supported a PDRA to develop a tool to estimate the number of internally-displaced people across 95 countries. An NGO, *The Internal Displacement Monitoring Centre*, has used this to challenge the assumption that disaster displacement is only short-term. In a different direction, in collaboration with the US non-profit organisation *Data for Black Lives* (of which he was co-founder), Titchmarsh Fellow Mason-Brown is working on projects investigating bias against blacks by predictive policing or mortgage underwriting algorithms, and the disproportionate impact of COVID on black minorities.

Through industrial engagements we give companies enhanced understanding of their processes (e.g. our work "*represents a significant step forward in a larger programme of modelling the entire* [coffee] *roasting process*", Jacobs Douwe Egberts), new algorithms (e.g. our work on derivative-free optimisation is now incorporated into NAG's library), and performance improvements (e.g. "*A computational gain of ~8 was achieved for these simulations which typically take a few months to complete*", CCFE).

4.4. ENGAGING WITH DIVERSE COMMUNITIES

As described in Section 1.2, we engage through various media and channels.

Lectures

The Oxford Mathematics Public Lectures (59 in period, 33 by Oxford researchers) showcase the beauty and breadth of research in the mathematical sciences. Lectures have an average of 25,000 views on our social media channels. Stephen Hawking spoke in 2017. Since 2017 we have held an annual London Lecture, followed by a Q&A moderated by Hannah Fry; the 2017 lecturer was Andrew Wiles (150,000 views), 2018 was Roger Penrose. In 2019 Marcus du Sautoy went to the West Midlands, Tim Gowers to London, and Vicky Neale to Newcastle, to

reach areas under represented in our student population. Topics have ranged from Prime Numbers to Machine Learning.

Music

Most models of perception of musical form are based on tonal music. In *Bach and the Cosmos* (Oxford, Cambridge, London, Bristol, 2018), Sparks explained the explicit mathematical framing of Bach's work, and the City of London Sinfonia illustrated with excerpts from the Goldberg Variations. Du Sautoy, in three concerts with the Oxford Philharmonic, focussed on pieces by Bartok, Debussy, and Stravinsky, composers who were pushing the boundaries in their use of mathematical ideas. In 2017, with composer Emily Howard, he founded the centre for Practice and Research in Science and Music (PRiSM) at the Royal Northern College of Music. Their recent research (published in *Frontiers in Psychology*) is a study using the interactive *PRiSM Perception App* (developed in Oxford) of audience perception of segmentation in non-tonal contemporary music.

Art

Mathematical art is an integral part of the Andrew Wiles Building, with visitors entering across a Penrose tiling. A public café and gallery space provide an ideal venue for mathematically-themed art exhibitions such as *Illegitimate Objects,* a 2015 exhibition inspired by mathematical surfaces. In our first online exhibition, one exhibit, *Chaos Cat* (a demonstration of spatio-temporal chaos), attracted 20,000 views on social media.

Books and theatre

Du Sautoy's books *What We Cannot Know* (2016), *How to Count to Infinity* (2017), and *The Creativity Code* (2019), in which he addresses what it is to be creative in mathematics, draw directly on his mathematical research experiences. Numerous performances with *Complicité* of his mathematical play *I is a Strange Loop* (co-authored with Victoria Gould) culminated in a sold-out run at The Pit in the Barbican in 2019.

Online

Our 34 one-minute *What's On Your Mind?* films (over 5,000 views each) provide insight into the mind of an Oxford mathematical scientist. Our websites host 190 Research Case Studies and our researchers contributed to eight podcasts and three videos/animations through the *Oxford Sparks* online science portal.

4.5. RESPONSIVENESS TO NATIONAL AND INTERNATIONAL PRIORITIES AND INITIATIVES

The breadth of our research means that we bring multiple perspectives to national and international priorities. We illustrate with four themes in which we have strategically grown capacity and capability over the last decade:

Medicine and healthcare

Our statistical geneticists played central roles in some of the most important international collaborative projects in human genetics, including the Haplotype Reference Consortium (analysis co-led by Marchini, now at Regeneron), and UK Biobank (analysis led by Marchini and P Donnelly). Analysis of Biobank data promises to improve understanding of prevention, diagnosis, and treatment of a wide range of serious and life-threatening illnesses. Myers has ongoing research into phasing the Genomic England dataset (GEL) as an imputation resource for UK Biobank participants.

Addressing a major need within an ageing society, Holmes leads the Turing analytics team targeting the early detection of neurodegeneration in dementia, while Goriely and collaborators have developed the first full organ model of neurodegeneration spreading in the brain, which predicts how the brain is systematically invaded and infected by diseases such as Alzheimer's or Parkinson's, and how it atrophies during disease evolution. In cancer research, the identification

of a signalling chemical that has since been shown to slow down invading tumour cells is the latest breakthrough by Baker, Maini, and experimental collaborators at the Stowers Institute for Medical Research.

Energy

In response to the UK Government's decision to establish the UK as a world-leader in battery design and manufacture through the Faraday Institution, our battery modelling group – led by Chapman and Please, in collaboration with Oxford Engineering, and supported early in the period by a £450k EPSRC grant – was instrumental in bringing together a collaboration of eight academic institutions to form the Multiscale Modelling Fast Start project. They have created and developed PyBaMM, a versatile open-source software, with 60 active users/developers from 28 academic institutions and ten companies, which enables optimisation of battery performance and reliability.

Solar cells offer a realistic method of generating energy sustainably. A collaboration between Goriely and Snaith (Oxford Physics) on modelling and optimising the production process for solar cells based on perovskite structures led to a US patent (filed in 2014, awarded in 2019) with one joint paper cited over 1,850 times.

Climate

Climate change is one of the most pressing issues of the 21st century, and mathematical models are key to assessing the scale of the problem. Novel optimisation algorithms that reduce the number of computationally-expensive model evaluations underpin Cartis' NERC-funded work with Tett (Edinburgh Geosciences) on parameter estimation for atmosphere and coupled ocean-atmosphere climate models. Related work with Khatiwala (Oxford Earth Sciences) develops new derivative-free Gauss-Newton methods in order to handle the biogeochemical climate model.

To better understand the role of surface meltwater in ice dynamics, and simulate the Greenland ice sheet's response to changes in surface melting expected under IPCC climate-warming scenarios, Hewitt and collaborators at the Lancaster Environment Centre are developing a new, robust, coupled hydrology/ice-sheet model which is thoroughly constrained and tested against new, and dedicated, observations.

Future cities

Sustainable development requires a significant shift in urban management practices. Grindrod is Co-I in the £7.25M (ESRC GCRF) PEAK programme, led by Oxford Anthropology, which uses complex systems framing to synthesise understanding of the development of future cities. Leveraging expertise at Oxford and the Turing, and with partners from China, India, South Africa, and Colombia, the project is growing research capacity and capability to meet the challenges faced by developing countries and promote sustainable urban development.

COVID-19

Researchers at all career stages have been at the forefront of efforts to inform the COVID-19 planning and response decisions of the UK Government and the World Health Organisation. The contribution of C Donnelly is the subject of a case study; Goriely and Maini head the RAMP Rapid Review Group, which scrutinises policy-relevant research literature and routes it through to SPI-M, SAGE, and other parts of Government; Teh is a member of the Royal Society DELVE working group; and Holmes leads the DECOVID programme at the Turing. Our researchers have also contributed to projects including understanding antibody response of individuals in receipt of the Oxford vaccine; developing ML techniques to propose novel molecules for treatments; developing new group testing algorithms; and predicting demand at the Oxford City Food Banks.

4.6. WIDER INFLUENCE, CONTRIBUTIONS, AND RECOGNITION

The prominence of our faculty and emeriti, both as researchers and in significant leadership roles, brings considerable influence, which they use to benefit the whole discipline.

Additional Funding Programme for Mathematical Sciences

Bridson, Keating, and Martin were members of the Review Board for the independent review, *The era of mathematics*, led by OCIAM Visiting Research Fellow Philip Bond. Deane, Giles, and Keating were involved in a subsequent visit to Downing Street and the follow-up work that preceded the Jan 2020 announcement of up to £300M of investment in Mathematical Sciences. Etheridge chairs the EPSRC Advisory Group for the Additional Funding Programme.

Contributions

Contributions to supporting the discipline are taken into account in workload allocation, and, where appropriate, we second staff to partner organisations. We are as flexible as possible. Thus, when Deane took over as Director of the UKRI COVID-19 response, at the request of UKRI we increased her secondment to EPSRC from 60% to 80%. Similarly, we have varied the conditions of Holmes' secondment as Programme Director for Health and Medical Sciences at the Turing to reflect extra demands during the pandemic.

We present a sample of the contributions made by our faculty and emeriti through (i) taking on significant external leadership roles, (ii) journal editorship, (iii) service to (inter)national research councils, and (iv) as members of advisory boards and conference chairs.

(i) Significant external leadership positions

These include: Royal Society (Tillmann, Vice-President; C Donnelly, Kirwan, Tillmann, Council), EPSRC (Deane, Deputy Executive Chair; Etheridge, Council), LMS (Lyons, Keating, President; Tillmann, President Designate; Dancer, Howison, Council), IMA (Breward, Council), RSS (Rogers, Vice-President External Affairs), UK Mathematics Trust (Kirwan, Chair), SIAM (Suli, UKIE Section President), Institute of Mathematical Statistics (IMS) (Etheridge, President; Goldschmidt, Reinert, Council), International Machine Learning Society (Teh, Board), European Academy of Science (Suli, Carrillo, Division Heads Computational and Information Sciences, Mathematics), European Mathematical Society (Carrillo, Applied Mathematics Committee Chair; Bridson, Prize Committee Chair), Societé National de France (Rousseau, Council), CMI (Bridson, President; Wiles, Board), HIMR (Keating, Chair), Fields Medal Committee (Kirwan).

(ii) Journal Editorship

Faculty and emeriti held the position of (co-)Editor-in-Chief for 19 journals: Acta Mathematica Scientia (Chen), Applied Mathematical Finance (Cartea, Hambly), Archive for Rational Mechanics and Analysis (Ball), Bulletin of Mathematical Biology (Maini), Electronic Journal of Combinatorics (Conlon), European Journal of Applied Mathematics (Howison), IMA Journal of Numerical Analysis (Süli), Information and Inference (Tanner), Journal of Computational Finance (Reisinger), Journal of Nonlinear Science (Goriely), Journal of Topology (Tillmann, Lackenby), Mathematical Finance (Cont), Mathematics and Financial Economics (Zhou), Mathematical Proceedings of the Cambridge Philosophical Society (Green), Probability Surveys (Hambly), Proceedings of the Royal Society of Edinburgh Section A (White), Quarterly Journal of Mathematics (Dancer, Szendrői, Lauder), Springer Briefs in Probability and Mathematical Statistics (Reinert), Statistics and Risk Modelling (Cont). In addition, Kim was editor of Springer Monographs in Mathematics.

Our faculty collectively held over 250 other editorial board memberships.

(iii) National/International Research Councils

Nationally, faculty have served on panels for BBSRC, EPSRC, MRC, STFC, and Wellcome, including chairing EPSRC Fellowship, GCRF, International Partnership, Prioritisation, and Programme Grant panels. For the Royal Society, they have served on the Research Professorships, Research Appointment, Dorothy Hodgkin Fellowship, International Exchanges, Wolfson Fellowship, and APEX Award panels.

Internationally, faculty served on panels for ERC (Advanced and Consolidator Grants, Horizon 2020) and for research funders including ANR (France), CIFAR (Canada), DFG (Germany), Fonds National de la Recherche (Luxembourg), Research grants Hong Kong, INRIA (France), Narodowe Centrum Nauki (Poland), NSERC (Canada), and NSF (USA). They also served on the International Evaluation Board for the Chinese Academy of Sciences, and the Hong Kong REF.

(iv) Advisory boards and conference chairs

Faculty have served on Scientific Advisory Boards of 25 international research institutes, including Aspen Center for Physics, the Fields Institute (Toronto), and Mathematisches Forschungsinstitut Oberwolfach; and Szendrői is on the Council of AIMS South Africa.

They have served on numerous international Conference Programme Committees. For example, Tillmann was a member of the Programme Committee for the 2018 ICM, and Etheridge chaired the 2016 World Congress on Probability and Statistics' Scientific Programme Committee.
They have been organisers of long research programmes at the INI (Chen, 2014; Cont, 2014; Drutu, 2017; Tillmann, 2018), MSRI (Drutu, 2016; McGerty, 2014; Szendrői, 2018), and the Mittag-Leffler Institute (Maini, 2018).

Recognition

Fellowships and elected memberships include:

Royal Society (FRS) (Etheridge, Maini, Pila, 2015; Bridson, C Donnelly, du Sautoy, Ekert, 2016; Hrushovski, 2020), Academy of Medical Sciences (C Donnelly, 2015; Maini, 2017), Royal Academy of Engineering (Martin, 2017), German National Academy of Sciences Leopoldina (Tillmann, 2017), Indian National Science Academy (Maini, Foreign Fellow, 2018), European Academy of Science (Ball, Carrillo, Kirwan, 2018; Chen, 2020), Academia Europaea (Pila, 2016; Trefethen, 2019), SIAM (Süli, Zhou, 2016; Cont, 2017; Giles, Goriely, 2018; Carrillo, Chapman, 2019), IMS (Hambly, Reinert, Rousseau, 2015; Etheridge, 2016; Doucet, 2017; Goldschmidt, 2019), American Mathematical Society (Bridson, 2015; Chen, 2017), American Physical Society (Waters, 2019), and Society of Mathematical Biology (Maini, Inaugural Fellow, 2017; Byrne, 2020).

Honours and Prizes awarded to faculty and emeriti include:

State honours were awarded to Kirwan (Damehood 2014), P Donnelly (Knighthood 2019), C Donnelly (CBE 2018), N Woodhouse (CBE 2019), and Etheridge (OBE 2017).

Honorary degrees were awarded to du Sautoy (University of South Wales), Etheridge (Edinburgh), Grindrod (Strathclyde), Hitchin (Warwick), Kirwan (York), Lyons (Waterloo), Neumann (Hull), Trefethen (Fribourg, Stellenbosch), and Wiles (Bristol).

Prizes include: the Abel Prize (Wiles 2016), International Prize in Statistics (Cox 2016), BBVA Foundation Frontiers of Knowledge Award (Cox 2016), Shaw Prize (Hitchin 2016), European Academy of Sciences, Leonardo da Vinci Award (Ball 2018), King Faisal International Prize for Science (Ball 2018), European Mathematical Society Prize (Maynard 2016), SASTRA Ramanujan Prize (Maynard 2014), ICTP Ramanujan Prize (Walsh 2014), Heinz Hopf Prize (Hrushovski 2020), Royal Society Medals (Green, Sylvester Medal 2014; Wiles, Copley Medal 2017), SIAM Prizes (Trefethen, George Polya Prize 2017, John von Neumann Prize 2020;

Martinsson, Germund Dahquist Prize 2017), LMS Whitehead Prizes (Baker 2014, Keevash, Maynard, Porter, Vella 2015, Harrington 2018, Conlon 2019, Mondino 2020), LMS De Morgan Medal (Wiles 2019), LMS Senior Whitehead Prize (Green 2019), LMS Polya Prize (Zilber 2015, Wilkie 2017) LMS Senior Anne Bennett Prize (Etheridge 2017), LMS Naylor Prize (Chapman 2015), LMS Fröhlich Prize (Joyce 2016), Royal Statistical Society Guy Medal in Silver (Doucet 2020), Royal Society Francis Crick Prize Lecture (Myers 2017), Zoological Society of London Frink Medal (C Donnelly 2020), LMS/IMA Christopher Zeeman Medal (du Sautoy 2014), AMS prizes (Maynard, Cole Prize in Number Theory 2020; Bridson, Steele Prize for Exposition 2020), Society for Mathematical Biology prizes (Byrne, Leah Edelstein-Keshet Prize 2019; Maini, Arthur T Winfree Prize 2017), Bernoulli Society Ethel Newbold Prize (Rousseau 2015), University of Cambridge Adams Prize (Harrington 2019; Ardakov 2020), and Philip Leverhulme Prize (Vella 2017).

These noteworthy prizes are typically awarded to more established researchers. We are extremely proud of the external recognition of, and prizes won by, our ECRs. For example, Seigal (Hooke Fellow) won the 2020 SIAM Richard C DiPrima Prize; Panzer (Research Fellow) won the 2020 Hermann Weyl Prize, Xiang (ex-Titchmarsh Fellow) won a 2020 Outstanding Young Scholars Award from the Hong Kong Mathematical Society; and in 2014 while still a Research Fellow, Maynard won the largest ever Erdös prize.

Notable **invited lectures** given by faculty include at the ICM (2014: Ardakov, Brown, Conlon, Green (plenary), Lyons, Pila (plenary), Sanders; 2018: Giles, Haydon, Keevash, Koenigsmann, Maynard, Walsh), and at the 2016 European Congress of Mathematics (Keevash, Maynard).

4.7. COLLABORATIVE ARRANGEMENTS FOR PGR TRAINING

Within the UK, we collaborate with Warwick (OxWaSP CDT) and Imperial (Random Systems and StatML CDTs), and the partners in the TCC and APTS (Section 2.2).

Internationally, the DFG funded Berlin-Oxford International Research Training Grant *Stochastic Analysis in Interaction* funds six-month long reciprocal student research visits and annual summer schools.

Our international presence in graduate education is reflected by the 80 short graduate courses delivered in 22 countries across six continents by our faculty.